A possible recipe for a friction law to describe seismic and aseismic faulting

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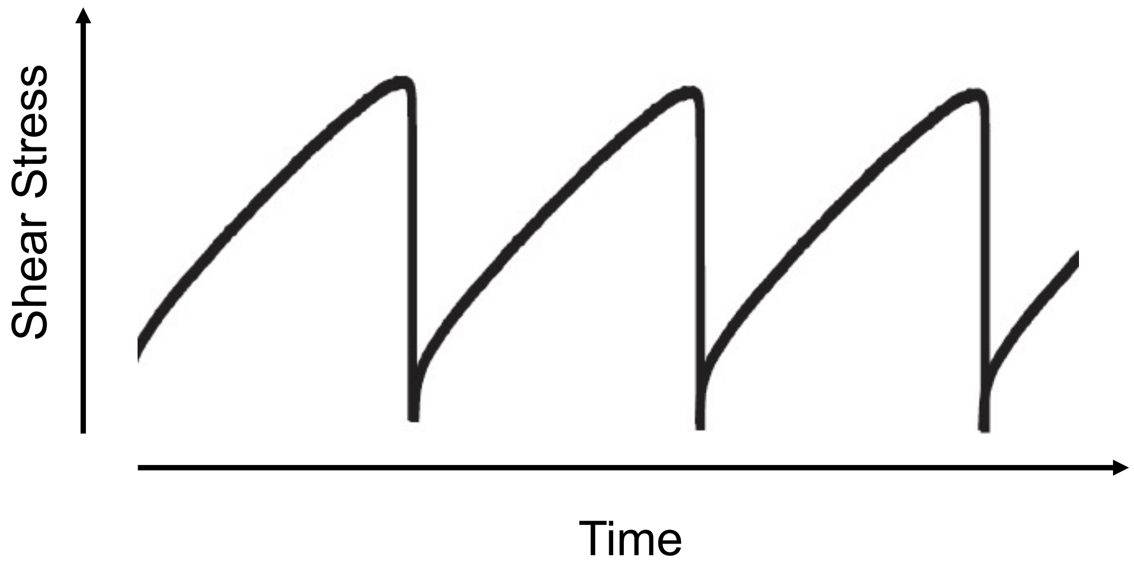
Advanced Workshop on Earthquake Fault Mechanics: Theory, Simulation and Observations
ICTP, Trieste 02 September 2019 - 14 September 2019



A good recipe should include

Microphysical framework (Adhesion theory of friction)

Slip dependent friction (static vs. kinetic)

Time dependent recovery of shear strength

Velocity dependent friction

Outline:

First slot:

- Historical introduction to friction
- Overview of experimental apparatuses
- Adhesion theory of friction
- Fault healing and frictional aging
- Slip and Velocity dependence of friction

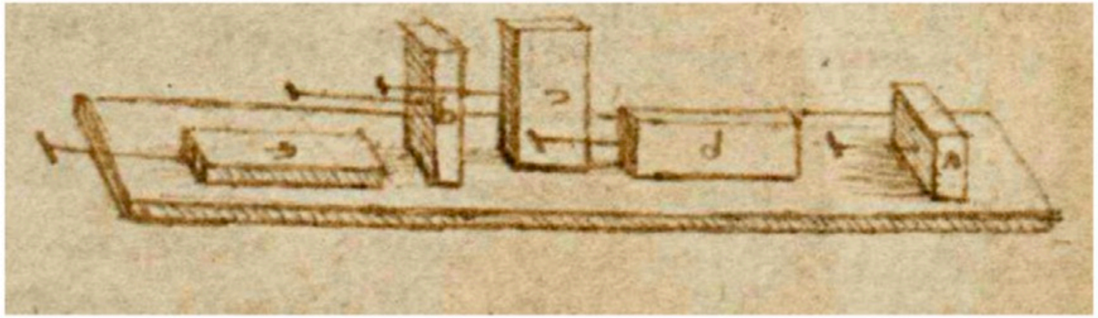
Second slot:

- Stability of frictional sliding
- Play with the spring-slider system
- From stable sliding to stick-slip in the laboratory
  (a.k.a. how theory meets the experiments)

Historical introduction to friction

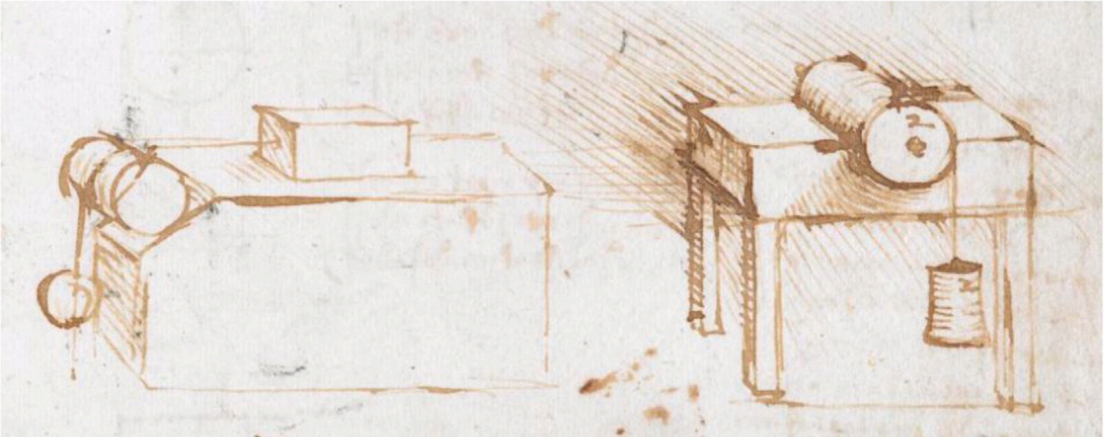
Leonardo Da Vinci

1452–1519



‘friction produces double the amount of effort if the weight be doubled’,

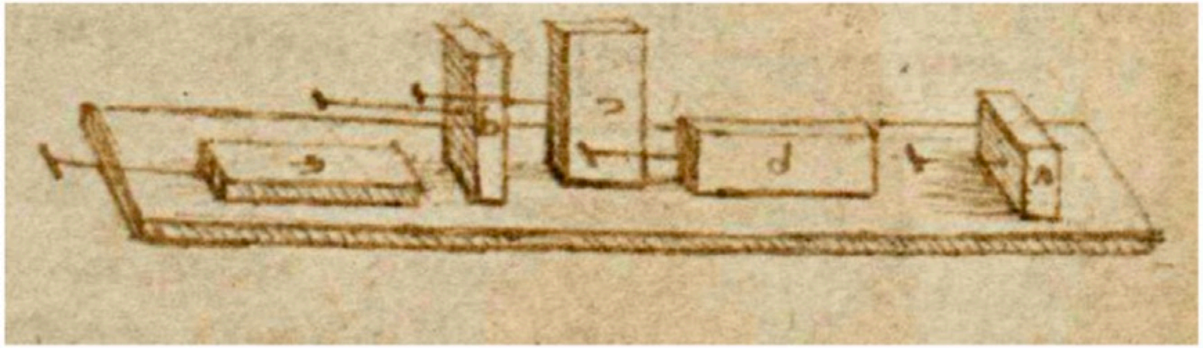
‘friction made by the same weight will be of equal resistance at the beginning of the movement though the contact may be of different breadths or lengths’



Hutchings, I. M. (2016). Leonardo da Vinci’s studies of friction. *Wear*, *360–361*, 51–66. https://doi.org/10.1016/j.wear.2016.04.019

Historical introduction to friction

Guillame Amontons
(1699)



- Amontons's first law: The frictional force is independent of the size of the surfaces in contact.
- Amontons's second law: Friction is proportional to the normal load.

Historical introduction to friction

<u>Coulomb failure criterion</u>: Failure in a rock will take place along a plane due to shear stress acting on that plane.

C.A. Coulomb
(1736-1806)

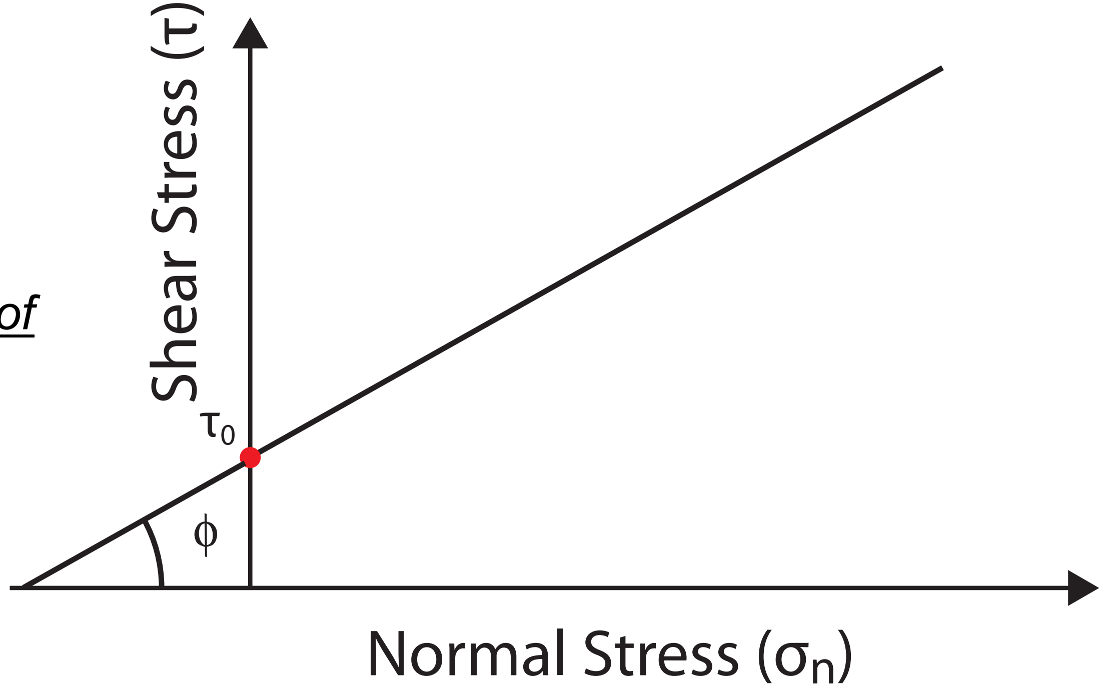
$$\tau = \tau_0 + \mu_i \sigma_n$$

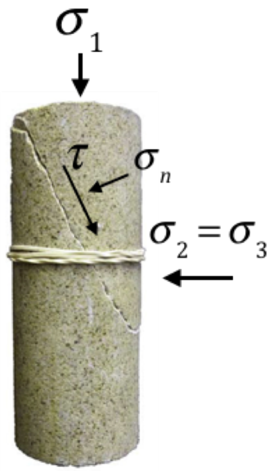
τ_0 Represent the cohesion

μ_i Represent the coefficient of internal friction

It is commonly related to the *<u>angle of internal friction</u>* by the relation:

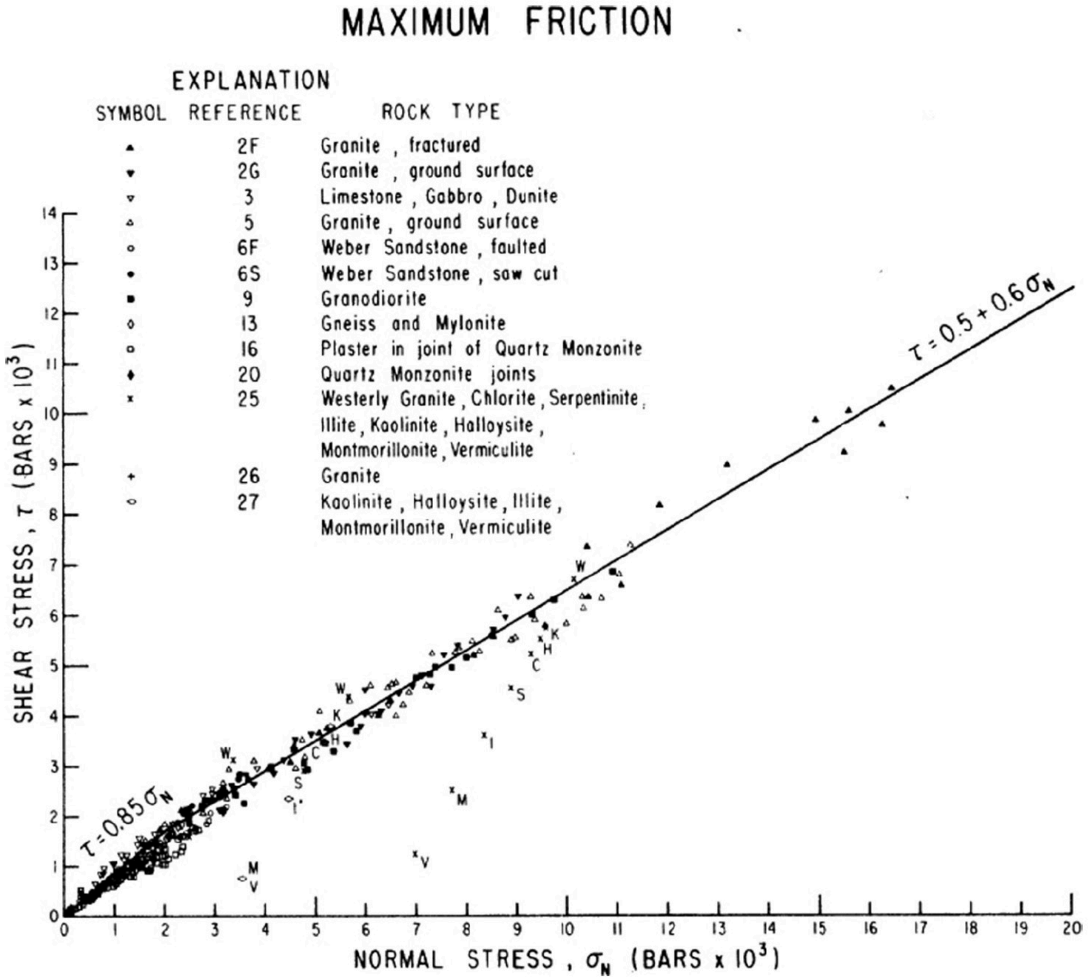
$$\mu_i = \tan\phi$$





Historical introduction to friction

Byerlee's Rule for Rock Friction (1978) $\tau = 50[MPa] + 0.6\sigma_n$

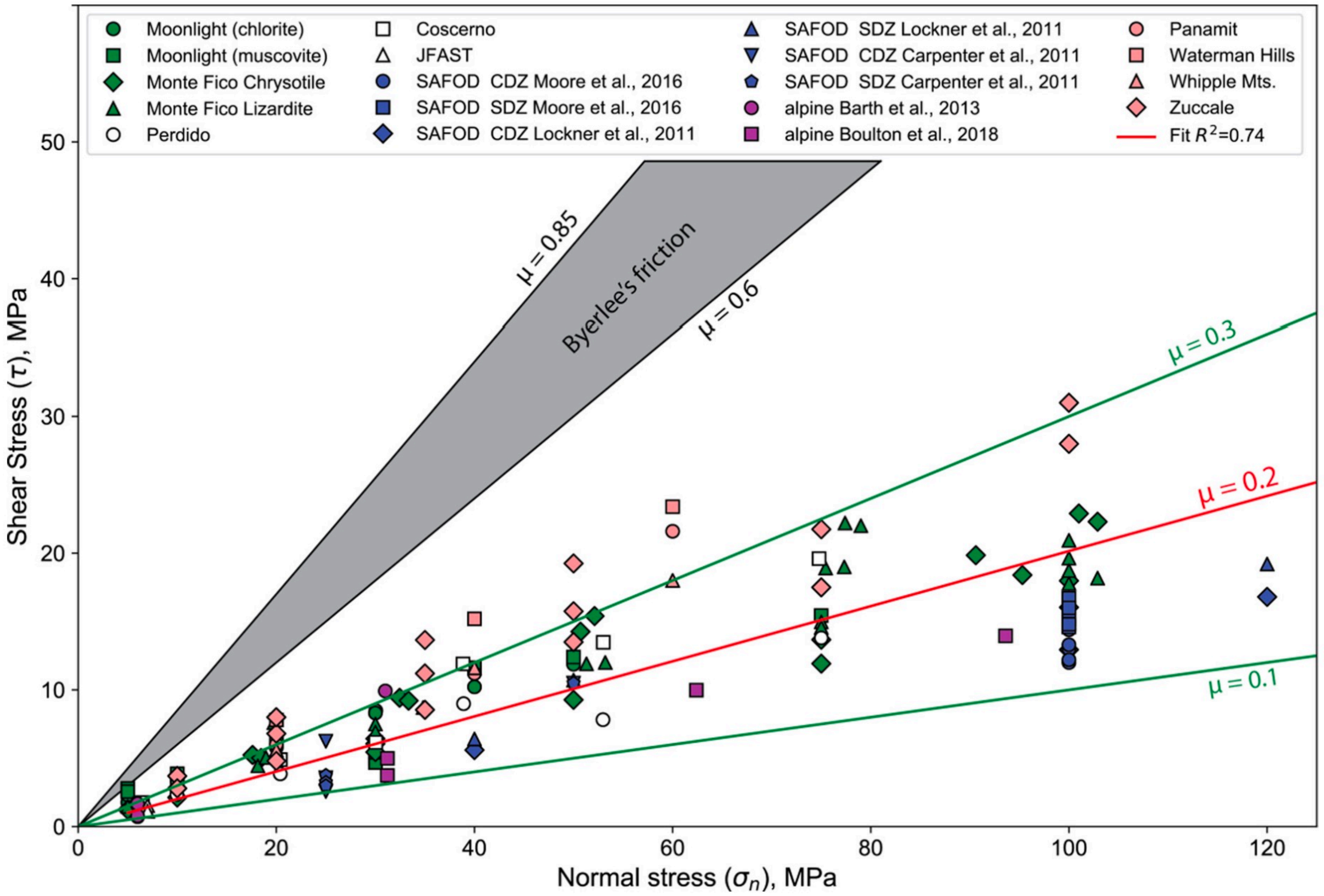


Note that Byerlee's law is just Coulomb Failure. It's simply a statement about brittle (pressure sensitive) deformation and failure.

Historical introduction to friction

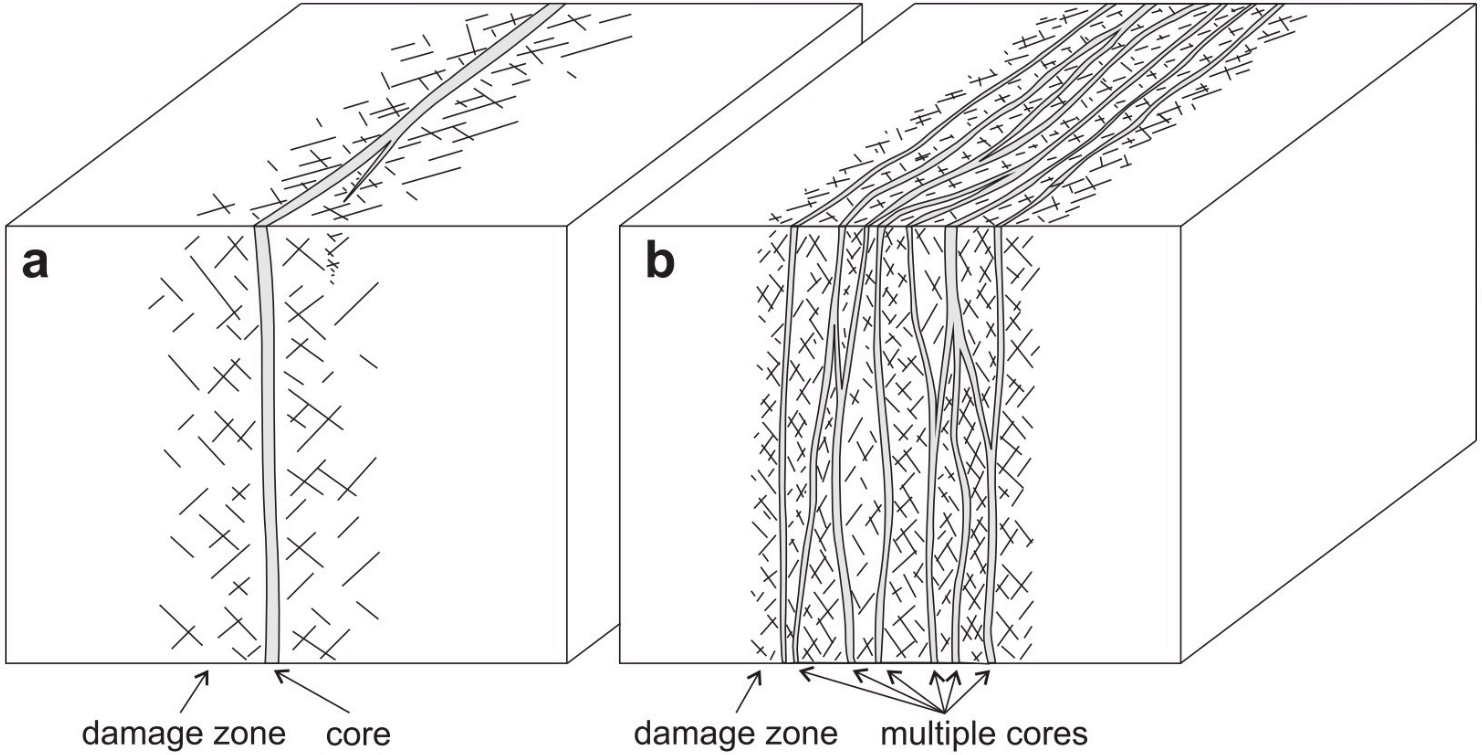
Strong vs. weak faults

However a great amount of fault zones show values of friction well below Byerlee's rule



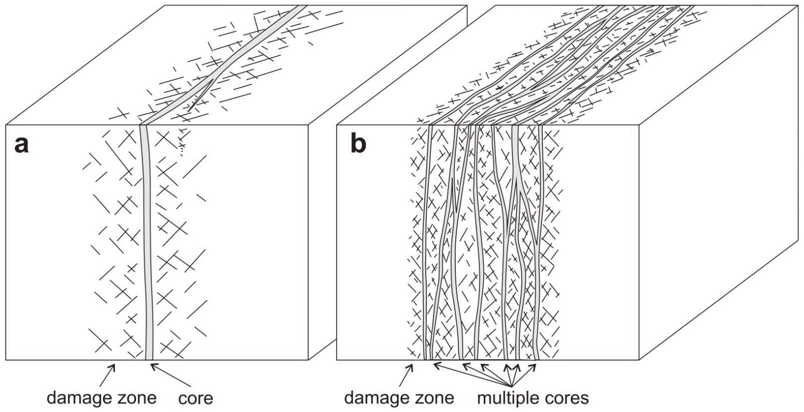
Collettini et al., 2019 EPSL

Natural fault zones and shear localization



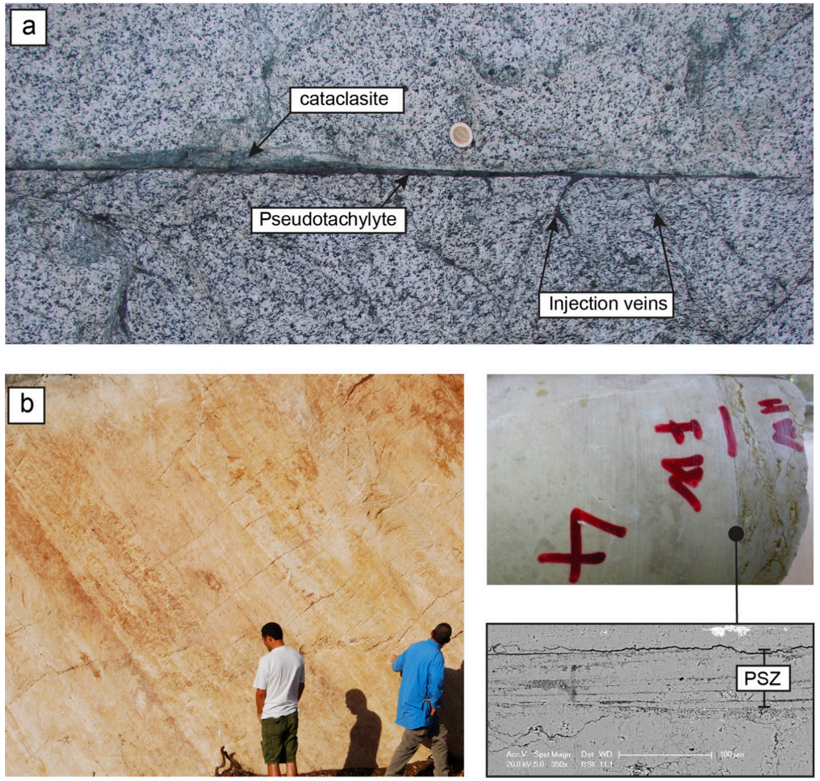
Faulkner, D. R., et al., (2010). A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. *Journal of Structural Geology*, doi.org/10.1016/j.jsg.2010.06.009

Natural fault zones and shear localization

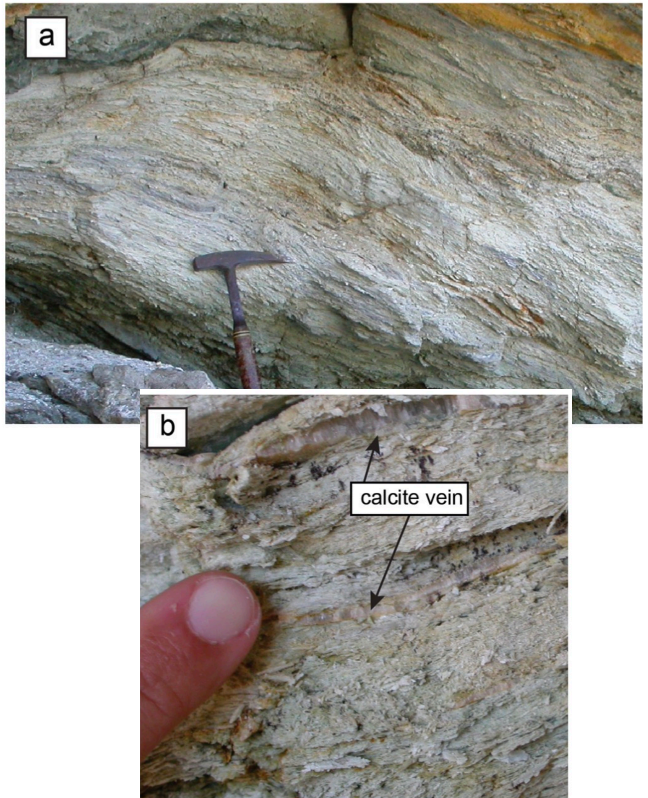


The fault core can be extremely different from fault to fault

Highly localized shear zone



Distributed deformation

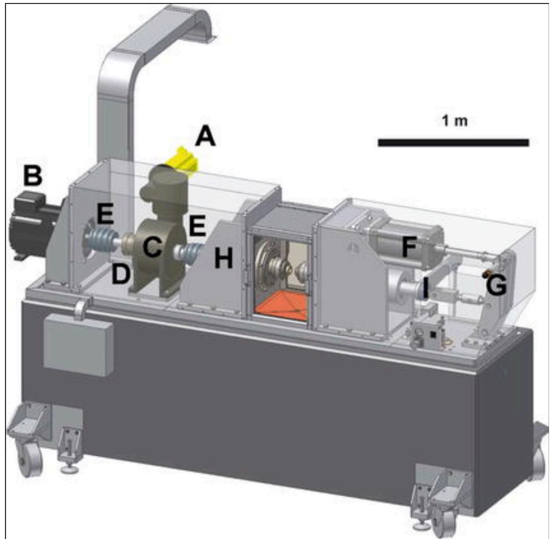


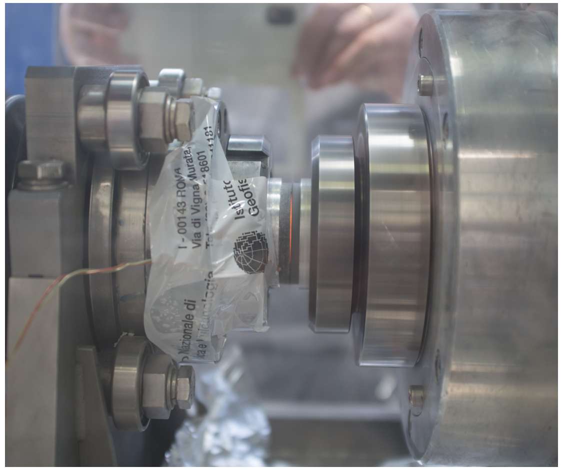
Empirical nature of friction laws – Laboratory experiments

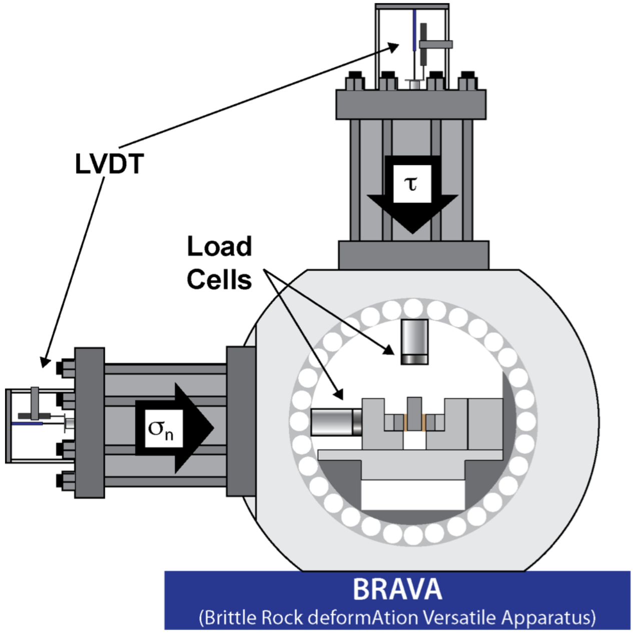
m/s

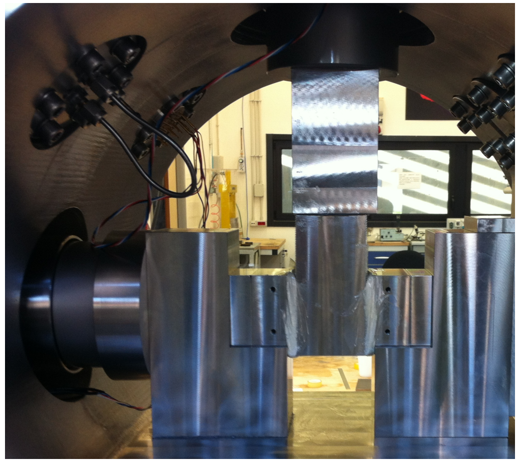
Displacement rate increases

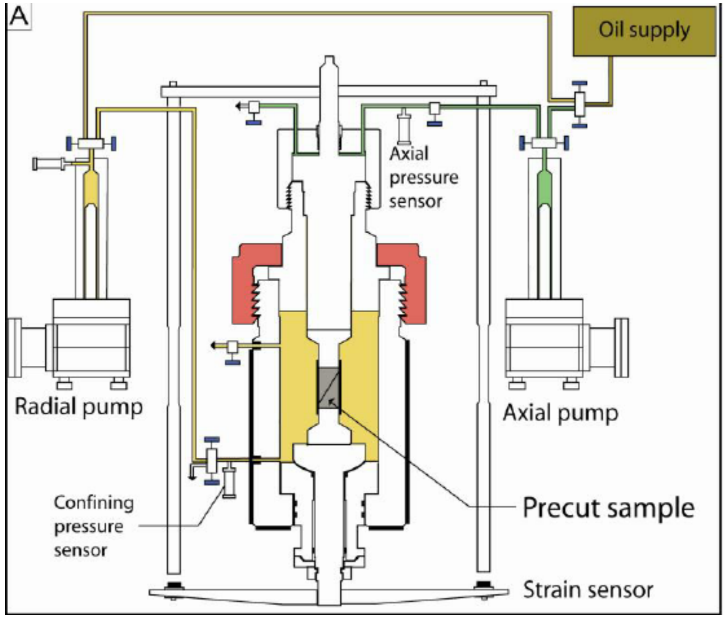
nm/s

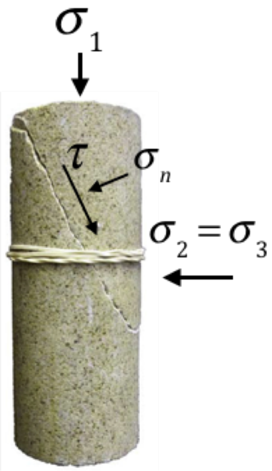










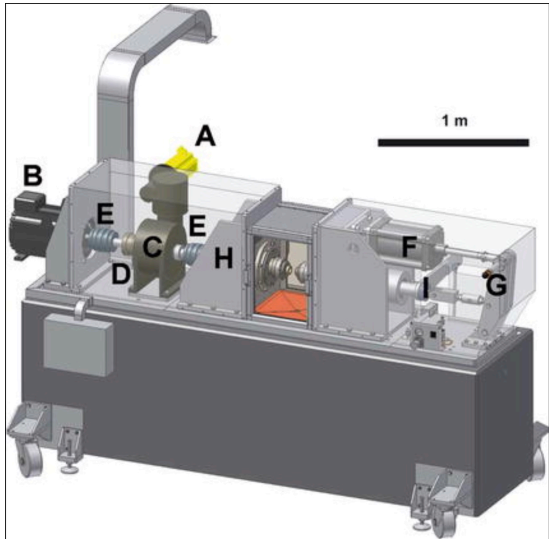


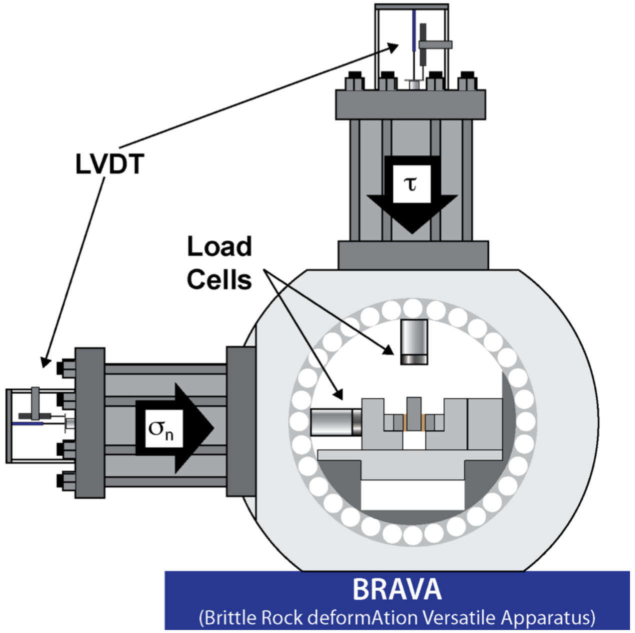
Empirical nature of friction laws – Laboratory experiments

