Slow Earthquakes: A Manifestation of Transitional Frictional Behavior

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

1 Introduction

Slow earthquakes, tectonic fault tremor and other modes of quasi-dynamic fault slip represent an important conundrum in earthquake mechanics. In the standard model, elastic energy is released catastrophically as the fault zone weakens, and dynamic rupture propagates at speeds of km/s. However, faults also fail in slow earthquakes and a spectrum of other slip modes that generally lack high the high frequency elastic radiation associated with rapid fault slip acceleration. The mechanics of slow earthquakes are poorly understood, in part because there are few laboratory observations of these phenomena. Here, we present the first systematic investigation of the spectrum of fault slip modes and show that the key control parameter involves a non dimensional stiffness k' given by the ratio of friction weakening rate and elastic loading stiffness. In the laboratory, we obtain repetitive slow stick-slip by carefully matching the elastic loading stiffness with the frictional rheology. Slow slip and quasi-dynamic modes of stick-slip occur for a narrow range of conditions near k' 1.0. Our results provide a generic mechanism for slow earthquakes, rather than a specific rate strengthening mechanism to arrest earthquake nucleation, consistent with the range of conditions under which slow slip has been observed.

Observations of slow-slip and low-frequency earthquakes in nature suggest that fault failure encompasses a spectrum of slip modes [1, 2, 3]. While the explanations for non-traditional earthquakes remain a topic of debate, they have been observed in many subduction zones, including Cascadia [4, 5], Mexico [6], Costa Rica [7], Japan [8], and New Zealand [9]. What causes strain energy to be released across a wide-range of failure behaviors is not well understood, but transitional frictional stability is a possible explanation. System stability is defined in terms of system stiffness (k) related to the critical stiffness (k_c) [10] and can be altered by environmental variables such as effective normal stress, critical slip distance, and the velocity dependence of friction. Clustering of slow and transitional events around traditional seismic faults in nature suggests that transitional behavior is responsible. Laboratory evidence of this behavior is scattered [11, 12, 13], mostly suggested by numerical models [10]. Here we present the first systematic investigation of the critical stiffness ratio and its effect on the frictional state of a laboratory fault. We also show that stiffness can control the slip mode and that the slip mode can change as stiffness is influenced by accumulated fault slip and damage zone evolution.

2 Main

The observation of non-traditional slip modes (slow slip, very low frequency earthquakes, episodic tremor and slip, etc) in a wide variety of locations over the last decade suggests that this is a common occurrence. There have been suggestions that these behaviors, often observed at the down-dip limit of traditional seismic slip, can influence, interact with, or trigger up-dip earthquakes [14, 15]. There has also been the suggestion that these events occur at the transition between stable and locked patches of a fault and that non-traditional slip areas could influence earthquake nucleation in those areas [16].

The rate-and-state friction framework is commonly used to describe the dynamic frictional behavior of natural and experimental systems to perturbations. This empirical relation consists of the parameters a and b which describe the velocity dependence of friction. For materials in which $(a - b) > 0$ the friction increases with increased driving velocity, termed velocity strengthening. Likewise, materials with $(a - b) < 0$ are velocity weakening. The model also consists of an e-folding critical slip distance D_c, and a state variable θ. D_c is thought of, in the laboratory, as the distance required to completely renew a contact population. The state variable is thought to be a proxy for the age of the frictional contacts, and evolves according to a state evolution relation, commonly the Dieterich 'slowness' or Runia 'slip' relation [17, 18, 19].

For unstable behavior to occur: 1) that the material be velocity neutral to velocity weakening, and 2) that the system stiffness be at or below the critical stiffness [17, 20]. If a material is velocity strengthening, any acceleration leading to slip is immediately arrested by increased shearing resistance and the energy is frictionally dissipated. The stiffness of the system governs the rate at which energy stored as strain can be released. If the energy release occurs in such a way that the drop in shear resistance with displacement occurs faster than the drop in applied shearing force with displacement, the system can support unstable failure. The critical stiffness can be described in terms of the rate-and-state parameters as (eq.1). The aggregate stiffness of the loading system and sample can be measured by fitting the linear-slope of the load-point displacement vs. shear load curve on either an unload/reload cycle or on the loading portion of a single stick-slip event [13].

$$K_c = \sigma'_n \frac{b - a}{D_c} \tag{1}$$

We conducted a suite of biaxial double-direct shearing experiments with a fine quartz fault gouge simulant (Min-U-Sil®), chosen for its geologic relevance, reproducible results, and well controlled composition and size distribution. This study systematically examines the behavior of an experimental fault as a function of nearness to the stability criterion $k \sim k_c$. Using the same, well controlled sample material for each experiment and humidifying the samples, we ensure that the rate-and-state parameters (a, b, D_c) remain essentially constant between experiments. We then explore the stability of the system by modifying the stiffness directly by changing the forcing block configuration and by changing the applied effective normal stress (σ'_n).

In order to define/measure the RSF parameters for each experiment, we use a range of measurements. For experiments in which K is high, stable sliding behavior is observed and we use velocity steps to obtain the rate-and-state frictional parameters and therefore K_c. We assume that the evolution of these material and layer properties is not dependent on the mode of slip, and therefore we use the values measured on stably sliding experiments as a framework for evaluating/comparing results from the suite of experiments.

