Constructing constitutive relations for faulting at high and low sliding speeds

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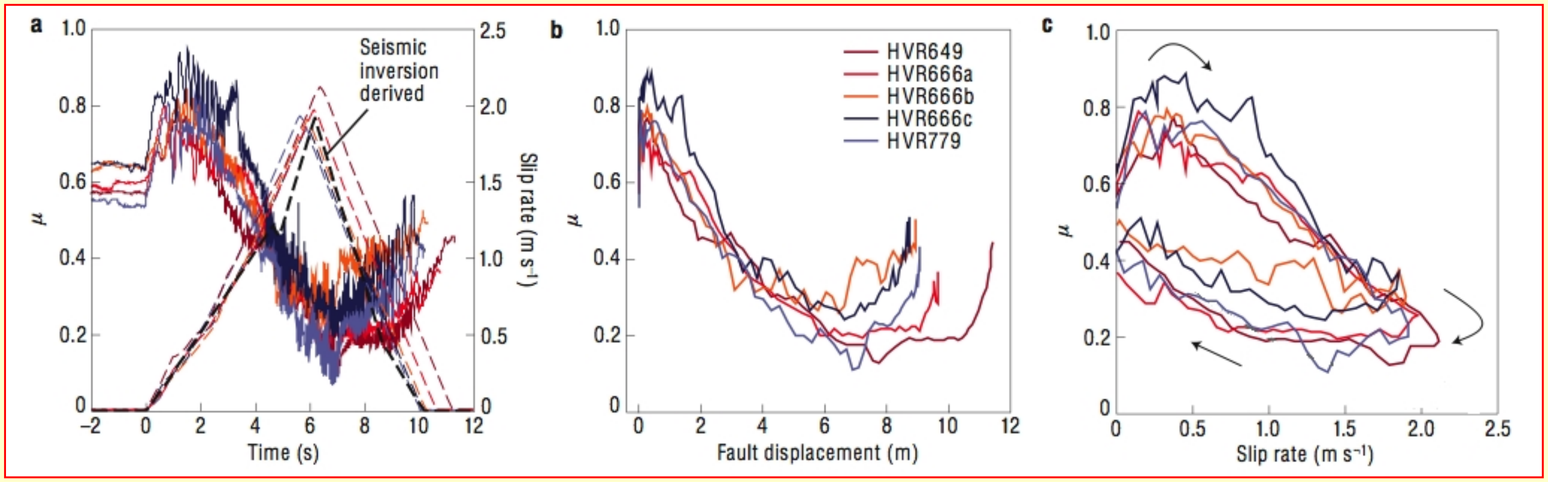
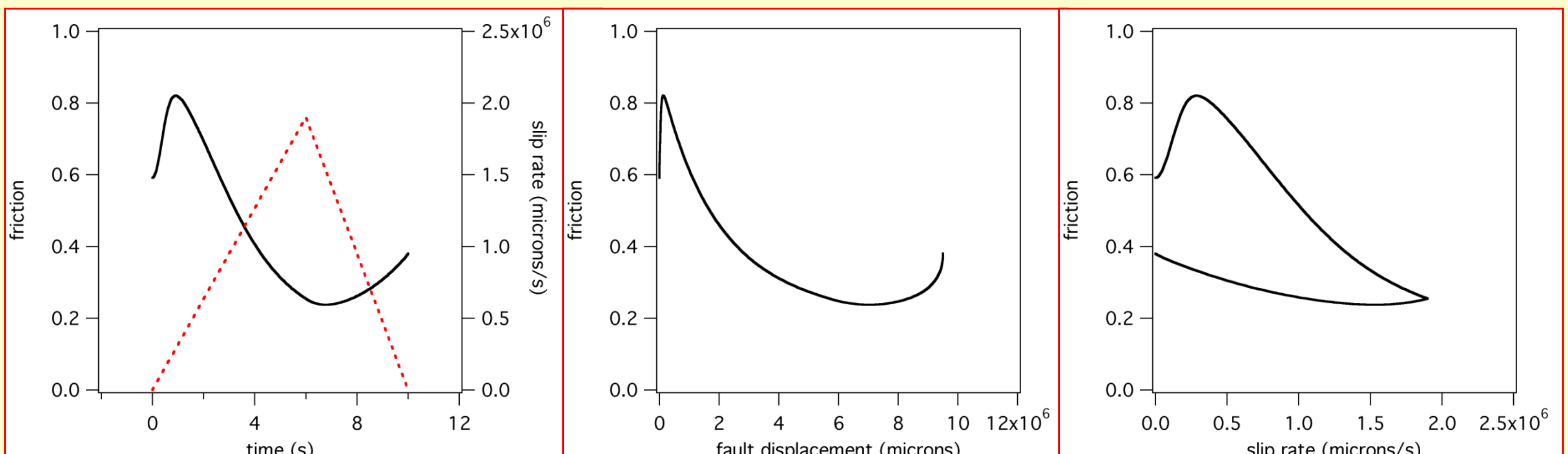


Sone and Shimamoto (2009)



outline

1) introduction - standard lab friction + why it's not good enough

2) constitutive equations with transitions in rate dependence at low speeds

low speed transition to rate strengthening ('brittle-ductile')

the high speed cutoff

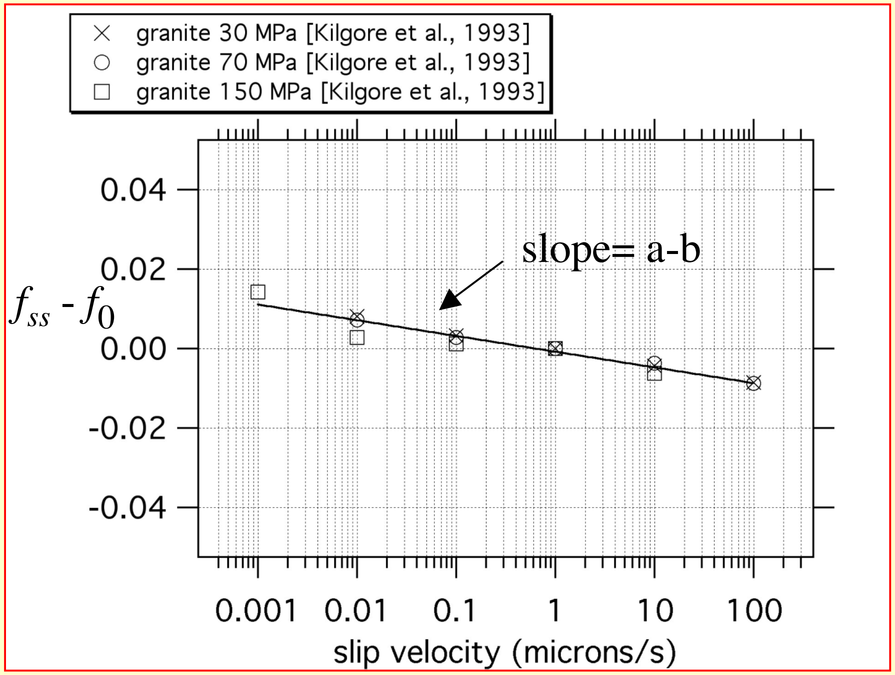
3) ***constructing constitutive equations for high speed slip***

a) shear weakening (fixed weakening distance, onset velocity fixed)

'true' shear weakening

b) thermal weakening (weakening distance and onset speed depend on normal stress, average slip speed)

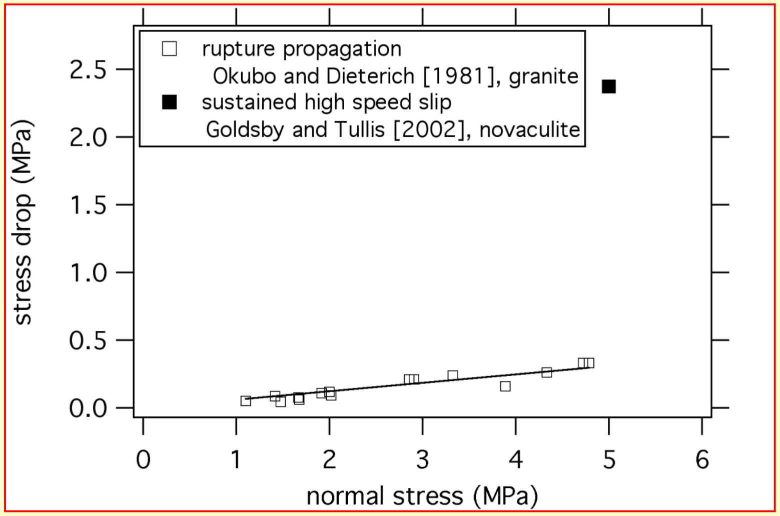
phase changes (melting, other reactions) *low speed quartzofeldspathic friction, lab-based earthquake faulting models ….*



