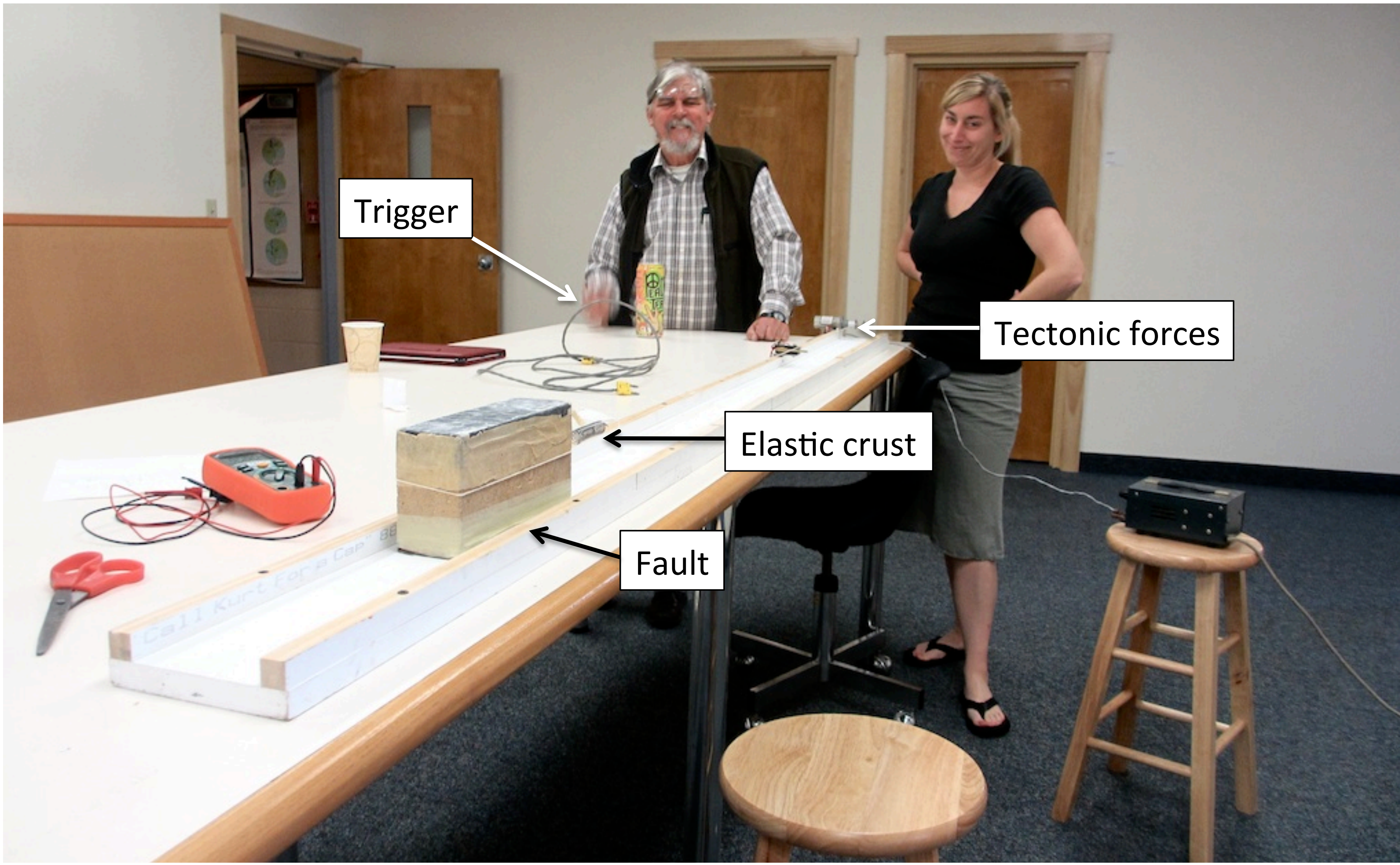
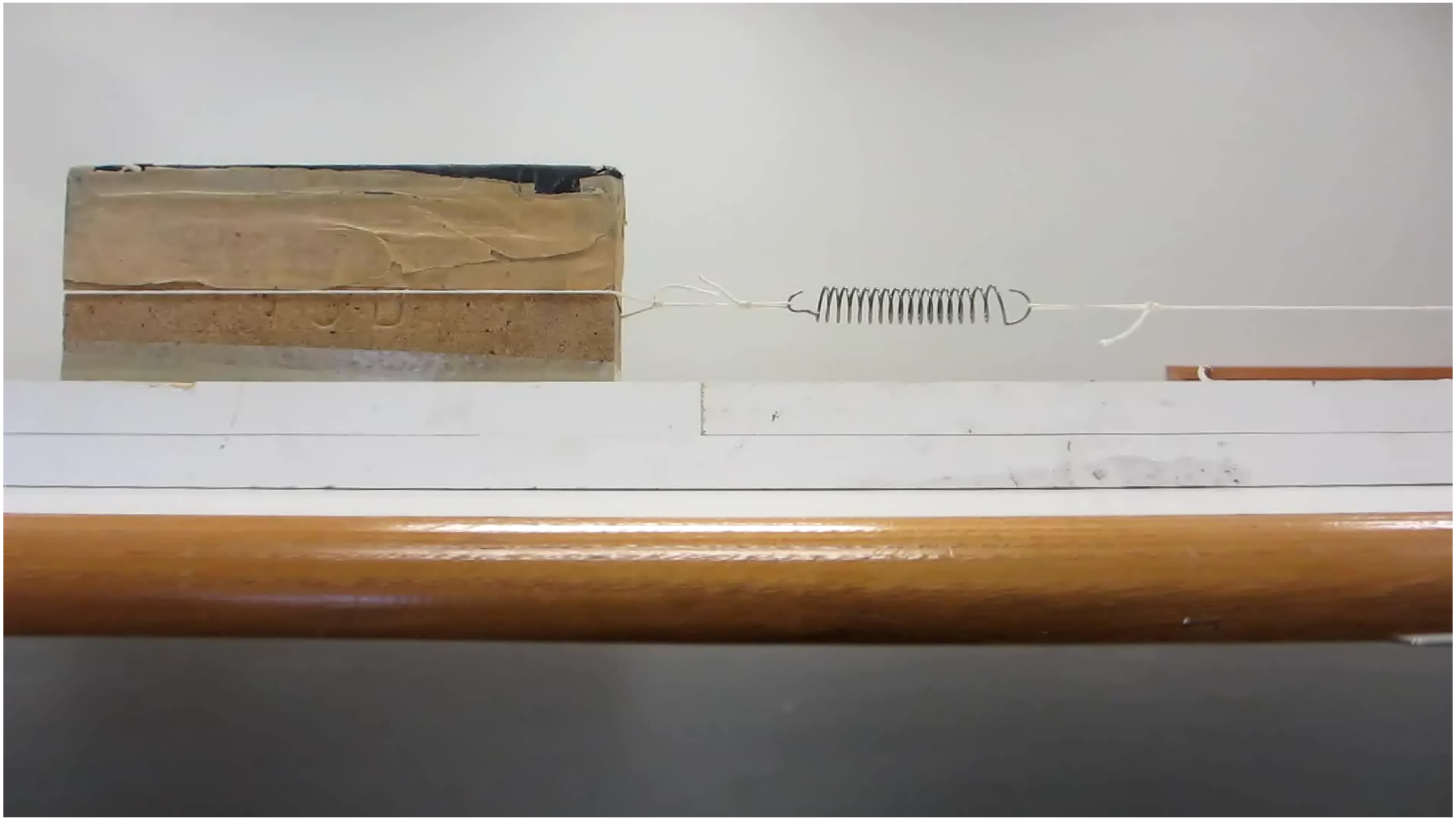
Earthquake Triggering

Nicholas van der Elst
NSF Postdoctoral Fellow
Lamont-Doherty Earth Observatory

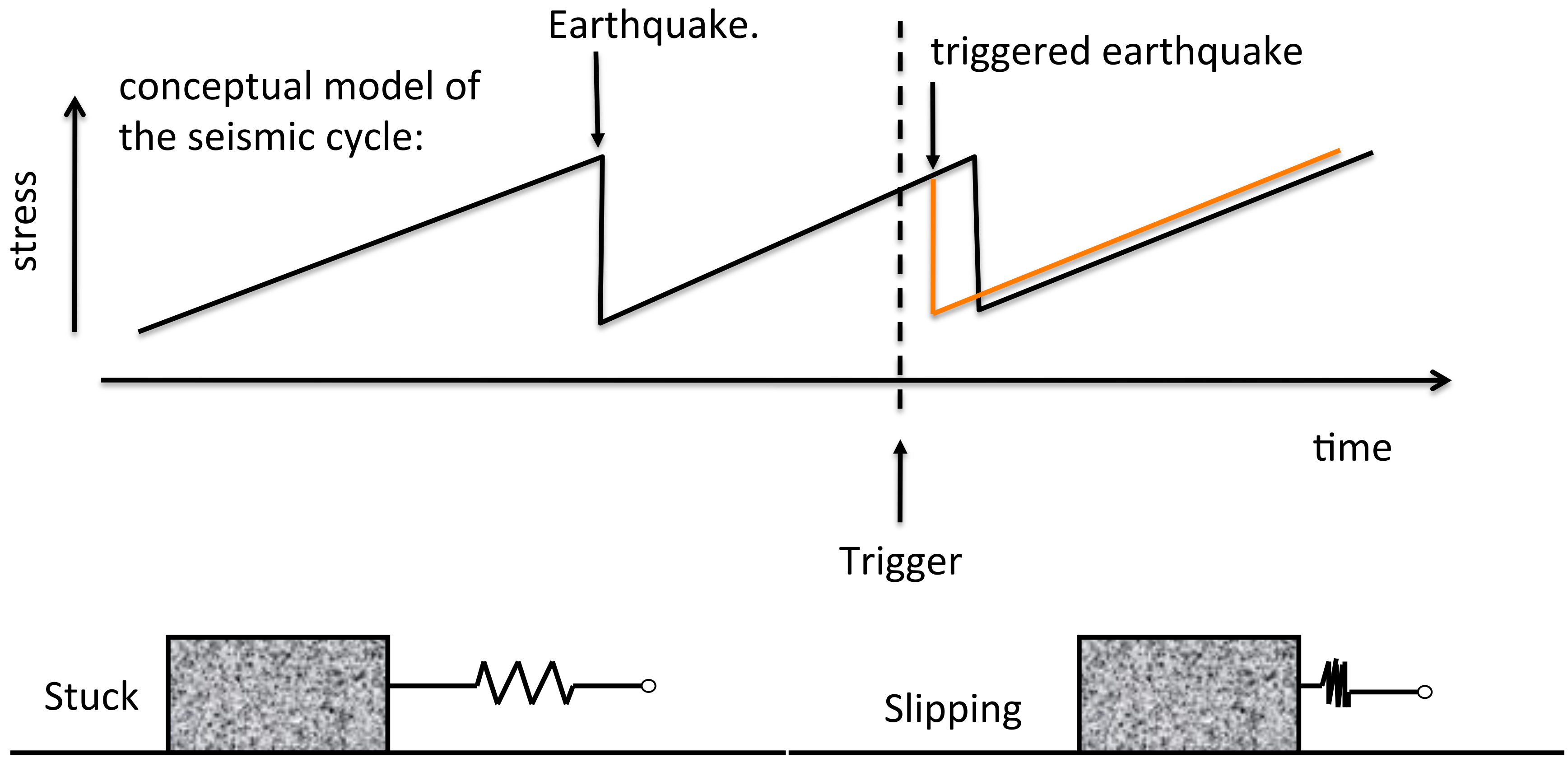
Earthquake machine



Earthquake machine



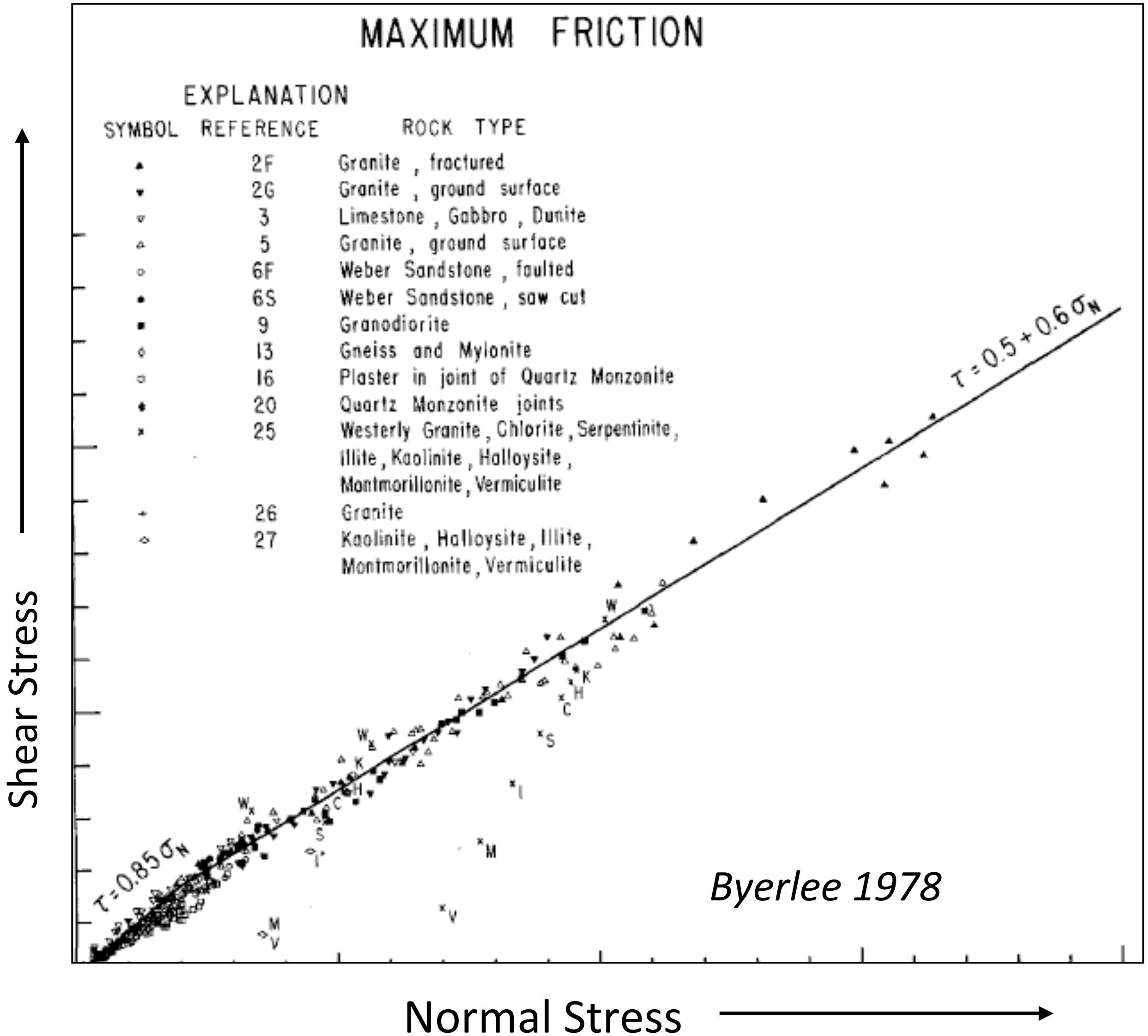
Triggering terminology



Triggered earthquake is statistically associated in time and space with some trigger event

