Mechanics of spontaneously arrested laboratory earthquakes

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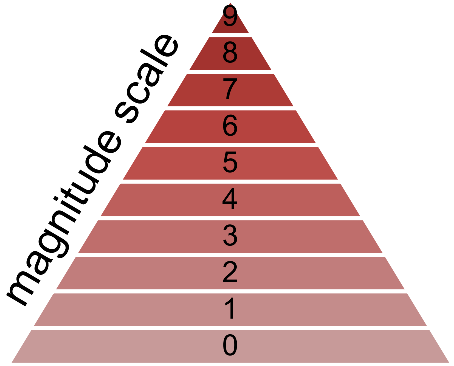
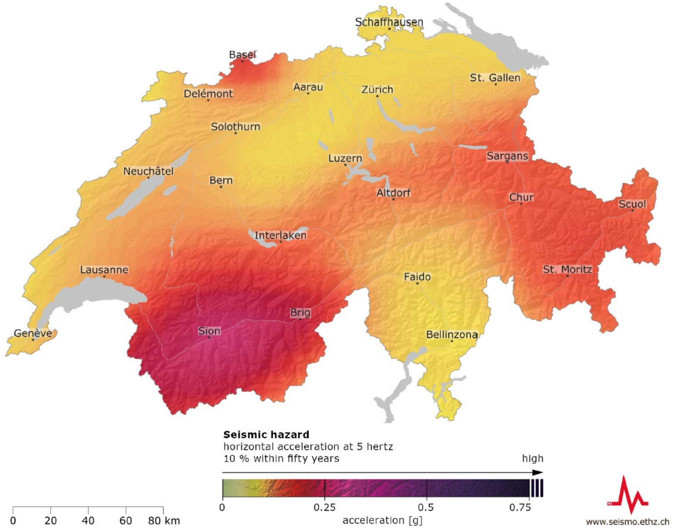
The 101 of earthquakes and seismic hazard

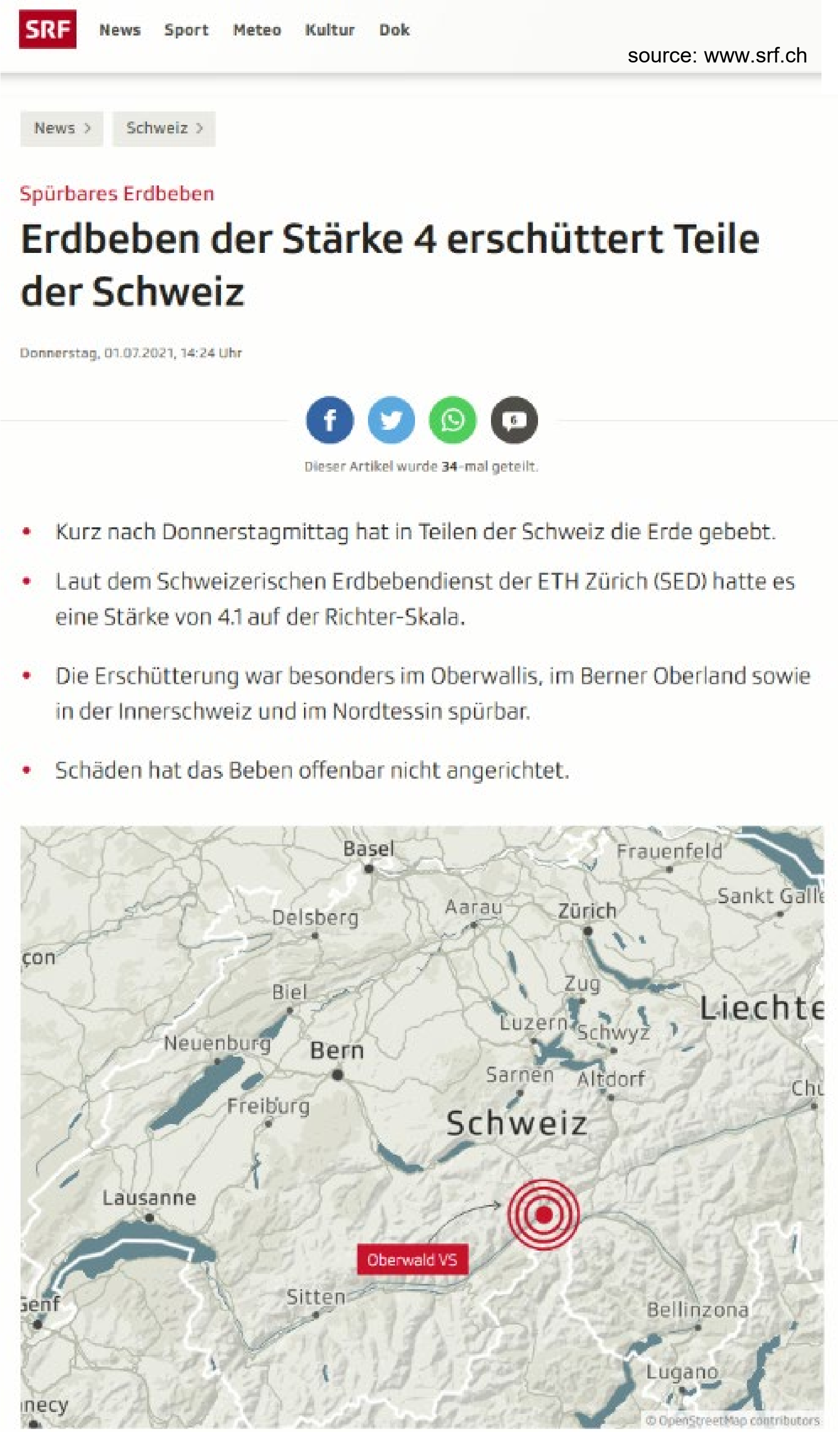
Earthquakes

1. occur at a location (e.g., epicenter)
2. have an intensity (e.g., magnitude)
3. cause ground shaking (→ hazard)
4. are result of motion between tectonic plates



source: John Wiley





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News › Schweiz ›

Spürbares Erdbeben

Erdbeben der Stärke 4 erschüttert Teile der Schweiz

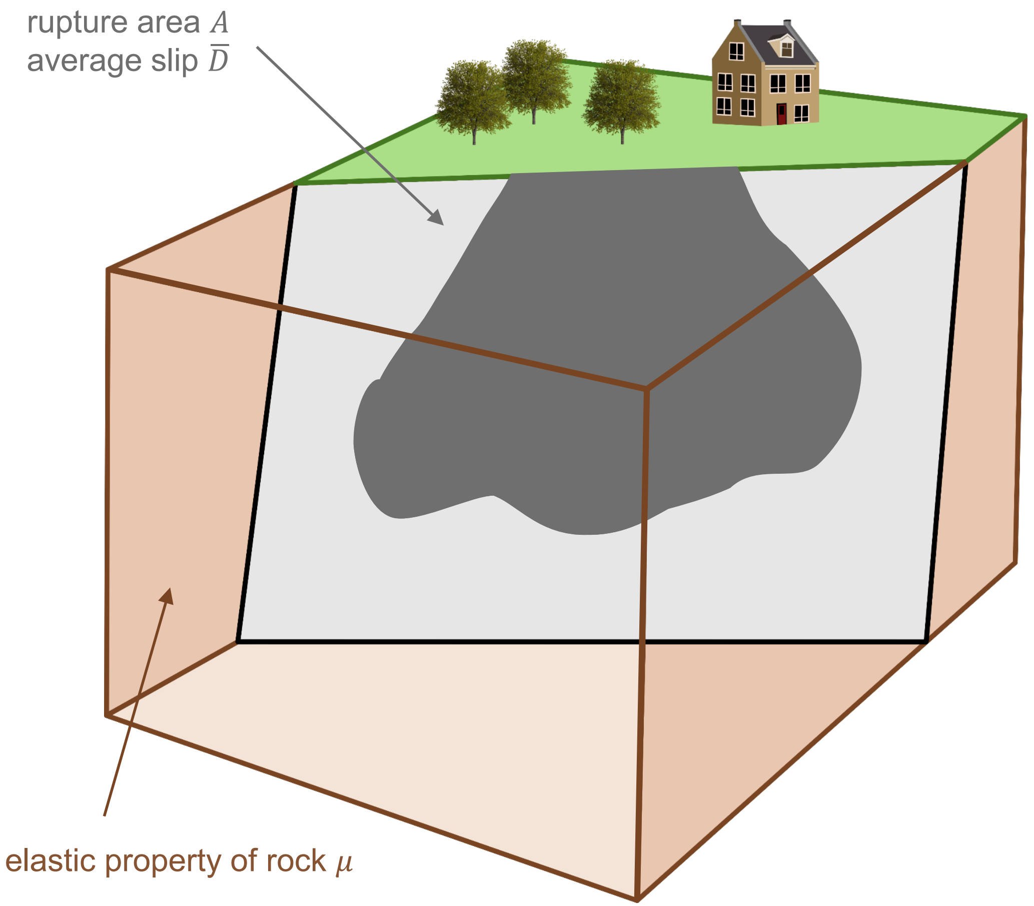
Donnerstag, 01.07.2021, 14:24 Uhr

Dieser Artikel wurde 34-mal geteilt.

- Kurz nach Donnerstagmittag hat in Teilen der Schweiz die Erde gebebt.
- Laut dem Schweizerischen Erdbebendienst der ETH Zürich (SED) hatte es eine Stärke von 4.1 auf der Richter-Skala.
- Die Erschütterung war besonders im Oberwallis, im Berner Oberland sowie in der Innerschweiz und im Nordtessin spürbar.
- Schäden hat das Beben offenbar nicht angerichtet.

source: www.srf.ch

Earthquakes are ruptures propagating across tectonic faults



Initiation when and where?

Propagation how “loud”?

Arrest how large?

moment magnitude: $M_W = \frac{2}{3}\log_{10}(M_0) - 10.7$

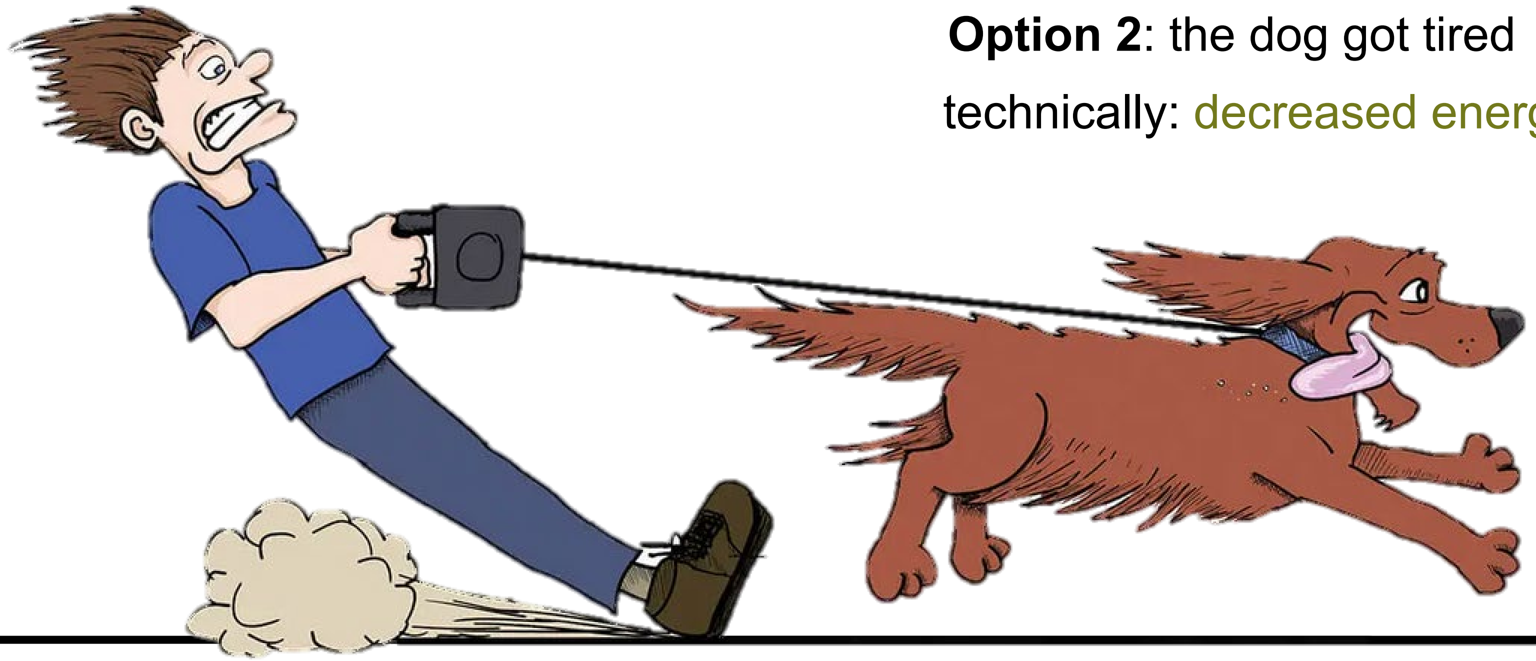
with seismic moment: $M_0 = \mu \bar{D} A$

How to make an earthquake stop?
Conceptually, there are two options to stop moving

Earthquake: tectonic stresses
&
fault properties

Option 2: the dog got tired

technically: decreased energy



source: https://www.groomertogroomer.com

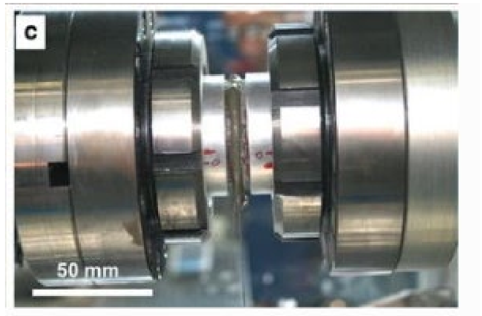
Option 1: you are strong and break well enough

technically: increased friction

Earthquake: fault properties

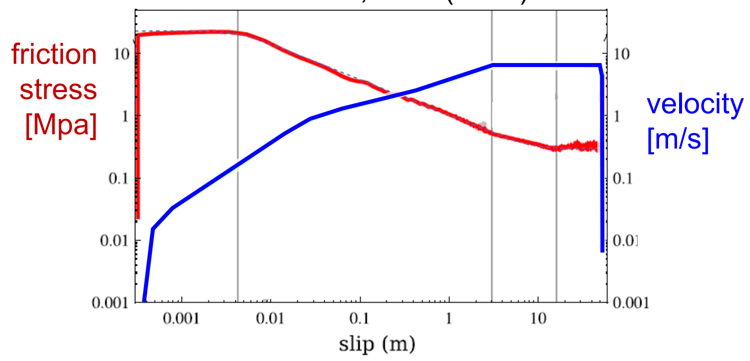
Fault (friction) properties can be measured in small-scale laboratory experiments

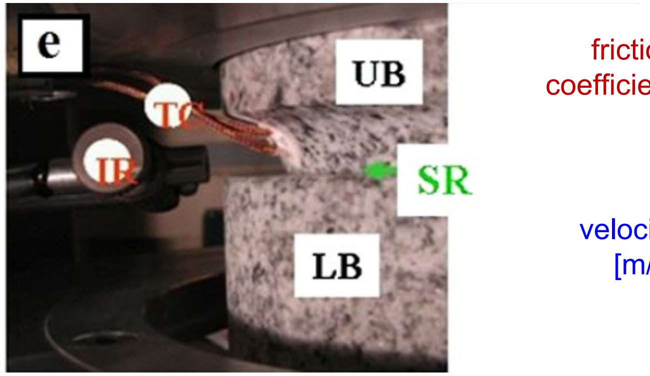
For example: high-velocity rotary shear experiments



