SCEC Code Validation Workshop, Pomona, CA, 17 November 2008

Rupture Dynamics with Strong Rate Weakening

James R. Rice

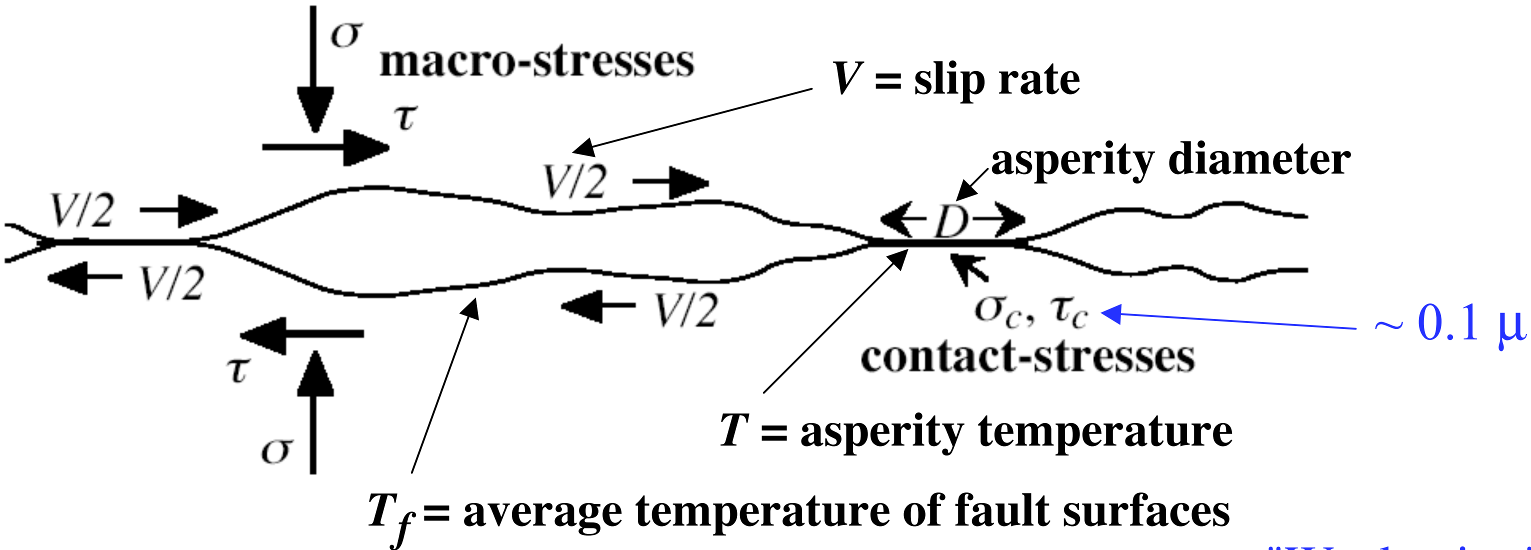
- Physical theory and experimental basis, strong velocity weakening at seismic slip rates

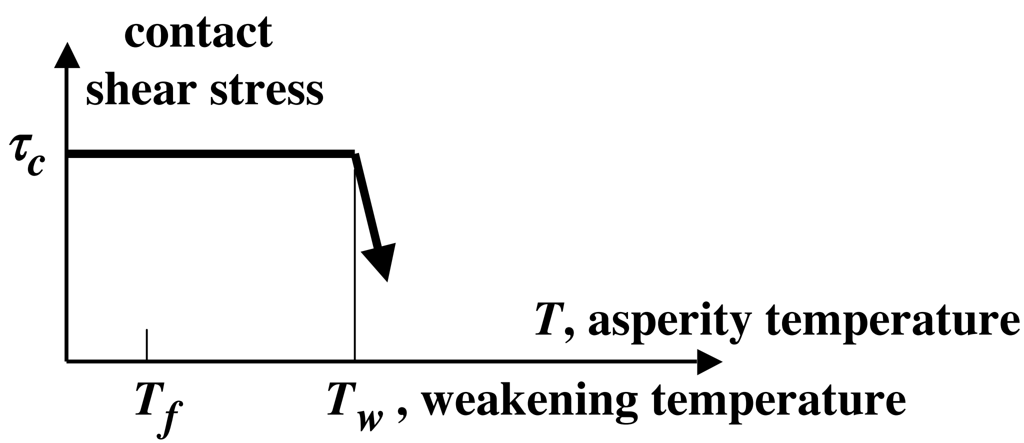
- How it promotes a self-healing rupture mode (at sufficiently low pre-stress levels)

- Project (Dunham, Noda & Rice) to use fully lab constrained friction descriptions to predict earthquake ruptures

- Relation to earlier studies (Lapusta & Rice) and to SCEC Code Validation project (*TPV103 and TPV104, Rate-and-State Friction, Slip Law, Strong Rate-Weakening*)

Flash heating of microscopic frictional asperity contacts





"Weakening" slip rate:

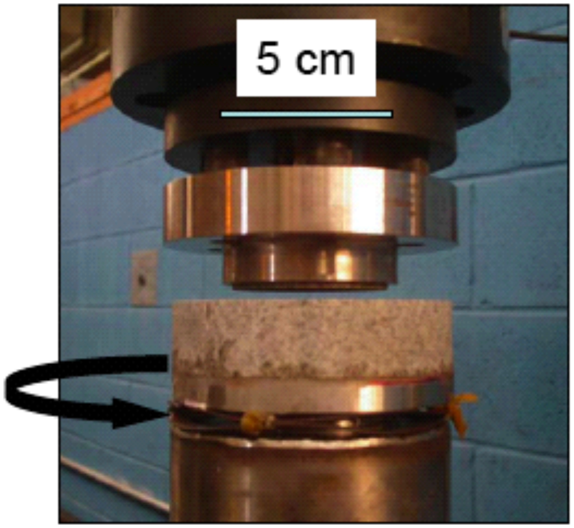
$$V_w = \pi \frac{\alpha_{th}}{D}\left(\frac{T_w - T_f}{\tau_c/\rho c}\right)^2$$

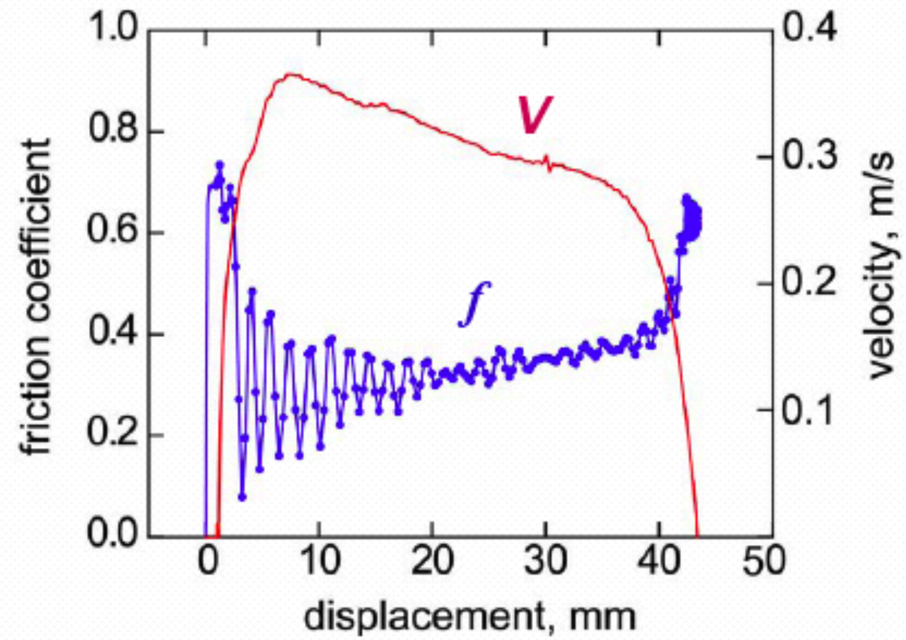
(when $V > V_w$, asperity is weak for some of its lifetime)

[Tullis & Goldsby, *SCEC*, 2003; *EOS*, 2003]

***Arkansas novaculite** (~100% **quartzite**)*

Rotary Shear Apparatus





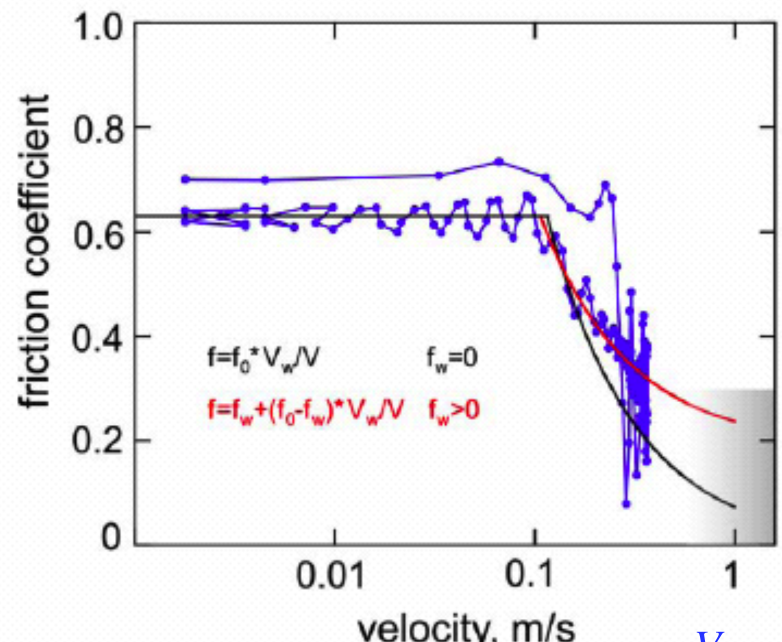
High speed $V \leq 0.36$ m/s

$\sigma_n = 5$ MPa

Rotary shear, 1.2 mm pre-slip at ~10 μm/s, followed by rapid slip for remaining 43 mm.

At low V, $f \approx 0.65$

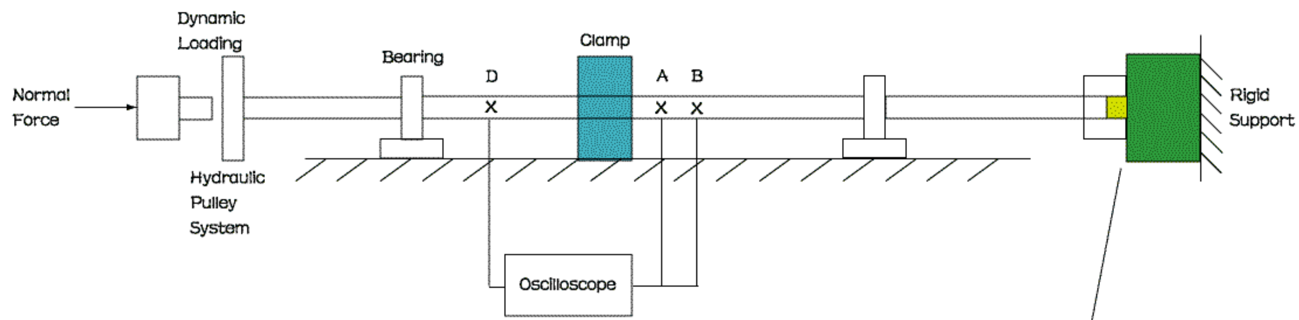
At $V > 0.3$ m/s, $f \approx 0.30$

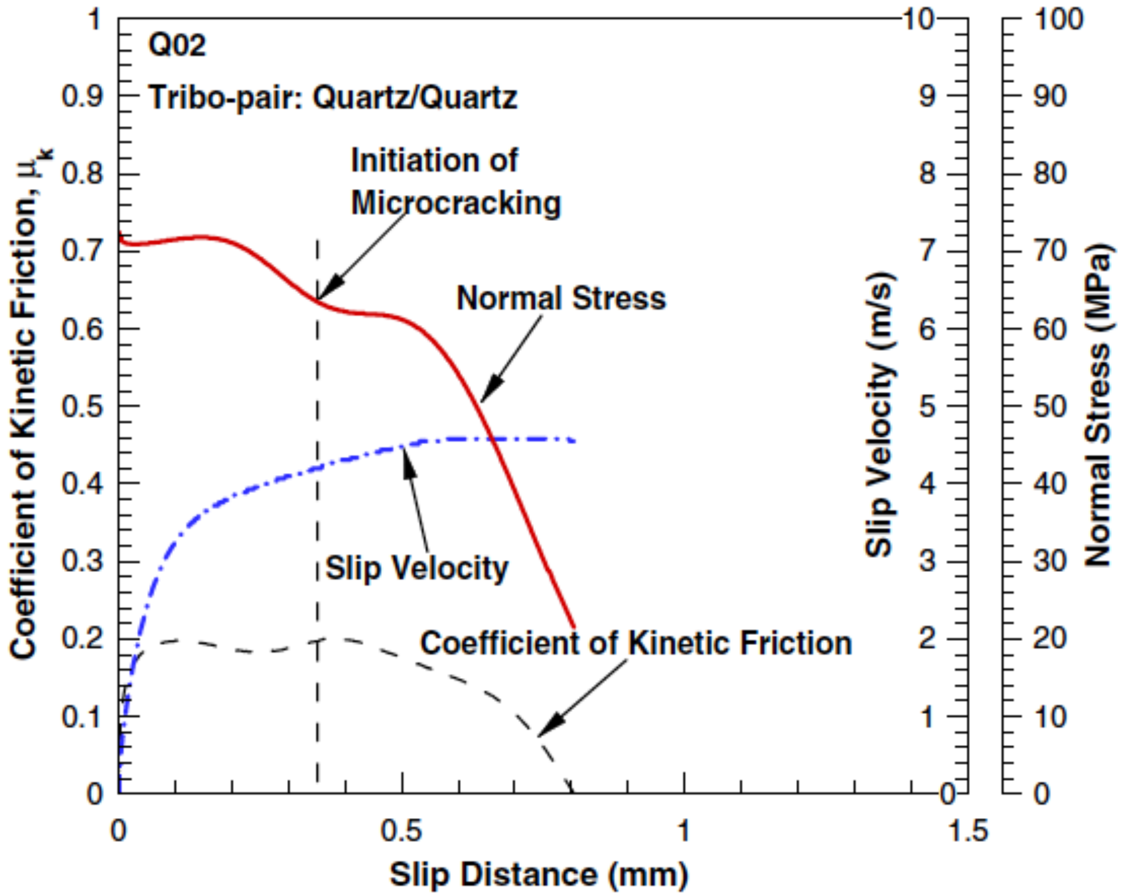


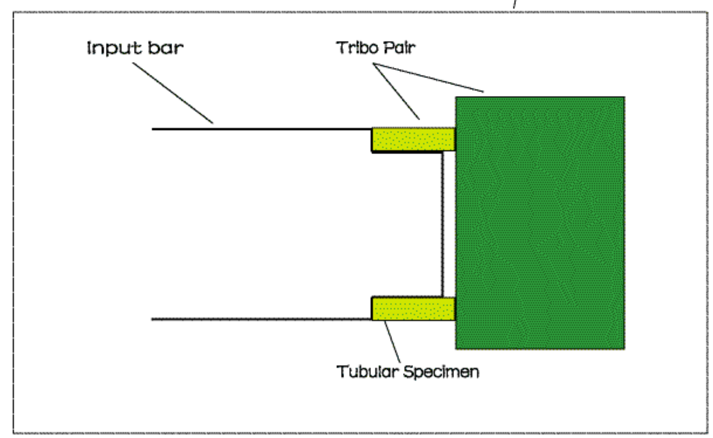
$V_w \approx 0.14$ m/s

Torsional Kolsky bar apparatus

[Yuan & Prakash, *Int. J. Solids & Structures,* 2008]







Arkansas novaculite (quartzite)

Slip at $V \approx$ 2-4 m/s, resulting in $f \approx 0.20$.

(Experiment becomes uninterpretable after small slip, marked, due to cracking in wall of specimen.)

Punchbowl PSS, composite based on Chester & Chester [*Tectonophys* '98] & Chester & Goldsby [*SCEC* '03]

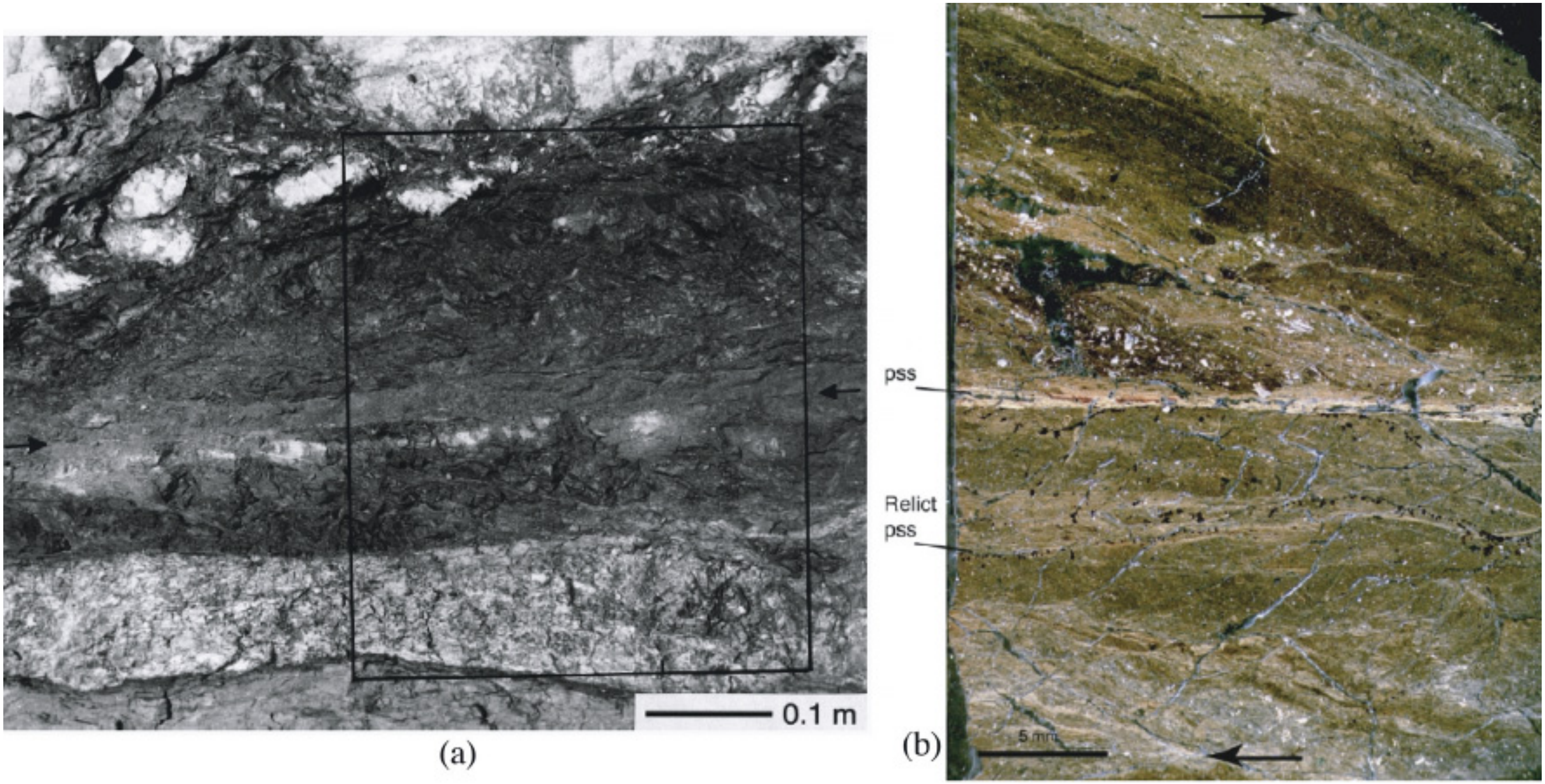


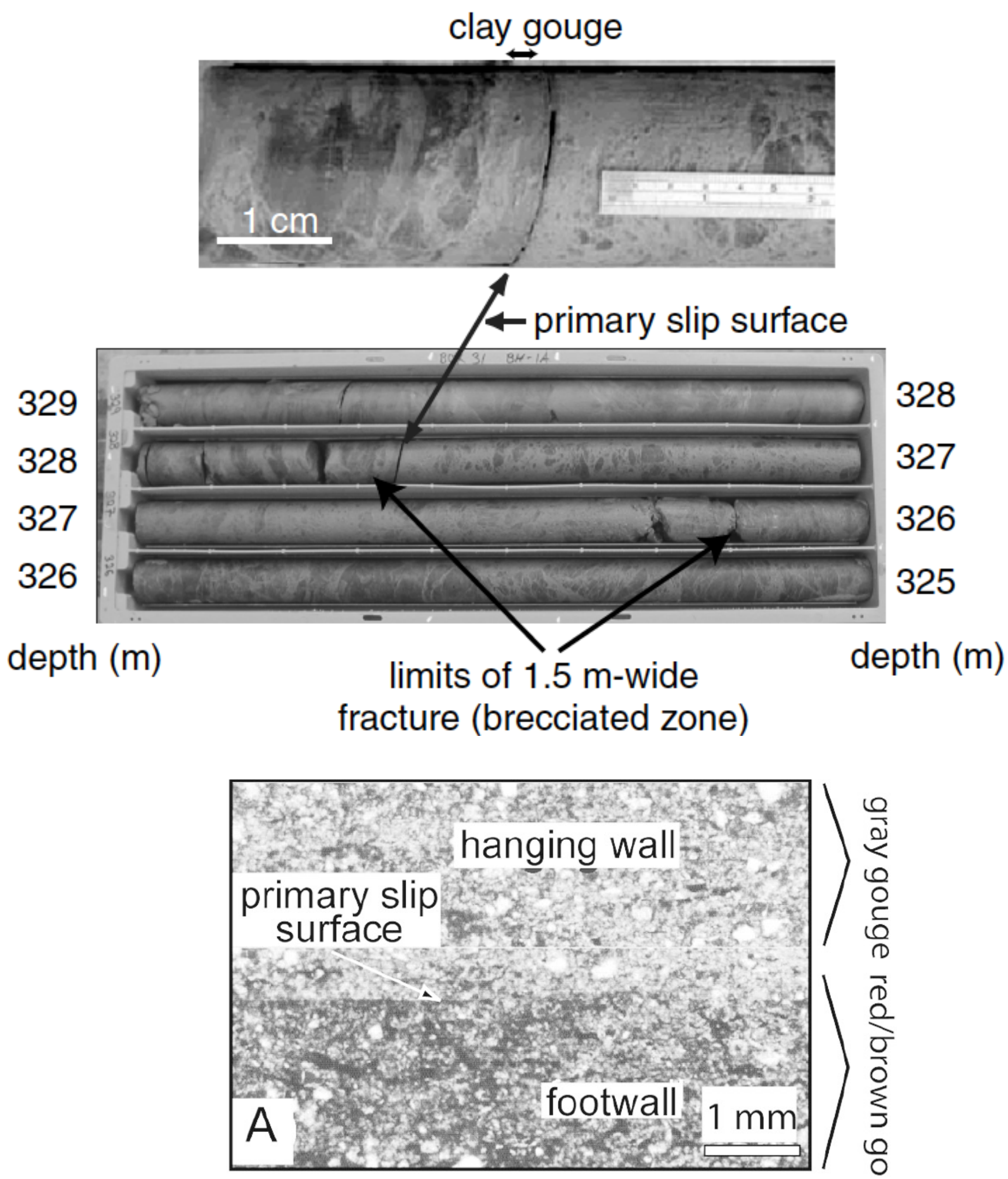
Figure 1. Principal slip surface (PSS) along the Punchbowl fault. (a) From *Chester and Chester* [1998]: Ultracataclasite zone with PSS marked by black arrows; note 100 mm scale bar. (b) From Chester et al. (manuscript in preparation, 2005) [also *Chester et al.*, 2003; *Chester and Goldsby*, 2003]: Thin section; note 5 mm scale bar and ~1 mm localization zone (bright strip when viewed in crossed polarizers due to preferred orientation), with microshear localization of most intense straining to ~100–300 μm thickness.

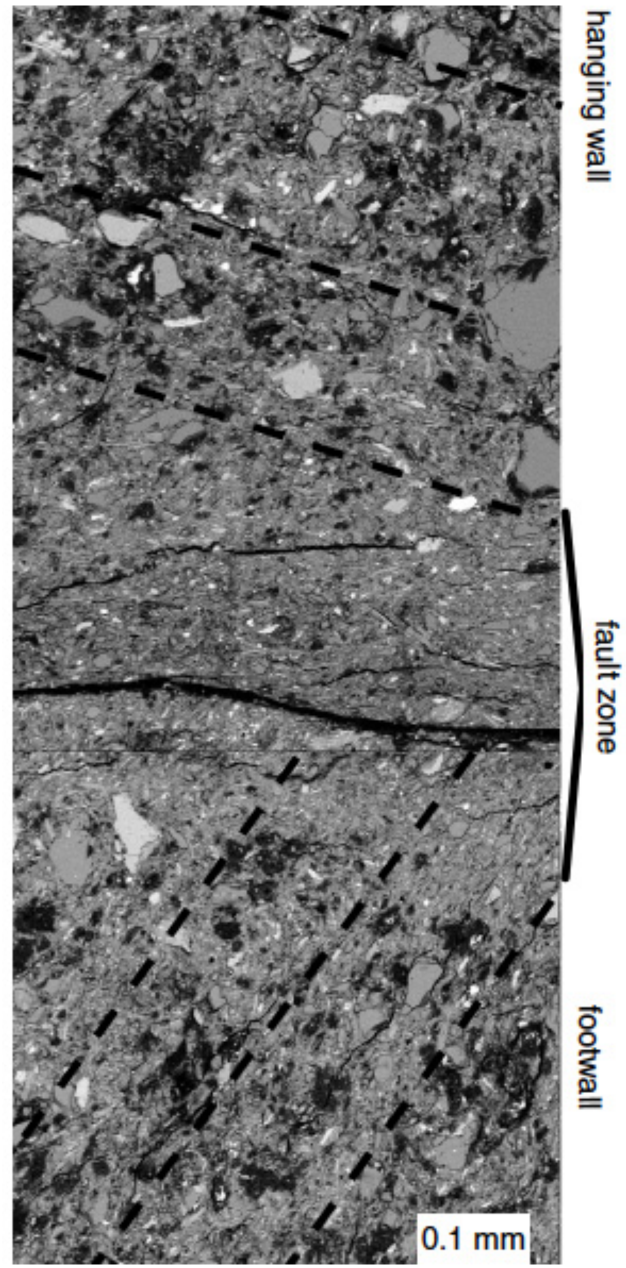
[Rice, *JGR* 2006]

[Heermance, Shipton & Evans, BSSA, 2003]

Core retrieved across the Chelungpu fault, which hosted the 1999 Mw 7.6 Chi-Chi, Taiwan, earthquake.

Suggests slip accommodated within a zone ~ 50–300 μm thick.





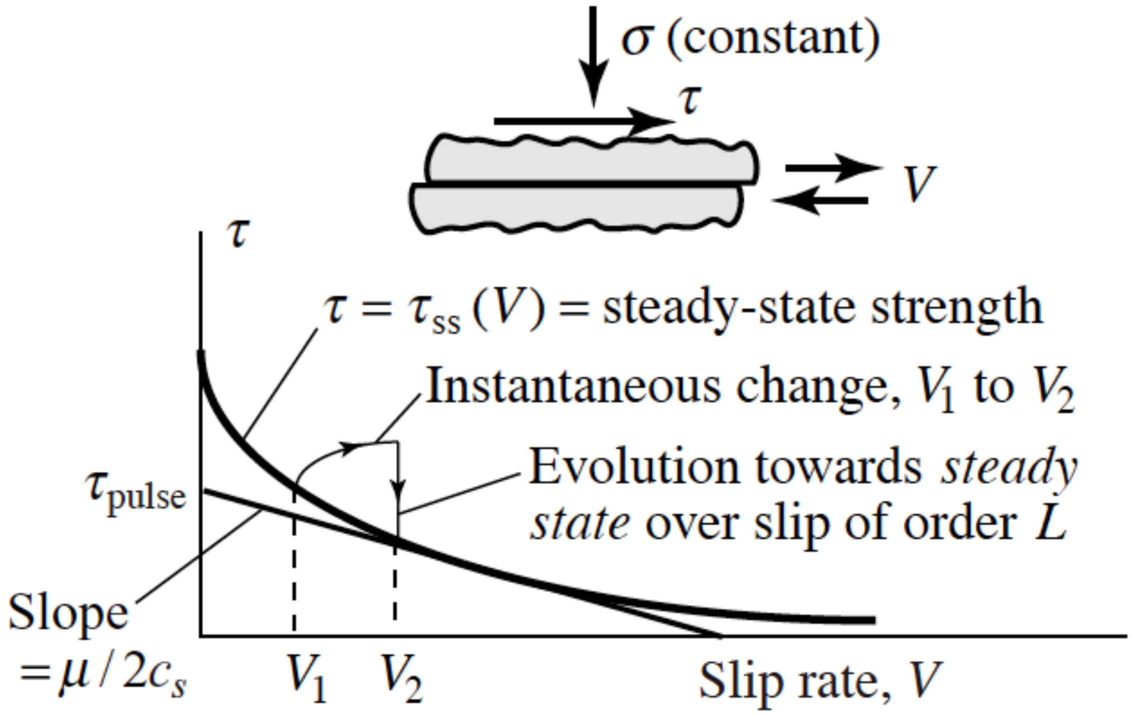
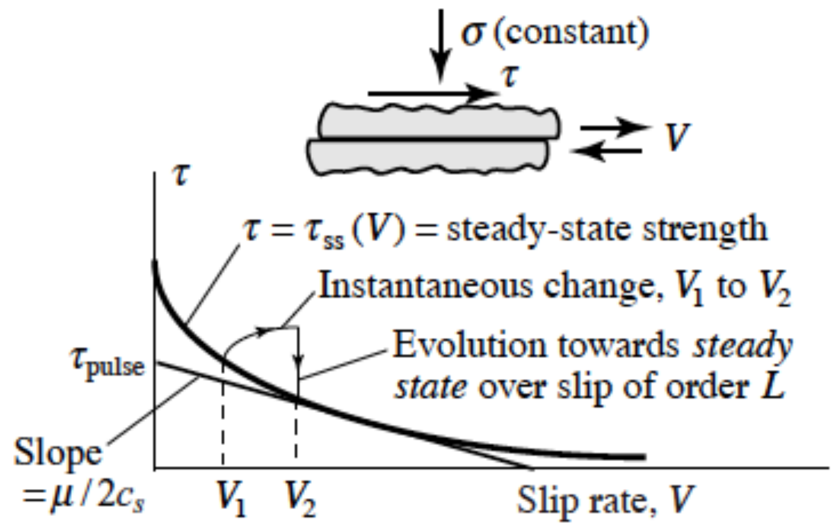


Figure 5 Velocity weakening friction. Interpreted in the rate and state framework, including laboratory-based state evolution features that also regularize ill-posed or paradoxical features in models of sliding between two identical elastic solids. A stress level τ_{pulse} is also shown, below which crack-like ruptures become impossible.

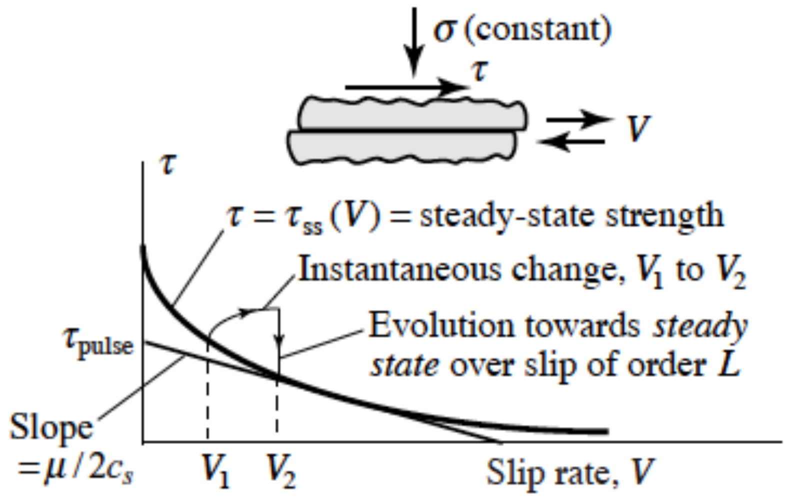


for applications to tectonic faulting. So the question arises, why use rate- and state-dependent friction instead of a pure rate-dependent friction law, say, $\tau = \tau_{\mathrm{ss}}(V)$? The answer is that in addition to attaining consistency with laboratory evidence and with the microphysical understanding of friction, we eliminate the following [51]:

- Ill-posedness of the pure rate-dependent formulation when $-\infty < \mathrm{d}\tau_{\mathrm{ss}}(V)/\mathrm{d}V < -\mu/2c_s$. An e^{ikx} perturbation of a steady sliding state, with $V = V_0$, then elicits response $V(x,t) - V_0 \sim e^{ikx}e^{\alpha|k|c_s t}$, $\alpha > 0$; see the discussion of a similar issue in the next section.

- Supersonic propagation of rupture fronts [52] when $-\mu/2c_s < \mathrm{d}\tau_{\mathrm{ss}}(V)/\mathrm{d}V < 0$. An e^{ikx} perturbation elicits response $V(x,t) - V_0 \sim e^{ik(x \pm rt)}$ where $r > c_p$ for mode II and $r > c_s$ for mode III slip. (While supersonic propagation of rupture fronts seems to be precluded in the rate and state formulation, phase velocities at sufficiently low $|k|$, within the range for which there is unstable response to e^{ikx} perturbations, do become supersonic [53]).

$$\tau = f\bar{\sigma}$$



Familiar from standard R & S: $$\frac{df}{dt} = \frac{a}{V}\frac{dV}{dt} - \frac{V}{L}\left[f - f_{ss}(V)\right]$$

Equivalent: $$f = f(V,\psi) = a\ln\left(\frac{V}{V_o}\right) + \psi, \quad \frac{d\psi}{dt} = -\frac{V}{L}\left[\psi - \psi_{ss}(V)\right]$$

Proposed [Dunham] for TPV 103, 104:

$$f(V,\psi) = a \operatorname{arcsinh}\left[\frac{V}{2V_0}\exp\left(\frac{\psi}{a}\right)\right].$$

$$\psi_{ss}(V) = a\ln\left\{\frac{2V_0}{V}\sinh\left[\frac{f_{ss}(V)}{a}\right]\right\}$$

$$f_{ss}(V) = \begin{cases} f_{LV}(V), & V < V_w \\ f_w + \left[f_{LV}(V) - f_w\right]V_w/V, & V > V_w \end{cases}$$

where

$$f_{LV}(V) = f_0 - (b-a)\ln(V/V_0)$$

$$f_w = \text{weakened friction}, \sim 0.2$$

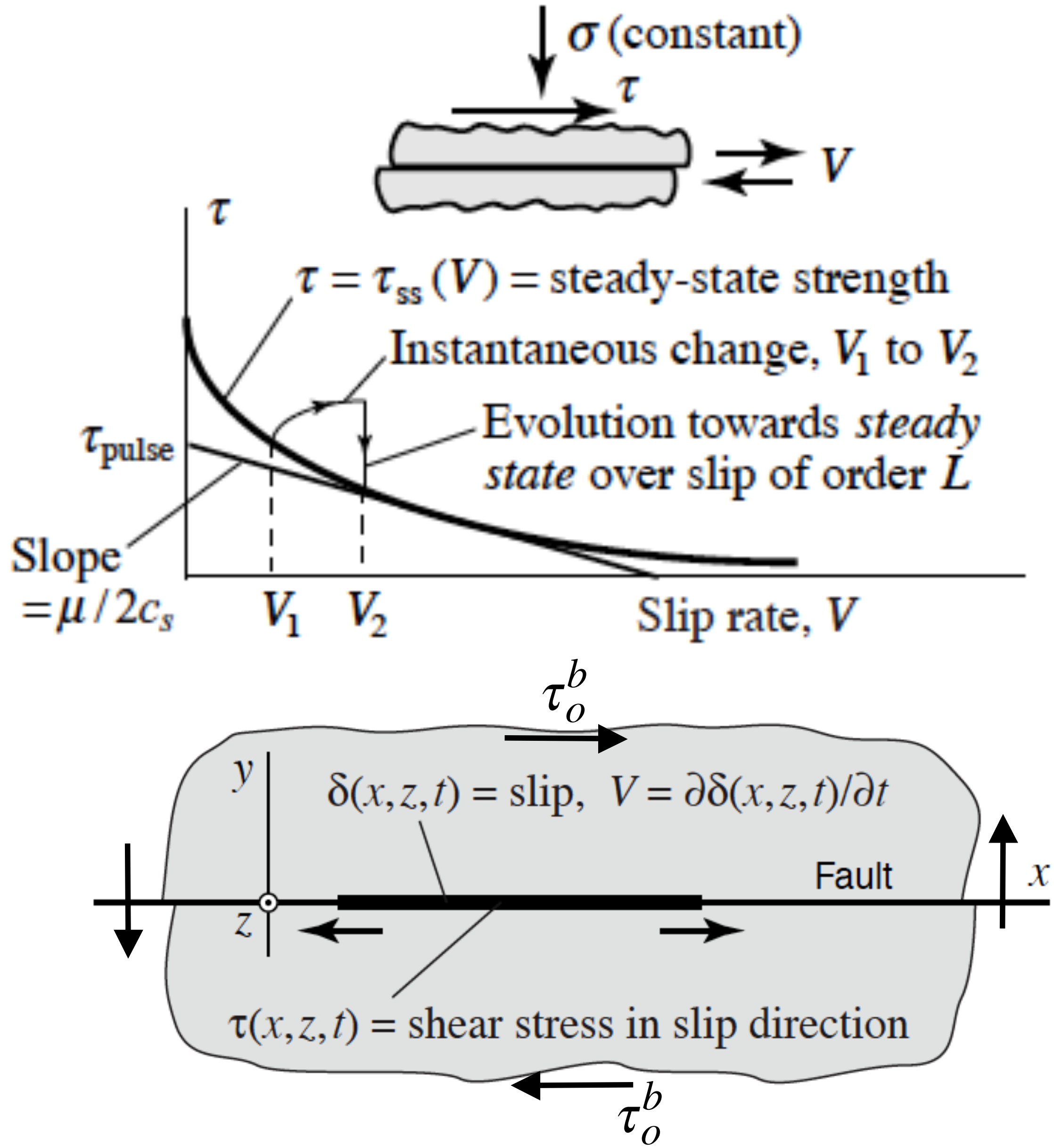


Figure 6 Identical elastic half-spaces meeting on a fault plane $y = 0$; for discussion of crack-like versus self-healing rupture mode.

Zheng & Rice [*BSSA* 1998]:

No crack-like rupture is possible if

$$\tau_o^b < \tau_{pulse}$$

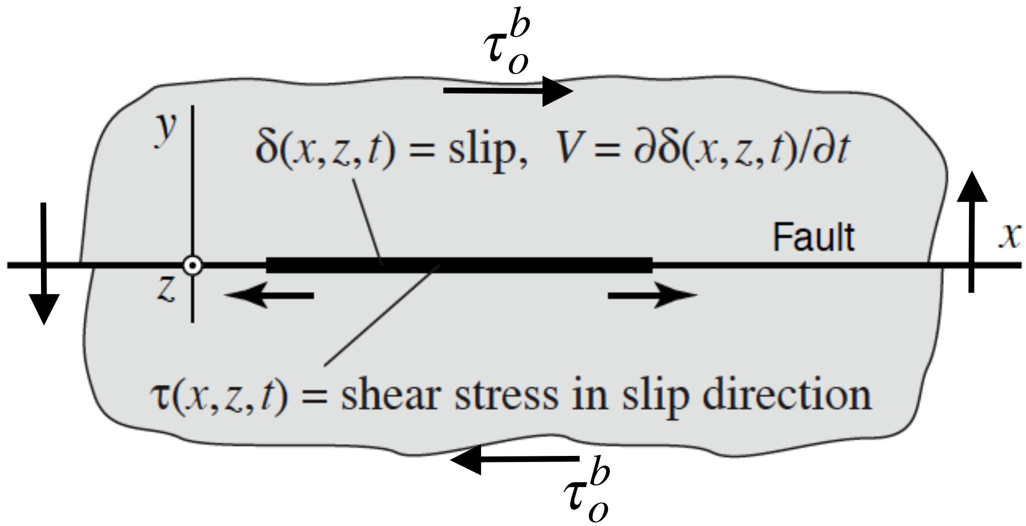


Figure 6 Identical elastic half-spaces meeting on a fault plane $y = 0$; for discussion of crack-like versus self-healing rupture mode.

Elastodynamic conservation theorem (rupture on plane in a full space):

$$\iint_{S_\infty} \left[\tau(x,z,t) - \tau_0(x,z) + \frac{\mu V(x,z,t)}{2c_s}\right] \mathrm{d}x\, \mathrm{d}z = 0$$

For a hypothesized crack-like rupture with $\tau_o^b < \tau_{pulse}$, must be the case that

$$\iint_{S_{\text{out}}(t)} (\tau - \tau_0^b)\, \mathrm{d}x\, \mathrm{d}z < 0 \quad (\text{and} \to -\infty \text{ as } S_{\text{rupt}} \to \infty)\,.$$

$\Rightarrow$ Shear force carried by area *outside* the rupture would have to decrease.
Seems implausible in general; provably impossible, thus far, only in Mode III.

[Noda, Dunham & Rice, to *JGR* `08]

Based on Tullis and Goldsby [SCEC, `03] parameters f_o, f_w and V_w for granite.

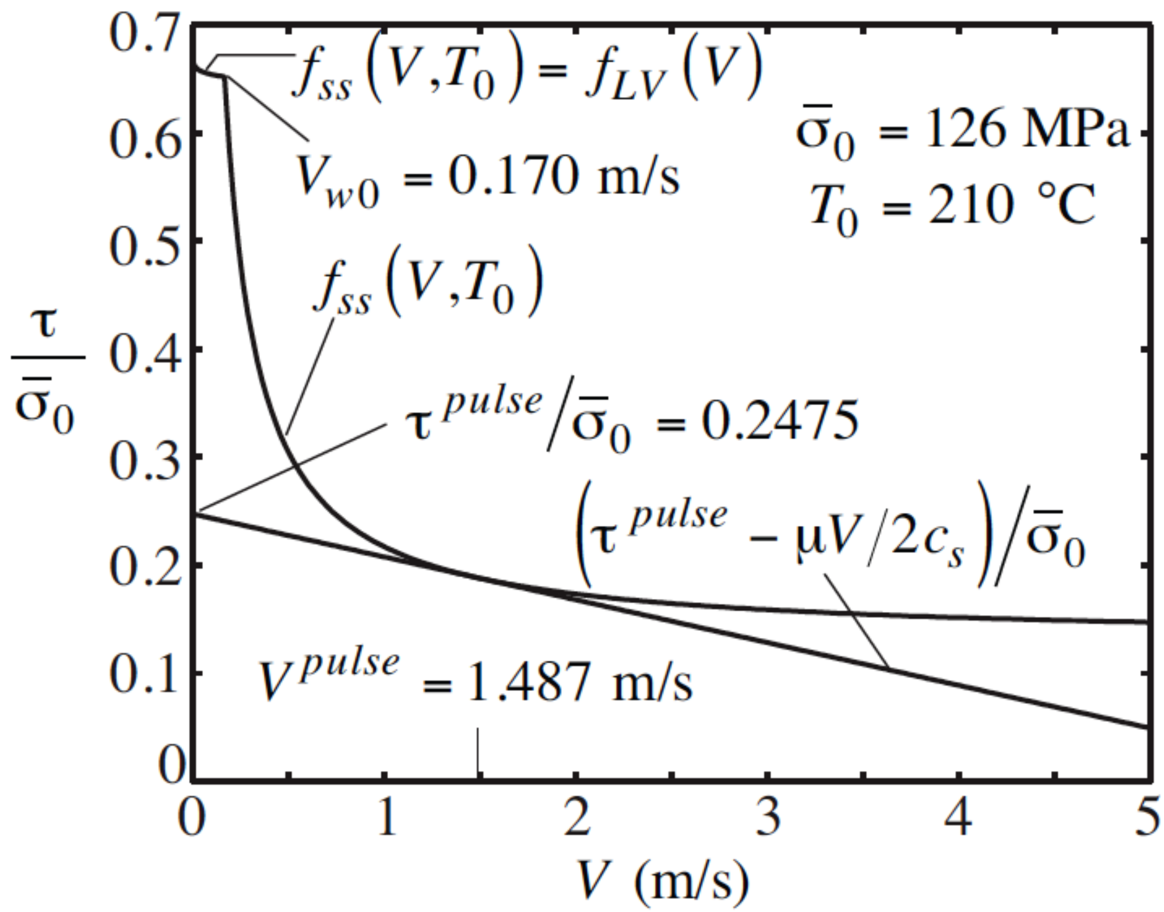


Figure 1. Steady state frictional shear stress, τ_{ss}, normalized by initial effective normal stress, $\overline{\sigma}_0$, as a function of slip velocity, V. τ^{pulse} is defined for the initial ambient conditions at 7 km depth ($T = 210$ °C, $\sigma = 196$ MPa, $p = 70$ MPa) by the radiation-damping line which fits tangentially to $\tau_{ss}(V)$ at $V = V^{pulse}$ ($= 1.487$ m/s). The weakening slip rate is $V_w = 0.170$ m/s. Due to extreme velocity weakening at elevated slip rates, τ^{pulse} is very small ($0.2475\ \overline{\sigma}_0$).

Flash heating ***(in dynamic rupture simulations, Noda, Dunham & Rice, to JGR 08)***

Effective stress law:

given, fixed compressive normal stress

$$\tau = \sigma_e f = (\sigma_n - p|_{z=0}) f$$

friction coefficient

pore pressure on slip surface

Flash heating at microscopic contacts, model for f_{ss} (*steady state* friction)

[similar to Beeler & Tullis, 2003, 2006; Rice, 1999, 2006]

$$f_{ss} = \begin{cases} f_{LV}(V)\,, & V \le V_w, \\ f_w + \left(f_{LV}(V) - f_w\right)\dfrac{V_w}{V}, & V \ge V_w, \end{cases} \quad \text{with } V_w = \pi \frac{\alpha_{th}}{D}\left(\frac{T_w - T}{\tau_c/\rho c}\right)^2$$

Thermal pressurization *(in dynamic rupture simulations, Noda, Dunham & Rice, to JGR 08)*

Effective stress law:

given, fixed compressive normal stress

$$\tau = \sigma_e f = (\sigma_n - p|_{z=0}) f$$

friction coefficient

pore pressure on slip surface

Thermal pressurization, finite thickness of slipping zone; Gaussian shear distribution, *r.m.s.* width w)

Conservation of energy:

$$\frac{\partial T}{\partial t} = \alpha_{th}\frac{\partial^2 T}{\partial z^2} + \frac{\tau}{\rho c}\frac{V}{\sqrt{2\pi}\ w}\exp\left(-\frac{z^2}{2w^2}\right)$$

Conservation of fluid mass:

$$\frac{\partial p}{\partial t} = \alpha_{hy}\frac{\partial^2 p}{\partial z^2} + \Lambda\frac{\partial T}{\partial t}$$

B.C.

$$\left.\frac{\partial T}{\partial z}\right|_{z=0} = 0$$

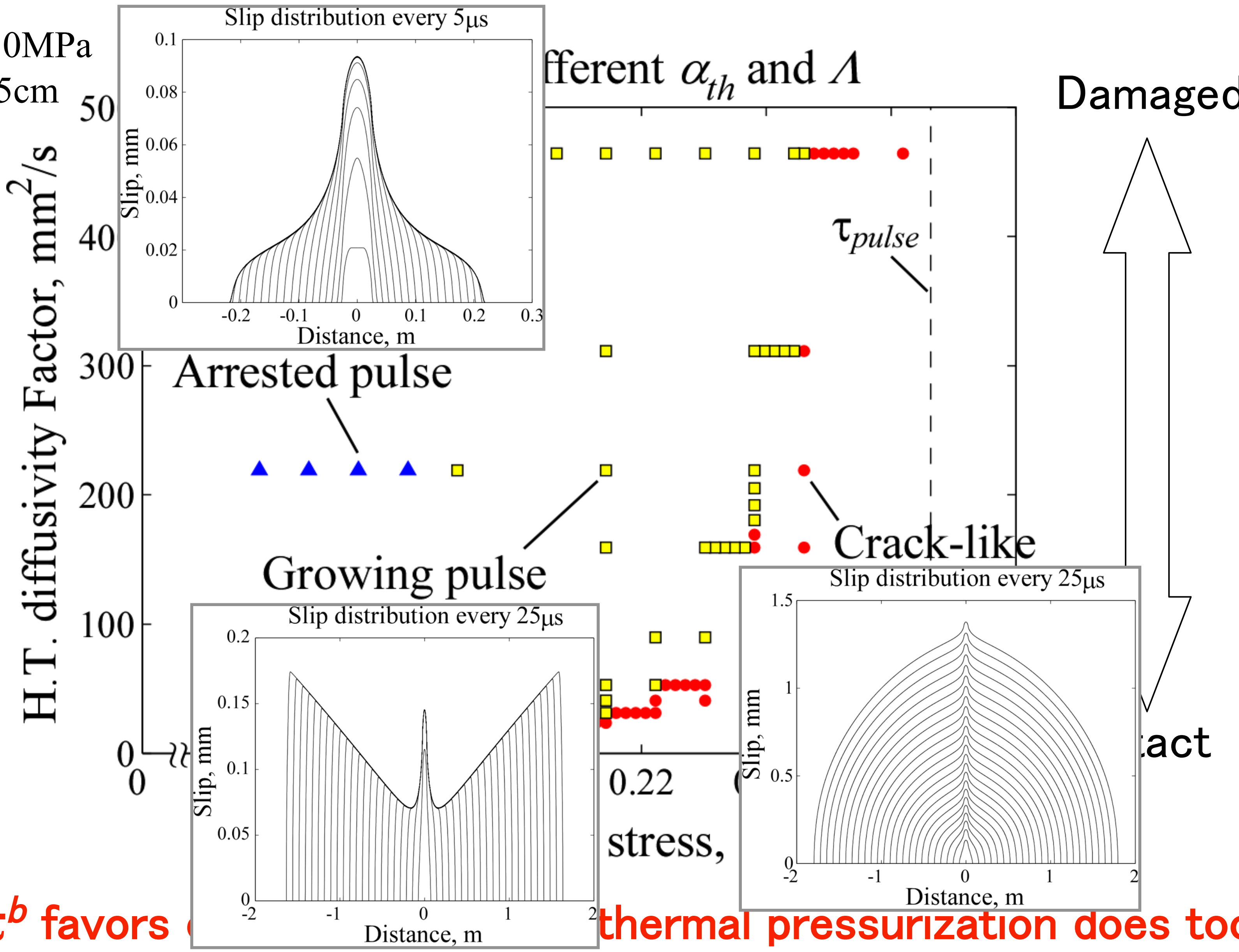
$$\left.\frac{\partial p}{\partial z}\right|_{z=0} = 0$$

α_{th} ~ 0.7 mm^2/s; α_{hy} ~ 0.9 - 6 mm^2/s at mid-seismogenic depths; ρc ~ 2.7 MJ/m^{3}K; Λ ~ 0.3 - 1.0 MJ/m^{3}K (Rice [*JGR* 2006] & Rempel & Rice [*ibid*], based on Wibberley [*EPS* 2002, *priv comm* 2003] & Wibberley & Shimamoto [*JSG* 2003], and estimates of damage)

[Noda, Dunham & Rice, *in prep.*]

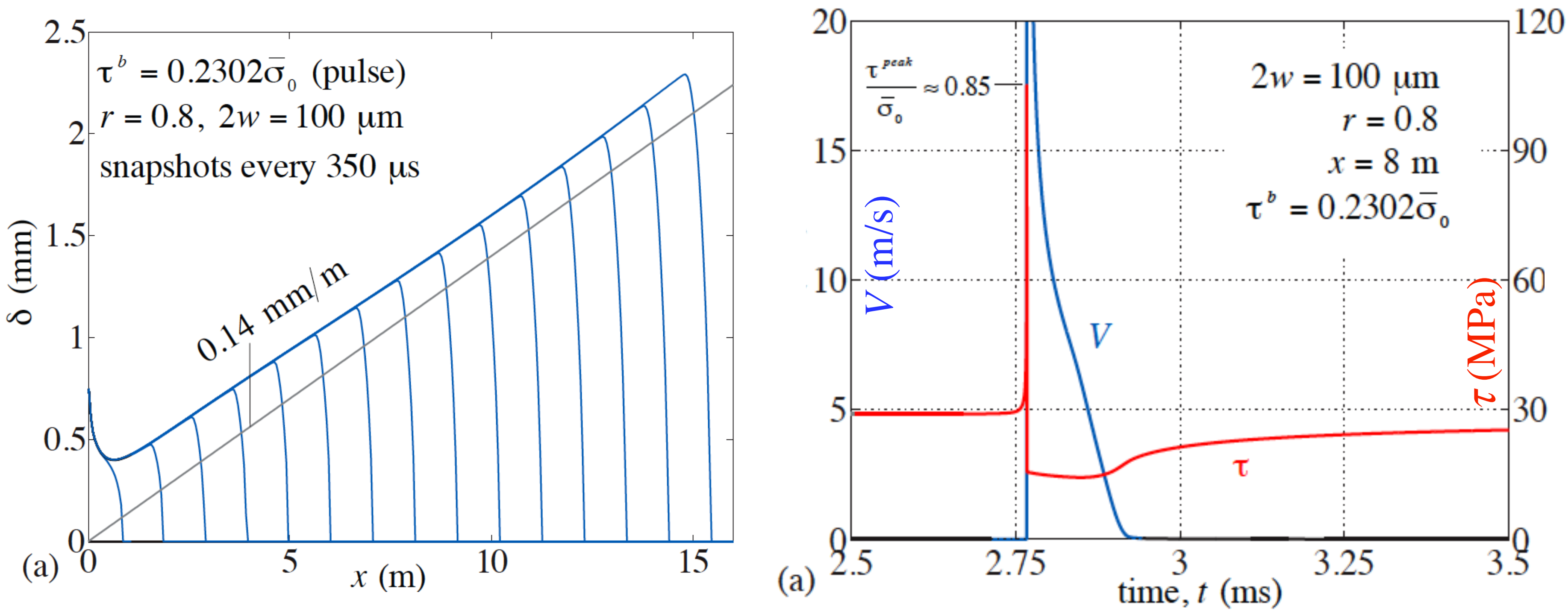
Effect of hydrothermal properties

$\tau^{per} = 30\text{MPa}$
$D^{per} = 5\text{cm}$



High τ^b favors … **thermal pressurization does too.**

[Noda, Dunham & Rice, *in prep*.] Longest simulation to date: ~30 m of rupture length

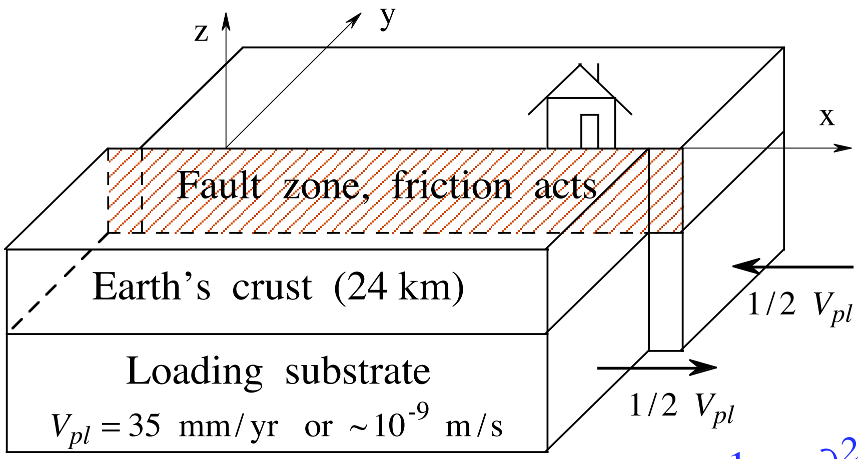


left: Distribution of slip δ showing a ~linear increase with x by 0.14 mm/m.

right: History of slip rate V and shear stress τ at $x = 8$ m:

- Peak V is extremely high (> 100 m/s).
- τ^b (= initial shear stress) ~ 29 MPa = 0.23 $(\sigma - p_o)$ [$\sigma - p_o$ = 126 MPa].
- τ^{peak} (= peak stress at rupture front) ~ 107 MPa = 0.85 $(\sigma - p_o)$
- $\tau^b - \tau^{final}$ (= seismic stress drop) ~ 3 MPa

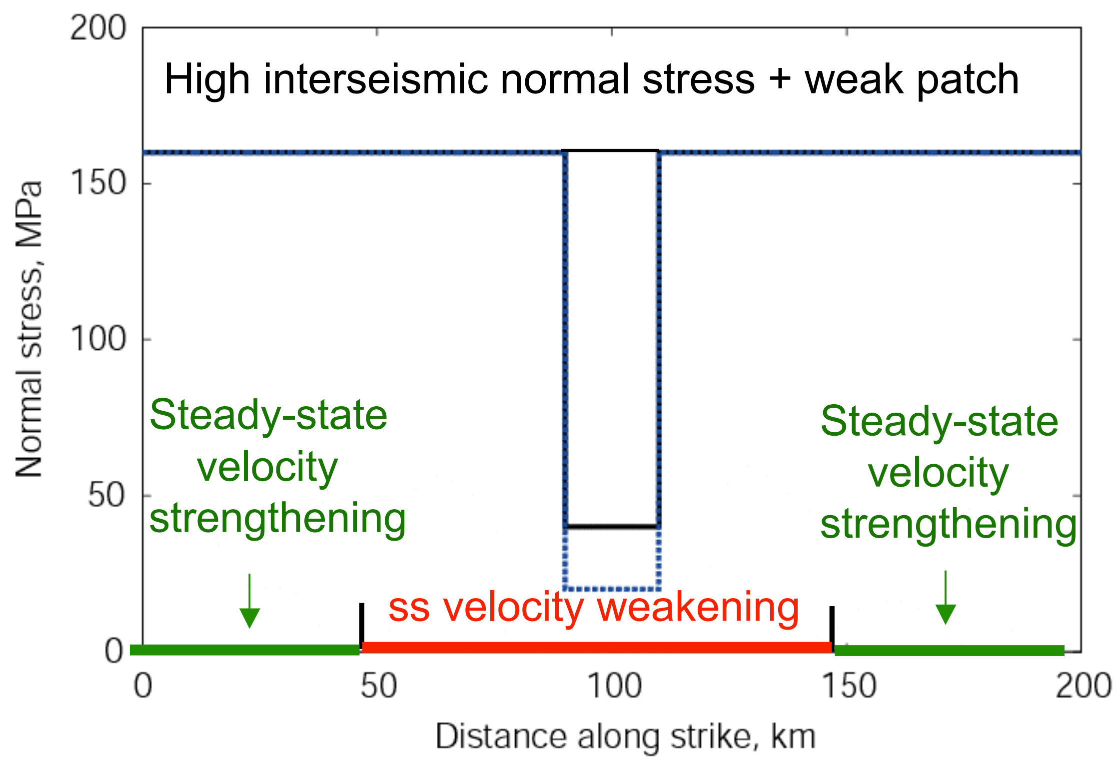
2D crustal plane model of a vertical strike-slip fault



Lapusta & Rice
[*EOS*, 2004]

- Constrained continuum, **the only displacement** is in the **direction of *x***.
- ***u = u*(*x,y,t*)** is its **depth-averaged value** over the seismogenic thickness H_{seis}.
- The equation of motion **is depth-averaged in *z***; the fault plane becomes a fault line.

$$\frac{1}{(1-\nu)^2}\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{16}{\pi^2 H_{seis}^2}\left(\frac{1}{2}sign(y)V_{pl}t-u\right)=\frac{1}{c_s^2}\frac{\partial^2 u}{\partial t^2}$$



A *simplified* law: Strong weakening with seismic slip velocities *V*

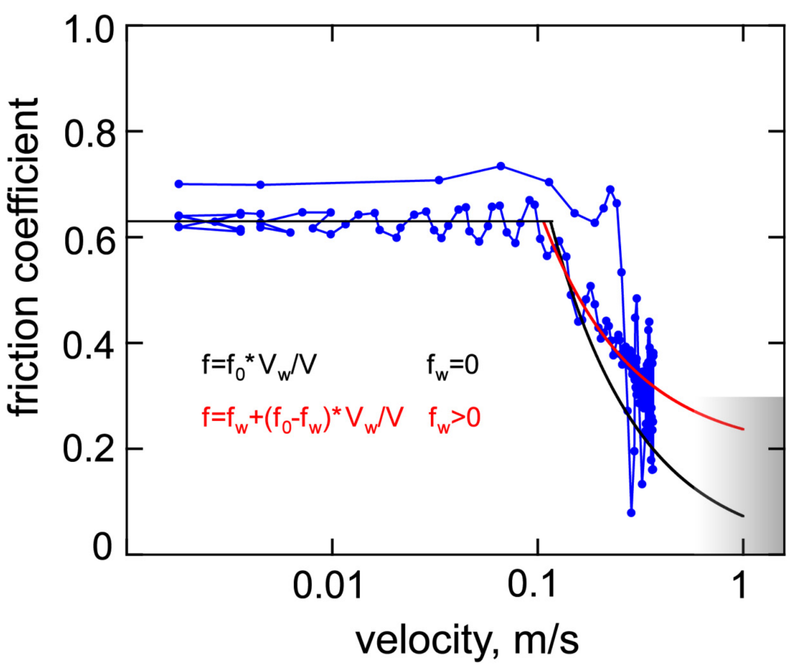
$$f = \frac{f_o + a\ln(V/V_o) + b\ln(V_o\theta/L)}{1 + L/V_w\theta}\ , \quad \frac{d\theta}{dt} = 1 - \frac{V\theta}{L} \quad \Rightarrow \quad f_{ss} = \frac{f_o + (a-b)\ln(V/V_o)}{1 + V/V_w}$$

$V << V_w,\ \theta >> L/V_w \ \Rightarrow$ denominator $\approx 1 \ \Rightarrow$ ordinary rate and state friction

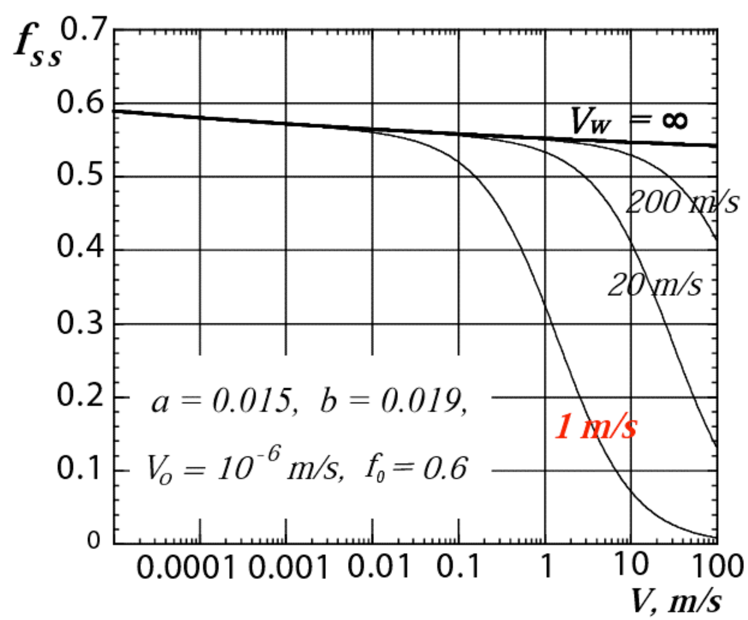
$V >> V_w \ \Rightarrow$ strong dynamic weakening in steady state

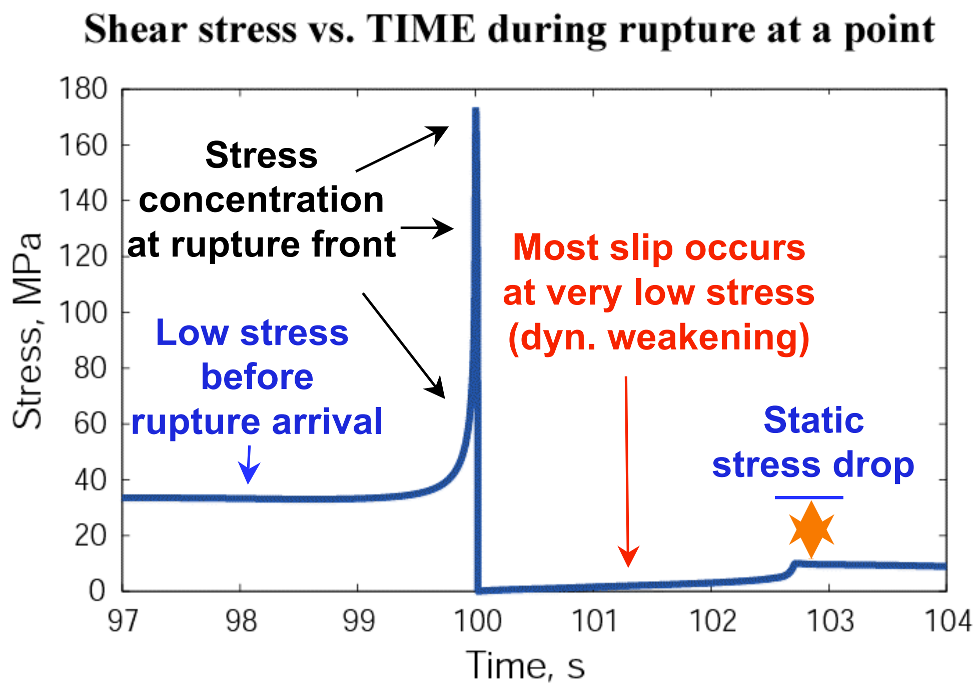
From theory and experiments: $V_w \sim 0.1$ m/s

Experiments



Above law

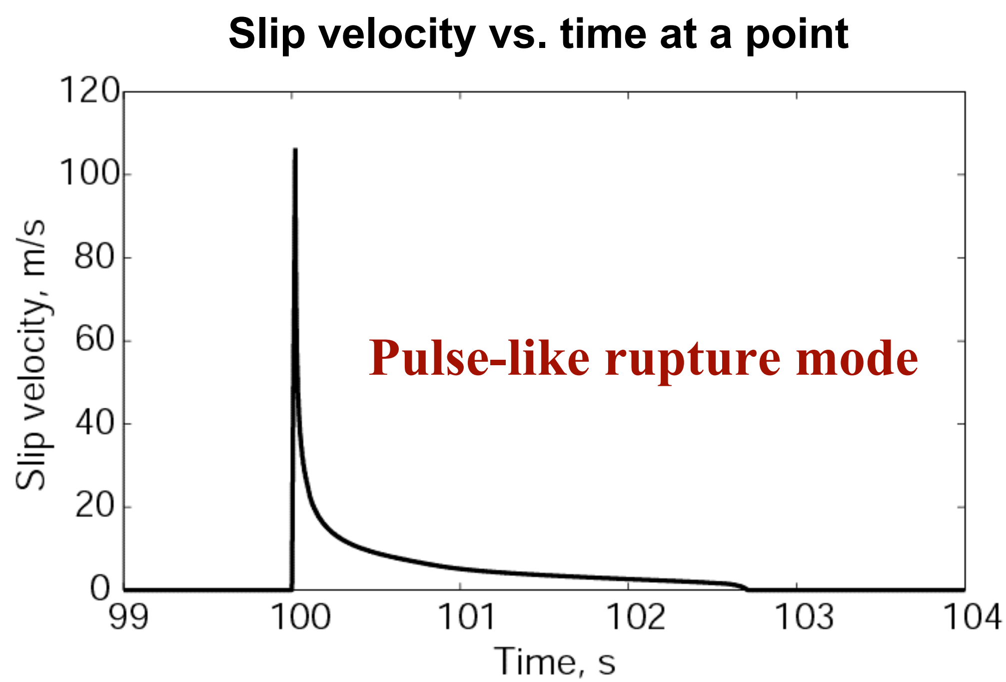




Shear stress evolution at a *statically strong* fault point during dynamic rupture

Static stress drop is ***much smaller*** than what one would expect ***because*** shear stress before the earthquake is much smaller than static strength.

Pulse-like rupture, slip duration is about 2.5 seconds



Stress state on the fault through many earthquake cycles

[Lapusta and Rice, in preparation]

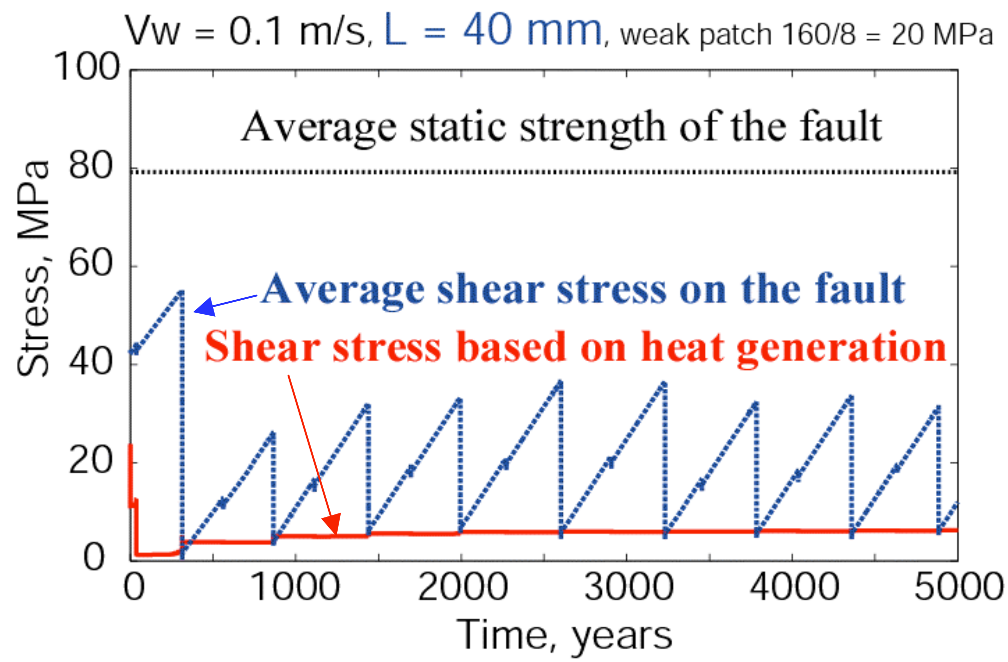
$$\tau_{av} = \frac{\int_{fault} \tau \, dA}{\text{fault area}}$$

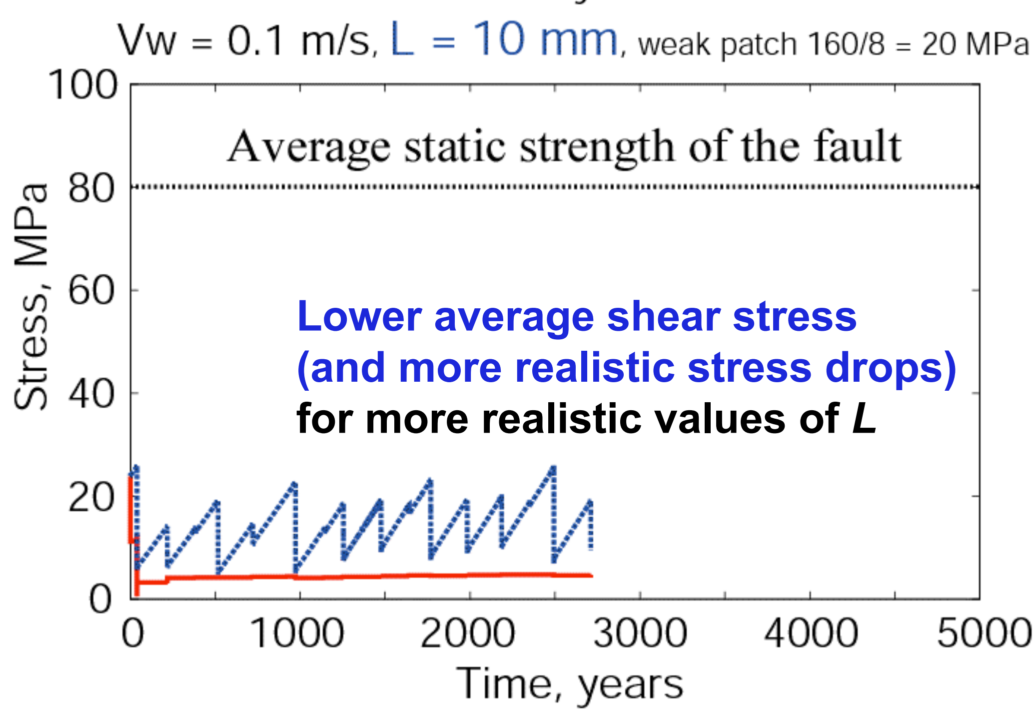
$$\tau_{heat} = \frac{\int_{time} \int_{fault} \tau V \, dA dt}{\int_{time} \int_{fault} V \, dA dt}$$

V_w = 0.1 m/s

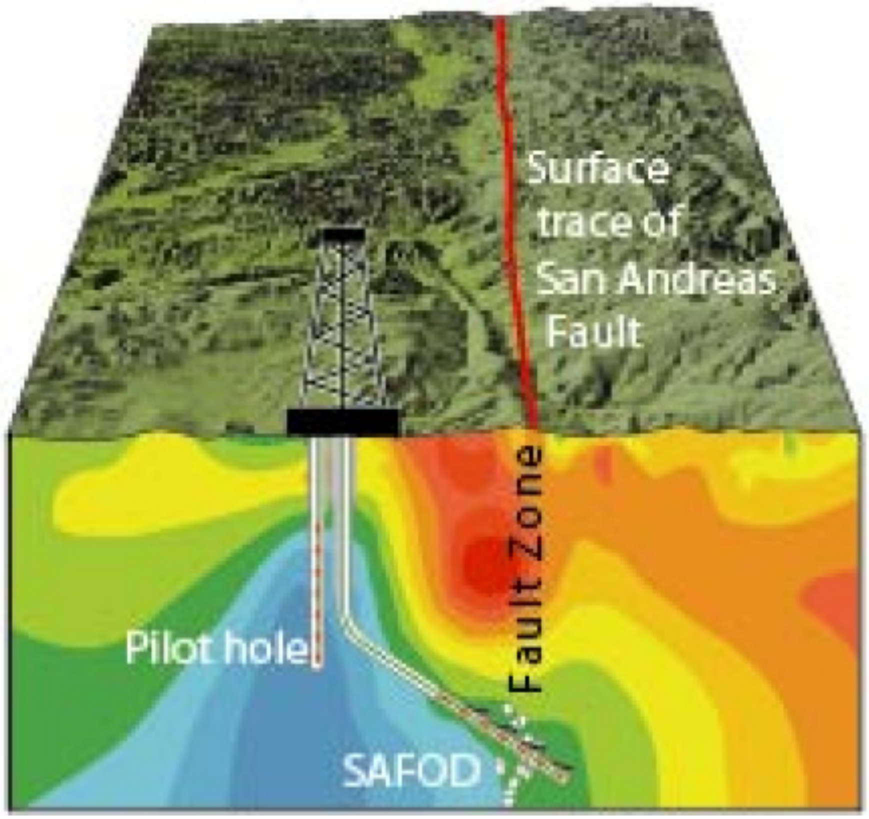
Low-stress fault operation

Low heat production



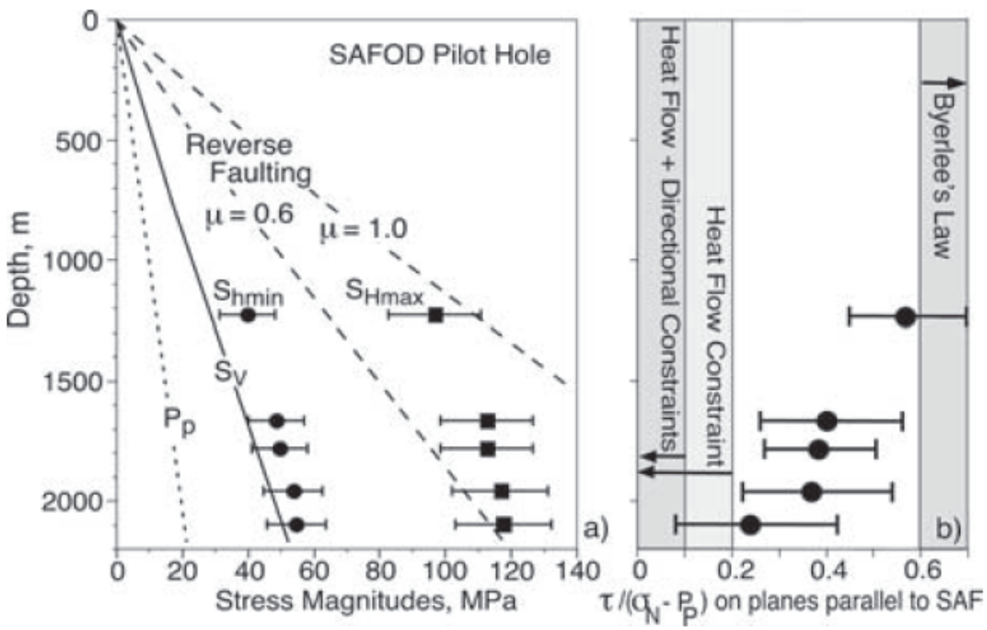


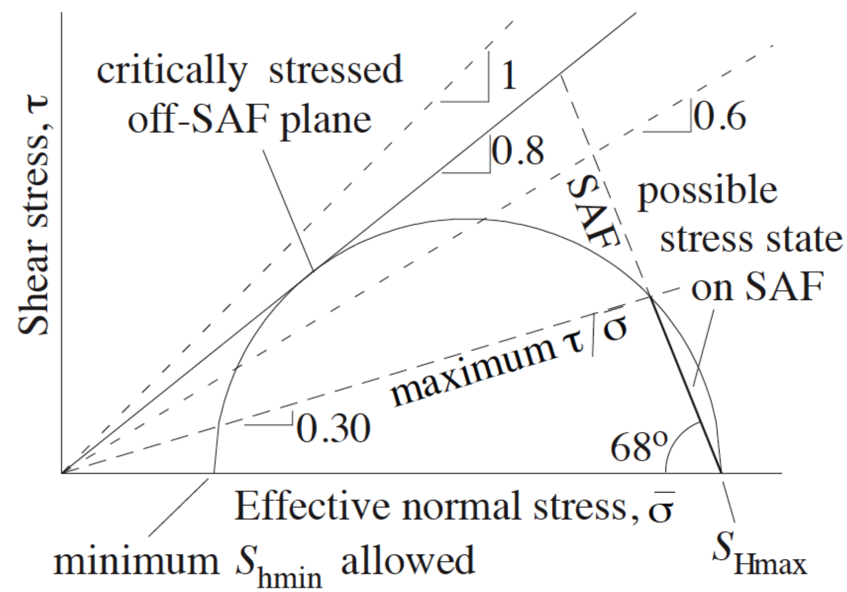
Parkfield: San Andreas Fault Observatory at Depth



Schematic cross section of the San Andreas Fault Zone at Parkfield, showing the drill hole for the San Andreas Fault Observatory at Depth (SAFOD) and the pilot hole drilled in 2002. Red dots in drill holes show sites of monitoring instruments. White dots represent area of persistent minor seismicity at depths of 2.5 to more than 10 km. The colors in the subsurface show electrical resistivity of the rocks as determined from surface surveys; the lowest-resistivity rocks (red) above the area of minor earthquakes may represent a fluid-rich zone.

[Hickman & Zoback, *GRL* 2004]





- Physical theory and experimental basis, strong velocity weakening at seismic slip rates

- How it promotes a self-healing rupture mode (at sufficiently low pre-stress levels)

- Project (Dunham, Noda & Rice) to use fully lab constrained friction descriptions to predict earthquake ruptures

- Relation to earlier studies (Lapusta & Rice) and to SCEC Code Validation project (*TPV103 and TPV104, Rate-and-State Friction, Slip Law, Strong Rate-Weakening*)

Quandary in seismology:

• Lab estimates of rock friction coefficient f usually high, $f \sim 0.6\text{-}0.8$.

Shear strength $\tau = f \times (\sigma_n - p)$, where:

σ_n = normal stress clamping the fault shut
p = pore pressure in infiltrating fluid phase (groundwater)

• Fault slip zones are thin.

==> If those f prevail during seismic slip, we should find

• ***measurable heat outflow*** near major faults, and

• ***extensive melting*** along exhumed faults.

Neither effect is <u>generally</u> found.

One line of explanation: <u>Weak faults</u>:

$$\boxed{\tau = f \times (\sigma_n - p)}$$

- Fault core materials are different, have very low f.
- f isn't low, but pore pressure p is high over much of the fault.

Another line: <u>Statically strong</u> but <u>dynamically weak</u> faults, e.g., due to thermal weakening in rapid, large slip:

- *Processes expected to be important from start of seismic slip:*

  - Flash heating of asperity contacts, reduces f in rapid slip.
  - Thermal pressurization of pore fluid, reduces effective stress.

- *Other processes that may set in at large enough slip or rise in T*:

  - Thermal decomposition, fluid product phase at high pressure.
  - Gel(?) formation at large slip in wet silica-rich faults.
  - Melting at large slip, *if* above set has not limited increase of T.