Advanced Workshop on Earthquake Fault Mechanics: Theory, Simulation and Observations

ICTP, Trieste, Sept 2-14 2019

Lecture 3: fault friction

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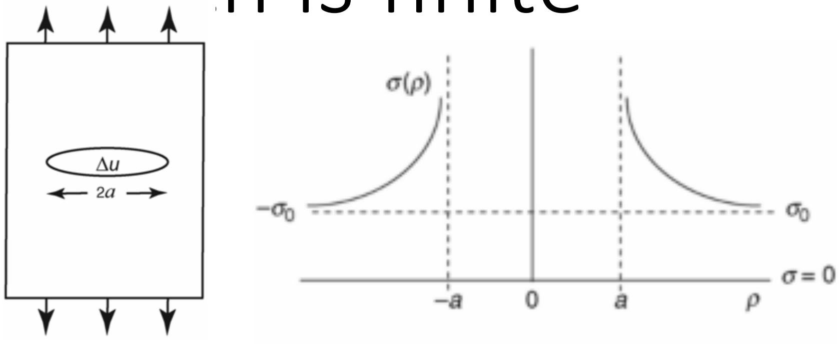
Lecture 3: earthquake dynamics from the standpoint of fault friction

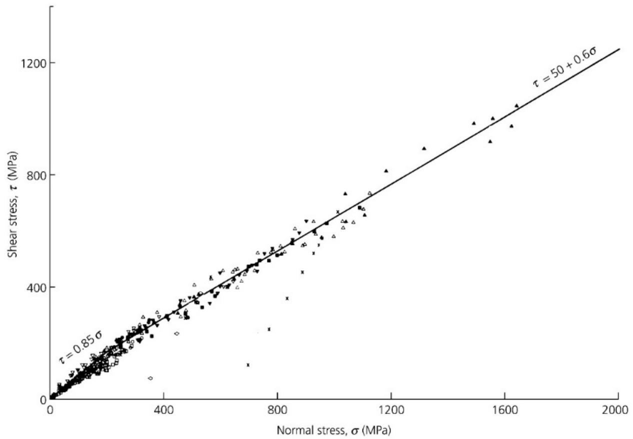
- Zoom on the process zone
- Laboratory-based friction laws
- Rupture pulses
- Stress drop scaling

Rock strength is finite



$$\sigma = \frac{K_I}{\sqrt{2\pi r}}$$

Figure 5.7-10: Relation between shear stress and normal stress for frictional sliding.

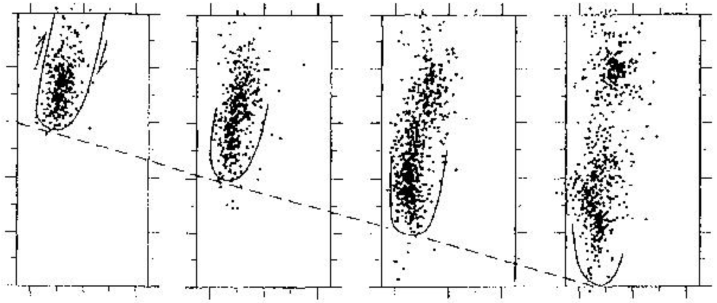


Byerlee's law

$\tau \sim 0.6\sigma$

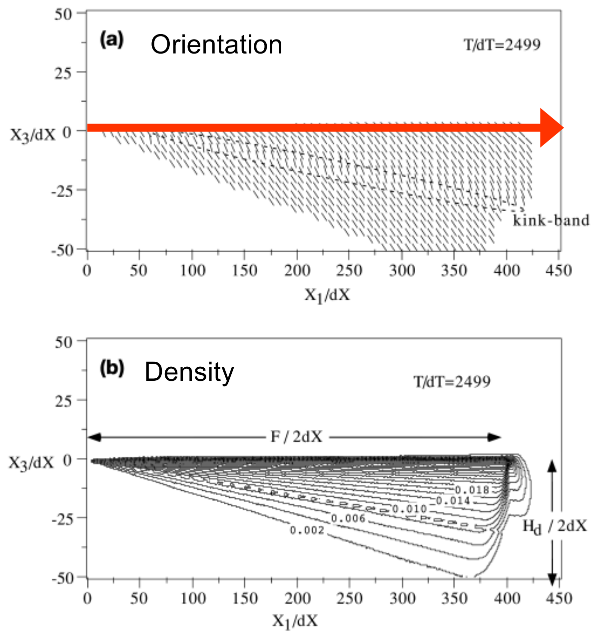
The process zone

Process zone imaged by acoustic emissions in laboratory fracture of intact rock

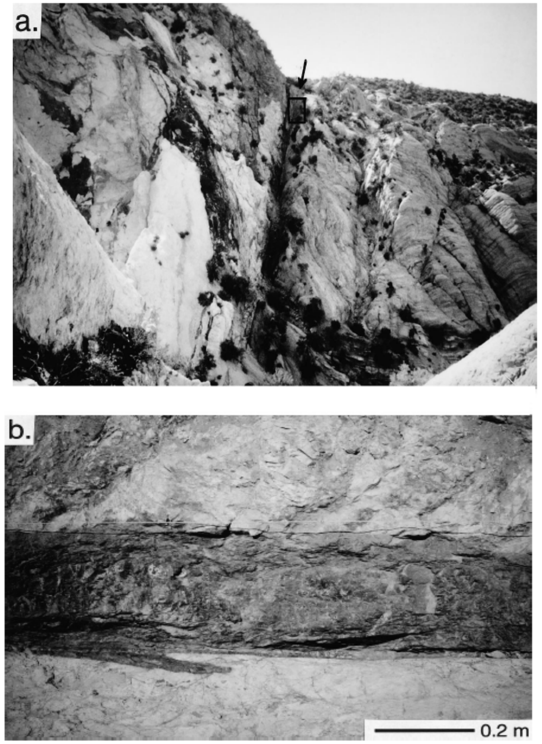


Stress singularities are unphysical:
inelastic processes occur at the small scale (damage, weakening)

Secondary micro-cracks generated by a dynamic rupture
(mode II, numerical simulation by Yamashita 2000)



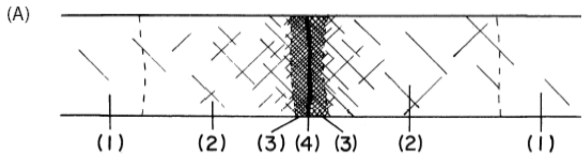
Fault zone thickness



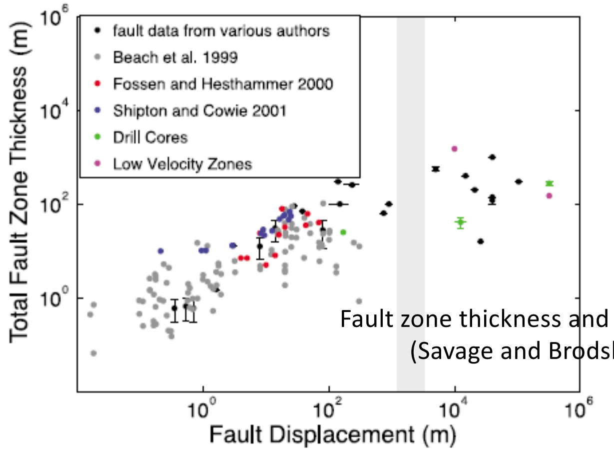
[Chester and Chester, 1998]

Internal Structure of a Major Fault Zone

(after Chester et al., 1993; Chester & Chester, 1998; Sibson, 2003)



(1) Undamaged host rock
(2) Damage zone, highly cracked; 10s m to 100 m wide, minor faults may reach 1 km
(3) Gouge or foliated gouge; 1 m to 10s m wide
(4) Central ultracataclasite shear zone, may be clay rich; 10s mm to 100s mm wide
(5) [within (4), not marked above] Prominent slip surface; may be < 1 to 5 mm wide



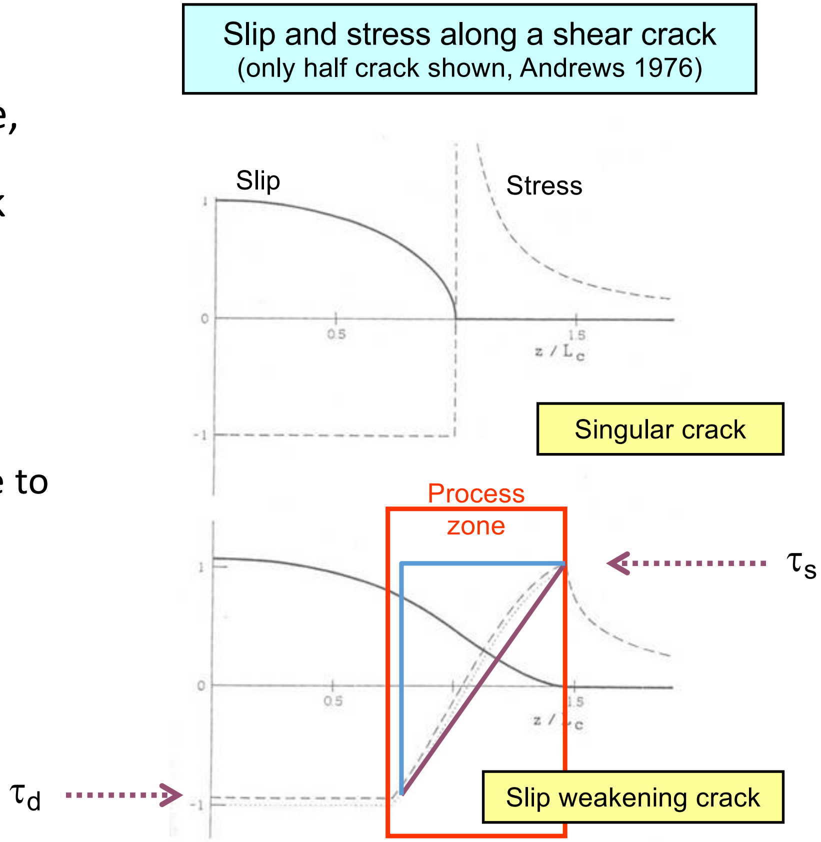
Fault zone thickness and maturity
(Savage and Brodsky, 2011)

Cohesive zone models

Assumption: dissipative processes are mapped onto the fault plane, represented by a distribution of **cohesive stresses** near the crack tip

Usual cohesive models:

- constant (Dugdale, Barenblatt)
- linearly dependent on distance to crack tip (Palmer and Rice, Ida)
- linearly dependent on slip (Ida, Andrews)



Cohesive zone size

- Cohesive stresses $\tau(x)$ generate a negative stress intensity factor

$$K_c = -\sqrt{\frac{2}{\pi}}\int_0^{\Lambda}\frac{\tau(\xi)-\tau_d}{\sqrt{\xi}}\,d\xi$$

  that cancels the singularity :

$$K + K_c = 0$$

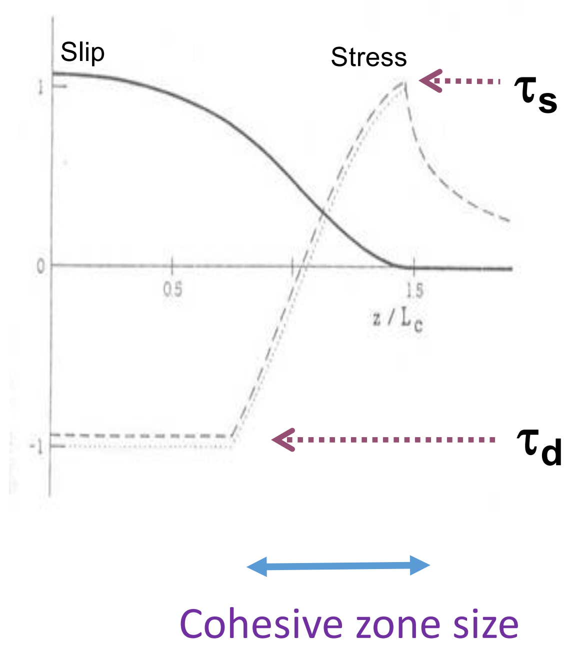
- That condition determines the **size of the cohesive zone**

$$\Lambda = C_1 \frac{K^2}{(\tau_s - \tau_d)^2}$$

  with $C_1 \approx 1$ (for a linear distribution: $C_1 = 9\pi/32$)

From last lecture (mode III):

$$G_c = \frac{K_{III}^2}{2\mu\sqrt{1 - v^2/\beta^2}}$$



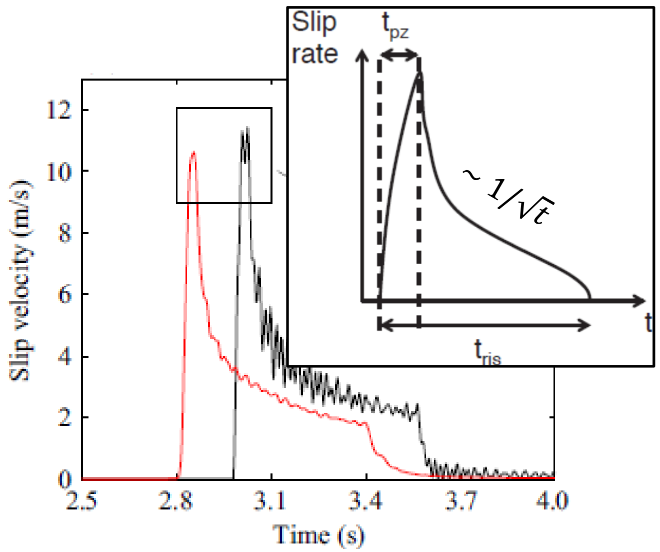
$$\Lambda = \sqrt{1 - v^2/\beta^2}\,\Lambda_0 \quad \text{where } \Lambda_0 = C_1 2\mu G_c/(\tau_s - \tau_d)^2$$

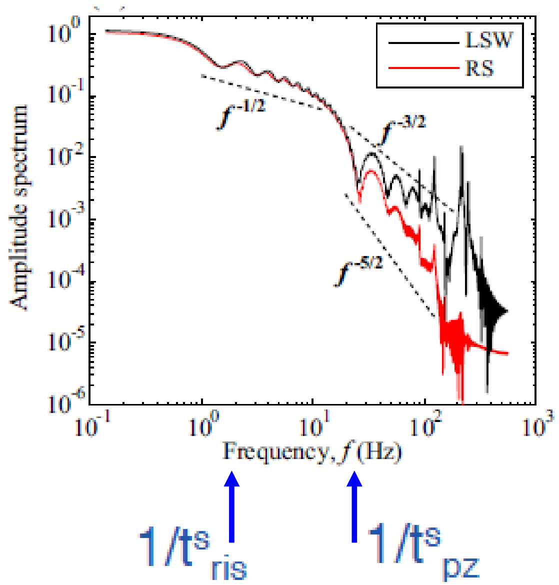
Cohesive zone size

$$\Lambda = \sqrt{1 - v^2/\beta^2}\,\Lambda_0 \quad \text{where } \Lambda_0 = C_1 2\mu G_c/(\tau_s - \tau_d)^2$$