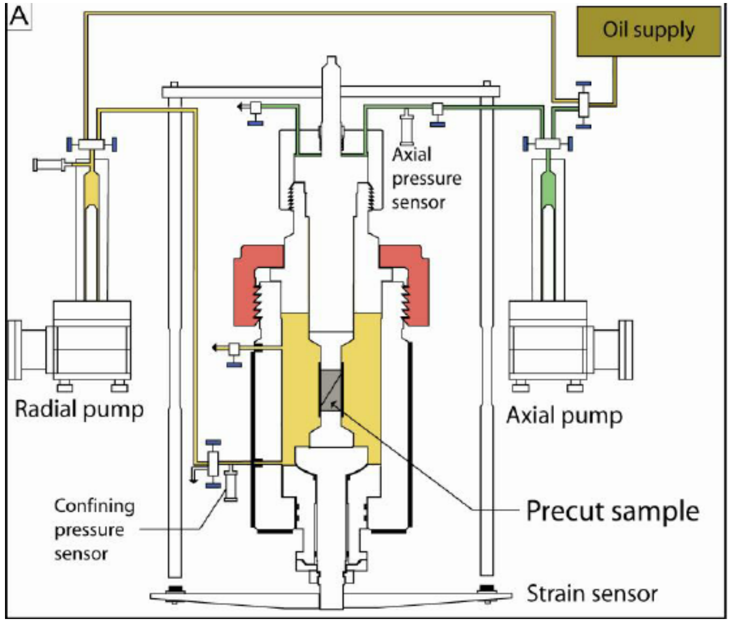
m/s

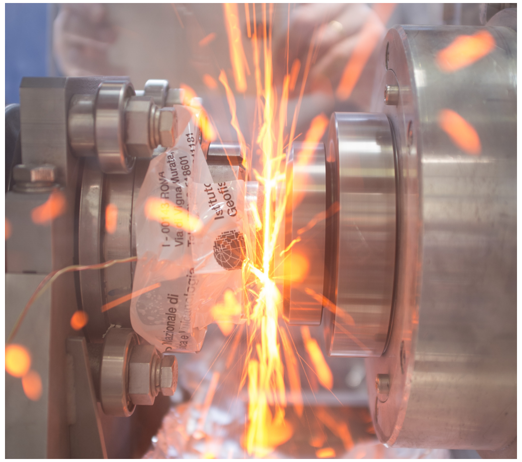
Displacement rate increases

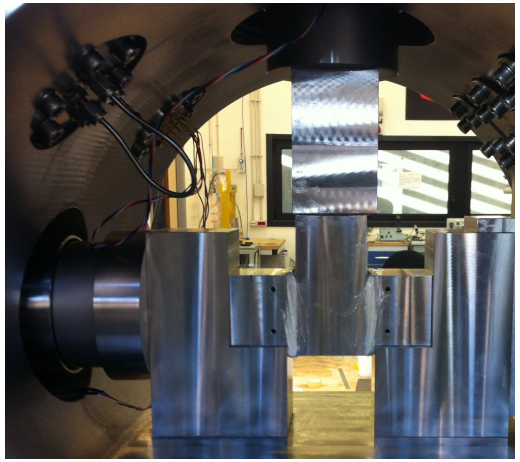
nm/s

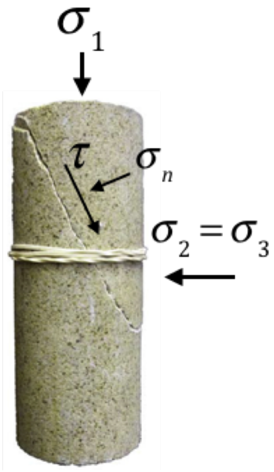










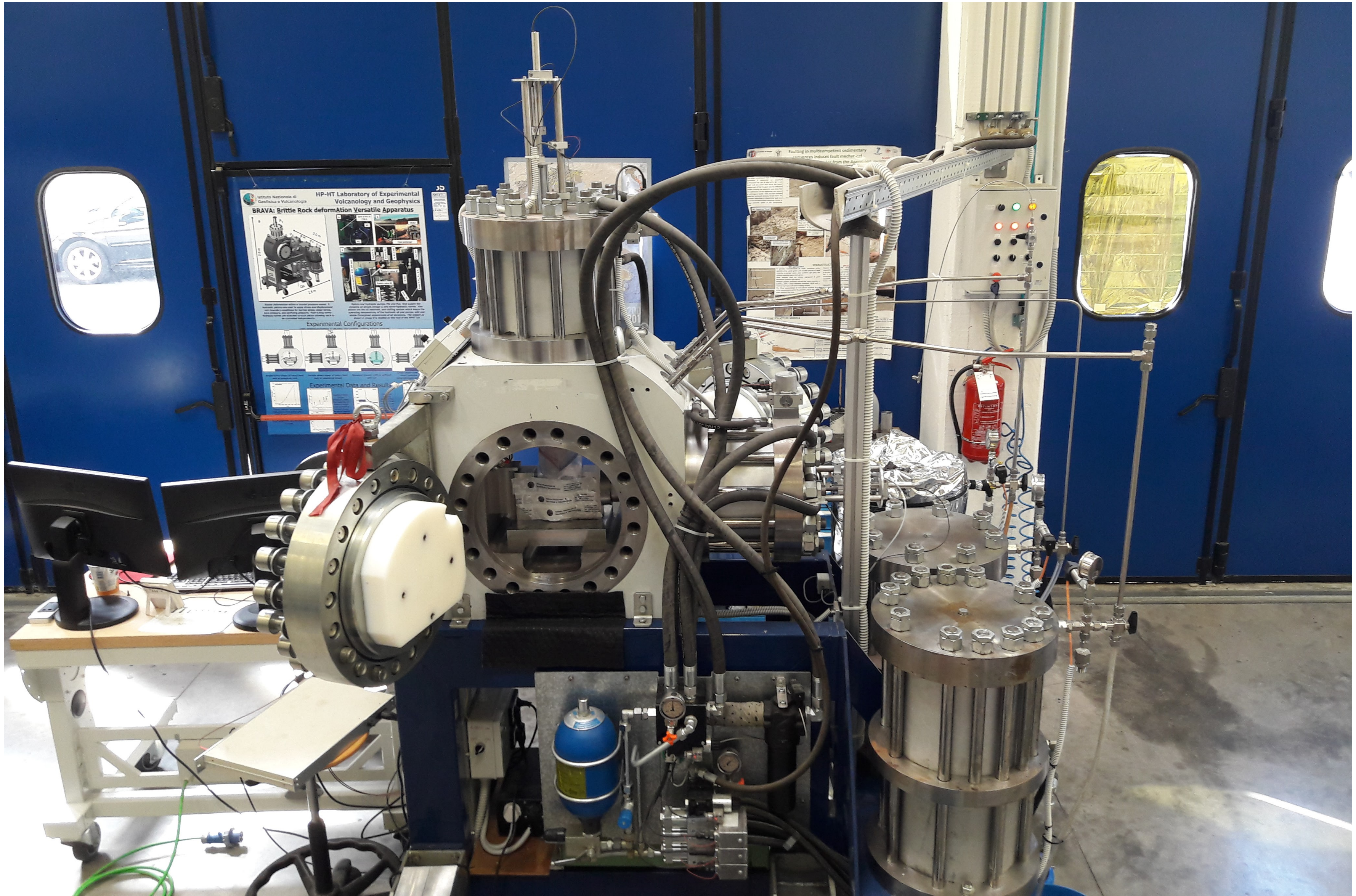


Empirical nature of friction laws – Laboratory experiments

The “Biax” Penn State Univesity, USA

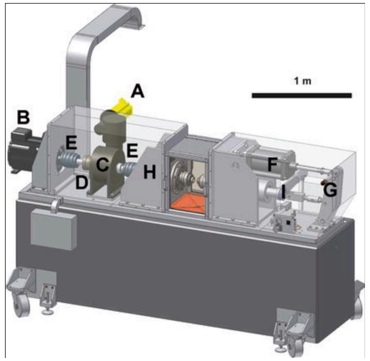
Empirical nature of friction laws – Laboratory experiments

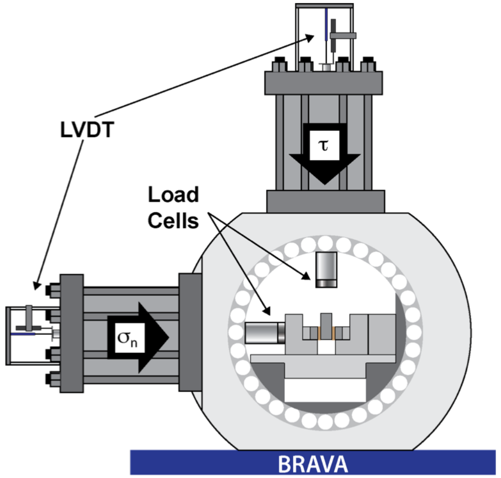
BRAVA (Brittle rock deformation versatile apparatus) Rome, Italy

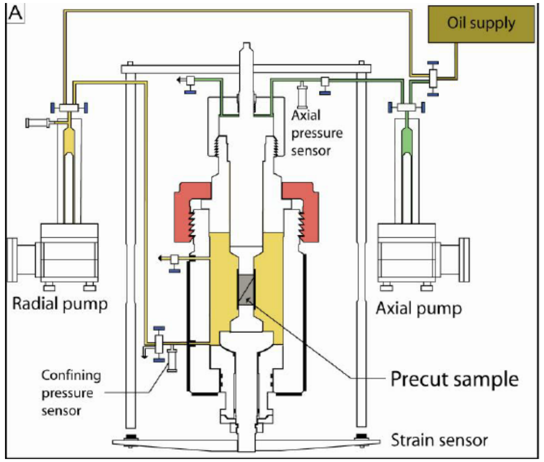


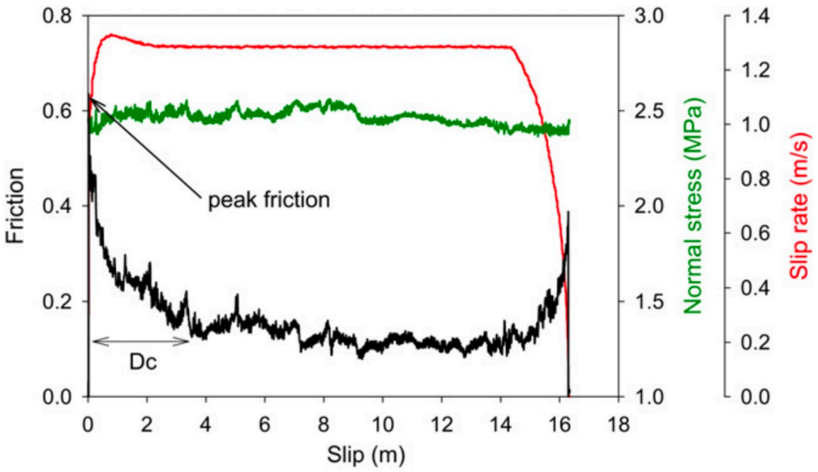
Empirical nature of friction laws – Laboratory experiments

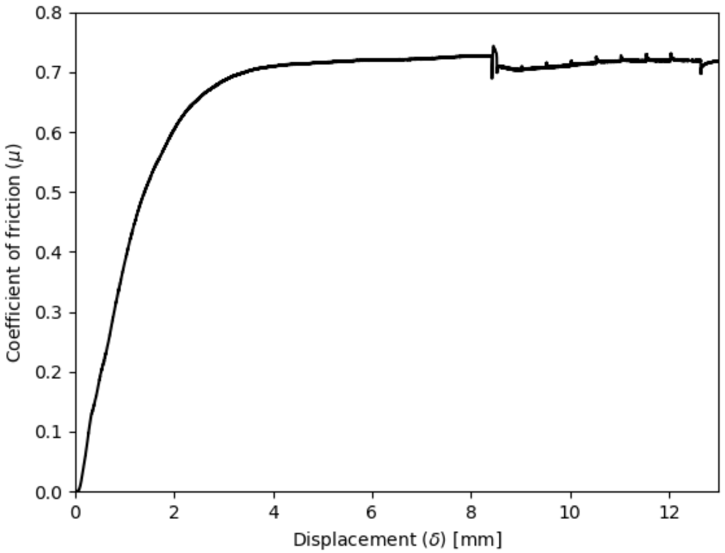
m/s Displacement rate increases nm/s

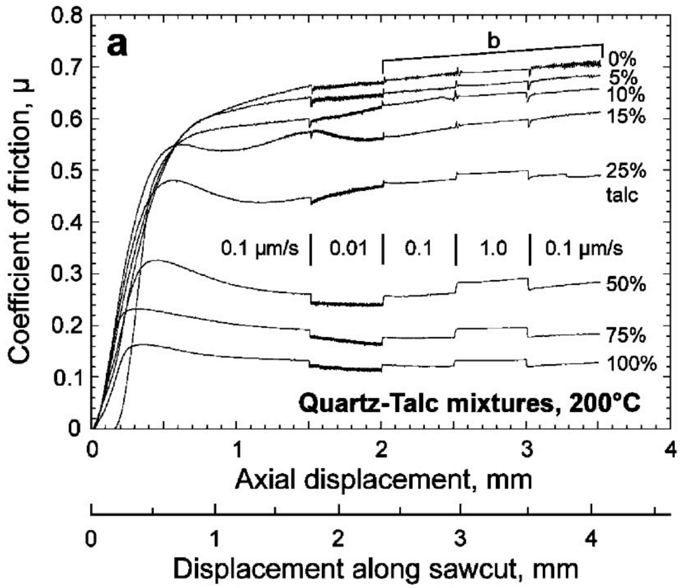




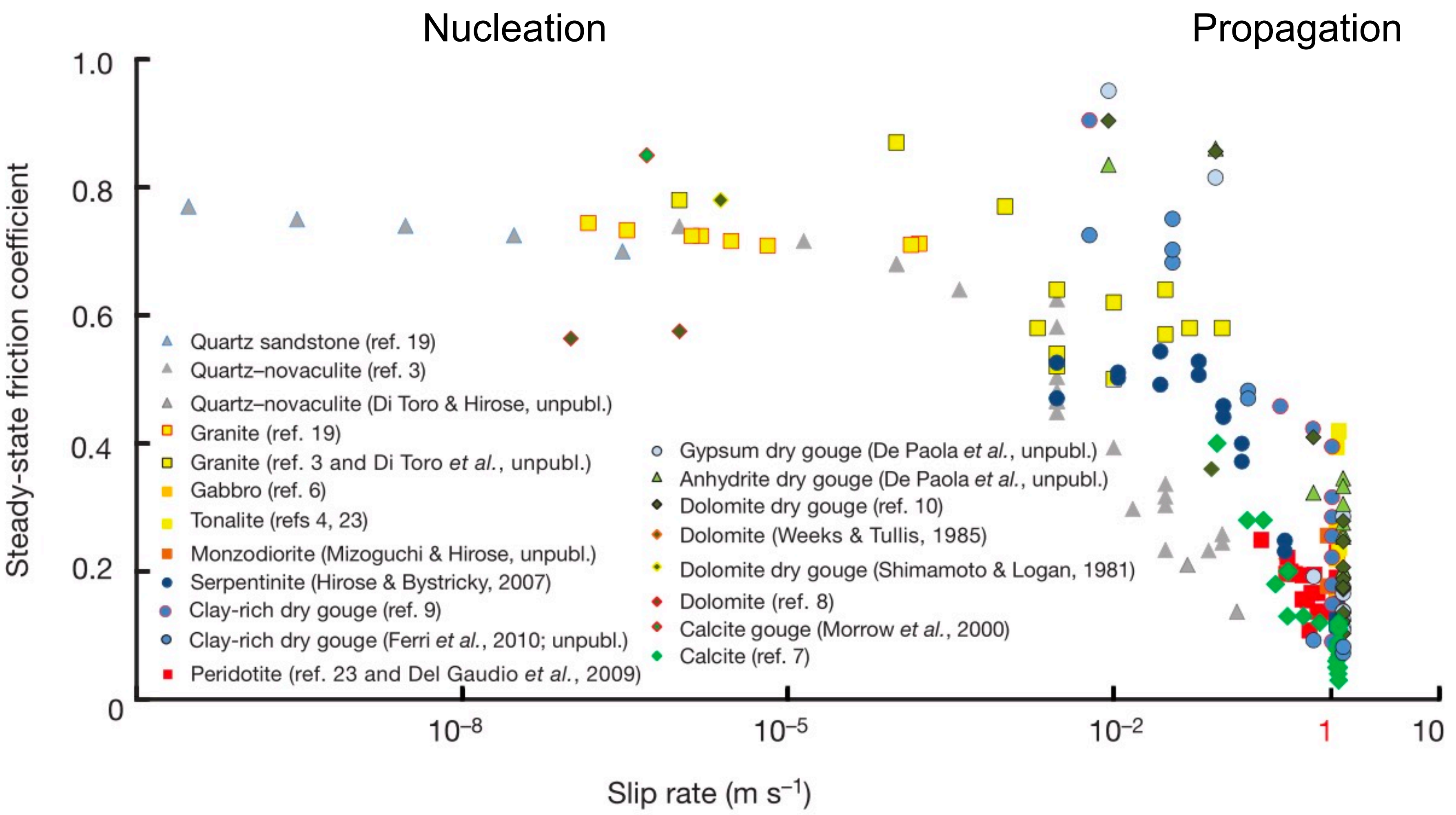






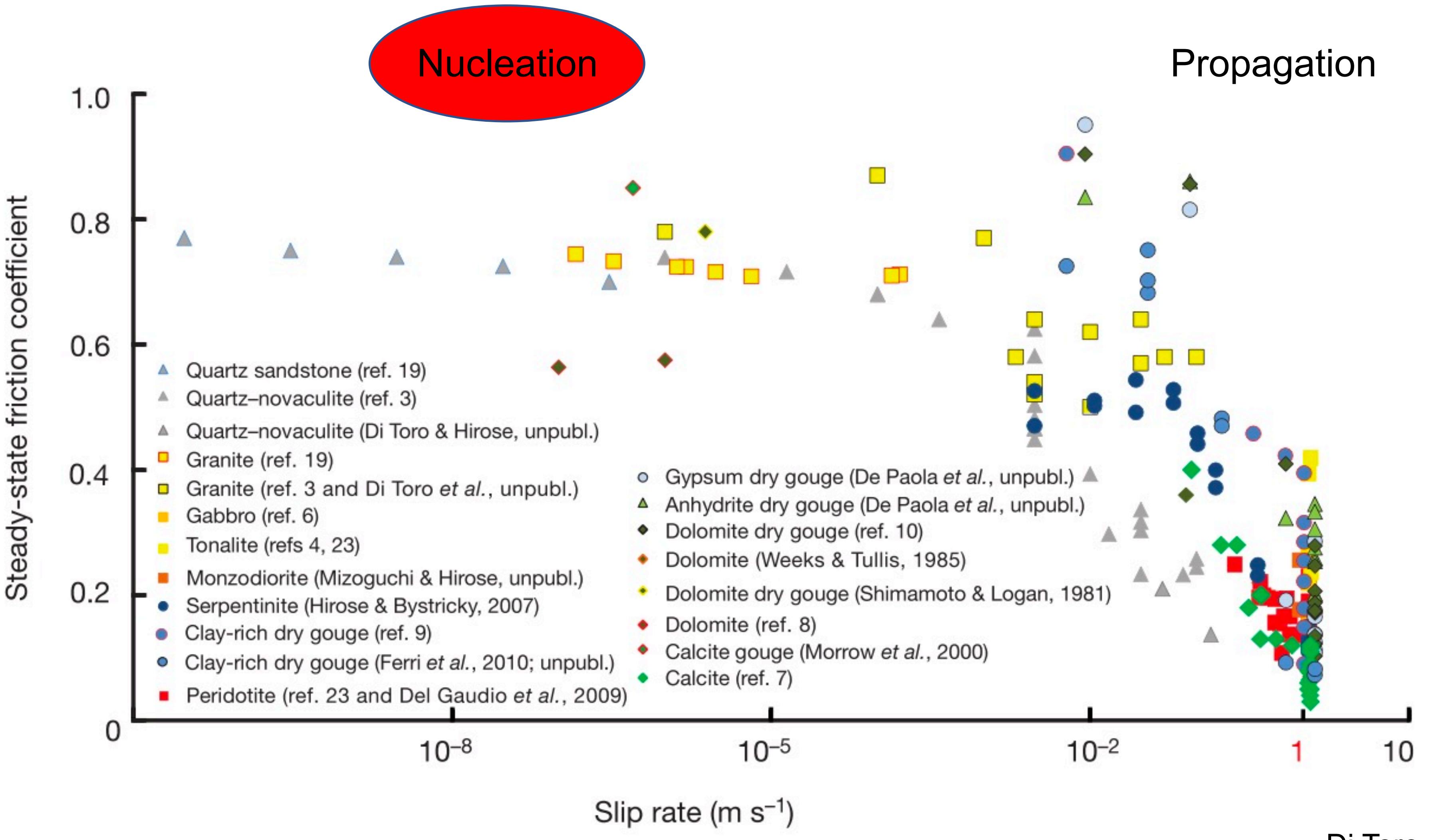


Empirical nature of friction laws – Laboratory experiments



Di Toro et al., 2011 Nature

Empirical nature of friction laws – Laboratory experiments



Di Toro et al., 2011 Nature

A good recipe should include

Microphysical contact evolution (Adhesion theory of friction)

Slip dependent friction (static vs. kinetic)

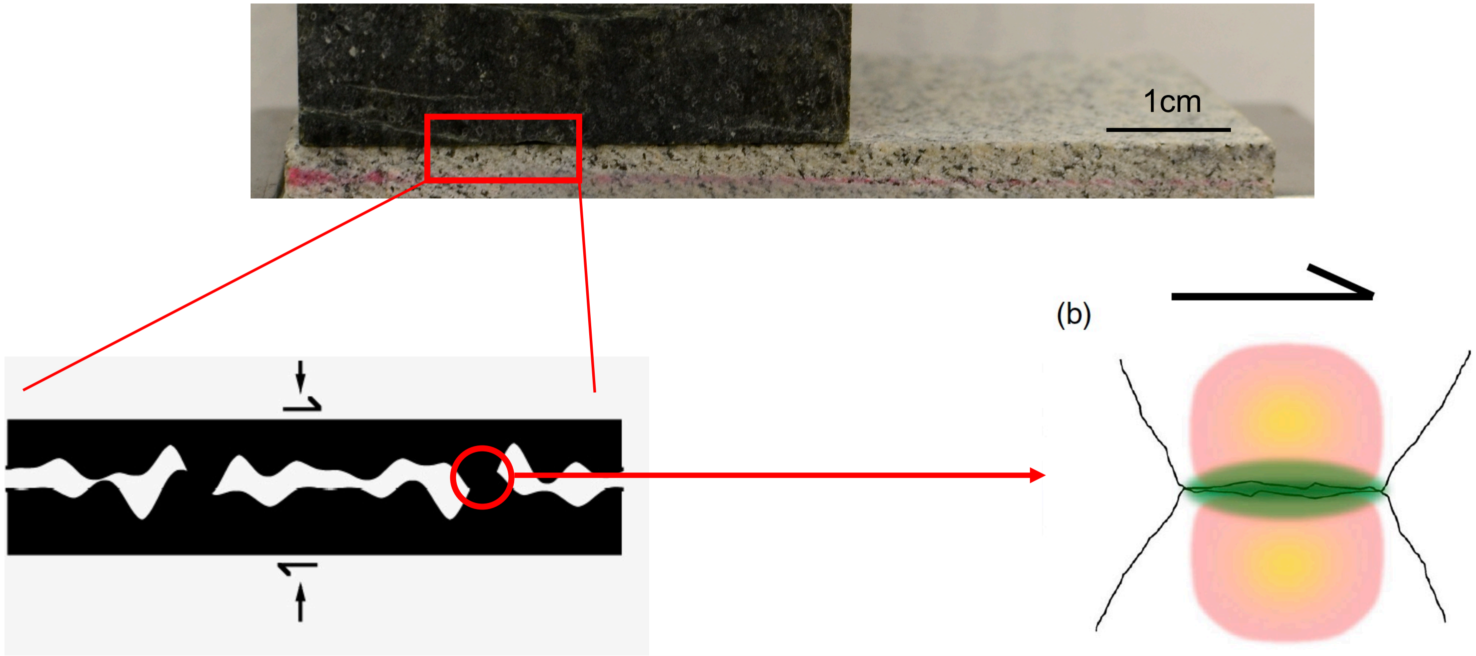
Time dependent recovery of shear strength

Velocity dependent friction

Micromechanics of contacts – Adhesion theory of friction

Bowden and Tabor (1964)

Real area of contact between surfaces, A_r, is much smaller than the apparent area of the surface, A.
$A >> A_r$



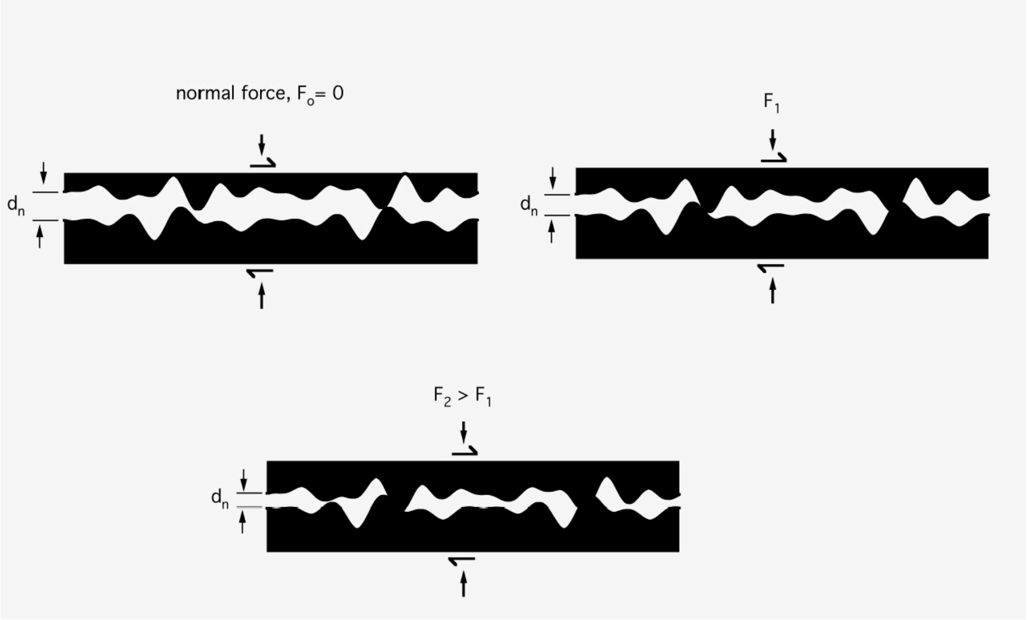
Ar~10% of A

Micromechanics of contacts – Adhesion theory of friction

Bowden and Tabor (1964)

$A >> A_r$

Stress at contact junctions



$$\sigma_c A_r = \sigma_n$$

Where:
σ_n is the normal load
σ_c is the indentation hardness of the material

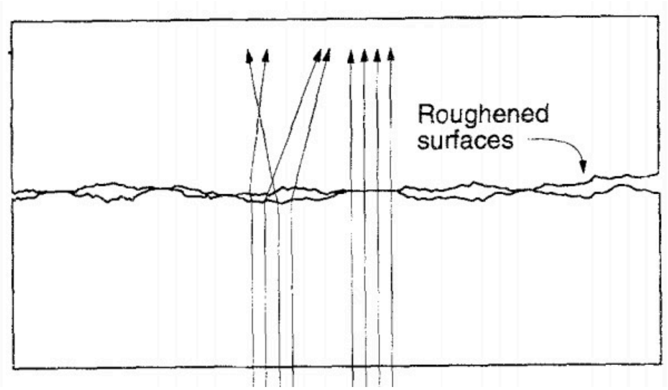
Each contact is under a much higher normal stress than the nominal stress σ_n

contact stress is:

$$\sigma_c = \sigma_n \frac{A}{A_r}$$

C. Scholz, The mechanics of earthquakes and faulting, Chapter 2 (2019)

Micromechanics of contacts – Adhesion theory of friction



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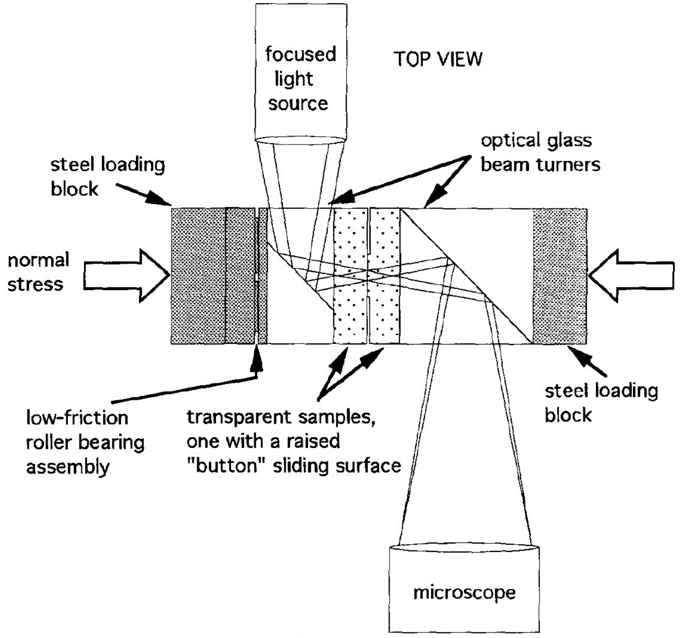
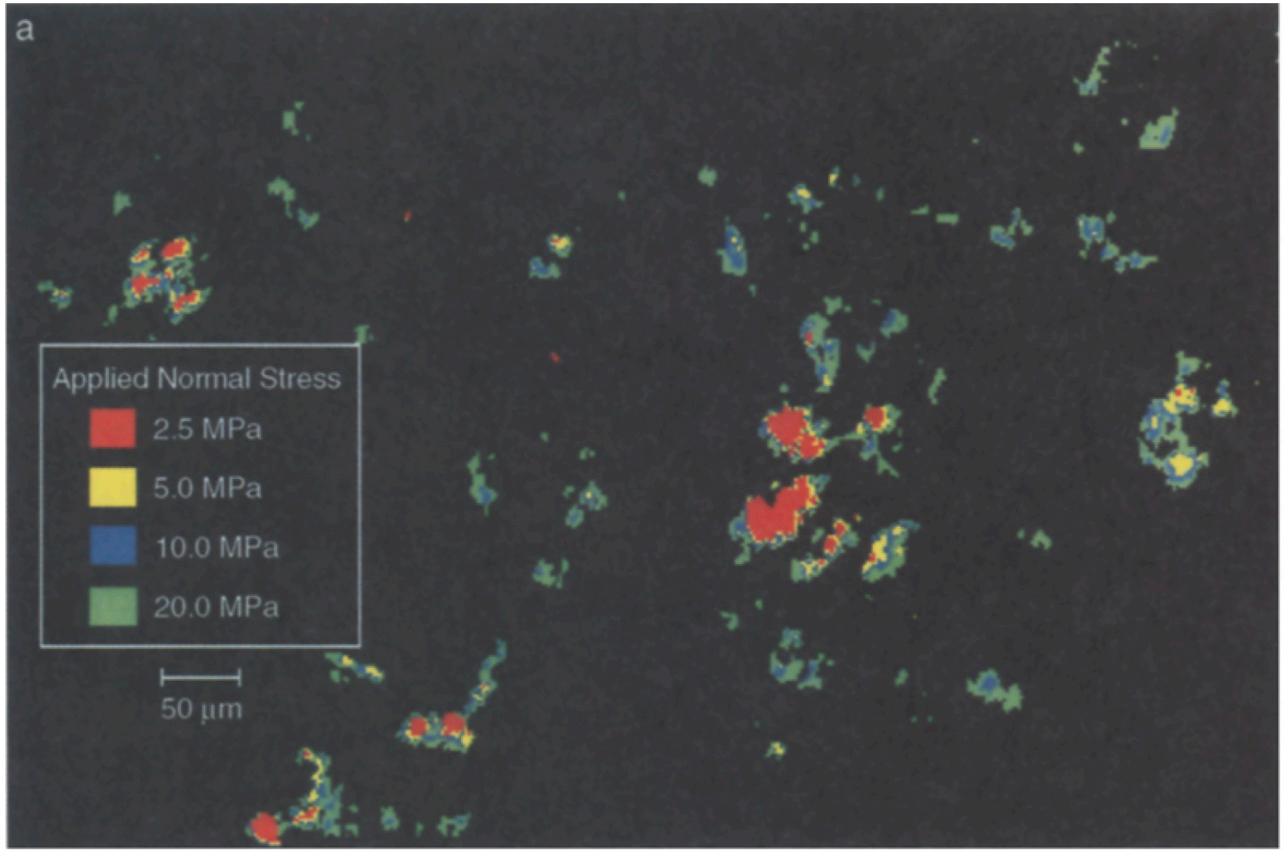


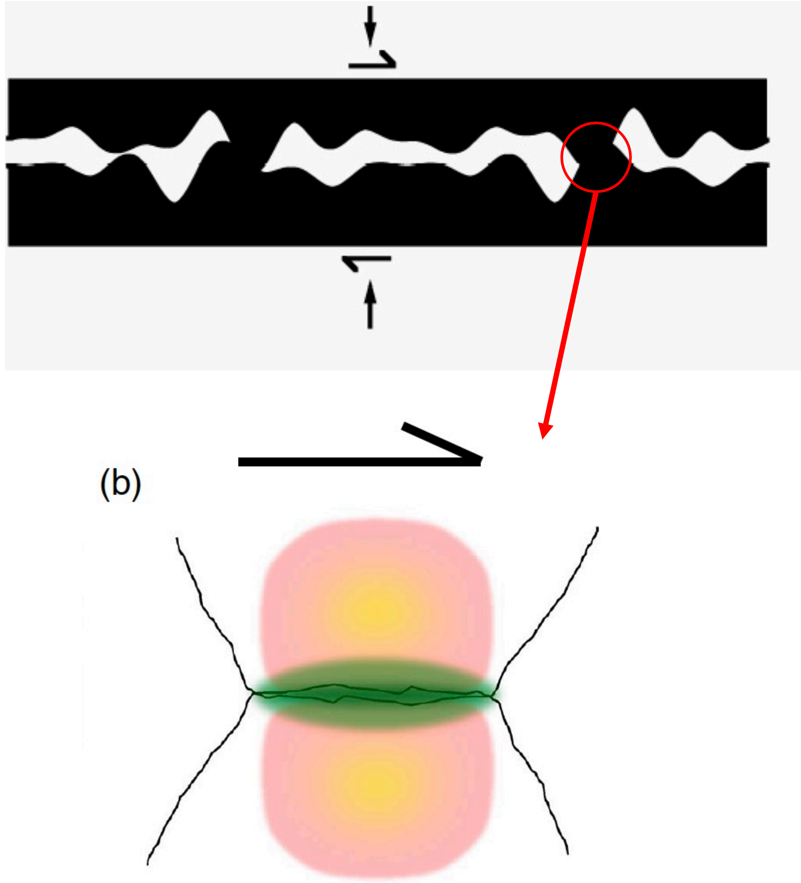


contact stress is: $\sigma_c = \sigma_n \frac{A}{A_r}$

Dieterich and Kilgore, 1994 PAGEOPH

Micromechanics of contacts – Adhesion theory of friction

Bowden and Tabor (1964)



$A >> A_r$

Normal force:

$$\sigma_c A_r = \sigma_n$$

Shear force needed to shear the asperities is:

$$\tau = \tau_c A_r$$

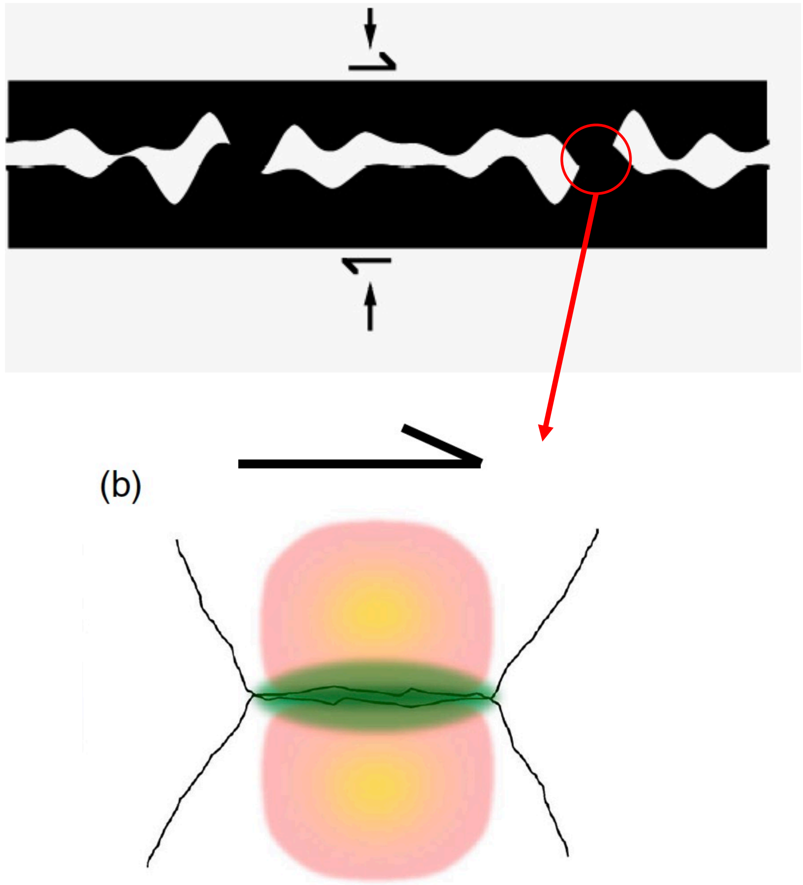
τ_c is a specific shear stress

The resulting coefficient of friction is:

$$\mu = \frac{\tau}{\sigma_n} = \frac{\tau_c A_r}{\sigma_c A_r} = \frac{\tau_c}{\sigma_c}$$

Micromechanics of contacts – Adhesion theory of friction

Bowden and Tabor (1964)



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$$\mu = \frac{\tau}{\sigma_n} = \frac{\tau_c A_r}{\sigma_c A_r} = \frac{\tau_c}{\sigma_c}$$

This idea, of existence and yielding of microscopic contacts as the origin of macroscopic friction, is one of the pillars of present-day understanding of friction.

Micromechanics of contacts – Adhesion theory of friction

• Although the adhesion theory of friction conceptualizes the physical essence of the frictional interaction, in most cases it does not predict the correct value for μ.

• This is because overcoming junction adhesion is usually not the only work done in friction. Other processes such as interlocking, wear, surface production, ploughing and dilational work (and many other) can contribute to the measured friction.

• Furthermore, A_r is a minimum value, and it may increase and evolve with time, shear and shear rate.

• The adhesion theory of friction therefore can be used only as a conceptual framework.

• It is **especially important** for geological applications, where, in order to scale from laboratory to geological conditions, we must understand the micromechanisms involved in the process.

A good recipe should include

Microphysical contact evolution (Adhesion theory of friction)

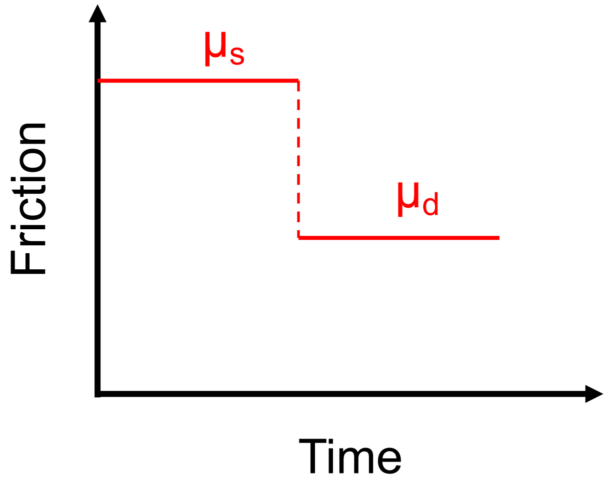
Slip dependent friction (static vs. kinetic)

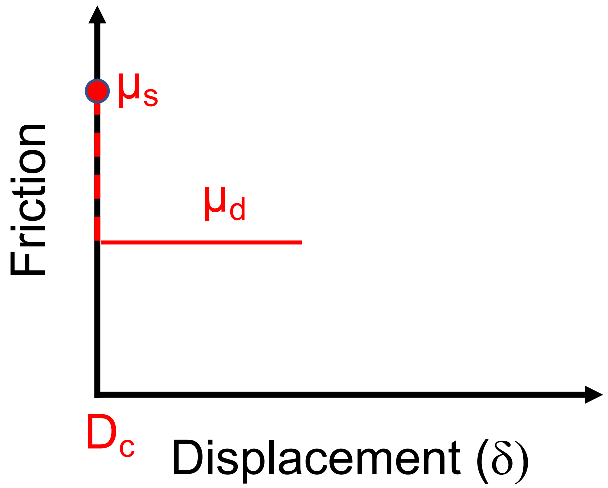
Time dependent recovery of shear strength

Velocity dependent friction

Slip dependence of frictional strength from static to kinetic friction

Classical view





μ_s Static friction (force to start motion)

μ_d Dynamic friction (Force to keep a surface moving)

$\mu = \mu_s$ for $\delta < D_c$

$\mu = \mu_d$ for $\delta > D_c$

D_c critical slip distance

Slip dependence of frictional strength from static to kinetic friction

E. Rabinowicz 1951, 1956, 1958

JOURNAL OF APPLIED PHYSICS VOLUME 22, NUMBER 11 NOVEMBER, 1951

The Nature of the Static and Kinetic Coefficients of Friction

ERNEST RABINOWICZ
Lubrication Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received May 23, 1951)

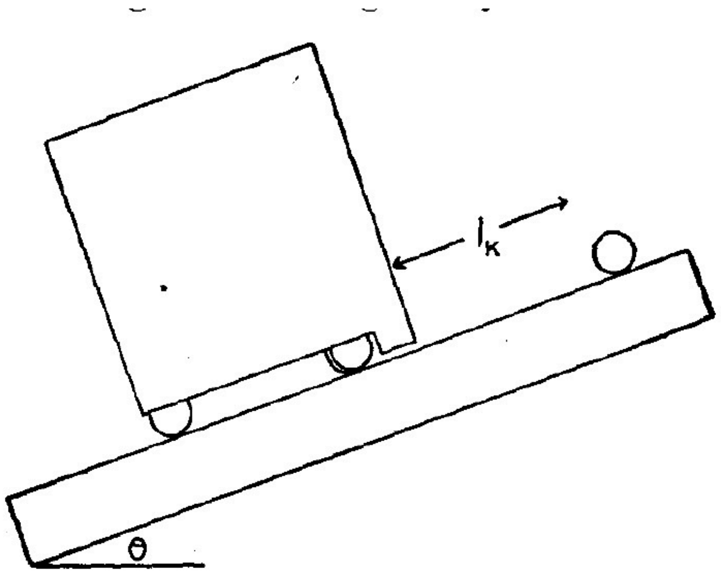
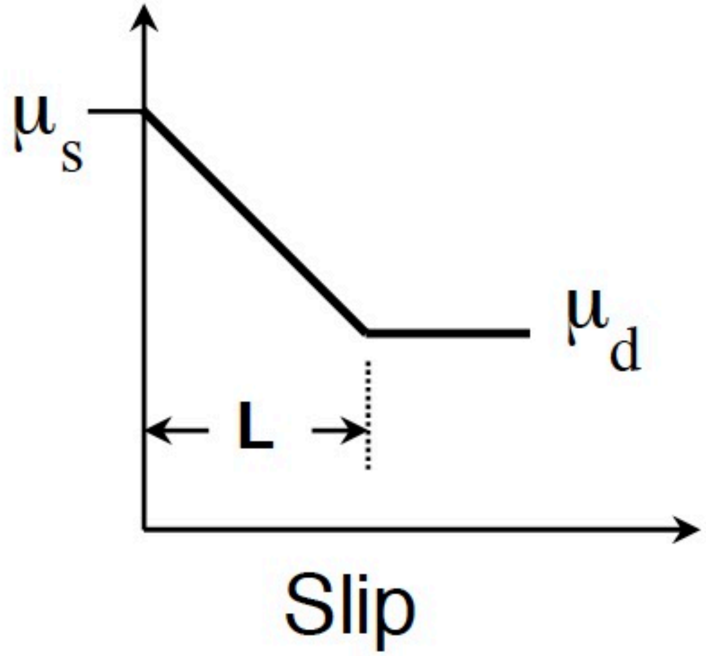


FIG. 5. Sketch of the apparatus.