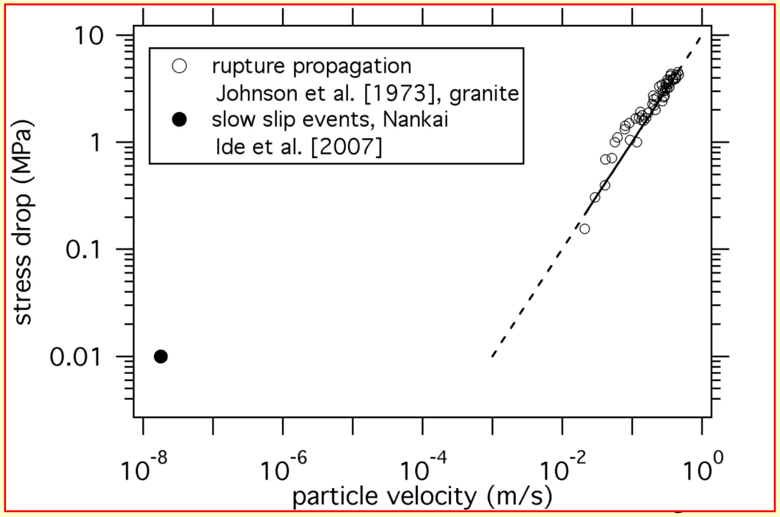
friction: $$f = f_o + a \ln \frac{V}{V_o} + b\psi$$

steady-state: $$\frac{df_{ss}}{d \ln V} = a - b$$

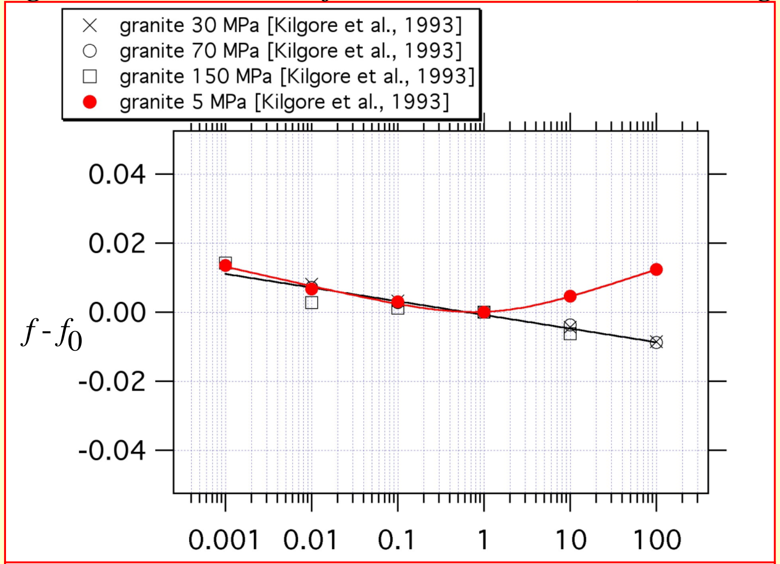
strength at high speed (lab)



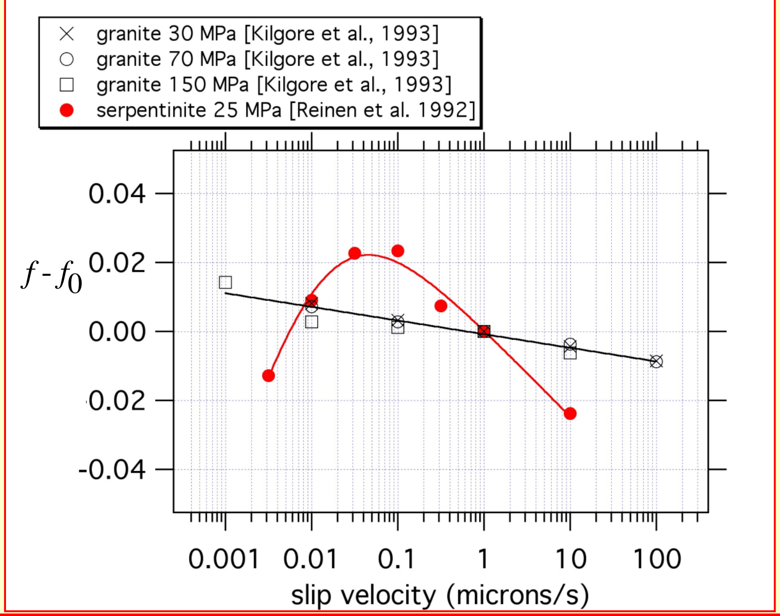
strength at low slip speed (natural)



granite - near surface stabilization ('the high speed cut off')

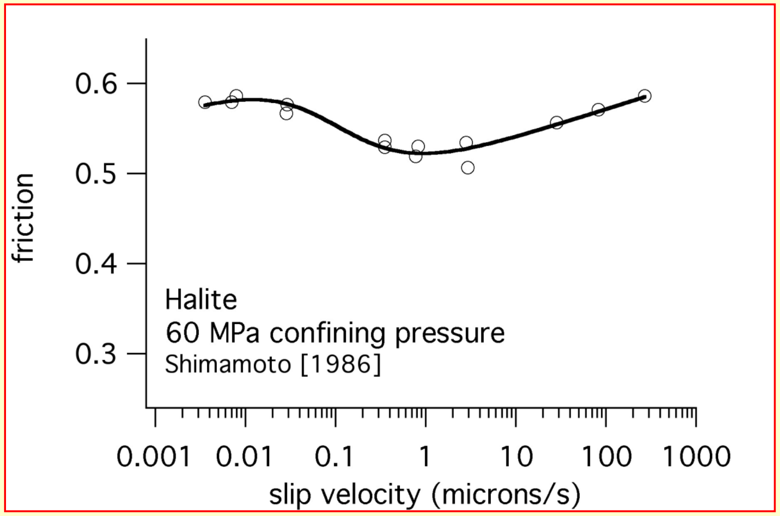


phyllosilicates



more examples (low sliding speed):

(analog) two transitions



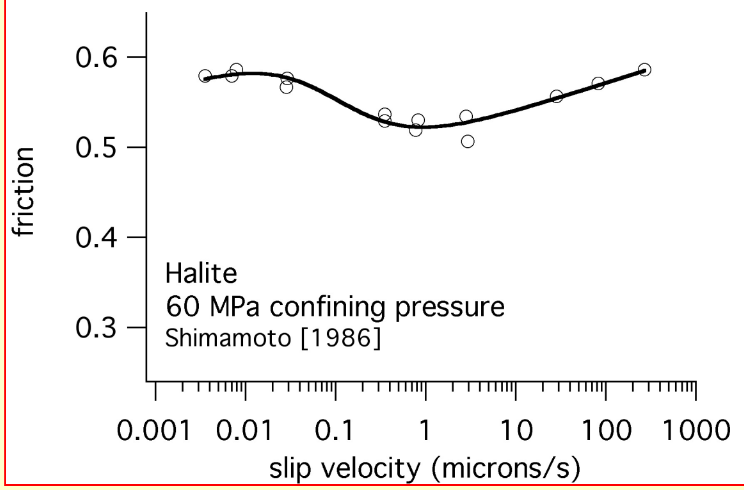
two transitions - Shimamoto

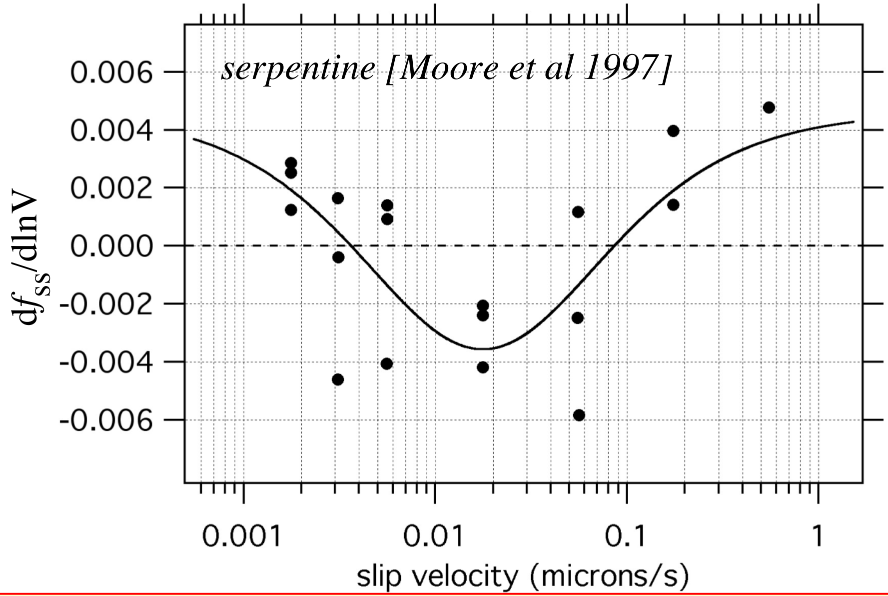
$$f = f_o + a \ln \frac{V}{V_o} + \mathrm{b}\psi$$

$$\frac{d\psi}{dt} = \frac{V_0}{d_c}(1-\psi) - \frac{V\psi}{d_c}$$

$$f = f_o + a \ln \frac{V}{V_0} + \mathrm{b}\frac{V_0}{V_0 + V}$$

$$\frac{df_{ss}}{d\ln V} = a - \mathrm{b}\frac{V/V_0}{\left(1 + V/V_0\right)^2}$$