Frictional stability: the rock mechanics perspective

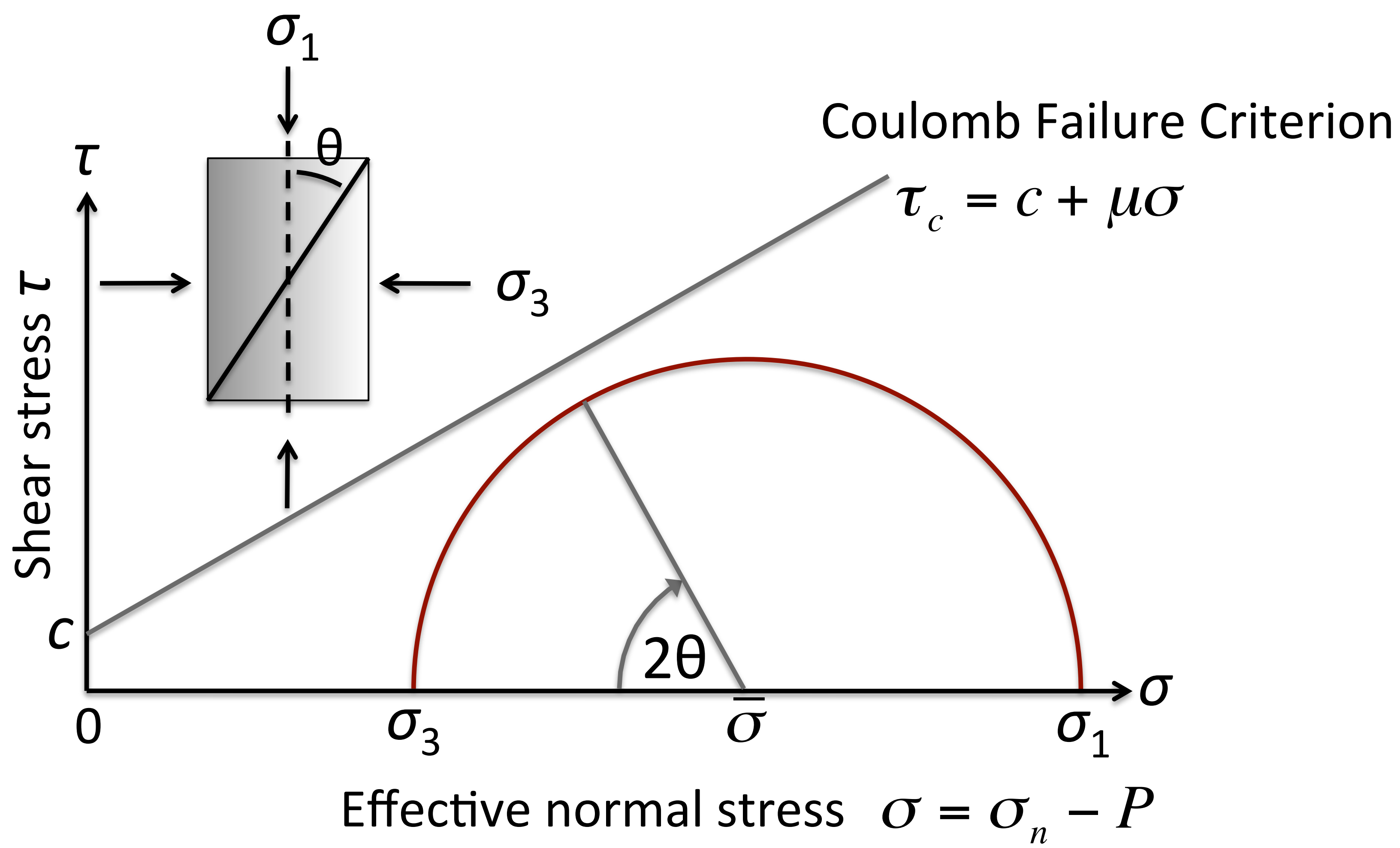
Back to basics: Why do faults fail?



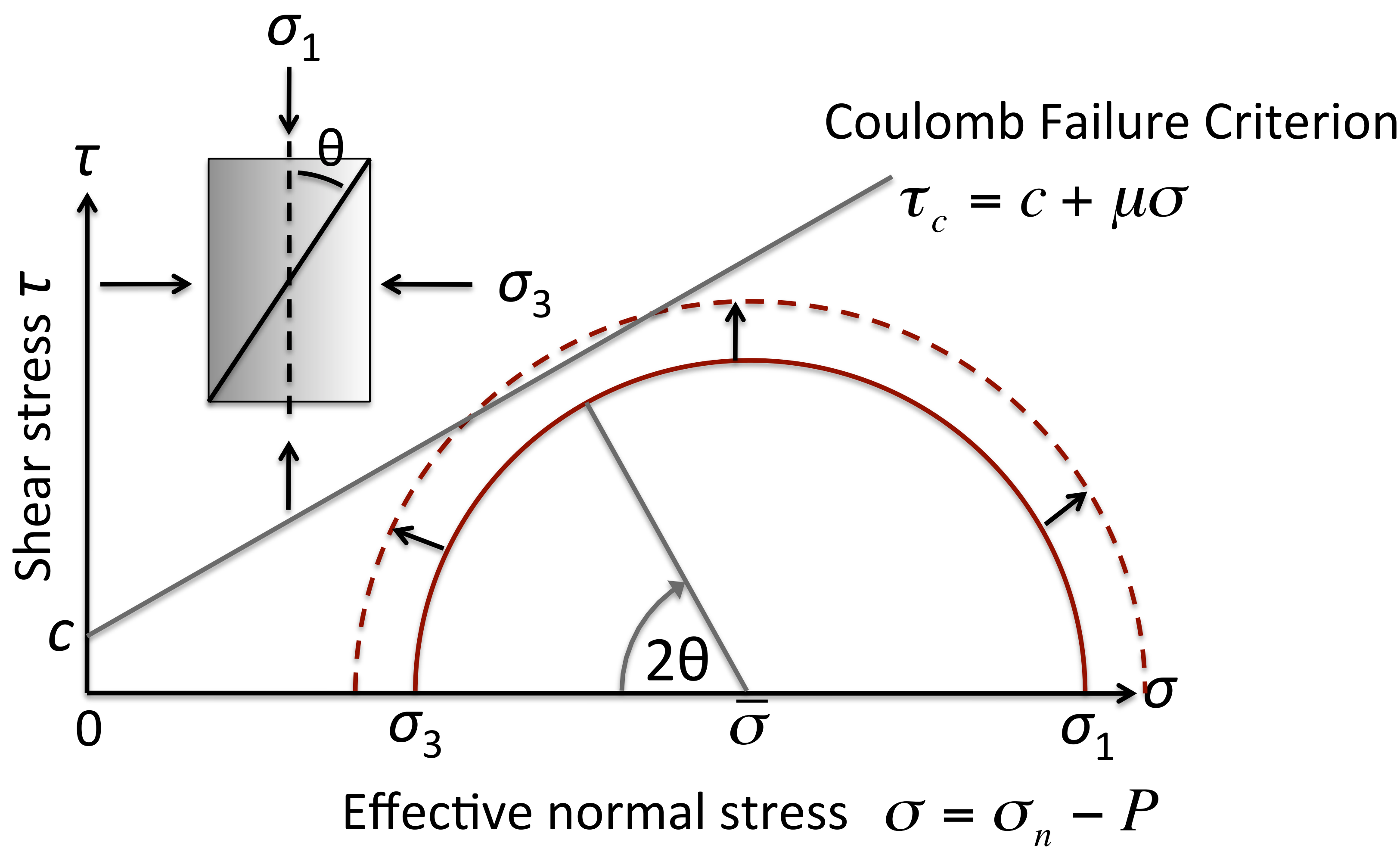
Coulomb Friction

$$\tau_f = c + \mu\sigma_n$$

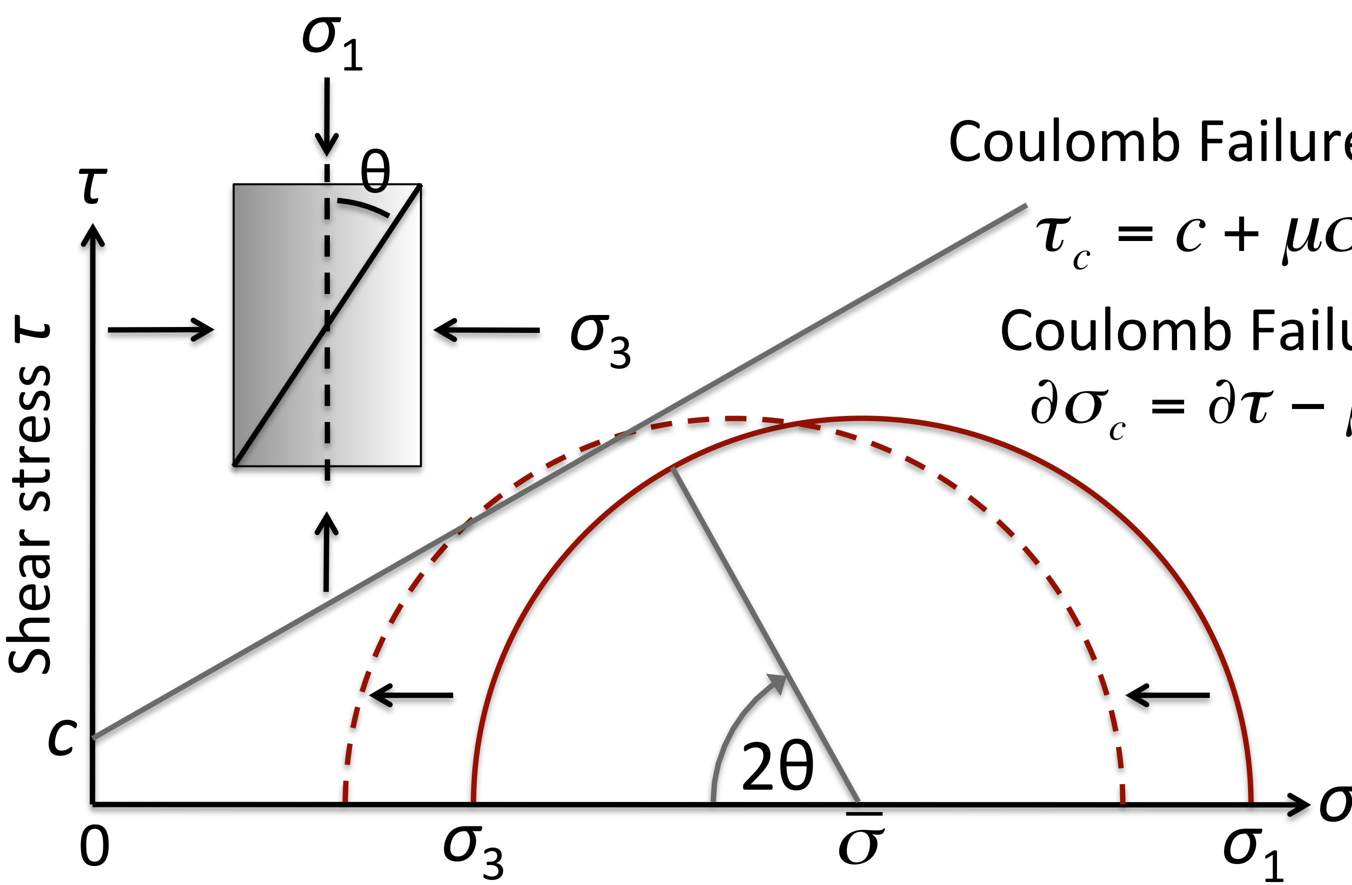
Coulomb Failure



Coulomb Failure



Coulomb Failure



Coulomb Failure Criterion

$$\tau_c = c + \mu\sigma$$

Coulomb Failure Stress

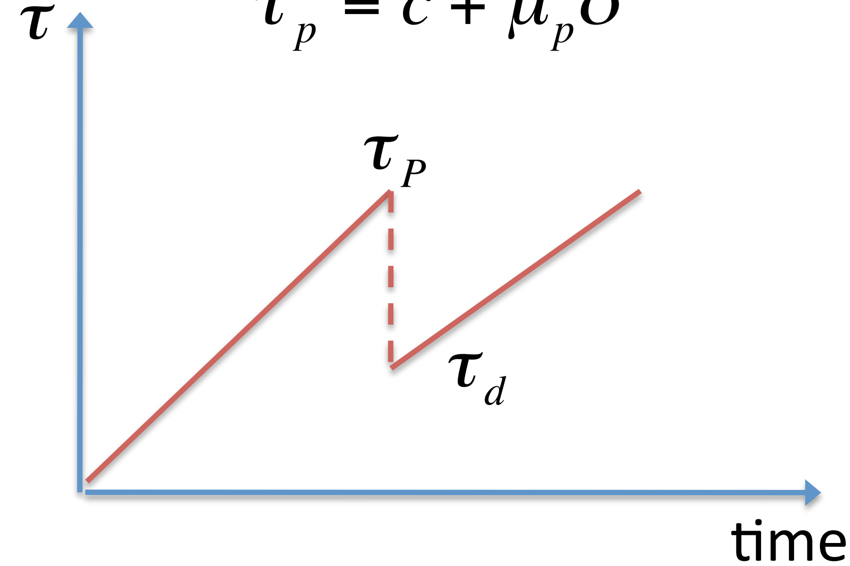
$$\partial\sigma_c = \partial\tau - \mu\left(\partial\sigma - \partial P\right)$$

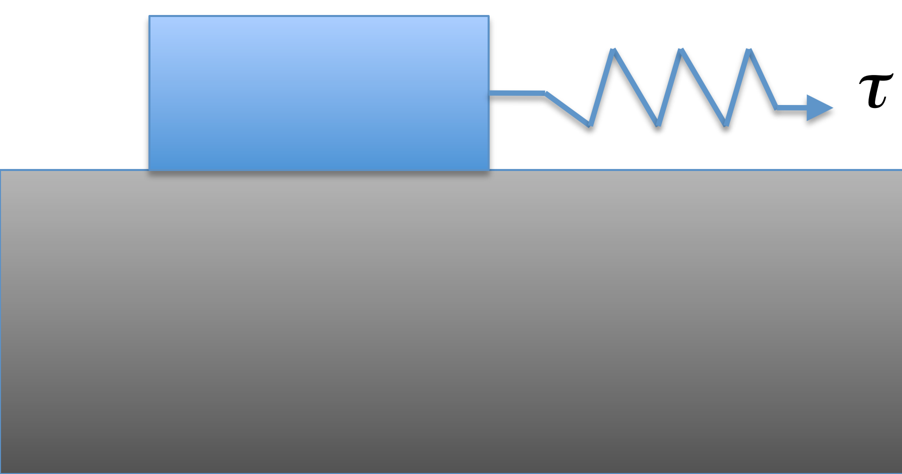
Effective normal stress $\sigma = \sigma_n - P$

Static and dynamic friction

$$\mu(v) = \begin{cases} \mu_s, & v = 0 \\ \mu_d, & v \neq 0 \end{cases}$$

$$\tau_p = c + \mu_p \sigma$$





Where Does Friction Come From?