Slip dependence of frictional strength – from static to kinetic friction

Rabinowicz's work solved a major problem with friction theory: he introduced a way to deal with the singularity in going from μ_s to μ_d



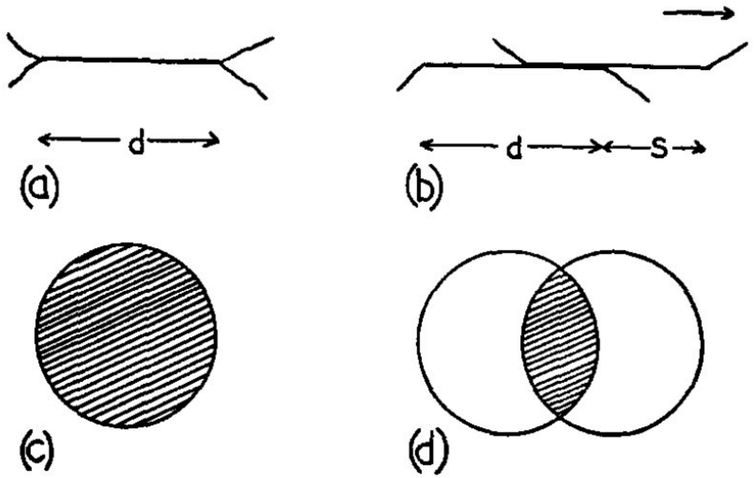


FIG. 12. Idealized representation of a typical metallic junction in elevation and plan, the shaded region being the true area of contact. (a) and (c) :—as formed during static loading. (b) and (d) :—after sliding a distance *s*.

For solid surfaces in contact (without wear materials), the critical slip L represents the slip necessary to break down adhesive contact junctions formed during 'static' contact and create a new population.

Slip dependence of frictional strength – from static to kinetic friction

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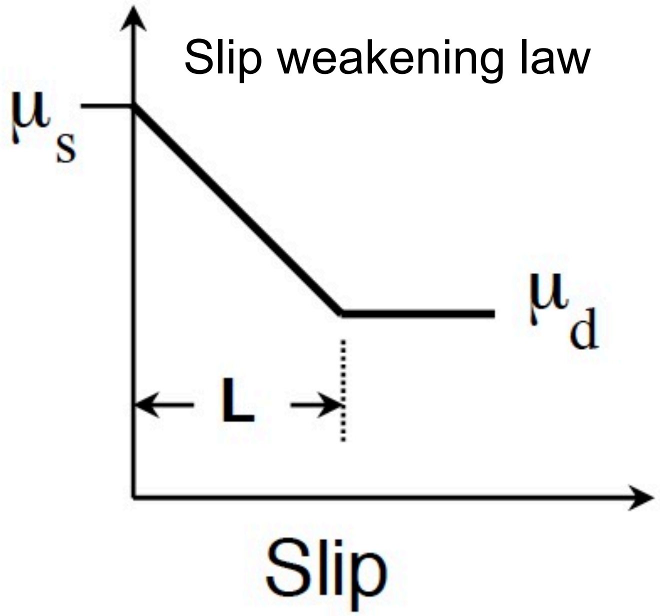
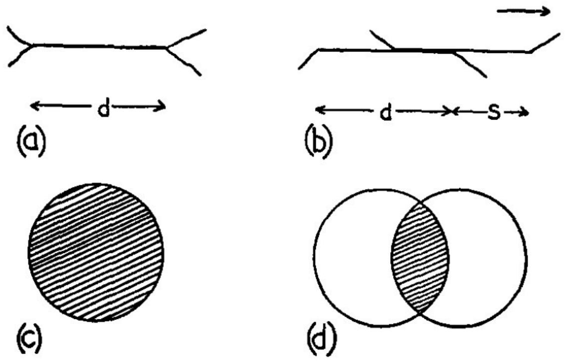




$$\mu(x) = \mu_s - \frac{x}{L}\Delta\mu \quad (for\ L > x > 0)$$

$$\mu(x) = \mu_s - \Delta\mu \quad (for\ x > L)$$

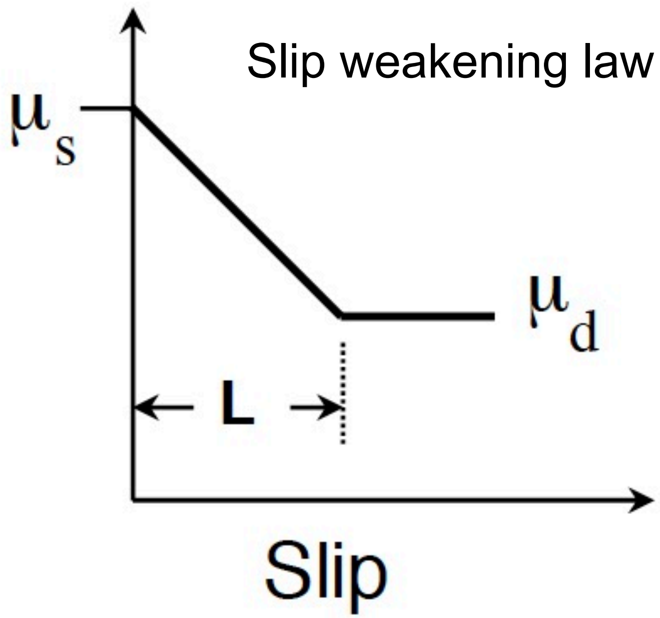
Palmer and Rice, 1973
Ida, 1972 JGR
Rice, 1980 JGR
Ohnaka, 2003 JGR (Review)

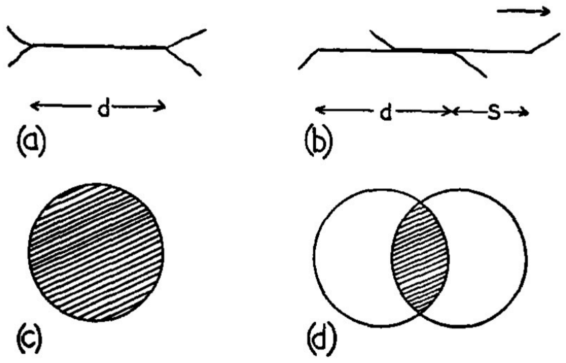
For solid surfaces in contact (without wear materials), the critical slip L represents the slip necessary to break down adhesive contact junctions formed during 'static' contact and create a new population.

Slip dependence of frictional strength – from static to kinetic friction

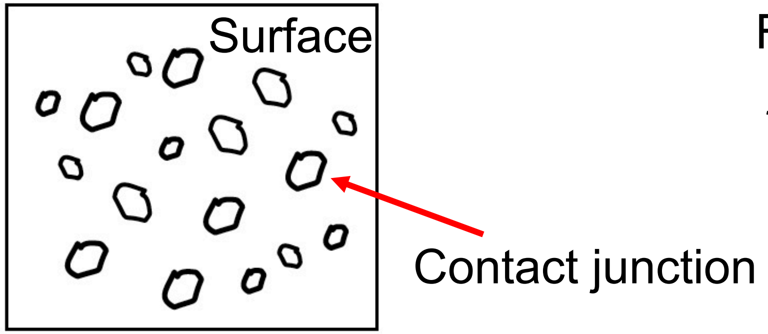
Rabinowicz's work solved a major problem with friction theory: he introduced a way to deal with the singularity in going from μ_s to μ_d

Slip weakening law





Critical distance scales with surface roughness



For a surface with distribution of contact junction sizes, L, will be proportional to the average contact dimension.

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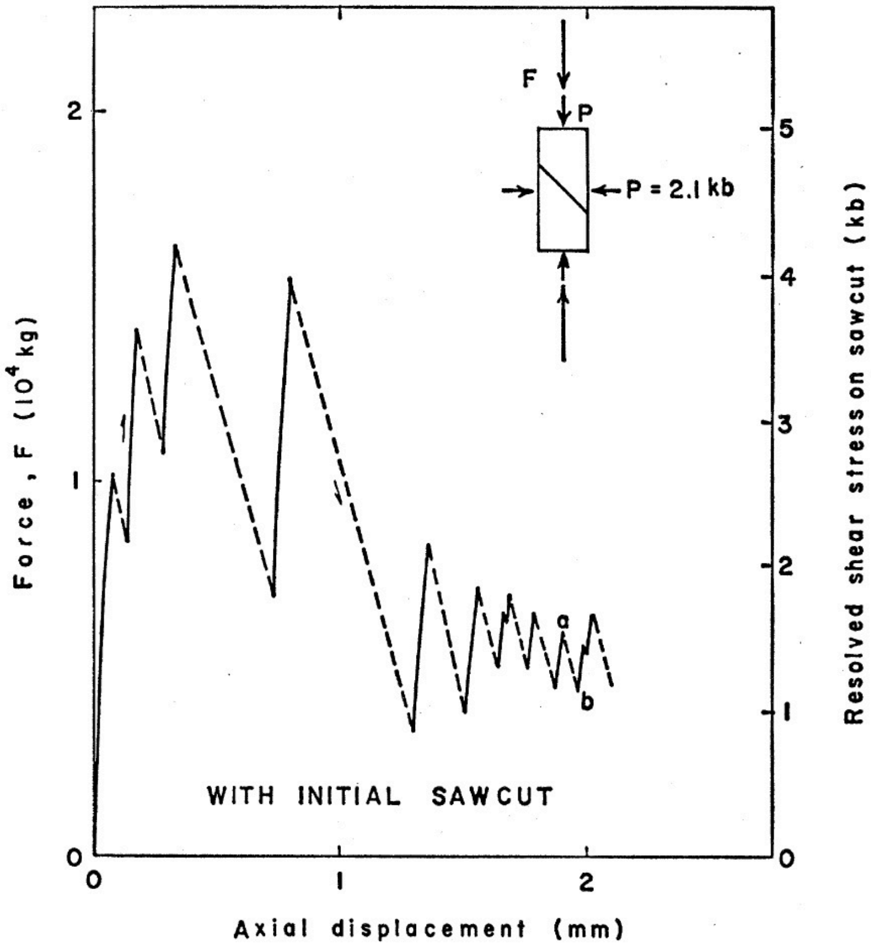
What all of these talking of asperities has to deal with earthquakes?

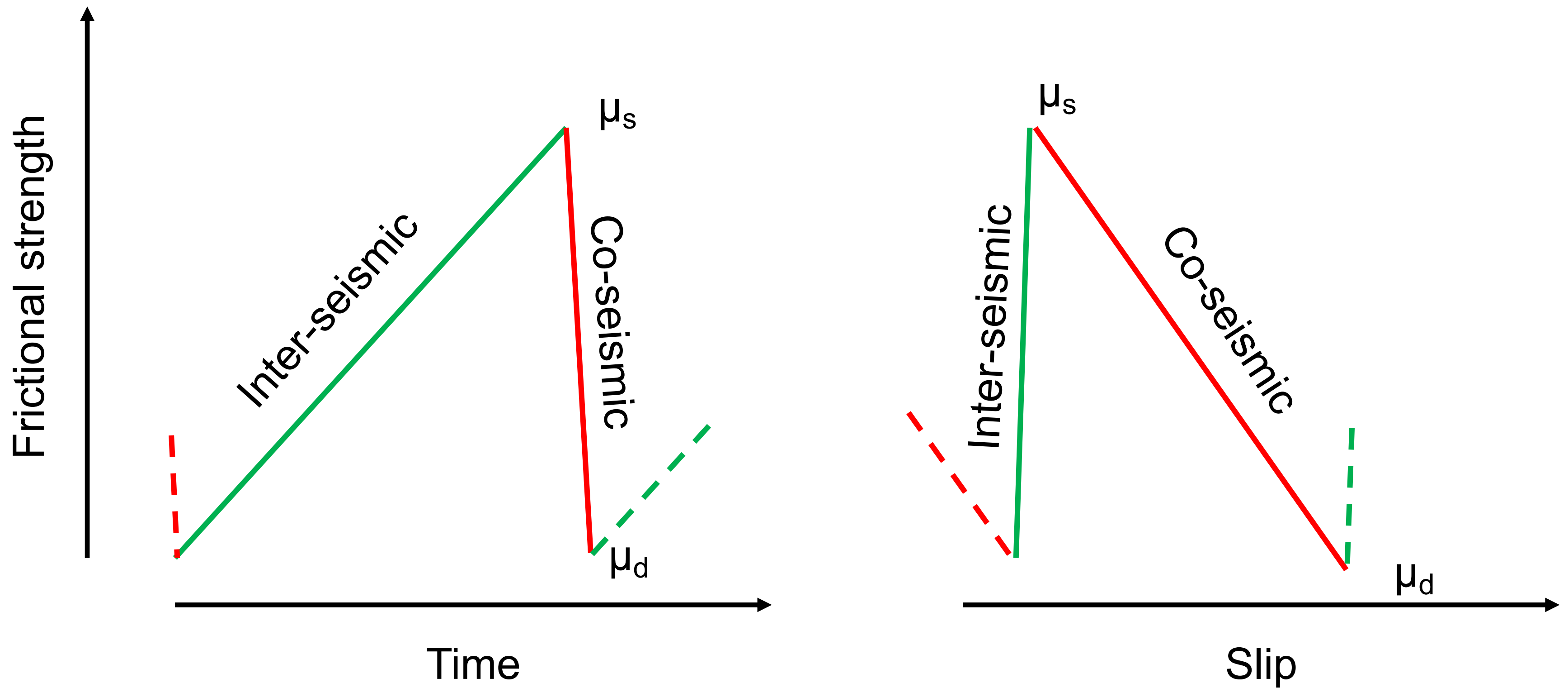
Brace and Byerlee, 1966

Stick-Slip as a Mechanism for Earthquakes

Abstract. *Stick-slip often accompanies frictional sliding in laboratory experiments with geologic materials. Shallow-focus earthquakes may represent stick-slip during sliding along old or newly formed faults in the earth. In such a situation, observed stress drops represent release of a small fraction of the stress supported by the rock surrounding the earthquake focus.*



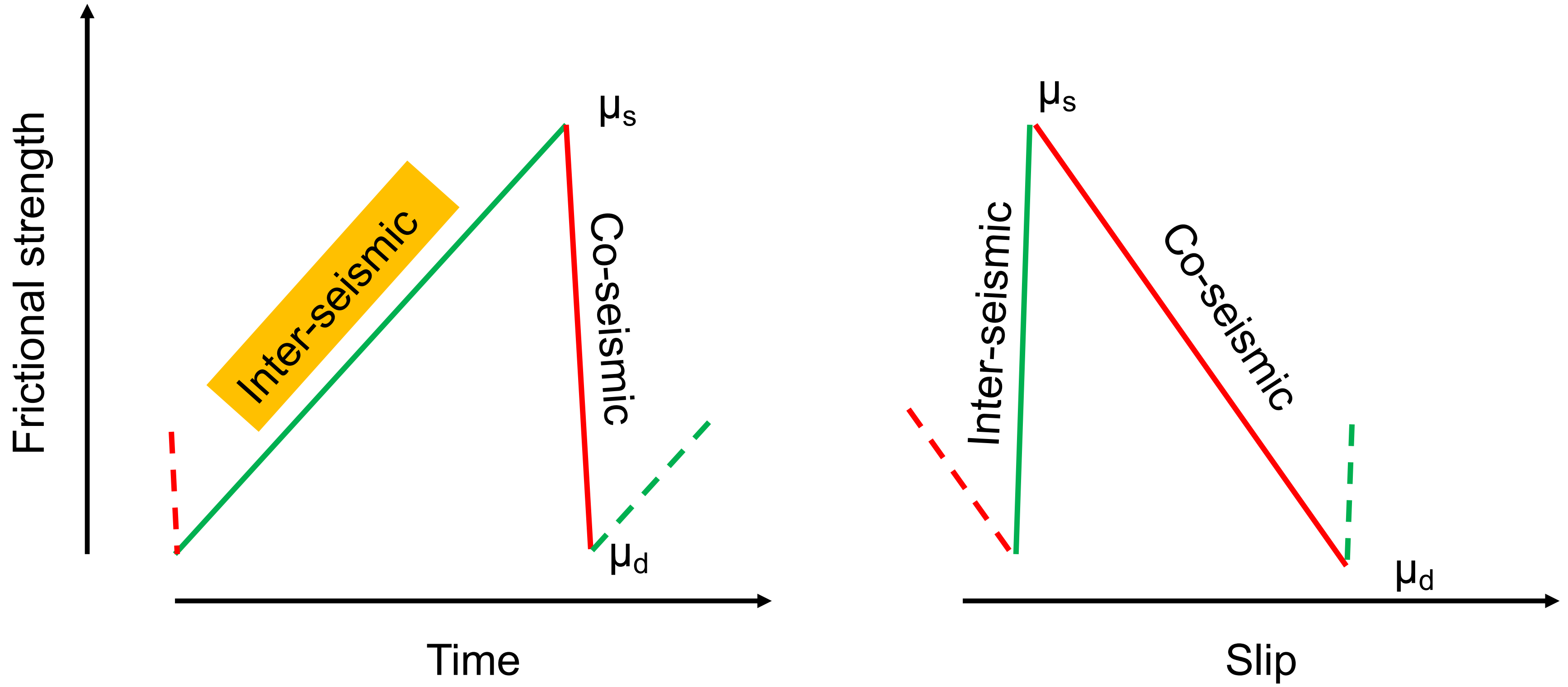
The seismic cycle



The seismic cycle

Time dependence of frictional strength – Frictional aging

We need a mechanism to reset frictional strength between two seismic events



Time dependence of frictional strength – Frictional aging

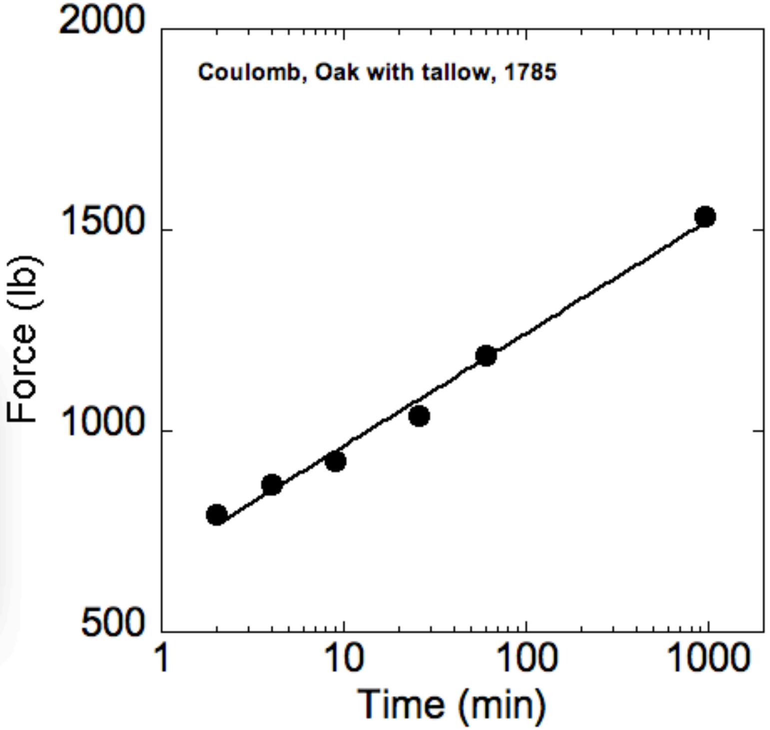
Time dependence of “static” friction
Aging of frictional contacts

Coulomb, 1785

Table 9.1

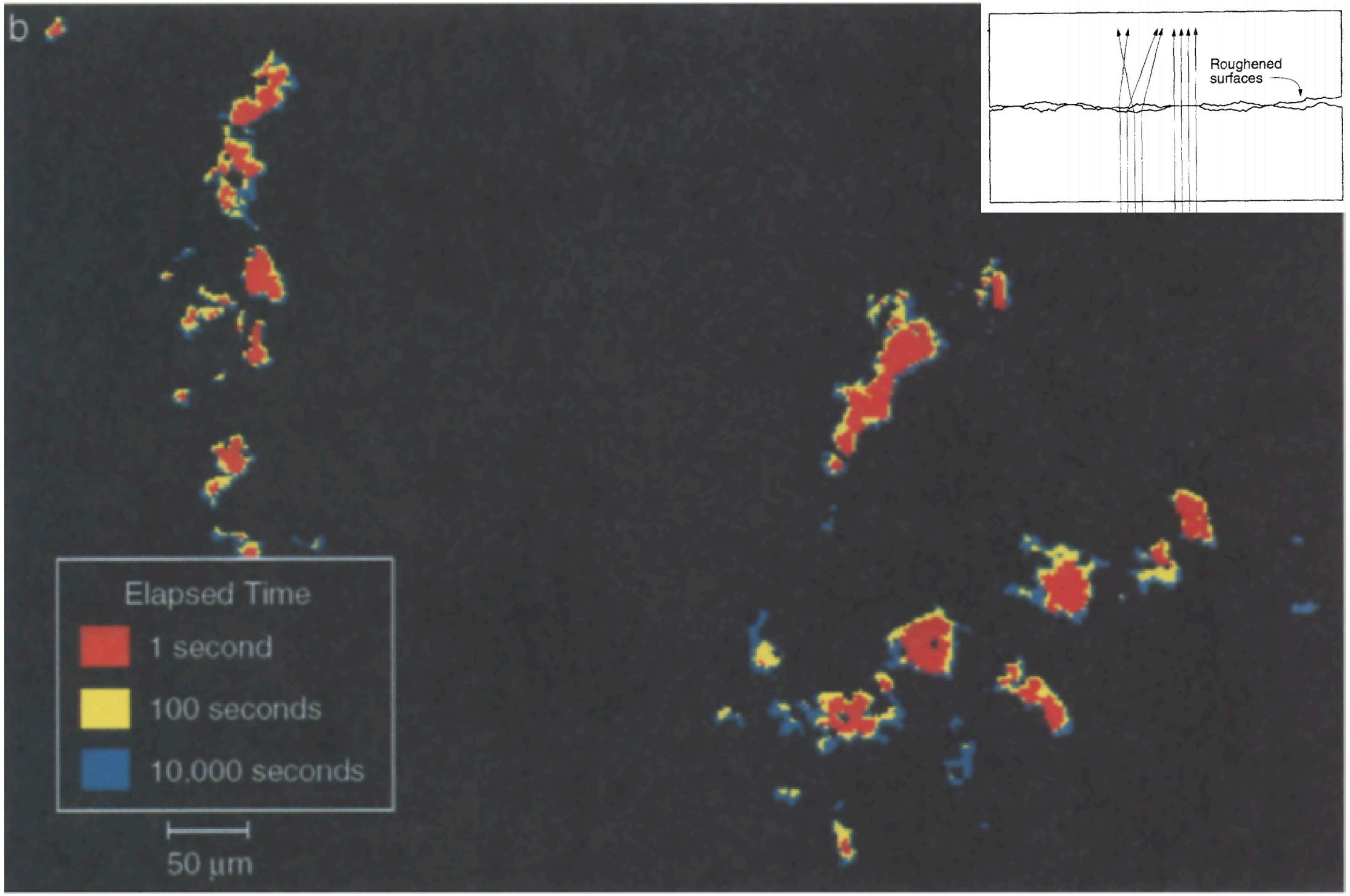
	T (time of repose, min)	$A+mT^{\mu}$ (static friction force, lbf)
I[re] observation	0	A=502
II[e]	2	790
III[e]	4	866
IV[e]	9	925
V[e]	26	1,036
VI[e]	60	1,186
VII[e]	960	1,535

static friction of two pieces of well-worn oak lubricated with tallow.



Time dependence of frictional strength – Frictional aging

Contacts grow (age) with elapsed time

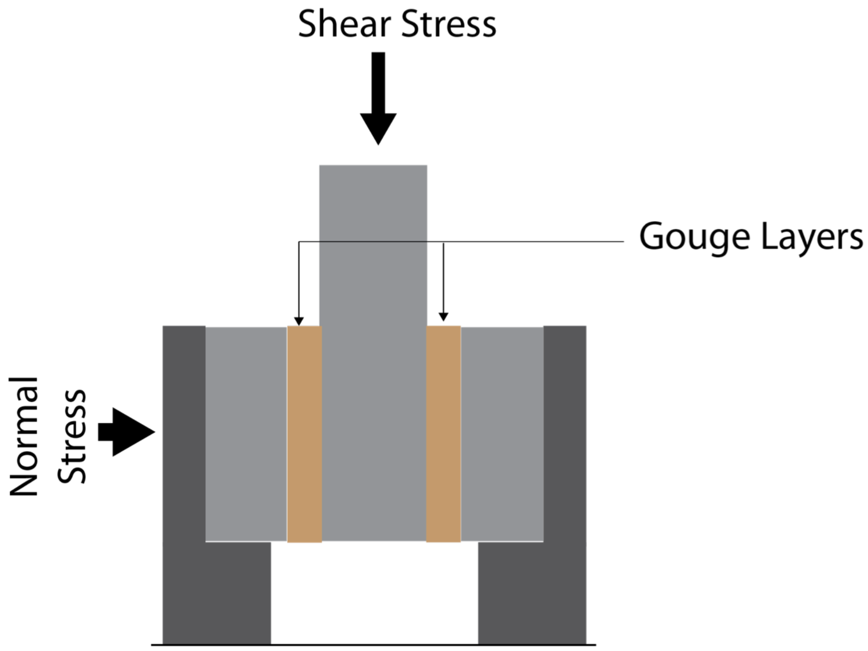


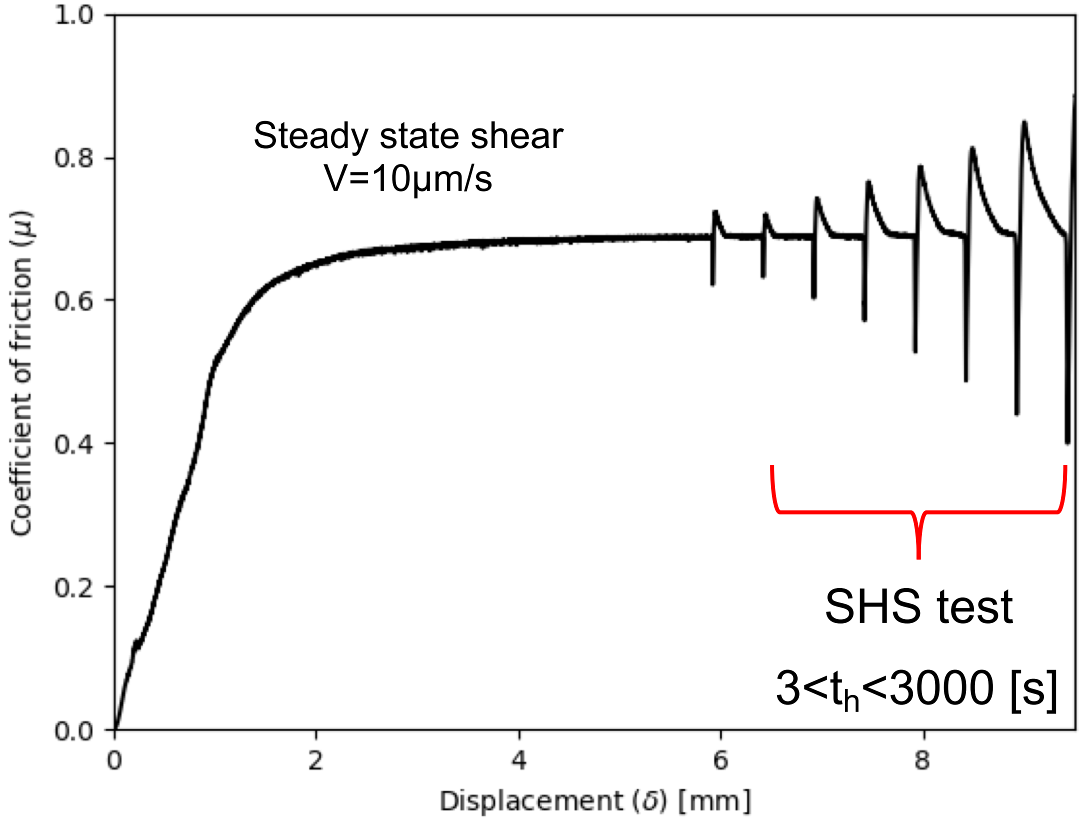
Dieterich and Kilgore, 1994 PAGEOPH

Time dependence of frictional strength – Frictional aging

Contacts grow (age) with elapsed time

Slide – hold – slide test in the laboratory



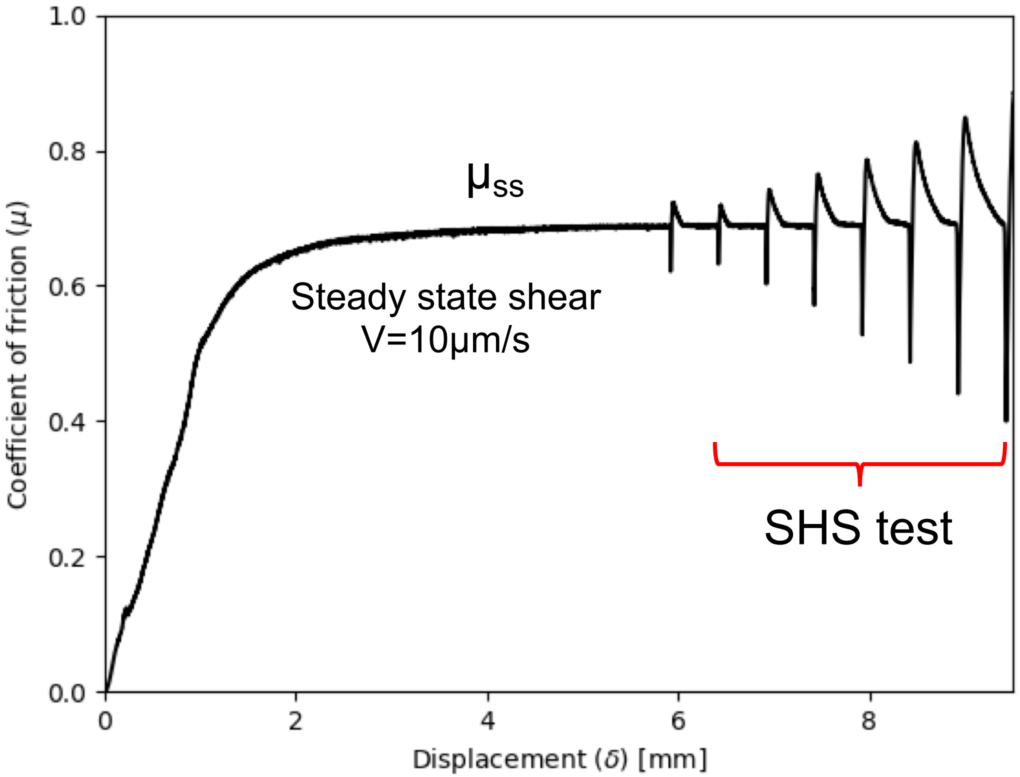


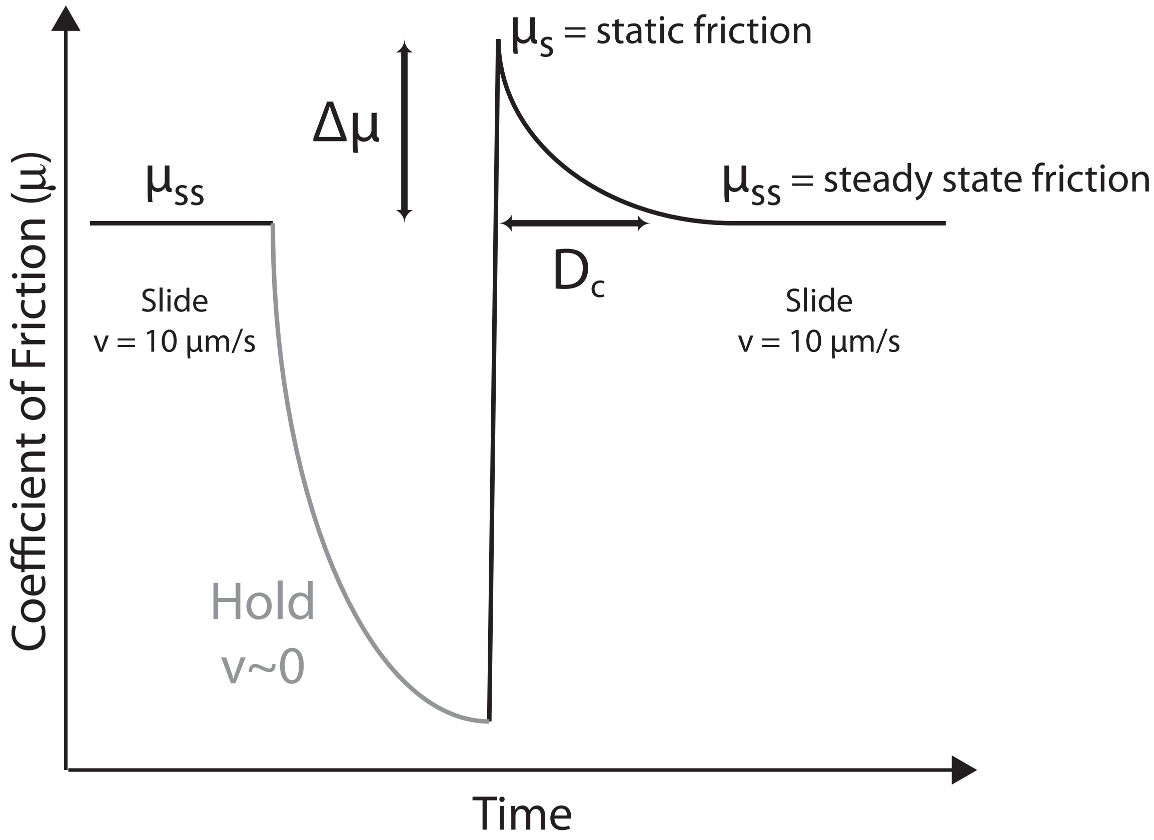
t_h Hold time

Time dependence of frictional strength – Frictional aging

Contacts grow (age) with elapsed time

Slide – hold – slide test in the laboratory

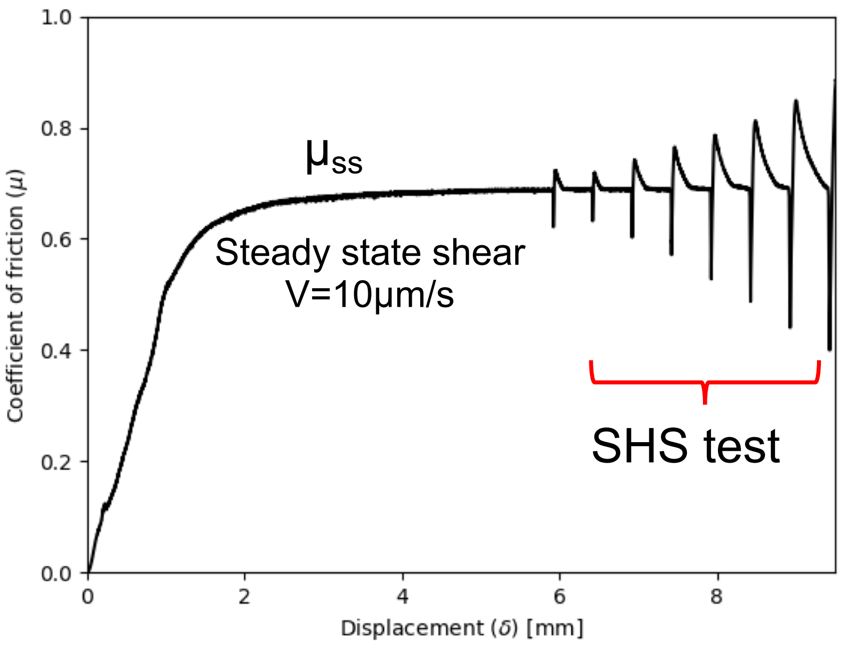




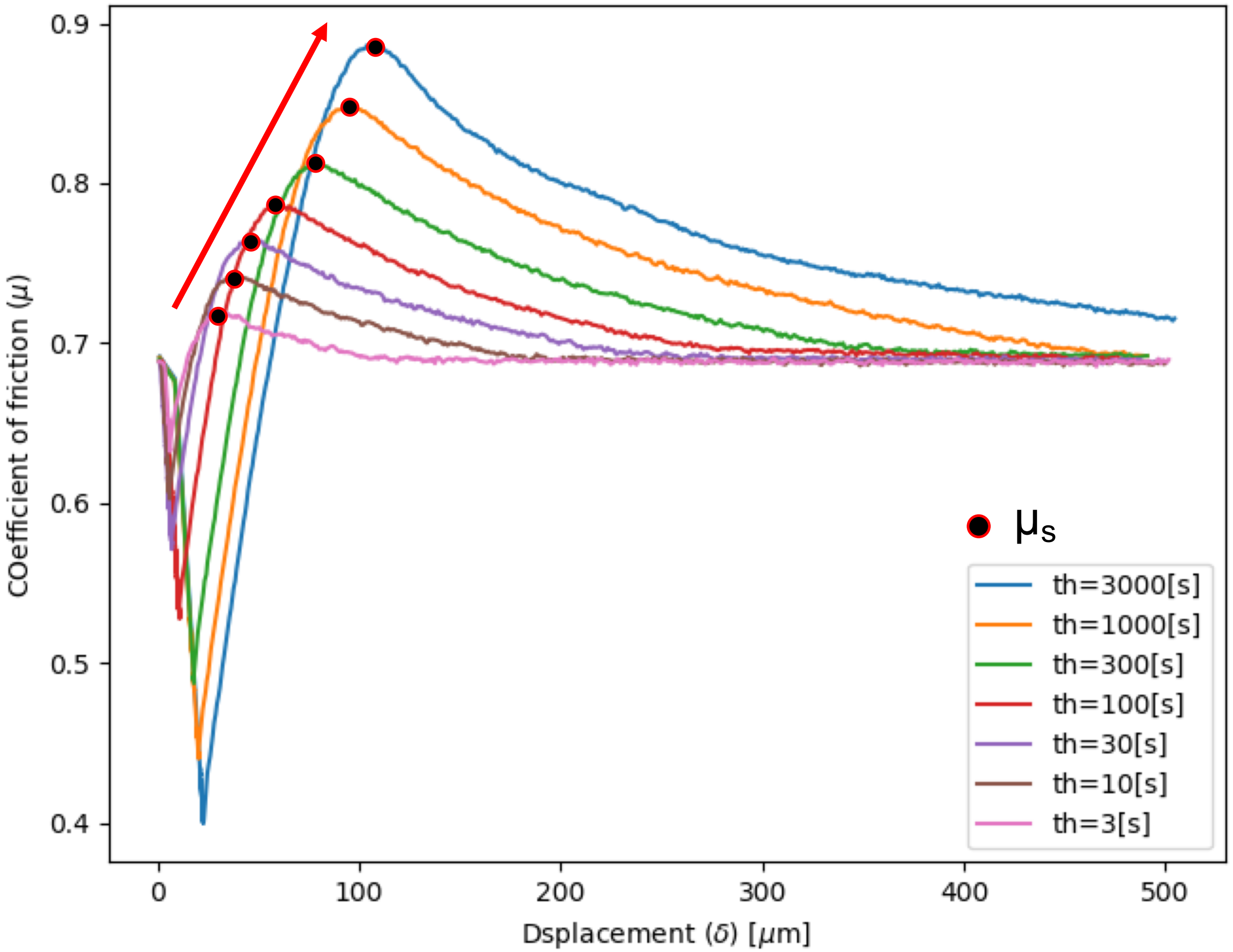
Time dependence of frictional strength – Frictional aging