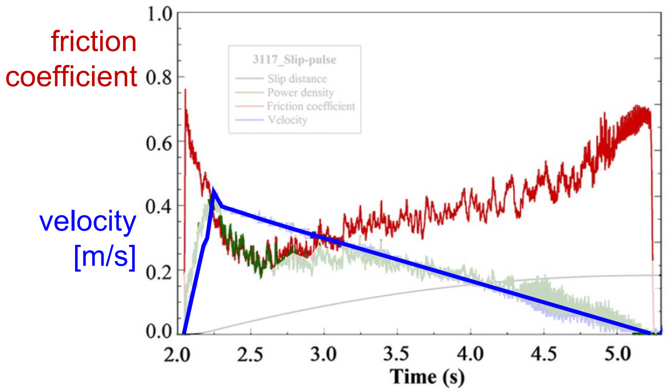
Di Toro *et al.*, *Rend. Fis. Acc. Lincei* (2010)

Nielsen et al., GRL (2016)





Liao *et al.*, *Earth Planet Sci. Lett.* (2014)



and many more…

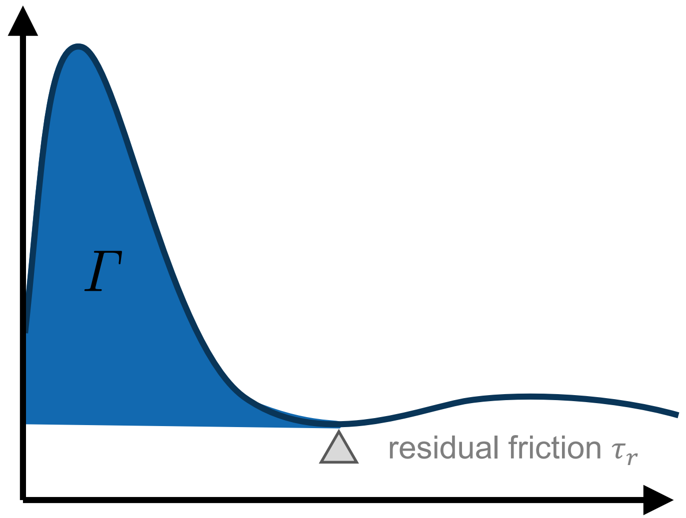
Studied effects:

- rock type
- normal pressure
- slip distance
- slip velocity
- …

Still many questions open:

- natural conditions
- fault heterogeneities
- …

One key friction parameter is the fracture energy



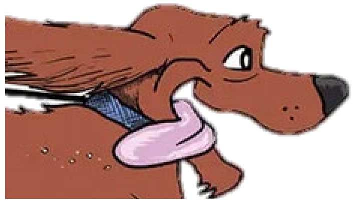
the fracture energy is the energy dissipated
during the frictional weakening process

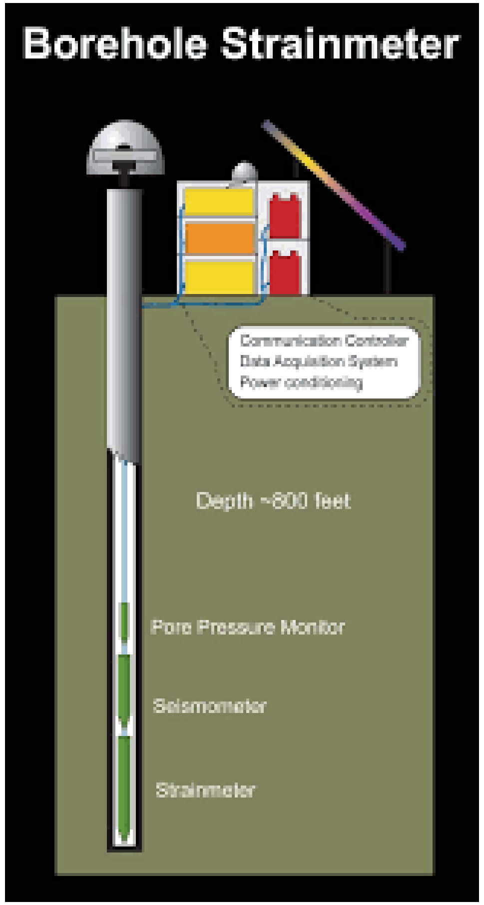
$$\Gamma = \int_0^\infty \left[\tau(\delta) - \tau_{\mathrm{r}}\right] \, \mathrm{d}\delta$$

[Rice, 1968; Ida, 1972]

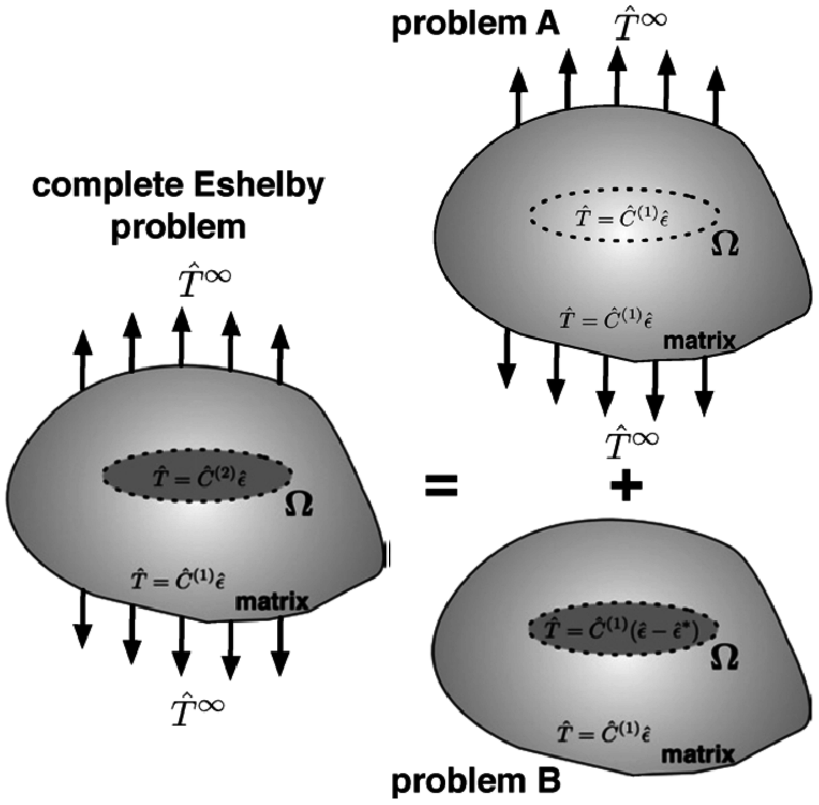
the fracture energy is crucial
for earthquake rupture propagation and arrest

Tectonic stresses and stress changes are difficult to measure





Mencin, (2009). Advanced Workshop on Evaluating, Monitoring and Communicating Volcanic and Seismic Hazards in East Africa

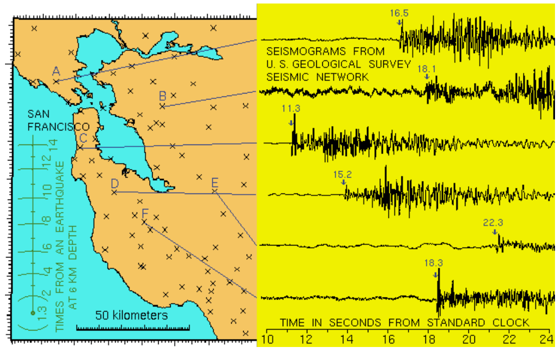


Colombo & Giordano, Rep. Prog. Phys. (2011).

Uniform initial stress assumption

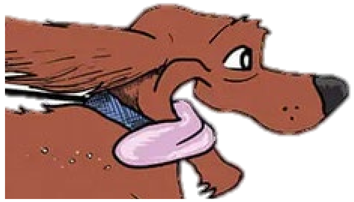
$$\overline{\Delta\tau} = \frac{7}{16}\frac{M_0}{r_0^3}$$

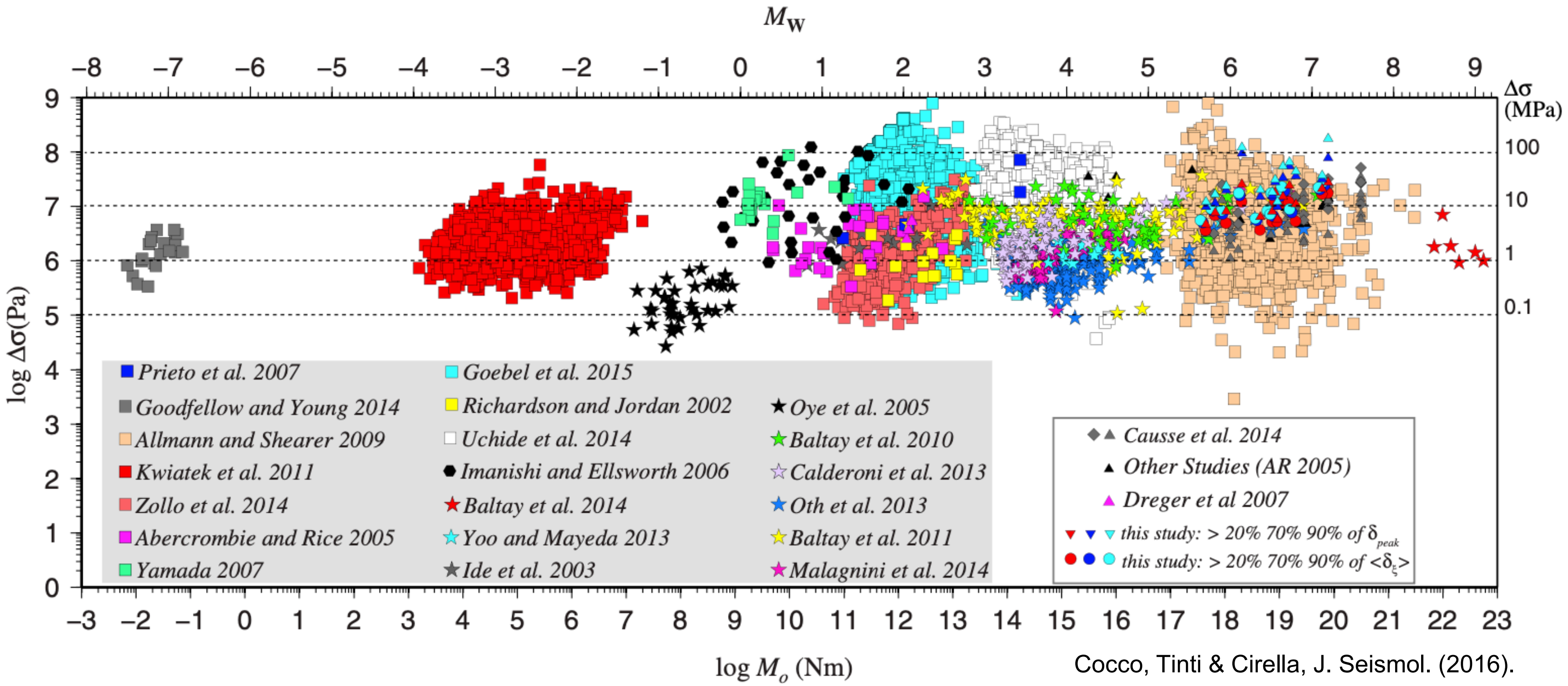
[Kanamori & Anderson, 1975]



https://www.usgs.gov/faqs/how-do-seismologists-locate-earthquake

Seismologically-estimated stress drops vary over multiple orders of magnitude





Cocco, Tinti & Cirella, J. Seismol. (2016).

part of variation is due to uncertainty

$$\overline{\Delta\tau} = \frac{7}{16}\frac{M_0}{r_0^3}$$

How to make an earthquake stop?
Conceptually, there are two options to stop moving

Earthquake: tectonic stresses
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fault properties

Option 2: the dog got tired

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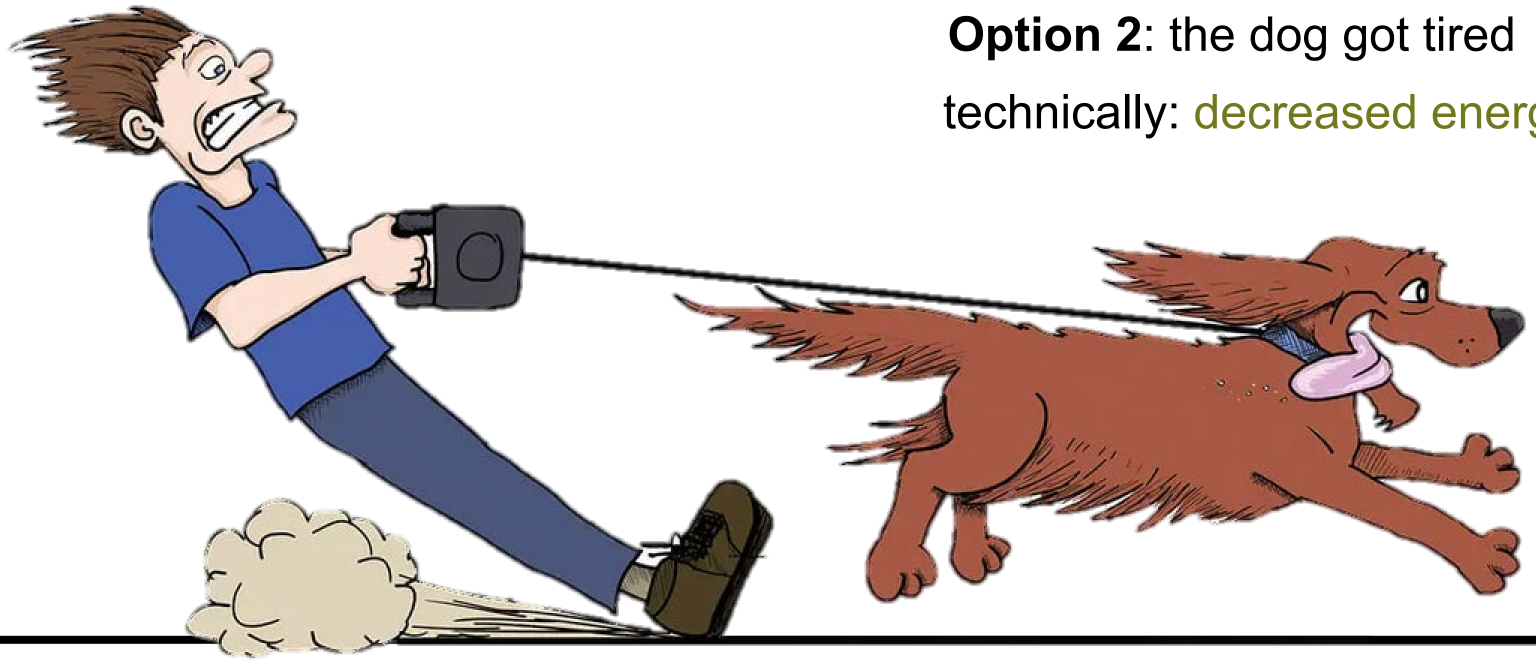


source: https://www.groomertogroomer.com

Option 1: you are strong and break well enough

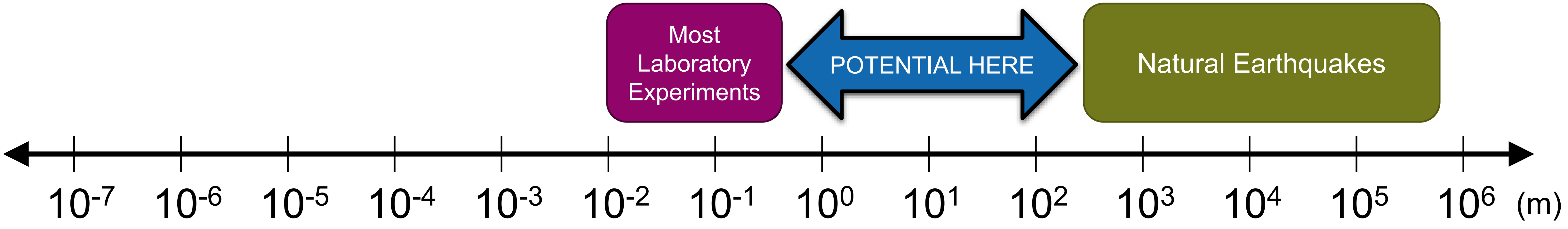
technically: increased friction

Earthquake: fault properties

How can we find out how earthquakes arrest?
Large-scale laboratory earthquakes may provide insight!

