The dynamics of elongated earthquake ruptures

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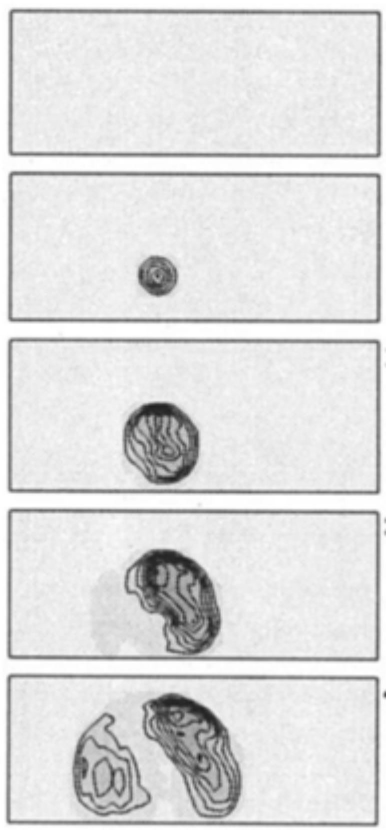
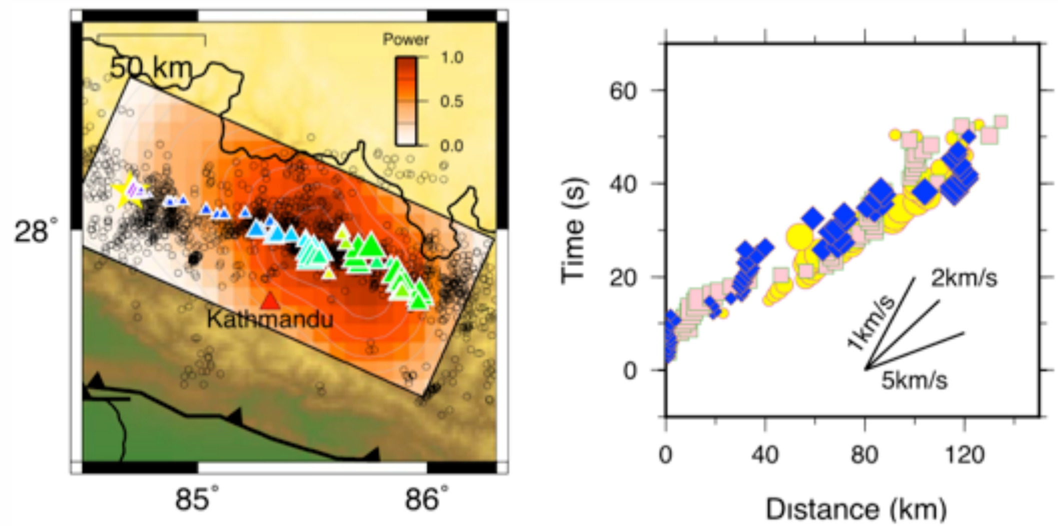
Earthquake kinematics



Ide, 1997



Meng et al. (2016)

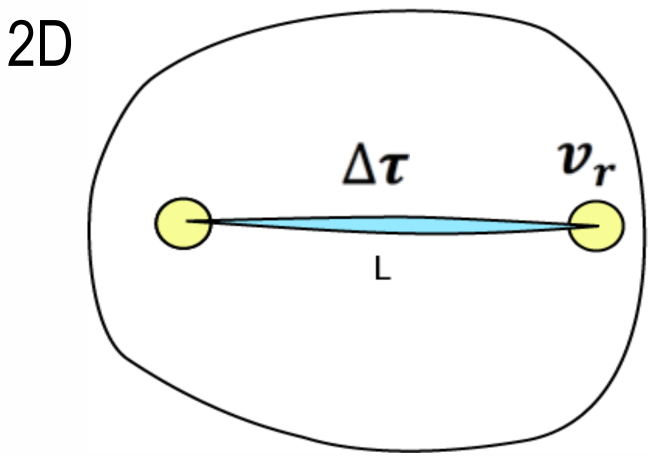
How to link kinematics and dynamics of earthquakes?

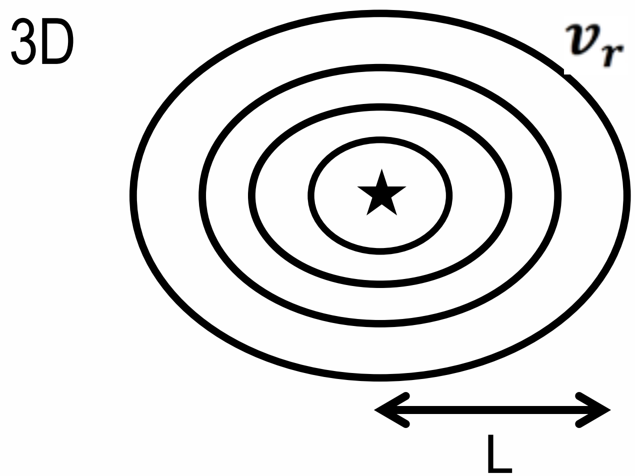
Can we predict the earthquake size based on earthquake dynamics theory?

Outline

- Motivations
- Model (theory and simulations)
- Implications
- Ongoing work

Linear elastic fracture mechanics



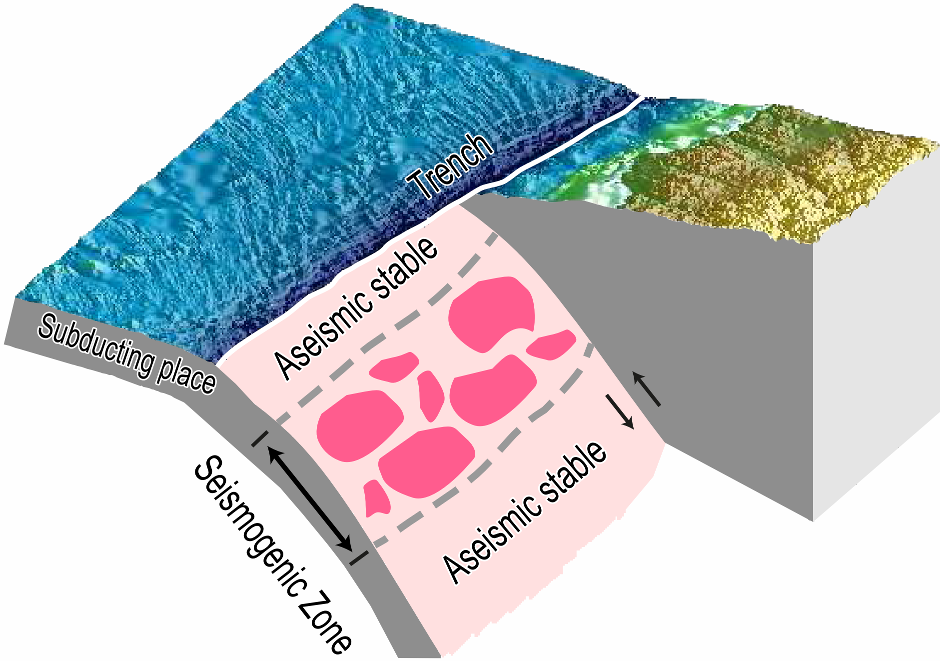


For crack-like ruptures in 2D and 3D (unbounded):

