Workshop on
Mechanics of the Earthquake Cycle

ICTP, Trieste, 16-17 October 2023

Lecture 4. Dynamics of large earthquakes.
Segmentation and rupture potential

Jean Paul Ampuero (IRD/UCA Geoazur)

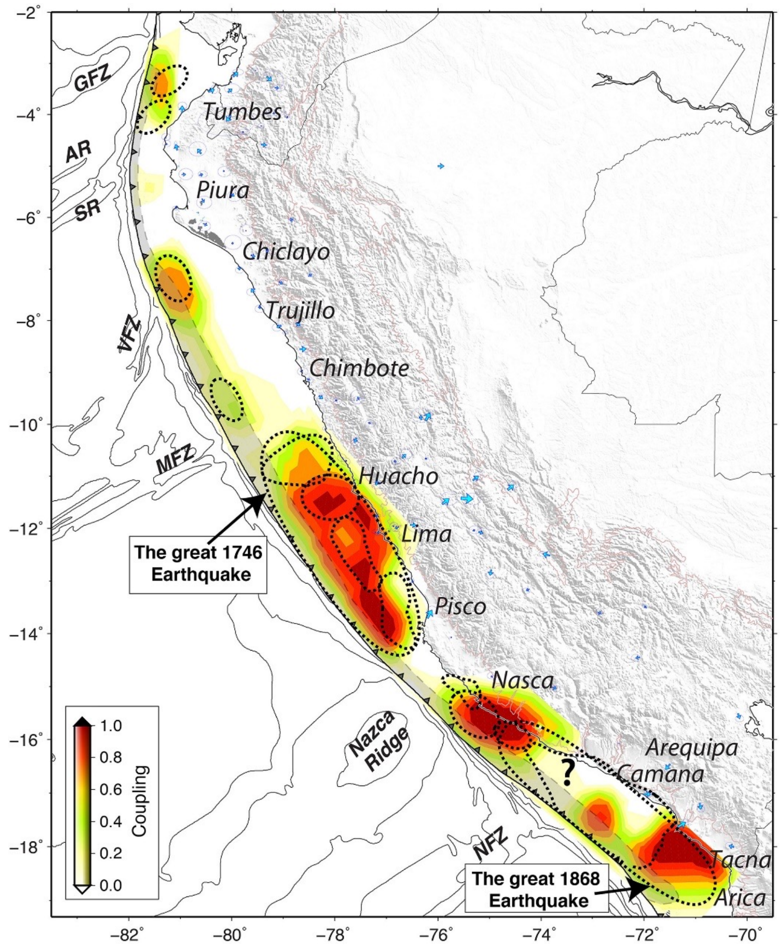
Towards physics-based seismic hazard assessment

Slip deficit → how much slip can happen in the next earthquake

But how far can the next rupture propagate?

Will it break multiple asperities / segments?

Inferred seismic coupling



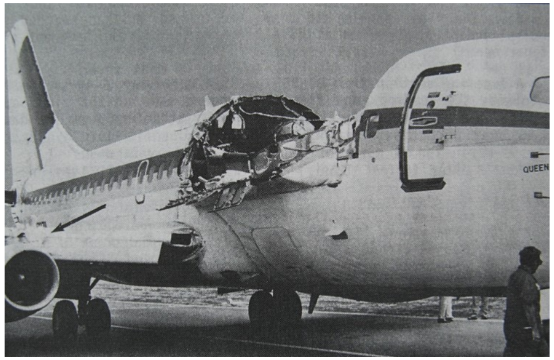
Villegas-Lanza et al (2016)

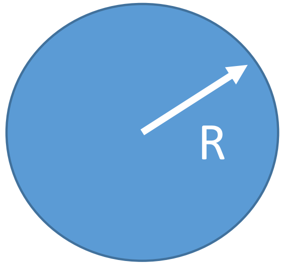
Overview

- Theoretical advances on: what controls the **arrest** and **rupture speed** of very large earthquakes?
- Applications to subduction zones and induced seismicity
- Challenges in complex fault networks. Ex: Turkey

“very large” = rupture Length ≫ rupture Width

Fracture mechanics: the crack-tip equation of motion

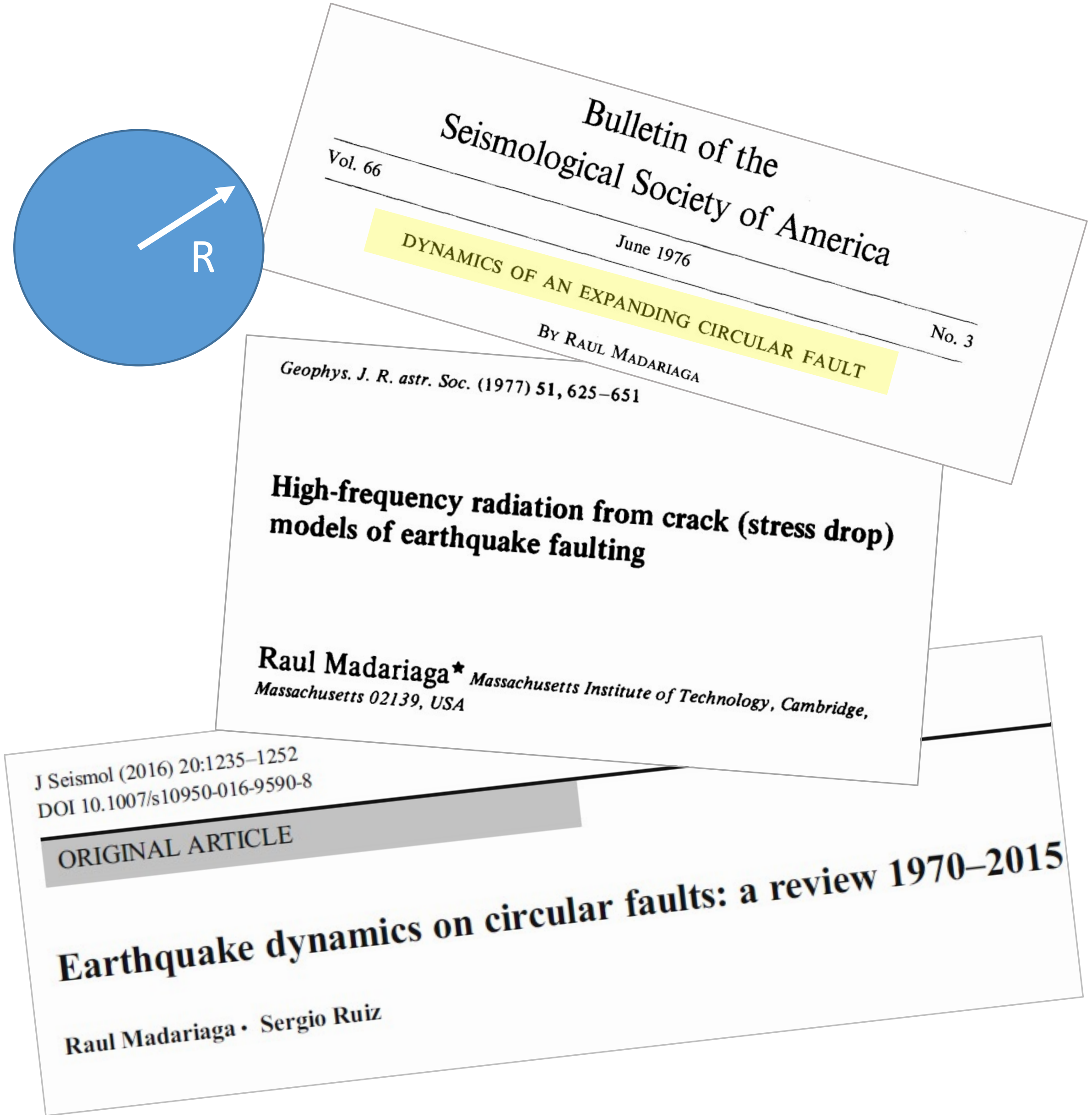




Energy balance for circular ruptures with rupture speed $\dot{R}(t)$:
Energy dissipated by fracture = energy flow to the rupture front

$$G_c = g(\dot{R})G_0(R)$$

Ordinary Differential Equation $\dot{R} = f(R, \dots)$
Solve → $R(t)$



Bulletin of the Seismological Society of America
Vol. 66 June 1976 No. 3

DYNAMICS OF AN EXPANDING CIRCULAR FAULT

BY RAUL MADARIAGA

Geophys. J. R. astr. Soc. (1977) **51**, 625–651

High-frequency radiation from crack (stress drop) models of earthquake faulting

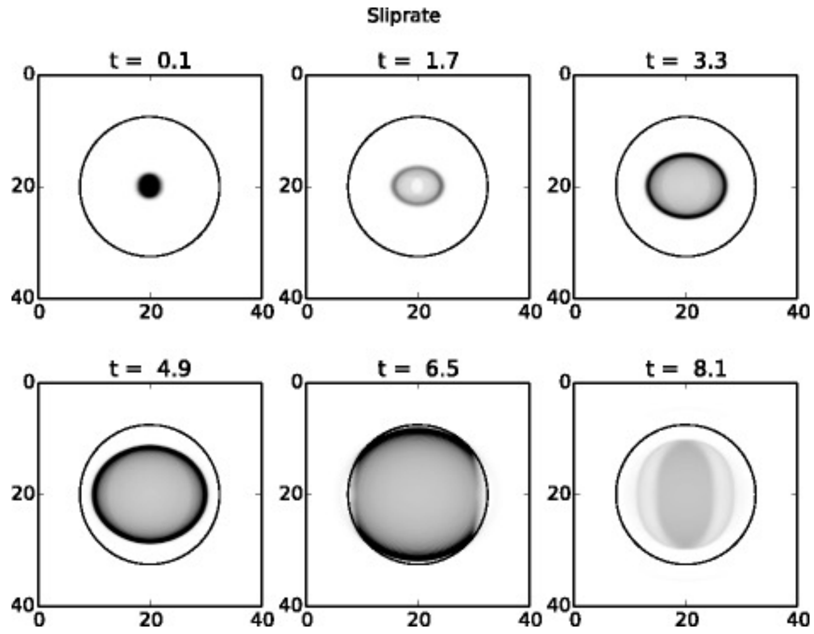
Raul Madariaga* *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

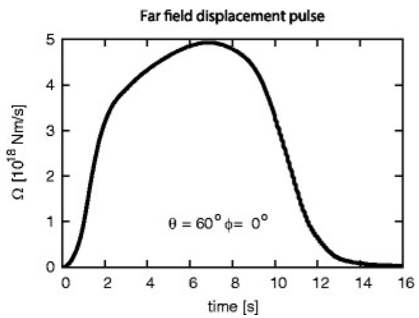
J Seismol (2016) 20:1235–1252
DOI 10.1007/s10950-016-9590-8

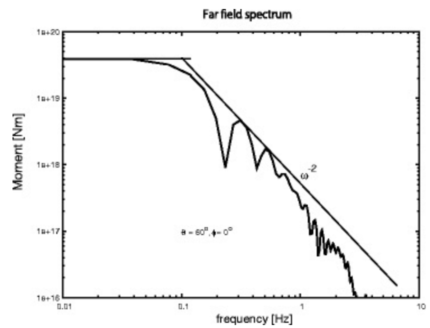
ORIGINAL ARTICLE

Earthquake dynamics on circular faults: a review 1970–2015

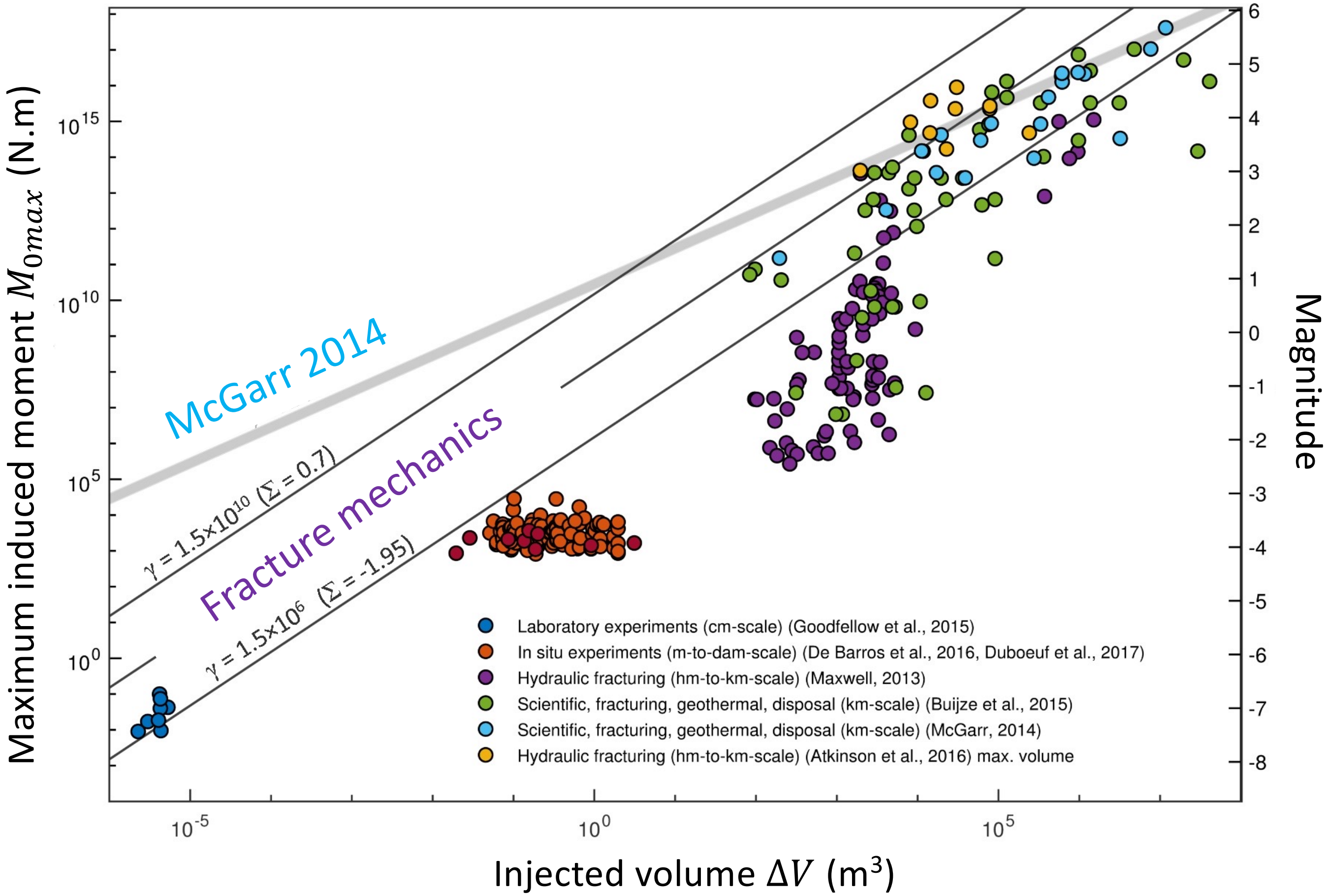
Raul Madariaga · Sergio Ruiz







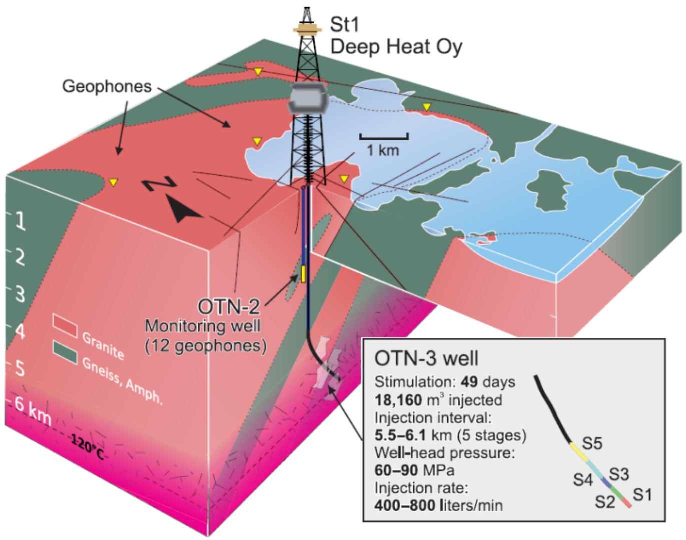
Fracture mechanics of rupture arrest applied to induced seismicity: $M_{0max} \propto \Delta V^{3/2}$