- fault properties

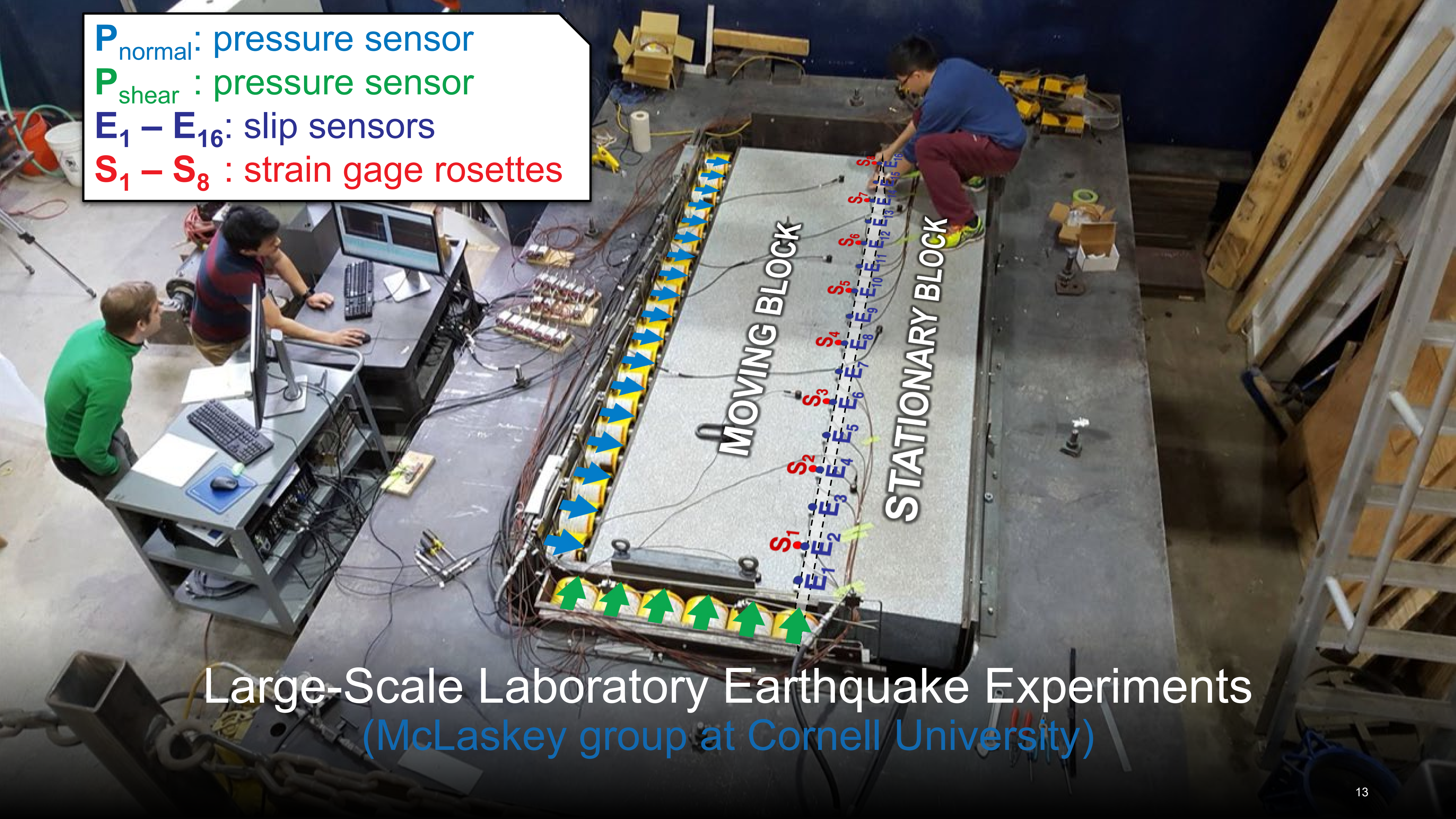
- tectonic stress (drop)
- natural loading condition
- system heterogeneities



Overview of three parts

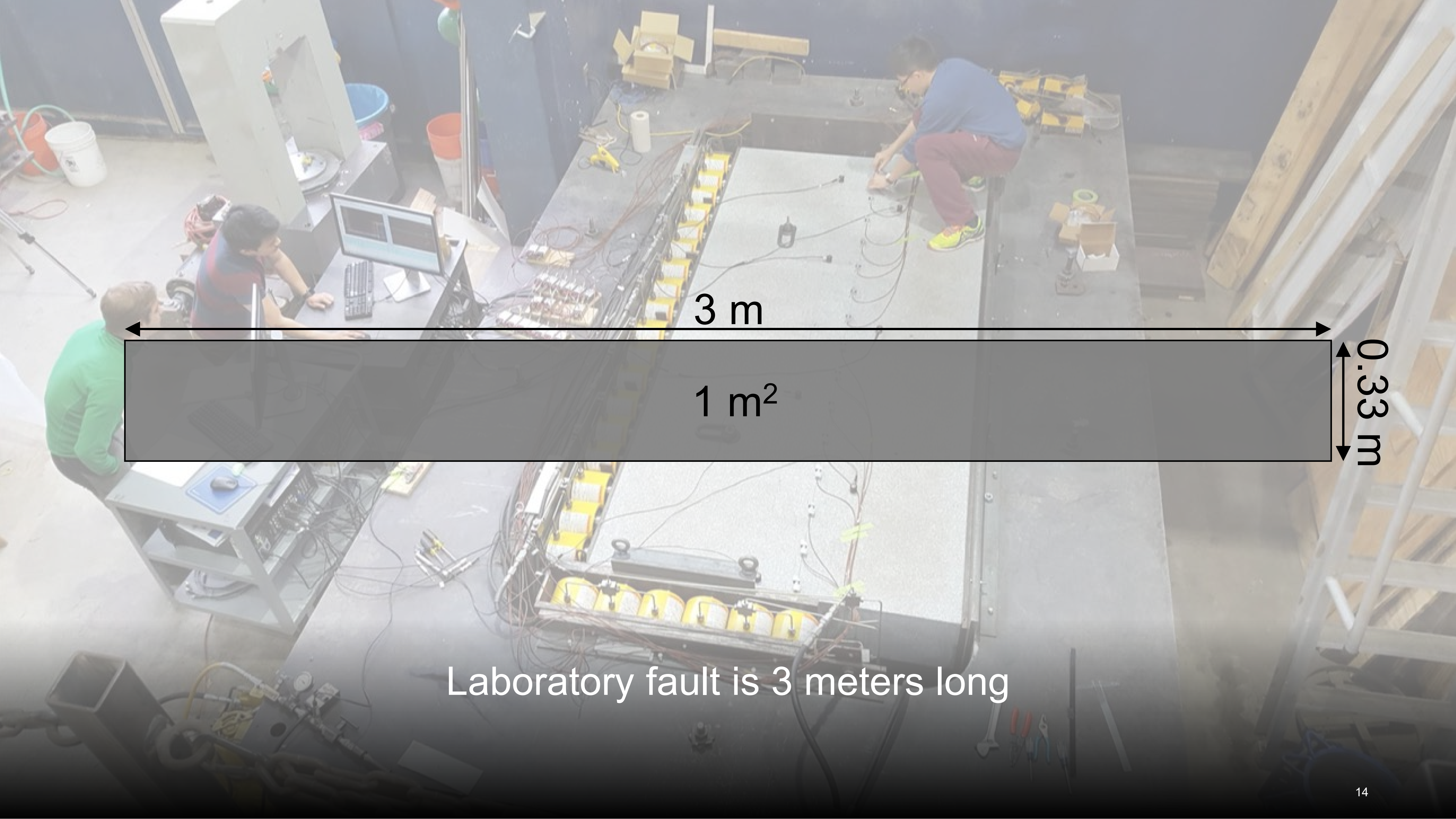
a. Summary of experiments
b. Why laboratory earthquakes arrest
c. Laboratory earthquakes arrest from a seismology perspective

Summary of experiments
(conducted at Cornell University)



Large-Scale Laboratory Earthquake Experiments

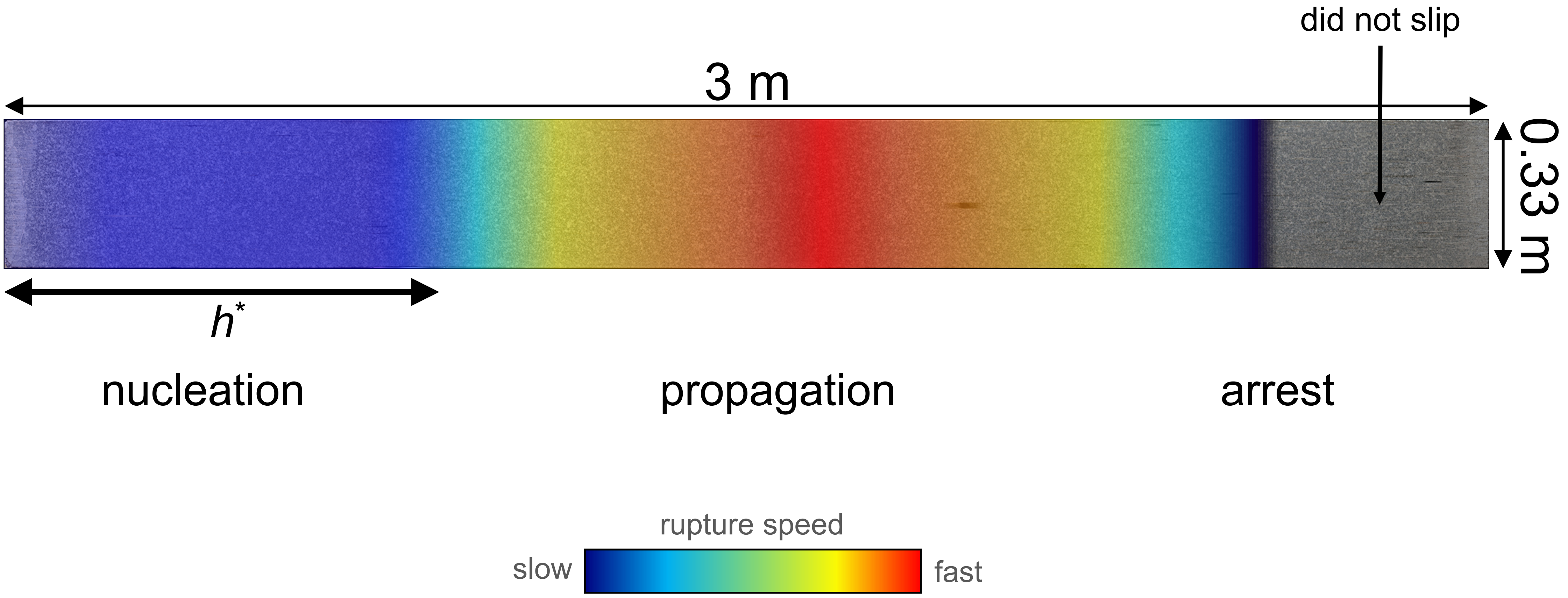
(McLaskey group at Cornell University)



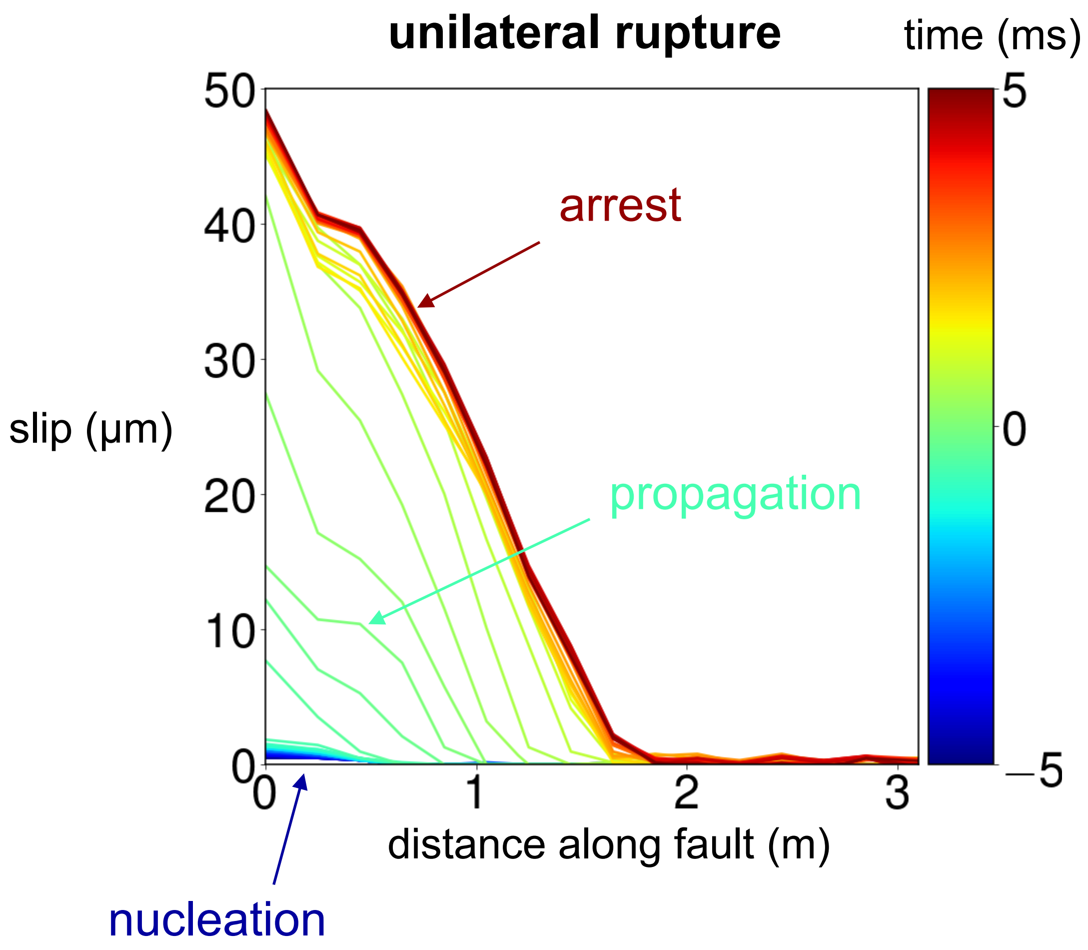
Laboratory fault is 3 meters long

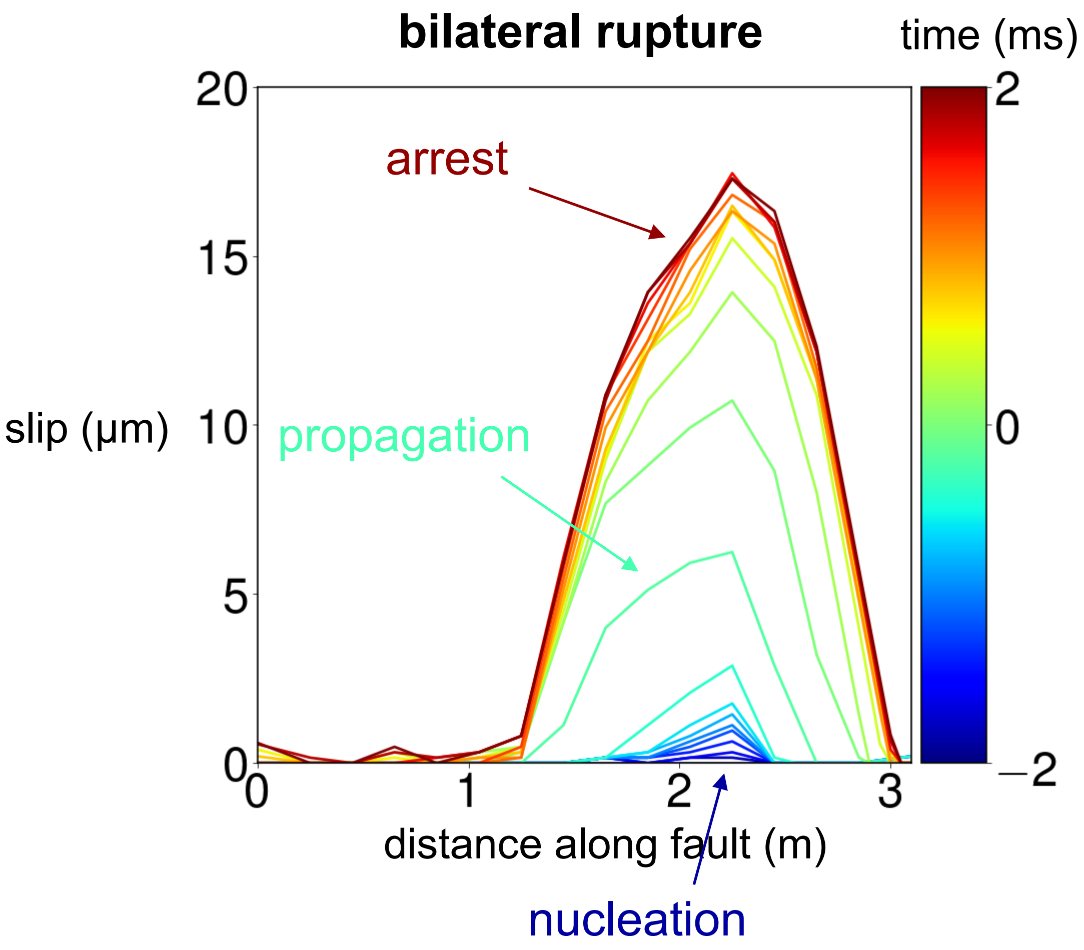
Why 3 meters?