Contacts grow (age) with elapsed time

Slide – hold – slide test in the laboratory



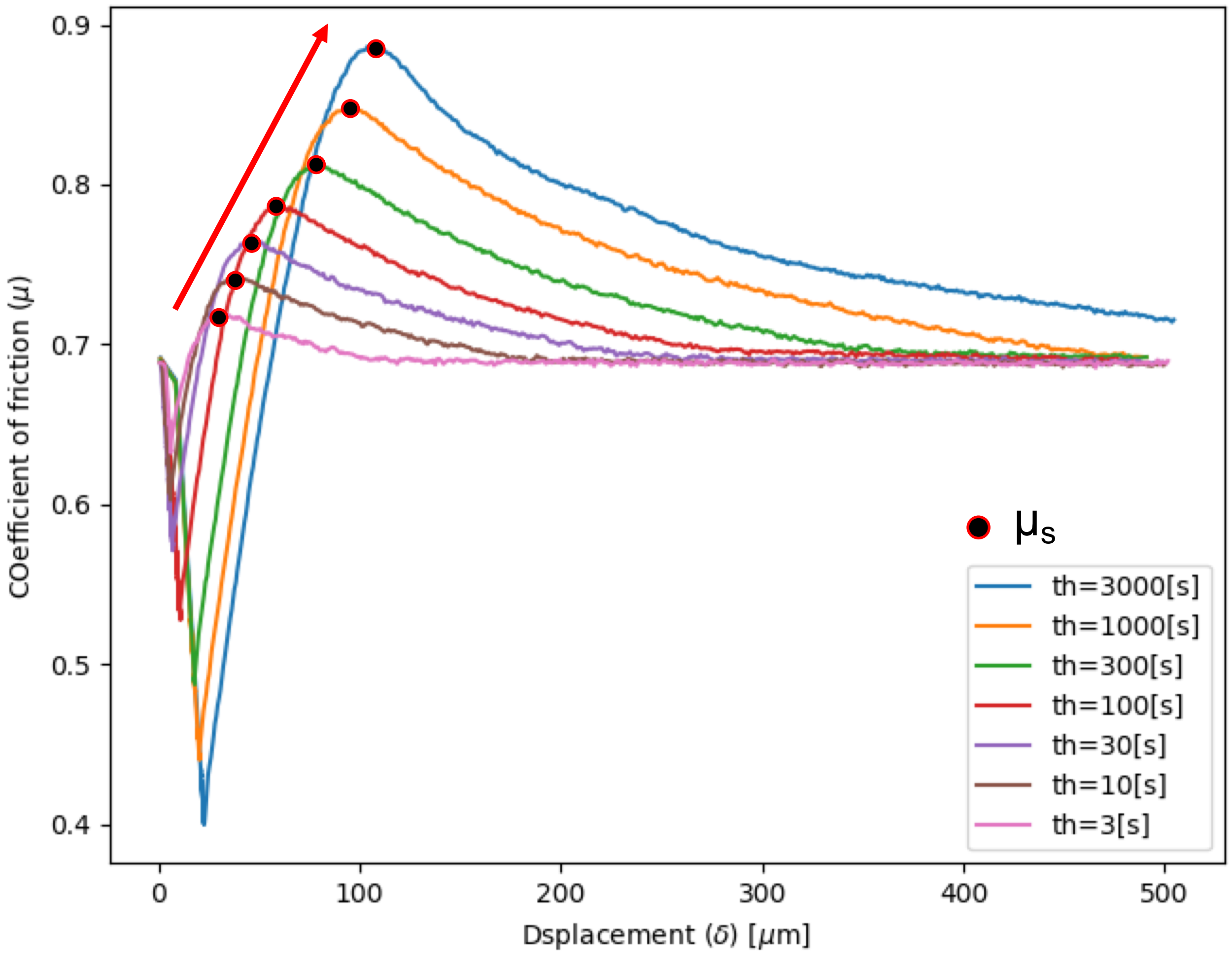
Static friction (μ_s) increases as a function of hold time (t_h)

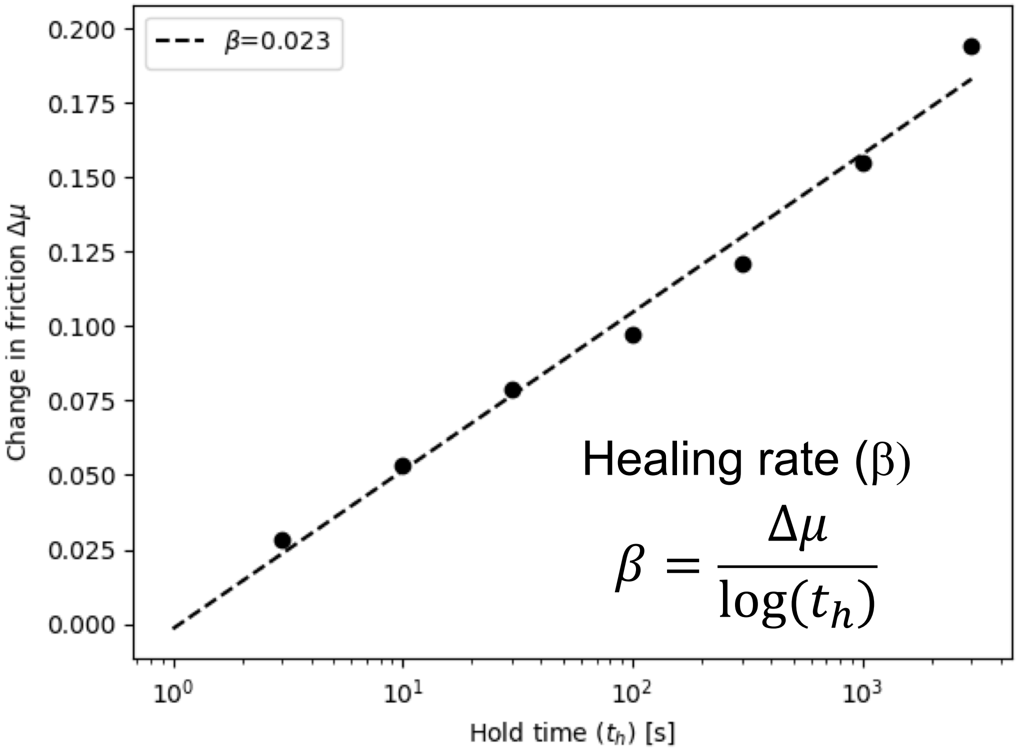


Time dependence of frictional strength – Frictional aging

Contacts grow (age) with elapsed time

Slide – hold – slide test in the laboratory





$$\beta = \frac{\Delta\mu}{\log(t_h)}$$

4.05 The Mechanics of Frictional Healing and Slip Instability During the Seismic Cycle

C Marone and DM Saffer, The Pennsylvania State University, University Park, PA, USA

Treatise on Geophysics, Second Edition

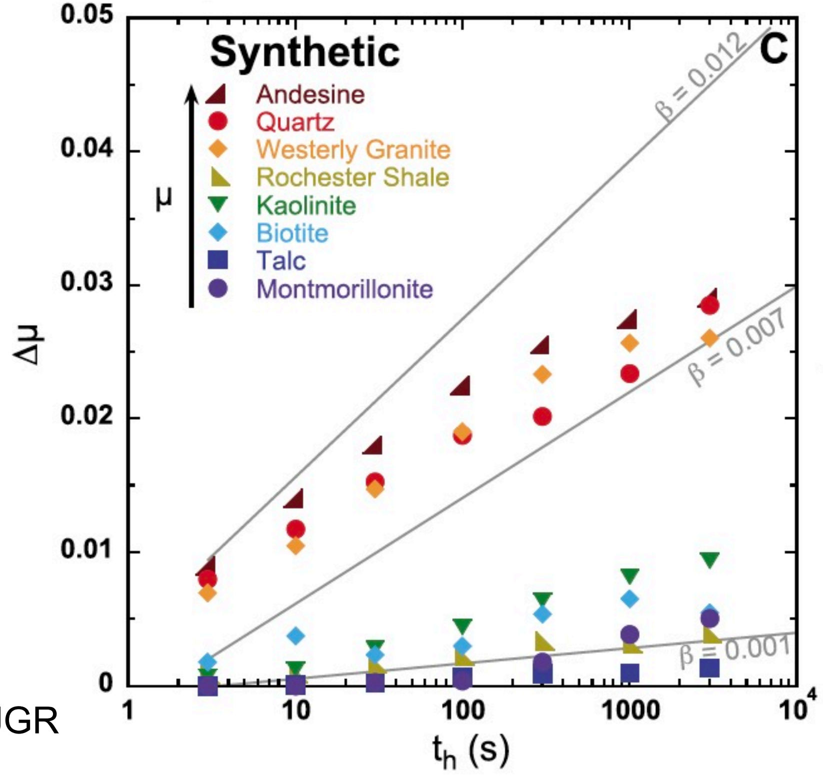
http://dx.doi.org/10.1016/B978-0-444-53802-4.00092-0

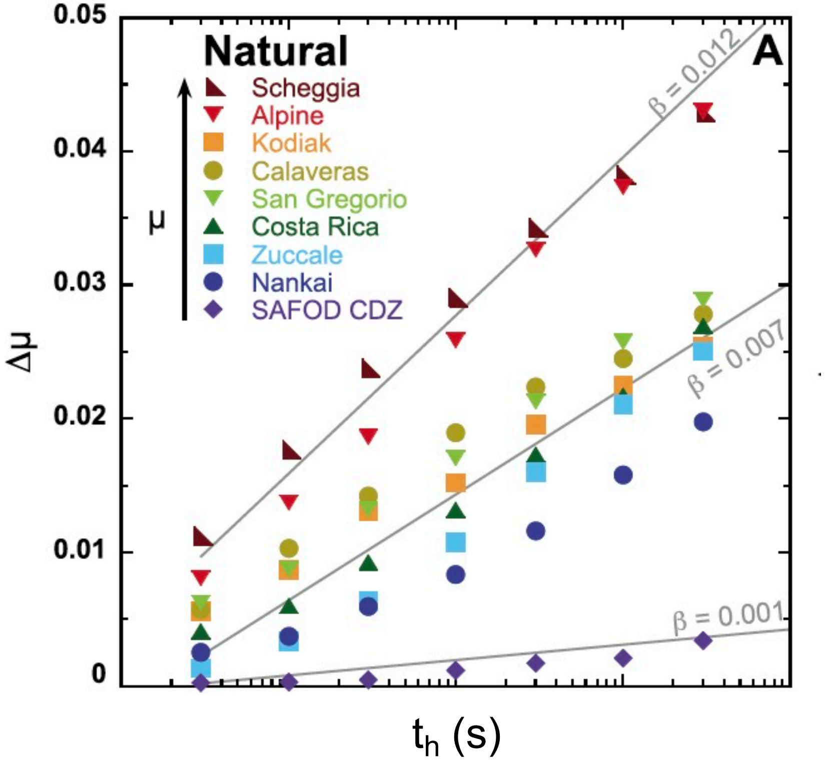
Time dependence of frictional strength – Frictional aging

Contacts grow (age) with elapsed time

Major factors that controls frictional healing:

Fault gouge mineralogy, in other words the shape of minerals (platy vs. granular)





Carpenter et al., 2016 JGR
Ikari et al., 2016 G[3]

Time dependence of frictional strength – Frictional aging

Contacts grow (age) with elapsed time

Major factors that controls frictional healing:

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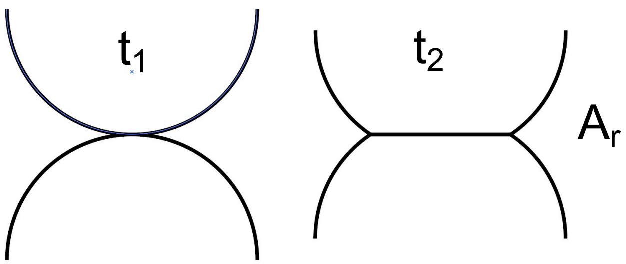
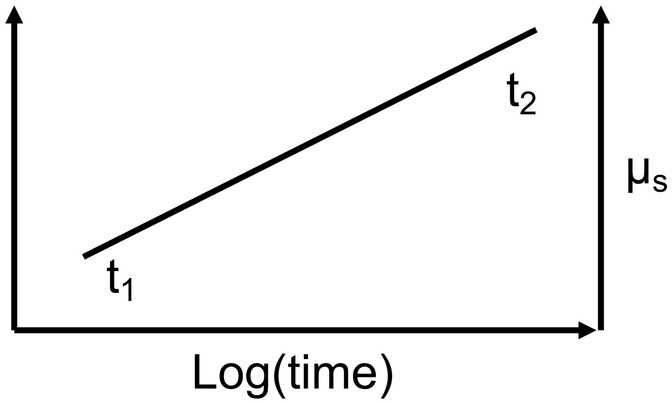
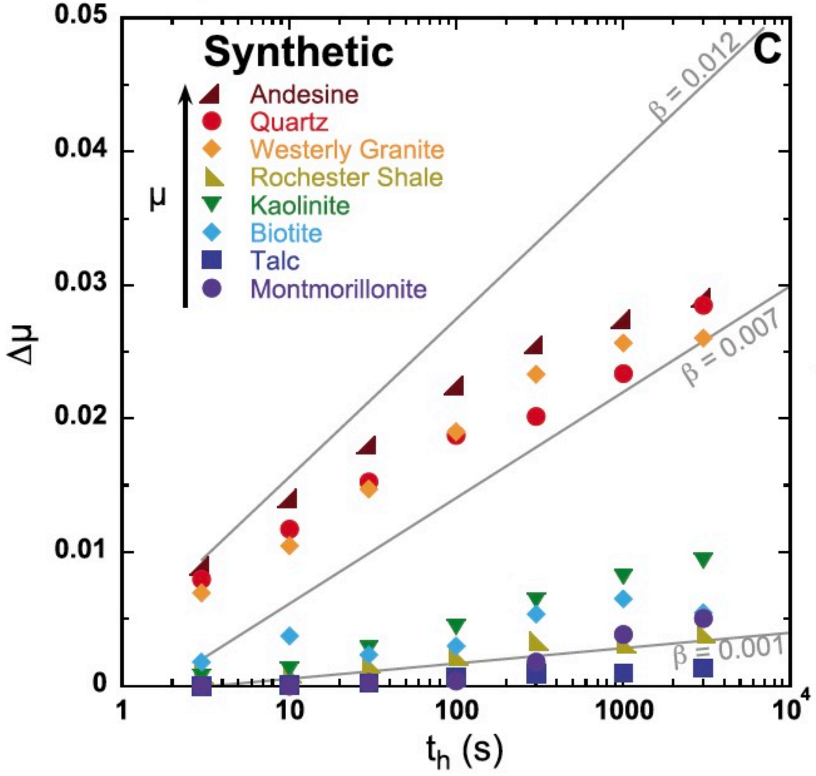
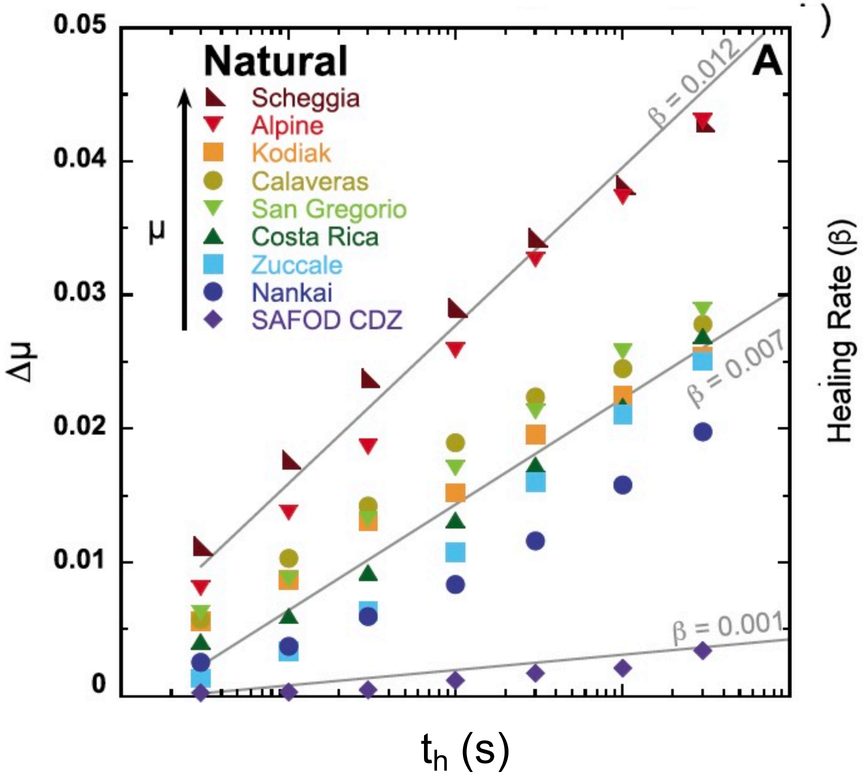
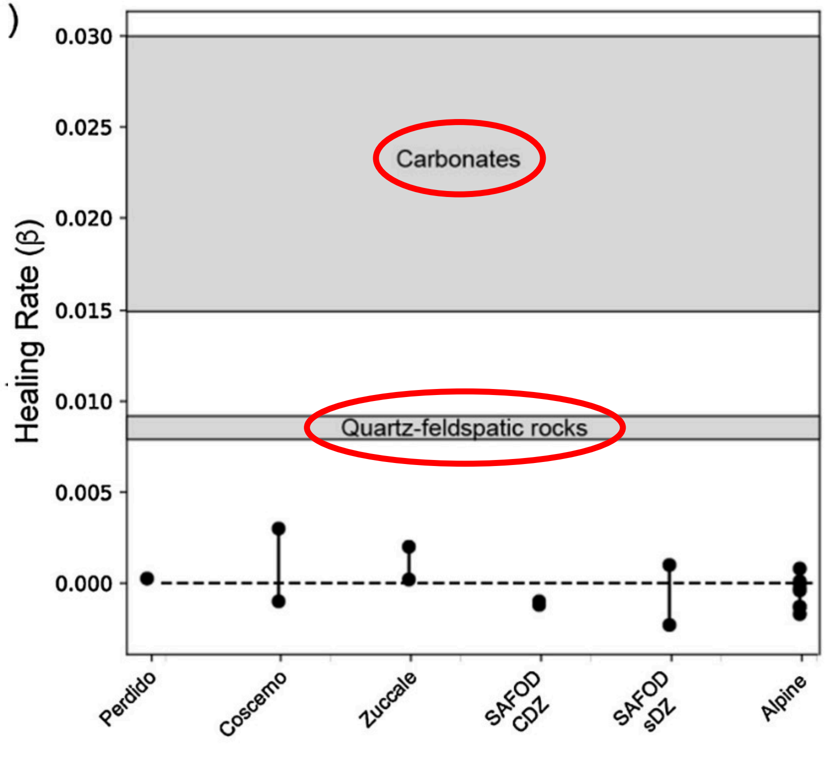


Contacts grow with time







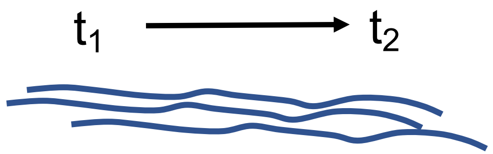


Time dependence of frictional strength – Frictional aging

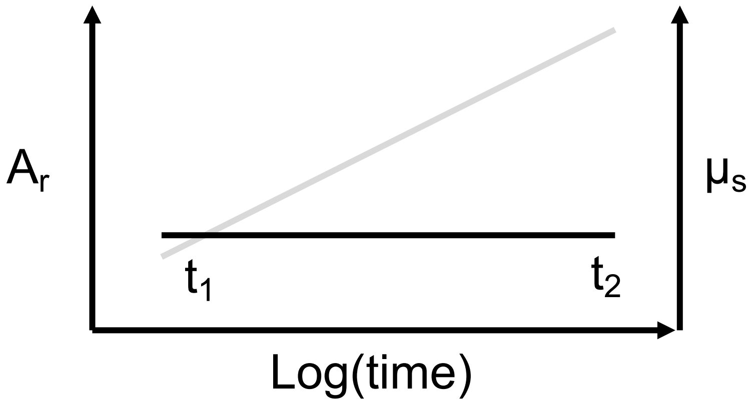
Contacts grow (age) with elapsed time

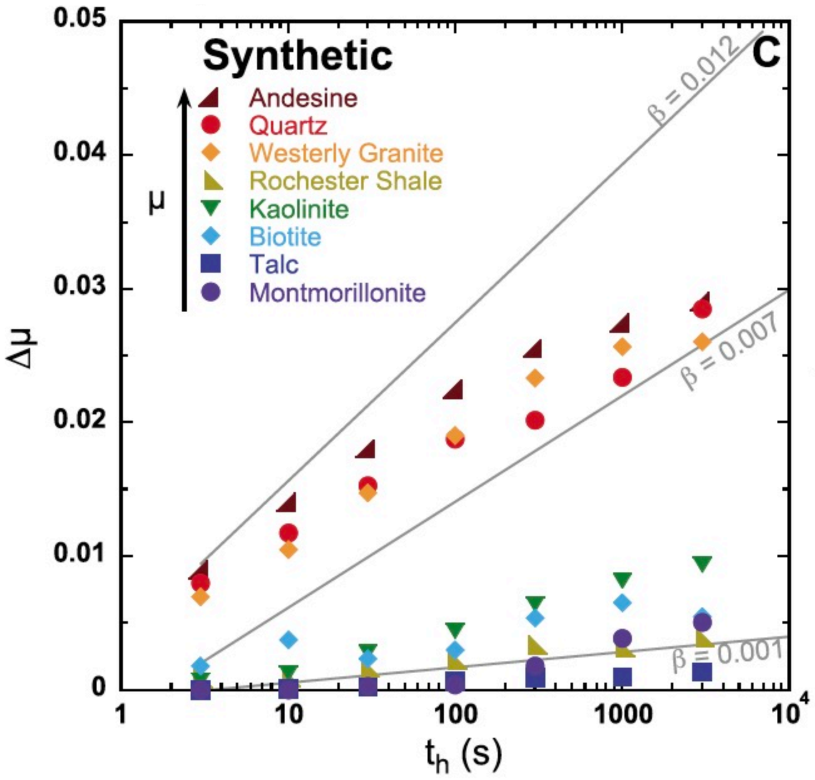
Major factors that controls frictional healing:

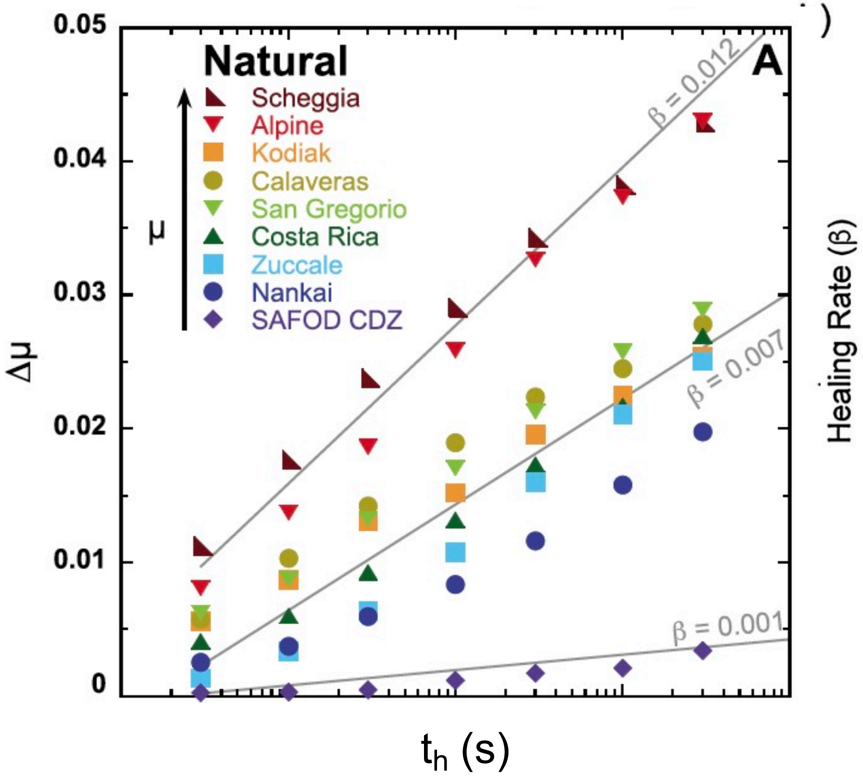
Fault gouge mineralogy, in other words the shape of minerals (platy vs. granular)

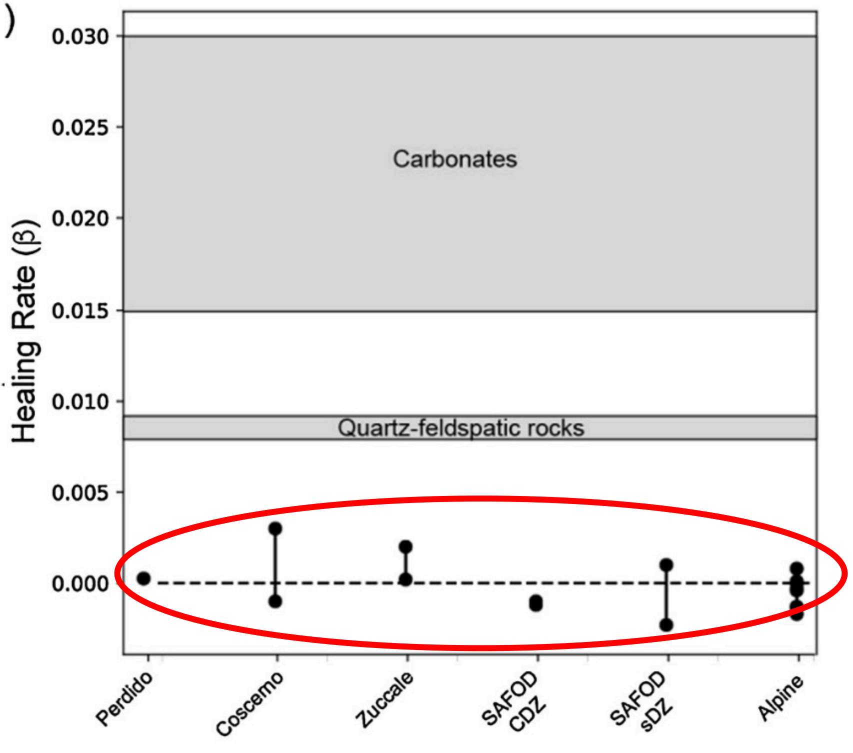


Ar doesn't change with time









Time dependence of frictional strength – Frictional aging

Contacts grow (age) with elapsed time

Major factors that controls frictional healing:

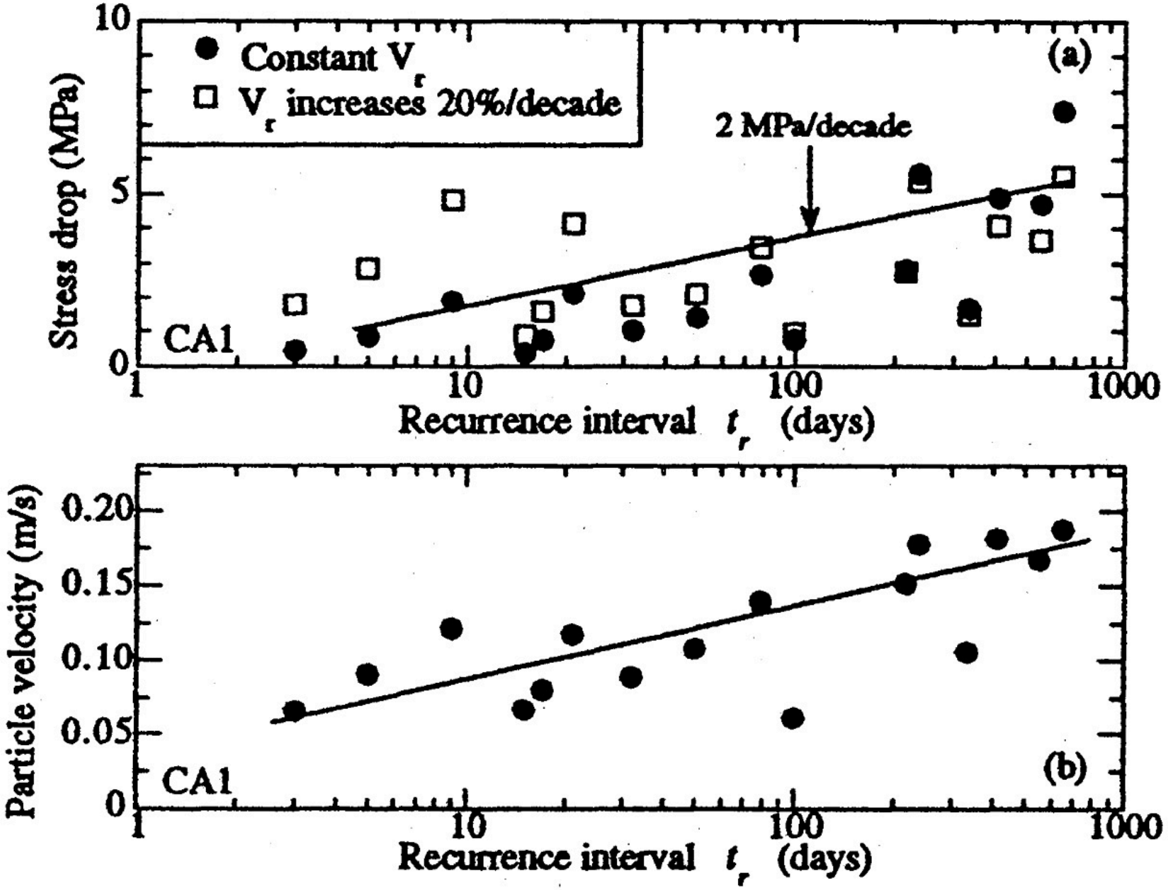
- Shear stress (Karner and Marone, 2001)
- Humidity and fluids (e.g. Frye, 2002)
- Dynamic changes in normal stress (Richardson 1999)
- Shear velocity (Marone 1998)
- Physico-chemical reactions (e.g. Scuderi et al., 2014)
- Degree of granular consolidation (e.g. Bos and Spiers, 2002; Niemeijer et al., 2008)
- And much more

Time dependence of frictional strength – Frictional aging

Contacts grow (age) with elapsed time

Nonetheless, this theoretical framework it is consistent with observations repeating earthquakes

Calaveras Fault (CA, USA) repeating earthquakes



Marone et al., 1995 GRL

A good recipe should include

Microphysical contact evolution (Adhesion theory of friction)

Slip dependent friction (static vs. kinetic)

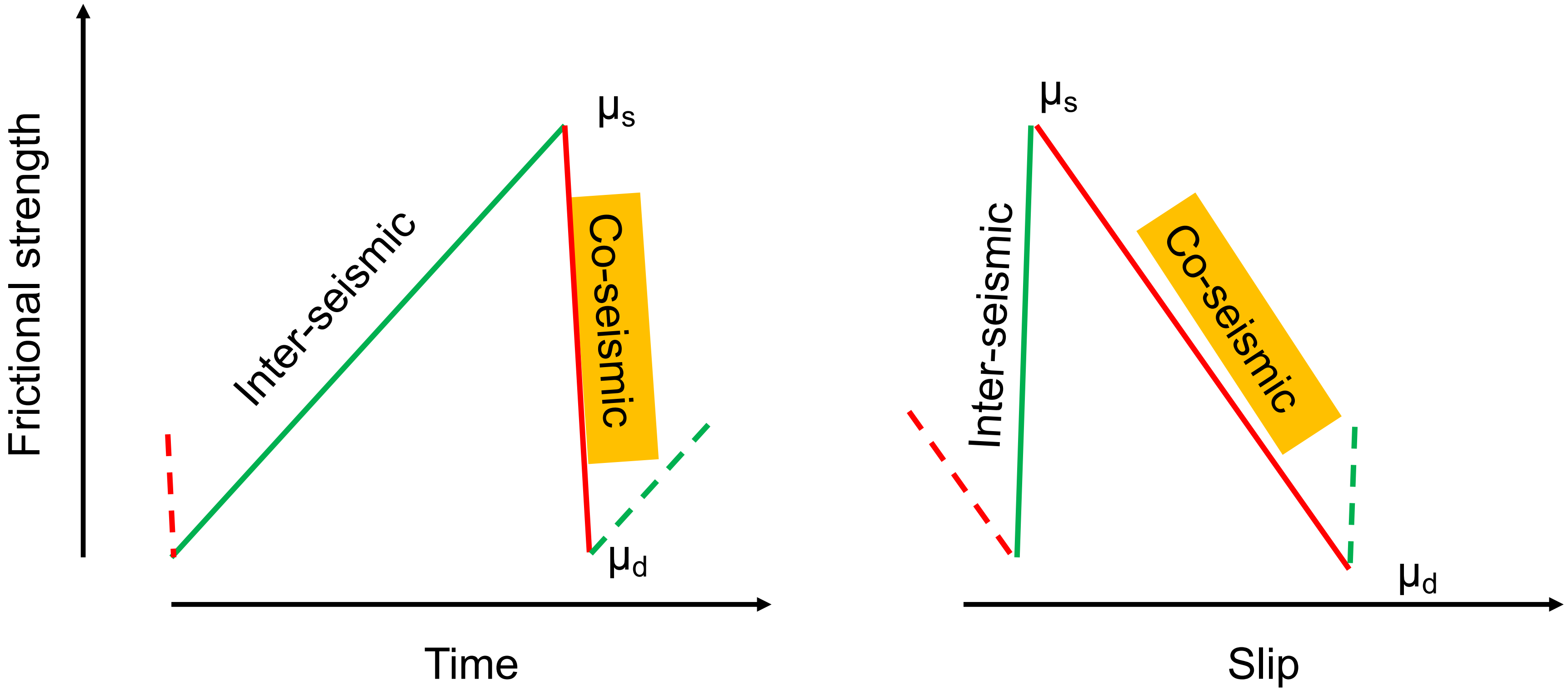
Time dependent recovery of shear strength