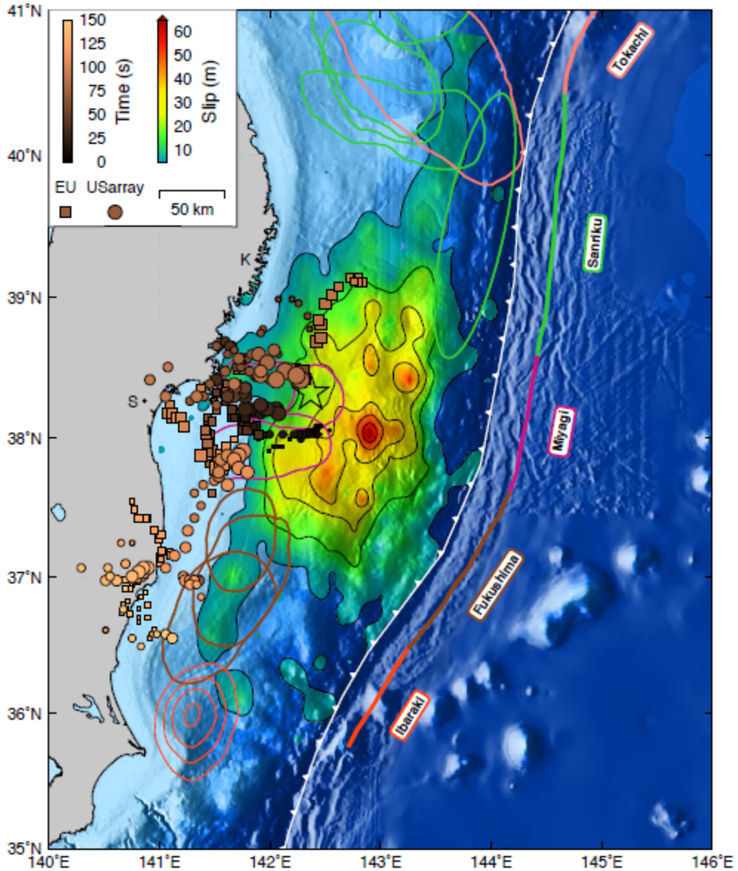
$$t_{pz} = \Lambda/v$$

Increasing rupture velocity
→ contraction of the process zone
→ higher frequency radiation
→ larger ground acceleration





Tohoku: high-frequency radiation deeper than low-freq slip

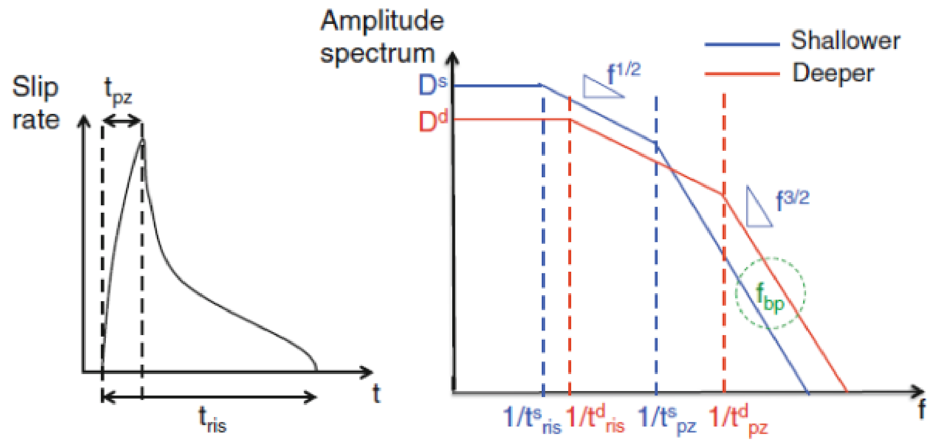


Brownish symbols: 1Hz radiators extracted from back-projection movies

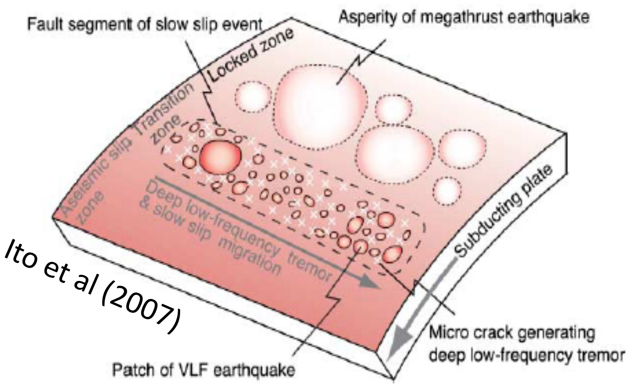
Colored contours: static slip from GPS & tsunami data

Spatial complementarity of high- and low-frequency slip:
HF radiation is deeper than static slip

HF radiation occurs even where the rupture is slow

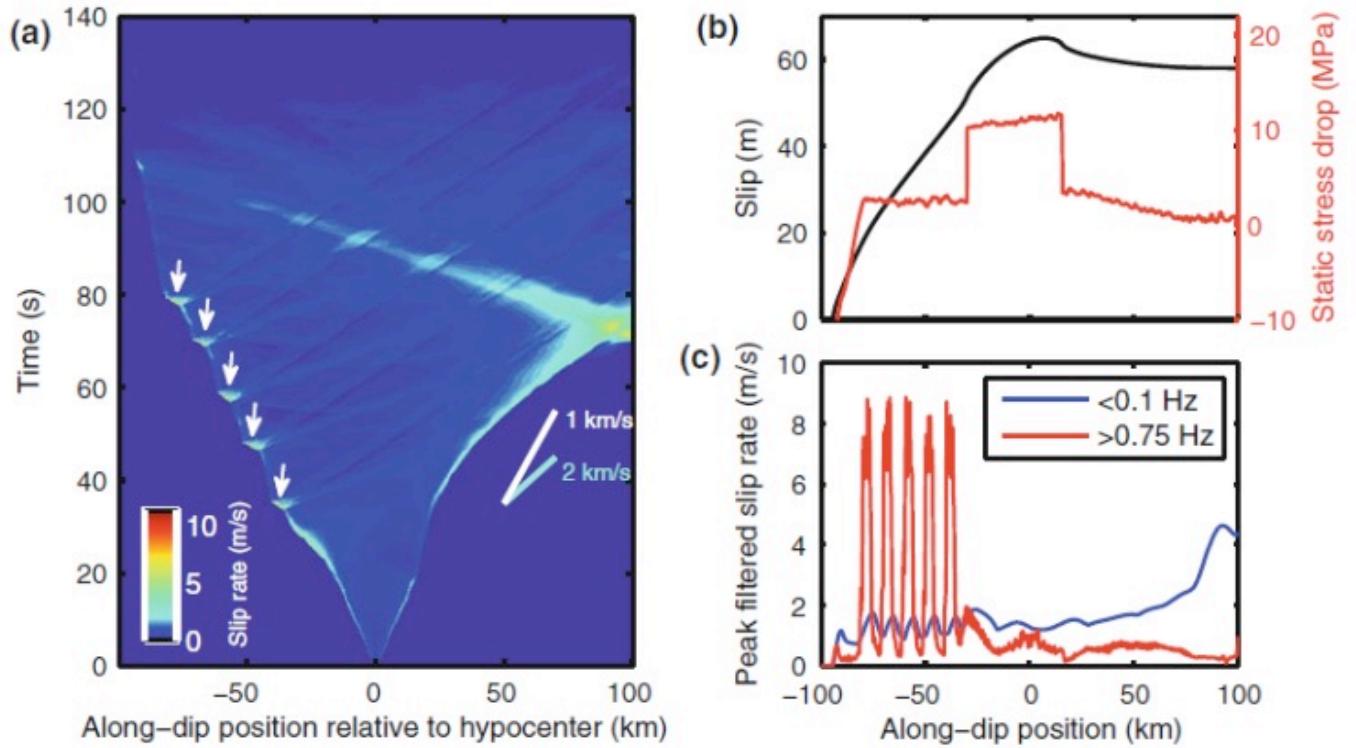


Tohoku: high-frequency radiation deeper than low-freq slip



Ito et al (2007)

|<- Bottom Trench ->| |<- Bottom Trench ->|



Huang, Ampuero, Kanamori (2013)

Friction

Fault resistance is classically described by friction

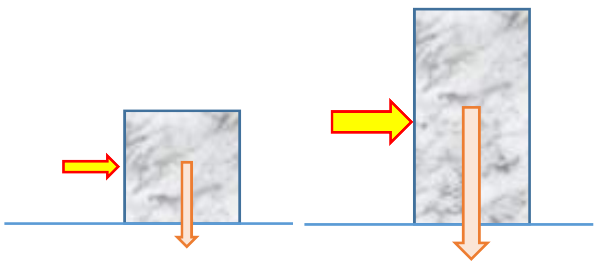
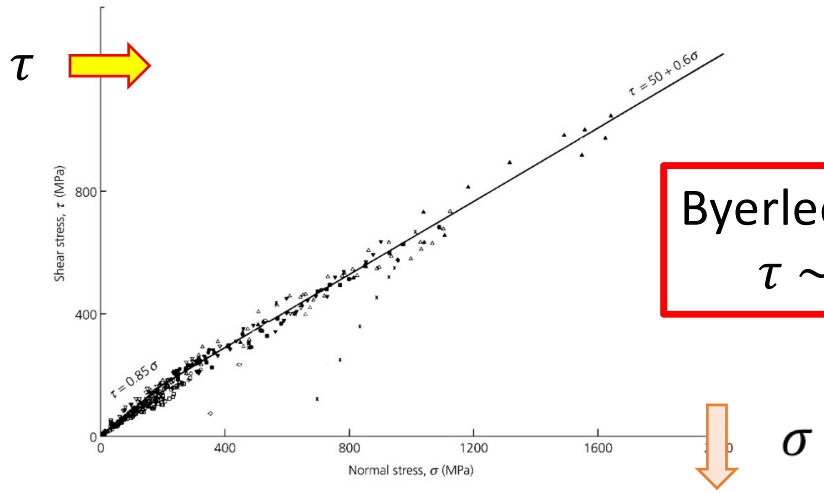


Figure 5.7-10: Relation between shear stress and normal stress for frictional sliding.



Byerlee's law

$$\tau \sim 0.6\sigma$$

More lateral force is needed to slide a taller, heavier object

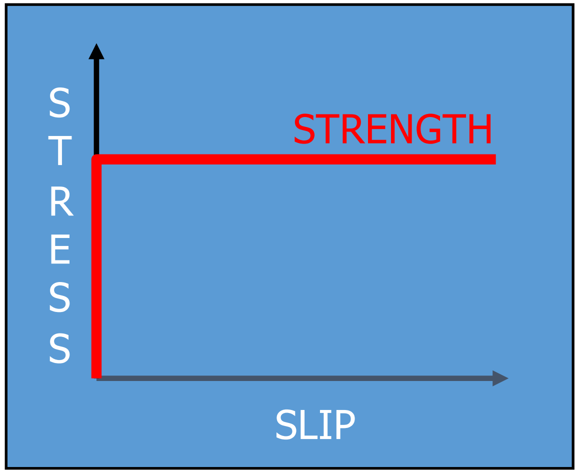
The resisting force is friction at the base of the object

Friction force ⇨ is proportional to the compressive force ⇩

$$\tau = \mu\sigma$$

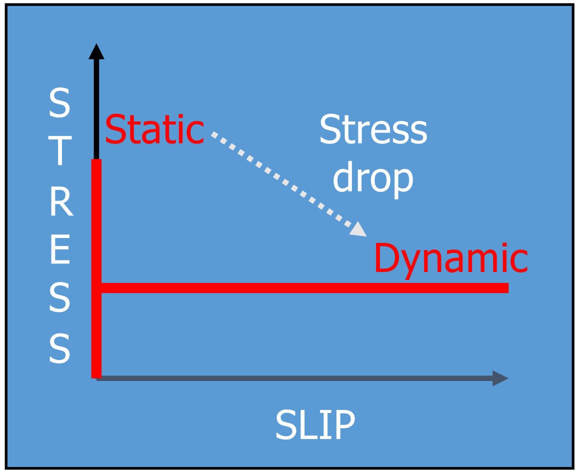
A brief history of fault friction

- Coulomb friction: strength



A brief history of fault friction

- Coulomb friction: strength
- Static/dynamic friction: stress drop



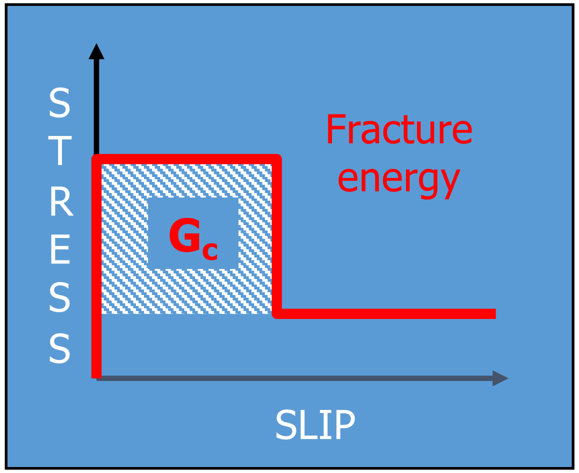
A brief history of fault friction

- Coulomb friction: strength
- Static/dynamic friction: stress drop
- Cohesion models: fracture energy G_c

↓

Nucleation size

$L_c \sim \mu G_c / \Delta\tau^2$

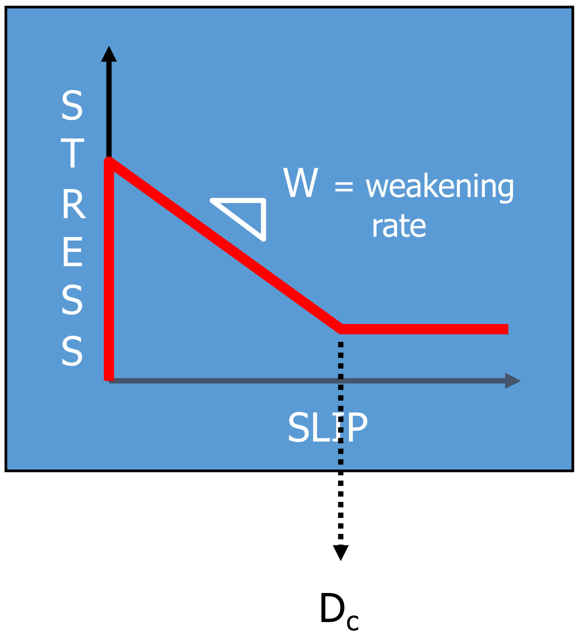


A brief history of fault friction

- Coulomb friction: strength
- Static/dynamic friction: stress drop
- Cohesion models: fracture energy Gc
- Slip weakening friction: critical slip Dc, weakening rate W

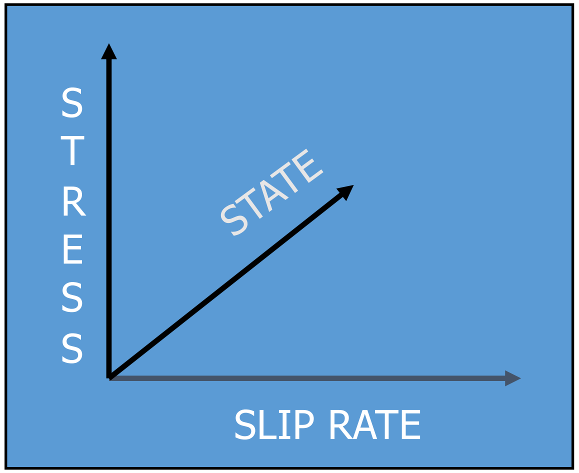
↓

Lc ~ μ / W



A brief history of fault friction

- Coulomb friction: strength
- Static/dynamic friction: stress drop
- Cohesion models: fracture energy Gc
- Slip weakening friction: critical slip Dc, weakening rate W
- Rate-and-state friction: healing, velocity weakening (a,b)