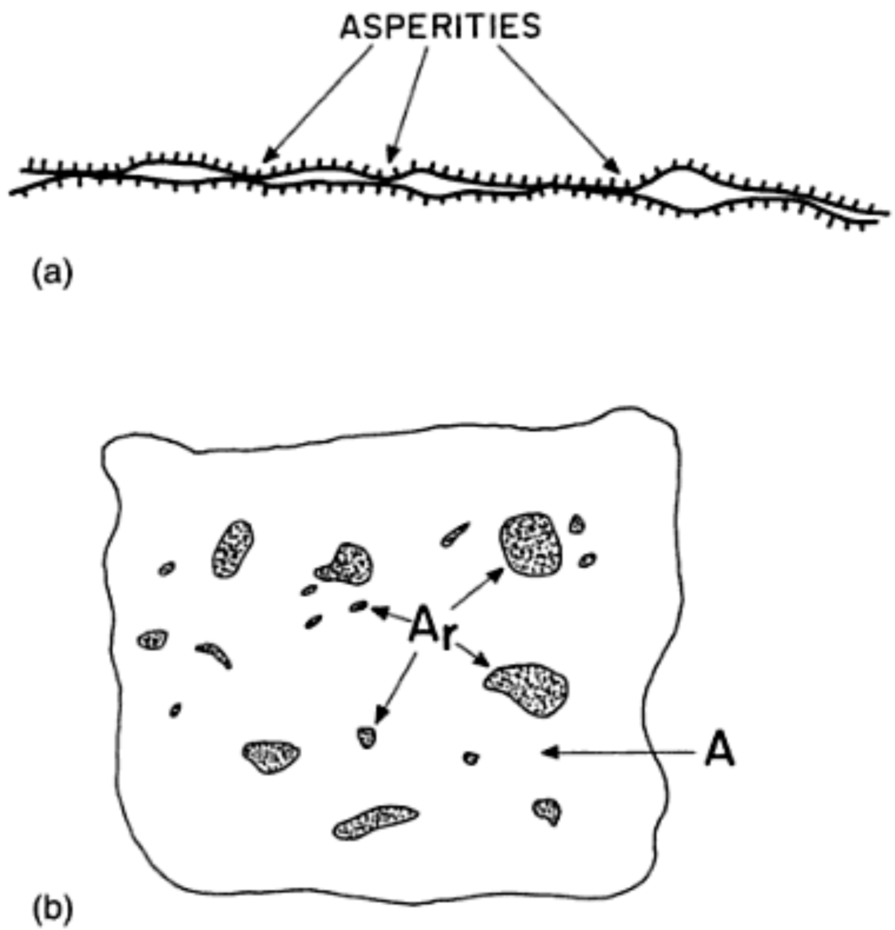
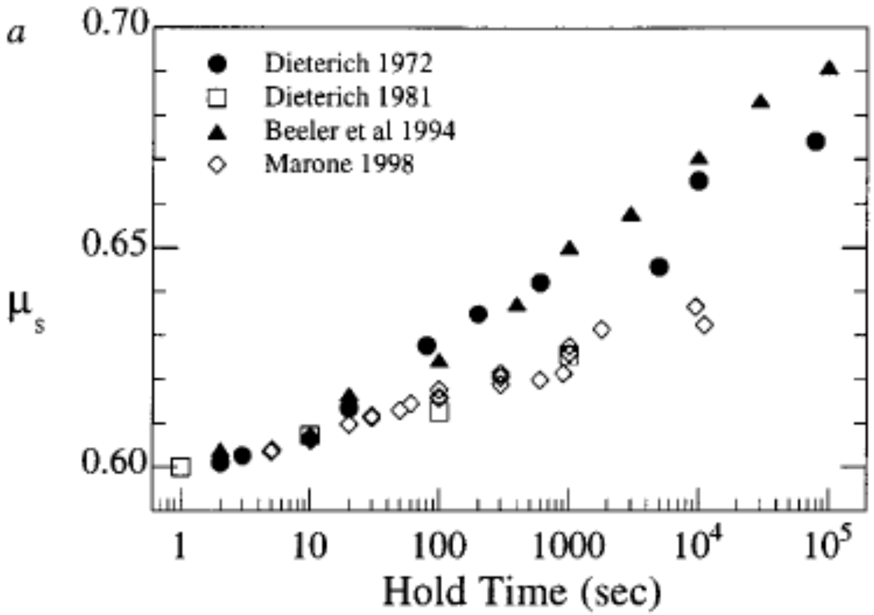
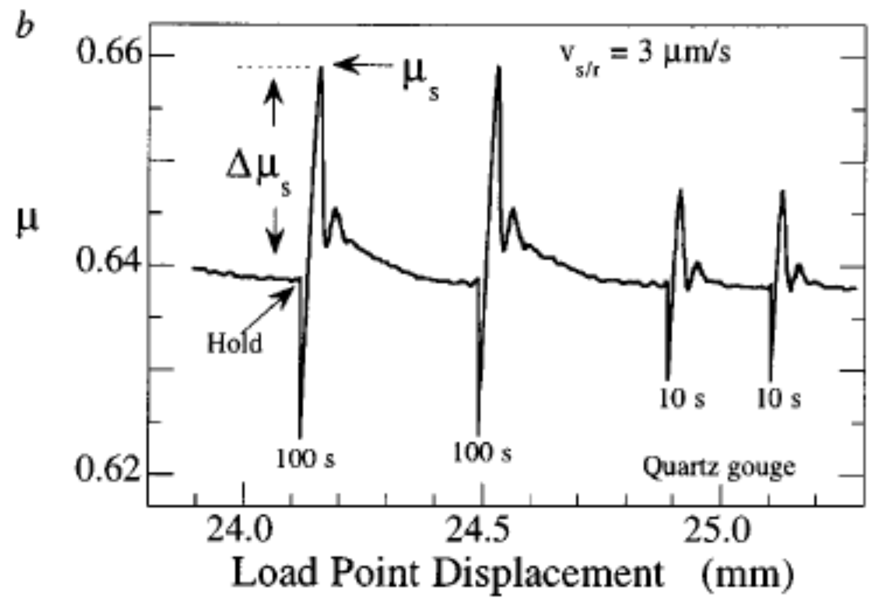


Fig. 2.1. Schematic diagram, in section and plan view, of contacting surface. The stippled regions in plan view represent the areas of asperity contact, which together comprise the real contact area A_r.

Scholz 2002

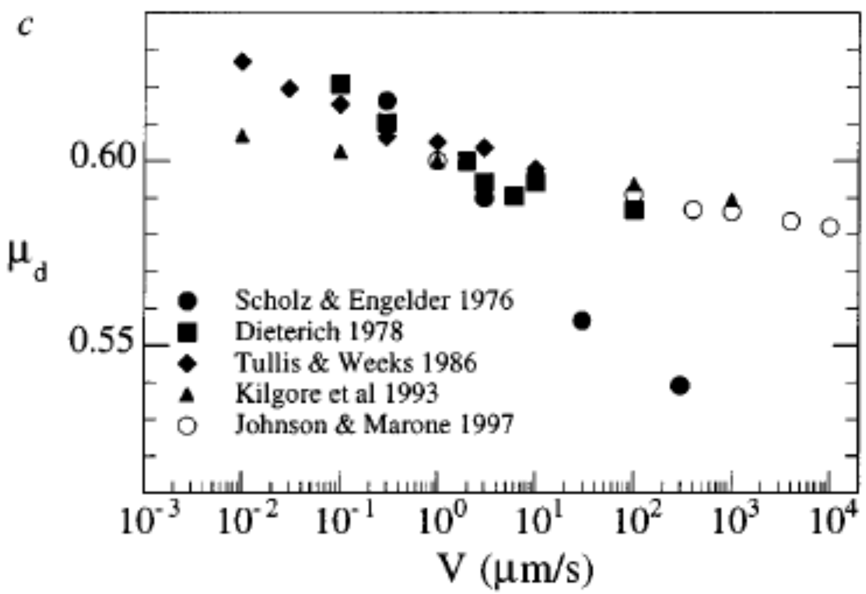
1. Static Friction is Not Static

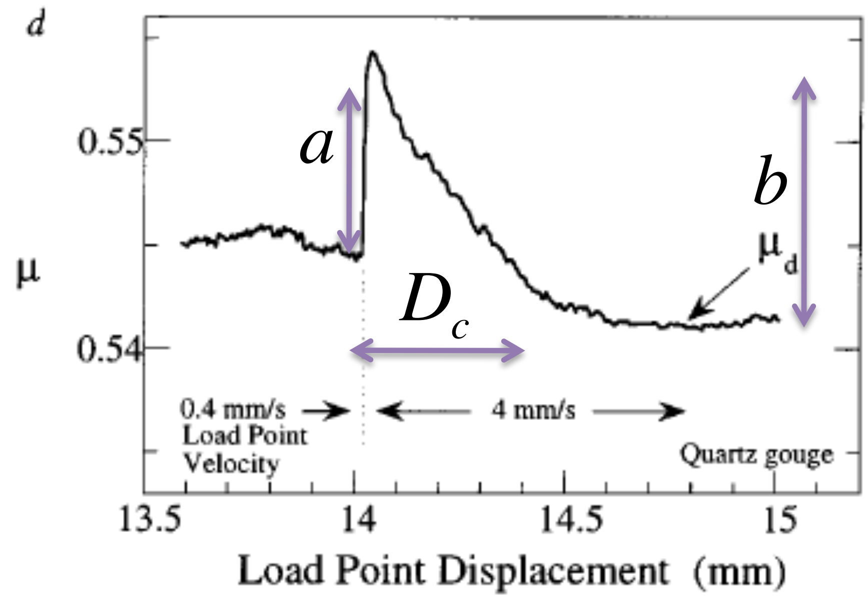




Marone 1998

2. Dynamic Friction Depends on Sliding Velocity



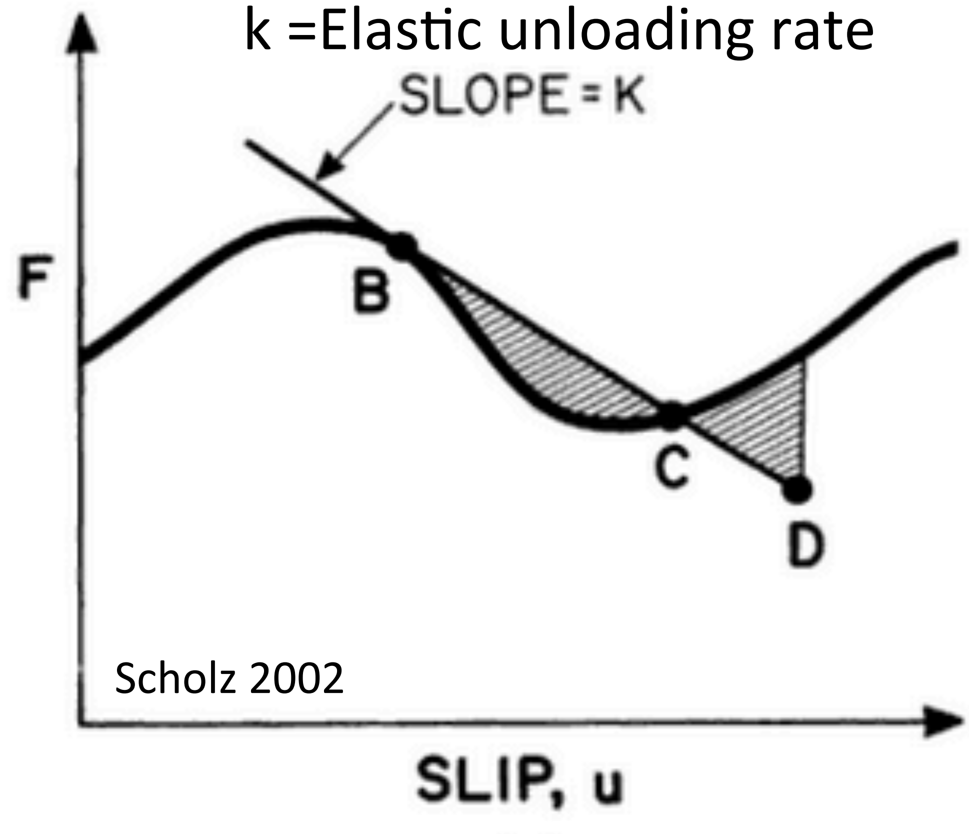


Sliding stability depends on the friction rate parameter: (a – b)

Marone 1998

So What if My Frictional Rate Parameter is Negative?

k =Elastic unloading rate

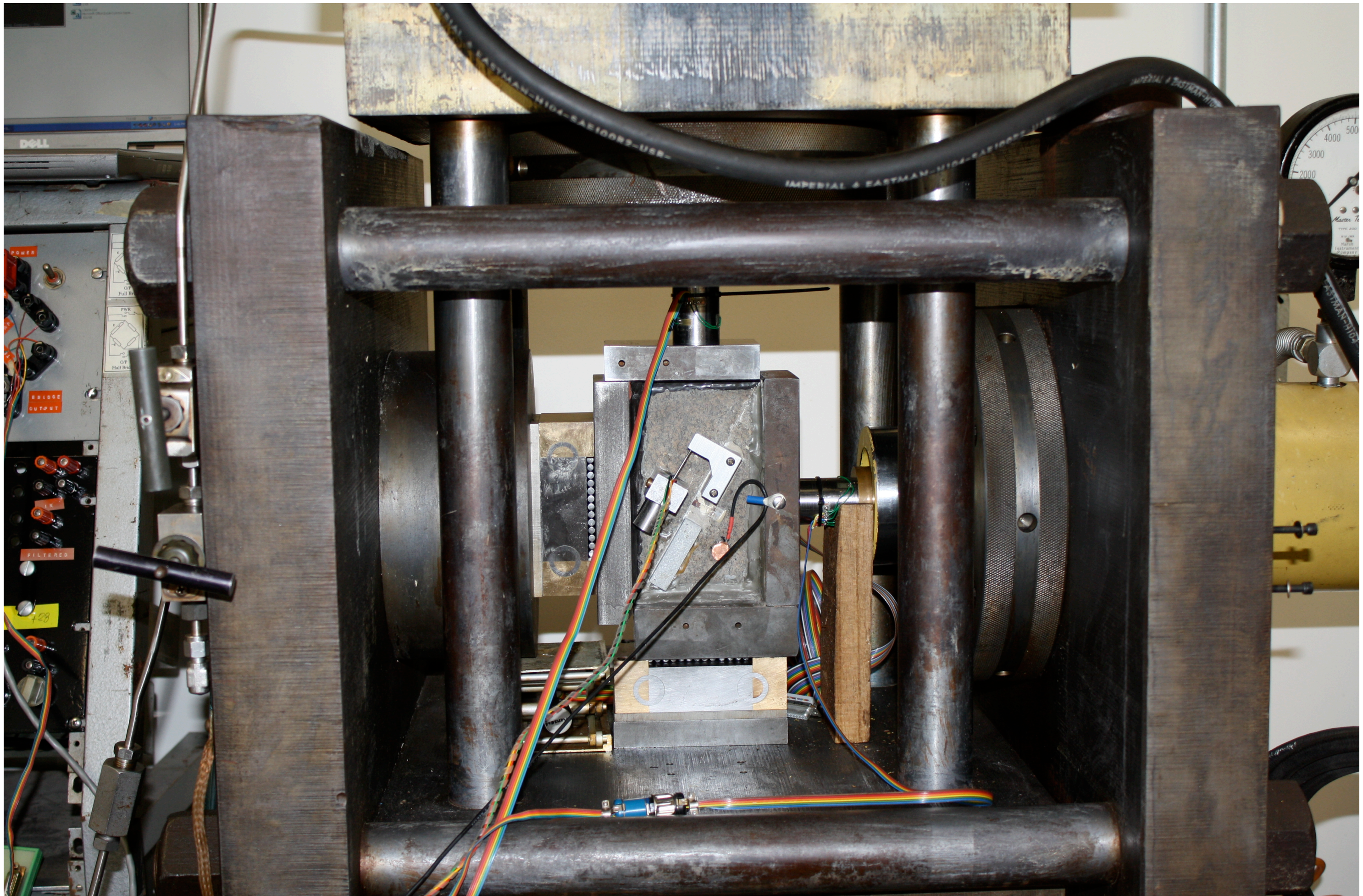


Slip stability depends on the frictional unloading rate:

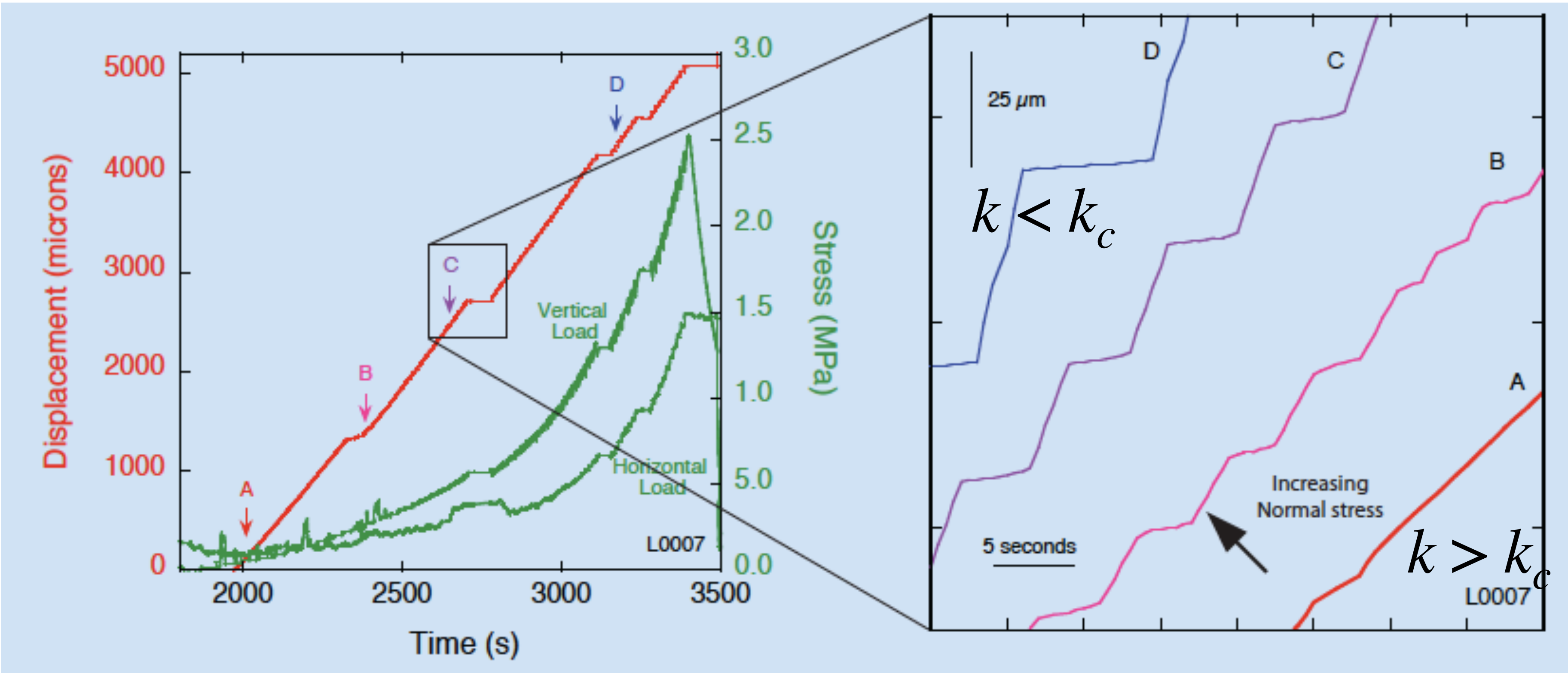
$$k_c = \frac{(b-a)\sigma}{D_c}$$

if k < k_c slip is unstable

Critical stiffness transition in the lab



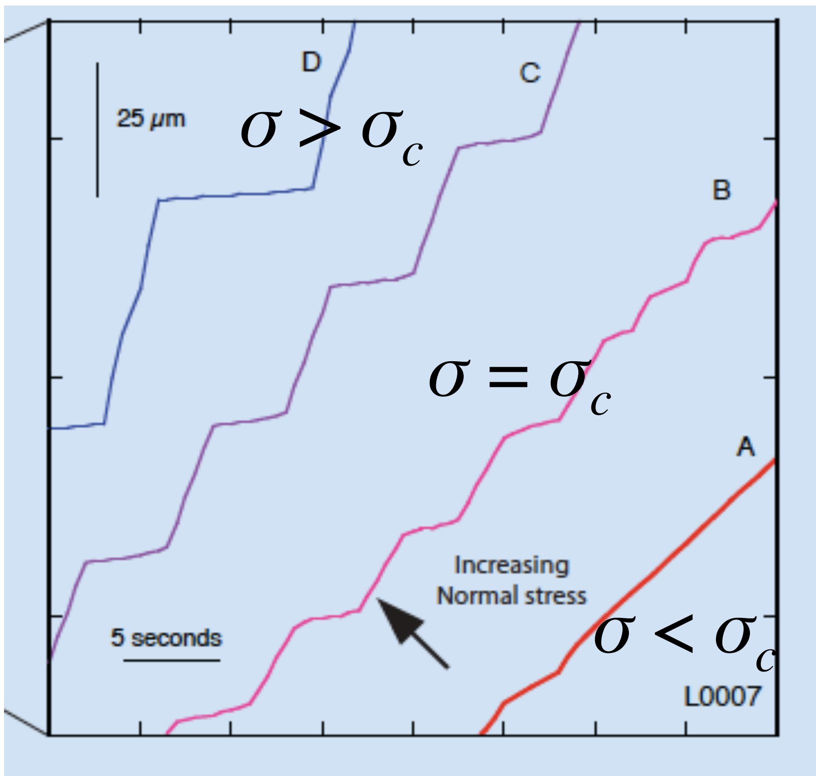
Critical stiffness in the lab

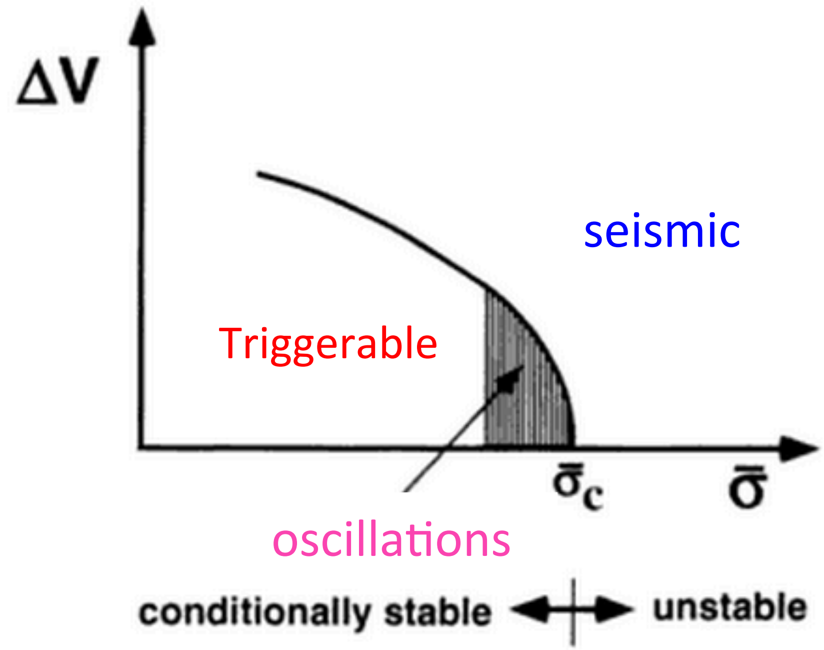


$$k_c = \frac{(b-a)\sigma}{D_c}$$

Courtesy H. Savage

Triggering and conditional stability





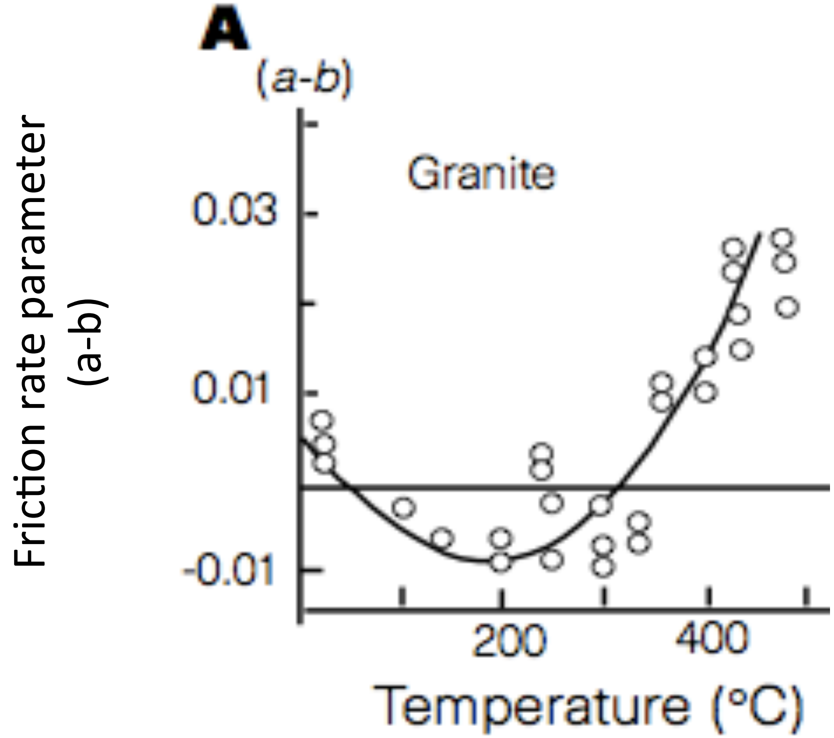
$$k_c = \frac{(b-a)\sigma}{D_c}$$

Very easy to trigger a stably sliding fault near the stability threshold

Courtesy H. Savage

Scholz, 1998

The stability transition in faults

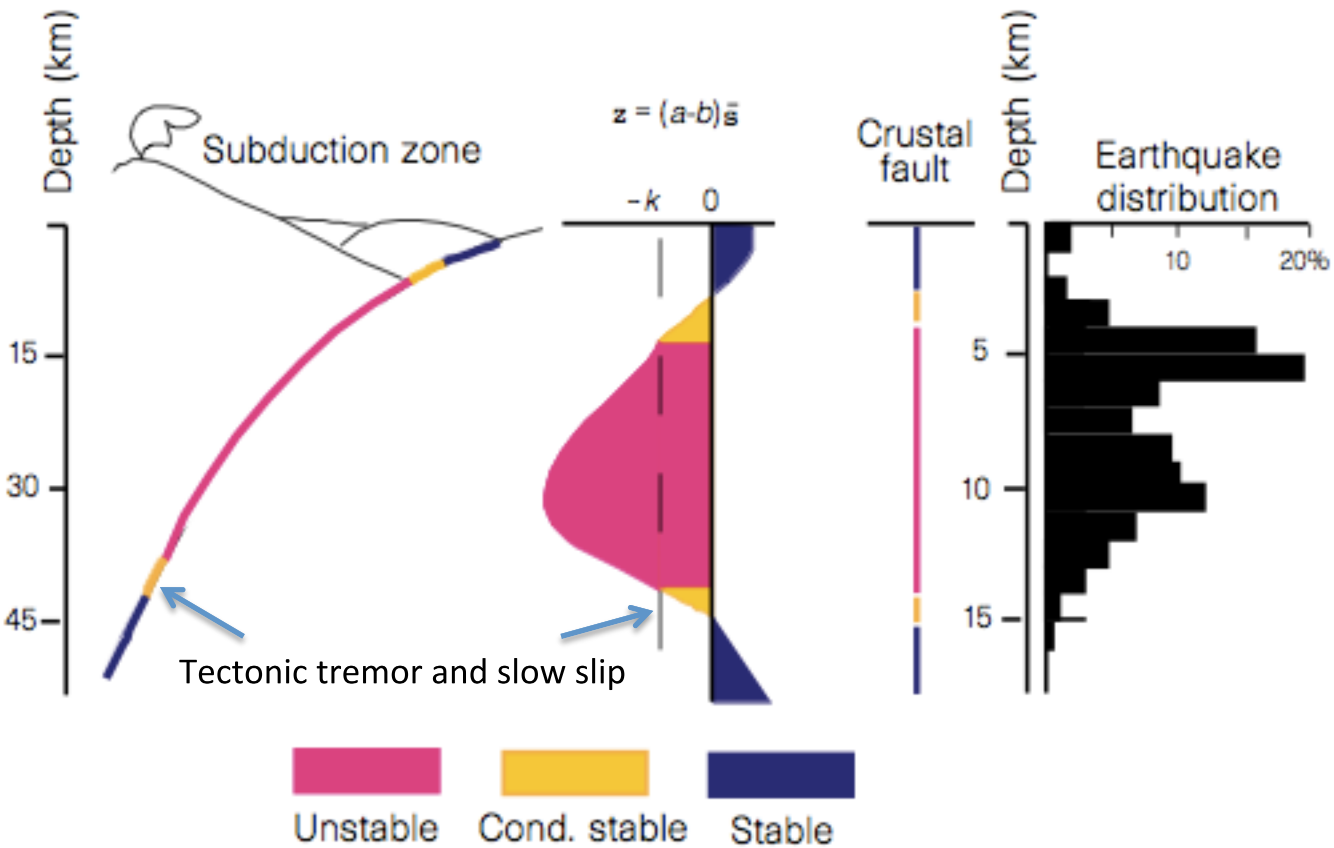


$$k_c = \frac{(b-a)\sigma}{D_c}$$

The frictional rate parameter varies with temperature

Scholz 1998

The stability transition in faults

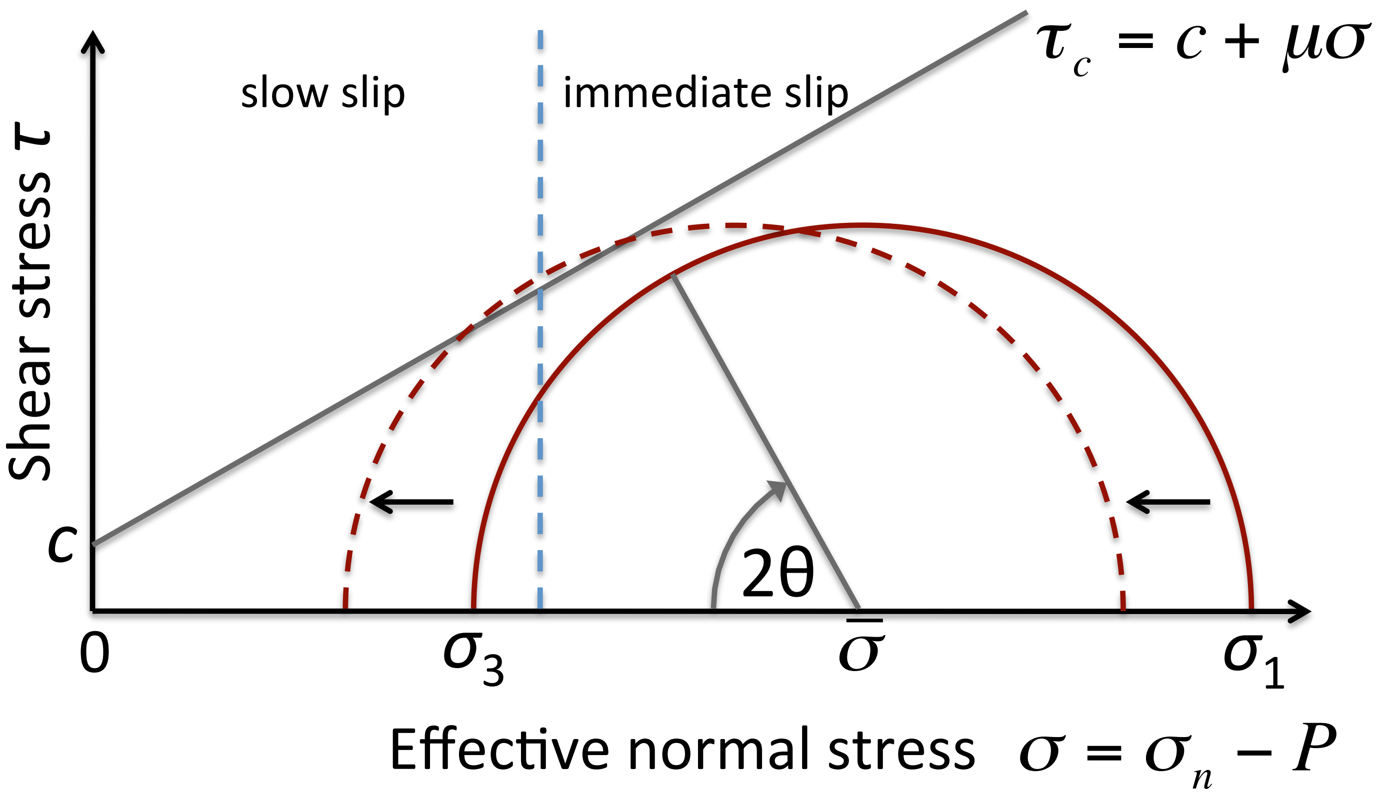


$$k_c = \frac{(b-a)\sigma}{D_c}$$

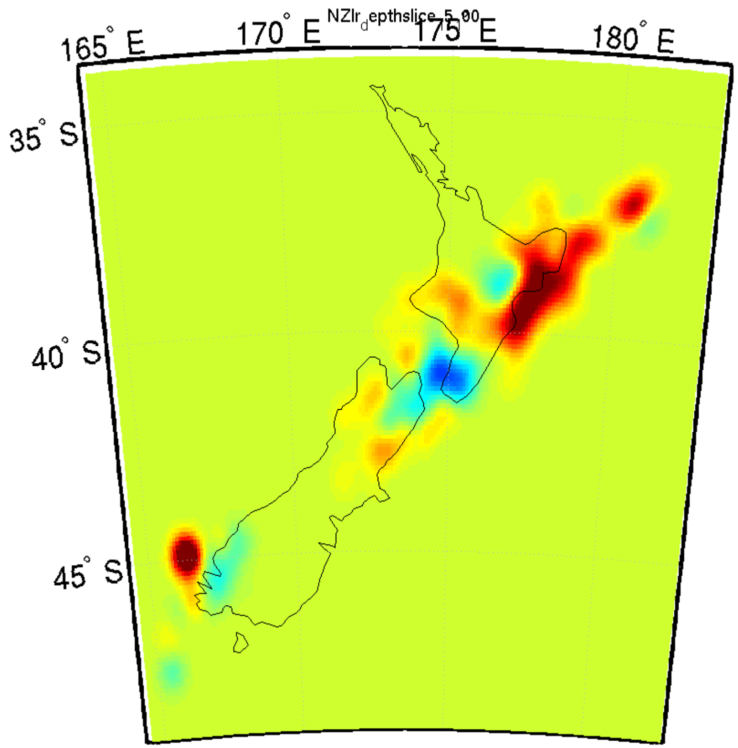
Scholz 1998

Conditionally stable failure

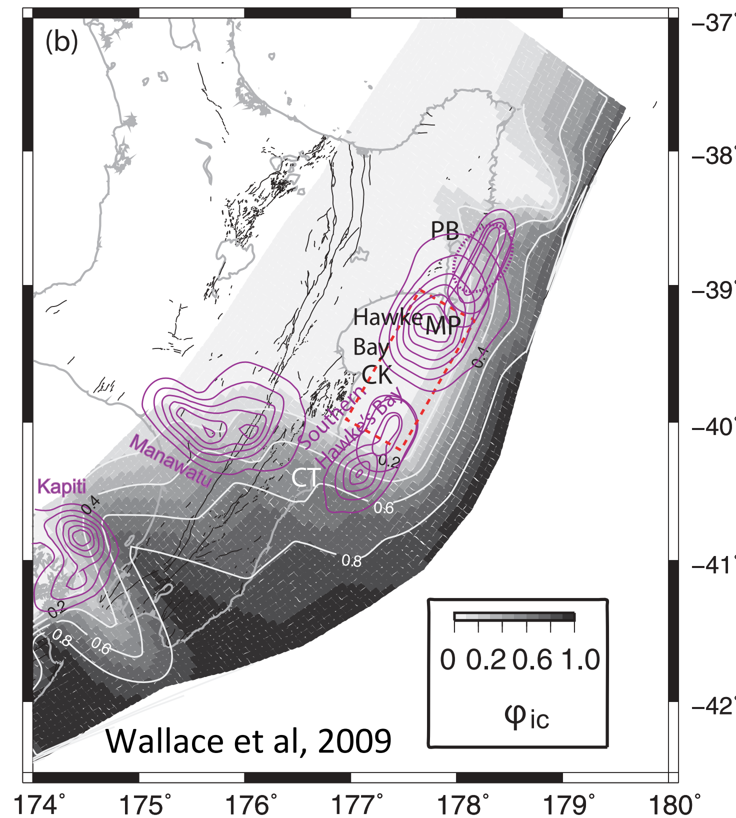
$$k \leq \frac{(b-a)(\sigma_n - P)}{D_c}$$



Are conditionally stable faults more triggerable?

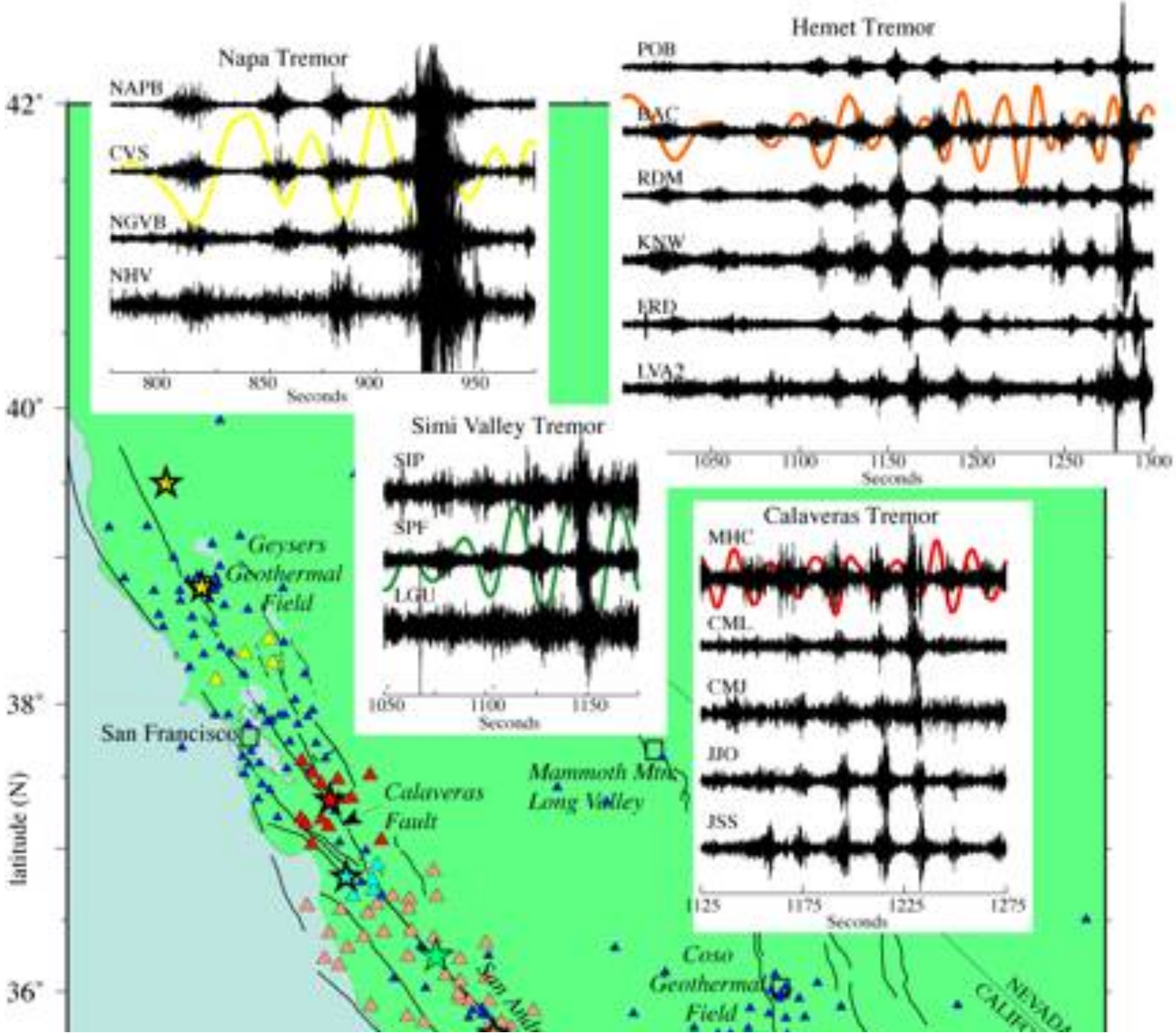


Dynamic triggering susceptibility



Seismic coupling (grey) and locations of episodic slow slip and tremor (purple).

Are conditionally stable faults more triggerable?



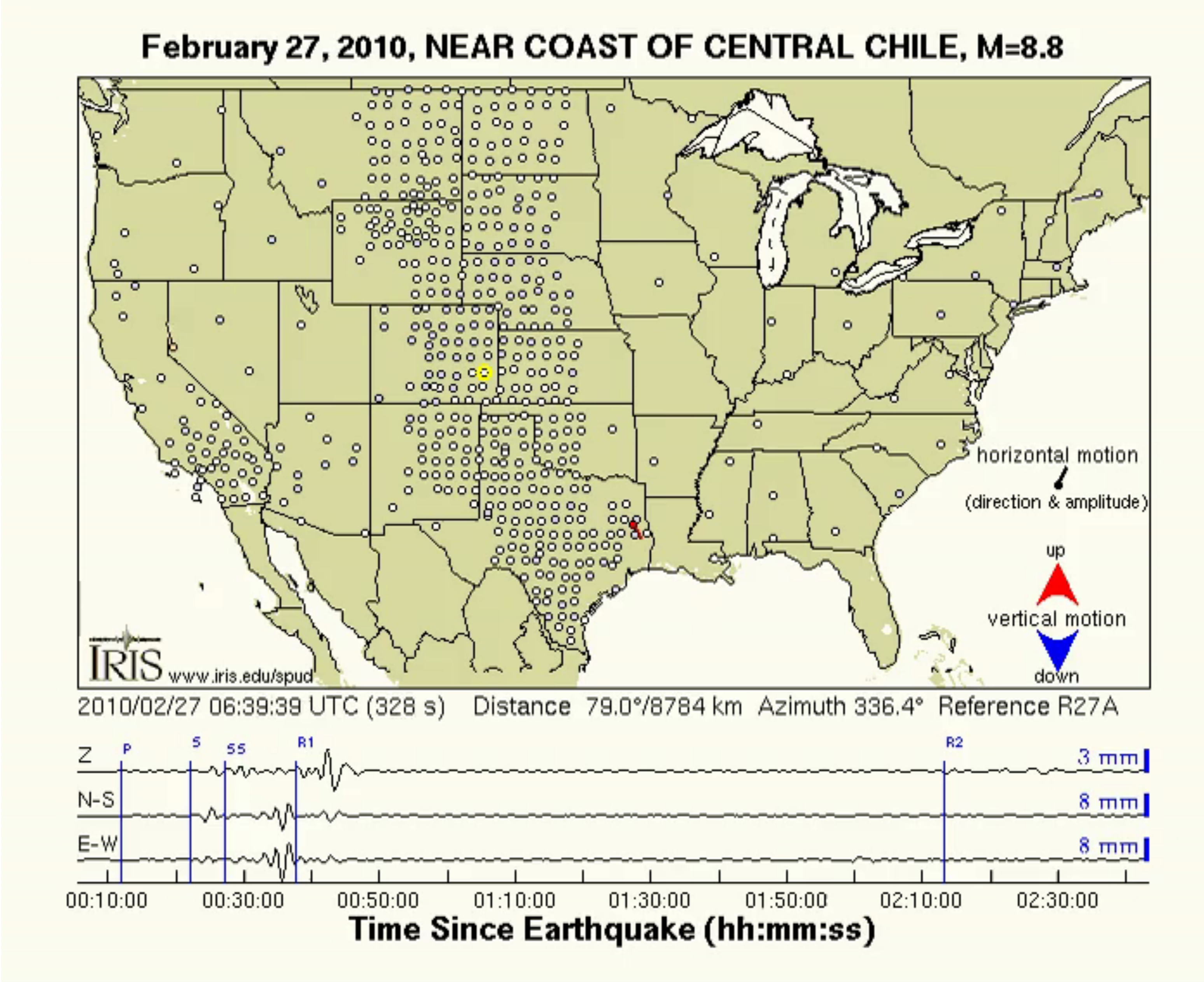
Gomberg et al 2008

Implications for volcanic regions

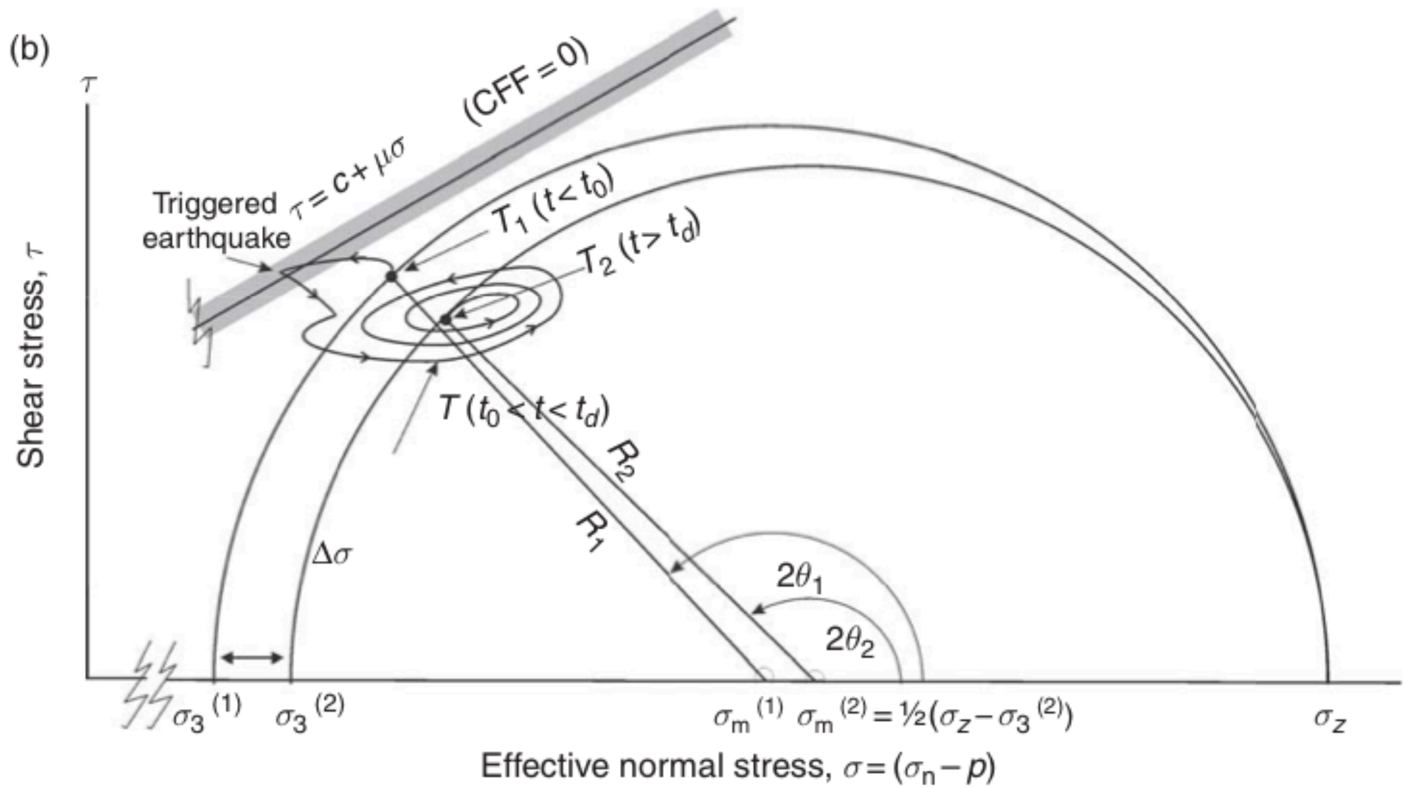
- Volcanic and hydrothermal regions may pass repeatedly through the stability transition
  1. varying temperatures (*b* - *a*)
  2. high and heterogeneous pore pressure (*σ* - *P*)
  3. variable elastic stiffness (*k*)
- Volcanoes may be critical for the same reason as deep subduction zones.
- Frictional slip at low effective stress may be aseismic or tremor-like.

$$k_C = \frac{(b-a)(\sigma - P)}{D_c}$$

Evidence for the role of fluids in dynamic earthquake triggering


February 27, 2010, NEAR COAST OF CENTRAL CHILE, M=8.8
IRIS www.iris.edu/spud
horizontal motion
(direction & amplitude)
up
vertical motion
down
2010/02/27 06:39:39 UTC (328 s) Distance 79.0°/8784 km Azimuth 336.4° Reference R27A
Z
N-S
E-W
P
S
SS
R1
R2
3 mm
8 mm
8 mm
00:10:00
00:30:00
00:50:00
01:10:00
01:30:00
01:50:00
02:10:00
02:30:00
Time Since Earthquake (hh:mm:ss)

Dynamic triggering



Hill and Prejean, 2007

What can triggering sensitivity tell us about the importance of fluids?

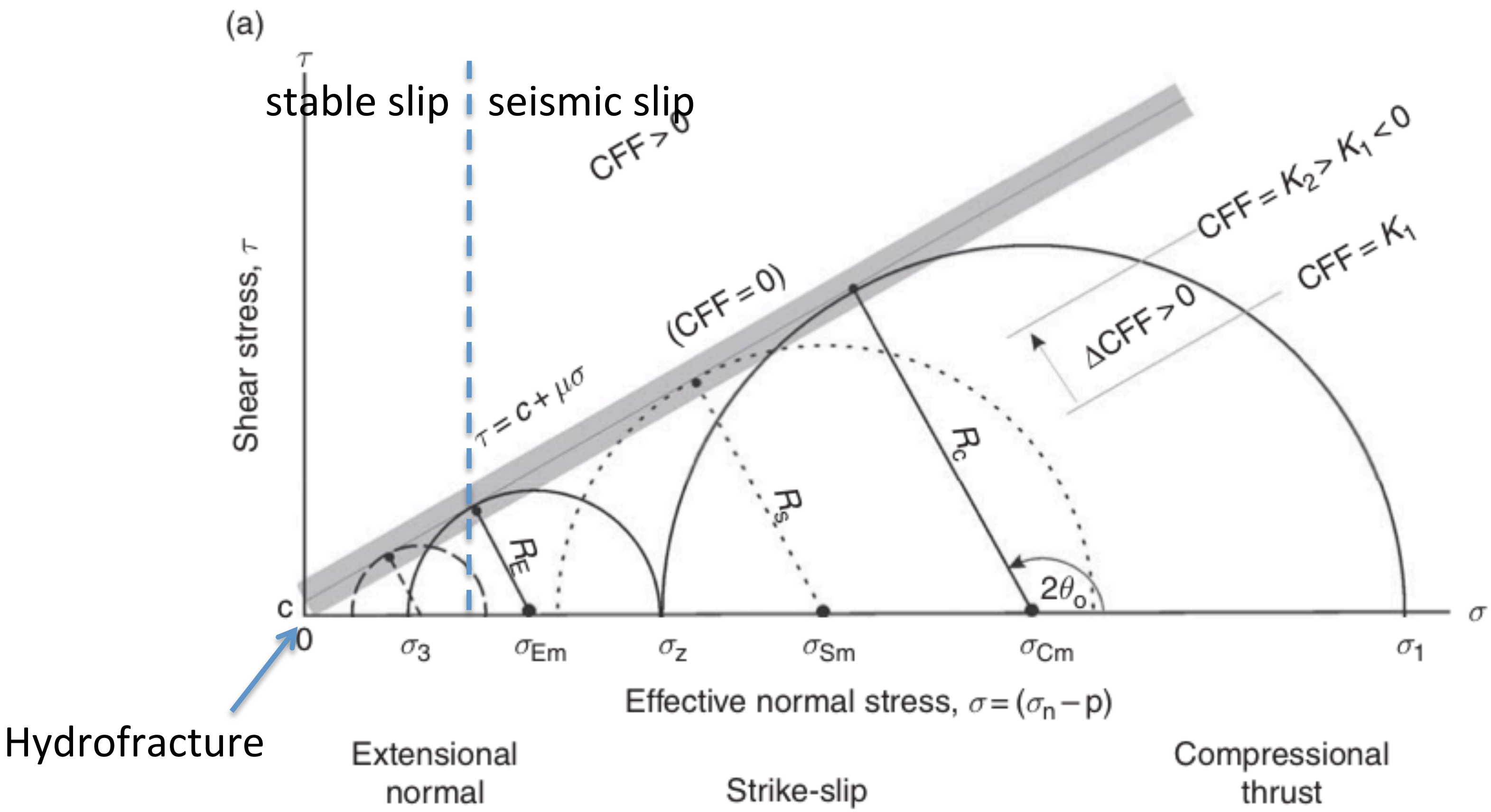
Table 2 Reported instances of remote dynamic triggering

	Responses			Triggering mainshocks		
Site	**Number**	**Mmax**	**Regime**	**M min–max**	**Distance (km) min–max**	**References**
Mt. Wrangell, AK	1	$M<1$	V	9.1	~11 000	West *et al.*, 2005
Katmai, AK	4	$M=2.3$	G, V	7.9	115–740	Moran *et al.*, 2004
South B.C., Canada	1	N/A	C	7.9	1800–2200	Gomberg *et al.*, 2004
Mt. Rainer, WA	1	$M<1$	V	7.9	3108	Prejean *et al.*, 2004
Geysers, CA	~11?	$M<3$	E, G, V	6.5–7.9	202–3120	Gomberg, 1996, Prejean *et al.*, 2004
Coso, CA	>4	$M=3.2$	E, G, V	to 7.9	165–660	Prejean *et al.*, 2004
Long Valley, CA	2	$M=3.4$	E, G, V	7.4–7.9	414–3454	Gomberg *et al.*, 2001, Prejean *et al.*, 2004
Mammoth Mtn, CA	2	$M<2$	E, G, V	7.2–7.9	420–3454	Prejean *et al.*, 2004; Johnston *et al.*, 2004
Lassen Peak, CA	1	$M=2.8$	E, V	7.4	840	Hill *et al.*, 1995
Burney, CA	1	$M=2.8$	E	7.4	900	Hill *et al.*, 1995
Salton Sea area, CA	1	$M=4.7$	E, V, G	7.1	120–150	Hough and Kanamori, 2002
Central and South CA	>5	$M=5?$	E & C	5.8–6.1	70–120	Hough, 2005
Offshore S. CA	1	$M=2.5$	E	7.9	4003	Prejean *et al.*, 2004
Western Nevada	1	$M\sim4$	E, G	7.4	450–650	Anderson *et al.*, 1994
Little Skull Mtn, NV	1	$M=5.6$	E	7.4	240	Anderson *et al.*, 1994
Yellowstone, WY	2	$M=3.0$	E, G, V	7.4–7.9	1250–3100	Husen *et al.*, 2004b
Wasatch front, UT	2	$M=3.2$	E, G	7.4–7.9	3000–3500	Pankow *et al.*, 2004
Cascade, ID	2	$M=1.7$	E, G	7.4	1100	Husker and Brodsky, 2004
Eastern US (1811-12)	1	$M\sim5?$	C	M>7	~1000	Hough, 2005
Cerro Prieto, Mexico	1	$M=4.1$	E, V, G	7.1	260	Glowacka *et al.*, 2002
Valley of Mexico	~7	$M\sim4$	E, G, V	7.6–8.0	303–588	Singh *et al.*, 1998
Aso, Japan	5	$M\sim2$	E, V	7.1–7.7	900–2213	Miyazawa *et al.*, 2006
Iwo Jima, Japan	4	$M<2$	IA, G, V	7.1–8.0	1228–2002	Ukawa *et al.*, 2002
SISZ, Iceland	1	$M\sim5$	E, G	6.5	80–100	Arnadottir *et al.*, 2004
Roer Valley, Holland	1	$M=3.7$	E	5.4	40	Camelbeeck *et al.*, 1994
Greece	1	$M<3.5$	E	7.4	400–1000	Brodsky *et al.*, 2000
Syria-Lebanon border	1	$M=3.7$	C	7.3	500	Mohamad *et al.*, 2000
Tiawan region	9	$M>4$	?	6.5–7.1	138–2959	Wan *et al.*, 1996
Nanki Trough, Japan	2	N/A	S	7.3–8.1	900–4000	Miyazawa and Mori, 2005
Tonga trench	2	$M=5.9–7.7$	S	7.1–7.6	260–290	Tibi *et al.*, 2002

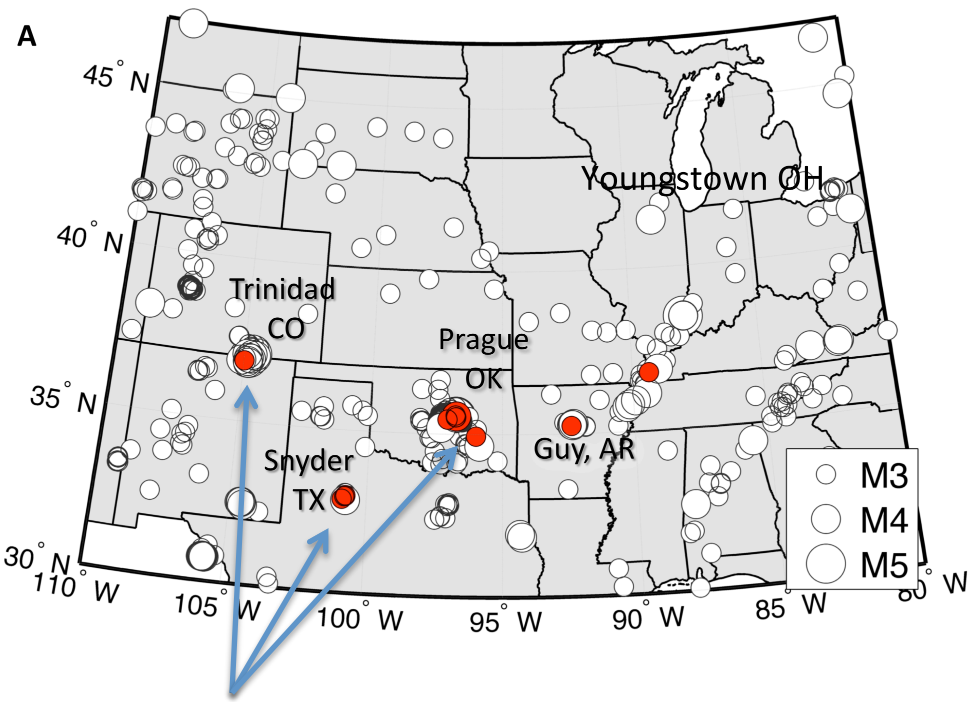
Tectonic regimes: E, extensional, transtensional; C, convergent, transpressional; G, geothermal; V, volcanic; IA, island arc; S, Subcrustal subduction zone; SISZ, South Iceland Seismic Zone.

Hill and Prejean

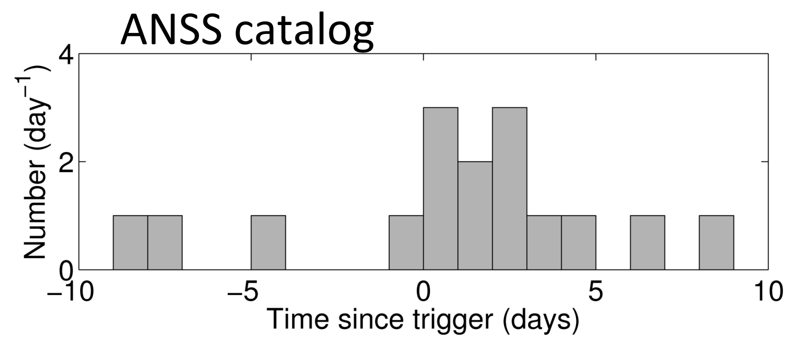
Why might extensional regions be more triggerable?

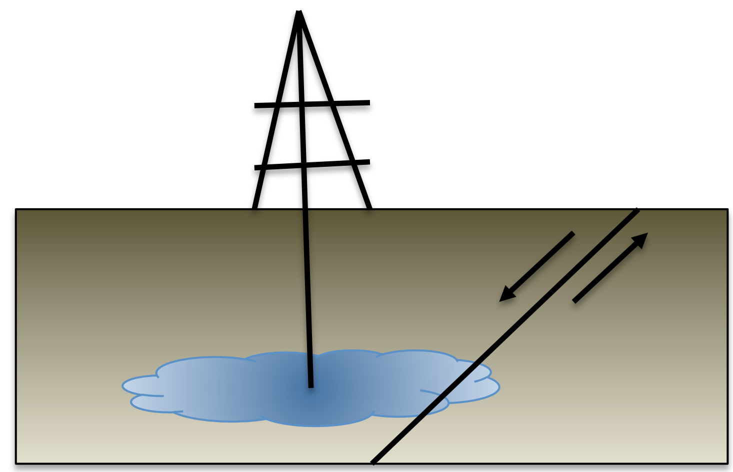


Are sites with non-volcanic fluid flow triggerable?

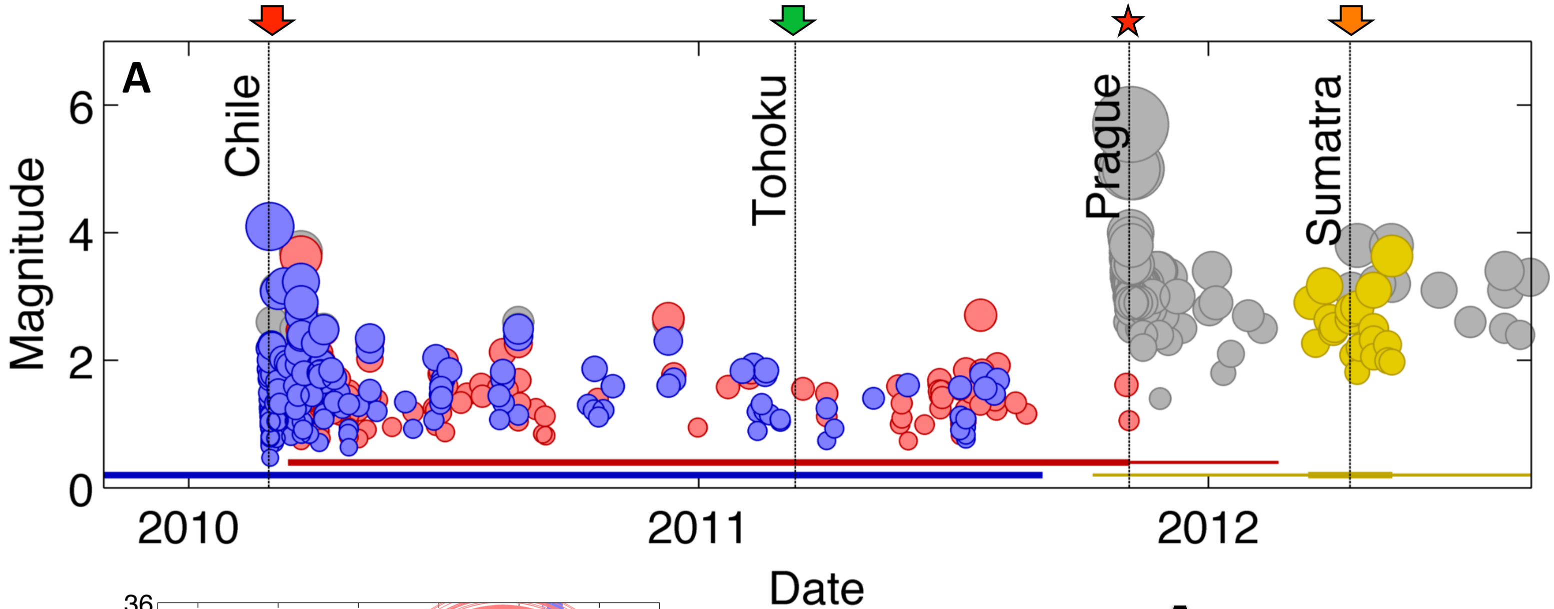


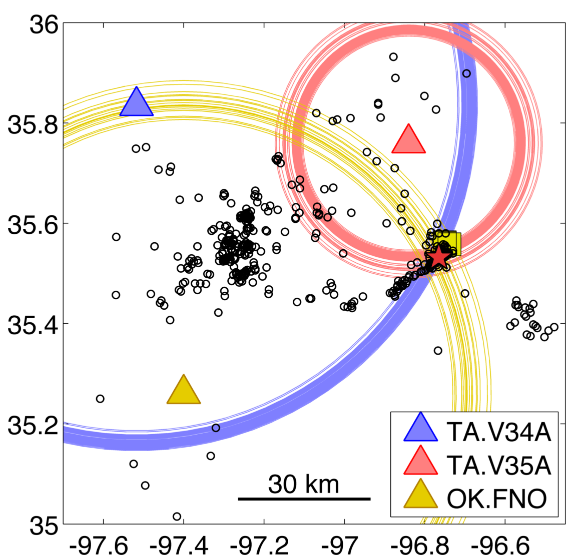
Sites of dynamic triggering in Feb. 2010 and Mar. 2011

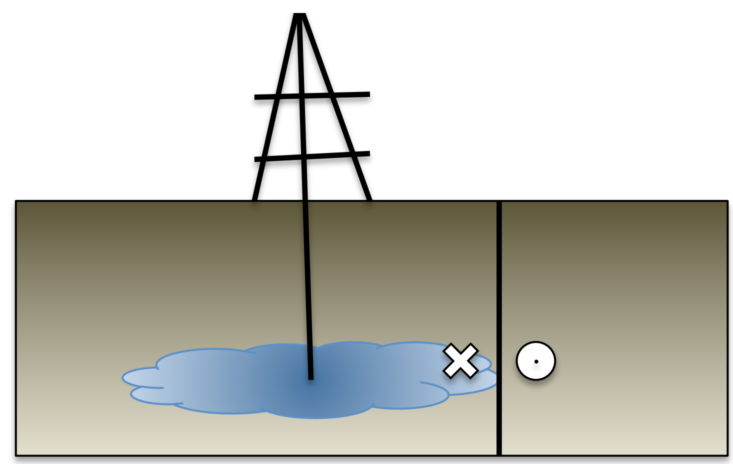


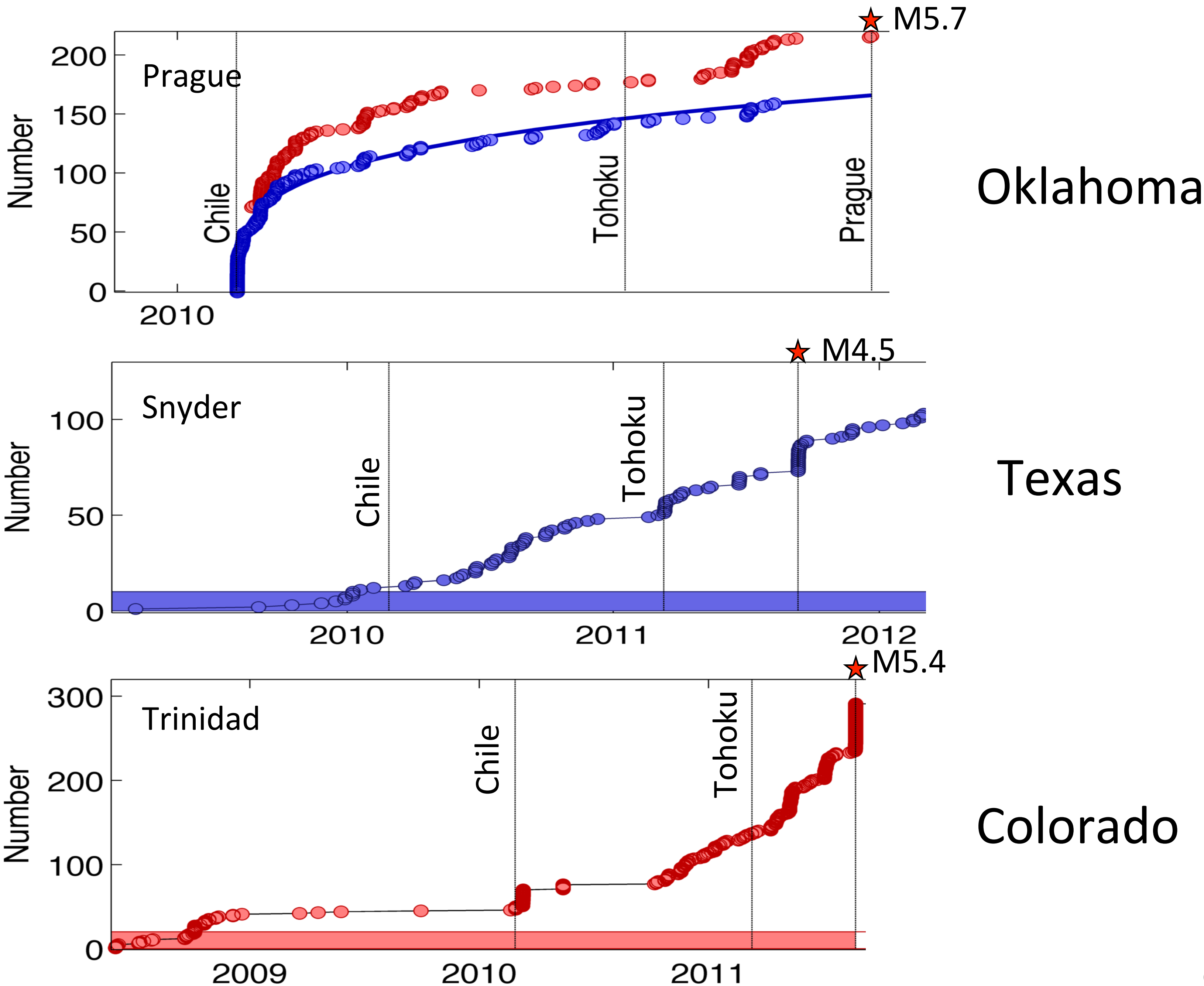


Triggering at Prague, Oklahoma









M5.7
Prague
Number
Chile
Tohoku
Prague
2010
Oklahoma
M4.5
Snyder
Number
Chile
Tohoku
2010
2011
2012
Texas
M5.4
Trinidad
Number
Chile
Tohoku
2009
2010
2011
Colorado

Summary of triggering observations in induced regions

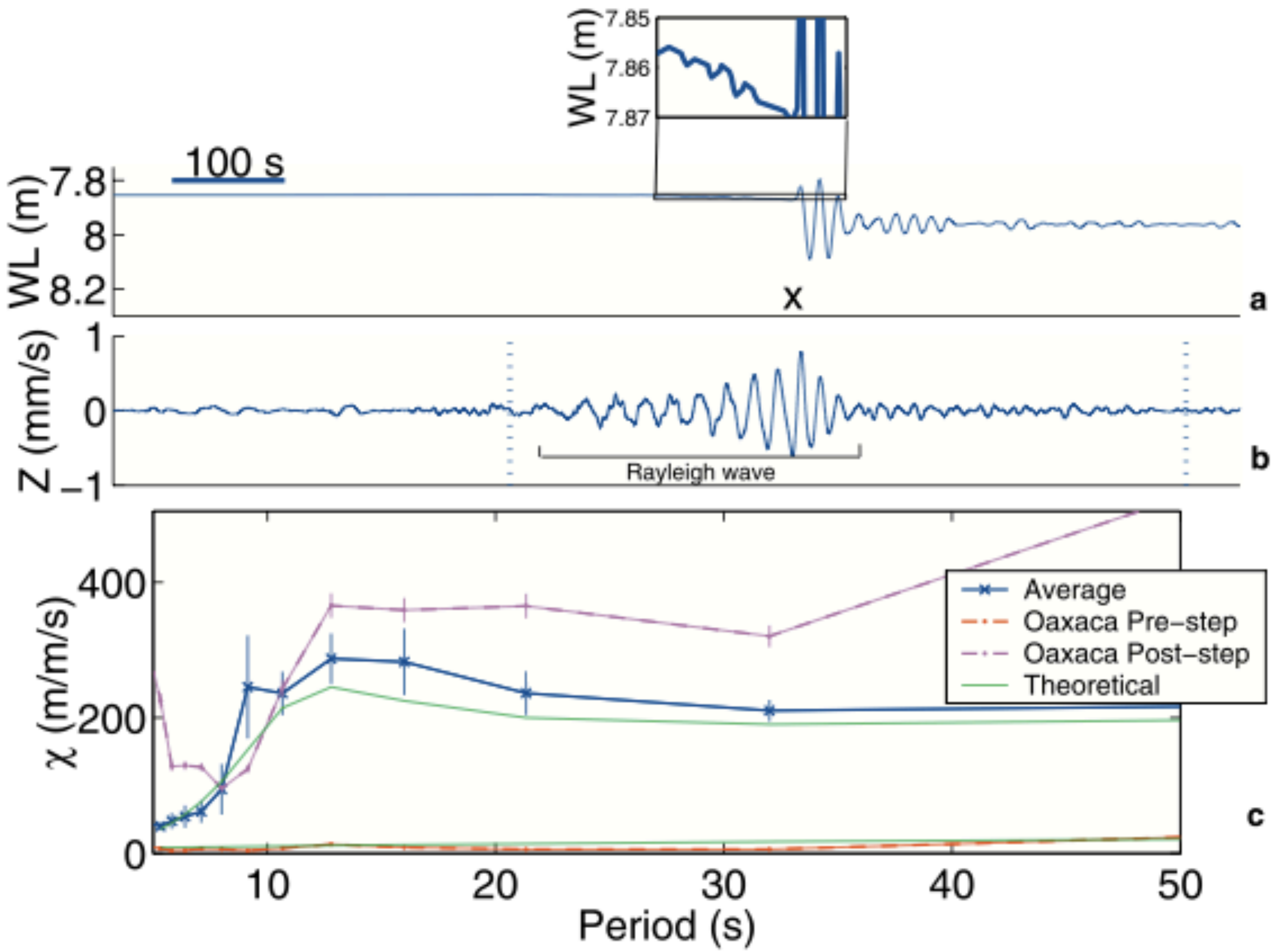
- Injection pressure at all sites is *hydrostatic*
- Only one shot at triggering (recharge needed)
- Long periods may be more effective triggers.
- Triggering *only* at long-term injection sites that hosted large earthquakes within 6-20 months.
- Triggering at *all* long-term injection sites that hosted large earthquakes within 6-20 months.

Evidence for fluid involvement in dynamic triggering

- Fluids can promote conditional stable slip.
- down dip subduction zones are triggerable
- extensional environments are more triggerable than compressional
- regions of fluid induced seismicity are very triggerable
- volcanic and hydrothermal regions are triggerable

the Mechanism of dynamic triggering

Triggering Mechanism: permeability enhancement



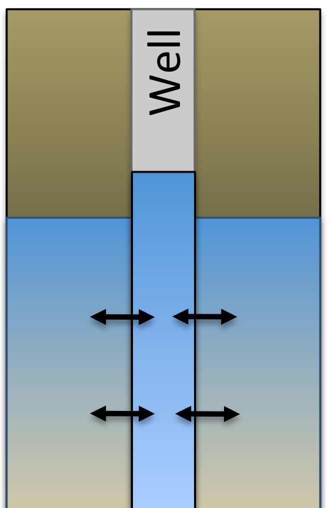
Water level step

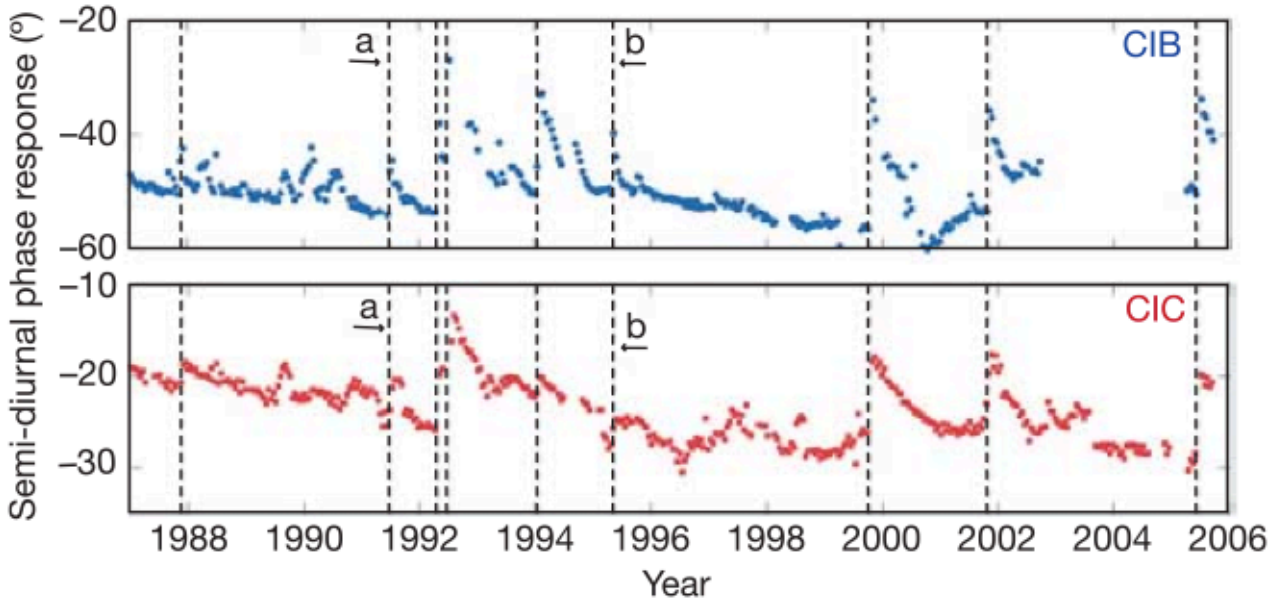
Spectral Amplification increase

1999 M7.4 Oaxaca earthquake: (static stress change < 0.2 Pa)

Brodksy et al, 2003

Triggering Mechanism: permeability enhancement

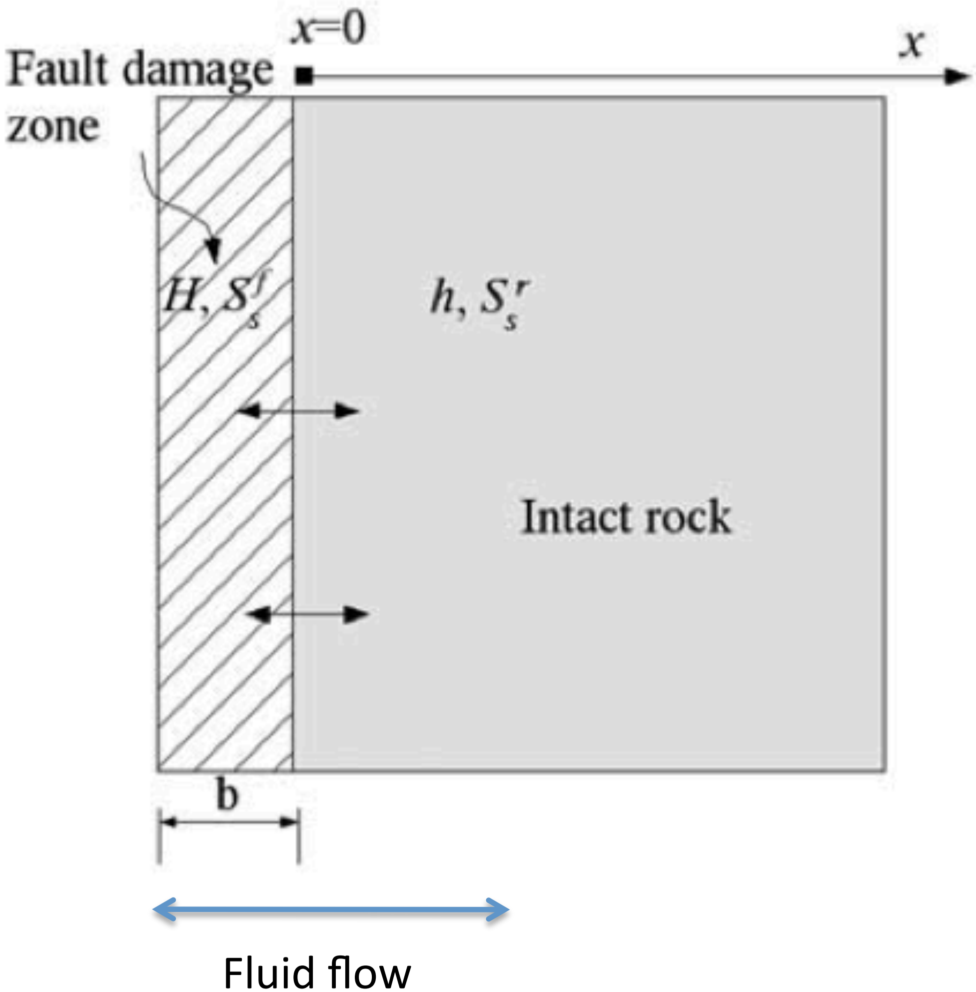




Aquifer permeability is enhanced by seismic waves

Elkhoury and Brodsky 2006

Fluid pumping and fracture unclogging

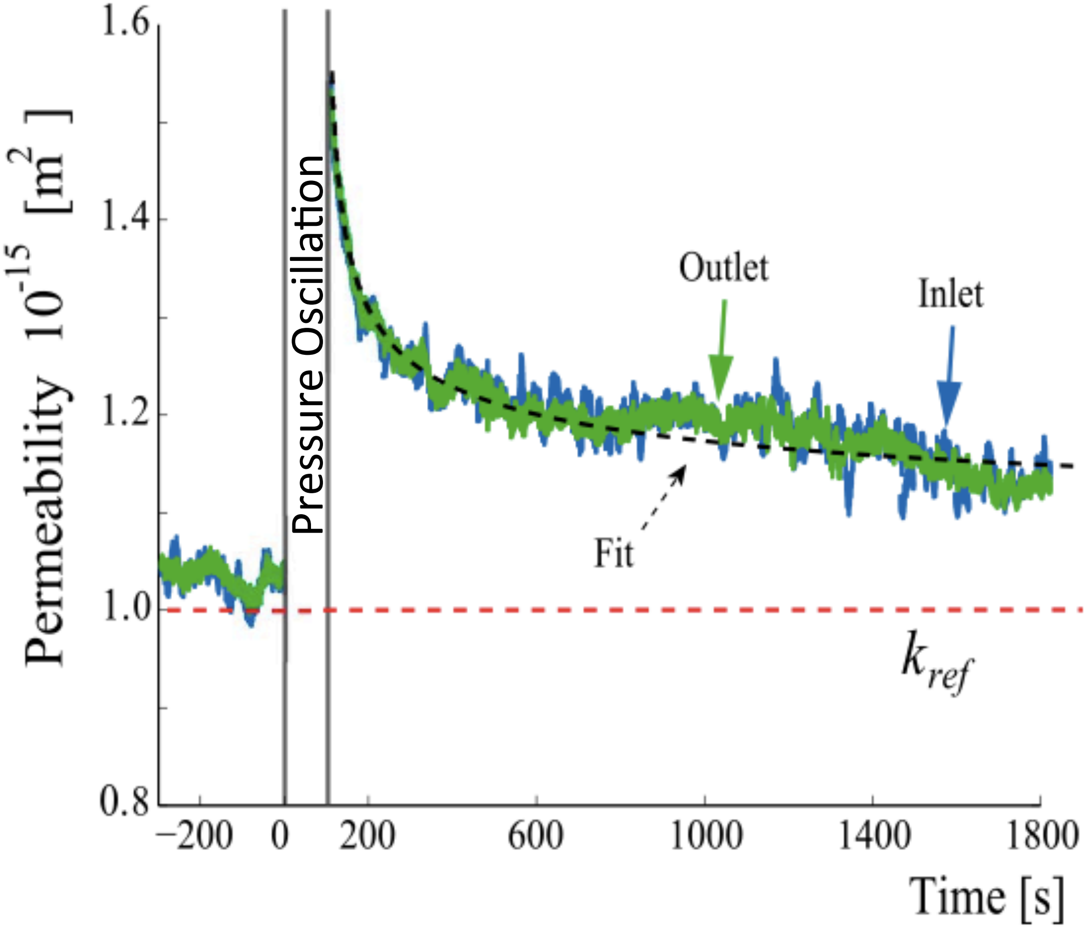


Differences in poro-elastic compressibility (specific storage) drives flow into fault

Diffusion timescale means pressure change in the fault is larger for long period waves.

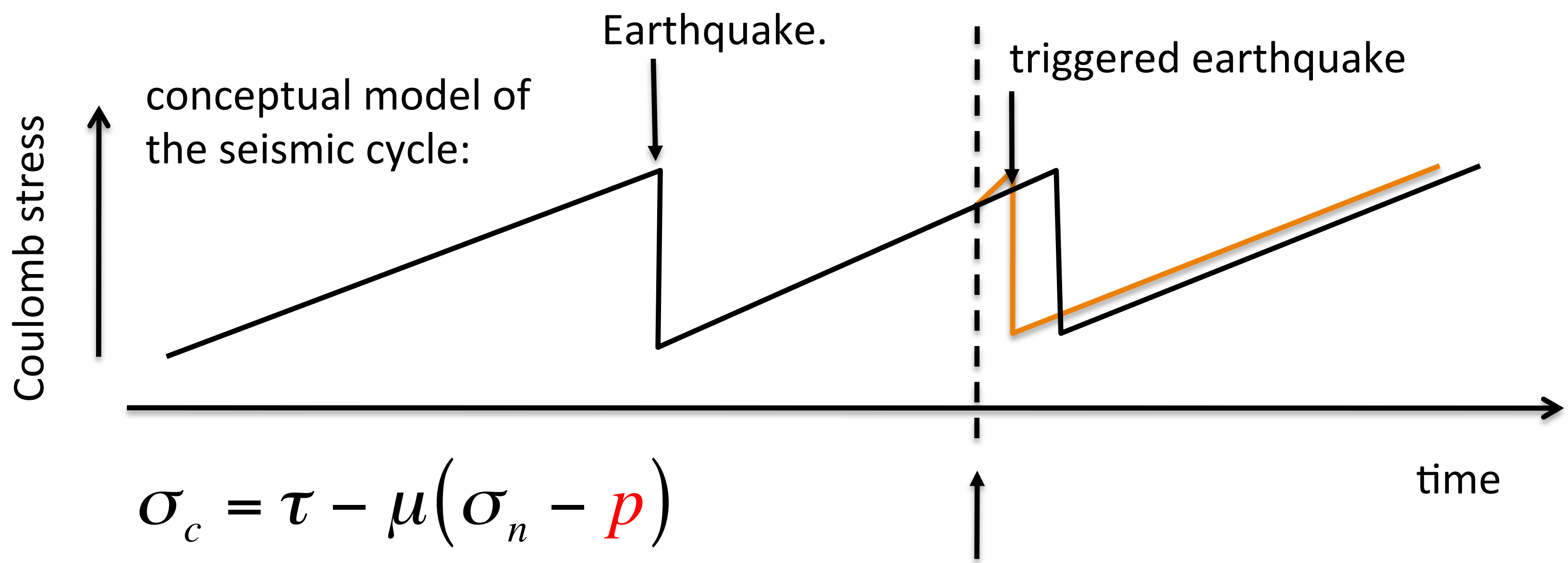
Brodksy and Prejean, 2005

Fracture unclogging in the lab



Elkhoury, et al. 2011

Triggering by changing pore pressure pressurization rate



$$\sigma_c = \tau - \mu\left(\sigma_n - \color{red}{p}\right)$$

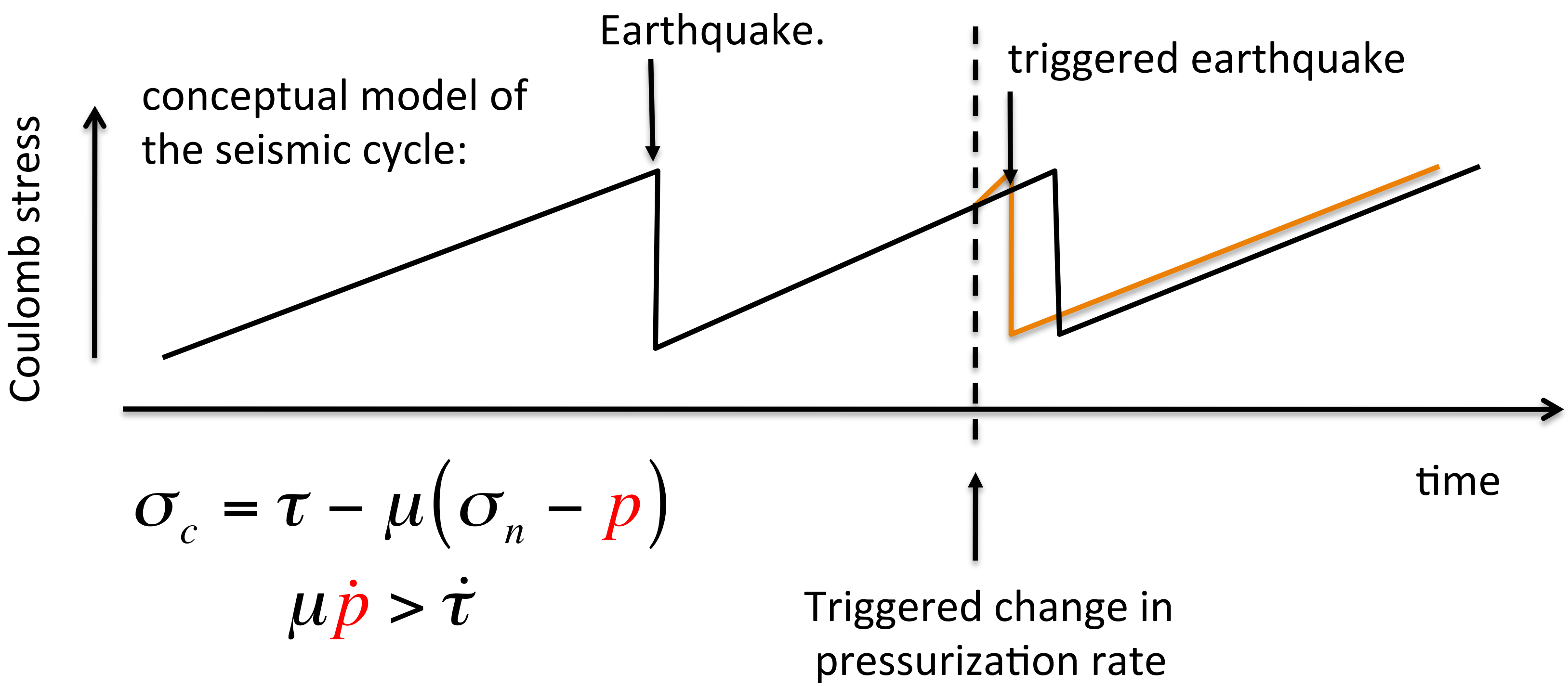
$$\mu \color{red}{\dot{p}} \overset{?}{>} \dot{\tau}$$

Triggering by permeability enhancement explains…

- Enhanced Sensitivity to long periods
- Selective or inconsistent triggering
- Recharge needed between triggers
- Delayed triggering (diffusion of fluids along fault)
- Extreme susceptibility of hydrothermal/volcanic/induced fields

Conclusion

- Water may play an important role in the seismic cycle.



$$\sigma_c = \tau - \mu(\sigma_n - p)$$

$$\mu\dot{p} > \dot{\tau}$$