THE EFFECTS OF FRICTION ON EARTHQUAKE TRIGGERING AND FAULT ZONE EVOLUTION

A Thesis in
Geosciences
by
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Submitted in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy

August 2007
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ABSTRACT

Variations in frictional fault strength caused by oscillating stresses and slip are analyzed. Laboratory experiments of oscillating shear stress, equivalent to oscillating stresses that trigger seismicity on natural faults, highlight changes to stick-slip instabilities such as clock advance of failure, strength of the fault at failure and pre and coseismic slip. I test both continuous and transient oscillations. Correlation between oscillations and stick-slip events are determined by the timing of dynamic failure with respect to the oscillation phase or by the change in recurrence interval from background rates. The correlation of failure with the shear stress oscillation depends on oscillation frequency and amplitude at low frequencies and predominantly on oscillation amplitude at high frequencies. The frequency boundary between these two regimes is analogous to the inverse of the time needed to displace the frictional critical slip distance.

The role of fault zone architecture in determining a fault’s susceptibility to triggering is also investigated by varying gouge layer thickness (2 - 6 mm) and studying bare granite surfaces. Varying fault zone architecture shows that stick-slip triggering depends on both properties of the transient oscillation, as already noted, and fault zone properties. In these experiments, the load point displacement must be greater than the critical slip distance ($D_c$) in order for triggering to occur. Faults with large $D_c$ creep throughout the interseismic period and the triggering threshold is therefore a function of oscillation amplitude and frequency as well as fault state. Faults with small $D_c$ are locked throughout most of the interseismic period, so that the triggering threshold is not a function of fault state. Frequency can inhibit failure when $D_c$ is achieved as velocity is
increasing and encourages failure if $D_c$ is achieved during velocity reduction. Increasing velocity temporarily strengthens the fault whereas a velocity reduction further weakens and promotes failure.

In addition to laboratory experiments, numerical simulation of strong and weak faults, as well as slip-weakening faults, are compared to determine differences in damage zone patterns. Tensile fractures form along the fault where slip gradients between elements are high. The presence of off-fault fracturing changes fault zone properties, which in turn influence slip patterns and work partitioning in the fault system. The weak and slip-weakening fault systems demonstrate that after seismic radiation and fracture propagation energy are accounted for, excess energy is available for further damage around the fault. This damage is most likely asymmetric and concentrates in areas that have already fractured.
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ACKNOWLEDGEMENTS

I would like to thank my advisor Chris Marone and my special committee member Michele Cooke for all of their help over many years and for making work a lot of fun. Thanks as well to my committee members for insightful advice at different stages of my doctorate. Funding for parts of this dissertation came from a USGS grant to Chris Marone. Finally, I would like to thank my husband, Pratigya, for all of his love and support.
Chapter 1
INTRODUCTION AND BACKGROUND

Frictional fault strength determines myriad aspects of tectonic deformation including: fault slip stability, stress drop during earthquakes, and subsequently generation of seismic waves and heat associated with earthquakes. Friction is the resistance to shear motion along a surface and is determined to the first order by surface roughness. However the second order variations in friction are what determines the stability of crustal faults and is the main focus of this dissertation. Second order friction changes can depend on how long stationary surfaces have been in contact, whether surfaces are in static contact or sliding and the speed of sliding, in addition to conditions such as temperature, humidity, fluids and chemistry. The stability of friction also determines the mode of failure. Surfaces will fail stably if friction increases with slip or velocity. Unstable sliding, where surfaces are locked until the strength of the contacts is overcome and the surfaces then slip faster than the rate at which they are loaded, occurs when friction decreases with slip or velocity. Many interesting questions can be addressed by studying the changes in friction over the course of the interseismic cycle, under variable stress conditions and during unstable slip. Two broad topics are addressed in this thesis:

1. How do periodic variations in stress affect frictional fault stability?
2. How do material properties of the fault zone affect frictional stability and subsequently affect evolution of the fault zone?
I have written my dissertation as a series of manuscripts. This introductory chapter provides some background on each chapter and summarizes how the chapters relate to each other. The second and third chapters report on laboratory experiments. First, I explore the effects of continually oscillating shear stresses (which is a proxy for naturally oscillating stresses on faults such as earthquake waves, earth tides, and seasonal loading) on frictional strength and stability in laboratory sliding experiments. The third chapter focuses further on oscillating stresses, but instead of continuous oscillations, the fault experiences short vibration transients whose effects in terms of timing of failure depend on the interseismic period and the fault zone architecture (granular media vs. bare rock surfaces). Finally, a modeling study compares faults which fail in creep (constant friction coefficient) with faults that slip quasi-statically as a function of a slip-weakening friction criterion and analyzes the effects of friction on the generation of fault gouge and damage zones. The first appendix is a manuscript on which I am the second author and further examines earthquake triggering in a laboratory setting, however acoustic waves are used to simulate seismic waves.

Since the 1992 Landers, California earthquake, the ability of earthquake waves to trigger additional seismicity, sometimes at great distances from the original event, has been recognized [Hill, et al., 1993]. Over the last several years, other natural oscillations in stress within the Earth have also shown correlation with timing of seismicity including tides [Cochran, et al., 2004] and seasonal loading [Heki, 2003]. Although variations in stress within the crust are common, the stress change needed to trigger earthquakes is unknown and may depend on amplitude or frequency of the oscillation, as well as tectonic setting or surface characteristics of faults. Prevailing wisdom on the effects of
oscillating stresses, guided by the rate and state variable friction law, suggest that at high frequencies faults should be less susceptible to triggering because the fault cannot track the increases in stress before stress starts to fall again. Due to this insensitivity, larger amplitude stresses are thought to be required to trigger earthquakes from high frequency oscillations (Figure 1.1; [Scholz, 2003]). Additionally, above a certain critical frequency, which in these experiments is approximately equal to the loading stress divided by the critical slip distance, the stress amplitude threshold should be constant. Earthquake waves, tides and seasonal loading would fall within the high frequency regime for natural faults.

Because of the number of unconstrained parameters in the natural fault setting, I undertook a suite of laboratory experiments to study this problem in more detail. In the second chapter of this thesis, I look in depth at the effects of continuous shear velocity oscillations on the timing, strength and displacement on granular layers. When timing of failure could be correlated to oscillation phase, the failure is considered to be caused by the shear stress variations. I test a variety of amplitude and frequency combinations to map out the correlation thresholds. In addition, various background shearing rates were tested. The results show that the triggering threshold is more complicated than the schematic shown in Figure 1.1. For frequencies lower than the critical frequency but above the frequency of stick-slips, the slope of the threshold suggests a lower threshold amplitude than would be predicted for the low frequency regime. The high frequency threshold appeared fairly constant in two sets of experiments. In the third, the correlation threshold decreased with higher frequencies.
Subsequent experiments using transient oscillations reveal that the high frequency regime is dependent on fault properties and not necessarily independent of frequency.

In the third chapter, I focus solely on high frequency oscillations. Instead of continuous oscillations, these tests were done with short oscillation bursts, which are meant to represent a single seismic waveform, rather than continually oscillating conditions. The wave amplitudes were also larger than in the previous suite of experiments. The main hypothesis tested in this chapter was whether properties of the fault experiencing the oscillation, such as whether fault strength was determined by asperity contacts or by the interactions of grains in a layer, affected the fault’s susceptibility to triggering. The bare surface experiments as well as various thicknesses of granular layers all showed that oscillation frequency affected timing of failure. I found that the relationship between the critical slip distance, which is the amount of displacement needed to renew frictional contacts, and the load point displacement during the transient determined whether high frequency oscillations encouraged or discouraged failure. This suggests that critical slip distance on a natural fault will make that fault susceptible to seismic waves with energy concentrated in specific frequency bands. Because the critical slip distance of a fault evolves as the fault grows, immature faults will be susceptible to different earthquakes than mature faults. One study of triggered events in Long Valley caldera has documented that the faults in that area are sensitive to seismic waves with frequencies less than 0.033 Hz [Brodsky and Prejean, 2005]. These observations could help explain the lack of a universal triggering threshold.

The implications of the third chapter, that faults with different critical slip distances are susceptible to different changes in stress, inspired the work for the final
The development of damage and gouge along a fault alters frictional properties and changes the likelihood of failure (e.g. from oscillating stresses), however little is known about how gouge and damage are generated, whether damage occurs early in the displacement history of the fault, and the proportion of the seismic energy that goes into damage versus radiated in earthquake waves during failure. The work here focuses on numerical simulations of the generation of damage along small faults that are presumably experiencing their initial failure since coalescing from opening mode fractures into a larger shear fracture. We compare the fracture pattern generated from static displacement to that created during unstable failure due to a slip-weakening failure criterion. This analysis could point towards outcrop differences in fracture patterns surrounding exhumed faults and allow some assessment of whether the fault failed seismically or aseismically. In addition, we calculate the energy budget differences between a slip-weakening fault and two static faults with high and low coefficient of friction values to determine how much energy is sunk into the generation of damage and gouge during displacement.

In conclusion, this dissertation uses various tools (experimental friction tests, simple one-dimensional rate and state friction simulations, and more complex two-dimensional numerical models) to answer relevant questions about variations in fault strength through time and the subsequent effects on the evolution of fault zones.
Figure 1.1 The two frequency regimes are demonstrated. The low frequency threshold shows that lower stress amplitudes are required to trigger seismicity at higher frequencies (up to the critical time). At frequencies above the inverse of the critical time, triggering thresholds are independent of frequency. From Scholz [2003].
Chapter 2
EFFECTS OF SHEAR VELOCITY OSCILLATIONS ON STICK-SLIP BEHAVIOR IN LABORATORY EXPERIMENTS

Abstract

We report on laboratory friction experiments in which simulated faults are exposed to shear velocity oscillations at different amplitudes and frequencies. Granular layers are sheared in a servo-controlled biaxial apparatus at constant normal stress and background shear velocity, with a shear velocity sinusoid superimposed. Correlation between oscillations and stick-slip events is determined by the timing of dynamic failure with respect to the oscillation phase. Schuster’s test is used to calculate the statistical likelihood of phase recurrence. We find that correlation of failure with the shear stress oscillation depends on oscillation frequency and amplitude at low frequencies and solely on oscillation amplitude at high frequencies. The frequency boundary between these two regimes is proportional to the inverse of the time needed to displace the frictional critical slip distance. We evaluate changes in failure characteristics, including failure strength, recurrence time between events, creep, and phase of the oscillation at failure, to assess the effects of stressing rate oscillations. Failure occurs at maximum shear stressing rate at low frequencies and lags peak stressing rate in the high frequency regime. Friction at the onset of dynamic failure decreases with increasing frequency. The distribution of events through time depends on the frequency of the shear oscillation; low frequency oscillations produce bimodal distributions and high frequency oscillations produce unimodal distributions. If the transition between the failure regimes depends on the
critical displacement length as our experiments imply, the critical frequency will vary for faults with different gouge layer thicknesses and total displacement.

**Introduction**

Fault zones experience periodic deviations in their stress state at various magnitudes and timescales. These range from long time scale static changes, such as tectonic loading due to interaction with a nearby fault, to transient high-frequency changes such as seismic waves or solid Earth tides [Cochran et al., 2004]. Whereas static stress transfer alters the fault boundary conditions, transient stresses can change material response of the fault zone but do not permanently alter the stress state. Both static and dynamic stress variations induce changes in seismicity rates, however, only transient stresses can trigger remote earthquakes (greater than a few fault lengths from the source). The effects of static stress transfer have been relatively well-studied and are considered in earthquake hazard assessments. In contrast, the effects of transient stress transfer are poorly understood. For example, not all large earthquakes trigger remote seismicity and certain geographic regions seem more susceptible to triggering [Gomberg et al., 1997; Brodsky et al., 2003; Gomberg et al., 2004; Brodsky and Prejean, 2005]. When stresses are periodic, high-frequency oscillations require larger stress amplitudes to induce seismicity than static stress changes [Beeler and Lockner, 2003]. Understanding transient stress effects on fault strength and stability would enhance our knowledge of how earthquakes are triggered.

Dynamic triggering in natural earthquake settings does not seem to depend on the magnitude of the triggering earthquake nor distance from the event, but could be a
function of the oscillating stress frequency [Brodsky and Prejean, 2005] or amplitude [Gomberg and Johnson, 2005; Johnson and Jia, 2005; Felzer and Brodsky, 2006].

Furthermore, the time delay between triggering and the triggered event varies. Triggered earthquakes may be events that were inevitable, such that dynamic triggering merely sped along their occurrence [Gomberg et al., 1997]. Additionally, the time delay between trigger and triggered event may depend on how close the fault was to failure. Simple models for fault zone failure, such as the Coulomb-Amonton failure law, predict that failure occurs instantaneously when the shear stress resolved on the fault exceeds the fault strength, which is independent of rate or time. Therefore, time/stress path dependence of failure due to dynamic stressing is not explained by such models and requires a more complicated context.

Recent studies have shown that large tidal variations can trigger earthquakes. However, both location and type of event seem to dictate whether high or low tides trigger instabilities. For example, Cochran et al. [2004] found a correlation between high tides and thrust earthquakes around the Pacific Rim, especially in areas with larger high tides (and consequently larger loading amplitudes). In contrast, microseismicity on the Juan de Fuca Ridge peaks with low tide [Tolstoy et al., 2002]. Studies of earthquakes in Antarctic glacial till have found that tidally-modulated driving stress at the end of the ice sheet may induce a daily displacement pattern, that is analogous to episodic slipping on a locked fault. The largest tides support the end of the ice sheet and thereby relieve load, such that the lowest shear stress applied to the till layer occurs during high tide. Unstable slip of the ice sheet tends to occur during falling tides, when shear stress on the till layer
is increasing \cite{Bindschadler2003}. Studies of deep moonquakes also suggest a strong tidal influence \cite{Lammlein1977}.

Longer period stress fluctuations may also trigger seismicity. Seasonal groundwater recharge creates a peak in seismicity lagging the spring snowmelt at Mt. Hood by 151 days \cite{Saar2003}. The increase in compression associated with snow load may also induce seismicity. Heki \cite{Heki2003} found an increase in magnitude \( \geq 7.0 \) earthquakes in spring and summer months in regions where there is a winter snow pack that did not exist in regions without significant snow pack.

Past laboratory studies of stress vibrations have focused on normal stress perturbations \cite{Richardson1999, Boettcher2004, Hong2005} or oscillations of principal stresses \cite{Beeler2003}. Normal stress vibrations experienced by a locked fault can cause frictional relaxation during vibrations and greatly increase healing effects after vibrations cease \cite{Richardson1999}. Other studies have shown that high-frequency, large-amplitude vibrations reduce the shear strength of a creeping fault and that intermediate frequencies induce a lag between normal and shear stress peaks, leading to fault destabilization \cite{Boettcher2004}. However, additional work has shown that normal load modulation on a stick-slipping fault can lead to stabilization \cite{Cochard2003}. Beeler and Lockner \cite{Beeler2003} tested the effect of shear and normal stress oscillations on bare granite surfaces and found that two different shear stress responses occurred, depending upon whether the frequency of the oscillation was greater or less than the nucleation time of a stick-slip event. In the low frequency regime, the timing of
instability was influenced by the wave period. Failure in the high frequency regime depended on the amplitude of the oscillations but not the period.

We analyzed shear stress response of a laboratory fault to periodic shear loading rate oscillations. Our experiments are similar to those reported in Lockner and Beeler [1999] and Beeler and Lockner [2003], however we oscillate shear loading rate and maintain a constant normal stress. Additionally, our experiments are conducted on a granular material. A constant shear loading velocity, representing remote stress, was summed with a sinusoidal wave simulating a transient oscillation. We deciphered how these oscillations influenced the material response by varying loading rate, as well as amplitude and frequency of the oscillations. Our laboratory faults experienced stick-slip instabilities analogous to the earthquake cycle both during shear vibrations and under non-oscillating load conditions. We measured changes in the stick-slip cycle such as recurrence interval, failure strength, phase lag and the pre-seismic and coseismic slip to determine how shear oscillations may affect fault stability. Changes in failure strength would eliminate the possibility that instabilities are due to a simple Coulomb-style failure where instability occurs at a constant stress threshold. We also measure recurrence interval, phase lag and slip because these may be measurable quantities on natural faults that could point us to potential examples of earthquake triggering.

**Experimental Technique**

Experiments were conducted using a servo-controlled, biaxial apparatus with a double-direct shear configuration (Figure 1 inset). The samples were loaded in shear displacement servo-feedback with 0.1 µm resolution to achieve a constant displacement
rate of a load point at the top of the center block of the double-direct shear assembly (Figure 1 inset). The load point displacement history consisted of a linear function with a sinusoid superimposed to mimic a tectonic load and oscillating stress. A constant normal stress of 5 MPa was implemented with a servo-controlled load-feedback mechanism (with 0.1 kN resolution); such low normal stresses eliminate comminution of the sample and any associated changes in stick-slip behavior. The stiffness of the vertical loadframe is 5 MN/cm or 250 MPa/cm when expressed as the shear stress on a double direct shear sample with nominal friction contact dimensions of 10 cm x 10 cm. Stiffness of the apparatus and sample assembly is approximately 0.017 MPa/µm, as determined in-situ by measuring shear stress–displacement curves.

We sheared 3-mm thick layers of soda lime glass beads (size distribution 105-149 µm, Mo-Sci Corporation, Rolla, Missouri) at room temperature and humidity. Humidity has been shown to affect the shear strength and recurrence interval of laboratory faults [Frye and Marone, 2002], so we do not make inter-experiment comparisons of strength and recurrence interval. Instead, we only discuss the absolute value of changes in recurrence and failure strength within one experiment, but demonstrate how patterns in the changes with frequency are similar between experiments. Glass beads have material properties similar to quartz and are an ideal substance for these tests due to the repeatability of the magnitude and recurrence interval of stick-slip events. The samples were sheared between steel forcing blocks of size 10 cm x 10 cm x 2 cm (side blocks) and 10 cm x 15 cm x 3 cm (center block) so that a constant nominal contact area of 10 cm x 10 cm was maintained throughout shear. On the surfaces that are in contact with the sample, the steel blocks have triangular grooves 0.8 mm deep and 1 mm in wavelength.
cut perpendicular to the shear direction. These grooves force shear to occur within the sample layer instead of along the boundary. Steel guide plates and tape were attached to the unconfined sides of the sample configuration to hold the blocks together until loaded. Copper shims were attached at the bottom of the sample layers to minimize gouge loss. A latex rubber sheet of 0.01" thickness was taped over the copper shims, also to reduce gouge loss.

The positions of both rams were measured by displacement transducers (DCDTs) throughout each experiment. Using the position of the vertical ram and correcting for the stiffness of the loading apparatus allowed us to determine shear displacement at the gouge layer boundaries and shear strain within the layer. The amount of pre-seismic and co-seismic slip was recorded at each instability. Recording the displacement of the horizontal ram throughout the experiment allowed for reconstruction of the change in gouge thickness both over the course of the entire experiment due to geometric thinning, as well as for dilation and compaction of the sample during the stick-slip cycle.

The amplitude and frequency of the oscillation, as well as background loading rate, were varied to study the material response. Three background loading velocities were used: 5, 10, and 20 µm/s, which correspond to shear stressing rate oscillations of 0.085, 0.17, and 0.34 MPa/s, respectively (given a stiffness of 0.017 MPa/µm). Loading rate oscillation amplitudes ranged from 1 to 20 µm/s, depending on the background loading rate. In the figures herein, we present oscillation amplitudes in terms of shear stress amplitude, determined by integrating over one quarter of the stressing rate oscillation period. We varied mean loading rate and amplitude such that the effective loading rate was always positive and finite shear load was maintained on the sample.
throughout the experiment. Frequencies ranged from 0.01 Hz to 4 Hz. At frequencies above 4 Hz and amplitudes smaller than 1 $\mu$m/s our signal-to-noise ratio was too small to allow accurate measurements of the material response, thus this was our lower limit of amplitude and upper limit of frequencies.

The sample was pre-conditioned at a constant shear velocity for approximately 1 mm of displacement until a steady-state maximum shear stress was reached (Figure 1). Because the glass beads behaved unstably throughout shearing, we used the maximum shear stress to assess whether steady state strength had been reached. After achieving steady state conditions, the sinusoid was added to the computer controlled displacement signal (Figure 2A). The sinusoid signal remained at a constant amplitude and frequency for 2 mm of displacement, which was the approximate displacement needed to induce more than 20 stick-slip instabilities.

**Results**

The timing of the shear stress response, i.e. stick-slip instabilities, was measured in terms of the phase angle relative to the stressing rate sinusoid (Figure 2B and 2C). We define the peak in stressing rate as the zero phase of the oscillation. The phase angles at each failure time are tested for statistical similarity, which we call a correlation with the shear oscillation. Correlation between the oscillations and the stick-slip events was measured using a Schuster, or random walk test [Rydelek and Hass, 1994]. We test the probability that a series of events occurred non-randomly by treating each event as a step of unit length. Starting at the origin of a circle, each step is placed head to tail at the phase angle in which the event occurred in the oscillation (Figure 3A). If each event
occurred at a similar angle, the distance from the origin to the end of the walk, D, will be statistically significant. If the series of instabilities occur at random phases of the oscillation, the walk will end near the origin. The probability that a distance is random is described by:

$$ P = \exp \left( -\frac{D^2}{N} \right) $$

where $N$ is the number of events in the data set. We express non-randomness as a correlation percent, $(1-P) \times 100\%$. Values above 99.5% correlation are deemed strongly correlated. Figure 3B shows the same dataset as Figure 3A as histograms to illustrate how events are more distributed over the entire sinusoid when events are uncorrelated.

We find that correlation between stress oscillation and instability depends on both the amplitude and frequency of the oscillations (Figure 4). Oscillation amplitudes are presented here as shear stress values for comparison to similar studies of the correlation threshold [Lockner and Beeler, 1999; Beeler and Lockner, 2003]. The prescribed loading rate oscillation was recalculated as a shear stress oscillation by using the system stiffness (apparatus plus the sample; 0.017 MPa/µm) to compute a stressing rate and then integrating the stressing rate to obtain a shear stress. For example, a 1 Hz oscillation of velocity amplitude 10 µm/s is equivalent to a 0.17 MPa/s stressing rate amplitude and a 0.027 MPa stress amplitude. Points that experienced the same stressing rate amplitude lie on lines of constant slope (see dashed lines in Figure 4A). The correlation boundary was well-constrained for most of the data. Some points varied around the 99.5% threshold and are called “undecided” points (diamonds in Figure 4).
Correlation Threshold

We found that the correlation threshold exhibits two frequency regimes with respect to the stress amplitude perturbation required to produce correlation (Figure 4). In the low frequency regime, the correlation threshold is frequency dependent, and has a negative slope (-0.07, -0.22 and –0.37 MPa-s for background stressing rates of 0.085, 0.17 and 0.34 MPa/s respectively), such that

\[ \log A = m \log \omega \]  

where \( A \) is amplitude and \( \omega \) is frequency. The boundaries separating correlated and uncorrelated conditions in Figure 4 were determined by eye. In most cases, the placement of the thresholds was well constrained (Figure 4); however for our largest background stressing rate (Figure 4C) the (apparent) transition occurs near our upper limit of well constrained oscillations, and therefore is less well constrained.

The stress perturbation needed to overcome the correlation threshold is larger at lower frequencies and decreases towards higher frequencies before leveling off in a high frequency regime. For high frequencies, we find that changes in stress must exceed a minimum amplitude in order to induce a correlation between stick-slip instability and loading rate oscillation and that the correlation threshold is frequency independent (Figure 4). Both of these correlation regimes were observed for our two slower loading rates (Figure 4A & 4B), however the high frequency threshold is not well constrained at the fastest background loading rate (Figure 4C). At low frequencies, the amplitude of the correlation threshold was directly proportional to the background loading rate. This means that for higher loading rates, a larger stress amplitude was needed to achieve correlation conditions. However, the correlation threshold in the high frequency regime
did not change systematically with loading rate (Figure 4). This may mean that the threshold is constant (approximately 0.01 MPa) and/or that it varies at a level below the signal to noise ratio in our experiments.

The cross-over time, or inversely the critical frequency $f_c$, is the frequency at which the correlation threshold changes from frequency-dependent to frequency-independent. We determined $f_c$ by estimating where these thresholds intersected in Figure 4 (0.22, 0.55, and 2 Hz for 0.085, 0.17, and 0.34 MPa/s stressing rates, respectively).

The correlated points in Figure 4 represent instabilities that have been triggered by the stress oscillations. In the following sections, we look for changes in the seismicity pattern caused by the frequency and amplitude of the oscillations at the correlated points.

**Recurrence Interval**

In correlated experiments shown in Figure 4, the timing of stick-slips occurs at a specific phase angle, thereby altering the natural recurrence interval between stick-slip events compared to a non-oscillating loading rate. Recurrence interval was measured from the beginning of an instability to the beginning of the next instability (Figure 2). The recurrence interval for a non-oscillating load was calculated and averaged for each background loading rate and expressed as a frequency ($f_0$). The value of $f_0$ varied slightly between experiments conducted at the same loading rate (see value of $f_0$ between the two columns in Figure 5). We find an evolution of the recurrence interval pattern from low to high frequencies. For frequencies below the threshold $f_0$ recurrence interval is bimodal
whereas above \( f_0 \), stick-slip exhibits a unimodal recurrence interval. This pattern can be seen for all three background loading rates (Figure 5).