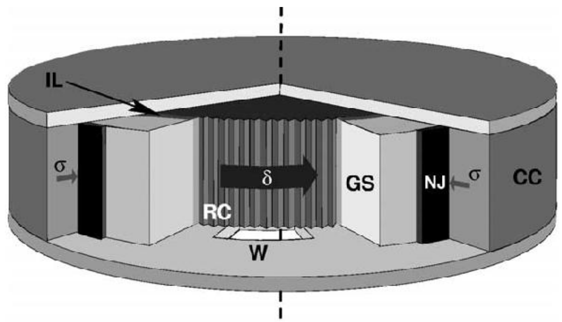


Laboratory-derived friction laws

Requirements :

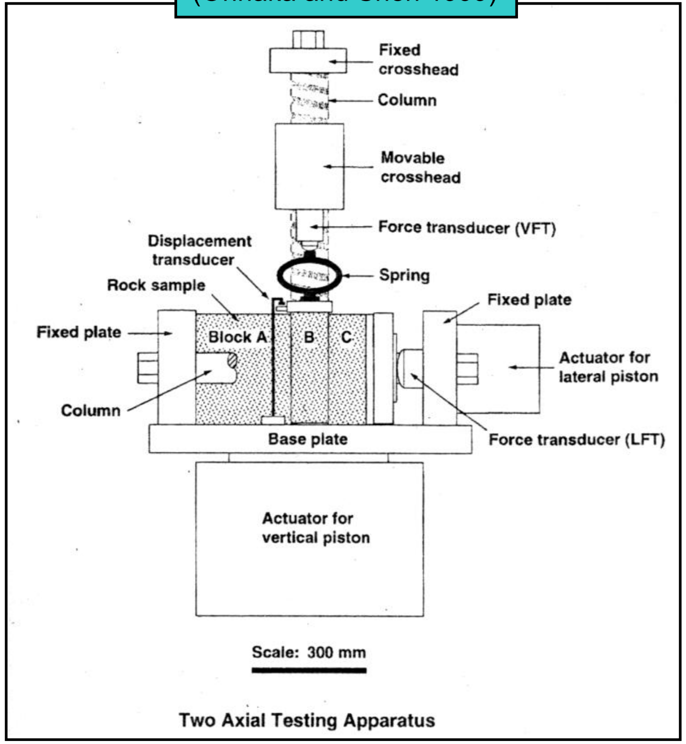
- High normal stress (100 MPa)
- High slip rate (1 m/s)
- Large displacements (>1 m)
- Large sample (>L_c) and high resolution
- Gouge + fluids

Only partially met by current experiments

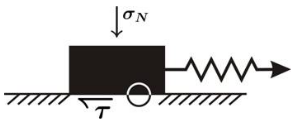


Rotary configuration (Chambon et al 2002)

Sandwich configuration (Ohnaka and Shen 1999)



Laboratory-derived friction laws



Low resolution experiments (≈ spring+block) record the average stress and slip

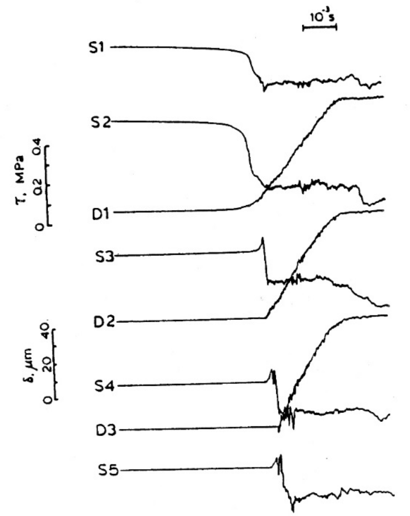
→ macroscopic friction

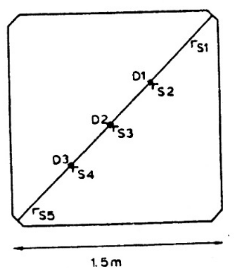
High resolution experiments are densely instrumented

→ local friction + rupture nucleation and propagation

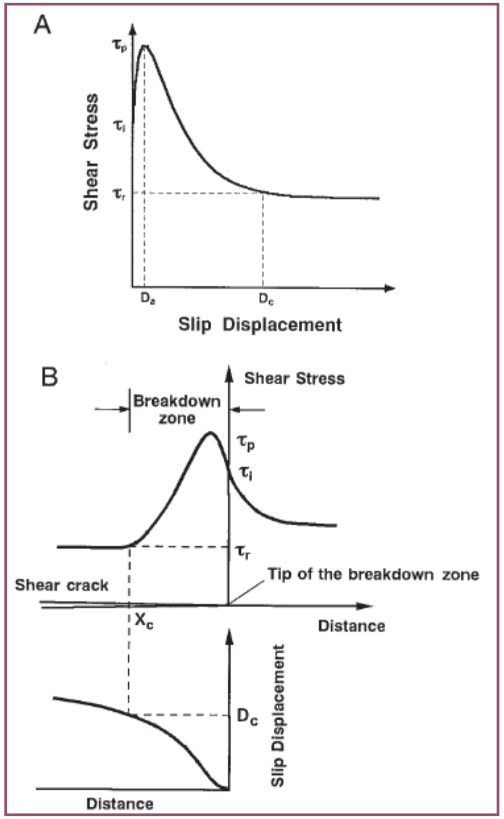
S = stress

D = slip

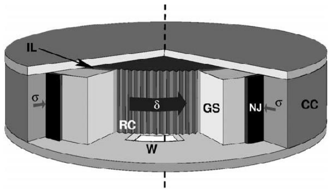


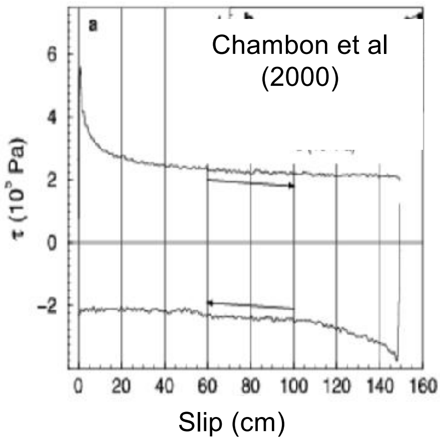


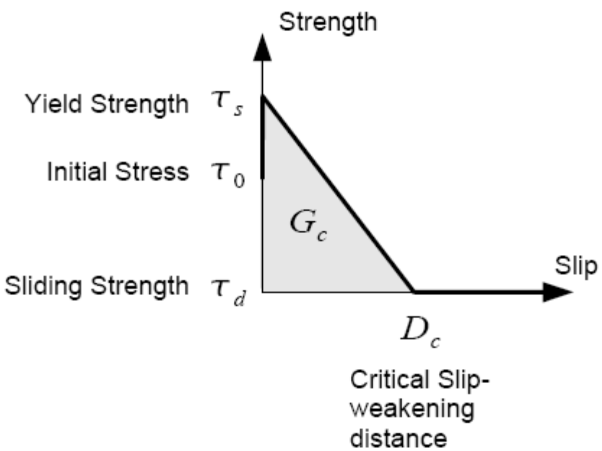
Large scale experiment
Dieterich (1980)



Slip weakening friction







Slip weakening occurs during fast dynamic rupture.

Linear slip weakening is a usual simplified model.

Important parameters:

- **D_c** = characteristic slip, associated to micro-contact evolution or grain rearrangement.

  Without gouge $D_c \approx 0.1$ mm.

  With gouge D_c >10 cm

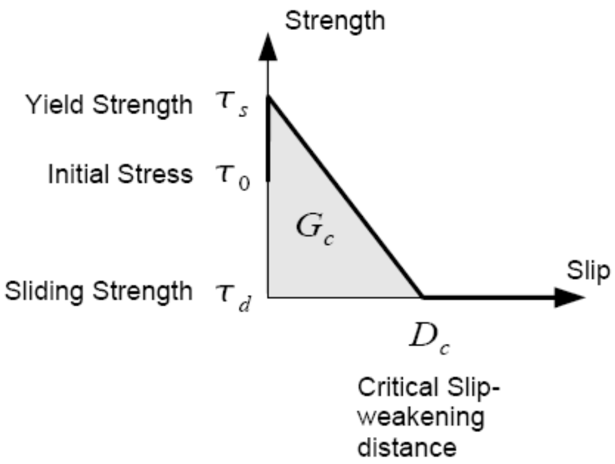
- Strength drop: $\tau_s - \tau_d$

  Usually a small fraction of normal stress ≈ 0.1 σ

- Fracture energy of a linear slip weakening model :

$$G_c = ½ (\tau_s - \tau_d) D_c$$

Slip-weakening friction model



Primary parameters: dynamic friction coefficient μ_d and fracture energy Gc

They control stress drop, rupture speed and rupture arrest

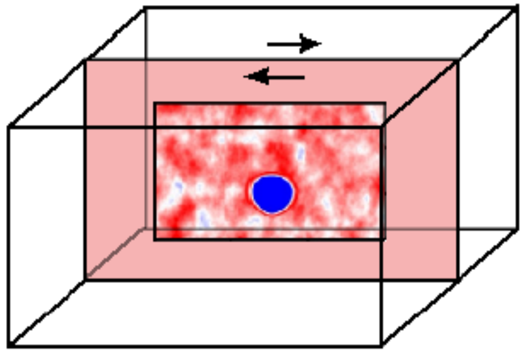
Secondary parameters: critical slip distance Dc and strength drop $\mu_s - \mu_d$

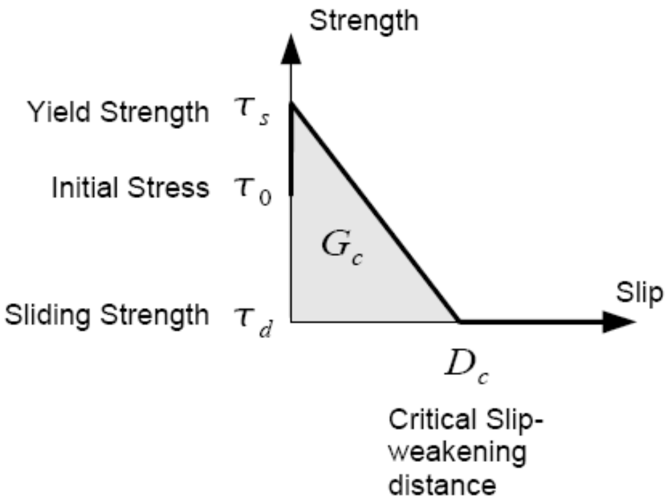
They control nucleation, supershear transition and peak slip velocity

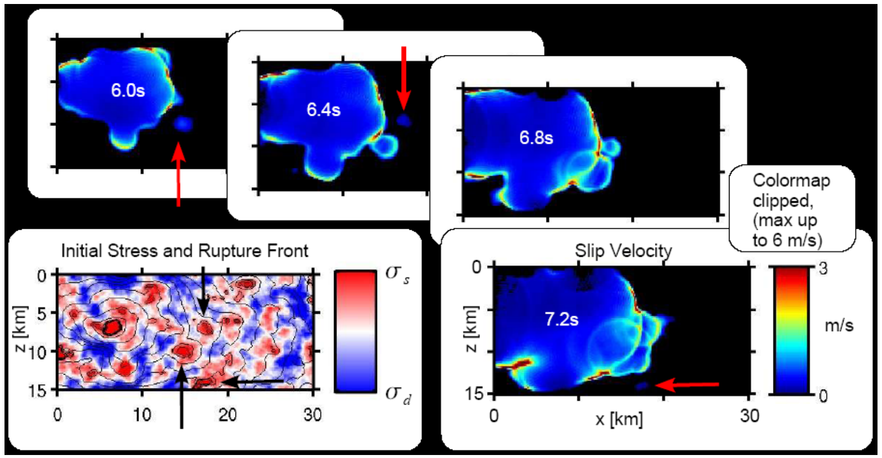
Dynamic Rupture Simulation

Setup:

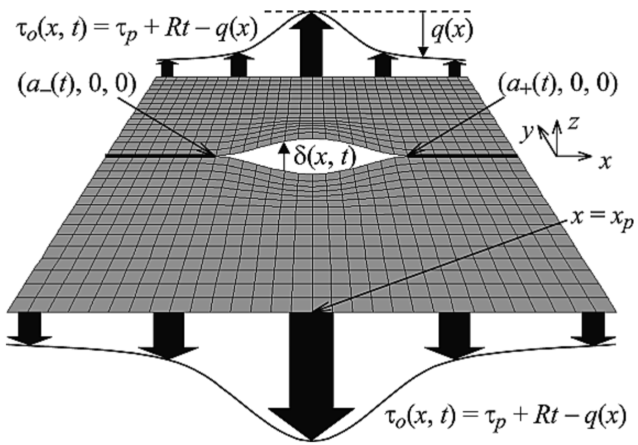
- Planar fault embedded in homogeneous elastic full space

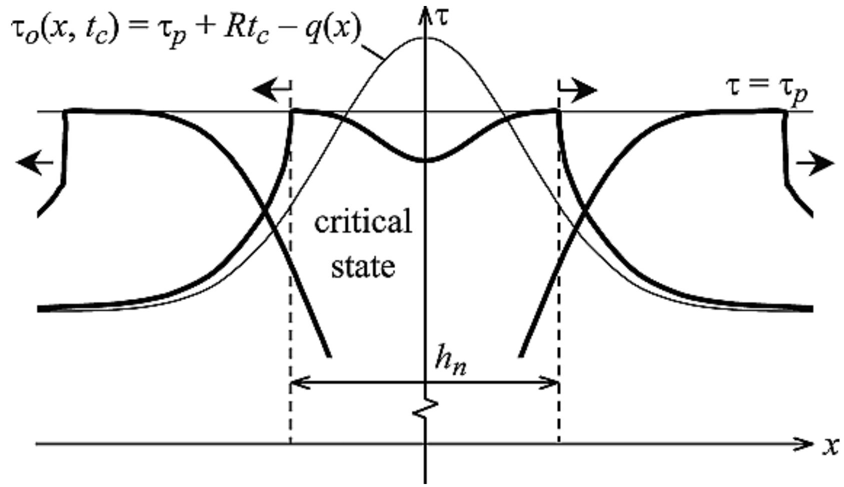






Nucleation size



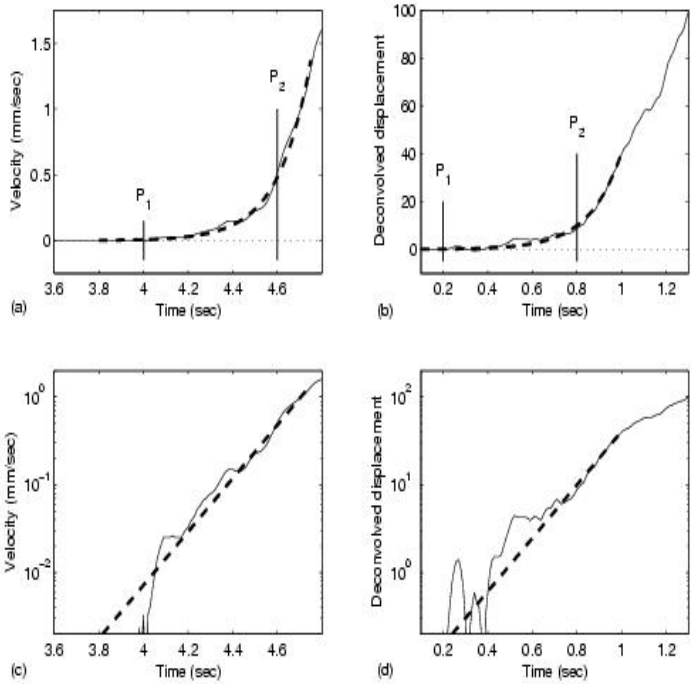


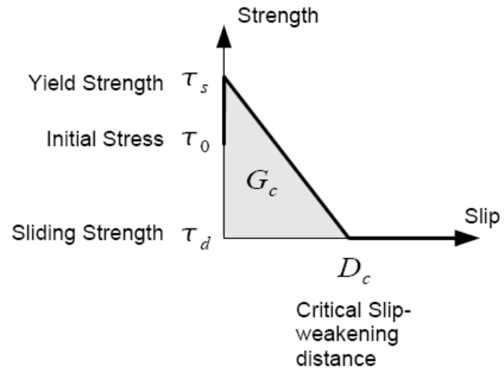
Nucleation size: $L_c = \dfrac{\mu D_c}{\tau_s - \tau_d}$