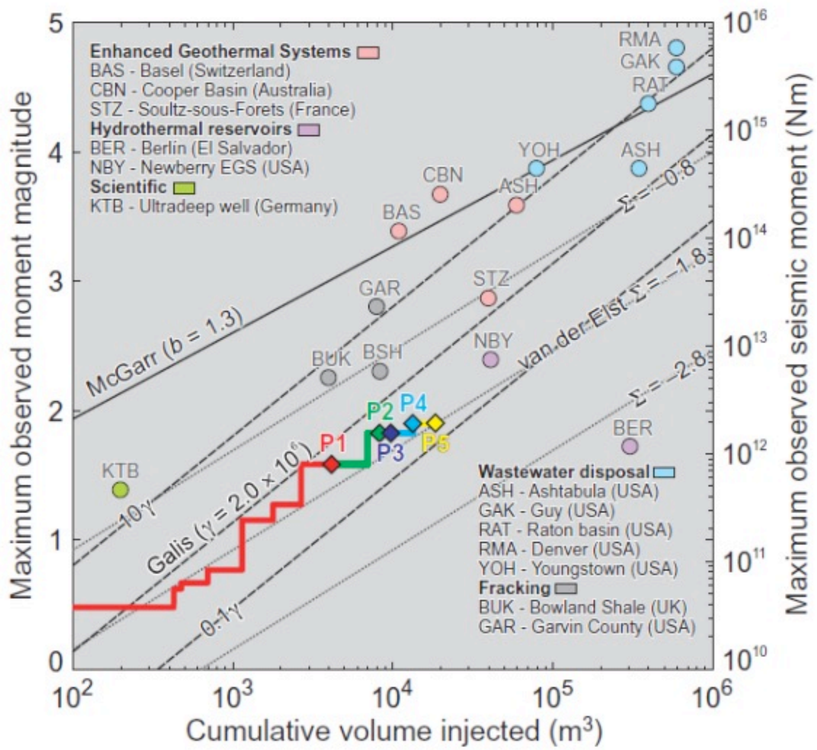


Galis et al (2017)

Application:

Controlling fluid-induced seismicity during a deep geothermal stimulation in Helsinki, Finland (Kwiatek et al, 2019)



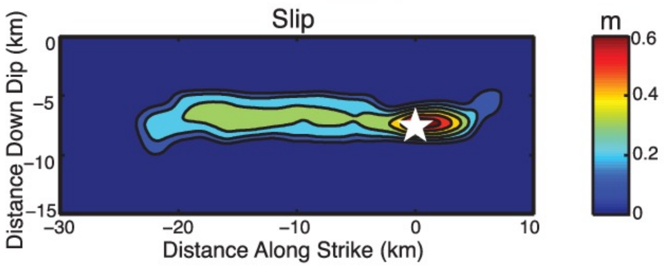


Large earthquakes have elongated ruptures

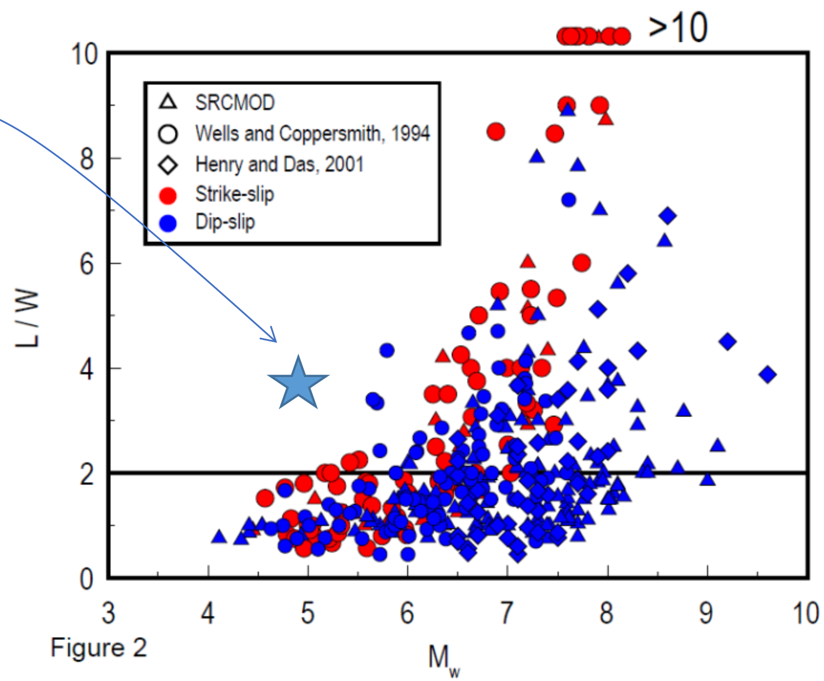
Large length/width ratio (L/W)

2019 Le Teil, France Mw 4.9

2004 M6 Parkfield

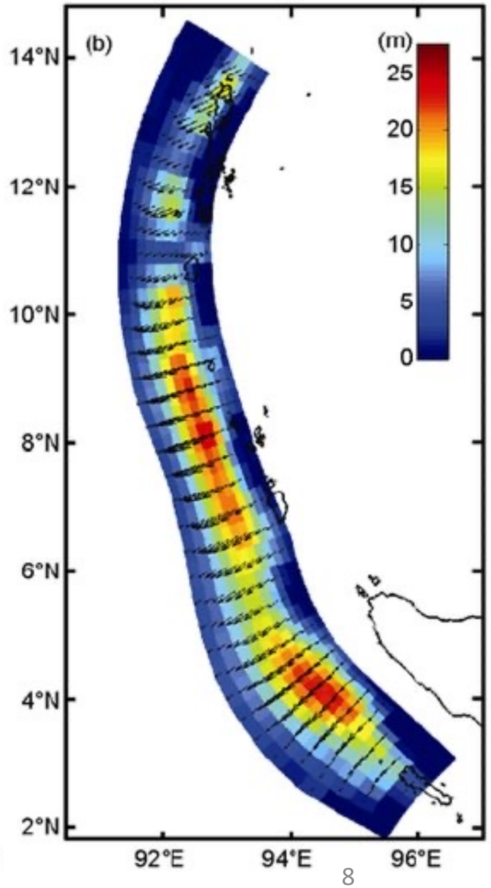


Ma et al (2008)

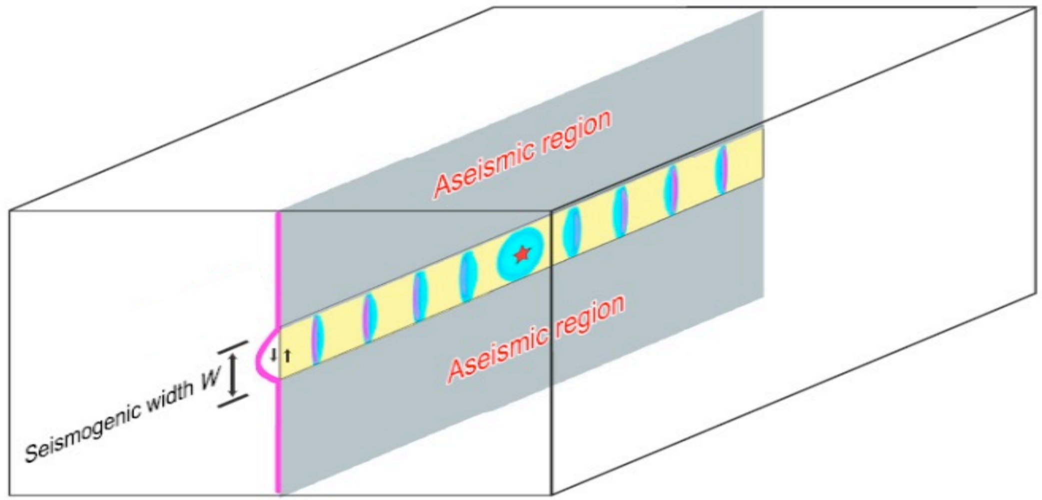


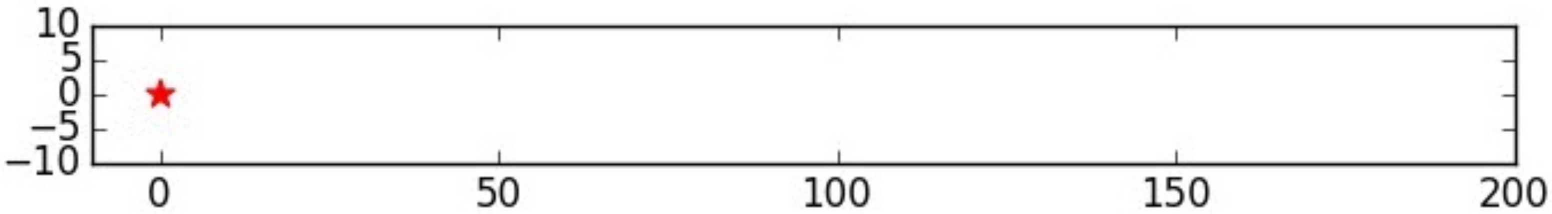
Weng and Ampuero (2019)

2004 M9.2 Sumatra



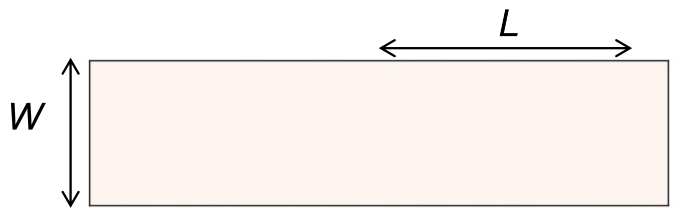
Long ruptures develop as slip pulses

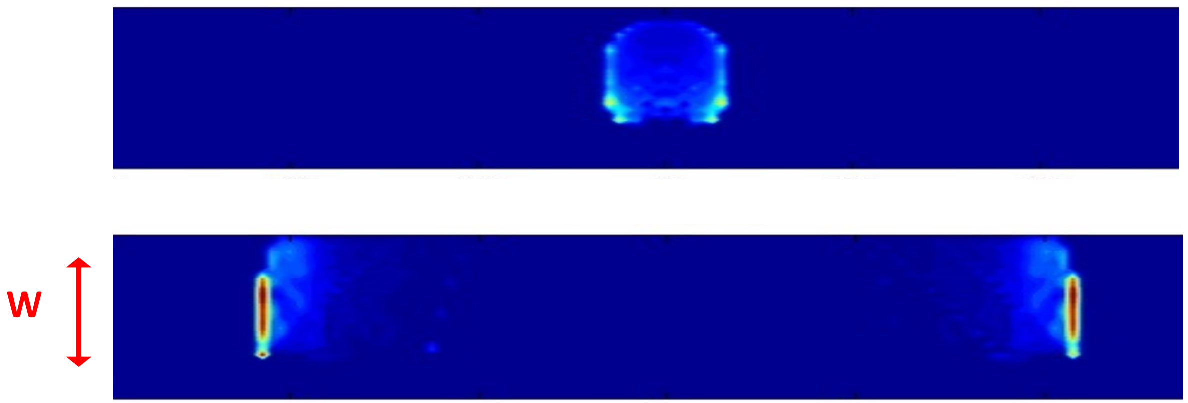




Long ruptures develop as slip pulses

Transition from circular rupture
to bilateral pulses
due to finite seismogenic width W





Energy scaling:

$$G_0 \propto R$$

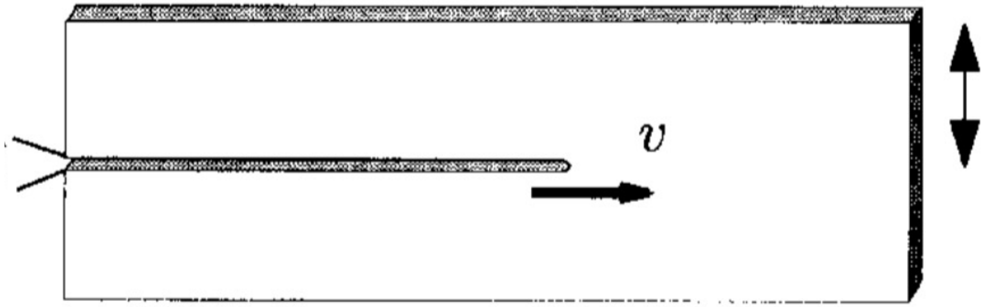
vs.

$$G_0 \propto W$$

Dynamic theory for long ruptures?

Nonsteady crack in a 2D strip

Marder (1998)



W = width of 2D bounded medium

Steady-state rupture: $G_c = G_0 \approx \Delta\tau\varepsilon \approx \Delta\tau^2 W/\mu$

PRL **104,** 114301 (2010) PHYSICAL REVIEW LETTERS week ending 19 MARCH 2010

Acquisition of Inertia by a Moving Crack

Tamar Goldman, Ariel Livne, and Jay Fineberg

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2019JB017684

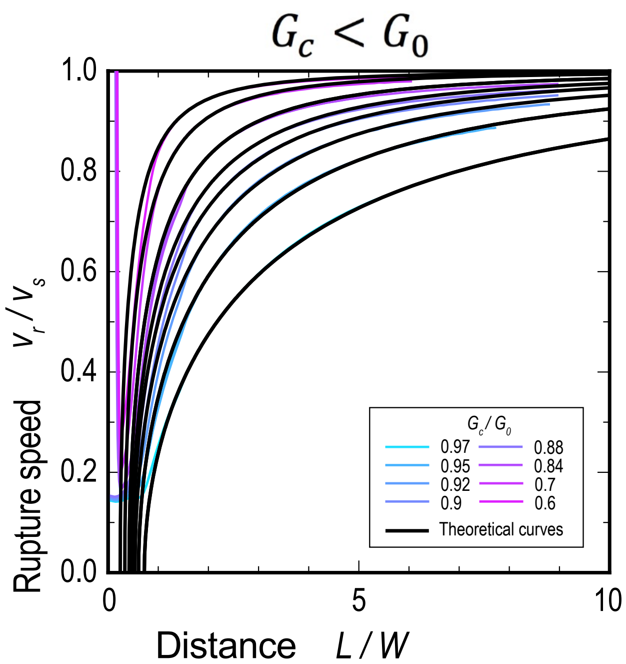
The Dynamics of Elongated Earthquake Ruptures

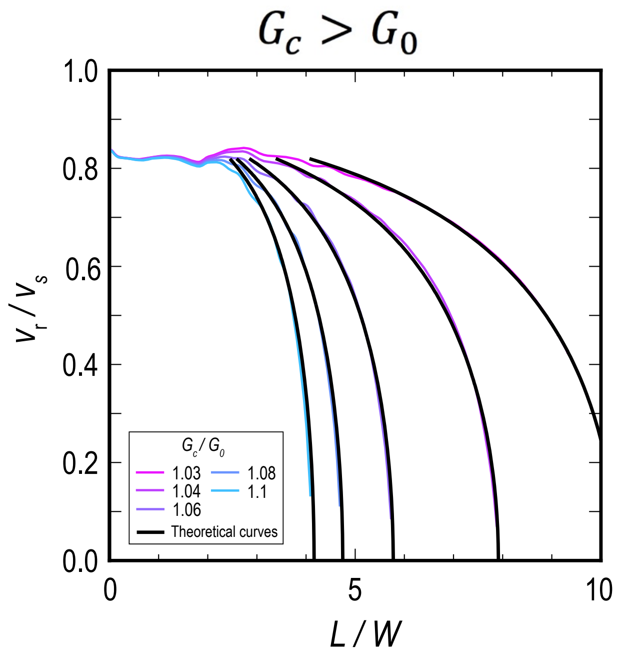
Huihui Weng[1] and Jean-Paul Ampuero[1,2]

2019

$G_0 = \frac{\Delta\tau^2 W}{\pi\mu}$ = potential energy

G_c = fracture energy





Equation-of-motion:

$$1 - G_c / G_0 = \mathcal{M}(v_r) \cdot \dot{v}_r$$

"Force" = "Mass" × Acceleration

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2019JB017684

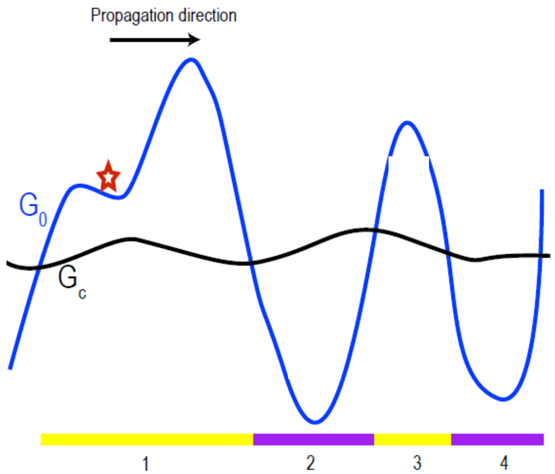
The Dynamics of Elongated Earthquake Ruptures

Huihui Weng[1] and Jean-Paul Ampuero[1,2]

2019

$$G_0 = \frac{\Delta\tau^2 W}{\pi\mu} = \text{potential energy}$$

$$G_c = \text{fracture energy}$$



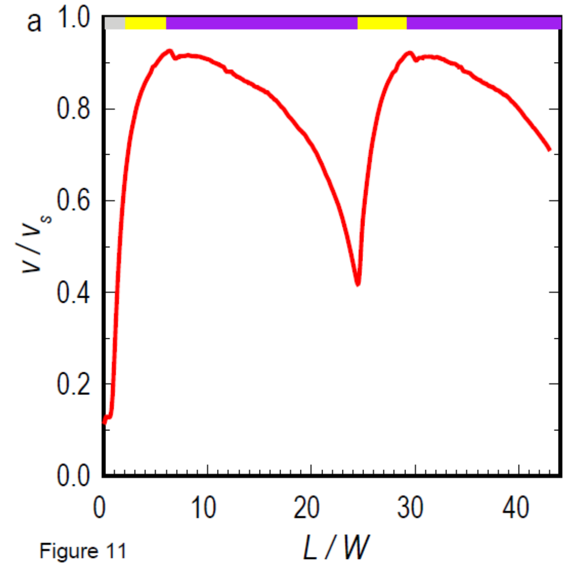
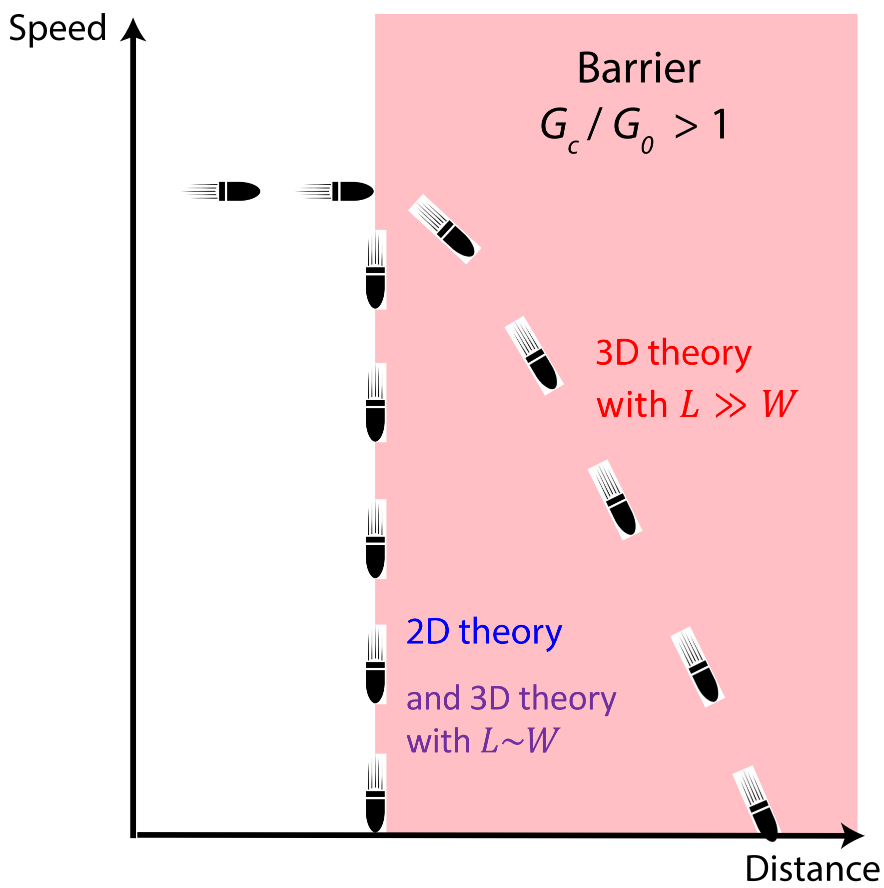


Figure 11

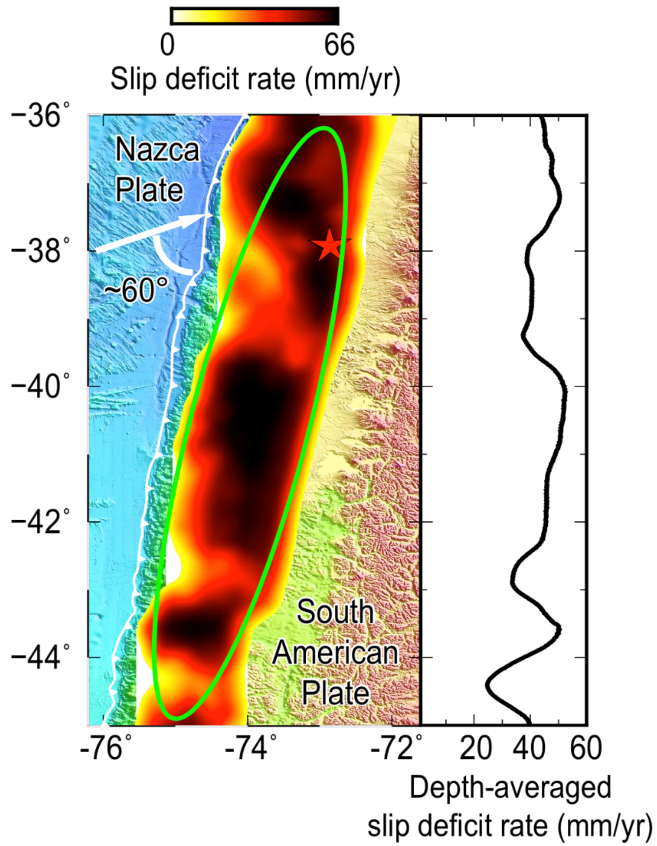
Equation-of-motion: $1 - G_c/G_0 = \mathcal{M}(v_r) \cdot \dot{v}_r$

"Force" = "Mass" × Acceleration

Implications for rupture arrest



Constraints on potential energy G_0

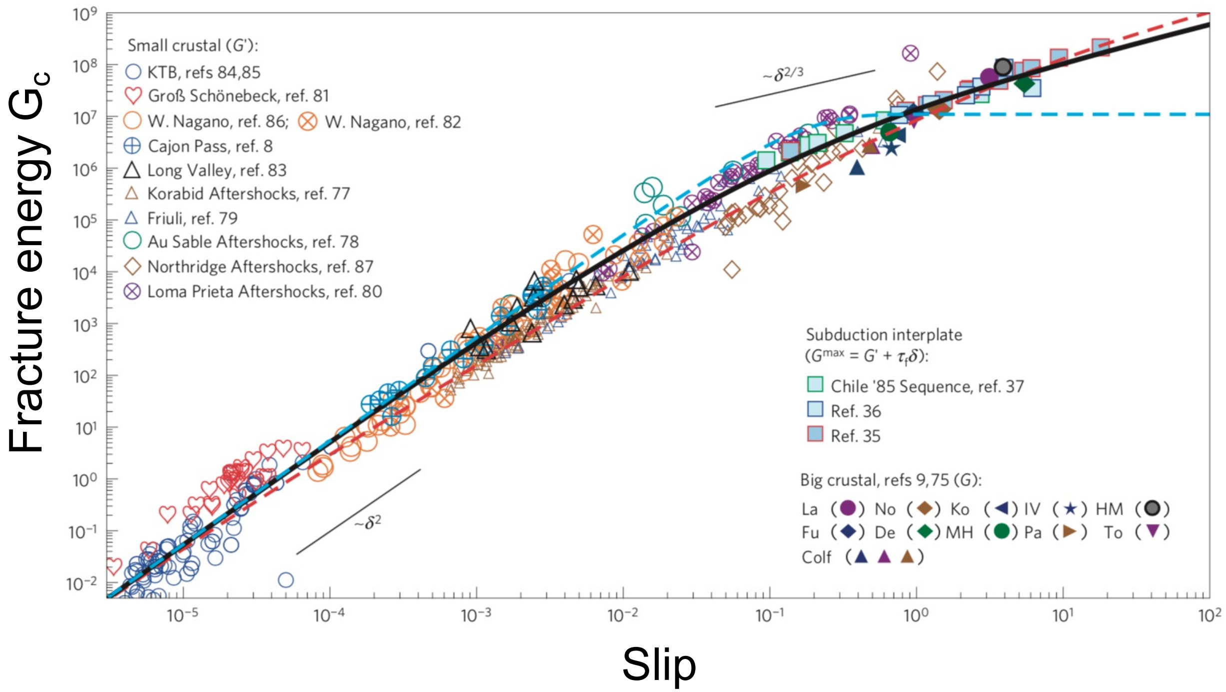


$$G_0 = \frac{\Delta\tau^2 W}{\pi\mu}$$

$$\Delta\tau = \frac{C\mu D}{W}$$

$$G_0 \sim \frac{\mu}{W} D^2$$

Constraints on fracture energy G_c



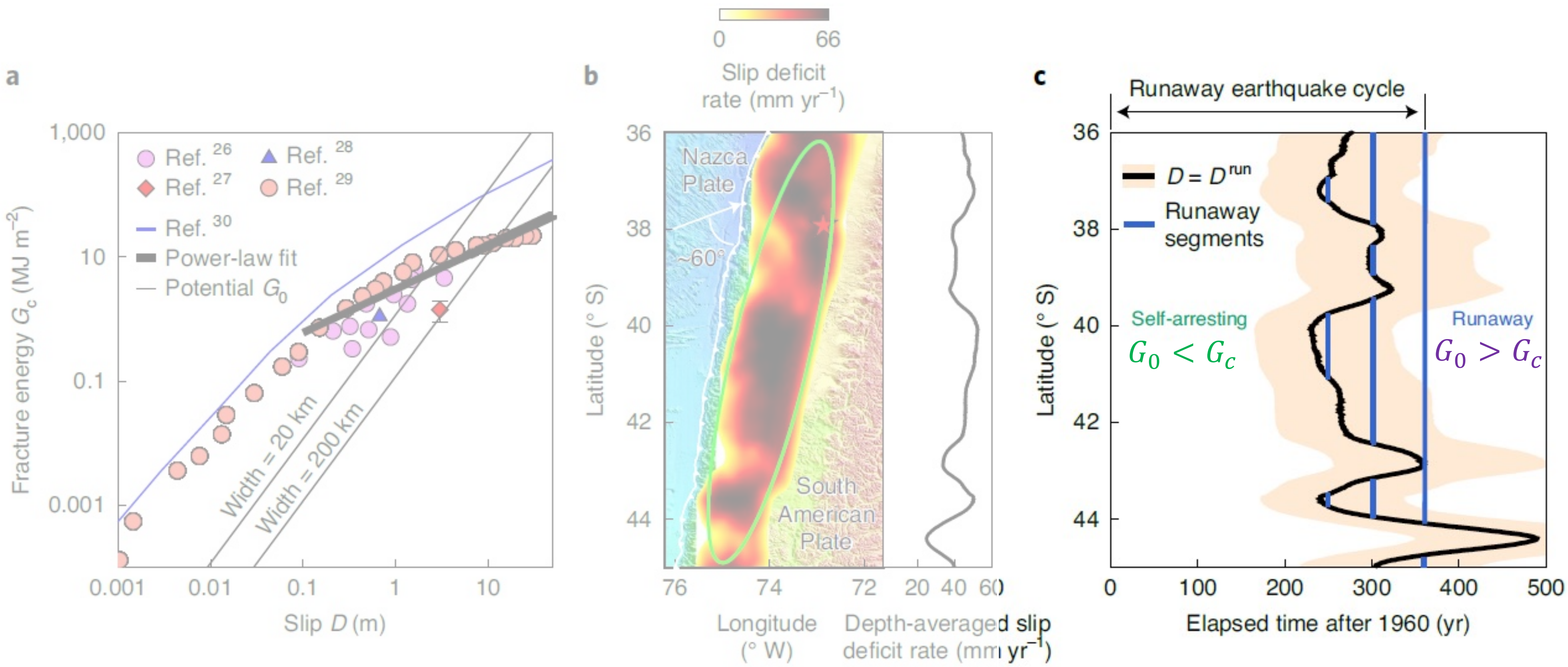
$$G_c \sim D^{0.7}$$

Viesca and Garagash, 2015

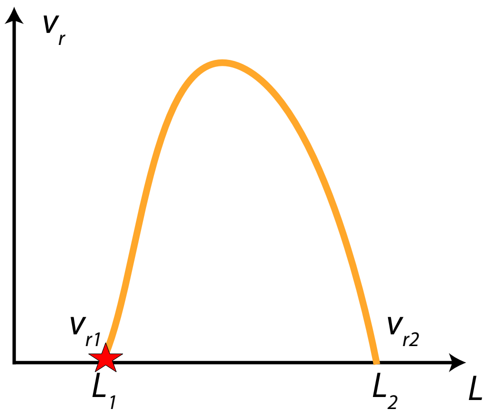
Physical constraints on future earthquake sizes

A fault is ready to host large ruptures if $G_0 > G_c$

Weng & Ampuero (2020)



Rupture potential



$$\mathcal{F}(G_c/G_0) = \mathcal{M}(v_r) \cdot \dot{v}_r$$

$$\dot{v}_r = v_r \frac{dv_r}{dL}$$

$$\int_{L_1}^{L_2} \mathcal{F}(G_c/G_0)\,dL = \int_{v_{r1}}^{v_{r2}} v_r \mathcal{M}(v_r)\,dv_r = 0$$

Potential energy change

Kinetic energy change

Rupture potential

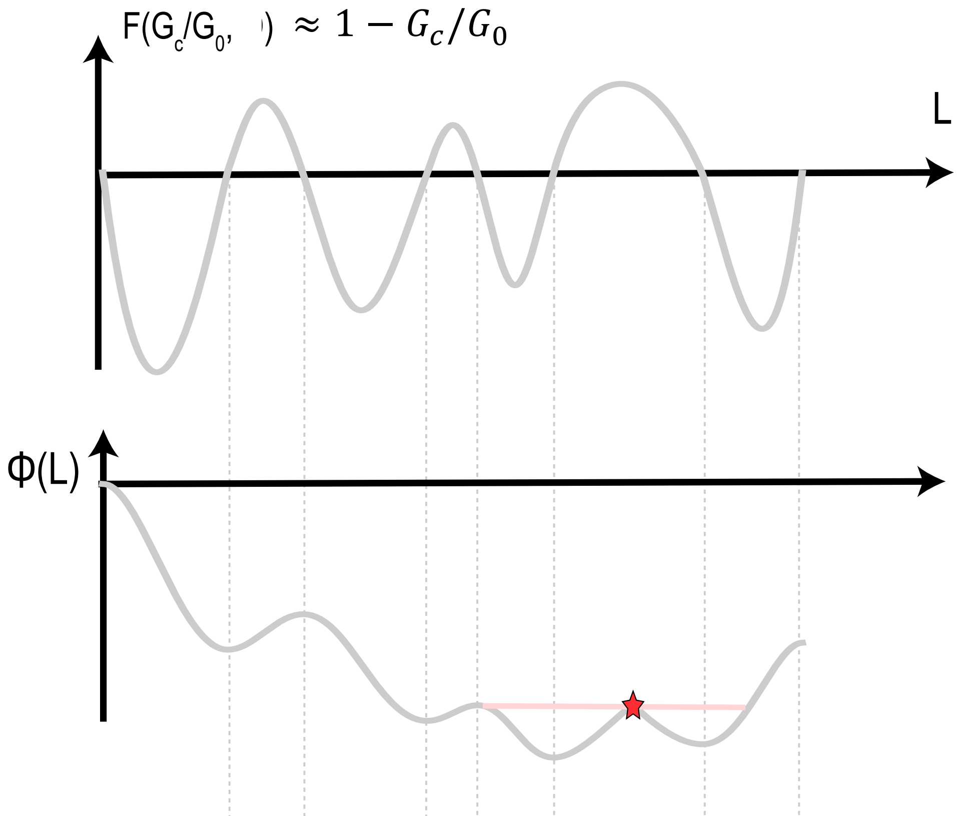
$$\int_0^{L_1} \mathcal{F}(G_c/G_0)\,dL = \int_0^{L_2} \mathcal{F}(G_c/G_0)\,dL$$

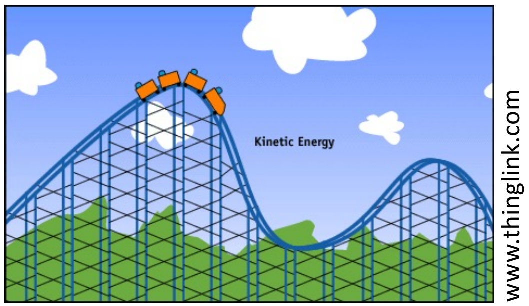
Determine earthquake size

Rupture potential

$$\Phi(L) = \int_0^L \mathcal{F}(G_c/G_0 \quad)dL$$

$$\Phi(L_1) = \Phi(L_2)$$





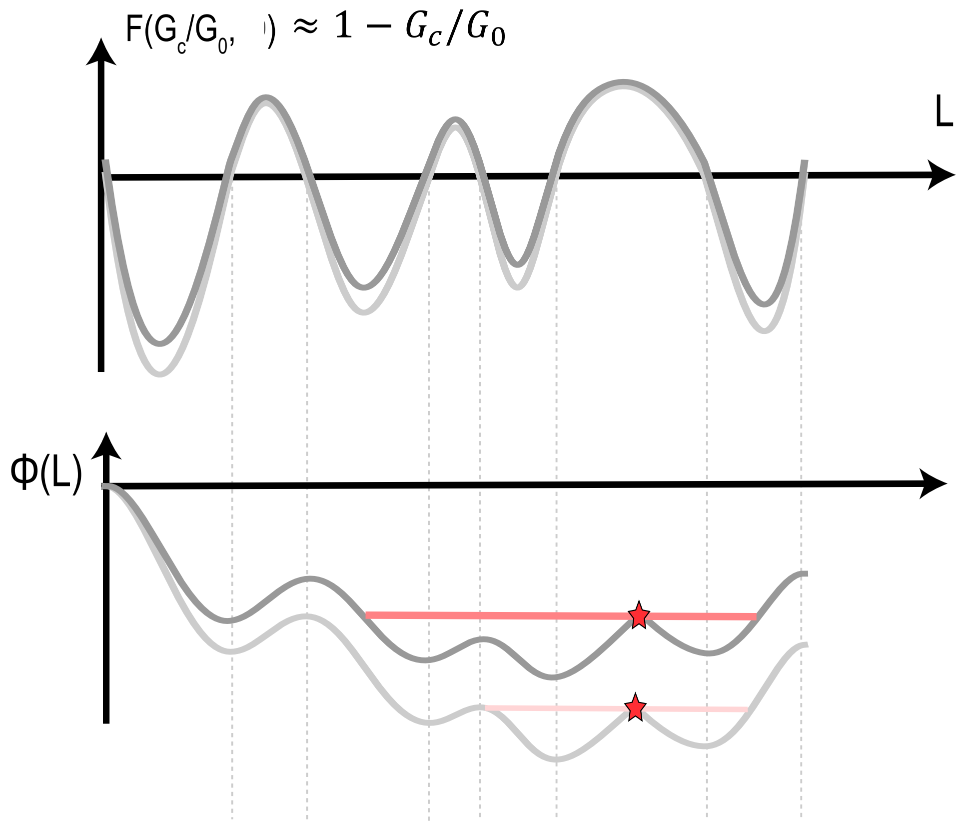
Analogy: gravity potential

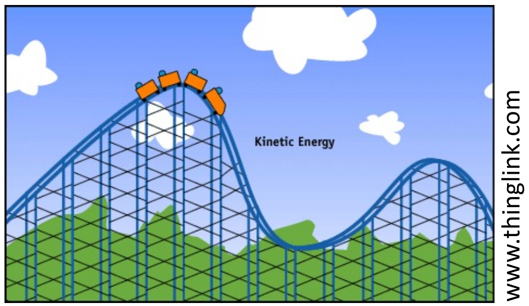
Determine earthquake size

Rupture potential

$$\Phi(L) = \int_0^L \mathcal{F}(G_c/G_0 \quad)dL$$

$$\Phi(L_1) = \Phi(L_2)$$





Analogy: gravity potential

Slip behavior of Velocity-Weakening barriers.

Diego Molina, Jean-Paul Ampuero, Andrés Tassara

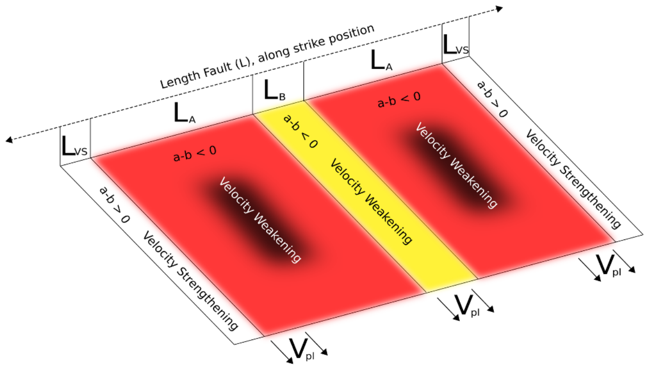
This is a preprint; it has not been peer reviewed by a journal.

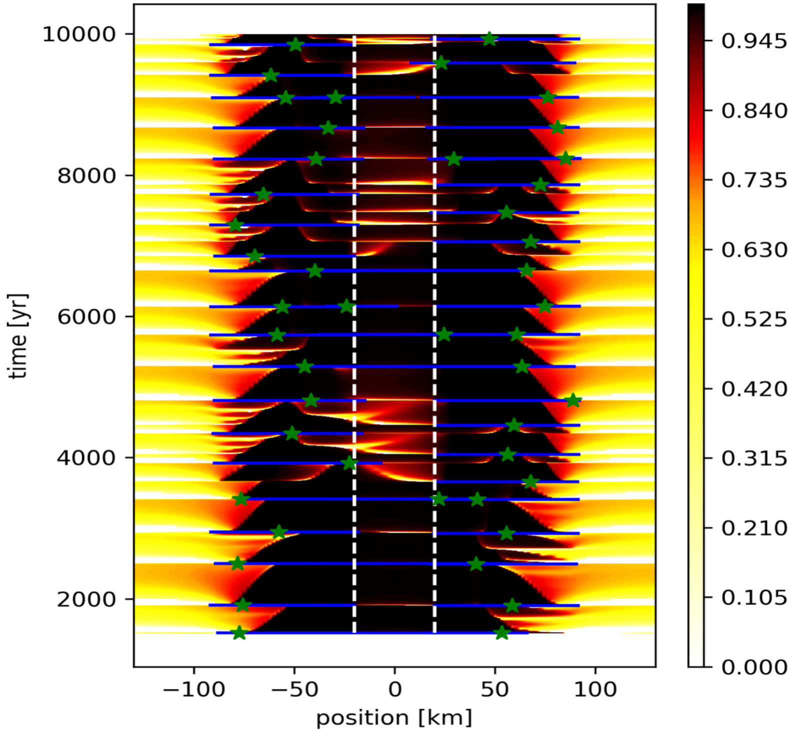
https://doi.org/10.21203/rs.3.rs-1479134/v1

Status: Under Review

nature portfolio

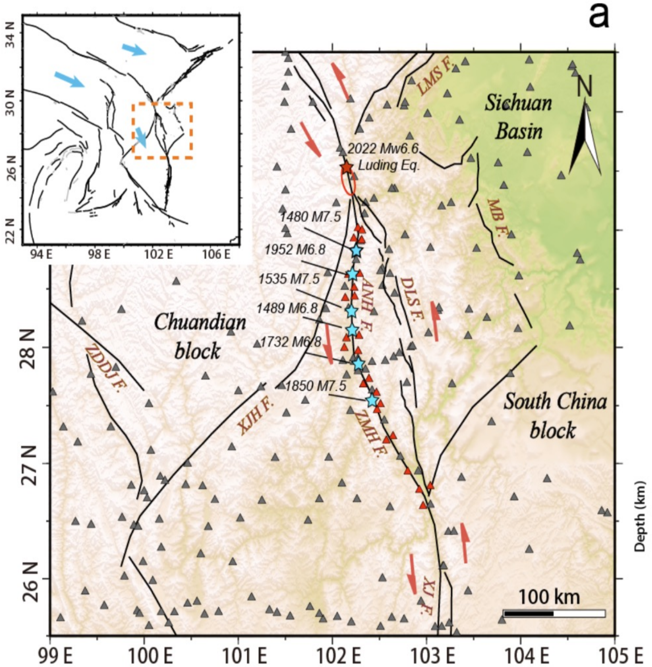
Version 1
posted 27 Apr, 2022

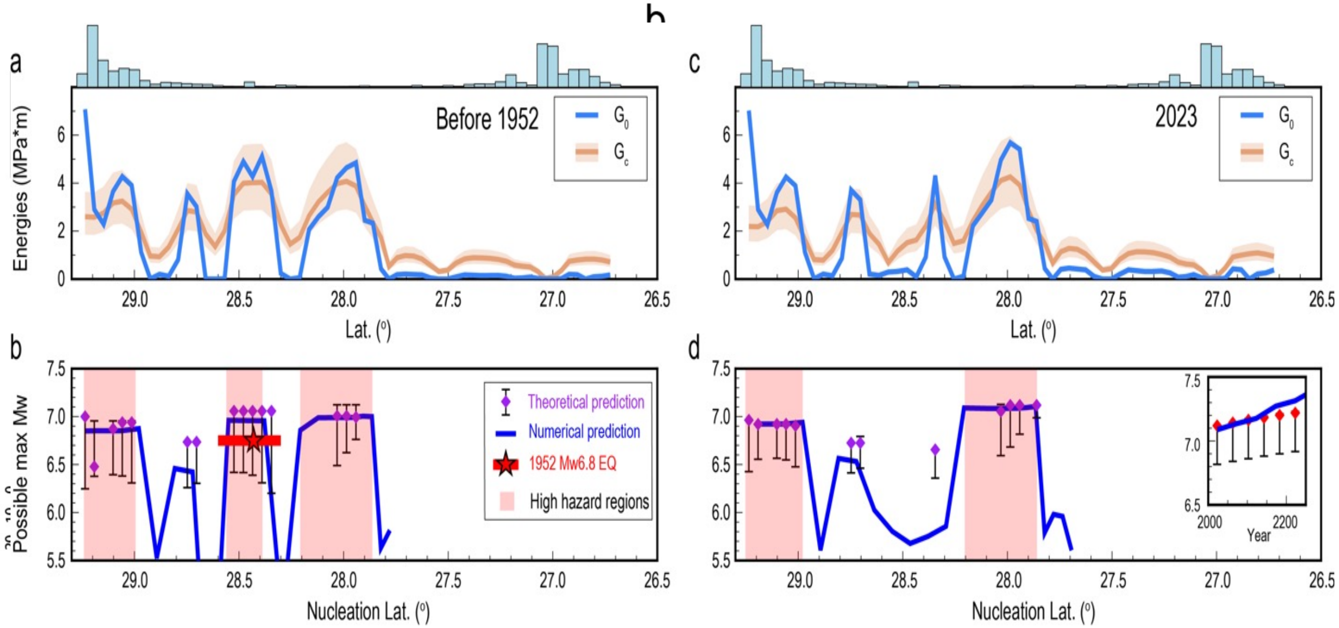


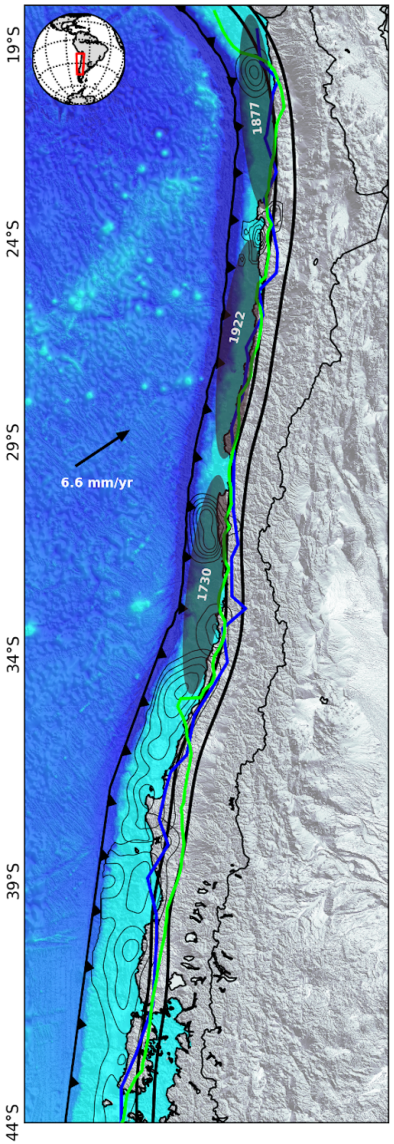


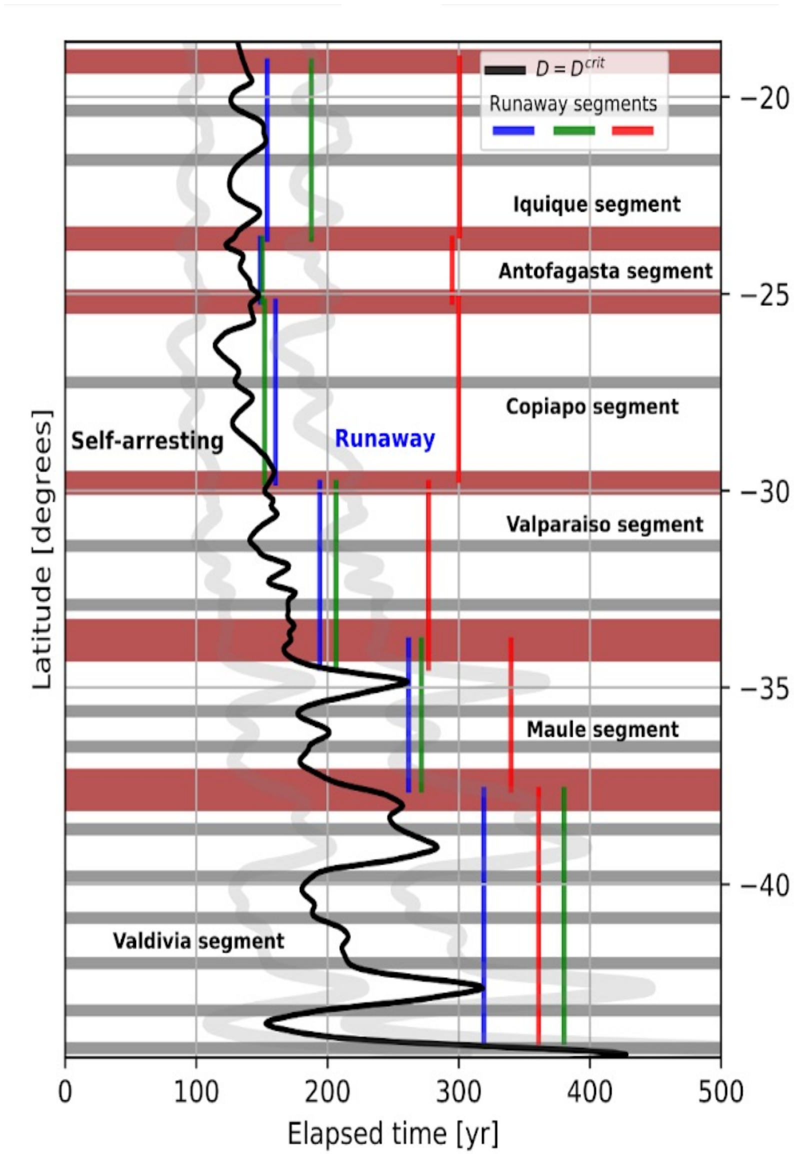
Rupture potential along the Anninghe-Zemuhe-Daliangshan fault system, SW China

with **Huihui Weng** (Nanjing U), **Faqi Diao (**IGG CAS Wuhan**)**







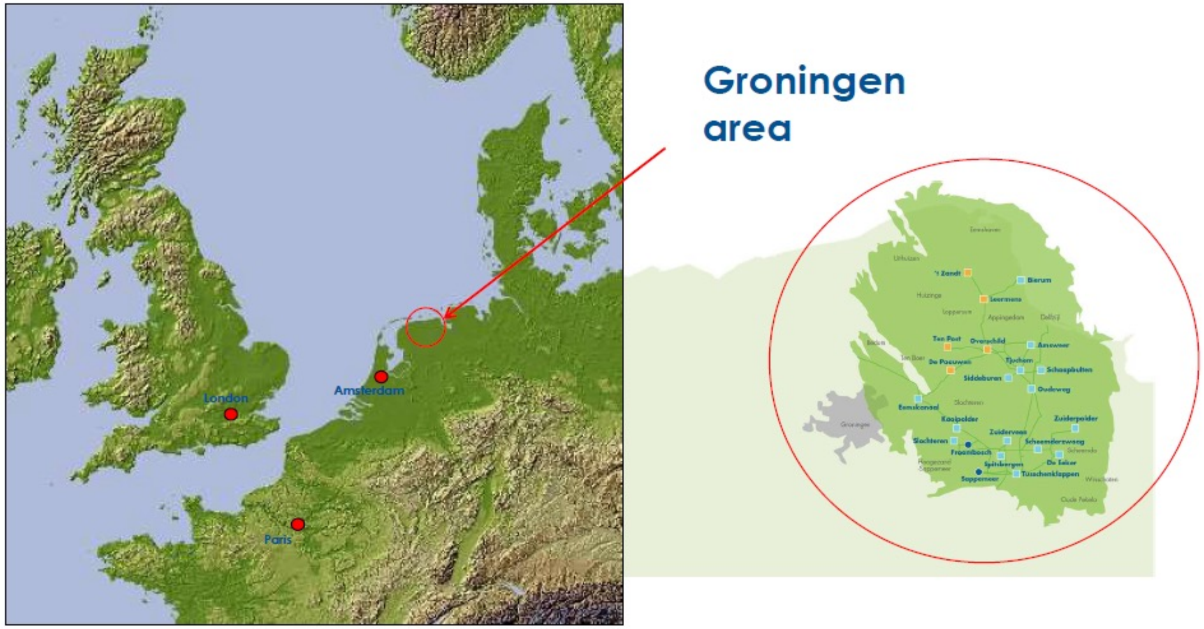


Rupture potential along the Chile subduction zone

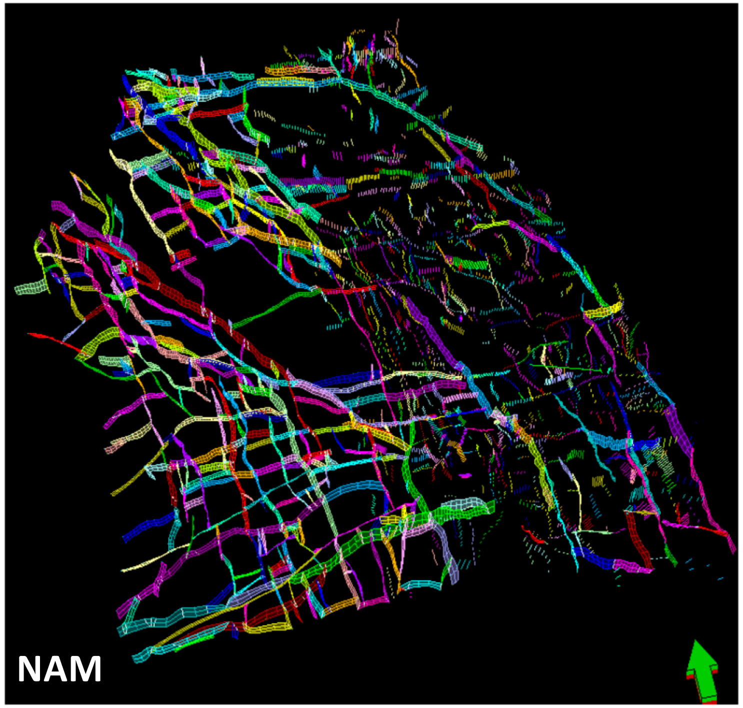
with **Diego Molina** (Grenoble),
Andrés Tassara (Concepción),
Sylvain Michel, Romain Jolivet
(ENS Paris)

Application to Groningen Mmax

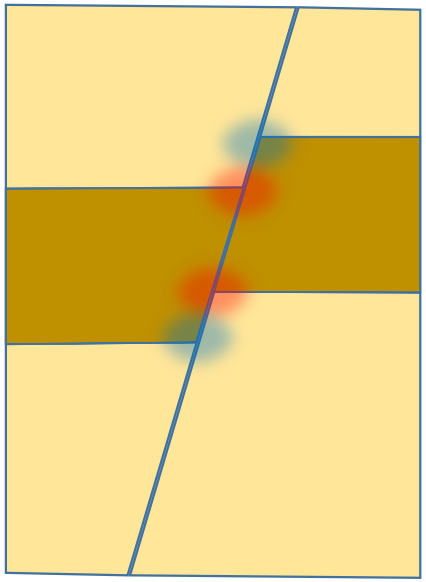
The largest gas field in Europe.
Production has induced earthquakes up to M3.6 (2012)



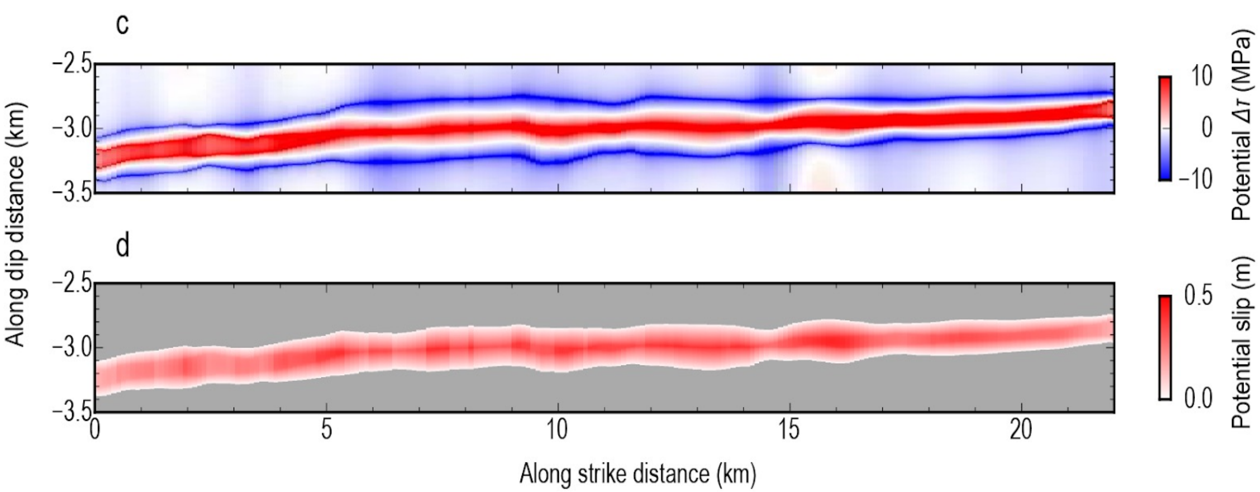
Visser (2022)



Depth-confined ruptures

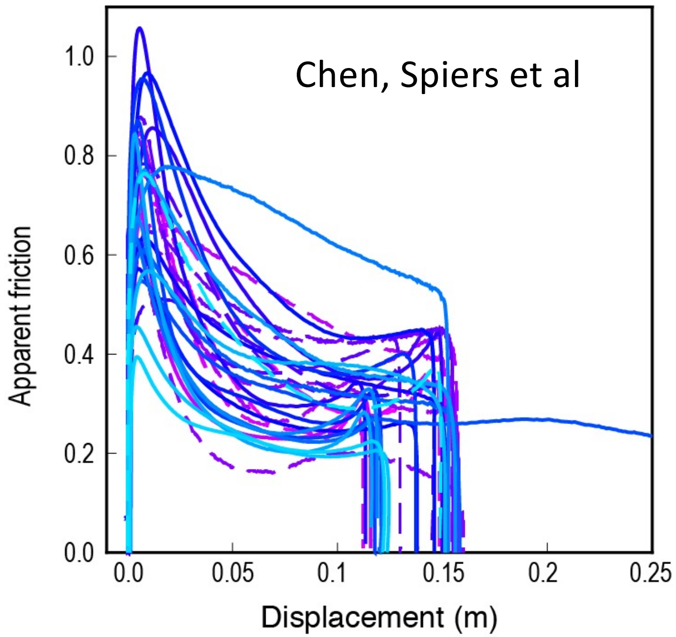


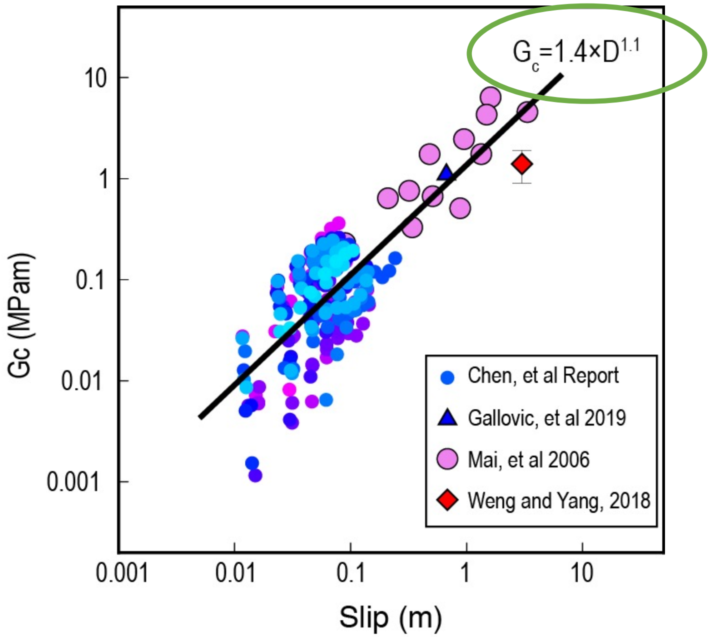
Stress concentrations due to differential reservoir compaction at fault offsets



Application to Groningen Mmax

Scaling of fracture energy vs slip
constrained by lab experiment and earthquake observations

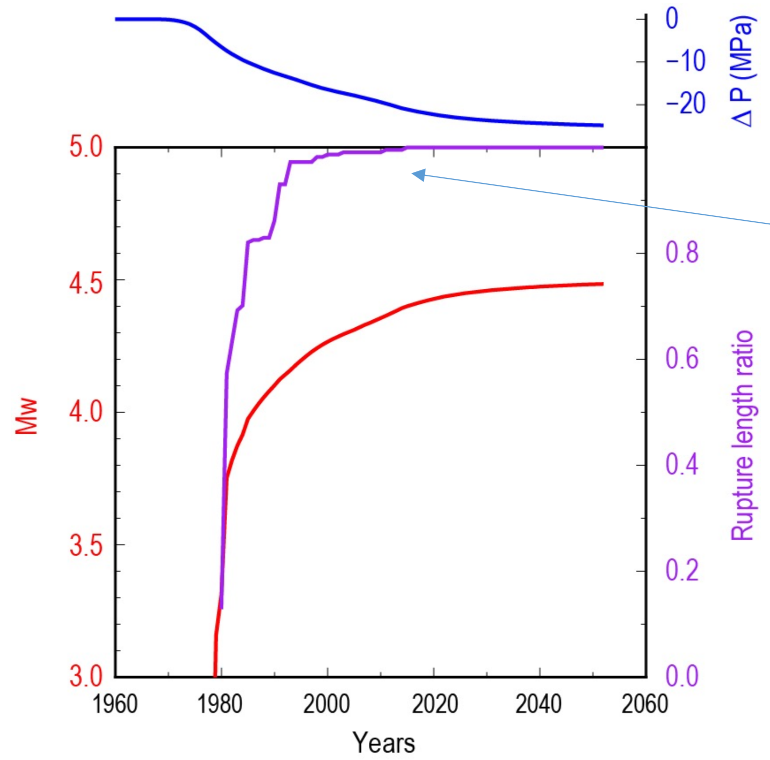




Scaling steeper than linear prevents runaway down-dip

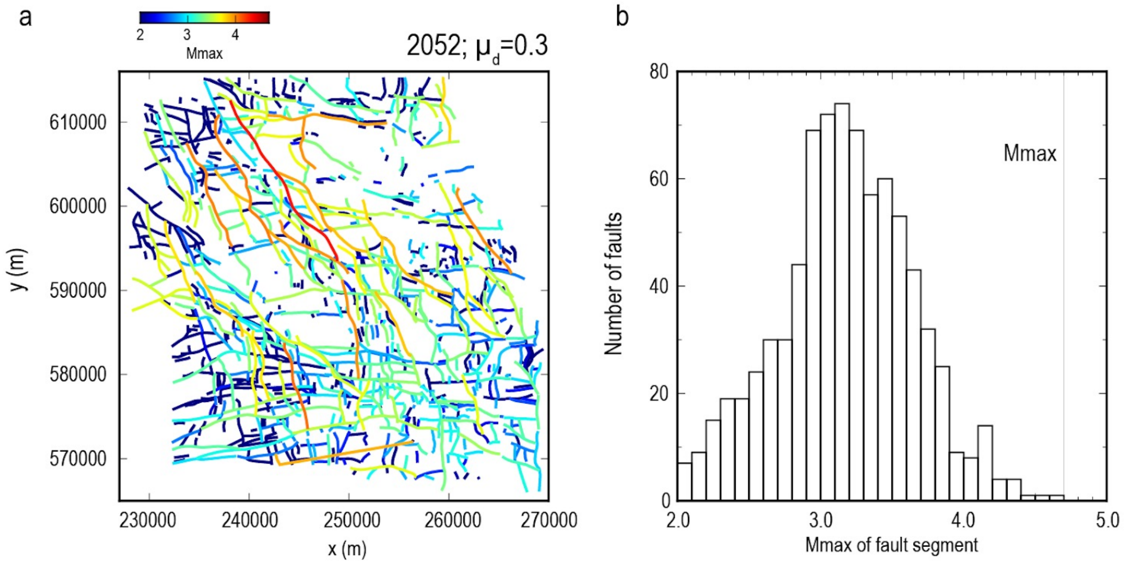
Application to Groningen Mmax

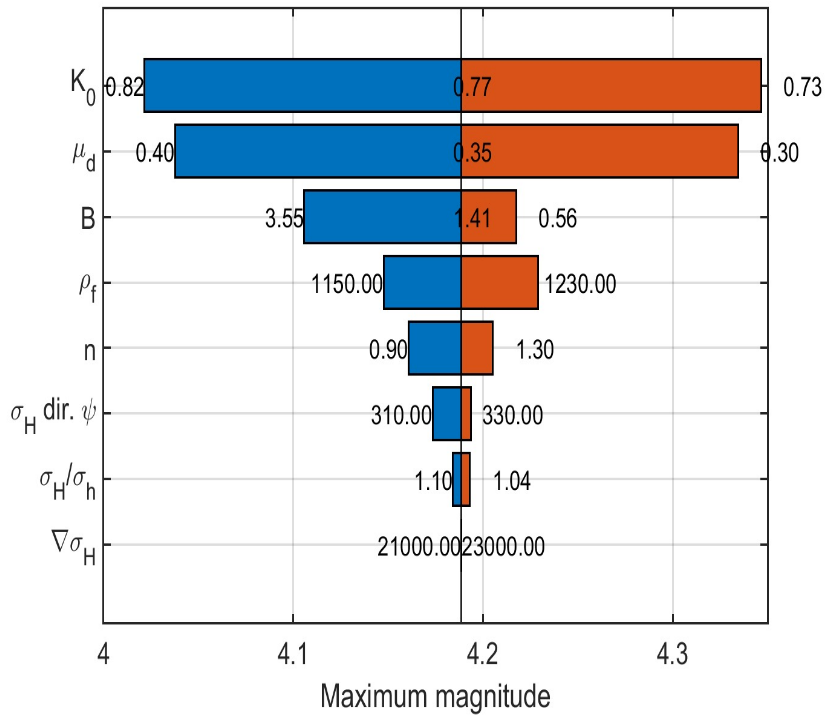
Example:
evolution of Mmax
on one fault



Onset of
full fault length rupture

Application to Groningen Mmax

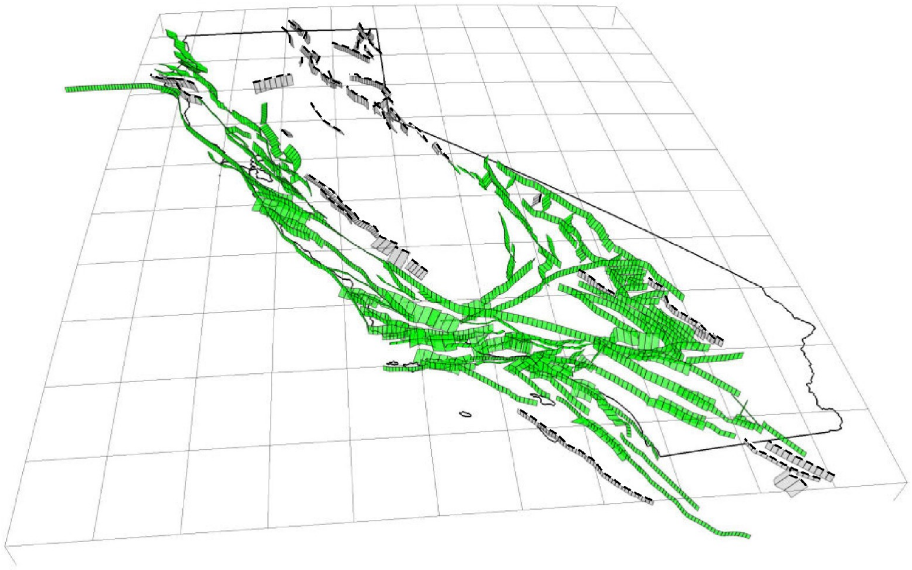


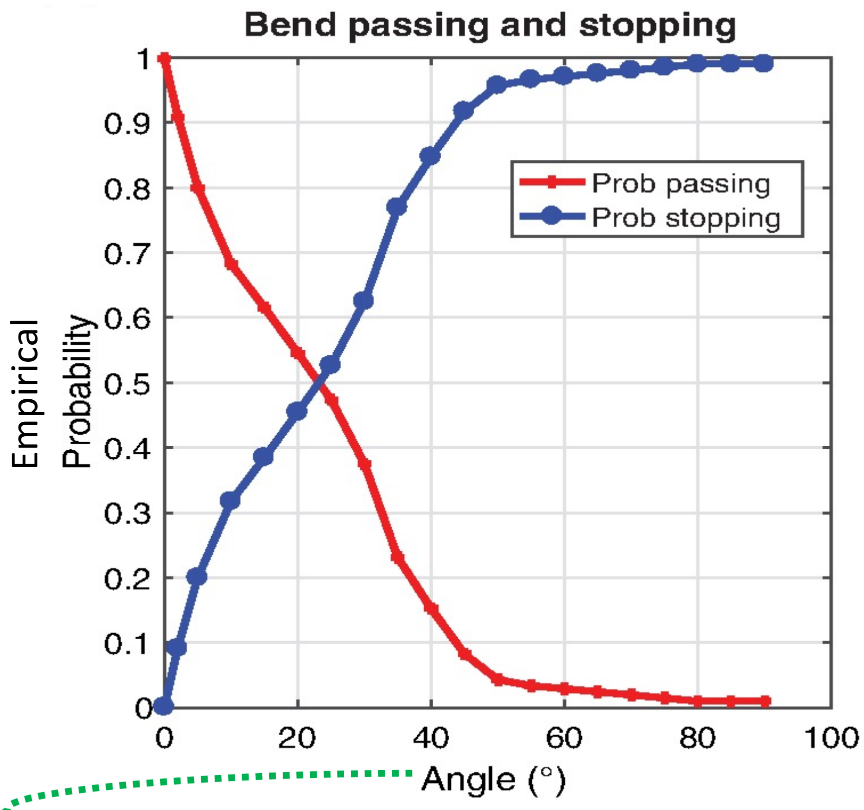


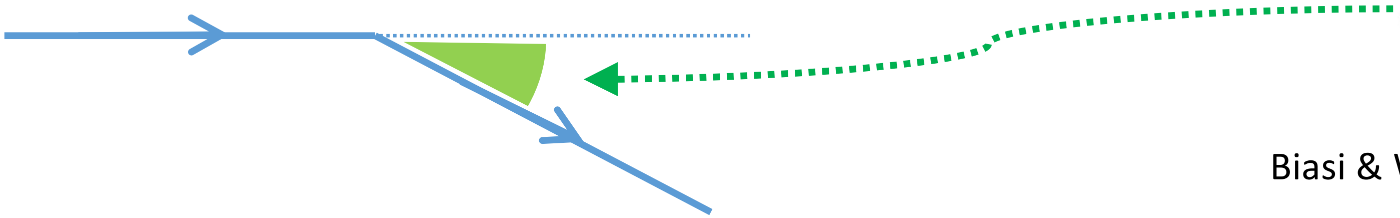
Computational efficiency of the model enables reservoir-scale application and sensitivity analyses

Current limitation: assumes single-fault ruptures

Multi-fault ruptures

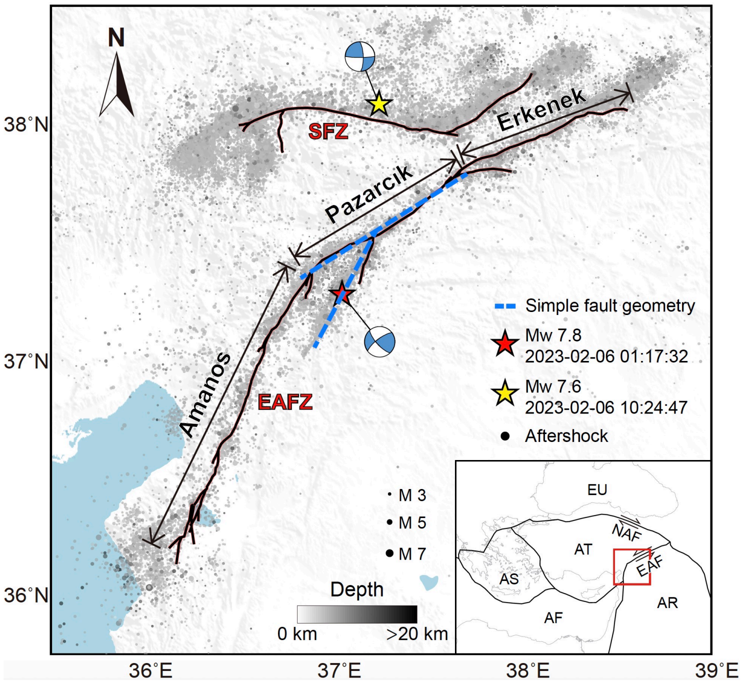


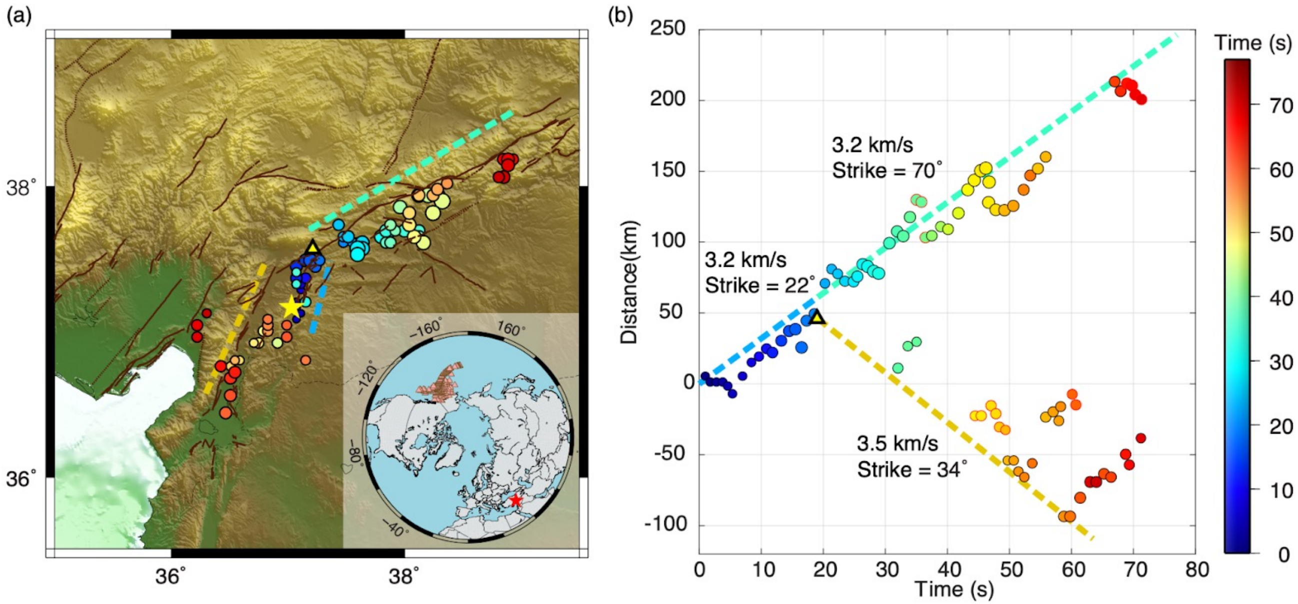




Biasi & Wesnousky (2021)

2023 Mw7.8 Kahramanmaraş, Turkey earthquake

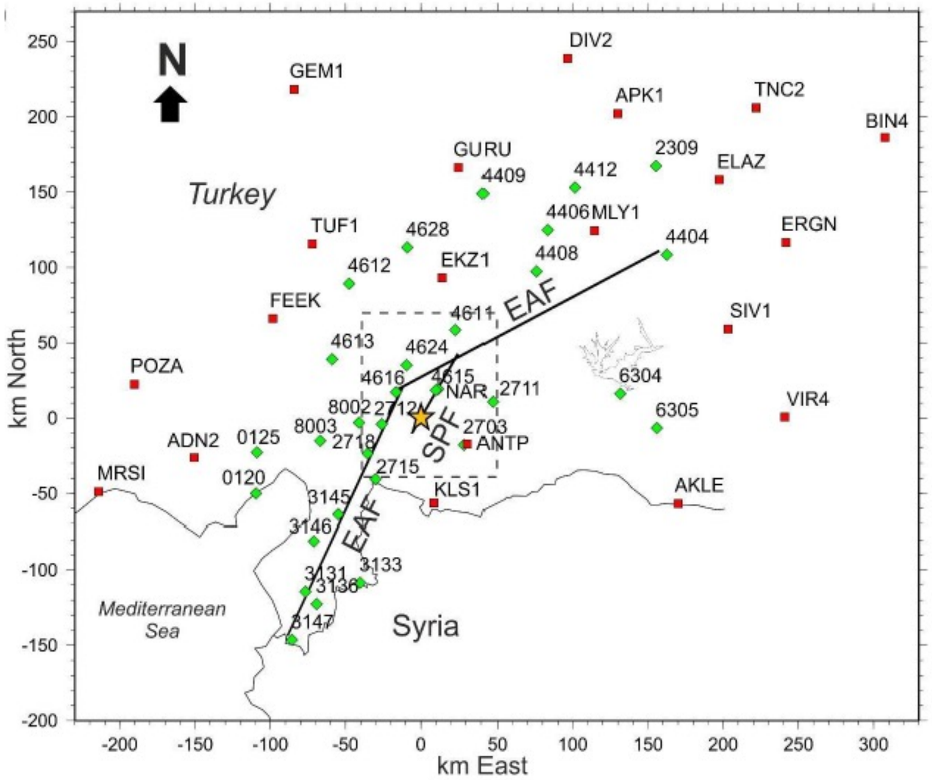


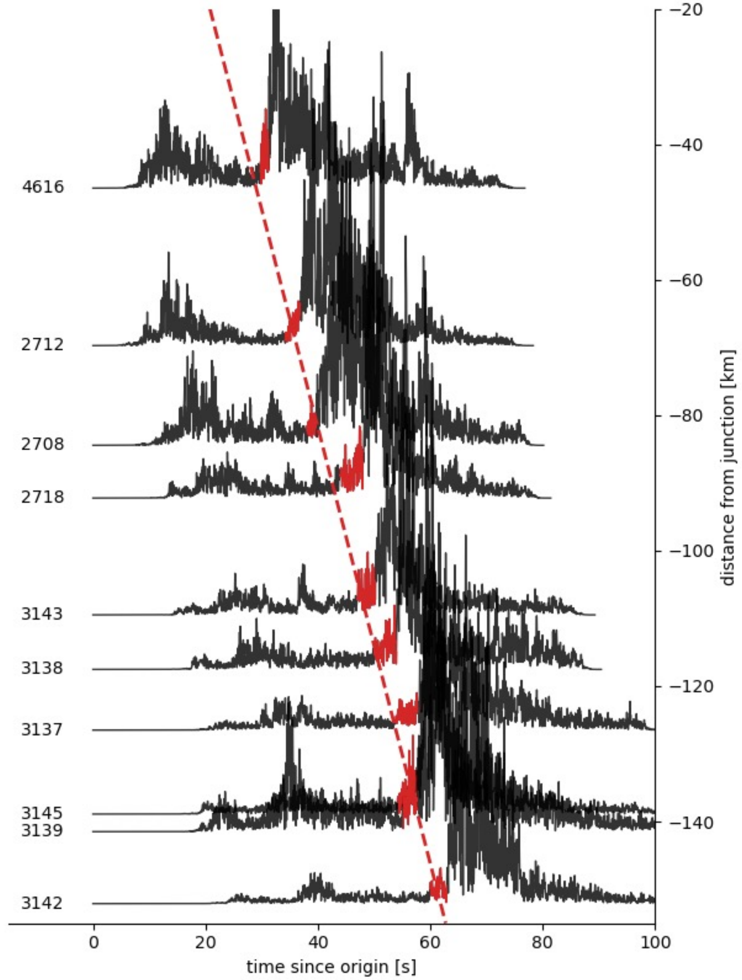


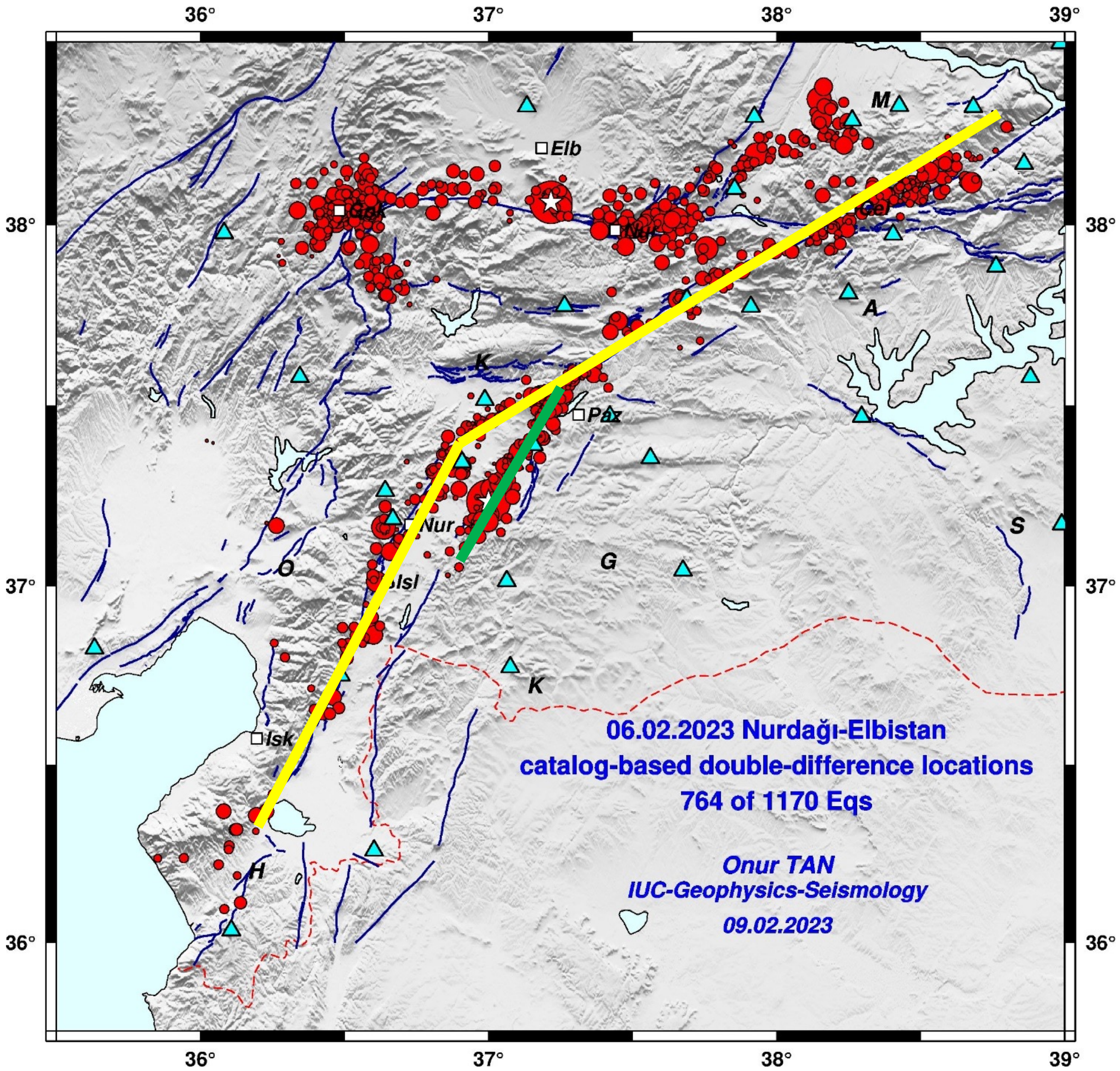
Teleseismic back-projection by Yuqing Xie (Geoazur)

Ding et al (2023)
https://doi.org/10.48550/arXiv.2307.06051

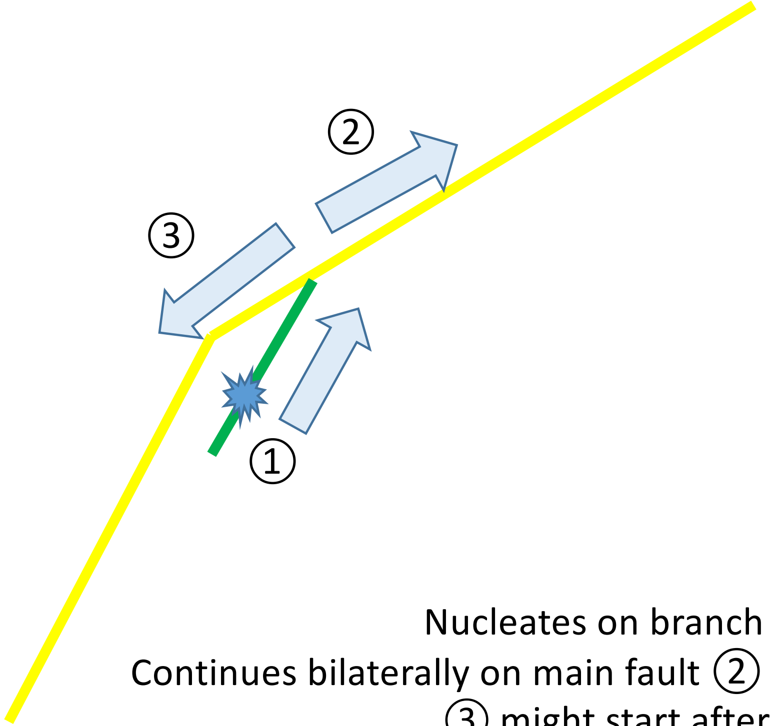
Local strong-motion data (AFAD)







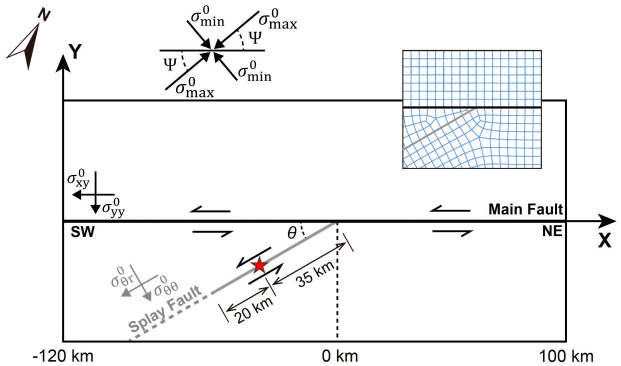
Left-lateral strike-slip faults
Main (yellow) and branch (green)

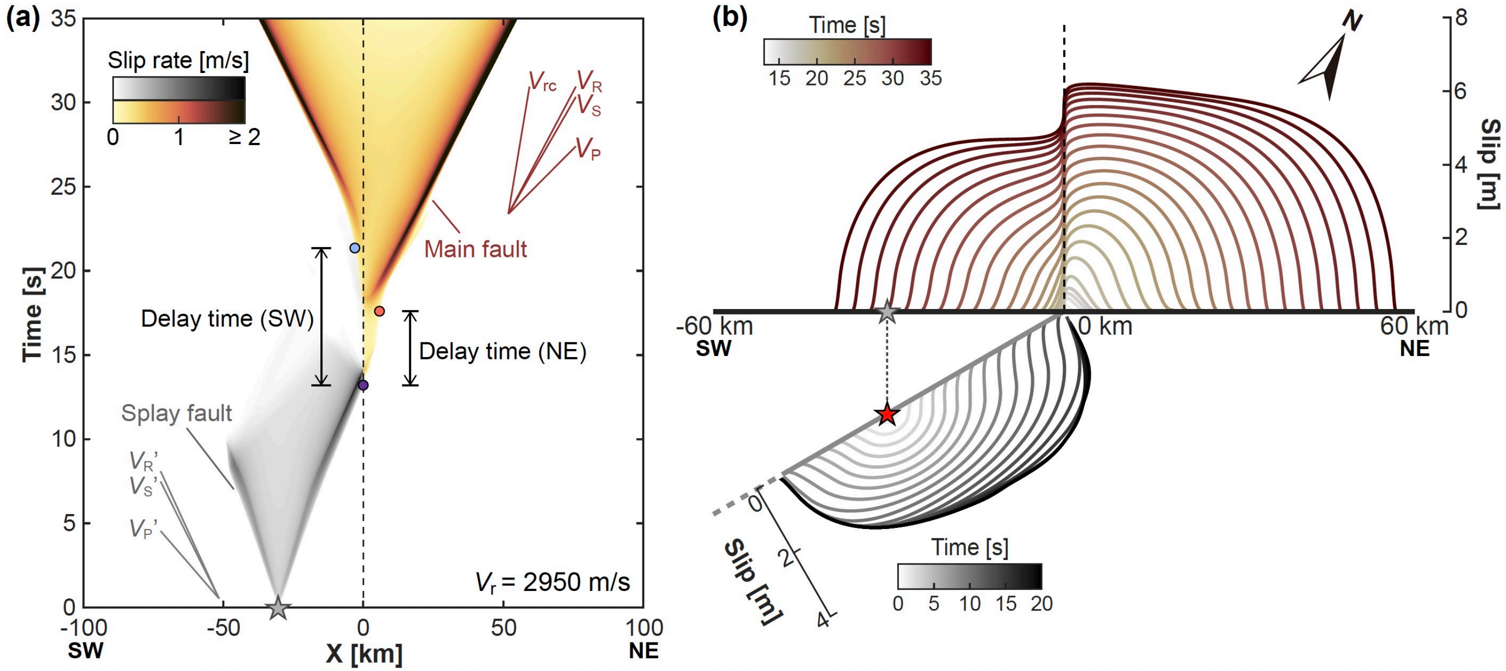


Nucleates on branch ①
Continues bilaterally on main fault ② ③
③ might start after ②

Dynamic rupture modeling

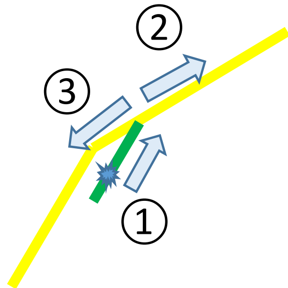
2.5D spectral elements
SEM2DPACK software
Shiqing Xu & team (SUSTech, China)

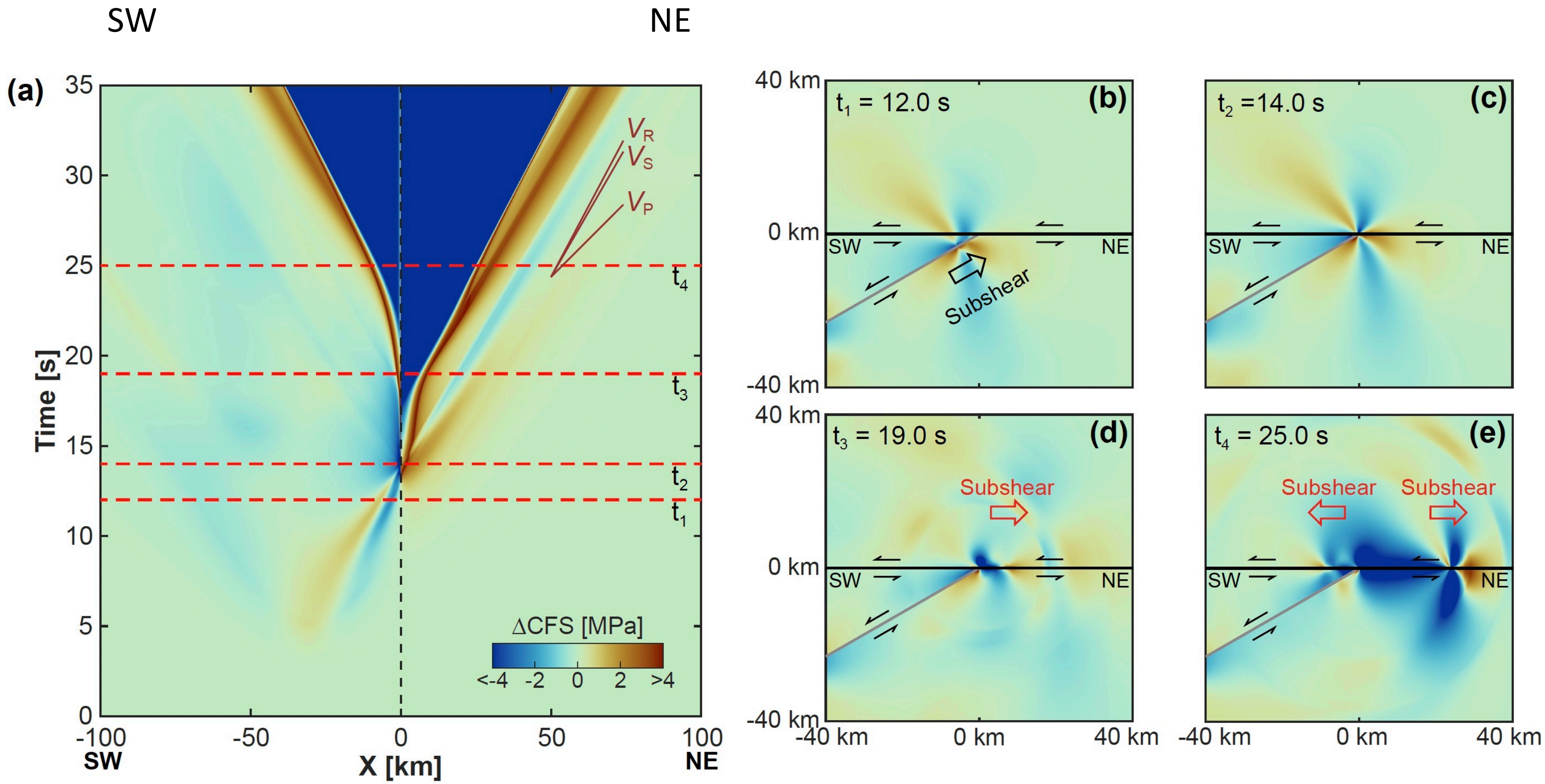




Dynamic rupture modeling

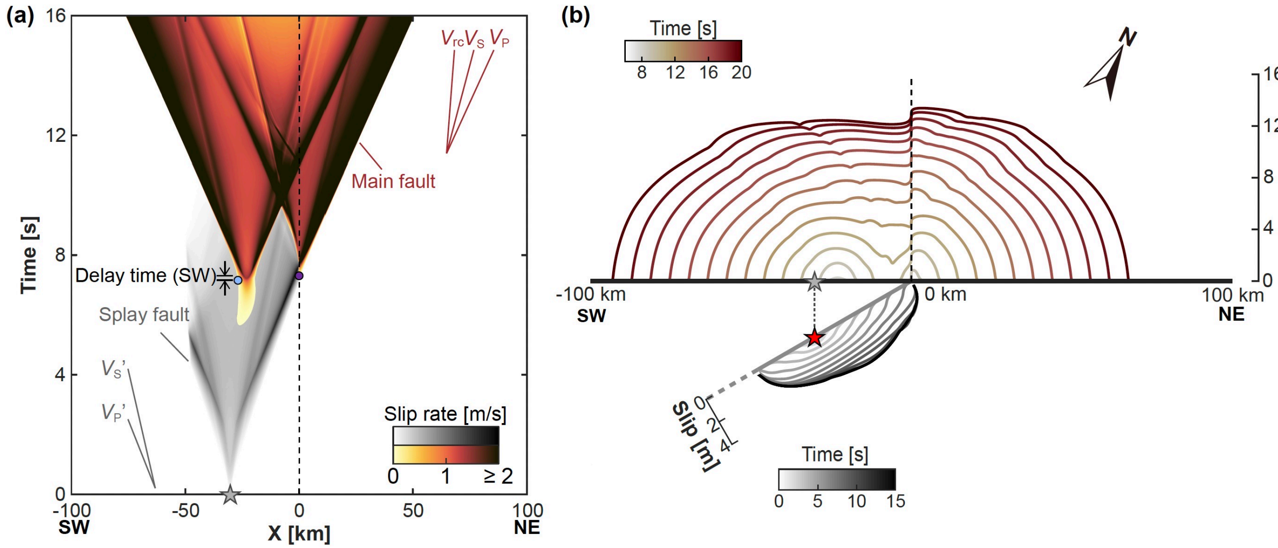
SW rupture ③ is not triggered by the splay ①, but by the NE rupture ②

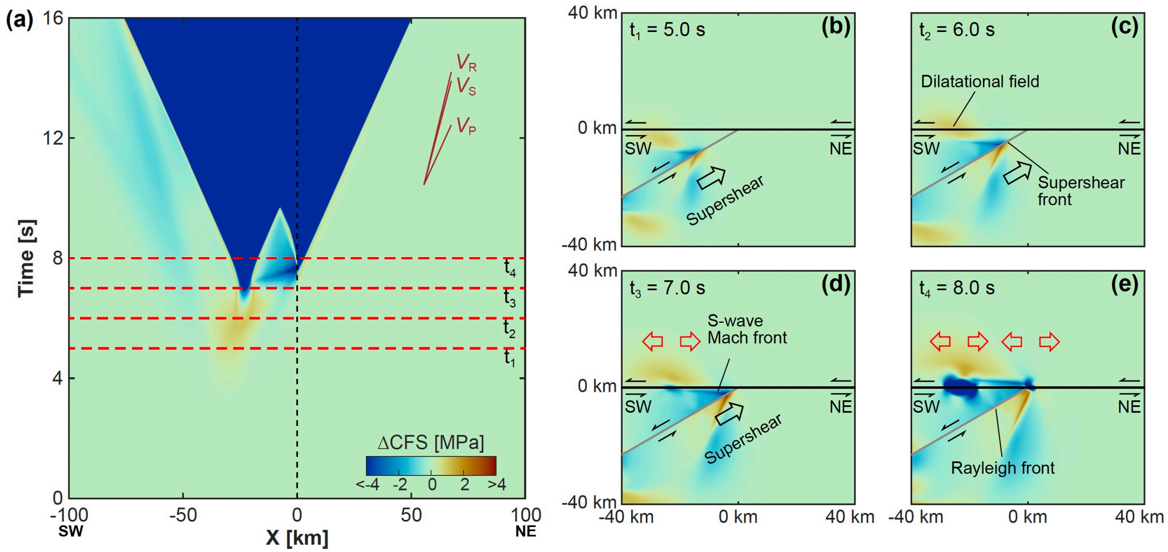




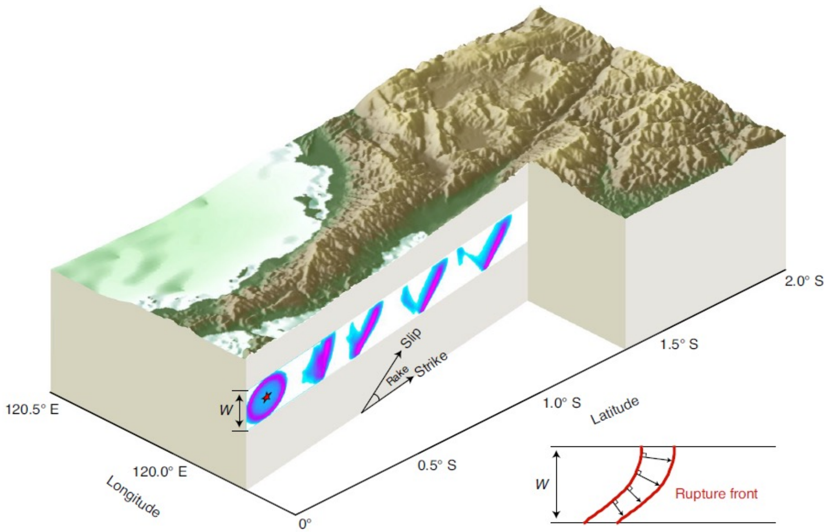
Another scenario:
SW rupture ③ is triggered by the splay ①,
and the NE rupture ② starts later

This scenario is unlikely:
it only happens for very high initial stress on the EAF





Conclusions and perspectives



New dynamic theory of large earthquakes ($L \gg W$)

→ runaway and arrest criteria

A framework to constrain the size of future large earthquakes

→ *Towards physics-based time-dependent hazard assessment*

Uncertainties remain, especially on fracture energy G_c

Open questions :

- Extend to multi-fault ruptures and non-planar faults?
- Equation of motion for supershear ruptures?
- Effect of off-fault dissipation?
- Laboratory validation?

Funding acknowledgments

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