3 Results/Discussion

Our results show that the mode of slip is consistent with that expected from the rate-and-state friction framework. Slip mode varies systematically with K, and transitional behavior is observed at $\frac{K}{K_c} \sim 1$. In a stiff (all steel) forcing setup, linearly stable behavior was observed, while in a more compliant loading system, emergent unstable behavior was observed. Unstable behavior began with frictional oscillations, transitionally to dynamic frictional failure. Oscillations and dynamic failure are characterized by relatively rapid accelerations and decelerations of the system above/below the load point velocity when the material yields under excessive shear force. In experiments with further increased compliance, rapid dynamic failure was observed. These events were audible and classified as fast stick-slip.

We also observe that there is a relation between the peak velocity or duration of slip and $\frac{K}{K_c}$. Systems near the stability transition exhibit lower peak velocities and long duration events, seen as frictional oscillations in the experiments. The further the system is from the transition, the events become shorter in duration and faster.

Both K and K_c, and thus mode of slip, evolve with net slip. As layer accumulates strain and strain is localized, it stiffens. At the same time, RSF parameters evolve, modifying the critical stiffness of the system. This explains a rich variety of behaviors that may appear unrelated or non-linear initially. This is supported by our observations that stick slip does not occur until a critical displacement is reached, because K_c is negative until the onset of rate weakening behavior. Most stiffness evolution occurs in the first 10 mm of shear, asymptotically approaching stead-state. Initial increases in stiffness could be due to layer compaction from grain rearrangement, layer thinning with increased shear strain, grain comminution, localization of shear, or reduction of compliant center block material above the sample due to geometric effects. Layer compaction due to rearrangement and geometric thinning with shear have been well documented [21]. At these low stresses, grain comminution is minimal. Shear localization effects have been shown to play a role in the evolution of layer behavior [22], especially before reaching mechanical steady-state as R and Y shears develop. The reduction in the amount of compliant center block material above the shearing zone with accumulated displacement is minimal compared to these other effects.

In our experiments, a remains relatively constant with displacement, but b evolves asymptotically upwards with increasing shear displacement. During this transitional period, the critical slip distance evolves downwards (Fig.**??**).

Our results support previous ideas about the role of transitional frictional properties in supporting a range of complex failure behaviors. Natural factors such as compliant and evolving damage zones, low effective normal stress [23, 24, 25], and fault evolution/aging [26] are all captured in the simple ratio of $\frac{K}{K_c}$. All of this suggesting that tectonic faults may change behavior as they accumulate slip and become mature fault zones.

With slow-slip failure events, we see little to no dynamic overshoot. This is observable by a period of no block motion or deformation after the rapid stress-drop (Fig.**??**C). In traditional fast stick-slip events, the system shears further than required to complete the force balance. Frictional oscillations and slow-slip show no such overshoot, with continual deformation of the system throughout the simulated seismic cycle. This provides some insight into the low frequency nature of emissions observed from slow-slip and lack of audible report in the laboratory. Lower shear stiffnesses will reduce the seed of rupture propagation, softening step-like acceleration/deceleration pulses that result in high frequency emission. Slowed rupture velocities would also influence disaster potential, as tsunamogenic earthquake have generally slow rupture velocities [27, 28].

We suggest that where in the spectrum of failure behavior a fault lies can be quantitatively described by the relation of the stiffness of the fault compared to the calculated critical stiffness. While factors such as pore pressure and material frictional response are important, they are already factored into the stiffness comparison.

4 Methods

All experiments were performed on a servo-controlled biaxial shearing apparatus. Displacements on the normal and shearing axes were measured by Direct Current Displacement Transducers (DCDTs) referenced at the end-platens and ram nose. The displacement of the shearing block was measured with a DCDT referenced at the end-platen and the top of the shearing block. Loads applied to the sample were measured with strain gauge load cells. All transducers are semi-annually calibrated with traceable transfer standards.

Samples were prepared in the double-direct-shear geometry using steel or titanium side blocks and steel or acrylic shearing blocks. All blocks were grooved 0.8 mm deep at 1 mm spacing to reduce boundary effects [29]. The sample area was 10 x 10 cm and filled with Min-U-Sil to a thickness of 3 mm. Granular layers were left in a sealed container overnight with a solution of anhydrous sodium carbonate to humidify the samples.

After samples were loaded into the load frame, a constant normal stress was applied and maintained by the servo system in a force feedback control mode. Samples were allowed to compact and accommodate grain rearrangement before shearing began. Shearing is conducted at a fixed rate in displacement feedback control mode.

Stiffness of the system was altered by changing the applied normal stress and by changing the material of the shearing block. Increasing normal stress decreases the effective stiffness of the system, as does switching the steel forcing block for a cast acrylic block.

Layers were built of Min-U-Sil® 40 fine ground silica from the U.S. Silica® company Berkeley Springs, West Virginia plant. The median diameter of grain is 10.5 μm. The product is 99.5 % SiO_2, with traces of metal oxides making up the remainder.