Uenishi and Rice (2003)

Exponential initiation

Kobe earthquake M7.2





Linear slip-weakening:

$$\Delta\tau = (\tau_s - \tau_d)D/D_c$$

If there is some viscosity in the fault behavior:

$$\Delta\tau = \eta\,\dot{D}$$

Equating both:

$$\dot{D} = sD$$

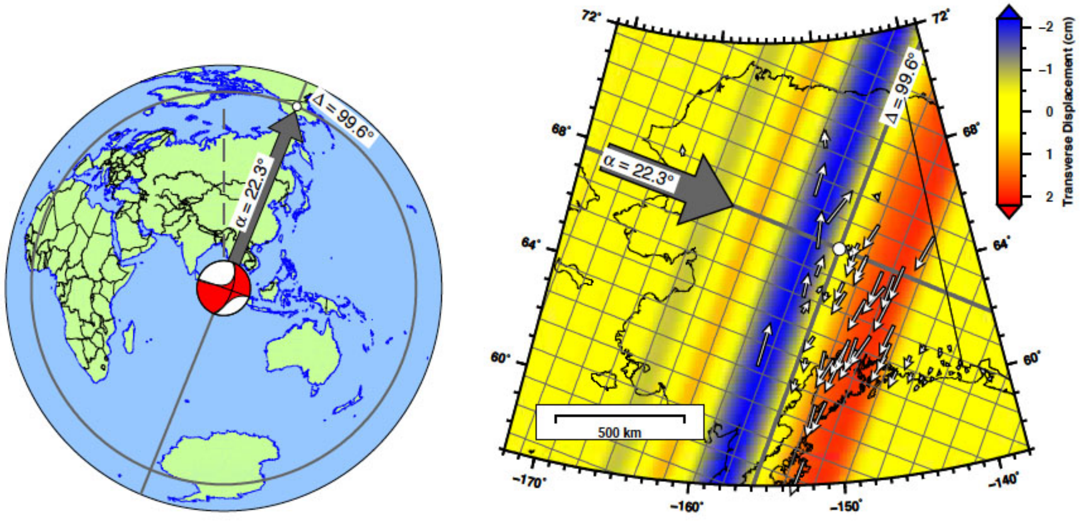
Hence

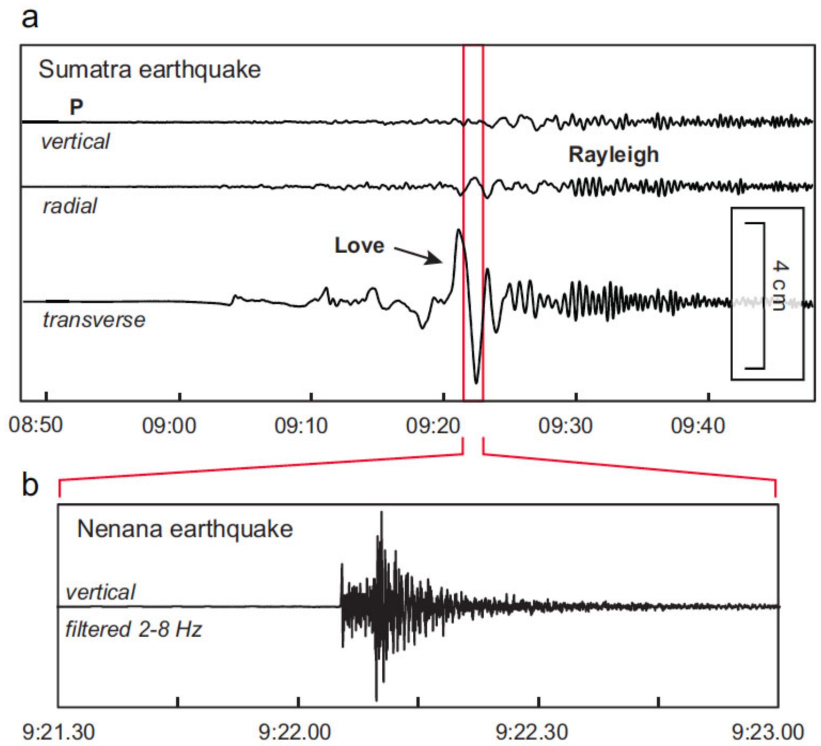
$$D(t) \sim \exp(st)$$

where $s = (\tau_s - \tau_d)/\eta D_c$

One form of viscosity is radiation damping, $\eta = \mu/2c_s$

Seismological observations

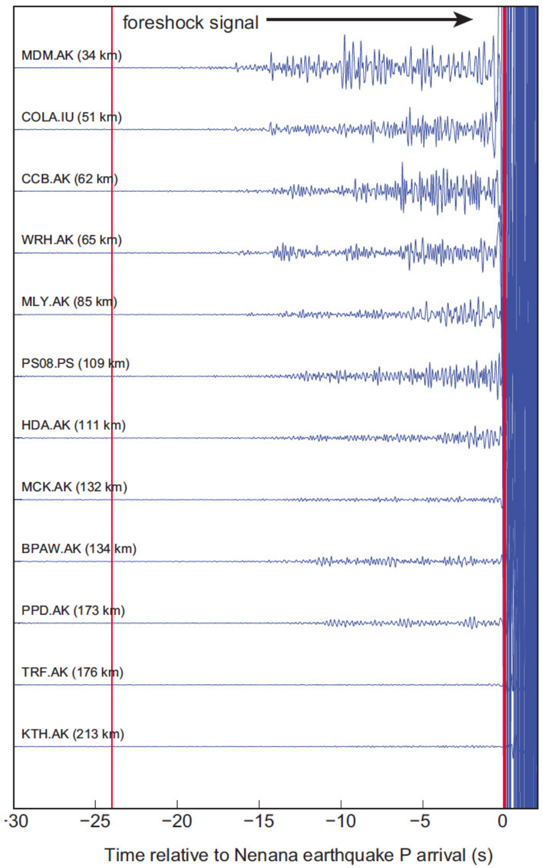


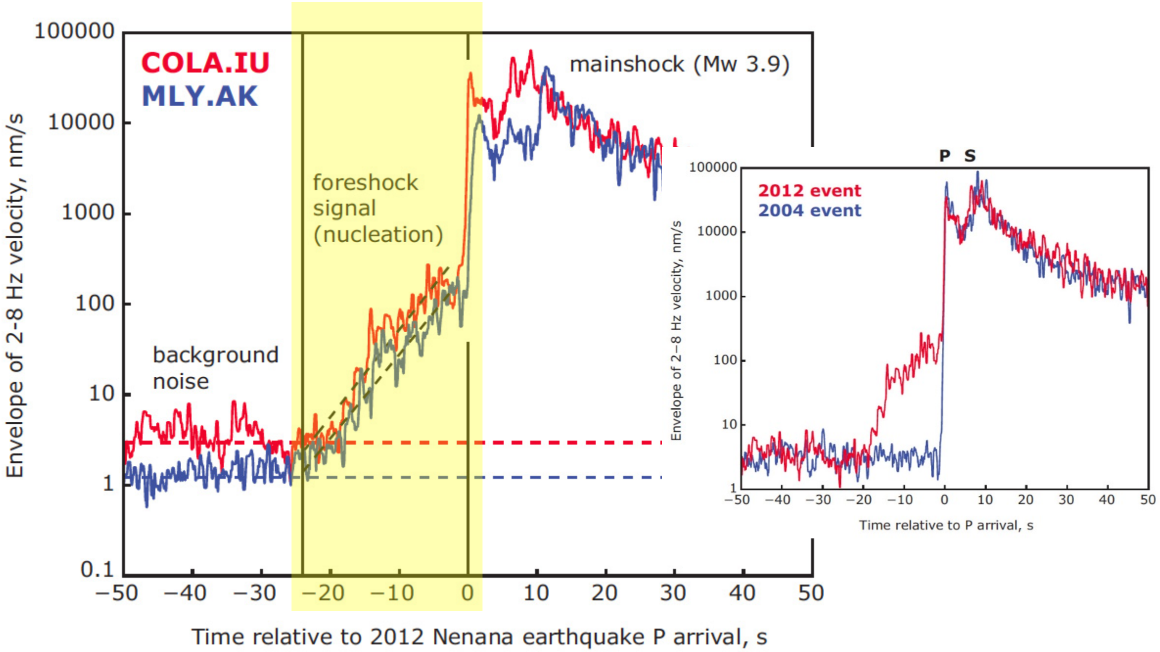


A Mw3.9 earthquake in Alaska triggered by Love waves from the April 11, 2012 Mw 8.6 Sumatra earthquake

Tape et al (2013)

Seismological observations

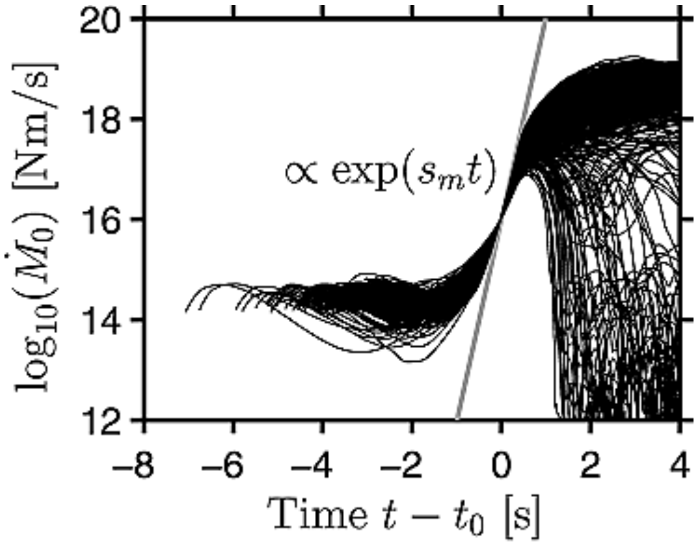




Nucleation phase of the Mw3.9 Alaska triggered earthquake
Tape et al (2013)

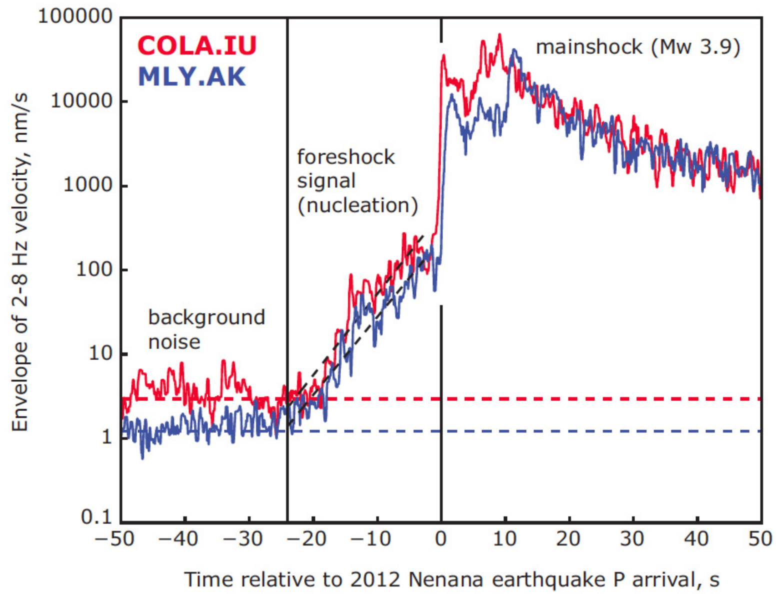
Exponential initiation

$$s_m = 2c_s(\tau_s - \tau_d)/\mu D_c$$



Simulations
Ripperger et al (2007)

$$s = (\tau_s - \tau_d)/\eta D_c$$

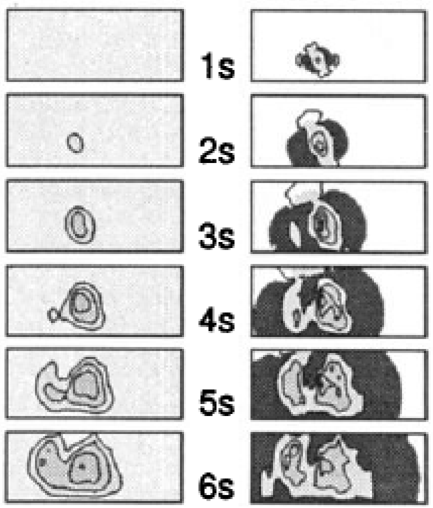


Observations
Tape et al (2013)

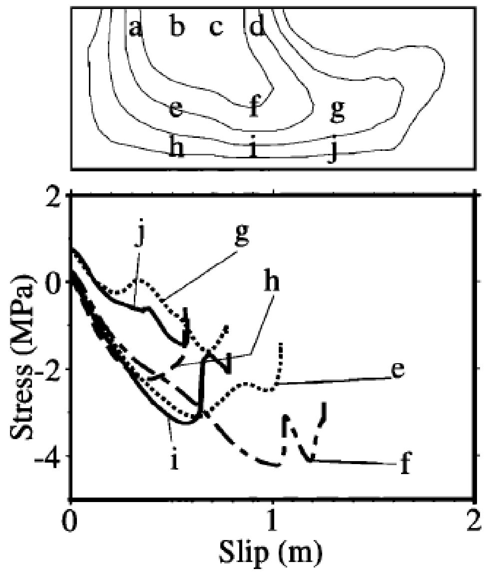
Seismological constraints

Finite source inversion
→slip

+ FDM
→stress

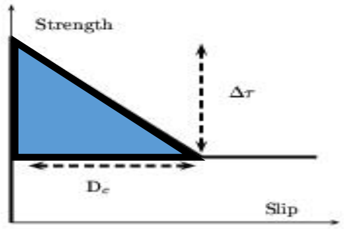


Ide and Takeo (1997)

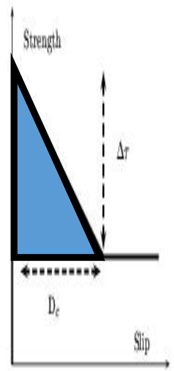


Guatteri and Spudich (2000)
Dynamic friction parameters suffer from strong **trade-off**

A



B



Same G_c → same strong motion <1Hz

Faults operating at low stress

How large is stre**ss** drop $\Delta\tau$ compared to stren**gth** drop $\tau_s - \tau_d$?