1. h^* – Critical nucleation length
2. For granite in lab conditions, $h^* \approx 0.5 - 1$ m



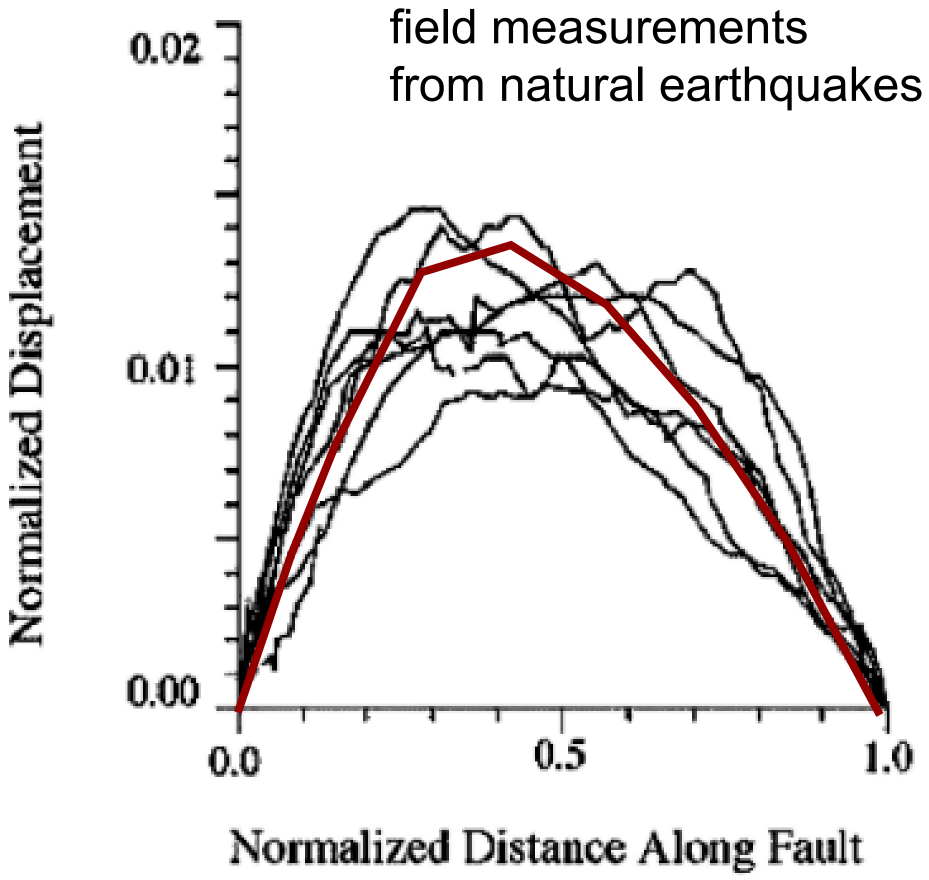
Confined laboratory earthquakes present all three phases: nucleation, propagation, and arrest



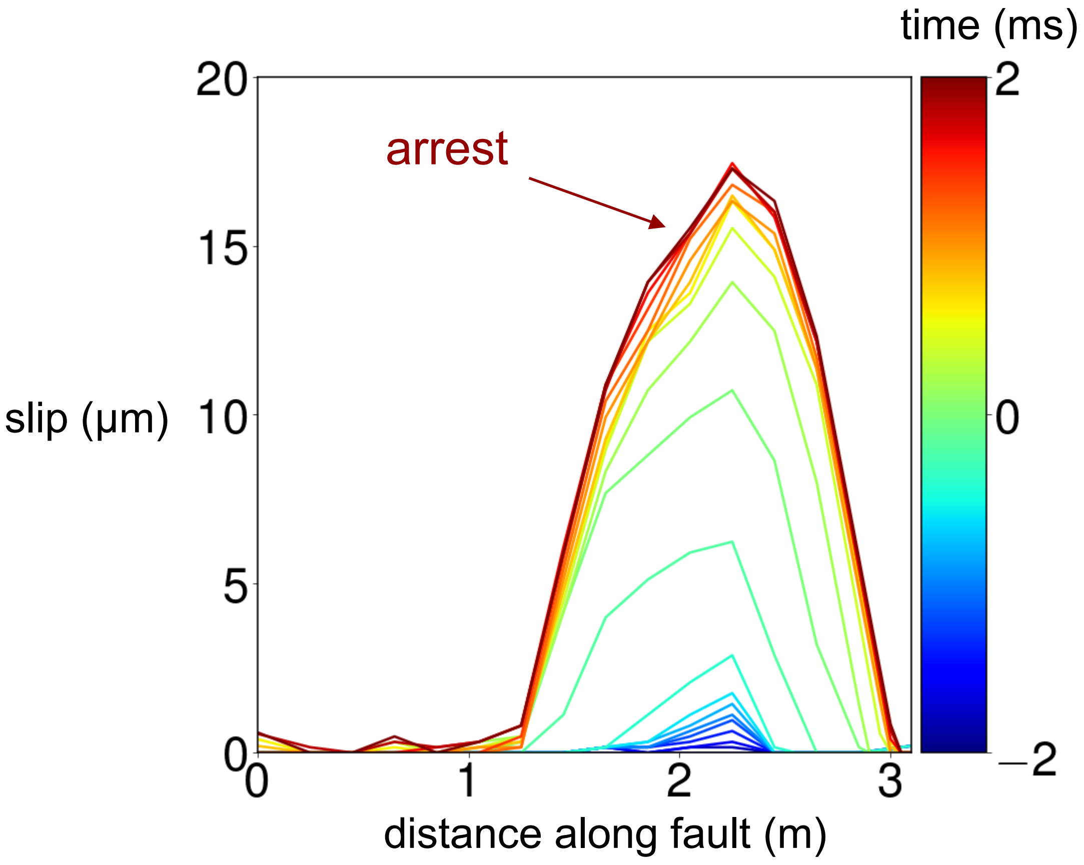


snapshots with Δt = 0.2 msec

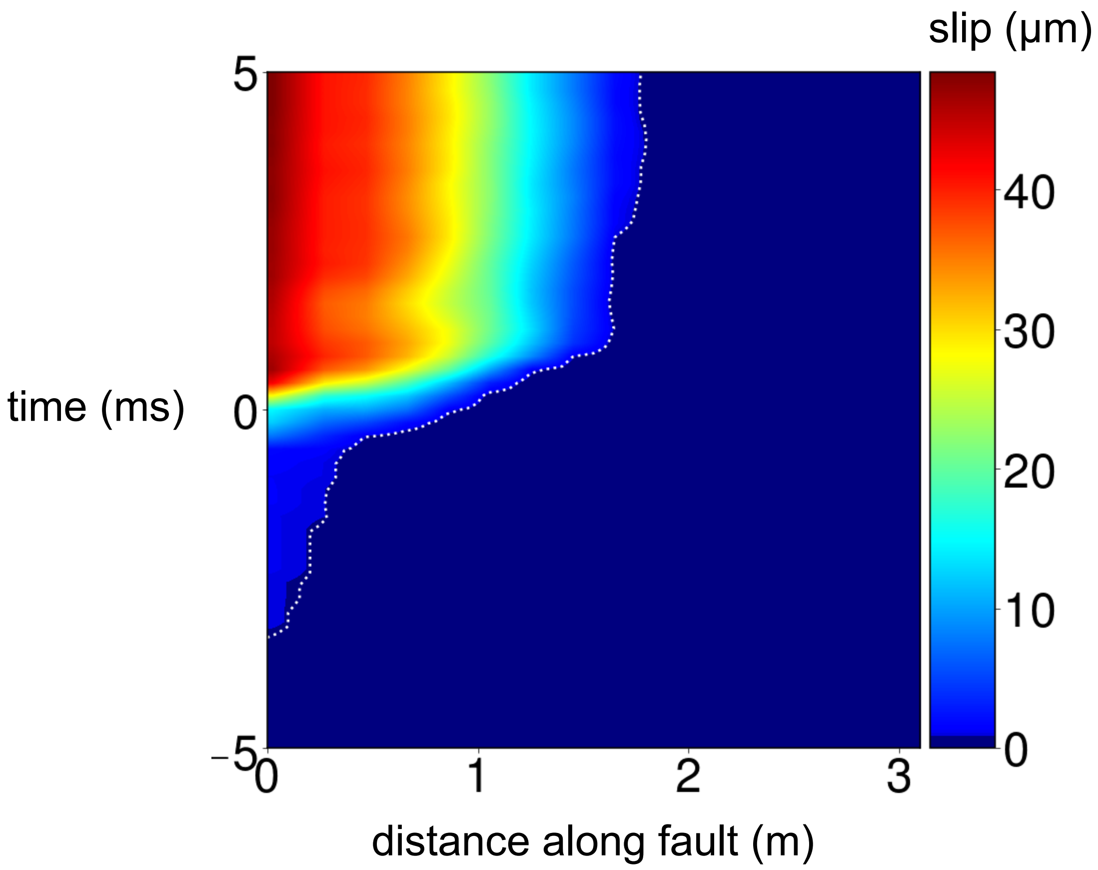
Slip distribution of arrested laboratory earthquakes is qualitatively comparable to natural earthquakes

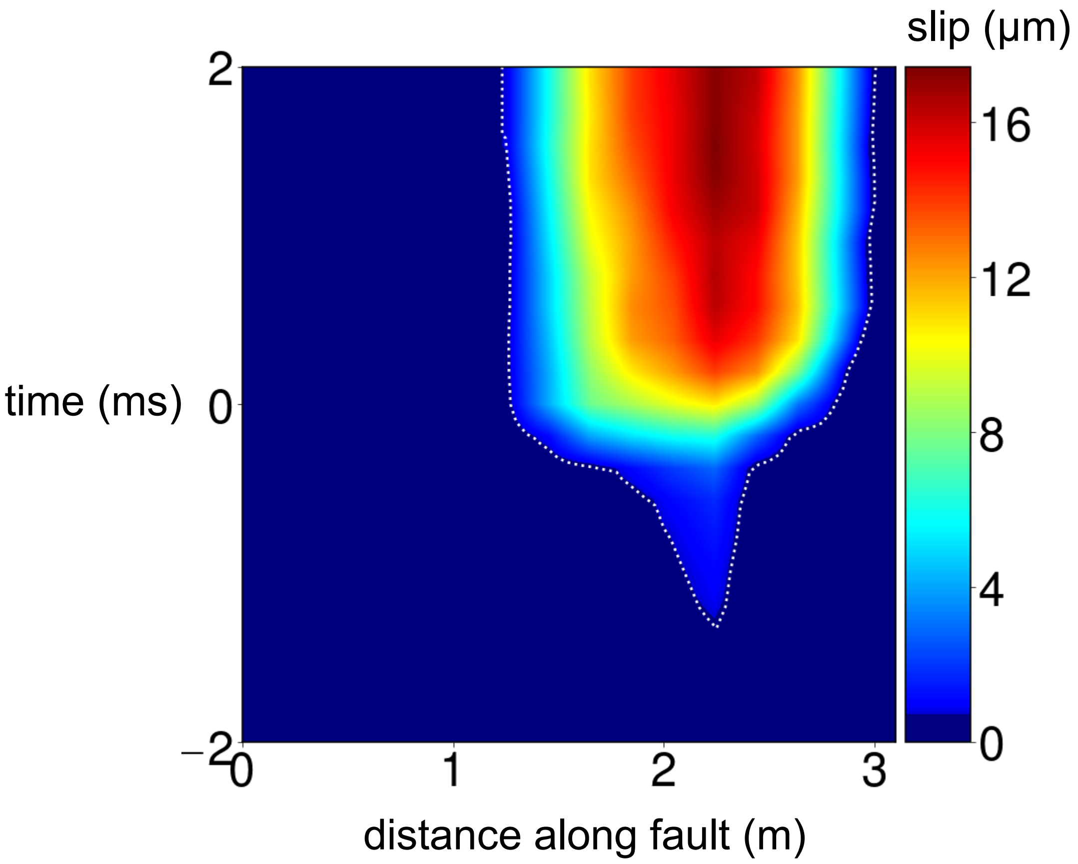


(Scholz and Lawler, 2004)