System stiffnesses from unload/reload shear stress cycles were calculated by a least-squares linear fit in friction vs. displacement for the interval $\mu = 0.3 - 0.4$. Stiffnesses from the loading portion of slow-slip and stick-slip events were obtained with a derivative based algorithm [13]. Rate-and-state models were fit with both the Dieterich and Ruina laws, with comparable results. Inversions were done with an iterative singular value decomposition technique.

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6 Author Contributions

All authors contributed to data interpretation, analysis schema, and writing. J. Leeman conducted experiments and data analysis.

7 Competing Financial Interests

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to J.R. Leeman.

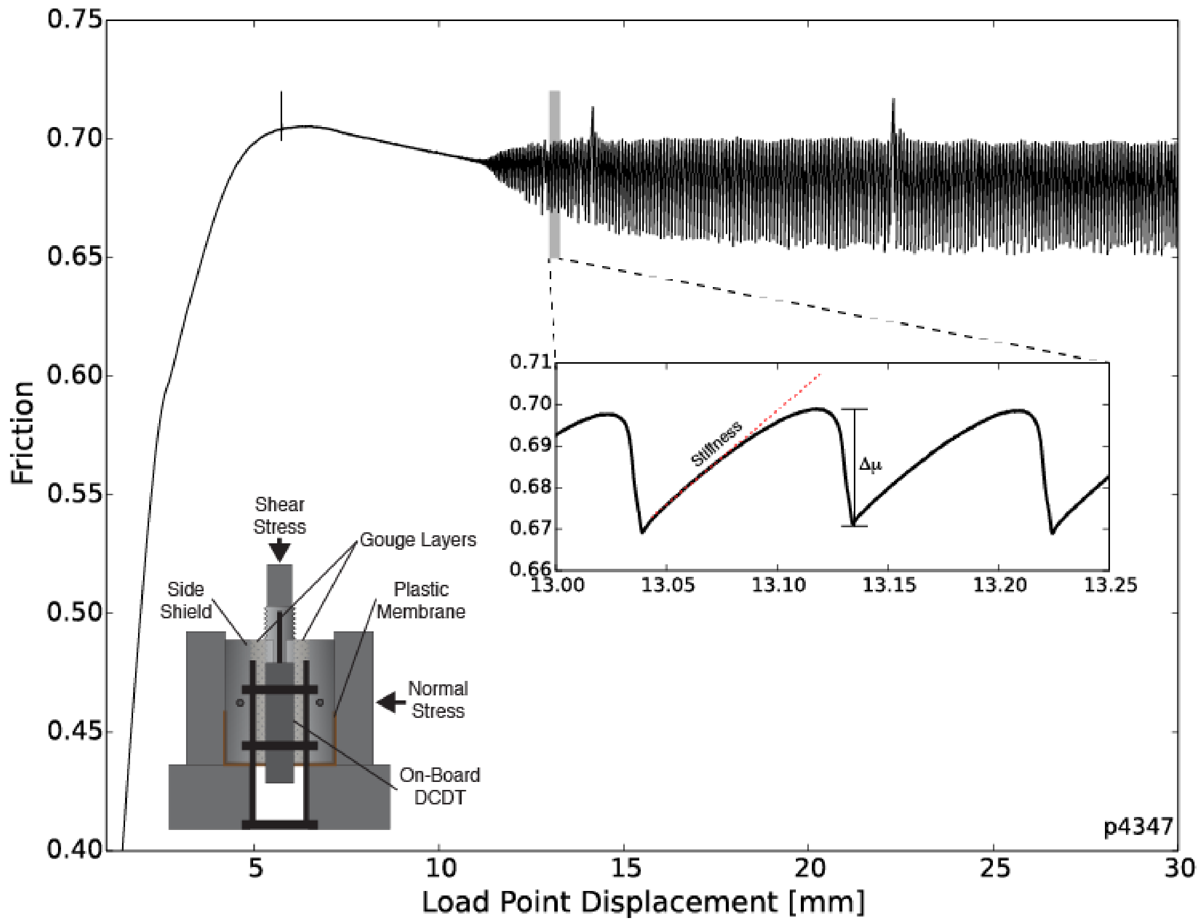


Figure 1:

8 Supplementary

Experiment	Blocks Used	Normal Stress [MPa]	Temperature [°C]	Relative Humidity [%]	Comments	Unload/Reloads
p4224	Titanium/Acrylic	5	26	16	Stable - Velocity Steps	N
p4228	Steel	4	24	100	Stable - Slide Hold Slide	N
p4229	Titanium/Acrylic	4	24	100	Failed Experiment	N
p4248	Titanium/Acrylic	4	24.2	100	Stable - Velocity Steps	N
p4249	Titanium/Acrylic	4	23.2	100	Stable - Velocity Steps	N
p4267	Titanium/Acrylic	2	23.2	100	Stable - Velocity Steps	Y
p4268	Titanium/Acrylic	8	23.4	100	Slow Slip	Y
p4269	Steel	4	23.4	100	Stable - Velocity Steps	Y
p4270	Steel	2		100	Stable - Velocity Steps	Y
p4271	Titanium/Acrylic	2		100	Stable - Velocity Steps	Y
p4272	Titanium/Acrylic	8	22.7	100	Slow Slip	Y
p4273	Steel	8	23.4	100	Stable - Velocity Steps	Y
p4309	Steel	8	23.2	100	Stable - Velocity Steps	Y
p4310	Titanium/Acrylic	8	24.2	100	Slow Slip	Y
p4311	Titanium/Acrylic	8	23.3	100	Slow Slip	Y
p4312	Steel/Acrylic	8	23.6	100	Slow Slip	Y
p4313	Titanium/Acrylic	8	23.5	100	Slow Slip	Y
p4314	Steel	12	24.3	100	Stable - Velocity Steps	Y
p4316	Titanium/Acrylic	12	23.6	100	Stick Slip	Y
p4317	Steel/Acrylic	12	24.2	100	Stick Slip	Y
p4327	Steel	6	22.5	100	Stable - Velocity Steps	Y
p4328	Titanium/Acrylic	6	22.7	100	Slow Slip	Y
p4329	Titanium/Acrylic	6	22	100	Slow Slip	Y
p4330	Steel	6	22.9	100	Stable - Velocity Steps	Y
p4338	Titanium/Acrylic	4	24.2	100	Stable - Velocity Steps	Y
p4339	Steel	4	24.8	100	Stable - Velocity Steps	Y
p4340	Titanium/Acrylic	8	24.0	100	Slow Slip	Y
p4341	Steel	12	23.4	100	Stable - Velocity Steps	Y
p4342	Titanium/Acrylic	12	24.3	100	Slow/Fast Slip	N
p4343	Steel/Acrylic	6	23.9	100	Slow Slip	N
p4344	Titanium/Acrylic	7	24.5	100	Slow Slip	N
p4345	Steel/Acrylic	8	24.2	100	Slow Slip	N
p4346	Titanium/Acrylic	9	24.2	100	Slow Slip	N
p4347	Steel/Acrylic	10	23.1	100	Slow/Fast Slip	N
p4348	Titanium/Acrylic	11	23.9	100	Slow/Fast Slip	N
p4350	Steel/Acrylic	13	22.7	100	Slow/Fast Slip	N
p4351	Titanium/Acrylic	14	23.1	100	Slow/Fast Slip	N