From seismological observations: $\Delta\tau = 1 - 10$ Mpa

From friction and lithostatic overburden:

$$\tau_s - \tau_d = \sigma(\mu_s - \mu_d) \sim 100\ MPa$$

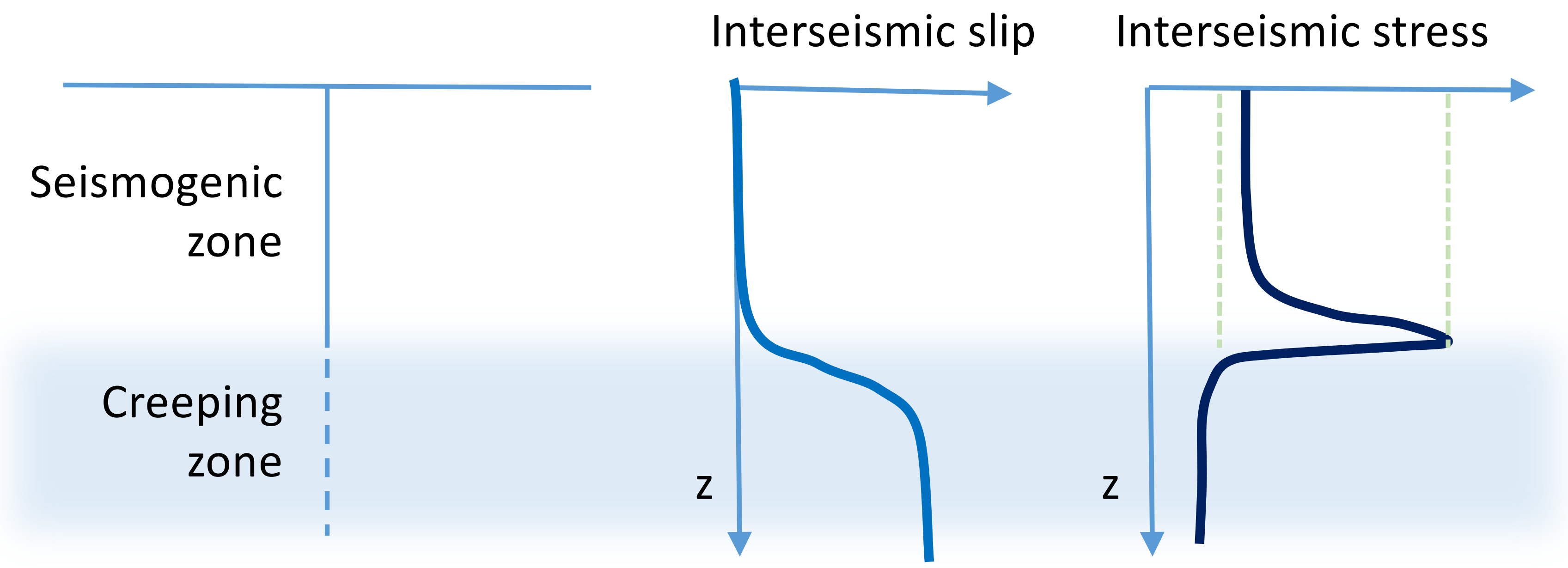
→ $\Delta\tau \ll \tau_s - \tau_d$

Why so small?

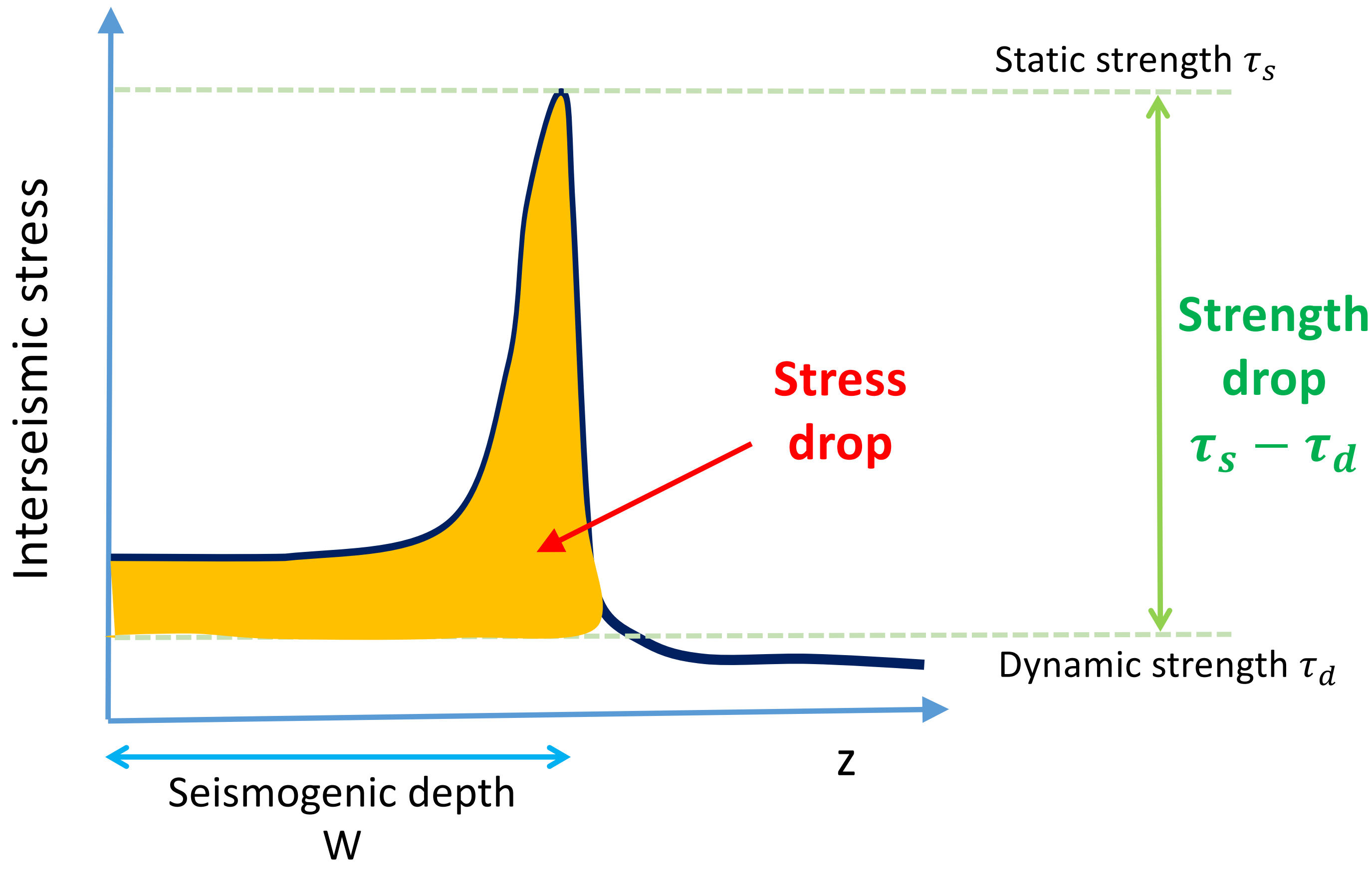
Faults operating at low stress

Fault loaded by deep creep

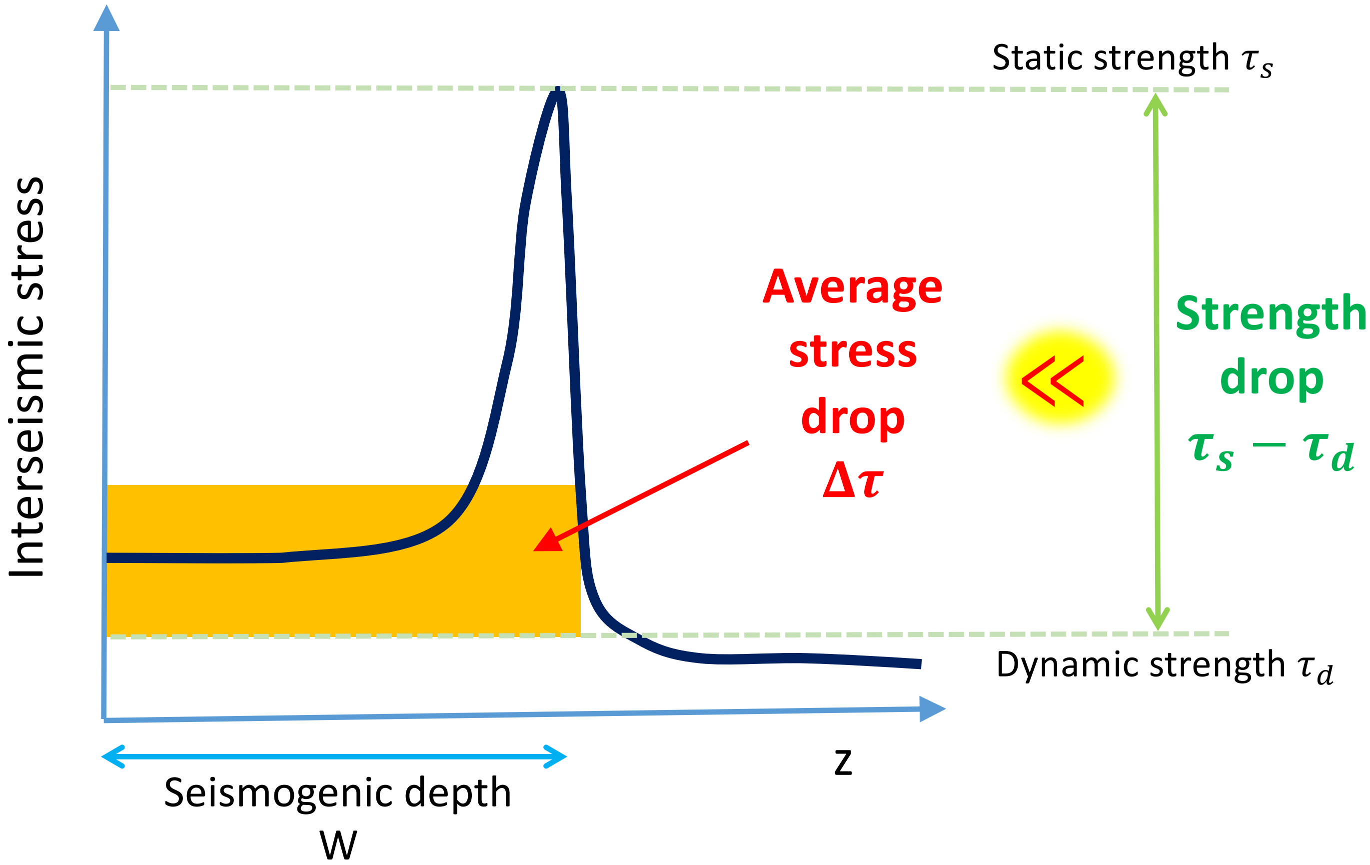
→ stress concentration at the base of the seismogenic zone



Faults operating at low stress



Faults operating at low stress



Faults operating at low stress

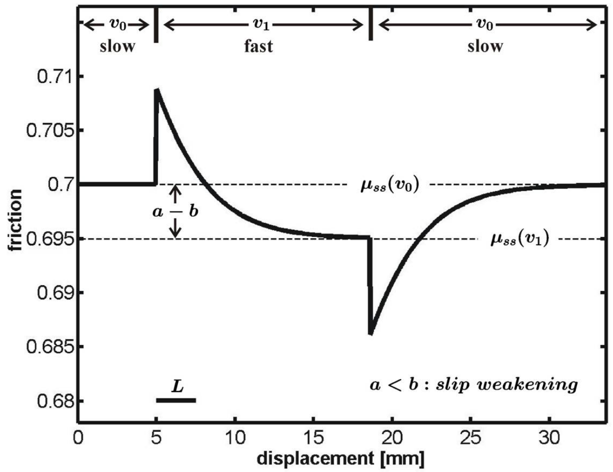
Fracture energy balance: $G_c = \frac{K^2}{2\mu} \sim \frac{\Delta\tau^2 W}{2\mu}$

$$\rightarrow \Delta\tau \sim \sqrt{2\mu G_c / W}$$

Uenishi and Rice's nucleation size: $L_c = \frac{\mu D_c}{\tau_s - \tau_d}$

$$\rightarrow \frac{\Delta\tau}{\tau_s - \tau_d} \sim \sqrt{\frac{L_c}{W}} \ll 1$$

Rate-and-state friction



$$\mu = \mu^* + a \ln\left(\frac{V}{V^*}\right) + b \ln\left(\frac{V^*\theta}{L}\right)$$

$$\dot{\theta} = 1 - \frac{V\theta}{L}$$

V = slip velocity, θ = state variable

Second order effects: logarithmic healing (micro-contact creep) and velocity-weakening

→ Phenomenological rate-and-state friction law introduced by Dieterich and Ruina in the early 1980s

Essential ingredients:

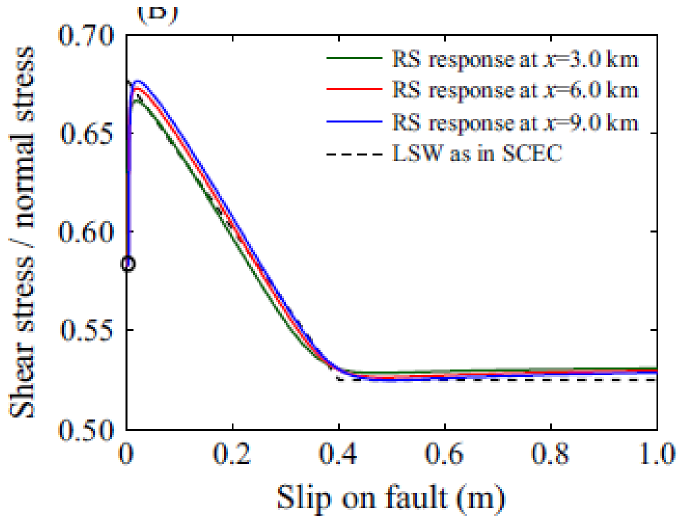
- non-linear viscosity
- evolution effect

Most important during slow slip (nucleation and post-seismic)

During fast dynamic rupture, an equivalent D_c can be estimated:

$D_c \approx 20\ L$

Rate-and-state friction at high speed?