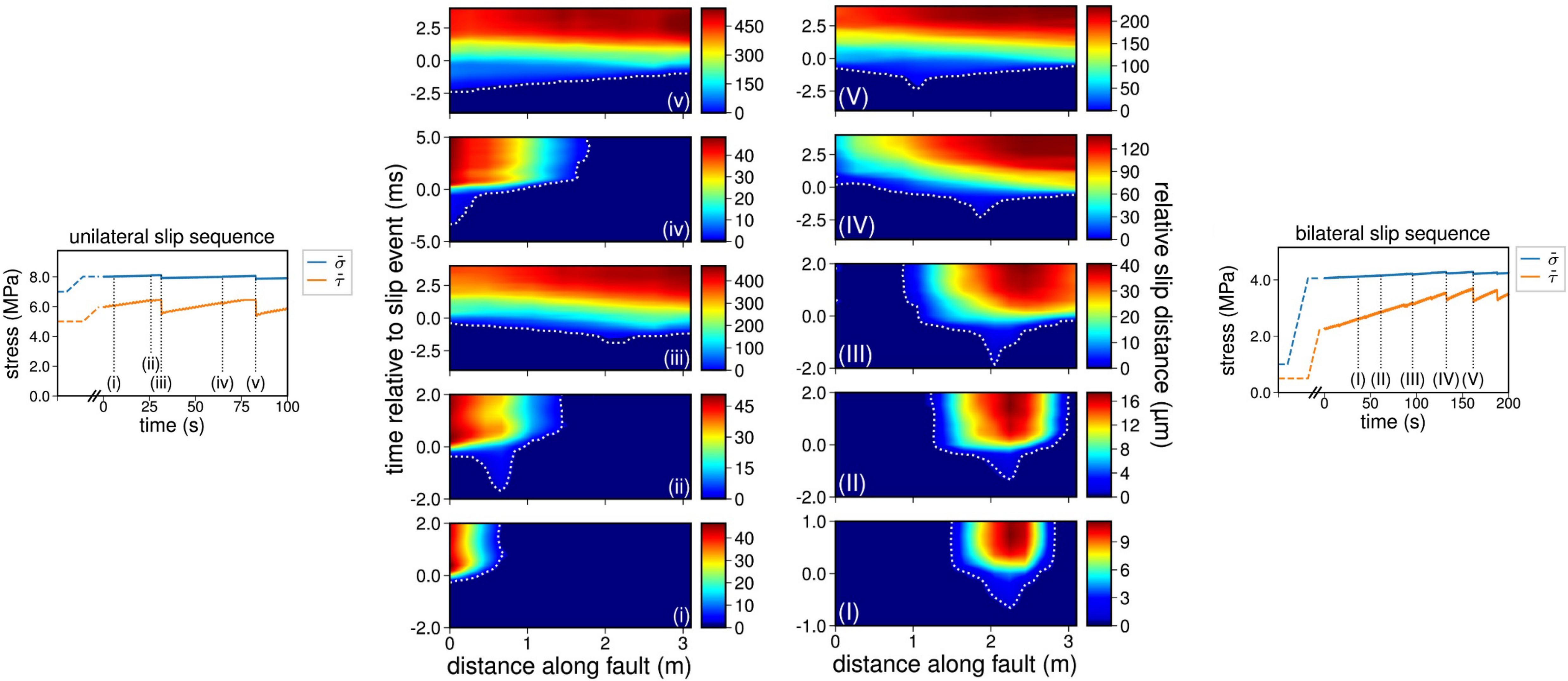


The three earthquake phases appear also in the space-time diagrams



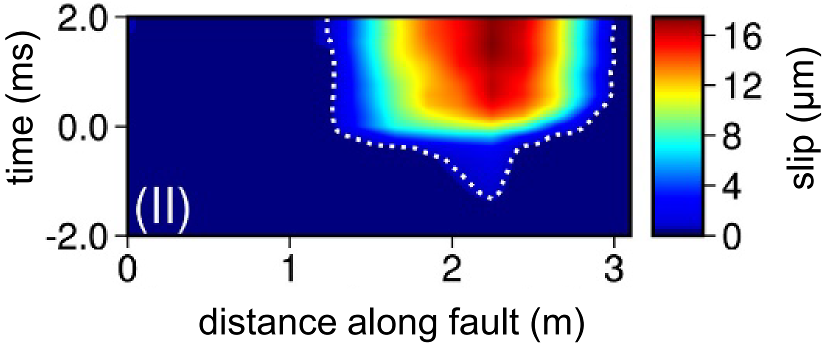


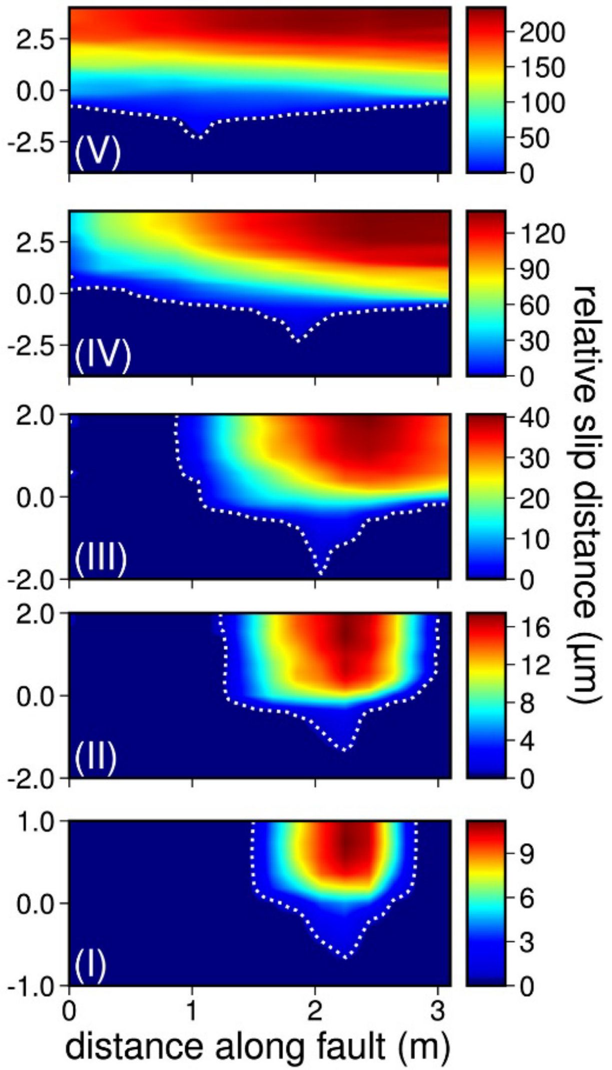
Earthquake sequences in the laboratory



[Ke *et al.*, *Geophys. Res. Lett.*, 2018]

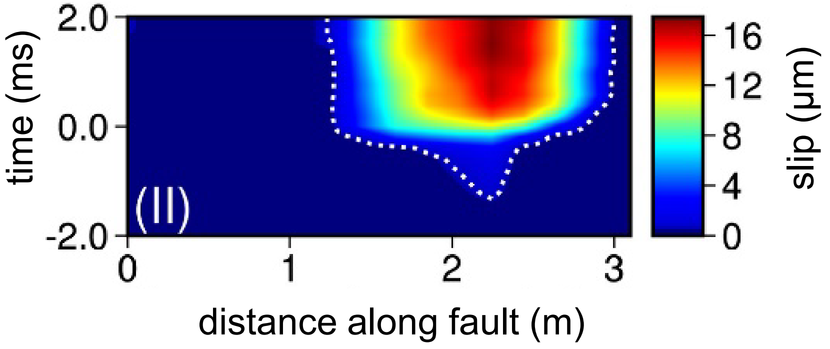
What governs the spontaneous arrest of laboratory earthquakes?

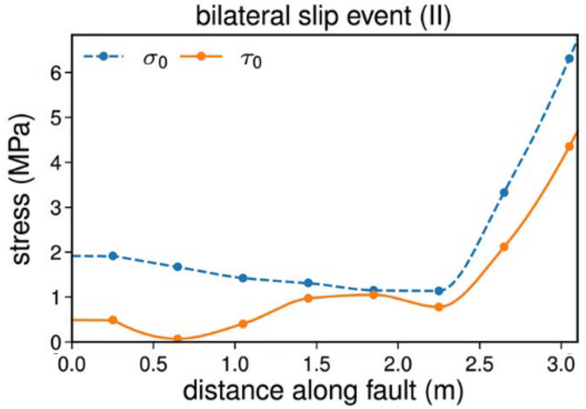




[Ke *et al.*, *Geophys. Res. Lett.*, 2018]

What governs the arrest of a fault rupture?



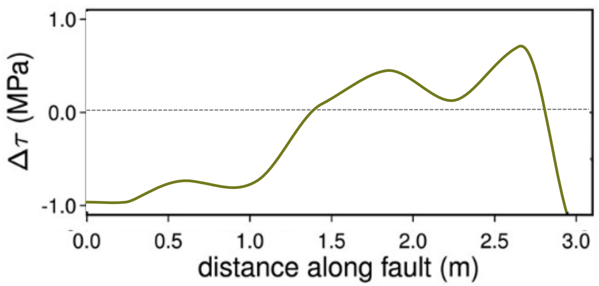


measured normal and shear stress along fault

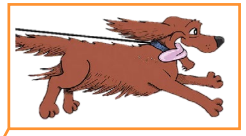
but really stress change matters

$$\Delta\tau_{pot} = \tau_0 - \tau_r$$

could come from friction law



$\Delta\tau_{pot} > 0$



$$G_{II}^s = \frac{\alpha}{E_0}(K_{II}^s)^2$$

$$K_{II}^s(x_c \pm a) = \frac{1}{\sqrt{\pi a}} \int_{-a}^{a} \Delta\tau_{pot}(x_c + s) \sqrt{\frac{a \pm s}{a \mp s}} ds$$

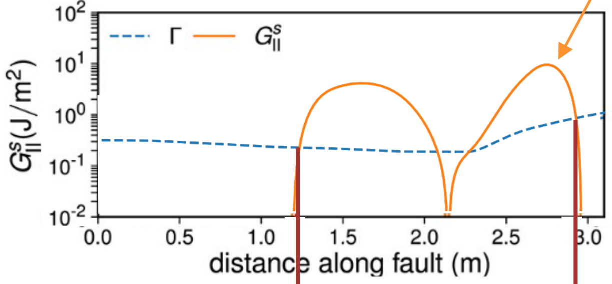
[Kammer *et al.*, *Tribol. Lett.*, 2015]

however, we should think in terms of energy

$$\boxed{G_{II}^s(x)} < \boxed{\Gamma(x)}$$

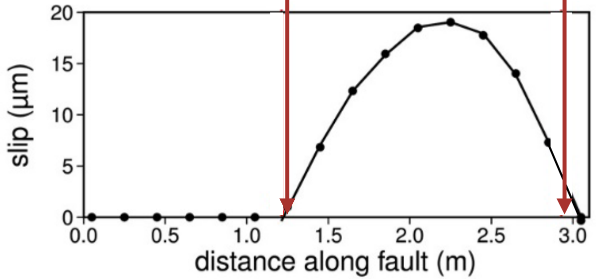
driving force: energy release rate

resistance: fracture energy



compare!

measured slip after arrest along fault



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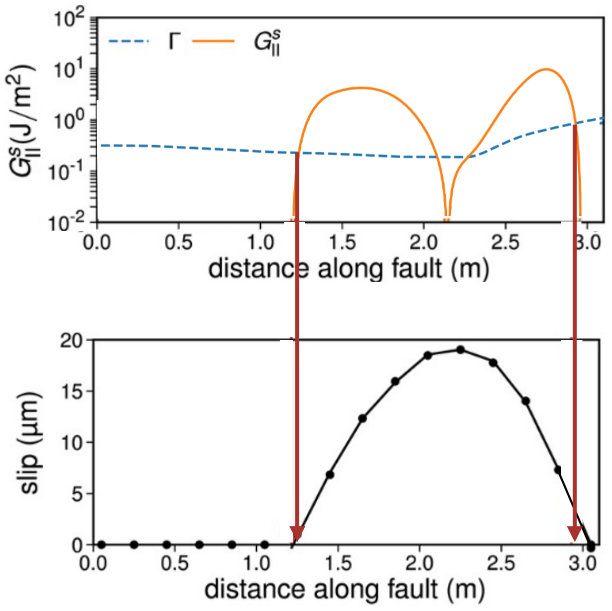
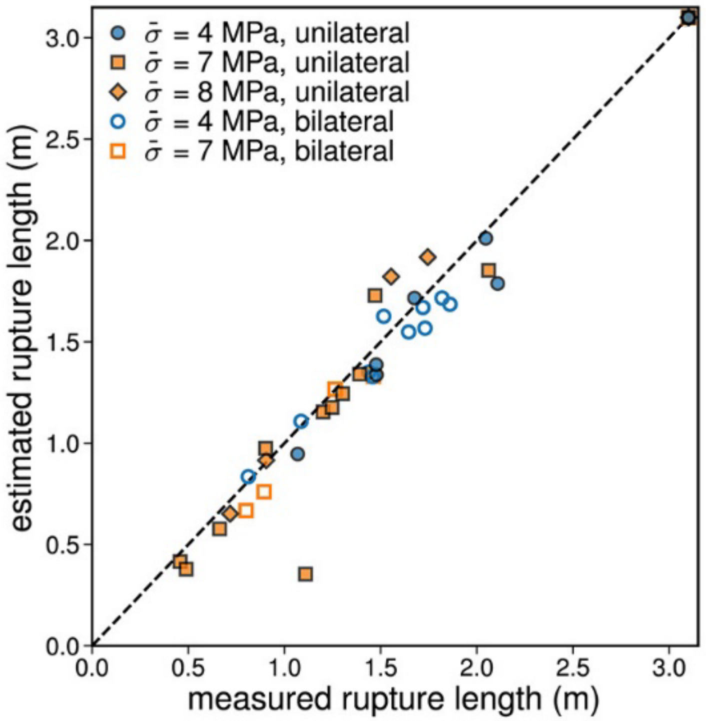
[Ke *et al.*, *Geophys. Res. Lett.*, 2018]

An energy balance governs arrest of fault ruptures

$$G_{II}^{s}(x) < \Gamma(x)$$

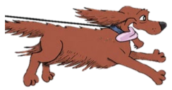


35 contained, and
24 complete ruptures

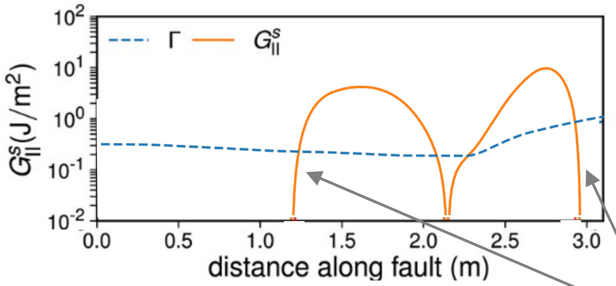


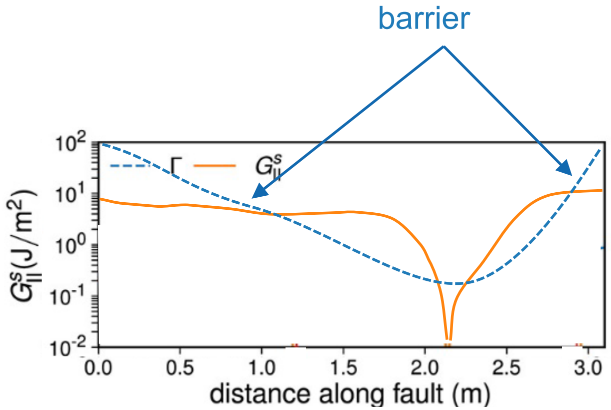
[Ke *et al.*, *Geophys. Res. Lett.*, 2018]

similar results for PMMA: Bayart et al., *Nat. Phys.*, 2016

Who made it stop? The dog owner  or the dog  ?

arrest criterion: $\boxed{\Gamma(x)} > \boxed{G_{II}^{s}(x)}$





The responsible is: 

the dog runs out of energy

lab earthquake: the rock is not pushing enough

?