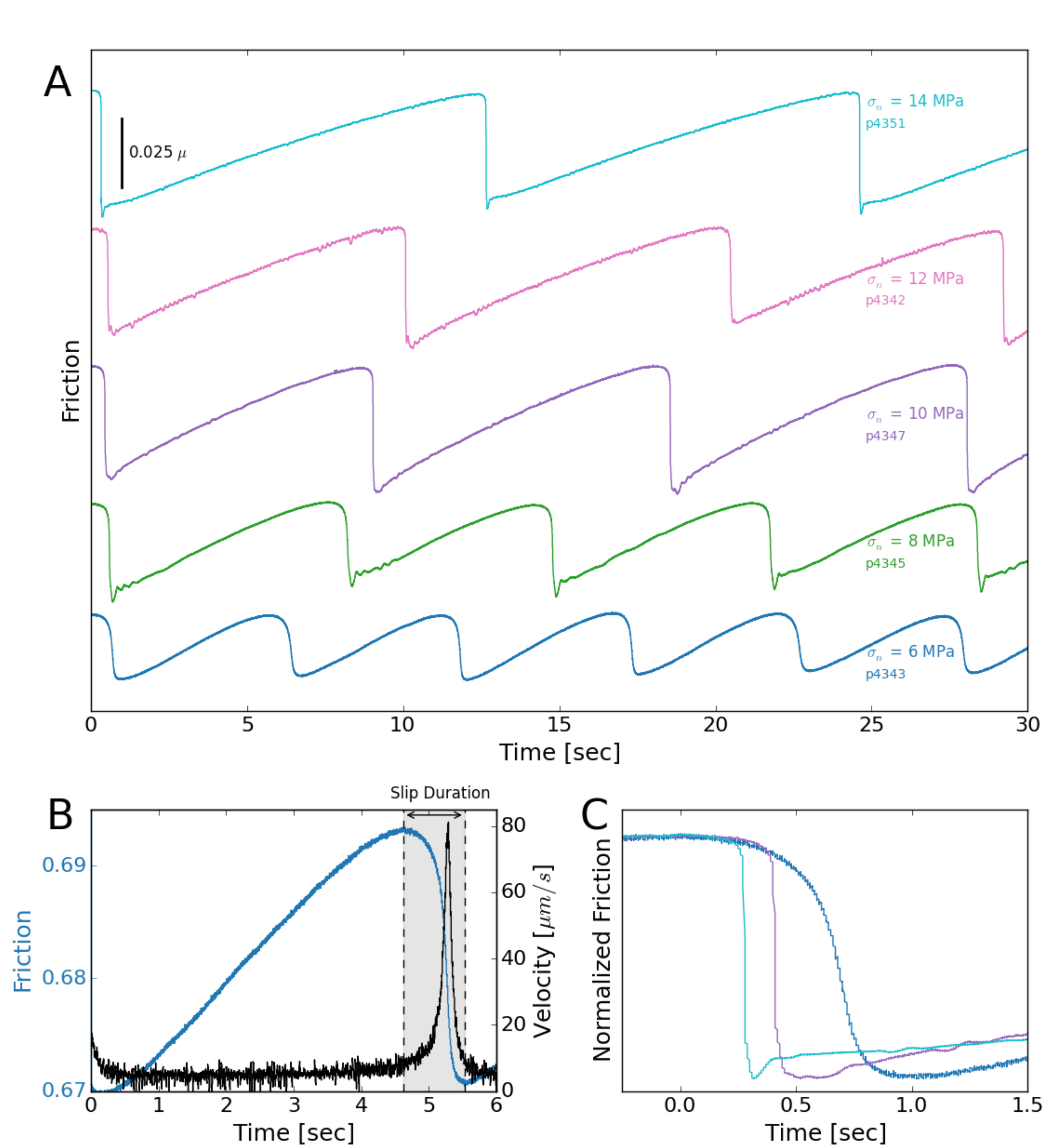

A
0.025 μ
σ_n = 14 MPa
p4351
σ_n = 12 MPa
p4342
σ_n = 10 MPa
p4347
σ_n = 8 MPa
p4345
σ_n = 6 MPa
p4343
Friction
Time [sec]
B
Slip Duration
Friction
Velocity [$\mu m/s$]
Time [sec]
C
Normalized Friction
Time [sec]

Figure 2:

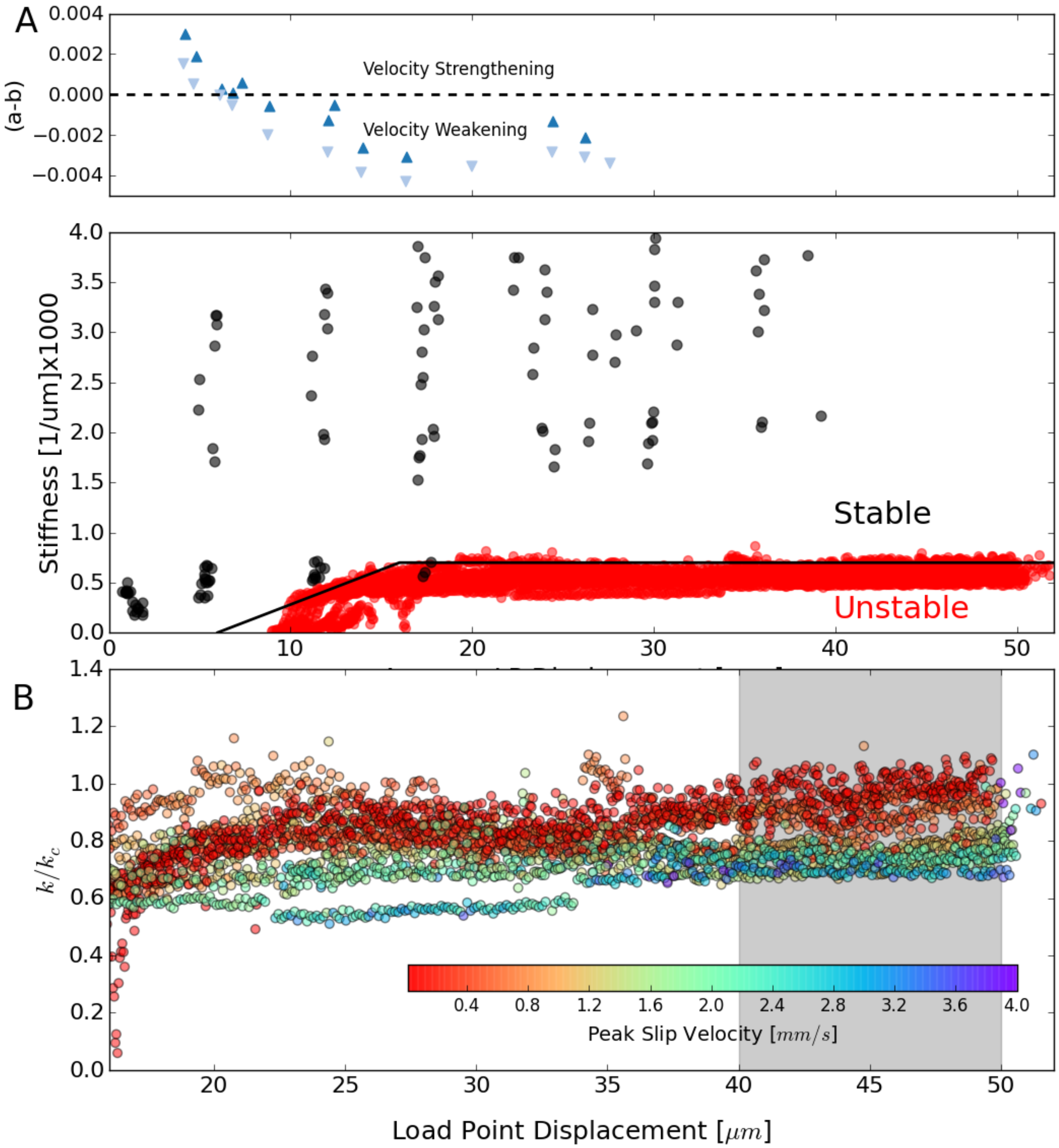

A
0.004
0.002
0.000
−0.002
−0.004
(a-b)
Velocity Strengthening
Velocity Weakening
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Stiffness [1/um]x1000
Stable
Unstable
0
10
20
30
40
50
B
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
k/k_c
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
Peak Slip Velocity $[mm/s]$
20
25
30
35
40
45
50
Load Point Displacement $[\mu m]$