Kaneko et al (2008)

Most important during slow slip (nucleation and post-seismic)

Rate-and-state behaves as slip-weakening during fast dynamic rupture

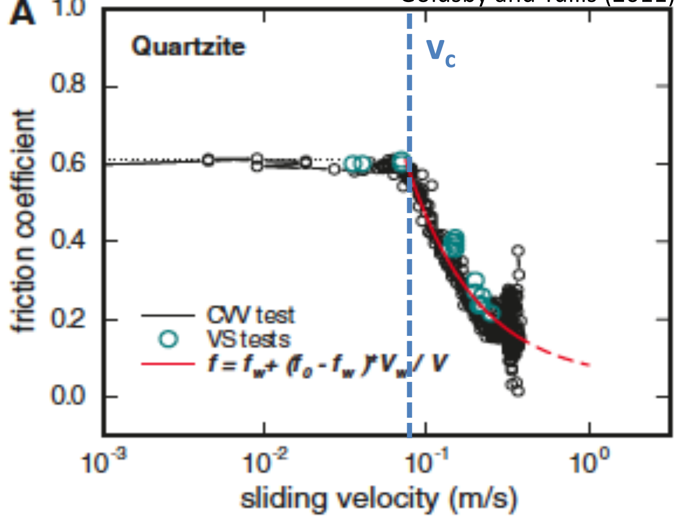
Equivalent :

$$D_c = L \ln\left(\frac{V}{V^*}\right) \approx 20\ L$$

$$G_c \approx \frac{1}{2} b\sigma L \ln\left(\frac{V}{V^*}\right)^2$$

Dramatic velocity-weakening at high speed

Di Toro et al

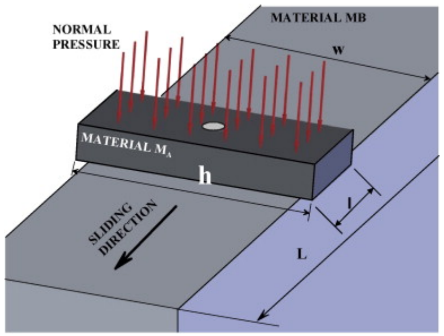


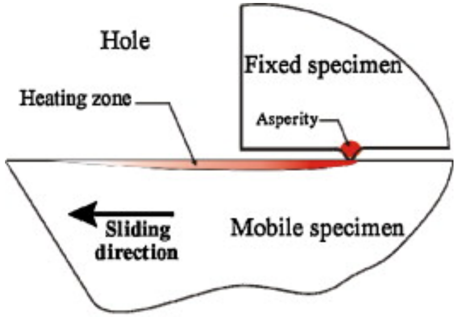
Goldsby and Tullis (2011)

When sliding at high velocity:

$$\mu \sim 1/V$$

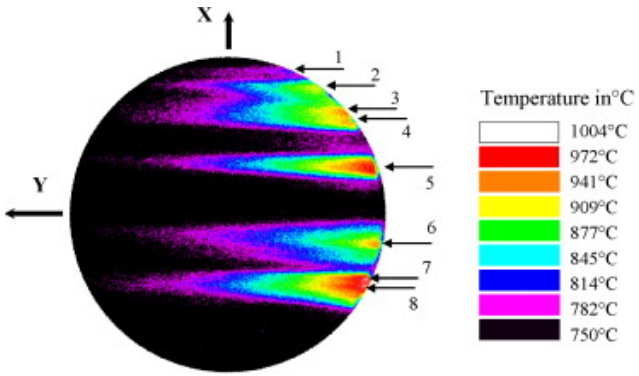
Dramatic velocity-weakening at high speed





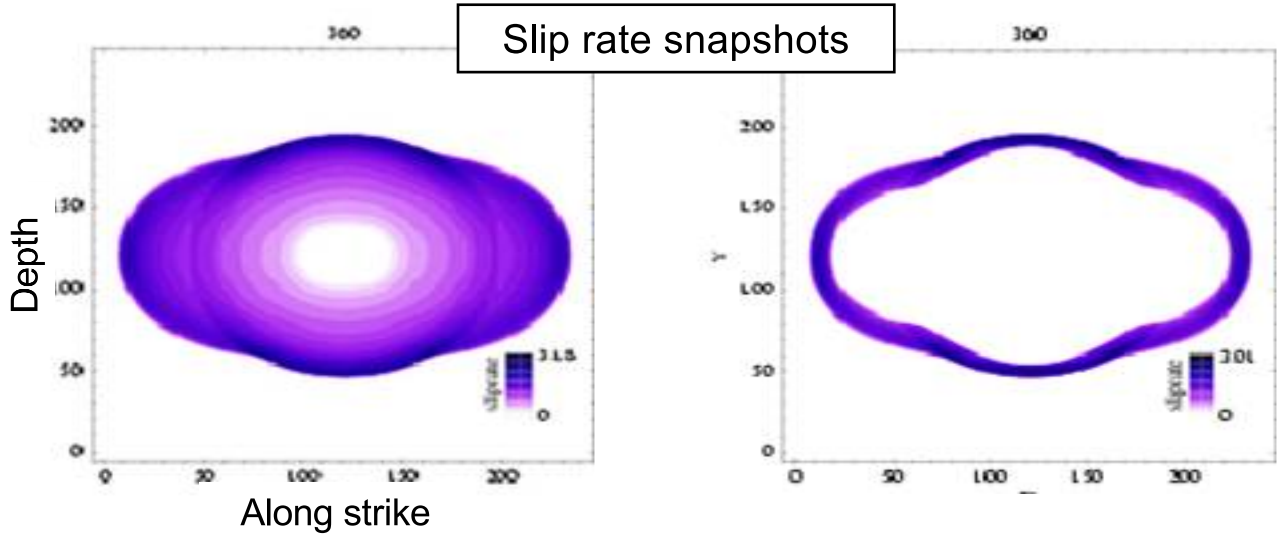
At high velocity: $\mu \sim 1/V$

Thermal weakening effects
Predicted by flash heating (Rice, 2005)



Sutter and Ranc (2010)

Rupture styles: cracks and pulses



Crack : slip continues behind the rupture front, long rise time

Pulse : slip heals soon behind the rupture front, short rise time

In a previous lecture we focused on **cracks**.

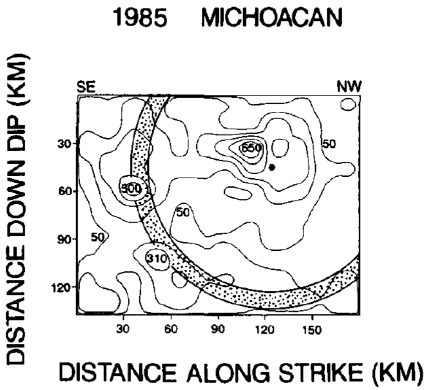
Pulses: observations

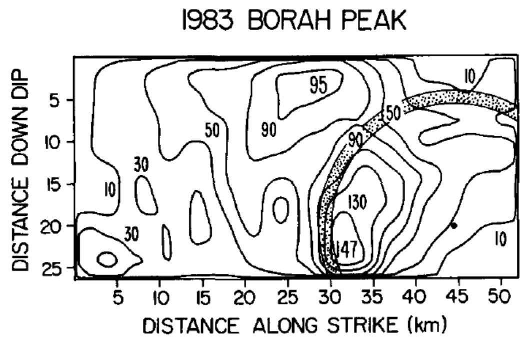
Source models from kinematic inversions.

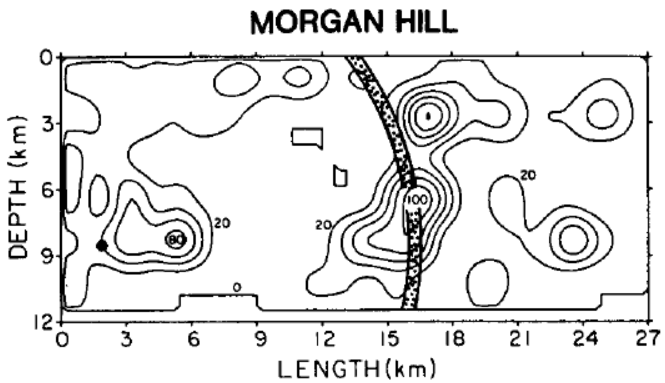
Contours = slip

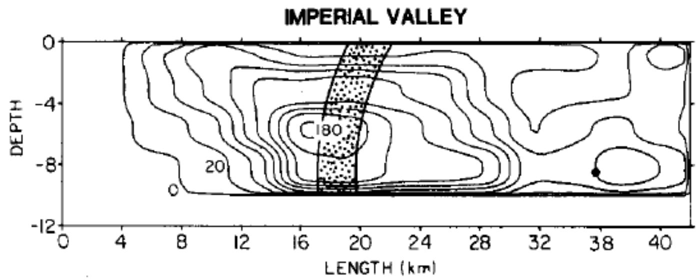
Shaded = snapshot of active slip

Heaton (1990) observed that **rise times are usually short** ≈10% of total earthquake duration

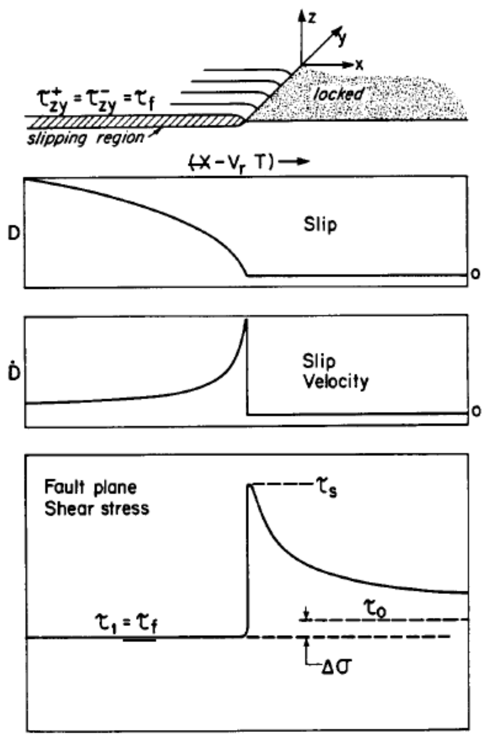


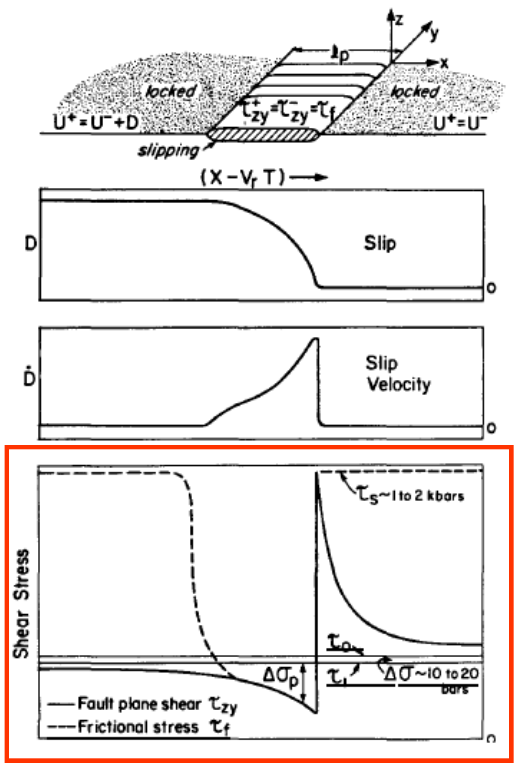






Cracks and pulses

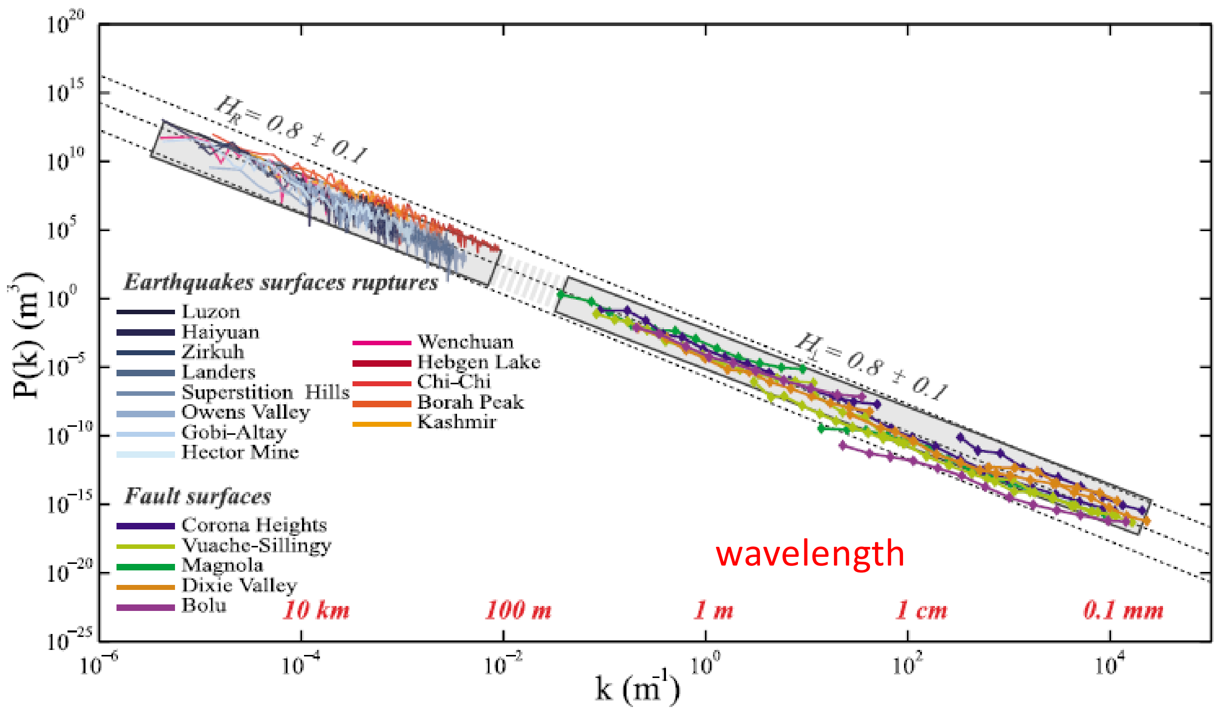


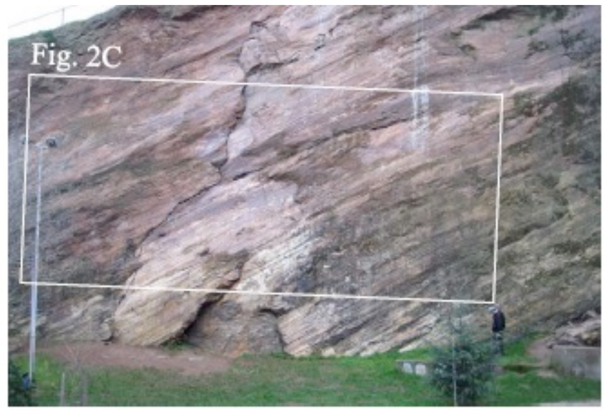


Self-healing pulses require fast strength recovery

→ velocity dependent friction

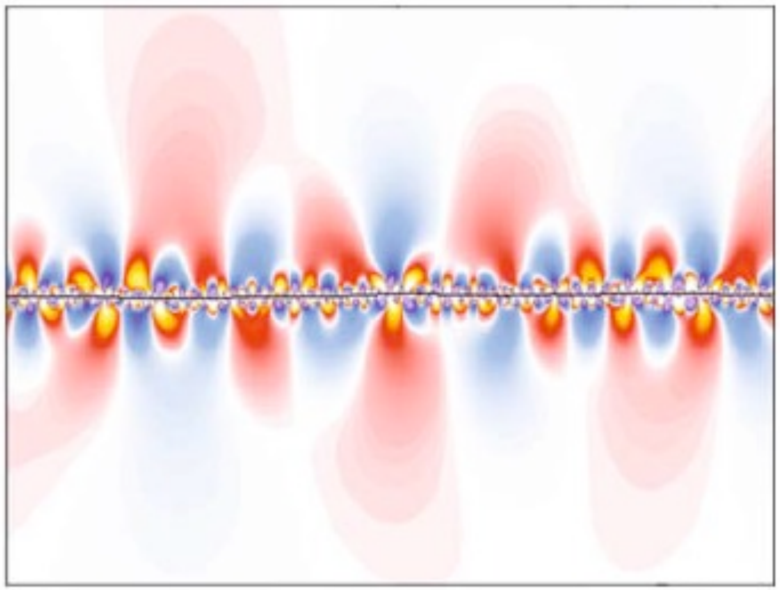
Non-planar, rough faults





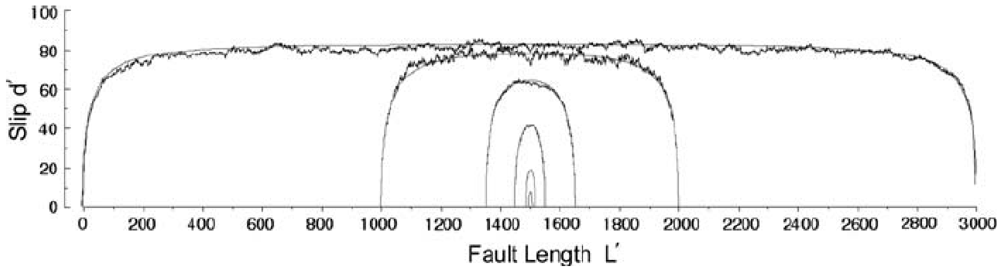
Candela et al (2012)