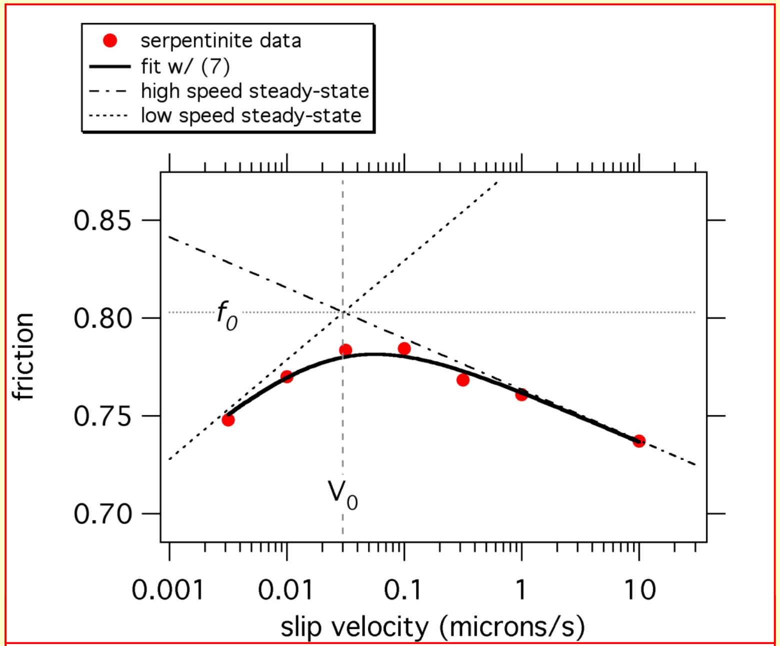
a low speed transition

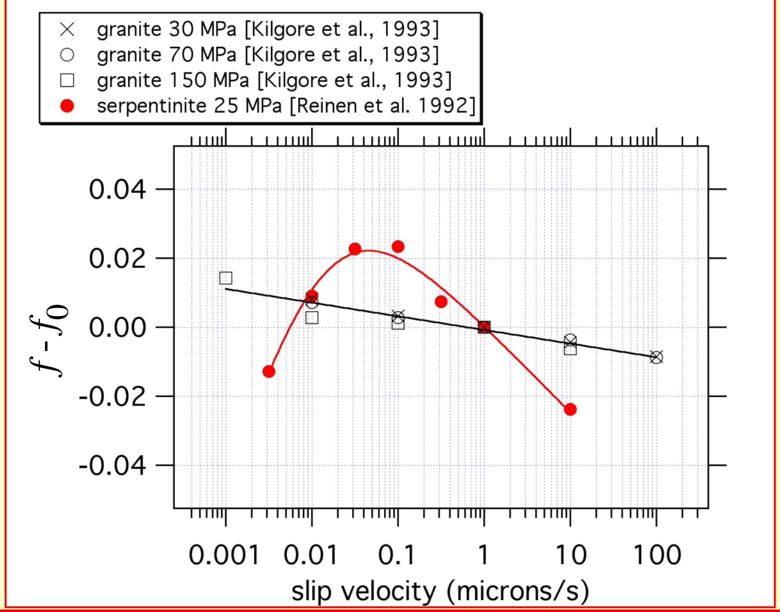
$$f = f_0 + a\ln\frac{V}{V_0} + \Delta a\ln\frac{V}{V+V_0} + b\psi$$

$$\frac{d\psi}{dt} = \frac{V_0}{d_c}\left(\exp[-\psi] - \frac{V_0+V}{V_0}\right)$$

$$f_{ss} = f_o + a\ln\frac{V}{V_0} + \Delta a\ln\frac{V}{V+V_0} + b\ln\frac{V_0}{V+V_0}$$

$$\frac{df_{ss}}{d\ln V} = a + \Delta a - \frac{V(\Delta a + b)}{(V_0+V)}$$





low speed summary:

it's relatively easy to construct semi-empirical constitutive equations for slow slip rates - examples :

• the low speed transition to pure rate strengthening - follow dieterich, use a low speed cutoff on state while turn on stronger rate strengthening

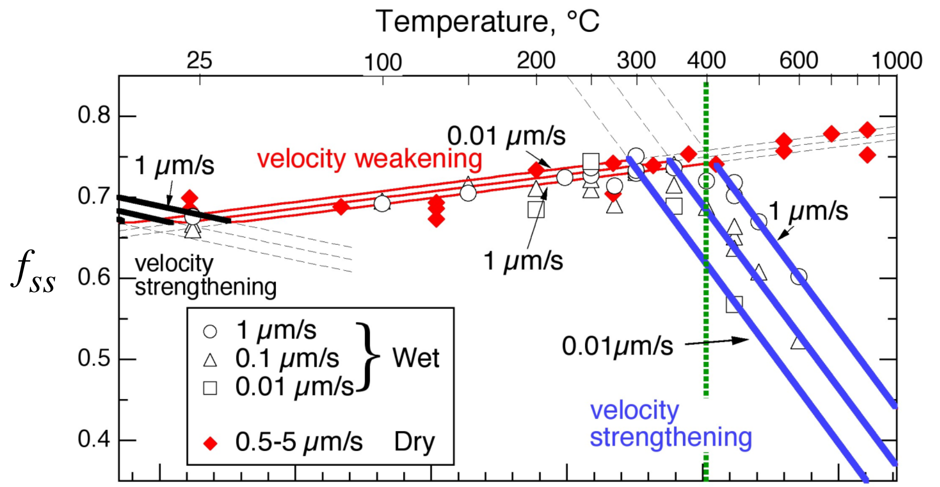
for some phyllosilicates (serpentine, micas, clays) at room temperature, presumably for more brittle materials at higher temperatures

• two transitions (high speed cutoff and low speed transition) - use a state variable with limits

perhaps all for brittle rocks near the base of the seismogenic zone?, analogs such as halite at room T

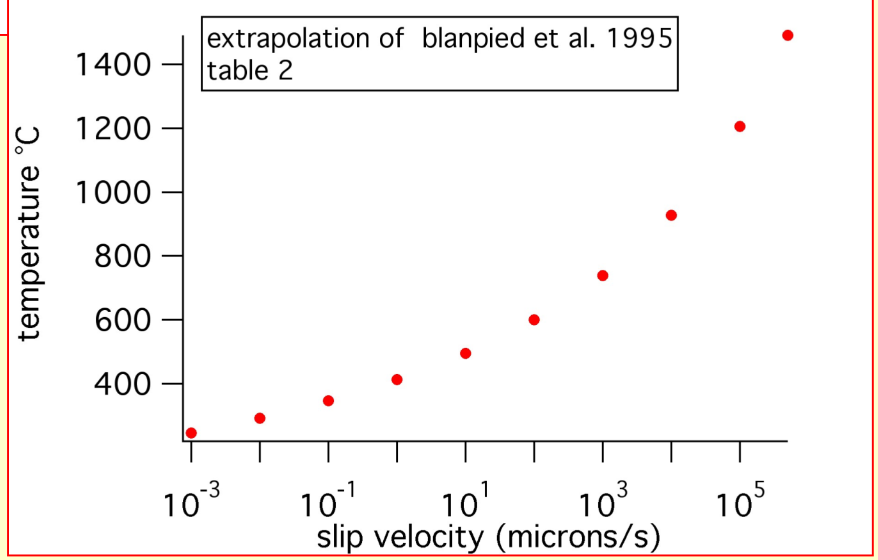
problems: there are temperature dependence and hidden rate dependencies not properly studied….

for example: the deep brittle ductile transition



Blanpied et al [1995]

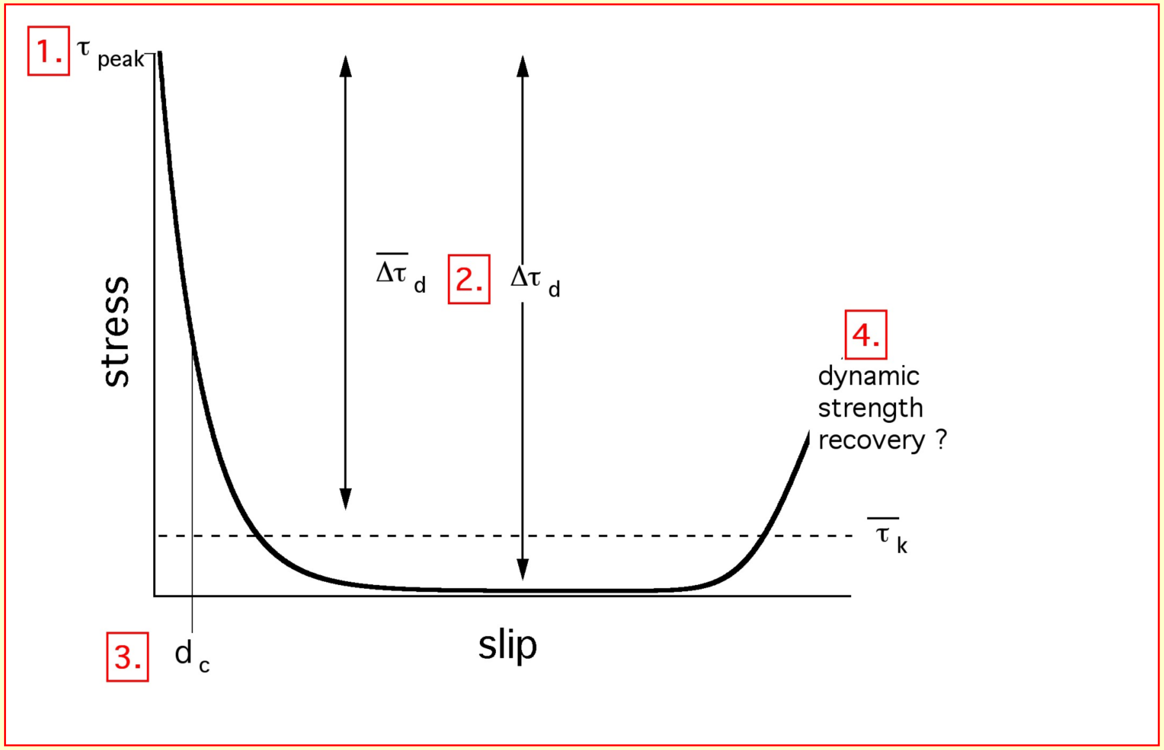
• brittle-ductile transition depth depends on temperature and slip rate