Figure 3:

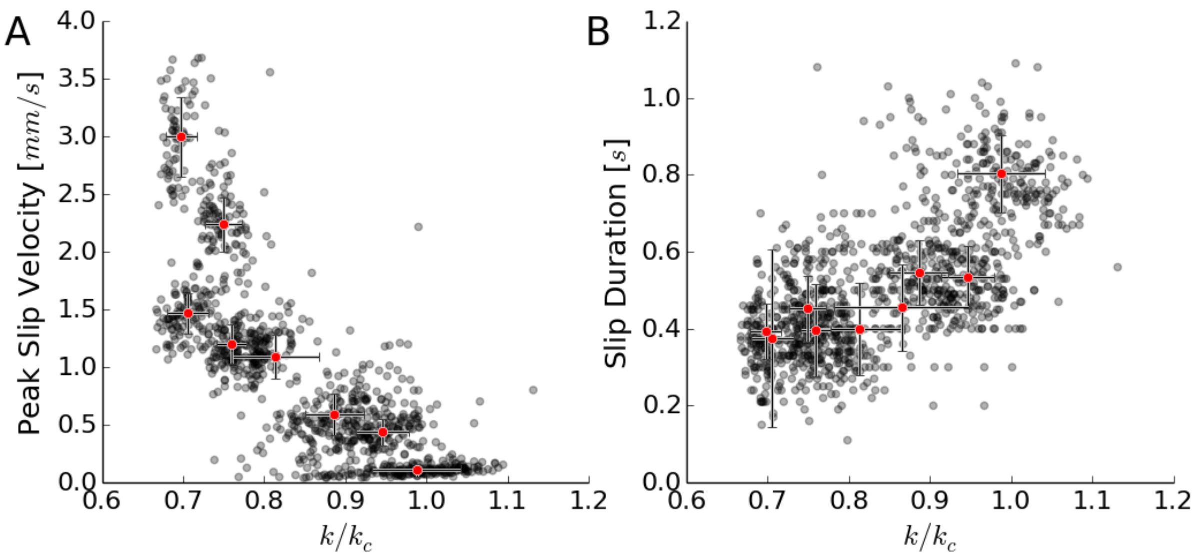

A
Peak Slip Velocity [mm/s]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.6
0.7
0.8
0.9
1.0
1.1
1.2
k/k_c
B
Slip Duration [s]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.6
0.7
0.8
0.9
1.0
1.1
1.2
k/k_c

Figure 4:

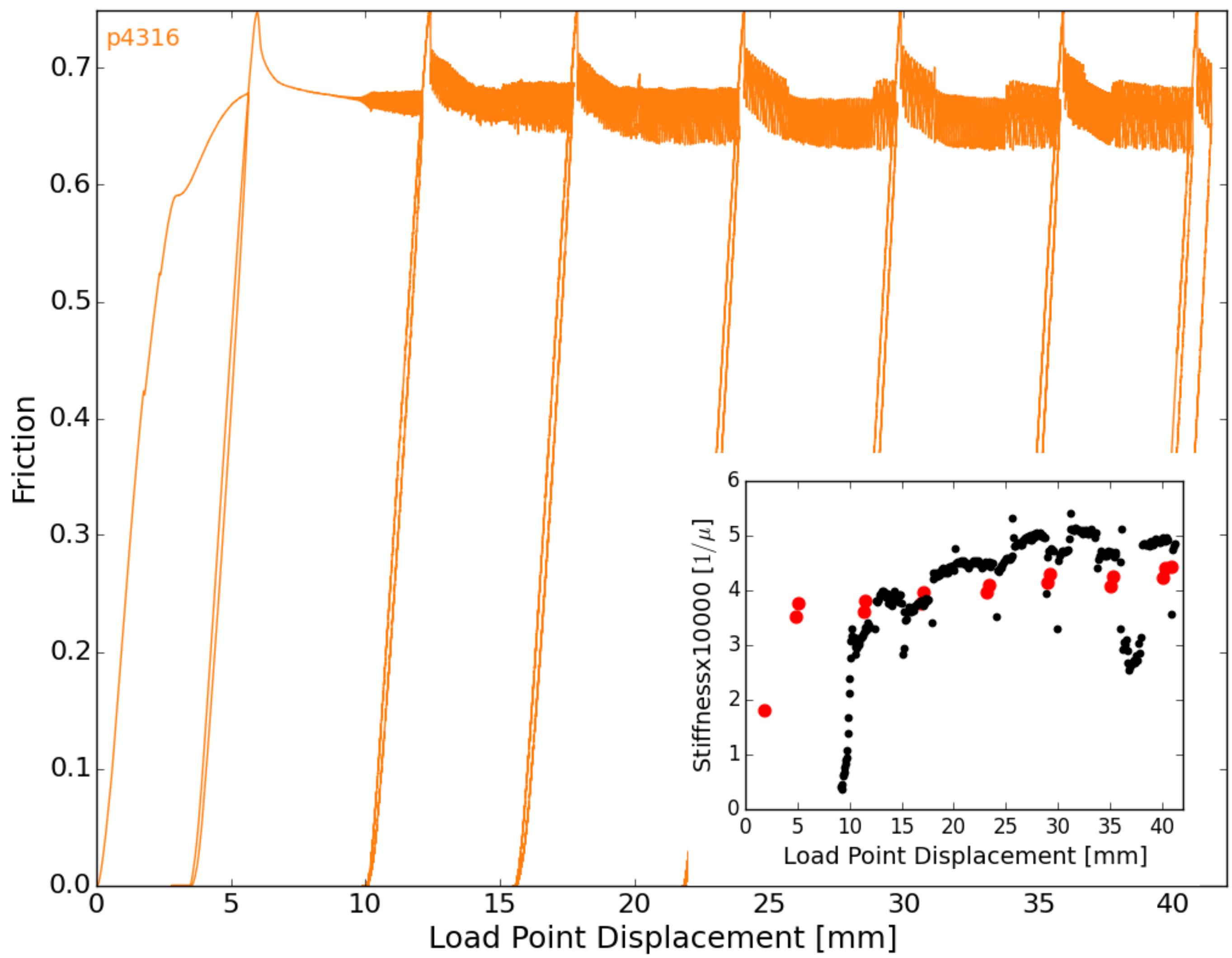
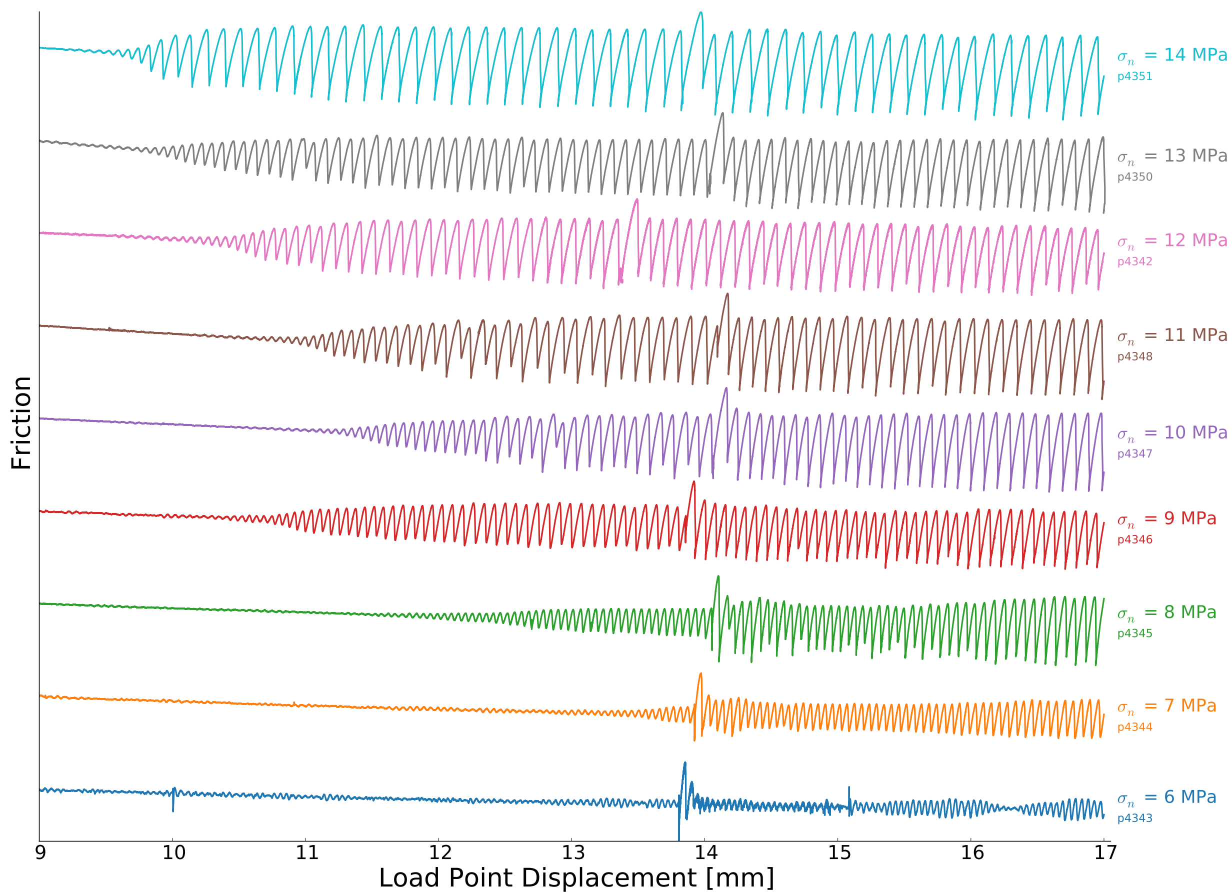

p4316
Friction
Load Point Displacement [mm]
Stiffnessx10000 [1/μ]
Load Point Displacement [mm]