Slip and stress on rough faults



Residual off-fault stresses

Dieterich and Smith (2009)



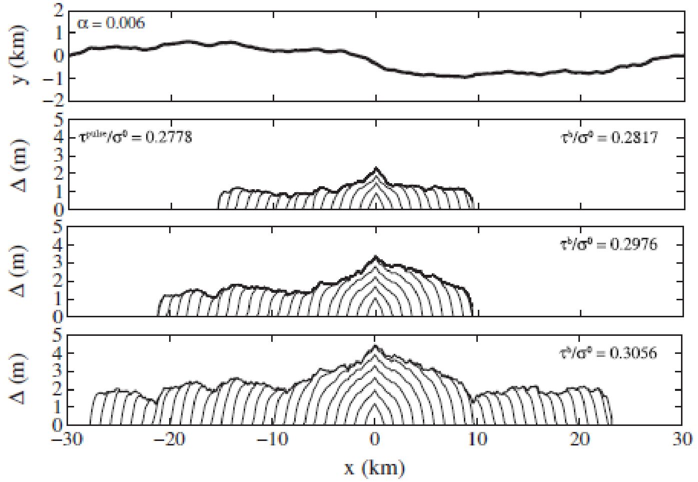
Flattening of slip profiles

Roughness drag

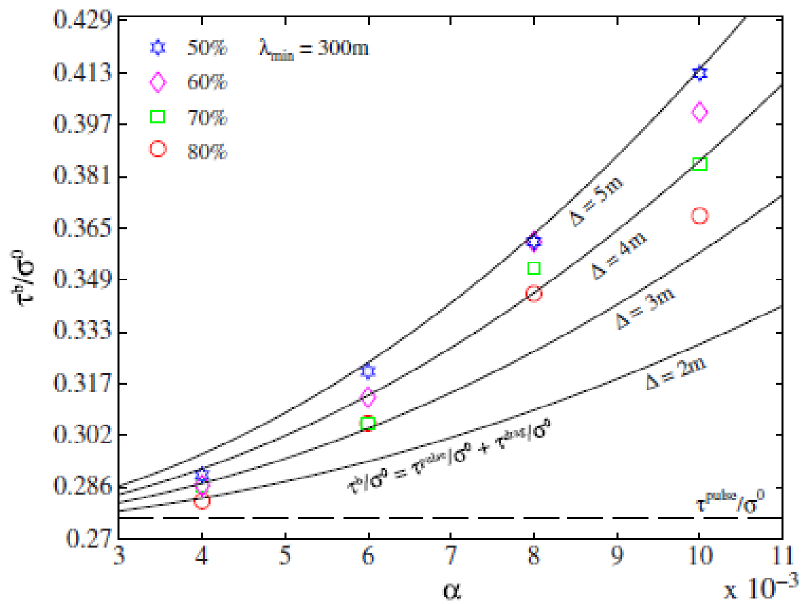
Fang and Dunham (2013): $$\tau^{\text{drag}} = 8\pi^3\alpha^2 \frac{G}{1-\nu}\frac{\Delta}{\lambda_{\min}}.$$

where Δ=slip, α =rms-amplitude-to-wavelength ratio (0.1~1 %), λ_{min} =small cutoff length

Ignoring friction, fault opening and off-fault inelasticity.



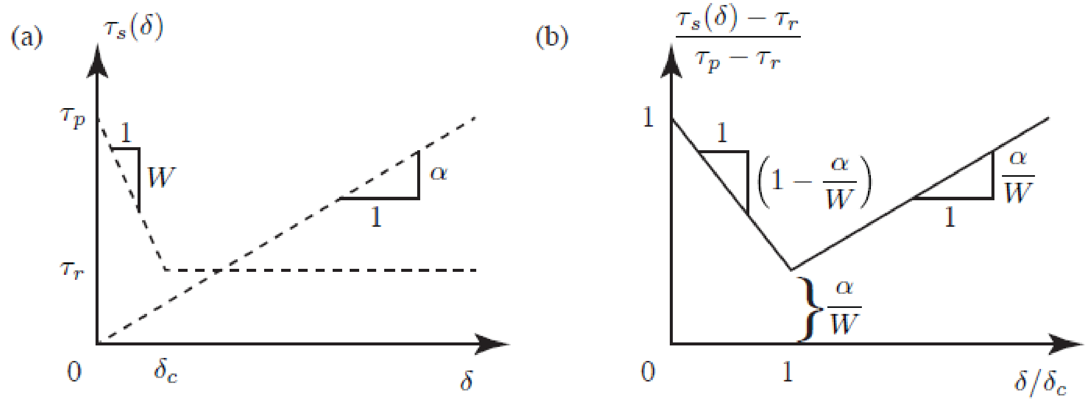
Rougher faults need higher stresses to sustain earthquakes



Mesoscopic model

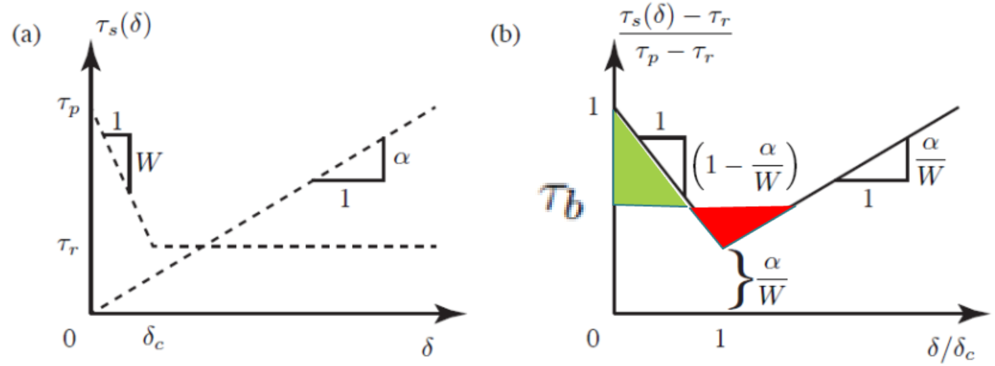
Meso-scale representation (~homogenization) of roughness effects:
Fault strength = friction (slip-weakening) + roughness drag (slip-strengthening)

Key parameters:
W=slip-weakening rate
α=slip-strengthening rate

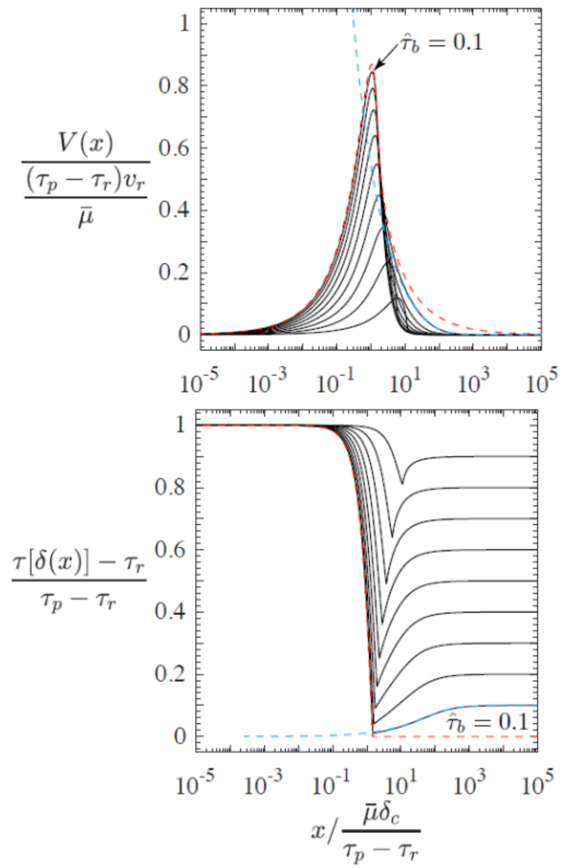


Scope: determine overall rupture features (rupture stability, speed, slip scaling) without resolving details of high-frequency radiation

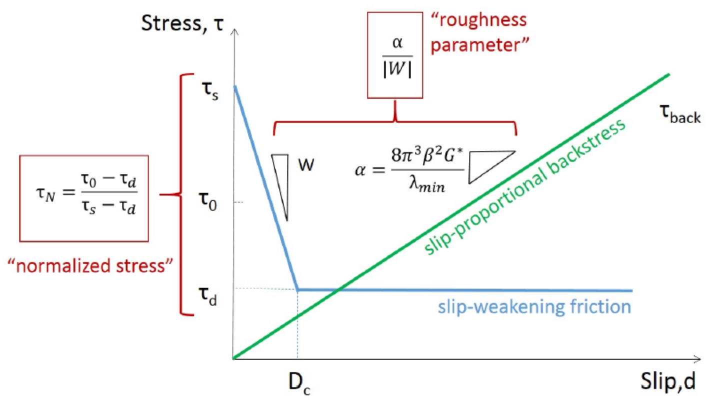
Slip-strengthening

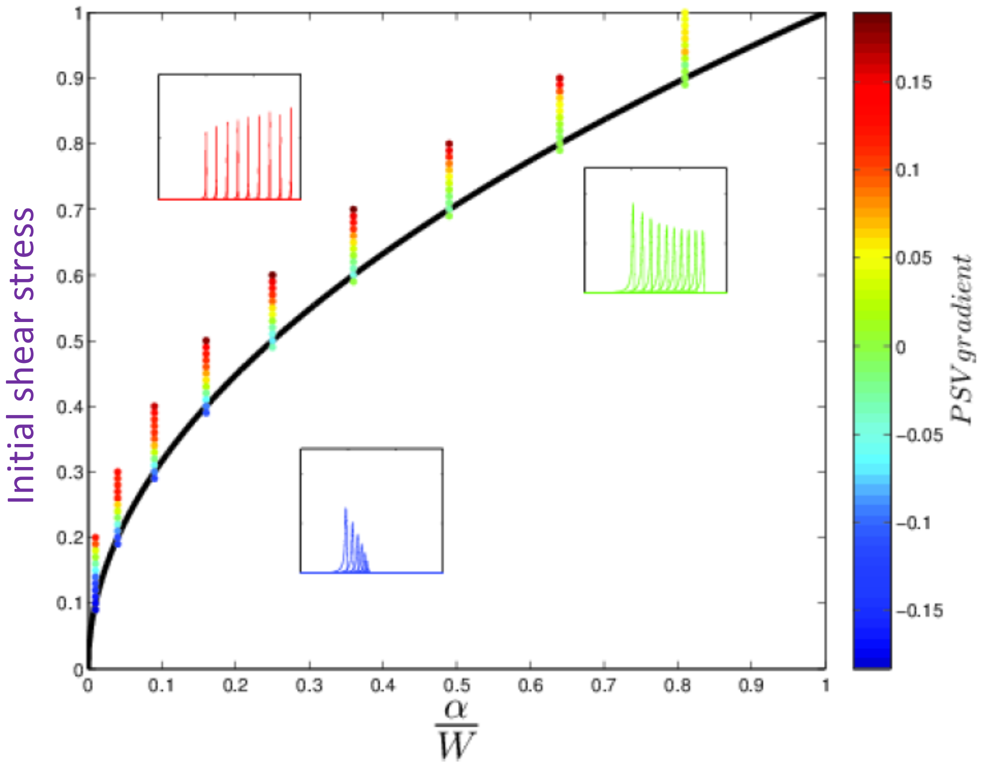


$$\frac{\delta_c}{\delta_L} = \frac{\tau_b - \tau_r}{\tau_p - \tau_r} = \sqrt{\frac{\alpha}{W}}$$



Numerical results (with Franklin Koch)





Steady pulses = boundary between decaying and sustained ruptures:

$$\frac{\tau_b - \tau_r}{\tau_p - \tau_r} = \sqrt{\frac{\alpha}{W}}$$

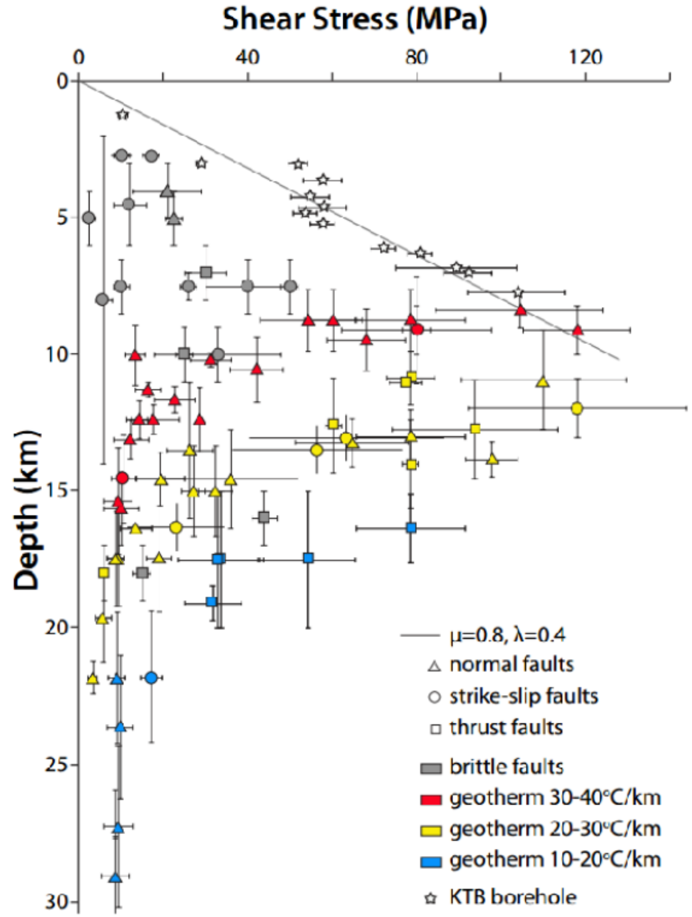
Implications for stress in the crust

$$\frac{\tau_b - \tau_r}{\tau_p - \tau_r} = \sqrt{\frac{\alpha}{W}}$$

Background stress = sqrt(roughness/weakening)

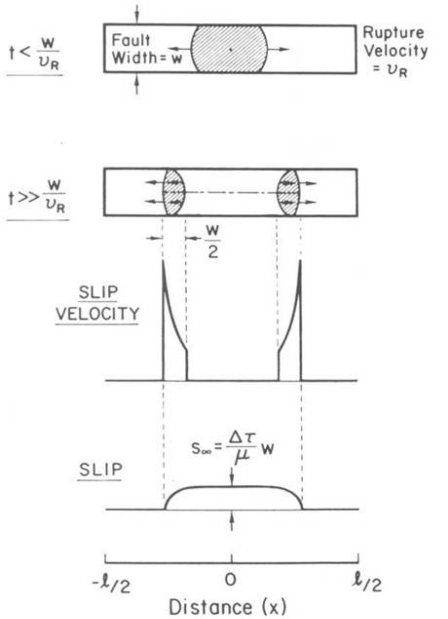
Rougher faults can operate seismically at higher stresses

→ Relation between fault maturity, geometry and strength



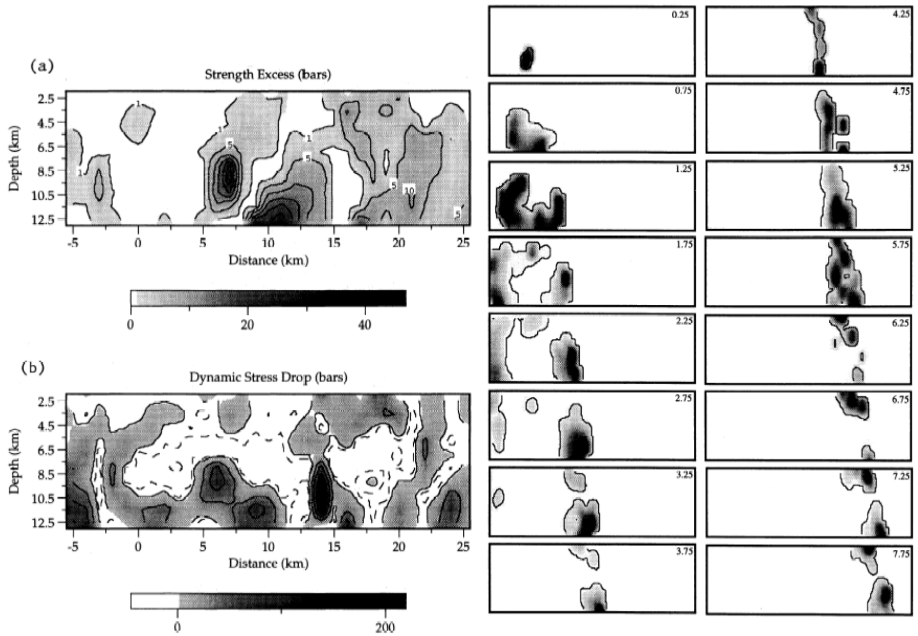
Behr and Platt, 2014

Pulses: other possible origins



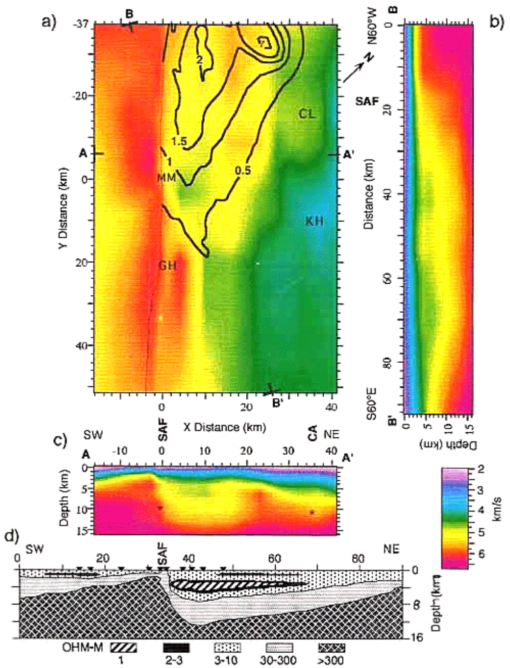
Pulses controlled by the depth of the seismogenic region (Day 1982)

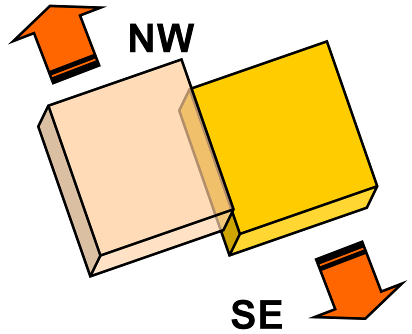
Pulses on very heterogeneous faults (Beroza and Mikumo 1996)

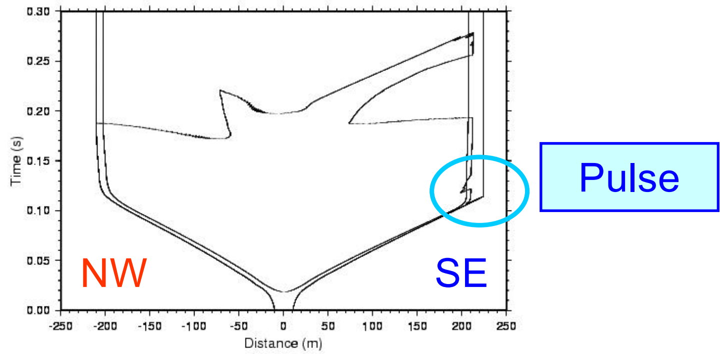


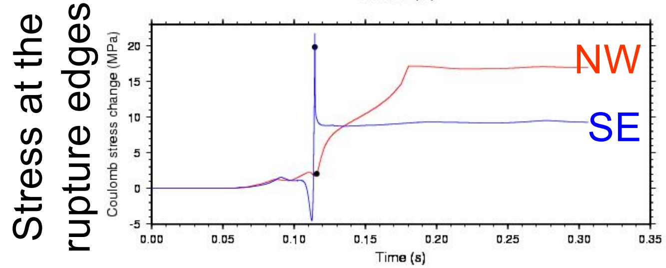
Pulses: possible origins

Rupture on a bimaterial interface (between two different materials) like in the San Andreas Fault



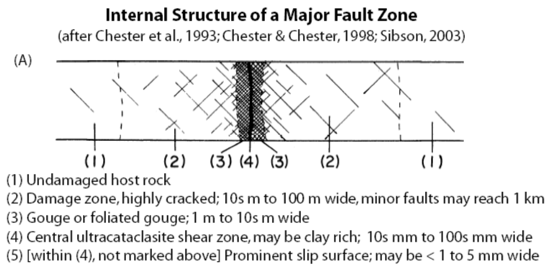




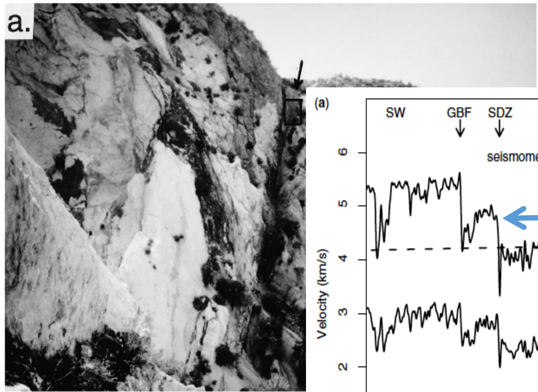


Origins of pulses: fault zone waves

[Chester and Chester, 1998]

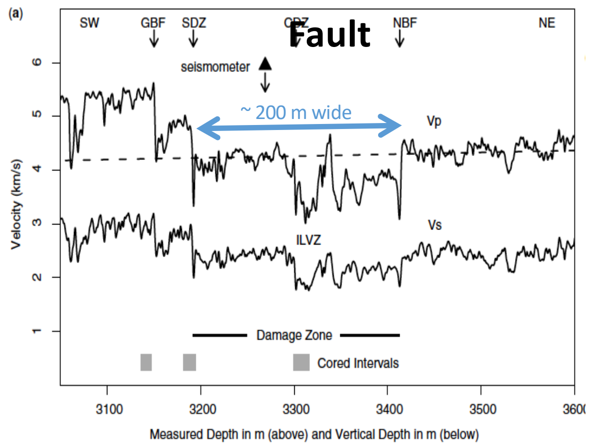


Origins of pulses: fault zone waves



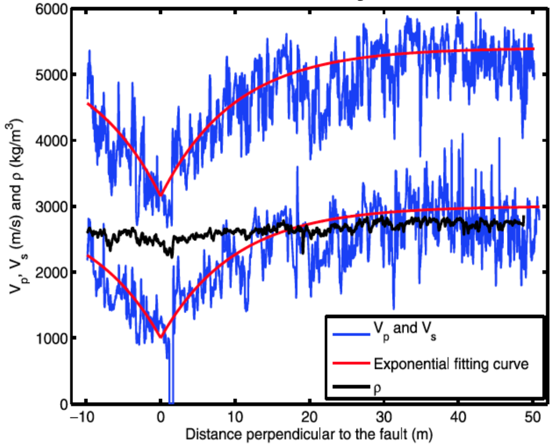
[Chester and Chester (1998)]

San Andreas Fault



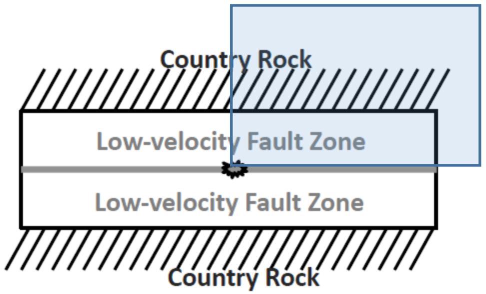
[Ellsworth and Malin, 2012]

Nojima Fault

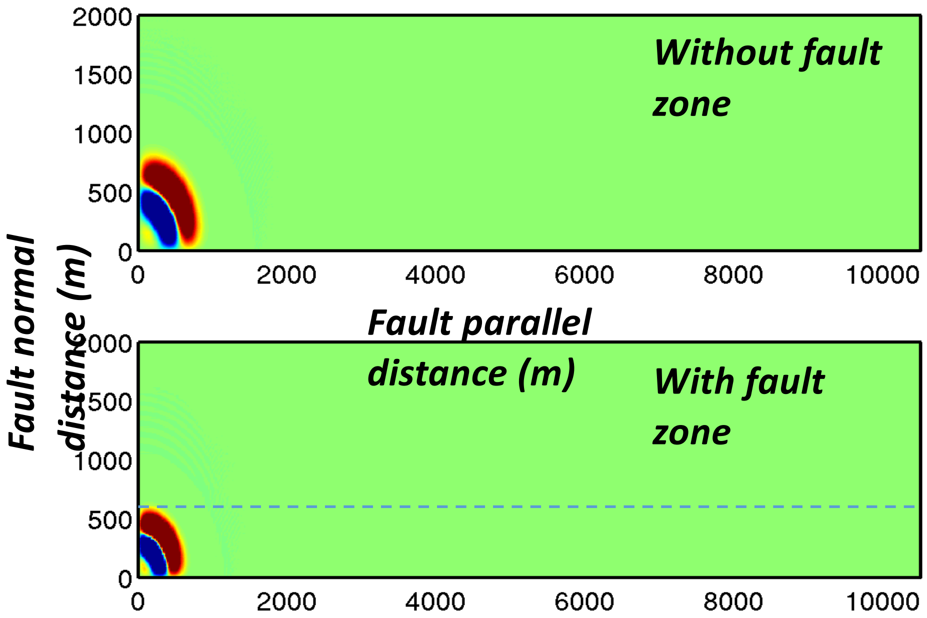


[Huang and Ampuero, 2011]

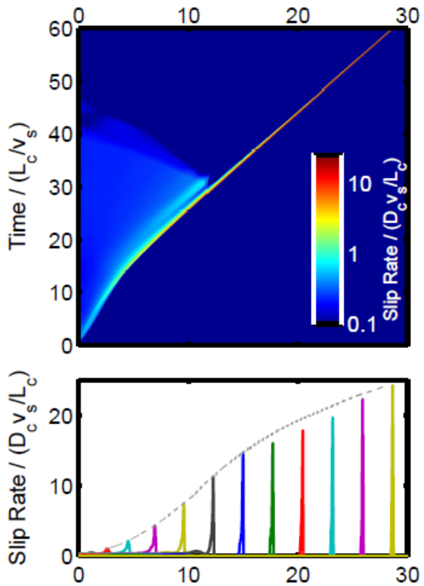
Origins of pulses: fault zone waves

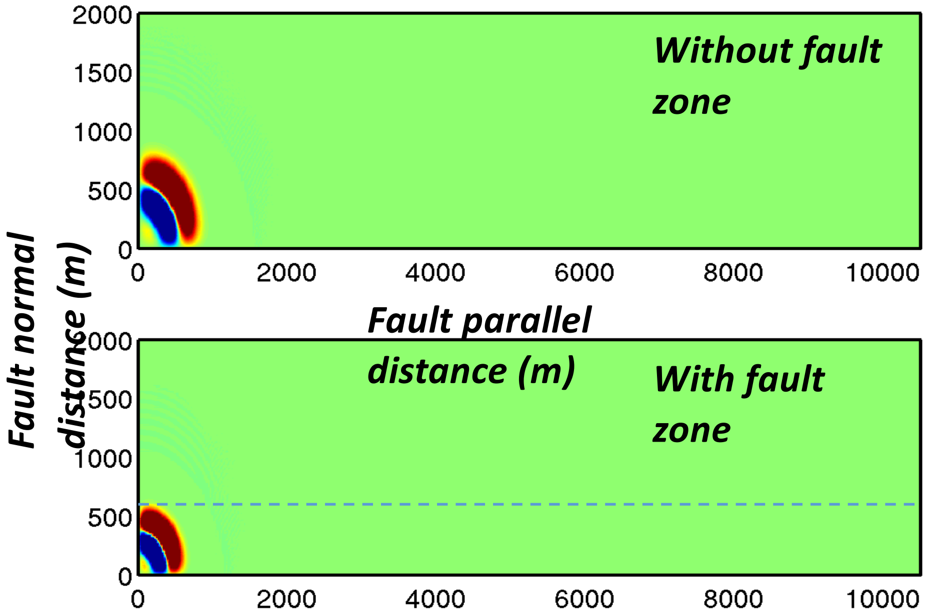


Huang and Ampuero (2011)
Huang, Ampuero and Helmberger (2014)



Origins of pulses: fault zone waves





Huang and Ampuero (2011)
Huang, Ampuero and Helmberger (2014)

Summary

- Friction laws:
  - slip-weakening: most basic
  - rate-and-state: low speed
  - velocity-weakening: high speed
- Fracture mechanics concepts (Gc) still useful to rationalize results of frictional rupture models:
  rupture arrest, acceleration at fault kinks
- Features require modeling with friction laws:
  nucleation, pulses (healing), supershear ruptures