

The Pennsylvania State University

The Graduate School

College of Earth and Mineral Sciences

LABORATORY STUDIES OF FAULT STABILITY AND SLOW  
EARTHQUAKES

A Dissertation in

Geosciences

by

John R. Leeman

© 2017 John R. Leeman

Submitted in Partial Fulfillment  
of the Requirements  
for the Degree of

Doctor of Philosophy

May 2017

The dissertation of John R. Leeman was reviewed and approved\* by the following:

Chris Marone  
Professor of Geosciences  
Dissertation Advisor  
Chair of Committee

Demian Saffer  
Dissertation Advisor  
Professor of Geosciences

Sridhar Anandakrishnan  
Professor of Geosciences

Richard Alley  
Professor of Geosciences

Derek Elsworth  
Professor of Energy and Mineral Engineering

Demian Saffer  
Associate Head for Graduate Programs and Research

---

\*Signatures on file in the Graduate School.

## Abstract

Fault zones are areas of localized deformation that accommodate strain in the Earth's crust accumulated over time due to tectonic motion or stress transfer from adjacent areas. Faults are traditionally considered to accommodate this strain by either constant slow movement (creep), or by rapid catastrophic failure events (earthquakes). The behavior of faults which produce earthquakes has been extensively studied, including characterization of the time and slip predictability of earthquakes, frequency-magnitude distributions, aftershock decay patterns, dynamic triggering, and frictional processes. Chance observations in global positioning system (GPS) data from the Vancouver Island area in 2001 revealed a new kind of fault slip that had not been considered before, slow-slip events. Since those early observations, slow-slip events have been observed at most major subduction interfaces and even in glacial systems.

In this dissertation, I strive to answer some of the fundamental questions about slow-slip systems. Little is known about the dynamics of these systems and how they operate. Scattered laboratory observations have provided clues, but this study is the first systematic examination of slow-slip earthquakes and their frictional behavior in the laboratory. I examine questions such as what controls how a fault zone will fail and what the velocity and normal stress sensitivities are, then connect those mechanisms to observations from a natural slow-slip system beneath Whillans Ice Stream in western Antarctica.

In chapter 1, I demonstrate how to modify the stiffness of the testing machine to create slow-slip events in the laboratory in an artificial granular material. I also present a method to automatically calculate the stiffness of each slip event in a given experiment. Chapter 2 extends this work into a synthetic fault gouge material and carefully examines the sensitivity of the system to the stiffness of the testing apparatus. Chapter 3 introduces the new parameter of velocity dependence into the test suite and demonstrates that designer frictional laws (those whose velocity dependence of friction is itself velocity dependent) are not necessary to explain observations of slow-slip. Chapter 4 introduces the field area of Whillans Ice Stream, a system that hosts slow-slip events daily at an ice-till interface approximately 1 km below the ice surface. I test samples of the till obtained by piston coring of the ice stream in 1989 and develop a simple hydrologic model to determine the potential stress states of the system and an effective medium model to predict the acoustic velocities under those stresses. The entire system is then examined in the light of stability theory to postulate why it has been able to remain in the slow-slip regime for as long as it has been observed. Finally, in chapter 5 I examine the generation of electrical potential differences on slipping experimental faults and critically evaluate the generation mechanisms proposed in the literature.

This dissertation provides insight into the mechanisms and controls of fault slip. I demonstrate that fault failure is not a bifurcation between stable and unstable, but rather a continuous spectrum of failure modes from slow to fast stick-slip. The evidence provided shows that the stiffness of the system is the dominant controlling mechanism and that higher order frictional terms are not required to explain the basic spectrum of behaviors observed.

## Table of Contents

List of Tables . . . . .	xii
List of Figures . . . . .	xiii
Acknowledgments . . . . .	xxxv
Preface . . . . .	xxxvi
Introduction . . . . .	1
Chapter 1. Stiffness evolution of granular layers and the origin of repetitive, slow, stick-slip frictional sliding . . . . .	6
1.1 Abstract . . . . .	6
1.2 Introduction . . . . .	7
1.3 Methods . . . . .	10
1.3.1 Experimental Configuration . . . . .	10
1.3.2 Data Analysis . . . . .	12
1.4 Algorithm Description . . . . .	13
1.5 Results . . . . .	15
1.6 Discussion . . . . .	17
1.7 Conclusions . . . . .	20

Chapter 2. Laboratory observations of slow earthquakes and the spectrum of tectonic fault slip modes . . . . .	36
2.1 Abstract . . . . .	36
2.2 Introduction . . . . .	37
2.3 Results . . . . .	40
2.3.1 Mechanical Behavior . . . . .	40
2.3.2 Stick-Slip Events . . . . .	40
2.4 Discussion . . . . .	41
2.5 Methods . . . . .	45
2.5.1 Experimental Apparatus . . . . .	45
2.5.2 Sample Preparation . . . . .	45
2.5.3 Testing Procedure . . . . .	46
2.5.4 Frictional Stability . . . . .	46
Chapter 3. Characterization of Laboratory Slow Earthquakes . . . . .	56
3.1 Abstract . . . . .	56
3.2 Introduction . . . . .	57
3.2.1 Rate-and-State Friction . . . . .	57
3.2.2 Critical Stiffness and Stability . . . . .	59
3.3 Materials and Methods . . . . .	60
3.3.1 Apparatus . . . . .	60
3.3.2 Sample Material . . . . .	62
3.3.3 Sample Preparation . . . . .	62

3.3.4	Experimental Procedure . . . . .	63
3.3.5	Data Analysis . . . . .	63
3.3.6	Modifying $\kappa$ . . . . .	65
3.4	Results . . . . .	65
3.4.1	Normal Stress Dependence of Stability . . . . .	66
3.4.2	Velocity Dependence of Stability . . . . .	66
3.4.3	Friction Drop . . . . .	67
3.4.4	Variation of $(a - b)$ . . . . .	69
3.5	Discussion . . . . .	69
3.5.1	Friction Drop . . . . .	69
3.5.2	Rate-and-State Modeling . . . . .	70
3.5.3	Evolution of Stiffness and Stability . . . . .	72
3.5.4	Velocity Dependent Behavior . . . . .	74
3.6	Conclusions . . . . .	75
3.7	Acknowledgments . . . . .	76

Chapter 4.	Mechanical and hydrologic properties of Whillans ice stream till: Im-	
	plications for basal strength and stick-slip failure . . . . .	99
4.1	Abstract . . . . .	99
4.2	Introduction . . . . .	100
4.2.1	Geologic Setting . . . . .	103
4.3	Materials and Methods . . . . .	104
4.3.1	Sample Preparation . . . . .	104

4.3.2	Tri-axial Loading . . . . .	105
4.3.3	Permeability and Compressibility . . . . .	106
4.3.4	Acoustic Velocity . . . . .	107
4.4	Results . . . . .	108
4.4.1	Consolidation and Compressibility . . . . .	109
4.4.2	Permeability . . . . .	110
4.4.3	Acoustic Velocity . . . . .	111
4.4.4	Hydrologic Model . . . . .	112
4.5	Discussion . . . . .	115
4.5.1	Till physical properties and relevance to sticky spot development	115
4.5.2	Shearing Processes . . . . .	117
4.5.3	Effective Stiffness Feedback Mechanism . . . . .	118
4.6	Conclusions . . . . .	119
4.7	Effective Medium Model Formulation . . . . .	121
Chapter 5. On the origin and evolution of electrical signals during frictional stick		
	slip in sheared granular material . . . . .	136
5.1	Abstract . . . . .	136
5.2	Introduction . . . . .	137
5.3	Previous Work . . . . .	138
5.3.1	Natural Occurrences . . . . .	138
5.3.2	Previous Experimental Work . . . . .	139
5.4	Methods . . . . .	142

5.4.1	Apparatus . . . . .	143
5.4.2	Sample Material & Preparation . . . . .	144
5.4.3	Potential Measurement . . . . .	145
5.4.4	Experimental Procedure . . . . .	146
5.4.5	Calibration and Control Tests . . . . .	147
5.4.6	Data Analysis . . . . .	148
5.5	Results . . . . .	149
5.5.1	Mechanical Data . . . . .	149
5.5.2	Electrical Data . . . . .	151
5.6	Discussion . . . . .	152
5.6.1	Electro-Mechanical Model . . . . .	154
5.7	Conclusions . . . . .	156
5.8	ESVM Calibration . . . . .	158
	Appendix A. List of Biaxial Experiments . . . . .	172
	Appendix B. List of Triaxial Experiments . . . . .	181
	Appendix C. Sample Preparation Procedures . . . . .	183
C.1	Biaxial Double Direct Shear . . . . .	183
C.1.1	Materials . . . . .	183
C.1.2	Procedure . . . . .	184
C.2	Triaxial Shrink Jacketing . . . . .	214
C.2.1	Materials . . . . .	214

C.2.2 Procedure . . . . .	215	
Appendix D. Load Cell Theoretical Response . . . . .		224
D.1 Introduction . . . . .	224	
D.2 Load Cell Design . . . . .	224	
D.2.1 Material properties . . . . .	225	
D.2.2 Mechanical design . . . . .	225	
D.2.3 Electrical design . . . . .	226	
D.3 Predicted response . . . . .	228	
Appendix E. Load Cell Calibration Procedure . . . . .		230
E.1 Introduction . . . . .	230	
E.2 Calibration procedure . . . . .	230	
E.3 Typical measured response . . . . .	234	
Appendix F. DCDT Calibration Procedure . . . . .		235
F.1 Introduction . . . . .	235	
F.2 Calibration procedure . . . . .	236	
F.3 Typical measured response . . . . .	237	
Appendix G. Look File Format Description and Biaxtools . . . . .		239
G.1 Purpose . . . . .	239	
G.2 Description . . . . .	239	
G.2.1 ASCII Files . . . . .	239	
G.2.2 Binary Files . . . . .	240	

G.3 Cautions . . . . .	241
G.4 Usage . . . . .	241
G.4.1 Return Formats . . . . .	241
G.4.2 ASCII Files . . . . .	241
G.4.3 Binary Files . . . . .	242
G.5 Acknowledgements . . . . .	242
G.6 Code . . . . .	243
Bibliography . . . . .	250

## List of Tables

1.1	Two state variable parameters obtained from friction data inversion with all steel forcing blocks (p4113). . . . .	34
1.2	Load up stiffnesses during run-in for different forcing block configurations. Note that the steel/acrylic combination is much closer to the stiffness of all steel blocks than that of all acrylic blocks. . . . .	35
4.1	Physical parameters used to construct the effective medium model of compressional and shear wave velocities. Values are based on Dvorkin [1999] and Wang [2001]. . . . .	135
5.1	List of Experiments . . . . .	170
5.2	Composition of glass beads. . . . .	171

## List of Figures

1.1	Experimental data showing examples of tests used to measure rate-and-state frictional parameters. (A) velocity step test in which loading velocity is changed from 150 $\mu\text{m/s}$ to 500 $\mu\text{m/s}$ . Note transient evolution of friction followed by attainment of a new steady-state. (B) results for four slide-hold-slide tests in which shearing velocity is set to zero for a period (the hold) before re-shearing, showing holds of 30, 100, 300, and 1000 seconds. Frictional healing ( $\Delta\mu$ ) increases with the logarithm of hold time. . . . .	22
1.2	The biaxial press with supporting and forcing blocks in place. Double-direct shear samples consist of three blocks: two side blocks and a center block. Gouge layers are between the forcing blocks and confined with side-shields and a rubber membrane. (After Leeman et al.) . . . . .	23
1.3	A scanning electron micrograph of undeformed baking flour. Grain sizes are observed to vary in the 10-200 $\mu\text{m}$ range. The material has a platy appearance reminiscent of clay and other phyllosilicate minerals. . . . .	24
1.4	Slow-slip and stick-slip events can be characterized by their slip duration, recurrence time, stress drop, and elastic loading stiffness. These quantities can be used to quantify the effective system stiffness and frictional properties including the rate of restrengthening (healing). . . . .	25

1.5 Data for three experiments with different forcing blocks and effective system stiffnesses. The acrylic only and steel-acrylic experiments exhibited slow stick-slip behavior, while steel forcing blocks produced only stable sliding. . . . .	26
1.6 (A) Friction data during slide-hold-slide tests over an entire experiment with steel forcing blocks. Note initial load-up: there is a region of peak strength followed by weakening and the attainment of steady-state strength after shear of $\sim 10$ mm. This test included three sets of holds lasting from 3 to 1000 seconds. (B) Friction parameter $\Delta\mu$ vs. the log of hold time for the slide-hold-slide tests shown in panel A. Healing exhibits log-linear behavior, independent of net shear displacement. . . . .	27
1.7 (A) Friction data for experiment p4113 with steel loading blocks, and (B) healing determined from slide-hold-slide tests. The sample exhibited limited stick-slip/slow-slip behavior, but only at a load point velocity of 5 $\mu m/s$ . Frictional instability appears as a wide band of noise at the scale shown, around 10 and 40 mm load point displacement. Holds ranged from 3 to 1000 seconds and velocity steps from 5 to 1500 $\mu m/s$ . . . . .	28
1.8 Velocity steps in an all steel forcing block configuration can only be fit by a two state variable model. A) 15 - 50 $\mu m/s$ B) 50 - 150 $\mu m/s$ C) 150 - 500 $\mu m/s$ . . . . .	29

1.9 (A) Stiffness and (B) Stress drop and slip duration for events in experiments with all acrylic forcing blocks. Stiffness increases on the rise to steady state by a factor of nearly two and remains remarkably constant. Stress drops rapidly increase by a factor of two over the first twenty events before reaching a steady state. Slip duration begins at nearly twenty-five seconds, then rapidly decreases to around five seconds. . . . .	30
1.10 (A) Stiffness and (B) Stress drop and slip duration for events in the steel/acrylic forcing block system. Stiffness follows a similar trend to the all-acrylic experiment, but exhibits a smaller increase with strain. Stress drop increases rapidly, but then returns and maintains its initial level until a second family of events occurs around events 80-120. Slip duration begins faster than for the all-acrylic blocks and stays lower with more scatter. . . . .	31
1.11 Two groups of stick-slip events are evident after sufficient shearing in the steel/acrylic system. At the expected shear failure point there are several small failures, but the layer recovers and continues to load to a higher stress before failure. . . . .	32
1.12 Response of the system with various effective stiffnesses. The stability boundary is crossed between the steel and steel/acrylic system. Stiffnesses shown are the initial load up stiffnesses of the sample. All data are from the same displacement range, but have been offset in shear stress for clarity. . . . .	33





2.4 Stiffness during an experiment. Friction data for one complete experiment (run p4316) with shear load-unload cycles. Slow slip events emerge spontaneously at a displacement of $\sim 8.5$ mm. (Inset) Stiffness measured from unload-reload cycles in the range $\mu = 0.3 - 0.4$ (large grey circles) and from the slope of the elastic loading segments of individual stick-slip events (small black circles). Both measurements indicate an initial increase in stiffness, caused by shear enhanced compaction. In this experiment we explored multiple shearing rates during slow slip (e.g., for events in the range 27-29 mm and 31-33 mm), which had a clear effect on stick-slip amplitude and stiffness. . . . .	51
2.5 Rate and State Parameters. Data and modeling procedure for obtaining rate-and-state friction parameters and their variation with shear displacement. A) Data from experiment p4309 (grey data points) and model (solid line) for a velocity step test from 10 to 1 $\mu\text{ms}^{-1}$ , with illustration of the friction direct effect a, evolution effect b, and critical slip distance Dc. B) Evolution of (b-a) with shear displacement (see also 4.3A). Note the transition from rate strengthening to rate weakening at $\sim 8$ mm displacement, after which a steady-state behavior is reached. C) The critical slip distance decreases with shear displacement as frictional steady-state is reached. D) Evolution of the critical stiffness ( $k_c$ ) with slip. . . . .	52





3.7 A) Friction drops decrease with increased loading velocity in a log-linear fashion. B) The division between stable (near zero friction drop) and unstable (significant friction drop) conditions is apparent as a nearly straight boundary in the normal stress - driving velocity space. For a given normal stress, the transition can be seen in the whitening of the data points. . . . .	83
3.8 Mean friction at a range of velocities for experiments with normal stresses ranging from 5–13 MPa show a linear decrease in friction with increasing velocity. The slope of this line is $(a - b)$ and has a value of $-0.00482$ for all data shown. . . . .	84
3.9 By fitting the mean friction at multiple velocities at each normal stress, $(a - b)$ estimates show a linear decrease in $(a - b)$ with normal stress. Assuming that all other factors remain constant, this would mean at a given velocity, an increase in normal stress would reduce $(a - b)$ making the system more unstable. This effect would be superimposed on increase of $k_c$ with normal stress. . . . .	85
3.10 The onset of instability occurs over tens of slip cycles in our data (A) and a simple rate-and-state friction model (B). Each successive friction drop is larger with increased slip displacement, velocity, and acceleration. The acceleration/deceleration magnitudes are nearly identical for these nearly sinusoidal onset events. In the model, the behavior was very sensitive to small perturbations in $(a - b)$ and $D_c$ . . . . .	86

3.11 A) An experimental plot of four slow-slip events, their time-friction curve, time-slider velocity curve, and phase plots. Notice that the top DCDT remains very close to the loading velocity, while the bottom DCDT becomes virtually stationary during the loading phase of the slip events. This indicates significant storage of strain energy in the forcing block. The bottom DCDT shows the slipping part of the experimental fault to slip faster than the top of the loading block, but with a nearly identical velocity profile. B) When setting $\kappa = 1$ in a single state-variable rate-and-state friction model, a small perturbation will setup a limit cycle in which the system continually slow-slips, retracing the same path in phase space. The magnitude of the friction drop and peak slip velocity are dependent upon the size of velocity perturbation imposed on the system. . . . .	87
3.12 The observed loading stiffness of our experimental system exhibits a slight increase with loading velocity. . . . .	88
3.13 Compiling data from 12 – 13 MPa normal stress where $(a - b)$ is roughly constant, we see that small variations in $(a - b)$ are not ruled out by our data. Variations as small as 0.0005 can make a significant difference in behavior when a system is near the stability boundary. . . . .	89
3.14 The critical slip distance $D_c$ , increases systematically with velocity in F110 experiments. While F110 is significantly larger than Min-U-Sil, it is of similar composition. Data from Mair [1999] . . . . .	90

3.15 The critical slip distance and frictional parameter ( $a - b$ ) trade off linearly to modify the critical stiffness ratio. When near the stability boundary, small changes in ( $a - b$ ) can produce stable behavior (vertical line), but changes of a few microns in $D_c$ can produce the same transition. The most likely scenario is that both parameters change with velocity, both increasing the stability of the system with increased driving velocity. . . . .	91
3.16 Particle size distribution (A) and cumulative size distribution (B) for Min-U-Sil 40. . . . .	92
3.17 An SEM micrograph of Min-U-Sil shows its angular nature. . . . .	93
3.18 The effective stiffness of each stick-slip event at a given normal stress as a function of displacement. Notice the quick rise once events begin and asymptotic approach of a final steady-state value. . . . .	94
3.19 Effective stiffness of each stick-slip event at a given driving velocity as a function of displacement. . . . .	95
3.20 Friction drop for each stick-slip event at a given normal stress as a function of displacement. . . . .	96
3.21 Friction drop for each stick-slip event at a given driving velocity as a function of displacement. . . . .	97
3.22 Duration, mean velocity (slip distance/slip duration), and peak velocity for events at a constant driving velocity (A) and constant normal stress (B). . . . .	98

4.1 Samples for this study were obtained from borehole 89-1-4 near the junction of the B1 and B2 branches of Whillans Ice Stream. Ice velocities of 600 m/yr are typical in the region [Rignot et al., 2011; Mouginot et al., 2014]. The grounding line is marked in solid black. . . . .	123
4.2 A) The completed sample assembly ready to be loaded into the pressure vessel. B) Schematic diagram of the tri-axial loading cell. Heat shrink tubing was used as a thin, low-strength jacketing material. A hydraulic syringe pump provided isotropic confining and axial loading stresses. A linearly variable displacement transformer (LVDT) measured sample stain. Two high-precision water syringe pumps imposed a hydraulic head to determine sample permeability. Piezoelectric transducers in the loading platens measured the elastic wave travel time through the core (inset). . . . .	124
4.3 To determine permeability, flow rates from the upstream (blue) and downstream (green) pumps are fit with a least squares fit (red) when the steady-state flow condition is achieved (shaded area). The procedure is repeated at multiple hydraulic heads for repeated permeability measurement. . . . .	125
4.4 An example acoustic waveform collected during the step-loading test. Inset shows changes in travel time with step loading to 1 MPa effective stress. First arrivals are picked with a cross-correlation technique for consistency. . . . .	126

4.5 A) Results of the isotropic step loading test show an expected compaction behavior. B) Effective stress and volumetric strain relationship. Initial loading (1) and unloading (2) shows near elastic recovery. Reloading to a 10MPa effective stress (3) created considerable permanent deformation upon the final unloading cycle (4). C) Evolution of axial strain during repeated tidal load cycling. All cycles had a 24-hour period with amplitudes of +/- 25, 50, 75, and 150 kPa. D) Strain was accumulated during all cycle sets, but the additional observed strain decreased with each subsequent set until the amplitude was increased. . . . .	127
4.6 A) Permeability evolution during the step-loading test. Initial permeability values of approximately $3.510^{-17} \text{ m}^2$ were reduced by over an order of magnitude during the initial loading (1) with little recovery upon unloading (2). Permeability was reduced by an order of magnitude during reloading (3) to an effective stress of 10 MPa. B) Initial porosity values of 28% are lower than field estimates. The trend mirrors that of volumetric strain. C) Evolution of permeability and porosity during the tidal loading test indicate that both can be significantly reduced with little additional loading stress, but with load cycling. Initial porosity of 32% was reduced by several percent over the 60 simulated tidal cycles. D) Permeability was also reduced by an order of magnitude during the cycling. All measurements shown were taken after cycling was complete and the sample had equilibrated. . . . .	128

4.7 (A) Predicted compressional and shear wave velocities from the effective medium model as a function of effective stress, (B) an expanded view showing field velocity measurements from seismic experiments, and porosity (C). The model is supported by experimental compressional wave velocity measurements, but no shear wave measurements could be obtained in the laboratory due to the very low effective pressures of the experiment. Black circles represent direct measurements from the laboratory, gray bars are velocity estimates by Luthra et al. [2016] and black triangles are estimates by Blankenship et al. [1987]. . . . .	129
4.8 A) Flow chart showing the sequence used when computing the 1-D hydrologic model. B) A cartoon version of the system with ice unloading the till beneath it on a tidal timescale. Upward drainage as a result of lower effective stress at the ice-till interface will quickly result in the formation of a hard layer that slows further drainage and limits the hard layer depth to tens of centimeters. C) Loading from the ice will inject water back into the till as the basal hydraulic pressure is increased. . . .	130
4.9 Model results for a coupled diffusion/compaction model of the till layer with an imposed 50 kPa effective stress perturbation at the top boundary. The perturbation can affect the till over several tens of centimeters in a 12 hour tidal time scale. Over a longer perturbation, such as moving over a rough area on the bed, the till can come close to equilibrium in a month. . . . .	131

4.10 XRD analysis shows very high clay content in the till samples with significant amounts of quartz as well. Some non-uniqueness exists in the type of clays present, but an effort was made to minimize the misfit with reasonable geological constraints. . . . .	132
4.11 A) Evolution of volumetric strain during repeated tidal load cycling. B) Strain was accumulated during all cycle sets, similar to the axial strain trends, but with some slight anomalies likely induced by thermal effects on pump volume measurements as volume changes are very small. . . .	133
4.12 Experimental data and fits used in loading portions of the simple hydrologic model. Porosity-permeability (A) was fit with an exponential, while effective stress - porosity (B) and effective stress - compressibility (C) were fit with logarithmic relationships. . . . .	134
5.1 Experimental setup. A) The biaxial hydraulic press: sample assemblies are supported by steel blocks in the sample area. B) Double direct shear geometry consists of two layers of gouge confined between three forcing blocks. Side shields and a plastic membrane are used to contain gouge material as the sample is sheared. C) Placement of the electrostatic voltmeter (yellow cylinder) in the side and top view positions. A window was cut into the side shield for the side view geometry. . . . .	159
5.2 Scanning electron microscope micrographs of the starting glass beads for all experiments. A) 100-150 $\mu m$ B) 420-500 $\mu m$ . . . . .	160

5.3 Experiments performed on glass beads (100-150 $\mu m$ diameter) under ambient humidity, 100% humidity, and submerged conditions exhibit similar mechanical behavior. Increased stress drops are observed with increased humidity and in the submerged case. Inset: Anatomy of a stick-slip event. The recurrence time is the time between peaks in shear stress. Initially the shear stress increases linear-elsastically. Deviation from line-elastic behavior marks the onset of elasto-plastic deformation and pre-seismic slip. When the ultimate strength of the layer is reached shear stress drops rapidly and the cycle begins again. . . . .	161
5.4 A) Samples exhibit a log-log linear relation between recurrence time and velocity. Faster loading rates result in shorter recurrence times. B) Friction drop increases with the recurrence time as there is more time for the layer to heal before the next stick-slip event. . . . .	162
5.5 During shearing two trends are observed: 1) A long-term charging/discharging trend in the electrical potential and 2) Potential change related to individual stick-slip events. The entire system initially charges, approximately until mechanical steady-state is reached. During this phase co-seismic potential changes are dominantly positive (top left inset). After attainment of mechanical steady-state, the system begins to maintain or discharge potential. During this phase the co-seismic potential changes are dominantly negative (top right inset). . . . .	163

5.6 Stick-slip events and associated ESVM measurements for three-different load point velocities of 1, 30, and 100 $\mu\text{m}/\text{s}$ . A) At slow loading velocities the electrical signal clearly mirrors the stress curve in most cases B) For intermediate velocities, the relation is still present. C) At high velocities, the electrical signal is a sharp pulse an order of magnitude higher than those observed at low velocities, and we observe small inter-seismic charging. . . . .	164
5.7 Each order of magnitude driving velocity change produces a $\sim 5\times$ increase in the electrical signal observed. All experiments shown are with the side-view sensor geometry. . . . .	165
5.8 A schematic representation of the stages of electrical behavior during an experiment: A) During the initial run-in there is massive grain rearrangement as force chain networks begin to form. This sliding motion tribo-electrically charges the system. B) After the force chain network forms there is minimal grain-boundary sliding. Shear loads are supported in the granular layer by highly stressed force chains (dark colors). Electron holes migrate away from highly stressed beads into the matrix creating an electrical potential gradient. C) When the layer fails and all grains are at roughly the same low stress, a return current redistributes the electrical gradient and the cycle begins again. . . . .	166

5.9 Calibration of the ESVM from a function generator source (bottom panel). A series of steps through the ESVM ‘response’ setting from 1-9 shows that the input square wave applied to the aluminium surface under test is well-recorded on each setting (top panel). The upward trend in ESVM data is a product of a DC offset that occurs each time the response setting is changed on the instrument. . . . .	167
5.10 A detailed comparison of a single waveform shows that at lower response settings (lighter colors) the waveform is smoothed slightly, with the nearly instantaneous voltage change distributed over up to 0.1 seconds on both the rise and fall. At higher resolutions (darker colors) the sharp transition is clearly seen, but at the price of a higher noise level during the flat hold states. . . . .	168
5.11 At all response settings the beginning of ESVM signal change corresponds well in the time domain with the leading and falling edge of the input signal. Smoothing due to longer integration times is observed at low response settings. . . . .	169
C.1 Gather all blocks and ensure that they are clean and free of debris. . . .	190
C.2 Stack shims to adjust the sample thickness. Note which shims are used. . . .	190
C.3 Measuring the sample thickness with a steel rule. . . . .	191
C.4 Carefully fold over the corner of the tape and trim any excess length. . . .	192
C.5 A fully taped side block. . . . .	193
C.6 Setup a jig to trim the excess tape height. . . . .	194

C.7 Carefully trim the tape on all four sides of the block. Note the angle of the razor blade. . . . .	194
C.8 Label the side blocks to help keep track of the mass of material in each layer. . . . .	195
C.9 Weigh the blocks after all taping and trimming is completed. . . . .	196
C.10 Carefully pour sample material into the taped area of the block. . . . .	197
C.11 Using a sliding and chopping action, evenly distribute the sample material over the side block. . . . .	197
C.12 Firmly compress the sample to ensure a good granular packing. . . . .	198
C.13 Drag the steel rule over the sample to flatten the layer. . . . .	199
C.14 A completed side block ready to be weighed and assembled. . . . .	200
C.15 Setup the jig for assembling the side and center blocks into the complete sample assembly. . . . .	200
C.16 Place the sideblock into the jig with the side shield mounts facing towards you. . . . .	201
C.17 Place a spacer at the top of the side block to help support the center block's weight. . . . .	202
C.18 Place the center block and secure it with small strips of tape. Note the counterweight block on top of the center block. . . . .	203
C.19 Rearrange the jig so that the sample can be taped without moving. . . . .	203
C.20 Place one strip of tape around the bottom and sides of the sample. . . . .	204
C.21 Add two more strips of tape, each offset from the others to provide the best seal of the sample material. . . . .	205

C.22 Stand the assembly up on the workbench. . . . .	206
C.23 Tape the top of the assembly. . . . .	207
C.24 Follow the same procedure to add the second side block to the assembly. . . . .	207
C.25 Using a razor blade, carefully trim out the holes for mounting side shields on each side block. . . . .	208
C.26 Mark the rubber skirt width and trim it to size. . . . .	209
C.27 Position the trimmed rubber skirt beneath the sample and make sure that no side shield mounting points will be covered. . . . .	210
C.28 Temporarily secure the rubber skirt with tape. . . . .	211
C.29 Secure the side shields to the sample assembly with the proper hardware. Replace any worn or stripped hardware. . . . .	212
C.30 Measure the bench thickness of the assembly using calipers and note it on the experiment run sheet. . . . .	213
C.31 If the sample is not going to be run immediately, store it with slight pressure from two steel blocks to help prevent the layers from reshaping. . . . .	213
C.32 The black jacket section used to seal to the bottom piston assembly. This jacket is as high as is acceptable. It is recommended to start much lower and raise the jacket later to clamp it into place. . . . .	218
C.33 The sample after shrink tube is applied with a heat gun and the bottom tie wire is fixed. Notice that there are no pockets or wrinkles in the jacket and it conforms smoothly to the sample surface. . . . .	219

C.34 The piston end of the sample completely assembled. The shrink jacket does not go inside the black jacket, but just to the top of it. Hose clamps are used for additional insurance against leaks. Care must be taken to avoid damaging the heat shrink or black jacket with sharp edges on the clamps. . . . .	220
C.35 To offset weak points in the sealing system, make sure that all clamp and tie points are offset by a minimum of 90°. . . . .	221
C.36 Both tie wires have been affixed. The wire does not overlap anywhere and sits on the groove in the end caps. Ends of the wire have been trimmed to $\sim \frac{1}{4}$ ". . . . .	222
C.37 The complete sample assembly, ready to be loaded into the pressure vessel and tested. . . . .	223
D.1 Mechanical drawings of the two styles of load cells used in the lab. Dimensions are in mm. Oblique view not to scale. . . . .	226
D.2 Electrical schematic of the 8-gauge load cell design. Orientation 1 and 2 are marked for identification convenience. . . . .	227
D.3 Physical construction of the load cell and arrangement of strain gauges. gauge sets are set apart by 90°. Electrical points marked * are connected. . . . .	227
E.1 A proper setup of the load cell, steel puck, proving ring stack. Notice the careful alignment of all members. . . . .	232
E.2 An example of a proving ring dial under no load that needs adjustment. Simply loosen the dial face set-screw to move the gauge legend. . . . .	233

E.3 An example calibration obtained from the 44mm solid load cell. . . . .	234
F.1 An example calibration obtained from a DCDT. . . . . . . . . . .	238

## Acknowledgments

I am forever indebted to my parents, Russell and Dianne Leeman for their lifelong support of my curiosity and for teaching me the value of hard work. Doctoral research is impossible without these. My wife, Lendi, has been more supportive and understanding than I ever knew was possible.

My colleagues in the department of geoscience provided many stimulating discussions. I especially would like to thank Dr. Charles Ammon for the large amounts of time we spent in discussion on many topics and side projects. Our talks broadened my interests and led me to a deeper understanding and appreciation of many subjects.

Last, but not least, thank you to all members of my committee. Without your guidance, help, and advice the work presented here would not have been possible. All of the work presented here is cross-disciplinary because of your collaboration, patience, and willingness to embark on new lines of inquiry.

## Preface

The work presented in this dissertation is a result of collaboration with faculty at Penn State, as well as other institutions. The motivation, data creation, analysis, and writing are my own work. Chapters 1, 2, 4, and 5 have been peer-reviewed and can be found in the literature with the following citations:

Leeman, J., Scuderi, M. M., Marone, C., and Saffer, D. (2015). Stiffness evolution of granular layers and the origin of repetitive, slow, stick-slip frictional sliding. *Granular Matter*, 17(4):447–457.

Leeman, J., Saffer, D., Scuderi, M., and Marone, C. (2016). Laboratory observations of slow earthquakes and the spectrum of tectonic fault slip modes. *Nature communications*, 7.

Leeman, J.R., Valdez, R.D., Alley, R.B., Anandakrishnan, S., and Saffer, D.M. (2016). Mechanical and hydrologic properties of Whillans ice stream till: Implications for basal strength and stick-slip failure. *Journal of Geophysical Research: Earth Surface*, 121(7):1295–1309, 2016.

Leeman, J. R., Scuderi, M. M., Marone, C., Saffer, D. M., and Shinbrot, T. (2014). On the origin and evolution of electrical signals during frictional stick-slip in sheared granular material. *Journal of Geophysical Research: Solid Earth*, 119(5):4253–4268.

Chapter 3 is currently being revised for submission with the following author list:

Leeman, J.R., Marone, C., and Saffer, D.

Somewhere, something incredible is waiting to be known.

—Carl Sagan

Out of the cradle onto the dry land here it is standing...

atoms with consciousness... matter with curiosity.

Stands at the sea... wonders at wondering... I... a universe  
of atoms... an atom in the universe.

—Richard P. Feynman

## Introduction

The movement of rocks relative to each other caused by tectonic strain accumulation results in zones of localized deformation. Strain energy is effectively released as slip, which is most efficiently accommodated in a relatively thin zone of movement oriented favorably with the regional stress field. These zones of slip host a variety of complex processes which are still poorly understood. The material properties of the rocks, and therefore the mineralogy, controls the frictional properties of the interface. Geochemical processes can move minerals around through dissolution-precipitation processes and even accommodate slow creep movement of the rock. Hydrologic properties of the system can serve to increase or decrease the fluid pressure on the fault and even determine if mechanisms such as dilation hardening are allowed to operate. The existing geologic system can introduce complications through many processes, including the roughening of the fault surface through subduction of seamounts and other structural processes. These slowly evolving geologic systems are transformed during seismic slip of meters/second into systems with rapid change and extreme conditions which are poorly understood. The transformation between the two is quite possibly the most important part of the process and is not able to be explored in the real world due to the distance and measurement limitations imposed by the geology.

Laboratory rock mechanics studies have been recreating portions of fault zone conditions and behavior on a very small scale (millimeters to meters), but have not been widely utilized by the broader earthquake community. Seismologists often have data that

is spatially limited by the location of measured events and cannot resolve the details that are observed in the laboratory. Experimentalists are often focused on the minutia of the frictional dynamics of the system and are not able to connect their observations to the large-scale global experiment of plate tectonics. This disconnect calls for the realization that rock mechanics could and should be treated as experimental seismology. In this dissertation, I attempt to study the general mechanisms of slip mode determination and connect them to a single natural system. While that is a limited scope, I believe that more of such work can begin to build the bridge between the experimental and observational fields that is desperately needed to understand this complex phenomena.

Friction, or the force resisting the movement of two surfaces relative to each other, is one of the key parameters that control the nucleation stage of earthquakes. In the case of a two-block slider model, friction is defined as the ratio of shear stress to normal stress. Early models of friction used a single value of friction for materials at all velocities and conditions. For most Earth materials, this number is in the range 0.6-0.8. Early explorations of friction began to discover that friction is not a static quantity, but that it was different when stationary versus when in motion. These so-called static and dynamic friction values are often as complicated as many analyses get, but even they do not explain all the observations of careful experimentation. Observations of the velocity dependence of friction, time dependence of friction, and memory effects from past states all indicated the need for a more complex formulation. The rate-and-state friction framework captures many of these observations, but is at its core an empirical relation with arbitrary frictional parameters.

The rate-and-state friction relation allows friction to change as a function of the sliding velocity of the system (rate) and the history of the system (state). The parameters in the basic relation are the direct effect,  $a$ , the evolution effect,  $b$ , and the critical slip distance  $D_c$  which are fully described in chapter 1. The state of the system is determined by a second equation, the state relation. Common state relations have the state as a function of either time or slip on the fault. This simple model can capture behaviors such as velocity strengthening/weakening, time dependent healing, and even a transition in behavior from stable to unstable. In recent years, there have been works which extend the basic model, from the use of multiple state variables and designer friction relations in which the frictional parameters are themselves functions of velocity, to more complex state relations.

Analysis of the rate-and-state friction relation shows that a Hopf bifurcation occurs under certain conditions and completely changes the behavior of the system. On one side of the bifurcation, the system is stable and responds to perturbations in a finite time and the system reaches a new state of equilibrium in which friction is constant. The other side of the bifurcation represents unstable behavior. In the unstable regime, the system never reaches a new equilibrium state and is continually experiencing accelerations. The sliding velocity of unstable systems is nearly zero for a period of time. During this stuck period the far field movement of the system accumulates energy stored as strain in the elastic media. Once the friction on the interface reaches a critical value, the system catastrophically fails and rapidly accelerates. During the slip phase of motion, heat is generated, material is pulverized, and elastic radiation is produced. This stick-slip cycle has often been cited as an analog for naturally occurring earthquakes, as

well as a variety of other phenomena including cutting tool chatter and animal sound production.

In terms of the rate-and-state friction framework, the bifurcation is observed to occur at a value of stiffness of the system termed the critical stiffness ( $k_c$ ). When the system is stiffer than the critical stiffness, energy can be released from the system faster than the system can weaken, so it remains in a stable sliding state. When the system is more compliant than the critical stiffness, the system weakens faster than energy can be released, resulting in a growing energy imbalance that produces large accelerations and stick-slip behavior.

While the strict bifurcation of behavior seemed to be adequate for earthquake science - faults either hosted earthquakes or did not - the engineering sciences were not satisfied. Examination of other dynamical systems shows that there are often regions of transitory or intermediate behavior. The boundary between the regions may indeed be sharp, but not infinitely sharp as predicted. For example, the behavior of control systems shows that regions of critical stability exist in which the system is not completely unstable and uncontrolled, but in which the controller is struggling to control the process variable. Likewise, with more comprehensive physics or complex relations, the rate-and-state friction relation can begin to exhibit more complex behaviors.

The discovery of slow earthquakes confirmed that the frictional behavior of faults is not a simple stable-unstable boundary, but in fact a continuum that hosts a rich variety of complex behaviors. In this dissertation, I use small-scale laboratory studies to explore this spectrum of behaviors and determine which frictional properties and complications are needed to explain the observations. I apply these ideas to a natural slow-slipping

system beneath Whillans Ice Stream in western Antarctica. My main contributions are demonstrations of how to generate the range of slip modes in the laboratory, to show that the critical stiffness ratio indeed explains many of the first order behaviors, and to show that the behavior of a system is indeed velocity dependent.

## Chapter 1

# Stiffness evolution of granular layers and the origin of repetitive, slow, stick-slip frictional sliding

### 1.1 Abstract

We demonstrate the frictional behaviors of steady state sliding, stick-slip, and repetitive, slow stick-slip sliding through a carefully-designed suite of laboratory experiments focused on exploring the role of loading system stiffness in controlling the frictional response to shear. We performed tests on sheared layers of baking flour, with three configurations of loading blocks made of steel and cast acrylic to achieve different stiffnesses. Slide-hold-slide and velocity step tests were conducted and analyzed in a rate-and-state friction framework. With compliant loading blocks, the material exhibits unstable stick-slip behavior with slow-slip events of duration up to twenty seconds. Slow-slip has been difficult to achieve in the lab and has only been observed for a narrow variety of boundary conditions and materials. Our results suggest that this behavior is strongly controlled by the stiffness of the system, the strain history of the sample, and shear fabric evolution. We describe a new suite of automated tools that greatly improve friction analysis and provide insight to the underlying mechanisms of slow stick-slip. We demonstrate that layer stiffness evolves with shear strain and modifies the mechanical behavior of stick-slip sliding. Our work suggests that slow earthquakes in tectonic fault zones may be linked to

shear fabric development and associated changes in local stiffness, likely in combination with variations in frictional constitutive properties and effective stress.

## 1.2 Introduction

Although stick-slip is generally considered an analog for earthquakes Brace and Byerlee [1969]; Johnson et al. [2013] in the framework of stable or unstable sliding, it has recently become evident that there is a spectrum of fault slip behaviors Peng and Gomberg [2010]. The discovery of slow earthquakes and non-volcanic tremor Ikari et al. [2013]; Beroza and Ide [2011]; Obara [2002]; Ide et al. [2007b] has raised questions about the link between fault zone frictional properties, in situ conditions, and the underlying mechanisms of slow-slip Kaproth and Marone [2013].

The rate and state frictional model provides a convenient framework in which to examine the frictional response of materials and characterize their second order frictional characteristics that are thought to control the stability of sliding Brace and Byerlee [1966, 1969]; Gu et al. [1984]; Marone [1998]. The rate and state equation (eq.1.1) describes friction ( $\mu$ ) in terms of a direct effect ( $a$ ), an evolution effect ( $b$ ), a state variable ( $\theta$ ), and the velocity of both the slider ( $V$ ) and load point or reference velocity ( $V_0$ ). The evolution of the state variable can be described by various relations Marone [1998]. Here, we consider the Dieterich (slowness) relation (eq.1.2) as it provides a scheme to interpret time dependent healing of materials, although we note that recent works favor the Ruina (slip) state evolution law Marone and Saffer [2015]; Bayart et al. [2006]. To describe more complex frictional behavior, a third term is often appended to equation 1.1 adding terms  $b_2$ ,  $D_{c2}$ , and  $\theta_2$ .

$$\mu = a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{D_c} \right) + b_2 \ln \left( \frac{V_0 \theta_2}{D_{c2}} \right) \quad (1.1)$$

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_c} \quad (1.2)$$

Materials may slide in a stable manner or fail in a stick-slip fashion. The transition between stable sliding and stick-slip is generally viewed as a Hopf bifurcation that can be thought of as occurring at a critical stiffness ( $k_c$ ), defined in Equation 1.3 for quasi-static motion Rice and Gu [1983]; Gu et al. [1984]. For values of stiffness greater than  $k_c$ , the system is stable. When  $k$  approaches and falls below  $k_c$ , the system undergoes damped oscillations and then enters an unstable regime that corresponds to stick-slip behavior. From Equation 1.3, it is clear that velocity strengthening materials ( $a - b > 0$ ) should slide stably, because the critical stiffness becomes negative. They therefore: 1) are unlikely to nucleate large earthquakes; and 2) should arrest rupture that propagates into them. Velocity weakening materials ( $a - b < 0$ ) may undergo stable sliding or stick-slip based on the stiffness of the system in relation to the effective normal stress and friction parameters, expressed by a critical stiffness. The idea of there being two modes of frictional failure (stable sliding and stick-slip) is a generalization of the spectrum of slip behaviors that occurs in the transition between the two Rice and Gu [1983].

$$k_c = \frac{b - a}{D_c} \quad (1.3)$$

For materials that exhibit stable sliding behavior, we can interrogate frictional parameters by imposing velocity steps or conducting slide-hold-slide tests (Fig.1.7). During velocity step tests, the load point velocity is instantaneously changed from one velocity to another and the frictional response of the material recorded. During slide-hold-slide tests, the sample is sheared until friction reaches steady-state ( $\mu_{ss}$ ), then shearing is stopped for a prescribed amount of time. After the hold time has elapsed, shearing begins again at a constant shearing rate and the frictional healing ( $\Delta\mu$ ) is measured as the difference between the peak re-load friction ( $\mu_{peak}$ ) and the initial steady-state value Marone [1998]. Healing can be summarized by the term  $\beta$ , describing a line fit to hold-time ( $t_h$ ) and frictional healing( $\Delta\mu$ ) data on a natural log-linear axis (eq.1.4).

$$\beta = \frac{\Delta\mu}{\ln(t_h)} + c \quad (1.4)$$

The purpose of this paper is to describe work on a novel friction system designed to improve understanding of slow, stick-slip frictional failure. We measure the frictional behavior of sheared layers of baking flour and characterize slip events in terms of stress drop, slip duration, and the loading stiffness in order to explore the relationship between macroscopically observed slip behavior, stiffness, and frictional properties. We vary the stiffness of the loading system and observe changes in frictional failure behavior.

As in most shearing experiments, there are likely deformation and fracture processes occurring at the grain-scale, but these processes do not detract from the goal of showing failure mode behavior with stiffness changes. While flour is a very compliant material, certainly more compliant than the loading system, energy can be stored by

the loading system while the fault zone is ‘locked’ and elastic strain energy accumulated in the loading blocks and load frame. Any air trapped in the granular layer is inconsequential as the low viscosity air can quickly escape as evidenced by our initial layer consolidation. Any remaining air is sufficiently compressible to produce negligible pressurization effects.

### 1.3 Methods

#### 1.3.1 Experimental Configuration

In our experiments, we sheared gouge layers in a double direct shear configuration using a biaxial deformation apparatus with a servo-hydraulic control system Karner and Marone [2000]; Frye and Marone [2002]. In this configuration, two granular layers are sheared between three roughened forcing blocks (Fig.1.7). All experiments were conducted with Gold Medal brand all-purpose flour, enriched, bleached, and pre-sifted. The baking flour is highly compressible and is poly-disperse with grains ranging from about 10-200  $\mu\text{m}$  in diameter (length) with a platy appearance (Fig.1.3).

We measured force with strain gauge load cells placed in series with the loading rams and sample. Displacement was measured with direct current displacement transducers (DCDTs) between the ram nose and end platens of the hydraulic rams. Data were recorded using a 24-bit analog to digital converter. Data were collected at 10 kHz and averaged to the desired rate from 1 Hz to 10 kHz.

In order to achieve different loading system stiffnesses, three combinations of forcing blocks were used: 1) all acrylic blocks; 2) center acrylic with steel side blocks,

and 3) all steel blocks. The forcing blocks were cut to size and machined with grooves (1 mm deep x 2mm spacing on acrylic, 0.8 mm deep x 1 mm spacing on steel) perpendicular to the shearing direction to ensure that shear occurred within the layer and not at the layer boundary Anthony and Marone [2005]; Knuth and Marone [2007]. The nominal frictional contact area was 10 cm x 10 cm.

Layers were built by placing the side forcing blocks on a leveling jig and applying cellophane tape around the perimeter. Two layers of flour were confined in a three forcing block assembly with a rubber membrane at the bottom and side-shields on the boundaries to avoid lateral extrusion of the layer (Fig.1.7). The top of the sample was unconfined.

In all experiments, samples were placed into the loading frame and a normal stress ( $\sigma_n$ ) of 1 MPa was applied and maintained constant in load-feedback servo-control. The layers were sheared by controlling the position of the vertical ram in displacement feedback servo-control, which was driven at a constant displacement rate. The force required to shear at this rate was measured and converted to the shear stress acting on each layer of the double-direct shear arrangement.

In all experiments, a ‘run-in’ period was necessary to reach a stable sliding friction (Fig.1.7). All tests were conducted at an initial load point velocity of 1  $\mu\text{m}/\text{s}$ . In systems that exhibited unstable behavior, the run-in driving velocity was maintained for the duration of the test and the evolution of the slow-slip/stick-slip monitored. When stable sliding behavior was observed, a series of velocity steps and/or slide-hold-slide tests were performed to independently measure second-order frictional properties Marone [1998].

### 1.3.2 Data Analysis

For each individual stick-slip event, we report stress drop, slip duration, recurrence time, and loading stiffness (Fig.1.4). Note that for each event, a period of increasing shear load is observed initially followed by inelastic yielding and plastic strain accumulation during fully-mobilized frictional slip. The stress drop, duration, and recurrence time of each event provide information about frictional properties, including the rate of frictional healing. The linear-elastic portion of the stress-displacement curve (Fig.1.4) is a measure of the system stiffness including testing machine, forcing blocks and sheared layers. This shear stiffness is a key parameter because it is the stiffness that will drive frictional instability if the value falls below the critical friction stiffness  $k_c$  dictated by Equation 1.3.

With large numbers of slow-slip/stick-slip events it is necessary to automate the analysis procedure for both repeatability and efficiency. This is made difficult by electrical and mechanical noise as well as changes in recording rate during the course of the experiment. We address these challenges by developing an algorithm to pick the beginning and end of each slip event in a reliable and repeatable manner with as few user-defined free parameters as possible. After the picks are obtained, the mechanical quantities of interest must be extracted. Some values, such as changes in peak friction, are trivial to compute. However, loading stiffness is slightly more complicated, and requires determining where the load-displacement curve deviates from linearity. We address this problem by using a goodness-of-fit approach, detailed below.

## 1.4 Algorithm Description

We define stick-slip by a stress increase over some time interval and a sudden drop in stress, followed by another event. There are many techniques in the literature of ‘change point detection’ such as CUSUM Page [1954], Student’s T test techniques Buishand [1982], and wavelet methods Raimondo and Tajvidi [2004]. These techniques are generally used for step detection and are not the ideal candidates for repetitive events such as repeating frictional slip. Picking based on derivatives is a more robust technique, and therefore we employ a first-derivative based approach. When the stress is at a peak or trough, the first derivative (with time or shear displacement) is zero by definition. We examine the derivative of shear stress for a sign change or zero crossing as it is unlikely that we will exactly capture the data points for which the derivative is zero to machine precision.

Taking the derivative of noisy, digital lab data can be challenging. In general, for an analytic function or data with no noise, we would approach the problem by using a forward, central, or backward difference approximation. These simplistic techniques work for well-behaved functions with no noise, but for lab data, a running average slope works better. Our method involves a user-defined window size over which a least-squares approach is used. This resulting running average slope technique is robust for noisy data.

To determine loading stiffness of each stick-slip event, we began with the derivative of the stress-displacement curve (Fig.1.4). We then computed an array of signs for the complete data set. Sign change detection identifies the zero-crossings of the running average slope derivative. Pairs of zero crossings are evaluated for their associated stress

drop, with anything below a user defined threshold discarded. This step is necessary to further filter noise and smaller failures. Using the zero crossing generally captures the true maximum and minimum of the data, but occasionally, due to smoothing of noise, may not capture the exact maximum or minimum. After observing the algorithm on many datasets, we found that max/min errors were always small and within the noise; therefore we did not implement a local search around the zero crossing.

The objective when determining the linear-elastic stiffness of each stick-slip is to fit a line to the displacement versus shear stress data, but only to the portion before inelastic deformation and creep begins. In the past this has been done by eye and resulted in limited estimates of stiffness for each experiment as well as inconsistency between picks. To automate this process, we calculate the correlation coefficient of the data (eq.1.5) for many data windows. The algorithm begins with the minimum shear stress for an event with  $n$  data, determined by the derivative technique, and calculates the correlation of three data points (the trough and the two following points). Next, the correlation is calculated for additional data points, up to  $n_{\max}$ . We assume that the deviation from linearity begins after the correlation is maximized. After we define the linear domain, a line is fit to that data segment using a least squares method. This process is repeated for each stick-slip/slow-slip event.

$$r_{xy} = \frac{\sum_{i=1}^n x_i y_i - \sum_{i=1}^n x_i \sum_{i=1}^n y_i}{\sqrt{n \sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i\right)^2} \sqrt{n \sum_{i=1}^n y_i^2 - \left(\sum_{i=1}^n y_i\right)^2}} \quad (1.5)$$

## 1.5 Results

We varied system stiffness by using a range of forcing blocks in the double direct shear assembly. Tests with all acrylic forcing blocks and with acrylic center/steel side block combinations produced slow slick-slip behavior, while tests with all steel blocks generally produced stable sliding behavior (Fig.1.5). For the experiments with steel forcing blocks, frictional sliding was stable. Thus, once friction reached a steady state, we imposed velocity step tests to measure rate/state friction parameters. We note that in one experiment, at  $5 \mu\text{m}/\text{s}$ , the steel block configuration exhibited slow-slip behavior, transitioning to stable sliding at higher velocities. During shear, extrusion and densification of the gouge material occurs Scott et al. [1994], sometimes introducing complicating strain effects.

Slide-hold-slide tests were used to measure frictional healing. Healing tests conducted with steel forcing blocks indicate healing rates ( $\beta$ ) of 0.015-0.018. These rates are consistent with rates obtained on geological materials of several percent Dieterich [1978, 1972]; Marone [1998]; Karner et al. [1997]; Beeler et al. [1994]. We imposed three sets of slide-hold-slide tests at successively higher shear displacements and found no correlation of the healing rate with shear strain, in contrast to previous results Richardson and Marone [1999]. We note however that those studies used granular silicate minerals at higher applied stresses, and thus higher rates of granular comminution. Also, the maximum shear strain in our experiments were less than those in other studies (Fig.1.6). We conducted slide-hold-slide tests before and after velocity step tests to determine any

variation with shear strain. Even after shear displacement of nearly 5 cm, no significant change in healing rate was observed (Fig.1.7). All of our data exhibit a log-linear relationship between healing and hold time.

Velocity step tests were conducted with both up-steps and down-steps in the range: 5, 15, 50, 150, 500, 1500  $\mu m/s$  in the steel forcing block configuration. At 5  $\mu m/s$  the system was unstable, but then exhibited stable behavior at higher velocities. Model fits of selected velocity steps are shown in Figure 1.8. These data show velocity weakening frictional behavior with ( $a - b$ ) values of  $\sim 0.01$  and friction evolution shows a clear two state variable behavior. Best fit parameters are summarized in Table 1.1.

In most friction studies, the system stiffness is taken from a linear portion of the loading curve prior to the sample yielding and attainment of fully mobilized, steady-state frictional sliding. Moreover, this stiffness is generally thought of as the stiffness of the system for the entire experiment. The values in table 1.2 represent the load up stiffness determined via this traditional approach. Load up stiffness values are obtained by fitting a line to the load up curves during experimental run-in. Values for all-steel and steel/acrylic are relatively similar, but the all-acrylic forcing system is about one-third less stiff than the steel system.

We applied our automated picking algorithm for experiments with unstable behavior in acrylic and acrylic/steel blocks. The steel system displayed dominantly stable sliding and could not be interrogated for stiffness with this method. The experiment with all acrylic forcing blocks showed a stress drop pattern that increased to a relatively steady value of 0.014MPa (Fig.1.9). Slip durations began at  $\sim 20$  seconds, then decreased to  $\sim 5$  seconds. Shear loading stiffness increased with shear strain from  $\sim 0.001$  MPa/ $\mu m$

to  $\sim 0.002 \text{ MPa}/\mu\text{m}$  with shear strain until frictional steady state behavior was reached, and then remained stable for the duration of the experiment. Experiments with the steel/acrylic combination (Fig.1.10) show similar stiffness evolution, but the slip durations are much more scattered compared to the all acrylic configuration. These data show the same initial increase in the stress drop, but then decrease to almost their initial states. Finally, there is a second ‘family’ of slip events that appear around event 80 with much larger stress drops (Fig.1.11). These events exhibit the same minimum shear stress, but reach a higher stress before failure. There is also a notable partial failure observed at the nominal shear strength.

## 1.6 Discussion

Our data show that stiffness evolves systematically as a function of shear strain and that stick-slip friction events reflect this evolution. Load point velocity also plays an important role in the transition from stable to unstable sliding.

It has long been known that loading stiffness plays an important role in frictional sliding Jaeger [1971]; Brace and Byerlee [1966], and since its introduction in the 1980’s, rate and state friction theory has provided an approach to quantifying the interplay between elastic stiffness and friction constitutive behavior (eq.1.3) Rice [1983]. Previous works show that the critical friction distance ( $D_c$ ) decreases with shear strain Marone and Kilgore [1993]. However, the evolution of fault zone stiffness with shear strain has not been similarly explored. Our results show that stiffness increases by nearly a factor of two during initial shearing, up to shear strains of  $\sim 3$ . These changes are likely a function of densification, shear localization, and fabric development as elongated particles align

and shear begins to attain its steady state behavior. The fact that characteristics of stick-slip events, such as stress drop and slip duration, evolve over this same range, suggests that both changes in frictional properties and elastic stiffness are important in controlling the mode of slip on faults.

Rate and state friction predicts increased event durations and decreased stress drops with increased effective stiffness, as the system transitions to stable behavior Baumberger and Berthoud [1999]. Our data comparing the different stiffnesses from the three forcing block configurations used seems to verify this prediction (Fig.1.12). However, during each experiment, we observe an increase in stiffness with shear strain that coincides with increased stress drop and reduced slip event duration (Figs.1.9,1.10). This suggests a more complex interplay between the evolution of fabric development, frictional constitutive properties, and system stiffness with shear strain that produces changes in material behavior. Coupling of the stored elastic energy is also believed to influence strain accumulation and release. Because the entire center forcing block acts as a spring (i.e. stores elastic strain), a simple 1-D spring-slider model is overly simplified in the context of our experiments. Accounting for the 2-D geometry and heterogeneity of the elastic loading system that includes both forcing blocks and the gouge layer itself is more realistic. This more complicated elastic coupling would influence the nature of strain accumulation, and the rate at which it is released during failure. The stiffness of the portions of the system where elastic strain energy is stored is most important, as the unloading stiffness of those materials will dictate the rate at which energy can be released to the system during dynamic failure and therefore dictate the failure mode. While the gouge is itself storing some strain energy, we believe that most energy is being

stored in the forcing blocks while the fault zone is locked, hence why the block stiffness exhibits such a strong control on failure mode.

Our data suggest that as strain localizes within the sheared layer, the stiffness of the gouge layer increases, resulting in an overall stiffer elastic system. Strain is localized onto shear surfaces oblique to the layer, such as R1 (cross cutting shear surfaces inclined approximately  $30^\circ$  to the shear direction), B (boundary parallel shears near the forcing block surface), and y (shear parallel surfaces completely contained within the layer) planes Logan et al. [1992]; Marone [1998]. The transition of slip behavior from steady-state sliding to stick-slip (Fig.1.12) is apparent and follows results obtained by Baumberger and Berthoud [1999]. By using compliant blocks that have the capability to store energy where the gouge is interacting with the surface roughness (i.e. rather than steel forcing blocks with a spring in series to modulate stiffness Kaproth and Marone [2013]), we believe that our approach is most analogous to natural fault zones, in which the gouge is coupled to adjacent wall rocks that store strain energy between slip events.