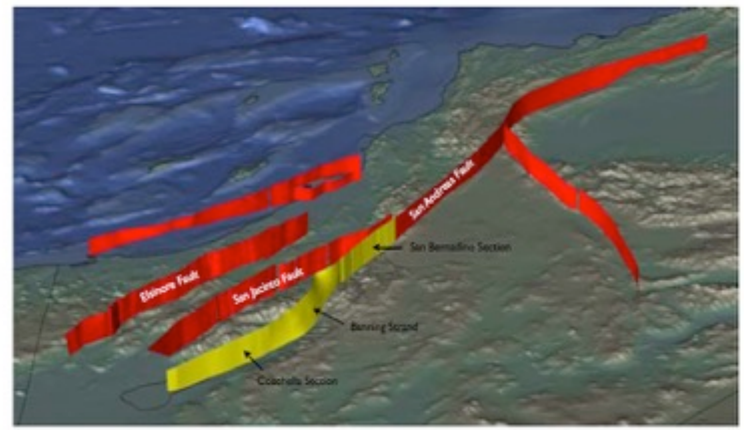
$$G_c = g(v)\,\frac{\Delta\tau^2 L}{2\mu}$$

Kostrov, Freund, Andrews (60-70s)

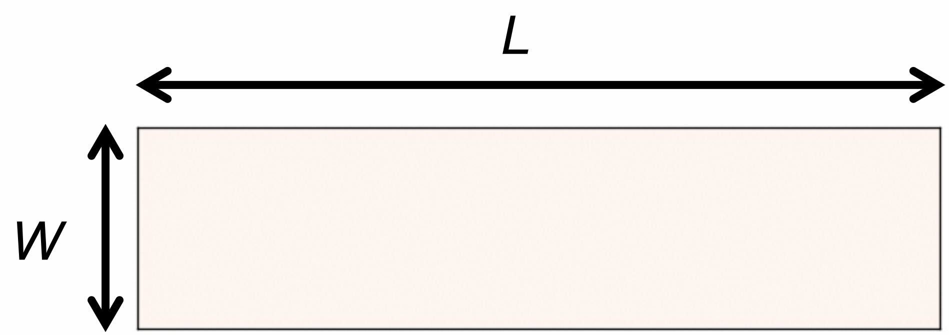
Finite seismogenic width



Weng and Ampuero, JGR, in revision

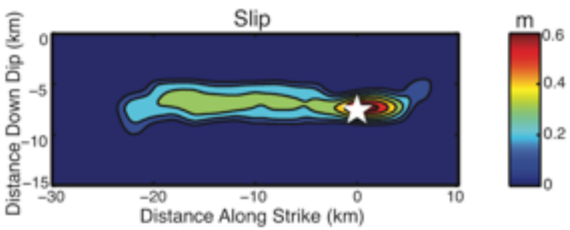


Fault and Rock Mechanics (FARM)

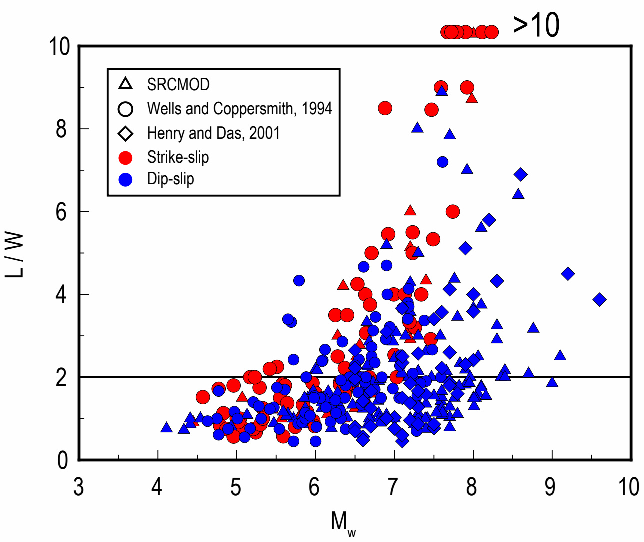


Elongated earthquake ruptures

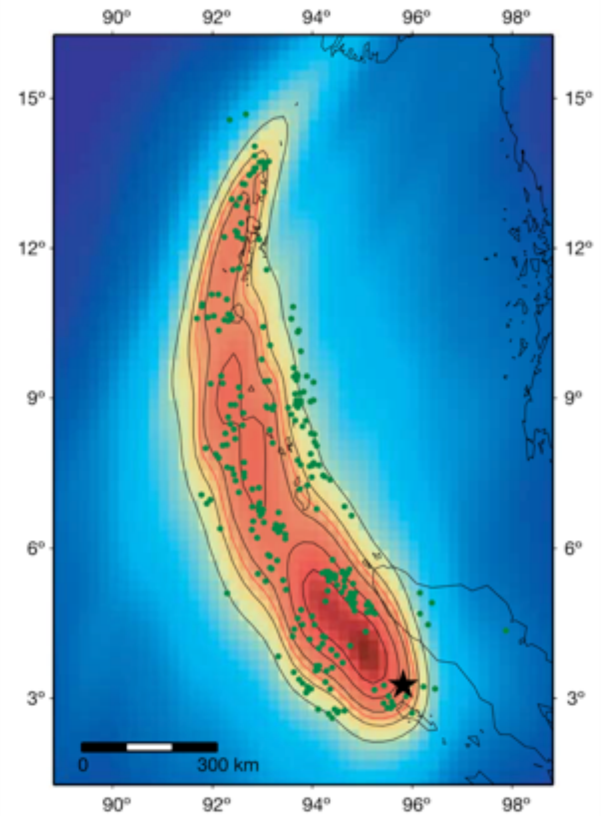
2004 Mw 6 Parkfield



Ma et al 2008

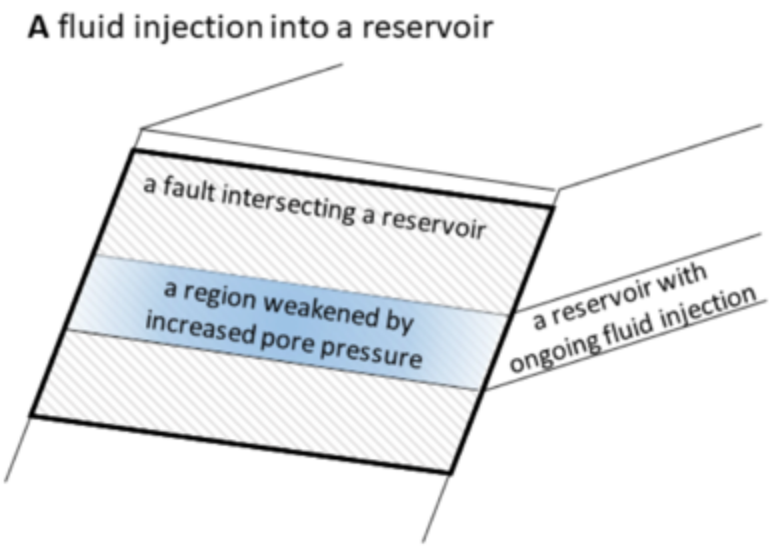


2004 Mw 9.3 Sumatra



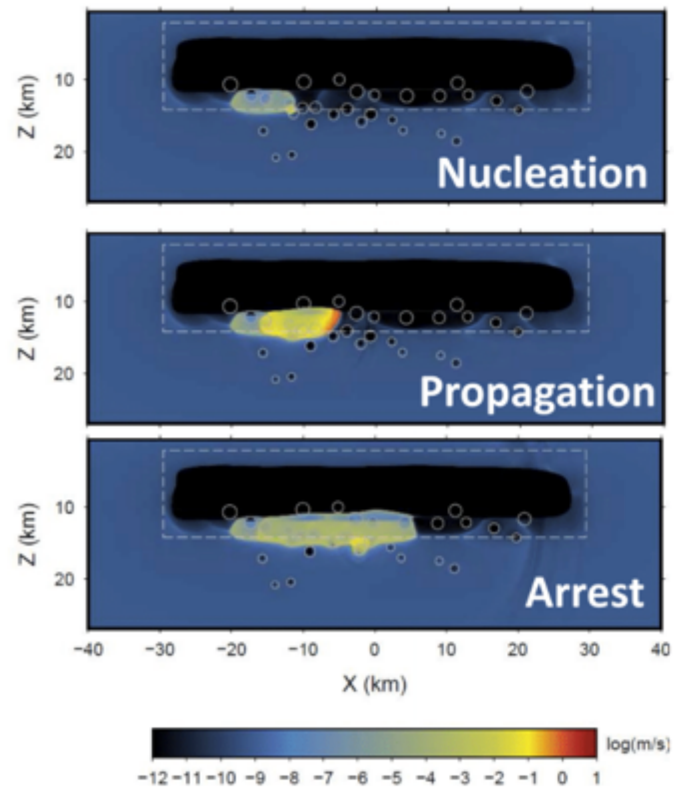
Ishii et al 2005

Elongated earthquake ruptures



Galis et al 2018

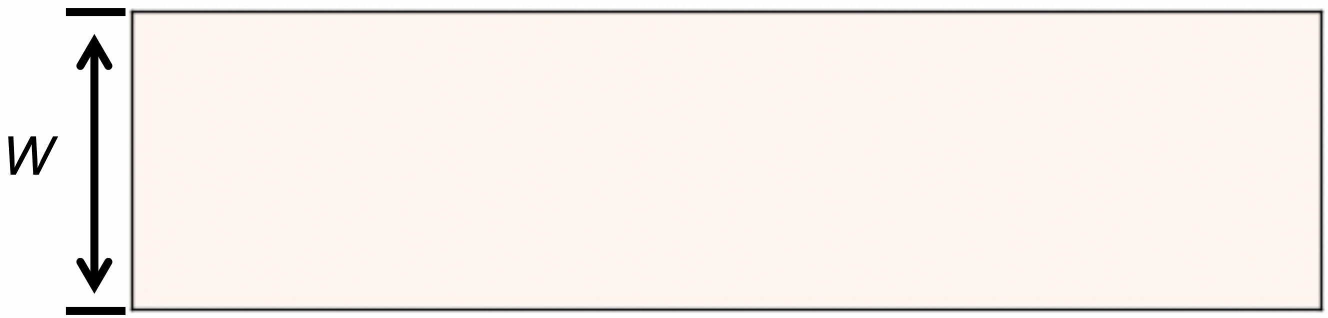
Rupture unzipping the lower edge of the seismogenic zone (simulation by Junle Jiang)



Outline

- Motivations
- Model (theory and simulations)
- Implications
- Ongoing work

Analytical model



Ingredients

- Anti-plane fault in 3D full-space
- Uniform elastic properties
- Uniform fault parameters
- Uniform seismogenic width
- Steady-state speed

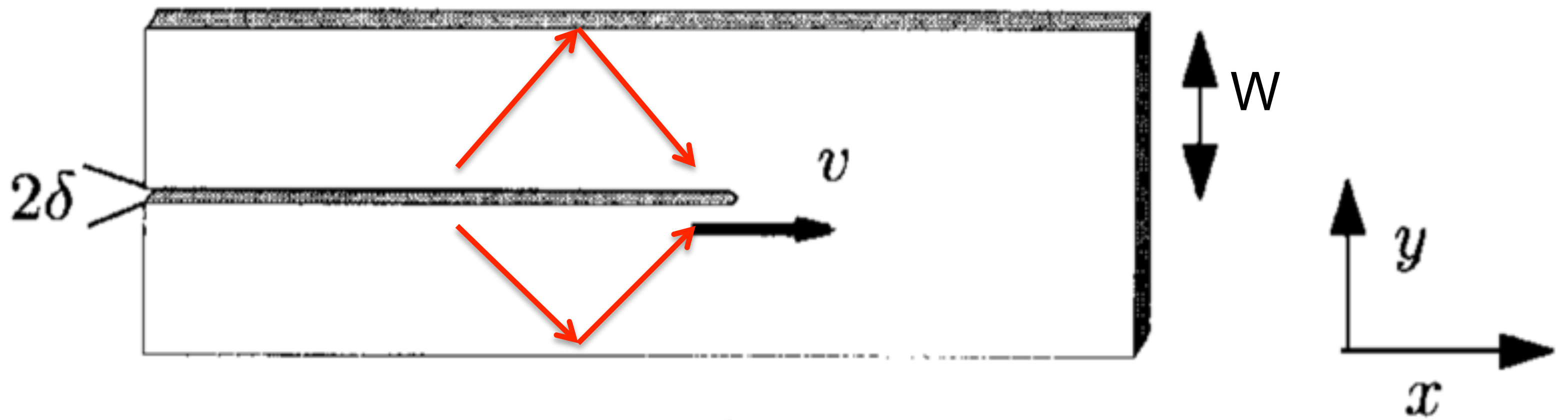
2.5D model

Energy release rate (*L*>*W*):

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

Weng and Ampuero, JGR, in revision

2D strip problem (mode I crack)

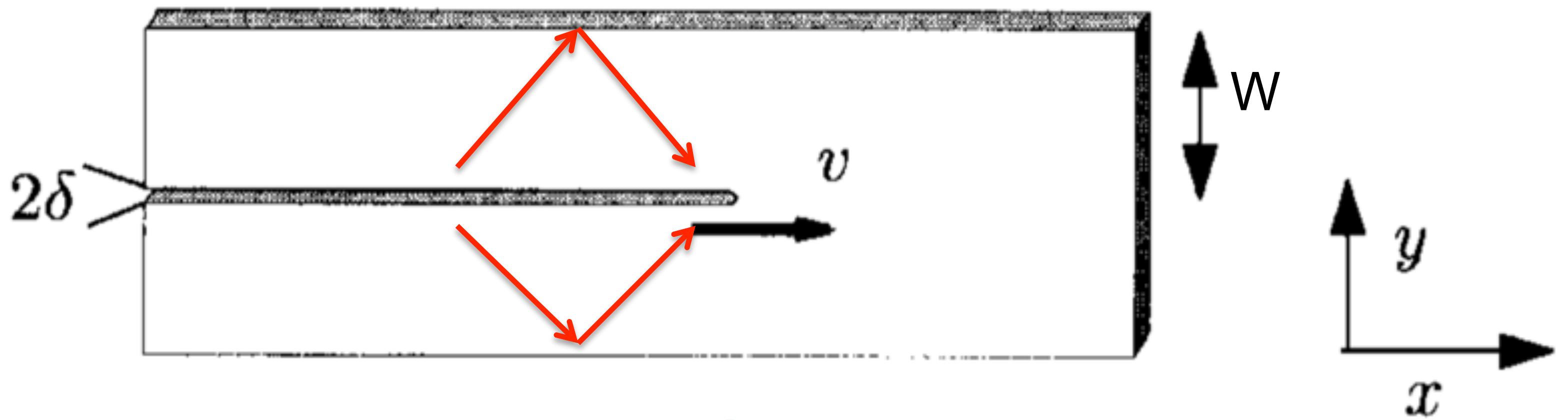


$$G_0 \propto \Delta\tau^2 W$$

Marder (1998)

- Steady-state energy release rate is proportional to width of strip
- $$G_c = G_0\left(1 - \frac{\dot{v}_r W}{v_s^2}\frac{1}{\alpha_s^4}\right) \qquad \alpha_s = \sqrt{1-(v_r/v_s)^2}$$

2D strip problem (mode I crack)



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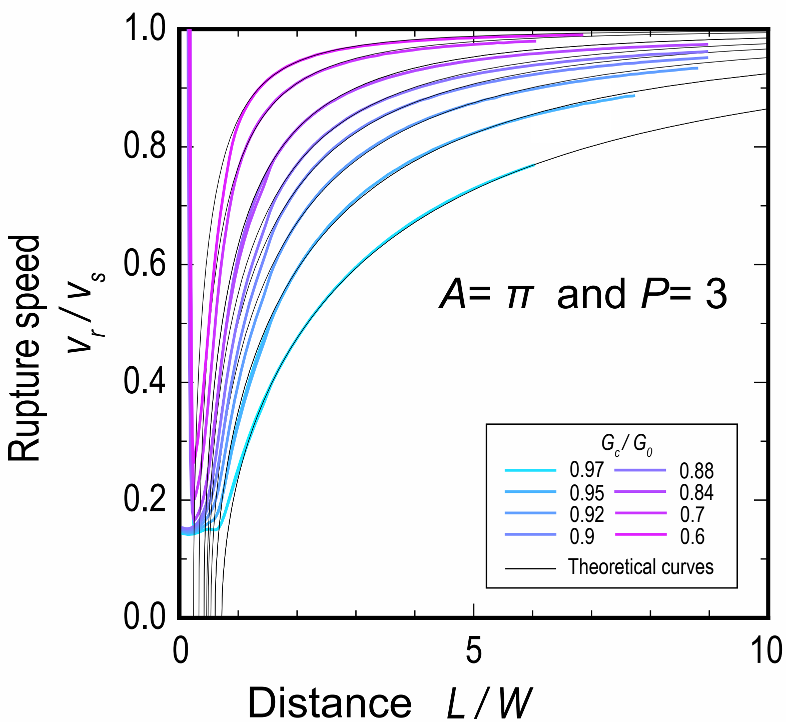
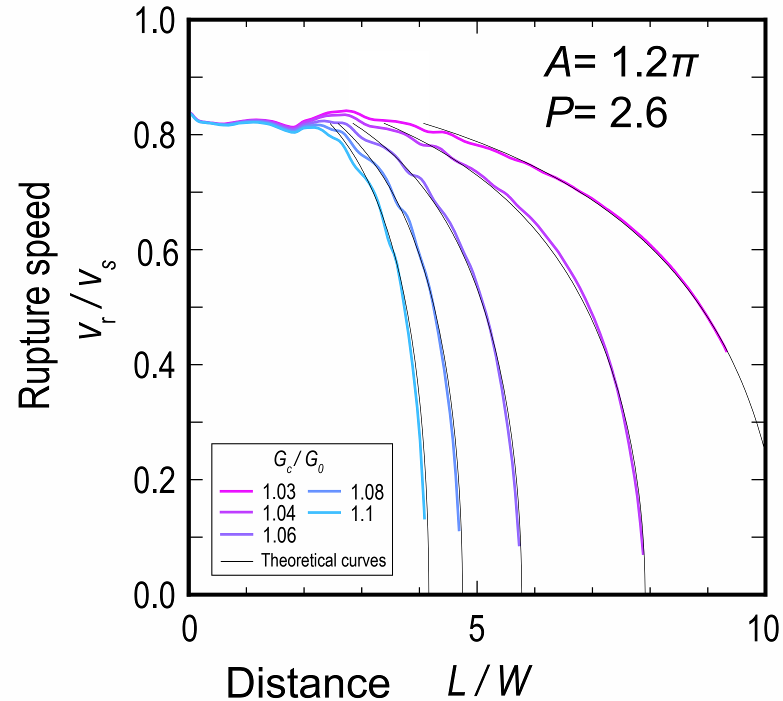
Validation in 3D simulations

Theoretical equation:

$$G_c = G_0\left(1 - \frac{\dot{v}_r W}{v_s^2}\frac{1}{A\alpha_s^P}\right)$$

$$\alpha_s = \sqrt{1-(v_r/v_s)^2}$$





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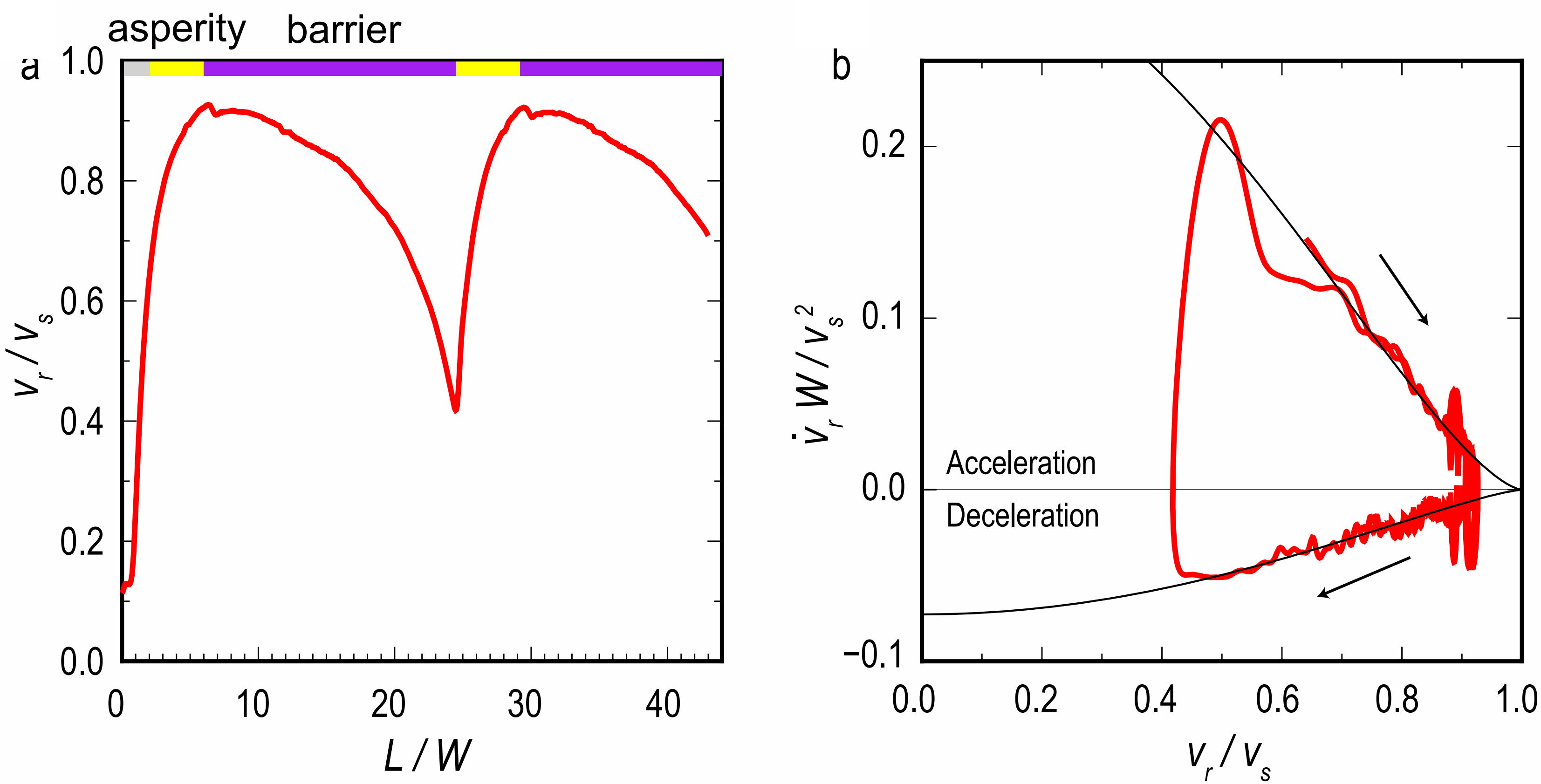
“Inertial” rupture



- Rupture evolution predicted by rupture-tip-equation-of-motion
- Rupture is also “inertial”

Weng and Ampuero, JGR, in revision

Outline

- Motivations
- Model (theory and simulations)
- Implications
    - Final earthquake size
    - Super-cycles
    - Seismicity frequency-size distr.
- Ongoing work

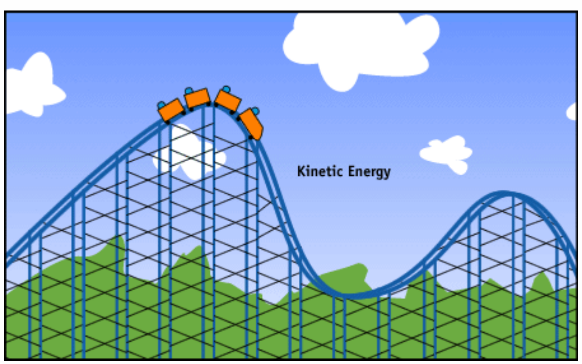
Determine earthquake size

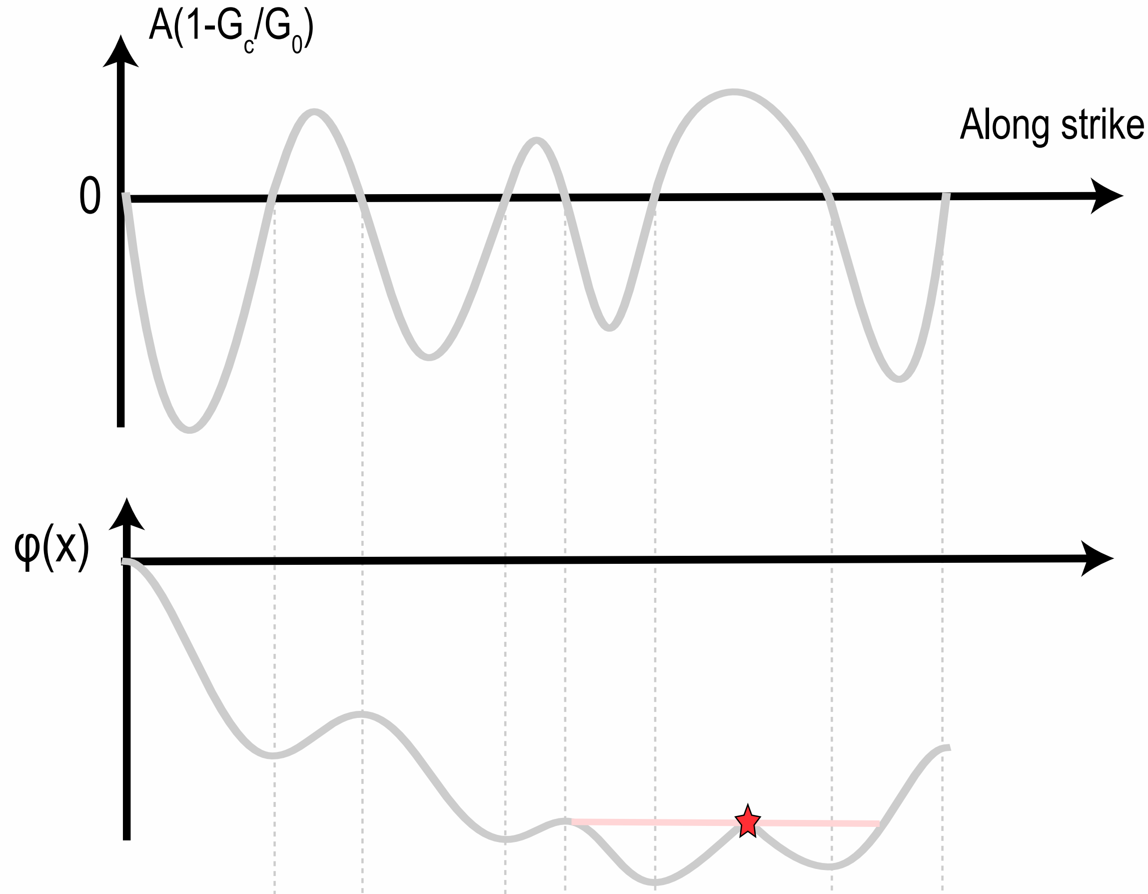
$$\frac{\dot{v}_r W}{v_s^2(1 - G_c/G_0)} = A\alpha_s^P$$

$$\varphi(L) = \int_0^L A(1 - G_c/G_0)dx/W$$

Rupture potential

Gravity potential





$$\varphi(L_2) = \varphi(L_1).$$

Weng and Ampuero, JGR, in revision

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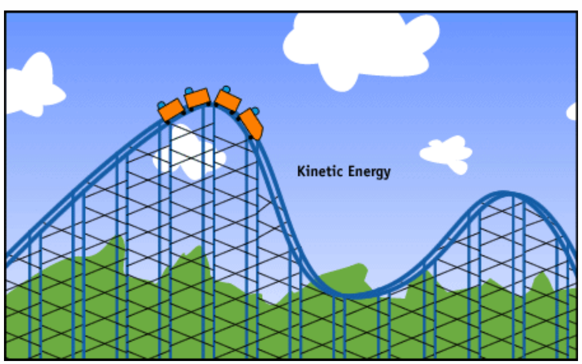
Determine earthquake size

$$\frac{\dot{v}_r W}{v_s^2(1 - G_c/G_0)} = A\alpha_s^P$$

$$\varphi(L) = \int_0^L A(1 - G_c/G_0)dx/W$$

Rupture potential

Gravity potential



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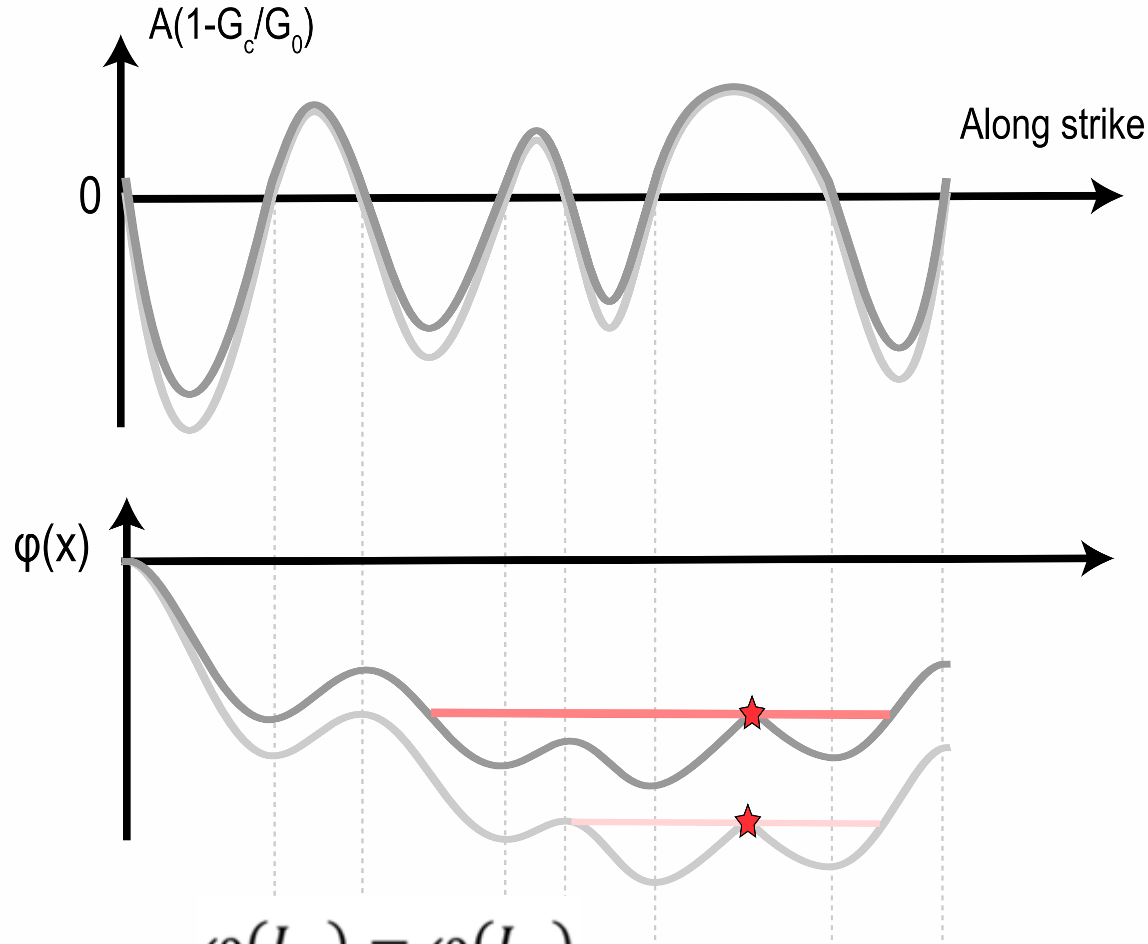


$$\varphi(L_2) = \varphi(L_1).$$

Weng and Ampuero, JGR, in revision

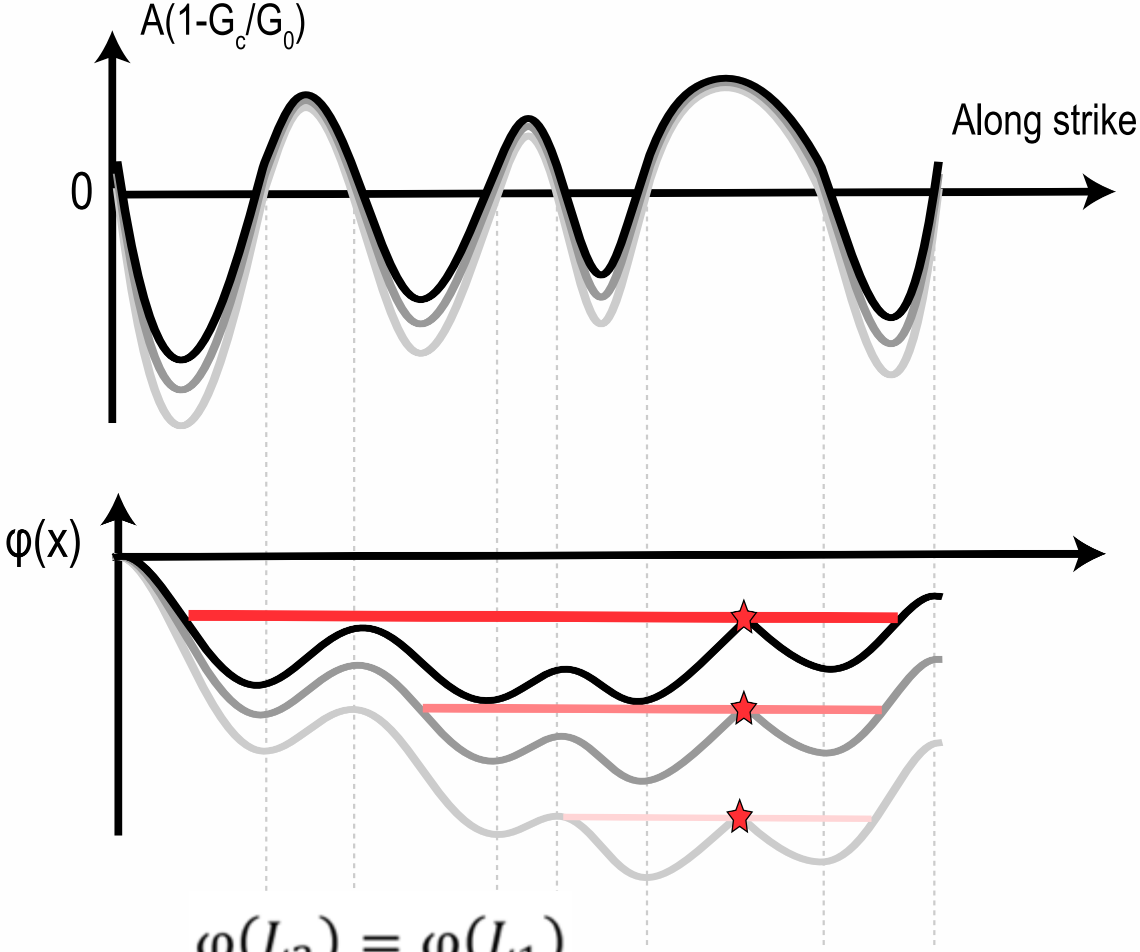
Determine earthquake size

$$\frac{\dot{v}_r W}{v_s^2(1 - G_c/G_0)} = A\alpha_s^P$$

↓

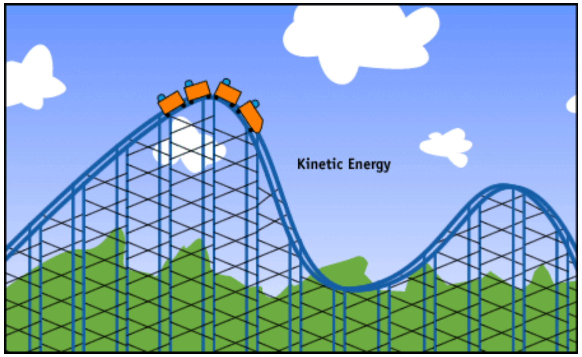
$$\varphi(L) = \int_0^L A(1 - G_c/G_0)dx/W$$

Rupture potential



$$\varphi(L_2) = \varphi(L_1)$$

Gravity potential



Weng and Ampuero, JGR, in revision

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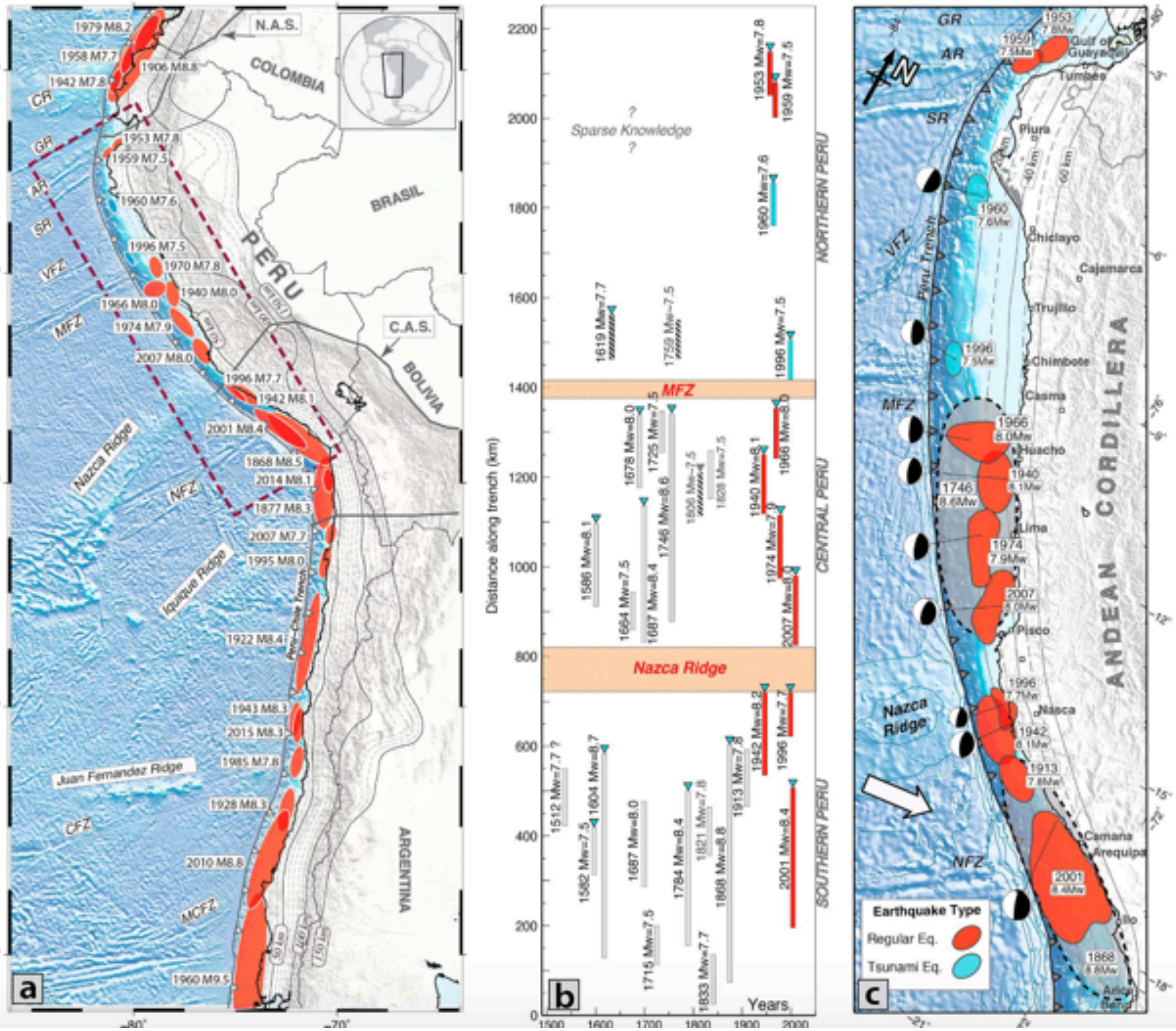
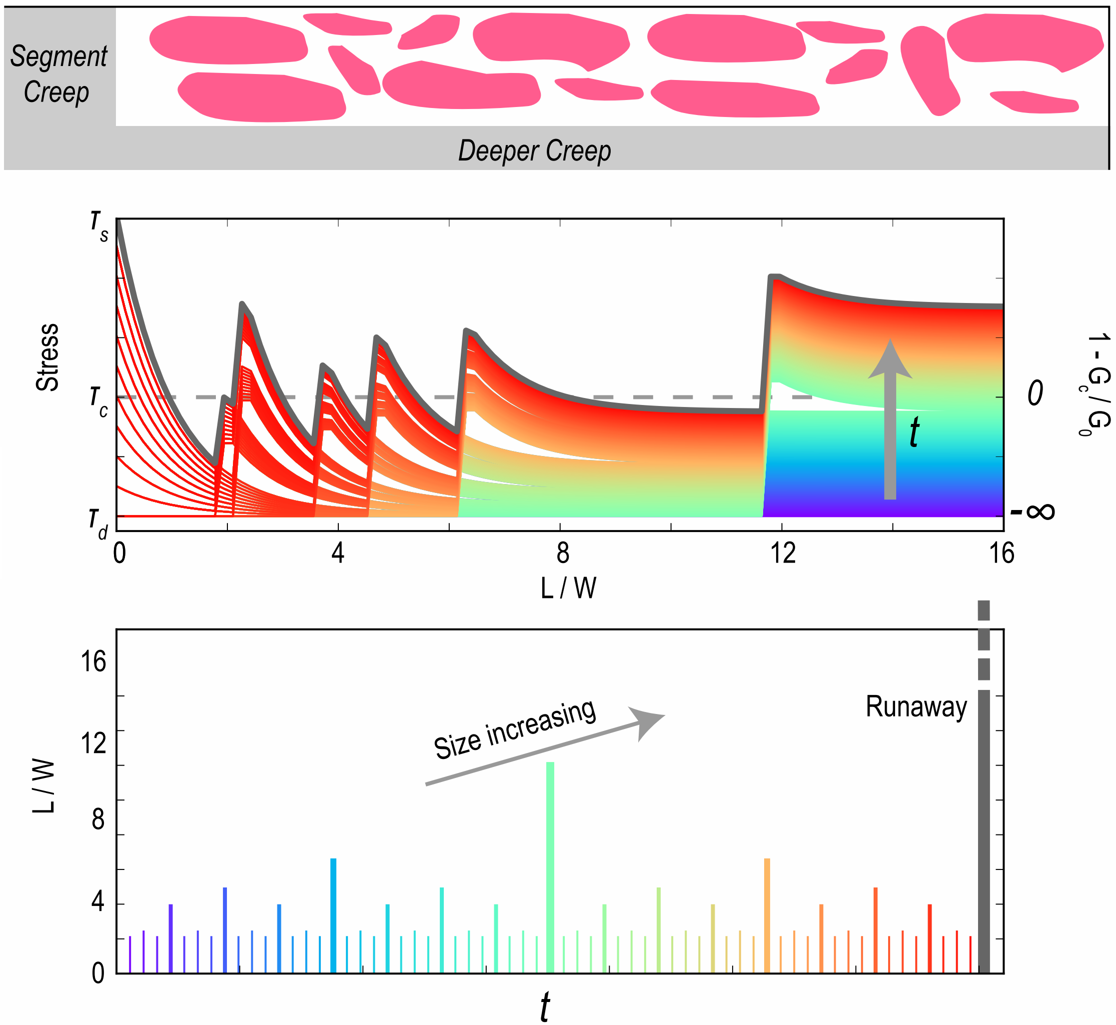
Super earthquake cycles?