• extrapolation of existing data to seismic speeds produces ‘crazy’ results

• similar problems for near surface transition - lab data are nearly non-existent

high speed slip



lab measurements

1. peak strength

2. sliding strength

3. d_c

4. dynamic strength recovery

constitutive relations →

dynamic rupture simulation

background

Lab properties necessary for constitutive relations for dynamic fault strength (small scale)

yield strength → determines heat production rate
dependencies - normal stress

strength loss (dynamic stress drop) → particle velocity - ground motion; → on-fault fracture energy
dependencies - normal stress, slip rate etc

weakening distance (d_c) → on-fault fracture energy
dependencies - normal stress, slip rate etc

dynamic strength recovery (time constant? slip distance?) → determines the mode of rupture propagation (crack or pulse)
dependencies - normal stress, fault thickness
thermal, hydraulic properties

Significance for earthquake rupture (large scale)

determines heat production rate

particle velocity - ground motion

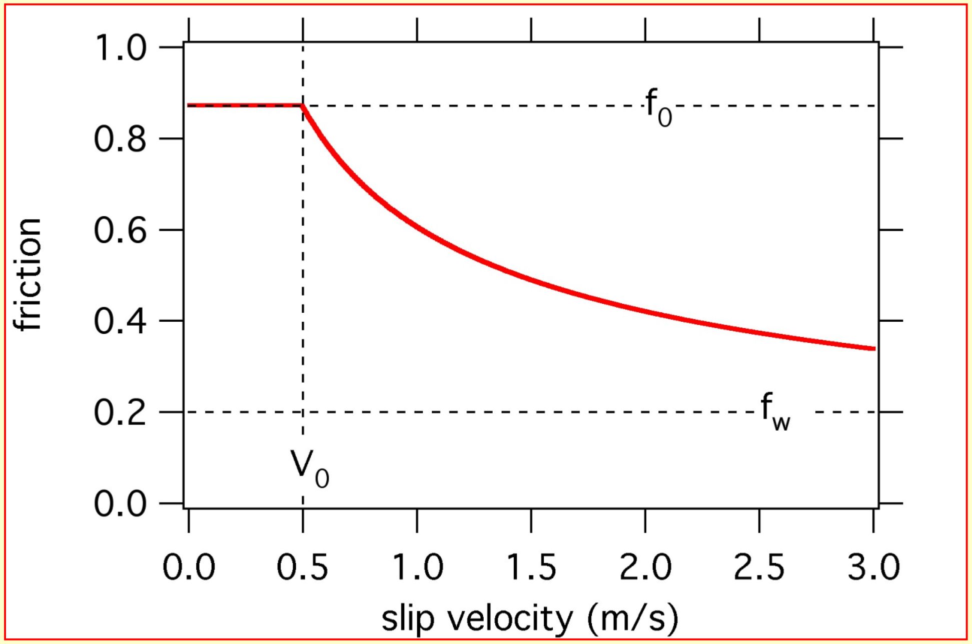
on-fault fracture energy
influences slip speed
rupture propagation rate
limits radiated energy

determines the mode of rupture
propagation (crack or pulse)

generic form for dynamic weakening

$$f = f_0, \qquad V < V_0$$
$$f = (f_o - f_w)\psi + f_w, \quad V > V_0$$

general weakening constitutive relation



V_0 - phase transition threshold
(may depend on normal stress)

f_0 - low speed friction
(may be rate and state or worse)

f_w - residual shear resistance
(the transformed strength, may be zero)

ψ - some function to be determined
(by experiment and by theory)

see Rice (1999); B (2006); BGT (2008)

shear weakening: true shear weakening

mechanical characteristics:

- strong negative rate dependence
- large slip weakening distance (~1 - 10 m) ? independent of velocity or normal stress ?
- strength recovery independent of temperature (in some cases)

materials:

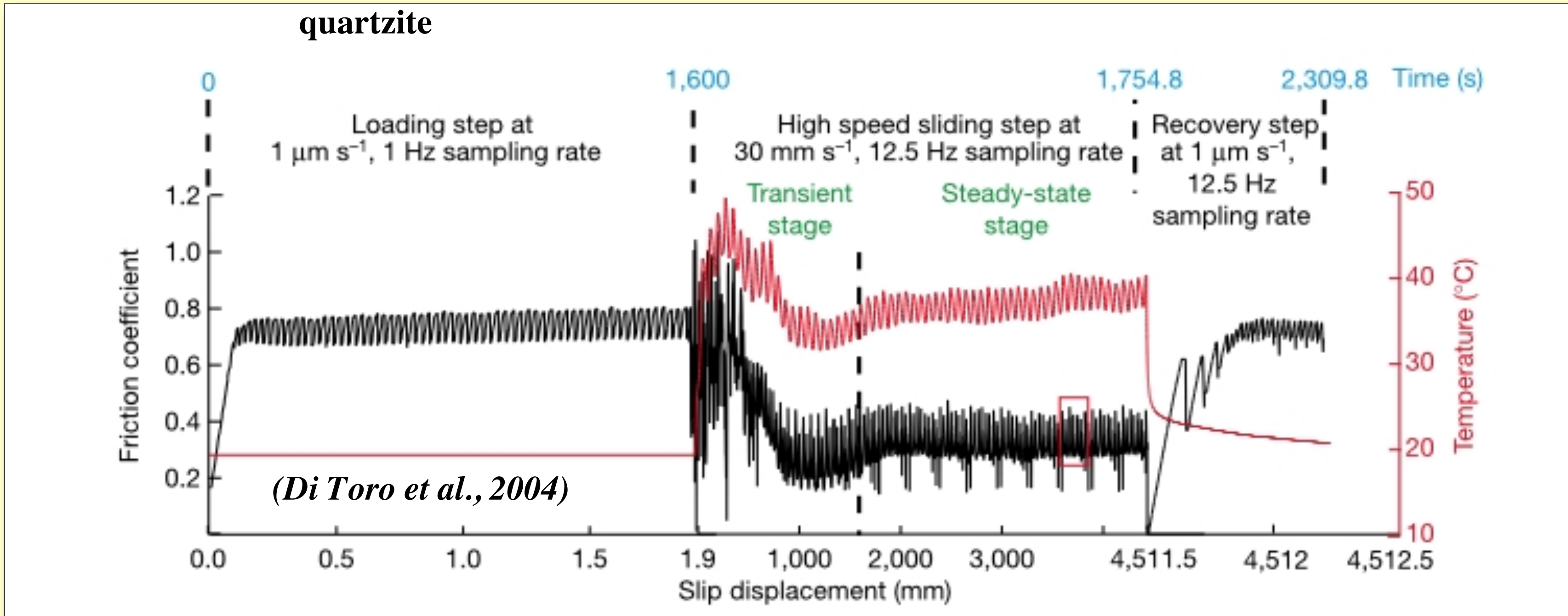
bare surfaces of quartzite, granite, feldspar *(Goldsby and Tullis, 2002) (DiToro et al., 2004)* 'gel weakening'

? clay fault gouge (*Sone and Shimamoto*, 2009)?

? gabbro low normal stress *(Mizoguchi et al.,2007)* 'moisture related weakening?

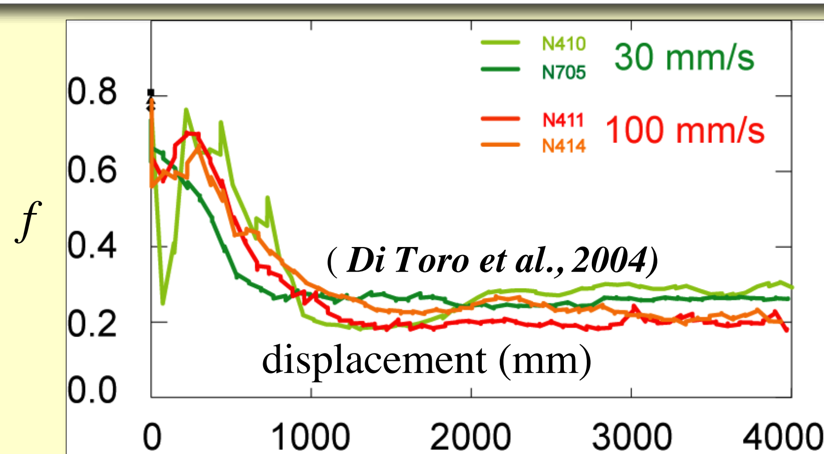
? granite *(Reches and Lockner, unpublished)* 'solid lubrication' ?

shear weakening: true shear weakening mechanisms: **silica gel formation** *(Goldsby and Tullis, 2002)*