Figure 5:



Friction
σ_n = 14 MPa
p4351
σ_n = 13 MPa
p4350
σ_n = 12 MPa
p4342
σ_n = 11 MPa
p4348
σ_n = 10 MPa
p4347
σ_n = 9 MPa
p4346
σ_n = 8 MPa
p4345
σ_n = 7 MPa
p4344
σ_n = 6 MPa
p4343
9
10
11
12
13
14
15
16
17
Load Point Displacement [mm]

Figure 6:

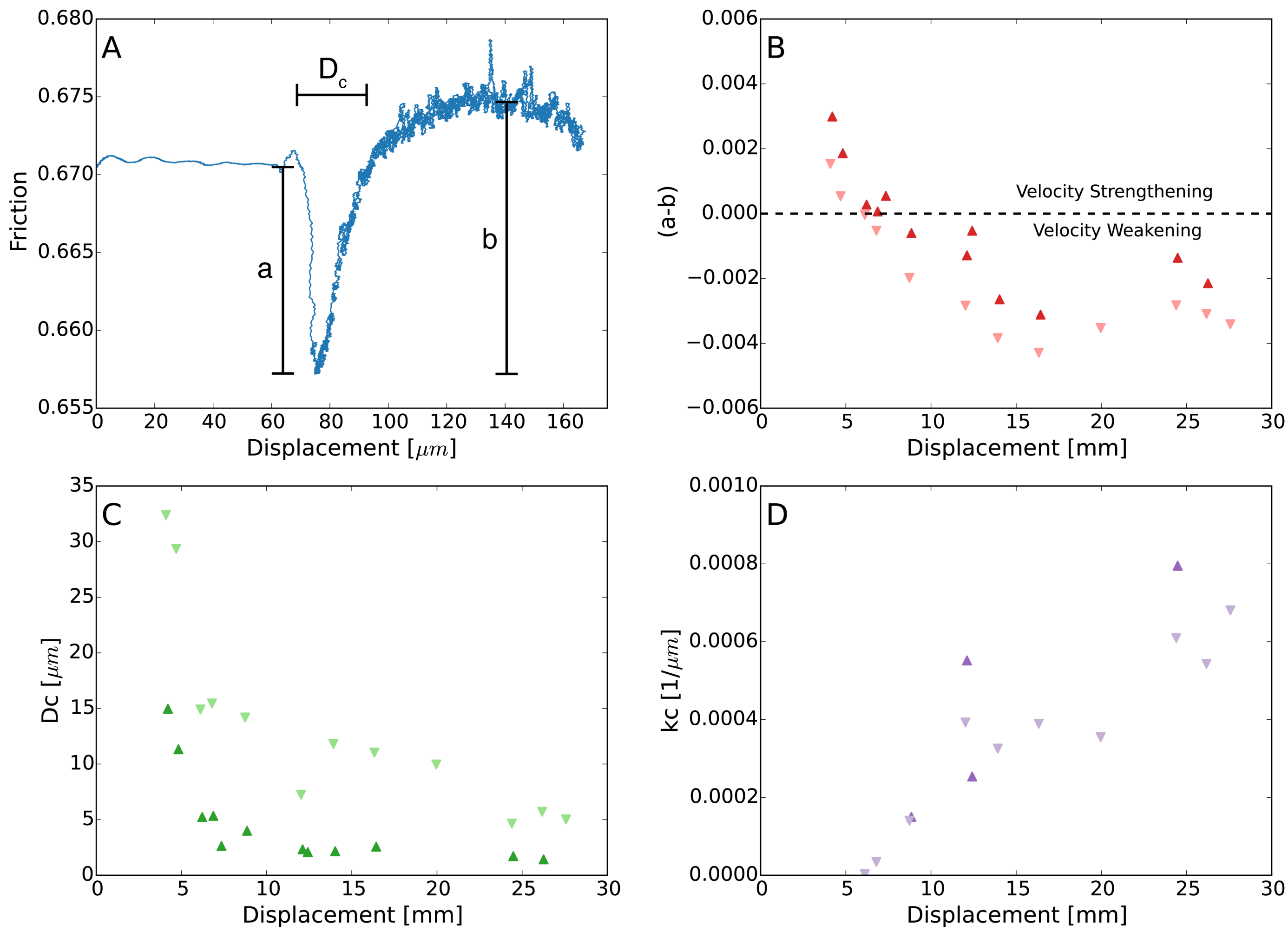

A
B
C
D
D_c
a
b
Friction
Displacement [μm]
(a-b)
Velocity Strengthening
Velocity Weakening
Displacement [mm]
Dc [μm]
Displacement [mm]
kc [1/μm]
Displacement [mm]

Figure 7: