Connecting models of natural and induced earthquakes

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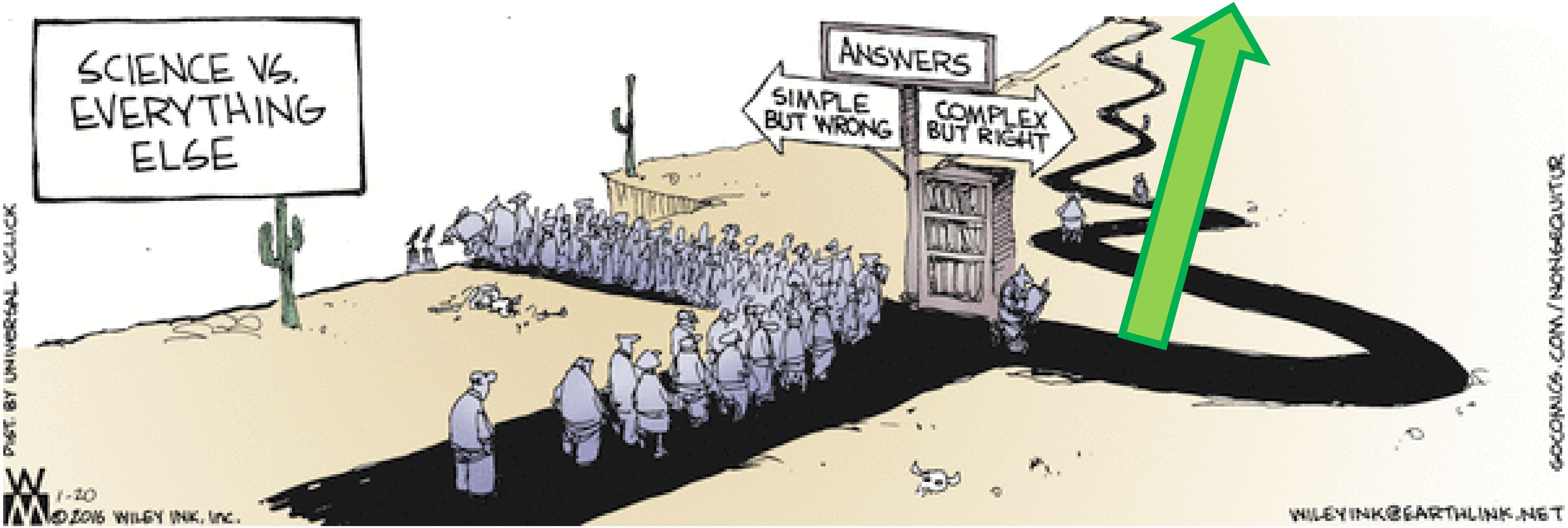
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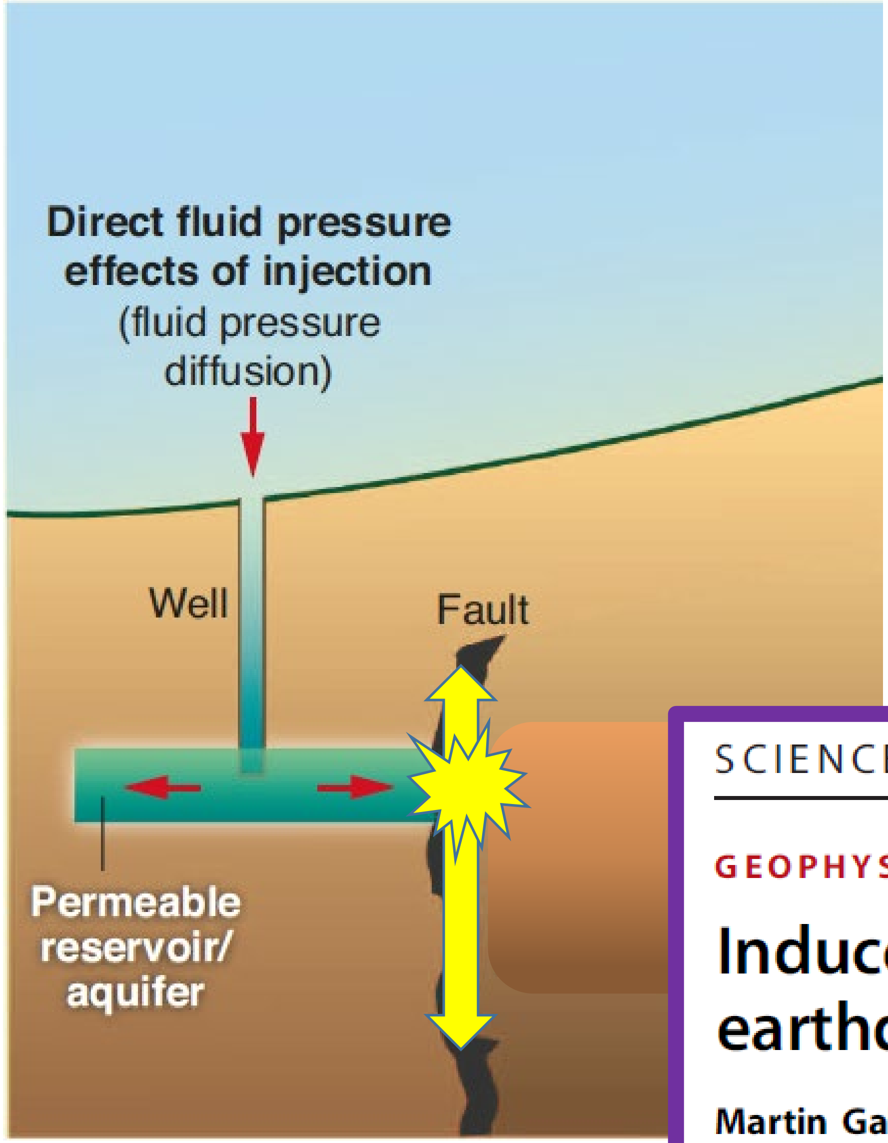

A rupture triggered by injection
can propagate beyond
the pressurized zone
if the fault has enough pre-stress.

SCIENCE ADVANCES | RESEARCH ARTICLE

GEOPHYSICS

Induced seismicity provides insight into why earthquake ruptures stop

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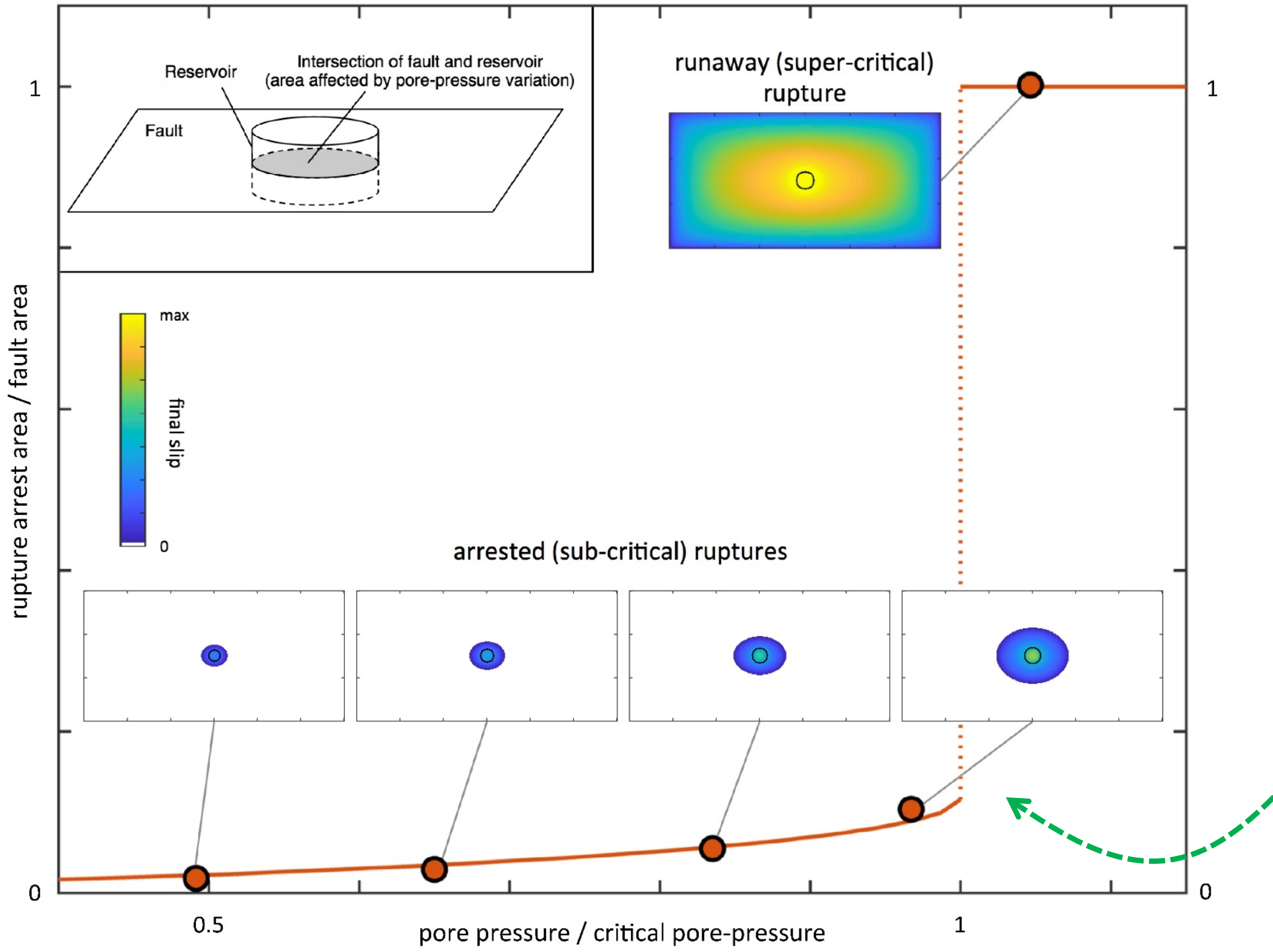
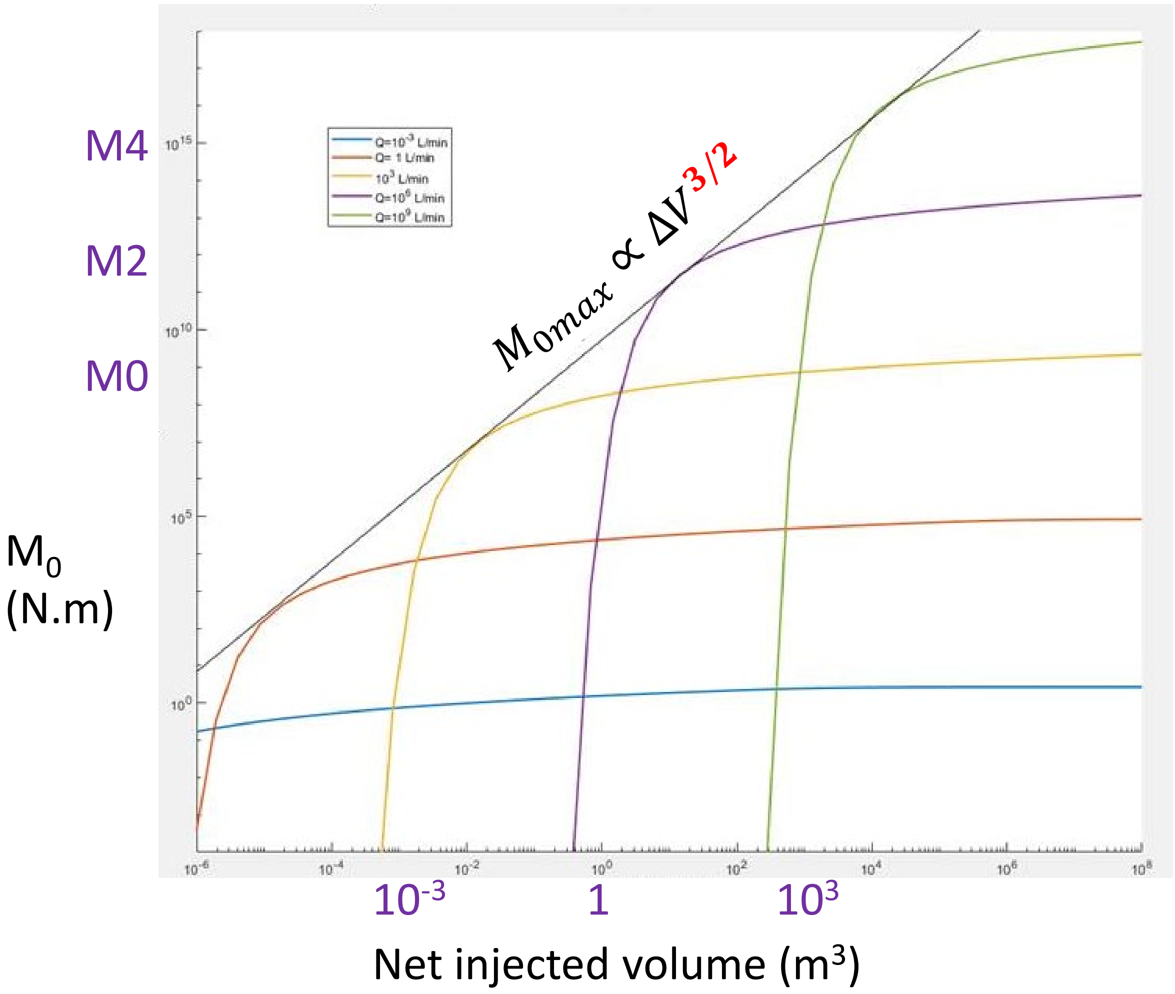
Size of earthquakes induced by fluid injection

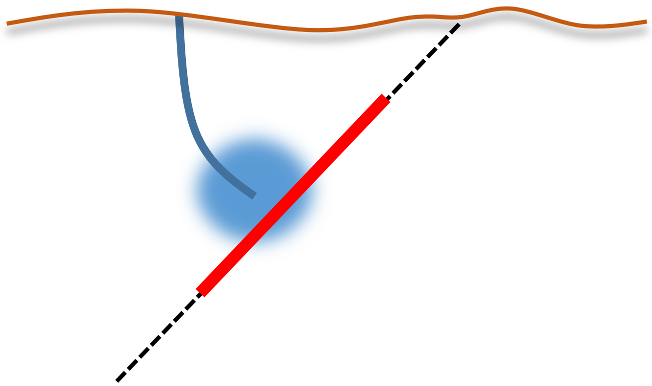


Largest arrested rupture → $M_{max-arr}$

(Galis et al 2017)

Size of earthquakes induced by fluid injection





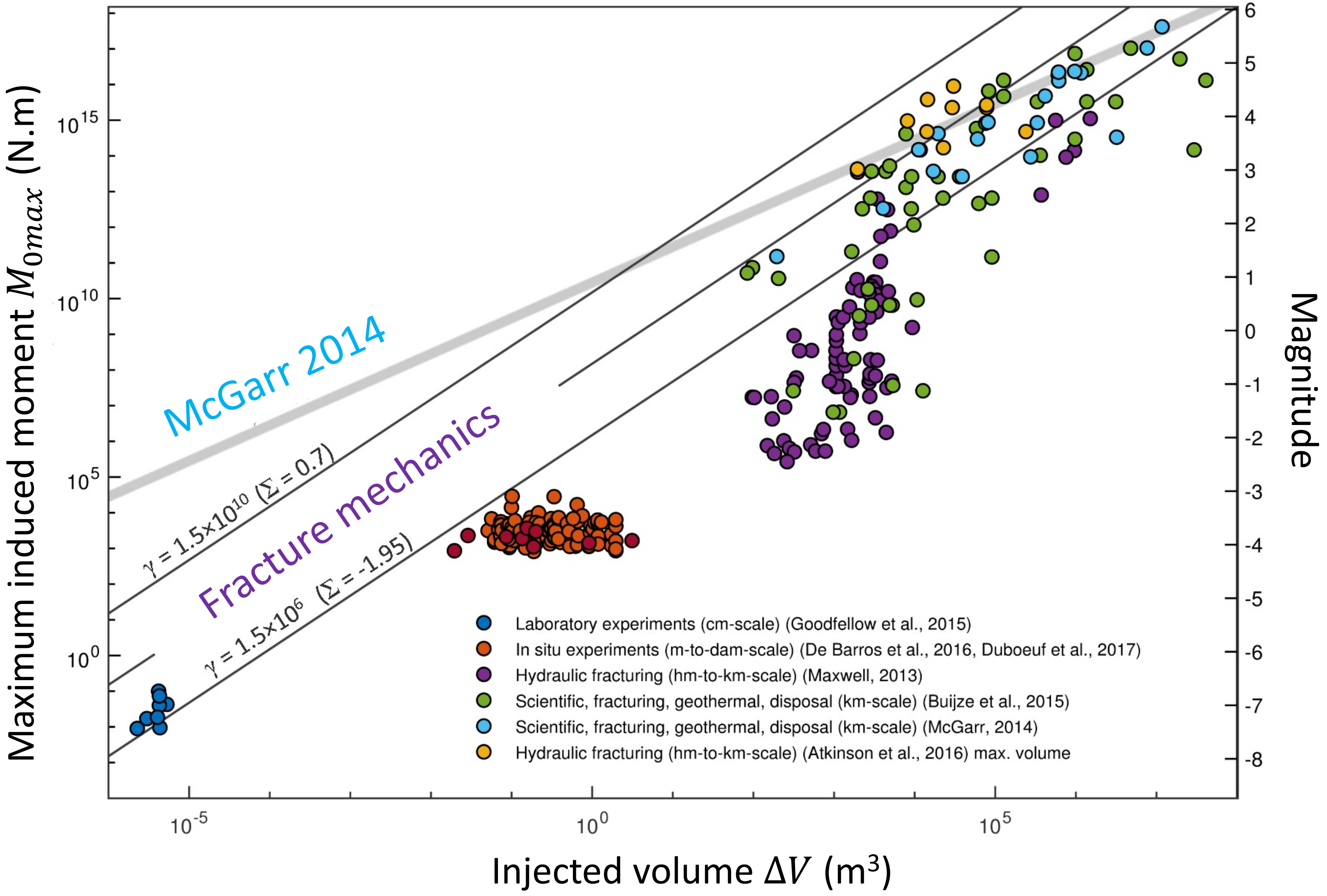
Injection at steady rate + isotropic diffusion
→ size of self-arrested ruptures
from fracture mechanics

Fault at given distance from injection point
Each curve: a different injection rate

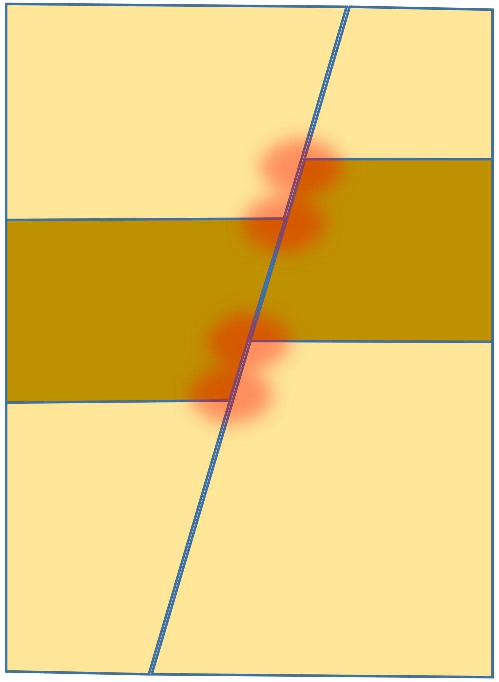
Envelope: the largest self-arrested rupture

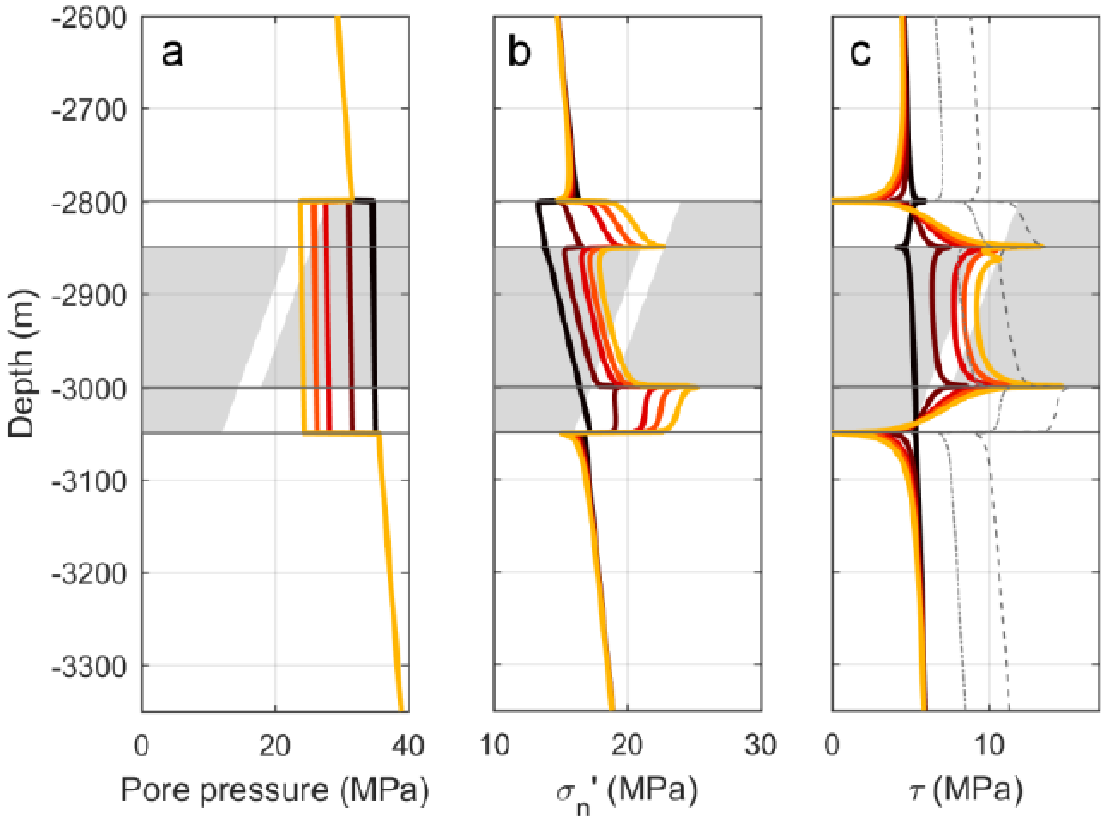
Fracture mechanics: $M_{0max} \propto \Delta V^{3/2}$

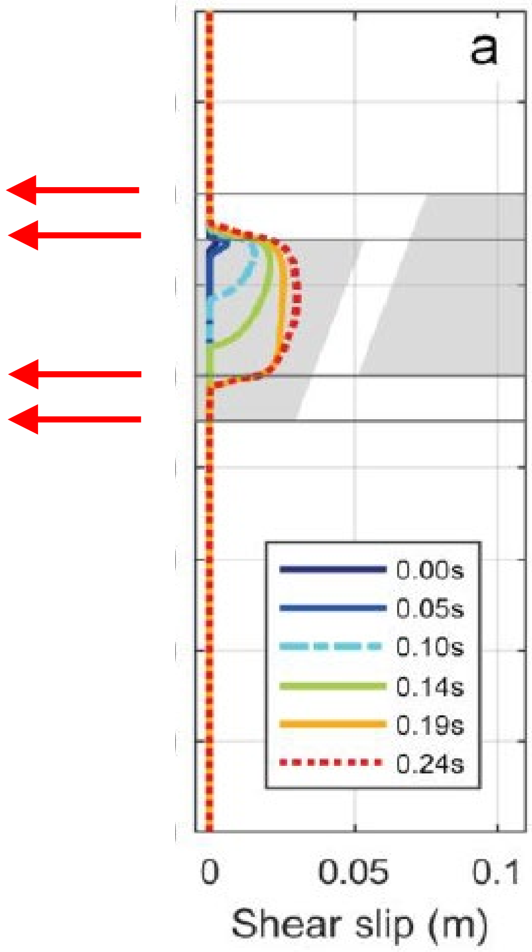
Galis et al (2017)



Depth-confined ruptures

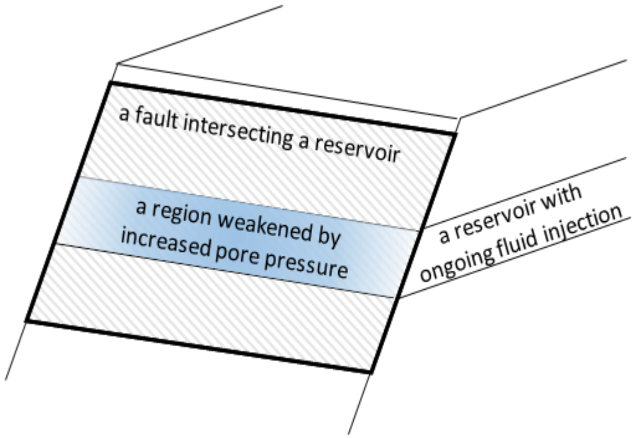


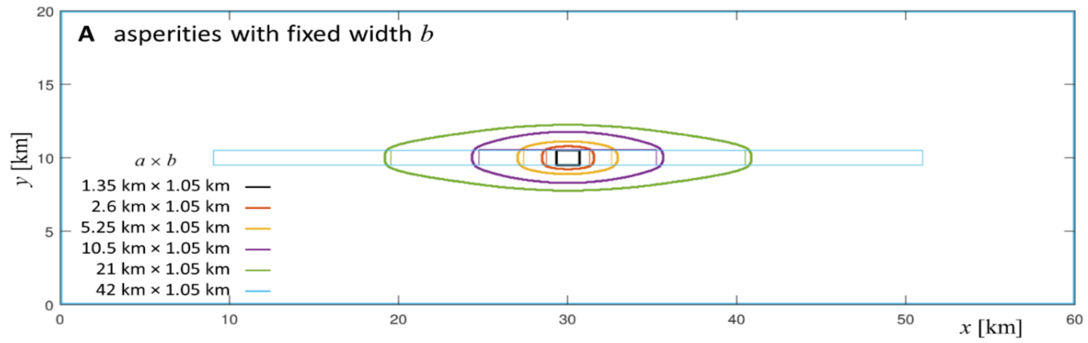


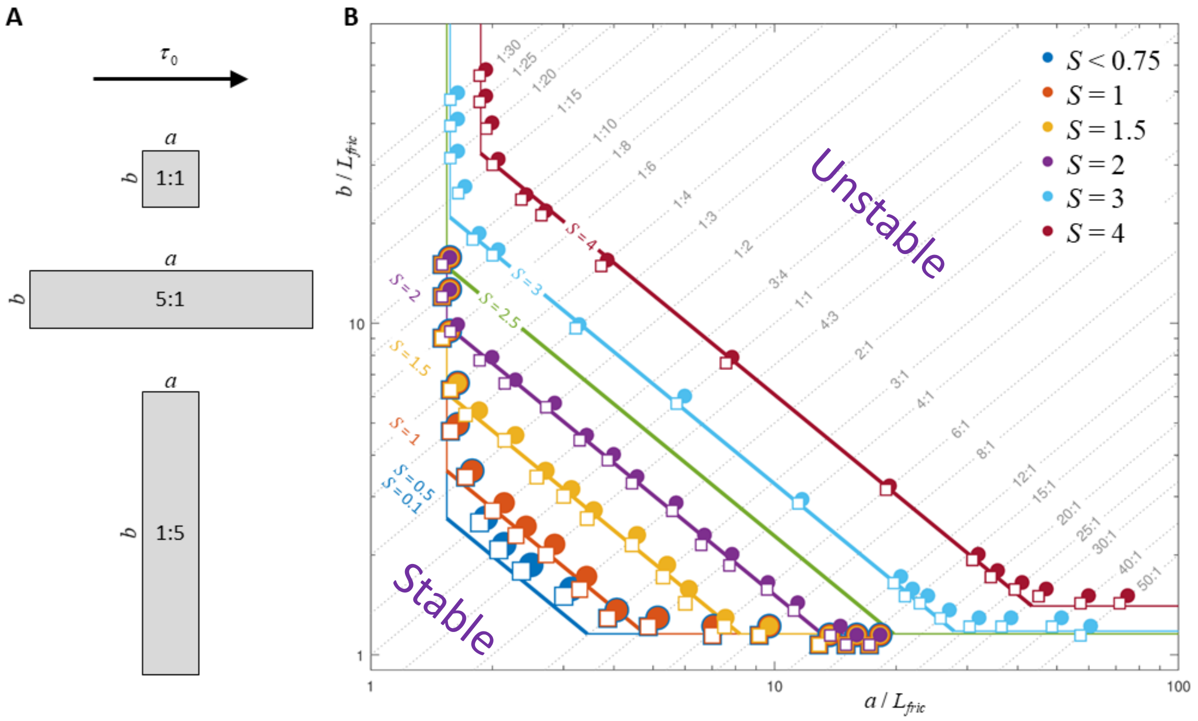


Buijze et al (2019)

Earthquake initiation and arrest of ruptures triggered by elongated overstressed regions

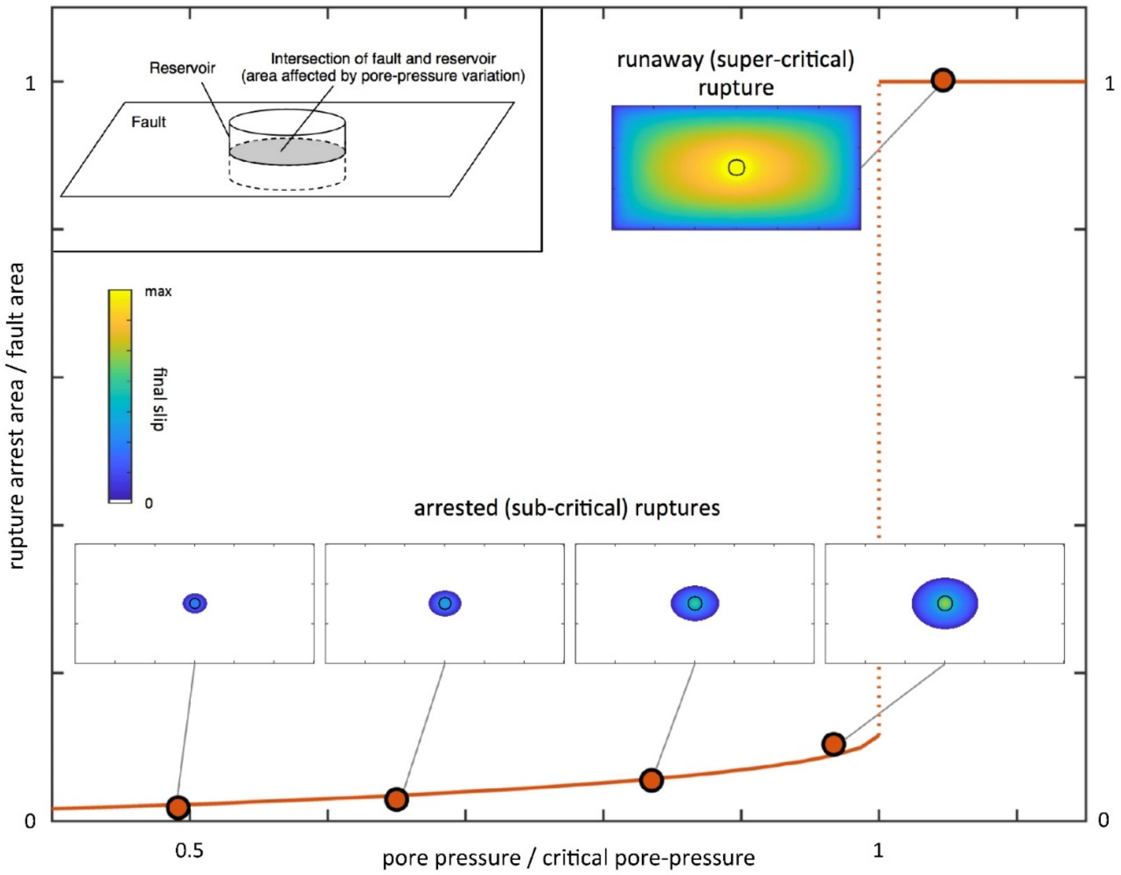






Galis et al (GJI 2019)

Size of earthquakes induced by fluid injection

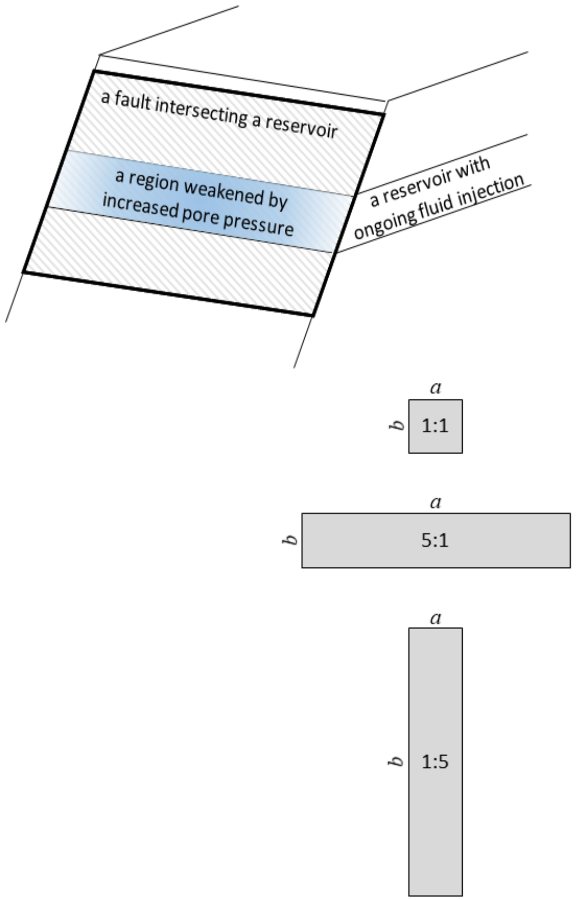


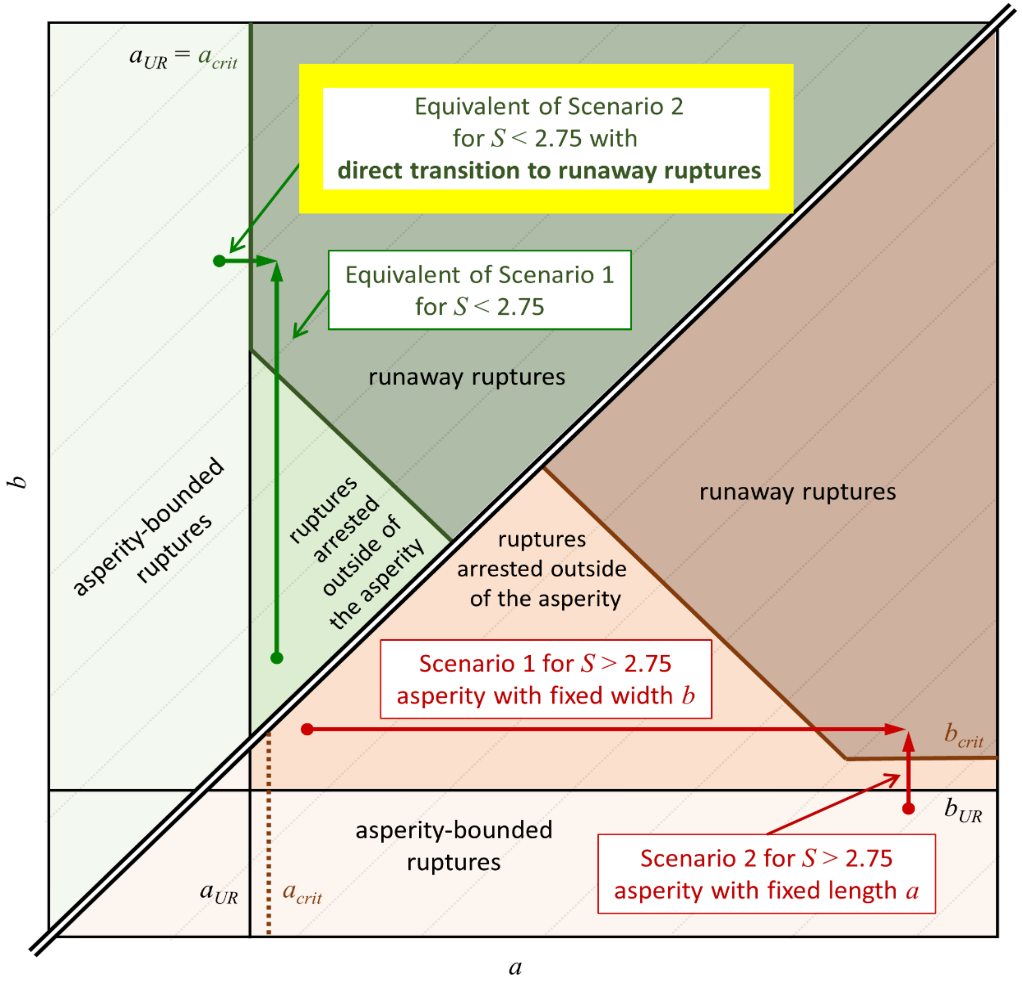
Runaway rupture with foreshocks

→ facilitates TLS

(Galis et al 2017)

Earthquake initiation and arrest of ruptures triggered by elongated overstressed regions



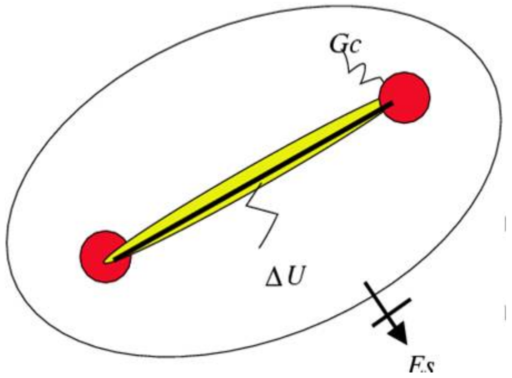


Runaway rupture without foreshocks is possible

→ challenging for TLS

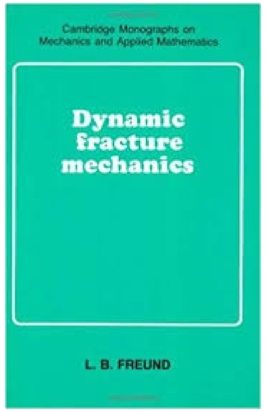
Galis et al (GJI 2019)

A crack-tip equation of motion for large earthquakes



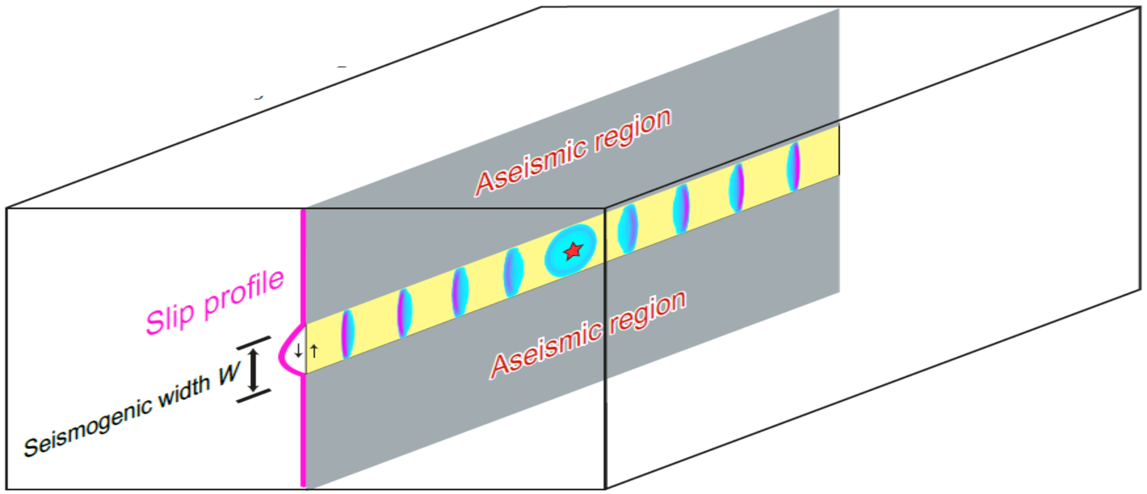
For crack-like ruptures in 2D:

$$G_c = g(v)\frac{\Delta\tau^2 L}{2\mu}$$



(Freund 1989)

For long ruptures in 3D
with fixed rupture width W?

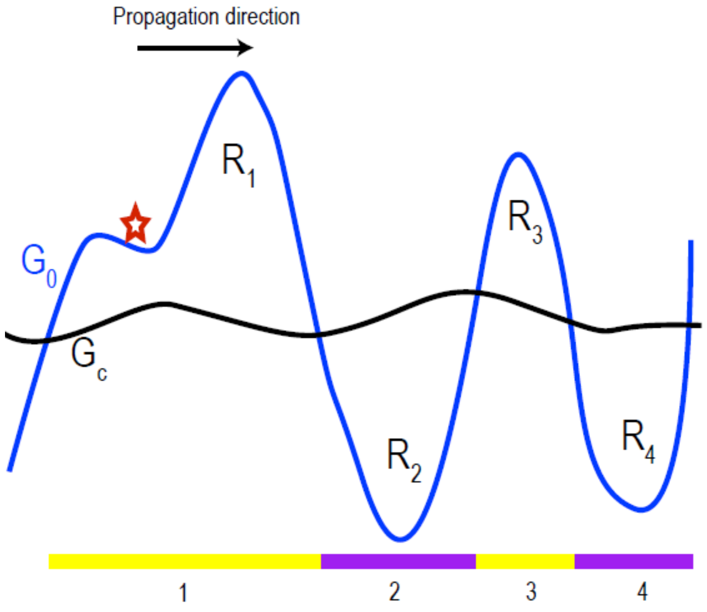


A crack-tip equation of motion for large earthquakes

New equation for long ruptures (L>W):

$$G_c = G_0 \left(1 - \frac{\dot{v}W}{v_S^2}\frac{1}{\pi \alpha_S^3}\right) \qquad \text{where } \alpha_S = \sqrt{1-\left(\frac{v}{v_S}\right)^2} \text{ and } G_0 \approx \frac{\Delta\tau^2 W}{\pi\mu}$$

Applied to faults with heterogeneous fracture energy and stress drop:



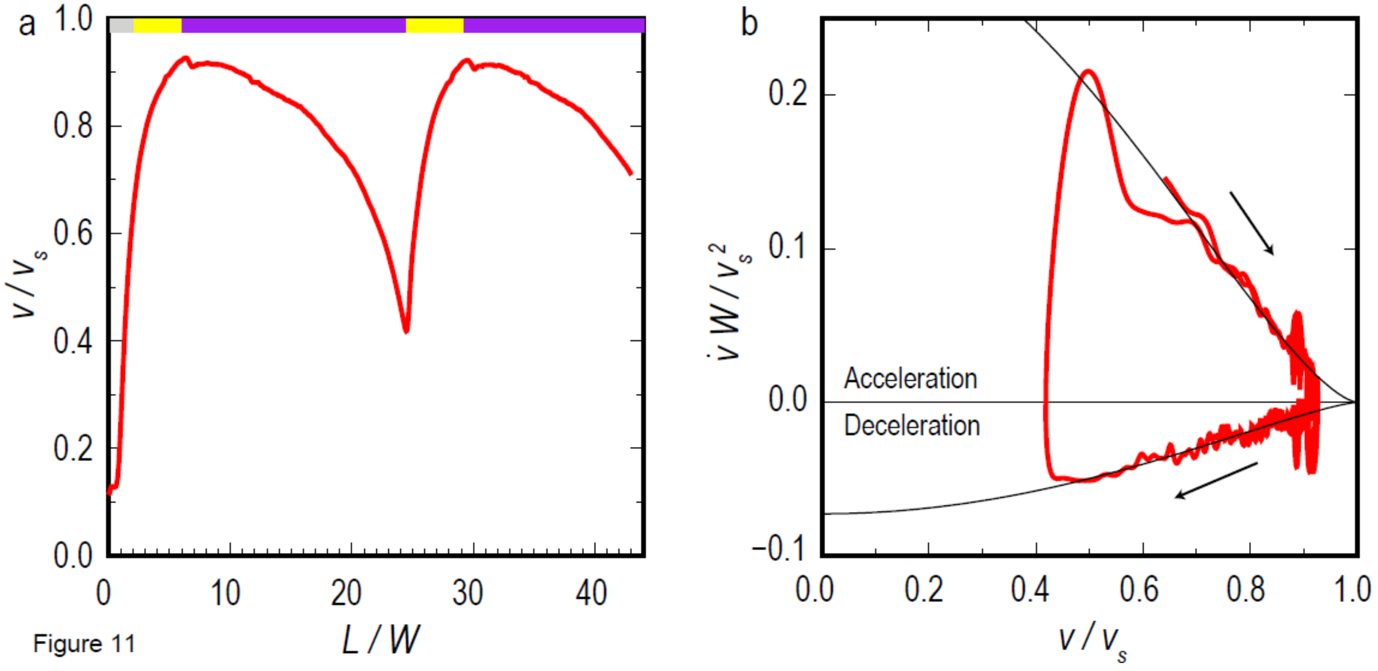
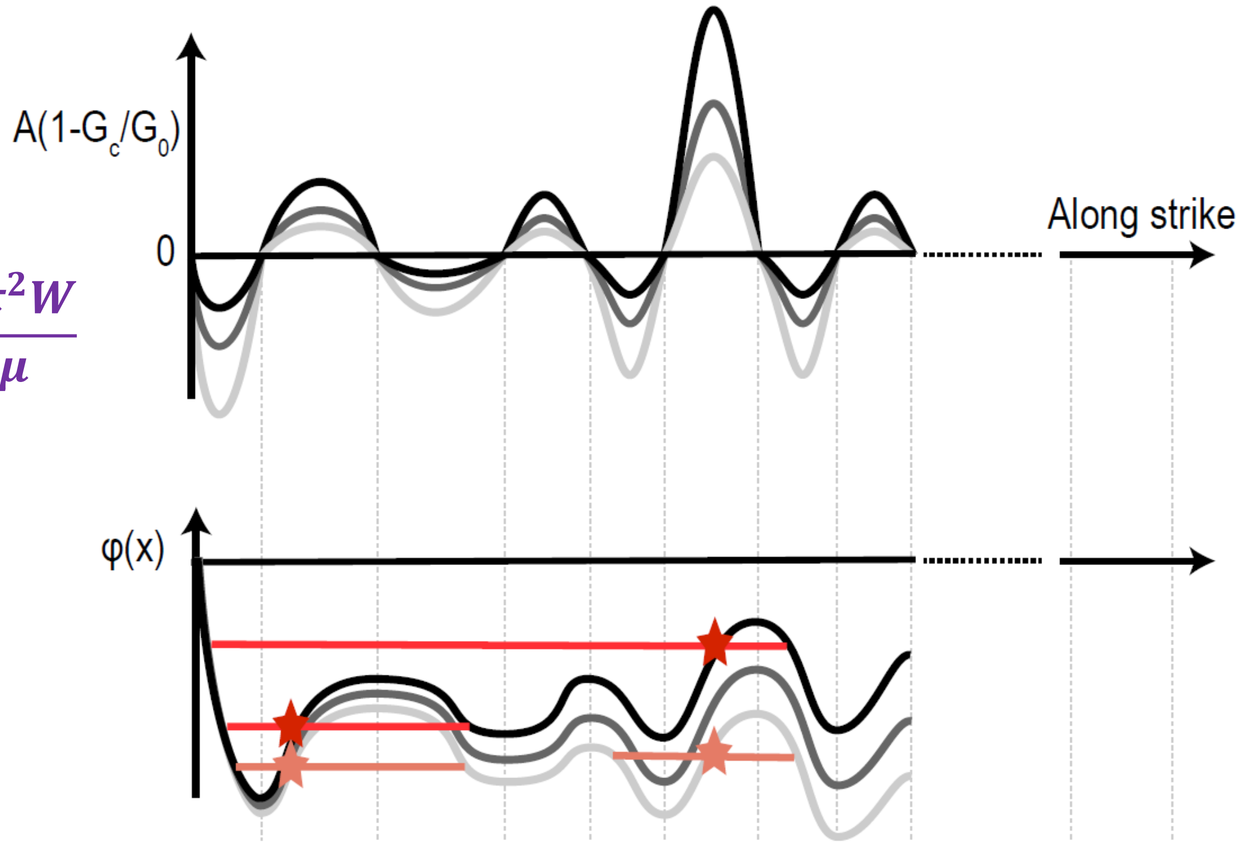


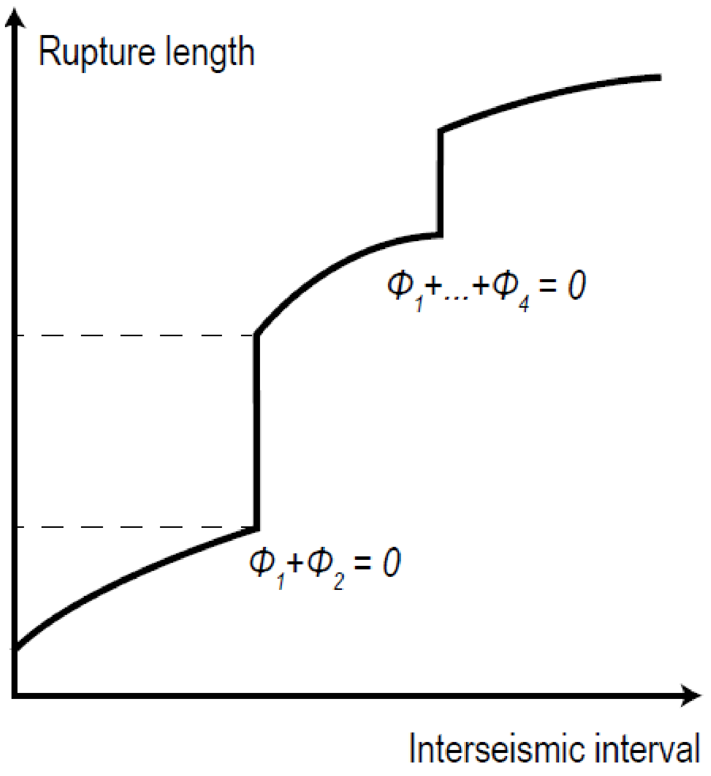
Figure 11

Weng and Ampuero (2019)

Arrest criterion for elongated ruptures

$$G_0 \sim \frac{\Delta\tau^2 W}{\mu}$$

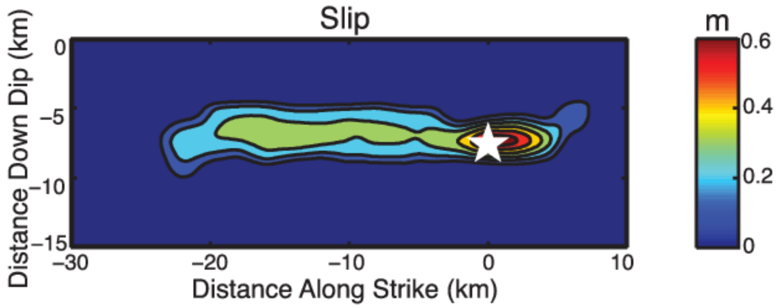




Elongated earthquake ruptures

2004 Mw 6 Parkfield

Ma et al (2008)



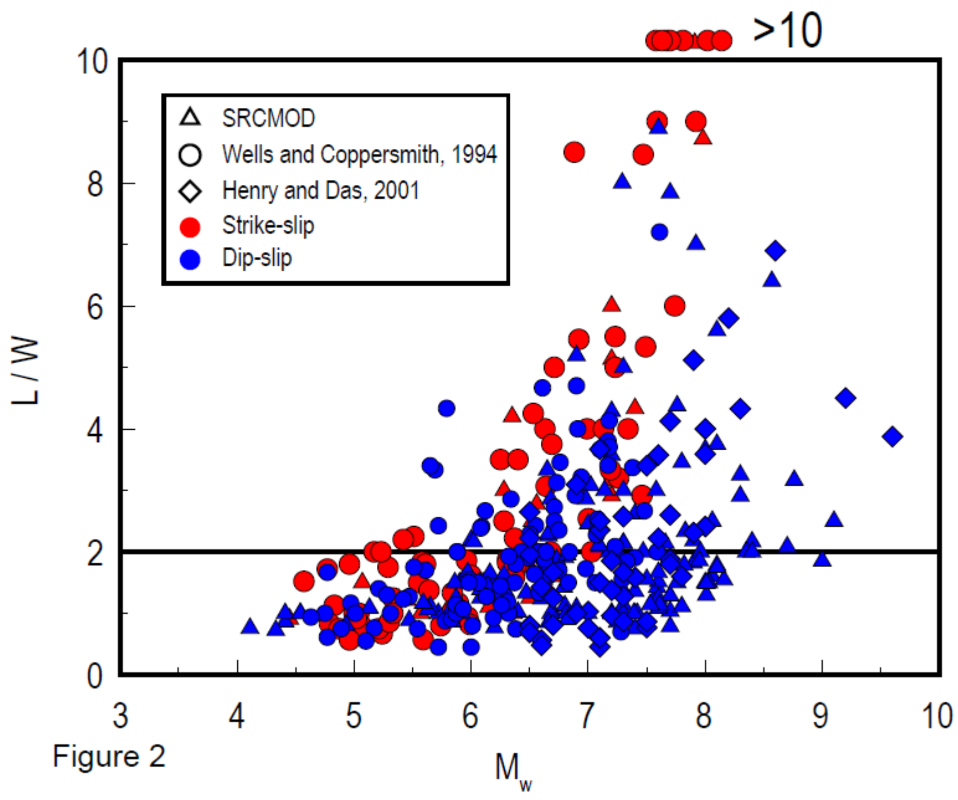
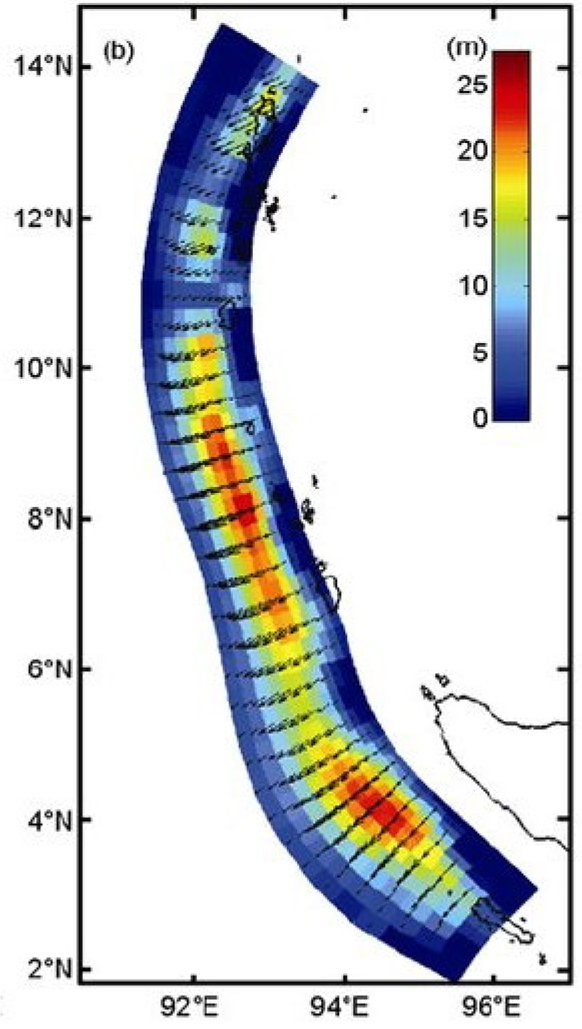


Figure 2

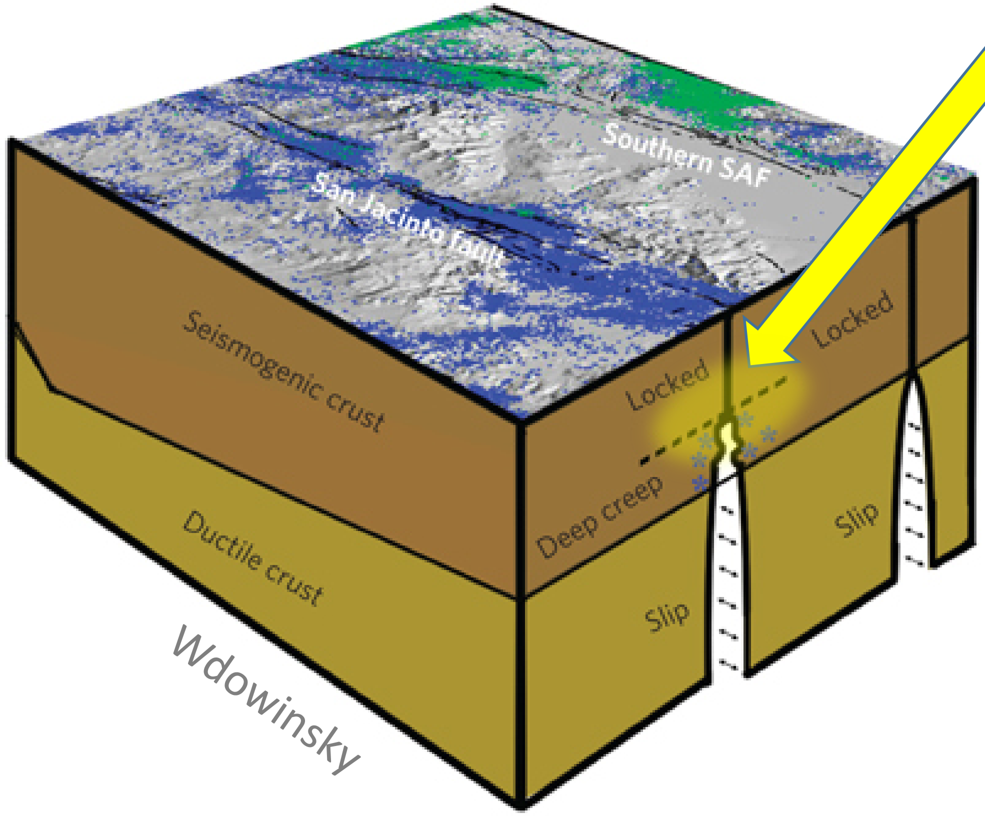
2004 Mw 9.3 Sumatra

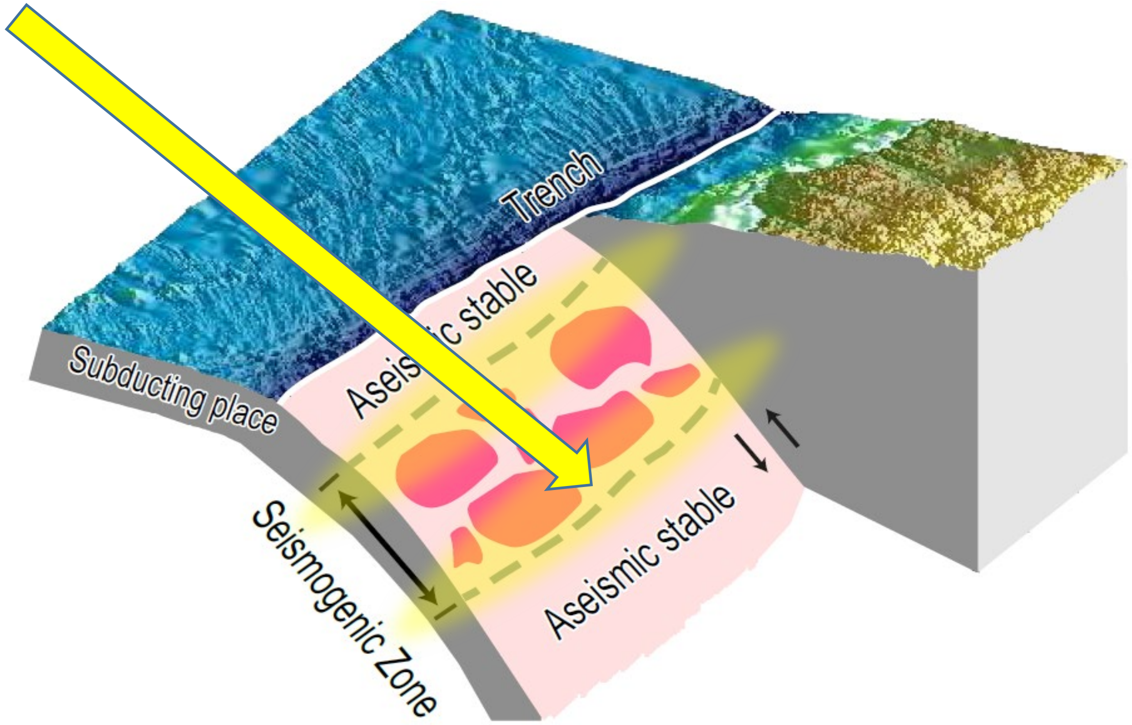


Faults driven by localized loads

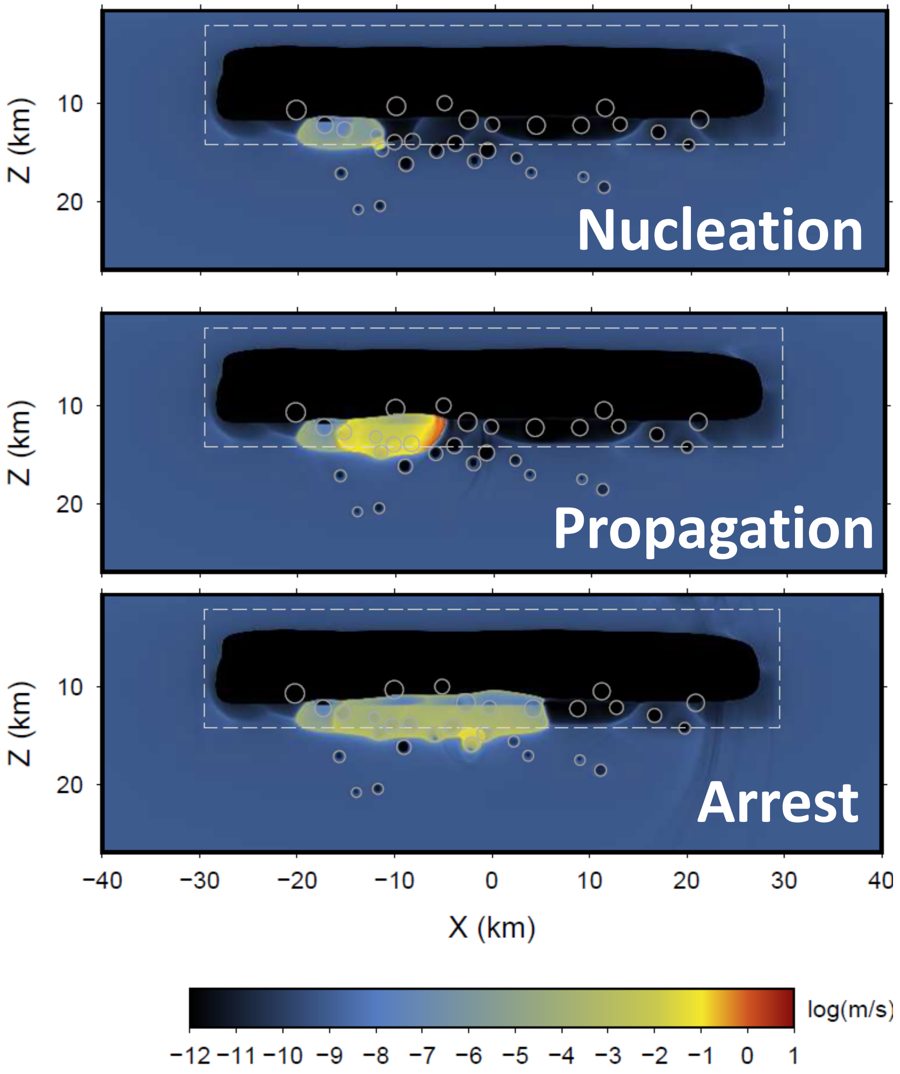
Fault loaded by deep creep

Stress concentration

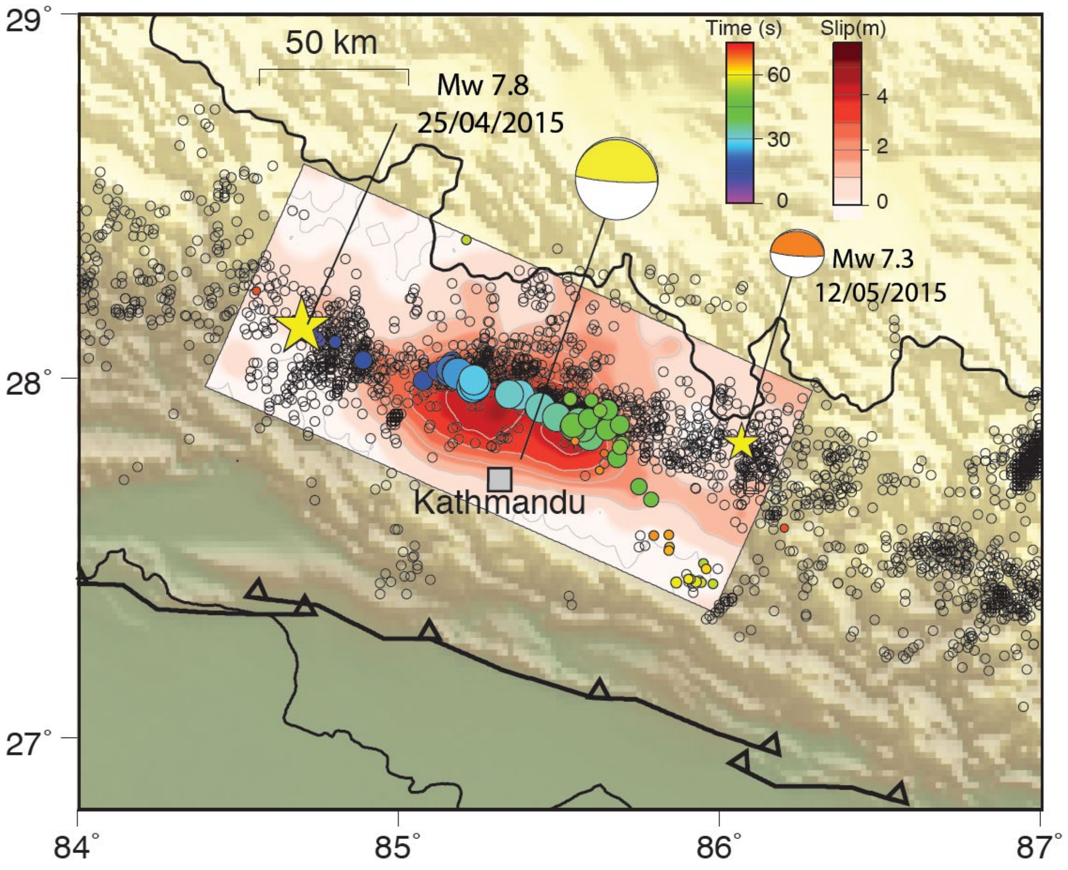




Rupture unzipping the lower edge of the seismogenic zone (simulation by Junle Jiang)