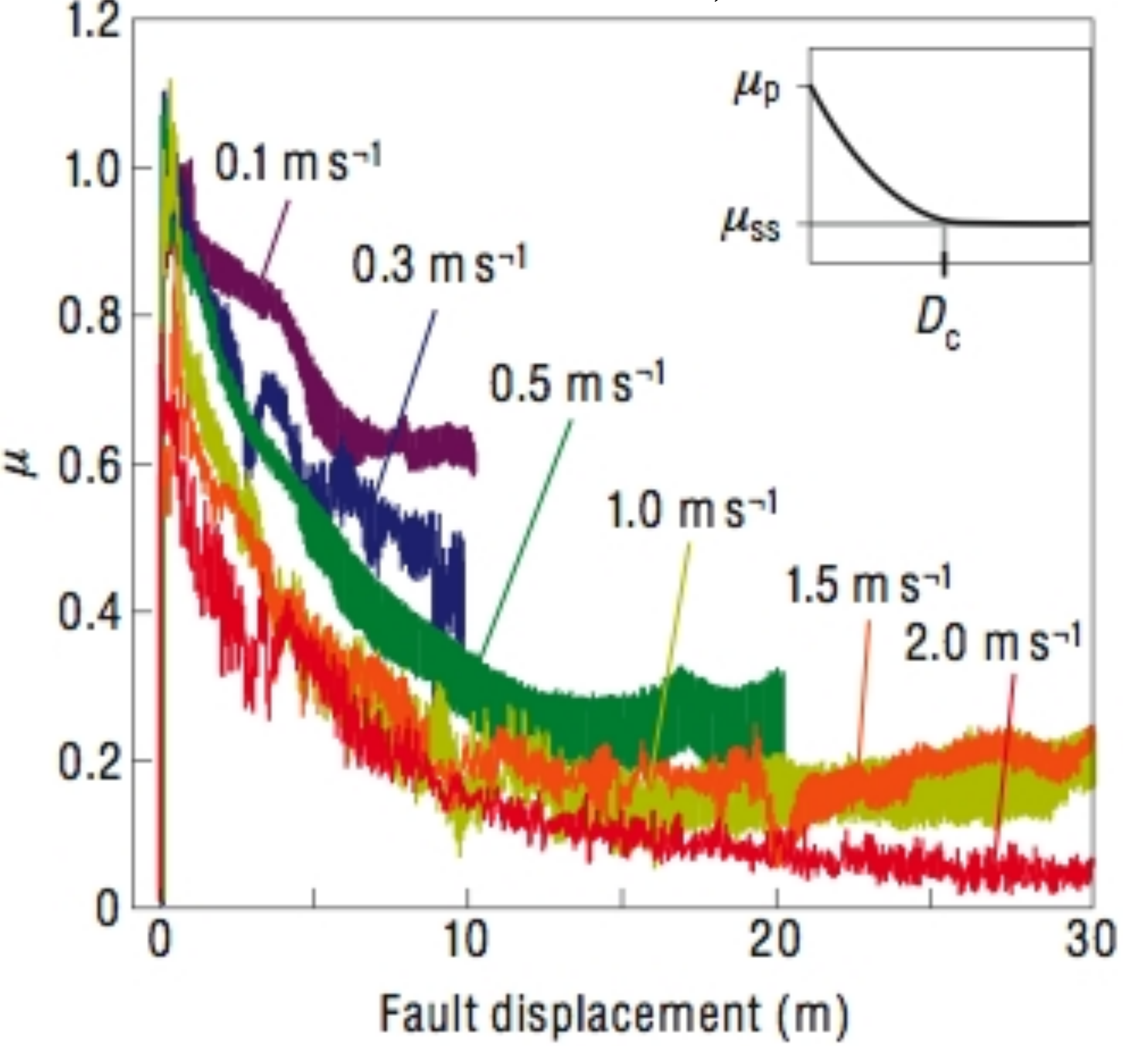
weakens: quartzite, granite, feldspar

doesn't weaken: calcite, gabbro



***shear weakening: true shear weakening mechanisms*: shear of Chelungpu fault gouge** *[Sone and Shimamoto, 2009]*

normal stress 0.5 MPa, V = 0.1 - 2.0 m/s



no dependence of slip weakening distance on slip rate

physical mechanism: unknown

shear weakening: true shear weakening mechanisms: a constitutive equation

$f = (f_0 - f_w)\psi + f_w$ general weakening constitutive relation

evolution equation for shear and time dependent effects:

- shear induced weakening
- time dependent strengthening

start w/ *Ruina (1983)*: $\frac{d\psi}{dt} = G(V,\psi) = g_1 + g_2$

$g_2 = -\psi V / d_c$ true slip weakening (exponential)

$g_1 = (1-\psi)/t_c$ true time dependent strengthening (first order chemical reaction rate equation)

$V_c = d_c / t_c$

$$\frac{d\psi}{dt} = \frac{V_c}{d_c}(1-\psi) - \frac{V\psi}{d_c}$$

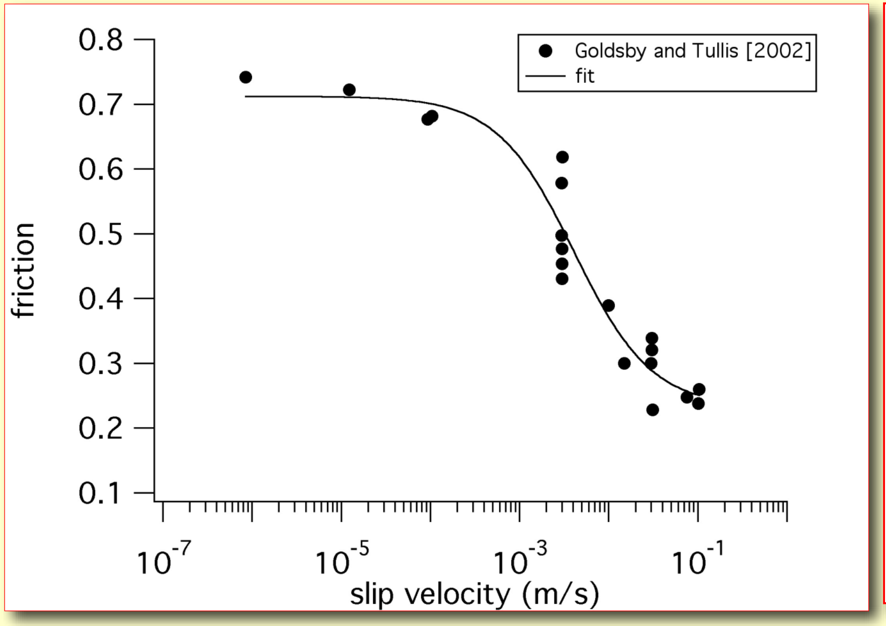
$$\psi_{ss} = \frac{V_c}{V_c + V}$$

shear weakening: true shear weakening mechanisms: steady state

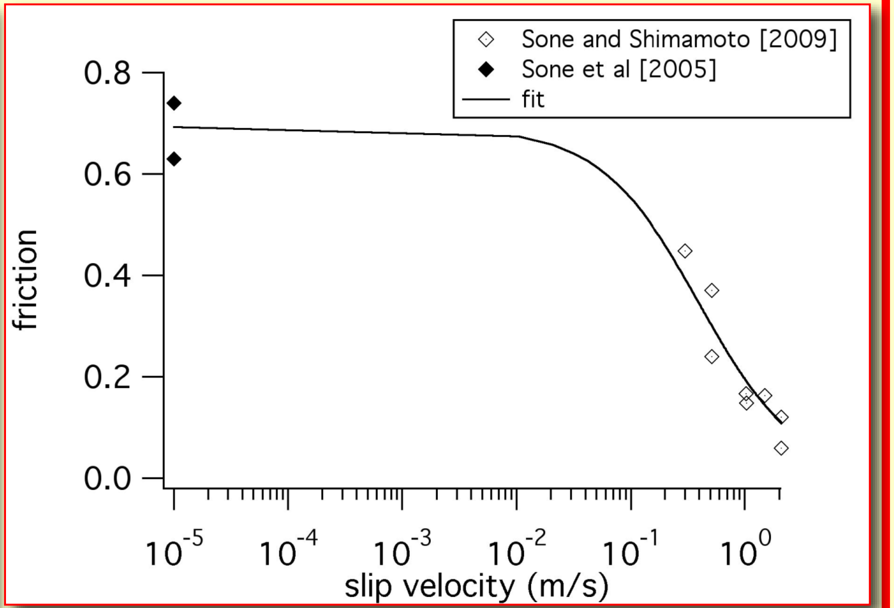
$f = (f_0 - f_w)\psi + f_w$ general weakening constitutive relation

$$f_{ss} = (f_0 - f_w)\frac{V_c}{V + V_c} + f_w \qquad \psi_{ss} = \frac{V_c}{V_c + V}$$

'gel' weakening

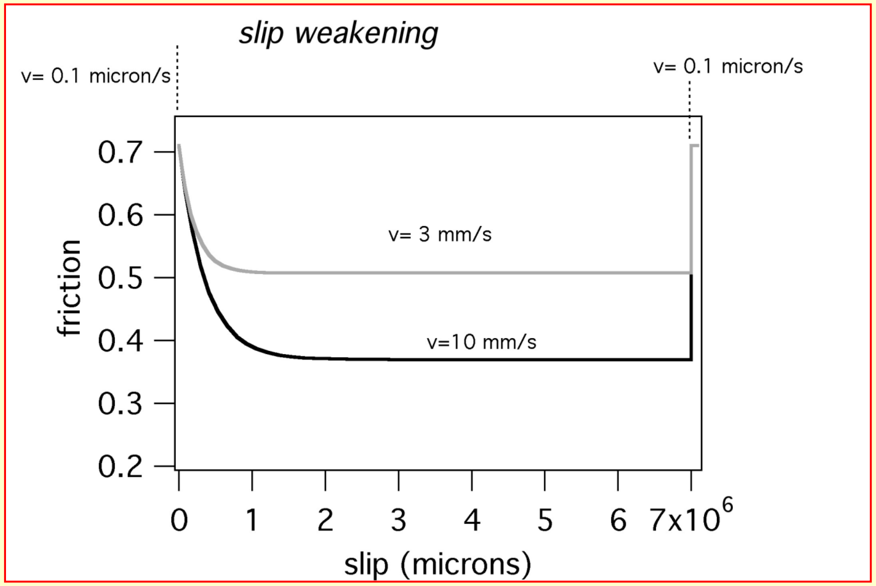


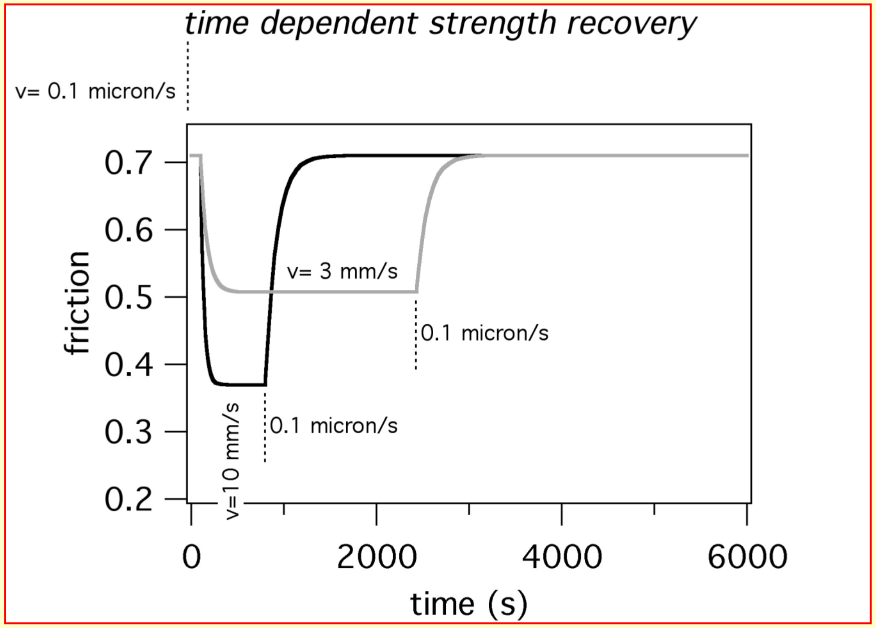
Chelungpu



shear weakening: true shear weakening mechanisms: transient response

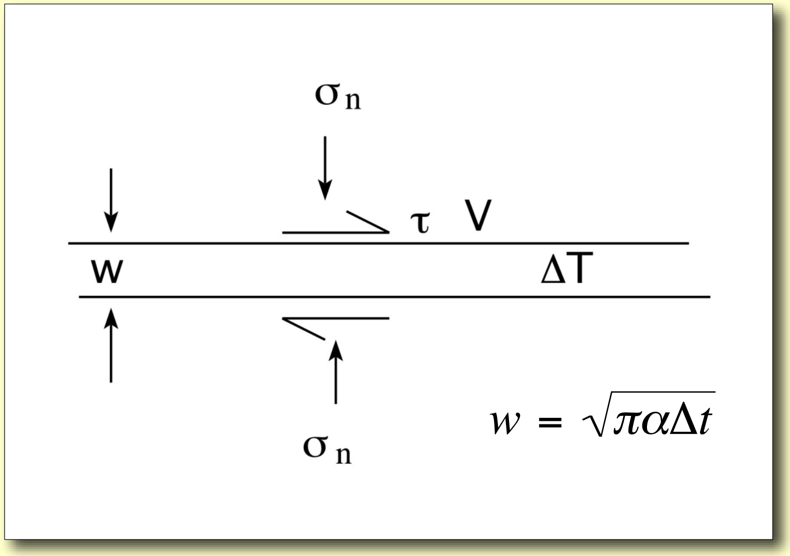
$$f = (f_0 - f_w)\psi + f_w \qquad \psi_{ss} = \frac{V_c}{V_c + V} \qquad \frac{d\psi}{dt} = \frac{V_c}{d_c}(1-\psi) - \frac{V\psi}{d_c}$$

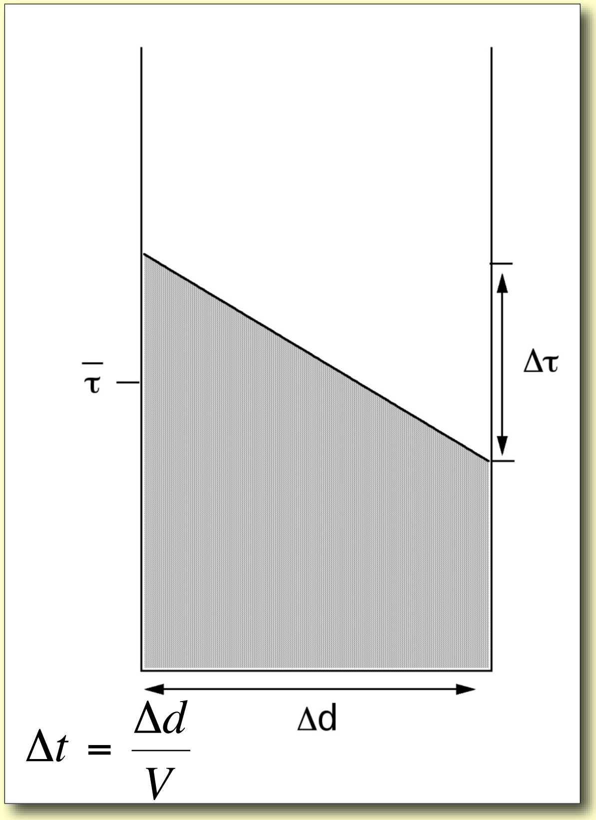




B (2009)

thermal weakening: ***strength should depend on sliding velocity***





Energy balance $\bar{\tau} \Delta d = \left(\rho \hat{c} \Delta T\right) w$

mechanical work = (change in thermal energy) * width
(shear heat)

$$\bar{\tau} = \frac{\rho \hat{c}\, \Delta T \sqrt{\pi \alpha}}{\sqrt{V \Delta d}}$$

(see Lachenbruch, 1980; Rice, 1999; B (2006)

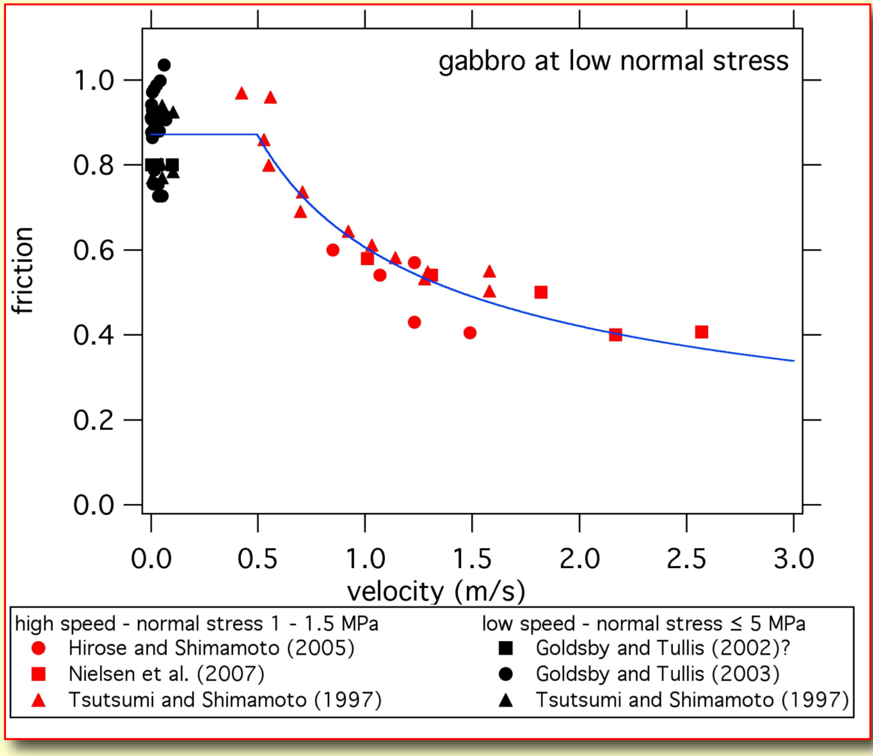
thermal weakening: steady-state examples

$$f_{ss} = f_0 \qquad V < V_0$$
$$f_{ss} = (f_0 - f_w)\psi + f_w \qquad V > V_0$$

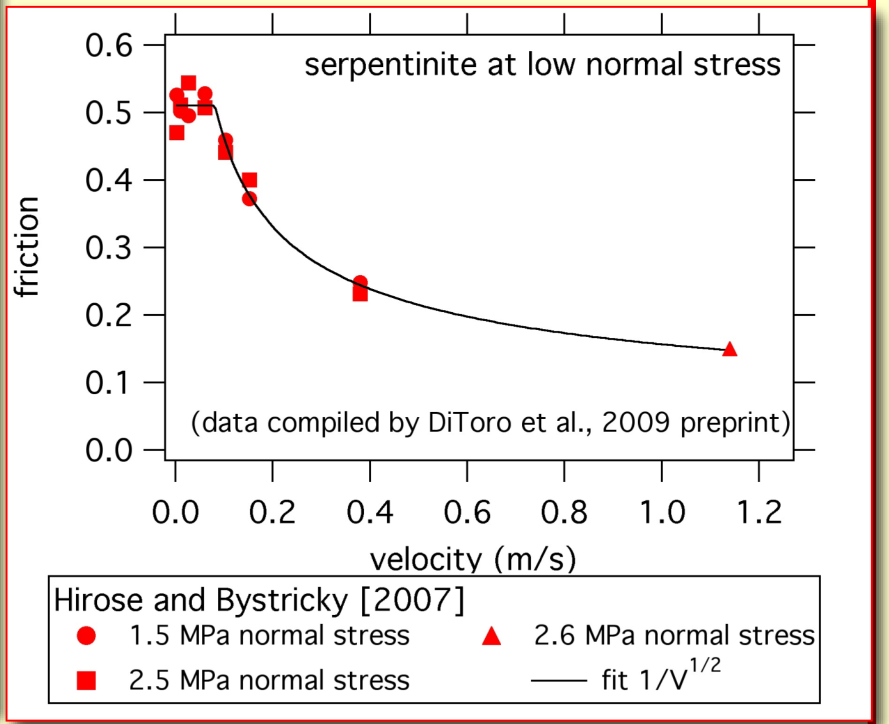
$$\psi_{ss} = \sqrt{\frac{V_0}{V}}$$

dimensional analysis

melting



shear heating, no melting



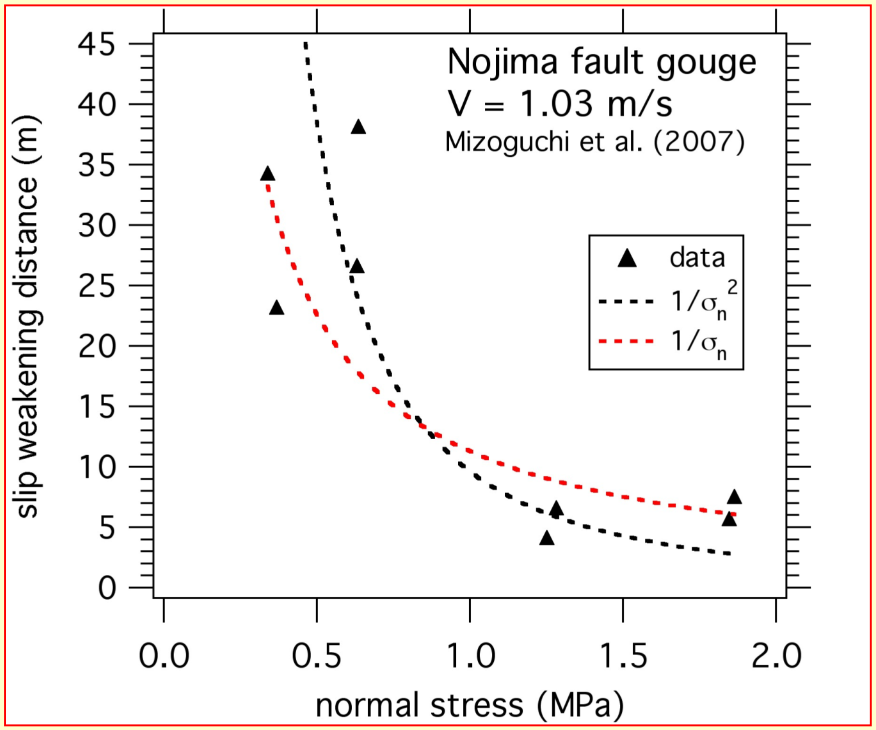
see *Nielsen et al [2008]* for better steady-state melt relation!

thermal weakening: ***weakening distance should depend on velocity, normal stress and shear resistance***

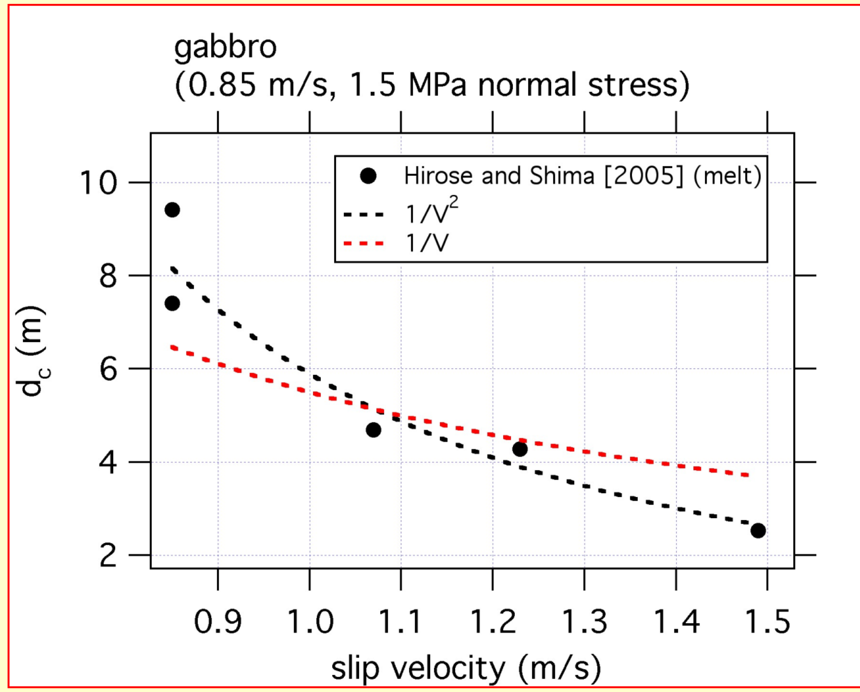
$$\bar{\tau} = \bar{f}\sigma_n \qquad \Delta d = \frac{\pi\alpha}{V}\left(\frac{\rho\hat{c}\Delta T}{\bar{f}\sigma_n}\right)^2$$

B (2006) also see Brantut et al (2009)

shear heating, no melt



melting



thermal weakening: an idea on how to incorporate in constitutive relations

$$f_{ss} = f_0 \qquad V < V_0$$
$$f_{ss} = (f_0 - f_w)\psi + f_w \qquad V > V_0$$

general weakening constitutive relation

evolution equation for shear for which the slip weakening distance decreases with increasing slip velocity

start w/ *Ruina (1983)*: $$\frac{d\psi}{dt} = G(V,\psi) = g_1 + g_2$$

$g_2 = -\psi V / d_c$ true slip weakening (exponential)- like ruina's 'slip' relation

$d_c = \dfrac{d_0 V_0}{V}$ slip weakening distance scales inversely with velocity $g_2 = -\psi V^2 / (V_0 d_0)$

assume $\psi_{ss} = \sqrt{\dfrac{V_0}{V}}$ solve for $g_1 = V^{3/2} / d_0 \sqrt{V_0}$

$$\frac{d\psi}{dt} = \frac{V}{d_0}\left(\sqrt{\frac{V}{V_0}} - \frac{V\psi}{V_0}\right)$$

thermal weakening: transient behavior

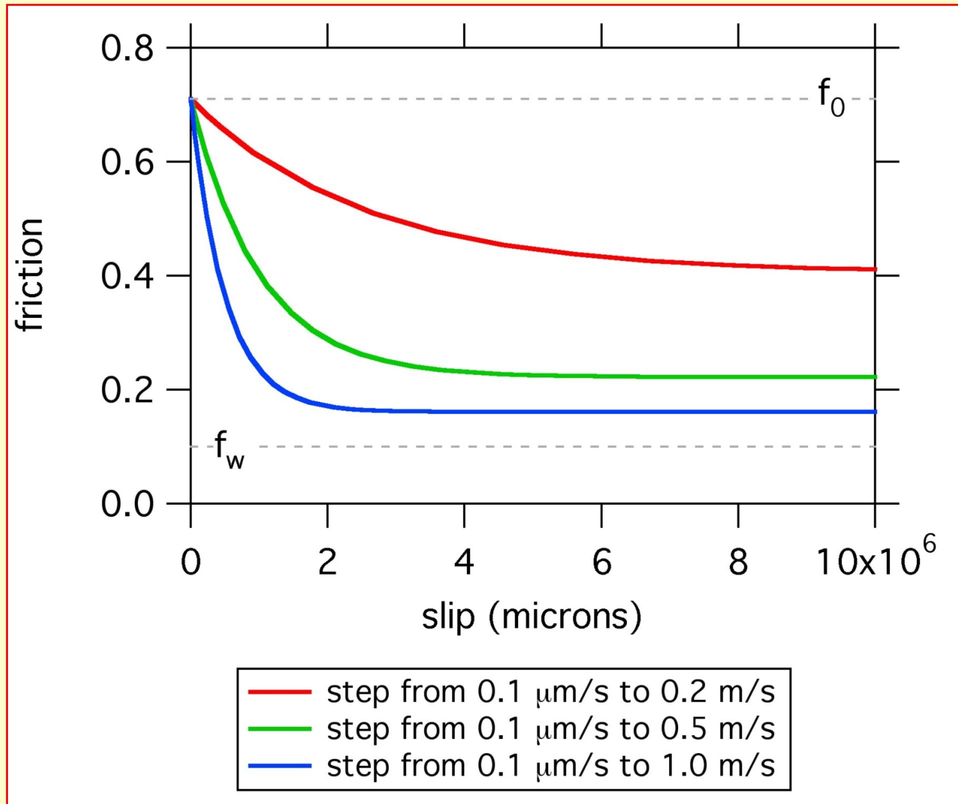
$$f = f_0 \qquad V < V_0$$
$$f = (f_0 - f_w)\psi + f_w \qquad V > V_0$$

$$d_c = \frac{d_0 V_0}{V}$$

$$\frac{d\psi}{dt} = \frac{V}{d_0}\left(\sqrt{\frac{V}{V_0}} - \frac{V\psi}{V_0}\right)$$

slip weakening term

weakening distance (increasing velocity)



- slip weakening distance scales inversely with slip rate (also with normal stress w/ appropriate modification)

- perfect exponential slip weakening
- (also onset slip velocity scales with normal stress - not shown)

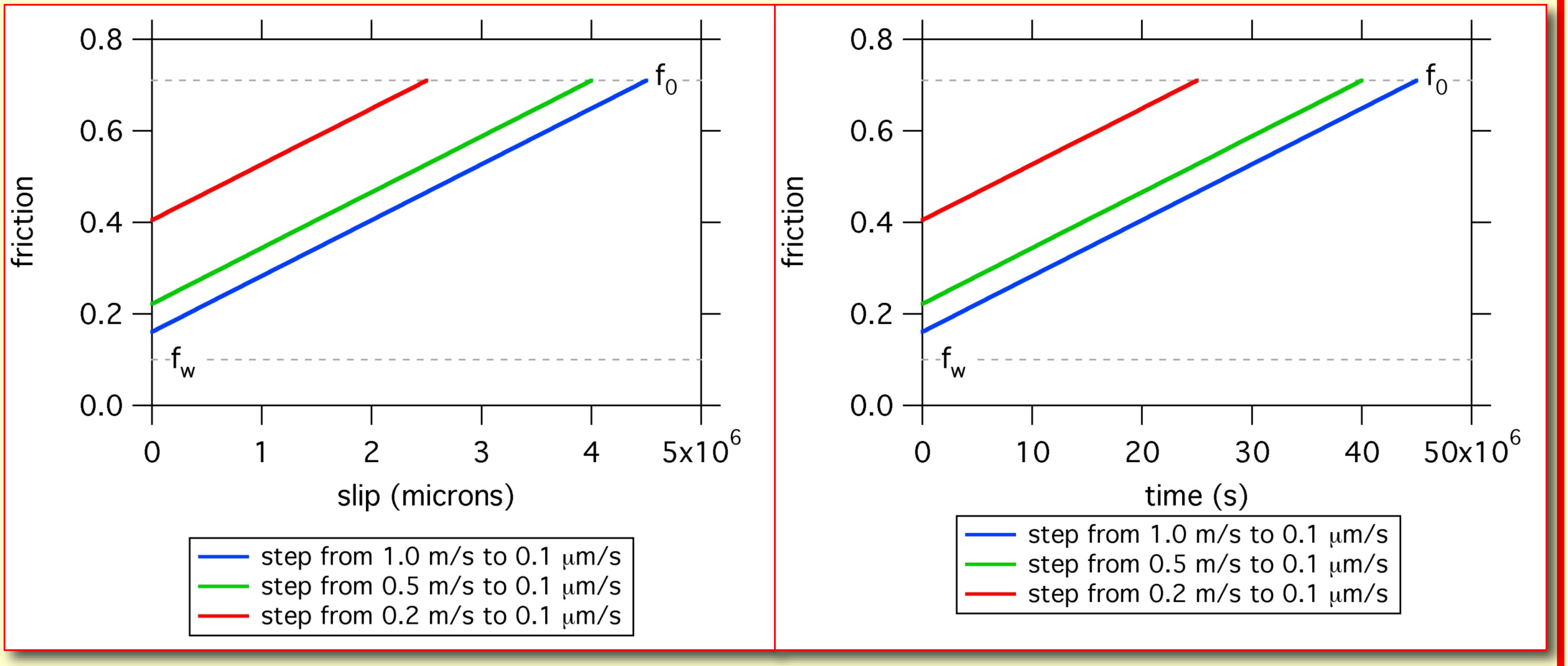
thermal weakening: strength recovery

$$d_c = \frac{d_0 V_0}{V}$$

$$f = f_0 \qquad V < V_0$$
$$f = (f_0 - f_w)\psi + f_w \qquad V > V_0$$

$$\frac{d\psi}{dt} = \frac{V}{d_0}\left(\sqrt{\frac{V}{V_0}} - \frac{V\psi}{V_0}\right)$$

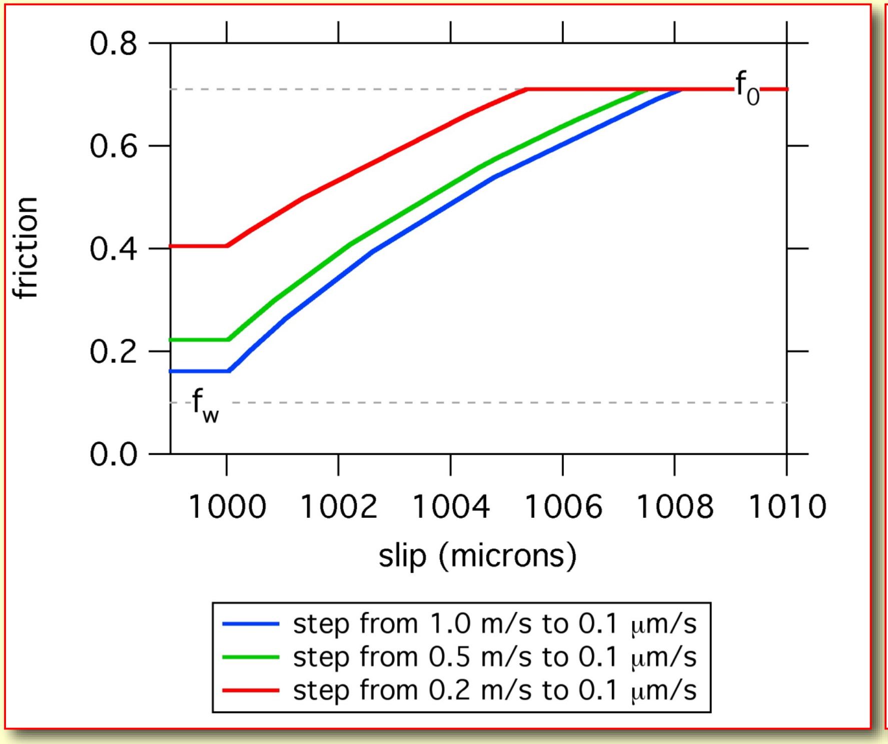
resulting strength recovery behavior (decreasing velocity) - an accident

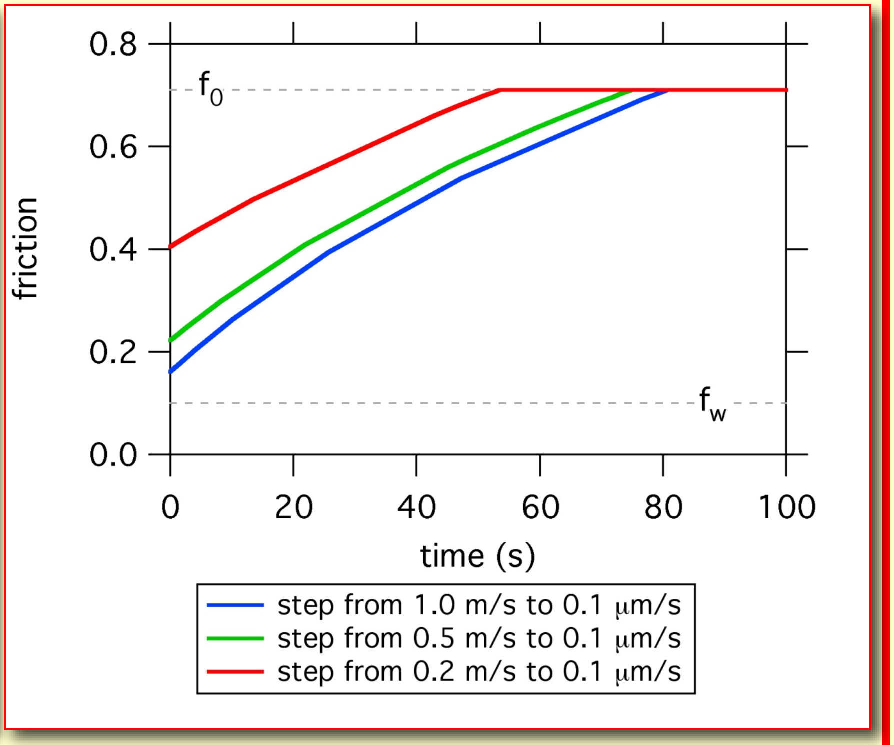


- 'long-term' weakening (slow strength recovery)

thermal weakening: strength recovery

added an explicit strength recovery term to the evolution equation





- 'short-term' weakening (rapid strength recovery)

summary of high speed

the differences in slip weakening distance - small and constant (flash weakening), large and constant (true shear weakening), large and variable with normal stress and slip rate (thermal weakening)

- these differences can be indicative of mechanism type

it's relatively easy to construct semi-empirical constitutive equations for the different mechanism types. examples from this talk:

- shear weakening relation balances true slip weakening against time strengthening

- thermal weakening relation has the slip weakening distance depend on velocity and normal stress (also onset slip speed)

problem: strength recovery poorly constrained by lab data *[this is changing, see Sone and Shimamoto (2009), Nielsen et al (in press?)]*

end