Velocity dependent friction

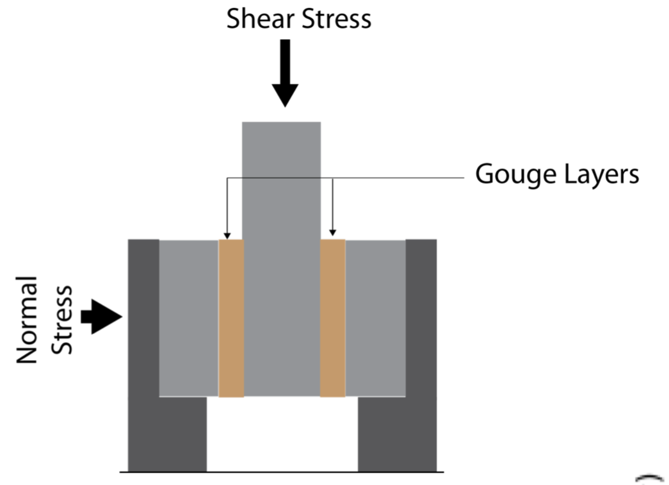
The seismic cycle

Velocity dependence of frictional strength

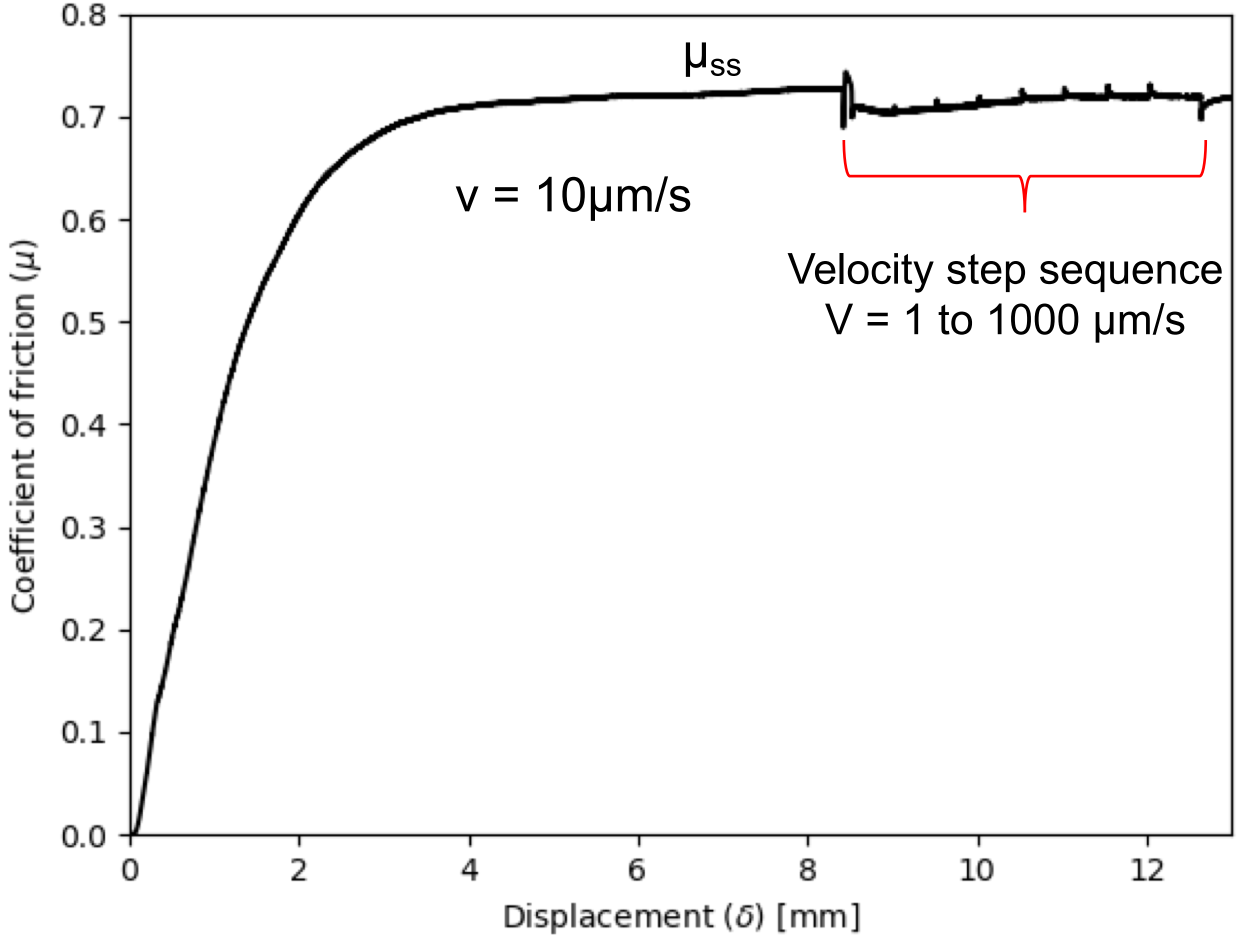
We need a mechanism to allow frictional weakening during slip acceleration to allow earthquake nucleation



Velocity dependence of sliding friction



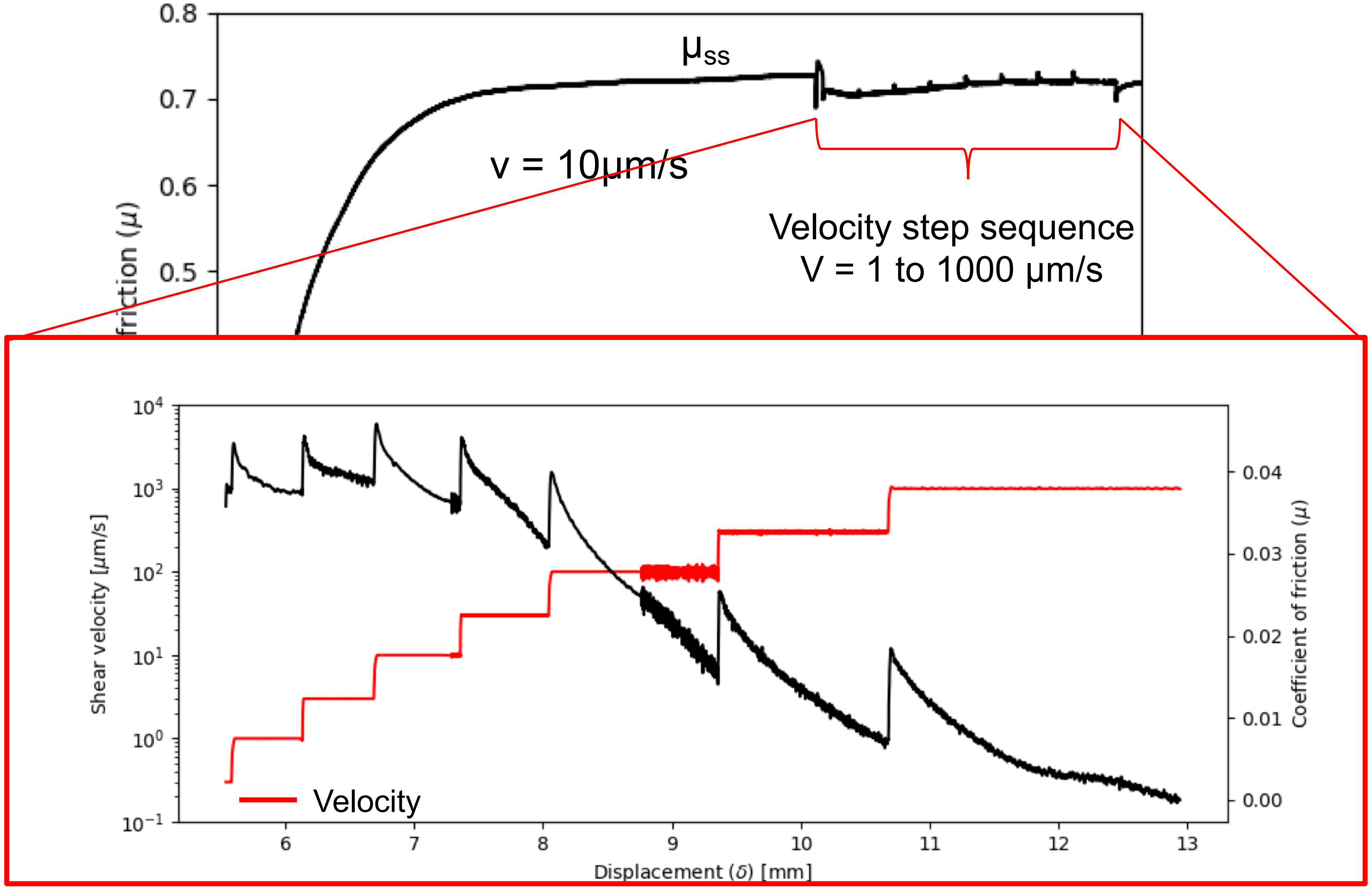
Velocity step experiments



Dieterich, J. H. (1978). *Pure and Applied Geophysics*

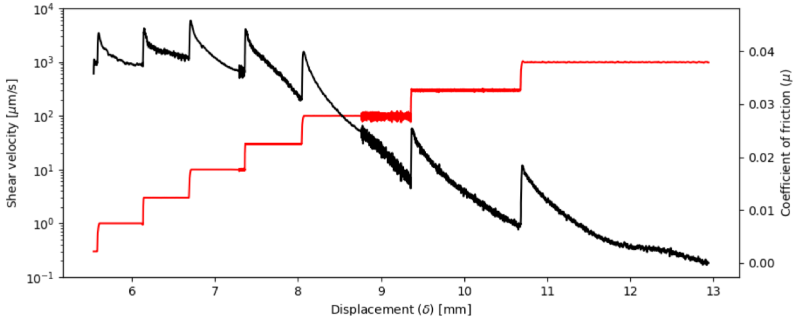
Velocity dependence of sliding friction

Velocity step experiments



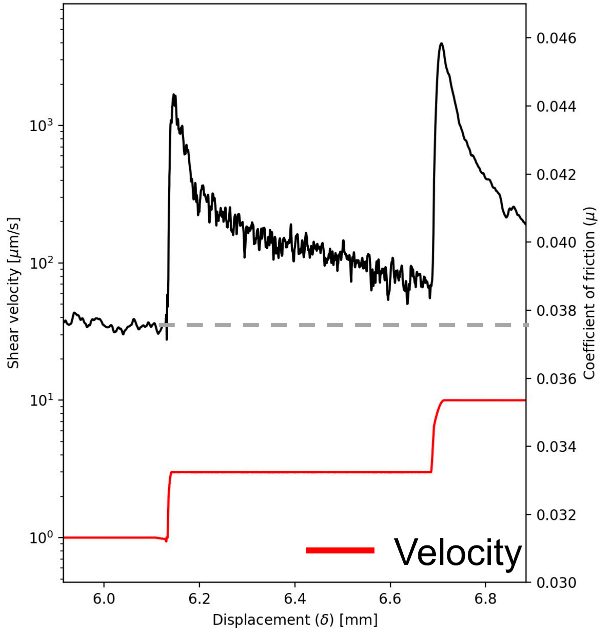
Velocity dependence of sliding friction

Velocity step experiments



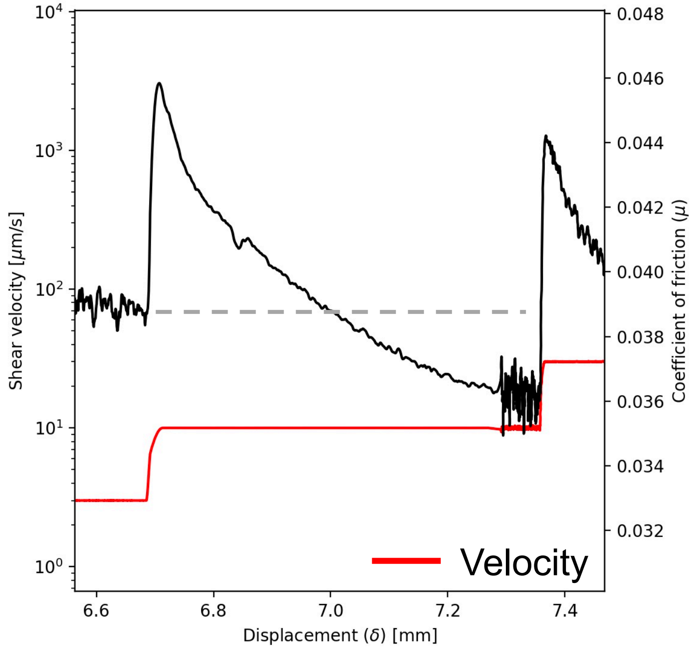
Velocity strengthening

Friction increases with increasing velocity, indicative of aseismic creep.



Velocity weakening

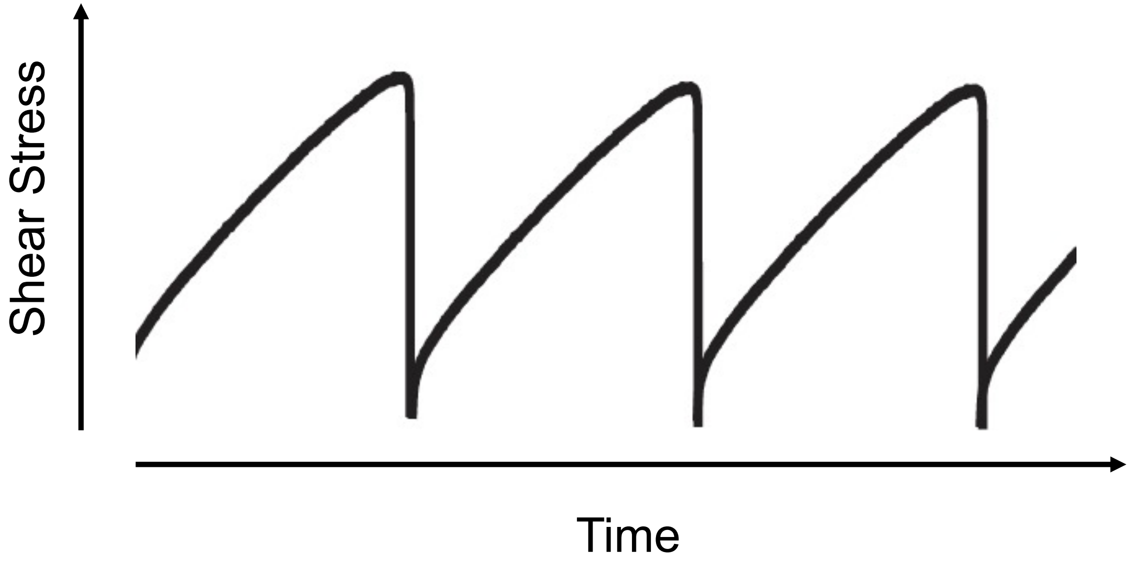
Friction decreases with increasing velocity, setting the stage for an instability.



How can we relate measurement of:

(1) Static friction that increases with time

(2) Kinetic friction that changes with velocity

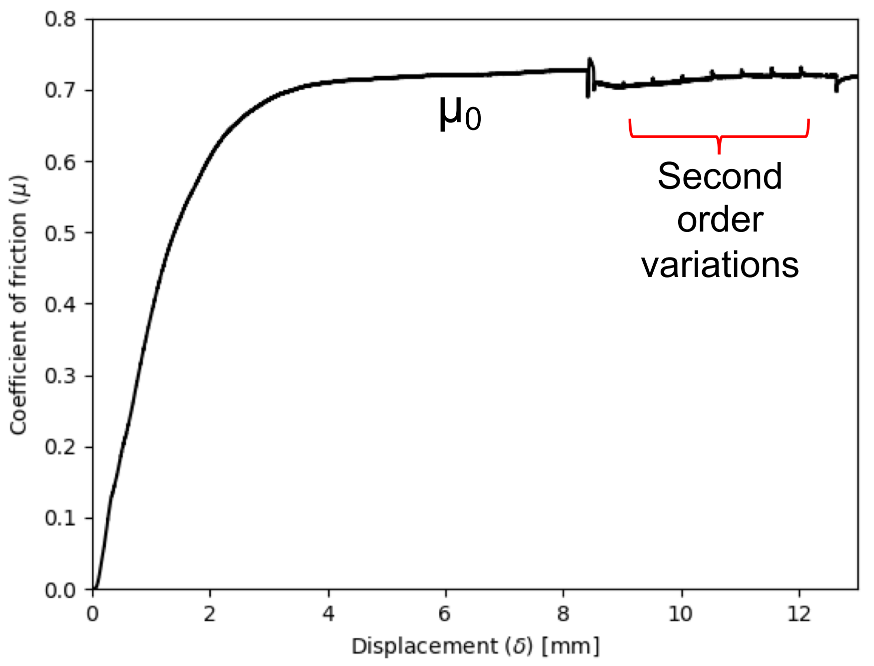


To model repetitive stick-slip frictional sliding we need a constitutive law that can describe slip weakening to promote unstable failure, but also frictional healing to reset strength between events.

Rate(v) and state(θ) friction constitutive equations

1) Friction law

$$\frac{\tau(\theta,v)}{\sigma_n} = \mu_0 + a\ln\left(\frac{v}{v_0}\right) + b\ln\left(\frac{v_0\theta}{D_c}\right)$$



Dieterich, 1978 PAGEOPH , 1979a,b JGR
Ruina 1983 JGR
Review of:
Scholz, 1998 Nature
Marone, 1998 Reviews of Geophysics

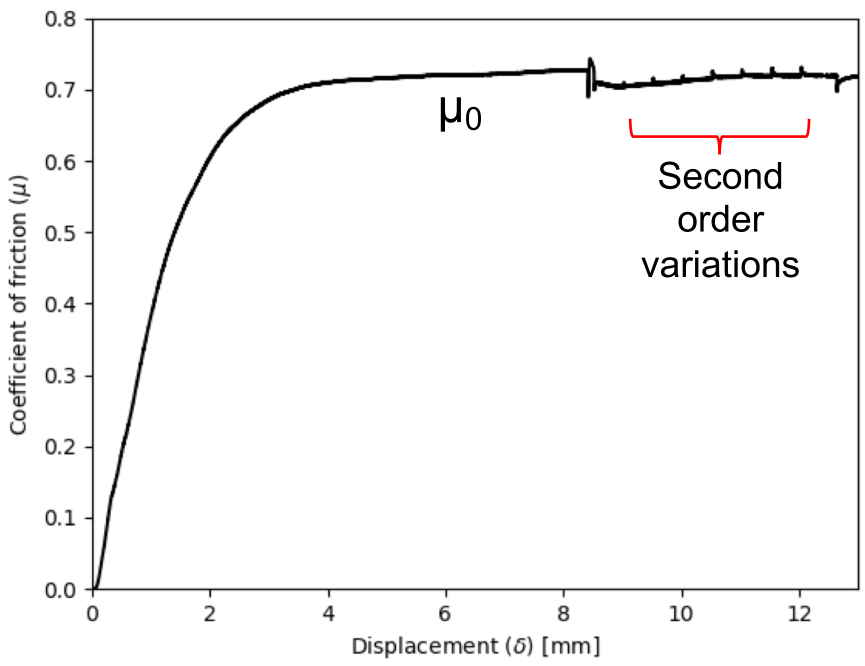
Rate(v) and state(θ) friction constitutive equations

1) Friction law

Second order variations

$$\frac{\tau(\theta,v)}{\sigma_n} = \mu_0 + \underbrace{a\ln\left(\frac{v}{v_0}\right) + b\ln\left(\frac{v_0\theta}{D_c}\right)}$$

To the first order friction is constant



Rate(v) and state(θ) friction constitutive equations

1) Friction law

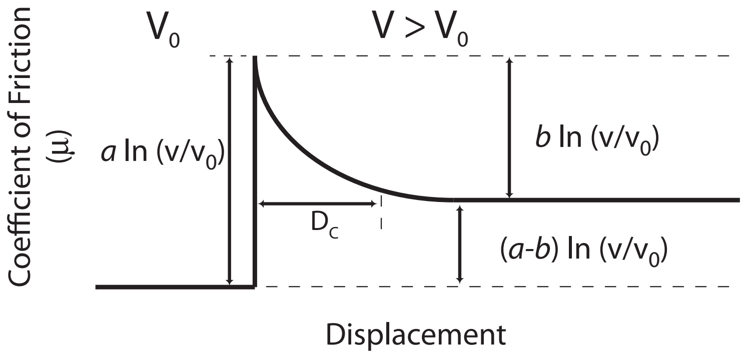
Second order variations

$$\frac{\tau(\theta,v)}{\sigma_n} = \mu_0 + a\ln\left(\frac{v}{v_0}\right) + b\ln\left(\frac{v_0\theta}{D_c}\right)$$

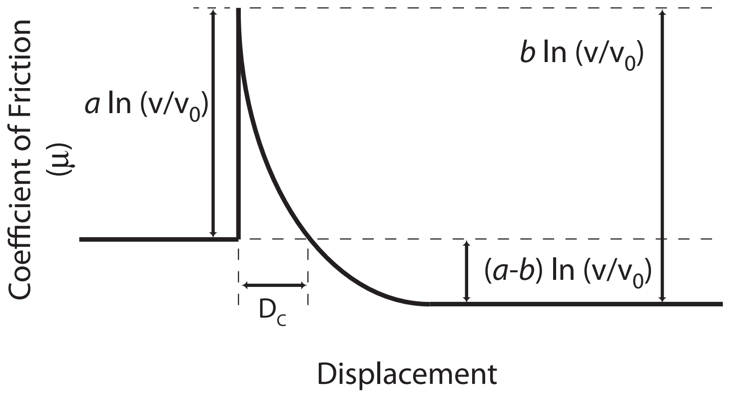
Direct effect (*a*)

Slip rate dependent increase in shear resistance (non-linear viscous).

Velocity Strengthening (aseismic creep)



Velocity Weakening (potentially unstable)



Rate(v) and state(θ) friction constitutive equations

1) Friction law

Second order variations

$$\frac{\tau(\theta,v)}{\sigma_n} = \mu_0 + a\ln\left(\frac{v}{v_0}\right) + b\ln\left(\frac{v_0\theta}{D_c}\right)$$

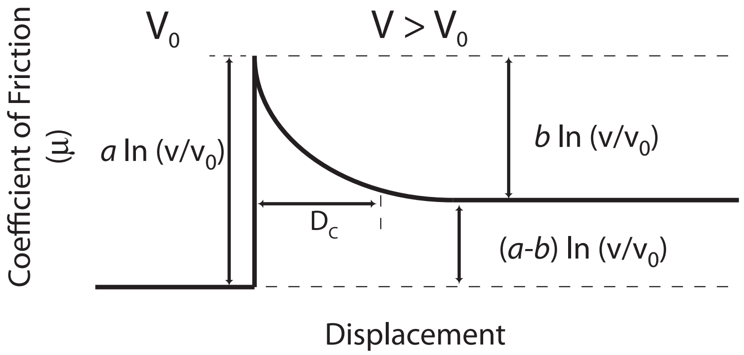
Evolution effect (*b*):

- Slip dependent evolution in contact area
- Time dependent increase in contact area

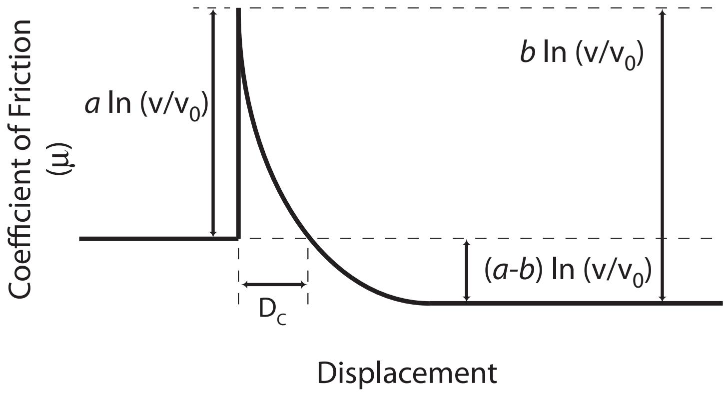
D_c = Critical slip distance, defined as the distance required to renew a population of asperity contacts.

θ = State variable, describes the "state" of the contacts and it is related with the characteristic contact lifetime (it has units of time).

Velocity Strengthening (aseismic creep)



Velocity Weakening (potentially unstable)



Rate(v) and state(θ) friction constitutive equations

1) Friction law

Second order variations

$$\frac{\tau(\theta,v)}{\sigma_n} = \mu_0 + a\ln\left(\frac{v}{v_0}\right) + b\ln\left(\frac{v_0\theta}{D_c}\right)$$

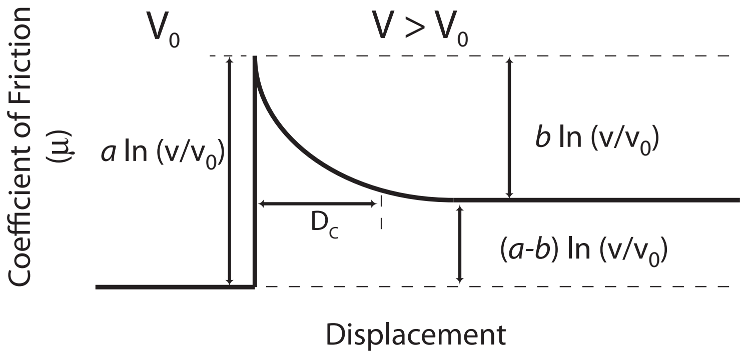
2) Evolution law

$$\frac{d\theta}{dt} = 1 - \left(\frac{v\theta}{D_c}\right)$$

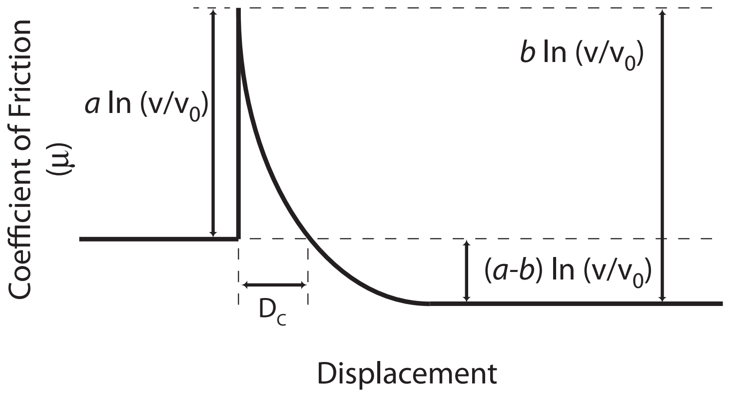
Aging Law (or Dieterich law)

This formulation allow the state (θ), and thus friction, to evolve even for truly stationary contact, when V=0. That is, it can be used to model frictional healing.

Ↄ Velocity Strengthening (aseismic creep)



Velocity Weakening (potentially unstable)



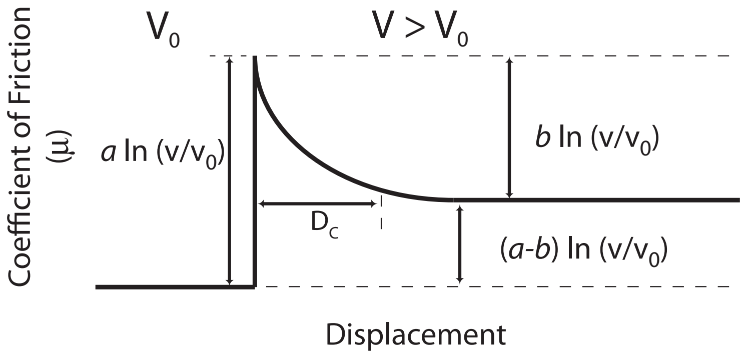
Rate(v) and state(θ) friction constitutive equations

1) Friction law

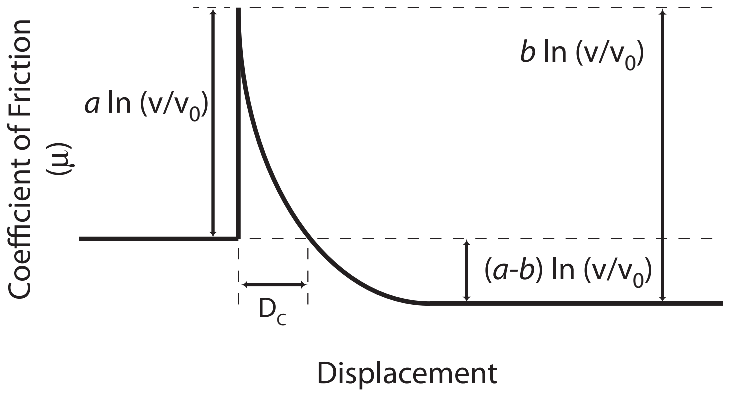
Second order variations

$$\frac{\tau(\theta,v)}{\sigma_n} = \mu_0 + a\ln\left(\frac{v}{v_0}\right) + b\ln\left(\frac{v_0\theta}{D_c}\right)$$

Velocity Strengthening (aseismic creep)



Velocity Weakening (potentially unstable)



2) Evolution law

$$\frac{d\theta}{dt} = 1 - \left(\frac{v\theta}{D_c}\right)$$

Aging Law (or Dieterich law)

$$\frac{d\theta}{dt} = -\frac{v\theta}{D_c}\ln\left(\frac{v\theta}{D_c}\right)$$

Slip Law (or Ruina law)

Emphasize the importance of slip and slip velocity in the evolution of friction rather than time.

Rate(v) and state(θ) friction constitutive equations

1) Friction law

Second order variations

$$\frac{\tau(\theta,v)}{\sigma_n} = \mu_0 + a\ln\left(\frac{v}{v_0}\right) + b\ln\left(\frac{v_0\theta}{D_c}\right)$$

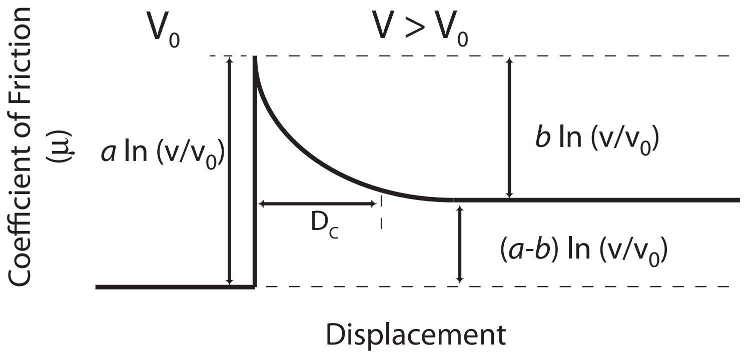
2) Evolution law

$$\frac{d\theta}{dt} = 1 - \left(\frac{v\theta}{D_c}\right)$$ Aging Law (or Dieterich law)

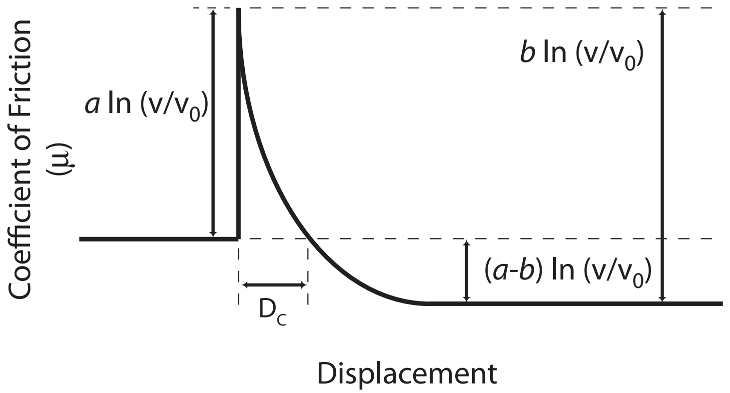
Which one ?

$$\frac{d\theta}{dt} = -\frac{v\theta}{D_c}\ln\left(\frac{v\theta}{D_c}\right)$$ Slip Law (or Ruina law)

Ↄ Velocity Strengthening (aseismic creep)



Velocity Weakening (potentially unstable)



Ampuero, J. P., & Rubin, A. M. (2008). Earthquake nucleation on rate and state faults – Aging and slip laws. *Journal of Geophysical Research*, *113*(B1), B01302. https://doi.org/10.1029/2007JB005082

Rate(v) and state(θ) friction constitutive equations

1) Friction law

Second order variations

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2) Evolution law

$$\frac{d\theta}{dt} = 1 - \left(\frac{v\theta}{D_c}\right)$$

Aging Law (or Dieterich law)

For steady state shear
(i.e. shear at constant velocity)

$$\frac{d\theta}{dt} = 0$$

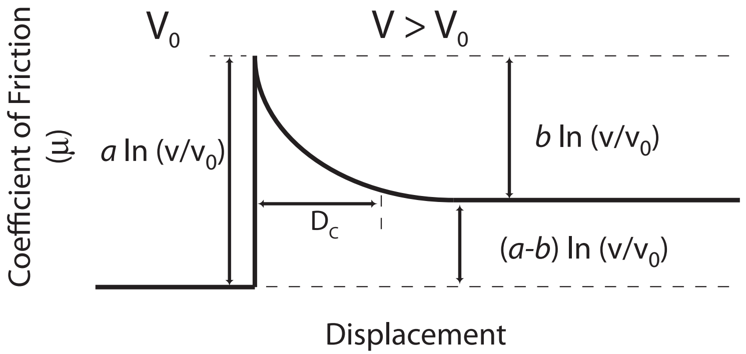
Resulting in

$$\theta_{ss} = \frac{D_c}{v}$$

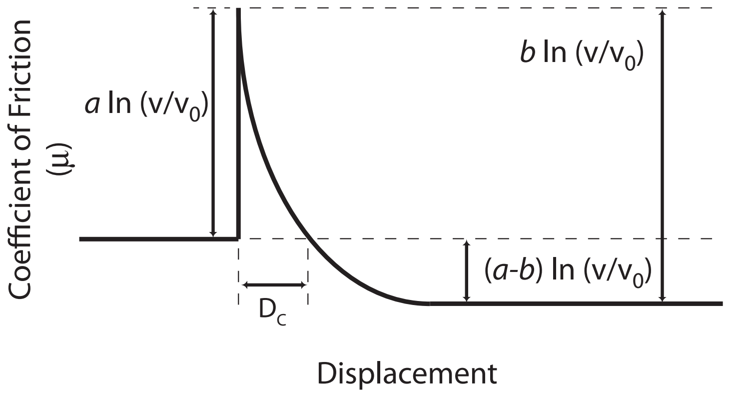
Stability parameter

$$(a-b) = \frac{\Delta\mu_{ss}}{\log(v/v_0)}$$

Velocity Strengthening (aseismic creep)



Velocity Weakening (potentially unstable)

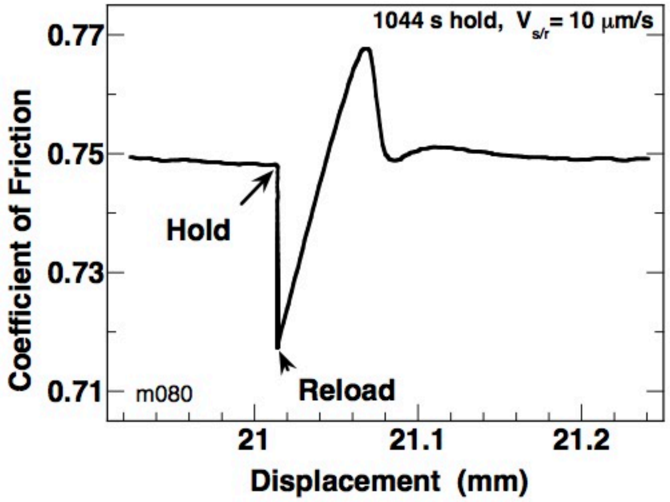


Rate(v) and state(θ) friction constitutive equations

1) Friction law

Second order variations

$$\frac{\tau(\theta,v)}{\sigma_n}=\mu_0+a\ln\left(\frac{v}{v_0}\right)+b\ln\left(\frac{v_0\theta}{D_c}\right)$$



2) Evolution law

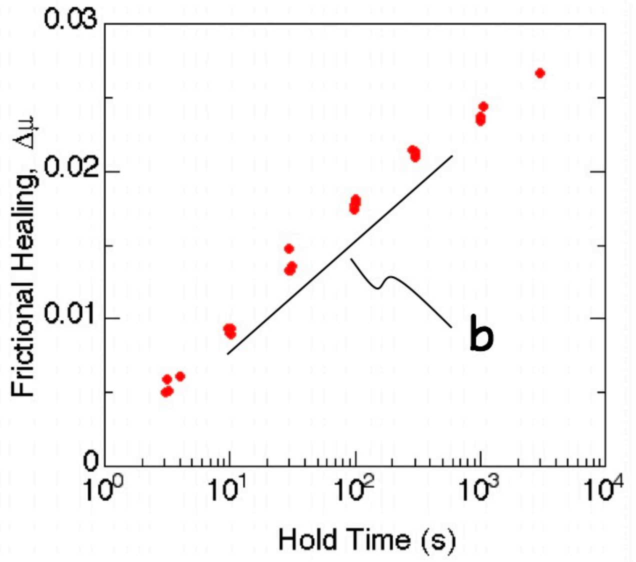
$$\frac{d\theta}{dt}=1-\left(\frac{v\theta}{D_c}\right)$$

Aging Law (or Dieterich law)

During quasi-stationary contact

$$\Delta\mu \approx b ln\frac{\theta}{\theta_o}$$

$$\frac{\Delta\mu_s}{\Delta\log(t_h)}=b$$



Is (a-b) a universal parameter?

Is it a material property?

The answer is NO.

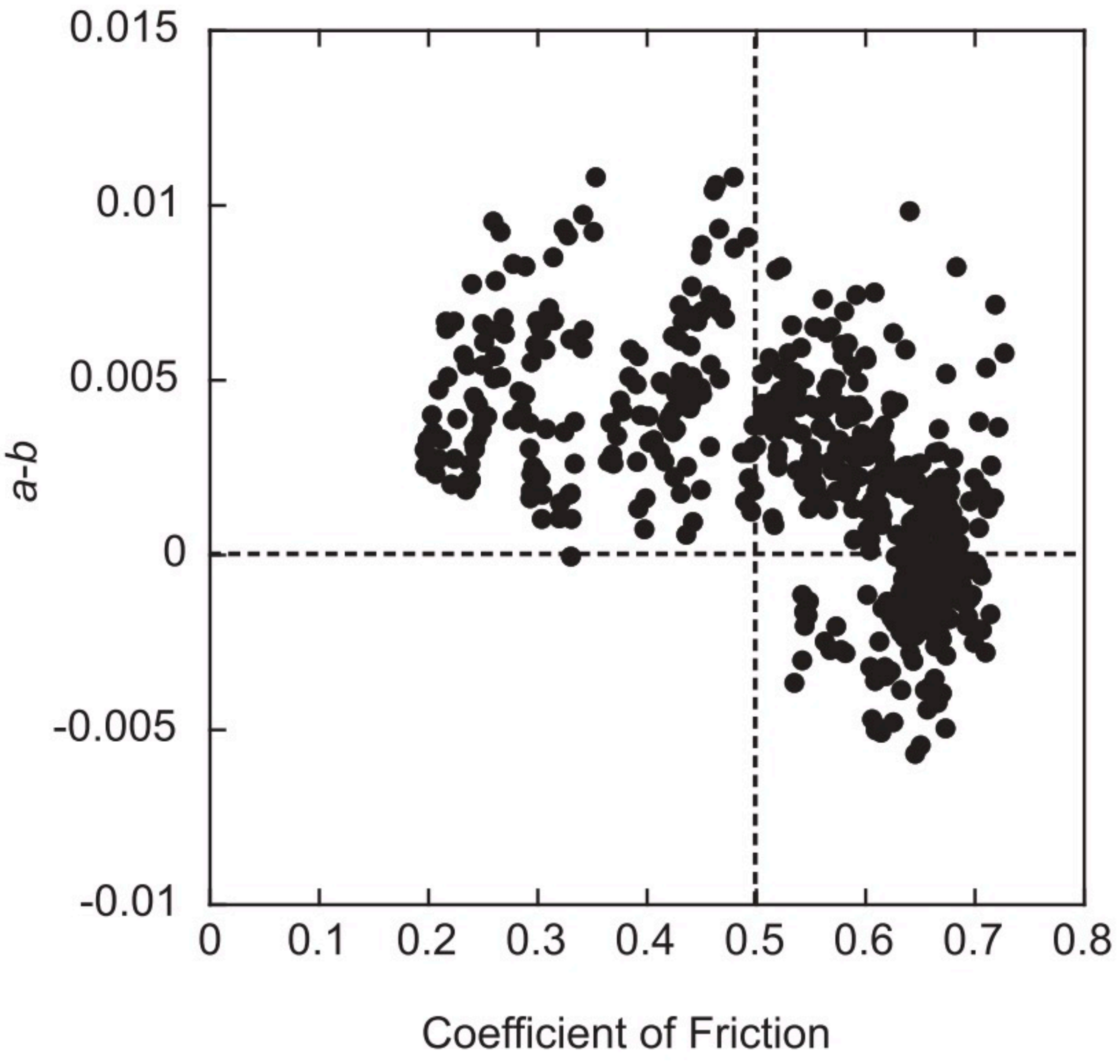
(a-b) greatly varies depending on a variety of boundary conditions, fault mineralogical composition and fault maturity (i.e. strain localization)

Scaling of rate parameters derived in the laboratory to seismic faulting

Identify the mechanical conditions and constitutive properties that distinguish stable from unstable sliding.

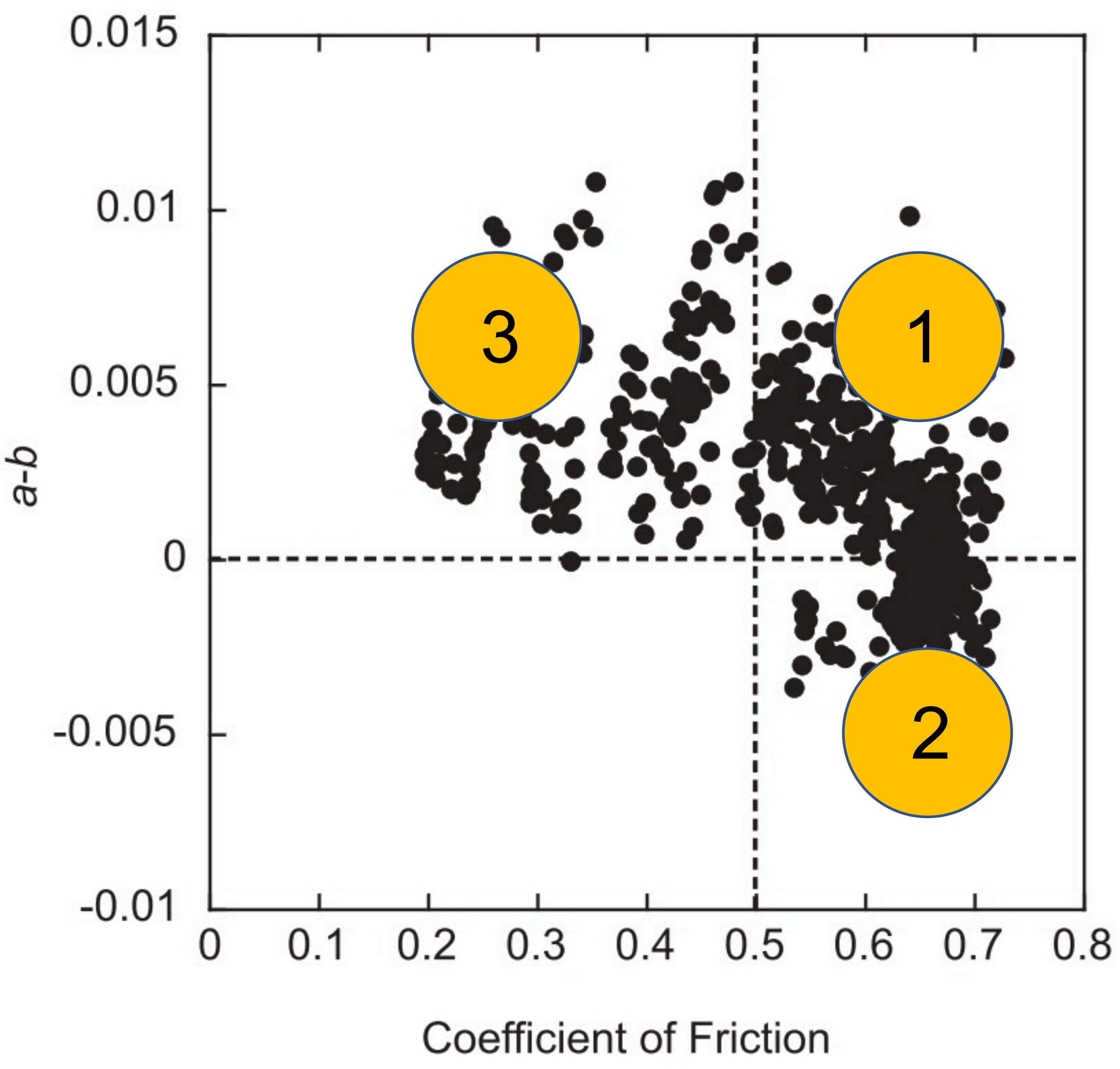
Determine these friction parameters for a range of conditions, with the hope that key processes can be identified and appropriate scaling relations can be derived to connect the laboratory data with field observations

Major factors controlling (a-b) and frictional stability



Ikari et al., 2011 Geology

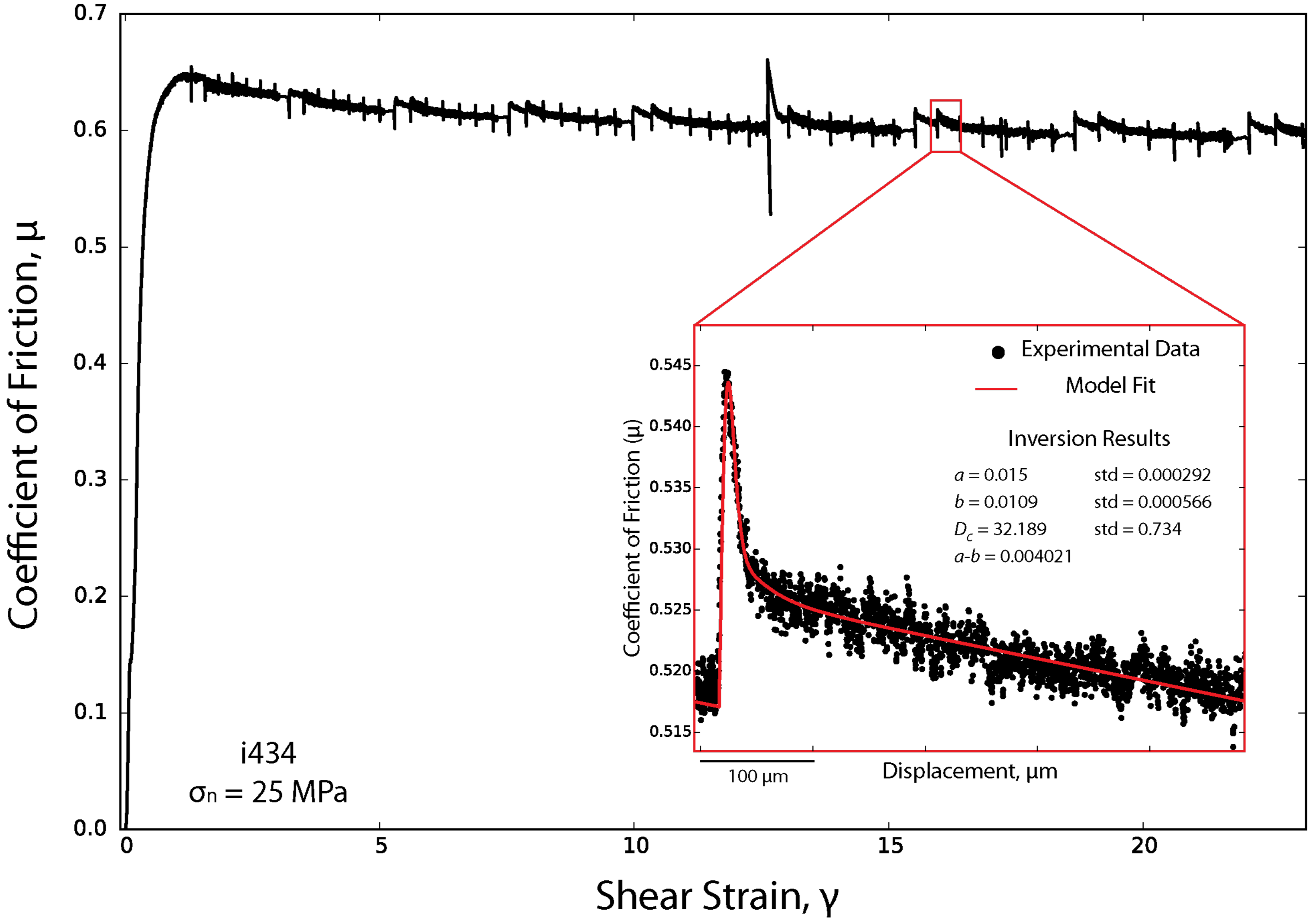
Major factors controlling (a-b) and frictional stability



Major factors controlling (a-b) and frictional stability

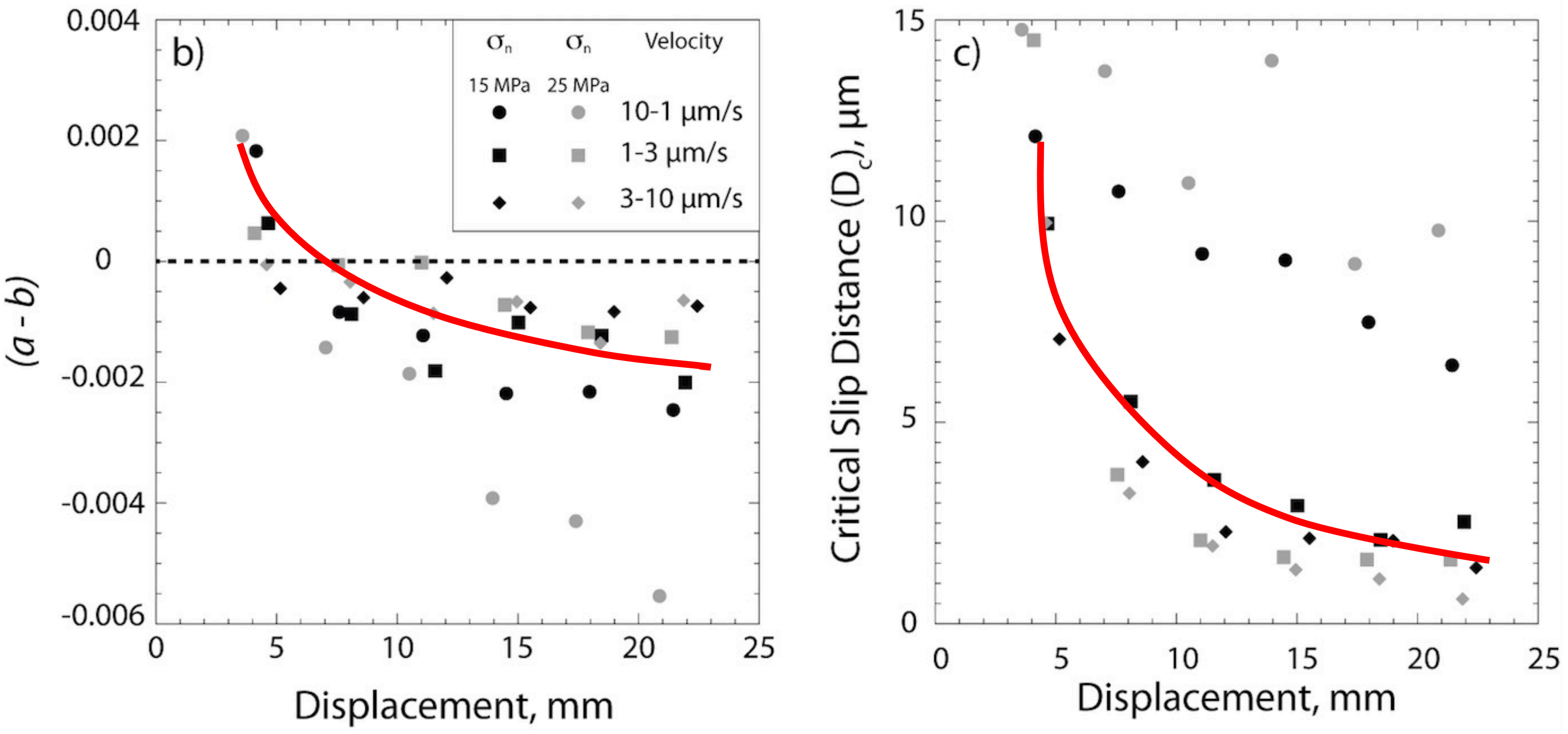
The effect of strain localization – regimes 1 to 2

(quartz fault gouge example)



Major factors influencing (a-b) and frictional stability

The effect of strain localization – regimes 1 to 2
(quartz fault gouge example)



Major factors influencing (a-b) and frictional stability

The effect of strain localization – regimes 1 to 2
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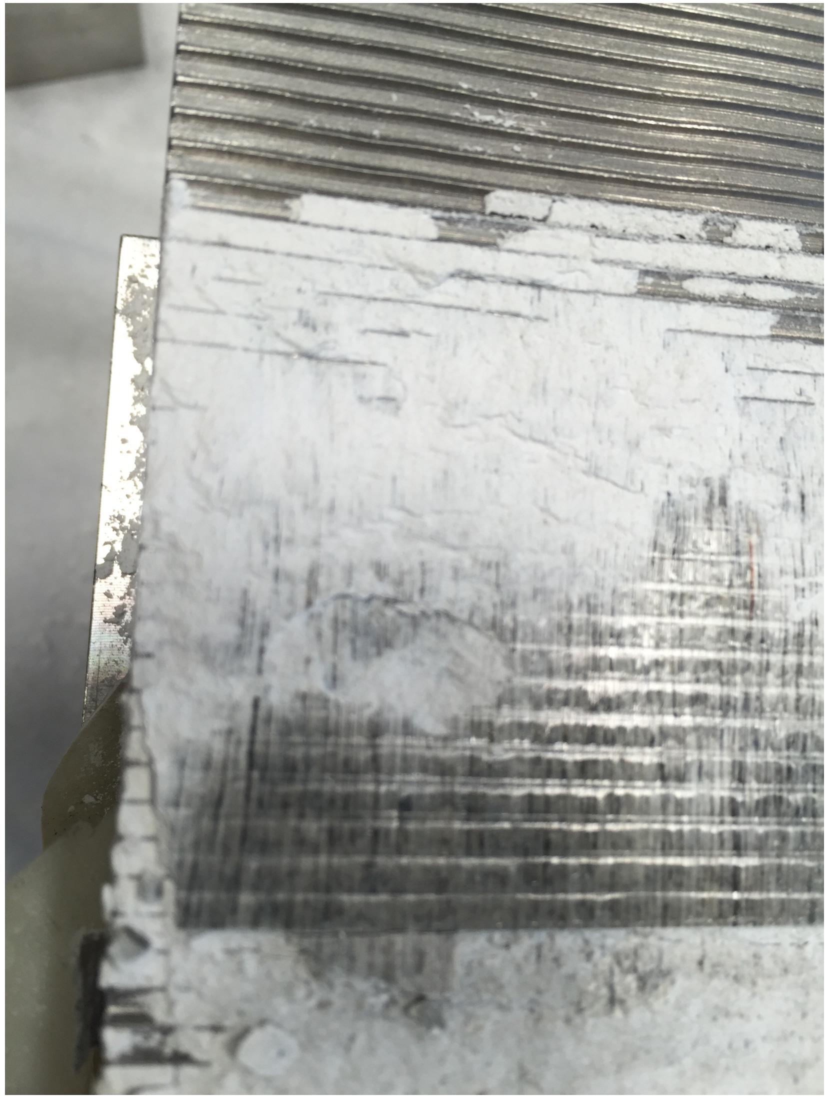
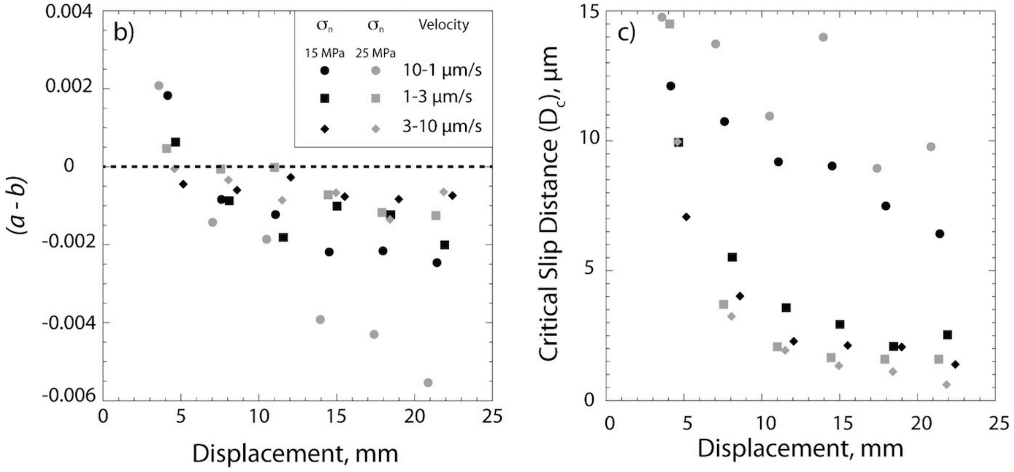
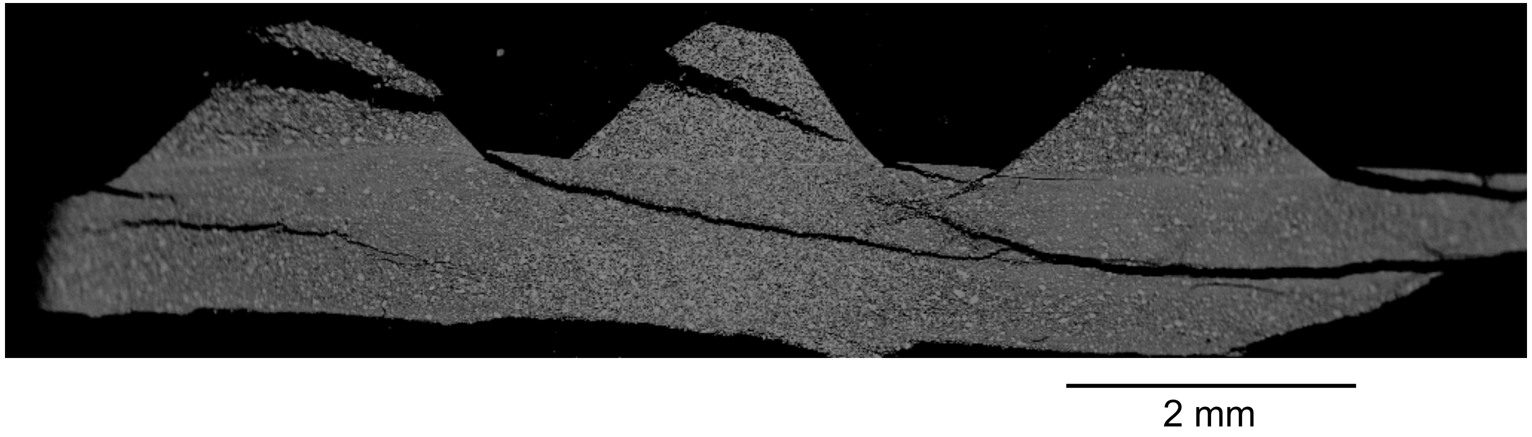




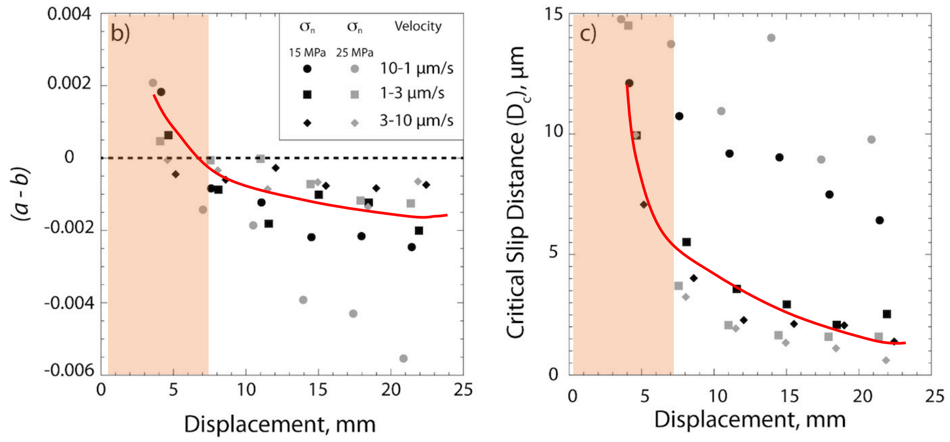
Microstructural observations of the resulting fault zone

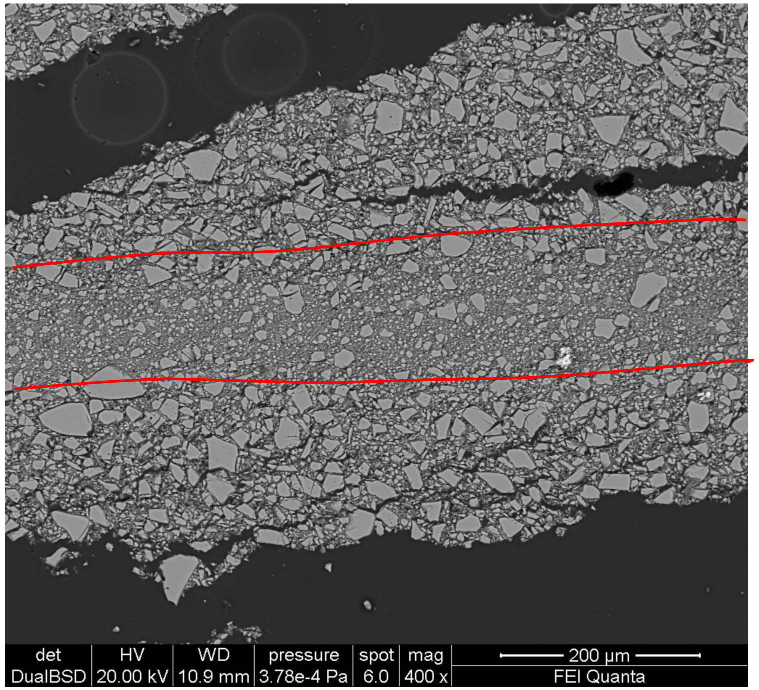


Scuderi et al., 2017 Geology

Major factors influencing (a-b) and frictional stability

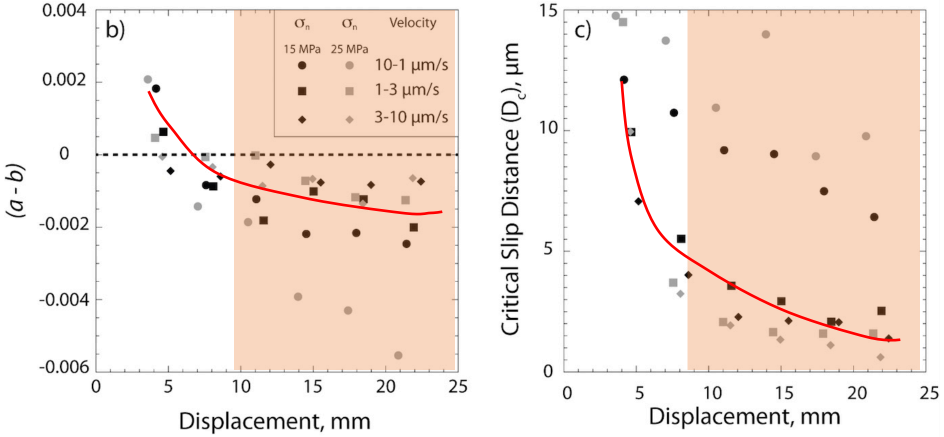
The effect of strain localization – regimes 1 to 2
(quartz fault gouge example)

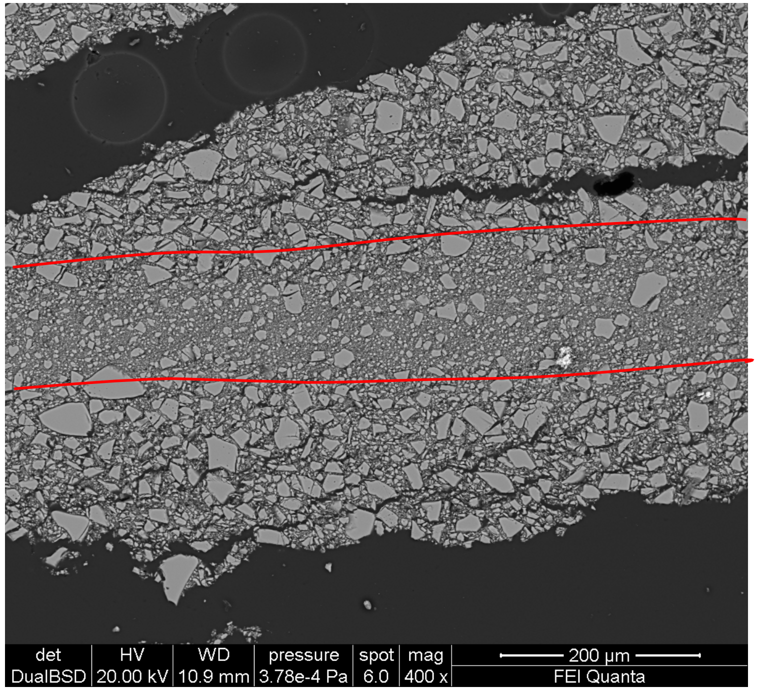


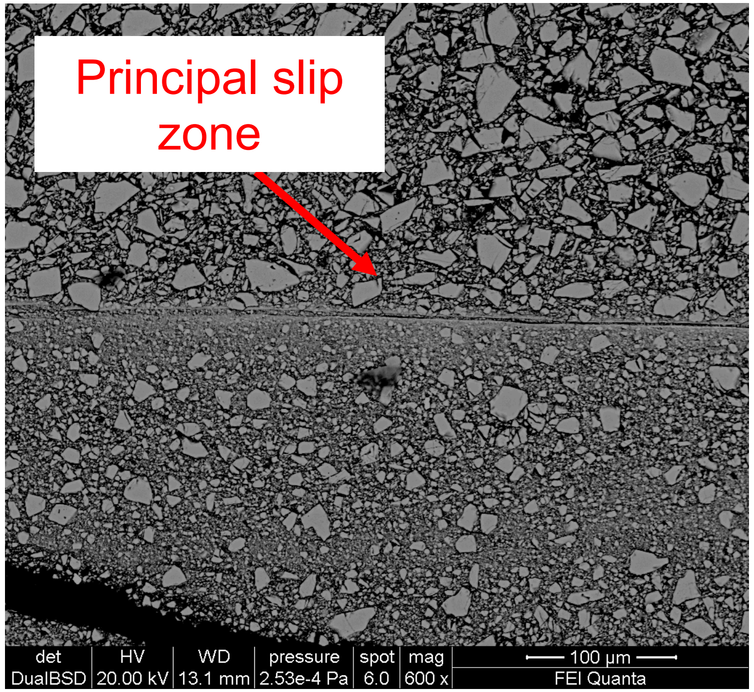


Major factors influencing (a-b) and frictional stability

The effect of strain localization – regimes 1 to 2
(quartz fault gouge example)



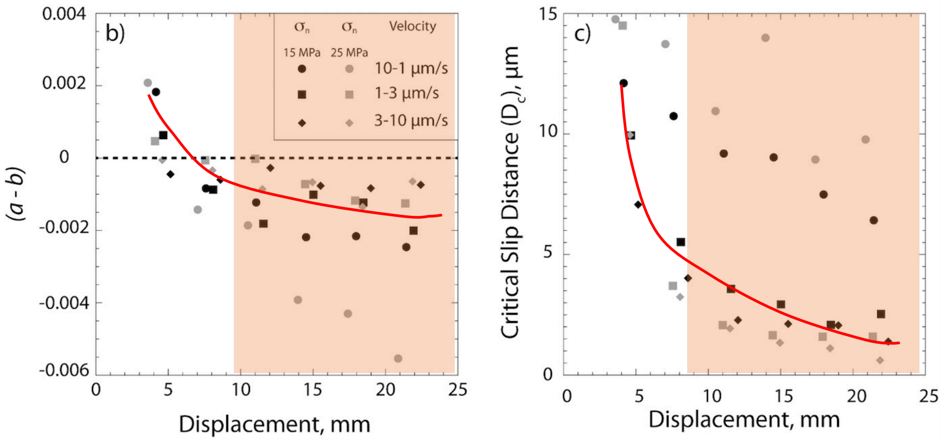


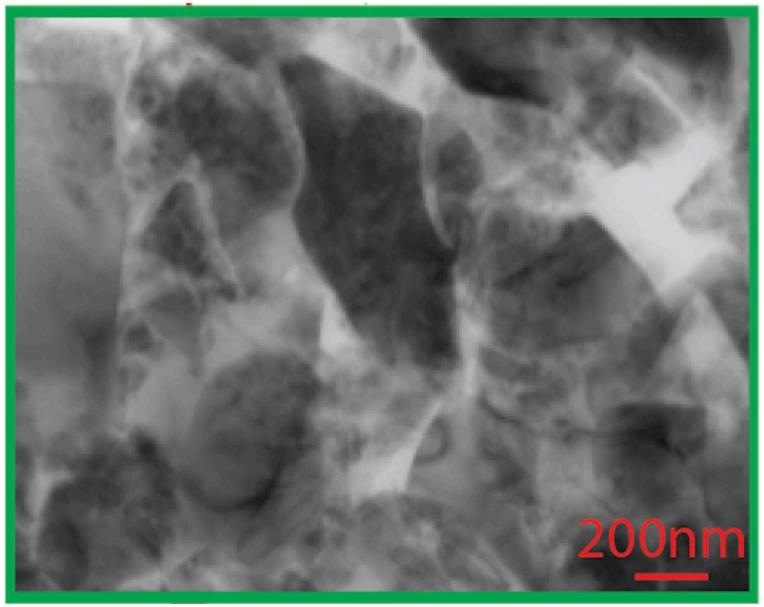


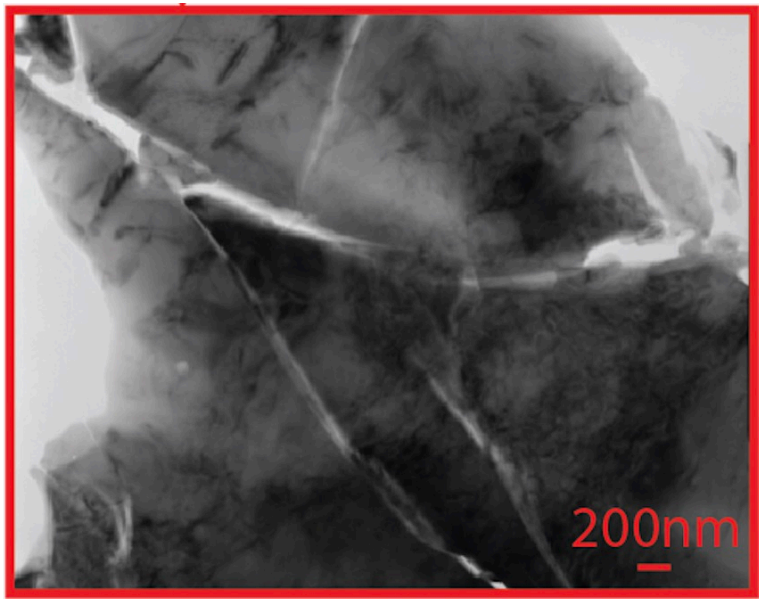
Major factors influencing (a-b) and frictional stability

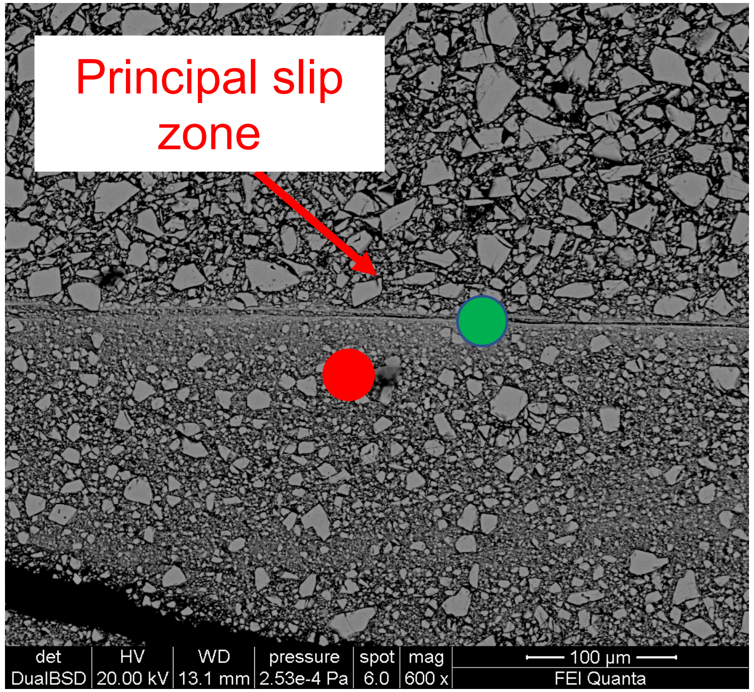
The effect of strain localization – regimes 1 to 2

(quartz fault gouge example)





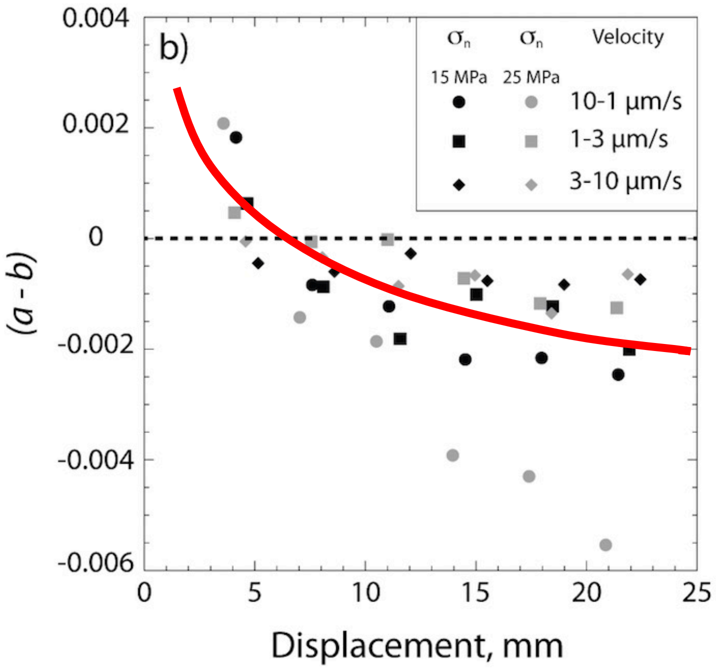


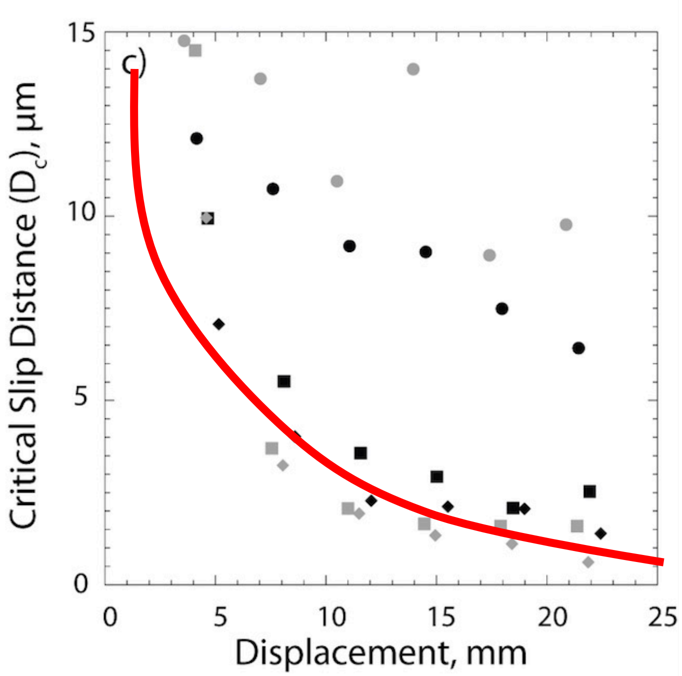


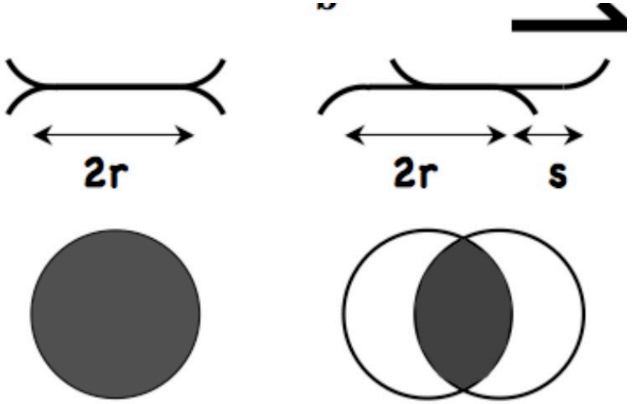
Major factors influencing (a-b) and frictional stability

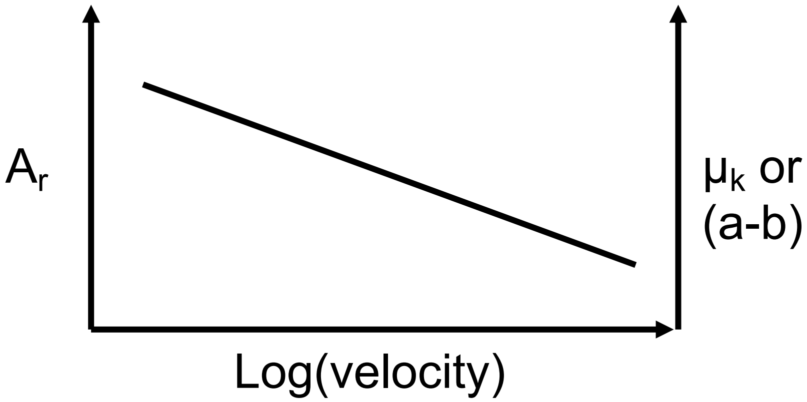
The effect of strain localization – regimes 1 to 2

(quartz fault gouge example)









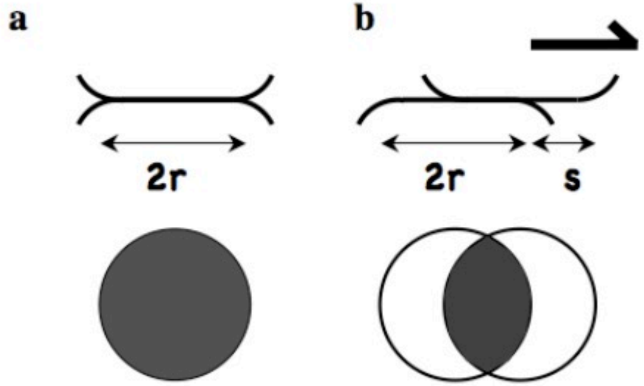
Major factors influencing (a-b) and frictional stability

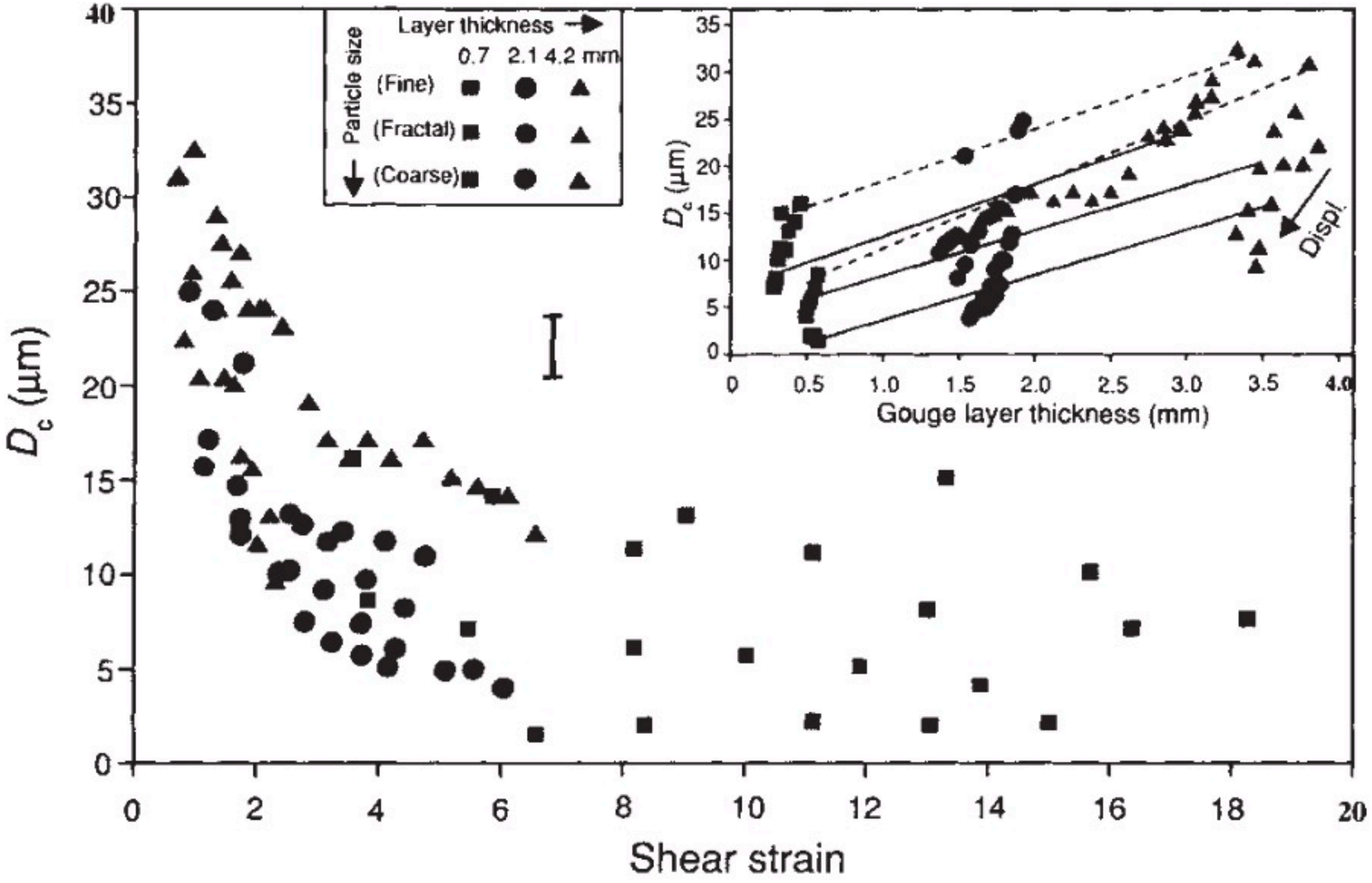
The effect of strain localization – regimes 1 to 2
(quartz fault gouge example)

Scaling of the critical slip distance for seismic faulting with shear strain in fault zones

Chris Marone* & Brian Kilgore†

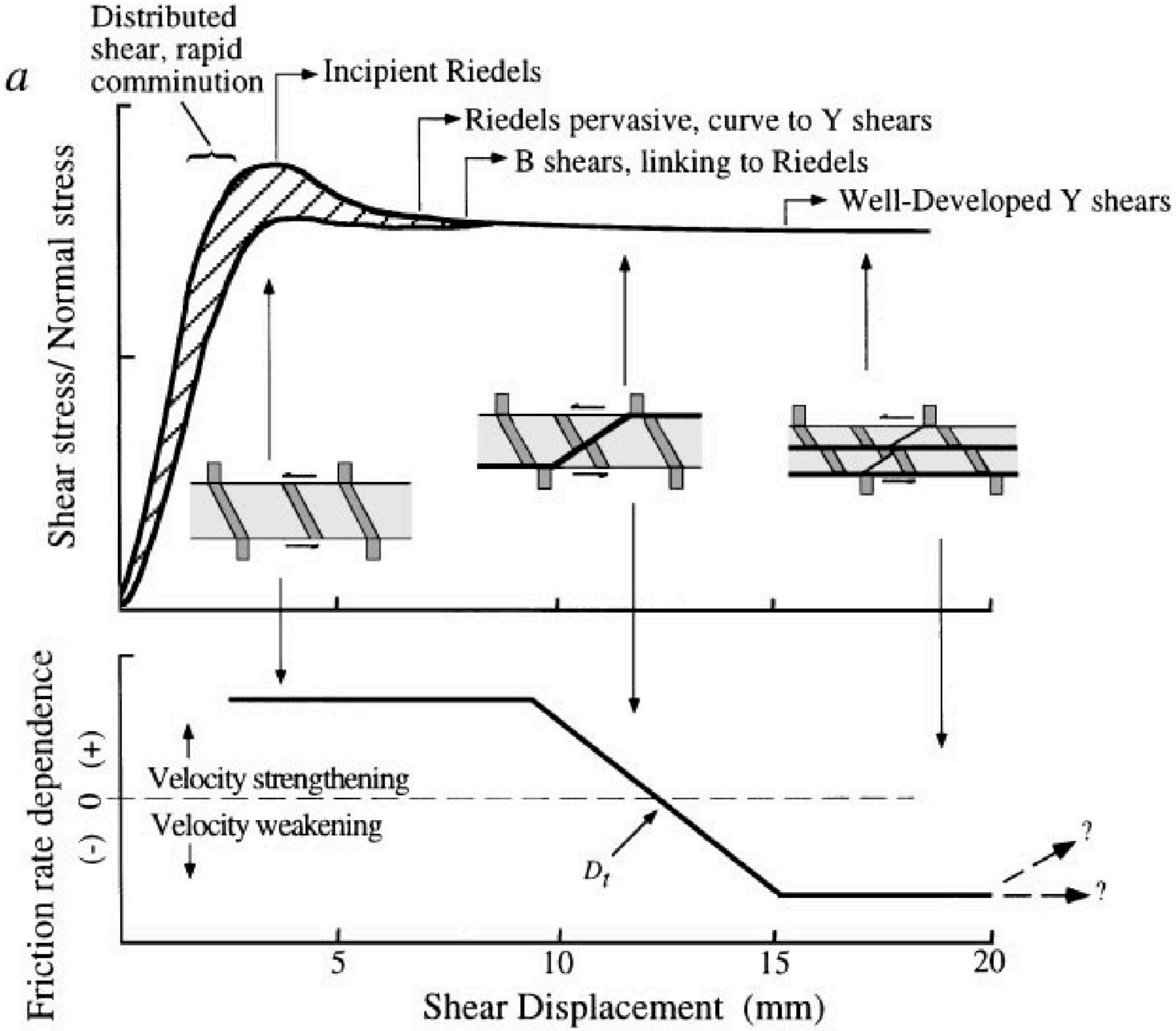
1993, Nature





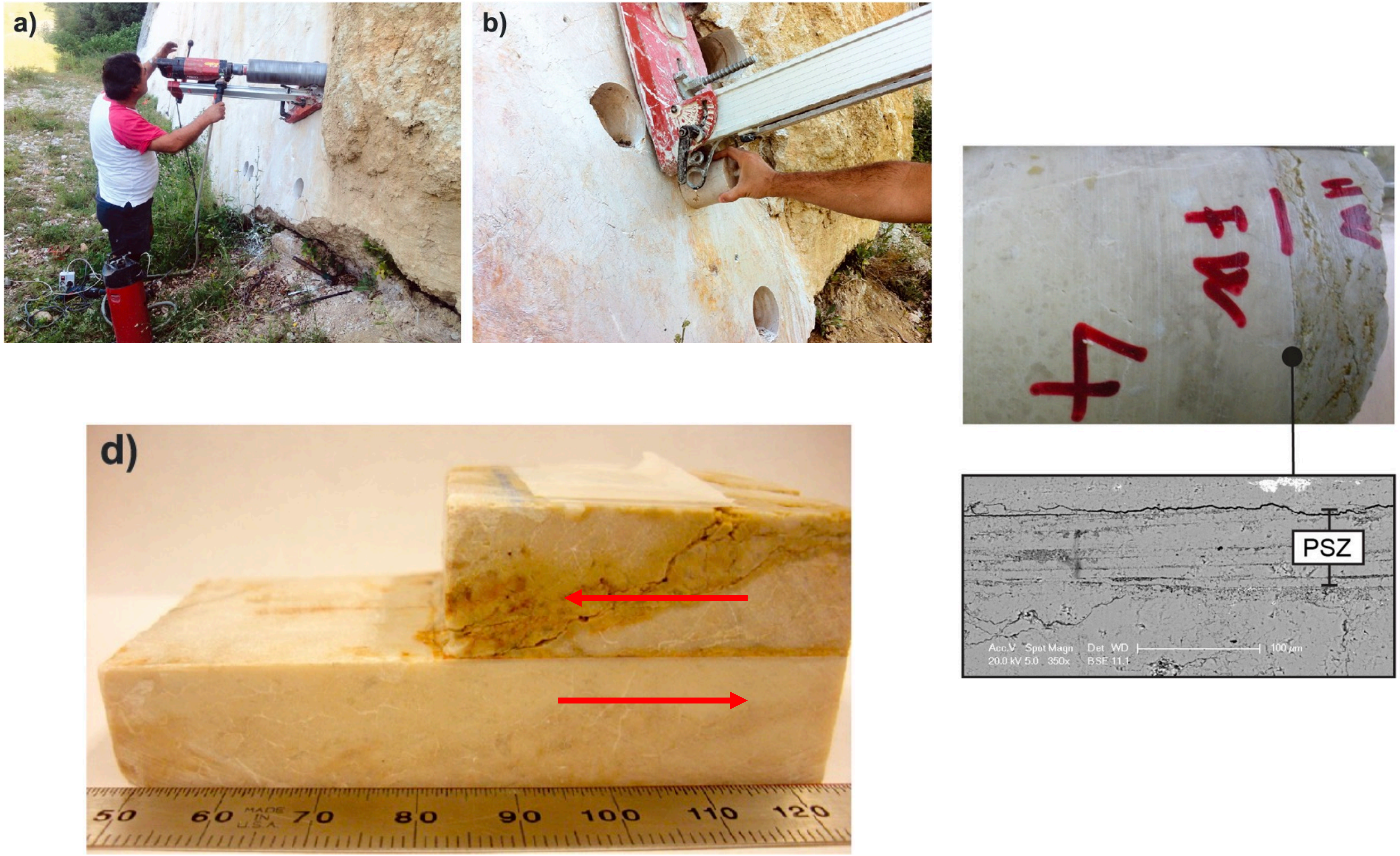
Major factors influencing (a-b) and frictional stability

The effect of strain localization – regimes 1 to 2



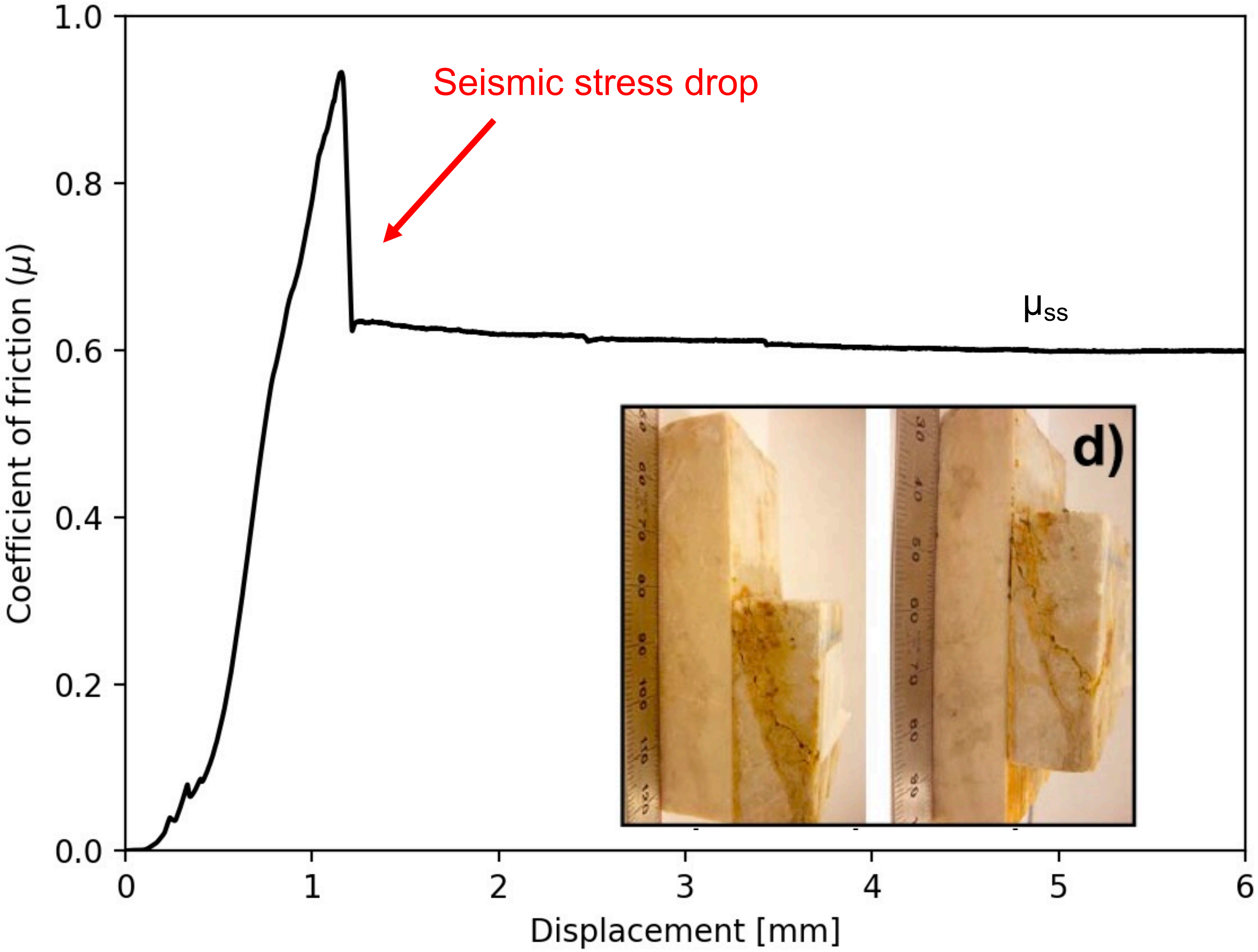
Marone, 1998
Beeler et al., 1996 JGR

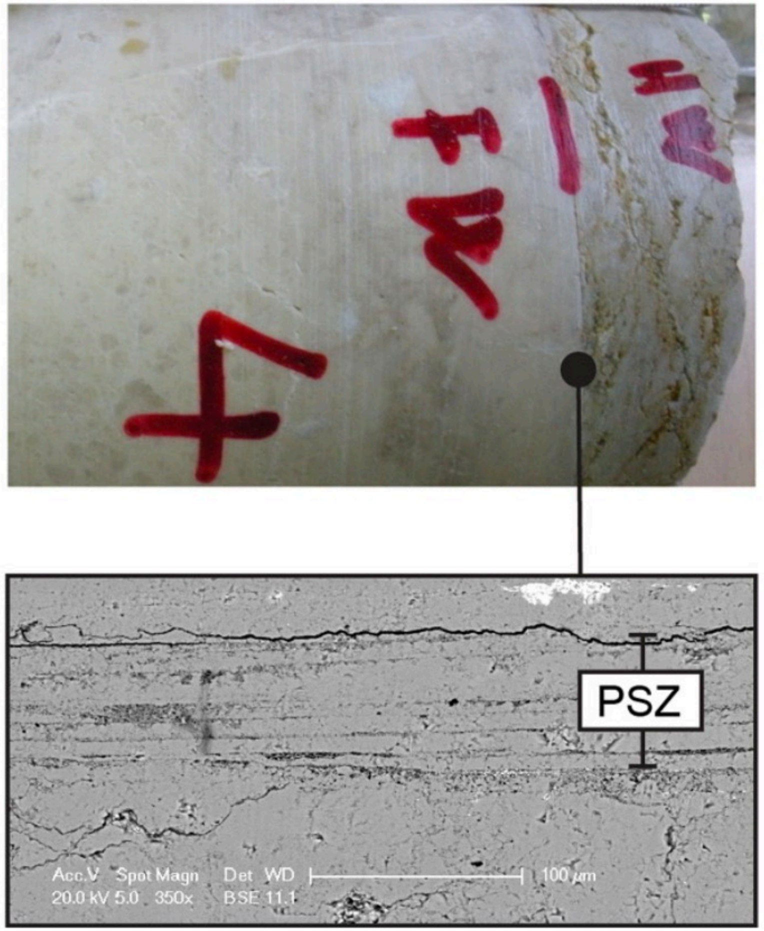
Rocchetta fault zone, Italy



Carpenter et al., 2014 JGR

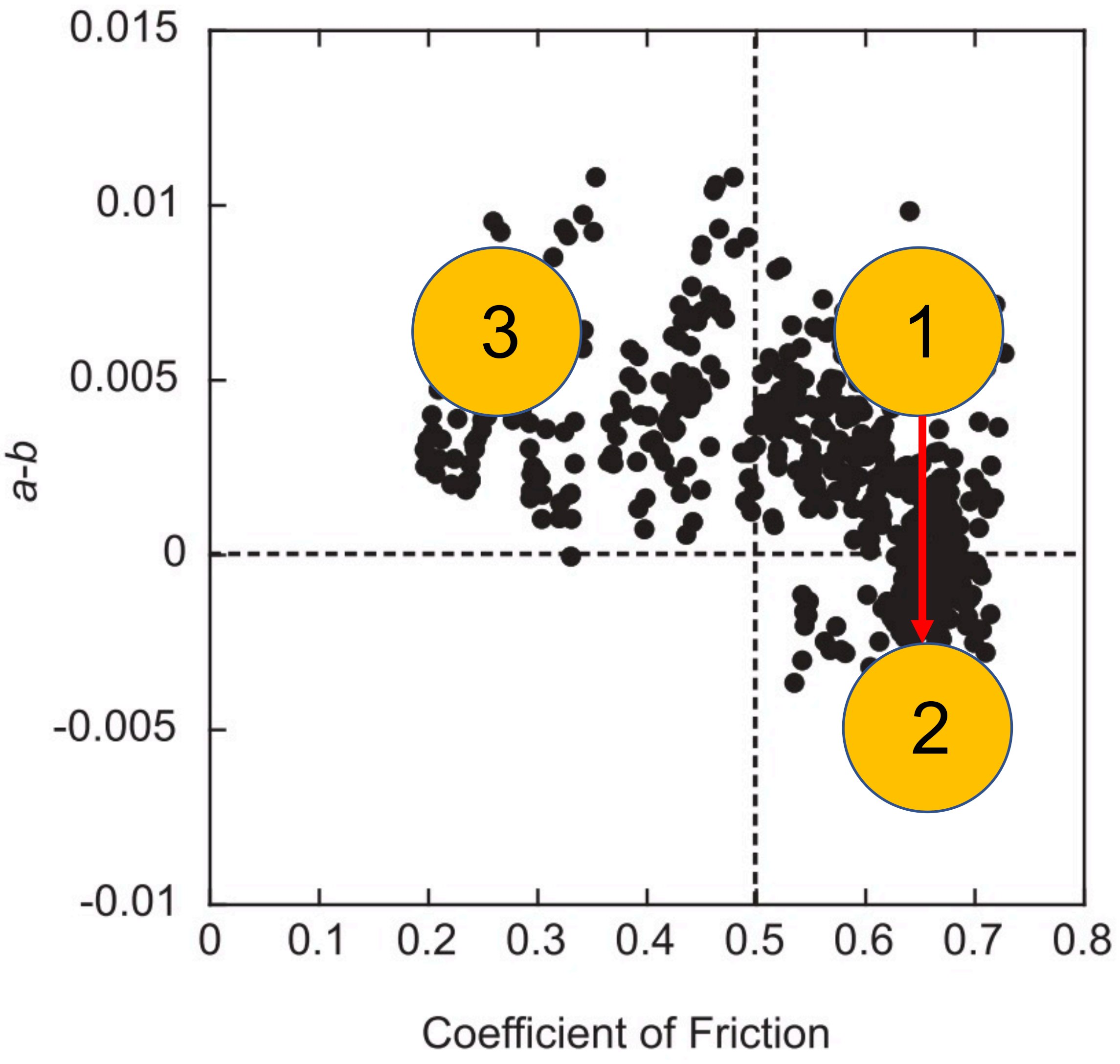
Rocchetta fault zone





Carpenter et al., 2014 JGR

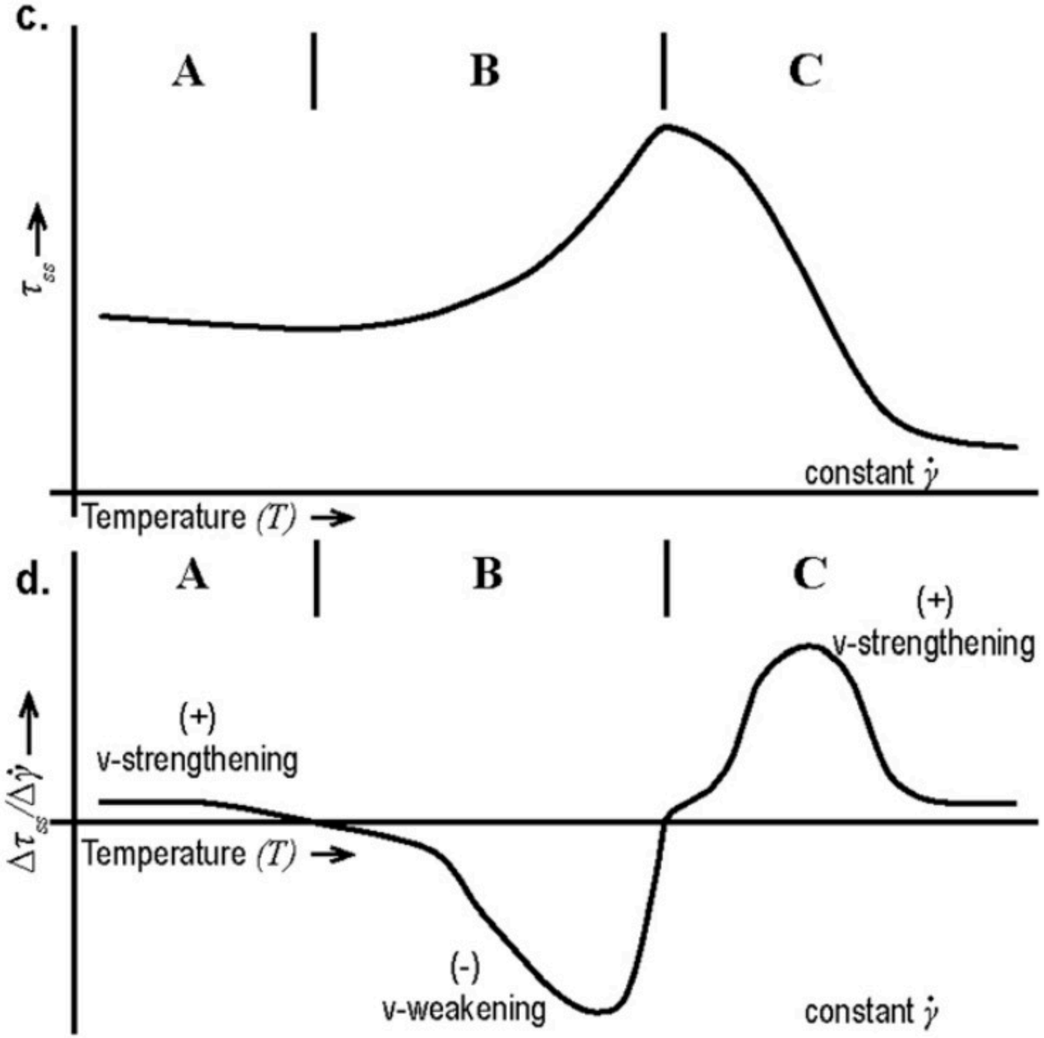
Major factors controlling (a-b) and frictional stability



One of the main mechanism to pass from velocity strengthening to weakening is associated to shear localization in quartzo-feldspatic and carbonate rocks.
By no means this is the only mechanism.

Major factors controlling (a-b) and frictional stability

Temperature

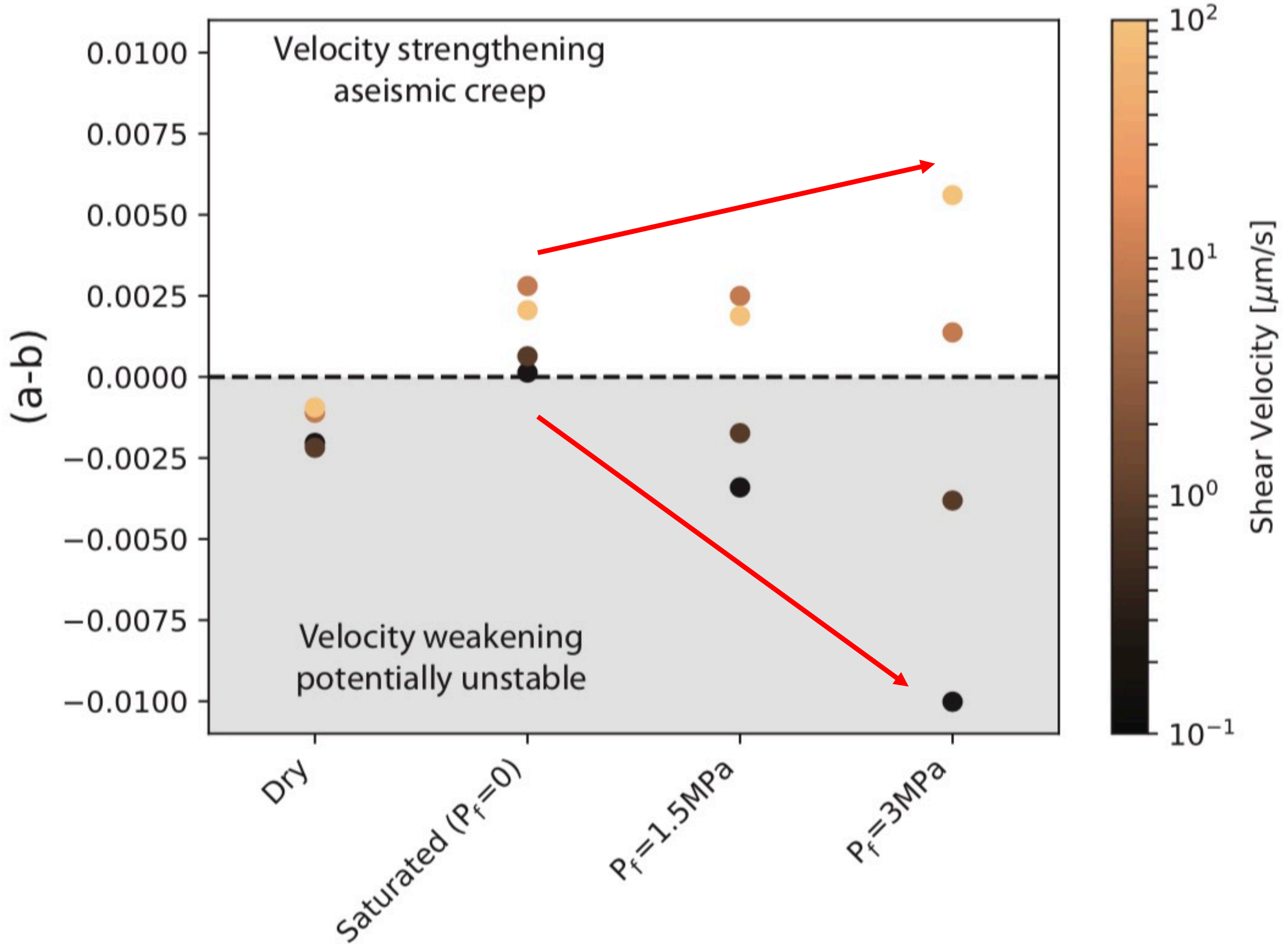


Increasing in temperature usually causes a transition from velocity strengthening to velocity weakening. As temperature continues to increase ductility kicks in and frictional stability comes back to velocity strengthening

Chester and Higgs, 1992
Banpied et al., 1995
Verberne et al., 2015
Niemeijer and Spiers, 2007

Major factors controlling (a-b) and frictional stability

Fluid pressure

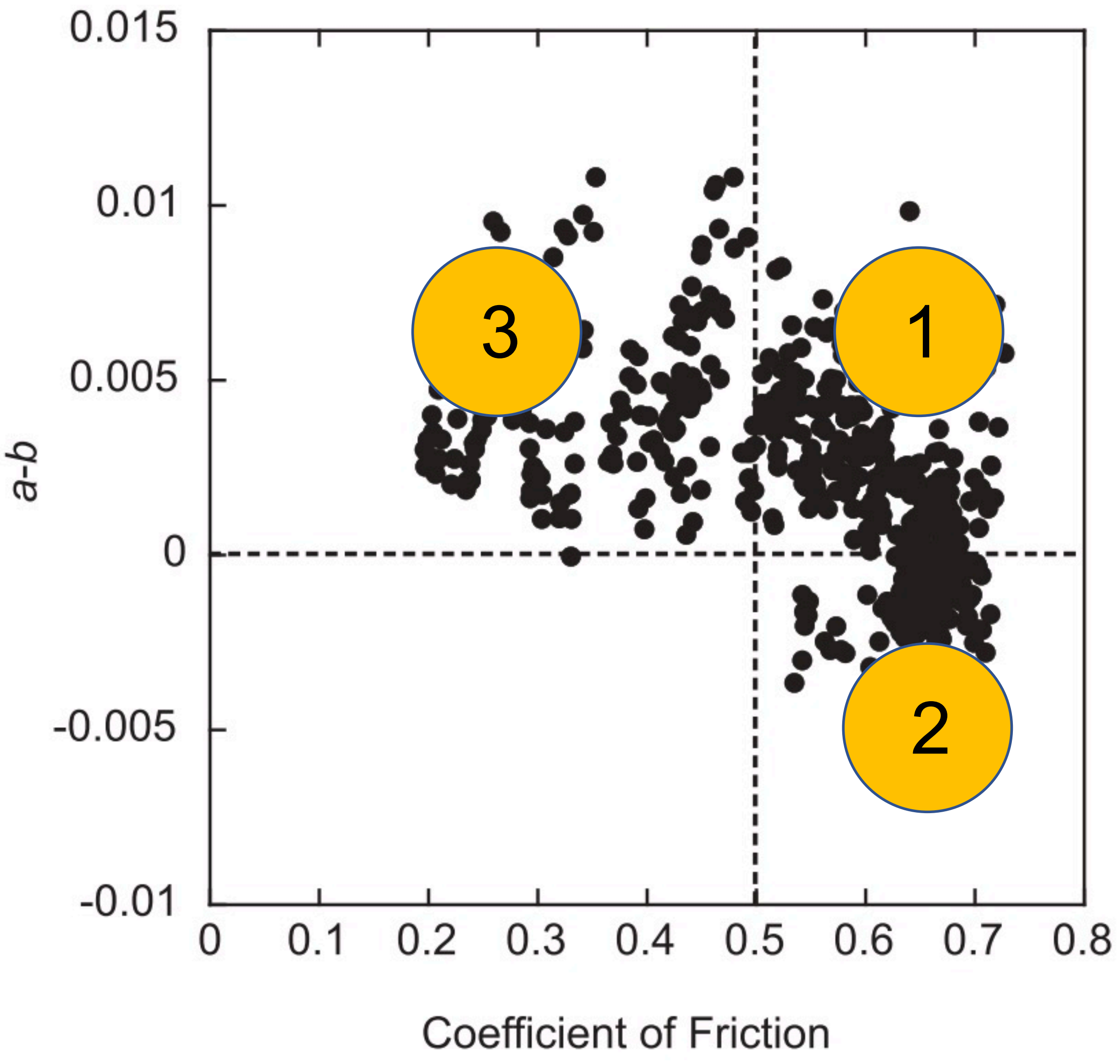


Increasing fluid pressure causes a transition from velocity strengthening to weakening in carbonate bearings rocks. We also observe a strong dependency on shear velocity.

However, data are scarce !!