In the low frequency regime, the bimodal distribution of recurrence intervals is caused by the clustering of instabilities around loading rate peaks (Figure 6). Most of the instabilities are close together in time and occur at or near the loading rate peak. The second group of longer recurrence intervals is the result of shear velocity falling to zero in the trough of the stressing rate oscillation, which causes instabilities to cease. After velocity begins to increase, instabilities resume. The mean of this group of longer recurrence intervals generally decreases as the vibration frequency decreases (Figure 5), until the vibration frequency becomes higher than \( f_0 \). The recurrence interval stays generally constant under high frequency oscillations (Figure 5), however they must be slightly perturbed in order to correlate with the oscillation.

**Instability Phase**

We calculate the mean phase shift of dynamic failure from the maximum stressing rate for correlated points (Figure 2). The lower frequency oscillations (below \( f_c \)) produce stick-slips with an average phase of zero, with a possible trend towards negative numbers at frequencies lower than \( f_0 \) (Figure 7). The most negative phase shift coincides with oscillation frequencies just below \( f_0 \) (0.05 Hz, 0.1 Hz, and 1 Hz for background loading rates 0.085 MPa/s, 0.17 MPa/s, and 0.34 MPa/s respectively). The higher frequency oscillations (above \( f_c \)) force stick-slips to occur after the stressing rate peak (between around 33°-44°) for all background stressing rates. Oscillation amplitude (when frequency is held constant) does not produce a consistent phase shift. For instance, at 2
Hz, the smallest amplitude oscillations create the largest phase shift, the intermediate amplitude creates the smallest phase shift and the largest amplitude creates an intermediate phase shift (Figure 7C).

**Friction at Failure**

For experiments in which stick slip was correlated with stressing rate oscillations, the maximum friction value at dynamic failure varied as a function of the amplitude and frequency of the shear stressing rate oscillation (Figure 8). Primarily, frictional failure strength decreases with increasing frequency below $f_0$ and is relatively constant above $f_0$. The amount of weakening that occurred was greatest at the fastest background loading rate (Figure 8C) however, the amount of weakening is not linearly dependent on loading rate. Slight deviations from the weakening rate include an increase in the weakening effect at frequencies just below $f_0$ (at 0.02 Hz, 0.05 Hz and 0.1 Hz for background loading rates 0.085 MPa/s, 0.17 MPa/s and 0.34 MPa/s respectively) and a strengthening effect that occurs at frequencies higher than $f_0$ and at or near the critical frequency ($f_c$) and fall above the solid line showing the trend of friction at failure. The weakening effect loosely coincides with the frequency that exhibits the anomalously shorter recurrence interval (Figure 5).

**Preseismic and Coseismic Slip**

Preseismic slip, or creep, was measured as the shear displacement that occurred between unstable slip events (during the dilational phase of the stick-slip cycle), whereas
coseismic slip was defined as the amount of dynamic slip during stick-slip stress drops (Figure 2D). The pattern of coseismic slip follows that for preseismic (Figure 9). The fastest background loading rate demonstrated the most preseismic slip however there is little variation between the amounts of slip at the lower background loading rates. Coseismic slip does not vary with background loading rate. Like the recurrence interval pattern, the preseismic slip varies widely at the lower frequencies. Recurrence interval and preseismic slip covary because as time between events increases, so will the length of time the layer is creeping. The failure strength, as well, is negatively correlated with slip. Where preseismic slip is greater, the failure strength decreases (as we see in frequencies less than \( f_0 \)) because the failure strength depends on age of grain contacts. However, the amount of preseismic slip measured in our experiments is more significant than any preseismic slip before before a natural earthquake (which indeed may not be measurable). This indicates that the fault weakening we see at frequencies below \( f_0 \) may not occur in nature.

**Discussion**

**Correlation Threshold**

We find that stick-slip instabilities correlate with shear loading rate oscillations, possibly in two regimes; one regime in which the correlation is determined by both the amplitude and frequency of the oscillation and a second where only the amplitude of the oscillation affects correlation. Simple triggering by static stress changes (such as the Coulomb failure model) cannot explain the two regimes. We plot the correlation
boundary predicted by the Coulomb failure model (dashed lines in Figure 10). The assumptions made in the Coulomb model include fault shear strength of 2.2 MPa and a stress drop of 0.6 MPa when the failure threshold is reached. Both of these values are averages determined from our data (Figure 1). The Coulomb threshold follows a constant stressing rate amplitude because events are triggered more quickly as stressing rate increases and the failure threshold is reached more often. This boundary underpredicts the correlation threshold in the low frequency regime, however the slope of the boundary is consistent with the slope of the correlation threshold for our laboratory data (Figure 10). Figures 10A & 10B show that the threshold is overpredicted between $f_0$ and $f_c$. The high frequency regime does not follow the slope of the Coulomb threshold except perhaps in Figure 10C where the high frequency threshold is not well established. Figures 10A &10B show that the high frequency threshold requires larger stress amplitudes than predicted by the Coulomb failure model. However, even if a frequency-independent high-frequency threshold is not well established, the data show breaks in the slope so that a linear threshold cannot fit the data.

To explore the possible implications of our observations for triggering by dynamic stresses, we make use of Dieterich’s theory of seismicity rate changes after an earthquake [Dieterich, 1994]. Dieterich [1987, 1994] proposed that the increase in seismicity rates following an earthquake generally decays to background seismicity rates over a relaxation time, $t_a$, determined by:

$$t_a = \frac{a \sigma}{\tau_r} \quad (3)$$

where $\sigma$ is normal stress on the fault, $\tau_r$ is the reference shear stressing rate and $a$ is the rate-state friction parameter, which is proportional to the direct change in friction
following a step change in loading rate. Subsequent studies have suggested the relaxation
time is analogous to the inverse of the critical frequency [Beeler and Lockner, 2003].
The friction parameter $a$ for our experiments, obtained through an iterative, least-squares
inversion of the frictional response to a velocity step, was determined to be
approximately 0.008 for glass beads. This inversion was performed on several velocity
steps in an experiment run at low normal stress to create stable sliding. Our laboratory-
derived value of $a$ yields predicted critical frequencies of 2.1, 4.3, 8.5 Hz for the three
loading rates used in our experiments. This means that Equation 3 overestimates our
values of the critical frequency (Figure 10) at all loading rates. Dieterich’s formulation
of seismicity rate change simplifies laboratory rate and state friction laws [Dieterich,
1979]. In the seismicity rate formulation, friction evolution is not dependent on the
critical slip distance whereas in the original rate and state friction equations, the steady-
state state variable (average contact lifetime) is determined by slip velocity and the
critical slip distance. We propose that the steady-state state variable may be analogous to
the inverse of the critical frequency so that:

$$f_c = \frac{V_{lp}}{D_c}$$  \hspace{1cm} (4)

where $V_{lp}$ is the load point velocity (equal to slip velocity at steady-state) and $D_c$ is the
critical displacement needed for friction evolution according to rate and state friction
laws. The value of $D_c$ for glass beads was also calculated by an inversion of the frictional
response to a velocity step and was found to be approximately 12 µm, which is similar to
critical friction distances for granular materials [Mair and Marone, 1999]. Equation 4 is
similar to the inverse of the critical period discussed by Perfettini et al. (2001) and
predicts critical frequencies of 0.4, 0.83, and 1.67 Hz for 0.085, 0.17, and 0.34 MPa/s
stressing rates (Figure 10). Although these values are not precise, our critical frequencies were determined by eye and some variability is acceptable. As can be seen in Figure 10, the critical frequencies predicted by Equation 4 are always closer to those measured in the lab than those predicted by Equation 3.

**Change in Recurrence Intervals and Phase Lag with Frequency**

The dependence of recurrence interval and phase lag on the frequency of stressing rate variations is a potentially measurable quantity with seismic data. We model the recurrence and phase lag of stick-slips using both the Coulomb failure law and the Dieterich rate and state friction law [Marone, 1998] where the constitutive friction law formulation is:

\[
\mu = \mu_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{D_c} \right) \tag{5}
\]

\[
\frac{d\theta}{dt} = 1 - \frac{V \theta}{D_c} \tag{6}
\]

where \(\mu_0\) is the reference friction value, \(V_0\) is the reference sliding velocity, \(V\) is the fault slip rate, \(D_c\) is the critical slip distance needed to renew fault contacts, \(\theta\) is the state variable and \(a\) and \(b\) are empirically derived constants. We ran a simple spring-slider block forward model using the parameters described above, a value of 0.05 for the friction parameter \(b\) and a stiffness of 0.0175 MPa/\(\mu\)m. We describe the elastic interaction between our sample and testing apparatus as:

\[
\frac{d\mu}{dt} = k(V_{lp} - V) \tag{7}
\]

where \(k\) is stiffness divided by normal stress. In the rate and state model, we determine slip to be unstable when the sliding velocity exceeds 110% of the load point velocity...
whereas the Coulomb model fails when shear stress levels exceed a constant shear strength threshold. As in our experiments, we define recurrence interval as the time between the beginning of one instability and the beginning of the next. Phase lag is the phase of the oscillation in which the instability occurs, with the maximum stressing rate at zero phase.

Both models mimic the recurrence rates seen in our experiments (Figure 11). This result is not surprising at low frequencies where the changes in the stress perturbations are slow enough that surfaces have enough time to evolve to a new friction level before loading rate starts decreasing. The two laws should differ at high frequencies where evolution of frictional strength lags the changes in stressing rate, thereby damping the response to the oscillations (and creating the frequency-independent high-frequency threshold seen in our experiments), however the resultant change in recurrence time is small enough that the recurrences predicted by the two laws become indistinguishable from one another and from the average recurrence for a non-oscillating system (as they do in the lab experiments as well).

We also compare phase lags predicted by a Coulomb failure law and a rate and state friction law to our experimental data (Figure 12). The Coulomb model consistently fails near the maximum stressing rate (zero phase) at all frequencies. In this case, the rate and state friction law better fits our dataset which shows a positive shift in phase lag at frequencies higher than $f_c$. However, this positive phase shift is only approximately $30^\circ$ rather than the $90^\circ$ phase shift seen in previous lab experiments [Beeler and Lockner, 2003] and studies of seismicity and solid Earth tides [Cochran et al., 2004].
Granular force chains

Although we do not observe force chains directly, their importance in granular mechanics is sufficiently well established that we propose the following interpretation of our results. We posit that force chain mechanics coupled with adhesive frictional contact mechanics produce three regimes in terms of loading oscillation frequency. The high frequency regime \( f > f_c \) is defined in terms of the correlation threshold as described above. The low frequency regime \( f < f_0 \) is bounded by \( f_0 \), which represents the inverse of recurrence time between stick-slip events in a non-oscillating system. This is the length of time needed to create and subsequently break force chains at a given background loading rate. Previous work shows that recurrence time increases with shear layer thickness and implies that \( 1/f_0 \) increases with the number of particles in a force chain [Anthony and Marone, 2005]. We propose that at oscillation frequencies lower than \( f_0 \), force chains form, buckle, and break much the same way they would in a non-oscillating system; however, the failure strength decreases with increasing frequency. If we consider a given stick-slip cycle, our hypothesis is that shear load oscillations bend force chains, but only transiently, because shearing ceases before chains fail. However, successive oscillations progressively weaken the chains, such that failure occurs at a lower friction level compared to non-oscillating systems, as we observe (Figure 8). This weakening in failure strength may be reflected in the fact that the correlation threshold at low frequencies has a greater negative slope than the Coulomb failure law predicts. At frequencies higher than \( f_0 \) the oscillation period is shorter than the time needed to shear a force chain by the effective critical slip distance for a granular layer, which is proportional to the contact critical slip distance scaled by the number of contacts in the
chain [Marone and Kilgore, 1993; Marone, 1998]. This indicates that incremental contact weakening by shear oscillations, which at lower frequencies was effective in disrupting adhesive frictional aging, becomes negligible, and failure strength becomes independent of frequency, as our data for the two lower background shearing rates show (Figure 8). The effect is clearest at the intermediate background shearing rate. At the highest background loading rate, the 0.34 MPa/s oscillations show a tendency to flatten out in the range 0.2-1 Hz, however, yield strength continues to decrease for higher oscillation frequencies in one experiment. This may be related to larger-scale particle rearrangement and effects that are not represented by rate/state friction theory.

Our model also supports an explanation for the preseismic slip data (Figure 9). For frequencies below $f_0$, oscillation-induced disruption of contact aging causes increasing inelastic (preseismic) slip with increasing frequency. This is consistent with a model in which creep accumulates with each load oscillation and force chains fail via progressive creep prior to unstable buckling. The trend of increasing preseismic creep with increasing frequency up to $f_0$ is observed at each background loading rate and indicates that force chains are made less brittle by loading oscillations (Figure 9). For frequencies above $f_0$, preseismic slip becomes constant for our two lowest loading rates, consistent with the observation of constant yield stress in this regime. For our highest background loading rate, preseismic slip decreases for $f > f_0$. This observation may be related to the continued reduction in yield stress in that case. The positive correlation between preseismic slip and coseismic slip is consistent with the work of Anthony and Marone [2005]. In summary, the two important frequencies in our model, $f_c$ and $f_0$,
reflect the time necessary to slip the frictional critical slip distance for a single contact junction and that which corresponds to the force chain as a whole.

**Tectonic Implications**

The important parameters that need to be scaled up to tectonic faults are the critical frequency and the critical displacement length. Our equation for critical frequency (Equation 4) implies that the nucleation time is approximately 3 years for a fault with a tectonic plate rate of 30 mm/year (such as the San Andreas) and critical displacement length of 10 mm [Marone and Kilgore, 1993]. Previous calculations have estimated the crossover time for tectonic faults to be in the range of approximately one year [Toda et al., 2002] to 18.2 years [Beeler and Lockner, 2003]. This implies that seasonal loading, Earth tidal stresses and earthquake waves would be in the high frequency regime. Timing of failure in this regime is controlled by rate and state friction, i.e. a small non-dynamic displacement must occur before unstable slip occurs, explaining why unstable slip is delayed relative to the maximum stressing rate. Plots of earthquake occurrence over the tidal period show that the maximum number of events occurs at the peak tidal stress [Cochran et al., 2004], as predicted by rate and state laws. Toda et al. [2002] suggested that the stressing rate near a tectonically active area (e.g. dike intrusions) would have a shorter crossover time (on the order of hours) which would make the tidal frequency in active seismic areas near the critical frequency or in the low frequency regime. We should note that our shear velocity experiments do not simulate a seismic wave but represents the small shear velocity that would be resolved across a fault as the wave impinged and caused different displacement rates on different sides of the fault.
The critical displacement $D_c$ depends not only on asperity contacts but also on gouge zone width and/or shear localization width and thus will vary with net fault offset and shear strain. Laboratory experiments have shown that the critical displacement decreases with an increase in shear strain as strain localizes into thinner bands of deformation [Marone and Kilgore, 1993]. This implies that faults with a thick gouge layer and low shear strain would have larger $D_c$ and therefore a lower critical frequency than faults with thinner gouge layers and less shear strain. Additionally, the correlation threshold for tectonic faults may depend on the degree of gouge formation and the interaction of grains within that gouge layer. Faults lacking a gouge layer or with a highly developed gouge layer (with discrete shear bands) may be less sensitive to high frequency oscillations because of the absence or diffusiveness of force chains. However, in less consolidated material high frequency oscillations should trigger earthquakes at smaller stress amplitudes than expected.

**Conclusions**

Shear loading rate experiments show that amplitude and frequency of shear stress oscillations determine whether instabilities are triggered. Two regimes of failure are documented: a low frequency regime where the correlation condition depends on both amplitude and frequency of the shear oscillation and a high frequency regime where the correlation condition was frequency independent. The phase lag of failure with respect to the stressing rate curve, the frictional strength and the recurrence time between events are all influenced by frequency of the oscillation. Some aspects of our data, such as
recurrence patterns, can be explained by simple failure laws, whereas aspects such as phase lag suggest more complicated behavior. Two important frequencies in determining changes in failure characteristics are the inverse of the time needed to break force chains and the time needed to renew grain-grain contacts.
Figure 2.1. Time series of shear stress measured over one experiment. Rapid drops in stress are stick-slip instabilities. On shorter time scales (insets), changes to the stick-slip cycle can be identified between the high and low oscillation frequency sections of the experiment, as well as their consistency under constant load. Lower right inset shows double-direct shear geometry.
Figure 2.2. Illustration of key experimental parameters and boundary conditions for loading. (A) A constant load point displacement of 5 μm/s (shear stress rate of 0.085 MPa/s) was prescribed and an oscillation of 0.085 MPa/s was superimposed. (B) Phase lag is defined as the difference between the peak in the shear velocity curve (zero phase) and the oscillation phase at the time of failure. Instabilities occurring after the peak have a positive phase shift whereas failure prior to the peak is defined as a negative shift. (C) Shear stress at failure is the shear stress value at the onset of dynamic failure and recurrence interval is the time between successive stick-slip events. (D) The creep that occurs between stick-slips is referred to as preseismic slip and the displacement that occurs during dynamic failure is called coseismic slip.
Figure 2.3. Correlation between instabilities and loading rate oscillations for experiments with a constant frequency of 0.05 Hz was determined using Schuster’s test (A). Correlated series walked out a distance greater than the radius of the 99.5% probability circle (the experiment with a 0.34 MPa/s shear loading rate oscillation amplitude), while uncorrelated series did not walk far from the origin. The scalloped pattern of the walk (seen most clearly in the 0.34 MPa/s data) is characteristic of low frequency experiments (where the wavelength of the “scallop” is determined by the period of the stressing rate). The histograms in (B) demonstrate the relationship between stick-slip frequency and loading rate (sinusoid) for the data shown in (A).
**Figure 2.4.** Correlation thresholds for three loading rates. At low frequencies, increasing the background loading rate required larger shear amplitudes to produce consistent correlation. Generally, doubling the background loading rate required a ~2.5 fold change in amplitude to achieve correlation. At high frequencies, the threshold boundary did not vary systematically with stressing rate amplitude. The minimum shear amplitude needed for correlation at high frequencies varied between ~0.04-0.1 MPa. The critical frequency, $f_c$, is positively correlated with shear loading rate.
Figure 2.5. Stick-slip recurrence interval for correlated points in Figure 4. Two experiments are shown for each loading rate to demonstrate repeatability. The frequencies $f_0$ and $f_c$, which represent the seismicity rate of a non-oscillating experiment and the critical frequency, respectively, are shown for each background loading rate. Solid black lines highlighting trends in recurrence intervals are estimated by eye.
Figure 2.6. Two examples of correlated response to (A) low frequency and (B) high frequency oscillations. (A) shows a 0.01 Hz stressing rate oscillation where most instabilities cluster around the peak stressing rate. (B) shows a 1Hz stressing rate oscillation where shear instabilities occur after the stressing rate maximum.
Figure 2.7. Instability phase shift for correlated points in Figure 4. As in Figure 5, two experiments are plotted for each background loading rate. The mean phase shift for all stick-slips at a given frequency is plotted with error bars representing ± one standard deviation. A positive shift in phase is seen at \( f_c \). Solid black lines highlighting trends in recurrence intervals are estimated by eye.
Figure 2.8. Friction at failure for correlated points in Figure 4. Failure strength decreases with frequency for $f < f_0$ for each background loading rate. Above $f_0$, frictional failure values are constant or in one case decrease (p707). Frictional strength is independent of loading rate oscillation amplitude for the range of conditions studied. Error bars represent one standard deviation. Solid black lines highlighting trends in recurrence intervals are estimated by eye.
**Figure 2.9.** Changes in creep and co-seismic slip with varying frequency. Creep is shown with open symbols whereas co-seismic slip is represented with black symbols. Each row represents a background loading rate (with two experiments in each row to demonstrate repeatability). Preseismic slip and coseismic slip tend to covary but the variation in displacement for coseismic slip is smaller. Solid black lines highlighting trends in recurrence intervals are estimated by eye.
Figure 2.10. Correlation data shown in Figure 4 with correlation threshold predicted the Coulomb failure model (dashed line) and critical frequencies predicted by Equations 3 & 4.
Figure 2.11. The dependence of recurrence intervals on stressing rate frequency from (A) the laboratory and predicted by (B) the Coulomb failure criterion and (C) the rate and state friction equations. The gap in low frequency data points in (C) represents conditions in which the model becomes unstable. Stressing rate is 0.085 MPa/s in all plots. All point on the plot represent amplitude and frequency combinations that produce failure times correlating with the oscillating stress with 95% confidence.
Figure 2.12. The dependence of phase lag on stressing rate frequency from (A) the laboratory and predicted by (B) the Coulomb failure criterion and (C) the rate and state friction equations. All points in (B) and (C) represent the same model conditions as those in Figure 11.
## Tables

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**Table 2.1** List of Experiments
Chapter 3

THE POTENTIAL FOR EARTHQUAKE TRIGGERING FROM TRANSIENT DEFORMATIONS

Abstract

We report on laboratory friction experiments in which stick-slipping shear surfaces are subject to transient stressing to simulate earthquake triggering by seismic waves. Granular layers and bare granite surfaces were sheared in a servo-controlled deformation apparatus in double direct shear. The seismic waves from a triggering earthquake and tectonic load were simulated by superimposing a transient shear load sinusoid on a constant shear loading rate. We analyze the dependence of triggered stick-slip failure on amplitude and frequency of dynamic stressing and on fault zone state and architecture. Fault zone architecture was evaluated by varying gouge layer thickness (2 - 6 mm) and studying bare granite surfaces. We use glass beads to simulate granular fault gouge because they exhibit highly-reproducible stick-slip and similar behavior to quartzofeldspathic rocks. Faults that are sheared at constant loading rate fail with a consistent recurrence interval. We compare these to the recurrence times for faults under transient load conditions.

Our results imply that earthquake triggering depends on both the amplitude and frequency of the transient deformation, as well as properties of the fault zone. In our experiments, the load point displacement must be greater than the critical slip distance \(D_c\) in order for triggering to occur. Larger amplitude stresses correlate with decreasing
recurrence intervals on granular layers. Granite surfaces are locked throughout most of the interseismic period, so that the triggering threshold is not a function of fault stress state. Faults with granular layers also tend to have shorter recurrence rates at higher frequency whereas the recurrence intervals of granite surfaces are lengthened or unaffected by high frequency oscillations. High frequencies can inhibit failure when $D_c$ is achieved as velocity is increasing and encourages failure if $D_c$ is achieved during velocity reduction. Increasing velocity temporarily strengthens the fault whereas a velocity reduction further weakens and promotes failure. Such behavior is predicted by the rate and state friction laws. Our results may explain the variation seen in triggering thresholds between different geographic locations. One of the most important implications of this study is that the high frequency threshold (failure threshold for oscillations higher than the critical frequency) may not be constant, as has been previously proposed.

**Introduction**

Earthquake triggering from the passage of seismic waves has been shown to be a ubiquitous process, occurring in both the far field [Hill, et al., 1993; Kilb, et al., 2000; Gomberg, et al., 2001; Husen, et al., 2004; Prejean, et al., 2004; West, et al., 2005] as well as close to the source of the triggering event [Gomberg, et al., 2003; Felzer and Brodsky, 2006]. Dynamic triggering can occur as the wave train passes [Gomberg, et al., 2004], or for days and weeks after the triggering event [Brodsky, 2006]. Earthquakes can be triggered at active plate boundaries or in seismically stable environments [Hough, et al., 2003; Gomberg, et al., 2004].
Despite well-documented occurrence of earthquake triggering, our understanding of triggering thresholds is incomplete. The maximum amplitude of the seismic waves has been proposed as a likely threshold for triggering [Gomberg and Johnson, 2005; Johnson and Jia, 2005]. Gomberg et al. [2004] demonstrated that earthquake triggering from the Denali earthquake followed the direction of rupture and therefore the path with greatest wave amplitude. However, if a seismic wave amplitude threshold exists, it varies between faults and/or geographic locations [Brodsky, et al., 2000; Gomberg and Davis, 1996]. Indeed, Harrington and Brodsky [Harrington and Brodsky, 2006] found that earthquakes were not triggered in Japan by seismic waves with amplitudes similar to triggering events elsewhere. An alternate hypothesis is that frequency of the triggering event determines the threshold. One study of triggered seismicity at Long Valley Caldera found that triggering required low frequency energy [Brodsky and Prejean, 2005], however others indicate that high frequencies are more likely to trigger seismicity [Gomberg and Davis, 1996].

Existing field observations and friction theory indicate that triggering almost certainly depends on a fault’s stress state, i.e. how close the fault is to failure when the transient deformation occurs, which in turn depends on the time since the last major earthquake on that fault and the tectonic loading rate. Once a fault fails in an earthquake, healing or strengthening processes begin while at the same time slowly applied tectonic forces stress the fault. As it is stressed, the nature of the fault zone also evolves, but eventually the accumulating stresses and creep strain will again produce the failure condition and an earthquake recurs. Although studies have shown that faults are more likely to be dynamically triggered when the fault is closer to failure (i.e. has been stressed
by tectonic loading for a longer time) [Gomberg, et al., 1997], this does not imply that the transient stresses have simply caused the fault to reach its failure strength; instead the failure strength is altered by the change in stressing rate associated with the seismic wave. Faults may not be susceptible to dynamic triggers unless the fault has reached a state of critical stress in its interseismic period.

In addition to properties of the seismic wave and fault state, fault zone architecture (i.e. the presence or absence of a gouge layer) may influence a fault’s susceptibility to dynamic triggering. Faults whose frictional strength is controlled by a gouge layer may react differently to dynamic stresses than a fault without a significant gouge layer. Marone and Scholz [1988] found that the upper stability limit of crustal faults depends on whether a thick gouge layer is present; faults without a significant gouge layer are capable of nucleating earthquakes at shallower depths. In laboratory experiments, the generation of a gouge layer with progressive slip has a stabilizing effect, tending to inhibit stick slip [Engelder, et al., 1975; Byerlee and Summers, 1976; Wong and Zhao, 1990]. Our study investigates whether different fault architectures have a similar stabilizing effect in relation to transient triggers.

Our experiments are conducted on laboratory faults experiencing violent stick-slip behavior analogous to the earthquake cycle [Brace and Byerlee, 1966]. We explore aspects of earthquake triggering such as dependency on fault zone architecture, stress state with respect to the seismic cycle, and properties of the seismic wave by superimposing bursts of oscillating shear velocity on a constant background loading rate. Sinusoids of different amplitude, frequency and duration were used to simulate a range of
triggerring event sizes. To recreate fault zones of differing maturity, we shear gouge layers of different thicknesses ranging from 0 (bare granite surfaces) to 6 mm.

**Experimental Procedure**

Experiments were conducted in a servo-controlled biaxial deformation apparatus with a double-direct shear configuration (Figure 1). For experiments with synthetic gouge, layers of glass beads were sheared between 10 x 10 x 2 cm side steel blocks and a center block 10 x 15 x 3 cm so that a constant nominal contact area of 10 x 10 cm was maintained throughout shear. The forcing blocks have triangular grooves 0.8 mm deep and 1 mm in wavelength perpendicular to the shear direction. These grooves force shear to occur within the layer instead of along the boundary. The samples were loaded in controlled shear displacement with 0.1 μm resolution and at constant normal stress of 5 MPa (with 0.1 kN resolution). This normal stress is high enough for stresses at contact junctions to reach the inelastic yield point and to activate physicochemical processes that govern time-dependent and rate/state friction effects, yet low enough to eliminate grain comminution and the resulting variations in frictional behavior with net fault offset. The stiffness of the vertical loadframe is 5 MN/cm or 250 MPa/cm when expressed as the shear stress on a double direct shear sample with nominal friction contact dimensions of 10 cm x 10 cm. The load point displacement history consisted of a linear function with a sinusoid sporadically superimposed to mimic a tectonic load and seismic waves, respectively (Figure 2). The background loading rate was held constant at 5 μm/s. The
amplitude, frequency and duration of the triggering stress were varied to assess triggering thresholds (Table 1).

We conducted experiments on both Westerly granite and soda lime glass beads (size distribution 105-149 µm, Mo-Sci Corporation, Rolla, Missouri). Glass beads have material properties similar to quartz and are ideal for these tests due to the repeatability of the magnitude and recurrence interval of stick-slip events. Steel guide plates and tape were attached to the unconfined sides of the sample configuration to hold the blocks together until loaded. Copper shims were attached at the bottom of the sample layers to minimize gouge loss. A latex rubber sheet of 0.01” thickness was taped over the copper shims, to minimize avalanching along the unconfined edges of the layers. For experiments with granite, we created a double-direct shear configuration with one center block and two side blocks composed of Westerly granite, again with nominal contact area of 10 x 10 cm throughout the experiment. We varied the granite surface roughness in different experiments. Initially, the surfaces are finished with 60-grit polish (rough granite experiment – p936) and we evaluate changes in behavior as they were progressively smoothed out over subsequent experiments (smooth granite experiments: Table 1).

Results

We compare the recurrence interval, \( t_r \), defined as the time between the onset of dynamic failures (Figure 3), of stick-slip under transient loading to recurrence intervals under constant loading conditions. Because the transient generally reduces the time to failure, the recurrence interval of triggered events should be measurably smaller than
under constant loading. We refer to this as a positive clock advance. To understand the importance of both fault zone properties and properties of the transient stressing, we vary the transient signal in our forcing function for all fault zone configurations. We also change where in the seismic cycle the transient oscillation occurs. It is convenient to define the parameter time-since-failure \( (t_{sf}) \) as the origin time of the transient relative to the onset of the previous dynamic failure (Figure 3). In this way, we quantify the transient’s position in the interseismic cycle. We measure stress drop of each event as the difference between the shear stress at the onset and the end of dynamic failure.

Under constant loading conditions, stick-slip recurrence intervals are remarkably consistent for both glass beads [Savage and Marone, 2007] and granite surfaces. Recurrence rates depend not only on load point velocity, but also on the properties of the fault zone (Figure 4). Shear surfaces with and without gouge display a linear increase in stress immediately after a stick-slip, which reflects the combined elastic stiffness of the machine and sample. As loading progresses there is a distinct break in the loading curves, which reflects the onset of inelastic stressing and creep. The inelastic yield point decreases systematically with increasing roughness and gouge layer thickness (Figure 4). Smooth granite surfaces show a kink in the loading curve close to failure (Figure 4A) whereas rough granite surfaces show a kink about half way through the stick-slip cycle (Figure 4B). We interpret this as the onset of full slip at asperity contacts [Boitnott, et al., 1992]. Granular layers show a more prolonged transition to inelastic behavior, which reflects the time (and slip) necessary for interparticle slip and rolling to extend across the layer. The transition period and the degree of inelastic creep increases with layer thickness (Figures 4C and 4D), which results in an increase in stick-slip recurrence
interval. The failure strength and the dynamic, minimum strength also decrease with increasing layer thickness, as can be seen from the shear stress values before and after stick-slip failure (Figure 4).

**Definition of Triggering**

We employ a two-part definition of triggering for our experiments. First, the instability must occur during the transient deformation. These are shown by the closed symbols in Figure 5, where recurrence interval is plotted against time since failure. The events define a straight line and demonstrate the consistency of the time between trigger and stick slip. This time is dictated by the frequency of the stress oscillation, and because our minimum frequency is 1Hz, all transients reach peak stress in less than one second. The second part of our triggering definition requires that the recurrence interval of the earliest triggered event (Figure 5) for a given set of conditions must be two standard deviations away from the average recurrence interval for the same conditions under constant loading. The earliest triggered event represents the shortest recurrence interval possible for a set of boundary conditions. This instability is important because it represents the greatest clock advance that can occur. This second part of the triggering definition becomes important when deciphering the amplitude threshold of triggering.

**Influence of Fault State**

Triggering sensitivity depends on the period of the interseismic cycle at which the transient occurs (Figure 5). The data points at the upper left in each panel (open
symbols) represent cases where the transient occurs early in the stick-slip cycle, and does not trigger failure. In these cases the recurrence time falls within the normal recurrence interval range. Once the fault has reached a critical state, almost all events fall during the transient. This is shown by the abrupt shift between untriggered and triggered events (e.g. at a time since failure of 3.5 seconds in Figure 5A). Interestingly, there is no precursory change in the recurrence rate from the average, even immediately before the fault reaches its critical state. For example, if the transient had a small weakening effect on the fault surface, but not enough to trigger slip immediately, we might expect to see decreasing recurrence rates before triggering during the transient began. This implies that our experiments do not show any delayed triggering effects.

**Transient Amplitude Effects**

As can be seen from the timing of the earliest triggered event in Figure 5, larger amplitudes produce greater clock advance. We plot the recurrence interval of the earliest triggered events versus amplitude to quantify this effect among different fault types (Figure 6). The zero amplitude point represents the average recurrence interval without transient oscillations. The error bars represent two standard deviations. Solid symbols represent triggered events and open symbols are non-triggered events; the boundary between the open and closed symbols represents the triggering threshold. Below certain amplitudes of the transient stress, the recurrence interval of triggered events is not statistically different from background values. This is the second part of our triggering definition above. Note also that the thickest gouge layers (Figure 6D) exhibit a greater rate of clock advance with increasing amplitude than thinner layers. Indeed, smooth
granite surfaces show little change in recurrence interval with increasing amplitude. We plot the amplitude thresholds outlined in these experiments as a function of gouge layer thickness (Figure 6E). The bars represent the range of possible thresholds (which is the range between the correlated and uncorrelated points in Figures 6A-D). The triggering amplitude threshold decreases with increasing gouge layer thickness. The smooth granite surfaces show a high threshold whereas the rough granite surface shows a low threshold, although neither is well constrained (Figure 6A).

When considering fault state and triggering thresholds, it is useful to think not only in terms of timing with respect to the interseismic period, but also in terms of the interseismic period normalized by the average recurrence interval under constant loading rate (Figure 7). In this way, we can compare where in the interseismic cycle triggering commences for fault types with different recurrence intervals. For constant loading rate, the average recurrence time of a fault is determined by fault zone thickness, with thicker fault zones showing longer recurrence times. Figure 7 shows the same experiments from Figure 6, however time-since-failure is normalized by the average recurrence time for that experiment. In this plot, the zero amplitude point would plot at 1 on the normalized time-since-failure axis, representing a full interseismic cycle. Error bars represent uncertainty in the average recurrence. Figure 7 shows that larger amplitudes trigger events earlier in the seismic cycle, but that this effect is enhanced for thicker granular layers. The roughened granite surfaces show the earliest triggered events for a given transient stressing amplitude. The 2 mm-thick granular layers show that for the largest amplitude tested (60 µm/s), triggered events commence roughly halfway through the seismic cycle, whereas triggering commences at ~30% of the background recurrence
interval for 3 and 6 mm layers. For the smooth granite surfaces, triggered events begin at ~80% of the background interseismic interval and show almost no variation with the amplitude of the transient stressing.

**Transient Frequency and Duration Effects**

In order to isolate the effects of frequency from those of amplitude, we varied the dynamic forcing frequency for a constant transient stress amplitude. To do this, we increased the transient shear velocity for higher frequencies so as to keep a constant shear stress amplitude of approximately 0.12 MPa, except for the roughened granite surface experiment where stress amplitude is smaller. Figure 8 shows the earliest triggered event for each frequency, all events fit our two-part definition of triggering. Six mm-thick layers show increasing clock advance as frequency is increased, indicating that the layers are more susceptible to triggering from high frequencies (Figure 8B). Three mm-thick layers also show increasing positive clock advance with increasing frequency (Figure 8B). Data for granite surfaces show a pronounced effect of roughness (Figure 8C). The frequency of transient stressing has different effects on smooth granite surfaces than on faults with gouge layers. Smooth granite surfaces show an initial decrease in recurrence interval and then a slight increase with increasing frequency. For rougher granite surfaces, recurrence interval was smaller than for smoother surfaces and indicate a slight increase in clock advance with increasing frequency, although the noise in this experiment was significant. All experiments with transient stressing showed positive clock advance (Figure 8C).

We again normalize the time-since-failure by an average recurrence interval to
compare the effects of the interseismic period on transient triggering between experiments with different average recurrence times (Figure 9). The effect of frequency is similar to that of amplitude, inasmuch as there is a greater clock advance in thick gouge layers compared to thinner layers. Smooth granite surfaces show at most a 20% change in recurrence interval, whereas rougher surfaces show up to a 90% change as a function of transient loading. The rougher surfaces experiments were conducted at a lower transient stress amplitude than the other experiments and we should note that if these experiments were run at a comparable stress amplitude, the clock advance would be even greater. The three mm layer experiment shows slightly less dependence of triggering on frequency than the six mm layer, but the two experiments are within error.

To ensure that any frequency effects are not due to the number of stress oscillations, we varied the duration of dynamic stressing (Figure 10). For example, a transient of 1 Hz frequency and 1 second duration will produce one maximum stress peak, whereas a transient with a 3 Hz frequency and the same duration will produce three stresses above background (Figure 8A). We ran a series of experiments with varying frequency and duration of the transient, such that higher frequencies had shorter duration and each set of conditions produced one oscillation peak (Figure 10A). Transient stressing caused positive clock advance and shorter recurrence interval as a function of higher frequency, but the variable duration experiments are not statistically different from those with constant 1-second duration. (Figure 10B). This result is perhaps not surprising because all triggered events fail during the first peak in stress, regardless of transient frequency. However, similar studies conducted under continuous oscillations show
triggering at lower amplitudes, indicating that much longer duration vibrations have a significant weakening effect [Savage and Marone, 2007].

Effects of Transient Deformation on Stress Drop

In addition to influencing the timing of instabilities, transient deformation also affects the magnitude of the stick-slip stress drop, compared to the size of non-triggered events (Figure 11). Previous work shows that stress drop increases with the log of stick-slip recurrence time (e.g. [Dieterich, 1972; Karner and Marone, 2001]). Our data show that triggered events (such as the closed symbols in Figure 5) have larger stress drops for a given recurrence interval than non-triggered events (Figure 11). In all fault zone types, the triggered events plot to the left and above the non-triggered events, meaning that triggered events show larger stress drops. Triggered events on the granite surface and 2 mm granular layer show an increase in stress drop with increasing recurrence interval however the two thicker gouge layers indicate a more constant stress drop at all recurrence intervals.

We also investigate whether the amplitude and frequency of the transient affect the size of the stress drop. These data bear on the question of whether the magnitude of the triggering earthquake influences the size of the triggered event. Figures 12 and 13 show the average stress drop as a function of amplitude and frequency for several experiments. For the granular experiments, amplitude has no effect on stress drop (Figures 12B, 12C, and 12D), whereas higher frequency transients may cause slightly greater stress drops (Figures 13B and 13C). However, the bare granite surfaces show a slight increase in stress drop with increasing amplitude (Figure 12A), but no trend with
frequency (Figure 13A). The slight trends in Figure 12A, 13B, and 13C are very subtle and when considering the standard deviation of our results, arguably nonexistent, indicating that the size of the triggering earthquake does not determine the size of the triggered earthquake.

**Discussion**

Our results imply that earthquake triggering depends both on the amplitude and frequency of the transient deformation, as well as properties of the fault zone. Larger amplitude stresses correlate with decreasing recurrence interval on granular layers. Faults with granular layers also tend to have shorter recurrence rates at higher frequency whereas the recurrence intervals of granite surfaces are lengthened or unaffected by high frequency oscillations. Because loading conditions were similar for all experiments, we can assume that the systematic variations we see with respect to amplitude and frequency are related to physical properties of each fault zone type. Studies of failure on frictional surfaces indicate that a small amount of inelastic slip, known as the critical slip distance \( D_c \), must occur before a surface fails unstably. According to rate and state friction theory, the critical slip distance is proportional to the displacement needed to renew asperity contact junctions [Rabinowicz, 1951; Dieterich, 1979]. For bare granite surfaces, \( D_c \) is proportional to mean asperity size. For granular layers, the critical distance is proportional to shear band width and mean grain size, because all of the grain contacts within a shear zone or granular force chain must be renewed [Marone, 1998; Marone and Kilgore, 1993; Savage and Marone, 2007]. To determine why amplitude and frequency of transient stressing have different effects on granite surfaces and
granular layers, we investigate the relationship between critical friction distances for the various experimental fault zones.

**Critical Displacement Lengths and Transient Effects**

Because a fault must weaken prior to failure in the context of slip- or velocity-weakening, a fault slip distance proportional to $D_c$ must be achieved during triggering by transient stressing. The critical slip distance may be the parameter that modulates the sensitivity to triggering. If the amplitude threshold is related to $D_c$, then we can assume that for a transient deformation to trigger an event, the transient-induced slip must be greater than or equal to $D_c$. We posit that the variations in amplitude threshold observed in our experiments (Figure 6) represent this effect. Because of inelastic creep prior to failure, the threshold most likely represents the summation of the displacement during the transient and the creep displacement, which may be why timing of the transient in the interseismic period has a larger role in determining clock advance in granular layers (Figure 7). For gouge layers, creep displacements increase during most of the interseismic period (unlike the granite layers which displace much less during the interseismic period). Therefore the displacement needed to achieve $D_c$ becomes smaller as the interseismic period progresses, which explains why smaller transients can trigger events later in the interseismic cycle (such as in Figure 6D). In comparison, triggering of the granite surfaces and thin gouge layers is not as strongly influenced by fault state relative to the interseismic period. This indicates that the “critical state” at which faults are susceptible to triggering can be achieved late in the interseismic cycle (as in the
smooth granite surfaces) or it can be a function of the transient amplitude and achieved after only a fraction of the interseismic period has passed.

Our data show that triggering by transient stresses also varies with frequency and fault zone thickness (Figure 8). High frequencies had the largest effect on the thick gouge layers. The granite surface experiments hint that increasing frequency may reduce clock advance. We hypothesize that the effects of frequency result from systematic variation of $D_c$ with fault zone thicknesses and that the difference in frequency effects as a function of fault type (Figure 8) results from differences in load point velocity when the critical displacement has been reached. Because our transient load point velocity is a sinusoid, velocity can be either increasing or decreasing as the fault fails (Figure 14A). According to rate and state friction theory, when velocity increases, frictional strength increases as well and then decays to a new value as slip accumulates. Similarly, a decrease in velocity instantaneously lowers the frictional strength of the fault. This increase or decrease in fault strength, just as the fault is ready to fail (i.e. the fault has slipped $D_c$), could hinder or enhance triggering.

Therefore, we compare the effective critical displacement of each fault type with the load point displacement at peak velocity to determine if the direct effect of rate and state friction affects triggering. We measure the fault slip that occurs after the onset of the transient and before dynamic failure begins (Figure 14A), and use this displacement as a proxy for $D_c$. As shown in Figure 4, inelastic slip begins prior to failure in all cases, and therefore our estimates of $D_c$ represent lower bounds on the true values. To minimize this effect, we only use slip values for the earliest triggered events for each fault type. This ensures that most of the pre-instability slip occurs during the transient and not
beforehand. Where possible, we measured slip for the earliest triggered events at different transient velocity amplitudes (but equal stress amplitudes) so that our $D_c$ values represent an average for each fault type. Some points represent the largest amplitude tested for that fault type and not an average (shown as points without error bars in Figure 14B).

Figure 14B shows $D_c$ for each fault type as a function of the load point displacement at peak loading velocity during the transient. The reference line shows where the load point displacement at peak velocity equals $D_c$. The critical displacements for granite surface experiments p1173 and p1166 were in fact too small to measure accurately, so we assume it is smaller than 1 µm as this is near our slip resolution above the noise level in these data. In these experiments, $D_c$ is less than the load point displacement when transient velocity peaks (left of the line in Figure 14B) and therefore the load point velocity is increasing as the surface begins to fail. This increasing velocity should result in transient strengthening via the friction direct effect. Because we use larger velocity amplitudes at higher frequencies to maintain constant stress amplitudes, the change in velocity is greater at higher frequencies. The thickest gouge layer experiments fall well to the right of the line, meaning that velocity is decreasing as the layer fails and likewise the transient strength of the material decreases, due to the friction direct effect. This negative velocity excursion results in reduced frictional strength. As shown in Figure 8, thicker gouge layers show the greatest clock advance. The thinner gouge layer and roughened granite surface experiments fall close to the reference line so that velocity is near or just past its peak. Because velocity is not changing at the peak,
there is not a significant change to the strength of the layer. These experiments showed
the smallest change in clock advance due to frequency effects.

To demonstrate that there is indeed a change in velocity phase at failure, we plot
the phase as a function of frequency (Fig.15). We plot the velocity phase at failure for
the events shown in Figure 8. The velocity peak is defined as zero phase, such that
negative phase indicates failure during increasing velocity and positive phase indicates
failure during decreasing velocity. The smooth granite surfaces fail before the velocity
peak except at 2 Hz frequency (although phase is very weakly positive). The three and
six mm layers both fail after the velocity peak in all cases, and have similar phase to each
other.

Previous studies have indicated that earthquake triggering is frequency
independent when the oscillation frequency is above the critical frequency [Beeler and
Lockner, 2003; Lockner and Beeler, 1999; Savage and Marone, 2007]. The critical
frequency is the inverse of the time needed to slip the critical friction distance. In theory,
above this frequency, the stress amplitudes need to be much larger than predicted by
simple failure models in order to trigger earthquakes. This change in triggering
thresholds between high and low frequencies has been used to explain why tidal
oscillations and some large earthquakes do not trigger seismicity. According to standard
thinking, if the period of the oscillation is shorter than the nucleation time, the effect of
the oscillation on friction is no longer phase coherent, and therefore friction could be
increasing or decreasing. This would be true for all frequencies above the critical
frequency, so that failure is independent of frequency. Our frequency range is above the
critical frequency in most experiments (except smooth granite surfaces), however our
results show that frequency in most cases affects phase at failure. We propose that the immediate change in strength due to a transient change in slip velocity affects the triggering potential at certain frequencies, but that it can reduce or strengthen the potential depending on the value of $D_c$.

The smooth granite surface experiments in Figure 8B suggest that at higher frequencies than we tested, not only would triggering cease but failure may be inhibited as well by high frequency vibrations. The experiments of Beeler and Lockner [2003] were also conducted on granite surfaces and show a frequency strengthening effect. We suggest that for the behavior of a fault to be independent of stressing frequency, the transient load point displacement amplitude at peak velocity must be equal to $D_c$. Our hypothesis suggests that any material can exhibit fault strengthening, weakening or independence, but that the thresholds for each of these behaviors will depend on the length of $D_c$. For example, thick granular layers would show frequency strengthening at larger amplitudes than tested in this study.

The strengthening of the layer with a positive velocity excursion can also explain why the triggered events have larger stress drops compared to their non-triggered counterparts. Even events that fail as velocity is decreasing still fail when the velocity is greater than the background rate ($5 \mu m/s$) so that some strengthening occurs in every triggered event. This indicates that triggered events are larger in magnitude than if the fault had failed with a constant tectonic loading rate. The lack of a convincing trend in the change in stress drop with amplitude or frequency, however, supports studies of seismic data showing that the size of the triggered event should be independent of the size of the triggering earthquake [Felzer, et al., 2004].
Rate and State Friction Models

In order to understand how $D_c$ affects the changes in clock advance at different amplitudes and frequencies, we evaluate our results in the context of rate and state friction laws \cite{Dieterich, 1979; Ruina, 1983}. The constitutive law states that friction is a function of velocity and fault state, such that:

$$
\mu = \mu_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{D_c} \right)
$$

(1)

$$
\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_c}
$$

(2)

where $\mu_0$ is the reference friction value, $V_0$ is a reference sliding velocity, $V$ is the fault slip rate, $D_c$ is the critical slip distance, $\theta$ is the state variable and $a$ and $b$ are empirically derived constants. Equation 2 is the Dieterich aging law for the evolution of the state variable \cite{Dieterich, 1979}, where the fault state can evolve while the fault is stationary.

We describe the elastic interaction of our sample with our testing apparatus as:

$$
\frac{d\mu}{dt} = k(V_{lp} - V)
$$

(3)

where $k$ is stiffness divided by normal stress and $V_{lp}$ is the load point velocity. The parameters used for the model results are shown in Table 2. We attempt to capture our experimental conditions by using the same load point velocity and stiffness, as well as approximating $a$, $b$, and $D_c$ from previous work on similar materials \cite{Mair and Marone, 1999}. The frictional parameters are constrained so that the critical stiffness equals the system stiffness to create an unstably sliding system, similar to our experimental stick-slip conditions. The onset of unstable failure is defined as the maximum friction value
before rapid slip. We use a range of transient amplitudes and a constant $D_c$ to
demonstrate the effects of load point displacement during the transient as a function of $D_c$
(Figure 16A). Similar results could be obtained by holding the transient amplitude
constant and varying $D_c$.

The frequency effects on recurrence interval are shown in Figure 16B. In each of
these models, the oscillation begins at the same time within the interseismic cycle. Below
the smallest amplitude shown here, failure always occurs after the first oscillation peak.
The models shown here fail during the first peak, similar to what we see in experiments,
until the recurrence interval begins increasing again, which occurs at different
frequencies for different amplitudes. The decrease in recurrence interval in the model
occurs because higher frequencies reach their first maximum peak faster. The 0.18 MPa
amplitude in Figure 16B shows that the recurrence interval decreases with increasing
frequency until 10 Hz, at which time the recurrence interval starts to lengthen again. The
smallest amplitude shows that same trend except that the recurrence interval decreases
until 2 Hz. The increase in recurrence seen in the model results is always due to the fault
failing after the first maximum amplitude peak, whereas our experiments always fail
during the first maximum amplitude peak. Therefore, the model never demonstrates an
increase in recurrence interval with frequency such as seen in the smooth granite block
experiments. Indeed, the model always predicts a decrease in recurrence for events
triggered at higher frequencies.

The majority of the models stick slip as velocity is decreasing (positive phase
lag). The exceptions are the two points showing the largest amplitude studied (we only
show one and two hertz frequencies because the model was unstable at higher
frequencies and we could not determine a recurrence interval). Based on our experimental results, we hypothesize that the increase or decrease in velocity during the transient deformation will temporarily increase or decrease frictional strength of the fault. To investigate this specifically, we look at the friction at the onset of failure in our models (Figure 17). Friction values are positively correlated with frequency, regardless of whether the failure occurs as velocity is increasing or decreasing. From our hypothesis, we would expect to see events triggered at higher frequency to fail at lower friction values for the events with positive phase lag. However, as load point velocity amplitudes are greater at higher frequencies, the velocity at failure can be quite higher than the load point velocity, even if the maximum peak has past.

The failure of the rate and state model capture the increase in recurrence interval with frequency in the granite surface experiments could indicate that the changes in recurrence intervals are not due to the friction direct effect, although it is clear from the experimental results that recurrence interval is influenced by whether load point velocity is increasing or decreasing when failure occurs. A more extensive investigation of the rate and state friction theory, perhaps including a randomization of the model to more accurately capture the experimental conditions, could prove insightful.

**Tectonic Implications**

Our experiments indicate that the apparent complexity of triggering (as indicated by differences in the effects of amplitude and frequency of transient stressing in different geographic regions), may be the result of differences in fault zone properties. One of the most important implications is that the high frequency threshold (failure threshold for
oscillations higher than the critical frequency) may not be constant, as has been previously proposed. For faults with a thicker gouge zone, and hence larger $D_c$, the threshold may not be remarkably different from a threshold predicted by simple failure models, such as a Coulomb-type failure, and the triggering threshold at high frequencies could be quite low. Therefore, geographic regions with a comparably low amplitude threshold may have faults with larger $D_c$.

The difference in frequency response between the bare granite surfaces and the granular layers suggest an explanation for discrepancies in the observed effect of seismic frequency, as well as possibly providing a new way to estimate $D_c$ for earthquake faults. For instance, the study at Long Valley Caldera [Brodsky and Prejean, 2005] found that earthquakes with enhanced low frequency energy were more likely to trigger additional seismicity. The amplitude thresholds listed by Brodsky and Prejean [2005] are 0.04-0.08 cm/s for vertical amplitudes and ~0.15 cm/s for horizontal amplitudes for wave periods longer than 30 seconds. Because they saw a transition from non-triggering to triggering at 30 seconds, we may assume that above this frequency, the critical displacement is not reached during the transient and earthquakes are not triggered. At periods longer than 30 seconds, the displacement during the transient becomes equal to or greater than $D_c$ and events are triggered. A wave with a 30 s period and within the range of amplitudes specified has a maximum displacement of 3.9-14.5 mm. The faults at Long Valley should have minimal gouge layers; we can assume that these faults are immature because the source of their activity is the recent volcanism in the area. Their shallow seismicity may also be an indication that the faults have a limited gouge layer. Marone and Scholz [1988] attributed the upper stability transition of 5 km depth to be due to the velocity
strengthening behavior of unconsolidated gouge layers, however faults lacking a significant gouge layer can nucleate earthquakes at shallower depths. The critical displacement length in this area may be approximately 4-15 mm and is more likely controlled by surface roughness of the faults, which is a reasonable assumption for faults with small total shear strain.

Estimates of the critical displacement length for natural faults range over several orders of magnitude. Measurements of $D_c$ in the lab are thought to scale up to earthquake faults (which are rougher and have much wider gouge zones), however Abercrombie and Rice [2005] argued that $D_c$ values on some areas of a fault may be on the same scale as laboratory measurements (0.01 to 0.1 mm) but rougher patches such as step-overs may require 0.5 mm of slip to instigate failure. More importantly, they suggest that weakening continues throughout slip, so that the value of $D_c$ may not have much meaning. Marone and Kilgore [1993] estimated $D_c$ values of 1 mm for active strands of mature fault zone (in this case the San Andreas) due to the effect of microstructural fabrics on strain distribution. Similarly, Scholz [1988] proposed $D_c$ to be on the order of 1–10 mm on surfaces with fractal roughness. Estimates of $D_c$ for small faults in gold mines are 0.1 mm and suggest that $D_c$ scales with the thickness of the gouge zone [Richardson and Jordan, 2002]. Ide and Takeo [1997] found an upper limit of $D_c$ at 50 cm from waveform inversions of the 1995 Kobe earthquake. Mair and Marone [1999] found that in laboratory experiments, $D_c$ increases with a log increase in velocity.

We have presented our results as a proxy for how “immature” versus “mature” fault zones would respond to dynamic stressing. However, we should make clear that there are many gradations between “mature” and “immature” and the critical slip distance
most likely varies accordingly. Figure 18 shows a schematic of the development of a fault zone starting from the coalescence of *en echelon* fractures. The initial fault zone would have a very large $D_c$ because of the extreme non-planarity of the fault. As displacement increases, the largest asperities are sheared off and the fault walls become more planar, in addition to a gouge zone forming from the sheared material. However, if asperity height is greater than the thickness of the gouge layer, the strength of the fault is still achieved by asperity contact. $D_c$ is related to the asperity contact and smaller than it was initially. Our granite block experiments are most likely a proxy for this case. With continued displacement, the fault eventually builds up a thick gouge layer. Before microstructures (such as shear bands) form, fault strength is determined by grain-grain contact and force chains, such as in our granular layer experiments. The entire layer participates in shearing and $D_c$ is large compared to the previous case. Finally, shear bands develop along the gouge zone, minimizing the actively deforming sections of the fault. $D_c$ scales with the width of the actively deforming layers and is subsequently smaller than when the whole layer participates in shearing. If $D_c$ is in fact the parameter that controls a fault’s susceptibility to dynamic triggering, then faults with the smallest $D_c$, namely faults with small asperity contacts or highly worked gouge zones, should be the most susceptible.

In our experiments we have focused on the triggering effects of shear oscillations, however, seismic waves will more likely impinge a fault at an angle, meaning that the fault will experience both shear and normal loading oscillations. Previous studies have generally found that faults weaken during normal load perturbation and quickly regain strength when constant load resumes [Boettcher and Marone, 2004; Hong and Marone,
Dynamic weakening is greatest under large amplitude, high frequency vibrations for granular materials [Boettcher and Marone, 2004], indicating that the clock advances seen in our granular experiments could be even greater under both shear and normal vibrations. The decrease in clock advance seen in our high frequency granite surface experiments could be somewhat negated by an induced decrease in fault strength, however, it is not immediately clear whether the same dynamic weakening effect would occur on bare surfaces.

**Conclusions**

The triggering potential of a transient deformation on shear surfaces depends on the amplitude and frequency of the wave, as well as the properties of the fault zone. Larger amplitude events generally increase clock advance of earthquakes, however greater changes in clock advance are witnessed on faults with greater interseismic creep. Bare surfaces are more susceptible to triggers where energy is concentrated at low frequencies, whereas gouge layers are encouraged to fail by high frequencies. The threshold between the different frequency responses seems to scale with maximum load point displacement during transient deformation and the critical slip length. Triggered events have larger stress drops than non-triggered events with the same recurrence time. The velocity amplitude of the transient has little discernible effect on stress drop, meaning that the size of the triggering earthquake may not have an effect on the size of the events it triggers.
Figures

**Figure 3.1.** Diagram of double-direct shear configuration. A constant normal stress of 5 MPa was applied in most experiments. This figure shows a granular gouge layer between the three block configuration; experiments shearing bare granite surfaces were also conducted.

**Figure 3.2.** Time series of shear stress and shear velocity. Transient stressing was implemented using sinusoidal oscillation superimposed on a constant shear velocity of 5 µm/s. Note the shear stress response to the velocity oscillation. Transients that occur early in the seismic cycle do not trigger failure. A triggered event takes place at approximately 1445 seconds.
**Figure 3.3.** Time series for a stick-slip event and definitions of the measured parameters. Recurrence interval is the time between the onset of dynamic failures. Shorter recurrence intervals (relative to the average for constant loading) represent clock advance. Time since failure represents how far into the interseismic period the transient deformation occurs. Stress drop measures the shear stress released during dynamic failure.
Figure 3.4. Stick-slip cycles for different fault zone architectures, (A) granite surfaces, (B) three millimeter glass bead layer, and (C) six millimeter glass bead layer.
Figure 3.5. Recurrence interval is plotted versus time since failure. Stress transients that occur near the beginning of the interseismic period do not trigger failure. We chose the earliest triggered events (shortest recurrence interval) to demonstrate the effects of oscillation amplitude and frequency on triggering.
**Figure 3.6.** Recurrence interval for the earliest triggered events (Figure 5) versus transient stressing amplitude. Frequency is held constant at 1 Hz. Each point represents a result from a dataset such as in Figure 5. The recurrence interval at zero amplitude represents the average for constant loading rate and error bars show ±two standard deviations. The closed symbols represent recurrence intervals that are two standard deviations from the mean value at zero amplitude, which meet our criteria for triggering
Figure 3.7. Time since failure of earliest triggered events normalized by background recurrence interval versus transient stressing amplitude. For a given amplitude, triggering by transient stressing commences (circled points on Figure 5) earlier for thicker gouge layers. Dashed lines approximate the slope for each fault configuration and suggest that thinner layers are less affected by transient amplitude.
Figure 3.8. (A) Time series of 1, 2, and 3 Hz velocity oscillations and their effect on shear stress. Shear velocities are 40, 80 and 120 µm/s for 1, 2, and 3 Hz signals, respectively, in order to keep a constant shear stress amplitude. Recurrence interval plotted versus frequency show that granular layers (B) are more susceptible to triggering from transients with high frequency waves whereas granite surfaces (C) show no effect or a dampening in susceptibility with increasing frequency. Error bars represent two standard deviations from the average recurrence at background loading rates and are smaller than the plot symbols in some cases.
Figure 3.9. Time since failure normalized by background recurrence interval plotted versus transient stressing frequency. Dashed lines approximate the slope for each fault configuration and suggest that thinner layers are less affected by transient frequency.
Figure 3.10. Effects of transient duration on recurrence interval. (A) Time series showing 1, 2, and 3 Hz transient oscillations of 1, 0.5, and 0.33 second duration and their effect on shear stress. (B) Effect of transient duration and frequency on clock advance. Note that the effects of frequency are independent of oscillation number.
Figure 3.11. Stress drop over recurrence interval for both triggered and non-triggered stick-slips. Triggered events have larger stress drops per recurrence time than non-triggered events.
Figure 3.12. Average stress drop over amplitude for (A) granite surfaces, (B) 2mm layer, (C) 3 mm layer and (D) 6 mm layer. Only the granite surfaces show any correlation between the size of the event and the amplitude of the triggering event.
Figure 3.13. Average stress drop over frequency for (A) granite surfaces, (B) 3 mm layer and (C) 6 mm layer.
Figure 3.14. (A) The fault slip that occurs after the onset of the transient deformation but before the onset of dynamic failure is an approximation of the critical displacement. We also demonstrate that the maximum shear velocity occurs at $\pi/2$ in the transient displacement oscillation. The overshoot shown in the fault slip curve (after unstable failure) is the response of the ram to displacing more during unstable failure than the input signal prescribed. (B) The average value of $D_c$ measured for all triggered events in different fault configurations. The error bars represent one standard deviation.
Figure 3.15. Load point velocity phase of stick-slip failure. Smooth granite surfaces fail before load point velocity peaks whereas granular layers fail post peak.

Figure 3.16. (A) Time series of frictional instabilities in our model. The velocity oscillation begins at 4 s in each frame. (B) Rate and state friction models of recurrence as a function of frequency.
Figure 3.17. Friction as a function of frequency for rate and state friction model. Models where failure occurred after the first load point velocity peak are not included.

Figure 3.18. Sketch of the evolution of a fault zone and subsequent changes in the critical slip distance.
Table 3.1. List of Experiments

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Table 3.2. Model Parameters

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Chapter 4
THE ROLE OF FAULT FRICTION IN DAMAGE ZONE EVOLUTION

Abstract

Numerical models of a linear horizontal fault show the generation of off-fault tensile failure that results from inelastic slip along the fault. We explore models with a constant coefficient of friction (both strong and weak faults) as well as with slip-weakening friction to compare the damage patterns created from the different fault types. Tensile fractures form where tangential stresses along the fault exceed the tensile strength of the rock. These stresses result from locally high slip gradients. We find that static friction faults generate fractures solely at the fault tip in the tensile quadrant of the fault. Alternatively, the slip-weakening fault generates fractures along the entire fault; fractures form mostly at the rupture tip as the rupture migrates along the fault. These results could guide field studies of small faults as to whether the fault failed in small seismic events or in creep.

In addition to the study of fracture development, we investigate the amount of energy available for additional damage generation through a work budget analysis for each fault type. The strong fault had the greatest proportion of internal work, which indicates excess energy for microcracking and comminution of the host rock, however the work is dispersed throughout the elastic space and not heavily concentrated around the fault. For the weak and slip-weakening fault models, maps of internal work show areas of high strain energy along the fault that are most likely to create pockets of intense
damage. These areas tend to cluster at the rupture tip and around off-fault fractures that slip. The pockets of high internal work are asymmetric around the fault.

**Introduction**

Fault damage zones nucleate and evolve from repeated deformation and displacement along faults [Sibson, 1977; Chester and Logan, 1986; Cowie and Shipton, 1998; Shipton and Cowie, 2003; Kim, et al., 2004; Okubo and Schultz, 2005] and have implications for several outstanding questions in fault mechanics and structural geology including earthquake propagation along multiple fault branches [Poliakov, et al., 2002] [Rice, et al., 2005], fluid flow [Caine, et al., 1996], and facilitation of fault propagation [Graham, et al., 2003]. The generalized, mature fault zone consists of a fault core made of highly comminuted and sheared gouge material, surrounded by a zone of damaged host rock which contains shear and tensile fractures. Although evidence suggests that the size and intensity of damage zones is generally related to the total displacement on a fault, the evolution of faults and their associated damage is unclear. Gouge is produced due to wear on rough surfaces [Engelder, 1974] and gouge zone thickness scales with fault displacement [Scholz, 1987]. However, active faults tend to concentrate slip in a principal slip zone (PSZ), which can be 10s of cm or less [Chester, et al., 1993; Chester and Chester, 1998; Sibson, 2003]. Studies suggest that the PSZ forms early in the displacement history of the fault [Shipton, et al., 2007], obfuscating how gouge zones continue to thicken. Recent studies show that gouge can form through dynamic pulverization at the rupture tip [Wilson, et al., 2007], however in most cases damage along large faults reflects work done over several seismic cycles and the overprinting of
multiple events obscures how damage is generated in a single event. For instance, a calculation of the fracture energy output for the Punchbowl fault, California showed that much less energy was expended in generation of damage than created along the fault through seismic slip [Chester, et al., 2005]. In order to understand how the gouge and damage zone develop in early stages of fault displacement when damage patterns should be more straightforward, we perform numerical experiments of the initial stages of off-fault fracture development and the excess energy available for processes such as comminution. This study highlights some potential differences in damage patterns and intensity between faults that fail in creep and those that experience seismic slip.

**Early Fracture Damage from Shear Displacement**

In the incipient stage of fault development, shear fractures and small faults tend to generate off-structure damage in the form of process zones and tail cracks. Process zones at the fault tips generate tensile microfractures oriented subparallel [Segall and Pollard, 1983] to oblique to the fault [D'Alessio and Martel, 2004; Vermilye and Scholz, 1998]. The density of microfractures shows a logarithmic decay away from the fault [Vermilye and Scholz, 1998]. As propagation occurs, the fault grows through the process zone by linking microcracks.

On the macrofracture scale, tail cracks are tensile fractures that form in the tensile quadrants of the fault during displacements (e.g. [Martel, 1997]). They generally form at fault tips and the angle of the tail crack with respect to the main shear fracture is a function of the strength of the process zone [Cooke, 1997]. Faults with a more diffuse process zone can generate tail cracks inboard of the fault tip [Cooke, 1997], but primarily
fractures cluster at fault tips. These features form due to the slip gradient created at the change in frictional strength within the process zone. Complex fault geometry, such as fault bends, also create off-fault damage due to changes in slip gradient along the fault [Sibson, 1986] [Andrews, 1989] as do areas of increased fault roughness.

**Damage Due to Dynamic Shear Failure**

Off-fault damage can result from specifically dynamic processes as well and models indicate that the resulting fracture pattern should be distinct from the damage pattern mentioned above. Studies have shown that the slip gradient preceding a rupture front produces fractures [Yamashita, 2000; Dalguer, et al., 2003; Andrews, 2005]. In these models, the zone of damage generated is thinnest where the rupture begins and widest at the end of the rupture in the tensile quadrants. Yamashita [2000] predicted that joints formed in the tensile quadrant make a more oblique angle to the fault than joints formed in the compressive quadrant. However, in these numerical models fracture orientation must fall along a prescribed regular mesh. Dalguer et al. [2003] show that the majority of tensile fractures form in the tensile quadrants. These models all predict that the generation of off-fault damage slows rupture propagation during an earthquake, as energy is absorbed through the creation of new fractures (e.g. [Andrews, 2005]).

Pre-existing damage may affect the path of rupture as well. Rupture branching may result from activation of shear fractures off the main fault [Rice, et al., 2005]. Manighetti et al. [2004] suggested that slip profiles along a fault are modulated by pre-existing damage. Models of dynamic rupture with different material properties on opposite sides of the fault show that damage will occur on only one side of the fault [Ben-
This idea may be supported by studies of the asymmetric distribution of pulverized rock zones along the San Andreas fault [Dor, et al., 2006].

Role of Fault Friction in Off-fault Fracturing and the Partitioning of Work in Fault Systems

In this paper, we examine off-fault damage directly in the form of tensile fractures generated along small faults. This is a proxy for damage zone development during the initial shear failures on a new fault. We focus on tensile fractures because rock fails in tension. The formation of fractures alter the properties of the fault zone that effect rupture propagation and subsequent failures, such as: reducing stiffness of the host rock, absorbing energy through the creation of new surfaces, and, once the rock becomes highly fractured, providing additional material to crush into gouge. We test different frictional fault strength conditions that affect the generation of off-fault structures. Fault can fail stably (i.e. creep) or unstably (i.e. seismically). The first model examines a strong fault that has a constant coefficient of friction of 0.6, representing a fault that fails in creep. Laboratory experiments on the coefficient of friction for bare rock surfaces indicate that friction values are typically between 0.6-0.8 [Byerlee, 1978]. In our model, this fault type represents a small fault with no gouge layer. The second end-member is a fault that has a small coefficient of friction (0.2), representing a weak fault that fails in creep. The coefficient of friction of fault gouge depends on mineralogy but tends to be lower than bare surfaces. Therefore, our weak fault model represents a small fault with a gouge layer. Studies of faults in the Sierras found that small faults with little displacement (20 cm) had already developed a gouge layer [Shipton, et al., 2007]. The
third model has fault elements with a slip-weakening failure criterion and represents a fault that fails unstably (i.e. seismically). Rate and state friction theory demonstrates that friction along a fault that fails unstably will drop as the fault slips [Dieterich, 1979; Ruina, 1983]. By studying a slip-weakening frictional fault, we can observe how the change in friction during fault rupture affects fracture generation. We investigate fracture patterns for the three fault types in an effort to distinguish how the early frictional properties of the fault influenced the development of a damage zone. These numerically generated fracture patterns can be compared with field-based damage measurements.

In addition to the fracture analysis, we analyze damage in a more indirect way by assessing the mechanical work budget of the three fault types studied. Work budget analyses look at the balance between the external work done on the system (stemming from stress and displacement at the boundaries) and the total work done within the system during fault displacement [Cooke and Murphy, 2004]. Elements of total work include: work against friction, internal strain energy, surface energy for creating new fractures and propagating faults, work against gravity and seismic radiation. In a balanced tectonic system, the external work equals the total work [Cooke and Murphy, 2004]. We can examine how work is partitioned in the different fault zone types, and distinguish which scenarios have the highest internal energy budget for the creation of additional damage. In addition, we compare the components of work for each of our three fault types to investigate the most mechanically efficient system. As fault zones tend towards increased efficiency through time, from this analysis we may infer how fault zones evolve.
Methods

Numerical Method

Numerical models based upon continuum mechanics have been used to model various geologic processes such as earthquake triggering (e.g. [Stein, 1999]), fault interaction (e.g. [Maerten, et al., 1999; Savage and Cooke, 2004; Willemse, et al., 1996]) and folding (e.g. [Pollard and Johnson, 1973; Cooke and Pollard, 1997; Johnson and Johnson, 2002]). Mechanical models incorporating discontinuities (faults) describe changes in stress along the fault surface with specified displacements or applied remote stress.

Mechanical models are based upon the three governing equations of continuum mechanics. To satisfy the equilibrium equation, all stress applied must be accommodated by elastic strain; the deforming body cannot translate or rotate, such that, in two dimensions:

\[
\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{zx}}{\partial z} + \beta_x = 0 \\
\frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{zz}}{\partial z} + \beta_z = 0
\]  

(1)

where \(\sigma_{ij}\) represents the symmetric stress tensor and \(\beta_i\) is a known body force (e.g. [Crouch and Starfield, 1990]). The second principal is the compatibility equation, which requires that the displacement in each direction be continuous and single-valued to prevent gaps and overlaps from occurring. In plane strain, the compatibility equation can be written as:
where $\varepsilon_{ij}$ represents the strain tensor [Crouch and Starfield, 1990]. The final governing equation is the constitutive equation, which relates applied stress to the resulting strain. For linear elastic materials, this can be described with the generalized Hooke’s Law:

\[
\begin{align*}
\varepsilon_{xx} &= \frac{1}{E}(\sigma_{xx} - \nu(\sigma_{zz} + \sigma_{yy})) \\
\varepsilon_{zz} &= \frac{1}{E}(\sigma_{zz} - \nu(\sigma_{xx} + \sigma_{yy})) \\
\varepsilon_{xz} &= \frac{1}{2G}\sigma_{xz}
\end{align*}
\]

where $E$ is Young’s Modulus, $\nu$ is Poisson’s Ratio and $G$ is the shear modulus [Crouch and Starfield, 1990].

The Boundary Element Method (BEM) is a numerical formulation of the governing equations of continuum mechanics. The BEM considers discontinuities (e.g. faults) in an otherwise elastic homogenous space. Fault surfaces and boundaries are discretized into a mesh of polygonal planar elements. Tractions or displacements are prescribed for each element. Analytical functions calculate the effect of an element’s traction or displacement on the rest of the elements within the model. The model determines a matrix of influence coefficients that quantify the effects of all of the other elements. The size of the matrix is determined by the number of elements and the degrees of freedom (two in the two-dimensional model). Thus, the influence coefficients form a system of linear equations that determines the resultant displacement or traction when the prescribed displacement or traction is summed with the influence of the other elements. Once the internal and external boundary tractions or displacements are known,
the tractions or displacement for any point within the body can be calculated. This method is less computationally expensive than other methods such as Finite Element Method codes which discretize the entire elastic body.

Fric2D is a two-dimensional, open-source BEM code that simulates fractures using the displacement discontinuity method [Crouch and Starfield, 1990] and incorporates a frictional failure criterion for fault slip, as well as fracture propagation [Cooke, 1997]. Certain boundary elements, called fault elements, can accommodate some elastic strain before experiencing inelastic frictional slip [Crouch and Starfield, 1990]. In the Fric2D code, inelastic slip begins when the frictional strength of the element is exceeded as defined by the Coulomb criterion:

\[ \sigma_s \geq c + \sigma_n \mu_s \]

(4)

where \( c \) is cohesion, \( \mu_s \) is static friction, and \( \sigma_s \) and \( \sigma_n \) are shear and normal stress respectively. In models where the coefficient of friction is constant, regardless of slip, the element will slip until shear stress falls below the frictional strength. In models where a slip-weakening criterion is imposed on the element, once the static frictional strength has been exceeded and the element commences inelastic slip, the frictional strength of the element decreases linearly as a function of displacement:

\[ \mu = \mu_s - \frac{(\mu_s - \mu_d)}{L} \]

(5)

where \( \mu_d \) is a prescribed dynamic friction value and \( L \) is a characteristic slip length. Once the element has slipped the length of \( L \), the frictional strength of the element will remain at the dynamic friction value. For the results presented in this paper, we prescribe an \( L \) value of zero, so as to create the largest slip gradient possible at the rupture front. For
both the static and slip weakening models, after the element slips, stresses on all of the elements are recalculated because the shear strength could have been exceeded on a neighboring element.

**Model Setup**

We chose our boundary conditions to reflect the conditions on a fault at approximately seismogenic depths subjected to shear stresses that are close to the frictional strength of the fault (reflecting a fault that is critically stressed). Our boundary conditions include constant shear and normal stresses along each edge of the body (Figure 1). One element along the bottom edge is pinned to prevent displacement of the body and a second element along the bottom edge is prescribed zero normal displacement to prevent rotation. Normal stresses are calculated to reflect the lithostatic stress associated with a fault buried approximately 3.5 km. Loading is applied in one step (rather than monotonically) and changes in stress and displacement in the ensuing iterations represent the system reaching convergence. The fault is 10.1m long and horizontal (0° dip). We prescribe a freely slipping center element of the fault so that the element fails first. In this way, we create a nucleation point at which the rupture begins and propagates toward either end of the fault.

New tensile fractures grow where the tangential stresses along a fault element exceed the tensile strength of the host rock, prescribed here as 20 MPa. Tensile stresses occur due to slip gradients between elements. Because our model does not have a pre-existing mesh, fractures are free to form at any orientation and nucleate perpendicular to the local maximum tensile direction. Fractures form in the center of the element and can
grow by one element length during each iteration. Propagation continues until the stress intensity factor ($K_I$) is less than the fracture toughness, prescribed here as 2.5 MPa m$^{1/2}$. When new fractures nucleate, only opening displacement can occur. Existing fractures can open as well as experience shear displacement with frictional resistance equal to the static friction value of the fault element that spawned the new fracture. Fractures are not allowed to interpenetrate.

**Analysis of Mechanical Work**

Total work of the fault system describes all of the energy expended during tectonic deformation of the fault and the surrounding host rock. Energy is consumed during deformation from work against gravity ($W_{grav}$), propagation of new surfaces ($W_{prop}$), work to overcome frictional resistance to sliding along the fault ($W_{fric}$), work that promotes ground motion in the form of seismic radiation ($W_{seis}$), and finally work that goes into off-fault deformation which we refer to as an internal strain energy ($W_{int}$). The total work reflects the summation of each of these components:

$$W_{tot} = W_{grav} + W_{prop} + W_{fric} + W_{seis} + W_{int}$$

Each component of the total work done on the fault system can be evaluated from our model. In the following section, we describe how each work term is calculated. In our analyses, we do not consider the effects of gravity because our fault is horizontal and our surface has no topography. For a complete description of each work term, see Cooke and Murphy (2004).
**Frictional Work**

In order for a tectonic fault to slip, the shear stress along the fault must overcome the frictional strength of the fault. The work done against frictional resistance at a single fault segment is calculated as:

\[
W_{\text{fric}} = -\sigma_N \mu s dA
\]  

(7)

where \(\sigma_N\) is normal stress, \(\mu\) is the coefficient of friction, \(s\) is slip and \(dA\) is the ruptured areas of the fault. When stresses along the fault are tensile so that normal stresses are zero or positive, the work done against friction is zero. The complete frictional work in two dimensions is integrated over the loading path and the length of the fault, \(l\):

\[
W_{\text{fric}} = \int \int \sigma_N(\varepsilon_{\text{hor}}, l) \mu s(\varepsilon_{\text{hor}}, l) d\varepsilon_{\text{hor}} dl
\]  

(8)

where \(\varepsilon_{\text{hor}}\) is the horizontal strain. Frictional work will vary depending on the coefficient of friction we assign to the fault. In the case of the slip-weakening model, work against friction changes as the rupture propagates. Work done against friction is expended as heat.

**Work of Fracture Propagation**

The work done in the creation of new surfaces through the nucleation and propagation of off-fault tensile cracks is a function of the surface energy of a crack, width of the cataclastic zone and length of new fracture [Mitra and Boyer, 1986]. Because our newly generated cracks have zero fault width, the propagation work depends solely on surface energy and fracture length:
\[ W_{prop} = \gamma p \]  

where \( \gamma \) is the surface energy per unit length and \( p \) is the added length of the fault. We prescribe \( \gamma = 56 \text{ J/ m}^2 \) which is the fracture energy for Mode I cracks in Westerly granite [Scholz, 2002].

**Seismic Energy**

The energy lost to ground shaking during an earthquake is proportional to the shear stress drop during slip. This stress drop represents the release of some portion of the stored elastic strain that accumulates as a fault is stressed, however stress drop is thought to represent only a small fraction of the total shear stress on the fault. The seismic energy released during a slip event from a fault of length \( l \) is:

\[
W_{seis} = \iint \Delta \tau(\varepsilon_{hor}, l)s(\varepsilon_{hor}, l)d\varepsilon_{hor}dl \tag{10}
\]

where \( \Delta \tau \) is shear stress drop.

**Internal Work**

The internal work of the fault system is measured strain energy density. Timoshenko and Goodier (1934) derived the total strain energy for a two-dimensional system to be the sum of stress multiplied by strain over a infinitely small increment of strain:

\[
V_0 = \frac{1}{2}(\sigma_{xx}\varepsilon_{xx} + \sigma_{zz}\varepsilon_{zz} + 2\sigma_{xz}\varepsilon_{xz}) \tag{11}
\]
where $V_0$ is strain energy density, $\sigma_{ij}$ is stress and $\varepsilon_{ij}$ is strain. The integral of the strain energy over the entire body yields:

$$W_{\text{int}} = \iint V_0(x,z) dx dz \quad (12)$$

Although the internal strain energy represents elastic (and therefore recoverable) strain, the internal work term also represents the energy available for consumption by inelastic processes such as microcracking and comminution. Because these are the processes that produce gouge, internal strain energy density can elucidate the processes of gouge formation during fault displacement.

**External Work**

The external work represents the amount of work applied at the external boundaries of our system. The complete external work term is defined as:

$$W_{\text{ext}} = \iint \sigma_{\text{hor}}(\varepsilon_{\text{hor}}, z) A \varepsilon_{xx}(z) d\varepsilon_{\text{hor}} dz \quad (13)$$

where $\sigma_{\text{hor}}$ is the horizontal stress, $\varepsilon_{\text{hor}}$ is the horizontal strain, $z$ is depth, and $A$ is area of the external boundary. In a closed system, the total work must equal the external work.

**Results**

**Fracture Patterns**

We compare the off-fault fracture patterns generated along faults with varying frictional properties from the application of 55 MPa shear stress and 100 MPa normal stress at the boundaries of our model. New fractures develop perpendicular to the
direction of greatest tensile stress and at positions along fault with the highest slip gradients (i.e. at the rupture front, which is where an element that slipped juxtaposes an element that has not). The strong fault, with a constant coefficient of friction of 0.6, does not generate off-fault fractures under 55 MPa shear stress. If the applied shear stress were greater than 60 MPa, the entire fault surface would slip (i.e. shear stress must equal or exceed the normal stress multiplied by friction). Under 55 MPa applied load, the strong fault sustains limited slip adjacent to the weak central element and slip gradients are small. The weak fault ($\mu = 0.2$) generates fractures in the tensile quadrants near the tips of the fault, similar to tail cracks observed on natural faults (Figure 2). Fractures at the fault tips are perpendicular to the fault trace. The entire weak fault ruptures within two iterations because the shear stresses are large enough to overcome the strength on each element. Although the strong fault did not generate significant slip at the prescribed stress levels in this study, models with larger shear stresses produce fracture patterns on a slipped strong fault identical to the fracture pattern on the static weak fault at lower stresses.

The slip-weakening fault shows the most complex behavior because frictional strength drops from 0.6 to 0.2 once an element has slipped. This shear stress drop further encourages slip and sets off a propagating rupture that we can track over several iterations. The length of the rupture is shown in red in Figure 3. Within the slip-weakening model, fractures form in the tensile quadrants of the rupture tip. Behind the rupture front, fractures can form in the overall compressive quadrants of the fault (Figures 3C and 3D). While the right-lateral direction of overall slip predicts compression in the upper right and lower left quadrant, the episodic nature of rupture propagation
gives rise to locally high tensile stress within these same quadrants. The rupture propagates in a wrinkle-like pulse, so that the rupture patch has a front and back tip which both produce fractures but the back tip produces new tensile fractures in the overall compressional quadrant. Fractures can form along the back tip because there is an incremental slip gradient there which is in the opposite sense of the slip gradient at the front. This effect is somewhat muted by the large slip patch in the center of the fault associated with the freely-slipping center element. Initial fractures form sub-perpendicular to the fault. When the entire fault is ruptured, fractures have formed along the length of the fault (Figure 3D). This pattern contrasts the pattern of fracturing along the weak fault (and strong fault at higher shear stress) where fractures only form near the fault tips. As new fracture tips continue to propagate, their tips grow in various directions, highlighting the locally changing stress fields due to the presence of other nearby fractures. The lack of perfect symmetry of the fracture pattern arise from slight asymmetry in boundary conditions; to prevent rigid body motion, one corner of the model is pinned while another corner has one degree of freedom. Once a small degree of fracture asymmetry is introduced, the asymmetry of the model is further enhanced.

Slip profiles of the different fault types provide insight into the resultant fracture pattern (Figure 4). The slip values are normalized by the maximum slip at the final iteration for each fault type for ease of comparison of slip profiles. The maximum displacements by which all slip values are normalized are 0.0825 m, 0.0214 m, and 0.00099 m for the weak, slip-weakening and strong fault types, respectively. The weak fault shows a nearly perfect elliptical slip distribution, as predicted for elastic cracks with uniform stress drop. The slip-weakening fault has a more complex slip profile and lesser
slip than the weak fault. The slip grows over successive iterations and the slip profile becomes less elliptical as slip continues. This irregularity in slip distribution results from the off-fault fractures. The indentations along the slip profile are each areas of high fracture density. The opening and sliding along new fractures accommodates deformation so that less slip occurs along the primary fault. The strong fault slip profile shows a small amount of slip that is concentrated on the freely-slipping middle element and the closest adjoining elements. The slip profile is not elliptical because this slip is recoverable.

**Mechanical Work**

We analyze the mechanical work for the models discussed in Section 3.1. We look at both the components of work at the final iteration in each fault type, as well as how each component of the total work changes as the rupture propagates.

**Total Work Under Constant Stress and Constant Strain Boundary Conditions**

The total work for each fault type was calculated from the stresses and displacements on the external boundaries of the model (Figure 5A). The weak fault has the largest amount of total work, because this fault had the largest displacements along the external boundary in response to 55 MPa of shear stress. The strong fault has the most internal work because this fault has very little slip and no fracture propagation so almost all of the external work is translated into internal work. The slip-weakening model falls between the weak and strong faults in terms of total work. The slip-
weakening fault accumulates less internal work than the strong fault because some portion of internal work is accommodated instead as deformation along the fault and new fractures; however this accommodation comes at the cost of greater work against friction. Thus, a tradeoff occurs within the models between the release of internal work via deformation along faults and new fractures and the increase in frictional heating along these faults and fractures. The slip-weakening model includes work dissipated through seismic radiated energy, related to the stress drop during rupture. Seismic work dissipates energy out of the system that would have contributed towards internal work. Similarly, work due to nucleation and propagation of off-fault fractures expends work that would have increased the internal work of the system of a system that did not produce new fractures. Using an empirical fracture surface energy, \( \gamma = 56 \text{ J/ m}^2 \), \( W_{\text{prop}} \) contributes such a small amount to the total energy budget (>>1 MJ) that this portion of the work does not show up on the plot. Our models suggest that the strong fault is the most mechanically efficient when a similar applied shear stress is used for each model. However, this result is tempered by the fact that the weak and slip-weakening faults would have failed at much lower shear stresses than those applied. Comparing faults with the same level of shear stress may not appropriately simulate tectonic conditions. A comparison of different strength faults with similar displacement may provide more fruitful comparison.

Tectonic deformation may more closely resemble a displacement controlled experiment than a stress controlled experiment, so we also compare the work budget of our three fault types by varying the applied shear stress so that the displacements at the boundaries are the same. We adjusted the shear stress on the weak and strong faults until
their displacements along the model boundaries match the boundary displacements for the slip-weakening model in Figure 5A. Figure 5B shows that the weak fault has the least total work, which implies the greatest efficiency, under these boundary conditions. The weak fault still has the greatest slip and therefore the most energy in work against friction. The strong fault has the most internal work and is the least efficient, implying that newly formed faults with little gouge are the least efficient type of fault system.

Other studies of work balance on static fault systems have demonstrated that the sum of $W_{\text{seis}}$ and $W_{\text{prop}}$ is approximately equal to the change in modeled external work between a faulted and unfaulted system [Cooke and Murphy, 2004; Del Castello and Cooke, submitted]. The difference in work between the unfaulted and faulted model reflects the energy lost to the system due to new fault surfaces and seismic radiated energy. However, when we compare our fault systems to an unfaulted system with equivalent boundary strains, we find that the change in external work is significantly larger than the work that is dissipated through other energy sinks, especially for the weak and slip-weakening faults (the difference in external work for the unfaulted system and the total work for each fault system in Figure 5B). Once the work that has gone into seismic radiation is accounted for, the excess energy represents energy that is available for fracture propagation. This energy available for fracturing exceeds the empirical estimate of fracture energy based on $\gamma = 56 \text{ J/m}^2$ [Scholz, 2002] suggesting that greater energy may be available for processes such as dynamic pulverization [Wilson, et al., 2005].
**Change in Work With Rupture Propagation**

In this section, we investigate how the partitioning of the work budget changes throughout the rupture process. Figure 6 shows how the external work is partitioned among the various work terms in the slip-weakening fault type. At the onset, no slip has occurred and therefore no work has gone into friction or propagation energy, so that the internal work equals the external work. External work increases during the model because as more elements along the fault slip, the average strength of the fault becomes weaker until finally all of the elements have slipped and there is large displacements at the boundary. Work against friction, seismic work and propagation energy increase as the rupture propagates. During this period, the internal work steadily decreases. The slope of the work against friction increases around the 9th iteration due to a large increase in slip. A significant amount of fracture propagation also takes place at this point because the rupture has reached the prescribed fault tip. As the rupture cannot propagate along the fault further, the slip gradients at the fault tip become large, inducing new fractures.

**Spatial Changes in Internal Work with Rupture Propagation**

The previous sections have discussed temporal changes in integrated work terms for the entire system. In this section, we look at strain energy density (SED) maps at different iterations to see the areas along the fault which have the highest internal work. This highlights the areas susceptible to off-fault damage. SED is high at the boundaries, however this is an edge effect of the model. Figures 7, 8, and 9 show strain energy
density for the strong, weak and slip-weakening faults, respectively, with the constant stress boundary condition. The strong fault shows the most intense SED at the compliant middle element where slip is concentrated (Figure 7), although intensity at the rupture tip is low compared to deformation associated with the other fault types. The strong fault had the highest internal work out of the three fault types because strain is distributed throughout the body. The weak fault shows the highest strain energy density in the compressive quadrants of the fault tip (Figure 8). The SED pattern for both the strong and weak fault does not change over successive iterations because slip along the fault quickly converges (i.e. the rupture does not propagate as in the slip-weakening fault). Figure 9 shows the propagation of the rupture through time along the slip-weakening fault. The rupture front has lobes of high strain energy density in the compressive quadrants. Behind the rupture front, areas that are highly fractured correspond with areas of high SED as stresses are concentrated at the tips of new fractures that are opening and sliding (e.g. near 8.5 m and 10.5 m on the top side of the fault). However, on the lower side of the fault, one highly fractured area (near 8.5 m) concentrates SED while another (from ~10m to 12 m) does not. Fractures that have not slipped since forming, such as those in the tensile quadrants at the rupture front, do concentrate SED.

Discussion

Fracture Patterns

The qualitative analysis of the off-fault damage pattern resulting from fault slip has some interesting applications for field observations. Many studies of small faults
have reported the concentration of fractures in the form of horsetail cracks [Rispoli, 1981; Granier, 1985; Petit, 1987; Martel, 1997] at the fault tip without many tensile fractures along the fault inboard of the fracture tip. This pattern is similar to the results of the static friction models of this study rather than the slip-weakening models, where fractures are generated along the entire fault. This could indicate that the small faults observed in the Sierras (the smallest of which are 5 m in length) and elsewhere may not have sustained dynamic slip. Studies of small shear failures in deep gold mines suggest the smallest rupture patch radius that generates seismic waves (M_o = 0.4) is 19 m [Richardson and Jordan, 2002], implying that faults smaller than approximately 40 m in length cannot sustain unstable slip.

The slip-weakening fault displays the densest fracture network overall, and this may indicate that faults that slip dynamically are more likely to generate continuous damage zones (rather than pockets of fractures at the fault tips as in the static models). Faults that creep can produce cracks inboard of their tips if the fault tips are permitted to propagate between creep events. The cracks at the former fault tip would be inboard of the final tip. If propagation is steady, the resultant fracture pattern could resemble that of dynamically sliding fault. However, fracture generation could still be limited to the tensile quadrants, so that the compressive sides may still be unfractured, unlike the slip-weakening fault. The continuity of fracture pattern along a fault trace could be one useful way of assessing paleoseismicity on exhumed faults. As the continuity of dense fractures is also related to creation of a gouge layer, unstable faults should be more likely to have a well-developed, continuous gouge zone. Clusters of fractures along a fault could also serve as a marker of rupture terminations, in both the static and slip-weakening scenarios.
The complexity associated with damage overprinting in mature fault zones limits this comparison to immature faults with small displacements

**Mechanical Work Analysis**

In terms of the generation of microfracturing and comminution, the internal work and the excess work in each system quantify energy that may be available for these processes. The comparison in Figure 5 between the three fault types suggests that the strong fault should have the most internal energy, in both the constant stress and constant displacement boundary conditions, because little energy is used towards work against friction. However, the maps of strain energy density show that the energy is dispersed throughout the fault system, and not concentrated in pockets where damage would be more likely to occur. This could produce more distributed deformation throughout the host rock, such as calcite twinning. Alternatively, the slip-weakening fault shows that strain energy density is highest at the rupture tip, but also distributed along the fault. The pockets of high strain energy density along the slip-weakening fault are complex and asymmetric. The most strained areas cluster around off-fault fractures that have sustained at least $10^{-4}$ m slip. Because the slipping fractures further concentrate deformation, these areas are the most likely to be crushed and comminuted. The unfractured areas do not concentrate deformation and would be more likely to remain intact. Interestingly, this process would actually promote roughness along the wall of the initially planar fault with increasing displacement because the unfractured areas would eventually become promontories surrounded by gouge.
The excess external energy between the faulted and unfaulted models illuminates energy that may go to processes not explicitly accounted for in our model, such as rock pulverization during an earthquake. Recent work has shown that a large portion of gouge formation may occur during rock pulverization at a fast propagating rupture tip, rather than wear during frictional sliding, due to large tensile stresses [Reches and Dewers, 2005; Wilson, et al., 2005]. Because this process can create small particle sizes (>1 µm) much more work is required for the creation of new surfaces than for the creation of the macroscale tensile cracks empirically determined [Wilson, et al., 2005].

The total work budget analysis showed that for a realistic strain boundary condition, the weak fault is the most efficient fault system, which is intuitive because this system slips the most. The work against friction portion of the budget is proportional to fault slip.

**Future Work**

This paper represents the beginning of our work on the development of mature fault zones and their mechanical work budgets. The following topics are questions that have arisen during this pilot study that are of keen interest:

- Can the differences in fracture patterns between the slip-weakening fault and the static fault models be observed in outcrop? Clustering of fractures as we see in our static models has been well documented in small faults. Can we see distributed fractures along small faults that could indicate a propagating rupture front? The size criterion for the faults of interest could be guided by the Richardson and Jordon (2002) study.
• If faults in the model are allowed to propagate, do they propagate along any of the off-fault fractures? This would provide valuable insight into fracture patterns where the fault has propagated through the damage zone.

• When a fault with pre-existing fractures is deformed, do the pre-existing fractures dampen the propagation of the rupture and mute further damage creation?

• Look at faults with more realistic geometry. For this study we picked the simplest fault geometry so as to study only fractures related to slip. However, the fracture patterns around dipping or bending faults could be quite different.

• Investigate the effects of slip-weakening more fully by changing the slip weakening distances. How large does this value have to be before the slip-weakening fault damage zone resembles the weak fault damage zone?

**Conclusions**

Our results suggest that faults with slip-weakening friction (i.e. those that fail unstably) create the most tensile fractures. These faults generate fractures along the entire length of the rupture. Weak faults that do not generate seismicity only produce fractures at the fault tips. These results may be useful for guiding field observations of off-fault fractures and estimating paleoseismicity. Faults that have little slip have comparatively high internal strain energy which contributes to microcracking and comminution. However, faults that slip concentrate strain energy at fault tips, rupture fronts and in areas where tensile fractures have formed. Because strain energy concentrates in areas of fractured rock, this may imply that gouge will be produced in these pockets and that this process is non-uniform along the length of the fault.
Figures

**Figure 4.1.** Schematic diagram of model setup. Boundary conditions as well as work terms are outlined. Normal stress values are 100 MPa and shear stresses are 55 MPa along each side of the body.
Figure 4.2. Fracture pattern generated from slip along a weak fault. The fractures cluster in the tensile quadrants of the fault tips. Fracture density is determined by the slip gradient at the end of the fault. The strong fault creates a similar fracture pattern when the boundary stresses are large enough to make the fault slip.
Figure 4.3. Fracture pattern generated from slip along a fault with slip-weakening frictional strength. The successive pictures of the fault show how the fracture pattern changes as the fault ruptures (rupture length is shown in red). Fractures form in the tensile quadrant of the rupture tip, however, additional fractures can form in the compressive quadrants after the rupture front has passed.
Figure 4.4. Slip profiles along the length of each fault type. The maximum displacements by which all slip values are normalized are 0.0825 m, 0.0214 m, and 0.00099 m for the weak, slip-weakening and strong fault types, respectively. Slip distributes in a symmetrical ellipse along the weak fault, whereas the slip-weakening fault has a more complex slip distribution due to the influence of off-fault damage along the entire fault. The strong fault shows a concentration of slip around the compliant middle element.
Figure 4.5. Total work and change in work from an unfaulted system. A) The summation of total work for each fault type under 55 MPa shear stress shows that the weak fault has the largest total work, however the strong fault has the most internal work which can cause off-fault damage. B) Work budgets for the three fault types under constant boundary displacement conditions. The shear stress applied on the weak fault, slip-weakening, and strong fault systems are 35.25 MPa, 55 MPa, and 76.5 MPa, respectively. The weak fault is the most efficient in this model.
Figure 4.6. Change in work during rupture. External work increases slightly as the fault ruptures, while internal work steadily decreases due to energy needed for seismic radiation, fracture propagation and work against friction.
Figure 4.7. Strain energy density in a strong fault system, calculated assuming 1 meter thickness in and out of the page. Concentration of strain energy density is seen near the compliant middle element. High SED around the borders of the model represent edge effects.
Figure 4.8. Strain energy density in a weak fault system, calculated assuming 1 meter thickness in and out of the page. Because the entire fault ruptures in this model, the strain energy density is highest at the fault tips in the compressive quadrants.
Figure 4.9. Strain energy density in a slip-weakening fault system, calculated assuming 1 meter thickness in and out of the page. The distribution of SED changes as the rupture propagates; SED is highest at the rupture tips. As off-fault fractures begin slipping, SED is concentrated in these pockets along the fault as well.
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Appendix A

THE EFFECT OF ACOUSTIC WAVES ON STICK-SLIP BEHAVIOR IN SHEARED GRANULAR MEDIA: IMPLICATIONS FOR EARTHQUAKE RECURRENCE AND TRIGGERING

This appendix is a paper on which I am an author. Although I am not the primary author and therefore cannot include it in the body of my thesis, the work is relevant to Chapters 2 & 3 in that it represents a different, yet complimentary, laboratory approach to investigating earthquake triggering.

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Abstract
Dynamic earthquake triggering remains a compelling mystery: how do transient seismic waves with strains of order $10^{-6}$ trigger earthquakes, often with failure occurring long after the waves have passed\textsuperscript{1-6}? To better understand the physics of dynamic triggering, we conducted laboratory studies of stick—slip in granular media and its response to applied acoustic waves. Glass beads were used to simulate granular fault zone wear material, sheared in a double-direct configuration under constant normal stress, while subject to transient or continuous perturbation by acoustic waves. Here we show that small magnitude failure events, corresponding to triggered aftershocks in the glass bead layers, occur when applied sound-wave amplitudes exceed several microstrain.
These events frequently occur as part of a cascade of small magnitude events. The acoustic waves also cause large slip events to be delayed significantly relative to those observed without wave perturbation. Remarkably, the effects are observed for several major-event cycles after the termination of the acoustic signal, indicating a strain memory in the granular material despite the severe material reset that takes place during a large stick-slip event.

Introduction

Laboratory studies of granular friction have emerged as a powerful tool for investigating tectonic fault zone processes and earthquake phenomena including post-seismic slip, interseismic frictional restrengthening, and earthquake nucleation. In this work, we explore experimentally the effects of dynamic loading on stick-slip behaviour and speculate how our results impact understanding of earthquake processes, in particular, earthquake recurrence and dynamic earthquake triggering. Dynamic earthquake triggering is the process whereby seismic waves from one earthquake promote or inhibit failure on faults they disturb. It has been clearly documented in a few cases far from an earthquake source, at distances much longer than the fault radius of the triggering source (outside the traditional ‘aftershock zone’), and mounting evidence suggests it commonly occurs near the earthquake source. In our experimental study of acoustic waves interacting with a laboratory-scale fault system, we employ a double-direct shear configuration to shear 4-mm layers of glass beads at constant normal stress (1-10 MPa), using shearing rates of 1-100 µm/s (Fig. 1). Layers were subject to either continuous vibration or wave pulses of 10-20 cycles at 1-20 kHz, or to no wave excitation. We measured stresses, displacements, and wave-induced strains continuously.
throughout shearing. We report other details of the experimental approach in the Methods section below.

Granular layers of glass beads exhibit a repetitive recurrence pattern of stick—slip failure when sheared without acoustic wave perturbation. The recurrence characteristics of stick—slip vary from experiment to experiment based on shear displacement rate, confining stress, relative humidity, granular media thickness, and particle characteristics\textsuperscript{10,11,12}; however, Figure 2 shows that for fixed experimental conditions stick-slip characteristics are remarkably . Once shearing commences, it takes several tens of seconds to reach steady state conditions (Fig. 2). Leading up to steady state, one observes a general material dilation and nonlinear shear stress increase accompanied by intermittent stick—slips. After a shear strain of ~0.5, the shear strength exhibits a steady state behaviour characterized by stick—slip with large shear stress drop of magnitude that ranges from 10-30\% of the maximum frictional strength. Each primary or ‘major’ stick—slip event, which is accompanied by layer compaction, is followed by elastic and then inelastic stress build up and layer dilation (not shown)that is reflected in the nonlinear behaviour of the shear stress. For constant shearing rate without acoustic waves, major stick—slip events recur very regularly but include rare, small stick—slip events such as that seen at ~1375 sec in Fig. 2b. The cycles of stress build-up and stress drop vary somewhat from event to event but overall they are remarkably similar.

Figure 3a shows results from an experiment identical to that of Figure 2 except that we applied acoustic waves during shearing, starting a few seconds prior to failure of a major event, and maintained until the major stick—slip occurred. The lower portion of Figure 3a shows the rectified, peak strain amplitude measured by the accelerometer
attached to the sample (Fig. 1). The three intervals for which strain exceeds $1.3 \times 10^{-6}$ and denoted by thick horizontal lines represent applied-vibration-strains; other strain spikes represent acoustic emission from both small amplitude and major stick—slip failures.

Vibration extends the recurrence period of inelastic stress increase prior to failure of major events and induces small amplitude stick—slip events. In many cases a cascade of small amplitude stick—slip events occurs. In all cases, application of acoustic waves—even for brief intervals—has a lasting effect on stick-slip characteristics, such that successive major events appear to have a memory of the loading during previous cycles, despite the violent mechanical reset that occurs during stick slip. As examples of the above, in Figure 3a the applied vibration at ~2050 sec produces an immediate small-magnitude stick-slip. The vibration is terminated when the next major stick-slip event occurs. Two more major stick slips follow where no vibration is applied, but they exhibit longer recurrence times as well as multiple small-amplitude failures inbetween. Similarly, irregular cycles occur following the applied vibration at 2155 sec. Vibration applied at ~2255 sec produces immediate stick slip of a small magnitude event and an increased major-event recurrence interval. We find that stick-slip events evolve back to a more regular (non-vibration) behaviour, but never truly recover even when we wait for 10 or more major events before reapplying vibration. In all experiments with vibration, we find that stick-slip cycles are more complex compared to those without vibration, as illustrated in Figure 3b.

Wave pulses, rather than the more extended duration waves described above, are more analogous to a seismic wave in Earth. Vibration may be more analogous to the near source region where near continuous wave energy may exist for significant periods of
time in the form of aftershocks. We employed wave bursts of approximately 3.3 msec
duration and a centre frequency of 6100 Hz. Fig. 4 shows a typical sequence of stick-slip
events. A pulse was applied at ~1470 sec, and this in turn triggers a cascade of small
stick-slip failures with accompanying acoustic emissions (e.g., ~1470-1483 sec). A
consequence appears to be a delayed, major stick-slip event at ~1485 sec. The next
acoustic pulse is applied at ~ 1585 sec, triggering a cascade of small events with acoustic
emission (e.g., ~1596-1650 sec), again leading to a delayed major event at ~1655 sec. In
general, once a pulse is broadcast, we observe induced small stick-slip events, some
delayed from the pulse, in addition to delayed major events. We also observe some creep-
like events (no acoustic emission) induced by pulses as well as vibration. These may be
followed by small stick-slips events that exhibit acoustic emission.

When we apply vibration or pulsed sound at times in the cycle when stresses are
below ~95% of the failure strength we observe little or no effect on stick-slip cycles. This
observation implies that the system must be in a critical state to be susceptible to dynamic
triggering, which is consistent with seismic data on earthquake triggering\textsuperscript{13} and recent
modelling\textsuperscript{14}. Further, wave strain amplitudes must exceed approximately $10^{-6}$ for the
above effects to be observed, consistent with dynamic triggering observations for real
earthquakes\textsuperscript{15}.

Analysis of the primary stick-slip recurrence intervals for otherwise identical
experiments with and without applied acoustic waves shows that stick-slip recurrence
becomes progressively more erratic and lengthens with time in experiments with wave
excitation (Figure 5a). Compared to the shaded region, which shows the mean recurrence
interval ±1 standard deviation from non-vibration experiments, both the scatter and
average recurrence interval increases progressively in experiments with vibration. Repeated experiments with both vibration and pulse-mode verify that this effect is not an artefact. We find that the scatter relative to the mean increases with accumulated time in experiments with sustained wave and wave pulses. This suggests that increasingly erratic stick—slip behaviour with accumulated time (Fig. 5a) is primarily a function of accumulated wave-duration.

Another noteworthy observation is the fact that although the primary stick—slip recurrence interval increases significantly due to acoustic waves, the stress drop magnitude and variation increases only slightly (Fig. 5b). We cannot compare stress drop amplitudes directly due to minor differences from one experiment to the next; however, when we compare the variation of stress drop to the experiment mean, we see a clear trend of longer recurrence interval for a given change in stress drop.

We have described three primary experimental observations: (1) acoustic waves increase recurrence intervals and to a lesser degree, stress drops of large magnitude events; (2) acoustic waves induce triggering of small magnitude events; and (3) strain memory of acoustic excitation is maintained through successive large magnitude stick—slips. In the following we address each, relating them to underlying physics and earthquake processes.

The overall trend of increasing stress drop with recurrence interval is consistent with a large body of previous laboratory and field observations\(^8\). These show that maximum frictional strength increases linearly with the log of recurrence interval or waiting time between slip events. The commonly employed class of rate-state frictional models explicitly predicts that the rate of strengthening is proportional to the product of
the normal stress and the frictional constitutive parameters. Since we hold the normal stress constant, this implies that acoustic loading changes the frictional properties. A strain wave of $10^{-6}$ applies a pressure of order $10^4$ Pa, meaning that the applied vibration must be of order 1% of the of the normal stress. This is consistent with the rate-state framework with friction parameter $a = 0.001-0.01$.

We assess the implications of our experiments for dynamic earthquake triggering by considering that the primary slick-slip events represent earthquakes and that the acoustic wave-induced events represent triggered aftershocks. When the mainshock is far from the triggered event, these ‘aftershocks’ often are referred to as ‘remotely triggered’ events, although in this context the difference is semantic only. The small amplitudes of the laboratory triggered events, both of their stress drops and acoustic emissions, are consistent with studies of earthquake stress drops, particularly those of aftershock sequences. These studies show that aftershock stress drops range over one to two orders of magnitude in a single sequence. Previous studies show that to trigger earthquakes with high probability, strains should exceed $\sim 10^{-6}$ (15). The experiments described here show a corresponding behaviour: when the system is driven with vibration amplitudes corresponding to strains $<10^{-6}$ there is no obvious effect on the stick-slip behaviour.

In our experiments we apply sound when the system is in a critical state, approaching failure (e.g., see Fig. 3b and 4a). When we apply sound before the material is in a critical state, during elastic loading, we observe little or no effect. Our experiments are conducted at relatively small normal stresses, and when we apply larger normal loads, of more than approximately 5 MPa, the application of acoustic waves has no or little effect. Thus laboratory experiments imply that dynamic earthquake triggering is most
effective at low effective stress (normal load minus pore pressure). Numerous field-based studies also conclude that earthquake triggering requires low effective stress, weak faults, or faults near failure\textsuperscript{22}.

An additional mystery of dynamic earthquake triggering is the fact that it can take place minutes, hours or days after the seismic perturbation. Our experiments show delayed failures following acoustic perturbations, evident as cascades of small events. In most cases these generate acoustic emissions although we also occasionally observe triggered aseismic creep. All these are delayed triggered events. The delay process(es) remain unknown, but it seems likely that it is related to memory-effects documented in our experiments.

Previous experiments examining the effects of dynamic loading in granular media illustrate wave-induced material softening above strain amplitudes of approximately $10^{-6}$, which has been explained in terms of nonlinear-elastic induced softening-to-weakening\textsuperscript{15,21}. The experiments described here support, but do not prove, such a theory: we show that frictional weakening does indeed take place in response to acoustic waves as evidenced by the small stick-slip events, as well as creep.

The origin of the weakening may be related to the force chains within the granular glass bead pack. Other laboratory and numerical modelling studies conducted on quasi-statically sheared granular layers have suggested that stress is spatially-heterogeneous in granular materials and that much of the layer parallel shear stress is borne by force-chains\textsuperscript{12,23}. Thus, we posit that acoustic waves disrupt force chains, leading to the material softening and simultaneous weakening. Continued particle rearrangement within the force chains leads to the small, individual or cascades of shear stress drops, with or
without acoustic emission, that are observed in the experiments, and sequences of rearrangements could explain delayed failure of major events. The net effect that as recurrence interval increases so does the stress drop of major events (and maximum frictional strength). However, the rate at which stress drop increases diminishes with increasing recurrence interval. This suggests that the irregularity in stick-slip recurrence interval observed in our experiments, which indeed is observed for tectonic faults in Earth’s crust, may reflect a complex process of deforming the fault gouge itself that may be in part due to dynamical wave effects.

The memory effect we observe, manifest by the failure of the material to return to the pre-disturbed stick-slip recurrence pattern after acoustic waves cease is surprising. One might expect that the mechanically violent nature of stick slip would naturally reset the arrangement of grains and new force chains should form after each event. We have attempted to erase this memory effect by ceasing shear loading to allow the material to heal, as well as by changing normal stress to repack the grains. Neither of these attempts succeeded. This may imply that force chains persist, in some form, through several stick-slip cycles. That is, although failure of force chains causes stick-slip failure, the chains are reformed in part from previous segments and/or from lateral grain bridges that form between chains and support them by limiting bending. These secondary grain bridges that support force chains have been imaged in discrete element models and are known to play a key role in granular flow. In other words, during a major failure event only a small number of grains may dislodge along the slip plane and become quickly replaced so that most of the grains remain in the same force chain, providing the means for the material to “remember” that sound had been applied previous to the slip event.
Alternatively, due to the fact that loading may be inhomogeneous, only part of the strong network collapses in response to an acoustic signal. Thus, other strong parts of the network might persist and respond to recent past signals after there is a relatively localized failure elsewhere (R. Behringer, Pers. Comm.) We cannot attribute the memory to permanent damage to the grains themselves, because our previous work on the role of grain angularity and fracture implies that this factor is negligible\textsuperscript{12}. Moreover, there is no obvious visual change to the glass beads after our experiments with or without vibration.

Application of sound induces immediate as well as delayed triggering due to granular flow in our system. In the field and the laboratory, observations show a strain amplitude greater than about $10^{-6}$ is necessary for triggering to occur, pointing to an approximate threshold behaviour that appears to be universal. In the Earth, the origin of triggering may be due to granular flow as well as other mechanisms, some requiring the presence of fluids or vapor\textsuperscript{1,3,5,6}. In our experimental configuration, fluids would logically modify material response in manners that we intend to explore. How one might demonstrate whether or not the other behaviours we observe, increased recurrence and stress drop, take place in the Earth may be challenging, but model studies may aid in this question. If seismic waves provide the kind of influence we observe in the laboratory, the implications to earthquake processes in zones of low effective pressure may be substantial.

Laboratory studies of stick slip

We employ a double-direct shear configuration in a biaxial load frame that applies a horizontal stress to three steel forcing blocks that contain symmetric layers of glass beads at the block interfaces (Fig. 1). A vertical piston drives the central block
downward at a constant displacement rate to create shear. The apparatus is servo-controlled so that constant horizontal load and vertical displacement rate are maintained to ±0.1 kN and ±0.1 µm/s, respectively. The applied stresses on the shearing layers are measured with strain-gauge load cells in series with each of the loading axes. The apparatus is controlled via computer and recordings of the load, displacement, and stresses are monitored throughout an experiment. The granular media thickness was 4 mm, the nominal frictional contact dimensions are 10 cm x 10 cm, the vertical displacement of the central block was 5 microns/sec, corresponding to a strain rate of approximately 1.2x10^{-3}/sec., and the horizontal stress was 4 MPa. The beads are class IV spheres and range in dimension from 105-149 microns. In the experiments presented here, horizontal loads of 1-15 MPa were explored as well. Background noise emanating from the building and instrument was well under 5x10^{-7} strain.

Vibration is applied via an acoustic source (Figure 1): a Matec M50-2, 50-KHz central-frequency piezoceramic is attached mechanically with clamps to the central block using vacuum grease as couplant and driven by a Samson 150, 75 Watt amplifier. The signal is detected on the opposite face of the central block using a Brüel and Kjær model 4393 accelerometer attached with beeswax, amplified by a Brüel and Kjær 2635 charge amplifier, and recorded on computer. Sound frequencies ranged from 1-20 kHz. In preliminary measurements, sound was swept in frequency over this full band in order to locate resonances where amplitudes were largest. Resonances were then selected for both wave and pulsed measurements in order to maximize amplitude dependent effects. Such high frequencies are not part of the seismic spectrum in nature, which extends to 10-100 Hz at maximum, but are used to provide laboratory-scale physical insight that can
be applied in nature. We initiated waves at a shear stress equal to 95% of the failure strength by first measuring the stick-slip recurrence interval without wave for approximately 30 events and then timing the initiation of wave from the end of the previous stick slip.

In the pulse experiments a toneburst of 10-20 cycles with frequency ranging from 6.1-8.67 kHz. Results shown are for 6100 Hz. In general, sound was applied every third cycle after steady state conditions were reached.

Elastic wave strain is calculated as follows. In a harmonic wave, strain $\varepsilon = du/dx$ is related to acceleration $\ddot{u} = d^2u/dx^2$

$$\varepsilon = \frac{\partial u}{\partial x} = \frac{\ddot{u}}{\omega^2} \frac{1}{\omega^2} = \frac{\ddot{u}}{\omega^2} k \cos(\omega t - kx)$$

(1)

where $u$ is displacement, $k$ is wavenumber $\omega/c$, and $\omega$ is angular frequency. So

$$\varepsilon = \frac{\partial u}{\partial x} = \frac{d}{\omega^2} \frac{\ddot{u}}{\omega^2} = \frac{\ddot{u}}{\omega^2} \cos(\omega t + kx)$$

(2)

in the time average amplitude. We digitize the acceleration data and record the absolute value of the sinusoidal waveform with a sampling rate of 10kHz at 16 bits giving a minimum vertical resolution of $1.53 \times 10^{-2}$ mV.
References


Figure A.1. Experimental apparatus with zoom (top right) showing the blocks and planes of granular media as well as the location of the sound source in relation to the three blocks.
Figure A.2. Stick slip behaviour under constant shearing rate without vibration. (a) Shear stress versus time for a typical experiment. (b) Detail of the stick-slip cycles. Note consistent failure strength, recurrence interval, and creep prior to stick-slip (indicated by non-linear stress increase). p1108 refers to experiment number.
Figure A.3. (a) (top) Shear stress versus experimental time; (bottom) measured, rectified strain amplitudes of the detected acoustic waves for vibration experiments. Horizontal bars show times and durations of vibrations. (b) Comparison of non-vibration versus vibration experiment showing increased recurrence and irregular behaviour due to acoustic waves. P1170 & p870 refer to experiment numbers.
(top) Shear stress versus experimental time; (bottom) measured, rectified strain amplitudes of the detected acoustic waves for pulse experiments. Vertical arrows indicate acoustic pulse excitation times. p1087 refers to experiment number.
Figure A.5. Recurrence and stress drop. (a) recurrence versus experiment time for experiment conducted with vibration (solid circles) and without (grey region contained in dashed lines). (b) Stress drop variation versus recurrence for experiments conducted with and without vibration.
Appendix B
LIST OF EXPERIMENTS

Experiment: p157S3gr005  Date: 12/19/02

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa
Layer Thickness: 3 mm  Background Shear Velocity: 10 μm/s

T (°C):  RH(%):

Shear Velocity Amplitudes: 1 μm/s
Shear Velocity Frequencies: 1 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes:

Experiment: p158S3gr005  Date: 02/13/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa
Layer Thickness: 3 mm  Background Shear Velocity: 10, 20 μm/s

T (°C):  RH(%):

Shear Velocity Amplitudes: 10, 20, 30 μm/s

Shear Velocity Frequencies: 0.01, 0.1, 1, 10 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes: Horizontal load jumped to 650 kN
Experiment: p184S3gr005 Date: 04/01/03

Project: Shear Velocity Oscillations

Material: glass beads Normal Load: 5MPa

Layer Thickness: 3 mm Background Shear Velocity: 10, 20 µm/s

T (°C): 23.4 RH(%): 20.5

Shear Velocity Amplitudes: 10, 20, 30 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 1, 10 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes: Horizontal load jumped to 650 kN three times, significant sample loss

Experiment: p185S3gr005 Date: 04/09/03

Project: Shear Velocity Oscillations

Material: glass beads Normal Load: 5MPa

Layer Thickness: 3 mm Background Shear Velocity: 10, 20 µm/s

T (°C): 22.5 RH(%): 20.4

Shear Velocity Amplitudes: 10, 20, 30 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 1, 10 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes: began experiment in high gain, change to low gain ~9 minutes in
Experiment: p189S3gr005  Date: 05/14/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 10, 20 µm/s

T (°C): 23.9  RH(%): 26.9

Shear Velocity Amplitudes: 10, 20, 30 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 1, 10 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes: began using latex sheets on bottom of sample to prevent gouge loss

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Experiment: p190S3gr005  Date: 05/15/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 10, 20 µm/s

T (°C): 24.15  RH(%): 29.9

Shear Velocity Amplitudes: 10, 20, 30 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 1, 10 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes: large sample loss
Experiment: p223S3gr005  Date: 07/12/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 10 µm/s

T (°C): 24.54  RH(%): 

Shear Velocity Amplitudes: 10, 20, 30 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 1, 10 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes:

Experiment: p227S3gr005  Date: 07/13/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 10, 20 µm/s

T (°C):  

RH(%): 

Shear Velocity Amplitudes: 10, 20, 30 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 1, 10 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes: experiment halted due to sample loss
Experiment:  p232S3gr005  Date: 07/15/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 0.1, 1, 10, 20 µm/s

T (°C):  RH(%):

Shear Velocity Amplitudes: 10, 20, 30 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 1, 10 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes: shear velocity amplitudes up to this point were incorrectly calculated

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Experiment:  p240S3gr005  Date: 07/18/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 0.1, 1, 10, 20 µm/s

T (°C):  RH(%):

Shear Velocity Amplitudes: 1, 10, 20, 30 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 1, 10 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes:
Experiment: p269S3gr005  Date: 08/11/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 0.1, 1, 10, 20 µm/s

T (°C):  RH(%): 

Shear Velocity Amplitudes: 1, 5, 10 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 1, 10 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes:

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Experiment: p286S3gr005  Date: 08/17/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 10, 20 µm/s

T (°C): 29.9  RH(%): 48

Shear Velocity Amplitudes: 5, 10, 20 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 1 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes:
Experiment: p298S3gr005  Date: 08/22/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 10, 20 µm/s

T (°C): 28.5  RH(%): 49.5

Shear Velocity Amplitudes: 5, 10, 20 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 1, 10 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes: rerunning p286 for reproducibility

Experiment: p302S3gr005  Date: 08/23/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 0.1, 1, 10, 20 µm/s

T (°C):  RH(%): 

Shear Velocity Amplitudes: 1, 5, 10 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 1, 10 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes: rerunning p269 for reproducibility
**Experiment:** p313S3gr005  
**Date:** 08/26/03

**Project:** Shear Velocity Oscillations

**Material:** glass beads  
**Normal Load:** 5MPa

**Layer Thickness:** 3 mm  
**Background Shear Velocity:** 0.1, 1, 10, 20 µm/s

**T (°C):**  
**RH(%):**

**Shear Velocity Amplitudes:** 1, 10, 20, 30 µm/s

**Shear Velocity Frequencies:** 0.01, 0.1, 1, 10 Hz

**Continuous Oscillations or Pulses:** Continuous Oscillations

**Acoustic Vibration:** no

**Notes:** rerunning p240 for reproducibility

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**Experiment:** p329S3gr005  
**Date:** 10/08/03

**Project:** Shear Velocity Oscillations

**Material:** glass beads  
**Normal Load:** 5MPa

**Layer Thickness:** 3 mm  
**Background Shear Velocity:** 10 µm/s

**T (°C):** 29  
**RH(%):** 28

**Shear Velocity Amplitudes:** 10 µm/s

**Shear Velocity Frequencies:** 0.5 Hz

**Continuous Oscillations or Pulses:** Continuous Oscillations

**Acoustic Vibration:** no

**Notes:** ran one frequency and amplitude for entire experiment
Experiment: p332S3gr005  
Date: 10/16/03

Project: Shear Velocity Oscillations

Material: glass beads  
Normal Load: 5MPa

Layer Thickness: 3 mm  
Background Shear Velocity: 10 µm/s

T (°C): 26  
RH(%): 21.9

Shear Velocity Amplitudes: 10 µm/s

Shear Velocity Frequencies: 1 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes: running one amp and frequency the entire experiment, lots of gouge loss

Experiment: p337S3gr005  
Date: 10/21/03

Project: Shear Velocity Oscillations

Material: glass beads  
Normal Load: 5MPa

Layer Thickness: 3 mm  
Background Shear Velocity: 10 µm/s

T (°C): 28.1  
RH(%): 26.5

Shear Velocity Amplitudes: 10 µm/s

Shear Velocity Frequencies: 1 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes: rerunning p332
Experiment: p338S3gr005

Project: Shear Velocity Oscillations

Material: glass beads
Normal Load: 5MPa

Layer Thickness: 3 mm
Background Shear Velocity: 10 µm/s

T (°C): 27.7
RH(%): 15.3

Shear Velocity Amplitudes: 10 µm/s
Shear Velocity Frequencies: 0.1 Hz
Continuous Oscillations or Pulses: Continuous Oscillations
Acoustic Vibration: no
Notes: running one amp and frequency the entire experiment, some gouge loss

Experiment: p346S3gr005

Project: Shear Velocity Oscillations

Material: glass beads
Normal Load: 5MPa

Layer Thickness: 3 mm
Background Shear Velocity: 10 µm/s

T (°C): 22.5
RH(%): 27.8

Shear Velocity Amplitudes: 10 µm/s
Shear Velocity Frequencies: 0.5 Hz
Continuous Oscillations or Pulses: Continuous Oscillations
Acoustic Vibration: no
Notes: rerunning p329
Experiment: p355S3gr005  
Date: 11/03/03

Project: Shear Velocity Oscillations

Material: glass beads  
Normal Load: 5MPa

Layer Thickness: 3 mm  
Background Shear Velocity: 10 µm/s

T (°C): 28  
RH(%): 29.4

Shear Velocity Amplitudes: 
Shear Velocity Frequencies: 
Continuous Oscillations or Pulses: none

Acoustic Vibration: no

Notes: no oscillations, adjusting gain throughout experiment to determine if there is an effect on recurrence interval

Experiment: p358S3gr005  
Date: 11/05/03

Project: Shear Velocity Oscillations

Material: glass beads  
Normal Load: 5MPa

Layer Thickness: 3 mm  
Background Shear Velocity: 10 µm/s

T (°C): 22.5  
RH(%): 27.8

Shear Velocity Amplitudes: 10 µm/s
Shear Velocity Frequencies: 0.12 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes:
Experiment: p367S3gr005

Project: Shear Velocity Oscillations

Material: glass beads                Normal Load: 5MPa

Layer Thickness: 3 mm                Background Shear Velocity: 50 µm/s

T (°C): 22.9                         RH(%) : 11

Shear Velocity Amplitudes: 50 µm/s

Shear Velocity Frequencies: 1 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes:

Experiment: p371S3gr005

Project: Shear Velocity Oscillations

Material: glass beads                Normal Load: 5MPa

Layer Thickness: 3 mm                Background Shear Velocity: 50 µm/s

T (°C): 22.5                         RH(%) : 27.8

Shear Velocity Amplitudes: 0, 10 µm/s

Shear Velocity Frequencies: 1 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes:
Experiment: p377S3gr005  Date: 11/13/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 1, 50 µm/s

T (°C):  RH(%):  

Shear Velocity Amplitudes: 0, 1, 50 µm/s

Shear Velocity Frequencies: 0.1, 1 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes:

Experiment: p387S3gr005  Date: 11/20/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 10, 50 µm/s

T (°C):  RH(%):  

Shear Velocity Amplitudes: 1, 2, 5 µm/s

Shear Velocity Frequencies: 1 Hz

Continuous Oscillations or Pulses: Continuous Oscillations

Acoustic Vibration: no

Notes:
Experiment: p393S3gr005  
Date: 11/23/03

Project: Shear Velocity Oscillations

Material: glass beads  
Normal Load: 5MPa

Layer Thickness: 3 mm  
Background Shear Velocity: 10, 50 µm/s

T (°C):  
RH(%):

Shear Velocity Amplitudes: 1, 2, 5 µm/s

Shear Velocity Frequencies: 0.1, 0.5, 1 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes:

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Experiment: p395S3gr005  
Date: 11/24/03

Project: Shear Velocity Oscillations

Material: glass beads  
Normal Load: 5MPa

Layer Thickness: 3 mm  
Background Shear Velocity: 10, 50 µm/s

T (°C):  
RH(%):

Shear Velocity Amplitudes: 1, 2, 5 µm/s

Shear Velocity Frequencies: 0.1, 1 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes:
Experiment: p396S3gr005  Date: 11/24/03

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa
Layer Thickness: 3 mm  Background Shear Velocity: 1, 10 µm/s
T (°C):  RH(%): 
Shear Velocity Amplitudes: 0.5, 1, 2 µm/s
Shear Velocity Frequencies: 0.5, 1 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no
Notes:

Experiment: p481G005  Date: 04/24/04

Project: Shear Velocity Oscillations

Material: bare granite surface  Normal Load: 5MPa
Layer Thickness: 0 mm  Background Shear Velocity: 10 µm/s
T (°C):  RH(%): 
Shear Velocity Amplitudes: 1, 5, 10 µm/s
Shear Velocity Frequencies: 0.1, 1, 5 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no
Notes: running continuous oscillations on granite blocks
Experiment: p482S3gr005  Date: 04/24/04

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa
Layer Thickness: 0 mm  Background Shear Velocity: 10 µm/s
T (°C): 23  RH(%): 41.3

Shear Velocity Amplitudes: 0, 1, 50 µm/s
Shear Velocity Frequencies: 1, 5, 10 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no
Notes: no stick-slips

Experiment: p484G005  Date: 04/26/04

Project: Shear Velocity Oscillations

Material: granite blocks  Normal Load: 10MPa
Layer Thickness: 0 mm  Background Shear Velocity: 10 µm/s
T (°C):  RH(%):

Shear Velocity Amplitudes: 1, 2, 5 µm/s
Shear Velocity Frequencies: 1 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no
Notes: no stick-slips
Experiment: p485G005  Date: 04/26/04

**Project:** Shear Velocity Oscillations

**Material:** granite block  **Normal Load:** 10 MPa

**Layer Thickness:** 0 mm  **Background Shear Velocity:** 10 µm/s

**T (°C):**  **RH(%):**

**Shear Velocity Amplitudes:** 1, 5, 10 µm/s

**Shear Velocity Frequencies:** 0.1, 1, 5 Hz

**Continuous Oscillations or Pulses:** continuous

**Acoustic Vibration:** no

**Notes:** stable sliding, polished with 60 grit

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Experiment: p486G010  Date: 04/27/04

**Project:** Shear Velocity Oscillations

**Material:** granite blocks  **Normal Load:** 10MPa

**Layer Thickness:** 0 mm  **Background Shear Velocity:** 10 µm/s

**T (°C):**  **RH(%):**

**Shear Velocity Amplitudes:** 1, 5, 10 µm/s

**Shear Velocity Frequencies:** 0.1, 1, 5 Hz

**Continuous Oscillations or Pulses:** continuous

**Acoustic Vibration:** no

**Notes:** no stick-slips, sand-blasted in machine shop
Experiment: p487G010  Date: 04/27/04

Project: Shear Velocity Oscillations

Material: granite block  Normal Load: 10 MPa

Layer Thickness: 0 mm  Background Shear Velocity: 10 µm/s

T (°C):  RH(%):

Shear Velocity Amplitudes: 1, 5, 10 µm/s

Shear Velocity Frequencies: 0.1, 1, 5 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes: stick-slip, used smooth side of blocks (mirror surfaces)

Experiment: p492S3gr005  Date: 05/13/04

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 10 µm/s

T (°C):  RH(%):

Shear Velocity Amplitudes: 1, 5, 10 µm/s

Shear Velocity Frequencies: 5, 10 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes: using 300 sample/second update rate to reduce ram overshoot
Experiment: p494S3gr005  Date: 05/17/04

Project: Shear Velocity Oscillations

Material: granite block  Normal Load: 10 MPa

Layer Thickness: 0 mm  Background Shear Velocity: 10 µm/s

T (°C): 25  RH(%): 51.6

Shear Velocity Amplitudes: 1, 5, 10 µm/s

Shear Velocity Frequencies: 5 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes:

Experiment: p496G010  Date: 05/23/04

Project: Shear Velocity Oscillations

Material: granite blocks  Normal Load: 10 MPa

Layer Thickness: 0 mm  Background Shear Velocity: 10 µm/s

T (°C): 54  RH(%): 25.9

Shear Velocity Amplitudes: 1, 5, 10 µm/s

Shear Velocity Frequencies: 0.01, 0.1, 0.5, 1, 5 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes: no stick-slips, broke blocks
Experiment: p501S3gr005  Date: 06/06/04

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5 MPa

Layer Thickness: 3 mm  Background Shear Velocity: 10 µm/s

T (°C): 24  RH(%): 55

Shear Velocity Amplitudes: 2, 3, 4, 5, 10 µm/s

Shear Velocity Frequencies: 1, 2, 3, 5, 10 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes:

Experiment: p503S3gr005  Date: 06/08/04

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 10 µm/s

T (°C): 25.6  RH(%): 60.7

Shear Velocity Amplitudes: 2, 3, 5 µm/s

Shear Velocity Frequencies: 0.2, 0.5 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes:
Experiment:  p505S3gr005  Date: 06/16/04

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5 MPa

Layer Thickness: 3 mm  Background Shear Velocity: 5, 10 µm/s

T (°C): 26.1  RH(%): 62

Shear Velocity Amplitudes: 3, 4, 5, 10 µm/s

Shear Velocity Frequencies: 0.02, 0.05, 0.1, 1 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes:

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Experiment:  p506S3gr005  Date: 06/16/04

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5 MPa

Layer Thickness: 3 mm  Background Shear Velocity: 20 µm/s

T (°C): 26.1  RH(%): 62

Shear Velocity Amplitudes: 5, 10, 20 µm/s

Shear Velocity Frequencies: 0.1, 0.5, 1, 2 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes:
Experiment: p518S3gr005  Date: 07/20/04

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5 MPa
Layer Thickness: 3 mm  Background Shear Velocity: 10 µm/s
T (°C): 24  RH(%): 64

Shear Velocity Amplitudes: 3, 5, 10 µm/s
Shear Velocity Frequencies: 1, 2 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no
Notes: 

Experiment: p586S3gr005  Date: 01/05/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa
Layer Thickness: 3 mm  Background Shear Velocity: 5, 20 µm/s
T (°C): 23.5  RH(%): 31

Shear Velocity Amplitudes: 3, 5, 10 µm/s
Shear Velocity Frequencies: 0.01, 0.02, 0.05, 0.5, 1, 2 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no
Notes: 
Experiment: p589S3gr005  Date: 01/11/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5 MPa
Layer Thickness: 3 mm  Background Shear Velocity: 5, 10, 20 µm/s

T (°C): 21.6  RH(%): 32

Shear Velocity Amplitudes: 3 µm/s
Shear Velocity Frequencies: 0.1, 0.5 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no

Notes:
irreparable gouge loss 1/3 of the way through the experiment

Experiment: p591S3gr005  Date: 01/12/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa
Layer Thickness: 3 mm  Background Shear Velocity: 5 µm/s

T (°C): 21.7  RH(%): 36.8

Shear Velocity Amplitudes: 1, 2, 3 µm/s
Shear Velocity Frequencies: 0.5, 1 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no

Notes:
Experiment: p595S3gr005 Date: 01/15/05

Project: Shear Velocity Oscillations

Material: glass beads Normal Load: 5 MPa

Layer Thickness: 3 mm Background Shear Velocity: 5, 20 µm/s

T (°C): 24.2 RH(%): 16

Shear Velocity Amplitudes: 1, 2, 3 µm/s

Shear Velocity Frequencies: 0.2 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes:

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Experiment: p598S3gr005 Date: 01/25/05

Project: Shear Velocity Oscillations

Material: glass beads Normal Load: 5 MPa

Layer Thickness: 3 mm Background Shear Velocity: 5, 20 µm/s

T (°C): 25 RH(%): 15

Shear Velocity Amplitudes: 2, 3, 5, 10, 20 µm/s

Shear Velocity Frequencies: 0.01, 0.02, 0.025, 0.5, 1, 3 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes:
Experiment: p600S3gr005
Date: 02/02/05

Project: Shear Velocity Oscillations

Material: glass beads
Normal Load: 5 MPa

Layer Thickness: 3 mm
Background Shear Velocity: 5, 20 µm/s

T (°C): 25.2
RH(%): 12.5

Shear Velocity Amplitudes: 3, 5, 20 µm/s
Shear Velocity Frequencies: 0.01, 0.5, 1, 2, 3 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no

Notes:

Experiment: p605S3gr005
Date: 02/11/05

Project: Shear Velocity Oscillations

Material: glass beads
Normal Load: 5MPa

Layer Thickness: 3 mm
Background Shear Velocity: 20 µm/s

T (°C): 25.2
RH(%): 12

Shear Velocity Amplitudes: 20 µm/s
Shear Velocity Frequencies: 0.01, 0.02, 0.05, 0.1, 0.5, 1, 2, 3 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no

Notes:

running all frequencies in one experiment so as to compare recurrence, etc.
Experiment: p616S3gr005  Date: 02/15/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5 MPa
Layer Thickness: 3 mm  Background Shear Velocity: 5 µm/s
T (°C): 25  RH(%): 34

Shear Velocity Amplitudes: 5 µm/s
Shear Velocity Frequencies: 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2, 3 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no

Notes:
running all frequencies in one experiment so as to compare recurrence, etc.

Experiment: p620S3gr005  Date: 02/17/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa
Layer Thickness: 3 mm  Background Shear Velocity: 20 µm/s
T (°C): 24  RH(%): 18

Shear Velocity Amplitudes: 5 µm/s
Shear Velocity Frequencies: 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no

Notes:
running all frequencies in one experiment so as to compare recurrence, etc.
repeat of p616
Experiment: p648S3gr005  
Date: 05/12/05

Project: Shear Velocity Oscillations

Material: glass beads  
Normal Load: 5 MPa

Layer Thickness: 3 mm  
Background Shear Velocity: 10 µm/s

T (°C): 27  
RH(%): 31

Shear Velocity Amplitudes: 10 µm/s

Shear Velocity Frequencies: 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes: running all frequencies in one experiment so as to compare recurrence, etc.

Experiment: p650S3gr005  
Date: 05/17/05

Project: Shear Velocity Oscillations

Material: glass beads  
Normal Load: 5 MPa

Layer Thickness: 3 mm  
Background Shear Velocity: 10 µm/s

T (°C): 24  
RH(%): 27

Shear Velocity Amplitudes: 10 µm/s

Shear Velocity Frequencies: 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes: repeat of p648
Experiment: p705S3gr005  Date: 07/15/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5 MPa

Layer Thickness: 3 mm  Background Shear Velocity: 10 µm/s

T (°C): 26  RH(%): 29

Shear Velocity Amplitudes:

Shear Velocity Frequencies:

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes: tried to control humidity by baking beads and keeping them in a bag overnight, produced stable sliding

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Experiment: p707S3gr005  Date: 07/17/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5 MPa

Layer Thickness: 3 mm  Background Shear Velocity: 20 µm/s

T (°C): 25.3  RH(%): 68

Shear Velocity Amplitudes: 3, 5, 10, 20 µm/s

Shear Velocity Frequencies: 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2, 3 Hz

Continuous Oscillations or Pulses: continuous

Acoustic Vibration: no

Notes: running all frequency and amplitude combinations in one experiment to control for humidity effects
Experiment: p708S3gr005  Date: 07/17/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5 MPa
Layer Thickness: 3 mm  Background Shear Velocity: 10 µm/s
T (°C): 27  RH(%): 31

Shear Velocity Amplitudes: 10 µm/s
Shear Velocity Frequencies: 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2, 3 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no
Notes: running all frequencies and amplitudes in one experiment to control for humidity effects

Experiment: p713S3gr005  Date: 07/25/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa
Layer Thickness: 3 mm  Background Shear Velocity: µm/s
T (°C): 25  RH(%): 54

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no
Notes:
Experiment: p714S3gr005  Date: 07/25/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5 MPa
Layer Thickness: 3 mm  Background Shear Velocity: 5 µm/s
T (°C): 26  RH(%): 54

Shear Velocity Amplitudes: 1, 2, 3, 5 µm/s
Shear Velocity Frequencies: 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no

Notes: running all frequencies and amplitudes in one experiment to control for humidity effects

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Experiment: p725S3gr005  Date: 08/07/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa
Layer Thickness: 3 mm  Background Shear Velocity: 5 µm/s
T (°C): 25  RH(%): 48

Shear Velocity Amplitudes: 1, 2, 3, 5 µm/s
Shear Velocity Frequencies: 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no

Notes: running all frequencies and amplitudes in one experiment to control for humidity effects, rerunning p714
Experiment: p762GR005  Date: 09/21/05

Project: Shear Velocity Oscillations

Material: granite  Normal Load: 5 MPa
Layer Thickness: 0 mm  Background Shear Velocity: 10 µm/s
T (°C): 24.6  RH(%): 42.3

Shear Velocity Amplitudes: 3, 5, 10 µm/s
Shear Velocity Frequencies: 0.01, 0.05, 0.1, 0.2, 0.5, 1, 2, 3 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no

Notes: running granite block continuous oscillation experiments

Experiment: p773S3gr005  Date: 09/24/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5 MPa
Layer Thickness: 3 mm  Background Shear Velocity: 5 µm/s
T (°C): 24.1  RH(%): 41.5

Shear Velocity Amplitudes: 3, 5, 10 µm/s
Shear Velocity Frequencies: 3 Hz
Continuous Oscillations or Pulses: pulses, 1 s duration
Acoustic Vibration: no

Notes: testing out transient shear oscillations, these first few experiments have a displacement jump in the beginning
Experiment: p832S3gr005

Project: Shear Velocity Oscillations

Material: glass beads
Normal Load: 5 MPa

Layer Thickness: 3 mm
Background Shear Velocity: 5 µm/s

T (°C): 22.2
RH(%): 17

Shear Velocity Amplitudes: 3, 5, 10 µm/s
Shear Velocity Frequencies: 2, 3 Hz

Continuous Oscillations or Pulses: pulses
Acoustic Vibration: no

Notes: still using wrong pulses control file


Experiment: p833S3gr005

Project: Shear Velocity Oscillations

Material: glass beads
Normal Load: 5MPa

Layer Thickness: 3 mm
Background Shear Velocity: 5 µm/s

T (°C): 23.5
RH(%): 17.2

Shear Velocity Amplitudes: 3, 5, 10 µm/s
Shear Velocity Frequencies: 1 Hz

Continuous Oscillations or Pulses: pulses
Acoustic Vibration: no

Notes: testing out transient shear oscillations, these first few experiments have a displacement jump in the beginning
Experiment: p834S3gr005  Date: 12/08/05

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5 MPa

Layer Thickness: 3 mm  Background Shear Velocity: 5 µm/s

T (°C): 23.4  RH(%): 12.2

Shear Velocity Amplitudes: 10, 15, 20 µm/s

Shear Velocity Frequencies: 2 Hz

Continuous Oscillations or Pulses: pulses, duration is 1, 2 and 3 s

Acoustic Vibration: no

Notes: still using wrong pulses control file


Experiment: p844S3gr005  Date: 1/06/06

Project: Shear Velocity Oscillations

Material: glass beads  Normal Load: 5MPa

Layer Thickness: 3 mm  Background Shear Velocity: 5 µm/s

T (°C): 22.6  RH(%): 20

Shear Velocity Amplitudes: 3, 5, 10, 15, 20, 25, 30 µm/s

Shear Velocity Frequencies: 1 Hz

Continuous Oscillations or Pulses: pulses, duration is 1 s

Acoustic Vibration: no

Notes: still using wrong pulses control file
Experiment:  p845S3gr005
Date: 01/08/06

Project: Shear Velocity Oscillations

Material: glass beads
Normal Load: 5 MPa

Layer Thickness: 3 mm
Background Shear Velocity: 5 µm/s

T (°C): 22.5
RH(%): 21

Shear Velocity Amplitudes: 20, 40, 60 µm/s

Shear Velocity Frequencies: 1, 2, 3 Hz

Continuous Oscillations or Pulses: pulses, duration is 1 s

Acoustic Vibration: no

Notes: still using wrong pulses control file

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Experiment:  p852S3gr005
Date: 01/24/06

Project: Shear Velocity Oscillations

Material: glass beads
Normal Load: 5MPa

Layer Thickness: 3 mm
Background Shear Velocity: 5 µm/s

T (°C): 23
RH(%): 20

Shear Velocity Amplitudes: 15, 20, 30, 40, 60 µm/s

Shear Velocity Frequencies: 1, 2, 3 Hz

Continuous Oscillations or Pulses: pulses, duration is 1 s

Acoustic Vibration: no

Notes: using control file that is continuous in both displacement and velocity
Experiment: p866S4gr004  Date: 02/07/06

Project: acoustic vibrations

Material: glass beads  Normal Load: 4 MPa
Layer Thickness: 4 mm  Background Shear Velocity: 2 µm/s
T (°C): 23.3  RH(%): 15.1

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses: n/a
Acoustic Vibration: yes

Notes:

Experiment: p867S4gr004  Date: 02/08/06

Project: acoustic vibrations

Material: glass beads  Normal Load: 4MPa
Layer Thickness: 4 mm  Background Shear Velocity: 2, 5 µm/s
T (°C): 23.2  RH(%): 15.1

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses: n/a
Acoustic Vibration: yes

Notes:
Experiment: p868S4gr004  Date: 02/08/06

Project: acoustic vibrations

Material: glass beads  Normal Load: 4 MPa
Layer Thickness: 4 mm  Background Shear Velocity: 5 µm/s
T (°C): 23.5  RH(%): 13.6

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses: n/a
Acoustic Vibration: yes
Notes:

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Experiment: p869S3gr004  Date: 02/08/06

Project: acoustic vibrations

Material: glass beads  Normal Load: 4 MPa
Layer Thickness: 4 mm  Background Shear Velocity: 5 µm/s
T (°C): 23.9  RH(%): 14

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses: n/a
Acoustic Vibration: yes
Notes: changed to 5 MPa in the middle of the experiment
Experiment: p870S4gr004
Date: 02/09/06

Project: acoustic vibrations

Material: glass beads
Normal Load: 4 MPa

Layer Thickness: 4 mm
Background Shear Velocity: 5 μm/s

T (°C): 22.7
RH(%): 12.4

Shear Velocity Amplitudes: μm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses: n/a
Acoustic Vibration: yes
Notes: 

Experiment: p871S4gr004
Date: 02/08/06

Project: acoustic vibrations

Material: glass beads
Normal Load: 4 MPa

Layer Thickness: 4 mm
Background Shear Velocity: 5 μm/s

T (°C): 24
RH(%): 12

Shear Velocity Amplitudes: μm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses: n/a
Acoustic Vibration: yes
Notes: conducted conditioning test on steel block without sample
Experiment: p899S3gr005  Date: 02/26/06

Project: shear velocity oscillation

Material: glass beads  Normal Load: 5 MPa

Layer Thickness: 3 mm  Background Shear Velocity: 5 µm/s

T (°C): 23  RH(%): 8.3

Shear Velocity Amplitudes: µm/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses: pulses

Acoustic Vibration: no

Notes: check why there is no excel file for this exp.

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Experiment: p900S3gr005  Date: 02/27/06

Project: shear velocity oscillations

Material: glass beads  Normal Load: 5 MPa

Layer Thickness: 3 mm  Background Shear Velocity: 5 µm/s

T (°C): 23.5  RH(%): 13

Shear Velocity Amplitudes: 30, 40, 60, 80, 120 µm/s

Shear Velocity Frequencies: 1, 2, 3 Hz

Continuous Oscillations or Pulses: pulses, 1 s duration

Acoustic Vibration: no

Notes:
Experiment: p908S3gr005          Date: 03/10/06

Project: shear velocity oscillation

Material: glass beads             Normal Load: 5 MPa

Layer Thickness: 3 mm             Background Shear Velocity: 5 µm/s

T (°C): 24                        RH(%): 28

Shear Velocity Amplitudes: 30, 40, 60, 80, 120 µm/s

Shear Velocity Frequencies: 1, 2, 3 Hz

Continuous Oscillations or Pulses: pulses

Acoustic Vibration: no

Notes: rerunning p900

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Experiment: p923S3gr005          Date: 03/19/06

Project: shear velocity oscillations

Material: glass beads             Normal Load: 5 MPa

Layer Thickness: 3 mm             Background Shear Velocity: 5 µm/s

T (°C): 23.4                      RH(%): 14.5

Shear Velocity Amplitudes: 40, 80, 120 µm/s

Shear Velocity Frequencies: 1, 2, 3 Hz

Continuous Oscillations or Pulses: pulses, 1 s duration

Acoustic Vibration: no

Notes:
Experiment: p935GR005  Date: 03/26/06

Project: shear velocity oscillation

Material: granite blocks  Normal Load: 5 MPa
Layer Thickness: 0 mm  Background Shear Velocity: 5 µm/s
T (°C): 23.5  RH(%): 19

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no
Notes:

Experiment: p936GR005  Date: 03/26/06

Project: shear velocity oscillations

Material: granite blocks  Normal Load: 5MPa
Layer Thickness: 0 mm  Background Shear Velocity: 5 µm/s
T (°C): 23.5  RH(%): 19

Shear Velocity Amplitudes: 15, 25, 35, 50, 75 µm/s
Shear Velocity Frequencies: 1, 2, 3 Hz
Continuous Oscillations or Pulses: pulses, 0.33, 0.5, 1 s duration
Acoustic Vibration: no
Notes:
Experiment: p937S3gr005  
Date: 03/26/06

Project: shear velocity oscillation

Material: glass beads  
Normal Load: 5 MPa

Layer Thickness: 3 mm  
Background Shear Velocity: 5 µm/s

T (°C): 24  
RH(%): 19

Shear Velocity Amplitudes: 40, 80, 120 µm/s

Shear Velocity Frequencies: 1, 2, 3 Hz

Continuous Oscillations or Pulses: pulses

Acoustic Vibration: no

Notes: rerunning p923

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Experiment: p961S6gr005  
Date: 04/08/06

Project: shear velocity oscillations

Material: glass beads  
Normal Load: 5 MPa

Layer Thickness: 6 mm  
Background Shear Velocity: 5 µm/s

T (°C): 23  
RH(%): 19.3

Shear Velocity Amplitudes: 15, 25, 40, 60, 80, 120 µm/s

Shear Velocity Frequencies: 1, 2, 3 Hz

Continuous Oscillations or Pulses: pulses, 1 s duration

Acoustic Vibration: no

Notes:
Experiment: p962GR005  
Date: 04/09/06

Project: shear velocity oscillation

Material: granite blocks  
Normal Load: 5 MPa

Layer Thickness: 0 mm  
Background Shear Velocity: 5 µm/s

T (°C): 24  
RH(%): 17

Shear Velocity Amplitudes: 25, 50, 75 µm/s

Shear Velocity Frequencies: 1, 2, 3 Hz

Continuous Oscillations or Pulses: pulses

Acoustic Vibration: no

Notes: rerunning p936

Experiment: p969GR005  
Date: 05/01/06

Project: shear velocity oscillations

Material: granite blocks  
Normal Load: 5 MPa

Layer Thickness: 0 mm  
Background Shear Velocity: 5 µm/s

T (°C): 23.4  
RH(%): 20.4

Shear Velocity Amplitudes: µm/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses:

Acoustic Vibration: no

Notes: blocks resurfaced and polished with 60 grit powder, stable sliding
Experiment: p970GR005          Date: 05/01/06

Project: shear velocity oscillation

Material: granite blocks          Normal Load: 5, 10 MPa

Layer Thickness: 0 mm          Background Shear Velocity: 5 µm/s

T (°C): 23.4          RH(%): 20.4

Shear Velocity Amplitudes: µm/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses:

Acoustic Vibration: no

Notes: blocks polished with 150 grit, no stick-slips at 5 or 10 MPa normal stress

Experiment: p977GR005          Date: 05/03/06

Project: shear velocity oscillations

Material: granite blocks          Normal Load: 5MPa

Layer Thickness: 0 mm          Background Shear Velocity: 5 µm/s

T (°C): 23.6          RH(%): 31

Shear Velocity Amplitudes: µm/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses:

Acoustic Vibration: no

Notes: blocks polished with 60 grit powder, tried 4, 5, 10, 12 MPa normal stress, stable sliding in all cases
Experiment: p978GR005  
Date: 05/03/06

Project: shear velocity oscillation

Material: granite blocks  
Normal Load: 5 MPa

Layer Thickness: 0 mm  
Background Shear Velocity: 5 µm/s

T (°C): 23.6  
RH(%): 31

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses:
Acoustic Vibration: no

Notes: velocity steps using rathbun/andy_upsteps

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Experiment: p997S3gr005  
Date: 05/12/06