What if the responsible was: 

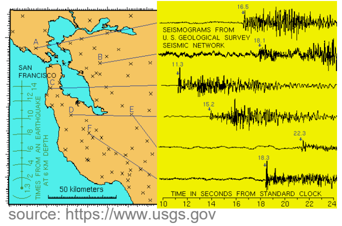
the friction would have to increase (→ fault barrier)

commonly assumed scenario for natural earthquake

Arrest by fault barrier has been used out of necessity and because it worked

Arrest by fault barrier is commonly assumed because…

1) we still do not know much about stress drop



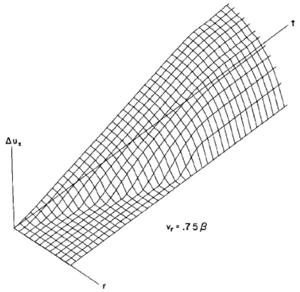
source: https://www.usgs.gov

$$\overline{\Delta\tau} = \frac{7}{16}\frac{M_0}{r_0^3}$$

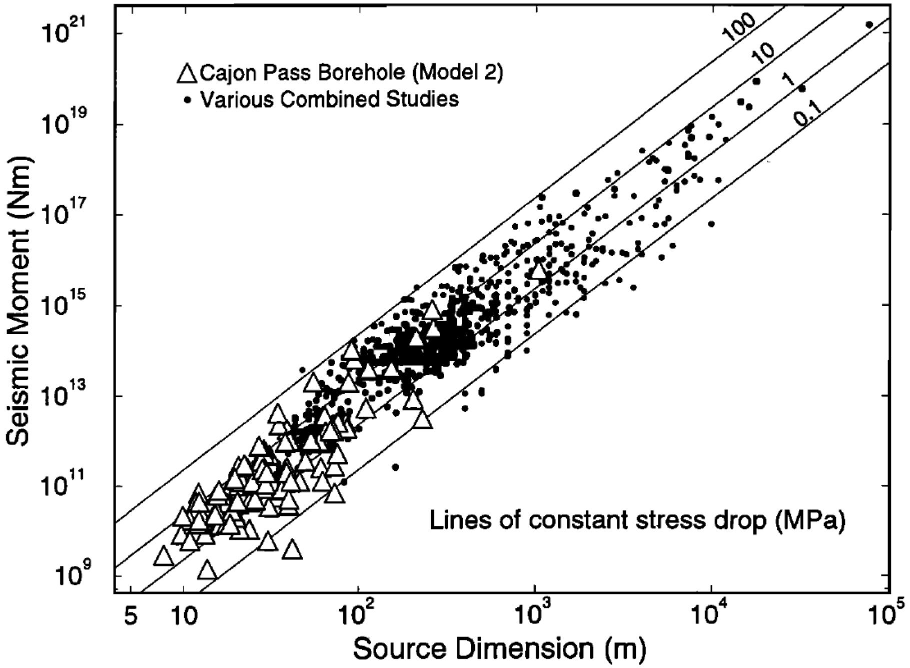
[Kanamori & Anderson, 1975]

hence, stress drop is assumed to be <u>constant</u>

2) it was implicitly assumed in early (numerical) work
that was instrumental for analysis of natural earthquakes

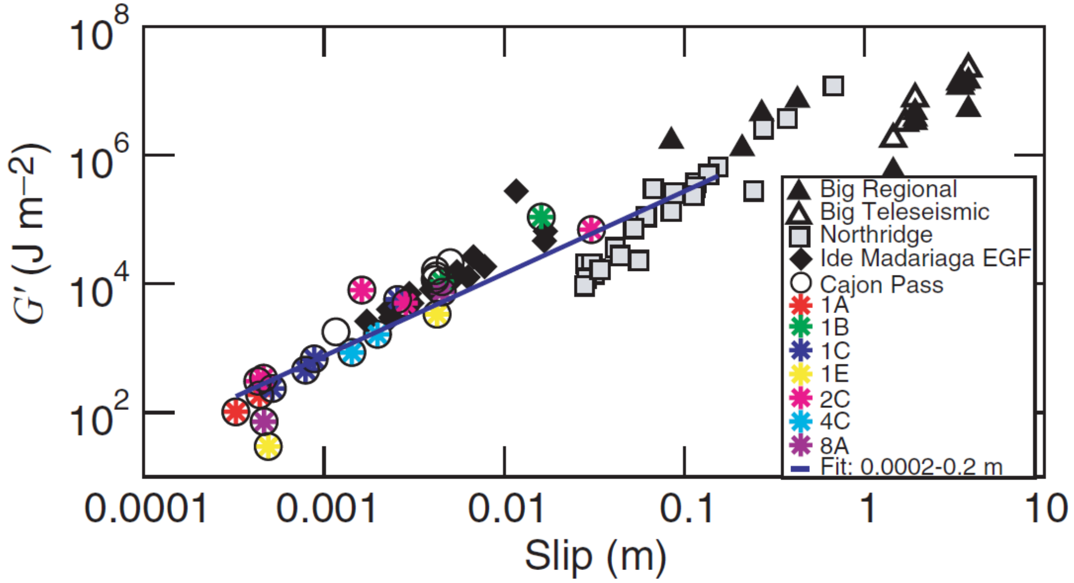


Brune, *J. Geophys. Res.*, 1970
Madariaga, *Seismol. Soc. Am., Bull.*, 1976



Abercrombie, *J. Geophys. Res.*, 1995

Seismologically inferred breakdown energy appears to scale

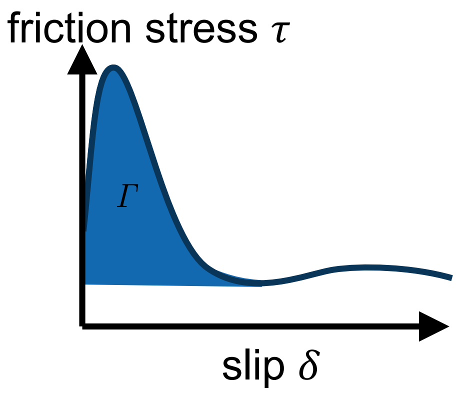


Abercrombie & Rice, *Geophys. J. Int.*, 2005

also: Viesca & Garagash, *Nat. Geo.*, 2015

given a few assumptions:

seismologically inferred breakdown energy G'
is equal
to the fault fracture energy Γ



"This implies the unlikely result that the early weakening behaviour of the fault depends on the ultimate slip that the fault will sustain." (Abercrombie & Rice, 2005)

Is scaling of seismologically inferred breakdown energy reasonable?

Since we assumed <u>constant</u> stress drop $\Delta\tau$,

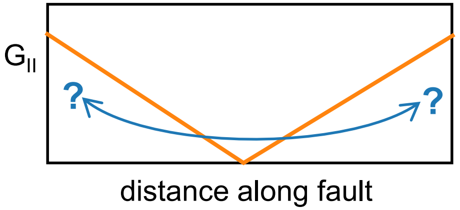
$$G_{II} \sim (\Delta\tau)^2\, a$$

from self-similar model: $a \sim D$

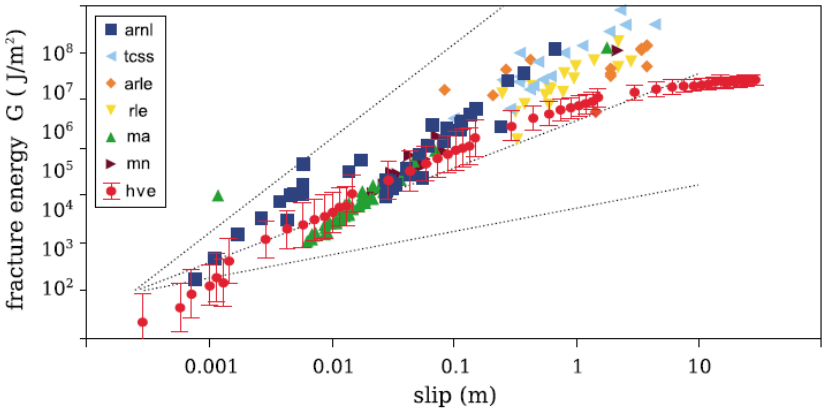
arrest criterion:

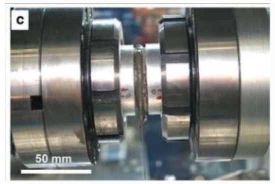
$$\Gamma = G_{II} \sim (\Delta\tau)^2\, D$$

it is the <u>only</u> way to stop earthquakes



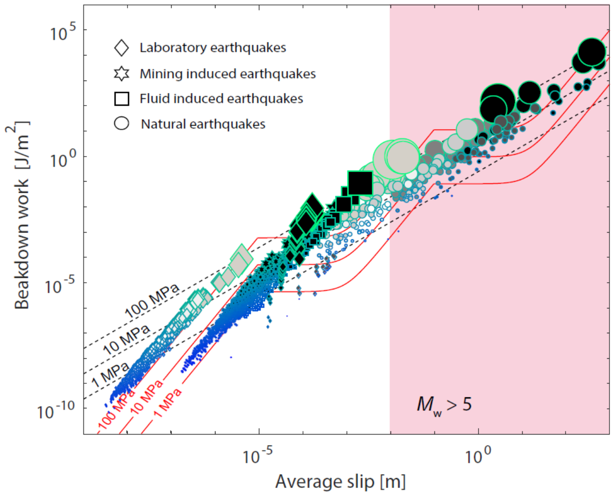
See also barrier model: Aki, *J. Geophys. Res.*, 1979





Di Toro *et al.*, (2010)

Nielsen et al., GRL (2016)



Paglialunga et al., arXiv:2104.15103 (2021)

Yes, but …

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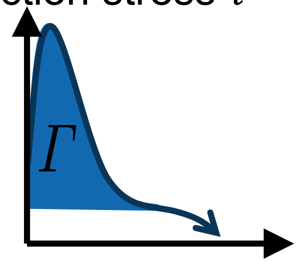
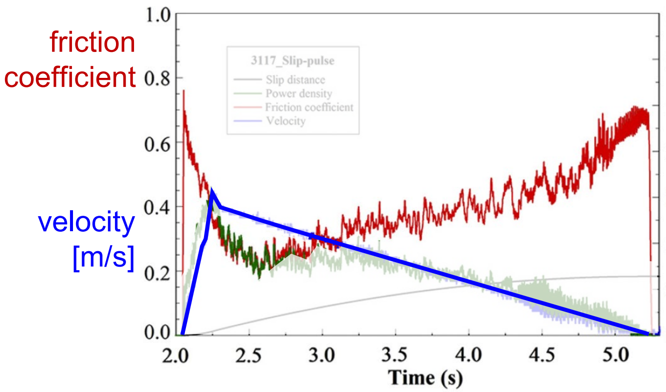
Some inconsistencies raise questions about scaling of seismologically inferred breakdown energy

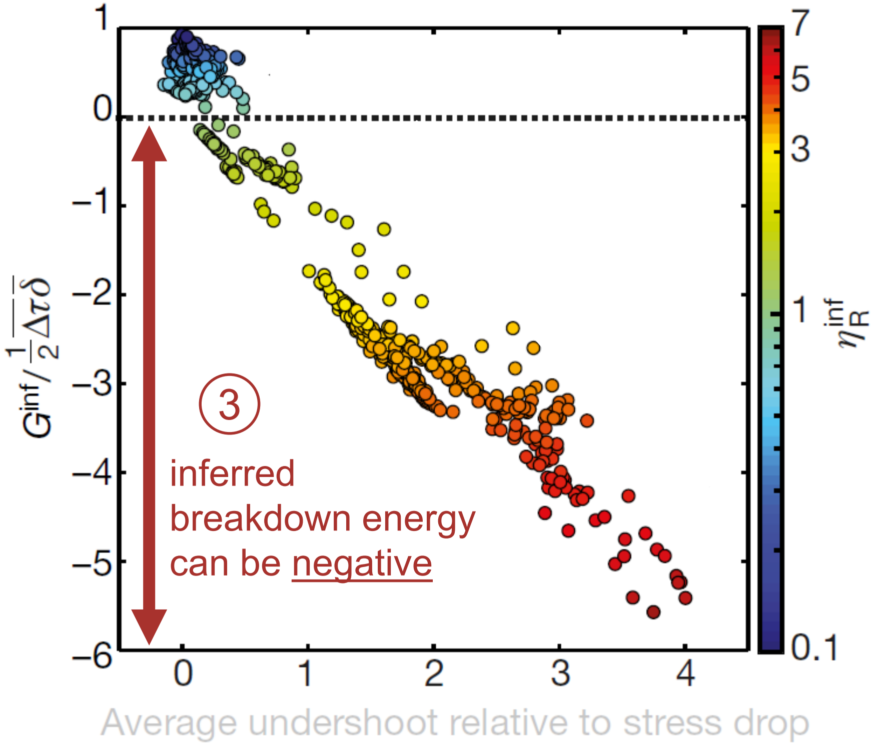
1 there is a limit to further weakening (friction cannot go negative)



2 fast-loading experiments present much shorter weakening lengths



Liao *et al.*, *Earth Planet Sci. Lett.* (2014)



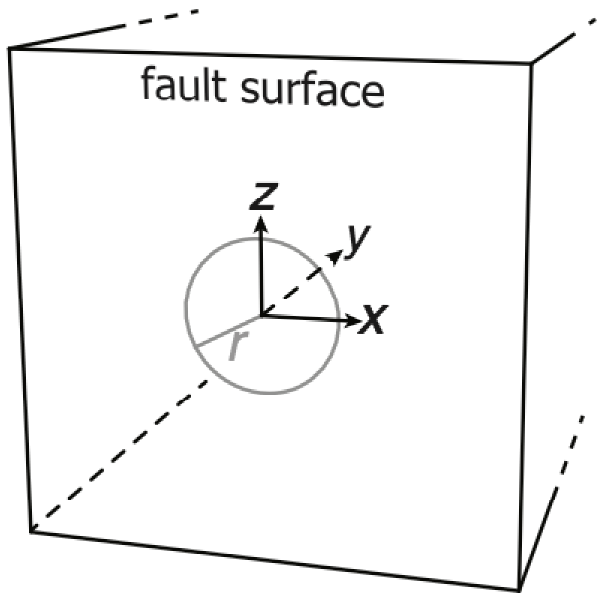
Lambert *et al.*, *Nature*, 2021

What if we relax the assumption of constant stress drop?

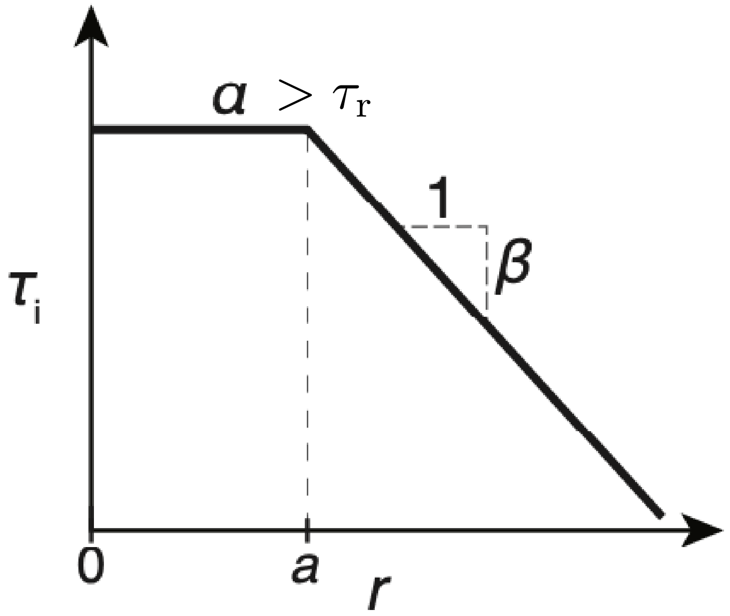
Laboratory earthquakes arrest from a seismology perspective