Scuderi and Collettini, 2016 NatSciRep; Cappa et al., 2019 SciAdv

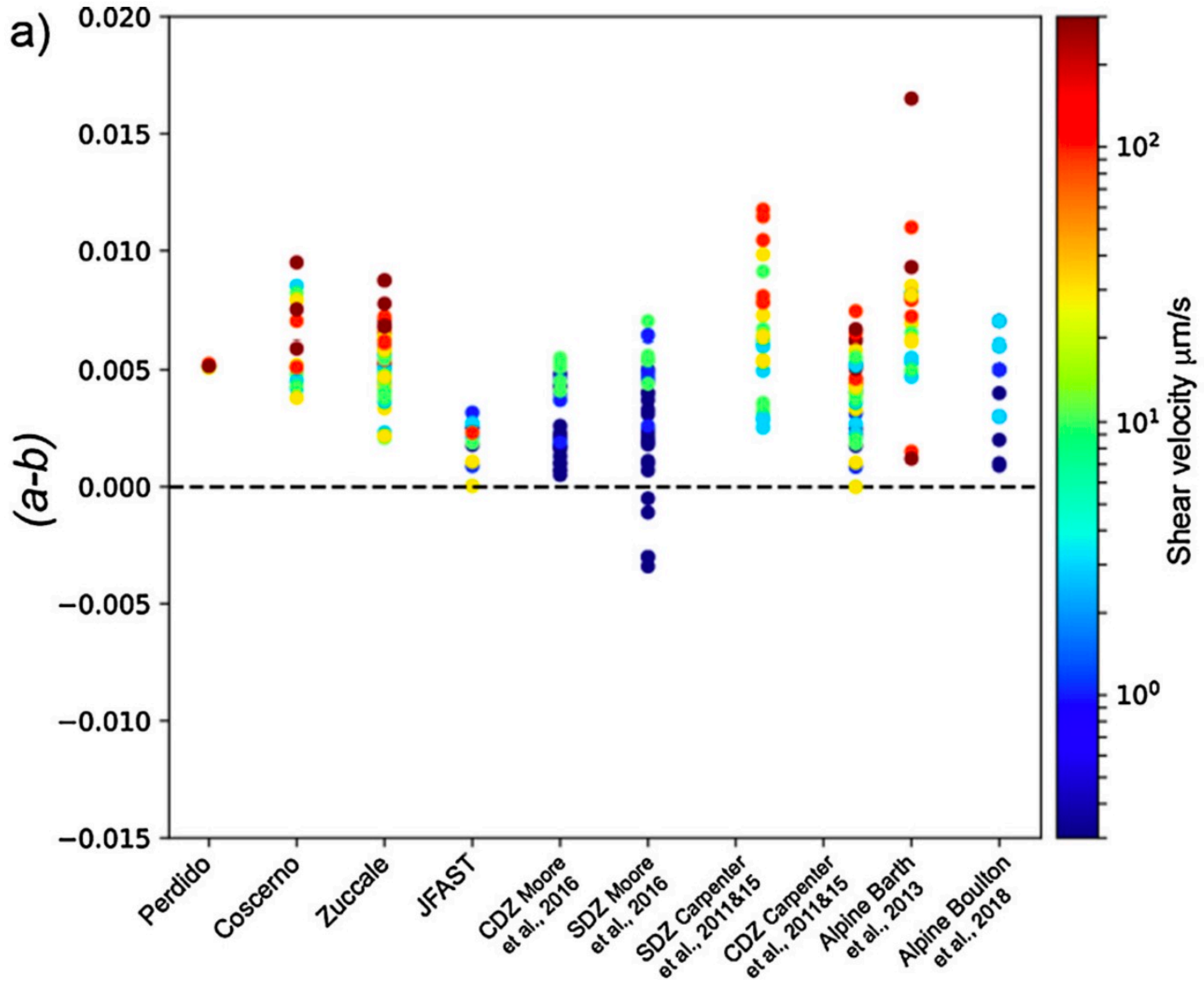
Major factors controlling (a-b) and frictional stability



Major factors influencing (a-b) and frictional stability

The effect of strain localization – regime 3

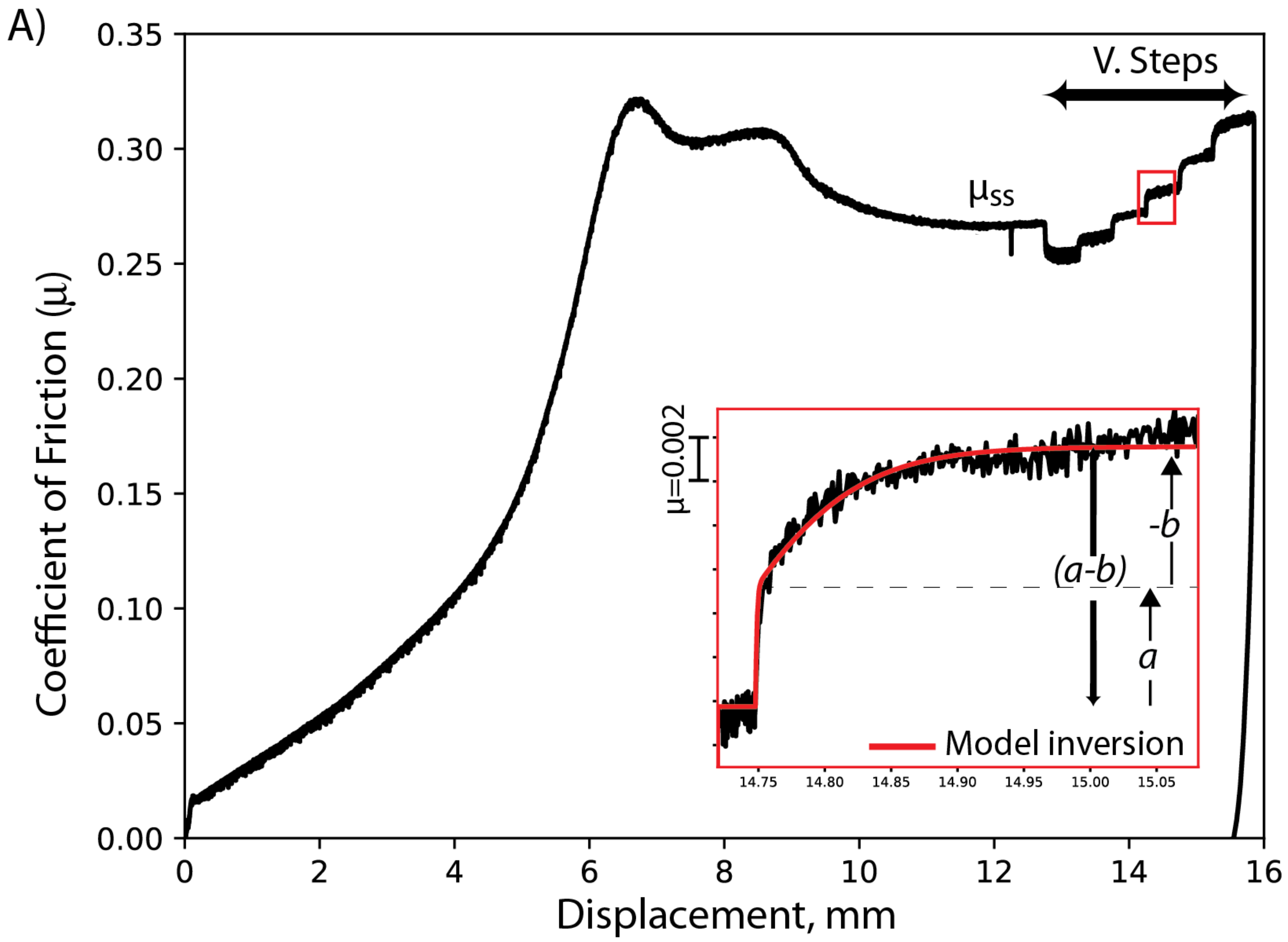
Phyllosilicate rich fault zones



Major factors influencing (a-b) and frictional stability

The effect of strain localization – regime 3

Illite rich fault gouge



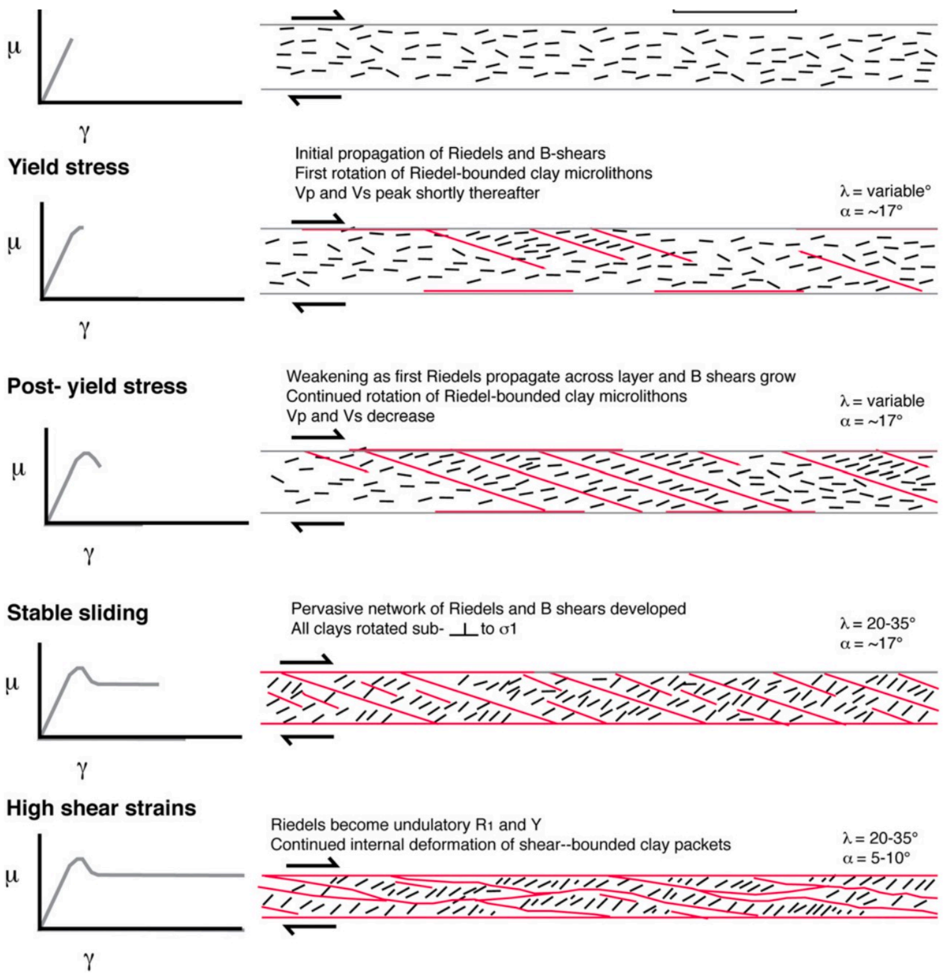
(1) Strain weakening to reach steady state friction (μ_{ss})

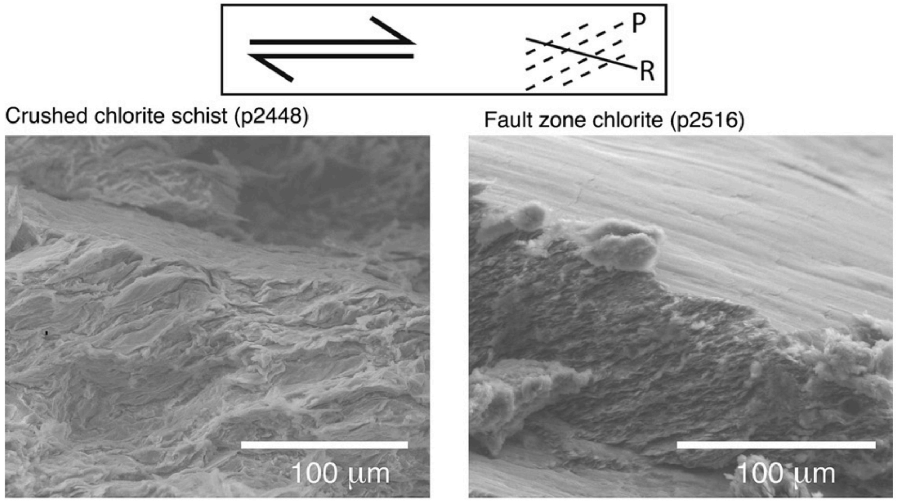
(2) During velocity step test friction strongly increases with velocity.

Major factors influencing (a-b) and frictional stability

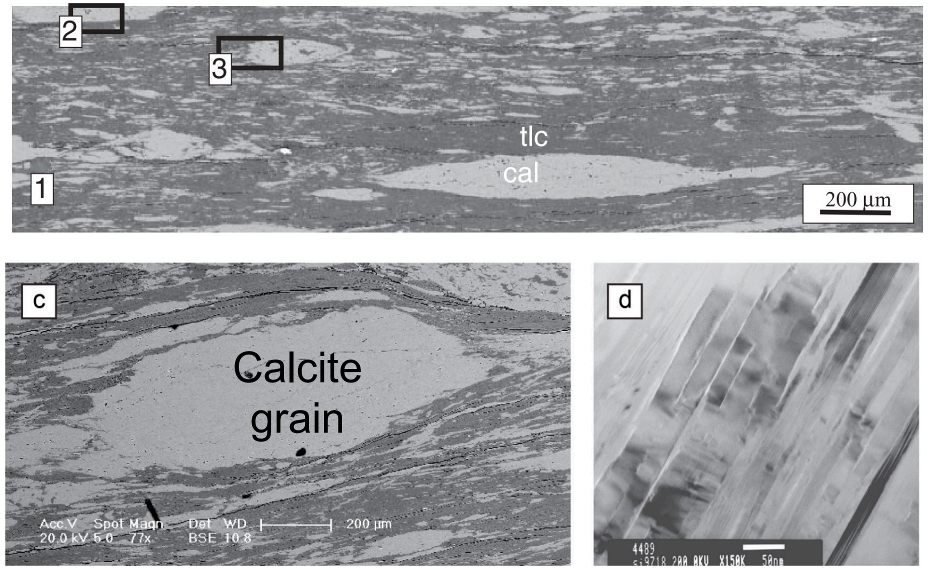
The effect of strain localization – regime 3

Fault strength and shear fabric





3D view of the resulting fault zone

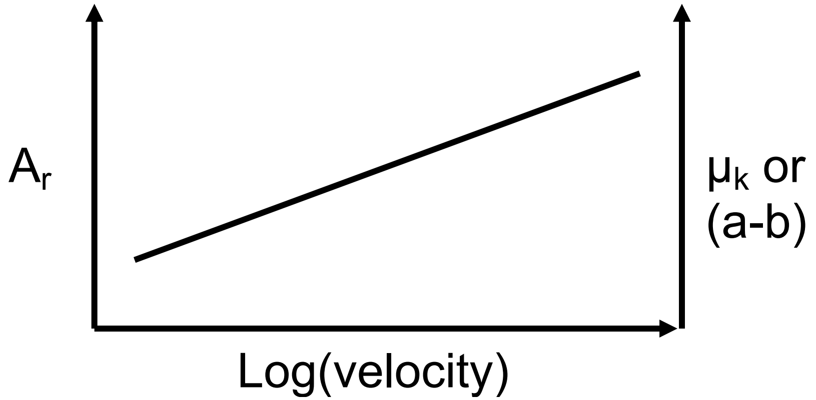


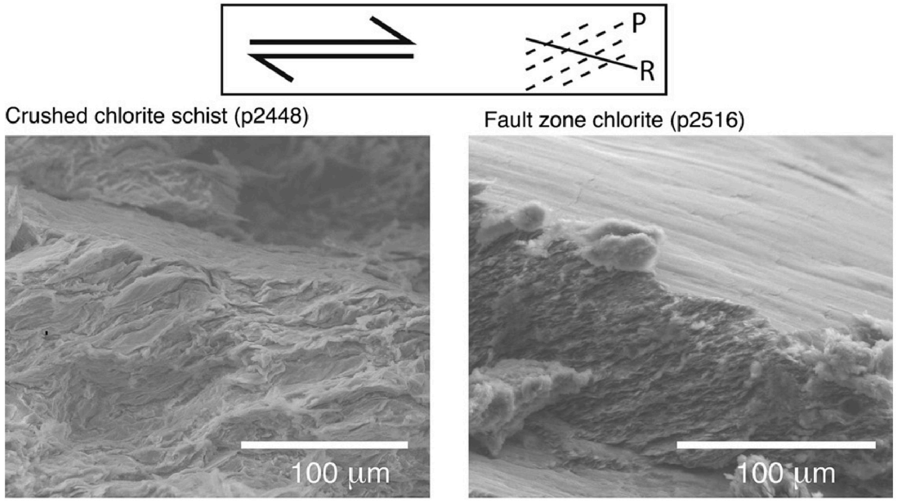
2D section view of the resulting fault zone

Haines et al., 2013 JSG

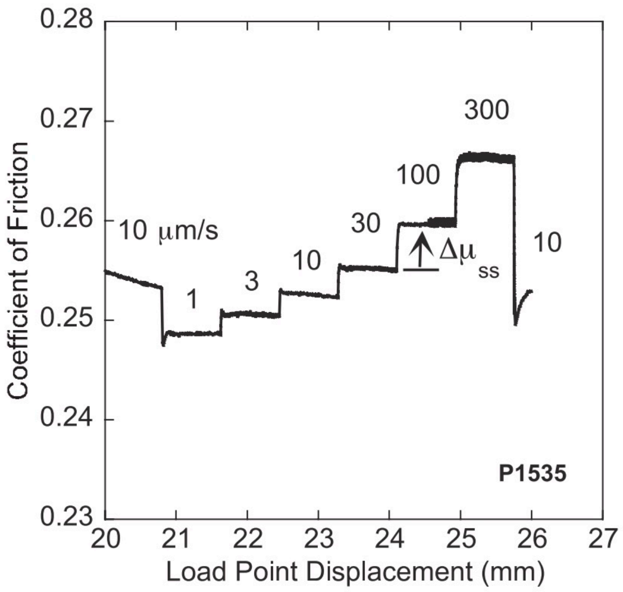
Major factors influencing (a-b) and frictional stability

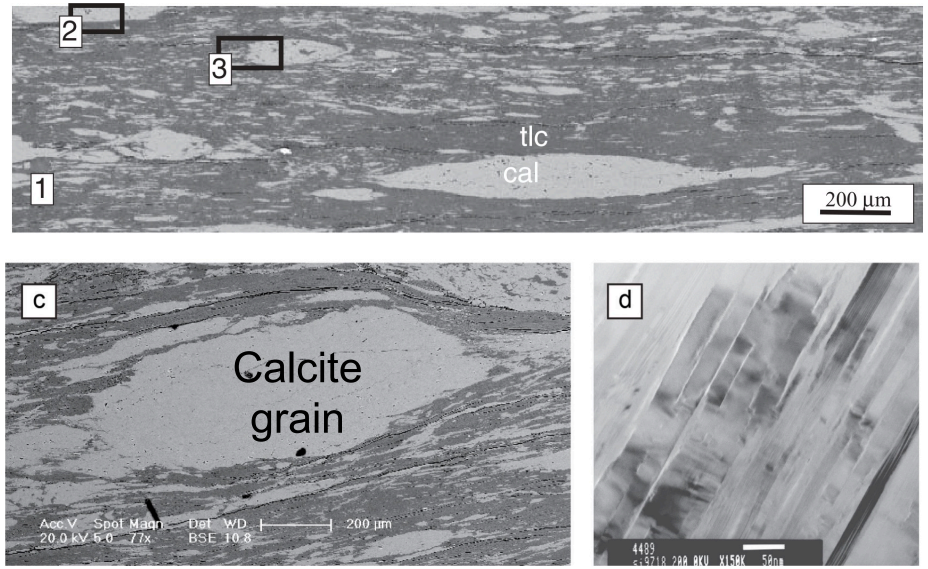
The effect of strain localization – regime 3





3D view of the resulting fault zone

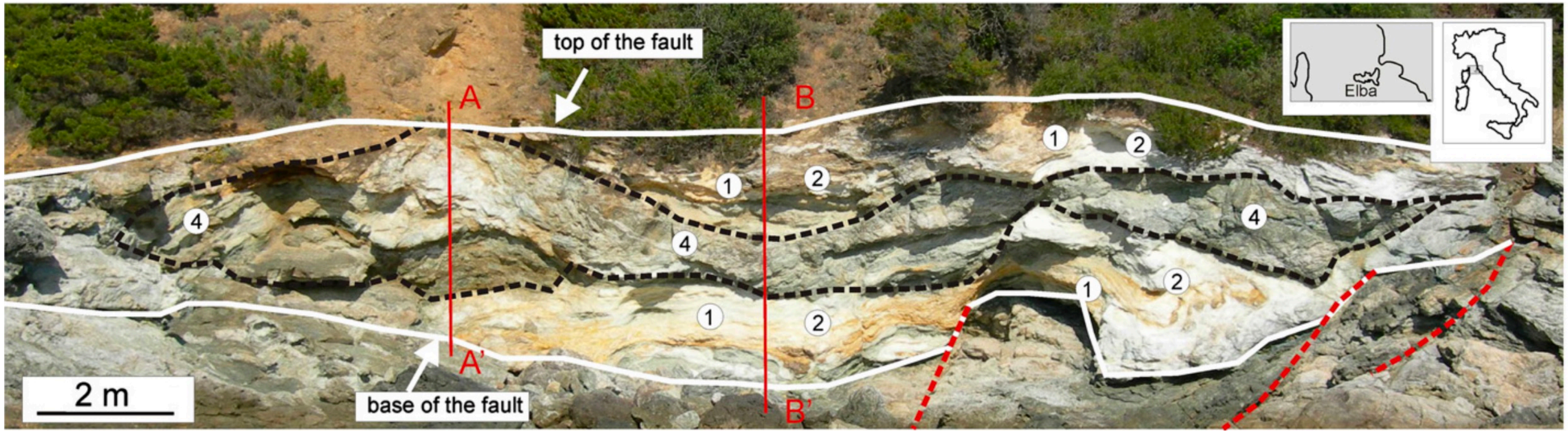


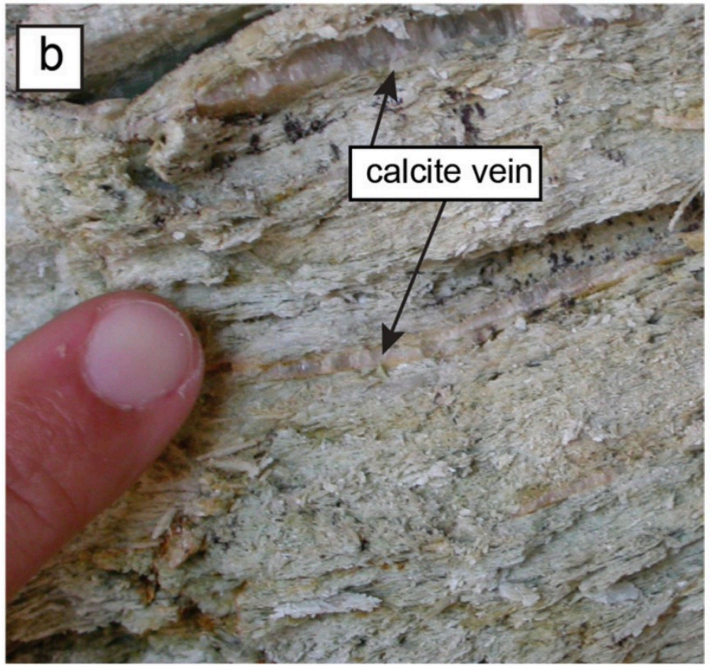


2D section view of the resulting fault zone

Saffer and Marone 2003
Ikari et al., 2009

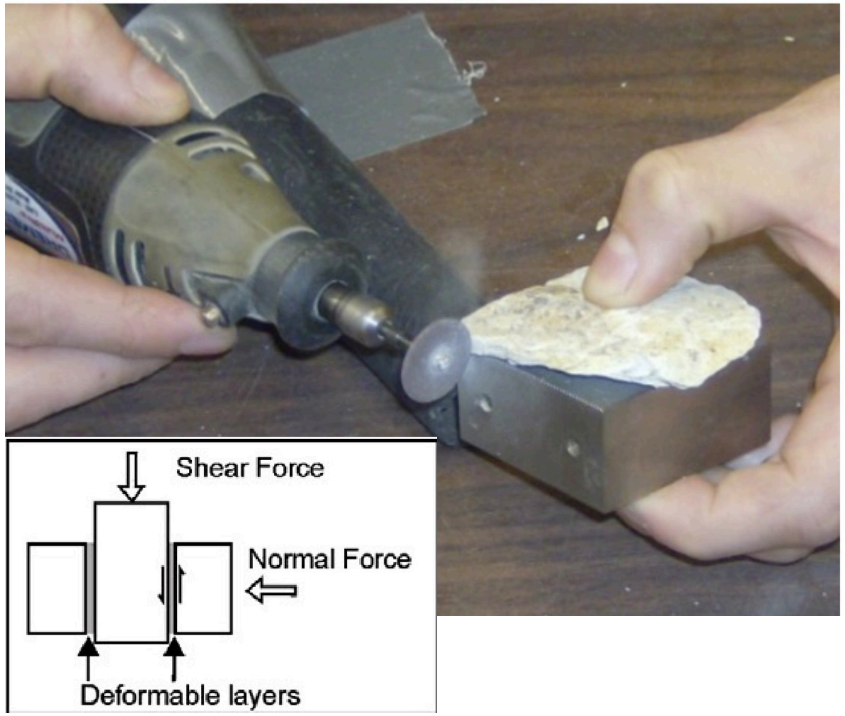
Zuccale fault zone, Elba Island, Italy

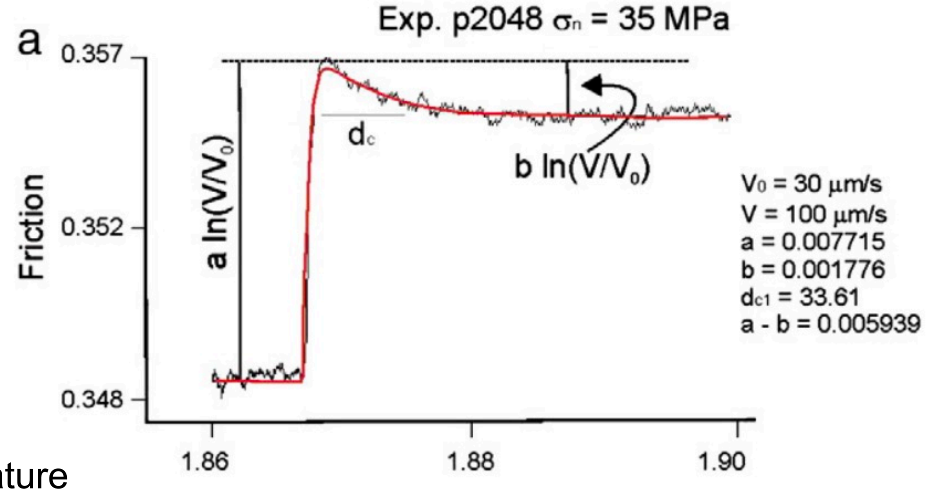


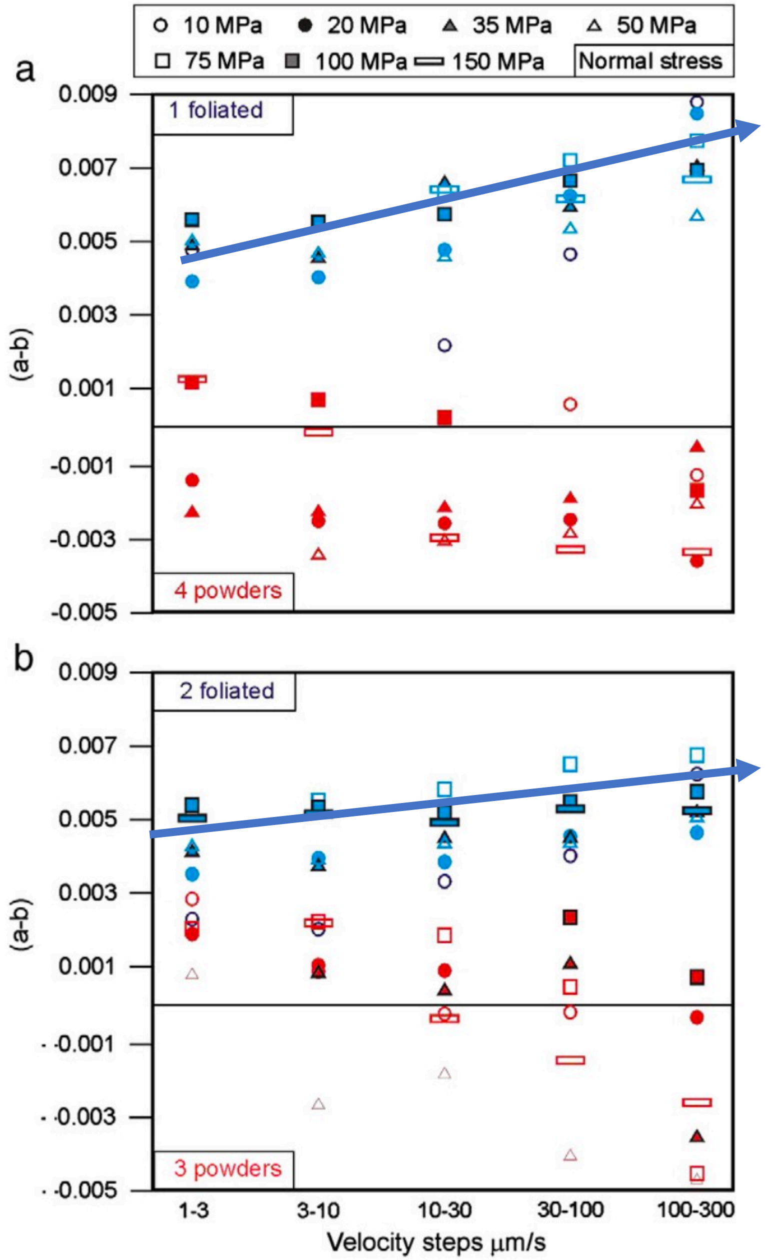


Collettini et al., 2009 Nature
Collettini et al., 2011 EPSL

Zuccale fault zone

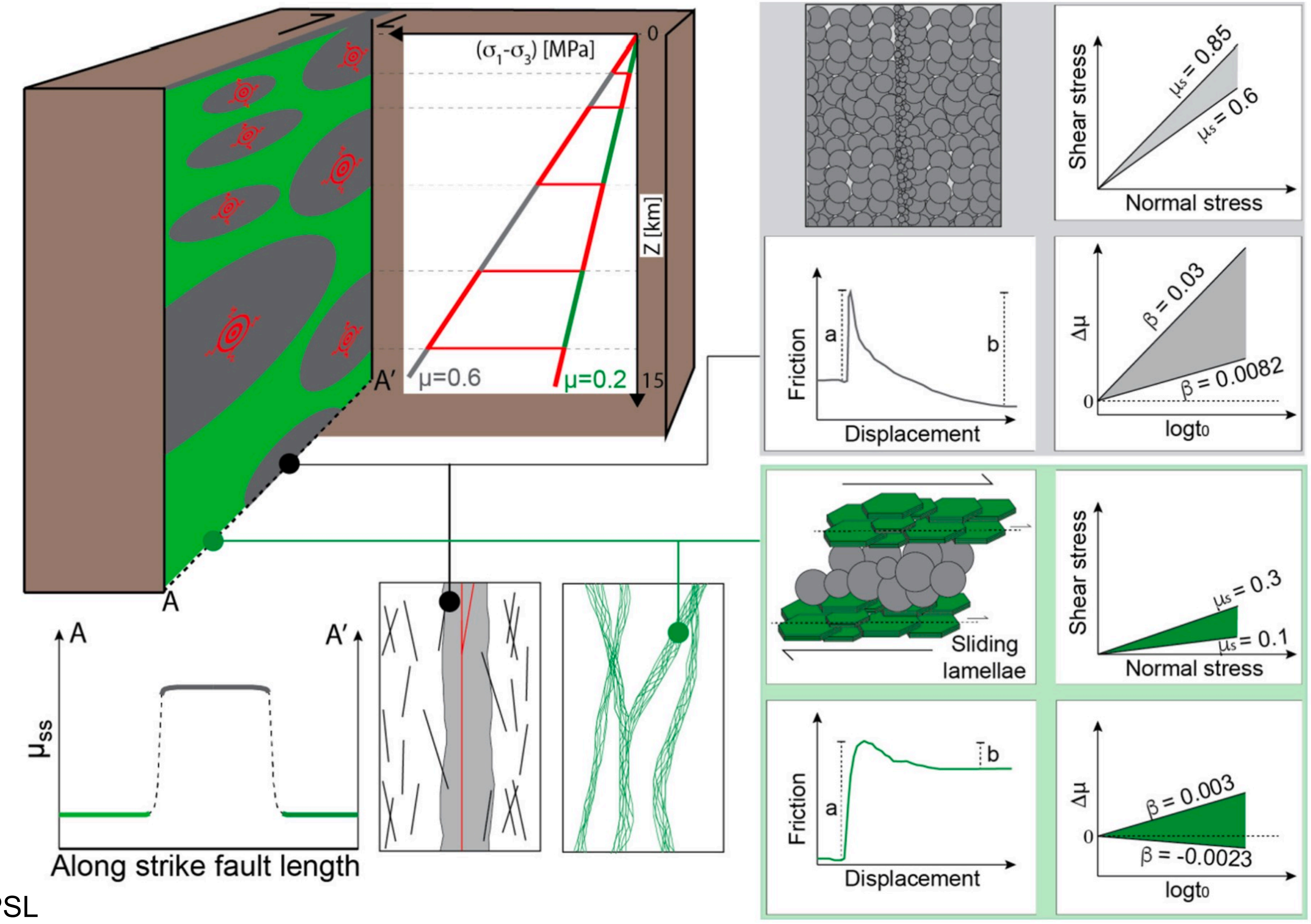






Collettini et al., 2009 Nature
Collettini et al., 2011 EPSL

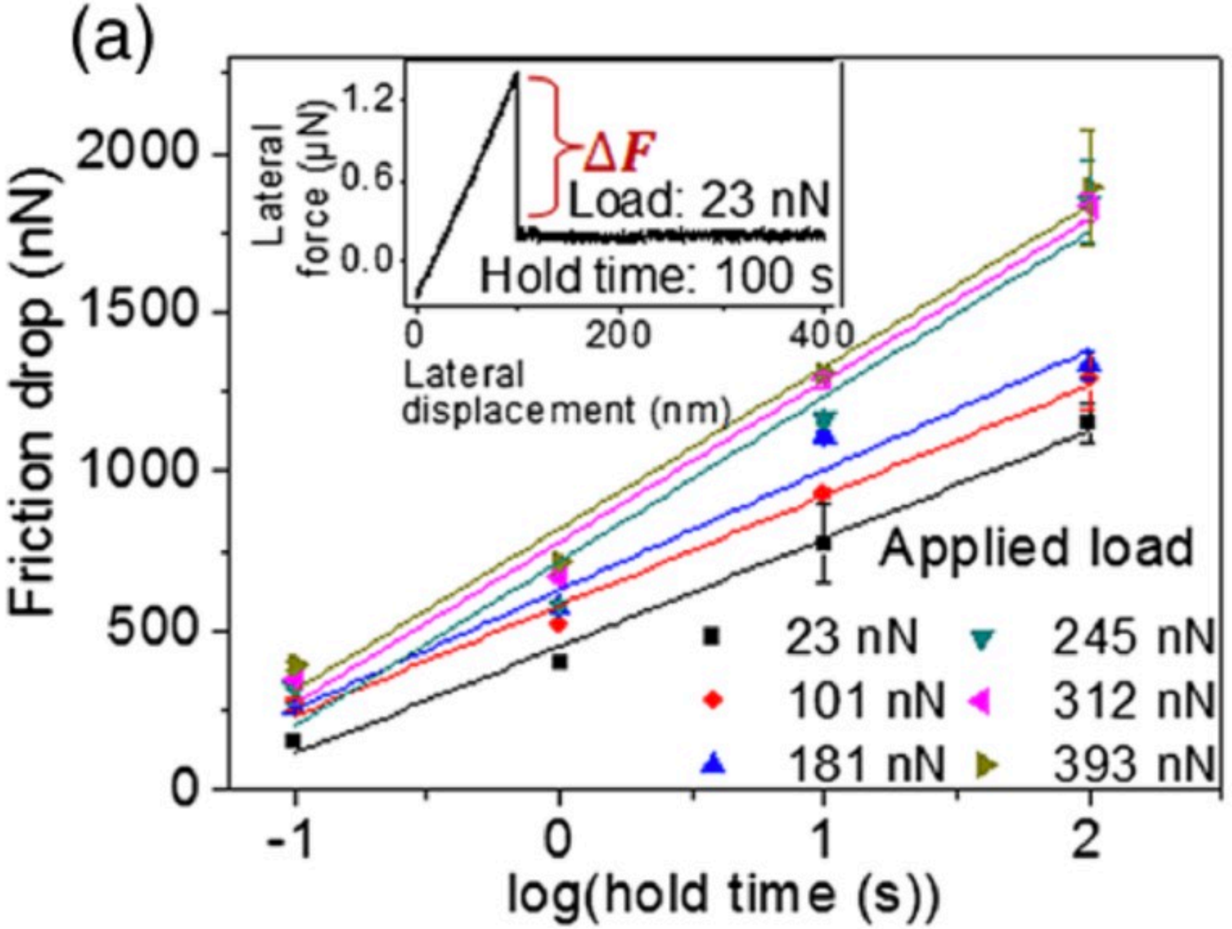
Synoptic view of fault zone strength and slip behavior



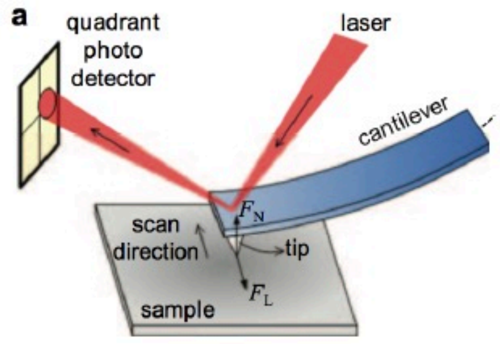
Collettini et al., 2019 EPSL

Load and Time Dependence of Interfacial Chemical Bond-Induced Friction at the Nanoscale

Kaiwen Tian,[1] Nitya N. Gosvami,[2,†] David L. Goldsby,[3] Yun Liu,[4] Izabela Szlufarska,[5] and Robert W. Carpick[2,*]



Friction force microscopy (FFM)



THE JOURNAL OF PHYSICAL CHEMISTRY B

Article

Cite This: J. Phys. Chem. B 2018, 122, 991−999

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Stick–Slip Instabilities for Interfacial Chemical Bond-Induced Friction at the Nanoscale

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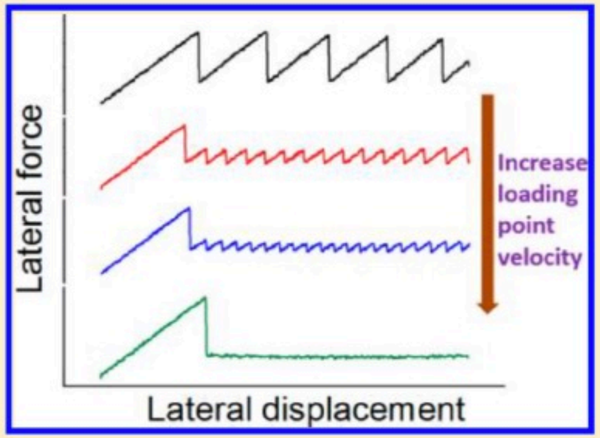
Supporting Information

ABSTRACT: Earthquakes are generally caused by unstable stick–slip motion of faults. This stick–slip phenomenon, along with other frictional properties of materials at the macroscale, is well-described by empirical rate and state friction (RSF) laws. Here we study stick–slip behavior for nanoscale single-asperity silica–silica contacts in atomic force microscopy experiments. The stick–slip is quasiperiodic, and both the amplitude and spatial period of stick–slip increase with normal load and decrease with the loading point (i.e., scanning) velocity. The peak force prior to each slip increases with the temporal period logarithmically, and decreases with velocity logarithmically, consistent with stick–slip behavior at the macroscale. However, unlike macroscale behavior, the minimum force after each slip is independent of velocity. The temporal period scales with velocity in a nearly power law fashion with an exponent between −1 and −2, similar to macroscale behavior. With increasing velocity, stick–slip behavior transitions into steady sliding. In the transition regime between stick–slip and smooth sliding, some slip events exhibit only partial force drops. The results are interpreted in the context of interfacial chemical bond formation and rate effects previously identified for nanoscale contacts. These results contribute to a physical picture of interfacial chemical bond-induced stick–slip, and further establish RSF laws at the nanoscale.



Mass transfer Reaction softening decrease friction

Fig. 8. Schematic representation of reaction softening with increasing strain. a) At the onset of deformation fracturing associated to cataclasis increases permeability favoring the influx of fluids (blue arrows) into the fault zone. b) Fluids react with the fine-grained cataclasite promoting dissolution of the strong granular phases and precipitation of phyllosilicates (green lines). c) At high strains the microstructure consists of an interconnected phyllosilicate-rich network where the deformation is predominantly accommodated by frictional sliding along the (001) phyllosilicate lamellae. The phyllosilicate network is also a low-permeability horizon for transversal fluid flow favoring the development of fluid overpressure testified by foliation parallel veins with crack-and-seal texture (dark-blue). Key-references on the processes highlighted in this picture are reported on the main text.