Another curious aspect of these experiments is the unstable behavior observed in steel blocks, but only at low velocity in p4113 (the least stiff of the steel experiments). Even in acrylic blocks, the system would only stick-slip at velocities below  $100 \mu\text{m/s}$ . This is consistent with previous observations of the transition from stick-slip to stable sliding Heslot et al. [1994]. In our experiments, it is possible that healing cannot occur fast enough to support repeated stick-slip behavior at higher velocities. Flour maintains its strong velocity weakening behavior at velocities up to  $1500 \mu\text{m/s}$ , suggesting that stiffness and/or velocity dependent rate and state parameters are necessary to explain the velocity dependent behavior.

Stiffness relations used in arguments about stick-slip and slow-slip events often cite critical rupture patch sizes by assuming an inverse relationship between effective stiffness and nucleation patch size Ikari et al. [2011]. While this argument is valid and physically required, it is likely equally important to consider that effective stiffness evolves during the transition from distributed to localized shear Marone and Saffer [2015]. This combination of factors modifying stiffness likely leads to a more complex fault zone evolution than previously believed. Local variations in stiffness could modulate shear behavior and velocity during rupture propagation or even aid in stopping fast rupture. One possible indication of the local variability of stiffness is the two families of stick-slip events observed in the steel/acrylic case. This behavior is reminiscent of period-doubling in chaotic systems near a critical point. These smaller events could represent local heterogeneities which are too small to rupture the entire layer. It is also very likely that the 1-D stiffness coupling is inadequate to fully describe the system.

## 1.7 Conclusions

We show that repetitive, slow, stick-slip frictional sliding can occur in a sheared layer and that the transition from stable to unstable sliding can be affected by a change in system loading stiffness. While it is not a surprising revelation that stiffness is a factor in frictional slip behavior, the evolution of stiffness with strain that we observe points to a more complicated story. We suggest that stiffness evolves as shear fabric is developed in the layer with increasing shear displacement. This indicates that fault slip style, which is partly dictated by stiffness, may not depend solely on the inverse relation of loading system stiffness to sample dimension. In our system, it is possible

that stiffness of the gouge evolves enough to cause a transition from stable sliding to slow-slip/stick-slip behavior. If our results apply to tectonic faults, they suggest that with progressively increasing net strain/offset, areas experiencing slow-slip events may evolve to an unstable slip condition with potential to host traditional seismic events. Our results were obtained for wheat flour, and it remains to be seen whether similar behavior occurs in geologic materials. We have found similar behavior in preliminary work on finely ground quartz. Further investigation is warranted to determine the range of conditions for which slow slip may occur and whether such behavior is possible for other types of elastic coupling. Work is also underway to measure strain energy stored in the system before, during, and after failure to attempt to quantify some of the possible explanations proposed in this work.

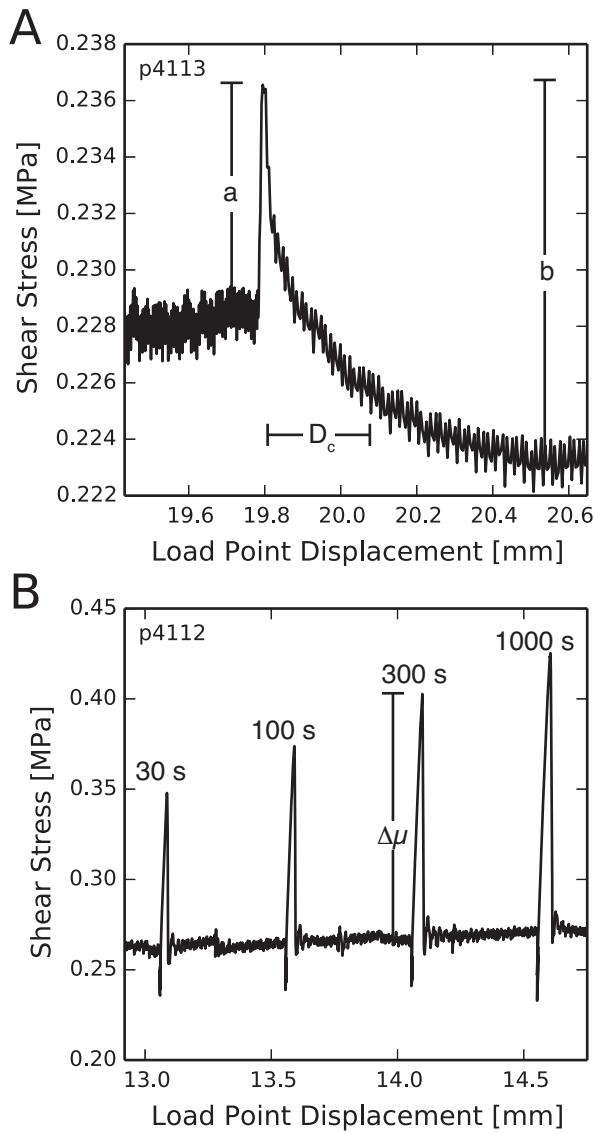


Fig. 1.1. Experimental data showing examples of tests used to measure rate-and-state frictional parameters. (A) velocity step test in which loading velocity is changed from 150  $\mu\text{m}/\text{s}$  to 500  $\mu\text{m}/\text{s}$ . Note transient evolution of friction followed by attainment of a new steady-state. (B) results for four slide-hold-slide tests in which shearing velocity is set to zero for a period (the hold) before re-shearing, showing holds of 30, 100, 300, and 1000 seconds. Frictional healing ( $\Delta\mu$ ) increases with the logarithm of hold time.

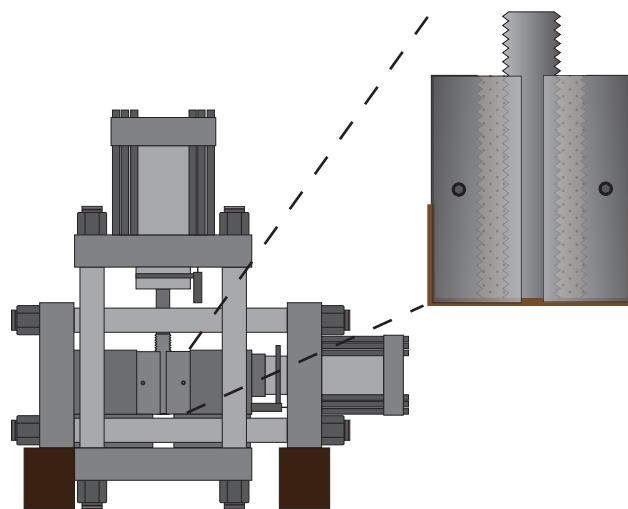


Fig. 1.2. The biaxial press with supporting and forcing blocks in place. Double-direct shear samples consist of three blocks: two side blocks and a center block. Gouge layers are between the forcing blocks and confined with side-shields and a rubber membrane. (After Leeman et al.)

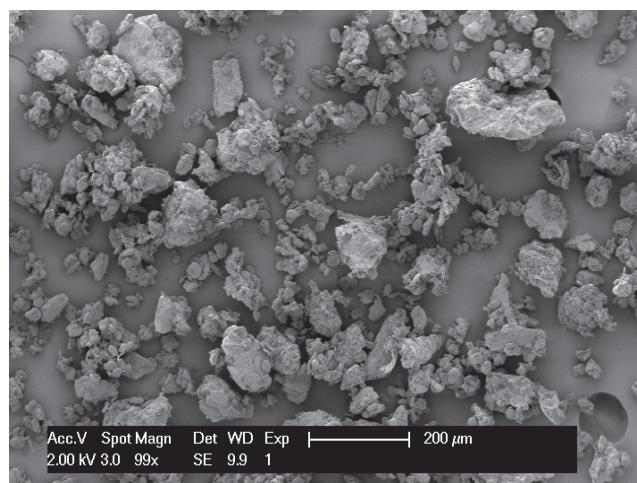


Fig. 1.3. A scanning electron micrograph of undeformed baking flour. Grain sizes are observed to vary in the  $10\text{--}200\ \mu\text{m}$  range. The material has a platy appearance reminiscent of clay and other phyllosilicate minerals.

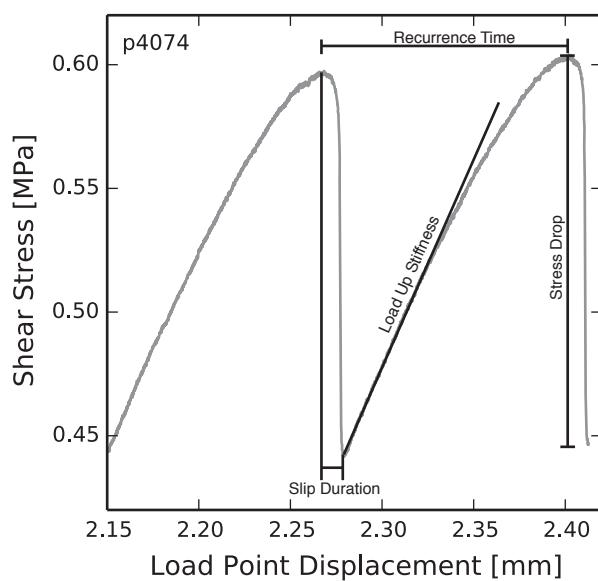


Fig. 1.4. Slow-slip and stick-slip events can be characterized by their slip duration, recurrence time, stress drop, and elastic loading stiffness. These quantities can be used to quantify the effective system stiffness and frictional properties including the rate of restrengthening (healing).

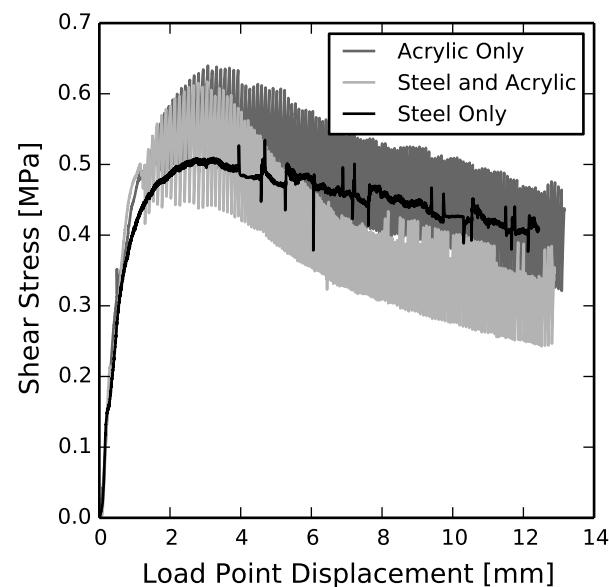


Fig. 1.5. Data for three experiments with different forcing blocks and effective system stiffnesses. The acrylic only and steel-acrylic experiments exhibited slow stick-slip behavior, while steel forcing blocks produced only stable sliding.

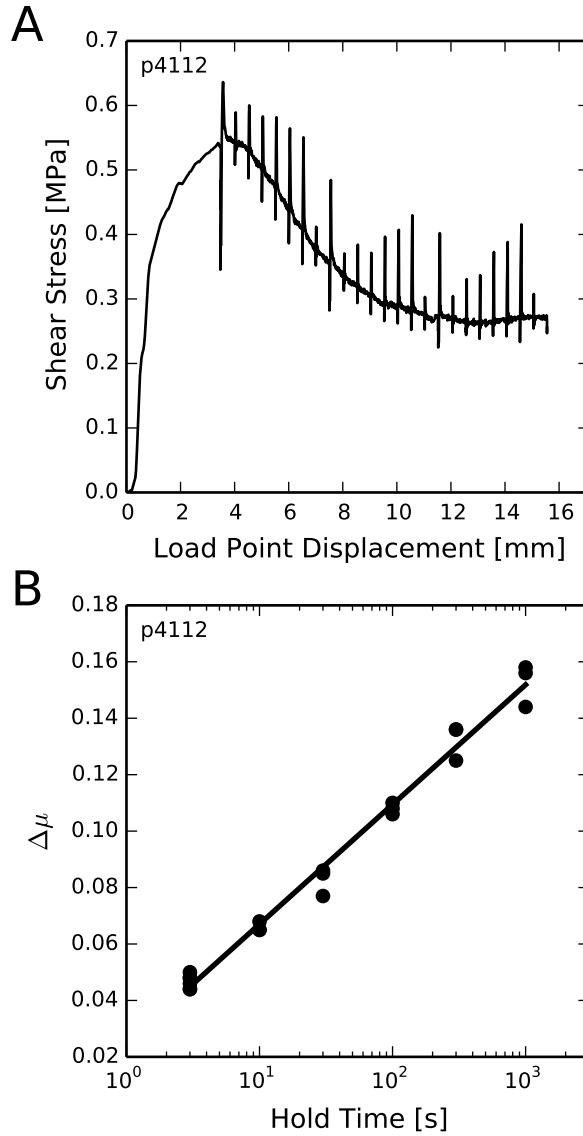


Fig. 1.6. (A) Friction data during slide-hold-slide tests over an entire experiment with steel forcing blocks. Note initial load-up: there is a region of peak strength followed by weakening and the attainment of steady-state strength after shear of  $\sim 10$  mm. This test included three sets of holds lasting from 3 to 1000 seconds. (B) Friction parameter  $\Delta\mu$  vs. the log of hold time for the slide-hold-slide tests shown in panel A. Healing exhibits log-linear behavior, independent of net shear displacement.

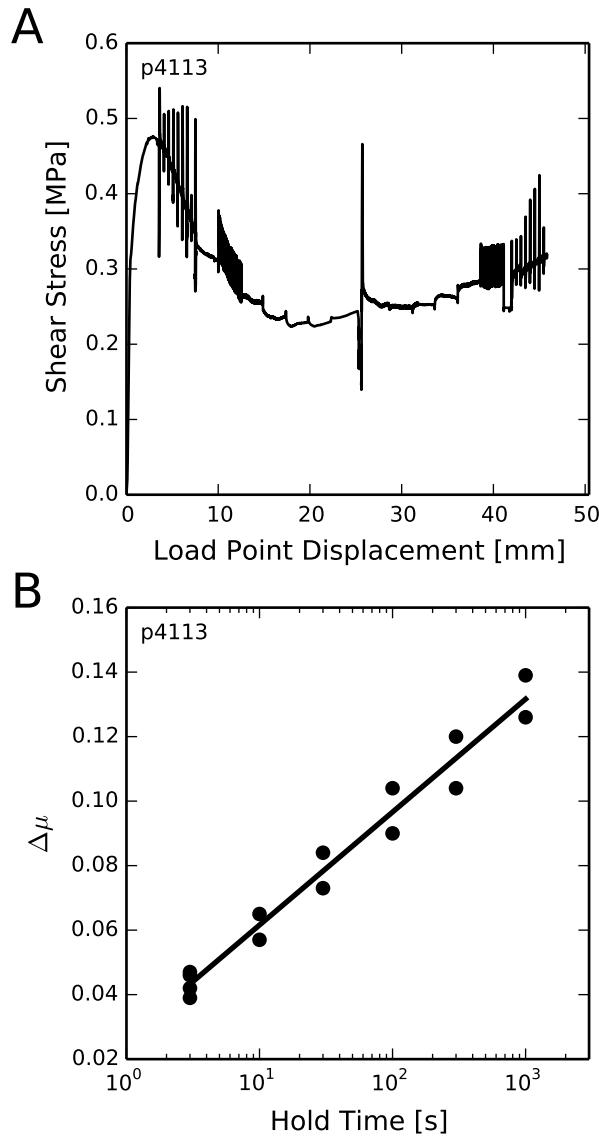


Fig. 1.7. (A) Friction data for experiment p4113 with steel loading blocks, and (B) healing determined from slide-hold-slide tests. The sample exhibited limited stick-slip/slow-slip behavior, but only at a load point velocity of  $5 \mu\text{m}/\text{s}$ . Frictional instability appears as a wide band of noise at the scale shown, around 10 and 40 mm load point displacement. Holds ranged from 3 to 1000 seconds and velocity steps from 5 to  $1500 \mu\text{m}/\text{s}$ .

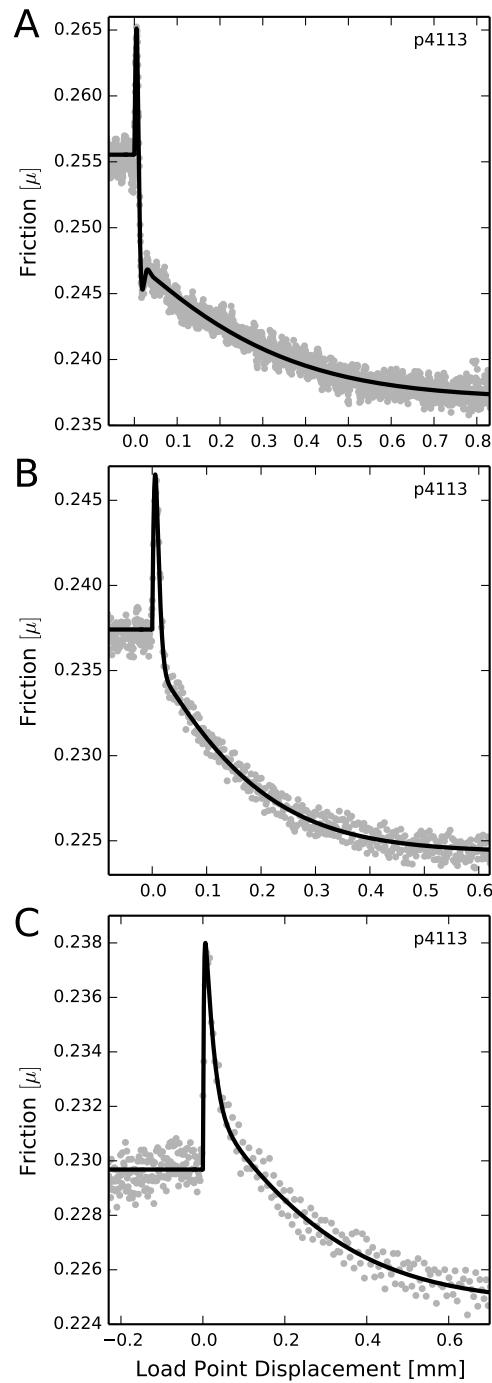


Fig. 1.8. Velocity steps in an all steel forcing block configuration can only be fit by a two state variable model. A) 15 - 50  $\mu\text{m}/\text{s}$  B) 50 - 150  $\mu\text{m}/\text{s}$  C) 150 - 500  $\mu\text{m}/\text{s}$

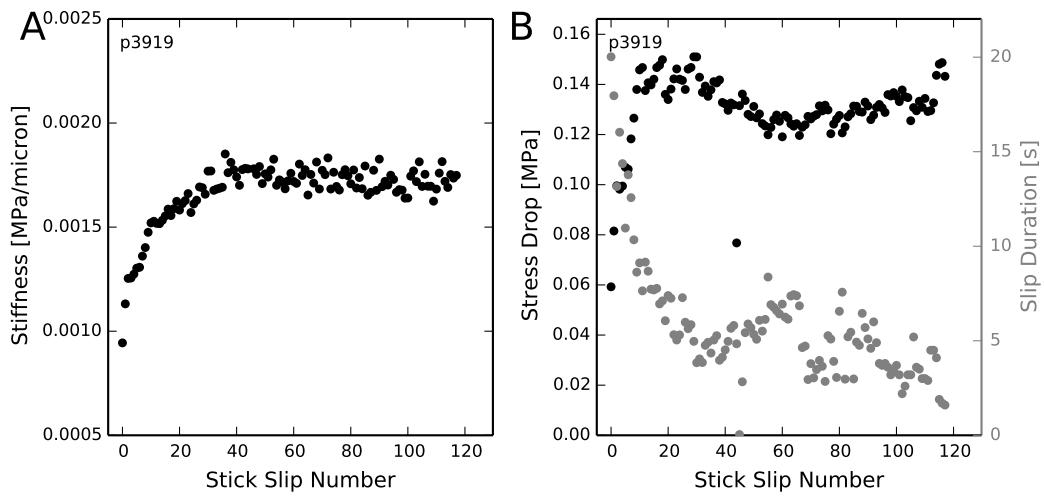


Fig. 1.9. (A) Stiffness and (B) Stress drop and slip duration for events in experiments with all acrylic forcing blocks. Stiffness increases on the rise to steady state by a factor of nearly two and remains remarkably constant. Stress drops rapidly increase by a factor of two over the first twenty events before reaching a steady state. Slip duration begins at nearly twenty-five seconds, then rapidly decreases to around five seconds.

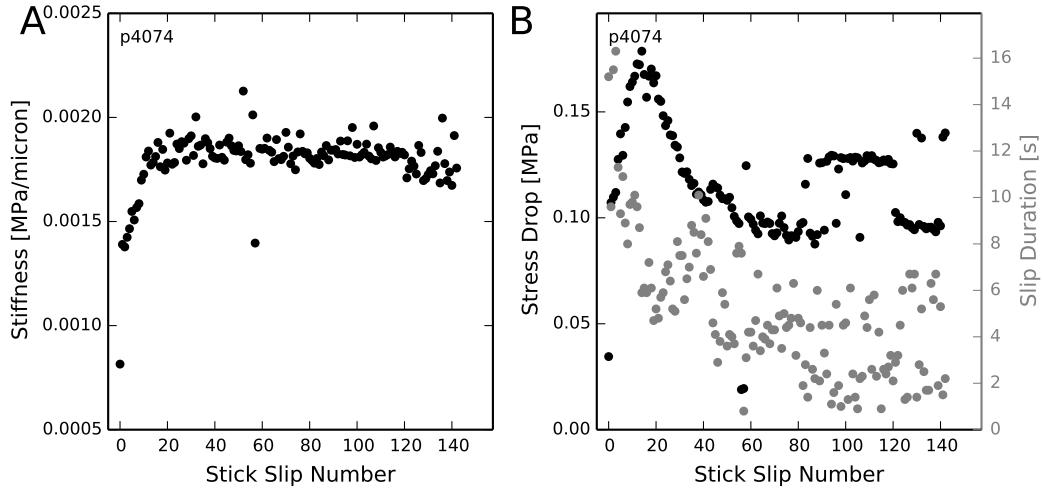


Fig. 1.10. (A) Stiffness and (B) Stress drop and slip duration for events in the steel/acrylic forcing block system. Stiffness follows a similar trend to the all-acrylic experiment, but exhibits a smaller increase with strain. Stress drop increases rapidly, but then returns and maintains its initial level until a second family of events occurs around events 80-120. Slip duration begins faster than for the all-acrylic blocks and stays lower with more scatter.

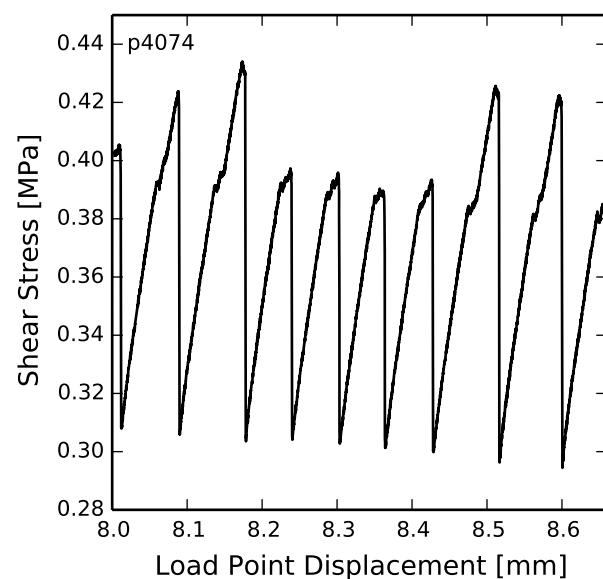


Fig. 1.11. Two groups of stick-slip events are evident after sufficient shearing in the steel/acrylic system. At the expected shear failure point there are several small failures, but the layer recovers and continues to load to a higher stress before failure.

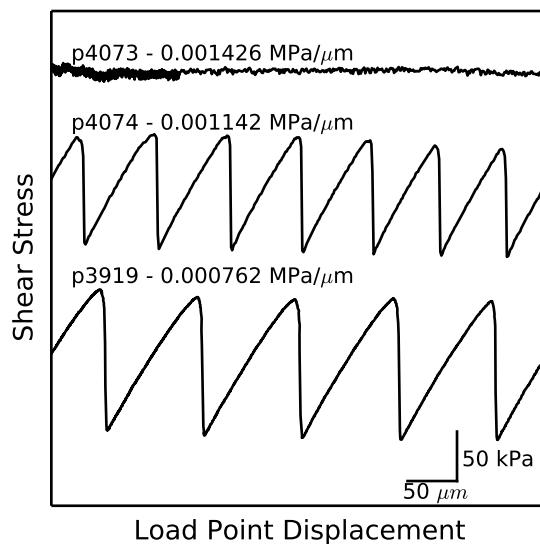


Fig. 1.12. Response of the system with various effective stiffnesses. The stability boundary is crossed between the steel and steel/acrylic system. Stiffnesses shown are the initial load up stiffnesses of the sample. All data are from the same displacement range, but have been offset in shear stress for clarity.

$V_0$	$V$	$a$	$b_1$	$D_{c_1}$	$b_2$	$D_{c_2}$	$a - b$
15	50	0.0120	0.0185	5.351	0.0088	207.912	-0.0154
50	150	0.0110	0.0125	7.448	0.0105	127.545	-0.0119
150	500	0.0077	0.0056	15.432	0.0061	199.407	-0.0041

Table 1.1. Two state variable parameters obtained from friction data inversion with all steel forcing blocks (p4113).

Experiment	Blocks	Layer Thickness (mm)	Temperature (C)	Relative Humidity (%)	Loading Stiffness (MPa/ $\mu$ m)
p3916	Acrylic	7	23.5	22	0.000630
p3918	Acrylic	7	23.1	22	0.000917
p3919	Acrylic	7	24.2	23.9	0.000762
p3920	Acrylic	7	24.4	25	0.000871
p3917	Steel/Acrylic	7	22	21.9	0.001002
p4074	Steel/Acrylic	8	23.1	38.8	0.001142
p4073	Steel	8	23.4	28.4	0.001426
p4112	Steel	8	24.3	55.5	0.001184
p4113	Steel	8	24.3	56.1	0.001070

Table 1.2. Load up stiffnesses during run-in for different forcing block configurations. Note that the steel/acrylic combination is much closer to the stiffness of all steel blocks than that of all acrylic blocks.

## Chapter 2

# Laboratory observations of slow earthquakes and the spectrum of tectonic fault slip modes

### 2.1 Abstract

Slow earthquakes represent an important conundrum in earthquake physics. Whereas regular earthquakes are catastrophic events with rupture velocities governed by elastic wave speed, the processes that underlie slow fault slip phenomena, including recent discoveries of tremor, slow slip, and low frequency earthquakes, are less understood. Theoretical models and sparse laboratory observations have provided insights, but the physics of slow fault rupture remain enigmatic. Here we report on laboratory observations that illuminate the mechanics of slow slip phenomena. We show that a spectrum of slow slip behaviors arise near the threshold between stable and unstable failure, and is governed by frictional dynamics via the interplay of fault frictional properties, effective normal stress, and the elastic stiffness of the surrounding material. This generalizable frictional mechanism may act in concert with other hypothesized processes that damp dynamic ruptures, and is consistent with the broad range of geologic environments where slow earthquakes are observed.

## 2.2 Introduction

Slow earthquakes are a mode of self-sustained fault rupture in which slip accelerates but does not reach rates sufficient to radiate high-frequency seismic energy Linde et al. [1996]; Obara [2002]. Seismic and geodetic observations reveal that slow slip and the related phenomena of low-frequency earthquakes and non-volcanic tremor define a spectrum of slip behaviors that unfold over timescales ranging from seconds to months Obara [2002]; Rogers and Dragert [2003]; Ide et al. [2007a]; Shelly et al. [2007]; Peng and Gomberg [2010]. Slow earthquakes can be large, in some cases equivalent to M7+ earthquakes, and they may play a role in stress transfer and thus triggering of damaging regular earthquakes Kato et al. [2012]. Slow earthquakes have also been observed as precursors to regular earthquakes and thus they may provide insight into the processes of earthquake nucleation Houston [2015]; Hawthorne and Rubin [2010]. Although geophysical observations have resolved fine details of slow earthquake slip and propagation rates of tectonic fault tremor Peng and Gomberg [2010]; Houston [2015]; Hawthorne and Rubin [2010]; Shelly [2010], the fundamental and controlling mechanics of these phenomena remain enigmatic.

Regular earthquakes have long been understood in terms of stick-slip failure dictated by frictional and elastic properties of Earth's crust Brace and Byerlee [1966]. Laboratory studies have provided key insights into the physics of fault failure and its dynamics, both for repeating earthquake-like stick-slip failure and for more complex slip behaviors. For example, previous works have reported a range of observations including transient slip, oscillatory sliding behavior, and dynamic rupture at sub-Raleigh and

supershear propagation speeds Voisin et al. [2008]; Shimamoto [1986]; Baumberger et al. [1994]; Kaproth and Marone [2013]; Ben-David et al. [2010]; Passelègue et al. [2013]; Scholz et al. [1972]. Transient and oscillatory behavior have been interpreted as analogs for premonitory slip prior to earthquakes or transient aseismic slip Voisin et al. [2008]; Scholz et al. [1972]; Rubin [2011].

Despite their relevance to natural fault zones and slow earthquakes, detailed laboratory observations of repetitive slow slip transients are few and do not include systematic studies. These behaviors have been reported in some experimental work Voisin et al. [2008]; Baumberger et al. [1994]; Kaproth and Marone [2013], but have been interpreted and modeled in the context of specific fault rheologies, using so-called 'designer' friction laws. In one form of these laws, slow stick-slip is produced by an increase in frictional resistance with slip velocity, such that instability is quenched during acceleration Baumberger et al. [1994]; Kaproth and Marone [2013]; Rubin [2011]. Other explanations for slow earthquakes have focused on processes that may arrest slip acceleration during earthquake nucleation, including dilatancy hardening Liu and Rice [2007]; Segall et al. [2010] transitional frictional behavior as a function of slip Ikari et al. [2013] or slip rate, and fault zone heterogeneity. Some numerical simulations successfully predict complex slip behavior, including oscillatory behavior and the emergence of periodic slow slip Liu and Rice [2007]; Gu et al. [1984]. Two dimensional numerical models also show promise in reproducing natural events, with fewer free parameters than multiple state variable models<sup>26</sup>.

To date, the origin of slow earthquakes has been explored largely via seismic or geodetic data or through numerical experiments with only sparse, isolated laboratory

observations to probe the underlying mechanics. Although theoretical models can explain the emergence of slow-slip transients under certain conditions or for specific frictional rheologies Liu and Rice [2007]; Segall et al. [2010]; Gu et al. [1984], a fundamental mechanical explanation for these events remains elusive. Yet, slow modes of fault rupture are observed in a variety of tectonic and geologic settings, and with a wide range of durations, raising the question as to whether they arise from a universal mechanism Peng and Gomberg [2010]; Den Hartog et al. [2012].

Although many fault zones are rich in phyllosilicate minerals, which have been shown to exhibit both rate-weakening and rate-strengthening behavior under conditions comparable to those expected *in situ* in the seismogenic crust Ide et al. [2007b]; Saffer et al. [2001]; Den Hartog and Spiers [2013], we focus on quartz gouge to investigate the systematics of frictional failure, because it is a well-studied material that is common in natural faults, and is thought to play a key role in controlling their slip behavior Den Hartog and Spiers [2013]; Ikari et al. [2007]. Quartz gouge also exhibits frictional properties that enable us to probe the stability boundary using geophysically-relevant values of normal stress and sliding rates. This allows a detailed investigation of the frictional dynamics of slow slip, which provides a robust and generalized framework to apply to tectonic fault zones.

Here we describe laboratory experiments that reproduce the full spectrum of fault slip behaviors under geophysically relevant conditions of normal stress and fault composition, and which illuminate their underlying physics. Our experiments are designed to explore the full range of slip stability, as described by the stability parameter  $\kappa = k/k_c$ ,

from  $\kappa > 1$  (inherently stable slip) to dynamic stick-slip ( $\kappa \ll 1$ ). Consistent with previous works Baumberger et al. [1994]; Scholz et al. [1972]; Gu et al. [1984] near the stability boundary,  $\kappa \sim 1$ , we observe complex slip patterns that precede slow slip. We document a systematic and robust relationship between departure from the stability threshold, slip velocity, and duration of repetitive failure events. Our experimental results, to the best of our knowledge, are the first complete and systematic study to investigate the full spectrum of slip behaviors from slow to fast events, as observed for tectonic faults.

## 2.3 Results

### 2.3.1 Mechanical Behavior

In our experiments, gouge layers initially exhibited stable sliding, followed by the emergence of repeating slow stick-slip events (4.1, 4.2A). The slow slip events arose gradually, over an interval of up to 1.5 mm, and then increased in amplitude over as few as 10-20 slip events before reaching a mechanical steady-state, characterized by relatively uniform recurrence intervals and friction drops, up to the maximum imposed displacements of  $\sim 50$  mm. For our layers, which were 3-mm thick prior to shear, this corresponds to shear strains of 30-50. Each slow-slip event began with a gradual acceleration and culminated in a slip event and stress drop (4.1).

### 2.3.2 Stick-Slip Events

Our experimental results are consistent with theory, numerical experimentation Liu and Rice [2007]; Gu et al. [1984], and with existing lab data for stick-slip Brace and Byerlee [1966]. We document a spectrum of stick-slip behaviors in experiments

conducted over a range of normal stresses (4.2A). At low normal stress (6 MPa) and close to the stability transition described by Equation (1), slip events have systematically longer duration and smaller stress drops than their higher normal stress counterparts (4.2C). Details of the friction records for slow events show that slip begins gradually, well before the peak strength is reached, and then accelerates during the stress drop (4.2B). The maximum slip velocities for slow-slip events are in the range of  $50\text{-}100 \mu\text{m s}^{-1}$ , and slip speed increases systematically with increasing normal stresses, which leads to increasingly unstable behavior (Equation 1). For the lowest values of normal stress that produced repeating transient slip events, we measured peak slip velocities of only a few 10's of  $\mu\text{m s}^{-1}$ , on the order of the driving velocity. For a normal stress of 14 MPa, we observed audible fast stick-slip events with slip velocities  $> 2 \text{ mm s}^{-1}$ .

## 2.4 Discussion

The short duration, audible high slip velocity events are manifestations of dynamic instability and represent laboratory analogs of regular, fast earthquakes Brace and Byerlee [1966]. Likewise, we posit that the observed spectrum of slow to fast stick-slip events in our experiments are representative of the spectrum of slip behaviors observed on tectonic faults, including repeating slow slip events and low frequency earthquakes Ide et al. [2007a]; Peng and Gomberg [2010]. Near the stability transition, we also document complex and chaotic behaviors including period doubling and transient variations in stick-slip amplitude with long period modulation (4.2A), consistent with theoretical predictions Gu et al. [1984].

To investigate the mechanics of slow stick-slip events, we carefully measured both the elastic loading stiffness  $k$  and the critical stiffness  $k_c$  in each of our experiments. We measured  $k$  directly from the loading curves of stick-slip events and from unload/reload cycles (Supplementary 4.1). Stiffness increases with shear displacement up to 15 mm, and then reaches an approximately constant value (4.3; Supplementary 4.1). The increase in stiffness with shearing is consistent with shear-enhanced compaction and granular comminution during the first few mm of slip Marone [1998]. As noted above, we measure  $k_c$  directly from the parameters in Equation 1 using velocity step experiments (4.3A, Supplementary 4.2), and also empirically using the value of  $k'$  at the observed transition between unstable and stable slip (black line, 4.3B). The empirically defined threshold stiffness increases with displacement and reaches a steady value of  $\sim 7 \times 10^{-4} \mu\text{m}^{-1}$  at a displacement of  $\sim 16$  mm, equivalent to a shear strain of  $\sim 5-6$  (4.3B). Direct measurements of  $k_c$  yield similar values ( $6 - 7 \times 10^{-4} \mu\text{m}^{-1}$ ; Supplementary 4.2), and also show that  $k_c$  increases dramatically within the first  $\sim 10$  mm of shear displacement. This is due to the combined effects of increasingly velocity weakening friction (4.3A) and decreasing critical slip distance  $D_c$  with shear strain (Supplementary 4.2). The evolution of (b-a) is consistent with inferred shear localization and with the observation that unstable slip emerges after a finite shear strain (4.1). The shear displacement needed for the emergence of slow-slip decreases with increasing  $\sigma_n$  (4.2A), consistent with enhancement of shear localization and fabric development at higher  $\sigma_n$ .

Taken together, our direct (4.3A, Supplementary 4.2) and independent (4.3B) measurements of  $k'_c$  and  $k'$  (Supplementary Figures 1, 2) show that stick-slip event velocity and duration vary systematically as a function of distance from the stability

threshold. The slowest events occur for  $\kappa \sim 1$ , with progressively faster events for lower values of  $\kappa$  (4.3D, E). The peak slip velocity and stick-slip duration for all events, measured after reaching a steady-state (4.3C, shaded area), define a complete spectrum of slip behaviors between stable sliding and fast stick-slip (4.3D, E). For  $\kappa < 0.7$ , slip velocities of several  $\text{mm s}^{-1}$  were associated with audible failure events (4.3D). For values of  $\kappa$  approaching 1, the duration of slow-slip is on the order of seconds (not producing any audible emissions in the range of human hearing), with lower peak slip velocities (4.3D, 3E). The amplitude of the stick-slip events is systematically lower for the slow events (4.2), consistent with seismic and geodetic observations for tectonic faults Ide et al. [2007a]; Peng and Gomberg [2010]; Brodsky and Mori [2007].

Our data show that the full spectrum of stick-slip behaviors can occur over a relatively narrow range of conditions near the stability phase boundary, and further, that the mode and slip velocity of unstable sliding vary predictably as a function of departure from this threshold. Although the 1-D spring-slider model is simplified relative to the geometry and rheology of natural fault systems, the predicted stability regimes are remarkably consistent with our laboratory experimental data. It is also consistent with theoretical models that incorporate more complex 2-D fault geometries and elastic interactions Liu and Rice [2007], suggesting that to first order, the mechanics and dynamics of these systems are captured by this relatively simple and elegant model Kaproth and Marone [2013]; Scholz et al. [1972]; Gu et al. [1984]; Marone [1998]; Kodaira et al. [2004].

In total, our results illuminate the key ingredients required for slow earthquakes. Relative to areas where regular earthquakes occur,  $k_c$  must remain sufficiently small that it does not greatly exceed the local fault stiffness  $k$ . This can occur for specific

frictional properties (small ( $b - a$ ) or large  $D_c$ ) as may be the case at the upper and lower edges of the seismogenic zone or in areas of complicated fault zone architecture Liu and Rice [2007]. This condition would also be favored by low effective normal stress, as has been suggested in a wide range of settings Houston [2015]; Hawthorne and Rubin [2010]; Kodaira et al. [2004]; Bilek and Lay [1999]; Kitajima and Saffer [2012]; Winberry et al. [2014]. Additionally, we suggest that the mode of fault slip should evolve as tectonic faults accumulate shear strain, or through the earthquake cycle, due to progressive changes in fault stiffness and frictional constitutive properties Bilek and Lay [1999]; Winberry et al. [2014]. Finally, because fault stiffness is proportional to the ratio of shear modulus to rupture nucleation patch size, we expect that regions of large, coherent creep slip, which effectively reduce  $k$ , would favor nucleation of slow earthquakes.

Our results support previous hypotheses about the role of transitional frictional behavior in driving complex fault slip behaviors Liu and Rice [2007]; Gu et al. [1984]; Kodaira et al. [2004]; Bilek and Lay [1999]; Kitajima and Saffer [2012]. It is likely that transitional frictional behavior may act in concert with additional processes acting locally within a fault zone to produce the observed spectrum of slip behaviors. A wide range of key natural factors, such as compliant and evolving damage zones, low effective normal stress associated with elevated pore fluid pressure and, fault evolution are all captured by the stability parameter  $\kappa = k/k_c$ . Ultimately, our results suggest that slow earthquakes and transient fault slip behaviors arise from the same governing frictional dynamics as normal earthquakes, and provide a unified view of the spectrum of tectonic fault slip behaviors.

## 2.5 Methods

### 2.5.1 Experimental Apparatus

Experiments were performed in a servo-controlled biaxial shearing apparatus using the double direct shear configuration (4.1). Displacements on the normal and shearing axes were measured by Direct Current Displacement Transducers (DCDTs), referenced at the load frame and ram nose. The displacement of the shearing block was measured with DCDTs referenced at the end-platen and the top and bottom of the shearing block (4.1). Loads applied to the sample were measured with strain gauge load cells. All transducers are calibrated with instruments and methods traceable to NIST.

### 2.5.2 Sample Preparation

Samples were prepared using steel or titanium side blocks and steel or acrylic (PMMA) central shearing blocks (Supplementary Table 1). The forcing blocks were grooved 0.8 mm deep at 1 mm spacing to eliminate shear at the boundary. We used Min-U-Sil 40 powdered silica (U.S. Silica Co.) to simulate granular fault gouge. The product is 99.5%  $\text{SiO}_2$ , with traces of metal oxides, and has a median grain diameter of  $10.5\mu\text{m}$ . Samples were constructed as 3-mm thick layers, and with 10 cm x 10 cm frictional contact area. Layers were prepared and sheared under 100% relative humidity at room temperature.

### 2.5.3 Testing Procedure

After samples were placed in the testing machine, a constant normal stress was applied and maintained constant using force-feedback servo control. Samples were allowed to compact and accommodate grain rearrangement before shearing began. Shear was induced by imposing a displacement rate on the central forcing block (4.1), using a feedback servo control. The displacement rate was maintained constant at  $10\mu\text{m s}^{-1}$  for the majority of our experiments (Supplementary Table 1), and velocity step tests were used to determine the friction rate parameters ( $a - b$ ) and  $D_c$ . We used a range of shear loading stiffnesses  $k$  given by the summation, in series, of the apparatus stiffness, the stiffness of the loading blocks, and the stiffness of the layers of fault gouge. The effective loading stiffness of the testing machine  $k' = k/\sigma_n$  was altered by using a compliant central forcing block (PMMA) and by changing the applied normal stresses (4.2A). We measured  $k$  in experiments using a least-squares linear fit to friction vs. shear displacement for the interval  $\mu = 0.3 - 0.4$  and from the elastic loading portion of stick-slip events (Supplementary 4.1). Rate-and-state friction parameters were determined (Supplementary 4.2) using an iterative singular value decomposition technique.

### 2.5.4 Frictional Stability

In the context of frictional stability, the criterion for unstable stick-slip in a simplified 1-D system is defined by the interaction between loading system stiffness  $k$  and a rheologic critical stiffness of the fault,  $k_c$  2.1, where  $(b - a)$  is the friction rate parameter and  $D_c$  is the critical slip distance Marone [1998]. Negative rate parameters,  $(b - a) < 0$ , indicate velocity-strengthening behavior, which is inherently stable. Positive

values of  $(b - a)$  indicate velocity-weakening friction and are a prerequisite for instability and earthquake nucleation. Within the velocity weakening regime, if the condition in Equation 2.1 is satisfied (i.e. stiffness of the loading system,  $k$ , is less than the critical stiffness;  $k < k_c$ ), instability occurs because the fault weakening rate,  $k_c$ , exceeds the rate of elastic unloading, leading to a force imbalance. For stiffer systems (i.e.  $k > k_c$ ), in which elastic unloading outpaces frictional weakening, sliding is stable. For convenience, we normalize the stiffness and critical stiffness by the normal stress, appending a prime symbol to denote this;  $k' = k/\sigma_n$  and  $k'_c = k_c/\sigma_n$

We selected values of  $k$  and normal stress for our experiments to span the stability boundary for our fault gouge. To achieve this, we made careful measurements of the evolution of  $k$  and  $k_c$  with shear strain (4.10). For a given set of frictional properties, defined by  $(b - a)$  and  $D_c$ , the ratio  $k/\sigma_n$  defines an effective system stiffness,  $k'[\mu\text{m}^{-1}]$ , that governs sliding stability. In our experiments, the testing machine, sample assembly, and gouge layer together determine the system stiffness. We varied  $k$  using different forcing block materials (Supplementary Table 1) and  $k'$  via the normal stress.

$$k < k_c = \sigma'_n \frac{(b - a)}{D_c} \quad (2.1)$$

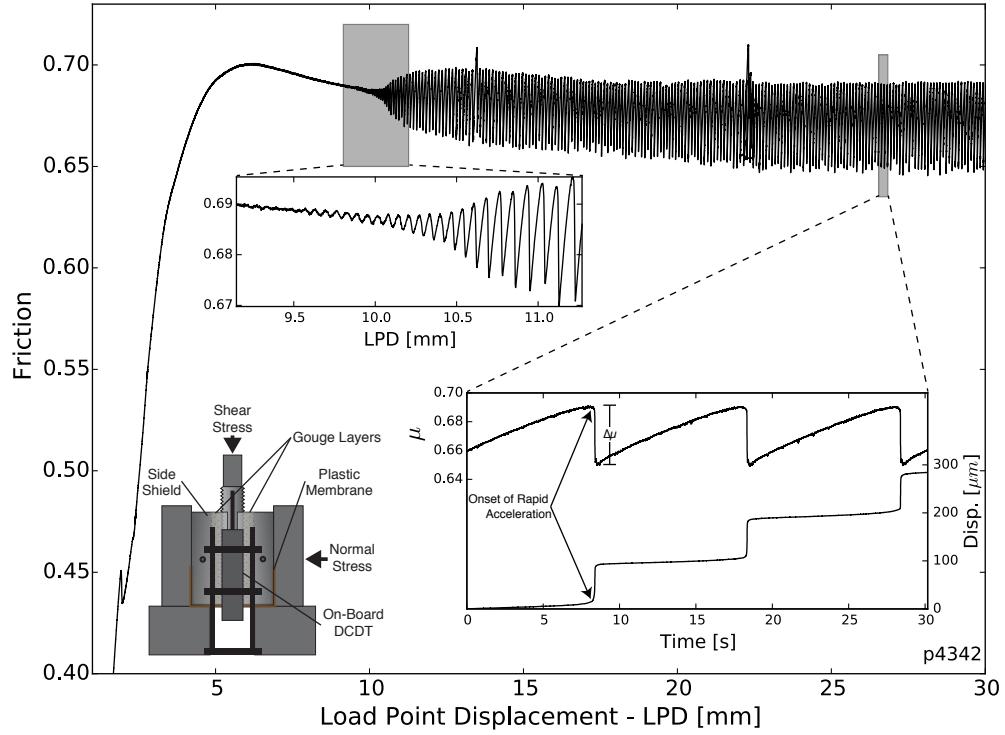


Fig. 2.1. Experimental run plot. Friction data for one experiment (p4342) at a normal stress of 12 MPa and shearing rate of  $10 \mu\text{ms}^{-1}$ . The upper inset shows spontaneous emergence of unstable slow slip. Stick-slip amplitude increases gradually over a few mm before reaching steady-state. The lower right inset shows details of fault slip events, note the gradual acceleration at the start of each failure event. The lower left inset shows the double direct shear configuration and locations of displacement transducers. Spikes at 13 mm and 22 mm displacement are due to brief pauses in shearing to reset displacement transducers.

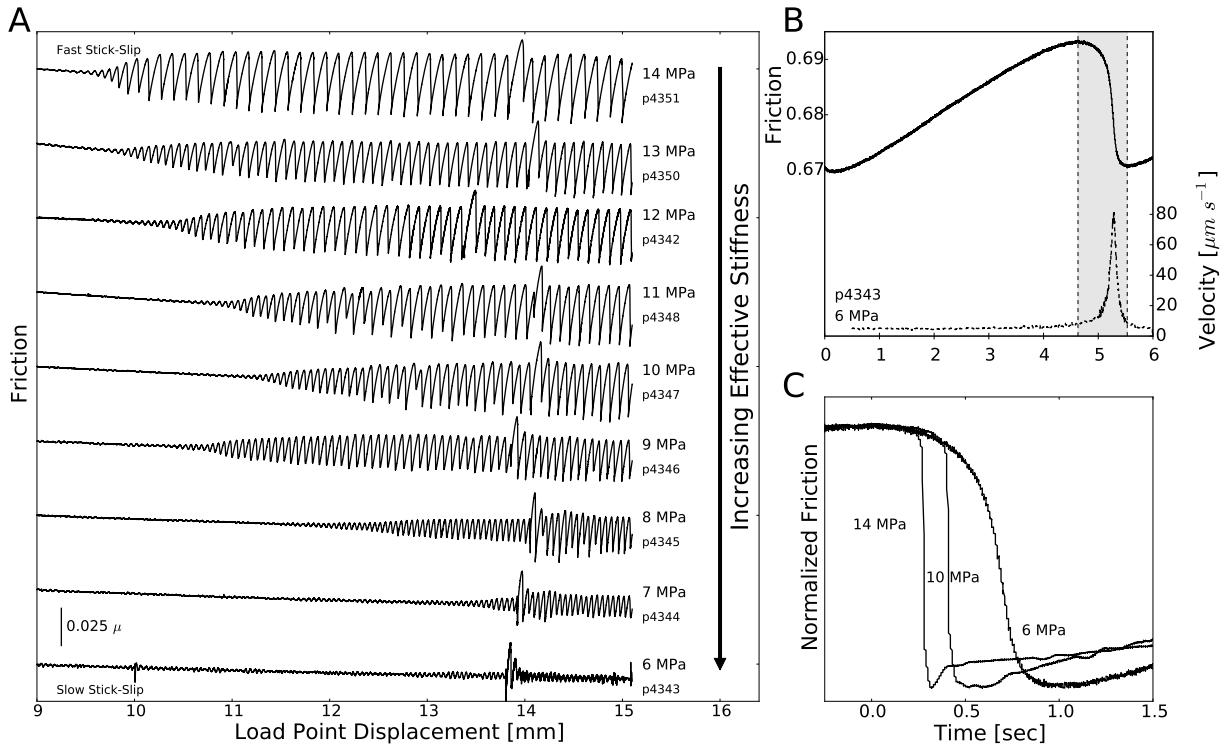


Fig. 2.2. Spectrum of Fault Slip Behavior. A) Friction data for experiments (p43XX run numbers) at different effective shear loading stiffness  $k' = k/\sigma'_n$ . Friction data are offset vertically for clarity. The emergence of slow stick-slip occurs at lower shear displacement, and stick-slip amplitude increases, for higher normal stress experiments. The spikes in friction at 13–15 mm are due to frictional aging caused by brief pauses in shearing to reset displacement transducers. B) Details of friction (solid line) and velocity (dashed) during a stick-slip event with a peak slip velocity of  $\sim \mu\text{ms}^{-1}$ , only a few times that of the background loading velocity of  $10 \mu\text{ms}^{-1}$ . C) Stick-slip events have systematically longer duration at lower normal stresses. Slip accelerates more slowly and event durations are correspondingly longer than at higher normal stress.

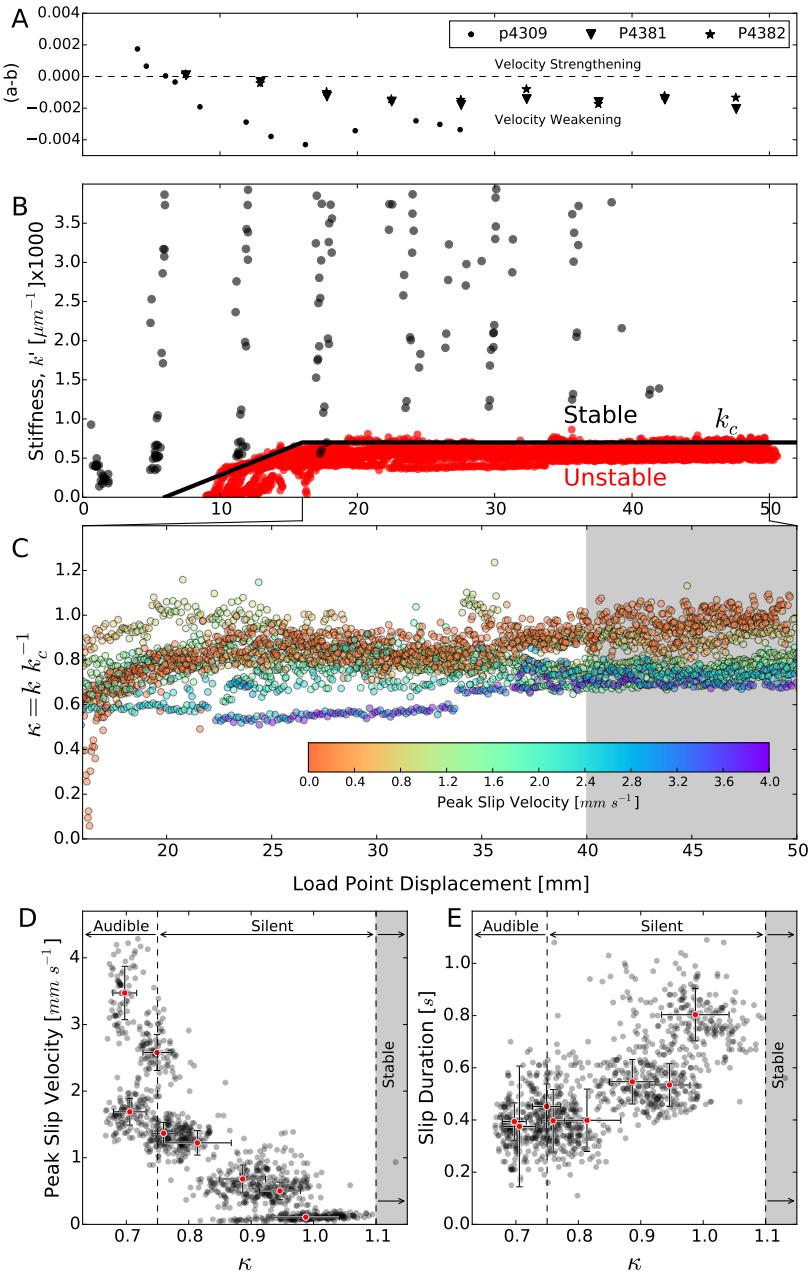


Fig. 2.3. Stick-slip event properties. A) The friction rate parameter ( $b-a$ ) transitions from velocity strengthening to velocity weakening at  $\sim 5-7$  mm displacement. B) Data from 29 experiments showing effective friction stiffness  $k' = k/\sigma'_n$  as a function of shear displacement for stable sliding (black dots) and stick-slip events (red dots). The heavy black line defines the evolution of  $k'$  based on the distinction between stable sliding and stick-slip. C) Data for unstable slip events shown in B are color coded by peak slip velocity and shown as a function of shear displacement. Stick-slip is slowest for  $\kappa \sim 1$ . The 40-50 mm interval marked by the gray box denotes data used to compile stick-slip properties. D) Stick-slip event velocity and E) duration as a function of normalized critical stiffness  $\kappa = k/k_c$ . Black dots show data from events in the displacement interval 40-50 mm for 8 experiments; red dots show mean values  $\pm 1$  standard deviation for each experiment.

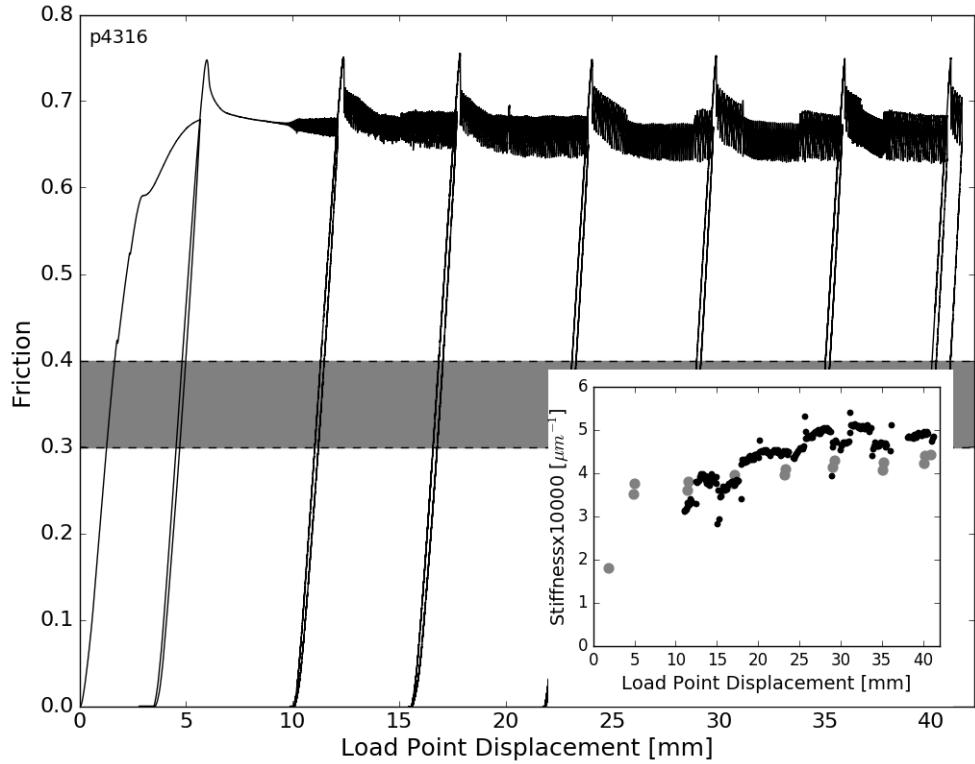


Fig. 2.4. Stiffness during an experiment. Friction data for one complete experiment (run p4316) with shear load-unload cycles. Slow slip events emerge spontaneously at a displacement of  $\sim 8.5$  mm. (Inset) Stiffness measured from unload-reload cycles in the range  $\mu = 0.3 - 0.4$  (large grey circles) and from the slope of the elastic loading segments of individual stick-slip events (small black circles). Both measurements indicate an initial increase in stiffness, caused by shear enhanced compaction. In this experiment we explored multiple shearing rates during slow slip (e.g., for events in the range 27–29 mm and 31–33 mm), which had a clear effect on stick-slip amplitude and stiffness.

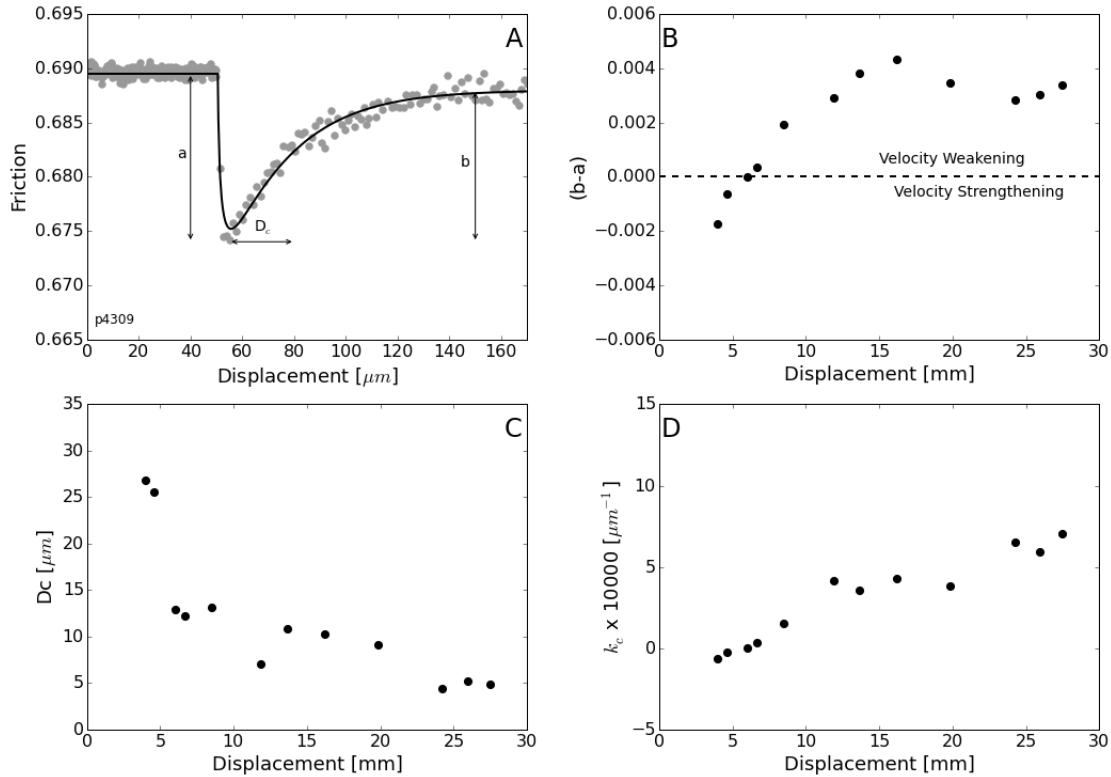


Fig. 2.5. Rate and State Parameters. Data and modeling procedure for obtaining rate-and-state friction parameters and their variation with shear displacement. A) Data from experiment p4309 (grey data points) and model (solid line) for a velocity step test from  $10$  to  $1 \mu\text{ms}^{-1}$ , with illustration of the friction direct effect a, evolution effect b, and critical slip distance  $D_c$ . B) Evolution of (b-a) with shear displacement (see also 4.3A). Note the transition from rate strengthening to rate weakening at  $\sim 8$  mm displacement, after which a steady-state behavior is reached. C) The critical slip distance decreases with shear displacement as frictional steady-state is reached. D) Evolution of the critical stiffness ( $k_c$ ) with slip.

Experiment	Blocks	Normal Stress [MPa]	Humidity [%]	Comments	Unload/Reload Cycles
p4224	Ti/Acrylic	5	16	Stable - Vel. Steps	N
p4228	Steel	4	100	Stable - Slide Hold	N
p4229	Ti/Acrylic	4	100	Failed	N
p4248	Ti/Acrylic	4	100	Stable - Vel. Steps	N
p4249	Ti/Acrylic	4	100	Stable - Vel. Steps	N
p4267	Ti/Acrylic	2	100	Stable - Vel. Steps	Y
p4268	Ti/Acrylic	8	100	Slow-Slip	Y
p4269	Steel	4	100	Stable - Vel. Steps	Y
p4270	Steel	2	100	Stable - Vel. Steps	Y
p4271	Ti/Acrylic	2	100	Stable - Vel. Steps	Y
p4272	Ti/Acrylic	8	100	Slow-Slip	Y
p4273	Steel	8	100	Stable - Vel. Steps	Y
p4309	Steel	8	100	Stable - Vel. Steps	Y

p4310	Ti/Acrylic	8	100	Slow-Slip	Y
p4311	Ti/Acrylic	8	100	Slow-Slip	Y
p4312	Steel/Acrylic	8	100	Slow-Slip	Y
p4313	Ti/Acrylic	8	100	Slow-Slip	Y
p4314	Steel	12	100	Stable - Vel. Steps	Y
p4316	Ti/Acrylic	12	100	Stick-Slip	Y
p4317	Steel/Acrylic	12	100	Stick-Slip	Y
p4327	Steel	6	100	Stable - Vel. Steps	Y
p4328	Ti/Acrylic	6	100	Slow-Slip	Y
p4329	Ti/Acrylic	6	100	Slow-Slip	Y
p4330	Steel	6	100	Stable - Vel. Steps	Y
p4338	Ti/Acrylic	4	100	Stable - Vel. Steps	Y
p4339	Steel	4	100	Stable - Vel. Steps	Y
p4340	Ti/Acrylic	8	100	Slow-Slip	Y

p4341	Steel	12	100	Stable - Vel. Steps	Y
p4342	Ti/Acrylic	12	100	Slow/Fast Slip	N
p4343	Steel/Acrylic	6	100	Slow-Slip	N
p4344	Ti/Acrylic	7	100	Slow-Slip	N
p4345	Steel/Acrylic	8	100	Slow-Slip	N
p4346	Ti/Acrylic	9	100	Slow-Slip	N
p4347	Steel/Acrylic	10	100	Slow/Fast Slip	N
p4348	Ti/Acrylic	11	100	Slow/Fast Slip	N
p4350	Steel/Acrylic	13	100	Slow/Fast Slip	N
p4351	Ti/Acrylic	14	100	Slow/Fast Slip	N
p4381	Steel	4	100	Stable - Vel. Steps	N
p4382	Ti	4	100	Stable - Vel. Steps	N

## Chapter 3

# Characterization of Laboratory Slow Earthquakes

### 3.1 Abstract

The discovery that a complete spectrum of fault slip behaviors exists from stable to unstable failure, including slow earthquakes and low frequency earthquakes requires a fundamental change in our view of frictional explanations of dynamic failure. Here we present a series of laboratory experiments that demonstrate slip spanning seconds to milliseconds in duration, the laboratory slow and regular earthquake. We show that the rheologically defined critical stiffness is the main controlling factor determining in which mode a system will fail, but that higher order effects such as velocity dependence of the stiffness, friction rate parameter, or critical slip distance also play an important role in controlling the rupture behavior of the system. By analyzing time series records of fault slip, we examine how event properties are controlled by the critical stiffness ratio of the system. We also explore connections between driving and slip velocity and how they modify the frictional properties of the material. The mechanism governing earthquake failure behavior should rely on a single set of physical parameterizations that can reproduce the entire spectrum of naturally observed behavior if the model is sufficiently detailed and complete. By conducting rate-and-state friction modeling, we show that even the simplest model can reproduce a surprising amount of complex behavior like that observed in the laboratory and in nature.

## 3.2 Introduction

Slow earthquakes are a peculiar form of fault slip in which a rupture propagates at a rate several orders of magnitude slower than regular earthquakes, but maintains its self-sustaining character over many time scales Linde et al. [1996]; Obara [2002]; Rogers and Dragert [2003]; Ide et al. [2007a]; Shelly et al. [2007]; Peng and Gomberg [2010]. There is a spectrum of fault failure modes including stable creep, slow earthquakes, low-frequency earthquakes, and regular earthquakes that should all be described by a single set of physics as they all manifest in similar materials and geologic settings. In fact, slow earthquakes have been found in many regions including Cascadia [e.g. Rogers and Dragert, 2003], Japan [e.g. Obara, 2002], New Zealand [e.g. Wallace and Beavan, 2006], and Mexico [e.g. Kostoglodov, 2003], as well as in non-tectonic settings such as beneath fast-moving ice streams in the Antarctic [e.g. Anandakrishnan and Bentley, 1993]. Here we describe a series of laboratory experiments in which we recreate fault slip events that span a range of temporal scales from milliseconds to seconds and analyze their characteristics. We show that the stiffness of the fault zone and the velocity dependent behavior of friction can offer a physical mechanism for slip to occur and propagate in the continuum of failure behaviors.

### 3.2.1 Rate-and-State Friction

The frictional behavior of materials has been known to be velocity and time dependent for quite some time and has been mathematically described by the empirical rate-and-state friction formulation Rabinowicz [1951]; Dieterich [1972, 1978]; Ruina

[1983]; Marone [1998]. In this framework, a frictional system responds to a perturbation with a direct effect that is proportional to the constant  $a$  and an evolution effect to its new steady-state that is described by the constant  $b$ . The evolution effect occurs over an e-folding length known as the critical slip distance,  $D_c$ . The formulation also includes a state variable, , that is often interpreted as a proxy for the average lifetime of a frictional contact within the system. The state variable is described by any one of several proposed state evolution relations, the most popular being the slowness and slip relations.

Two of the most important features of the rate-and-state friction relation are frictional healing and velocity dependence of friction. Frictional healing occurs when contacts within a system are in quasi-stationary contact for a period of time and the strength of the contact between them increases with the logarithm of hold time Dieterich [1972]; Marone [1998]. In a system with repeating stick-slip events (earthquakes), the loading rate and healing rate combine to determine what the maximum strength of the fault will be and therefore how big the next slip event could potentially be. The velocity dependence of friction describes how the steady-state frictional resistance to sliding changes as a function of the sliding velocity. Materials that become weaker with increasing velocity are termed velocity weakening and have  $(a - b) < 0$ . Materials that increase their frictional resistance with increasing sliding velocity are termed velocity strengthening and have  $(a - b) > 0$ .

Extensive laboratory work has shown that the velocity dependence of a material can be a function of temperature Blanpied et al. [1987]; Mitchell et al. [2013] and of sliding velocity itself Ikari et al. [2009]. These effects can manifest themselves in complex ways in natural materials. Materials have been observed to be velocity strengthening at

high and low velocities with velocity weakening regimes in the middle Den Hartog et al. [2012]; Den Hartog and Spiers [2013], and that trend can be shifted by changing the temperature of the system. Furthermore, the critical slip distance has also been shown to be a function of the loading velocity Mair and Marone [1999]. All of these behaviors indicate that simple rate-and-state frictional theory is not adequate to explain the full frictional behavior of a system, but is likely a valid way to empirically probe the system in some areas of parameter space.

### 3.2.2 Critical Stiffness and Stability

The stability of a system (whether it can host stick-slip events or only stable creep) is determined by the rate-and-state frictional parameters of the system and the stiffness of the loading system and sample. In nature this stiffness could be considered that of the fault zone and surrounding damage zone that takes place in the storage and release of elastically stored strain energy during a slip event. Frictional theory predicts that a bifurcation of energy release behaviors will occur when the system stiffness is below a rheologically defined critical stiffness,  $k_c$  (eq.3.1). Stability may also be discussed in terms of the critical stiffness ratio,  $\kappa$ , (eq.3.2). When  $k < k_c (\kappa < 1)$ , the system will be unstable, storing elastic strain energy, then releasing it rapidly in a dynamic fashion. As slip begins to occur, slip weakening outpaces the rate at which energy can be fed to the system (governed by the aggregate system stiffness  $k$ ) and a runaway rupture occurs. If the system is stiffer than the critical stiffness  $k > k_c (\kappa > 1)$  as soon as slip occurs the energy stored in the system is completely relieved with very little slip displacement.

The rate of energy release is constantly outpaced by slip weakening and the system continually slides in a stable, or creeping manner.

$$\frac{k_c}{\sigma'_n} = \frac{b-a}{D_c} \quad (3.1)$$

$$\kappa = \frac{k}{k_c} \quad (3.2)$$

A direct requirement of this bifurcation is that velocity weakening is a necessary but insufficient condition for unstable slip to occur. The aggregate stiffness of the system must be less than the critical stiffness for unstable slip to be possible. If the system is velocity strengthening, intuitively it cannot exhibit unstable behavior, because the critical stiffness is a negative value, requiring an impossibly compliant system.

### 3.3 Materials and Methods

#### 3.3.1 Apparatus

Experiments were conducted on a servo-hydraulic biaxial deformation machine Karner and Marone [2000]; Frye and Marone [2002]; Leeman et al. [2015] (Figure 4.1A). Two hydraulic rams (normal and shear) are controlled with proportional closed-loop control based on either displacement or load feedback signals. On stable systems, feedback control can maintain ram velocity to approximately  $0.1\mu\text{m/s}$  and load to approximately 10 N Hong and Marone [2005]; Rathbun et al. [2008].

Load is measured with Beryllium-Copper strain gauge load cells located at the nose of the hydraulic ram. Each load cell is semi-annually calibrated with a proving ring as a transfer standard. The position of each piston is measured by a direct current differential transformer transducer (DCDT). These transducers are mounted at the ram nose and referenced to the forcing platen to which the ram is affixed. Displacement transducers are semi-annually calibrated with a Starrett height gauge.

Displacement measurements were also made near the experimental fault. Two DCDTs were affixed to the center block of the sample assembly (Figure 4.1B,C). Each transducer was held in a bracket affixed to the base plate of the sample area with rare-earth magnets. The core assembly of the transducer was held out from the central block by a bracket that was glued to the central block. One transducer was affixed to the top of the center block and the other to the bottom. This allows us to measure the strain energy stored in the block, as well as examine any differences from measuring at and above the fault.

Sample forcing blocks used were made of acrylic, steel, or titanium. Each face of the block in contact with the gouge has teeth 0.8 mm deep and 1 mm apart to prevent pure boundary sliding by coupling the blocks into the layer more effectively Anthony and Marone [2005]; Knuth and Marone [2007]. Metal side barriers prevent lateral extrusion of the gouge under load. The top and bottom of the sample are unconfined, but show minimal extrusion other than the expected advection of material out of the system due to geometric thinning Scott et al. [1994].

The output voltages from each transducer are digitized at a rate of 10 kHz by a National Instruments NI PXI-4495. These data are then averaged down to a lower

data rate (nominally 1 kHz) for recording and storage. A NI PXI-6733 can be used to generate a control voltage for position or load and is used to set the displacement rate of the shear ram in these experiments.

### **3.3.2 Sample Material**

All experiments were conducted with Min-U-Sil 40 from U.S. Silica. This product is 99.5% pure silicon dioxide with traces of various metal oxides. It has a median grain size of  $10.5\mu\text{m}$  and is angular in nature (see supplemental material). Min-U-Sil exhibits typical healing and frictional properties, but has the unique advantage of having rate-and-state frictional properties that allow our apparatus to explore the stability transition.

### **3.3.3 Sample Preparation**

Samples were built using the double-direct-shear (DDS) geometry. Three forcing blocks, two side blocks and one center block confine two gouge layers (Figure 4.1B). A rubber membrane at the bottom of the sample helps prevent sample material losses and metal side barriers prevent lateral extrusion of the gouge. The top of the sample is unconfined.

All samples in this study had gouge layer thicknesses of 3 mm. Layers were constructed by creating a cellophane tape barrier around the side block that was trimmed to 3 mm height using a jig. Min-U-Sil was evenly distributed into the sample area, compacted by hand, and then leveled off in the same jig.

After sample layers were built on the side blocks, they were placed in a bag overnight to be fully saturated in a 100% relative humidity environment. The humidity

in the bag was increased and maintained by placing a container of anhydrous calcium carbonate and water (1:2 ratio by mass) inside.

The center block was affixed to a side block, then that assembly affixed to the second side block. The bottom rubber membrane was added and side barriers affixed. The entire assembly was then ready to be immediately loaded into the machine.

### **3.3.4 Experimental Procedure**

After the gouge layers were allowed to saturate in the 100% relative humidity environment overnight, they were assembled into the complete sample assembly and immediately loaded into the testing machine. The normal load was applied and held constant while the initial grain rearrangement and compaction occurred (generally taking 30-60 minutes).

Once compaction was complete, the vertical ram was driven at a constant shearing rate. Shearing continued until the displacement transducers needed to be reset. Shearing was halted, the transducers physically offset, then shearing was resumed. This continued until approximately 50 mm shear displacement, at which point the gouge layers were becoming very thin and the experiment was stopped. Samples of the in-tact shear zone were recovered when possible. Samples of the resulting powder were recovered by wire brushing the forcing block surface into a container.

### **3.3.5 Data Analysis**

All data are recorded in a raw binary format from the analog to digital converter. A series of calibrations and zeroing corrections is accomplished through the use of a script

and the tool ‘XLook’ (<https://github.com/PennStateRockandSedimentMechanics/xlook>).

After the data were reduced to time series of stresses and displacements, they were analyzed with a Python based toolchain.

Due to the sometimes small stress drops and associated noise with these events, fully automated picking methods such as those of Leeman et al. [2015] are not always effective. To mitigate this, a point on the rising slope of each event was manually picked. Between each set of points, the maximum and minimum values of friction in the raw data were used to define the beginning and end of each stress drop. We also generate a number of other derived products from the events such as friction drop, slip duration, and the peak slip velocity.

To measure the stiffness of the system, we rely on two methods: unload/reload cycles of the shear stress and the loading portion of individual stick-slip events Leeman et al. [2016]. For experiments that exhibit only stable sliding, unloading and reloading the shear stress is the only way to get a reliable measurement of the aggregate system stiffness. In experiments which exhibit unstable behavior, these unload/reload cycles are disruptive, resulting in healing of the layer and many altered stick-slip events upon reloading. This makes data interpretation complex and results in data gaps where non-representative stick-slip events occurred. For unload/reload cycles a line was fitted with a least-squares method to the range of data  $\mu = 0.3 - 0.4$ . For measurement from stick-slip events, the loading stiffness of the system was calculated by fitting a line to the loading portion of each event (between the previous event's minimum friction and the maximum friction of the next event). The number of points used to fit the line was determined by maximizing goodness of fit as described in Leeman et al. [2015].

### 3.3.6 Modifying $\kappa$

To examine how the frictional system behaves at various locations in the stability field, we changed the critical stiffness ratio via three methods. We modified the stiffness ratio by changing the material of the center block, by adding a series spring to the system at the load point, and by changing the normal stress.

By changing the material of the center forcing block from steel to acrylic we can greatly reduce the effective stiffness of the system, but we are subject to limitations of the material. The fine teeth grooved into the acrylic wear and can become damaged at high stresses. The experiments presented do not exceed 14 MPa normal stress, and we observed little wear during the suite of experiments. Another way to reduce the stiffness of the system is to use a compliant material in line with the shear loading column. This allows the all steel forcing block configuration to be used, but effectively destiffened by a compliant series spring. Acrylic cubes were used as the series spring for this range of stresses and conditions. The final way to modify the critical stiffness ratio is by changing the effective normal stress. Increasing the effective normal stress will increase the critical stiffness, thereby decreasing the critical stiffness ratio. Here we limit our scope to only change center block material and varying normal stress.

## 3.4 Results

During experiments in which unstable slip occurred, the initial shearing of the material exhibited stable behavior (Figure 4.2). After several millimeters of shear displacement, small instabilities nucleated and continued to grow over 10 – 20 slip cycles.

Each slip event during this onset of instability was characterized by increasing slip velocity and friction drop. Events were characterized by their loading stiffness, friction drop, slip duration, and slip velocity.

### **3.4.1 Normal Stress Dependence of Stability**

As seen from equations 3.1, 3.2 and demonstrated in Leeman et al. [2015, 2016], increasing normal stress increases the critical stiffness of the system, thereby decreasing the critical stiffness ratio and making the system increasingly unstable. By running experiments at constant velocities and normal stresses for their duration, we observe that this behavior is consistent across multiple velocities (Figure 4.3). Increasing normal stress results in larger, faster, more dynamic stress drop events with higher friction drops and peak slip velocities (Figure 4.4A). As normal stress is reduced, the events transition into slow events before becoming completely stable.

### **3.4.2 Velocity Dependence of Stability**

In exploratory experiments we observed that the stability of the system can be a function of velocity (Figure 4.4). When the load point velocity was increased from  $30\mu\text{m}/\text{s}$  to  $110\mu\text{m}/\text{s}$ , the system became stable and remained stable as the velocity was further increased to  $350\mu\text{m}/\text{s}$ . Upon decreasing the load point velocity to  $10\mu\text{m}/\text{s}$ , periodic slow slip events were observed. The amplitude of the slow slip events at  $10\mu\text{m}/\text{s}$  was several times larger than at  $30\mu\text{m}/\text{s}$  and the period increased. The events became regular after just a few cycles with a friction drop of about 0.02.

To further examine how the stability varies as a function of velocity and not convolve the effect with displacement dependent variables such as fabric development, we ran a suite of experiments, each of which was at a constant normal stress and constant load point velocity for the duration of the experiment (Figure 4.3). At 12 MPa normal stress we observed repeating stick-slip events at 3, 10, 30, 100, and  $300\mu\text{m}/\text{s}$  load point velocity. At lower load point velocities we document larger stress drops, some of which result in overshoot of the servo control system due to the rapid change in stress state. When the same set of experiments was performed at 7 MPa a more complex behavior emerged. At 3, 10, and  $30\mu\text{m}/\text{s}$  we observed repeating stick slip events. At  $100\mu\text{m}/\text{s}$  we observed stable sliding, with brief periods of frictional oscillations after holds to reset the transducers. In a reproduction experiment, we observed semi-chaotic, but generally sustained very small stress drop events. At  $300\mu\text{m}/\text{s}$ , the system was stable. When the normal stress was further reduced to 5 MPa, we observed small frictional oscillations at  $3\mu\text{m}/\text{s}$ , but stable sliding at 10and  $30\mu\text{m}/\text{s}$ . The systematics of the normalized peak velocity decrease and friction drop decrease with velocity (Figure 4.4B) are log-linear. Peak slip velocities must be normalized by the driving velocity to see relative differences in the slip velocity with respect to the driving velocity. The velocity dependence of system stability indicates that the critical stiffness or actual stiffness of the system must be a function of velocity.

### 3.4.3 Friction Drop

Friction drop decreases with both increasing load point velocity and decreasing normal stress. We observe that at higher normal stresses, the rate at which friction

drop decreases with increased load point velocity is reduced (Figure 4.6). At 12 MPa normal stress, friction drops decreased from approximately 0.059 at  $3\mu\text{m}/\text{s}$  to 0.029 at  $100\mu\text{m}/\text{s}$ , a decrease of 51%. At 7 MPa normal stress, friction drops decreased from 0.045 to 0 (stable sliding) over the same range of loading velocity. There is also a trend of increasing friction drop with increasing normal stress at a given load point velocity.

In a given experiment we observe friction drops that rapidly increase in magnitude after periodic failure has begun. Friction drop increases over a few tens of events, then quickly rolls over to a near steady value and generally remains there for the duration of the experiment. Many of the trends discussed previously are also easily visible when examining each friction drop as a function of displacement, broken up by normal stress (see supplementary material). At a given normal stress, the lower load point velocity experiments yielded higher friction drops than their higher load point velocity counterparts.

We also conducted a suite of experiments from 5 – 13 MPa in 0.5 MPa steps with 5 normal stress steps in each run. The velocity was varied at each normal stress in an effort to more thoroughly map the stability boundary of the system. Each velocity was windowed and the maximum and minimum friction values used to construct an upper-bound friction drop. We reproduce the trend of Figure 4.5 with decreasing friction drops with increasing velocity (Figure 4.7A). When plotted in velocity-normal stress space, the boundary between very low friction drops (noise on a stable sliding line) and unstable events is clearly seen (Figure 4.7B).

### 3.4.4 Variation of $(a - b)$

Velocity step tests this near to the stability boundary proved to be difficult to control and model, therefore  $(a - b)$  was measured in experiments by determining the mean value of friction at a given velocity and normal stress. For a constant  $(a - b)$  value, friction should decrease in a log-linear fashion with velocity. Our measurements (Figure 4.8) indicate a mean  $(a - b)$  value of  $-0.00482$  with data for all normal stresses lumped together.

When the normal stresses are separated out individually and a new fit obtained, we observe that increasing normal stress results in a more negative (velocity weakening) value of  $(a - b)$  (Figure 4.9). The absolute value decreases by roughly a factor of three from  $-0.001$  and  $5$  MPa to  $-0.0045$  at  $13$  MPa. From  $11.5 - 13$  MPa the value appears to be relatively constant, but data at higher normal stresses is required.

## 3.5 Discussion

### 3.5.1 Friction Drop

The reduction in friction drop amplitude with increased velocity is an often reported phenomena, and stable sliding could be viewed as the small amplitude limit. The process is often cited as a reduction in healing time for the contacts of the system to regain much strength before failing again. Our results show decreasing friction drop with increasing velocity, but also indicate that healing becomes less pronounced with increasing normal stress. The simple rate-and-state friction model does not predict the

observed normal stress dependence of healing or friction. Perhaps more puzzling, it does not explain the velocity dependence of friction drop amplitude either.

### 3.5.2 Rate-and-State Modeling

In an effort to understand the sensitivity of the system to variations in the rate-and-state friction constitutive model, we conducted a simple set of model runs with a single state variable, inertia free, spring-slider model. Data from our on-board DCDT located at the bottom of the center block was used to compute the slider displacement, velocity, and accelerations used for comparison to the models.

Modeling the onset of the slow-slip events requires the system to be in a  $k < k_c$  state for the instabilities to grow. In our model  $\kappa = 0.975$ . A tiny perturbation (a hold of  $0.1\mu\text{sec}$ ) is enough to eventually make the system become dynamic and unstable. The model and data (Figure 3.10) compare very favorably, but the model is sensitive to sub-micron variations in  $D_c$  and variations of  $(a - b)$  less than 1%. Making the system more velocity weakening or reducing  $D_c$  increases  $k_c$ , making the system become unstable more quickly. Even with fine tuning of the parameters, the model still takes more cycles to reach the same friction drop values as the data, easily seen by the number of circuits made in phase space. Slider velocities of  $\sim 60\mu\text{m/s}$  were obtained in both the data and model with very similarly shaped acceleration curves. The slowest events have saw-tooth shaped acceleration curves; a gradual increase in acceleration as the slip event begins, then a more rapid deceleration before immediately beginning to accelerate again. Once the events become faster and larger, the acceleration remains gradual initially, with a

sharp increase and decrease during the event. The acceleration then returns to near zero during the elastic loading of the system.

Modeling the repeating slow-slip events of our experiments requires the model be run exactly on the stability boundary,  $\kappa = 1$ . With  $\kappa < 1$ , the events will eventually become dynamic and the model is numerically unstable. For  $\kappa > 1$ , the slip events will gradually decrease in amplitude until stable sliding is produced. By fixing  $\kappa = 1$ , we cannot change  $(a - b)$  or  $D_c$  without also modifying  $k$ . Therefore, to change the behavior of the system we can only impose velocity perturbations. Changing the size of the velocity perturbation determines the amplitude of the friction drop and sliding velocity. The model matches the experimental data very well (Figure 3.11), producing events with very similar velocities, but slightly longer periods. The most obvious difference is that the model never shows the block sliding much below the driving velocity whereas the data does. This would indicate that our system is likely  $\kappa < 1$  in reality and another effect prevents it from becoming fully dynamic.

Comparing the two on-board DCDTs affixed to the top and bottom of the center block, we note that the bottom DCDT records velocities well below the driving velocity during the elastic loading period, but the top DCDT is much closer to the driving velocity. The bottom DCDT also records slightly higher peak velocities. We interpret this as the bottom DCDT representing real slider movement and the top showing the storage of elastic energy in the acrylic center block, as it is affixed well above the locked zone.

### 3.5.3 Evolution of Stiffness and Stability

Explaining the behavior of the system, from the initial stable sliding and transition to slow slip to repeating stick-slip behavior, must fundamentally stem from an understanding of how the system stiffness and critical stiffness evolve to create a time evolving stability parameter. Here we propose one possible explanation of such behavior that relies on the evolution of rate-and-state friction parameters as well as fabric development within the shearing zone.

From velocity step tests in a stiff system, we have observed that our system begins shearing as a velocity strengthening material. This is manifested as a negative critical stiffness, indicating that no amount of real compliance can make the system unstable. As shearing continues, the material becomes less velocity strengthening, until it is velocity neutral, and finally slightly velocity weakening. During this transition the critical stiffness becomes positive and asymptotically increases towards a steady-state value. While the system is in the space  $k_c < 0$ , it must be stable. It can be unstable if and only if  $k < k_c$  and  $k_c > 0$ .

The stiffness of the system itself begins at the lowest value it will be for the course of the experiment. Samples are not compacted and have no shear fabric at the beginning of each experiment. Initial compaction occurs after the application of normal stress, and the samples become slightly more stiff. After shearing begins, the compaction is enhanced by forcing grains to move and rearrange. Shear is also localized on narrow slip surfaces with stiffer walls of grains with much less movement than those near the sharing zone. The transition from a compliant unsheared material to a stiffer sheared

material results in a rapidly growing system stiffness that approaches the steady-state system stiffness.

The combination of the  $k_c$  and  $k$  evolution described above creates a complex evolution of stability with time. Initially the critical stiffness is negative and the stiffness of the system is in what we term ‘phase I’ of the experiment. As shearing progresses, the material becomes less velocity strengthening and the stiffness of the system begins to increase with enhanced compaction and shear fabric development. The system enters ‘phase II’ of shearing as it becomes velocity neutral to velocity weakening. In this phase, the critical stiffness is positive and growing. The stiffness of the system is still small, but rapidly increasing. The critical stiffness ratio is less than unity, therefore any perturbation should cause the system to become unstable. Perturbation sources may include stochastic processes in the layer and velocity fluctuations from the hydraulic servo control. Both of these sources of perturbations are small and unlikely to make the system instantly break into dynamic stick-slip. As observed with our modeling, small perturbations of systems with  $\kappa < 1$  create a growing instability that will eventually become fully dynamic, but possibly not for many cycles. As the instabilities nucleate, they grow and produce the spontaneous beginning of instability in the experiments. With continued shear, the stiffness of the system grows more rapidly than the critical stiffness. As the quantities approach steady-state,  $k$  must remain below  $k_c$  for the instability to continue, but it could be arbitrarily close to the stability boundary or even directly on it ( $k = k_c$ ). The rollover of  $k$  and  $k_c$  to their approximate steady-state values marks the beginning of phase III of the shear. In phase III, the stiffness of the system is very closely matched to the critical stiffness and it is possible to have repeating slow-slip

events that never become fully dynamic. Experiments with lower steady-state  $k$  values where  $k \ll kc$  may become fully dynamic in this stage.

### 3.5.4 Velocity Dependent Behavior

The velocity dependence of stability demonstrated by our experiments indicates that must be a function of velocity. Examining the variables that could be responsible (eq. 3.1, 3.2) we see that  $k$ ,  $(a - b)$ , and  $D_c$ , are possibly functions of velocity. Below we examine each of these parameters and discuss their potential contribution to the observed behavior.

After a complete run of experiment p4526, we performed a series of unload/reload cycles on the shear axis at different load point velocities to determine if there was any effect of the loading rate on the measured stiffness. We find that the apparent stiffness of the system increases with the logarithm of the load point velocity (Figure 3.12). This trend holds for both loading and unloading cycles. These changes in stiffness are believed to be either due to slip of the system during the loading/unload cycles and the nature of the hydraulic loading system. The changes are very small (a few percent) and increase with velocity, making the system more stable.

For the system to become more stable with velocity as a result of changes in  $(a - b)$ , the value would need to become more velocity neutral to velocity strengthening. We combined data from 12 – 13 MPa where  $(a - b)$  appears to be relatively constant (Figure 4.9) with normal stress and produced a linear fit, as well as three hypothetical situations in which  $(a - b)$  varies linearly with velocity (Figure 3.13). The hypothetical curves are not unreasonable given the scatter of our experimental data, but experiments

at higher velocities are necessary to further define the trend of  $(a - b)$  with velocity. Given our data, increases in  $(a - b)$  of nearly  $0.0005$  over  $10 - 1000\mu\text{m/s}$  are not out of the question. These changes would increase with velocity, increasing stability.

In our experiments, we have no way to directly measure  $D_c$  as a function of velocity given the unstable nature of any velocity steps performed. Results from a similar material, F110, by [Mair and Marone, 1999] indicate a systematic log-linear increase in  $D_c$  with increasing velocity. This trend would reduce the value of  $k_c$  with velocity, increasing and bringing the system close to stability.

We believe changes in  $(a - b)$  and  $D_c$  to be the dominating effects producing a change in stability with loading velocity. By computing for a range of reasonable values of  $(a - b)$  and  $D_c$ , we can see that minuscule changes in either parameter can significantly change the system behavior (Figure 3.15). Similar to what was observed from models, changes that are likely below the resolution of macroscopic friction measurements are easily able to change the value of enough to modify the slip behavior.

### 3.6 Conclusions

We have demonstrated that the spectrum of fault slip behaviors can be reproduced in the laboratory and that the behavior of the events can be systematically controlled by the critical stiffness ratio, . Peak slip velocity and friction drop both increase with increasing normal stress (decreasing ) at a fixed driving velocity. Increases in driving velocity at a given normal stress result in smaller friction drops and reduced normalized peak slip velocities, indicating that the system is becoming increasingly stable with increasing

velocity. We attribute this increase in stability to the increase in  $(a - b)$  and increases in  $D_c$ .

In a natural setting, the hypothesized low effective normal stress conditions and mildly velocity weakening conditions are ideal for a slow-slip event. Lowered effective normal stresses reduce the value of  $k_c$ , such that for a fixed  $k$ , is closer to unity. The velocity sensitivity of  $(a - b)$  suggested by [Ikari et al., 2009; Rubin, 2011] could explain the observed behavior of slip arresting at a low velocity instead of becoming fully dynamic. Further characterization of  $(a - b)$  and modeling efforts are needed to determine if the modified model can faithfully reproduce our experimental observations.

The complex transitional behavior observed in natural systems likely also depends on a number of other factors such as active shearing layer thickness, fluid interactions, and time dependent crack closure. Each of these ultimately modifies the effective stiffness ratio , making it an ideal parameter to describe the failure mode of a fault without neglecting the complicating factors.

### **3.7 Acknowledgments**

J.R Leeman was supported by the National Science Foundation under Grant No. DGE1255832. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. Data used are available through the Penn State Scholarsphere system.

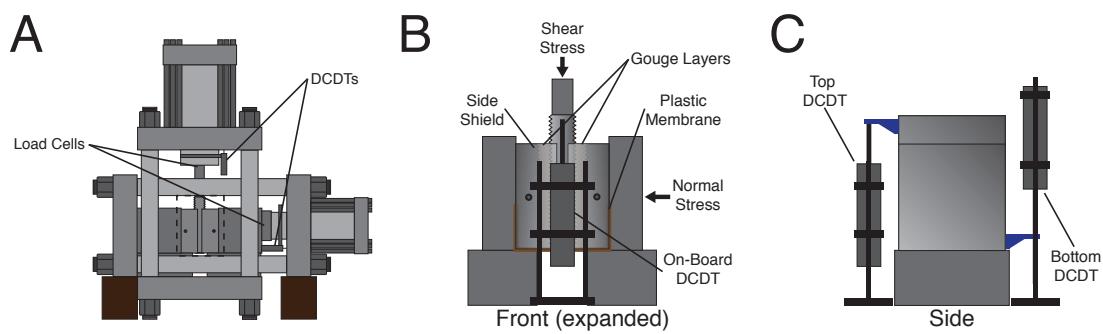


Fig. 3.1. A) The biaxial shearing apparatus with locations of load and displacement sensors indicated. The sample area is outlined with a dashed line. B) The double-direct-shear sample with an on-board displacement transducer mounted to the top of the center block and referenced to the base of the apparatus. C) A side view of the sample setup shows that an inverted displacement transducer is fitted on the back of the sample to measure the fault displacement at the bottom of the center block.

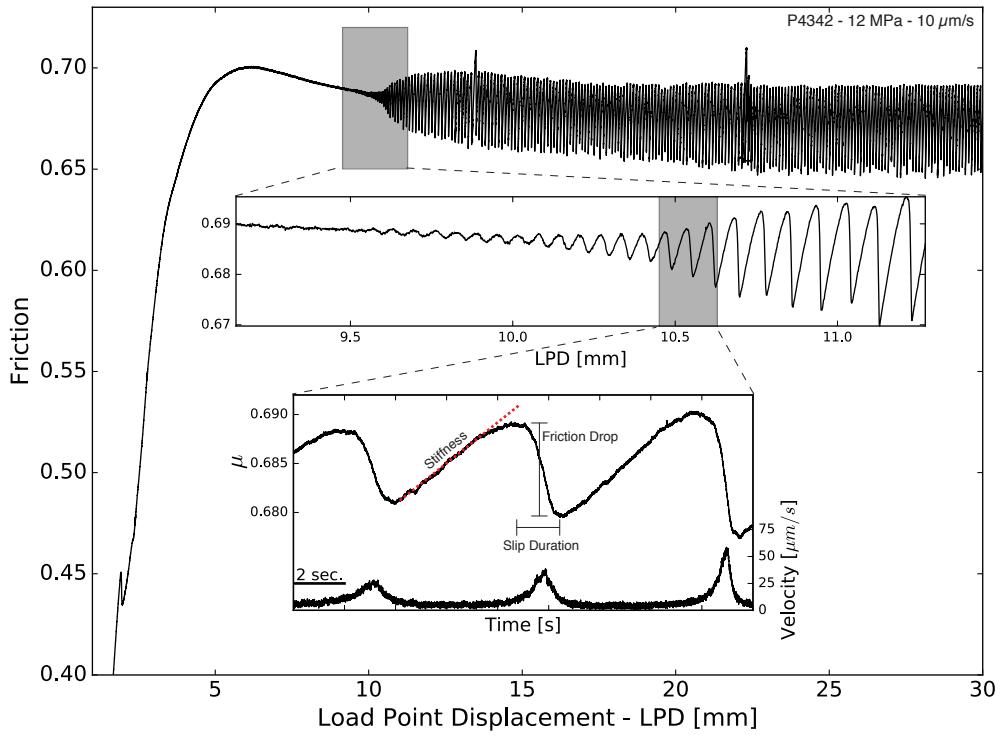


Fig. 3.2. Slow slip events spontaneously begin at approximately 10 mm load point displacement. The onset of the events is emergent, evolving to their final steady-state over 20 – 30 events. The friction drop of an event is defined as the difference between the maximum friction after the last event and the minimum friction prior to the next event. Slip duration is the time elapsed between these two friction values. The stiffness of a stick-slip event is the slope of the best-fit line to the loading portion of an event in a friction-displacement plot (shown here in time for convenience, only differing from the stiffness by a constant given a fixed load point velocity).

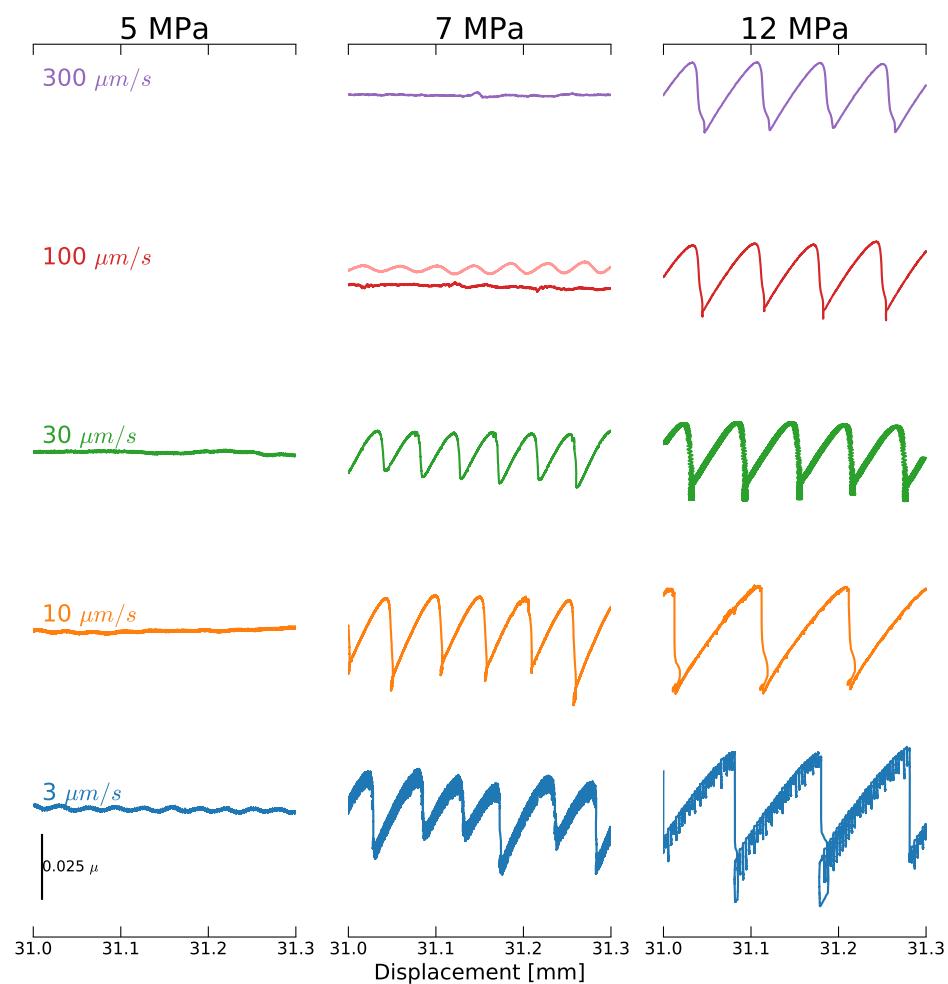


Fig. 3.3. Increased driving velocity or reduced normal stress can cause a system to become stable. Each experiment was run at a constant driving velocity and normal stress for its duration. Two experiments at 7 MPa and 100  $\mu\text{m}/\text{s}$  show different behaviors, indicating that those conditions are at the stability boundary.

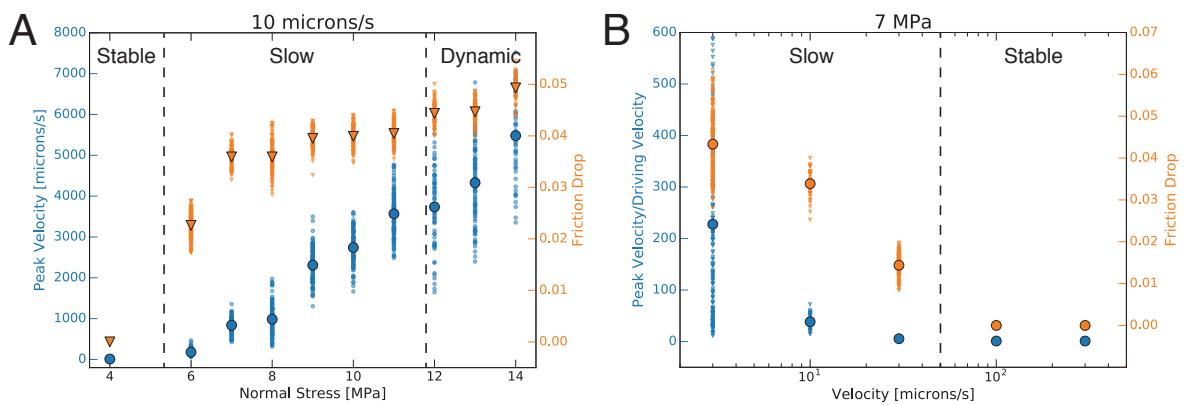


Fig. 3.4. A) At a fixed driving velocity of  $10\mu\text{m}/\text{s}$ , increasing normal stress decreases the critical stiffness ratio and makes the system more unstable. Friction drop and peak slip velocity both increase with increasing normal stress. B) For a fixed normal stress, higher driving velocities result in lower friction drops and normalized peak friction drops as the system gets closer to being stable until it becomes stable near  $100\mu\text{m}/\text{s}$ .

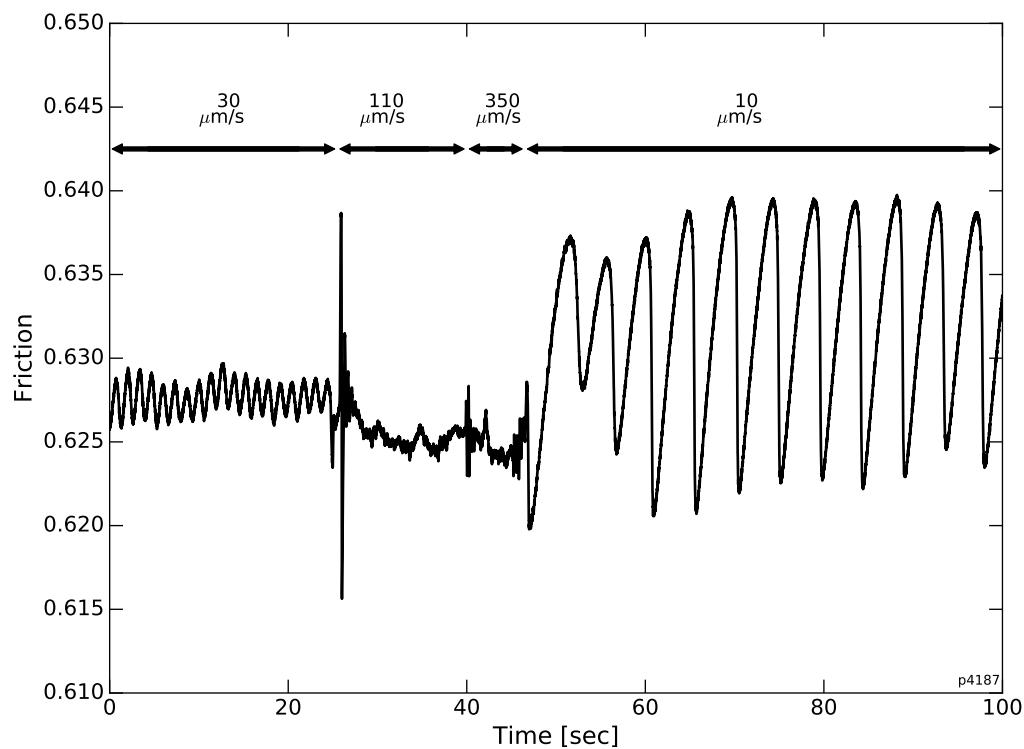


Fig. 3.5. In a given experiment, the stability of the system can be modified by changing the load-point velocity. As the load point velocity is increased from  $30\mu\text{m/s}$  to  $100\mu\text{m/s}$  and  $350\mu\text{m/s}$  the system transitions from small slow slipping stress oscillations to stable sliding. Upon an abrupt reduction in velocity to  $10\mu\text{m/s}$ , the fault switches back to slow-slip behavior, but this time with a larger amplitude due to the lower driving velocity.

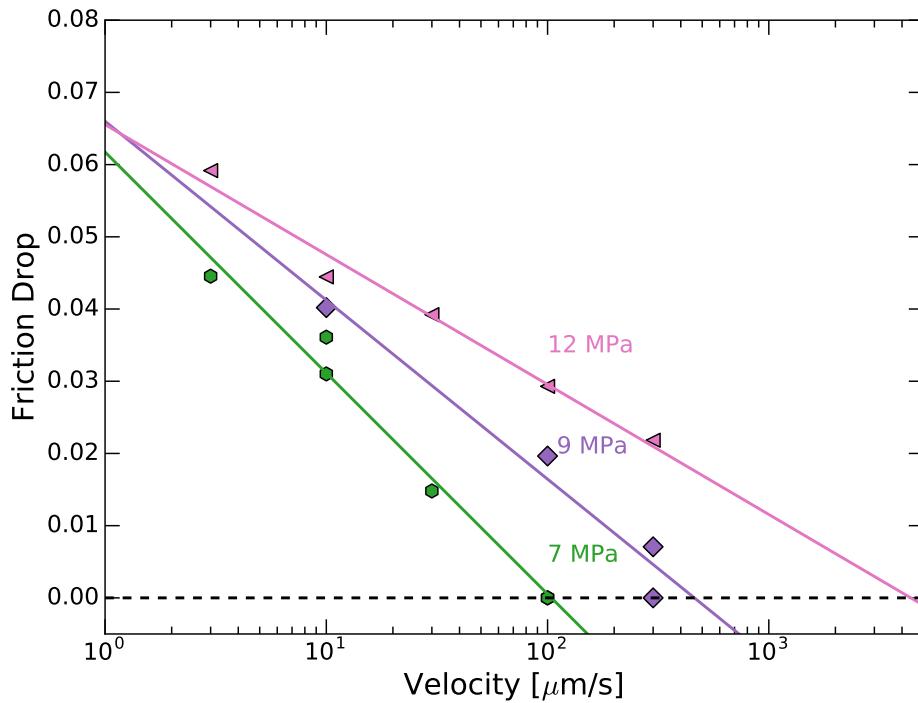


Fig. 3.6. Friction drop scales logarithmically with load point velocity. As the normal stress increases and the critical stiffness ratio decreases, the systems become more unstable and has higher friction drops at a given velocity. The scaling constant appears to decrease with higher normal stress, suggesting that higher normal stresses the friction drop is more weakly dependent on velocity.

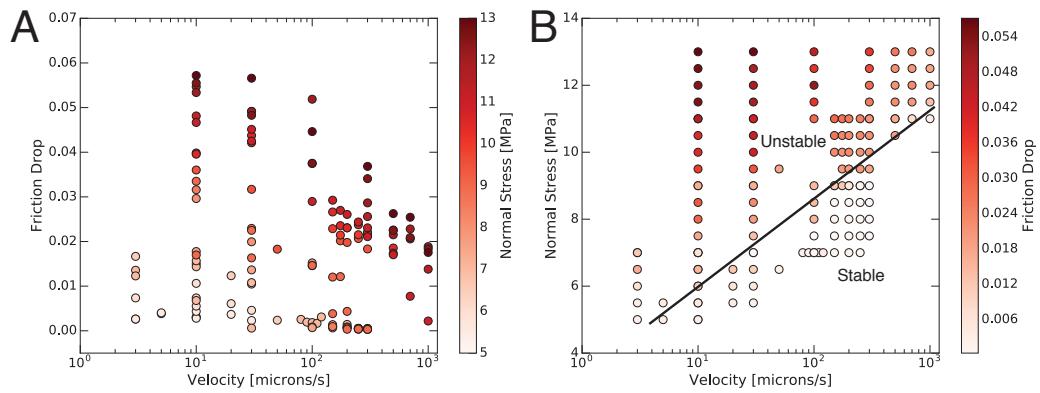


Fig. 3.7. A) Friction drops decrease with increased loading velocity in a log-linear fashion. B) The division between stable (near zero friction drop) and unstable (significant friction drop) conditions is apparent as a nearly straight boundary in the normal stress - driving velocity space. For a given normal stress, the transition can be seen in the whitening of the data points.

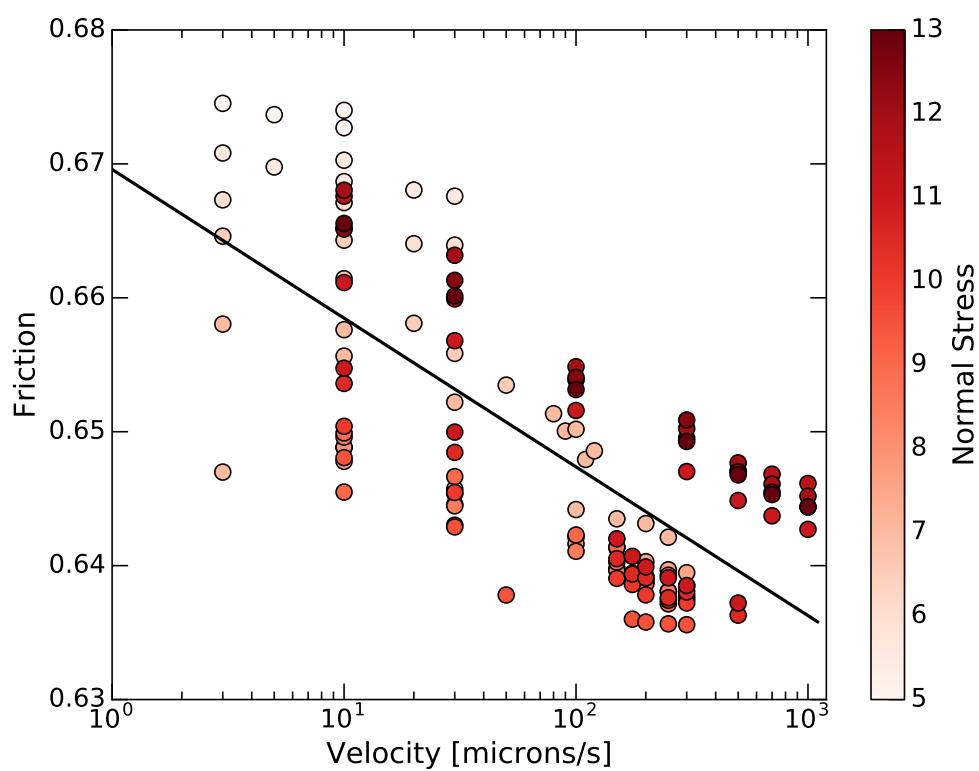


Fig. 3.8. Mean friction at a range of velocities for experiments with normal stresses ranging from 5 – 13 MPa show a linear decrease in friction with increasing velocity. The slope of this line is  $(a - b)$  and has a value of  $-0.00482$  for all data shown.

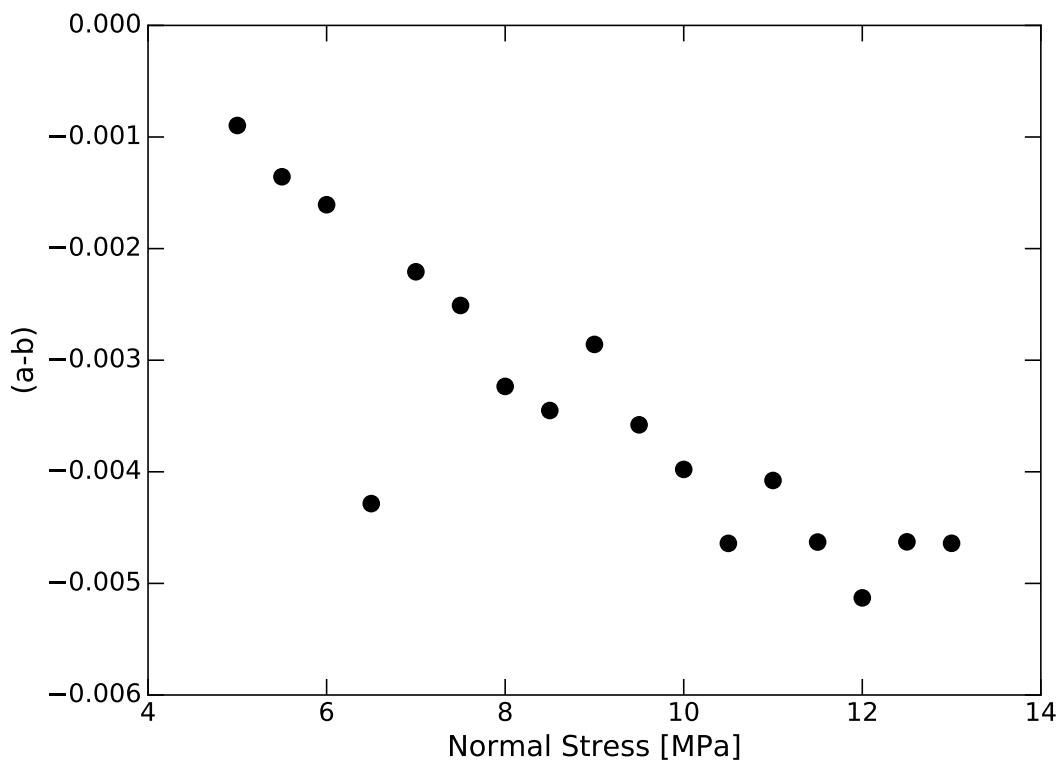


Fig. 3.9. By fitting the mean friction at multiple velocities at each normal stress,  $(a - b)$  estimates show a linear decrease in  $(a - b)$  with normal stress. Assuming that all other factors remain constant, this would mean at a given velocity, an increase in normal stress would reduce  $(a - b)$  making the system more unstable. This effect would be superimposed on increase of  $k_c$  with normal stress.

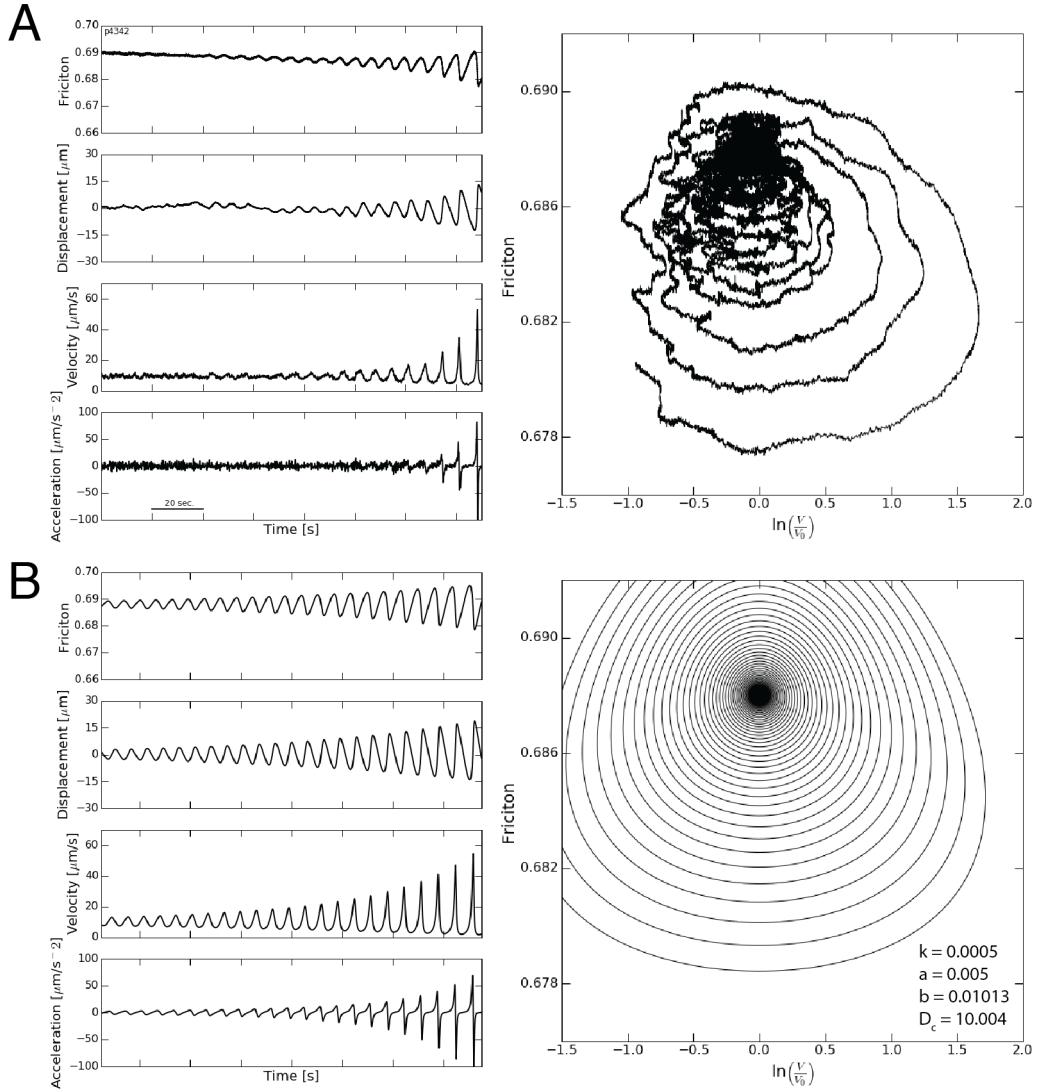


Fig. 3.10. The onset of instability occurs over tens of slip cycles in our data (A) and a simple rate-and-state friction model (B). Each successive friction drop is larger with increased slip displacement, velocity, and acceleration. The acceleration/deceleration magnitudes are nearly identical for these nearly sinusoidal onset events. In the model, the behavior was very sensitive to small perturbations in  $(a - b)$  and  $D_c$ .

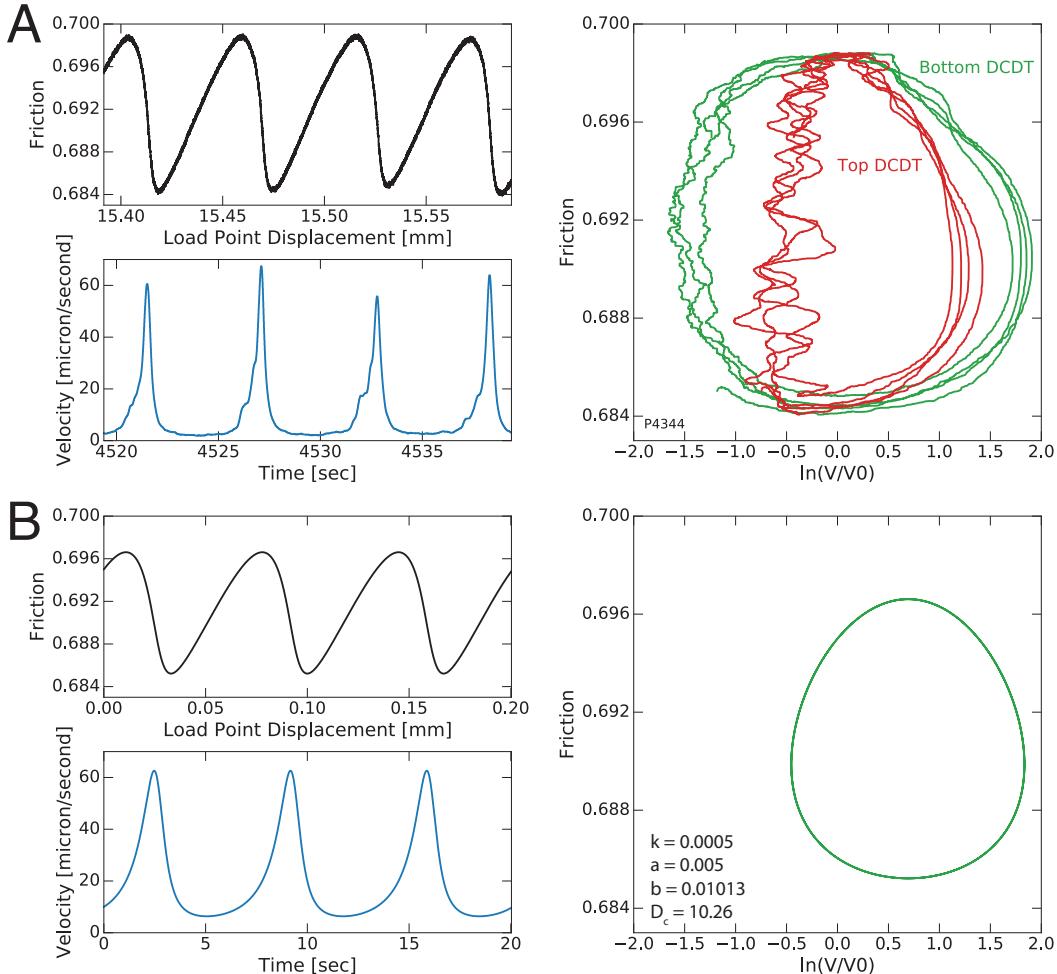


Fig. 3.11. A) An experimental plot of four slow-slip events, their time-friction curve, time-slider velocity curve, and phase plots. Notice that the top DCDT remains very close to the loading velocity, while the bottom DCDT becomes virtually stationary during the loading phase of the slip events. This indicates significant storage of strain energy in the forcing block. The bottom DCDT shows the slipping part of the experimental fault to slip faster than the top of the loading block, but with a nearly identical velocity profile. B) When setting  $\kappa = 1$  in a single state-variable rate-and-state friction model, a small perturbation will setup a limit cycle in which the system continually slow-slips, retracing the same path in phase space. The magnitude of the friction drop and peak slip velocity are dependent upon the size of velocity perturbation imposed on the system.

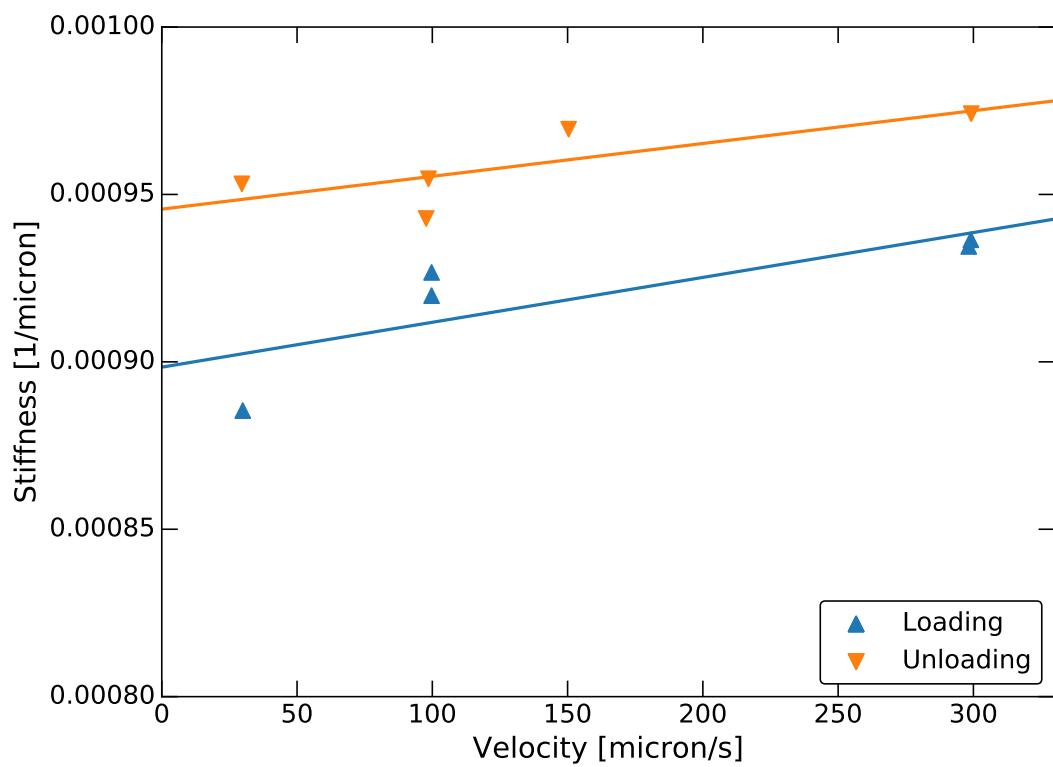


Fig. 3.12. The observed loading stiffness of our experimental system exhibits a slight increase with loading velocity.

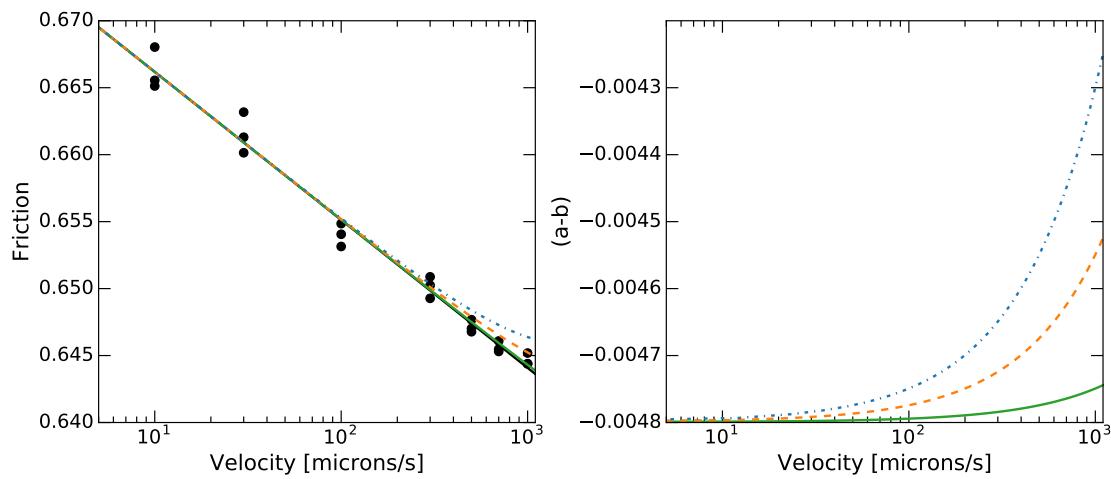


Fig. 3.13. Compiling data from 12 – 13 MPa normal stress where  $(a - b)$  is roughly constant, we see that small variations in  $(a - b)$  are not ruled out by our data. Variations as small as 0.0005 can make a significant difference in behavior when a system is near the stability boundary.

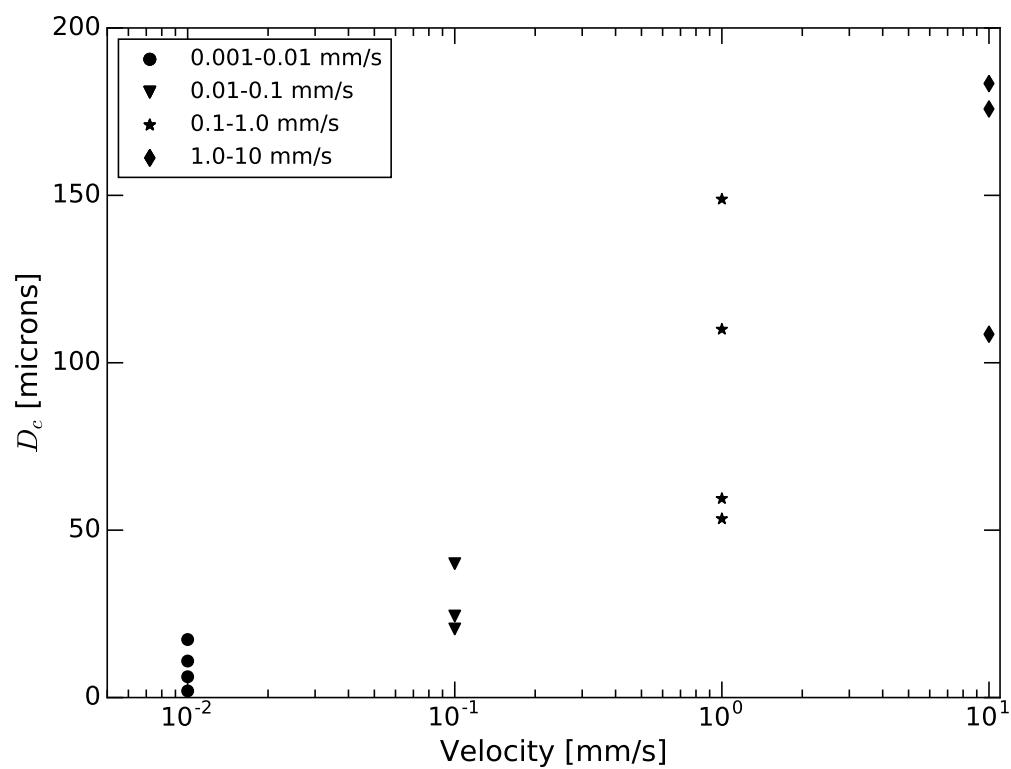


Fig. 3.14. The critical slip distance  $D_c$ , increases systematically with velocity in F110 experiments. While F110 is significantly larger than Min-U-Sil, it is of similar composition. Data from Mair [1999]

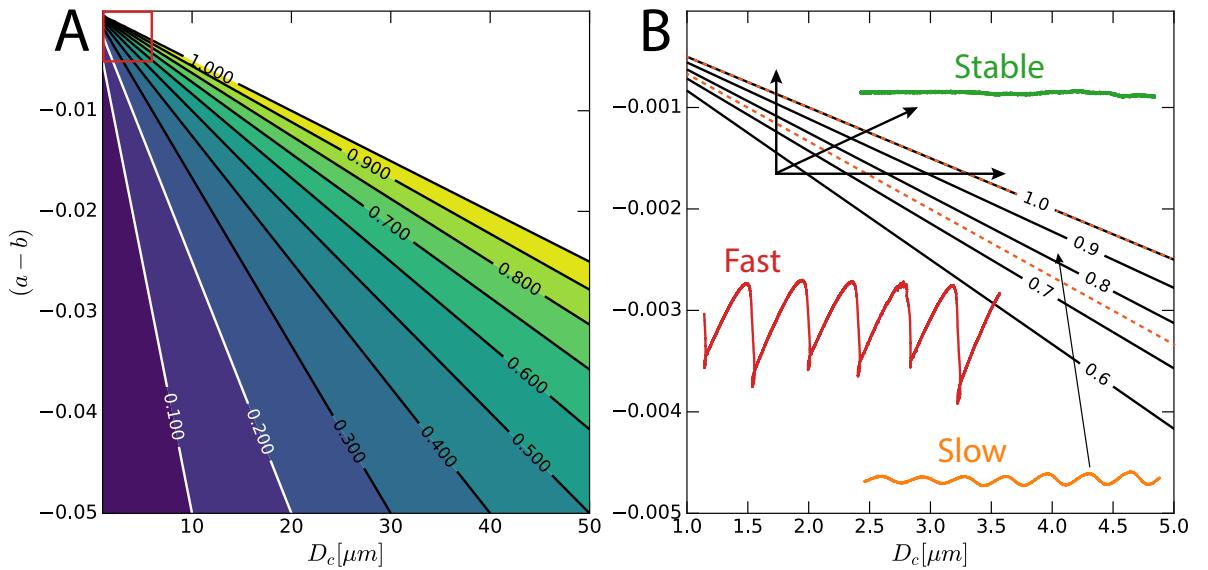


Fig. 3.15. The critical slip distance and frictional parameter ( $a - b$ ) trade off linearly to modify the critical stiffness ratio. When near the stability boundary, small changes in  $(a - b)$  can produce stable behavior (vertical line), but changes of a few microns in  $D_c$  can produce the same transition. The most likely scenario is that both parameters change with velocity, both increasing the stability of the system with increased driving velocity.

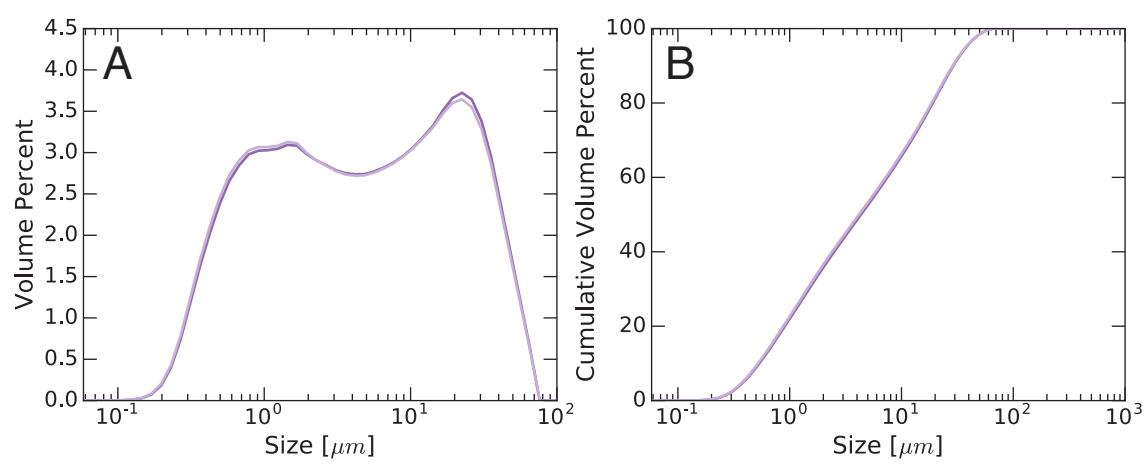


Fig. 3.16. Particle size distribution (A) and cumulative size distribution (B) for Min-U-Sil 40.

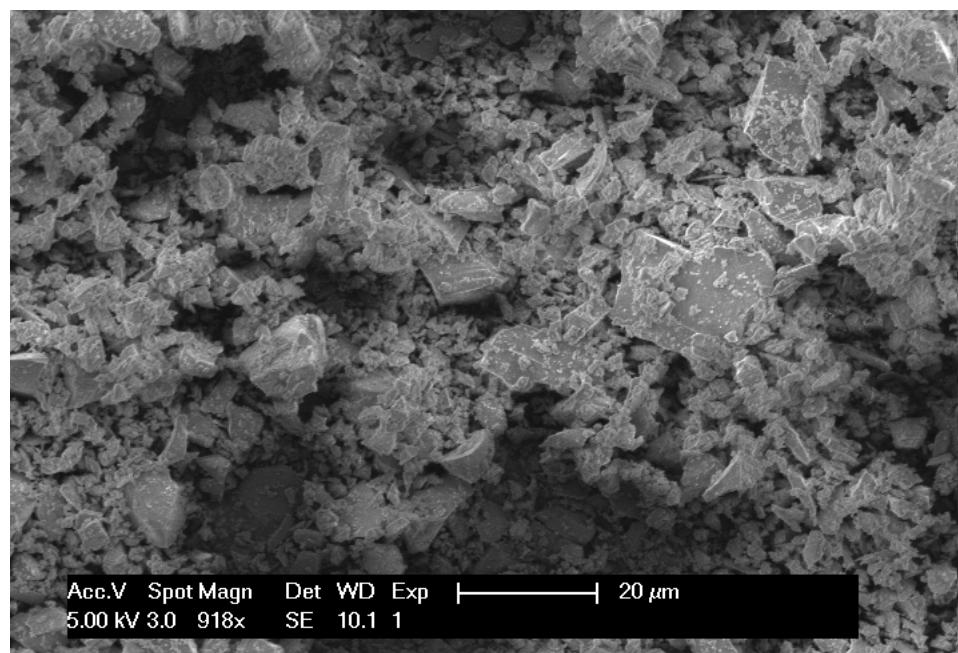


Fig. 3.17. An SEM micrograph of Min-U-Sil shows its angular nature.

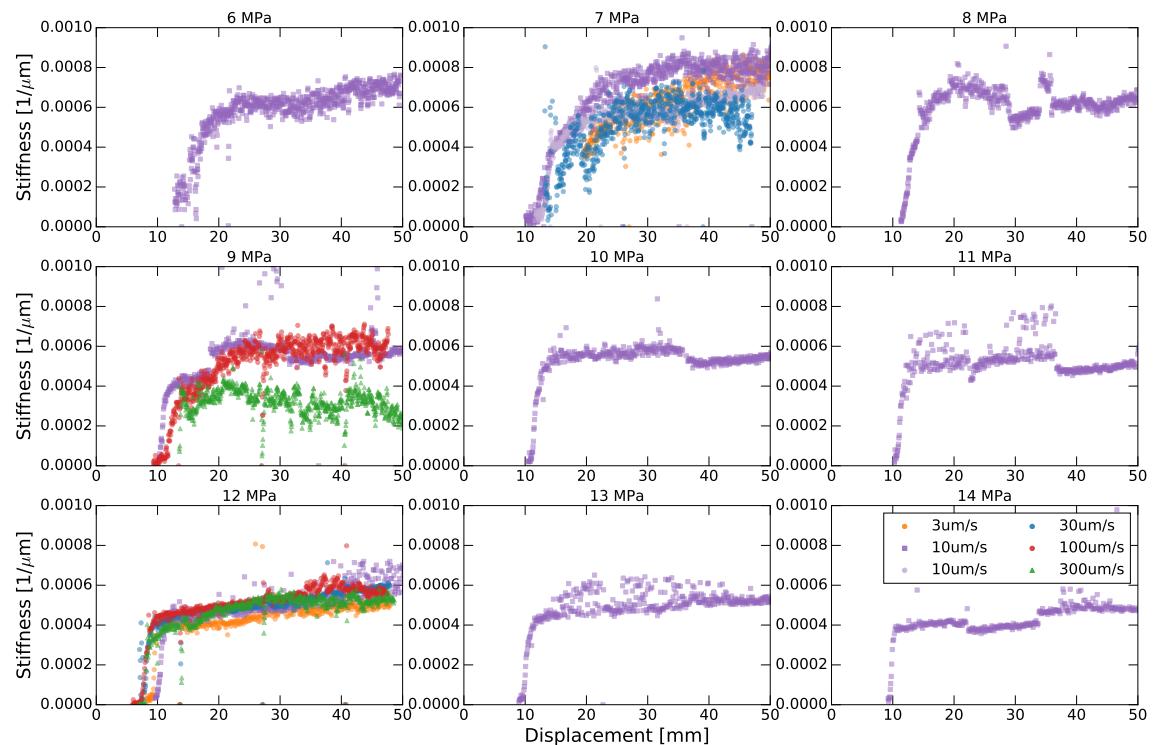


Fig. 3.18. The effective stiffness of each stick-slip event at a given normal stress as a function of displacement. Notice the quick rise once events begin and asymptotic approach of a final steady-state value.

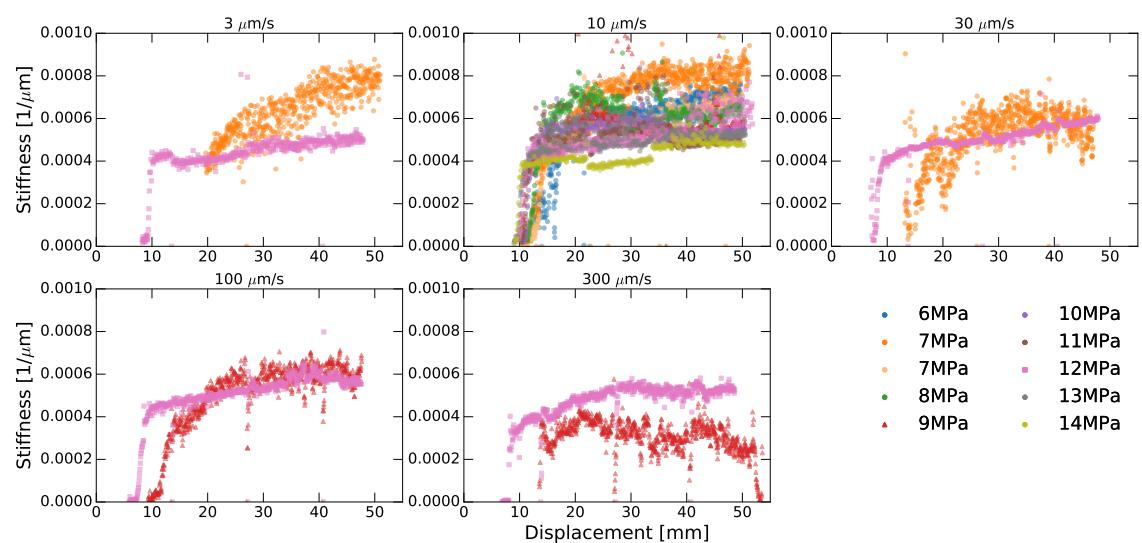


Fig. 3.19. Effective stiffness of each stick-slip event at a given driving velocity as a function of displacement.

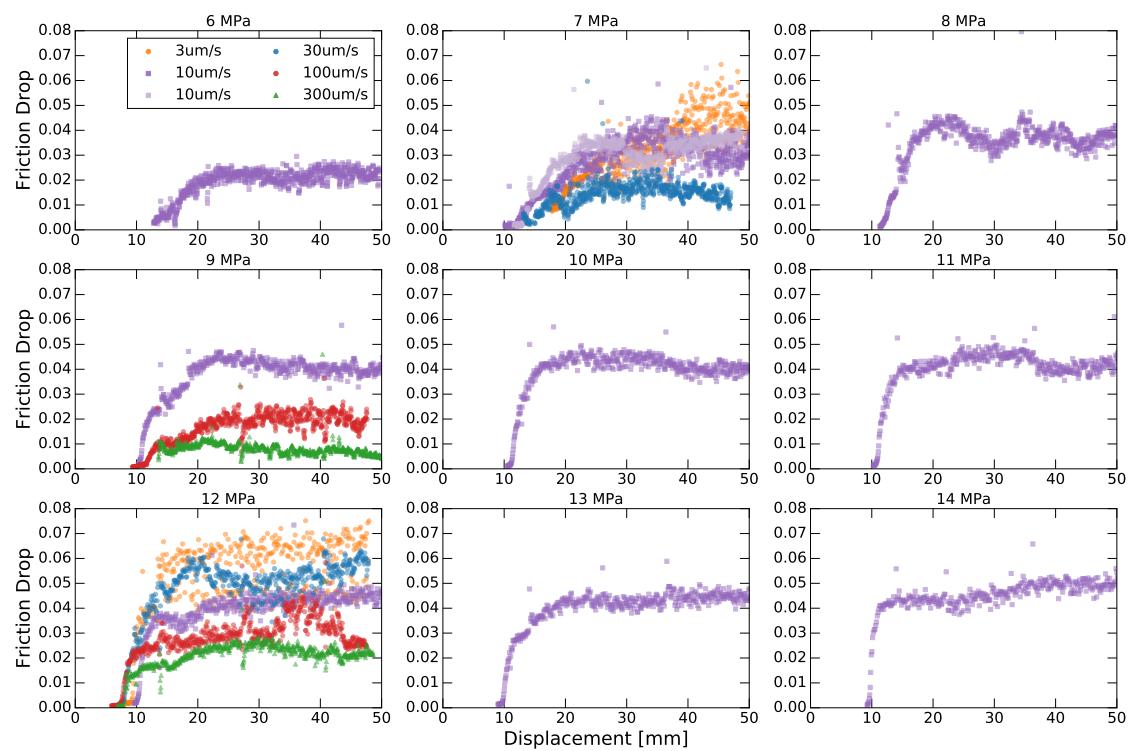


Fig. 3.20. Friction drop for each stick-slip event at a given normal stress as a function of displacement.

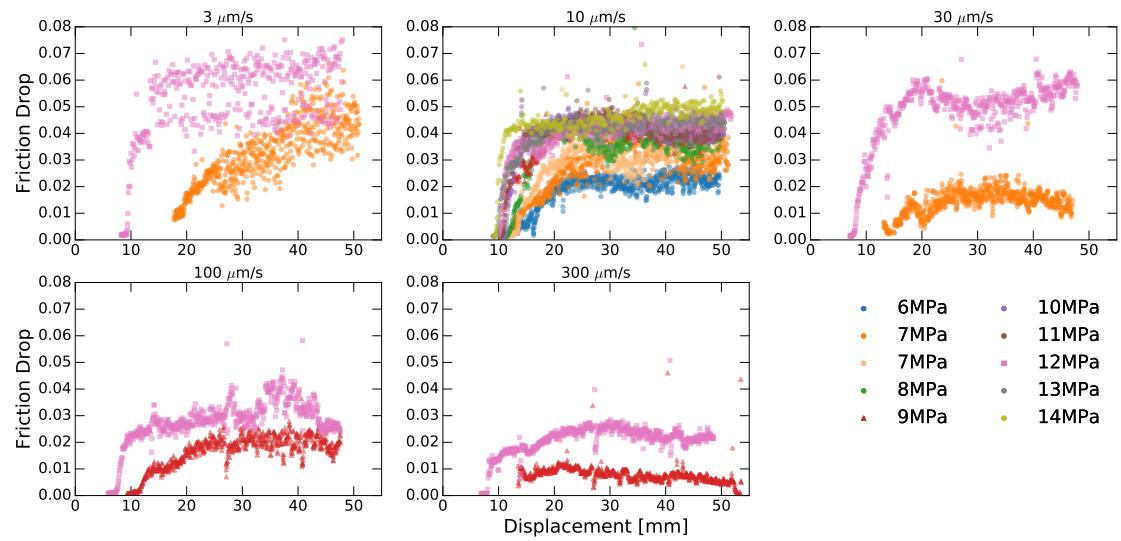


Fig. 3.21. Friction drop for each stick-slip event at a given driving velocity as a function of displacement.

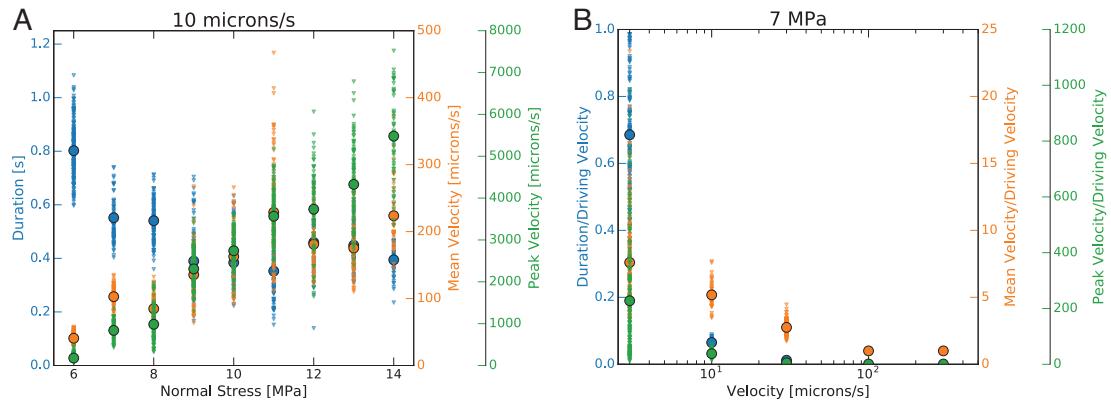


Fig. 3.22. Duration, mean velocity (slip distance/slip duration), and peak velocity for events at a constant driving velocity (A) and constant normal stress (B).

## Chapter 4

# Mechanical and hydrologic properties of Whillans ice stream till: Implications for basal strength and stick-slip failure

### 4.1 Abstract

Ice streams transport large volumes of inland ice to the ocean and play a key role in the mass balance of the Antarctic ice sheet. The rate and style of ice stream basal slip are governed, in part, by the underlying till whose physical properties are poorly constrained. To address this problem, we conducted a suite of laboratory measurements to document the permeability, stiffness, consolidation behavior, and compressional wave speeds of Whillans Ice Stream till samples. We investigated the effects of stepped and cyclic loading on the evolution of the till. Initial permeabilities were  $3.8 - 4.9 \times 10^{-17} \text{ m}^2$  (porosities 28.1-31.8%), which decreased to  $2.0 \times 10^{-19} \text{ m}^2$  (20.4%) at 10 MPa effective stress. P-wave velocities span from 2.26-3 km/s over this effective stress range, and are well described by an effective medium model. The laboratory measurements were used to parameterize a 1-D numerical model to predict the till's response to stress perturbations. Perturbations corresponding to tidal periods produce a drained and strengthened layer tens of cm thick. For perturbations over timescales of weeks to months, as expected for till motion over basement features, the drained zone is a few meters thick. This strong layer can become brittle upon unloading, and may facilitate observed stick-slip motion. Extrapolation of our effective medium model suggests low basal effective stresses, on the

order of a few tens of kPa, are needed to produce seismic velocities observed in the field ( $V_p$  1750 m/s;  $V_s$  160 m/s), and provides an approach to quantify and monitor in situ conditions.

## 4.2 Introduction

Ice streams are regions of fast-moving grounded ice shearing past slower-moving regions of ice. In Antarctica, ice streams discharge over 90% of the interior accumulation over only 13% of the coastline, making them critical to the ice sheet mass balance Morgan et al. [1983]. Motion of ice streams is complex, as the flow can migrate, stagnate, or even occur in a stick-slip fashion, inducing seismicity Anandakrishnan et al. [2003]; Wiens et al. [2008]; Walter et al. [2011]. Many models have attempted to explain the nature of ice stream movement, mostly invoking high basal water pressures, often coupled to soft subglacial sediments that smooth the bed and deform to lubricate motion Bentley [1987]; Alley et al. [2004]; Cuffey and Paterson [2010]. However, direct measurements sampling the subglacial environment of ice streams remain highly limited Cuffey and Paterson [2010].

Ice streaming is often observed to start over sedimentary basins, suggesting that flow begins where the bed first becomes deformable Anandakrishnan et al. [1998]; Bell et al. [1998]; Cuffey and Paterson [2010]. Understanding the mechanical properties of the till immediately underlying the ice is therefore of primary importance, as it may control the flow rate and stability of the ice stream, and ultimately play a key role in the ice sheet mass balance Tulaczyk et al. [2000]; Kamb [2001]. Sediment-water interactions

are also important in controlling grounding zone processes [e.g. Dowdeswell et al., 2008; Cowan et al., 2014].

Laboratory till-deformation experiments have provided important insights into the rheologic behavior of till Clarke [1987]; Iverson et al. [1997, 1998]; Kavanaugh and Clarke [2006]; Thomason and Iverson [2008]; Iverson and Zoet [2015], and the measured mechanical properties are comparable to the few reported field measurements, suggesting that the lab measurements can be upscaled effectively Tulaczyk [2006]. Since that important earlier work, there has been an increasing interest in the response of till to cyclic loading because of a growing body of evidence indicating that ice stream motion is tidally modulated in many cases. Examples include variations in velocity observed on Kamb Ice Stream (formerly ice stream C) Anandakrishnan and Alley [1997], on neighboring Bindschadler Ice Stream (formerly ice stream D) Anandakrishnan et al. [2003], and elsewhere Gudmundsson [2007]; Zoet et al. [2012]. Water-pressure observations beneath Whillans and Kamb Ice Streams also documented diurnal variations of 10-20 kPa, consistent with the dominant tidal frequency in the region Engelhardt and Kamb [1997]; Kamb [2001].

The downglacier part of Whillans Ice Stream exhibits two seismic motion events per day that are tightly linked to the tide, occurring just after high tide and just before low tide Bindschadler et al. [2003]; Winberry et al. [2014]. [Walker et al., 2013] proposed that the rising tide beneath an adjacent ice shelf causes downward bending extending a few ice thicknesses inland, compacting till beneath; the falling tide is then hypothesized to cause upwarp that may pump ocean water upglacier into the grounded flexural zone. The cyclic loading, with expected amplitude on the order of 50 kPa, leads to the development

of 'sticky spots' or asperities with higher shear strength and stiffness than the surrounding material, which promote the observed repeated stick-slip failure Winberry et al. [2011]; Pratt et al. [2014]; Winberry et al. [2014]; Walter et al. [2015]. Features observed near the grounding zone of Whillans Ice Stream, including upwarped surface topography, folded internal reflectors that indicate increased basal drag, and water/sediment exchange at the grounding line, are consistent with flexural behavior producing sticky spots through till compaction Christianson et al. [2013]; Horgan et al. [2013].

This prior work leads to a conceptual model wherein the interplay of material properties and time-dependent hydraulic processes produces a layer of till sufficiently stiff to support brittle stick-slip failure. Till hydrologic and consolidation properties ultimately govern the time scales of pore pressure diffusion and drainage Tulaczyk et al. [2000], which are central to the proposed tidal pumping mechanism, and also to hypothesized mechanisms of till weakening through generation of high pressures in front of ploughed debris Thomason and Iverson [2008]. Here, we report on a suite of tri-axial deformation experiments on till from beneath Whillans Ice Stream that include measurements of porosity, permeability, stiffness, and acoustic velocity under both stepped and cyclic loading conditions, aimed at understanding temporal and spatial scales of drainage-modulated processes in the till. We then incorporate these laboratory data into a transient 1-D model that couples till deformation (consolidation) and drainage to explore the hypothesis that cyclic loading produces a brittle layer that is able to support stick-slip failure.

#### 4.2.1 Geologic Setting

Whillans Ice Stream, formerly ice stream B, is one of five major ice streams located on the Siple Coast of Western Antarctica (Figure 4.1). Whillans is considered a fast-flowing ice stream, with over 400 m of surface displacement per year, though its velocity is currently decreasing and it may become stagnant within 100-200 years Whillans and Van Der Veen [1993]; Joughin et al. [2005]. The ice is approximately 1 km thick at the UpB camp, located approximately 400 km from the grounding line, where the ice stream has been most intensively studied Blankenship et al. [1986, 1987]; Rooney et al. [1987]; Engelhardt et al. [1990]. The ice flows over several meters of unconsolidated till that lie unconformably over a poorly lithified sedimentary sequence. Temperatures at the ice-till interface are at approximately the pressure melting point of -0.8° C Engelhardt et al. [1990]; Tulaczyk et al. [1998]. A surface slope of  $0.0013 \pm 0.003$  provides an average gravitational driving stress of 13-20 kPa Alley [1993]; Tulaczyk et al. [1998].

Cores of till were obtained at the UpB camp during field seasons from 1989-1993 (Figure 4.1). This unique suite of samples has been subjected to mechanical testing to measure several geotechnical properties, including texture, composition, and strength as a function of strain, strain rate, and effective stress Kamb [1991]; Tulaczyk et al. [1998, 2000]. After study, the samples were stored at room conditions (ambient humidity and temperature) by K. Licht at Indiana University-Purdue University Indianapolis and generously made available for this work. During drilling, observed fluid pressures in the borehole were within 50 kPa of the 9 MPa ice overburden (i.e. effective normal stresses less than 50 kPa and perhaps much less Tulaczyk et al. [2001]), such that shear stresses at

the bed are much less than those required to significantly deform the ice internally. This is consistent with laboratory shearing experiments showing that the cohesion of the tills is generally negligible and their shear strength is only a few kPa under a normal stress of 9 kPa Kamb [1991, 2001]. Such a low shear strength has led to the interpretation that rapid surface displacement of the ice stream is primarily the result of basal processes (sliding between ice and till, ploughing, and till deformation) Blankenship et al. [1986, 1987]; Engelhardt and Kamb [1997].

### **4.3 Materials and Methods**

#### **4.3.1 Sample Preparation**

We tested two samples from the Up-B expedition, obtained from depths of 0.3-0.4 m and 1.6-1.7 m (Samples 1744 and 1754) below the ice-till interface in borehole 89-1-4 (Figure 4.1). The till in general is a dark-grey unstructured diamicton, consisting of sand, silt, and clay-sized fractions in a bimodal distribution with scattered pebbles Tulaczyk et al. [1998]. Because the samples were stored at ambient conditions for many years, we used an ultrasonic humidifier with purified water to carefully re-hydrate the intact core samples. The samples were then trimmed into 2.54 cm diameter cylinders with lengths of 2.1 and 2.4 cm, with care taken to subsample only the most undisturbed parts of the core. Initial sample dimensions were recorded before jacketing and testing. The samples, together with end platens and porous frits, were jacketed with heat shrink tube. The shrink jacket was then sealed with tie-wire, and a thicker, stronger confining jacket was applied just over the ends of the specimen and secured with hose-clamps (Figure 4.2).

#### 4.3.2 Tri-axial Loading

Samples were loaded into a tri-axial pressure vessel. Confining (radial) and axial stresses were set to be equal in our tests (isostatic stress condition wherein  $\sigma_1 = \sigma_2 = \sigma_3$ ), and applied via a silicone oil pressurized by a piston syringe pump. Sample pore fluid pressure was controlled at each sample face using two additional high-precision syringe pumps. Prior to deformation, the samples were allowed to equilibrate for 24 hours under a pore pressure of 200 kPa and confining pressure of 300 kPa (effective pressure of 100 kPa) to ensure complete fluid saturation. During the equilibration stage, only one pore fluid pump was used to maintain pore pressure. Pore fluid pumps and the pressure vessel were maintained at a constant temperature of  $29.5 \pm 0.1^\circ\text{C}$  using a temperature chamber that surrounds the apparatus to minimize thermal expansion effects. Both pressure and volume were monitored continuously in both of the pore fluid pumps to a precision of  $\pm 1$  kPa and  $\pm 1$  mm<sup>3</sup> respectively, to document volumetric strain and changes in sample porosity.

The final porosity of the sample is obtained by weighing the fully saturated sample immediately after the test, and again after oven drying at 110 °C for 24-48 hours ASTM [2005]. The difference indicates the mass of interstitial water in the sample, from which the pore fluid volume is defined (assuming a water density of 1000 kg m<sup>-3</sup>); the total volume of the sample is determined from direct measurements of its dimensions using a micrometer. Using the final porosity value determined by this approach, porosity throughout the experiment is then calculated from the pore fluid pump volume measurements that record sample volume change (i.e. fluid expulsion or uptake).

Two loading paths were used to test the till samples. First, a simple incremental loading path was applied, in which the effective stress was increased step-wise and then allowed to equilibrate in a series of stages. Equilibration was defined as the point when pore volume and sample length were no longer changing significantly. Permeability and acoustic velocity were then measured after equilibration at each load step, as described in detail below. The second testing profile was designed to emulate cyclic loading as is hypothesized to result from tidally-driven ice flexure Walker et al. [2013]. We achieved this by applying a sequence of sinusoidal loading patterns with a period of 24-hours and amplitudes of 20, 50, 75, and 150 kPa. The amplitude of each sinusoid pattern was maintained for 5-10 days (5-10 cycles), starting with 20 kPa and increasing sequentially. Pore volumes and axial strain were monitored continuously during the tests, and permeability was measured following equilibration after each set of cycles at a given amplitude.

#### 4.3.3 Permeability and Compressibility

The permeability  $k$  [ $\text{m}^2$ ] of the samples was determined using a steady-state constant-head method. The upstream and downstream pore pressure pumps were held at constant pressures to maintain a pressure gradient across the specimen (ranging from 20-80 kPa in our tests). After reaching a steady-state, defined by equal flow rates in the two pumps to within 10%, water flux through the sample was determined from pump volume records (Figure 4.3). We then computed permeability using Darcy's relation:

$$k = \frac{Q\mu L}{A\Delta P} \quad (4.1)$$

where  $Q$  is the steady-state flow rate [ $\text{m}^3 \text{ s}^{-1}$ ],  $\mu$  is the dynamic fluid viscosity (0.0008 Pa s at 29.5°C),  $L$  is the sample length [m],  $A$  is the cross-sectional area of the sample [ $\text{m}^2$ ], and  $\Delta P$  is the difference in pressure between the upstream and downstream pumps [Pa]. For each effective stress step, we conducted permeability tests with three different pressure gradients, and report the permeability as the mean of these values (all data are provided in the Supplementary Materials). Sample compressibility,  $\beta$  [ $\text{Pa}^{-1}$ ], is calculated from the total sample volume change, as recorded in pore-fluid pump volumes, resulting from a known change in effective stress:

$$\beta = -\frac{1}{V} \frac{dV}{dP_e} \quad (4.2)$$

where  $V$  and  $dV$  are sample volume and change in sample volume [ $\text{m}^3$ ], respectively, and  $dP_e$  is the increment in effective stress [Pa].

#### 4.3.4 Acoustic Velocity

Compressional wave velocity was determined using a time-of-flight technique through the sample, corrected to account for travel time through the end-caps and porous frits Knuth et al. [2013]; Carpenter et al. [2014]. The end-caps used to apply axial load to the sample were equipped with lead-zirconate-titanate (PZT) transducers (Figure 4.2). A -900 VDC pulse was applied to one (transmitting) transducer, creating a propagating elastic wave with a center frequency of approximately 500 kHz. The signal from a second (receiving) transducer in the opposite end cap was recorded by a high-speed data acquisition system with a resolution of 16-bits over a 1 V range at 50 MHz sampling

rate (Figure 4.4). To reduce noise in individual waveform records, 100 waveforms were recorded and stacked to form one record. This was repeated a minimum of 25 times for each effective stress state. The P-wave arrivals are emergent at low stresses, but can be resolved accurately with a pattern cross-correlation technique, in which a pattern arrival is correlated with measured waveforms and the point of maximum correlation picked as the arrival. Velocity is then calculated from the corrected travel times for the first arrivals, and using directly measured sample length.

Acoustic velocities (both P- and S-wave speeds) in unconsolidated sediments and soils can also be predicted by effective-medium models [e.g. Dvorkin et al., 1999; Helgerud et al., 1999]. Application of such a model can provide a key link between in situ physical properties and conditions, including effective stress and pore-fluid pressure, and borehole or field-based geophysical data. Here we compose an effective-medium model following [Dvorkin et al., 1999] (see Appendix for details), incorporating X-Ray Diffraction (XRD) data that define the bulk till mineralogy, and then benchmark the model against our laboratory measurements of P-wave velocity.

#### 4.4 Results

The initial porosity of both core samples was 28-32%. This is lower than the estimated in situ porosity of 40% Engelhardt et al. [1990], and may be attributed to storage and sampling artifacts. Samples were obtained with a piston corer; the hammering action of the coring process may have compacted the samples from their in situ state. After initial characterization and cataloging, the samples were stored at room temperature and

humidity, and may have been subject to pore-space reduction associated with desiccation and matrix suction effects. To inform our effective-medium modeling, we conducted X-ray diffraction analyses on material from the two cores of till from beneath the ice stream that we tested in our deformation experiments (Figure 4.10). The diffraction patterns from both samples show almost identical mineralogy, with minor background count differences, and indicate that the till consists primarily of clay minerals, with a significant quartz fraction and some feldspar family minerals (Table 1).

#### 4.4.1 Consolidation and Compressibility

Our stepped loading tests (SAL1744) find a systematic decrease in porosity and concomitant increase in stiffness with increasing effective stress, following a strain-hardening trend typical of soils and sediments Wood [1990]. During stepped-loading, the effective confining pressure was increased from 100 kPa to 1 MPa in 100 kPa steps, decreased to 50 kPa, and then increased again (reloaded) to 10 MPa (Figure 4.5A). Volumetric and axial strain show very similar trends during the entire step loading test. The initial loading stages produced an integrated volumetric strain of about 3%, which was mostly recovered during unloading. Final strains of 6-10% were achieved at 10 MPa effective stress (Figure 4.5B). The initial porosity of the sample was 28.1% and the initial compressibility was  $\sim 5 \times 10^{-8} \text{ Pa}^{-1}$ . At 10 MPa effective stress, the porosity was reduced to 20.4% and compressibility to  $4.8 \times 10^{-9} \text{ Pa}^{-1}$ . Unloading the sample resulted in modest poroelastic rebound to a porosity of 23.6% (Figure 4.6B).

During our cyclic loading tests (SAL1754), strain continued to accumulate with each cycle, even though the effective stresses did not exceed those applied in preceding

cycles. The amount of incremental strain decreased asymptotically with each set of cycles at a given amplitude, and then increased sharply after increasing the amplitude of the oscillations (Figures 4.5C,D, 4.11). Initial loading produced 0.88% axial strain. After 10 cycles of 20 kPa, axial strain increased to 0.95% (corresponding to a porosity of 31.2%). After 25 cycles of 50 kPa, strain increased asymptotically to 1.04% (porosity of 31%); 10 cycles at 75 kPa increased strain to 1.09% (porosity of 30.5%). The final 15 cycles at 150 kPa increased the strain to 1.77% and reduced the porosity to 28.3%.

#### 4.4.2 Permeability

Permeability decreased systematically with loading, exhibiting nearly two orders of magnitude decrease upon loading to 10 MPa effective stress. Permeability decreases most rapidly early in the loading history, consistent with porosity loss and strain hardening. The samples had an initial permeability of  $3.8 \times 10^{-17} \text{ m}^2$  and  $4.9 \times 10^{-17} \text{ m}^2$  at an effective stress of 100 kPa, consistent with values reported for other till samples ( $1 \times 10^{-19} \text{ m}^2$  to  $1 \times 10^{-13} \text{ m}^2$ ) Freeze and Cherry [1979], and slightly lower than values of  $2 \times 10^{-16} \text{ m}^2$  reported from large scale field measurements at the Whillans drill site taken by a falling head permeameter Engelhardt et al. [1990]. We note that the higher permeabilities reported from the field measurements may reflect a component of non-Darcian flow at the ice-till interface. At 1 MPa effective stress (corresponding to 25.3% porosity), permeability was reduced by a factor of ~15-20, to  $2.5 \times 10^{-18} \text{ m}^2$ , and recovered only slightly to  $3.3 \times 10^{-18} \text{ m}^2$  upon unloading. After loading to 10 MPa effective stress (20.4% porosity), permeability was reduced to  $2.0 \times 10^{-19} \text{ m}^2$  (Figures 4.6A,B).

The cyclic loading test exhibited about an order of magnitude reduction in permeability over 60 loading cycles, despite the fact that the loading oscillations did not exceed the peak effective stress previously applied to the specimens, consistent with the trends of strain and porosity loss (c.f. Figures 4.5C-D). After 10 load cycles of 20 kPa (resulting in a porosity of 31.2%), the permeability of the specimen was reduced by a factor of 1.6, from an initial value of  $3.8 \times 10^{-17} \text{ m}^2$  to  $2.4 \times 10^{-17} \text{ m}^2$ . This was followed by 25 load cycles of 50 kPa (31% porosity) in which the permeability was reduced to  $1.3 \times 10^{-17} \text{ m}^2$ . Another 10 cycles of 75 kPa loading reduced the permeability to  $1.1 \times 10^{-17} \text{ m}^2$  (30.5% porosity). The final cycle set consisted of 15 cycles at 150 kPa, and the permeability was reduced to  $3.9 \times 10^{-18} \text{ m}^2$  (corresponding to 28.3% porosity) (Figure 4.6C,D).

#### 4.4.3 Acoustic Velocity

P-wave velocity increased systematically with effective stress in our stepped loading test. At an effective pressure of 0.7 MPa (corresponding to 26.4% porosity),  $V_p$  values of  $\sim 2.26$  km/s were observed, increasing to nearly 3 km/s at 10 MPa effective stress (20.4% porosity) (Figure 4.7A). The compressional wave velocity data from the laboratory are fit reasonably well by our effective medium model, assuming a critical porosity of 40% and grain contact number of 8 (Table 1; Appendix). Extrapolation of the effective medium model to slightly lower effective stresses predicts that in situ effective stresses  $<\sim 100$  kPa, and in situ porosities  $>\sim 40\%$  would be required to produce P and S wave velocities of  $\sim 1750$  m/s and 160 m/s, respectively, that are observed via field experiments Blankenship et al. [1986, 1987]; Luthra et al. [2016]. This provides new

evidence supporting inferences of low effective stresses, and thus low shear strength, at the base of the ice stream (Figure 4.7).

#### 4.4.4 Hydrologic Model

To explore the implications of our laboratory measurements for the hypothesized development of a 'hard layer' that enables stick-slip motion of the ice stream, we developed a simple 1-D transient finite-difference model implemented with the Python package FiPy Guyer et al. [2009] that simulates coupled compaction and drainage in a vertical column of till with heterogeneous properties (Figure 4.8). Because permeability and compressibility vary strongly and nonlinearly with effective stress, we use a 0.01 m nodal spacing and a time step of 0.01 - 1000 seconds, increasing as the model changes become more gradual. This allows us to quantify the evolution of till porosity, stiffness, permeability, and effective stress in response to perturbations at the ice stream bed. By incorporating the constitutive relations obtained from our laboratory measurements (Figure 4.12) we account for the significant and non-linear evolution of porosity, permeability, and compressibility during compaction Skarbek and Saffer [2009] that are typically not included in simple models having homogeneous and/or time-invariant physical properties [e.g. Gibson, 1958; Wissa, 1971].

This model provides first-order insights into the time-dependent behavior of the system and the time and length scales of drainage relevant to subglacial processes. The model is initialized with a hydrostatic pressure gradient, and the vertical effective stress at the top boundary (ice-till interface) is then increased instantaneously to explore the response to a perturbation. This value is then held constant (Dirichlet boundary), and

the till layer is allowed to evolve. The bottom boundary, 10 m below the till-ice interface, is controlled with Neumann boundary conditions of zero flux to emulate the harder semi-consolidated bedrock on which the till is deposited. The upper boundary is physically equivalent to allowing drainage into an ice-contact water system at the specified pressure, of the sort known to exist beneath Whillans Ice Stream Engelhardt and Kamb [1997]; Kamb [2001]. The governing equation for fluid flow is:

$$\frac{\partial}{\partial z} \left( \frac{K}{S_s} \frac{\partial h}{\partial z} \right) = \frac{\partial h}{\partial t} \quad (4.3)$$

where  $h$  is hydraulic head [m],  $S_s$  is specific storage [ $\text{m}^{-1}$ ], and  $K$  is hydraulic conductivity [ $\text{m s}^{-1}$ ]. Specific storage is in turn defined from compressibility, where  $\beta$  is the till compressibility and  $\beta_{\text{blah}}$  is the fluid compressibility and the sample porosity.

$$S_s = \rho g (\beta + \zeta \phi) \quad (4.4)$$

Hydraulic conductivity is defined from permeability by:

$$K = \frac{k \rho g}{\mu} \quad (4.5)$$

where  $\rho$  is the fluid density [ $\text{kg m}^{-3}$ ],  $g$  the acceleration of gravity [ $\text{m s}^{-2}$ ], and  $\mu$  is the fluid viscosity [Pa s]. Porosity, permeability, and compressibility are determined for each model cell from empirical least-squares fits to our experimental data (equations 4.6, 4.7, 4.8), and updated at each time step as hydraulic head and effective stress evolve (Figure 4.8A). The permeability prediction from our empirical fit slightly under predicts

observed permeabilities at the highest porosities, but errors are less than a factor of two and inconsequential in the modeling scheme. As the porosity is rapidly reduced during initial drainage, the empirical relation and model quickly converge. The model also provides a minimum estimate of active layer depth due to the slight under prediction of permeability in the early stages of the model run.

$$\beta = 1.69 \times 10^{-7} - 9.98 \times 10^{-9} \log(P_e) \quad (4.6)$$

$$\phi = 0.536 - 2.04 \times 10^{-2} \log(P_e) \quad (4.7)$$

$$k = 4.09 \times 10^{-25} e^{62.12\phi} \quad (4.8)$$

For a simple drop in pressure at the top of the till (or equivalently a step increase in pressure within the till caused by mechanical loading), there is initial drainage to the top of the column. The uppermost few cm of the till quickly drains, and as a result its porosity and permeability are significantly reduced and its stiffness increases (Figure 4.9). This results in self-limited drainage from the top of the layer relative to that predicted for a homogeneous case (i.e. in which the till properties are time invariant) Wissa [1971], and leads to the development of a thin zone at the top of the till where consolidation has progressed. This zone is characterized by increased effective vertical stress (and thus increased shear strength), increased stiffness, and decreased porosity (Figure 4.9). As the till layer responds and drains, a minimum in vertical effective stress, and in shear

strength, propagates downward. Over timescales of tidally-driven perturbations, this minimum in strength reaches approximately 0.7 m; by 30 days it propagates to 4 m. Upon unloading, during upward flexure of the ice, the till is in an overconsolidated state and has become embrittled Wood [1990], possibly promoting seismogenic failure.

## 4.5 Discussion

Despite the fact that samples were stored at room conditions for a number of years, we expect their properties to be representative of in-situ conditions. Once rehydrated during sample carving, then saturated in the pressure vessel and loaded to effective stresses of  $\sim 100$  kPa the properties should track undisturbed samples. Our observations of systematic behaviors and trends as well as generally low permeability measurements suggest that any permanent effects from dry storage are negligible. In fact, it is likely that piston coring had a larger effect than desiccation on the sample properties.

### 4.5.1 Till physical properties and relevance to sticky spot development

The evolution of porosity, permeability, and stiffness observed in our experiments is consistent with the conceptual model of a hard layer of till that enables stick-slip behavior. For example, during compaction in our experiments, till compressibility was reduced by a factor of 7 from an initial value of  $7 \times 10^{-8}$  Pa $^{-1}$ . We also observed that when subjected to load cycling, the till progressively compacts as a result of small-amplitude fluctuations in stress, even if the effective stresses never exceed values previously experienced by the material. These processes are likely to be increasingly important near the grounding line, where ice flexure due to ocean tides is continually changing the stress

state at the base of the ice and possibly produces persistent brittle layers of till. Drainage times obtained from the 1-D hydrological model are also consistent with this conceptual model. In a 12 hour tidal period a compacted zone a few tens of centimeters thick can form. In contrast, over timescales of a month, the expected drainage length is several meters, suggesting that any ice stream movement over sticky or rough bed features with a wavelength greater than  $\sim 30$  m should have enough time to fully equilibrate, drain, and consolidate. The decadal time scale for ice motion across the modeled flexural wavelength (a few km in most settings) of the grounding zone gives time for repeated tidal cycling to integrally effect large changes (i.e. decreased porosity and permeability, and increased stiffness) in till moving with ice or slower than the ice. To help test hypotheses about the in situ state of the till, direct measurements of pore pressure and effective stress are essential. Unfortunately, there are very few borehole measurements of key properties, and for Whillans ice stream they are concentrated at the UpB site. A calibrated effective medium model, defined by our laboratory measurements (Figure 4.7), can be used in conjunction with field seismic studies to estimate the in situ vertical stress, porosity, and pore pressure of the till. This allows mapping of these generally elusive physical properties using geophysical surveys in other areas, including those near known ‘sticky spots’ [e.g. Luthra et al., 2016], and provides a new line of evidence for inferred low in situ effective normal stresses and elevated pore pressures along the ice stream bed.

#### 4.5.2 Shearing Processes

The ice-stream is heavily influenced by tidal signals on a diurnal time scale. These periodic stressing events and patchy basal hydrologic connection can result in load/unload cycles over large regions. According to our model, such daily perturbations likely have little influence below a few tens of centimeters in the till. For longer term perturbations, such as passing over hard/rough spots in the flow path, the influenced layer could be on the order of several meters. The prediction of a shallow active layer is consistent with other work and matches observations in the field on glaciers with accessible till layers Boulton and Hindmarsh [1987]; Truffer et al. [2000]; Kamb [2001].

Under such periodic loading, upward drainage will reduce porosity just beneath the ice-till interface, producing a low-permeability cap. This layer will limit hydraulic communication between deeper till and any ice-contact water system, and upon subsequent unloading will be overconsolidated. A confined interval of lower effective stress, higher porosity and lower strength then will underlie this upper compacted centimeters-thick layer of till (Figure 4.9). The overconsolidated - and thus brittle - layer could easily break internally and/or slide on the till below. The depth variation in consolidation state and effective stress likely means that solid body sliding, ploughing, internal deformation, and brittle faulting could all be active in accommodating the movement of the ice stream Iverson et al. [1998]; Iverson and Iverson [2001]; Thomason and Iverson [2008]. During shearing, the upper layer of till will be remolded and dilated, potentially ‘resetting’ its properties and re-introducing porosity and permeability. Alternatively, if

the till properties are not completely reset by shearing, a widespread, persistent thin, hard, and brittle layer of till could develop.

#### **4.5.3 Effective Stiffness Feedback Mechanism**

The proposition of a thin active layer of plastic till poses a fundamental problem. Such materials are generally not associated with stick-slip movement and seismic radiation like that observed on many ice streams Anandakrishnan and Bentley [1993]; Anandakrishnan and Alley [1997]; Lipovsky and Dunham [2016]. In fact, the movement of ice streams is analogous to that of tectonic slow-slip phenomena with a very regular period and small rupture area/rupture time ratios Ide et al. [2007a]; Peng and Gomberg [2010]. There are multiple proposed controls on this style of fault rupture, including high pore pressure and concomitant low effective normal stress, and complex rheologies that allow instabilities to nucleate, but which limit slip speeds by strengthening at higher sliding velocities Peng and Gomberg [2010]; Rubin [2011]. Recent work shows that for frictional failure, the stiffness of the loading system relative to a rheologically defined critical stiffness of the sliding region (termed  $k_c$ ) may also be a key factor in controlling the style and speed of frictional slip Scholz [2002]; Leeman et al. [2015, 2016]. Systems that are less compliant (stiffer) than the critical stiffness are inherently stable and exhibit aseismic creep. Systems that are more compliant (less stiff) than the critical stiffness are unstable, because any slip that initiates causes weakening that outpaces the rate at which accumulated elastic strain energy can be released. The mismatch between weakening and energy release results in a force imbalance that produces acceleration and dynamic stick-slip events. The rheologically defined stiffness ( $k_c$ ) is a function of the

frictional properties of the sliding interface, as well as the effective normal stress across it; lower normal stress decreases  $k_c$  and leads to a tendency for stable slip. Systems at or near the stability threshold in which the stiffness approximately matches that of the critical stiffness may exhibit periodic slow-slip events, much like those observed in nature. It is possible that a feedback mechanism operates to buffer the aggregate stiffness of the highly deformable ice stream system at approximately the critical stiffness. Such a buffering effect could maintain the system in a regime of slow-slip failure, regardless of the shearing state of the till. In a system that is stiffer than  $k_c$ , we expect steady basal sliding. However, this rapid motion will result in vigorous reworking of the till, dilating it, reducing the system stiffness and bringing it nearer to or below the stability threshold. For systems more compliant than  $k_c$ , there would be long periods of 'sticking' during which consolidation and stiffening would occur as the system is loaded. From cyclic loading tests, we expect the till below the actively deforming layer to compact over multiple tidal cycles, also leading to stiffening. Increasing stiffness would drive the system back toward stability (i.e. toward  $k_c$ ). These competing effects could buffer the aggregate stiffness near the stability threshold. When coupled with low effective normal stress along the base of the ice stream, this may offer a plausible explanation for failure in slow but periodic transient slip events.

## 4.6 Conclusions

Since the discovery of soft, deformable till beneath ice streams in the 1980's, there have been more questions than answers about slip partitioning, till rheology, and

the connection between basal hydrology, ice-till interaction, and ice stream flow, particularly for fast-flowing streams. We provide laboratory data that can be used to constrain hydraulic property evolution in full ice-sheet models, and we show that tidal loading can have lasting effects on till properties that may or may not be completely erased during shearing and dilation. Our laboratory measurements and modeling provide a unique set of data and verification that is consistent with a limited body of existing work. We document systematic decreases in porosity and permeability with increasing effective stress. We also observed increasing stiffness, consistent with porosity reduction and strain-hardening behavior. Our cyclic loading tests show that non-recoverable strain, and associated reduction in permeability and increases in stiffness, may accumulate in till that is diurnally loaded through tidal processes. A numerical model incorporating these laboratory observations illustrates that the development of a thin strengthened and overconsolidated layer of till resulting from tidally-driven loading is plausible. The development of such a layer may explain strengthened 'sticky spots' at the base of the ice stream in areas where flexure is focused Walker et al. [2014]; Winberry et al. [2014]. Incorporation of our physical property measurements into more complex ice flow models could be a step towards reproducing the physics of stick-slip events. Finally, our measurements of acoustic velocity, coupled with effective medium modeling, defines - for the first time, and based on first-principles - a site-specific transform linking acoustic velocity and effective stress immediately beneath the ice stream. The results provide new and quantitative evidence for basal effective stresses < 100 kPa as inferred in previous work or measured in isolated locations in boreholes, and highlights a potentially fruitful approach to quantify and map basal conditions regionally. Furthermore, the low

effective stress and near critical stiffness conditions believed to exist at the bottom of stick-slip ice streams are analogous to conditions believed to exist in environments of tectonic slow-slip. Merging glacial and tectonic observations with ice streams serving as a natural laboratory may yield new and valuable insight to the conundrum presented by slow-slip and tremor observations.

#### 4.7 Effective Medium Model Formulation

Bulk modulus ( $K$ ), shear modulus ( $G$ ), and Poisson's ratio( $\nu$ ) of the solid matrix material are calculated as simple weighted averages upon the percent composition ( $f_i$ ) of each mineral (eq. 4.9,4.10,4.11).

$$K = \frac{1}{2} \left[ \sum_{i=1}^m f_i K_i + \left( \sum_{i=1}^m \frac{f_i}{K_i} \right)^{-1} \right] \quad (4.9)$$

$$G = \frac{1}{2} \left[ \sum_{i=1}^m f_i G_i + \left( \sum_{i=1}^m \frac{f_i}{G_i} \right)^{-1} \right] \quad (4.10)$$

$$\nu = \frac{1}{2} \left[ \sum_{i=1}^m f_i \nu_i + \left( \sum_{i=1}^m \frac{f_i}{\nu_i} \right)^{-1} \right] \quad (4.11)$$

Assuming the average number of grain contacts of each matrix of the particle ( $n$ ) and a critical porosity ( $\phi_c$ ), the effective bulk ( $K_{HM}$ ) and shear ( $K_{HM}$ ) moduli are then computed (eq. 4.12, 4.13).

$$K_{HM} = \left( P \frac{n^2(1 - \phi_c)G^2}{18\pi^2(1 - \nu)^2} \right)^{\frac{1}{3}} \quad (4.12)$$

$$G_{\text{HM}} = \frac{5 - 4\nu}{5(2 - \nu)} \left( P \frac{3n^2(1 - \phi_c)G^2}{2\pi^2(1 - \nu)^2} \right)^{\frac{1}{3}} \quad (4.13)$$

The effective dry bulk ( $K_{\text{Dry}}$ ) and shear ( $G_{\text{Dry}}$ ) moduli of the solid framework at an arbitrary porosity ( $\phi$ ) are then calculated as:

$$K_{\text{Dry}} = \left( \frac{\frac{1-\phi}{1-\phi_c}}{K_{\text{HM}} + \frac{4G_{\text{HM}}}{3}} + \frac{\frac{\phi-\phi_c}{1-\phi_c}}{\frac{4G_{\text{HM}}}{3}} \right)^{-1} - \frac{4}{3}G_{\text{HM}} \quad (4.14)$$

$$G_{\text{Dry}} = \left( \frac{\frac{1-\phi}{1-\phi_c}}{G_{\text{HM}} + \frac{G_{\text{HM}}}{6} \left( \frac{9K_{\text{HM}}+8G_{\text{HM}}}{K_{\text{HM}}+2G_{\text{HM}}} \right)} + \frac{\frac{\phi-\phi_c}{1-\phi_c}}{\frac{G_{\text{HM}}}{6} \left( \frac{9K_{\text{HM}}+8G_{\text{HM}}}{K_{\text{HM}}+2G_{\text{HM}}} \right)} \right)^{-1} - \frac{G_{\text{HM}}}{6} \left( \frac{9K_{\text{HM}}+8G_{\text{HM}}}{K_{\text{HM}}+2G_{\text{HM}}} \right) \quad (4.15)$$

The saturated media bulk ( $K_{\text{sat}}$ ) and shear ( $G_{\text{sat}}$ ) moduli are calculated as:

$$K_{\text{sat}} = \frac{K \left( \phi K_{\text{dry}} - \frac{(1+\phi)K_f K_{\text{Dry}}}{K} + K_f \right)}{(1 - \phi)K_f + \phi K - \frac{K_f K_{\text{Dry}}}{K}} \quad (4.16)$$

$$G_{\text{sat}} = G_{\text{dry}} \quad (4.17)$$

The compressional ( $V_p$ ) and shear ( $V_s$ ) wave velocities are finally calculated from the saturated moduli as:

$$V_p = \sqrt{\frac{K_{\text{sat}} + \frac{4G_{\text{sat}}}{3}}{\rho_b}} \quad (4.18)$$

$$V_s = \sqrt{\frac{G_{\text{sat}}}{\rho_b}} \quad (4.19)$$

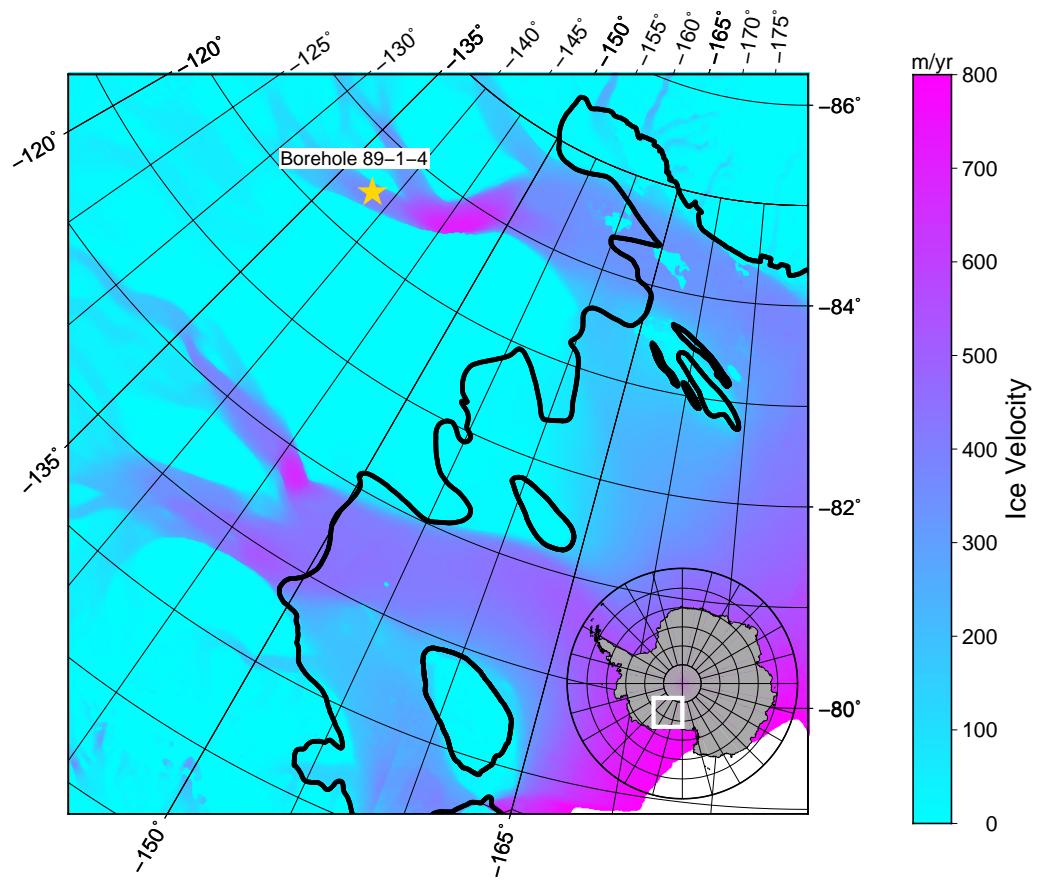


Fig. 4.1. Samples for this study were obtained from borehole 89-1-4 near the junction of the B1 and B2 branches of Whillans Ice Stream. Ice velocities of 600 m/yr are typical in the region [Rignot et al., 2011; Mouginot et al., 2014]. The grounding line is marked in solid black.

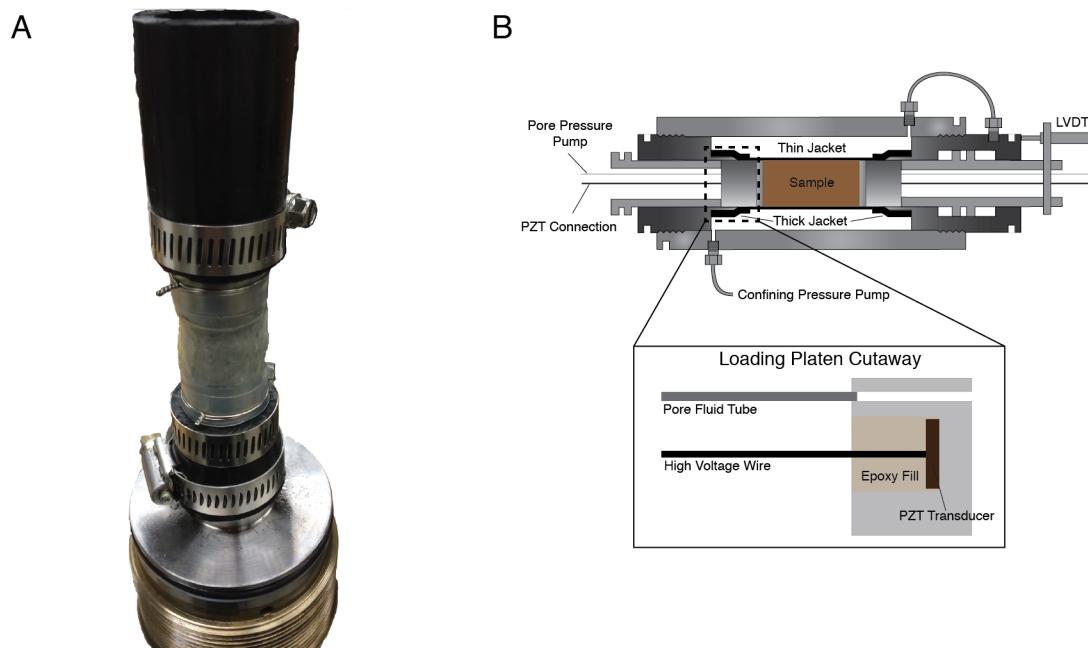


Fig. 4.2. A) The completed sample assembly ready to be loaded into the pressure vessel. B) Schematic diagram of the tri-axial loading cell. Heat shrink tubing was used as a thin, low-strength jacketing material. A hydraulic syringe pump provided isotropic confining and axial loading stresses. A linearly variable displacement transformer (LVDT) measured sample strain. Two high-precision water syringe pumps imposed a hydraulic head to determine sample permeability. Piezoelectric transducers in the loading platens measured the elastic wave travel time through the core (inset).

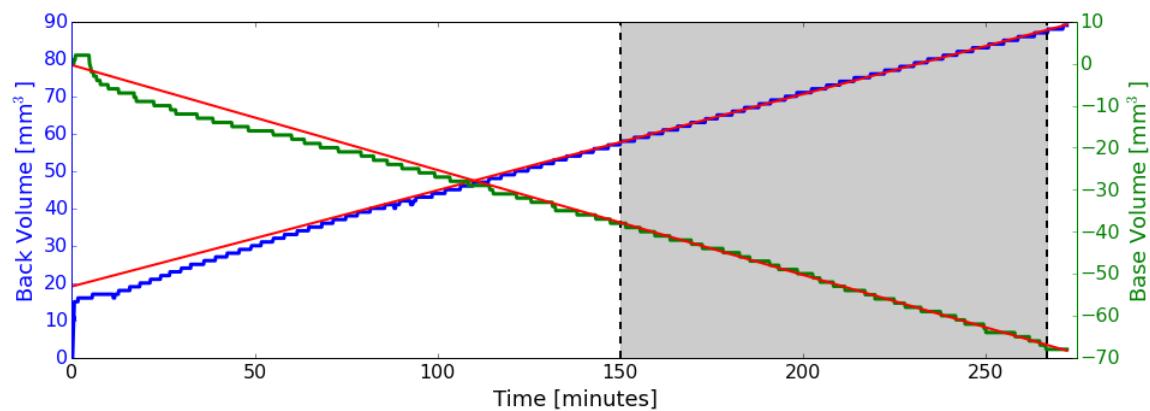


Fig. 4.3. To determine permeability, flow rates from the upstream (blue) and downstream (green) pumps are fit with a least squares fit (red) when the steady-state flow condition is achieved (shaded area). The procedure is repeated at multiple hydraulic heads for repeated permeability measurement.

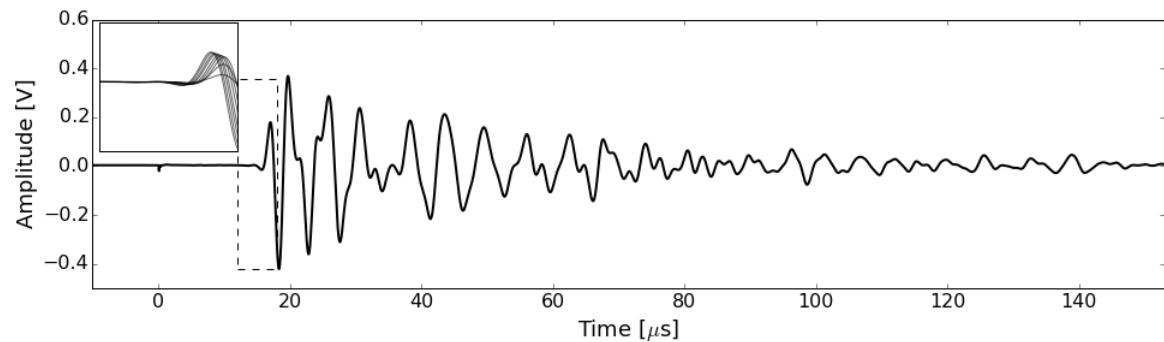


Fig. 4.4. An example acoustic waveform collected during the step-loading test. Inset shows changes in travel time with step loading to 1 MPa effective stress. First arrivals are picked with a cross-correlation technique for consistency.

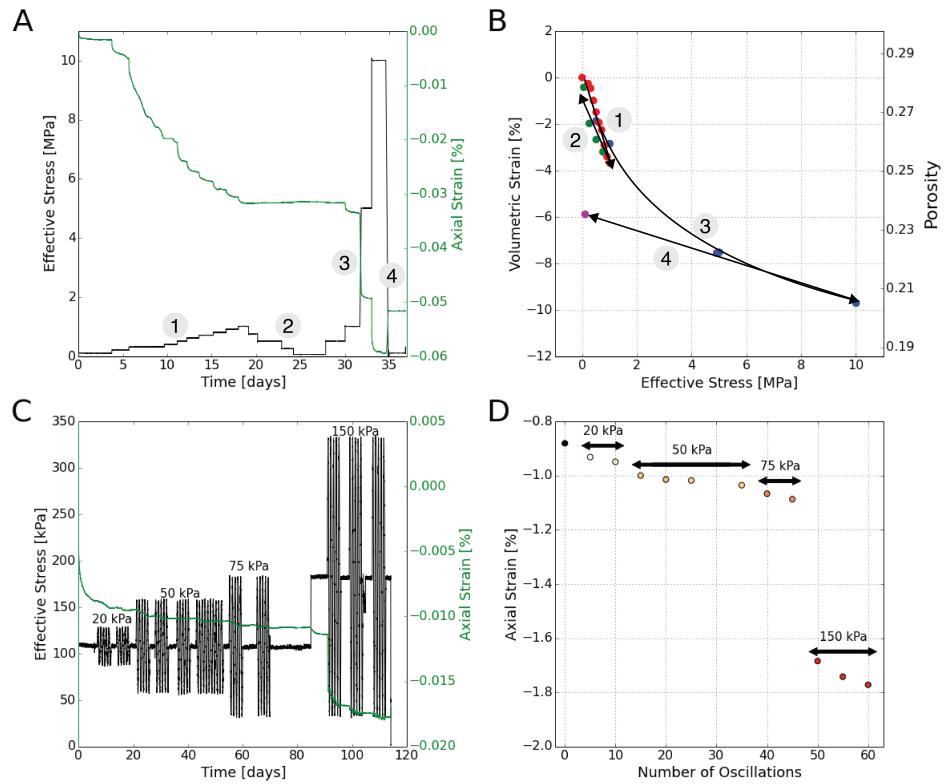


Fig. 4.5. A) Results of the isotropic step loading test show an expected compaction behavior. B) Effective stress and volumetric strain relationship. Initial loading (1) and unloading (2) shows near elastic recovery. Reloading to a 10MPa effective stress (3) created considerable permanent deformation upon the final unloading cycle (4). C) Evolution of axial strain during repeated tidal load cycling. All cycles had a 24-hour period with amplitudes of +/- 25, 50, 75, and 150 kPa. D) Strain was accumulated during all cycle sets, but the additional observed strain decreased with each subsequent set until the amplitude was increased.

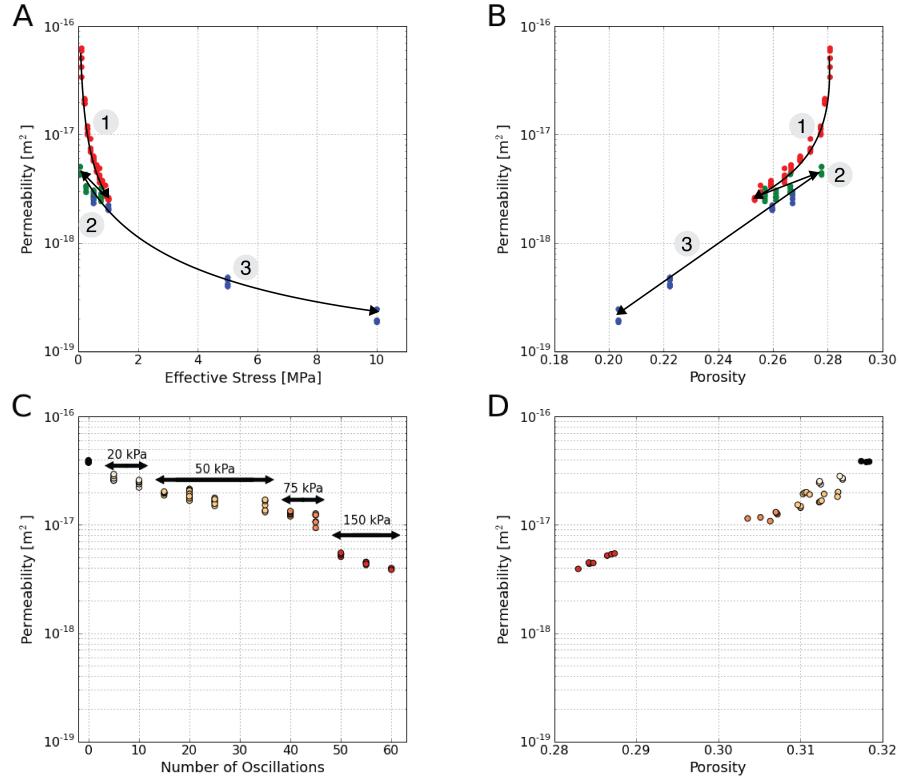


Fig. 4.6. A) Permeability evolution during the step-loading test. Initial permeability values of approximately  $3.5 \times 10^{-17} \text{ m}^2$  were reduced by over an order of magnitude during the initial loading (1) with little recovery upon unloading (2). Permeability was reduced by an order of magnitude during reloading (3) to an effective stress of 10 MPa. B) Initial porosity values of 28% are lower than field estimates. The trend mirrors that of volumetric strain. C) Evolution of permeability and porosity during the tidal loading test indicate that both can be significantly reduced with little additional loading stress, but with load cycling. Initial porosity of 32% was reduced by several percent over the 60 simulated tidal cycles. D) Permeability was also reduced by an order of magnitude during the cycling. All measurements shown were taken after cycling was complete and the sample had equilibrated.

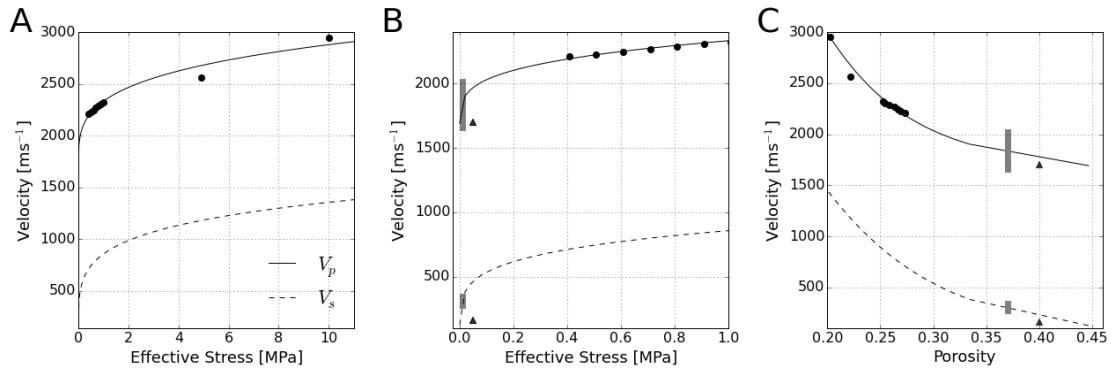


Fig. 4.7. (A) Predicted compressional and shear wave velocities from the effective medium model as a function of effective stress, (B) an expanded view showing field velocity measurements from seismic experiments, and porosity (C). The model is supported by experimental compressional wave velocity measurements, but no shear wave measurements could be obtained in the laboratory due to the very low effective pressures of the experiment. Black circles represent direct measurements from the laboratory, gray bars are velocity estimates by Luthra et al. [2016] and black triangles are estimates by Blankenship et al. [1987].

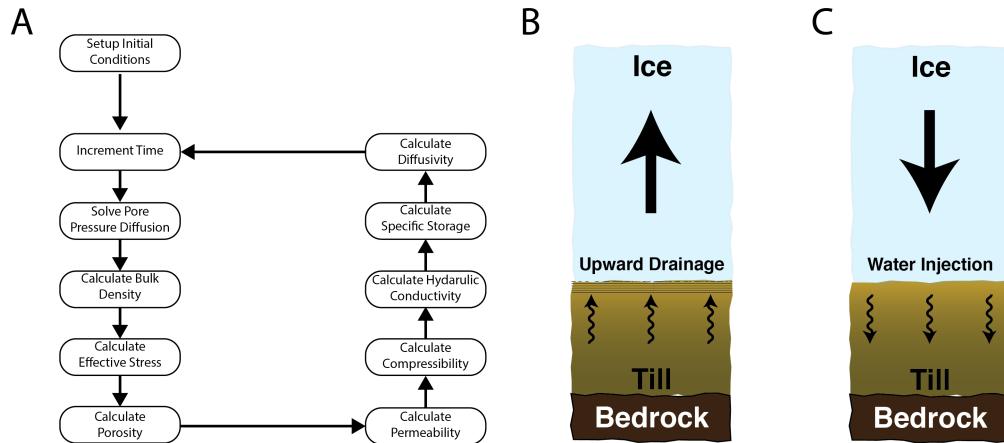


Fig. 4.8. A) Flow chart showing the sequence used when computing the 1-D hydrologic model. B) A cartoon version of the system with ice unloading the till beneath it on a tidal timescale. Upward drainage as a result of lower effective stress at the ice-till interface will quickly result in the formation of a hard layer that slows further drainage and limits the hard layer depth to tens of centimeters. C) Loading from the ice will inject water back into the till as the basal hydraulic pressure is increased.

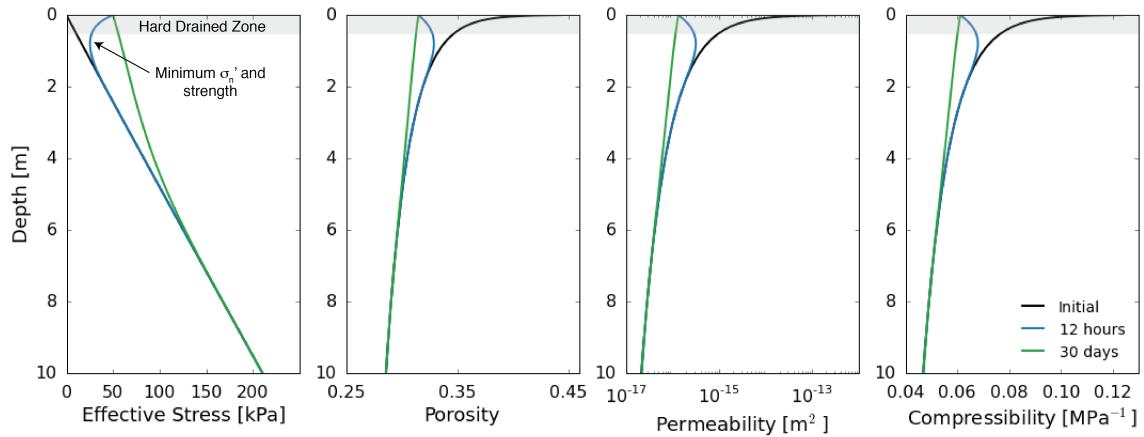


Fig. 4.9. Model results for a coupled diffusion/compaction model of the till layer with an imposed 50 kPa effective stress perturbation at the top boundary. The perturbation can affect the till over several tens of centimeters in a 12 hour tidal time scale. Over a longer perturbation, such as moving over a rough area on the bed, the till can come close to equilibrium in a month.

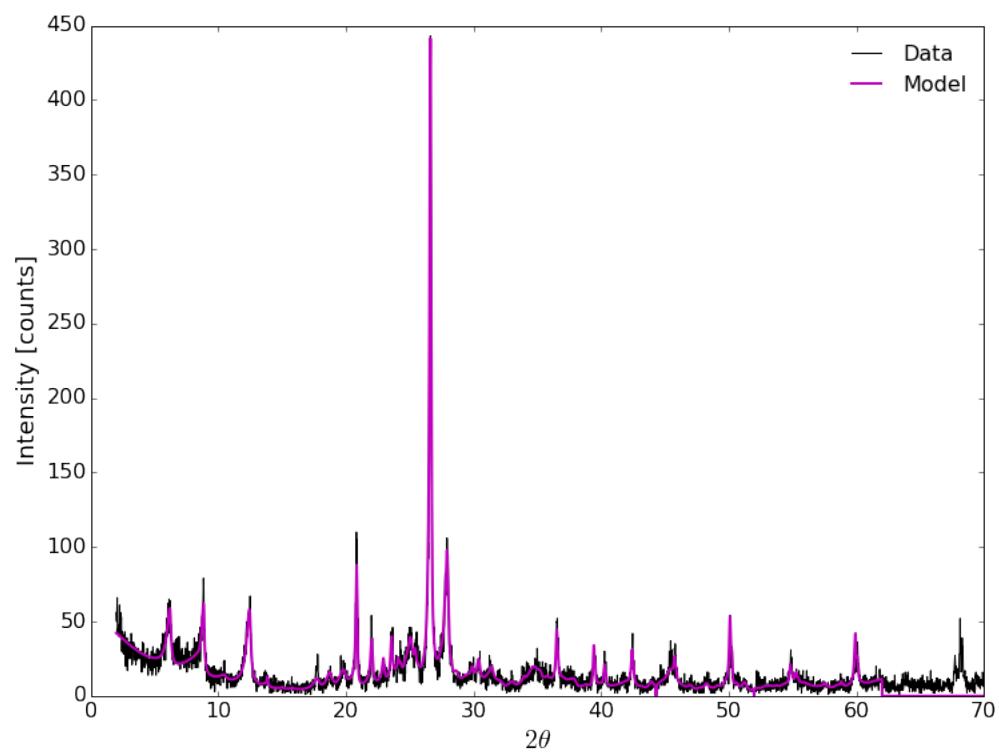


Fig. 4.10. XRD analysis shows very high clay content in the till samples with significant amounts of quartz as well. Some non-uniqueness exists in the type of clays present, but an effort was made to minimize the misfit with reasonable geological constraints.

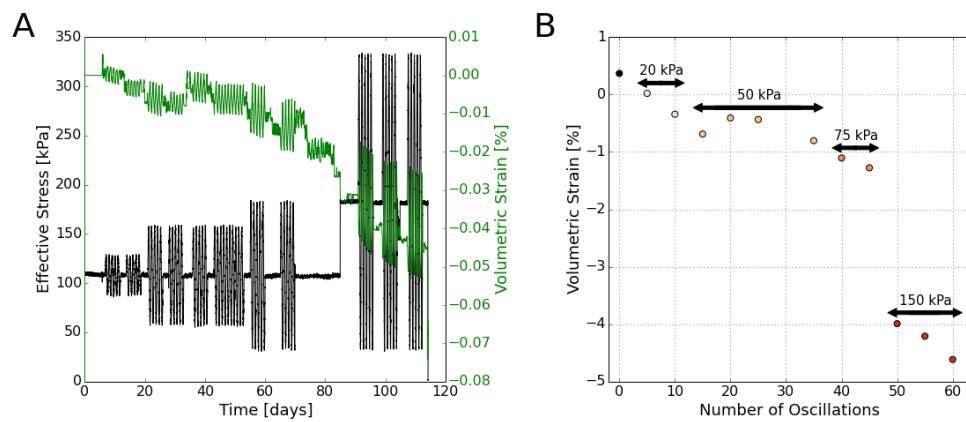


Fig. 4.11. A) Evolution of volumetric strain during repeated tidal load cycling. B) Strain was accumulated during all cycle sets, similar to the axial strain trends, but with some slight anomalies likely induced by thermal effects on pump volume measurements as volume changes are very small.

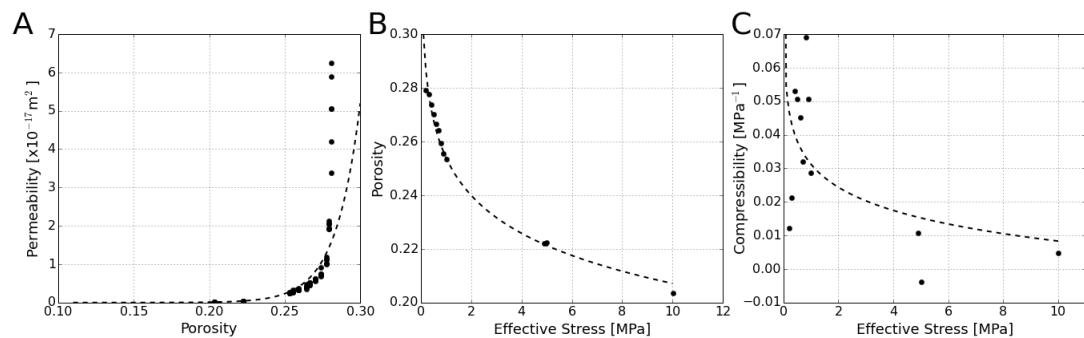


Fig. 4.12. Experimental data and fits used in loading portions of the simple hydrologic model. Porosity-permeability (A) was fit with an exponential, while effective stress - porosity (B) and effective stress - compressibility (C) were fit with logarithmic relationships.

Mineral	Volume Percent	Bulk Modulus [GPa]	Shear Modulus [GPa]	Density [kg/m <sup>3</sup> ]
Quartz	23.73	36.6	45	2650
Clay	50.49	48	20	2626
Feldspar	25.78	76	26	2560

Table 4.1. Physical parameters used to construct the effective medium model of compressional and shear wave velocities. Values are based on Dvorkin [1999] and Wang [2001].

## Chapter 5

# On the origin and evolution of electrical signals during frictional stick slip in sheared granular material

### 5.1 Abstract

Electromagnetic signals have been reported in association with geophysical phenomena including earthquakes, landslides, and volcanic events. Mechanisms that suggested to explain seismoelectrical signals include triboelectricity, piezoelectricity, streaming potentials, and the migration of electron holes, yet the origin of such phenomena remains poorly understood. We present results from laboratory experiments regarding the relationship between electrical and mechanical signals for frictional stick-slip events in sheared soda-lime glass bead layers. The results are interpreted in the context of lattice defect migration and granular force chain mechanics. During stick-slip events, we observe two distinct behaviors delineated by the attainment of a frictional stick-slip steady state. During initial shear loading, layers charge during stick-slip events and the potential of the system rises. After steady state stick-slip behavior is attained, the system begins to discharge. Coseismic signals are characterized by potential drops superimposed on a longer-term trend. We suggest that the observed signal is a convolution of two effects: charging of the forcing blocks and signals associated with the stress state of the material. The long-term charging of the blocks is accomplished by grain boundary movement during the initial establishment of force chain networks. Short-term signals associated

with stick-slip events may originate from produced electron holes. Applied to tectonic faults, our results suggest that electrical signals generated during frictional failure may provide a way to monitor stress and the onset of earthquake rupture. Potential changes could produce detectable signals that may forecast the early stages of failure, providing a modest warning of the event.

## 5.2 Introduction

A number of electromagnetic signals have been observed during tectonic faulting and mechanical failure of rocks, but the mechanisms underlying these phenomena are still unclear. Recently, efforts to couple observations by the physics and materials science communities with observations of natural phenomena in the geoscience community have begun to show promise [Enomoto and Zheng, 1998; Balk et al., 2009; Takeuchi et al., 2010; Freund, 2010; Onuma et al., 2011; Shinbrot et al., 2012]. Existing studies indicate that large earthquakes are, in some cases, preceded or accompanied by ultra low frequency electromagnetic emissions, residual magnetic anomalies, and even visible electrical atmospheric discharges known as ‘earthquake lights’ [Derr, 1973; Park et al., 1993; Uyeda et al., 2009]. Understanding these phenomena may improve our ability to provide early warning of seismic events or other hazardous material failures, and will provide insight into fault zone physical processes and stress conditions during the seismic cycle.

Several mechanisms have been proposed to explain the generation of electrical potentials in Earth, including: piezoelectric effects, streaming potential, contact/tribo electrification, fracto-emission, plasma excitation, and semiconductor-like effects [Finkelstein et al., 1973; Dickinson, 1982; Dickinson et al., 1982; Dickinson, 1984; Freund,

2000; Frid et al., 2000; Jouniaux and Ishido, 2013; Takeuchi and Nagao, 2013]. Even with an assumed mechanism of charging, there are still many mysterious aspects of the phenomenon, including conduction of the charge to the surface, charge residence time, and Earth/atmosphere interaction. Here, we examine electrical potentials observed for sheared granular layers that exhibit regular frictional stick-slip instabilities in the laboratory. We interpret the results of experiments on this fault gouge analog in the context of modern theories of charge separation in geologic materials.

### 5.3 Previous Work

#### 5.3.1 Natural Occurrences

Light emissions have been reported in association with rock failure during both seismic rupture at Earth's surface (so-called Earthquake lights) and during rock bursts in mines. Earthquake lights have been reported during various stages of the seismic cycle, in addition to other electromagnetic phenomena. Related electrical phenomena believed to be connected with rock failure include ultra low frequency electromagnetic emissions, resistivity variations [Park et al., 1993], and anomalous animal behavior [Kirschvink, 2000]. A summary of these phenomena by Uyeda et al. [2009] and the references therein illustrate the breadth of observations.

The first photographically well-documented sequence of earthquake lights (EQL) occurred during the 1965-1967 Matsushiro earthquake swarm [Derr, 1973]. Earthquake lights were also observed in the M7.2 November 29, 1975 Kalapana earthquake. The M7.2 1995 Kobe earthquake was reported to have EQL as well as observations of burned

plant roots at the rupture site, and natural remanent magnetization (NRM) anomalies [Enomoto and Zheng, 1998]. Anomalous NRM have been measured in pseudotachylite, suggesting that high remanent magnetizations were acquired in a co-seismic electrical process and locked into thin, rapidly cooling layers of melt [Ferré et al., 2005]. Visual electromagnetic phenomena were reported before the M6.3 April 6, 2009 L'Aquila earthquake [Fidani, 2010]. Although reports were confused by astronomical/meteorological events and coseismic power line flashes, a number of unexplained observations remain.

Most reported EQL have been generated on intraplate faults with relatively shallow sources, for magnitude 7 and greater events, and commonly for earthquakes with demonstrated surface rupture. Lockner et al. [1983] suggest that vaporization of water produces a charge separation that is then moved to the surface by a central fluid conductor. Reports of EQL phenomena often include descriptions of the anomalies being most intense at topographic highs, suggesting that surface charge on the ground was concentrated by the topography. EQL may be more common in high stress drop events and/or in association with branching and geometrically complex events [Scholz, 2002].

### **5.3.2 Previous Experimental Work**

Much experimental work has been done to test physical mechanisms that could cause electrical anomalies during seismic activity and rock failure. The most relevant explanations are briefly discussed here, but more in depth discussion may be found in Uyeda et al. [2009], Freund [2000], and references therein.

Early work by Nitsan [1977] investigating piezoelectric effects showed electromagnetic radiation in the 1-10 MHz range during the fracturing of quartz bearing rocks

under uniaxial compression. The idea of the piezoelectric effect causing changes in the electrical field during failure suggested that frequency content of the signal would be related to the rate of stress release. This relationship is supported by a spectral shift to higher frequencies with smaller particles [Nitsan, 1977]. Uniaxial compression studies using cores of Red Texas Granite, Barre Granite, Dakota Sandstone, Carthage Marble, and quartzite exhibited electromagnetic signals peaking below 40 kHz in association with failure. Observed signals also exhibited some degree of directionality [Rowell et al., 1981; Hanson and Rowell, 1982]. Signals peaking at 100 kHz were observed during impact and cratering tests by Bianchi et al. [1984] both in vacuum and at atmospheric pressure.

Mechanisms involving the formation of cold plasmas during fracture and impact have also been proposed to explain charge generation [Martelli and Cerroni, 1985], but have not been investigated thoroughly. Calculations considering a beam-plasma interaction producing an ion-acoustic instability suggest that the expected radiation frequencies are at  $\sim$ 50 kHz.

A recent study by Onuma et al. [2011] examined gabbro and quartz powders, used as simulated fault gouge and sheared between gabbro forcing blocks in a saw-cut geometry. Electrical signals in the co-seismic period were detected by direct contact electrodes as well as toroidal induction coils surrounding the sample. In 25% of their experiments, a possible pre-cursory signal was detected, but not consistently on all instruments. Piezoelectricity was ruled out as a dominant mechanism, because signals were observed in piezoelectric and non-piezoelectric gouges and there was no preferred c-axis orientation in the quartz powder. Signals were observed from piezoelectric and non-piezoelectric materials by Cress et al. [1987] as well, but in their experiments on

quartz produced larger signals than other materials. Onuma et al. [2011] did not observe signals during initial loading; however, such signals have been observed by other workers in natural and experimental cases [Takeuchi et al., 2010] who attributed them to frictional electrification because they scaled roughly linearly with slip.

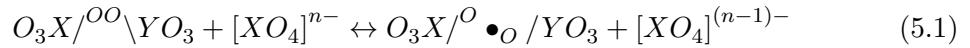
The presence of moving dislocations with respect to propagation of microcracks producing a ‘pressure stimulated current’ in marble samples has been examined [Triantis et al., 2008]. These currents are a result of charge separation during the beginning stages of failure, not during the initial loading stages.

Piezoelectric effects are well-documented in materials such as quartz, but geologic materials are not expected to have the required mineralogy or grain alignment to make this a viable mechanism in nature. Randomly oriented grains would produce a series of randomly oriented dipoles that would cancel to produce a net-neutral field. Streaming potentials and electrokinetic effects [Mizutani et al., 1976] are well-documented, but are generally not of sufficient magnitude to explain the observed phenomena, because large potentials are difficult to maintain with generally conductive fluids present. Electrification by relative surface movement (tribo-electrification) is also well-documented [Pingali et al., 2009; Pähzt et al., 2010], but does little to explain electrical signals produced while contacts are stationary to quasi-stationary.

Evidence for electrical signals during and possibly as precursors to failure in a low stress environment has been collected [Shinbrot et al., 2012] in experiments examining slope failure and crack opening or closing in powdered pharmaceutical materials. An electrostatic voltmeter (ESVM) like that used in this study was used to monitor rotating

and tilting drums of powder as well as flexure of powder layers resulting in opening and closing fissures of the material.

Another model of charge generation during deformation of geomaterials is the ‘semiconductor’ effect. In geologic materials, oxygen is generally considered to exist in the  $O^{-2}$  valence state, but the more oxidized form  $O^-$  is also present in a pair of coupled  $O^-$  atoms known as a peroxy defect. The peroxy link can be broken via mechanical strain such as during passage of a mechanical deformation front in the form of a propagating elastic wave or elastodynamic rupture front. In this case, an electron is sourced in an attempt to satisfy the newly formed electrical imbalance at the site of the broken peroxy bond. This oxidizes the donor, forming a single defect electron (eq.5.1). [Freund, 2000; Freund et al., 2006; Freund, 2010]



Electrons are not free as charge carriers, but holes remain mobile [Freund, 2000; Freund et al., 2006; Freund, 2010; Balk et al., 2009]. The semi-conductor effect has been explored in solids [Takeuchi and Nagao, 2013; St-Laurent et al., 2006], but few studies have been conducted on granular materials, which are likely to be important in the behavior of tectonic fault zones.

## 5.4 Methods

We conducted experiments on granular layers used to simulate fault gouge under controlled boundary conditions, with concurrent measurement of electrical potential,

stresses, and strains of the layer to explore the relationship between stress state and the evolution of electrical signals. We used glass beads to represent granular fault gouge because they exhibit repeated frictional stick-slip behavior and share key friction constitutive properties with rock. The main advantage of this choice lies in the reproducibility of stick-slip behavior, allowing investigation and isolation of the processes that cause electrical signals relevant to natural faults containing granular gouge by using a simple, well-characterized system. We note that glass should contain fewer starting defects than silicate minerals found in natural fault gouges, such that any effects observed in our glass bead experiments would likely be amplified in natural materials.

#### 5.4.1 Apparatus

All experiments were conducted on a biaxial deformation machine with a servo-hydraulic control system [Karner and Marone, 2000; Frye and Marone, 2002]. Hydraulic servo valves are operated in either displacement or force feedback modes through a series of analog amplifiers and comparators. Control displacement signals are generated by a 16-bit digital to analog converter capable of  $\pm 5\text{V}$  range. The apparatus (Figure 5.1A) is capable of 1 MN of force on the horizontal ram and 1.5 MN on the vertical ram. Ram velocity can be controlled to  $0.1 \mu\text{m/s}$  in displacement mode, or to about 10N in load mode [Hong and Marone, 2005; Rathbun et al., 2008].

We used forcing blocks of cast acrylic with a dielectric strength of 15-17 V/ $\mu\text{m}$  and a tensile strength of 55-77 MPa. Forcing blocks were cut to size and machined with grooves 1 mm deep and 2 mm wide perpendicular to the shearing direction to ensure that shear occurred within the layer and not at the layer boundary [Anthony and Marone,

2005; Knuth and Marone, 2007]. Acrylic side shields were also made to confine the sample material. The nominal frictional contact area was 10 cm x 10 cm.

Force was measured using Beryllium-Copper strain gauge load cells built in-house and placed in series with the loading ram and sample. The load cells and the wheat-stone bridge electronics are calibrated regularly with a proving ring traceable to the National Bureau of Standards. Displacement is measured with direct current displacement transducers (DCDTs) affixed to the ram nose and referenced to the end platens of the hydraulic rams. Positions of both classes of instrumentation are noted in Figure 5.1A.

We recorded data using a 24-bit, 16-channel simultaneous, delta-sigma style analog to digital system. Samples are collected at 10 kHz and averaged to the desired rate from 1 Hz to 10 kHz as necessary to maintain the appropriate signal-to-noise ratio. Recording rates may be changed during the experiment, and our tests show minimal cross-talk or dwell errors in this system.

#### **5.4.2 Sample Material & Preparation**

Samples were built in the double direct shear configuration (Figure 5.1B) using soda-lime glass beads [Anthony and Marone, 2005]. Two layers of beads were confined in a three forcing block assembly with a rubber membrane at the bottom and side-shields on the boundaries to avoid lateral extrusion of the material. The top of the sample was unconfined.

Layers were built by placing the side forcing blocks on a leveling jig and applying cellophane tape around the perimeter. The tape was then trimmed to the desired height

to produce uniform, reproducible layers. We used 5 mm thick layers for all experiments in this study (Table 1). Sample material was poured into the form, lightly compacted, and leveled. The center forcing block was affixed to one side block (and the sample) with additional cellophane tape, securing the blocks and gouge layer and providing enough strength to allow transport of the sample from the bench to the deformation apparatus. The process is repeated for the second layer.

We constructed layers using Class IV soda lime glass spheres (product GL0191B4/106-150) from Mo-Sci Specialty Products in Rolla, Missouri (composition shown in Table 5.2). Two mono-disperse size distributions were tested: 100-150  $\mu\text{m}$  and 420-500  $\mu\text{m}$ . Scanning electron microscopy (SEM) analysis of the beads shows that they are homogeneous, with few exceptions, and smooth (Figure 5.2). Past work has shown that bead comminution is minimal until  $\sigma_n > 10 \text{ MPa}$  [Mair et al., 2002; Mair and Abe, 2011].

#### **5.4.3 Potential Measurement**

Electrical potential on the layers was measured by a model 344 electrostatic non-contact volt meter (ESVM) manufactured by Trek Inc. This instrument reported the potential with respect to system ground sensed in its field of view. An analog output of the measured voltage was divided by 100 to provide a sensing range of  $\pm 2 \text{ kV}$  with a  $\pm 20 \text{ VDC}$  output signal recorded. A ‘response’ setting on the instrument controlled internal damping constants.

The sensor head contains two electromechanically oscillated plates. Plates are fixed parallel to each other with the surface normal facing the surface under test. The front plate is affixed to the instrument body and has a small aperture in the center.

The rear plate is inside the instrument and is the oscillating plate. The sensor operates by varying the voltage across the plates and sensing the alternating current (AC) signal resulting from the movement of the plates with respect to one another. When the AC component of the signal is nulled, the voltage across the plates exactly matches the voltage on the surface under test. This sensor configuration has several advantages: 1) no contact is required with the surface under test, which is excellent for systems where coupling is a challenge, 2) there is no arcing risk since the instrument and surface under test are at the same potential, and 3) the sensor is easily portable, allowing tests with different viewing positions.

Two different sensor geometries were used: side view and top view (Figure 5.1C). In the top view, all tape between the sensor and the sample was removed. In the side view, a notch was cut in the side shield, leaving only a thin layer of tape (necessary to prevent extrusion) for the sensor to observe through. In our calibrations, we found that the sensor operates normally when viewing signals through thin obstacles.

#### **5.4.4 Experimental Procedure**

Samples were placed into the testing machine and normal load of 4 MPa was applied and maintained to compact the layers. The shear load was then applied by driving the vertical ram at a constant displacement rate (1, 30, or 100  $\mu m/s$ ). Electrical potential was recorded by placing the sensor in either the top or side view geometry with a distance of  $\sim 1$  cm between the front of the sensor and the gouge layer. The response setting was set to the maximum value of 9.

We conducted experiments at room (ambient) humidity, at 100% relative humidity (RH), and under submerged conditions using de-aired water. 100% RH was achieved by placing the sample assembly in a plastic membrane with a beaker of anhydrous sodium carbonate solution (2:1 ratio with distilled water) within the membrane. This exothermic reaction produced a 100% RH environment in the membrane. For all experiments under controlled humidity, samples were left to equilibrate overnight with a small normal stress applied by a hand-clamp, and then placed in the testing machine. When the experiment began, we refreshed the anhydrous sodium carbonate solution, applied the normal stress and proceeded with our standard loading protocol. For these experiments, we cut a small window in the humidity-control membrane to provide access for the sensor. A capacitive sensor hygrometer (Lifft C200 with a maximum error of  $\pm 3\%$ ) verified that the relative humidity never fell below 100%. Saturated experiments were performed in a similar manner, but the membrane was filled with distilled water and the sample allowed to saturate as load was applied. The water level just covered the top of the blocks and a top-view ESVM geometry was employed.

#### **5.4.5 Calibration and Control Tests**

We performed tests to ensure calibration of the ESVM, as well as to evaluate the sensitivity of the response control. The ESVM probe was affixed to an electrically insulating base and placed approximately 1 cm from an aluminum plate. The plate was charged with a precision DC power supply (HP 6216B) and the true and measured plate voltages recorded. Performance was further evaluated by attaching the surface under

test to a function generator. Square waves were measured on each response setting (1-9) to evaluate ringing of the instrument (Appendix A).

In addition, an experiment identical to those testing electrical potential on the layers was performed with the ESVM pointed away from the load frames into the room and towards a DC charged aluminum plate. This test was performed to ensure that the signals we observed during shearing were not from electrical interference of the hydraulic control electronics or measurement/recording electronics. We note that our records include motion of the vertical hydraulic ram when it was not in contact with the sample, and no change in voltage was seen. This further indicates that no DC offsets or interference were experienced by the ESVM from the testing machine and/or control electronics and transducers.

All calibration and control tests were conducted with identical analog to digital conversion hardware as the experiments. ESVM calibration tests were also conducted on an independent logger (the LabJack U6) to ensure there was consistent performance and minimal measurement burden from either system.

#### **5.4.6 Data Analysis**

Changes in electrical voltage during stick-slip events were picked by hand to evaluate the electrical signal. ESVM data are more noisy than the mechanical data and electrical anomalies are not found with every stick-slip event, making manual picking the most accurate. Measured electrical potential and shear stress were plotted on the same x-axis and mouse position clicks were recorded. Interpretation was aided by superposition of a smoothed potential signal. The potential was smoothed using a Savitzky

Golay filter [Savitzky and Golay, 1964], as it preserves peaks, but decreases noise. With the Savitzky Golay filter, a line of specified low-order is fit to a certain data window using a linear least squares technique. The analysis is then stepped forward and fit signals convolved.

Data were recorded in a binary form, decoded, converted from bits to engineering units through use of calibrations derived from our transfer standards, and then written out as either a binary or ASCII for analysis. The Python environment was used for processing and analysis. All stick-slip events were automatically picked by first computing the smoothed derivative of shear stress with respect to time using a running-average slope tool. Zero-crossings of the derivative indicate a slope change from positive (like that during load up) to negative (like that during failure) or the reverse. The automatically determined stress drops were checked against a threshold value to ensure that no noise was picked as events. Automatic picks were visually inspected to ensure algorithm performance.

## 5.5 Results

### 5.5.1 Mechanical Data

The application of shear load resulted in a characteristic linear-elastic stress-displacement record during initial run-in (Figure 5.3). Stick-slip behavior began as we reached the failure strength of the material. As shear load increased during the stick-slip cycle, the material began to creep and deform elasto-plastically, as indicated by deviation of the stress-strain curve from the initial, linear-elastic trend. When the ultimate

strength of the layer was reached, layers failed and a stress drop was observed. We define the stress drop as the magnitude of shear stress change during stick-slip failure. In a series of repeating events, we define the recurrence time as the time between peak stresses of two slip events. For a summary of this terminology see Figure 5.3 inset. Mechanical steady-state (not to be confused with steady-state frictional sliding) refers to the system state after the initial run-in period, defined as the point at which stress drops in repeated stick-slip events become constant.

All experiments exhibited a maximum coefficient of friction during mechanical steady-state ( $\mu \equiv \tau/\sigma_n$ ) of 0.3-0.4. For experiments at 100% humidity or water saturated, we observed an increased stress drop and ultimate strength due to the activation of chemo-mechanical mechanisms such as solution-reprecipitation [Frye and Marone, 2002; Yasuhara, 2005; Scuderi et al., 2014].

The recurrence time between events has been shown to vary with load point velocity [Karner and Marone, 2000; Beeler et al., 2001]. We observe a power law relation between load point velocity and recurrence time with a characteristic slope of -1.14 (Figure 5.4A). For faster load point velocities, there is less time for contact healing to occur before the layer fails, resulting in lower maximum stresses and shorter recurrence times. Shorter healing times also result in smaller stress drops, which produce a correlation between longer recurrence times and larger stress drops (Figure 5.4B).

Experiments performed using the 420-500  $\mu m$  glass beads exhibited repeated stick-slip behavior and a lower coefficient of friction of  $\sim 0.2 - 0.3$ . The occurrence of stick-slip events was less regular than that of the 100-150  $\mu m$  experiments, as there were five times fewer beads spanning the same 5 mm layer thickness. For the larger

beads, we conducted experiments only at  $30 \mu\text{m}/\text{s}$  and we did not explore the role of loading velocity. Due to the large stresses applied to the acrylic forcing blocks by the large beads, some chipping of the grooves was observed, so no further experiments were conducted.

### 5.5.2 Electrical Data

During shearing we observe two common signals in the electrical potential. The first is characterized by a long period signal (lasting for the entire experiment) that is a general charging/discharging trend (Figure 5.5). The magnitude of this varies between experiments, but can be as much as 250 V. The second is characterized by signals that are of smaller magnitude and shorter duration. These are superimposed on the long-term trend, and are synchronous with individual stick-slip events. The polarity of these events (co-seismic charging or discharging) varies systematically during an individual experiment. During the initial charging stage of the experiment, prior to reaching mechanical steady-state sliding, the anomalies are generally positive. During the phase of overall discharging, the electrical anomalies coincident with stick-slip are generally negative. There are occasional events of unexpected polarity, but there is a strong polarity preference based on the stage of the long-term trend. We consistently observed that the long-term charging/discharging trends were marked by the attainment of mechanical steady-state (Figure 5.5).

After reaching mechanical steady-state, the electrical anomalies associated with each stick-slip event varied systematically with loading velocity (Figure 5.6). For experiments subject to loading at  $1 \mu\text{m}/\text{s}$ , voltage increased by 1-2 V during shear loading

between stick-slip events and then dropped rapidly during co-seismic failure. Similar behavior was observed at  $30 \mu\text{m}/\text{s}$ , where voltage changes were 2-4 V. For shearing at  $100 \mu\text{m}/\text{s}$  we found a change of electro-mechanical behavior. Initial loading still produced an increase of electrical potential, but during co-seismic slip the potential spiked by tens of volts with the peak occurring just after the stress drop.

We found that the magnitude of potential change during stick-slip events follows a power law relationship with sliding velocity, resulting in an increase of about 5x in voltage for the range of velocities we explored (Figure 5.7). For experiments at 100% RH (saturated) and submerged boundary conditions there was no regular electrical signal associated with the stick-slip events. Minor long-term charging/discharging trends were observed in some experiments.

Electrical anomalies were also observed in the three experiments run with larger ( $420\text{-}500 \mu\text{m}$ ) grain-size material. The anomalies were of similar nature and magnitude to those observed under identical conditions with the smaller grain-size material.

## 5.6 Discussion

One likely explanation for the electrical signals we observed during stick-slip events involves force chains and their role in the mechanical behavior of granular layers [Majmudar and Behringer, 2005]. Our experiments had no preferred c-axis orientation of piezoelectric grains, ruling out the piezoelectric effect as a main contributor to the observed potentials. Likewise, vaporization of porewater cannot explain our data, because we observe co-seismic signals in low humidity conditions. Streaming potentials are likewise not a major contributor in this configuration. Zeta potentials near individual grains

are insufficient to explain the net external voltage we observed, and would be expected to increase in the saturated and submerged conditions. The plasma model is not applicable to our conditions of low shear velocity and non-fracture experiments. Semi-conductor effects and tribo/contact electrification are two possible mechanisms operating in our experiments; each has the capability to create a potential gradient within the sheared granular samples. Broadly, semi-conductor effects are stress-dependent mechanisms and triboelectric effects are displacement dependent phenomena.

We note that cellophane tape was used in our experiments and that it is electrically active [Camara et al., 2008]. However, based on our calibrations and from tests with no tape, we believe this is not responsible for the signals we observe. Elastic strains in the forcing blocks, where the tape is attached are low and signals are observed when the system is stationary to quasi-stationary during elastic loading. Also, the observed change of sign, from charging to discharging is not consistent with signals from a single mechanism (tape peeling). Finally, we also observed very similar signals from a top-viewing geometry with no tape between the sensor and the layer.

Our experiments consider a fault zone on the order of 10 cm in length. This presents a potential challenge in upscaling our observations to natural fault zones. Additionally, the electrical potentials generated in our experiments are much smaller than those required to explain most field observations, and our measurements were conducted with direct access to the fault zone. One possible explanation is the low number of defects likely to be present in industrially produced glass versus natural silicate minerals.

### 5.6.1 Electro-Mechanical Model

We hypothesize that the shear load across our granular layers is supported primarily by a small percentage of grains that form layer-spanning chains of highly stressed particles. Granular force chains produce a ‘fragile’ configuration and are separated by regions of spectator grains that support little to no load [Sammis et al., 1987; Liu et al., 1995; Liu and Nagel, 1998; Cates et al., 1998; Boettcher, 1999; Albert et al., 2001; Aharonov and Sparks, 1999].

The observation that the overall electrical signal consists of two parts, charging and discharging, suggests that two mechanisms may be responsible for our observations. The long-term charging trend ceases at approximately the same time as the system reaches mechanical steady-state, suggesting a dependence on the mechanical evolution of the layers. During the initial load up of the system there is large-scale grain rearrangement as force chain networks form and the layers compact. This grain rearrangement involves enhanced grain boundary sliding that can triboelectrically charge the system (Figure 5.8A). The acrylic forcing blocks will hold surface charge, but the charge will slowly drain through various sinks, including contact with the metal loading platens. After a mature force chain network is formed, interparticle movement and grain boundary sliding at the forcing block interface are minimal, which would reduce charging of the forcing blocks. We posit that at this point the rate of discharge becomes equal to or greater than the rate of triboelectric charging, resulting in long-term discharging.

After the system reaches mechanical steady-state behavior, we expect a network of force chains to support the load during the loading portion of the stick-slip cycle. Grains

involved in supporting the load experience much higher local stresses than the spectator grains or the bulk stress measured on the layer. Any electron defects in the highly stressed grains will migrate to less stressed grains adjacent to the force chain. Grains involved in a force chain will be at a lower potential (thus serving as acting anodes) than the spectator grains that are now enriched in positive charge carriers (thus, acting as cathodes). This would result in the net measurement of a positive potential that increases with the shear load (Figure 5.8B).

When the force chain network can no longer support the applied load, the chains fail, resulting in stick-slip and returning the grains (temporarily) to a more homogeneous stress state. The resulting return current redistributes the potential, producing the observed net drop of potential on the layer during stick-slip failure (Figure 5.8C).

The nature of the sharp positive potential spikes just after co-seismic slip in the  $100 \mu m/s$  driving velocity case remains unexplained by our conceptual model, but the coincidence of the spike with the time during which grains are moving suggests a dominating tribo-electric mechanism at high load point velocities.

Co-seismic charging events observed during the initial loading and first few stick-slips of the experiments appear to be related to the attainment of mechanical steady-state. As the force gradient driving the electrical potential is released during the co-seismic slip, it is possible that instead of neutralizing the charge on layers that the charge follows a second electromotive gradient to the initially lower potential side blocks. This results in an increase in the net potential to ground in the viewing area of the instrument. It is also possible that the rapid charging is a result of triboelectric effects with boundaries during grain rearrangement as the slip occurs before the force chain

network is established. The lack of co-seismic charging events during the bulk system discharging phase after steady-state supports the latter hypothesis.

We note that the 100% RH experiments and the experiments where layers were submerged produced no consistent electrical signals. These experiments showed hints of the long-term potential variations, similar to the charging and discharging trends observed in ambient humidity experiments, but never over 50 V during the course of an experiment. In such moist environments, where conductivity is expected to be high, electrical potential gradients are difficult to maintain without a significant forcing mechanism. The high mobility of electrons in water would allow charge to move; in contrast, holes are not easily mobile in water, further reducing the potential gradient [Balk et al., 2009].

## 5.7 Conclusions

We show that reproducible electrical potential anomalies can be observed during laboratory shear experiments and are associated with repeated stick-slip failure events. The test material of soda-lime beads allows a well-controlled study, and is geologically relevant to faults containing granular gouge. We propose that our observations may be explained by a combination of the semiconductor effect, triboelectric charging, and a force chain model of loading in granular materials.

The results of this study suggest that small precursory stress drops (foreshocks) in nature may produce electromagnetic signals that could be used as an early warning mechanism for large earthquakes. Such signals would provide more warning than current methods, even if associated with the main shock because of their velocity of propagation.

Even in rock, the electromagnetic signal produced by a time-variant electrical field would propagate at many times the elastic p-wave velocity, producing seconds of warning for observers sufficiently far away. Our research may also find application in mines with relation to wall and column failure, and in slope failure research. In those cases, an understanding of the electrical signals produced could lead to the design of optimum receiver location and improved processing methods, which would increase warning time of natural disasters.

We note that questions about charge conduction to the surface in earthquake faulting, upscaling of laboratory experiments, and the nature of the charge release through the Earth/atmosphere system, remain unexplained. Complex resistivity and the frequency dependence of resistivity are likely important in natural systems. Further investigations of the natural observations and of how chemistry of the material and pore waters influences charge generation are necessary. Similarities in fault zones with reported observations may provide clues, but such observations are rare and generally poorly instrumented. Establishing small sensor networks of visual, spectral, and electromagnetic instruments is crucial to documenting the phenomena and beginning to understand its potential for early warning.

Future experiments will attempt to measure the flow of electrons to and from system ground required to hold the entire system at zero potential in contrast to the presented experiments, in which we isolated the system and measured the resulting potential. This technique allows conductive forcing blocks to be used, making contact with the entire layer and eliminating charging concerns. Spectral characterization of the electrical signals may also provide further insight into the charging mechanism.

## 5.8 ESVM Calibration

The electrostatic volt meter (ESVM) from Trek is a relatively new method of non-contact surface potential measurement and has not been applied in rock mechanics studies before. To gain confidence in the instrument, a series of tests were conducted by mounting the instrument to a set of non-conductive granite blocks with an adhesive backed paper tape as a bench-top jig. An aluminum plate of 5 cm diameter was placed 1 cm from the aperture of the probe (which has a viewing area of approximately 1:5 according to the manufacturer).

Constant DC voltages, stepped DC patterns, and a square wave pattern were utilized to check the response time of the instrument, calibrate the use of the ‘response’ setting, and to ensure there was negligible cross-talk between channels on the analog to digital converter. The input signal (true) to the plate was recorded simultaneously with the ESVM measured voltage for each of the 9 ‘response’ settings (Figure 5.9). DC offsets during this calibration come from changing the setting on the instrument. For all settings the power was not cycled and the instrument probe remained stationary.

Recorded waveforms at low response show smoothing of the sharp edges of the square wave. High response waveforms do not exhibit smoothing or ringing, but in both cases the waveform rapidly reaches the correct voltage (Figure 5.10). High response waveform recordings are more noisy, but share the mean of the smoothed waveforms. All waveform leading/falling edges corresponded well with changes in the input signal in the time domain (Figure 5.11).

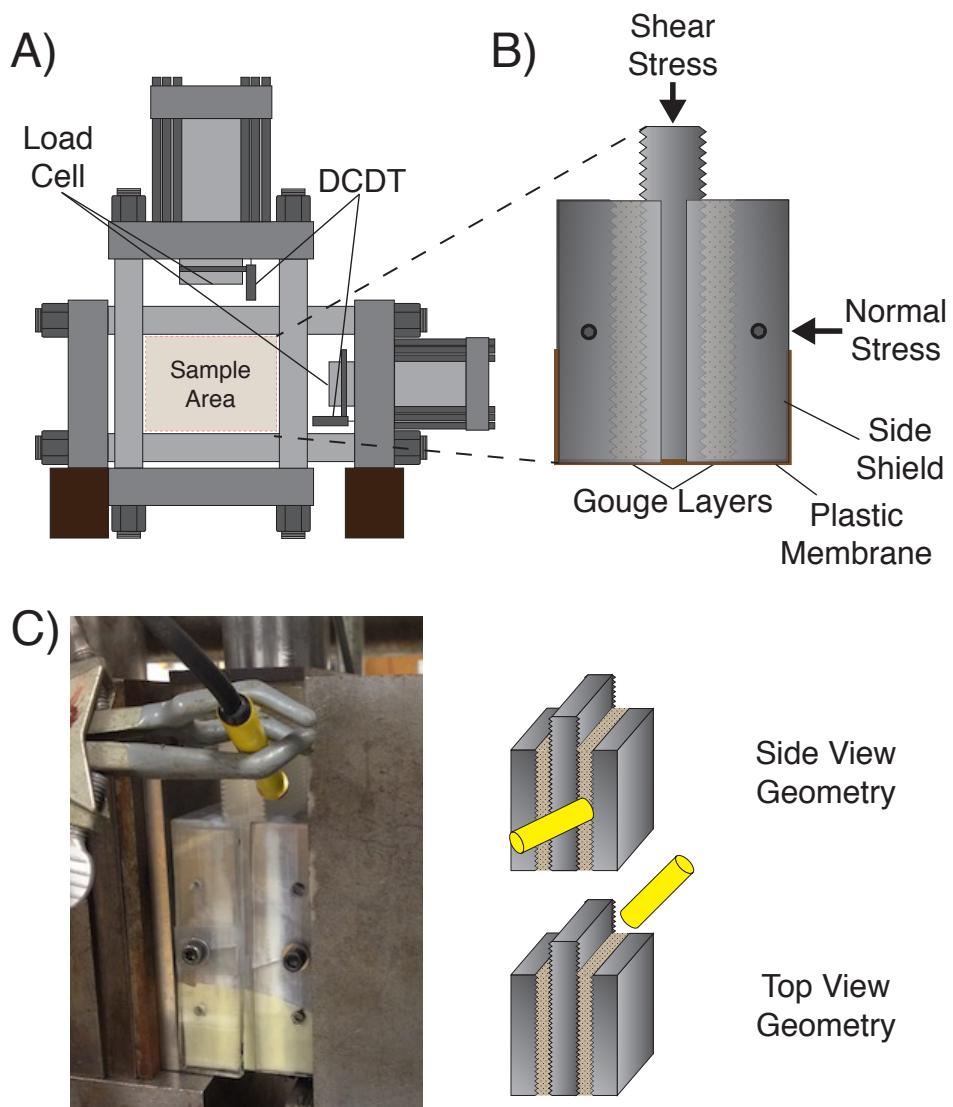


Fig. 5.1. Experimental setup. A) The biaxial hydraulic press: sample assemblies are supported by steel blocks in the sample area. B) Double direct shear geometry consists of two layers of gouge confined between three forcing blocks. Side shields and a plastic membrane are used to contain gouge material as the sample is sheared. C) Placement of the electrostatic voltmeter (yellow cylinder) in the side and top view positions. A window was cut into the side shield for the side view geometry.

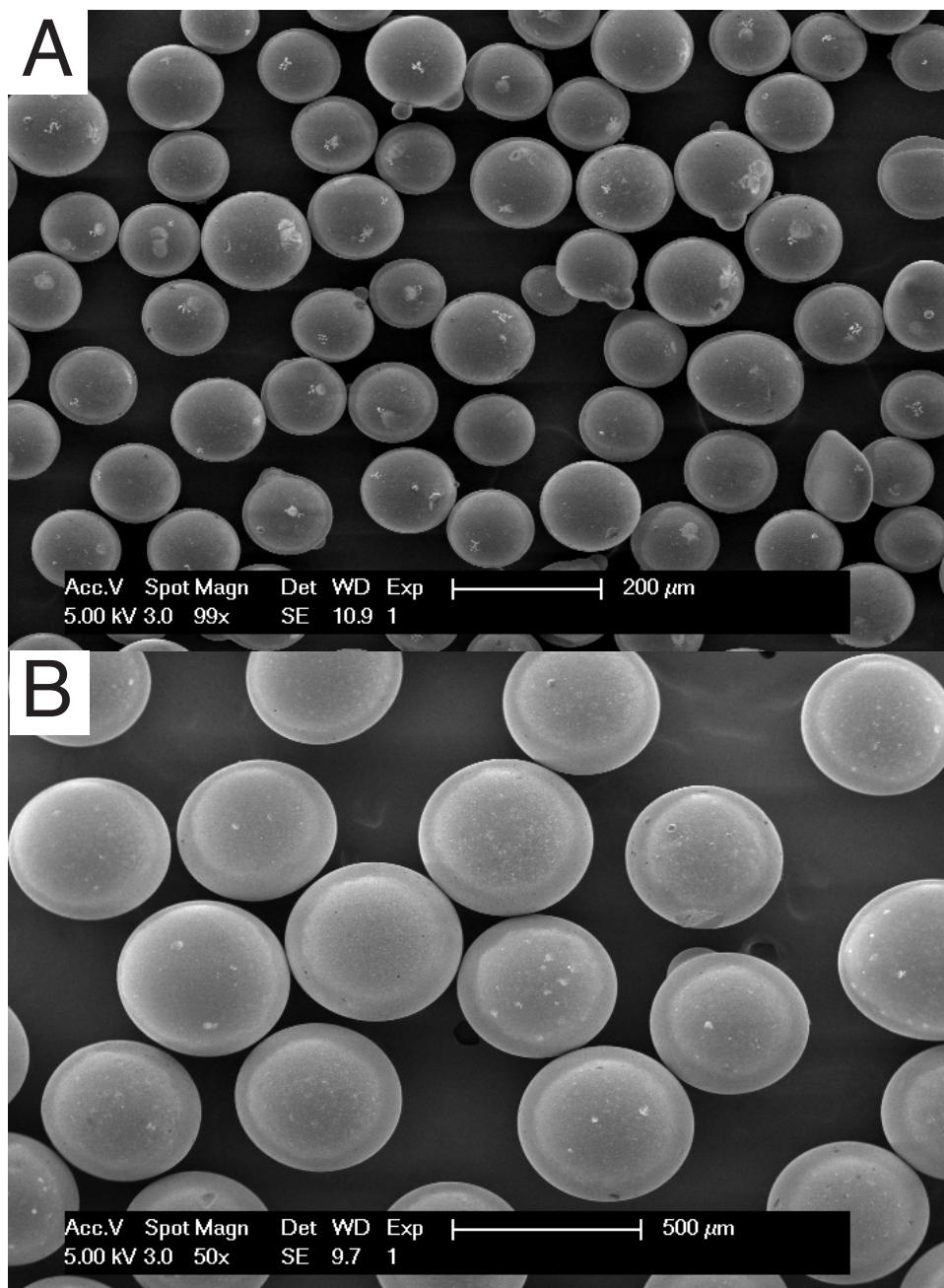


Fig. 5.2. Scanning electron microscope micrographs of the starting glass beads for all experiments. A) 100-150  $\mu\text{m}$  B) 420-500  $\mu\text{m}$

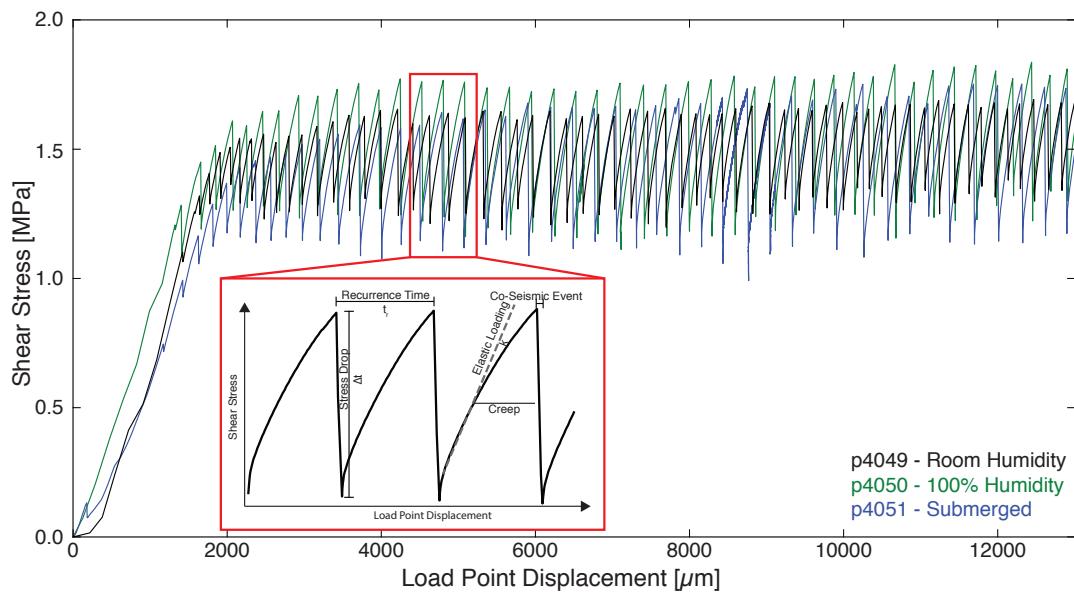


Fig. 5.3. Experiments performed on glass beads (100-150 $\mu\text{m}$  diameter) under ambient humidity, 100% humidity, and submerged conditions exhibit similar mechanical behavior. Increased stress drops are observed with increased humidity and in the submerged case. Inset: Anatomy of a stick-slip event. The recurrence time is the time between peaks in shear stress. Initially the shear stress increases linear-elastic. Deviation from line-elastic behavior marks the onset of elasto-plastic deformation and pre-seismic slip. When the ultimate strength of the layer is reached shear stress drops rapidly and the cycle begins again.

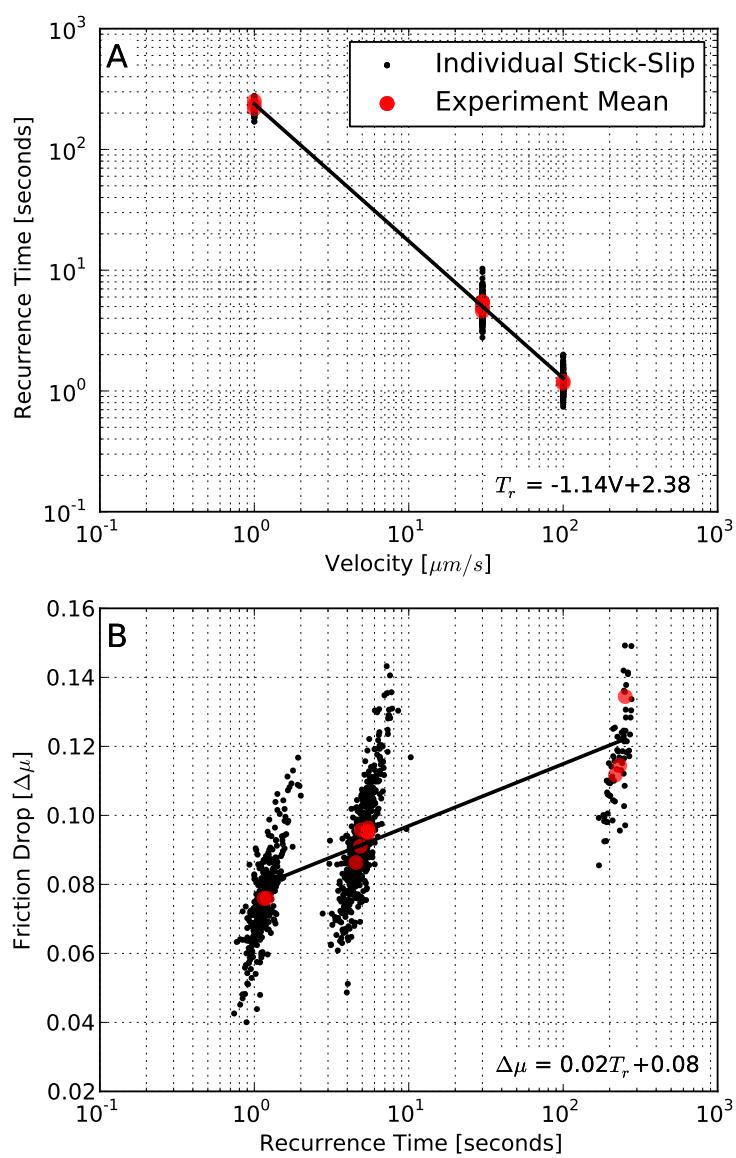


Fig. 5.4. A) Samples exhibit a log-log linear relation between recurrence time and velocity. Faster loading rates result in shorter recurrence times. B) Friction drop increases with the recurrence time as there is more time for the layer to heal before the next stick-slip event.

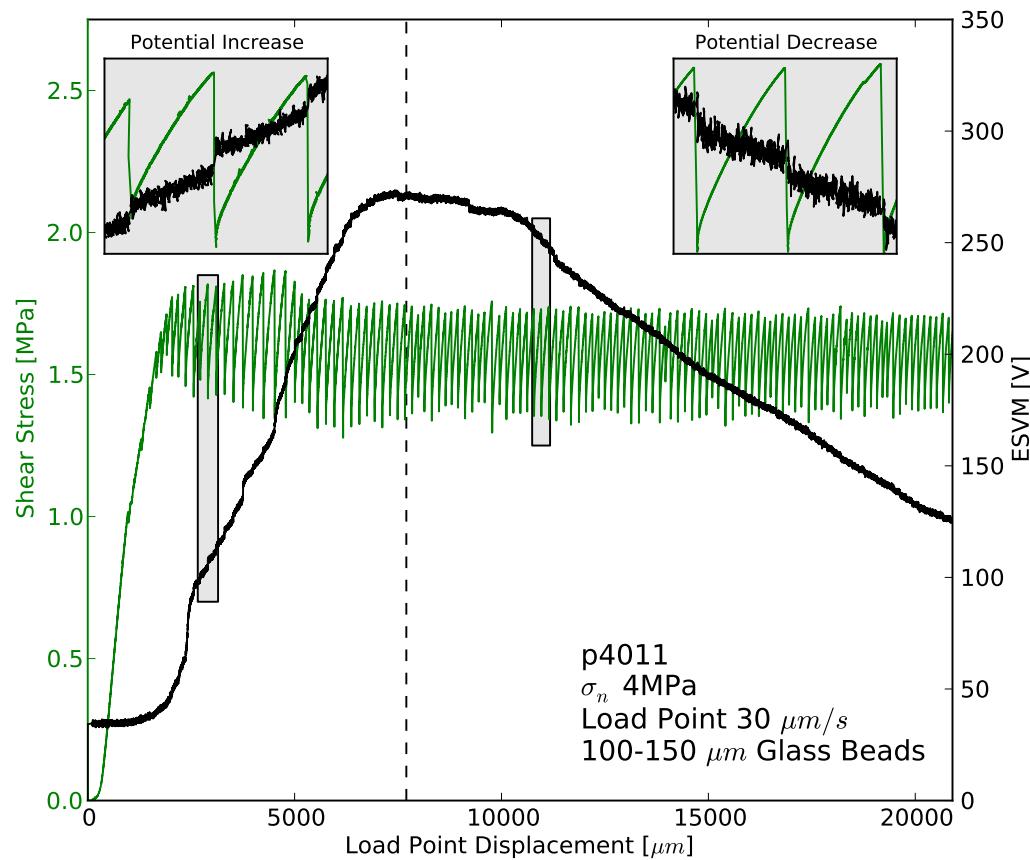


Fig. 5.5. During shearing two trends are observed: 1) A long-term charging/discharging trend in the electrical potential and 2) Potential change related to individual stick-slip events. The entire system initially charges, approximately until mechanical steady-state is reached. During this phase co-seismic potential changes are dominantly positive (top left inset). After attainment of mechanical steady-state, the system begins to maintain or discharge potential. During this phase the co-seismic potential changes are dominantly negative (top right inset).

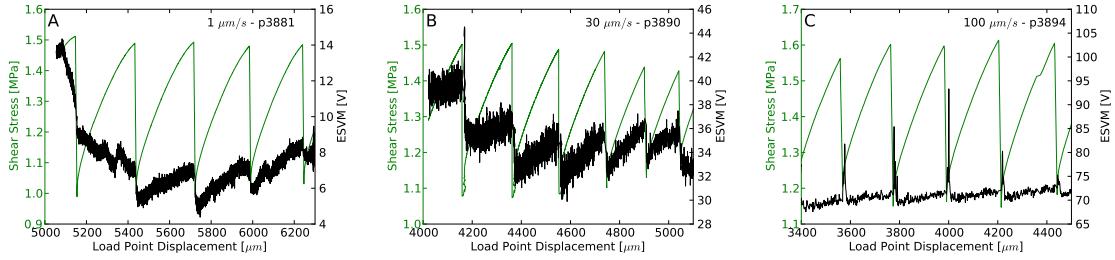


Fig. 5.6. Stick-slip events and associated ESVM measurements for three-different load point velocities of 1, 30, and 100  $\mu\text{m}/\text{s}$ . A) At slow loading velocities the electrical signal clearly mirrors the stress curve in most cases B) For intermediate velocities, the relation is still present. C) At high velocities, the electrical signal is a sharp pulse an order of magnitude higher than those observed at low velocities, and we observe small inter-seismic charging.

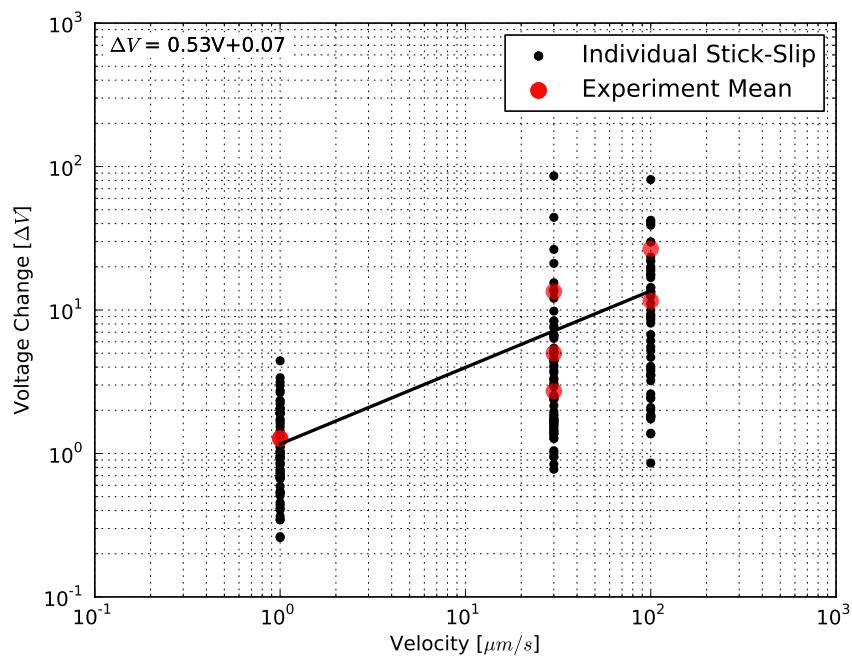


Fig. 5.7. Each order of magnitude driving velocity change produces a  $\sim 5\times$  increase in the electrical signal observed. All experiments shown are with the side-view sensor geometry.

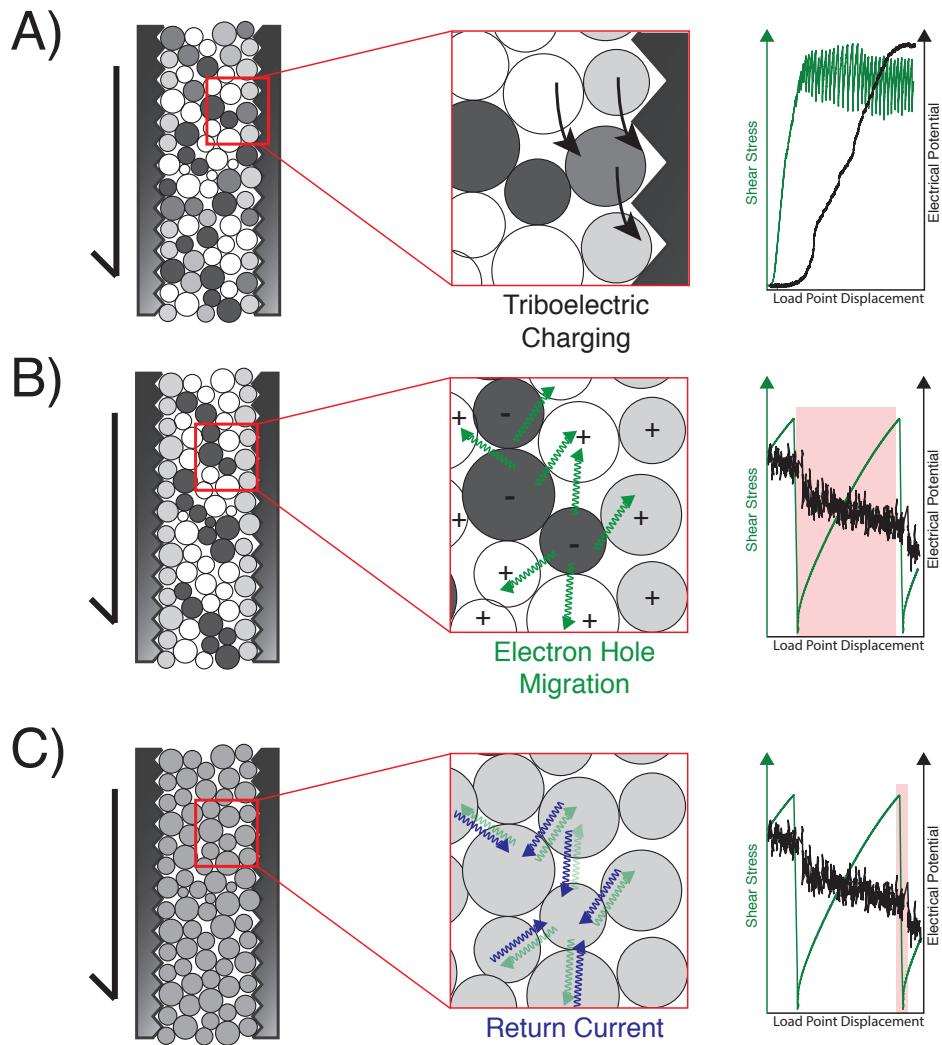


Fig. 5.8. A schematic representation of the stages of electrical behavior during an experiment: A) During the initial run-in there is massive grain rearrangement as force chain networks begin to form. This sliding motion tribo-electrically charges the system. B) After the force chain network forms there is minimal grain-boundary sliding. Shear loads are supported in the granular layer by highly stressed force chains (dark colors). Electron holes migrate away from highly stressed beads into the matrix creating an electrical potential gradient. C) When the layer fails and all grains are at roughly the same low stress, a return current redistributes the electrical gradient and the cycle begins again.

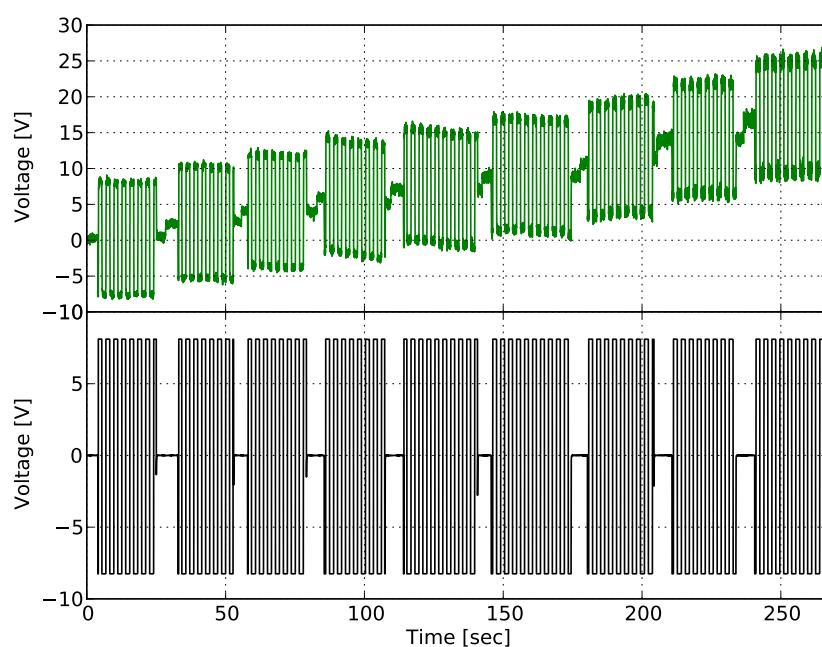


Fig. 5.9. Calibration of the ESVM from a function generator source (bottom panel). A series of steps through the ESVM ‘response’ setting from 1-9 shows that the input square wave applied to the aluminium surface under test is well-recorded on each setting (top panel). The upward trend in ESVM data is a product of a DC offset that occurs each time the response setting is changed on the instrument.

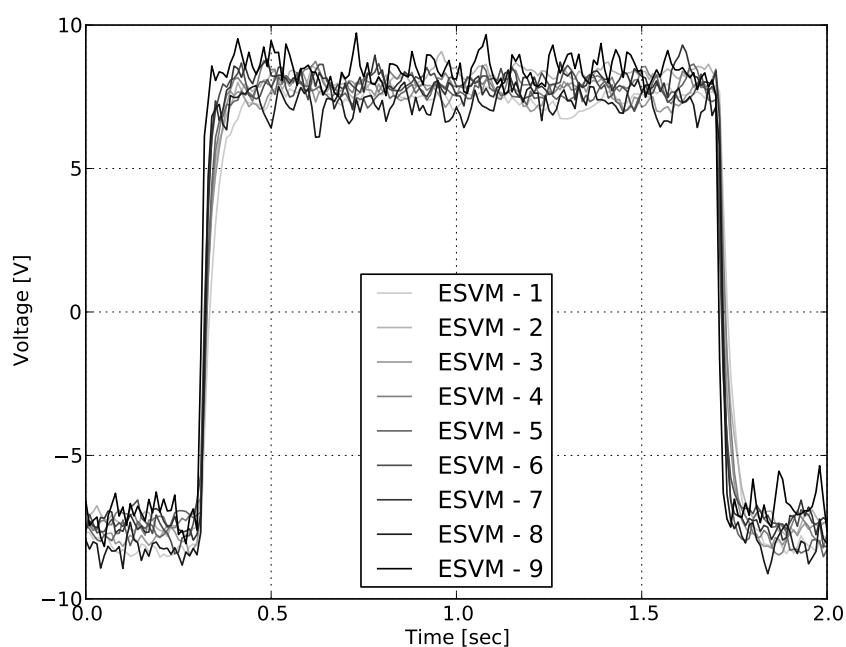


Fig. 5.10. A detailed comparison of a single waveform shows that at lower response settings (lighter colors) the waveform is smoothed slightly, with the nearly instantaneous voltage change distributed over up to 0.1 seconds on both the rise and fall. At higher resolutions (darker colors) the sharp transition is clearly seen, but at the price of a higher noise level during the flat hold states.

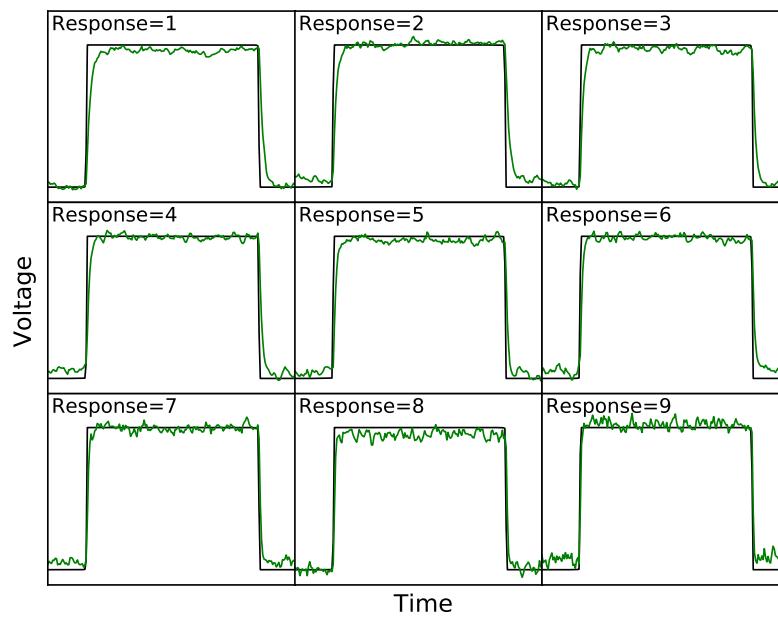


Fig. 5.11. At all response settings the beginning of ESVM signal change corresponds well in the time domain with the leading and falling edge of the input signal. Smoothing due to longer integration times is observed at low response settings.

Table 5.1. List of Experiments

Experiment	$V_{lp}, \mu m/s$	Bead Size, $\mu m$	Temperature, $C^\circ$	Humidity, %	Comment
p3853	30	420-500	23.3	41.2	Large Beads
p3878	30	100-150	23.8	23.8	Side View
p3879	30	420-500	24.7	20.2	Large Beads
p3880	30	420-500	25.7	20.7	Large Beads
p3881	30	100-150	26.9	20.7	Side View
p3882	30	100-150	26.0	14.0	Side View
p3887	30	100-150	22.7	22.5	Side View
p3889	1	100-150	23.4	24.8	Side View
p3890	100	100-150	24.1	33.8	Side View
p3893	100	100-150	21.9	19.9	Side View
p3894	1	100-150	22.7	19.8	Side View
p4010	30	100-150	23.9	23.0	Top View - Isolated Ground
p4011	30	100-150	24.2	23.7	
p4012	30	100-150	24.5	22.0	
p4013	1	100-150	24.3	22.3	
p4014	30	100-150	23.0	100	
p4015	30	100-150	23.3	N/A	Submerged
p4049	30	100-150	23.9	27.0	Control Test
p4050	30	100-150	23.8	100	Saturated
p4051	30	100-150	23.9	N/A	Submerged
p4052	30	100-150	23.8	100	Saturated

Table 5.2. Composition of glass beads.

Compound	Composition,%
SiO <sub>2</sub>	65-75%
Al <sub>2</sub> O <sub>3</sub>	0-5%
CaO	6-15%
MgO	1-5%
Na <sub>2</sub> O	10-20%
Fe <sub>2</sub> O <sub>3</sub>	<0.8%

## Appendix A

### List of Biaxial Experiments

Date	Exp.	Block	Material	Grain Size	Thickness	$\sigma_n$	Velocity	Temperature	Humidity	Purpose
Text	Num	Material	Text	um	mm	MPa	$\mu\text{m/s}$	C	%	Text
8/31/12	p3805	Granite	Glass Beads	100-150	5	5	5	24	57.4	ESVM
9/3/12	p3809	Granite	Glass Beads	100-150	5	5	10	24	80	ESVM
9/21/12	p3825	Granite	Glass Beads	100-150	5	1	10	-	-	ESVM
9/22/12	p3826	Granite	Glass Beads	100-150	5	31	10	23.4	65	ESVM
9/22/12	p3827	Steel	Glass Beads	100-150	5	2.5,4	1,10	23.1	63	ESVM
9/23/12	p3828	Steel	Glass Beads	100-150	5	2.5,4	10	22.8	39.9	ESVM
9/23/12	p3829	Steel	Glass Beads	100-150	5	10	10	23.5	38.1	ESVM
9/24/12	p3830	Steel	Glass Beads	100-150	5	10	10-500	21.9	41	ESVM
9/24/12	p3831	Steel	Glass Beads	100-150	5	10	10-100	22.3	16	Low RH ESVM
10/18/12	p3846	Acry/UMHW	Glass Beads	100-150	5	0.5,1	N/A	25.8	33	Test New Blocks
10/29/12	p3851	Acry	Glass Beads	100-150	5	4.3	10-100	22.4	44	ESVM
10/29/12	p3852	Acry	Glass Beads	420-500	5	4.3	10-100	22.7	42.9	ESVM
10/29/12	p3853	Acry	Glass Beads	420-500	5	4.3	30	23.3	41.2	ESVM
11/13/12	p3878	Acry	Glass Beads	100-150	5	4	30	23.8	23.8	ESVM
11/14/12	p3879	Acry	Glass Beads	420-500	5	4	30	24.7	20.2	ESVM
11/14/12	p3880	Acry	Glass Beads	420-500	5	4	30	25.7	20.7	ESVM
11/15/12	p3881	Acry	Glass Beads	100-150	5	4	30	26.9	20.7	ESVM
11/16/12	p3882	Acry	Glass Beads	100-150	5	4	30	26	14	Low RH ESVM
11/22/12	p3886	Ice Core	Ice	N/A	N/A	N/A	100	21.6	26.9	Signal from Ice
11/22/12	p3887	Acry	Glass Beads	100-150	5	4	30	22.7	22.5	ESVM
11/22/12	p3888	Acry	Glass Beads	Mixed	7	4	10	22.7	24.7	Video

11/23/12	p3889	Acry	Glass Beads	100-150	5	4	1	23.4	24.8	ESVM
11/23/12	p3890	Acry	Glass Beads	100-150	5	4	100	24.1	33.8	ESVM
11/23/12	p3891	Ice Core	Ice	N/A	N/A	N/A	100	23.8	30.4	Signal from Ice
11/23/12	p3892	Acry	Glass Beads	Mixed	7	4	10	23.3	28.7	Video of beads
11/24/12	p3893	Acry	Glass Beads	100-150	5	4	100	21.9	19.9	ESVM
11/24/12	p3894	Acry	Glass Beads	100-150	5	4	1	22.7	19.8	ESVM
11/24/12	p3895	Ice Core	Ice	N/A	N/A	N/A	100	22.5	20.1	Signal from Ice
12/13/12	p3916	Acry	Flour	Unknown	7	1	0.1-100	23.5	22	Flour Props.
12/14/12	p3917	Acry/Steel	Flour	Unknown	7	1	0.1-10	22	21.9	Flour Vel.
12/15/12	p3918	Acry	Flour	Unknown	7	1	10,1	23.1	22	Flour ESVM
12/15/12	p3919	Acry	Flour	Unknown	7	1	1	24.2	23.9	Flour ESVM
12/15/12	p3920	Acry	Flour	Unknown	7	1	1,10	24.4	25	Flour ESVM
3/13/13	p4010	Acry	Glass Beads	100-150	5	4	30	23.9	23	Top View - not gnded
3/13/13	p4011	Acry	Glass Beads	100-150	5	4	30	24.2	23.7	Top View - gnded
3/13/13	p4012	Acry	Glass Beads	100-150	5	4	30	24.5	22	Top View
3/13/13	p4013	Acry	Glass Beads	100-150	5	4	1	24.3	22.3	Top View
3/14/13	p4014	Acry	Glass Beads	100-150	5	4	30	23	100	High RH
3/14/13	p4015	Acry	Glass Beads	100-150	5	4	30	23.3	N/A	Submerged
4/13/13	p4049	Acry	Glass Beads	100-150	5	4	30	23.9	27	ESVM Control
4/14/13	p4050	Acry	Glass Beads	100-150	5	4	30	23.8	100	High RH
4/14/13	p4051	Acry	Glass Beads	100-150	5	4	30	23.9	N/A	Submerged
4/15/13	p4052	Acry	Glass Beads	100-150	5	4	30	23.8	100	High RH
5/5/13	p4061	N/A	Granite Core	N/A	N/A	N/A	N/A	-	-	P4000 Celebration

5/26/13	p4071	Steel/Acry	F110	-	3	2	various	23.3	30.1	Stable or SS
5/26/13	p4072	Steel/UMHW	F111	-	3	2	various	23.4	25.4	Stable or SS
5/27/13	p4073	Steel	Flour	-	8	1	various	23.4	28.4	Stable or SS
5/27/13	p4074	Steel/Acry	Flour	-	8	1	various	23.1	38.8	Stable or SS
6/28/13	p4080	Large Steel	N/A	N/A	N/A	N/A	5	24.1	66.4	Horiz k
6/28/13	p4081	Large Steel	N/A	N/A	N/A	N/A	5	24.2	65.9	Vert k
6/28/13	p4082	Large Steel	N/A	N/A	N/A	N/A	5	24.2	64.6	Poisson
6/28/13	p4083	Large Steel	N/A	N/A	N/A	N/A	5	24.4	64.6	Horiz k
6/28/13	p4084	Large Steel	N/A	N/A	N/A	N/A	5	24.6	64.1	Vert k
6/28/13	p4085	Large Steel	N/A	N/A	N/A	N/A	5	24.6	63.9	Poisson
7/1/13	p4086	Large Steel	N/A	N/A	N/A	N/A	5	24.1	68.4	Horiz k
7/1/13	p4087	Large Steel	N/A	N/A	N/A	N/A	5	23.9	68	Vert k
7/1/13	p4088	Large Steel	N/A	N/A	N/A	N/A	5	23.9	67.5	Poisson
7/22/13	p4108	Granite	N/A	N/A	N/A	2	various	25.5	58.5	Acou - Vel steps
7/25/13	p4111	Granite	N/A	N/A	N/A	2	various	25.2	49.2	Acou - Vel steps
7/26/13	p4112	Steel	Flour	Unknown	8	1	various	24.3	55.5	SHS
7/26/13	p4113	Steel	Flour	Unknown	8	1	various	24.3	56.1	SHS/Steps
7/30/13	p4115	Granite	N/A	N/A	N/A	4	various	24.5	55.5	Acou - Vel steps
7/30/13	p4116	Granite	N/A	N/A	N/A	4	various	N/A	N/A	Acou - Vel steps
7/30/13	p4117	Granite	N/A	N/A	N/A	4	various	24.7	54.7	Acou - Vel steps
7/31/13	p4118	Granite	N/A	N/A	N/A	4	various	24.3	57.5	Acou - Vel steps/SHS
7/31/13	p4119	Granite	N/A	N/A	N/A	4	various	24.5	56.1	Acou - Rubin/SHS
8/1/13	p4120	Granite	N/A	N/A	N/A	4	various	24.4	60.3	Acou - Rubin/SHS

8/2/13	p4121	Steel	F110	N/A	5	25	various	24.7	556.6	Acou - Rubin/V steps
11/9/13	p4175	steel	F110	N/A	5	25	10	24.3	24.1	Dry and submerged
11/10/13	p4176	steel	Alpine Fault	<125	5	30	10	23	19	SHS
11/10/13	p4177	steel	Alpine Fault	<125	5	30	10	23.6	26.5	SHS
11/10/13	p4178	steel	Alpine Fault	<125	5	30	10	23.8	22.5	SHS
11/15/13	p4181	Steel	Glass Beads	100-150	5	4.5	various	24.7	19.5	PJ - Acou
11/15/13	p4182	Steel	Glass Beads	100-150	5	4.5	various	24.6	21	PJ - Acou
11/16/13	p4183	Steel	Glass Beads	100-150	5	4.5	various	25.4	28.6	PJ - Acou
11/16/13	p4184	Steel/UMHW	Min-u-sil	10	3	1	various	26	30.2	PJ - Stiffness
11/16/13	p4185	Ti/Acry	Min-u-sil	10	3	4	various	24.3	33	PJ - Stiffness
11/17/13	p4186	Ti/Acry	Min-u-sil	10	3	4	various	23.9	42.7	PJ - Stiffness
11/17/13	p4187	Ti/Acry	Min-u-sil	10	3	4	various	25.5	42.2	PJ - Stiffness
11/17/13	p4188	Steel/Acry	Westerly Po	<125	3	4	various	25	46.5	PJ - Stiffness
11/17/13	p4189	Ti/Acry	Min-u-sil	10	3	4	various	26	45.3	PJ - Stiffness
11/18/13	p4190	Granite	N/A	N/A	N/A	3	various	24.3	34.1	PJ - Stiffness
11/18/13	p4191	Ti/Acry	Min-u-sil	10	3	4	various	24.6	30.1	PJ - Stiffness
1/10/14	p4206	Steel/Acry	Min-u-sil	10	3	4	various	23.3	22.4	Slow-Slip
1/10/14	p4207	Steel/Acry	Min-u-sil	10	3	4	various	23.2	23.3	Slow-Slip
1/23/14	p4211	Steel	F110	110	5	25	various	23.3	16	Kerry 508 Project
11/18/13	p4192	Steel	Min-u-sil	10	3	4	various	25.4	29.8	PJ - Stiffness
2/27/13	p4224	Ti/Acry	Min-u-sil	10	3	5	various	26	16	Test New Acry Block
2/28/14	p4225	Ti/Acry	Min-u-sil	10	3	5	various	22	16	Old Acry Block
2/28/14	p4226	Ti/Acry	Min-u-sil	10	3	4	various	22	16	Old Acry Block

3/1/14	p4227	Ti/Acry	Min-u-sil	10	3	4	various	24	100	Old Acry Block
3/1/14	p4228	Steel	Min-u-sil	10	3	4	various	24	100	SHS
3/3/14	p4229	Ti/Acry	Min-u-sil	10	3	4	various	24	100	New Acry
	p4238									
4/25/14	p4247	Ti/Acry	Min-u-sil	10	3	4	various	23	100	New 5x5 Acry
4/26/14	p4248	Ti/Acry	Min-u-sil	10	3	4	various	24.2	100	New Acry
4/26/14	p4249	Ti/Acry	Min-u-sil	10	3	4	various	23.2	100	New Acry
4/27/14	p4250	Ti/Acry	Min-u-sil	10	3	4	various	22.7	100	Old Acry
4/27/14	p4251	Ti/Acry	Min-u-sil	10	3	4	various	23.2	22	Old Acry
5/22/14	p4267	Ti/Acry	Min-u-sil	10	3	2	various	23.2	100	New Acry
5/23/14	p4268	Ti/Acry	Min-u-sil	10	3	8	10	23.4	100	New Acry
5/23/14	p4269	Steel	Min-u-sil	10	3	4	various	23.4	100	Steps
5/24/14	p4270	Steel	Min-u-sil	10	3	2	various		100	Steps
5/24/14	p4271	Ti/Acry	Min-u-sil	10	3	2	various		100	Steps
5/25/14	p4272	Ti/Acry	Min-u-sil	10	3	8	10	22.7	100	New Acry
5/25/14	p4273	Steel	Min-u-sil	10	3	8	various	23.4	100	Steps
8/28/14	p4308	Steel	N/A	N/A	N/A	4	N/A	23.5	57	P/S wave block
8/31/14	p4309	Steel	Min-u-sil	10	3	8	various	23.2	100	RSF
8/31/14	p4310	Ti/Acry	Min-u-sil	10	3	8	various	24.2	100	Fine Acry
9/1/14	p4311	Ti/Acry	Min-u-sil	10	3	8	various	23.3	100	Thick Acry
9/1/14	p4312	Steel/Acry	Min-u-sil	10	3	8	various	23.6	100	Thick Acry
9/2/14	p4313	Ti/Acry	Min-u-sil	10	3	8	various	23.5	100	Fine Acry
9/2/14	p4314	Steel	Min-u-sil	10	3	12	various	24.3	100	RSF

9/2/14	p4315	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Block k
9/3/14	p4316	Ti/Acry	Min-u-sil	10	3	12	various	23.6	100	Fine Acry
9/3/14	p4317	Steel/Acry	Min-u-sil	10	3	12	various	24.2	100	Fine Acry
10/11/14	p4327	Steel	Min-u-sil	10	3	6	various	22.5	100	RSF
10/11/14	p4328	Ti/Acry	Min-u-sil	10	3	6	various	22.7	100	Fine Acry
10/12/14	p4329	Ti/Acry	Min-u-sil	10	3	6	various	22	100	Fine Acry
10/12/14	p4330	Steel	Min-u-sil	10	3	6	various	22.9	100	RSF
11/3/14	p4336	Ti/Acry	Min-u-sil	10	3	8	10	24.8	100	Vp Slow Slip
11/4/14	p4337	Ti/Acry	Min-u-sil	10	3	8	10	24.8	100	Vs Slow Slip
11/15/14	p4338	Ti/Acry	Min-u-sil	10	3	4	10	24.2	100	Unload/reload k
11/15/14	p4339	Steel	Min-u-sil	10	3	4	various	24.8	100	Unload/reload, RSF
11/16/14	p4340	Ti/Acry	Min-u-sil	10	3	8	various	24	100	Dual DCDT
11/24/14	p4341	Steel	Min-u-sil	10	3	12	10	23.4	100	Dual DCDT,Audio,RSF
11/24/14	p4342	Ti/Acry	Min-u-sil	10	3	12	10	24.3	100	Dual DCDT,IMU,Audio
11/25/14	p4343	Steel/Acry	Min-u-sil	10	3	6	10	23.9	100	Dual DCDT
11/25/14	p4344	Ti/Acry	Min-u-sil	10	3	7	10	24.5	100	Dual DCDT
11/26/14	p4345	Steel/Acry	Min-u-sil	10	3	8	10	24.2	100	Dual DCDT
11/26/14	p4346	Ti/Acry	Min-u-sil	10	3	9	10	24.2	100	Dual DCDT
11/29/14	p4347	Steel/Acry	Min-u-sil	10	3	10	10	23.1	100	Dual DCDT,Audio
11/29/14	p4348	Ti/Acry	Min-u-sil	10	3	11	10	23.9	100	Dual DCDT,Audio
11/29/14	p4349	Steel	Glass Beads	100-150	3	6	10	24.1	16.3	Audio fast stick-slip
11/30/14	p4350	Steel/Acry	Min-u-sil	10	3	13	10	22.7	100	Dual DCDT,Audio
11/30/14	p4351	Ti/Acry	Min-u-sil	10	3	14	10	23.1	100	Dual DCDT,Audio

1/14/15	p4362	N/A	Si Powder	N/A	N/A	N/A	N/A	N/A	N/A	Chris House
3/3/15	p4379	Steel	Min-u-sil	10	3	4	various	24.5	12.5	Steps, OB DCDT
3/7/15	p4381	Steel	Min-u-sil	10	3	4	various	22.7	10.6	RSF
3/7/15	p4382	Ti	Min-u-sil	10	3	4	various	23.1	18.8	RSF
4/27/15	p4397	Granite	N/A	N/A	N/A	4	various	N/A	N/A	P&S Wave block
4/28/15	p4398	Steel	F110		3	25	various	21.8	33	P&S Wave block
10/20/15	p4462	Granite	Core	N/A	N/A	N/A	N/A	21.8	29.4	Strain gauges
1/29/16	p4522	Steel/Acry	Min-u-sil	10	3	7	10	21.6	18.7	Reproduce P4344
1/29/16	p4523	Ti/Acry	Min-u-sil	10	3	7	30	21.8	19.5	Vel. Dep.
1/30/16	p4524	Steel/Acry	Min-u-sil	10	3	7	3	20.8	16.1	Vel. Dep.
1/30/16	p4525	Ti/Acry	Min-u-sil	10	3	7	100	21.9	16.3	Vel. Dep.
1/31/16	p4526	Steel/Acry	Min-u-sil	10	3	7	300	N/A	N/A	Vel. Dep.
1/31/16	p4527	Ti/Acry	Min-u-sil	10	3	7	10, 30	21.9	23.8	Vel. Dep., Acou., Temp.
5/4/16	p4599	Ti/Acry	Min-u-sil	10	3	7	acc. file	22.3	47	Acc. File, AE
5/5/16	p4600	Steel	Min-u-sil	10	3	2	various	22.7	42.6	RSF
5/5/16	p4601	Steel/Acry	Min-u-sil	10	3	12	30	22.7	41.4	Vel. Dep.
5/6/16	p4602	Ti/Acry	Min-u-sil	10	3	12	3	22.7	41.6	Vel. Dep., AE
5/7/16	p4603	Steel/Acry	Min-u-sil	10	3	12	300	22.7	38.1	Vel. Dep.
5/7/16	p4604	Steel/Acry	Min-u-sil	10	3	12	100	22.1	38.5	Vel. Dep., Temp.
5/8/16	p4605	Steel/Acry	Min-u-sil	10	3	9	100	21.9	25.3	Vel. Dep.
5/8/16	p4606	Steel/Acry	Min-u-sil	10	3	9	300	21.9	26.7	Vel. Dep., Temp.
5/9/16	p4607	Steel/Acry	Min-u-sil	10	3	7	100	22.6	31.6	Reproduce P4525
5/9/16	p4608	Steel/Acry	Min-u-sil	10	3	7	300	22.6	30.8	Reproduce P4526

5/9/16	p4609	Ti	Kinetic Sand	Unkwn	3	7	various	22.5	29.2	Props.
5/10/16	p4610	Steel/Acry	Min-u-sil	10	3	5	10	21.1	29.4	Vel. Dep.
5/10/16	p4611	Steel/Acry	Min-u-sil	10	3	5	30	22.2	34.9	Vel. Dep., Temp.
5/11/16	p4612	Westerly	N/A	N/A	N/A	4	various	N/A	N/A	OB DCDT and control
5/12/16	p4613	Steel	Min-u-sil	10	3	7	10	21.9	63	Acry Spring
5/12/16	p4614	Steel/Acry	Min-u-sil	10	3	5	3	20.8	56.6	Vel. Dep., Temp.
10/31/16	p4726	Steel	Min-u-sil	10	3	5	various	20.5	33.5	RSF
10/31/16	p4727	Ti/Acry	Min-u-sil	10	3	5-7	various	N/A	N/A	Vel. Dep.
11/1/16	p4728	Steel/Acry	Min-u-sil	10	3	7-9	various	20.6	35	Vel. Dep.
11/1/16	p4729	Ti/Acry	Min-u-sil	10	3	9-11	various	21.5	44.2	Vel. Dep.
11/2/16	p4730	Steel/Acry	Min-u-sil	10	3	11-13	various	20.6	45.6	Vel. Dep.
11/2/16	p4731	Ti/Acry	Min-u-sil	10	3	12	30	20.7	54.3	Vel. Dep.
11/3/16	p4732	Ti/Acry	Min-u-sil	10	6	7	various	21.4	63.4	Vel. Dep.
11/3/16	p4733	Steel/Acry	Min-u-sil	10	1	7	10	21.9	66.9	Vel. Dep.
11/4/16	p4734	Ti/Acry	Min-u-sil	10	6	7	10	21.2	33	Vel. Dep.
11/4/16	p4735	Ti	Min-u-sil	10	3	5,2	various	21	32.4	Vel. Dep.
11/5/16	p4736	Ti/Steel	Min-u-sil	10	3	7	10	21.2	36.1	Vel. Dep.
11/5/16	p4737	Steel	Min-u-sil	10	3	7	30	21.6	32.8	Vel. Dep., Spring

## Appendix B

### List of Triaxial Experiments

Date	Experiment	Description
5/4/13	T_070_307_Berea_Resistivity	Test resistivity insulators in pressure vessel - insulators failed under load.
1/31/14	T_070_360_SAL1744	Step loading and unloading of Whillans Ice Stream till sample.
5/21/14	T_070_378_SAL1754	Tidal loading sequence of Whillans Ice Stream till sample.
5/15/15	T70-439-internal-LC	Testing and calibration of internal strain gauge load cell.

## Appendix C

### Sample Preparation Procedures

This appendix details the standardized sample preparation procedures used for the experiments in this dissertation. These techniques, if followed carefully, yield very repeatable results. Techniques for the double direct shear configuration for the biaxial apparatus and the low confining pressure triaxial jacket configuration are described.

#### C.1 Biaxial Double Direct Shear

Most of the experiments in this dissertation were completed using the double direct shear (DDS) geometry outside of the pressure vessel on the biaxial apparatus. This construction technique can easily be applied to solid block experiments in which blocks of rock take the place of the forcing blocks used and gouge is optional. This appendix will describe how to construct a granular DDS sample.

##### C.1.1 Materials

- (2) Side forcing blocks
- (1) Center forcing block
- (4) Side shields and screws
- (2) Large steel blocks

- (1) Cellophane tape
- (1) New razor blade
- (4) Jig blocks
- (1) Set of spacing shims
- (1) Steel rule
- (1) Flat metal plate
- (1) Rubber sheet
- (1) Beaker or measuring cup
- (1) Spoon
- (1) Scissors
- (1) Appropriate tool for side shield screws
- (1) Wire brush set
- (1) Large quick clamp
- (1) Isopropyl alcohol
- (1) Bulk granular material

### C.1.2 Procedure

1. Thoroughly clean all forcing blocks and sample preparation surface with brushes and alcohol. Let air dry. C.1

2. Setup one of the jig blocks at the rear of the sample preparation area. Find an appropriate combination of shims C.2 to make the space measured from the side block (across the groove direction) to the top of the jig block the desired layer thickness C.3.
3. Label the shim blocks, generally by making a unique set of permanent marker lines on the sides of the shims. This makes it easier to keep the shims together during your run of experiments.
4. Wrap a side block with a layer of cellophane tape. The tape should be about 3-5 mm back from the rough surface. Go around all four sides, using the dull back side of a razor blade to help hold the last corner square C.4.
5. Trim the tape and ensure a clean seal around the block.
6. Wrap a second layer of tape around the side block, this time with the back of the tape flush with the smooth side of the block.
7. Trim the second layer of tape and check that the seal is solid C.5.
8. Lay the side block down onto the spacing shims and surround it with jig blocks. Use a small piece of tape to secure the jig blocks together C.6.
9. Use the razor blade to trim the tape sticking above the jig blocks C.7. Using a sub-parallel angle seems to work best. Use a new razor blade for each experiment to ensure a clean cut. If the tape tears anywhere, remove all tape, clean the block, and start again.
10. Repeat steps 4-9 for the second side block.

11. Label the side blocks with a permanent marker using a letter to indicate the material and a block designation. For example, "SA" and "SB" for steel , "TA" and "TB" for titanium blocks C.8.
12. Weigh each block and record the weight C.9.
13. Dispense enough granular material to fill a side block into a beaker/cup and weigh the cup. Record this mass.
14. Place a side block back into the shim/jig block assembly and secure the jig blocks with tape.
15. Using the spoon, evenly distribute the granular material into the cavity of the side block C.10.
16. Using the edge of a steel rule, wipe the material around until the block is covered to depth, adding material if necessary.
17. Using a pulling/cutting motion, make an even layer of material a few millimeters higher than the surface of the jig blocks C.11.
18. Place the flat metal plate on top of the layer and press firmly. Using several CPR-like compressions to compact the material C.12.
19. Pull the steel rule across the surface of the jig blocks to make a clean and level layer of granular material C.13. Make sure any extra material goes back into the beaker/cup.
20. Repeat steps 15-19 a second time for the same side block.

21. Carefully untape the jig blocks and remove the side block. Using your palm, remove any material stuck to the outside surfaces of the block C.14.
22. Weigh the block and record its mass. From the two block mass measurements, calculate the weight of the granular material in the layer and record it. This should be very similar between each side block and each identical run. Differences of more than a few grams should be scrutinized and the layer possibly rebuilt.
23. Weigh the cup with the remaining granular material and determine the weight of the granular material used. This should be similar to, but generally more than, weighing the blocks due to material loss. This method is redundant for many experiments, but in 10 x 10 cm steel experiments, the weight of the loaded side blocks often exceed the maximum capacity of the lab balance and this method is necessary.
24. Repeat steps 13-23 for the second side block.
25. Using two large steel blocks and a quick clamp, build an “L” shaped structure as a jig for assembling the sample C.15.
26. Using a steel rule, place the shims in the bend of the “L” half of the sample width from each side so that they support the side block in its center.
27. Carefully place a side block on the shims with the mounting screw holes for the side shields facing you C.16. Take care to further orient the block if your blocks have special features such as holes for thermistors or other equipment.

28. Place a jig block across the end of the center block running in the front-back orientation C.17.
29. Place the center block in the corner of the “L” jig (above the side block) with the long dimension running left-right.
30. Lower the center block onto the sample. Place a jig block on the far right end of the block to serve as a counterweight and reduce uneven force on the sample due to the unsupported end of the block C.18.
31. Unclamp the steel blocks and move the back block to the far right of the center block to serve as a backstop when taping the sample. Set the block on the left off to the side C.19.
32. Take an approximately 8” length of tape from the dispenser and pass it close to all edges of the sample. Static electricity will often pull away any loose material. If your sample is especially difficult (such as glass beads) this step can be omitted as long as you pass each strip of tape over a grounded object to remove the static charge.
33. Tape the three exposed sides of the sample with a single strip of tape centered on the layer C.20.
34. Re-tape this seam with two more strips, one slightly above the layer centerline and one slightly below C.21.
35. Carefully peel any tape that has stuck to the jig block and stand the sample up C.22.

36. Using a razor blade, cut the tape running along the center block above the side block vertically and stick it over the top of the layer.
37. Using another piece of tape, completely seal the top of the layer C.23.
38. Repeat steps 25-37 for the second side block. Lowering the sample assembly is more difficult due to the increased weight, but great care should be taken to ensure that it remains square in the jig C.24.
39. Using a razor blade, trim out the holes for the side shield screws C.25.
40. Cut a strip of rubber sheeting and set the sample on it, centered in both directions.
41. Mark the location of the side shield holes and the side blocks on the sheet C.26.
42. Cut the sheet so it is the width of the side shield hole spacing of the sample assembly.
43. Cut the corners of the sheet diagonally using the marks for the location of the center block edges C.27.
44. Place the sample assembly onto the rubber sheet and tape the flaps to the center block C.28.
45. Attach and tighten the side shields C.29.
46. Measure the width of the sample using calipers and record this on the experimental log sheet C.30.
47. If the sample is not run immediately, store it between steel blocks C.31.



Fig. C.1. Gather all blocks and ensure that they are clean and free of debris.

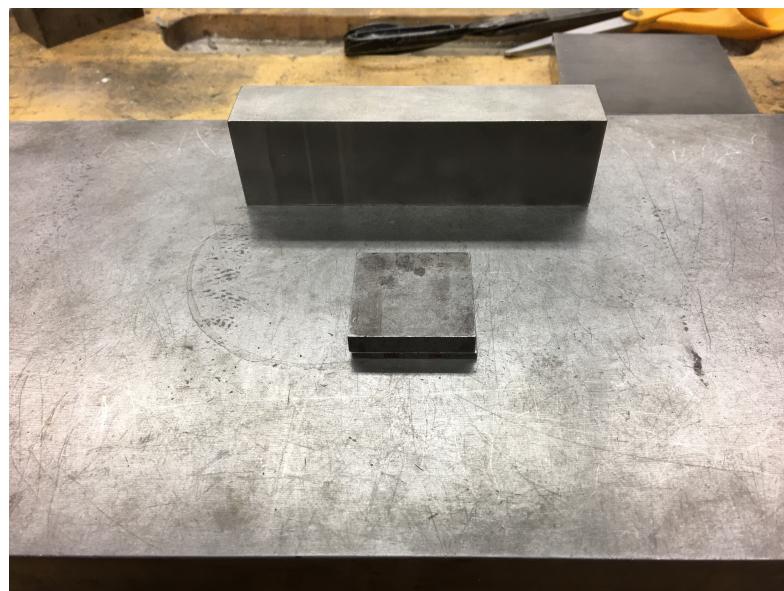


Fig. C.2. Stack shims to adjust the sample thickness. Note which shims are used.



Fig. C.3. Measuring the sample thickness with a steel rule.



Fig. C.4. Carefully fold over the corner of the tape and trim any excess length.

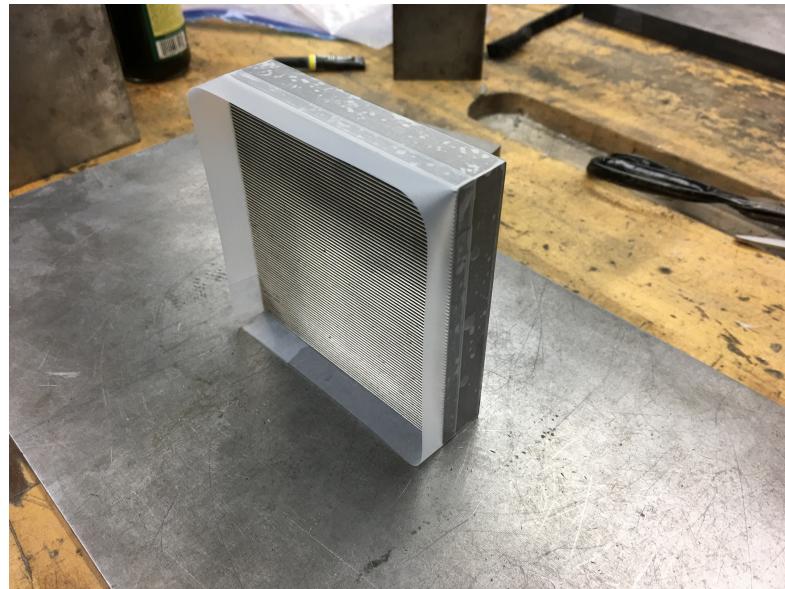


Fig. C.5. A fully taped side block.

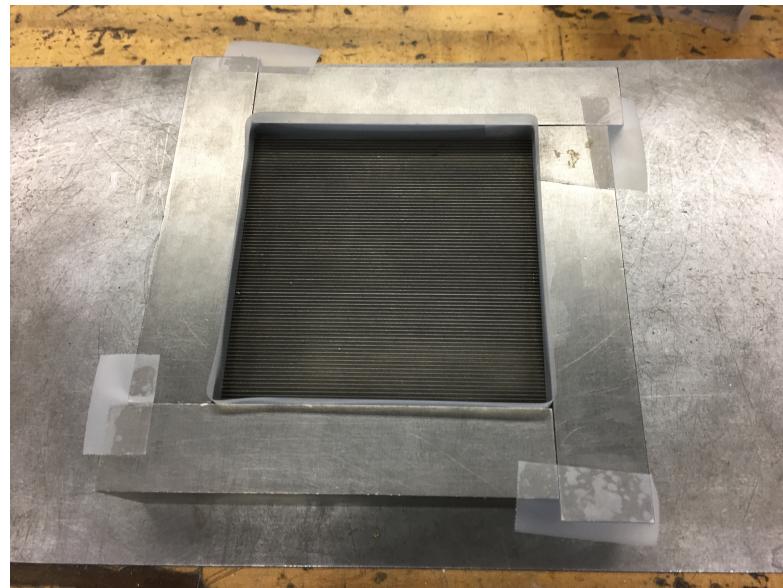


Fig. C.6. Setup a jig to trim the excess tape height.

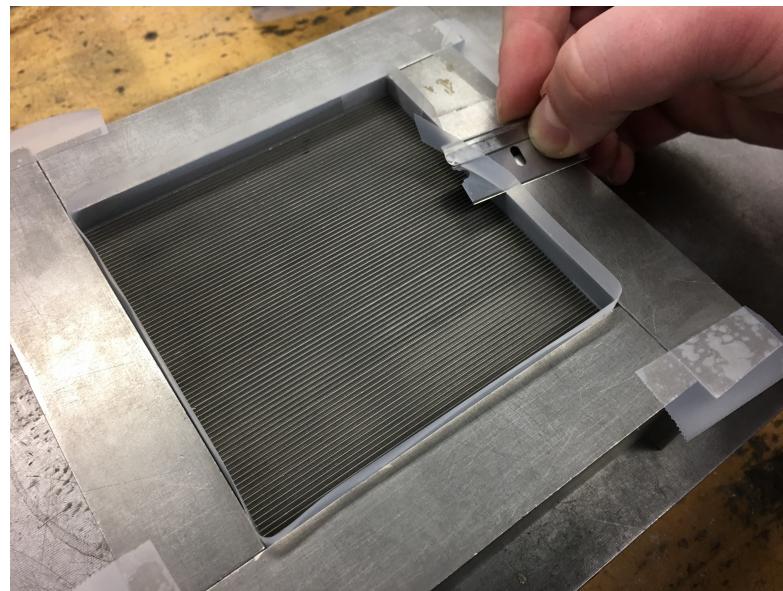


Fig. C.7. Carefully trim the tape on all four sides of the block. Note the angle of the razor blade.

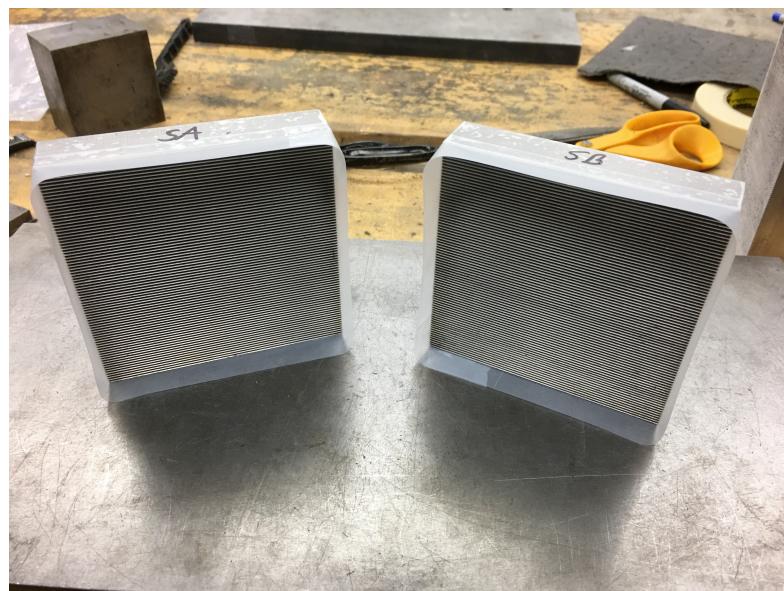


Fig. C.8. Label the side blocks to help keep track of the mass of material in each layer.

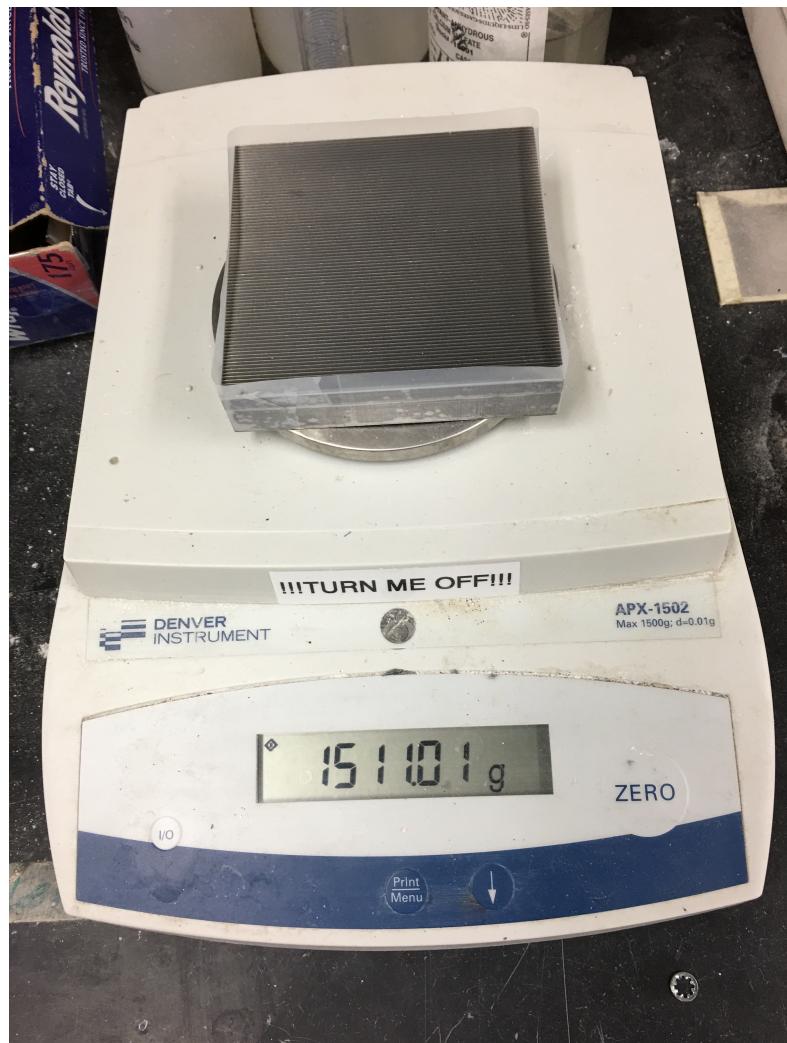


Fig. C.9. Weigh the blocks after all taping and trimming is completed.

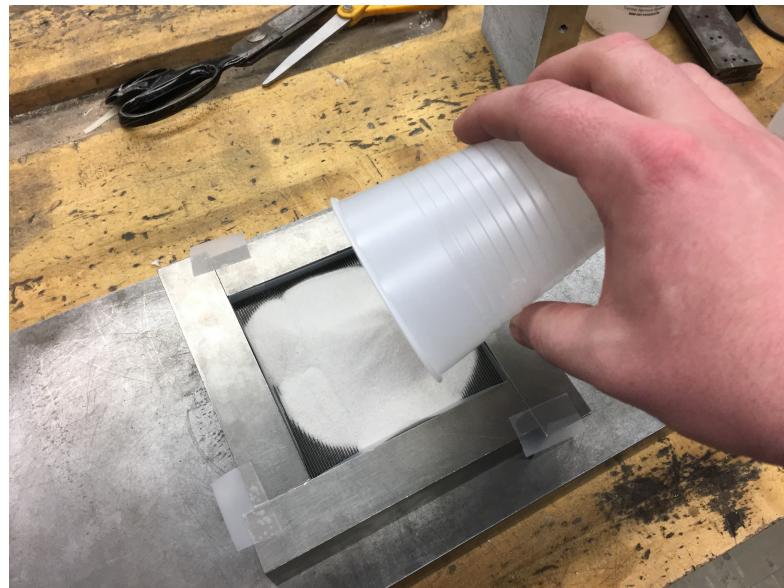


Fig. C.10. Carefully pour sample material into the taped area of the block.



Fig. C.11. Using a sliding and chopping action, evenly distribute the sample material over the side block.



Fig. C.12. Firmly compress the sample to ensure a good granular packing.

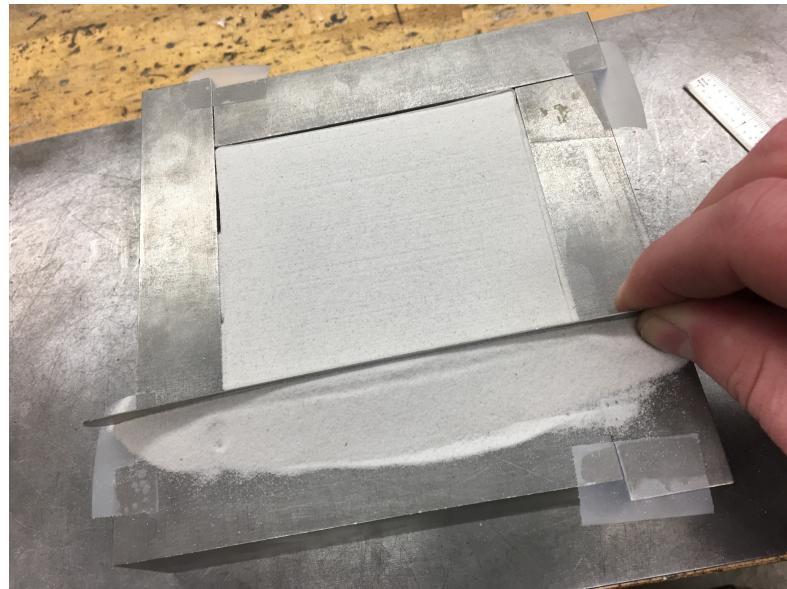


Fig. C.13. Drag the steel rule over the sample to flatten the layer.

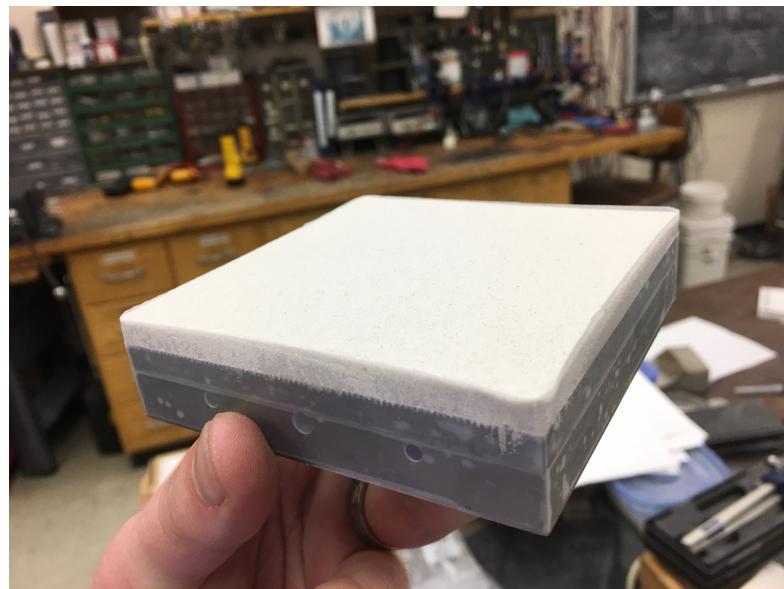


Fig. C.14. A completed side block ready to be weighed and assembled.

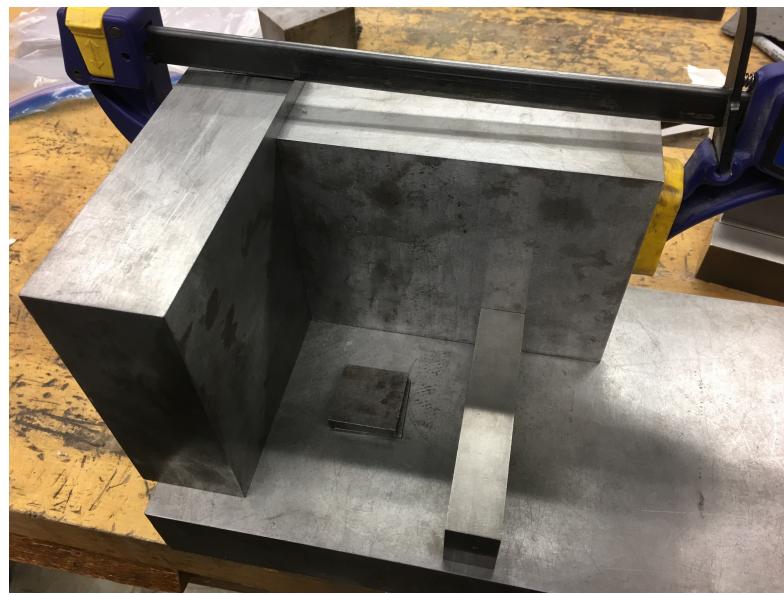


Fig. C.15. Setup the jig for assembling the side and center blocks into the complete sample assembly.



Fig. C.16. Place the sideblock into the jig with the side shield mounts facing towards you.



Fig. C.17. Place a spacer at the top of the side block to help support the center block's weight.



Fig. C.18. Place the center block and secure it with small strips of tape. Note the counterweight block on top of the center block.



Fig. C.19. Rearrange the jig so that the sample can be taped without moving.

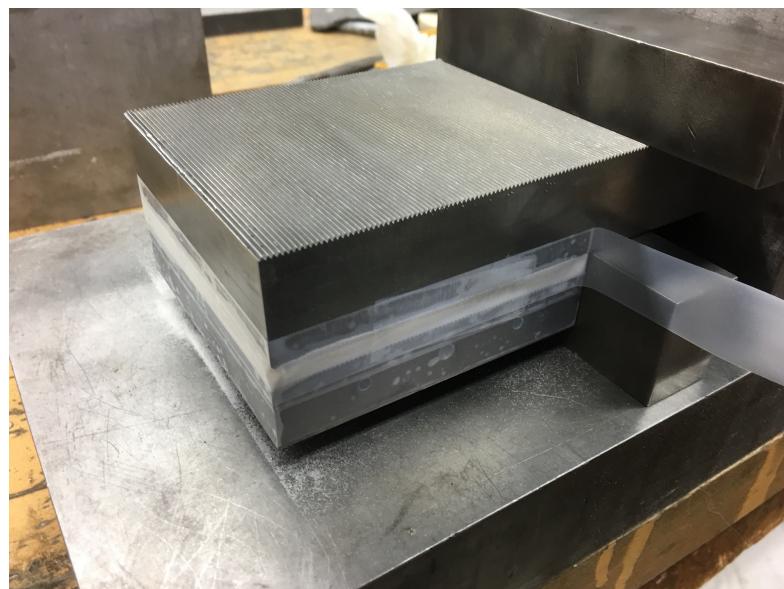


Fig. C.20. Place one strip of tape around the bottom and sides of the sample.

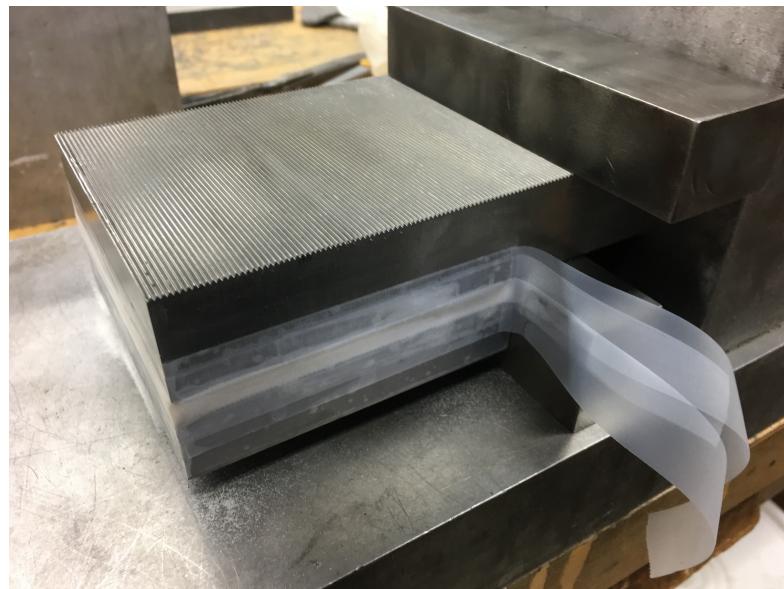


Fig. C.21. Add two more strips of tape, each offset from the others to provide the best seal of the sample material.

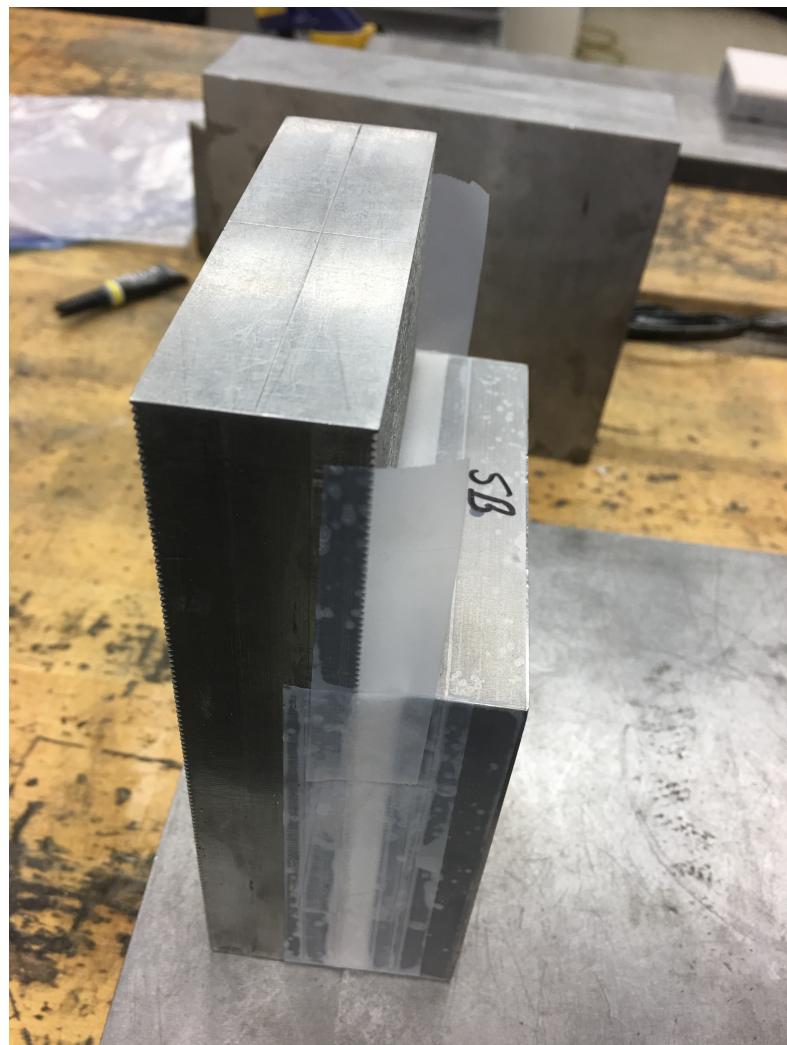


Fig. C.22. Stand the assembly up on the workbench.

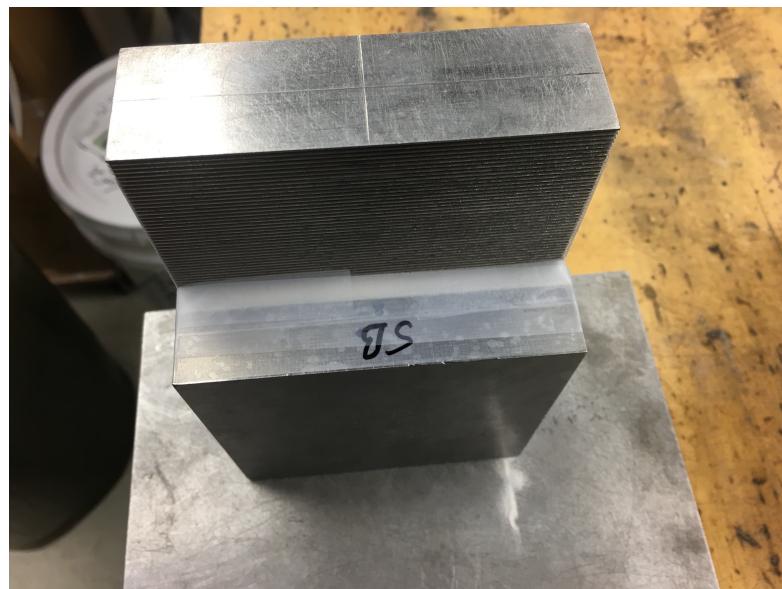


Fig. C.23. Tape the top of the assembly.

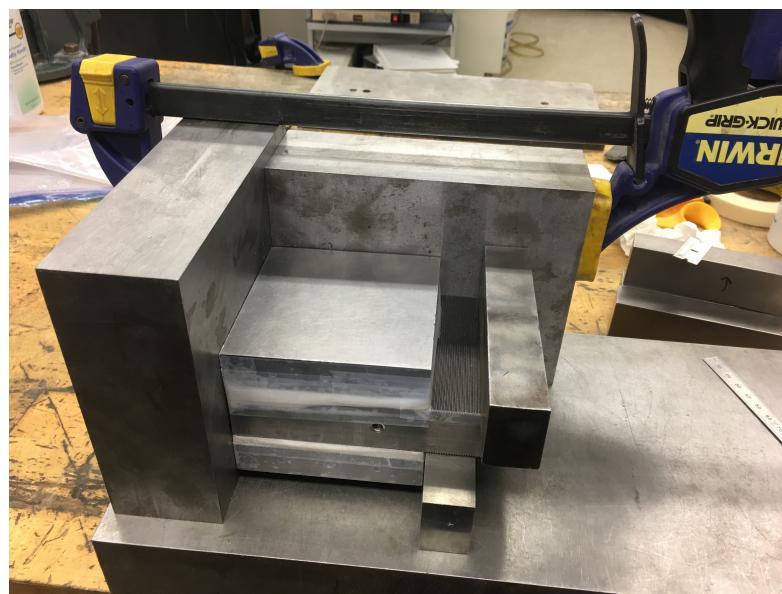


Fig. C.24. Follow the same procedure to add the second side block to the assembly.

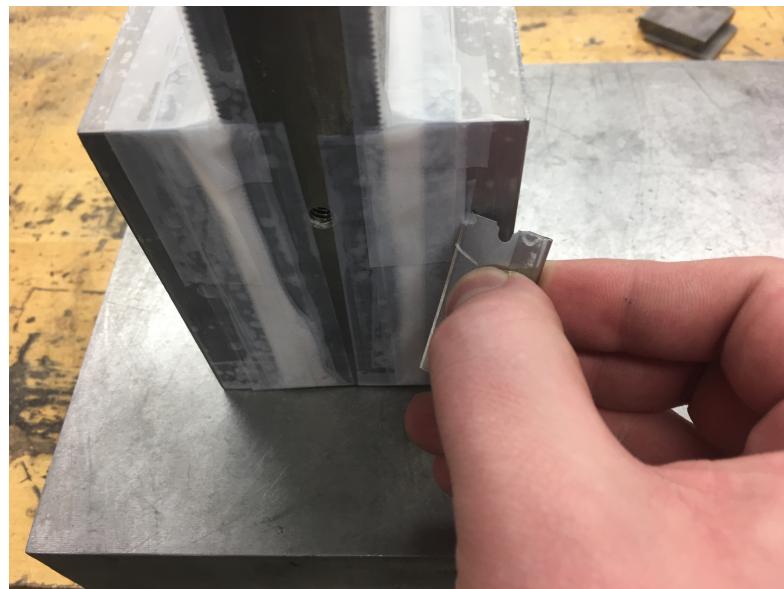


Fig. C.25. Using a razor blade, carefully trim out the holes for mounting side shields on each side block.

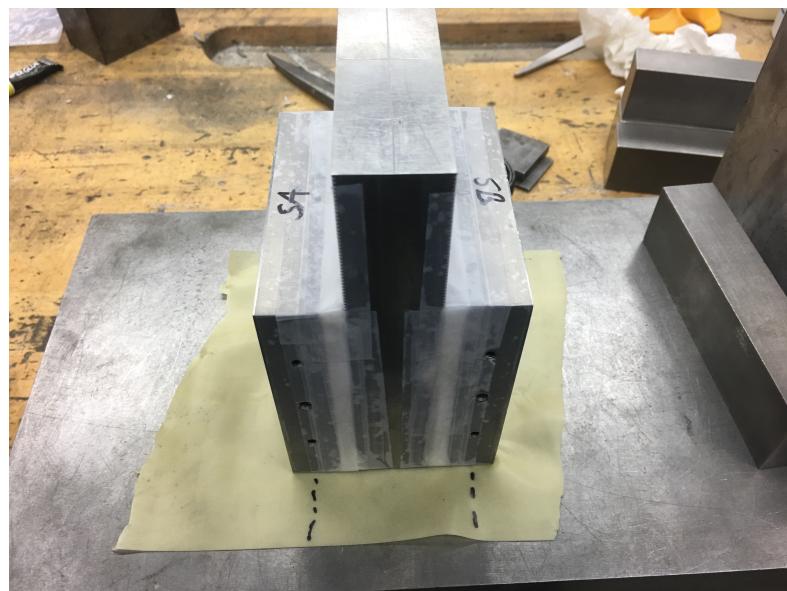


Fig. C.26. Mark the rubber skirt width and trim it to size.

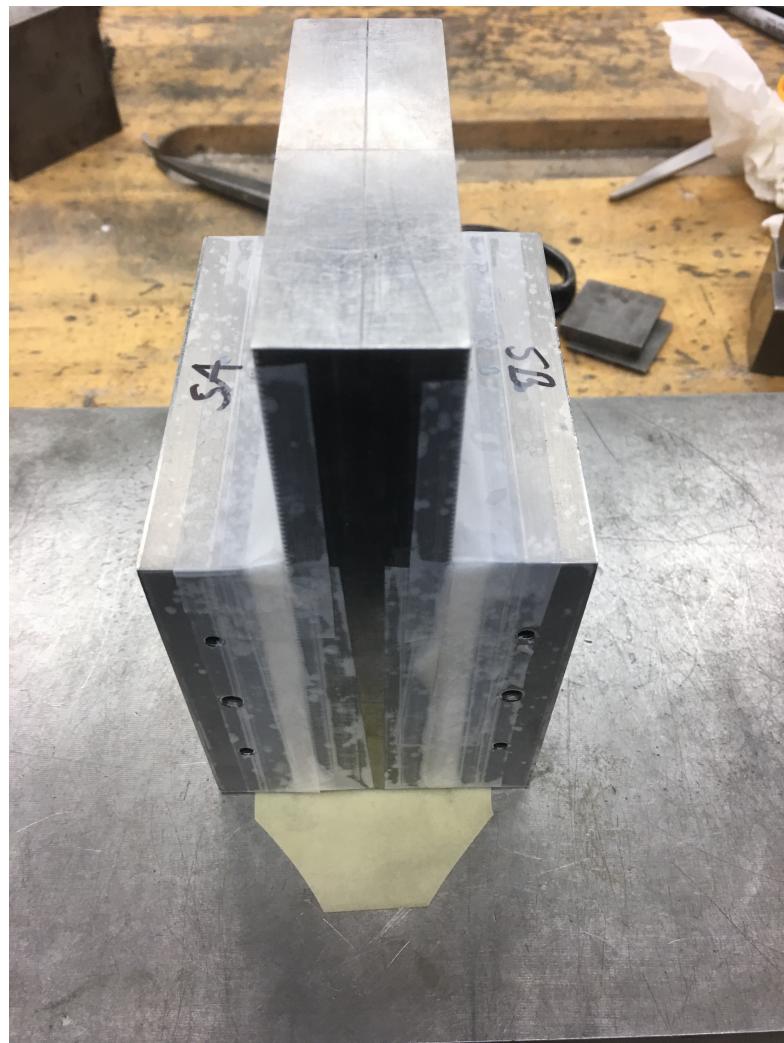


Fig. C.27. Position the trimmed rubber skirt beneath the sample and make sure that no side shield mounting points will be covered.

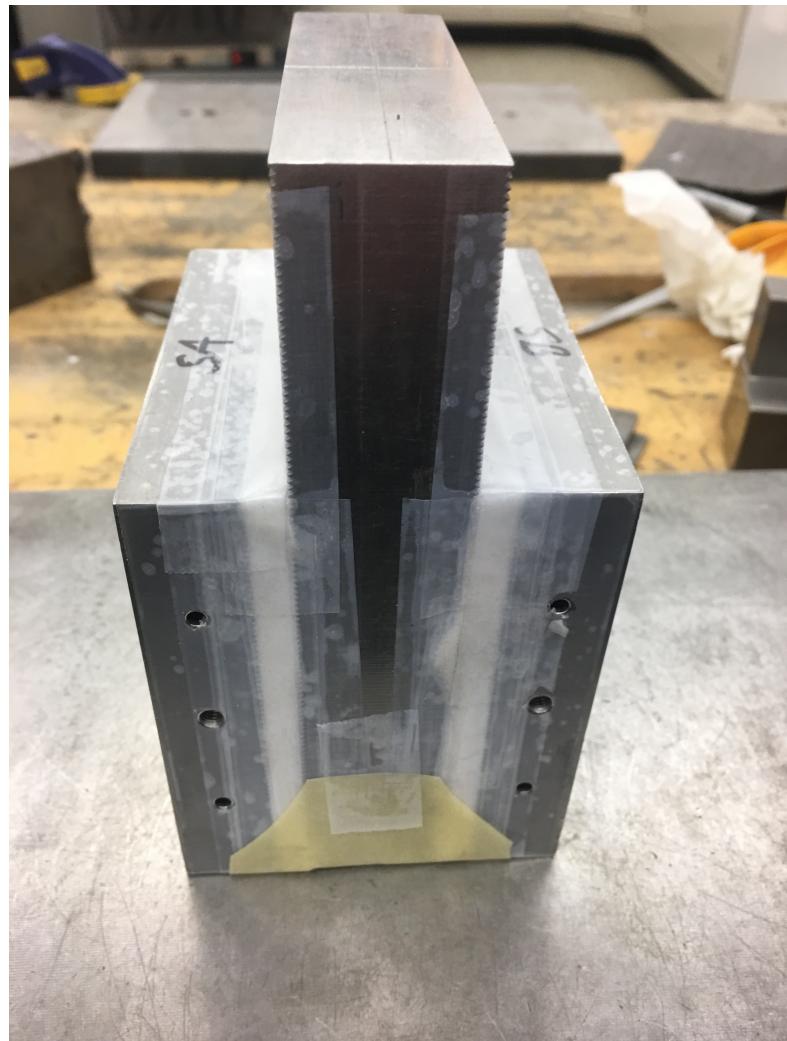


Fig. C.28. Temporarily secure the rubber skirt with tape.



Fig. C.29. Secure the side shields to the sample assembly with the proper hardware. Replace any worn or stripped hardware.



Fig. C.30. Measure the bench thickness of the assembly using calipers and note it on the experiment run sheet.



Fig. C.31. If the sample is not going to be run immediately, store it with slight pressure from two steel blocks to help prevent the layers from reshaping.

## C.2 Triaxial Shrink Jacketing

This section describes the process used to utilize shrink tube for jacketing rock and sediment samples in Temco pressure vessels. Using shrink tube jackets allows the sample to be interrogated at very low confining pressures (the normal ‘black jackets’ have a strength of  $\sim 200$  kPa). We have successfully tested this method with no leaks on multiple samples. There appears to be no side-flow even at confining pressures of just a few hundred kPa.

### C.2.1 Materials

- (2) Black jacket sections
- (1) Heat shrink tube
- (1) Tie wire
- (2) Frits
- (3) Hose clamps
- (1) Temco End caps and Piston Assembly
- (1) Lineman’s pliers
- (1) Diagonal cutters
- (1) Nutdriver for hose clamps
- (1) Large flathead screwdriver
- (1) Heat gun

- (1) Scissors

### C.2.2 Procedure

1. Prepare the sample plug as normal. The regularity of the sides of the sample is slightly more forgiving than with the traditional setup. Avoid any sharp surfaces that could puncture the jacket upon application of confining pressure. A recommended length of 1" seems to be the best setup.
2. Cut a section of heat-shrink tube approximately 3-4" long. This should cover the sample and most of the end-caps.
3. Ensure that the piston is retracted in the assembly. Gently hammer down with a soft mallet if needed. Watch out for oil being ejected during this process.
4. Place the short black jacket section over the piston and press most of the way down onto the shoulder, leaving a small gap of  $\leq \frac{1}{4}$ ".
5. Place the bottom end-cap and spacers in the Temco piston assembly and black jacket section. Ensure there is solid metal-to-metal contact between the end-cap and the spacers in the jacket.
6. Using the flathead screwdriver, move the black jacket up until it will seal on the end cap and piston assembly suitably.
7. Secure the black jacket to the piston assembly with a hose clamp. Tighten with the nut driver until snug.

8. Place the bottom porous frit, sample, and top porous frit on the assembly in that order.
9. Cover the sample assembly with the shrink tube.
10. Insert the top end-cap and align the column.
11. Ensure that the shrink tube covers the wire grooves on the end caps and does not cover the black jacket.
12. Holding the shrink tube in place, begin to heat it with the heat gun. Work the heat gun from the bottom to the top of the sample. Once the shrink tube will no longer slide down, begin the final shrinking. Work up from the bottom of the sample, keeping the heat gun in constant motion. This helps avoid any pockets forming between the sample and jacket. The tube will not make a solid mechanical connection, this is normal.
13. After the shrink tube has been fixed, cut two 12-16" lengths of tie-wire.
14. Wrap the tie-wire over the shrink tube in the tie-wire retaining groove on the bottom end-cap. Keep tension on the wire and pass it around the end-cap twice. Place a few twists to hold the wire. Be careful to not overlap the tie-wire!
15. Using a pair of pliers, grab the tie-wire at the base, pull to tighten, and rotate. Repeat this process several times to fully seal the joint. If the wire breaks, it was too tight. This part requires some practice to ensure the proper tension.
16. Repeat the wire sealing procedure on the top end cap. Be careful to not exert too much stress on the sample when doing this.

17. Trim excess tie wire to be  $\sim \frac{1}{4}$ " long.
18. Using a razor blade, trim away the excess shrink tube such that about  $\sim \frac{1}{8}$ " is present behind the tie wire seal. This metal surface area is necessary to ensure sealing of the black jacket and integrity of the shrink tube.
19. Seal the black jacket onto the bottom end-cap with a hose clamp.
20. Place the second black jacket segment onto the top end-cap.
21. Check the height of the column as compared to a normal, full length, black jacket. These should be within  $\sim \frac{1}{8}$ " of each other for proper sealing. Sample length and black jacket segment length both modify this spacing. Cut new black jacket segments to form the proper length assembly if necessary.
22. Clamp the black jacket segment onto the top end-cap with a hose clamp.
23. The sample is complete. The Temco pressure cell can be loaded as normal.



Fig. C.32. The black jacket section used to seal to the bottom piston assembly. This jacket is as high as is acceptable. It is recommended to start much lower and raise the jacket later to clamp it into place.



Fig. C.33. The sample after shrink tube is applied with a heat gun and the bottom tie wire is fixed. Notice that there are no pockets or wrinkles in the jacket and it conforms smoothly to the sample surface.



Fig. C.34. The piston end of the sample completely assembled. The shrink jacket does not go inside the black jacket, but just to the top of it. Hose clamps are used for additional insurance against leaks. Care must be taken to avoid damaging the heat shrink or black jacket with sharp edges on the clamps.

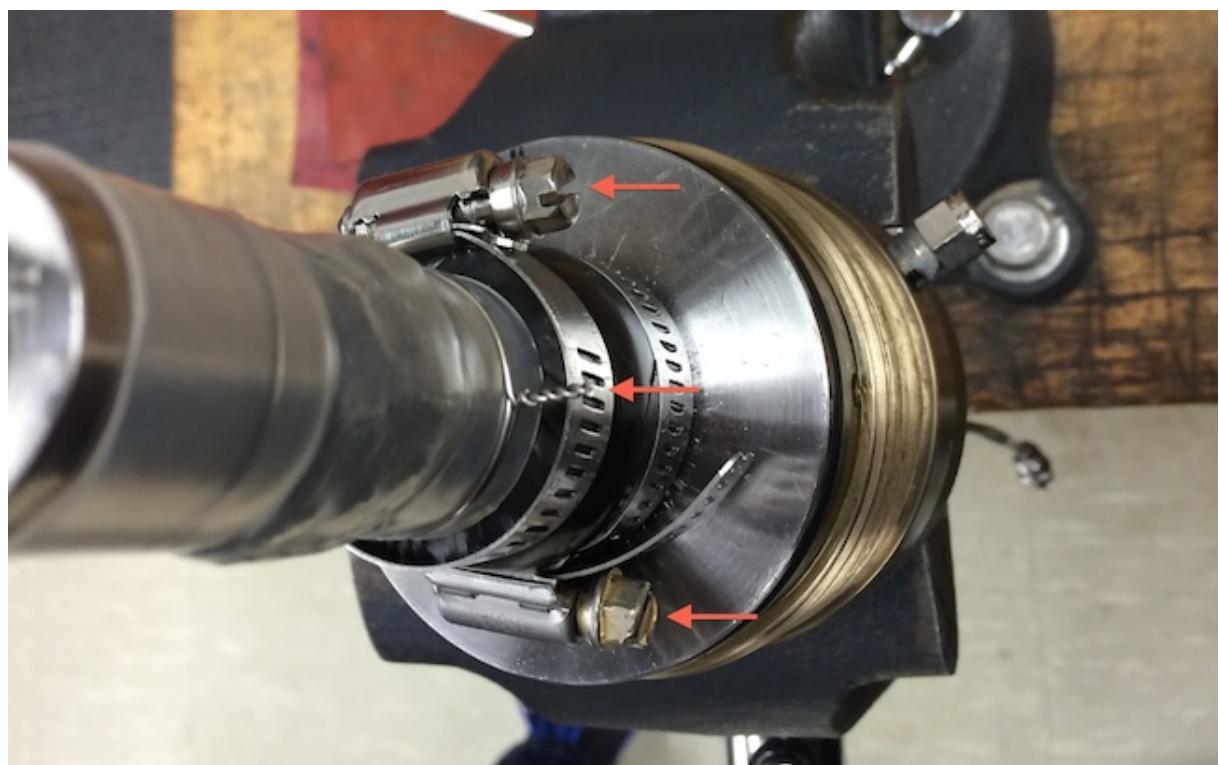


Fig. C.35. To offset weak points in the sealing system, make sure that all clamp and tie points are offset by a minimum of  $90^\circ$ .



Fig. C.36. Both tie wires have been affixed. The wire does not overlap anywhere and sits on the groove in the end caps. Ends of the wire have been trimmed to  $\sim \frac{1}{4}$ ".



Fig. C.37. The complete sample assembly, ready to be loaded into the pressure vessel and tested.

## Appendix D

### Load Cell Theoretical Response

#### D.1 Introduction

Load cells are essential tools to measuring force in any industrial or scientific system. One of the most common types of load cells is the strain gauge load cell. In this type of load cell the deformation of a test material is measured as a change in the electrical resistance of bonded strain gauge elements. The test material that the load cell is made of is ideally very rigid, otherwise significant elastic energy is stored by the load cell and it will account for a non-negligible amount of deformation in the total system. Large strains can also permanently damage the load cell by permanently deforming the load cell or strain gauges and/or breaking the bonding of the load cells to their substrate.

Here, I will summarize the load cells used in the biaxial deformation apparatus and provide a reference for calculations of the predicted load cell response and calibration procedures. Calibration and verification of that calibration against the predicted theoretical model is essential to performing accurate experiments and ensuring that the system is performing as expected and not in need of further maintenance/repair.

#### D.2 Load Cell Design

Load cells on the biaxial apparatus are generally constructed of beryllium-copper, but could be constructed of any material with the appropriate properties. We desire

a rigid material that can sustain several times the maximum designed load without permanent deformation. Temperature stability is also essential and resistive heating from the strain gauges and environmental temperature changes can introduce undesirable zero point drift in the system. Our design strives to cancel as much of these effects as possible.

### D.2.1 Material properties

Our loads cells are made of Beryllium copper (BeCu). This material was chosen for its resilience to repeated straining. It has long been a standard for load cells and is a non-ferrous, non-sparking material. The material properties are as follows in table 1.

### D.2.2 Mechanical design

Currently we employ two load cell geometries: 1) a hollow ring with an  $\sim 62$  mm outer diameter and  $\sim 54$  mm inner diameter, 2) a solid cylinder of  $\sim 44$  mm diameter (Fig.D.1). The load cells provide similar responses and are both linear with load under the applicable conditions. The area of loading is important for modeling cell response. Area of the load cell can be calculated via eq.D.1 assuming a load cell outer diameter  $r_o$  and inner diameter  $r_i$ .

$$A = \pi(r_o^2 - r_i^2) \quad (\text{D.1})$$

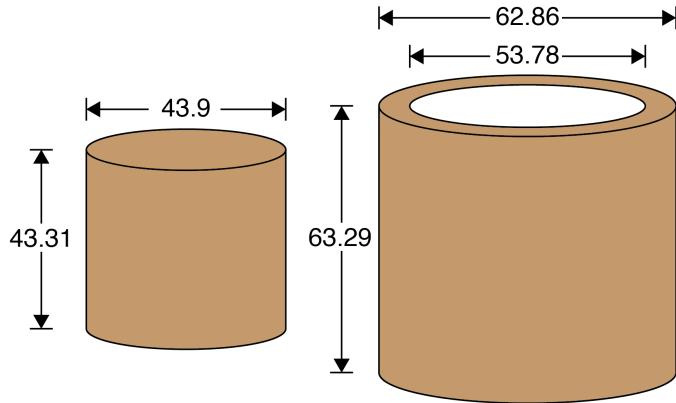


Fig. D.1. Mechanical drawings of the two styles of load cells used in the lab. Dimensions are in mm. Oblique view not to scale.

### D.2.3 Electrical design

Load cells are fitted with eight bonded foil strain gauges. This configuration provides high sensitivity and information from two orientations (axial and radial). A simple Wheatstone bridge configuration is used (Fig.D.2). Sets of gauges are placed at 90° intervals around the load cell and bonded following the manufacturer's instructions. A cartoon of the construction and electrical hook-up is often helpful when troubleshooting or constructing load cells (Fig.D.3).

The Wheatstone bridge is excited by 30 VDC provided by the strain gauge signal conditioner. The signal conditioner is a 1B31AN, manufactured by Analog Devices. A raw voltage from the load cell returns to the control system through an INA105 amplifier with switchable gain on the control panel (for the horizontal axis). The signal then passes to the 1B31AN for further gain and filtering.

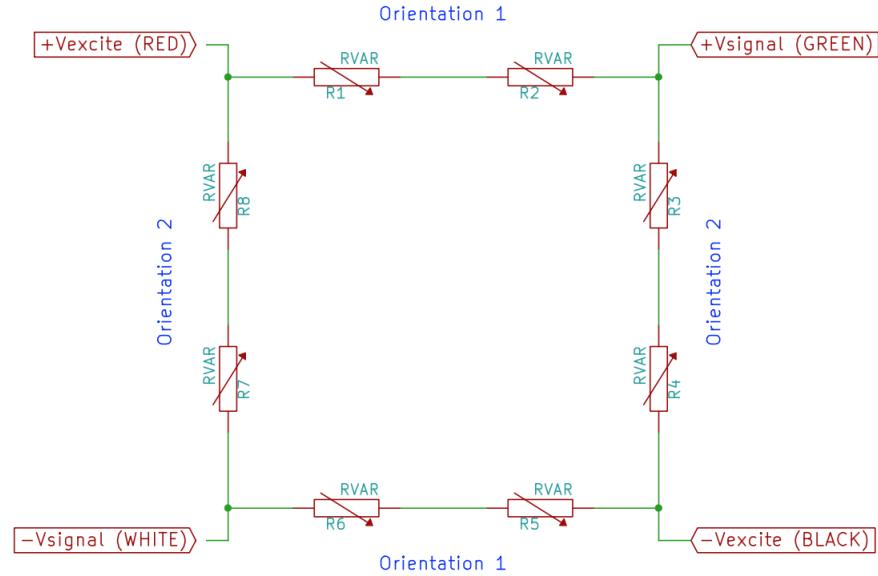


Fig. D.2. Electrical schematic of the 8-gauge load cell design. Orientation 1 and 2 are marked for identification convenience.

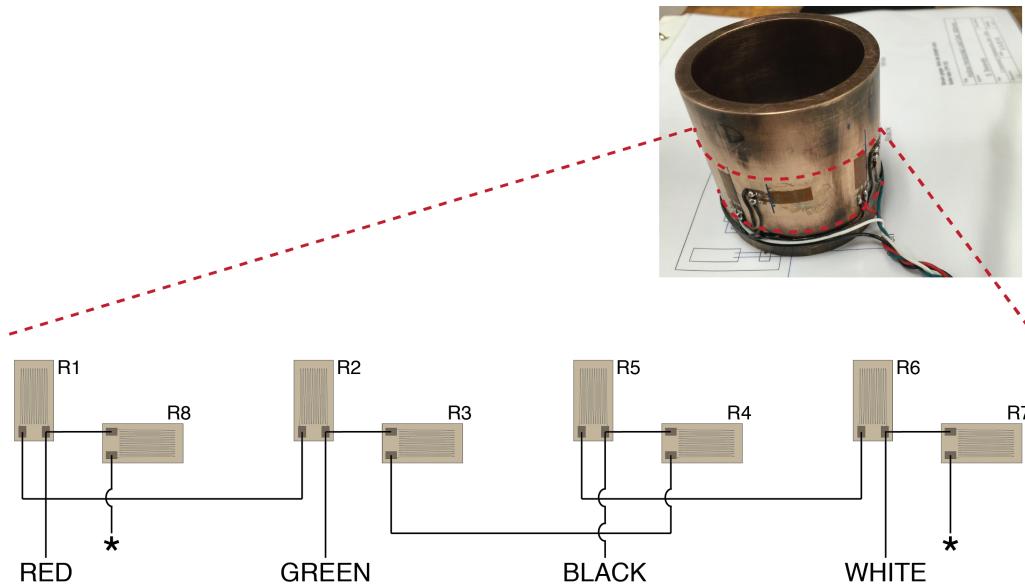


Fig. D.3. Physical construction of the load cell and arrangement of strain gauges. gauge sets are set apart by 90°. Electrical points marked \* are connected.

### D.3 Predicted response

Predicting the response of the load cell involves calculating the mechanical response to stress and then transferring that information to calculations about the response of the strain gauges and amplifier circuits. This has been accomplished in a jupyter notebook that can be easily modified and experimented with. Here I will outline the basic procedure for the calcualtions.

First we must ascertain the necessary mechanical properties of the load cell material. In this particular case, the shear modulus ( $G$ ) and Young's modulus ( $E$ ) were most easily obtained. Lame's first parameter can then be calculated using eq.D.2. With the elastic parameters in place, the response of the load cell to applied stress can be calculated. Since for the stresses applied in the lab BeCu behaves in a linear-elastic fashion, Hook's Law for elastic solids can be applied (eqs. D.3,D.4,D.5). These equations can be simplified for a case of uni-axial loading, but have been left in their full form to provide the most versatility for future application. Proof of equality is provided in the notebook. Initially intuition will say that a correction is needed for circumferential gauges, but writing out the equation for circumferential strain (eq.D.6) shows that no correction is needed since the diametric strain is equal to  $\epsilon_3, \epsilon_3$ .

$$\lambda = \frac{G(E - 2G)}{3G - E} \quad (\text{D.2})$$

$$\epsilon_1 = \sigma_1 \frac{(\lambda + G)}{G(3\lambda + 2G)} - \sigma_2 \frac{\lambda}{2G(3\lambda + 2G)} - \sigma_3 \frac{\lambda}{2G(3\lambda + 2G)} \quad (\text{D.3})$$

$$\epsilon_2 = -\sigma_1 \frac{\lambda}{2G(3\lambda + 2G)} + \sigma_2 \frac{(\lambda + G)}{G(3\lambda + 2G)} - \sigma_3 \frac{\lambda}{2G(3\lambda + 2G)} \quad (\text{D.4})$$

$$\epsilon_3 = -\sigma_1 \frac{\lambda}{2G(3\lambda + 2G)} - \sigma_2 \frac{\lambda}{2G(3\lambda + 2G)} + \sigma_3 \frac{(\lambda + G)}{G(3\lambda + 2G)} \quad (\text{D.5})$$

$$\epsilon_c = \frac{\Delta c}{c_i} = \frac{\pi(d_f - d_i)}{\pi d_i} \quad (\text{D.6})$$

Next the response of the strain gauges must be calculated. The fractional change in resistance per strain is characterized by the gauge factor ( $\xi$ ) of the particular strain gauge. This is a number typically near 2 for the strain gauges used in our applications. With slight manipulation the proportional resistance change to the no-strain resistance ( $R_g$ ) or the change in resistance is obtained through equation D.7.

$$\xi = \frac{\Delta R/R_g}{\epsilon} \quad (\text{D.7})$$

With a predicted resistance change for each gauge, it is possible to calculate the bridge balance with equation D.8.

$$V_{bridge} = V_{ex} \left( \frac{R_5 + R_6}{R_5 + R_6 + R_7 + R_8} - \frac{R_3 + R_4}{R_1 + R_2 + R_3 + R_4} \right) \quad (\text{D.8})$$

## Appendix E

# Load Cell Calibration Procedure

### E.1 Introduction

Load cells are essential tools to measuring force in any industrial or scientific system. One of the most common types of load cells is the strain gauge load cell. In this type of load cell the deformation of a test material is measured as a change in the electrical resistance of bonded strain gauge elements. The test material that the load cell is made of is ideally very rigid, otherwise significant elastic energy is stored by the load cell and it will account for a non-negligible amount of deformation in the total system. Large strains can also permanently damage the load cell by permanently deforming the load cell or strain gauges and/or breaking the bonding of the load cells to their substrate.

Here, I will summarize the load cells used in the biaxial deformation apparatus and provide a reference for calculations of the predicted load cell response and calibration procedures. Calibration and verification of that calibration against the predicted theoretical model is essential to performing accurate experiments and ensuring that the system is performing as expected and not in need of further maintenance/repair.

### E.2 Calibration procedure

Calibration of load cells is accomplished with a NIST traceable transfer calibration standard. The transfer standard is periodically sent out for recalibration or re-calibrated

if it encounters a physical shock such as dropping or hitting. The transfer standard and load cell are loaded in a series configuration and the readings of both recorded. From this a calibration curve can be constructed. The calibration procedure is as follows:

1. Connect the load cell to the appropriate electronics on the biax (i.e. vertical or horizontal axis). Allow a minimum of 30 minutes warm-up to ensure that the cell will not drift due to resistive heating from the strain gauges. The mechanical installation of the cell and preparation for calibration can take place during warm-up.
2. Plug the 4.5 digit multimeter into the appropriate load cell plugs on the biax front panel.
3. Adjust the zero point of the load cell on the biax control panel. A no-load voltage of around -4.5 VDC is best.
4. Attach the appropriate ram nose adapter on the vertical hydraulic ram and insert the load cell, gently tightening the set screws. Be sure the cell is inserted all the way into the adapter. Attach a DCDT to the adapter and connect it.
5. Place the proving ring beneath the load cell, centered in both axes. Centering is crucial to ensure no damage to the load cell or the proving ring. Be careful, the proving ring is heavy.
6. Place a steel loading puck between the proving ring and the load cell. Verify that the setup is aligned and that all parts are in-place (Fig.E.1).



Fig. E.1. A proper setup of the load cell, steel puck, proving ring stack. Notice the careful alignment of all members.

7. With the vertical servo control system set to displacement feedback, zero and unlock the machine. Be sure you are at the beginning of the displacement range for the DCDT.
8. Bring the piston down until it is almost touching the proving ring. Check and make sure that a DCDT offset isn't needed. Running out of DCDT range during calibration will result in severe damage to the proving ring.
9. Check the proving ring dial gauge readout. If needed, adjust it to read zero klf (Fig.E.2).
10. Begin recording on the LabView recorder. This data isn't used unless something goes wrong, in that case it provides a "black box" style recording of what occurred.
11. Set the controller to run the piston downward at 5 um/s. This setting will depend on which DCDT you have installed.

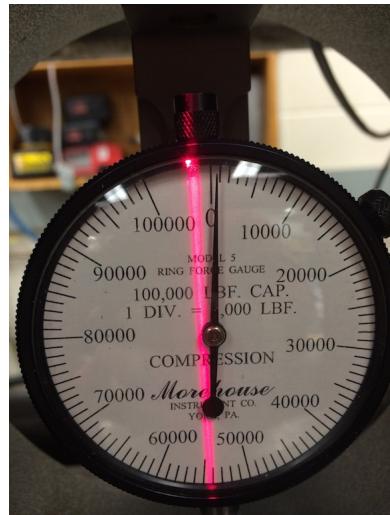


Fig. E.2. An example of a proving ring dial under no load that needs adjustment. Simply loosen the dial face set-screw to move the gauge legend.

12. Take a reading at zero load from the panel meter. Record this value.
13. Apply a load to the cell and record the voltage reading. Generally we calibrate low gain biax load cells from 0-65 klbf and high gain from 0-15 klbf. Low stresses should be sampled more often. A common sequence is 0,2.5,5,7.5,10,15,20,25,30,35,...,65 klbf).
14. Repeat step 12 for all loads listed in the loading table. Be sure to not go out of range on the DCDT or load cell.
15. Repeat the measurements for all loads during the unloading process as well. This characterizes any drift or repeatability issues.
16. Convert the loads from klbf to kN.  $1 \text{ kN} = 4.44822162 \text{ klbf}$

17. Plot the voltage (in mV) and load (in kN). Fit a line. There should not be any appreciable non-linear or hysteresis behavior. If there is, consider recalibrating or troubleshooting the load cell.
18. Update load cell calibration numbers in the calibration file, logsheets, and your notes.

### E.3 Typical measured response

As an example of a typical load cell response, a calibration of the 44mm solid load cell shows a very linear trend with no hysteresis (Fig.E.3).

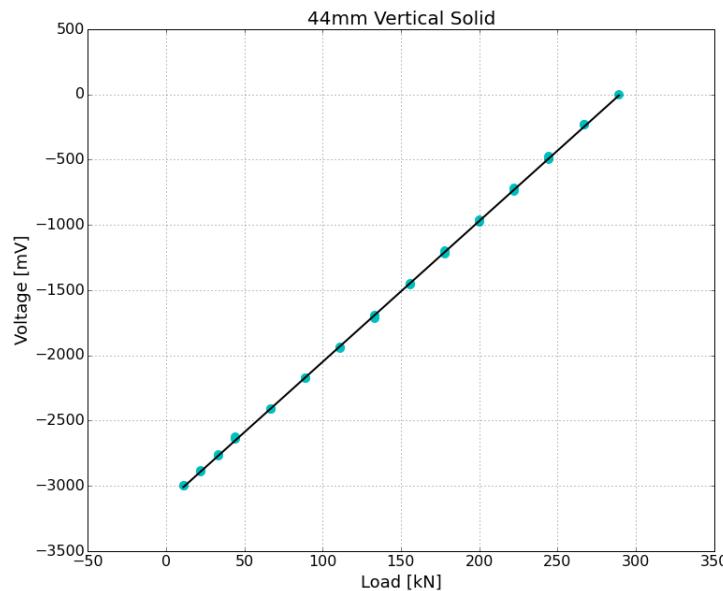


Fig. E.3. An example calibration obtained from the 44mm solid load cell.

## Appendix F

### DCDT Calibration Procedure

#### F.1 Introduction

Direct Current Displacement Transducers or Direct Current Differential Transformers (DCDTs) are devices used to very precisely measure rectilinear motion. In the transducer there are a primary and two secondary coils wound around a tube through which the core of the transducer travels. The primary coil is driven with a high frequency alternating current waveform. The alternating magnetic field created is coupled into the two counter wound secondary coils via a magnetically permeable core. The position of the core determines how much coupling there is between the primary and each of the secondary coils. Therefore the output of the secondary coils is a linear function of displacement. Which side of center the core is on is encoded by the phase of the output with respect to the input. We use DCDTs which are excited by a direct current input and provide a direct current output. The creation of the driving waveform and conditioning of the signal output is all done on board the transducer.

In this appendix I will briefly show the calibration procedures used to calibrate our DCDTs in the laboratory. Calibrations should be performed semi-annually. If a transducer's response has changed significantly, it could be time to replace the transducer. Other problems such as response hysteresis and noise should be noted as well.

## F.2 Calibration procedure

Calibration of displacement transducers is accomplished with a NIST traceable transfer calibration standard. Using the electronics that will be used during the experiment, the transducer is placed a number of displacements using a vernier height gage. The response is recorded and a calibration curve constructed. The calibration procedure is as follows:

1. Connect the DCDT to the appropriate electronics on the biax (i.e. vertical or horizontal axis). Allow a minimum of 10-15 minutes warm-up to ensure that the transducer will not drift. You will notice that the transducers and cores get very warm. It is best to have the transducer near its null position during warm-up.
2. Mount the transducer to a ring-stand using a universal clamp and adjust it to be perpendicular to the table.
3. Using a 4-40 all thread segment, mount the core of the transducer to the vernier height gage.
4. Set the height gage to an even millimeter increment.
5. Make sure the transducer zero settings are close to their minimum values and that no DC offsets are being applied.
6. Plug the 4.5 digit multimeter into the appropriate banana plugs on the biax front panel.
7. Slide the transducer over the core and find the bottom of the output range. Lock it in place on the ring stand.

8. Take a reading at this zero displacement condition from the panel meter. Record this value.
9. Move the transducer in 1 mm or 0.5 mm steps, depending on its range. A minimum of 10 displacement values should be measured over the range of the transducer. At each step record the output voltage of the system.
10. Plot the voltage (in mV) and displacement (in mm). Fit a line. There should not be any appreciable non-linear or hysteresis behavior. If there is, consider recalibrating or troubleshooting the transducer.
11. Update DCDT calibration numbers in the calibration file, logsheets, and your notes.

### F.3 Typical measured response

As an example of a typical load cell response, a calibration of a TransTek DCDT shows a very linear trend with no hysteresis (Fig.F.1).

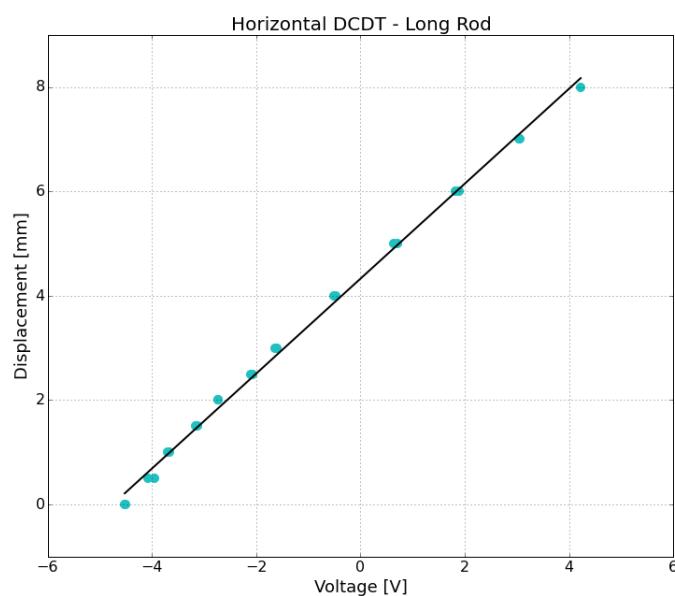


Fig. F.1. An example calibration obtained from a DCDT.

## Appendix G

# Look File Format Description and Biaxtools

### G.1 Purpose

This script was designed to read data into an easy to use format from xlook output in ASCII or binary form. Data is read, the header parsed for column names, lengths, etc., and a rec array or Pandas dataframe object returned that is easy to access and call from within a script. Column names are used to call the data columns, so as long as consistent naming is used the column order in the file is irrelevant.

### G.2 Description

#### G.2.1 ASCII Files

The function `read_ascii` first opens the text file with a standard open command. We know that each column in the data is written as 12 characters wide. The first line of the header is the number of records, the second is the column number, the third the column headings, the fourth the column units, and the fifth the number of records in each column. This information if parsed and stored. Numerical data is read into an array. A rec array is created with the numpy package and the labels of the column names that were parsed or the data is converted into a dataframe object.

### G.2.2 Binary Files

The function `read_binary` opens the binary file in 'read binary' mode. The initial file information is stored as follows (in big-endian format):

Information	Format	Bytes
Name	20 characters	20
Number of Columns	int	4
Sweep	int	4
Date/Time	int	4

For each possible column there are 84 bytes of information. There are 32 possible columns. We read the information for each column and store information for columns that have data. Blank columns are identified by the first 6 characters of the name 'no\_val'.

Information	Format	Bytes
Name	13 characters	13
Units	13 characters	13
Gain	int	4
Comment	50 characters	50
Number of Elements	int	4

Data is stored as the default machine format, which for modern Intel based computers in little-endian. This is the default for the module, but big-endian can be specified. Each column is written out as a sequence of doubles that are  $n_{elem}$  long. Doubles are read and stored in a numpy array. The array is then combined with datatype information collected from the headers and stored as a rec array.

```
To find the default machine binary format run: python -c "import struct;
print 'little' if ord(struct.pack('L', 1)[0]) else 'big'"
```

### G.3 Cautions

A few cautions should be observed when using the biaxread script:

1. The empty array is shaped by row number information from the header. If a datafile is cut, but the header is left unmodified there will be many extra zero data pairs at the end of the array.

## G.4 Usage

### G.4.1 Return Formats

By default data will be returned as a Numpy record array (recarray). Data can also be returned as a Pandas dataframe object that is indexed on the row number of the data. To do this, set `pandas=True` in the function call to either `read_ascii` or `read_binary`.

### G.4.2 ASCII Files

First process the experimental data in xlook and output a text file with headers. To do this input `type 0 -1 1 12 pxxxx_data.txt` at the xlook command line or add it to the data reduction file. Be sure to correct any column or row number specifications here. Start IPython or open your own Python script. Import `llookdata` from `biaxtools`

and pass the function `read_ascii` the name of the text output file from `xlook`. The array is now returned and ready to use.

#### G.4.3 Binary Files

Process the experimental data in `xlook` and output a binary file. This is done with the ‘write’ command with the syntax `write filename`. In IPython or your Python script import `lookdata` from `biaxtools` and pass the function `read_binary` the name of the binary file. The array is returned and ready to use.

Files that were written in a big-endian format by setting `dataendianess` to ‘big’. The function call would look like `read_binary(filename,dataendianess='big')`.

### G.5 Acknowledgements

Thank you to Marco Scuderi for using the code and being patient as little issues were worked out. Please send any bug reports to `kd5wxb@gmail.com` or as an issue in the `github` repository.

## G.6 Code

```

1 import numpy as np
2 import struct
3 import pandas as pd
4
5 def read_ascii(filename, pandas=False):
6     """
7         Takes a filename containing the text output (with headers) from xllook
8         and
9         reads the columns into a rec array or dataframe object for easy data
10        processing and access.
11    """
12    try:
13        f = open(filename, 'r')
14    except:
15        print "Error Opening %s" %filename
16        return 0
17
18    col_width = 12 # Columns are 12 char wide in header
19
20    # First line of the file is the number of records
21    num_recs = f.readline()
22    num_recs = int(num_recs.strip('number of records = '))
23    print "\nNumber of records: %d" %num_recs
24
25    # Second line is column numbers, we don't care so just count them
26    num_cols = f.readline()
27    num_cols = num_cols.split('col')
28    num_cols = len(num_cols)
29    print "Number of columns: %d" %num_cols
30
31    # Third line is the column headings

```

```

32     col_headings_str = f.readline()
33     col_headings_str = col_headings_str[5:-1]
34     col_headings = [ 'row_num' ] # Row number the the first (unlabeled)
35     column
36
37     for i in range(len(col_headings_str)/12):
38         heading = col_headings_str[12*i:12*i+12].strip()
39         col_headings.append(heading)
40
41     # Fourth line is column units
42     col_units_str = f.readline()
43     col_units_str = col_units_str[5:-1]
44     col_units=['.']
45
46     for i in xrange(len(col_units_str)/12):
47         heading = col_units_str[12*i:12*i+12].strip()
48         col_units.append(heading)
49     col_units = [x for x in col_units if x != '\n'] #Remove newlines
50
51     # Fifth line is number of records per column
52     col_recs = f.readline()
53     col_recs = col_recs.split('recs')
54     col_recs = [int(x) for x in col_recs if x != '\n']
55     col_recs.insert(0, num_recs)
56
57     # Show column units and headings
58     print "\n\n-----"
59     print "|%15s|%15s|%15s| " %( 'Name' , 'Unit' , 'Records' )
60     print "-----"
61
62     for column in zip(col_headings, col_units, col_recs):
63         print "|%15s|%15s|%15s| " %(column[0], column[1], column[2])
64     print "-----"
65
66     # Read the data into a numpy recarray
67     dtype=[]
68     #dtype.append(( 'row_num' , 'float' ))

```

```

65     for name in col_headings:
66         dtype.append((name, 'float'))
67     dtype = np.dtype(dtype)
68
69     data = np.zeros([num_recs, num_cols])
70
71     i=0
72     for row in f:
73         row_data = row.split()
74         for j in xrange(num_cols):
75             data[i,j] = row_data[j]
76         i+=1
77
78     f.close()
79
80     if pandas==True:
81         # If a pandas object is requested, make a data frame
82         # indexed on row number and return it
83         dfo = pd.DataFrame(data, columns=col_headings)
84         dfo = dfo.set_index('row_num')
85         return dfo
86
87     else:
88         # Otherwise return the default (Numpy Recarray)
89         data_rec = np.rec.array(data, dtype=dtype)
90         return data_rec
91
92 def read_binary(filename, dataendianess='little', pandas=False):
93     """
94     Takes a filename containing the binary output from xlook and
95     reads the columns into a rec array or dataframe object for easy
96     data processing and access.
97

```

```

98      The data section of the file is written in the native format of the
99      machine
100     used to produce the file. Endianness of data is little by default, but
101     may
102     be changed to 'big' to accomodate older files or files written on power
103     pc
104     chips.
105     """
106
107     try:
108         f = open(filename, 'rb')
109     except:
110         print "Error Opening %s" %filename
111         return 0
112
113     col_headings = []
114     # Unpack information at the top of the file about the experiment
115     name = struct.unpack('20c', f.read(20))
116     name = ''.join(str(i) for i in name)
117     name = name.split("\0") [0]
118     print "\nName: ", name
119
120     # The rest of the header information is written in big endian format
121
122     # Number of records (int)
123     num_recs = struct.unpack('>i', f.read(4))
124     num_recs = int(num_recs[0])
125     print "Number of records: %d" %num_recs
126
127     # Number of columns (int)
128     num_cols = struct.unpack('>i', f.read(4))

```

```

129     num_cols = int( num_cols[0] )
130     print "Number of columns: %d" %num_cols
131
132     # Sweep (int) - No longer used
133     swp = struct.unpack( '>i' , f.read(4) )[0]
134     print "Swp: " ,swp
135
136     # Date/time(int) - No longer used
137     dtime = struct.unpack( '>i' , f.read(4) )[0]
138     print "dtime: " ,dtime
139
140     # For each possible column (32 maximum columns) unpack its header
141     # information and store it. Only store column headers of columns
142     # that contain data. Use termination at first NUL.
143     for i in range(32):
144
145         # Channel name (13 characters)
146         chname = struct.unpack( '13c' , f.read(13) )
147         chname = ''.join(str(i) for i in chname)
148         chname = chname.split("\0") [0]
149
150         # Channel units (13 characters)
151         chunits = struct.unpack( '13c' , f.read(13) )
152         chunits = ''.join(str(i) for i in chunits)
153         chunits = chunits.split("\0") [0]
154
155         # This field is now unused, so we just read past it (int)
156         gain = struct.unpack( '>i' , f.read(4) )
157
158         # This field is now unused, so we just read past it (50 characters)
159         comment = struct.unpack( '50c' , f.read(50) )
160
161         # Number of elements (int)
162         nelem = struct.unpack( '>i' , f.read(4) )

```

```

163     nelem = int(nelem[0])
164
165     if chname[0:6] == 'no_val':
166         continue # Skip Blank Channels
167     else:
168         col_headings.append(chname)
169         col_recs.append(nelem)
170         col_units.append(chunits)
171
172
173     # Show column units and headings
174     print "\n\n-----"
175     print "|%15s|%15s|%15s| " %( 'Name' , 'Unit' , 'Records' )
176     print "-----"
177     for column in zip(col_headings, col_units, col_recs):
178         print "|%15s|%15s|%15s| " %(column[0], column[1], column[2])
179     print "-----"
180
181     # Read the data into a numpy recarray
182     dtype = []
183     for name in col_headings:
184         dtype.append((name, 'double'))
185     dtype = np.dtype(dtype)
186
187     data = np.zeros([num_recs, num_cols])
188
189     for col in range(num_cols):
190         for row in range(col_recs[col]):
191             if dataendianess == 'little':
192                 data[row, col] = struct.unpack('<d', f.read(8))[0]
193             elif dataendianess == 'big':
194                 data[row, col] = struct.unpack('>d', f.read(8))[0]
195             else:
196                 print "Data endian setting invalid, please check and retry"

```

```
197             return 0
198
199     data_rec = np.rec.array(data, dtype=dtype)
200
201     f.close()
202
203     if pandas==True:
204         # If a pandas object is requested, make a data frame
205         # indexed on row number and return it
206         dfo = pd.DataFrame(data, columns=col_headings)
207         # Binary didn't give us a row number, so we just let
208         # pandas do that and name the index column
209         dfo.index.name = 'row_num'
210
211         return dfo
212
213     else:
214         # Otherwise return the default (Numpy Recarray)
215         data_rec = np.rec.array(data, dtype=dtype)
216
217         return data_rec
```

## Bibliography

- Aharonov, E. and Sparks, D. (1999). Rigidity phase transition in granular packings. *Physical Review E*, 60(6):6890.
- Albert, I., Sample, J., Morss, A., Rajagopalan, S., Barabási, A.-L., and Schiffer, P. (2001). Granular drag on a discrete object: Shape effects on jamming. *Physical Review E*, 64(6):061303.
- Alley, R. B. (1993). In search of ice-stream sticky spots. *Journal of Glaciology*, 39(133):447–454.
- Alley, R. B., Anandakrishnan, S., Dupont, T. K., and Parizek, B. R. (2004). Ice streams—fast, and faster? *Comptes Rendus Physique*, 5(7):723–734.
- Anandakrishnan, S. and Alley, R. (1997). Tidal forcing of basal seismicity of ice stream c, west antarctica, observed far inland. *Journal of Geophysical Research: Solid Earth*, 102(B7):15183–15196.
- Anandakrishnan, S. and Bentley, C. (1993). Micro-earthquakes beneath ice streams b and c, west antarctica: observations and implications. *Journal of Glaciology*, 39(133):455–462.
- Anandakrishnan, S., Blankenship, D., Alley, R., and Stoffa, P. (1998). Influence of sub-glacial geology on the position of a west antarctic ice stream from seismic observations. *Nature*, 394(6688):62–65.

- Anandakrishnan, S., Voigt, D., Alley, R., and King, M. (2003). Ice stream d flow speed is strongly modulated by the tide beneath the ross ice shelf. *Geophysical Research Letters*, 30(7).
- Anthony, J. L. and Marone, C. (2005). Influence of particle characteristics on granular friction. *Journal of Geophysical Research*, 110(B8):B08409.
- ASTM, D. (2005). Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass. *West Conshohocken: American Society for Testing & Materials*, 2216.
- Balk, M., Bose, M., Ertem, G., Rogoff, D. A., Rothschild, L. J., and Freund, F. T. (2009). Oxidation of water to hydrogen peroxide at the rock–water interface due to stress-activated electric currents in rocks. *Earth and Planetary Science Letters*, 283(1):87–92.
- Baumberger, T. and Berthoud, P. (1999). Physical analysis of the state- and rate-dependent friction law. II. Dynamic friction. *Phys. Rev. B*, 60(6):3928–3939.
- Baumberger, T., Heslot, F., and Perrin, B. (1994). Crossover from creep to inertial motion in friction dynamics. *Nature*, 367:544–546.
- Bayart, E., Rubin, A., and Marone, C. (2006). Evolution of fault friction following large velocity jumps. In *AGU Fall Meeting Abstracts*, volume 1, page 0180.
- Beeler, N., Tullis, T., and Weeks, J. (1994). The roles of time and displacement in the evolution effect in rock friction. *Geophysical Research Letters*, 21(18):1987–1990.

- Beeler, N. M., Hickman, S. H., and Wong, T.-f. (2001). Earthquake stress drop and laboratory inferred interseismic strength recovery. *Journal of Geophysical Research: Solid Earth*, 106(B12):30701–30713.
- Bell, R., Blankenship, D., Finn, C., Morse, D., Scambos, T., Brozena, J., and Hodge, S. (1998). Influence of subglacial geology on the onset of a west antarctic ice stream from aerogeophysical observations. *Nature*, 394(6688):58–62.
- Ben-David, O., Rubinstein, S. M., and Fineberg, J. (2010). Slip-stick and the evolution of frictional strength. *Nature*, 463(7277):76–79.
- Bentley, C. R. (1987). Antarctic ice streams: a review. *Journal of Geophysical Research: Solid Earth*, 92(B9):8843–8858.
- Beroza, G. C. and Ide, S. (2011). Slow Earthquakes and Nonvolcanic Tremor. *Annual Review of Earth and Planetary Sciences*, 39(1):271–296.
- Bianchi, R., Capaccioni, F., Cerroni, P., Coradini, M., Flamini, E., Hurren, P., Martelli, G., and Smith, P. N. (1984). Radiofrequency emissions observed during macroscopic hypervelocity impact experiments. *Nature*, 308(5962):830–832.
- Bilek, S. L. and Lay, T. (1999). Rigidity variations with depth along interplate megathrust faults in subduction zones. *Nature*, 400(6743):443–446.
- Bindschadler, R. A., King, M. A., Alley, R. B., Anandakrishnan, S., and Padman, L. (2003). Tidally controlled stick-slip discharge of a west antarctic ice. *Science*, 301(5636):1087–1089.

- Blankenship, D. D., Bentley, C., Rooney, S., and Alley, R. B. (1987). Till beneath ice stream b: 1. properties derived from seismic travel times. *Journal of Geophysical Research: Solid Earth*, 92(B9):8903–8911.
- Blankenship, D. D., Bentley, C. R., Rooney, S., and Alley, R. B. (1986). Seismic measurements reveal a saturated porous layer beneath an active antarctic ice stream. *Nature*, 322:54–57.
- Blanpied, M. L., Tullis, T. E., and Weeks, J. D. (1987). Frictional Behavior of Granite at Low and High Sliding Velocities. *Geophysical Research Letters*, 14(5):554–557.
- Boettcher, M. S. (1999). Numerical simulations of granular shear zones using the distinct element method 1. Shear zone kinematics and the micromechanics of localization. *Journal of Geophysical Research*, 104(B2):2703–2719.
- Boulton, G. and Hindmarsh, R. (1987). Sediment deformation beneath glaciers: rheology and geological consequences. *Journal of Geophysical Research: Solid Earth*, 92(B9):9059–9082.
- Brace, W. F. and Byerlee, J. D. (1966). Stick-Slip as a Mechanism for Earthquakes. *Science*, 153(3739):990–992.
- Brace, W. F. and Byerlee, J. D. (1969). Mechanical instabilities observed in laboratory experiments on rocks. *Eos Trans. AGU*, 50(5):400.
- Brodsky, E. E. and Mori, J. (2007). Creep events slip less than ordinary earthquakes. *Geophysical Research Letters*, 34(16).

- Buishand, T. A. (1982). Some methods for testing the homogeneity of rainfall records. *Journal of Hydrology*, 58(1):11–27.
- Camara, C. G., Escobar, J. V., Hird, J. R., and Putterman, S. J. (2008). Correlation between nanosecond X-ray flashes and stick-slip friction in peeling tape. *Nature*, 455(7216):1089–1092.
- Carpenter, B., Kitajima, H., Sutherland, R., Townend, J., Toy, V., and Saffer, D. (2014). Hydraulic and acoustic properties of the active alpine fault, new zealand: Laboratory measurements on dfdp-1 drill core. *Earth and Planetary Science Letters*, 390:45–51.
- Cates, M., Wittmer, J., Bouchaud, J.-P., and Claudin, P. (1998). Jamming, force chains, and fragile matter. *Physical review letters*, 81(9):1841.
- Christianson, K., Parizek, B. R., Alley, R. B., Horgan, H. J., Jacobel, R. W., Anandakrishnan, S., Keisling, B. A., Craig, B. D., and Muto, A. (2013). Ice sheet grounding zone stabilization due to till compaction. *Geophysical Research Letters*, 40(20):5406–5411.
- Clarke, G. K. (1987). Subglacial till: a physical framework for its properties and processes. *Journal of Geophysical Research: Solid Earth*, 92(B9):9023–9036.
- Cowan, E. A., Christoffersen, P., Powell, R. D., and Talarico, F. M. (2014). Dynamics of the late plio–pleistocene west antarctic ice sheet documented in subglacial diamictites, and-1b drill core. *Global and Planetary Change*, 119:56–70.
- Cress, G. O., Brady, B. T., and Rowell, G. A. (1987). Sources of electromagnetic radiation from fracture of rock samples in the laboratory. *Geophysical Research Letters*, 14(4):331–334.

- Cuffey, K. M. and Paterson, W. S. B. (2010). *The physics of glaciers*. Academic Press.
- Den Hartog, S., Niemeijer, A., and Spiers, C. (2012). New constraints on megathrust slip stability under subduction zone p–t conditions. *Earth and Planetary Science Letters*, 353:240–252.
- Den Hartog, S. and Spiers, C. (2013). Influence of subduction zone conditions and gouge composition on frictional slip stability of megathrust faults. *Tectonophysics*, 600:75–90.
- Derr, J. S. (1973). Earthquake lights: a review of observations and present theories. *Bulletin of the Seismological Society of America*, 63(6):2177–2187.
- Dickinson, J. T. (1982). Fracto-emission accompanying adhesive failure. *Journal of Vacuum Science and Technology*, 20(3):436.
- Dickinson, J. T. (1984). Fracto-emission: The role of charge separation. *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films*, 2(2):1112.
- Dickinson, J. T., Jenson, L. C., and Park, M. K. (1982). Time-of-flight measurements of the mass-to-charge ratio of positive ion emission accompanying fracture. *Journal of Materials Science*, 17(11):3173–3178.
- Dieterich, J. H. (1972). Time-dependent friction in rocks. *Journal of Geophysical Research*, 77(20):3690–3697.
- Dieterich, J. H. (1978). Time-dependent friction and the mechanics of stick-slip. *Pure and applied geophysics*, 116(4-5):790–806.

- Dowdeswell, J., Ottesen, D., Evans, J., Cofaigh, C. Ó., and Anderson, J. (2008). Submarine glacial landforms and rates of ice-stream collapse. *Geology*, 36(10):819–822.
- Dvorkin, J., Prasad, M., Sakai, A., and Lavoie, D. (1999). Elasticity of marine sediments: Rock physics modeling. *Geophysical research letters*, 26(12):1781–1784.
- Engelhardt, H., Humphrey, N., Kamb, B., and Fahnestock, M. (1990). Physical conditions at the base of a fast moving antarctic ice stream. *Science*, 248(4951):57–59.
- Engelhardt, H. and Kamb, B. (1997). Basal hydraulic system of a west antarctic ice stream: constraints from borehole observations. *Journal of Glaciology*, 43(144):207–230.
- Enomoto, Y. and Zheng, Z. (1998). Possible evidences of earthquake lightning accompanying the 1995 Kobe earthquake inferred from the Nojima fault gouge. *Geophysical Research Letters*, 25(14):2721–2724.
- Ferré, E. C., Zechmeister, M. S., Geissman, J. W., Mathana Sekaran, N., and Kocak, K. (2005). The origin of high magnetic remanence in fault pseudotachylites: Theoretical considerations and implication for coseismic electrical currents. *Tectonophysics*, 402(1–4):125–139.
- Fidani, C. (2010). The earthquake lights (EQL) of the 6 April 2009 Aquila earthquake, in Central Italy. *Nat. Hazards Earth Syst. Sci.*, 10:967–978.
- Finkelstein, D., Hill, R. D., and Powell, J. R. (1973). The piezoelectric theory of earthquake lightning. *Journal of Geophysical Research*, 78(6):992–993.
- Freeze, R. A. and Cherry, J. A. (1979). Groundwater. Technical report.

- Freund, F. (2000). Time-resolved study of charge generation and propagation in igneous rocks. *Journal of Geophysical Research*, 105(B5):11001–11–019.
- Freund, F. (2010). Toward a unified solid state theory for pre-earthquake signals. *Acta Geophysica*, 58(5):719–766.
- Freund, F. T., Takeuchi, A., and Lau, B. W. S. (2006). Electric currents streaming out of stressed igneous rocks – A step towards understanding pre-earthquake low frequency EM emissions. *Physics and Chemistry of the Earth, Parts A/B/C*, 31(4-9):389–396.
- Frid, V., Bahat, D., Goldbaum, J., and Rabinovitch, A. (2000). Experimental and theoretical investigations of electromagnetic radiation induced by rock fracture. *Israel Journal of Earth Sciences*, 49:9–19.
- Frye, K. M. and Marone, C. (2002). Effect of humidity on granular friction at room temperature. *Journal of geophysical research*, 107(B11):2309.
- Gibson, R. (1958). The progress of consolidation in a clay layer increasing in thickness with time. *Geotechnique*, 8(4):171–182.
- Gu, J.-C., Rice, J. R., Ruina, A. L., and Simon, T. T. (1984). Slip motion and stability of a single degree of freedom elastic system with rate and state dependent friction. *Journal of the Mechanics and Physics of Solids*, 32(3):167–196.
- Gudmundsson, G. H. (2007). Tides and the flow of rutford ice stream, west antarctica. *Journal of Geophysical Research: Earth Surface*, 112(F4).
- Guyer, J. E., Wheeler, D., and Warren, J. A. (2009). Fipy: partial differential equations with python. *Computing in Science & Engineering*, 11(3):6–15.

- Hanson, D. R. and Rowell, G. A. (1982). Electromagnetic radiation from rock failure. *Bureau of Mines Report of Investigations.*
- Hawthorne, J. C. and Rubin, A. M. (2010). Tidal modulation of slow slip in Cascadia. *Journal of Geophysical Research: Solid Earth*, 115(B9).
- Helgerud, M., Dvorkin, J., Nur, A., Sakai, A., and Collett, T. (1999). Elastic-wave velocity in marine sediments with gas hydrates: Effective medium modeling. *Geophysical Research Letters*, 26(13):2021–2024.
- Heslot, F., Baumberger, T., Perrin, B., Caroli, B., and Caroli, C. (1994). Creep, stick-slip, and dry-friction dynamics: Experiments and a heuristic model. *Physical Review E*, 49(6):4973.
- Hong, T. and Marone, C. (2005). Effects of normal stress perturbations on the frictional properties of simulated faults. *Geochemistry Geophysics Geosystems*, 6(3).
- Horgan, H. J., Alley, R. B., Christianson, K., Jacobel, R. W., Anandakrishnan, S., Muto, A., Beem, L. H., and Siegfried, M. R. (2013). Estuaries beneath ice sheets. *Geology*, 41(11):1159–1162.
- Houston, H. (2015). Low friction and fault weakening revealed by rising sensitivity of tremor to tidal stress. *Nature Geoscience*, 8(5):409–415.
- Ide, S., Beroza, G. C., Shelly, D. R., and Uchide, T. (2007a). A scaling law for slow earthquakes. *Nature*, 447(7140):76–79.

- Ide, S., Shelly, D. R., and Beroza, G. C. (2007b). Mechanism of deep low frequency earthquakes: Further evidence that deep non-volcanic tremor is generated by shear slip on the plate interface. *Geophysical Research Letters*, 34(3).
- Ikari, M. J., Marone, C., and Saffer, D. M. (2011). On the relation between fault strength and frictional stability. *Geology*, 39(1):83–86.
- Ikari, M. J., Marone, C., Saffer, D. M., and Kopf, A. J. (2013). Slip weakening as a mechanism for slow earthquakes. *Nature Geoscience*, 6(6):468–472.
- Ikari, M. J., Saffer, D. M., and Marone, C. (2007). Effect of hydration state on the frictional properties of montmorillonite-based fault gouge. *Journal of Geophysical Research: Solid Earth*, 112(B6).
- Ikari, M. J., Saffer, D. M., and Marone, C. (2009). Frictional and hydrologic properties of clay-rich fault gouge. *Journal of Geophysical Research*, 114(B5):B05409–18.
- Iverson, N. R., Baker, R. W., and Hooyer, T. S. (1997). A ring-shear device for the study of till deformation: Tests on tills with contrasting clay contents. *Quaternary Science Reviews*, 16(9):1057–1066.
- Iverson, N. R., Hooyer, T. S., and Baker, R. V. (1998). Ring-shear studies of till deformation: Coulomb-plastic behavior and distributed strain in glacier beds. *Journal of Glaciology*, 44(148):634–642.
- Iverson, N. R. and Iverson, R. M. (2001). Distributed shear of subglacial till due to coulomb slip. *Journal of Glaciology*, 47(158):481–488.

- Iverson, N. R. and Zoet, L. K. (2015). Experiments on the dynamics and sedimentary products of glacier slip. *Geomorphology*, 244:121–134.
- Jaeger, J. C. (1971). Friction of Rocks and Stability of Rock Slopes. *Géotechnique*, 21(2):97–134.
- Johnson, P. A., Ferdowsi, B., Kaproth, B. M., Scuderi, M., Griffa, M., Carmeliet, J., Guyer, R. A., Le Bas, P.-Y., Trugman, D. T., and Marone, C. (2013). Acoustic emission and microslip precursors to stick-slip failure in sheared granular material. *Geophys. Res. Lett.*, 40(21):5627–5631.
- Joughin, I., Bindschadler, R., King, M. A., Voigt, D., Alley, R. B., Anandakrishnan, S., Horgan, H., Peters, L., Winberry, P., Das, S. B., et al. (2005). Continued deceleration of whillans ice stream, west antarctica. *Geophysical Research Letters*, 32(22).
- Jouniaux, L. and Ishido, T. (2013). Electrokinetics in Earth Sciences. *International Journal of Geophysics*, 2013:1–1.
- Kamb, B. (1991). Rheological nonlinearity and flow instability in the deforming bed mechanism of ice stream motion. *Journal of Geophysical Research: Solid Earth*, 96(B10):16585–16595.
- Kamb, B. (2001). Basal zone of the west antarctic ice streams and its role in lubrication of their rapid motion. *The West Antarctic ice sheet: behavior and environment*, pages 157–199.
- Kaproth, B. M. and Marone, C. (2013). Slow Earthquakes, Preseismic Velocity Changes, and the Origin of Slow Frictional Stick-Slip. *Science*, 341(6151):1229–1232.

- Karner, S. L. and Marone, C. (2000). Effects of loading rate and normal stress on stress drop and stick-slip recurrence interval. *Geophysical Monograph Series*, 120:187–198.
- Karner, S. L., Marone, C., and Evans, B. (1997). Laboratory study of fault healing and lithification in simulated fault gouge under hydrothermal conditions. *Tectonophysics*, 277(1):41–55.
- Kato, A., Obara, K., Igarashi, T., Tsuruoka, H., Nakagawa, S., and Hirata, N. (2012). Propagation of slow slip leading up to the 2011 mw 9.0 tohoku-oki earthquake. *Science*, 335(6069):705–708.
- Kavanaugh, J. L. and Clarke, G. K. (2006). Discrimination of the flow law for subglacial sediment using in situ measurements and an interpretation model. *Journal of Geophysical Research: Earth Surface*, 111(F1).
- Kirschvink, J. L. (2000). Earthquake prediction by animals: evolution and sensory perception. *Bulletin of the Seismological Society of America*, 90(2):312–323.
- Kitajima, H. and Saffer, D. M. (2012). Elevated pore pressure and anomalously low stress in regions of low frequency earthquakes along the nankai trough subduction megathrust. *Geophysical Research Letters*, 39(23).
- Knuth, M. and Marone, C. (2007). Friction of sheared granular layers: Role of particle dimensionality, surface roughness, and material properties. *Geochemistry Geophysics Geosystems*, 8(3).

- Knuth, M. W., Tobin, H. J., and Marone, C. (2013). Evolution of ultrasonic velocity and dynamic elastic moduli with shear strain in granular layers. *Granular Matter*, 15(5):499–515.
- Kodaira, S., Iidaka, T., Kato, A., Park, J.-O., Iwasaki, T., and Kaneda, Y. (2004). High pore fluid pressure may cause silent slip in the nankai trough. *Science*, 304(5675):1295–1298.
- Kostoglodov, V. (2003). A large silent earthquake in the Guerrero seismic gap, Mexico. *Geophysical Research Letters*, 30(15).
- Leeman, J., Saffer, D., Scuderi, M., and Marone, C. (2016). Laboratory observations of slow earthquakes and the spectrum of tectonic fault slip modes. *Nature communications*, 7.
- Leeman, J., Scuderi, M. M., Marone, C., and Saffer, D. (2015). Stiffness evolution of granular layers and the origin of repetitive, slow, stick-slip frictional sliding. *Granular Matter*, 17(4):447–457.
- Leeman, J. R., Scuderi, M. M., Marone, C., Saffer, D. M., and Shinbrot, T. *Journal of Geophysical Research: Solid Earth*, 119(5):4253–4268.
- Linde, A. T., Gladwin, M. T., Johnston, M., Gwyther, R. L., and Bilham, R. G. (1996). A slow earthquake sequence the san andreas fault. *Nature*, 383:5.
- Lipovsky, B. and Dunham, E. (2016). Tremor during ice-stream stick slip. *The Cryosphere*, 10(1):385–399.

- Liu, A. J. and Nagel, S. R. (1998). Nonlinear dynamics: Jamming is not just cool any more. *Nature*, 396(6706):21–22.
- Liu, C. h., Nagel, S. R., Schecter, D. A., Coppersmith, S. N., Majumdar, S., Narayan, O., and Witten, T. A. (1995). A Model for Force Fluctuations in Bead Packs. *Science*, 269:513–515.
- Liu, Y. and Rice, J. R. (2007). Spontaneous and triggered aseismic deformation transients in a subduction fault model. *Journal of Geophysical Research: Solid Earth*, 112(B9).
- Lockner, D. A., Johnston, M., and Byerlee, J. D. (1983). A mechanism to explain the generation of earthquake lights. *Nature*, 302:28–33.
- Logan, J., Dengoz, C., Higgs, N., and Wang, Z. (1992). Fabrics of Experimental Fault Zones: Their Development and Relationship to Mechanical Behavior. *Fault Mechanics and Transport Properties of Rocks*, 51:33.
- Luthra, T., Anandakrishnan, S., Winberry, J. P., Alley, R. B., and Holschuh, N. (2016). Basal characteristics of the main sticky spot on the ice plain of whillans ice stream, antarctica. *Earth and Planetary Science Letters*, 440:12–19.
- Mair, K. and Abe, S. (2011). Breaking Up: Comminution Mechanisms in Sheared Simulated Fault Gouge. *Pure and Applied Geophysics*, 168(12):2277–2288.
- Mair, K., Frye, K. M., and Marone, C. (2002). Influence of grain characteristics on the friction of granular shear zones. *Journal of Geophysical Research: Solid Earth*, 107(B10):ECV 4–1–ECV 4–9.

- Mair, K. and Marone, C. (1999). Friction of simulated fault gouge for a wide range of velocities and normal stresses. *Journal of Geophysical Research: Solid Earth*, 104(B12):28899–28914.
- Majmudar, T. S. and Behringer, R. P. (2005). Contact force measurements and stress-induced anisotropy in granular materials. *Nature*, 435(1079):1079–1082.
- Marone, C. (1998). Laboratory-derived friction laws and their application to seismic faulting. *Annual Review of Earth and Planetary Sciences*, 26(1):643–696.
- Marone, C. and Kilgore, B. (1993). Scaling of the critical slip distance for seismic faulting with shear strain in fault zones. *Nature*, 362(6421):618–621.
- Marone, C. and Saffer, D. (2015). The mechanics of frictional healing and slip instability during the seismic cycle. *Treatise on Geophysics*, pages 111–138.
- Martelli, G. and Cerroni, P. (1985). On the theory of radio frequency emission from macroscopic hypervelocity impacts and rock fracturing. *Physics of the Earth and Planetary Interiors*, 40(4):316–319.
- Mitchell, E. K., Fialko, Y., and Brown, K. M. (2013). Temperature dependence of frictional healing of Westerly granite: Experimental observations and numerical simulations. *Geochemistry, Geophysics, Geosystems*, 14(3):567–582.
- Mizutani, H., Ishido, T., Yokokura, T., and Ohnishi, S. (1976). Electrokinetic phenomena associated with earthquakes. *Geophysical Research Letters*, 3(7):365–368.

- Morgan, V., Jacka, T., Akerman, G., and Clarke, A. (1983). Outlet glacier and mass-budget studies in enderby, kemp and mac. robertson lands, antarctica. *Annals of Glaciology*, 3:204–210.
- Nitsan, U. (1977). Electromagnetic emission accompanying fracture of quartzbearing rocks. *Geophysical Research Letters*, 4(8):333–336.
- Obara, K. (2002). Nonvolcanic deep tremor associated with subduction in southwest japan. *Science*, 296(5573):1679–1681.
- Onuma, K., Muto, J., Nagahama, H., and Otsuki, K. (2011). Electric potential changes associated with nucleation of stick-slip of simulated gouges. *Tectonophysics*, 502(3–4):308–314.
- Page, E. (1954). Continuous inspection schemes. *Biometrika*, 41(1/2):100–115.
- Pähntz, T., Herrmann, H. J., and Shinbrot, T. (2010). Why do particle clouds generate electric charges? *Nature Physics*, 6(5):364–368.
- Park, S. K., Johnston, M. J. S., Madden, T. R., and Dale Morgan, F. (1993). Electromagnetic precursors to earthquakes in the ULF band: A review of observations and mechanisms. *Reviews of Geophysics*, 31(2):117–132.
- Passelègue, F. X., Schubnel, A., Nielsen, S., Bhat, H. S., and Madariaga, R. (2013). From sub-rayleigh to supershear ruptures during stick-slip experiments on crustal rocks. *Science*, 340(6137):1208–1211.
- Peng, Z. and Gomberg, J. (2010). An integrated perspective of the continuum between earthquakes and slow-slip phenomena. *Nature Geoscience*, 3(9):599–607.

- Pingali, K. C., Shinbrot, T., Hammond, S. V., and Muzzio, F. J. (2009). An observed correlation between flow and electrical properties of pharmaceutical blends. *Powder Technology*, 192(2):157–165.
- Pratt, M. J., Winberry, J. P., Wiens, D. A., Anandakrishnan, S., and Alley, R. B. (2014). Seismic and geodetic evidence for grounding-line control of whillans ice stream stick-slip events. *Journal of Geophysical Research: Earth Surface*, 119(2):333–348.
- Rabinowicz, E. (1951). The Nature of the Static and Kinetic Coefficients of Friction. *Journal of Applied Physics*, 22(11):1373–1379.
- Raimondo, M. and Tajvidi, N. (2004). A peaks over threshold model for change-point detection by wavelets. *Statistica Sinica*, 14(2):395–412.
- Rathbun, A. P., Marone, C., Alley, R. B., and Anandakrishnan, S. (2008). Laboratory study of the frictional rheology of sheared till. *Journal of Geophysical Research*, 113(F2):F02020.
- Rice, J. R. (1983). Constitutive relations for fault slip and earthquake instabilities. *Pure and applied geophysics*, 121(3):443–475.
- Rice, J. R. and Gu, J.-c. (1983). Earthquake aftereffects and triggered seismic phenomena. *Pure and Applied Geophysics*, 121(2):187–219.
- Richardson, E. and Marone, C. (1999). Effects of normal stress vibrations on frictional healing. *Journal of Geophysical Research*, 104(B12):28859.
- Rogers, G. and Dragert, H. (2003). Episodic tremor and slip on the Cascadia subduction zone: The chatter of silent slip. *Science*, 300(5627):1942–1943.

- Rooney, S., Blankenship, D., Alley, R., and Bentley, C. (1987). Till beneath ice stream b: 2. structure and continuity. *Journal of Geophysical Research: Solid Earth*, 92(B9):8913–8920.
- Rowell, G. A., Brady, B. T., Yoder, L. P., and Hanson, D. R. (1981). Precursors of laboratory rock failure. *Fracture Mechanics for Ceramics, Rocks, and Concrete*, edited by: Freiman, S.W. and Fuller, E.R., pages 196–220.
- Rubin, A. M. (2011). Designer friction laws for bimodal slow slip propagation speeds. *Geochemistry, Geophysics, Geosystems*, 12(4).
- Ruina, A. (1983). Slip instability and state variable friction laws. *Journal of Geophysical Research: Solid Earth*, 88(B12):10359–10370.
- Saffer, D. M., Frye, K. M., Marone, C., and Mair, K. (2001). Laboratory results indicating complex and potentially unstable frictional behavior of smectite clay. *Geophysical Research Letters*, 28(12):2297–2300.
- Sammis, C., King, G., and Biegel, R. (1987). The kinematics of gouge deformation. *Pure and Applied Geophysics*, 125(5):777–812.
- Savitzky, A. and Golay, M. J. E. (1964). Smoothing and differentiation of data by simplified least squares procedures. *Analytical Chemistry*, 36(8):1627–1639.
- Scholz, C., Molnar, P., and Johnson, T. (1972). Detailed studies of frictional sliding of granite and implications for the earthquake mechanism. *Journal of geophysical research*, 77(32):6392–6406.

- Scholz, C. H. (2002). *The mechanics of earthquakes and faulting*. Cambridge university press.
- Scott, D. R., Marone, C. J., and Sammis, C. G. (1994). The apparent friction of granular fault gouge in sheared layers. *Journal of Geophysical Research: Solid Earth* (1978–2012), 99(B4):7231–7246.
- Scuderi, M. M., Carpenter, B. M., and Marone, C. (2014). Physicochemical processes of frictional healing: Effects of water on stick-slip stress drop and friction of granular fault gouge. *Journal of Geophysical Research: Solid Earth*, 119(5):4090–4105.
- Segall, P., Rubin, A. M., Bradley, A. M., and Rice, J. R. (2010). Dilatant strengthening as a mechanism for slow slip events. *Journal of Geophysical Research: Solid Earth*, 115(B12).
- Shelly, D. R. (2010). Migrating tremors illuminate complex deformation beneath the seismogenic san andreas fault. *Nature*, 463(7281):648–652.
- Shelly, D. R., Beroza, G. C., and Ide, S. (2007). Non-volcanic tremor and low-frequency earthquake swarms. *Nature*, 446(7133):305–307.
- Shimamoto, T. (1986). Transition between frictional slip and ductile flow for halite shear zones at room temperature. *Science*, 231(4739):711–714.
- Shinbrot, T., Kim, N. H., and Thyagu, N. N. (2012). Electrostatic precursors to granular slip events. *Proceedings of the National Academy of Sciences*, 109(27):10806–10810.
- Skarbek, R. M. and Saffer, D. M. (2009). Pore pressure development beneath the décollement at the nankai subduction zone: Implications for plate boundary fault

strength and sediment dewatering. *Journal of Geophysical Research: Solid Earth*, 114(B7).

St-Laurent, F., Derr, J. S., and Freund, F. T. (2006). Earthquake lights and the stress-activation of positive hole charge carriers in rocks. *Physics and Chemistry of the Earth, Parts A/B/C*, 31(4-9):305–312.

Takeuchi, A., Futada, Y., Okubo, K., and Takeuchi, N. (2010). Positive electrification on the floor of an underground mine gallery at the arrival of seismic waves and similar electrification on the surface of partially stressed rocks in laboratory. *Terra Nova*, 22(3):203–207.

Takeuchi, A. and Nagao, T. (2013). Activation of hole charge carriers and generation of electromotive force in gabbro blocks subjected to nonuniform loading. *Journal of Geophysical Research: Solid Earth*, 118(3):915–925.

Thomason, J. F. and Iverson, N. R. (2008). A laboratory study of particle ploughing and pore-pressure feedback: a velocity-weakening mechanism for soft glacier beds. *Journal of Glaciology*, 54(184):169–181.

Triantis, D., Anastasiadis, C., and Stavrakas, I. (2008). The correlation of electrical charge with strain on stressed rock samples. *Nat. Hazards Earth Syst. Sci*, 8:1243–1248.

Truffer, M., Harrison, W. D., and Echelmeyer, K. A. (2000). Glacier motion dominated by processes deep in underlying till. *Journal of Glaciology*, 46(153):213–221.

- Tulaczyk, S. (2006). Scale independence of till rheology. *Journal of Glaciology*, 52(178):377–380.
- Tulaczyk, S., Kamb, B., and Engelhardt, H. F. (2001). Estimates of effective stress beneath a modern west antarctic ice stream from till preconsolidation and void ratio. *Boreas*, 30(2):101–114.
- Tulaczyk, S., Kamb, B., Scherer, R. P., and Engelhardt, H. F. (1998). Sedimentary processes at the base of a west antarctic ice stream: constraints from textural and compositional properties of subglacial debris. *Journal of Sedimentary Research*, 68(3).
- Tulaczyk, S., Kamb, W. B., and Engelhardt, H. F. (2000). Basal mechanics of ice stream b, west antarctica: 1. till mechanics. *Journal of Geophysical Research: Solid Earth*, 105(B1):463–481.
- Uyeda, S., Nagao, T., and Kamogawa, M. (2009). Short-term earthquake prediction: Current status of seismo-electromagnetics. *Tectonophysics*, 470(3):205–213.
- Voisin, C., Grasso, J.-R., Larose, E., and Renard, F. (2008). Evolution of seismic signals and slip patterns along subduction zones: Insights from a friction lab scale experiment. *Geophysical Research Letters*, 35(8).
- Walker, R. T., Parizek, B. R., Alley, R. B., Anandakrishnan, S., Riverman, K. L., and Christianson, K. (2013). Ice-shelf tidal flexure and subglacial pressure variations. *Earth and Planetary Science Letters*, 361:422–428.

- Walker, R. T., Parizek, B. R., Alley, R. B., Brunt, K. M., and Anandakrishnan, S. (2014). Ice-shelf flexure and tidal forcing of bindschadler ice stream, west antarctica. *Earth and Planetary Science Letters*, 395:184–193.
- Wallace, L. M. and Beavan, J. (2006). A large slow slip event on the central Hikurangi subduction interface beneath the Manawatu region, North Island, New Zealand. *Geophysical Research Letters*, 33(11):L11301–4.
- Walter, J. I., Brodsky, E. E., Tulaczyk, S., Schwartz, S. Y., and Pettersson, R. (2011). Transient slip events from near-field seismic and geodetic data on a glacier fault, whillans ice plain, west antarctica. *Journal of Geophysical Research: Earth Surface*, 116(F1).
- Walter, J. I., Svetlizky, I., Fineberg, J., Brodsky, E. E., Tulaczyk, S., Barchek, C. G., and Carter, S. P. (2015). Rupture speed dependence on initial stress profiles: Insights from glacier and laboratory stick-slip. *Earth and Planetary Science Letters*, 411:112–120.
- Whillans, I. and Van Der Veen, C. J. (1993). New and improved determinations of velocity of ice streams b and c, west antarctica. *Journal of Glaciology*, 39(133):483–590.
- Wiens, D. A., Anandakrishnan, S., Winberry, J. P., and King, M. A. (2008). Simultaneous teleseismic and geodetic observations of the stick-slip motion of an antarctic ice stream. *Nature*, 453(7196):770–774.

- Winberry, J. P., Anandakrishnan, S., Alley, R. B., Wiens, D. A., and Pratt, M. J. (2014). Tidal pacing, skipped slips and the slowdown of whillans ice stream, antarctica. *Journal of Glaciology*, 60(222):795–807.
- Winberry, J. P., Anandakrishnan, S., Wiens, D. A., Alley, R. B., and Christianson, K. (2011). Dynamics of stick-slip motion, whillans ice stream, antarctica. *Earth and Planetary Science Letters*, 305(3):283–289.
- Wissa, A. (1971). Consolidation at constant rate of strain. *Journal of Soil Mechanics & Foundations Div.*
- Wood, D. M. (1990). *Soil behaviour and critical state soil mechanics*. Cambridge university press.
- Yasuhara, H. (2005). Fault zone restrengthening and frictional healing: The role of pressure solution. *Journal of Geophysical Research*, 110(B6):B06310.
- Zoet, L. K., Anandakrishnan, S., Alley, R. B., Nyblade, A. A., and Wiens, D. A. (2012). Motion of an antarctic glacier by repeated tidally modulated earthquakes. *Nature Geoscience*, 5(9):623–626.

# Vita

## John R. Leeman

### Education

<i>The Pennsylvania State University</i>	State College, Pennsylvania	2012-2017
Ph.D in Geosciences, May 2017		
Advisors: Dr. Chris Marone and Dr. Demian Saffer		
<i>University of Oklahoma</i>	Norman, Oklahoma	2007-2012

B.S. in Meteorology, B.S. in Geophysics, minor in Mathematics

### Core Competencies

Experimental Design	Biaxial & Triaxial Deformation experiments	Python Programming
Electronics Design	3D CAD Design	3D Printing
Public Speaking	Microcontroller Programming	Data Processing
Scientific Visualization	System Administration	Mathematical Modeling

### Selected Grants & Awards

Peter Deines Lectureship	2016
AGU Outstanding Student Paper	2011, 2015
National Science Foundation Graduate Fellow	2013–2017
Shell Geosciences Energy Research Facilities Award	2013–2016
Hess Corporation Exploration & Production Technology Scholarship	2014, 2015

### Selected Publications

- JR Leeman, RD Valdez, RB Alley, S Anandakrishnan, and DM Saffer. Mechanical and hydrologic properties of whillans ice stream till: Implications for basal strength and stick-slip failure. *Journal of Geophysical Research: Earth Surface*, 121(7):1295–1309, 2016.
- JR Leeman, DM Saffer, MM Scuderi, and C Marone. Laboratory observations of slow earthquakes and the spectrum of tectonic fault slip modes. *Nature Communications*, 7, 2016.
- John Leeman, Marco Maria Scuderi, Chris Marone, and Demian Saffer. Stiffness evolution of granular layers and the origin of repetitive, slow, stick-slip frictional sliding. *Granular Matter*, pages 1–11, May 2015.
- J. R. Leeman, M. M. Scuderi, C. Marone, D. M. Saffer, and T. Shinbrot. On the origin and evolution of electrical signals during frictional stick slip in sheared granular material. *J. Geophys. Res. Solid Earth*, 119(5):4253–4268, May 2014.

### Professional & Service Activities

<i>Academic Integrity Committee</i>	The Pennsylvania State University	2014–2017
Graduate representative for academic integrity investigations and hearings.		
<i>Session Co-Chair</i>	American Geophysical Union	2014–2016
Co-chair a session on education and data visualization at the AGU Fall Meeting.		
<i>Instructor</i>	The Pennsylvania State University	2015–2016
Assist teaching seismology laboratory and develop and teach a 3 hour course on techniques in experimental geoscience.		