Simple(st) earthquake arrest model with non-uniform stress

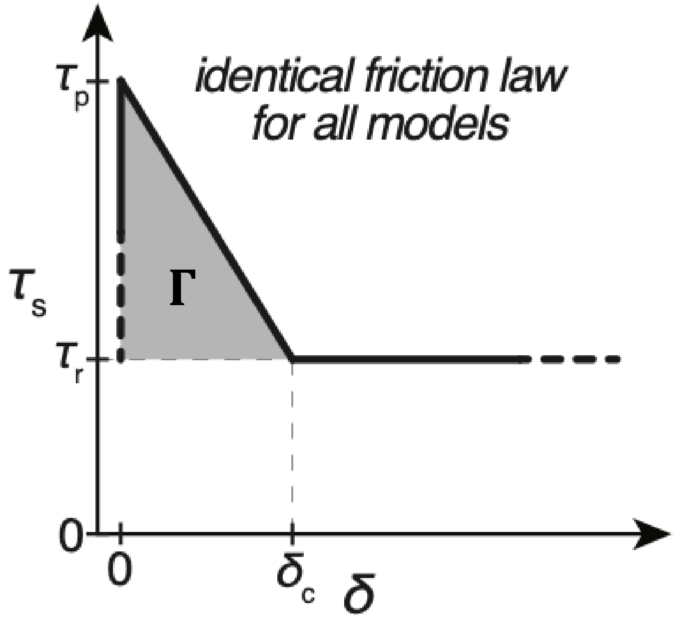
3D model



non-uniform stress



uniform & constant friction

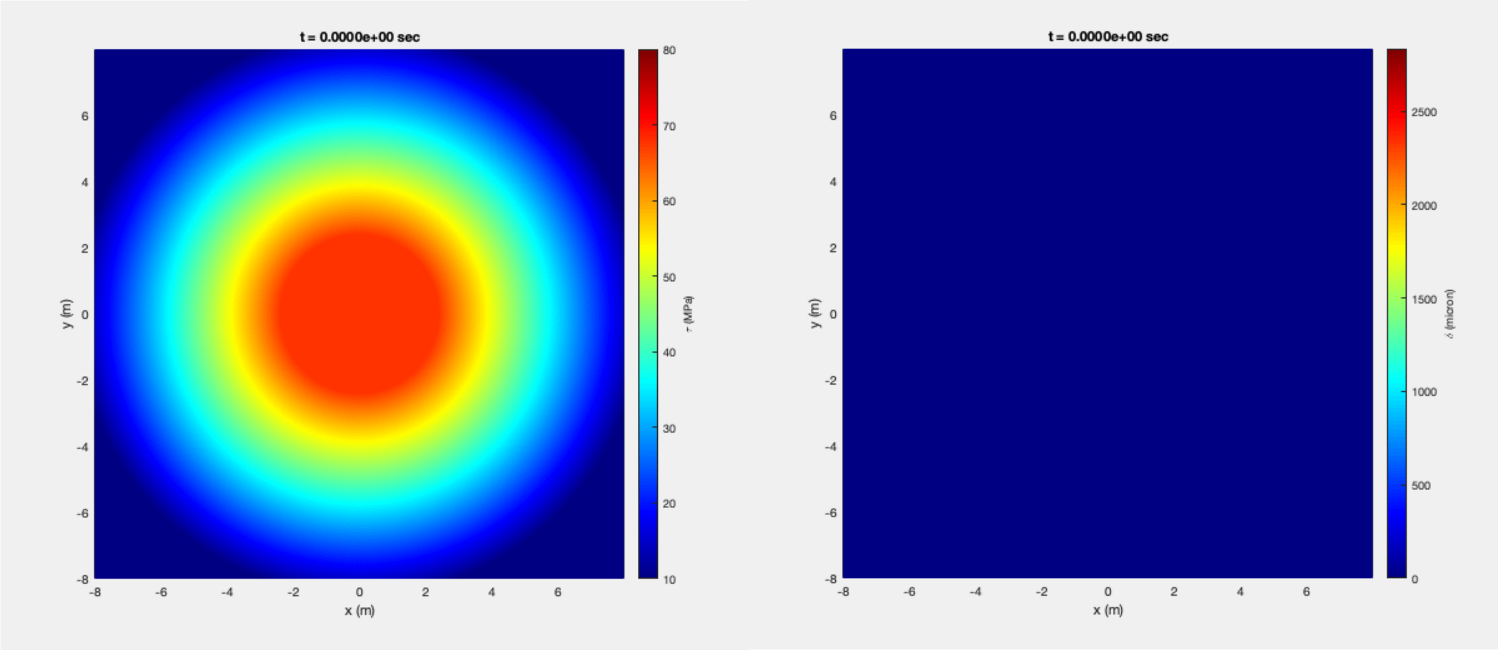


Ke, McLaskey, & Kammer (2021) arXiv:2105.06893

Simulated earthquake rupture arrests spontaneously

fault stress

fault slip



fully dynamic
spectral boundary integral method

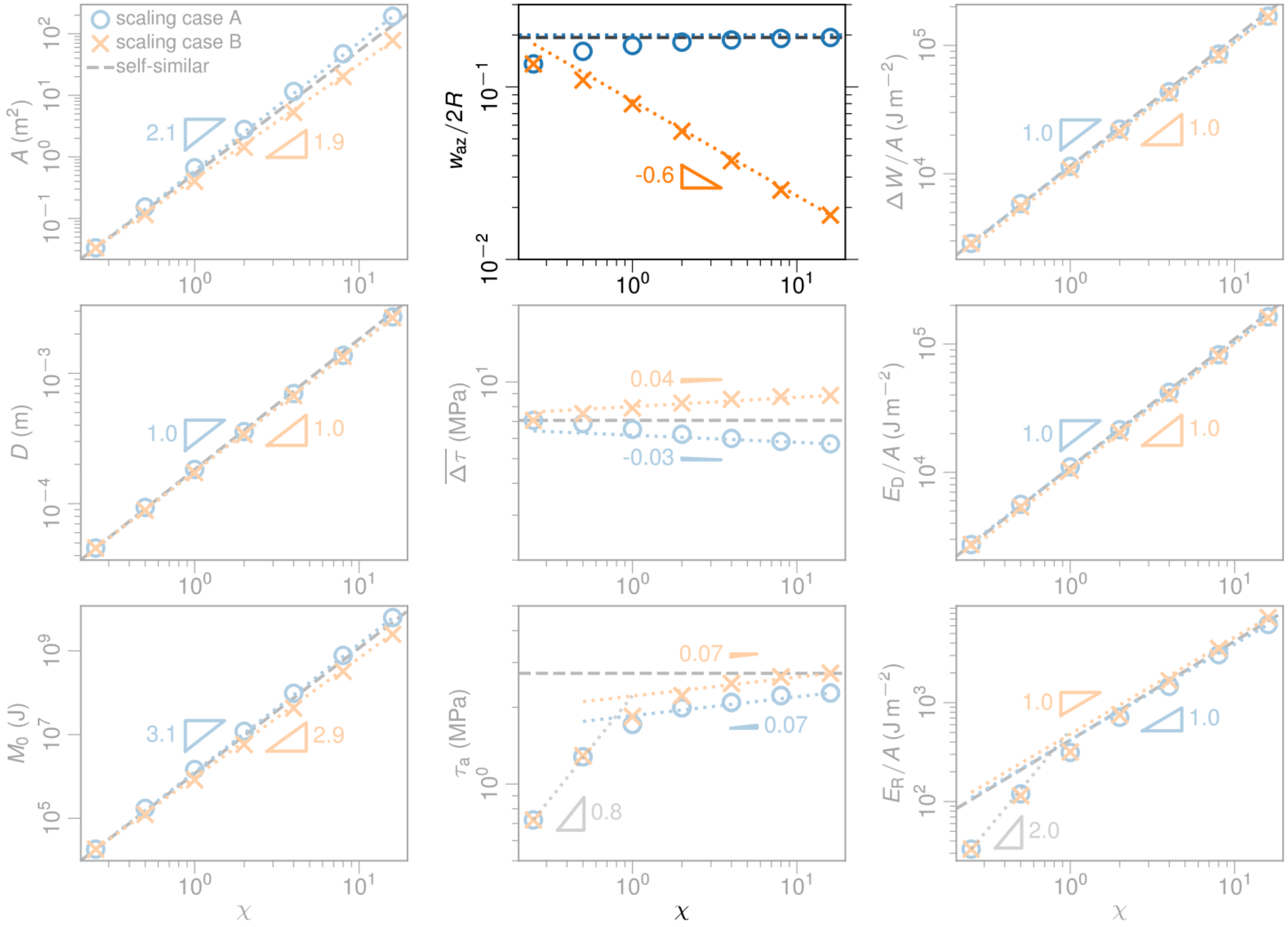
[Geubelle & Rice, JMPS, 1995]
[Breitenfeld and Geubelle, IJF, 1998]

code available online:
[Kammer *et al.*, SoftwareX, 2021]
https://gitlab.com/uguca/uguca

uguca

Ke, McLaskey, & Kammer (2021) arXiv:2105.06893

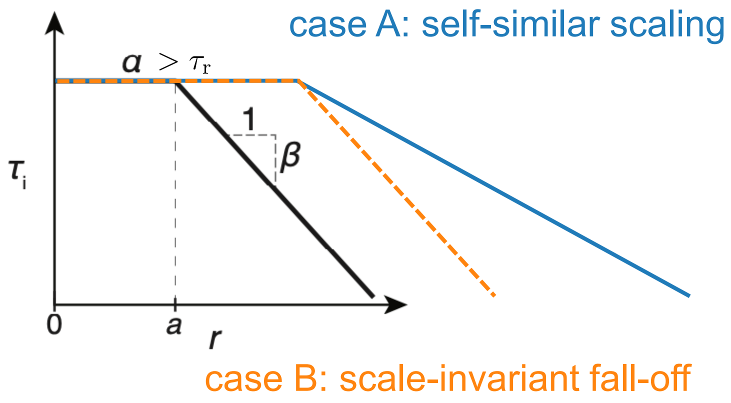
Scaling is coherent with widely used self-similar model



the earthquake arrest zone
is likely scale-invariant

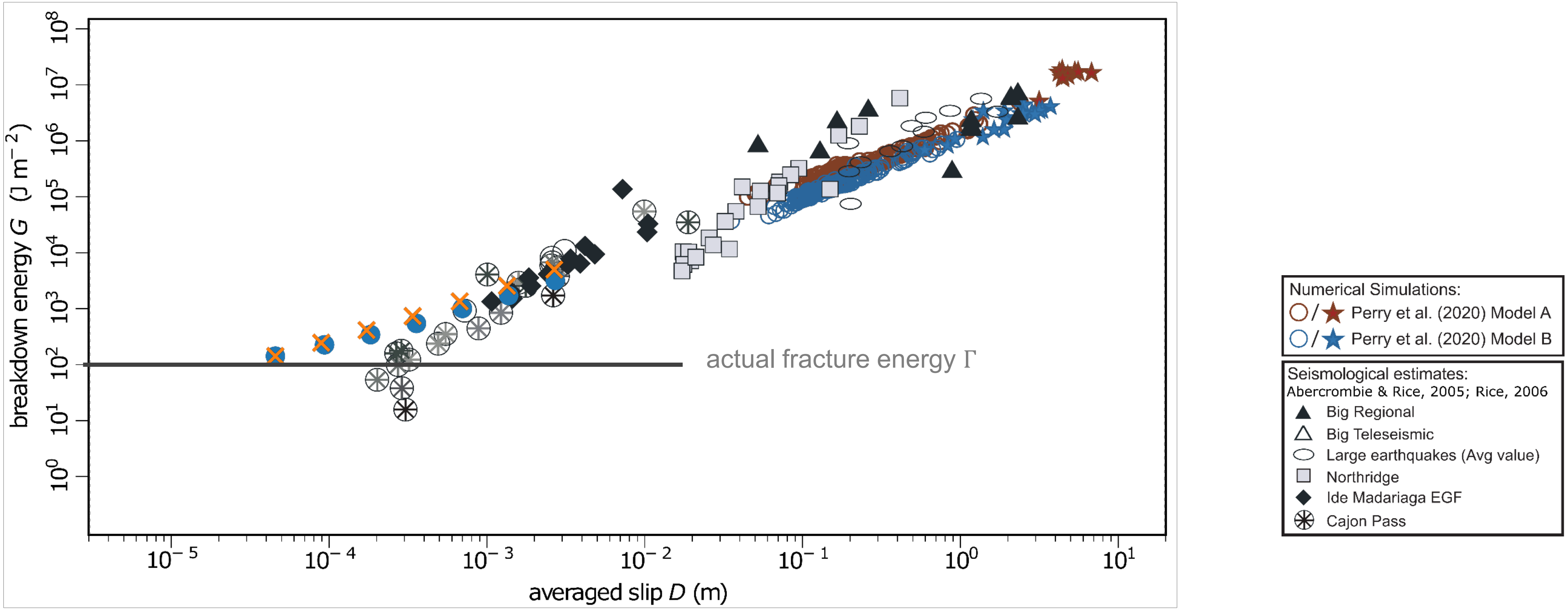
Ke et al., *Geophys. J. Int.*, 2021

→ scaling case A more reasonable



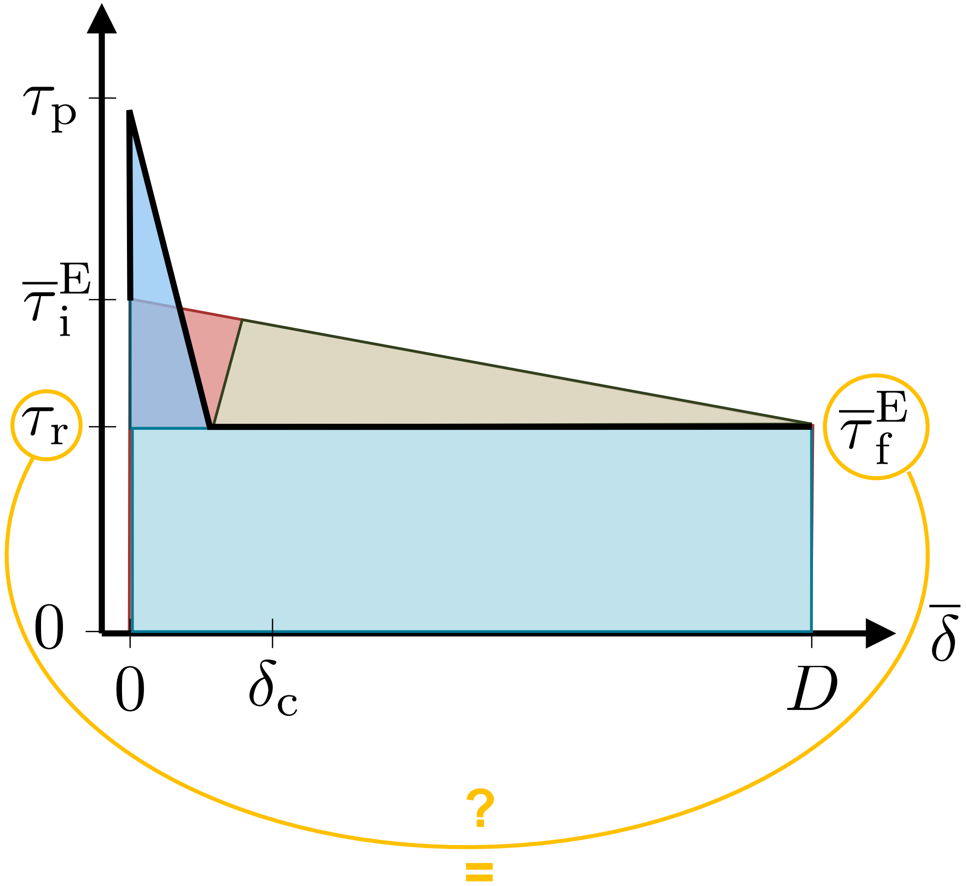
Ke, McLaskey, & Kammer (2021) arXiv:2105.06893

Seismologically inferred breakdown energy scales even though the imposed fracture energy is scale-invariant



Ke, McLaskey, & Kammer (2021) arXiv:2105.06893

Seismologically inferred breakdown energy is computed by total energy balance



$$\boxed{\Delta W/A} = \boxed{\bar{G}} + \boxed{E_H/A} + \boxed{E_R/A}$$

energy released — breakdown energy — heat — radiated energy — all averaged!

$$\rightarrow \bar{G} = \Delta W/A - E_H/A - E_R/A$$

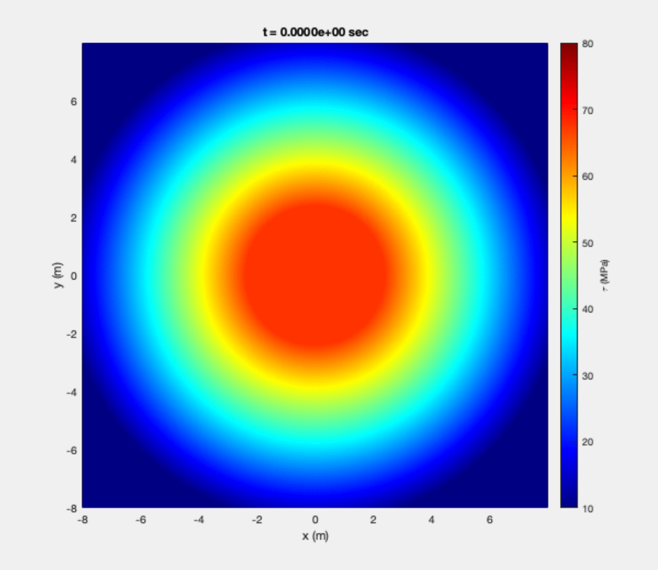
important assumption:

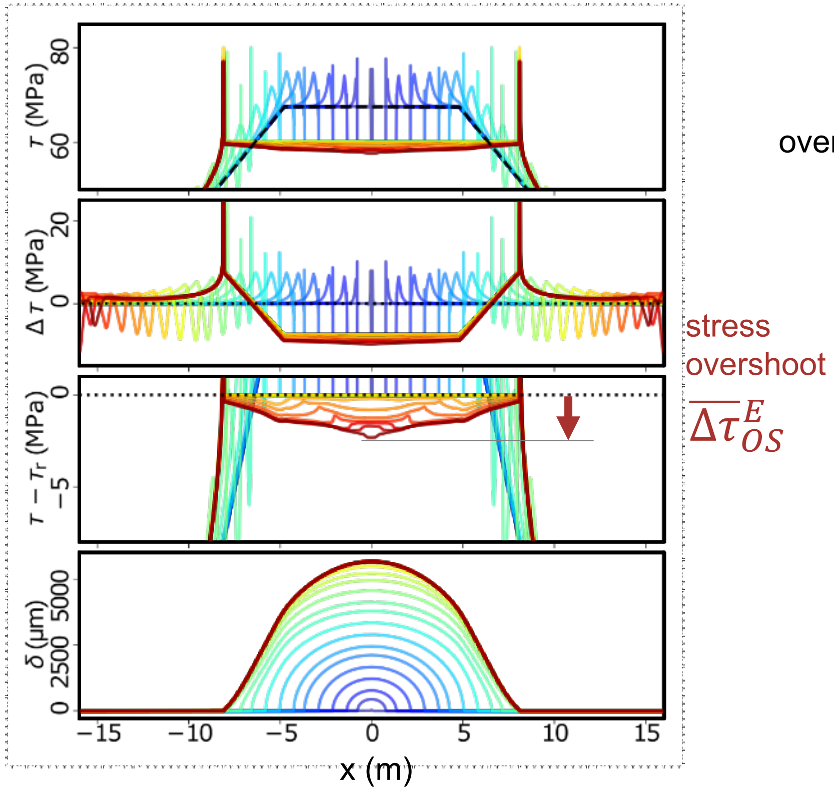
final stress = residual stress of friction law

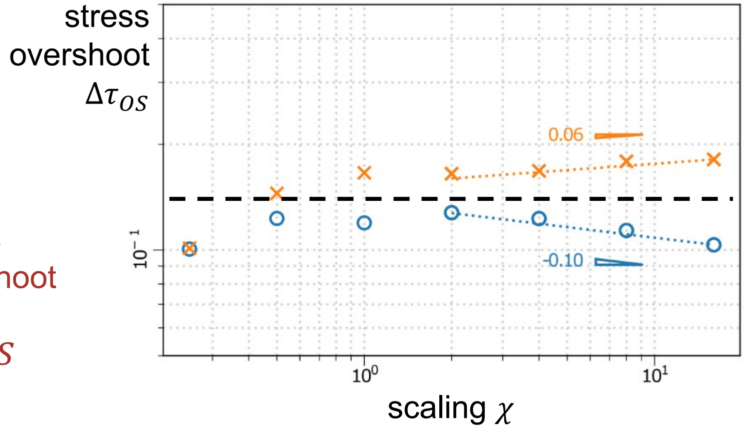
$$\bar{\tau}_f^E = \tau_r$$

Final stress is not equal residual stress in simulations

fault stress





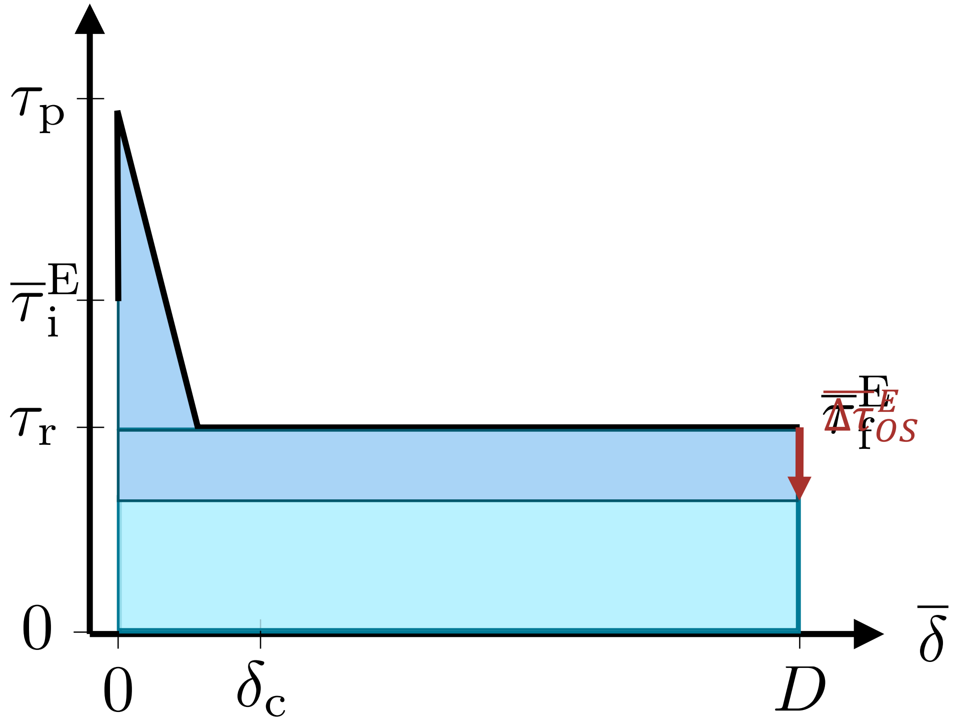


stress overshoot is

- common for crack-like ruptures
- scale-invariant
- of order of 15% of stress drop

Ke, McLaskey, & Kammer (2021) arXiv:2105.06893

Seismologically inferred breakdown energy scales because of scale-invariant stress overshoot



$$\boxed{\bar{G}'} = \Delta W/A - \boxed{E_H/A} - E_R/A$$

breakdown energy — heat

assumption: $\cancel{\bar{\tau}_f^E = \tau_r}$

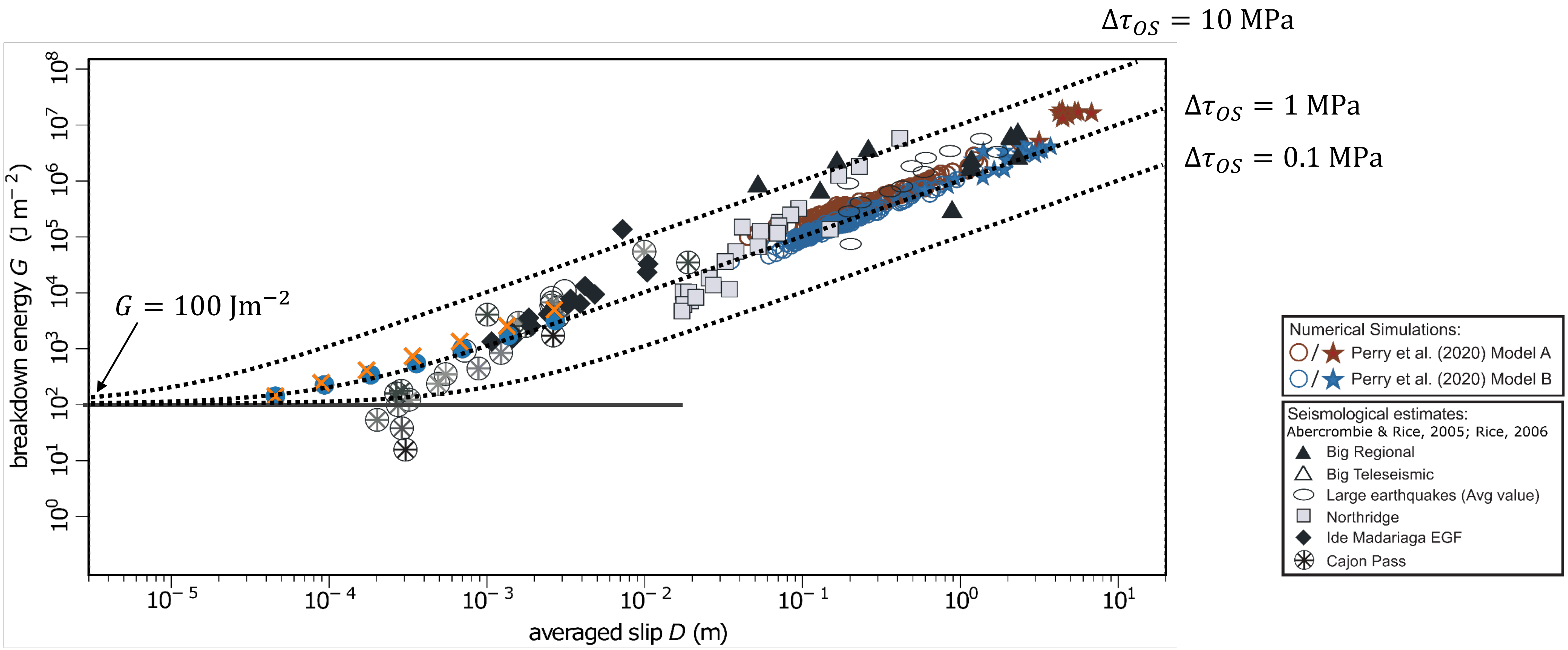
$\cancel{\rightarrow E_H/A = \bar{\tau}_f^E\, D}$

proper assumption: $E_H/A = \bar{\tau}_r\, D$

hence: $$G' = G + \overline{\Delta\tau}_{OS}^E\, D$$

Seismologically inferred breakdown energy scales because of scale-invariant stress overshoot

$$G' = G + \overline{\Delta\tau}_{OS}^{E}\, D$$



Ke, McLaskey, & Kammer (2021) arXiv:2105.06893

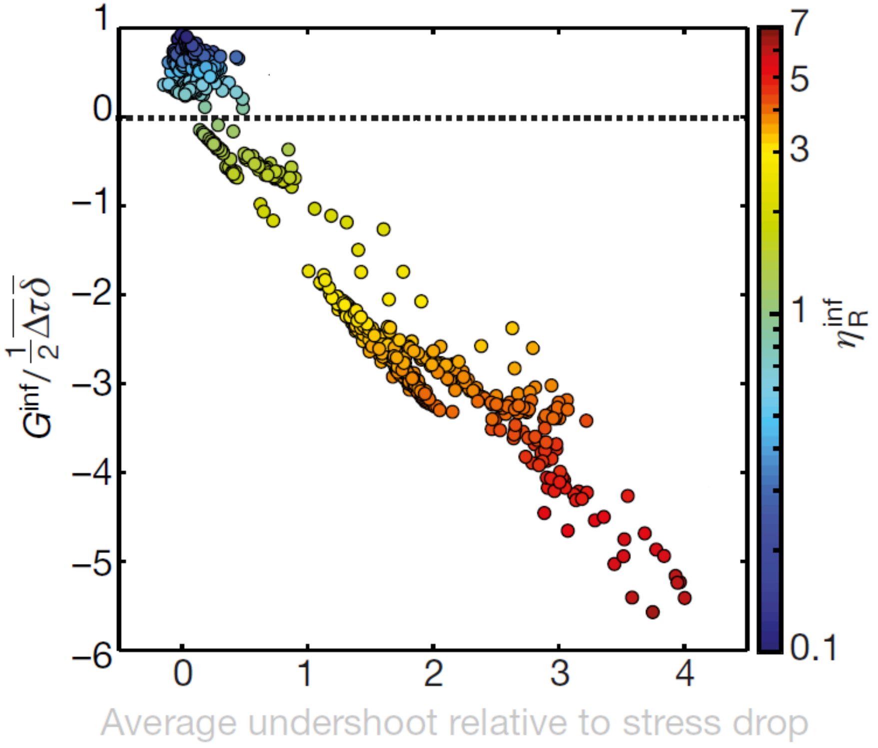
Negative seismologically inferred breakdown is result of stress undershoot (instead of overshoot)

$$G' = G + \overline{\Delta\tau}_{OS}^{E}\, D \quad < 0$$

< 0

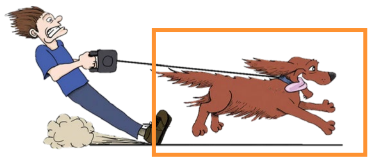
towards

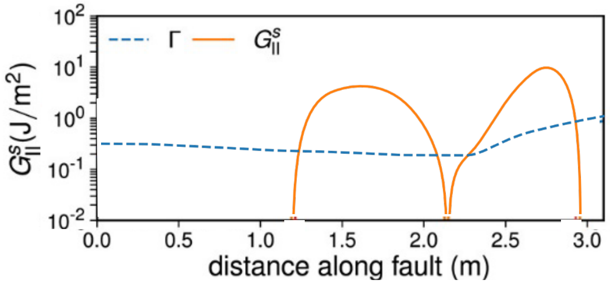
a different "type" of earthquakes (pulse-like) are known to cause stress undershoot



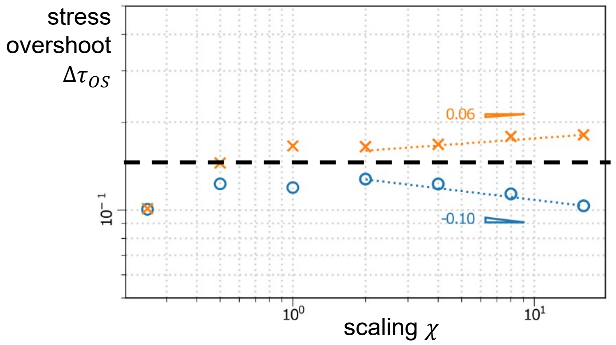
Lambert *et al.*, *Nature, 2021*

Conclusion

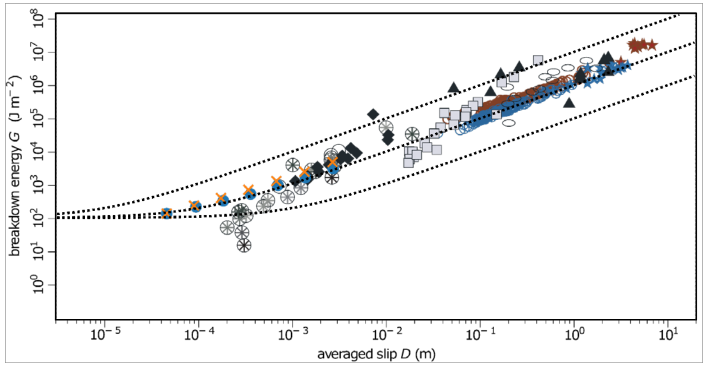




- Laboratory earthquakes arrest because they run out of energy



- Earthquake simulations with self-similar (non-uniform) stress state cause scale-invariant stress overshoot



- This scale-invariant stress overshoot may explain observed scaling of seismologically inferred breakdown energy

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Thank you!

Ke, McLaskey, & Kammer (2021) arXiv:2105.06893
Ke, McLaskey, & Kammer, *Geophys. Res. Lett.*, (2018)

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