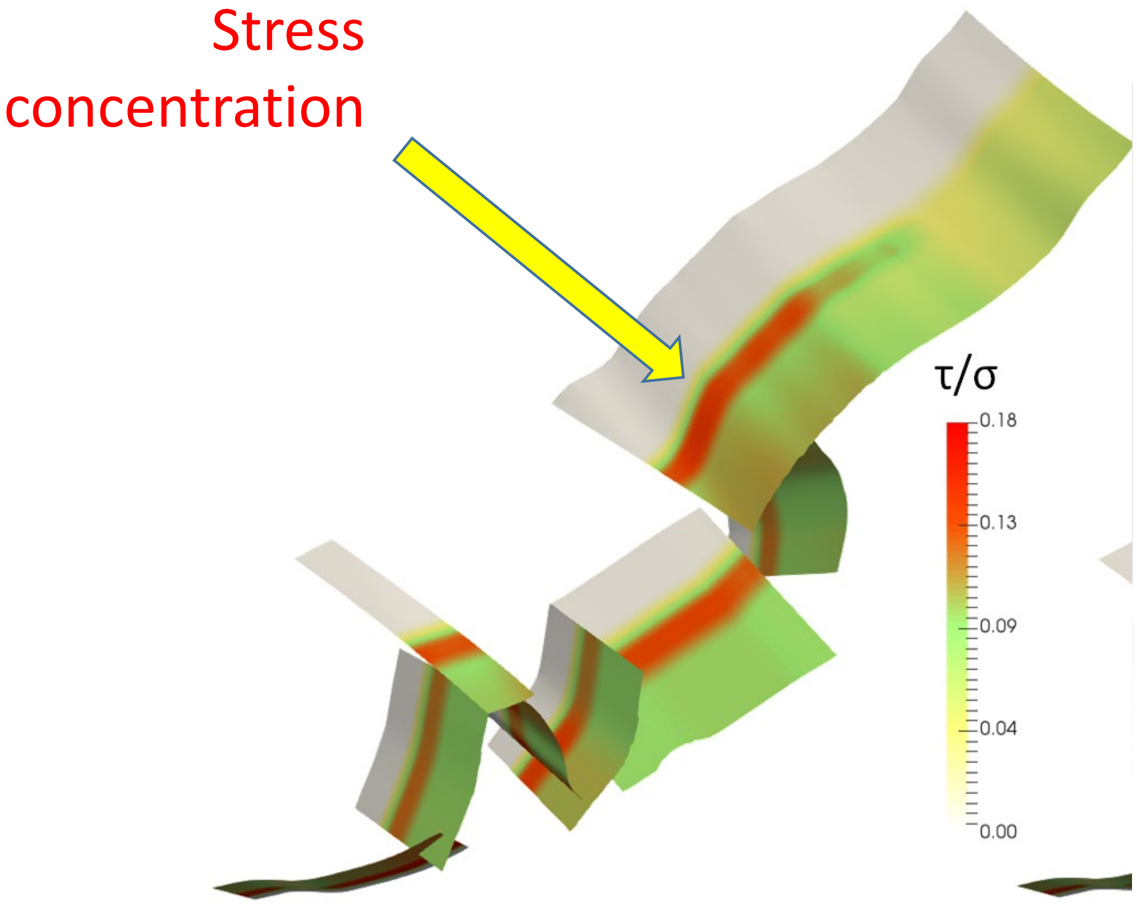


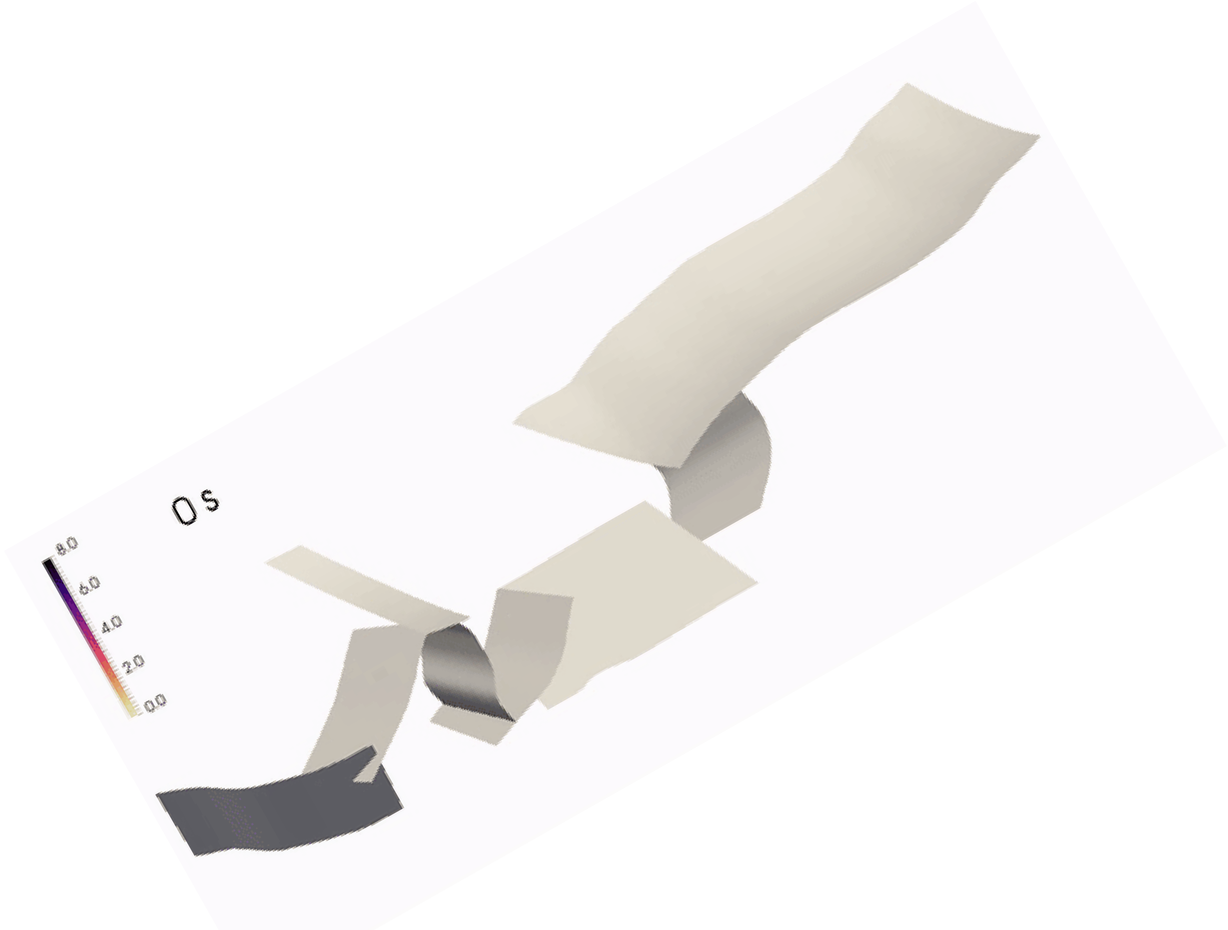
2015 Mw 7.8 Gorkha, Nepal earthquake



Avouac et al (2015)

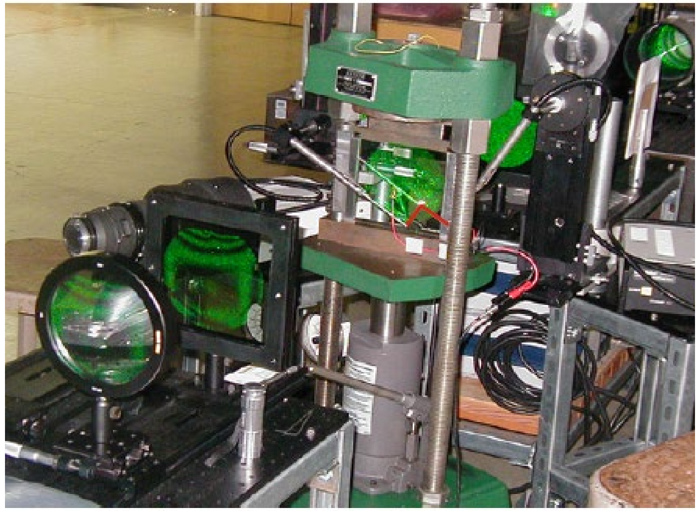
Dynamic model of the 2016 Mw 7.8 Kaikoura earthquake
A rupture cascade on weak faults



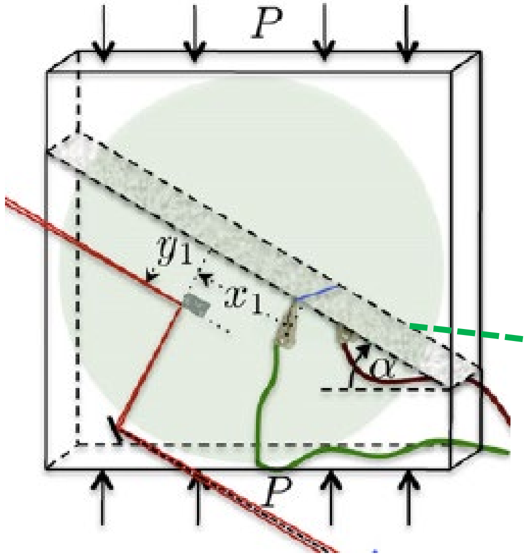


Ulrich, Gabriel, Ampuero, Xu (2018)

Long ruptures in the lab



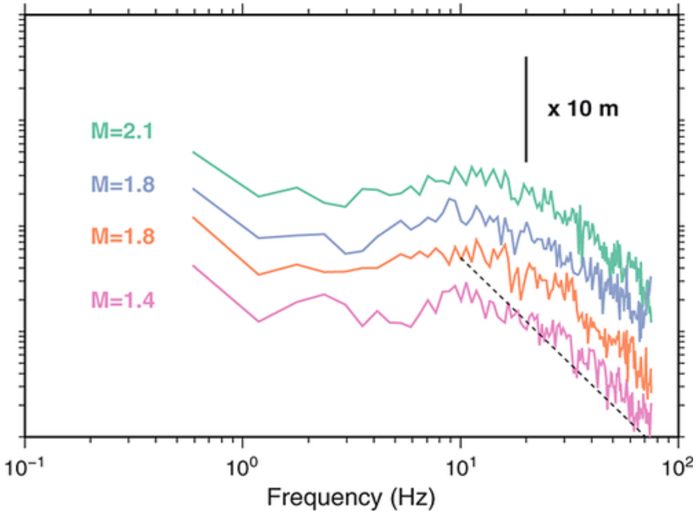
Laboratory earthquake experiment

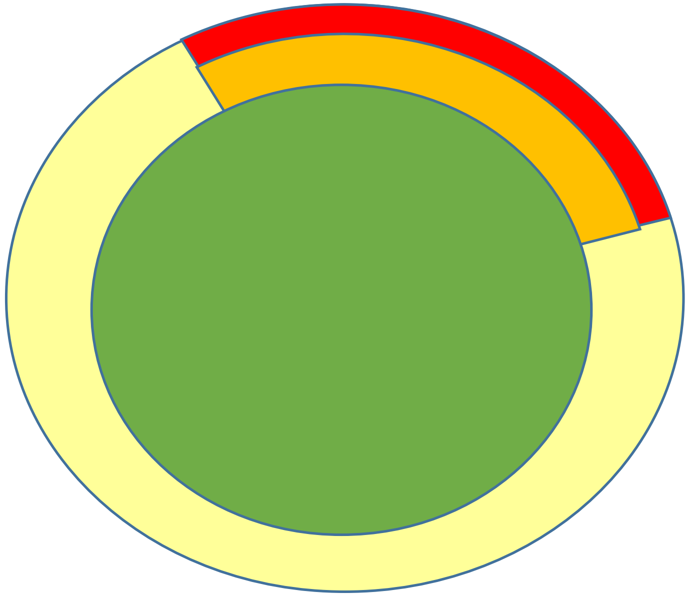


Mello et al (2014)
in Rosakis lab (Caltech)

$$G_0 \approx \frac{\Delta\tau^2 W}{\pi\mu}$$

Lengline et al (2014) Soultz





Observation (Soultz, etc):
Events with different M but same fc

Model:
Two events, same stress drop, different width
→ small and large events

Same length → same duration
→ same corner frequency

To do:
Look for second corner frequency (width-controlled)

Connecting models of natural and induced earthquakes

Natural and induced seismicity share some common features
Opportunities to understand rupture processes at a fundamental level

Classical fracture mechanics provides useful results
→ rupture initiation and arrest, time-to-failure, foreshocks, b-values
Non-conventional fracture mechanics can advance us further → large earthquakes