Project: shear velocity oscillations

Material: glass beads  
Normal Load: 5MPa

Layer Thickness: 3 mm  
Background Shear Velocity: 5, 10, 20 µm/s

T (°C): 24.2  
RH(%): 37

Shear Velocity Amplitudes: 2, 3, 5, 10, 15 µm/s
Shear Velocity Frequencies: 0.02, 0.05, 0.1, 0.2, 1, 4 Hz
Continuous Oscillations or Pulses: both
Acoustic Vibration: no

Notes:
**Experiment:** p998GR005  
**Date:** 05/12/06

**Project:** shear velocity oscillation

**Material:** granite blocks  
**Normal Load:** 5 MPa

**Layer Thickness:** 0 mm  
**Background Shear Velocity:** 5 \( \mu \text{m/s} \)

**T (°C):** 24.5  
**RH(%):** 35

**Shear Velocity Amplitudes:** \( \mu \text{m/s} \)

**Shear Velocity Frequencies:** Hz

**Continuous Oscillations or Pulses:**

**Acoustic Vibration:** no

**Notes:** surfaces ground and polished, no stick-slips

---

**Experiment:** p999GR005  
**Date:** 05/12/06

**Project:** shear velocity oscillations

**Material:** granite blocks  
**Normal Load:** 5 MPa

**Layer Thickness:** 3 mm  
**Background Shear Velocity:** 5, 10, 20 \( \mu \text{m/s} \)

**T (°C):** 25.2  
**RH(%):** 6

**Shear Velocity Amplitudes:** \( \mu \text{m/s} \)

**Shear Velocity Frequencies:** Hz

**Continuous Oscillations or Pulses:**

**Acoustic Vibration:** no

**Notes:** controlled humidity, no s-s
Experiment: p1000S3gr005  Date: 05/13/06

Project: shear velocity oscillation

Material: glass beads  Normal Load: 5 MPa
Layer Thickness: 6 mm  Background Shear Velocity: 5 µm/s
T (°C): 23.4  RH(%): 40

Shear Velocity Amplitudes: 5, 15, 25, 160µm/s
Shear Velocity Frequencies: 1, 4 Hz
Continuous Oscillations or Pulses: pulses, 1 s duration
Acoustic Vibration: no
Notes:

Experiment: p1001S2gr005  Date: 05/13/06

Project: shear velocity oscillations

Material: glass beads  Normal Load: 5MPa
Layer Thickness: 2 mm  Background Shear Velocity: 5 µm/s
T (°C): 23.4  RH(%): 40

Shear Velocity Amplitudes: 10, 15, 20, 30, 40, 80 µm/s
Shear Velocity Frequencies: 1, 2, 4 Hz
Continuous Oscillations or Pulses: pulses
Acoustic Vibration: no
Notes:
Experiment: p1005S3gr005  Date: 05/14/06

Project: shear velocity oscillation

Material: glass beads  Normal Load: 5 MPa
Layer Thickness: 3 mm  Background Shear Velocity: 5, 10 µm/s
T (°C): 23.5  RH(%): 43.5

Shear Velocity Amplitudes: 1, 2, 3, 5 µm/s
Shear Velocity Frequencies: 0.02, 0.05, 0.07, 0.1, 0.2 Hz
Continuous Oscillations or Pulses: continuous
Acoustic Vibration: no
Notes:

Experiment: p1017GR005  Date: 05/24/06

Project: large velocity steps (with A.R)

Material: granite blocks  Normal Load: 5MPa
Layer Thickness: 0 mm  Background Shear Velocity: 5 µm/s
T (°C): 23.5  RH(%): 26

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses:
Acoustic Vibration: no
Notes: velocity steps (control file is bigstep1)
Experiment: p1049S3mr005
Project: large velocity steps (w/ A.R.)

Material: F110
Layer Thickness: 3 mm
Normal Load: 5 MPa
Background Shear Velocity:

T (°C): 23.7
RH(%): 47.5

Shear Velocity Amplitudes:
Shear Velocity Frequencies:
Continuous Oscillations or Pulses:
Acoustic Vibration: no

Notes: big velocity steps (bigstep1 control file), using 2nd dcdt mounted on sample

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Experiment: p1059GR005
Project: large velocity steps (w/ A.R.)

Material: granite blocks
Layer Thickness: 0 mm
Normal Load: 5MPa
Background Shear Velocity:

T (°C): 24.7
RH(%): 55

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses:
Acoustic Vibration: no

Notes: velocity steps (control file is bigstep1), using 2nd dcdt mounted on sample
Experiment: p1060S3mr025  
Date: 05/14/06

Project: large velocity steps (w/ A.R.)

Material: F110  
Normal Load: 5 MPa

Layer Thickness: 3 mm  
Background Shear Velocity:

T (°C): 25.7  
RH(%): 57

Shear Velocity Amplitudes:

Shear Velocity Frequencies:

Continuous Oscillations or Pulses:

Acoustic Vibration: no

Notes: big velocity steps (bigstep2 control file), using 2nd dcdt mounted on sample

Experiment: p1061S3mr025  
Date: 06/20/06

Project: large velocity steps (w/ A.R.)

Material: F110  
Normal Load: 5MPa

Layer Thickness: 3 mm  
Background Shear Velocity:

T (°C): 25.1  
RH(%): 50

Shear Velocity Amplitudes: μm/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses:

Acoustic Vibration: no

Notes: velocity steps (control file is bigstep2), using 2nd dcdt mounted on sample
Experiment: p1068S3mr025  Date: 06/28/06

Project: large velocity steps (w/ A.R.)

Material: F110  Normal Load: 5 MPa
Layer Thickness: 3 mm  Background Shear Velocity:

T (°C): 25.1  RH(%): 52

Shear Velocity Amplitudes:

Shear Velocity Frequencies:

Continuous Oscillations or Pulses:

Acoustic Vibration: no

Notes: big velocity steps (rubinstep1 control file), using 2nd dcdt mounted on sample

Experiment: p1084S3mr025  Date: 07/16/06

Project: large velocity steps (w/ A.R.)

Material: F110  Normal Load: 5MPa
Layer Thickness: 3 mm  Background Shear Velocity:

T (°C): 25.4  RH(%): 51

Shear Velocity Amplitudes: µm/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses:

Acoustic Vibration: no

Notes: velocity steps (control file is part1,2,3,4), using 2nd dcdt mounted on sample
Experiment: p1085S3mr025 & Date: 07/17/06

Project: large velocity steps (w/ A.R.)

Material: F110 & Normal Load: 5 MPa

Layer Thickness: 3 mm & Background Shear Velocity:

T (°C): 26.1 & RH(%): 51.5

Shear Velocity Amplitudes:

Shear Velocity Frequencies:

Continuous Oscillations or Pulses:

Acoustic Vibration: no

Notes: velocity steps (control file is rubinsteps part1,2,3,4), using 2nd dc/dt mounted on sample, testing diff. frictional parameters for rubinsteps

Experiment: p1086S3gr004 & Date: 07/17/06

Project: acoustic vibrations

Material: glass beads & Normal Load: 5MPa

Layer Thickness: 3 mm & Background Shear Velocity: 5 µm/s

T (°C): 27 & RH(%): 53

Shear Velocity Amplitudes: µm/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses:

Acoustic Vibration: yes

Notes: running pulses of acoustic vibes, 20 V amp
Experiment: p1087S4gr004  
Date: 07/18/06

Project: acoustic vibrations

Material: glass beads  
Normal Load: 5 MPa

Layer Thickness: 3 mm  
Background Shear Velocity: 5, 10 µm/s

T (°C): 27  
RH(%): 50

Shear Velocity Amplitudes:  
Shear Velocity Frequencies:  
Continuous Oscillations or Pulses:  
Acoustic Vibration: yes  
Notes: pulses, run in for 2.5 mm

Experiment: p1088S4gr004  
Date: 07/18/06

Project: acoustic vibrations

Material: glass beads  
Normal Load: 4 MPa

Layer Thickness: 4 mm  
Background Shear Velocity: 5, 10 µm/s

T (°C): 27  
RH(%): 50

Shear Velocity Amplitudes: µm/s  
Shear Velocity Frequencies: Hz  
Continuous Oscillations or Pulses:  
Acoustic Vibration: yes  
Notes: running pulses of acoustic vibs, impulse every 100ms
Experiment: p1089S4gr004  
Date: 07/19/06

Project: acoustic vibrations

Material: glass beads  
Normal Load: 4 MPa

Layer Thickness: 4 mm  
Background Shear Velocity: 5 µm/s

T (°C): 29  
RH(%): 60

Shear Velocity Amplitudes:

Shear Velocity Frequencies:

Continuous Oscillations or Pulses:

Acoustic Vibration: yes

Notes: first half of the experiment is single pulses, the second half is repeating pulses

---

Experiment: p1090S2gr004  
Date: 07/19/06

Project: acoustic vibrations

Material: glass beads  
Normal Load: 4MPa

Layer Thickness: 2 mm  
Background Shear Velocity: 5 µm/s

T (°C): 30  
RH(%): 53

Shear Velocity Amplitudes: µm/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses:

Acoustic Vibration: yes

Notes: running single multiple pulses, tried to erase memory effect by backing off normal stress to 4 MPa
Experiment: p1091S6gr004  Date: 07/19/06

Project: acoustic vibrations

Material: glass beads  Normal Load: 4 MPa
Layer Thickness: 6 mm  Background Shear Velocity: 5 µm/s
T (°C): 29  RH(%): 60

Shear Velocity Amplitudes:

Shear Velocity Frequencies:

Continuous Oscillations or Pulses:

Acoustic Vibration: yes

Notes: first half of the experiment is single pulses, the second half is repeating pulses

Experiment: p1108S4gr004  Date: 08/04/06

Project: acoustic vibrations

Material: glass beads  Normal Load: 4MPa
Layer Thickness: 4 mm  Background Shear Velocity: 5 µm/s
T (°C): 30  RH(%): 47

Shear Velocity Amplitudes: µm/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses:

Acoustic Vibration: no

Notes: running control for acoustic experiments
Experiment:  p1110S4gr004       Date: 08/09/06

Project:  acoustic vibrations

Material:  glass beads           Normal Load:  4 MPa
Layer Thickness:  4 mm           Background Shear Velocity:  5 µm/s
T (°C):  30                      RH(%):  46

Shear Velocity Amplitudes:

Shear Velocity Frequencies:

Continuous Oscillations or Pulses:

Acoustic Vibration:  no

Notes:  running control for acoustic experiments


Experiment:  p1138GR005       Date: 08/30/06

Project:  shear velocity vibrations

Material:  granite blocks       Normal Load:  5MPa
Layer Thickness:  0 mm           Background Shear Velocity:  5 µm/s
T (°C):  25                      RH(%):  50

Shear Velocity Amplitudes:  µm/s

Shear Velocity Frequencies:  Hz

Continuous Oscillations or Pulses:

Acoustic Vibration:  no

Notes:  trying 3, 5, 10 MPa normal stress, adding Belleville washers, no stick slips
Experiment: p1140GR005  Date: 09/01/06

Project: shear velocity oscillations

Material: granite blocks  Normal Load: 5 MPa
Layer Thickness: 0 mm  Background Shear Velocity: 5 µm/s
T (°C): 23.4  RH(%): 49

Shear Velocity Amplitudes:
Shear Velocity Frequencies:
Continuous Oscillations or Pulses:
Acoustic Vibration: no
Notes: using Belleville washers

Experiment: p1141GR005  Date: 09/03/06

Project: shear velocity vibrations

Material: granite blocks  Normal Load: 5MPa
Layer Thickness: 0 mm  Background Shear Velocity: 5 µm/s
T (°C): 25  RH(%): 50

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses:
Acoustic Vibration: no
Notes: adding Belleville washers, washed off blocks halfway through and reloaded
**Experiment:** p1142GR010  
**Date:** 09/03/06

**Project:** shear velocity oscillations

**Material:** granite blocks  
**Normal Load:** 10 MPa

**Layer Thickness:** 0 mm  
**Background Shear Velocity:** 5 µm/s

**T (°C):** 23.4  
**RH(%):** 52.6

**Shear Velocity Amplitudes:** 15, 25, 35, 50, 75 µm/s

**Shear Velocity Frequencies:** 1, 2, 3 Hz

**Continuous Oscillations or Pulses:** pulses, 0.33, 0.5 s duration

**Acoustic Vibration:** no

**Notes:** using Belleville washers, got stick-slips, rerunning p936

---

**Experiment:** p1143GR005  
**Date:** 09/05/06

**Project:** shear velocity vibrations

**Material:** granite blocks  
**Normal Load:** 5MPa

**Layer Thickness:** 0 mm  
**Background Shear Velocity:** 5 µm/s

**T (°C):** 23.6  
**RH(%):** 61

**Shear Velocity Amplitudes:** 15, 25, 35, 50, 75 µm/s

**Shear Velocity Frequencies:** 1, 2, 3 Hz

**Continuous Oscillations or Pulses:**

**Acoustic Vibration:** no

**Notes:** adding Belleville washers
Experiment: p1144GR010  
Date: 09/06/06

Project: shear velocity oscillations

Material: granite blocks  
Normal Load: 10 MPa

Layer Thickness: 0 mm  
Background Shear Velocity: 5 µm/s

T (°C): 23  
RH(%): 56

Shear Velocity Amplitudes: 35, 50, 60, 100, 150, 200 µm/s

Shear Velocity Frequencies: 1, 2, 3 Hz

Continuous Oscillations or Pulses: pulses, 1 s duration

Acoustic Vibration: no

Notes: using Belleville washers

Experiment: p1145GR010  
Date: 09/06/06

Project: shear velocity vibrations

Material: granite blocks  
Normal Load: 10 MPa

Layer Thickness: 0 mm  
Background Shear Velocity: 5 µm/s

T (°C): 23  
RH(%): 50

Shear Velocity Amplitudes: 20, 60 µm/s

Shear Velocity Frequencies: 1 Hz

Continuous Oscillations or Pulses: pulses

Acoustic Vibration: no

Notes: adding Belleville washers
Experiment:  p1146GR010  Date: 09/07/06

Project: shear velocity oscillations

Material: granite blocks  Normal Load: 10 MPa
Layer Thickness: 0 mm  Background Shear Velocity: 5 \( \mu m/s \)

\( T (°C): \) 24  RH(%): 50

Shear Velocity Amplitudes: 60 \( \mu m/s \)
Shear Velocity Frequencies: 1 Hz
Continuous Oscillations or Pulses: pulses, 1 s duration

Acoustic Vibration: no
Notes:

Experiment:  p1165S3gr005  Date: 09/27/06

Project: shear velocity vibrations

Material: glass beads  Normal Load: 5MPa
Layer Thickness: 3 mm  Background Shear Velocity: 5 \( \mu m/s \)


\( T (°C): \)  RH(%):

Shear Velocity Amplitudes: 40, 80, 120, 160 \( \mu m/s \)
Shear Velocity Frequencies: 1, 2, 3, 4 Hz
Continuous Oscillations or Pulses: pulses

Acoustic Vibration: no
Notes:
Experiment: p1166GR005  
Date: 09/27/06

Project: shear velocity oscillations

Material: granite blocks  
Normal Load: 5 MPa

Layer Thickness: 0 mm  
Background Shear Velocity: 5 µm/s

T (°C):  
RH(%): 

Shear Velocity Amplitudes: 35, 40, 80, 120, 160 µm/s

Shear Velocity Frequencies: 1, 2, 3, 4 Hz

Continuous Oscillations or Pulses: pulses, 0.25, 0.33, 0.5, 1 s duration

Acoustic Vibration: no

Notes:

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Experiment: p1169S3mr025  
Date: 10/02/06

Project: large velocity steps

Material: F110  
Normal Load: 25MPa

Layer Thickness: 3 mm  
Background Shear Velocity: µm/s

T (°C): 23.2  
RH(%): 43

Shear Velocity Amplitudes: µm/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses: n/a

Acoustic Vibration: no

Notes: control file = p1169.200 (Rubinsteps)
Experiment: p1172GR005                    Date: 10/04/06

Project: shear velocity oscillations

Material: granite blocks                      Normal Load: 5 MPa

Layer Thickness: 0 mm                           Background Shear Velocity: 5 µm/s

T (°C): 23                        RH(%): 53

Shear Velocity Amplitudes: 40, 80, 120, 160 µm/s

Shear Velocity Frequencies: 1, 2, 3, 4 Hz

Continuous Oscillations or Pulses: pulses, 0.25, 0.33, 0.5, 1 s duration

Acoustic Vibration: no

Notes:

Experiment: p1173GR005                    Date: 10/04/06

Project: shear velocity oscillations

Material: granite blocks                      Normal Load: 5MPa

Layer Thickness: 0 mm                           Background Shear Velocity: 5 µm/s

T (°C):                               RH(%):  

Shear Velocity Amplitudes: 40, 80, 120, 160 µm/s

Shear Velocity Frequencies: 1, 2, 3, 4 Hz

Continuous Oscillations or Pulses: pulses

Acoustic Vibration: no

Notes:
Experiment:  p1176S2gr005  Date: 10/09/06

Project:  shear velocity oscillations

Material:  glass beads  Normal Load:  5 MPa

Layer Thickness:  2 mm  Background Shear Velocity:  5 µm/s

T (°C):  23  RH(%):  51

Shear Velocity Amplitudes:  5, 10, 15, 20, 30, 40, 60 µm/s

Shear Velocity Frequencies:  1 Hz

Continuous Oscillations or Pulses:  pulses, 1 s duration

Acoustic Vibration:  no

Notes: 

Experiment:  p1177S6gr005  Date: 10/09/06

Project:  shear velocity oscillations

Material:  glass beads  Normal Load:  5 MPa

Layer Thickness:  6 mm  Background Shear Velocity:  5 µm/s

T (°C):  23.2  RH(%):  53

Shear Velocity Amplitudes:  15, 20, 30, 40, 60 µm/s

Shear Velocity Frequencies:  1 Hz

Continuous Oscillations or Pulses:  pulses, 1 s duration

Acoustic Vibration:  no

Notes:  tried to get layers to slide stably at 3 MPa normal stress for vsteps but never got stable sliding
Experiment: p1178GR005          Date: 10/09/06

Project: shear velocity oscillations

Material: granite blocks        Normal Load: 5 MPa
Layer Thickness: 0 mm           Background Shear Velocity: 5 µm/s
T (°C): 23                      RH(%): 51

Shear Velocity Amplitudes: 30, 40, 50 µm/s
Shear Velocity Frequencies: 1 Hz
Continuous Oscillations or Pulses: pulses, 1 s duration
Acoustic Vibration: no
Notes:

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Experiment: p1180S3mr025       Date: 10/11/06

Project: large velocity steps

Material: F110                 Normal Load: 25 MPa
Layer Thickness: 3 mm           Background Shear Velocity: µm/s
T (°C): 24                      RH(%): 48

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies: Hz
Continuous Oscillations or Pulses: n/a
Acoustic Vibration: no
Notes: running rubin steps, control file is next.150
**Experiment:** p1195S6gr001  
**Date:** 10/24/06

**Project:** shear velocity oscillations

**Material:** glass beads  
**Normal Load:** 1 MPa

**Layer Thickness:** 6 mm  
**Background Shear Velocity:** 5 µm/s

**T (°C):** 23  
**RH(%):** 26

**Shear Velocity Amplitudes:** µm/s

**Shear Velocity Frequencies:** Hz

**Continuous Oscillations or Pulses:**

**Acoustic Vibration:** no

**Notes:** running velocity steps, changed normal load to 0.5 MPa

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**Experiment:** p1218GR005  
**Date:** 11/20/06

**Project:** large velocity steps

**Material:** F110  
**Normal Load:** 25 MPa

**Layer Thickness:** 3 mm  
**Background Shear Velocity:** µm/s

**T (°C):** 23  
**RH(%):** 22

**Shear Velocity Amplitudes:** µm/s

**Shear Velocity Frequencies:** Hz

**Continuous Oscillations or Pulses:** n/a

**Acoustic Vibration:** no

**Notes:** running rubin steps, no on board dcdt
Experiment:  p1220S3mr025                          Date: 12/04/06

Project: large velocity steps

Material: F110                          Normal Load: 25 MPa

Layer Thickness: 3 mm                  Background Shear Velocity: $\mu$m/s

T (°C): 22                           RH(%): 17

Shear Velocity Amplitudes: $\mu$m/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses:

Acoustic Vibration: no

Notes: running rubin velocity steps, control files are 12.4.part1, 12.4.part2

Experiment:  p1226GR005                          Date: 12/19/06

Project: shear velocity oscillations

Material: granite blocks                  Normal Load: 5MPa

Layer Thickness: 0 mm                  Background Shear Velocity: 5 $\mu$m/s

T (°C): 24                           RH(%): 20

Shear Velocity Amplitudes: $\mu$m/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses: pulses

Acoustic Vibration: no

Notes:
Experiment: p1227GR005  Date: 12/20/06

Project: shear velocity oscillations

Material: granite blocks  Normal Load: 5 MPa

Layer Thickness: 0 mm  Background Shear Velocity: 5 µm/s

T (°C): 25  RH(%): 18

Shear Velocity Amplitudes: 5, 10, 40, 80, 200, 400 µm/s

Shear Velocity Frequencies: 1, 2, 5, 10 Hz

Continuous Oscillations or Pulses: pulses

Acoustic Vibration: no

Notes: 5 and 10 Hz were no good

Experiment: p1359GR005  Date: 04/24/07

Project: acoustic vibrations

Material: granite blocks  Normal Load: 5MPa

Layer Thickness: 0 mm  Background Shear Velocity: 5 µm/s

T (°C): 29.3  RH(%): 21

Shear Velocity Amplitudes: µm/s

Shear Velocity Frequencies: Hz

Continuous Oscillations or Pulses: n/a

Acoustic Vibration: no

Notes: control experiment for vibration tests
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<td>T (°C): 29.4</td>
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<td>Shear Velocity Frequencies Hz</td>
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<td>Continuous Oscillations or Pulses: n/a</td>
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<td>Acoustic Vibration: yes, 5 kHz freq</td>
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<td>T (°C): 27.2</td>
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<td>Continuous Oscillations or Pulses: n/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Acoustic Vibration: yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Notes: played around to find resonance frequency</td>
</tr>
</tbody>
</table>
Experiment: p1362S4gr005  Date: 04/25/07

Project: acoustic vibrations

Material: glass beads  Normal Load: 5 MPa
Layer Thickness: 4 mm  Background Shear Velocity: 5 µm/s
T (°C): 27.2  RH(%): 27.4

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies Hz
Continuous Oscillations or Pulses: n/a
Acoustic Vibration: yes
Notes: tried removing horizontal and vertical loads to remove memory

Experiment: p1364S4gr005  Date: 04/26/07

Project: acoustic vibrations

Material: glass beads  Normal Load: 5MPa
Layer Thickness: 4 mm  Background Shear Velocity: 5 µm/s
T (°C): 25.3  RH(%): 33.1

Shear Velocity Amplitudes: µm/s
Shear Velocity Frequencies Hz
Continuous Oscillations or Pulses: n/a
Acoustic Vibration: yes
Notes: rerunning p1362 for repeatability
Experiment: p1366S4gr005                   Date: 04/27/07

Project: acoustic vibrations

Material: glass beads                   Normal Load: 5 MPa

Layer Thickness: 4 mm                   Background Shear Velocity: 5 µm/s

T (°C): 25.2                             RH(%): 38.7

Shear Velocity Amplitudes: µm/s

Shear Velocity Frequencies Hz

Continuous Oscillations or Pulses: n/a

Acoustic Vibration: yes

Notes: slide-hold-slides, vibrate during holds

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Experiment: p1367S4gr005                   Date: 04/27/07

Project: acoustic vibrations

Material: glass beads                   Normal Load: 5MPa

Layer Thickness: 4 mm                   Background Shear Velocity: 5 µm/s

T (°C): 26                               RH(%): 42

Shear Velocity Amplitudes: µm/s

Shear Velocity Frequencies Hz

Continuous Oscillations or Pulses: n/a

Acoustic Vibration: yes

Notes: running acoustic vibrations during velocity steps
Curriculum Vita: Heather M. Savage

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Education

The Pennsylvania State University, Ph.D., Geosciences, 8/07.  
Dissertation: The Effects of Friction on earthquake triggering and fault zone evolution. Chris Marone, advisor.

University of Massachusetts, Amherst, M.S., Geosciences, 2002.  


Awards, Grants and Fellowships

Marathon Alumni Centennial Graduate Fellowship (2004-2005)

Krynine Award, Dept. of Geosciences, PSU (2003, 2004)

Sigma-Xi Research Grant (2000)


Professional Experience

Graduate Research Assistant, Penn State University (2003-2007)
Graduate Teaching Assistant, Penn State University (2002,2004,2006)
Laboratory Instructor, Mount Holyoke College (2002)
Graduate Teaching/Research Assistant, University of Massachusetts (1999-2001)
Hydrogeologist, Lessard Environmental, Danvers, MA (1998-1999)