- Fault segmentation
- Maximum magnitude?



Villegas-Lanza et al., (2016)

Super cycles



Stressing rate:

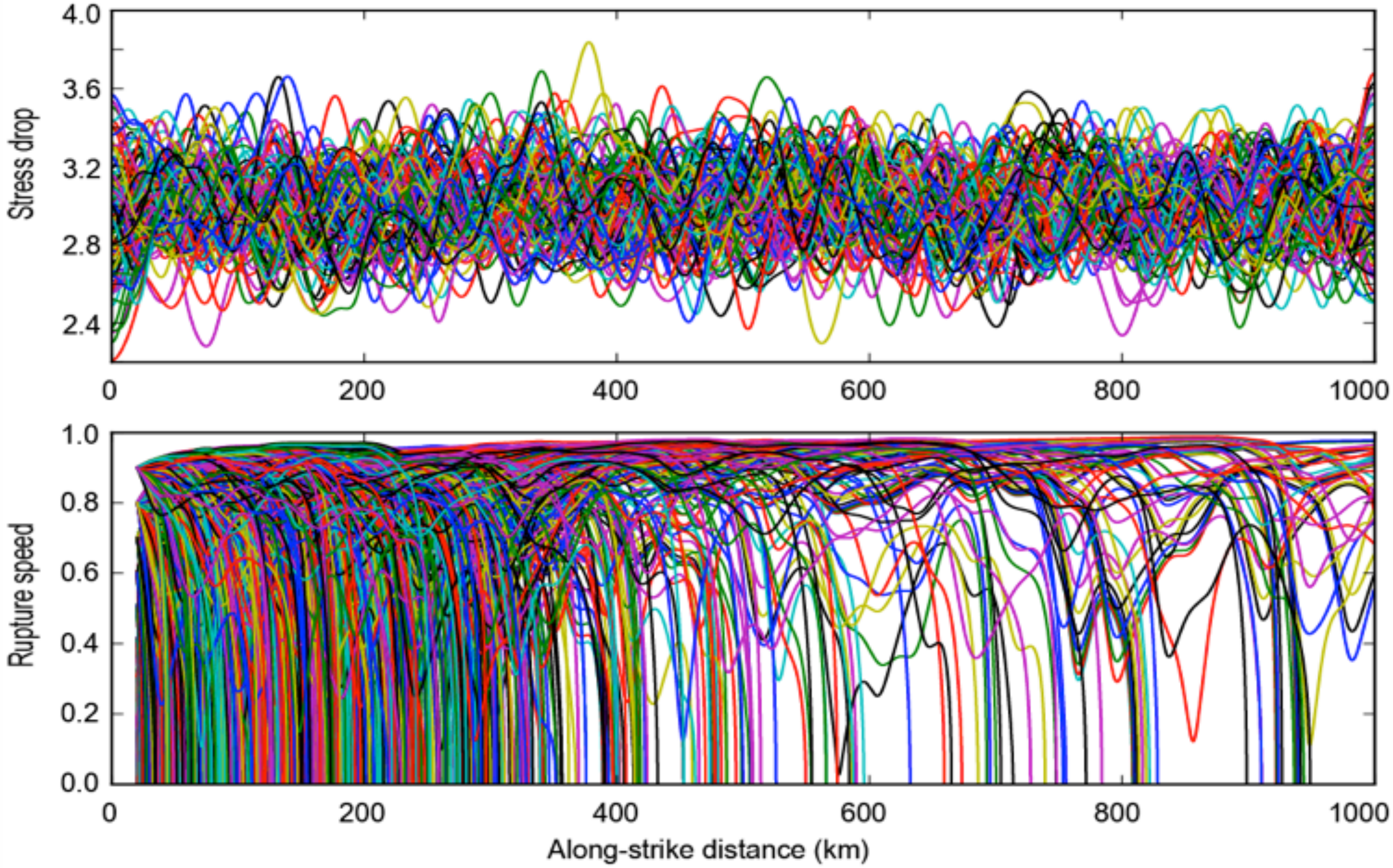
$$\dot{\tau}(L) = \gamma_l \exp(-L/W) + \gamma_b$$

Assumption:

$$G_c/G_0 = B\Delta\tau^{n-2}$$

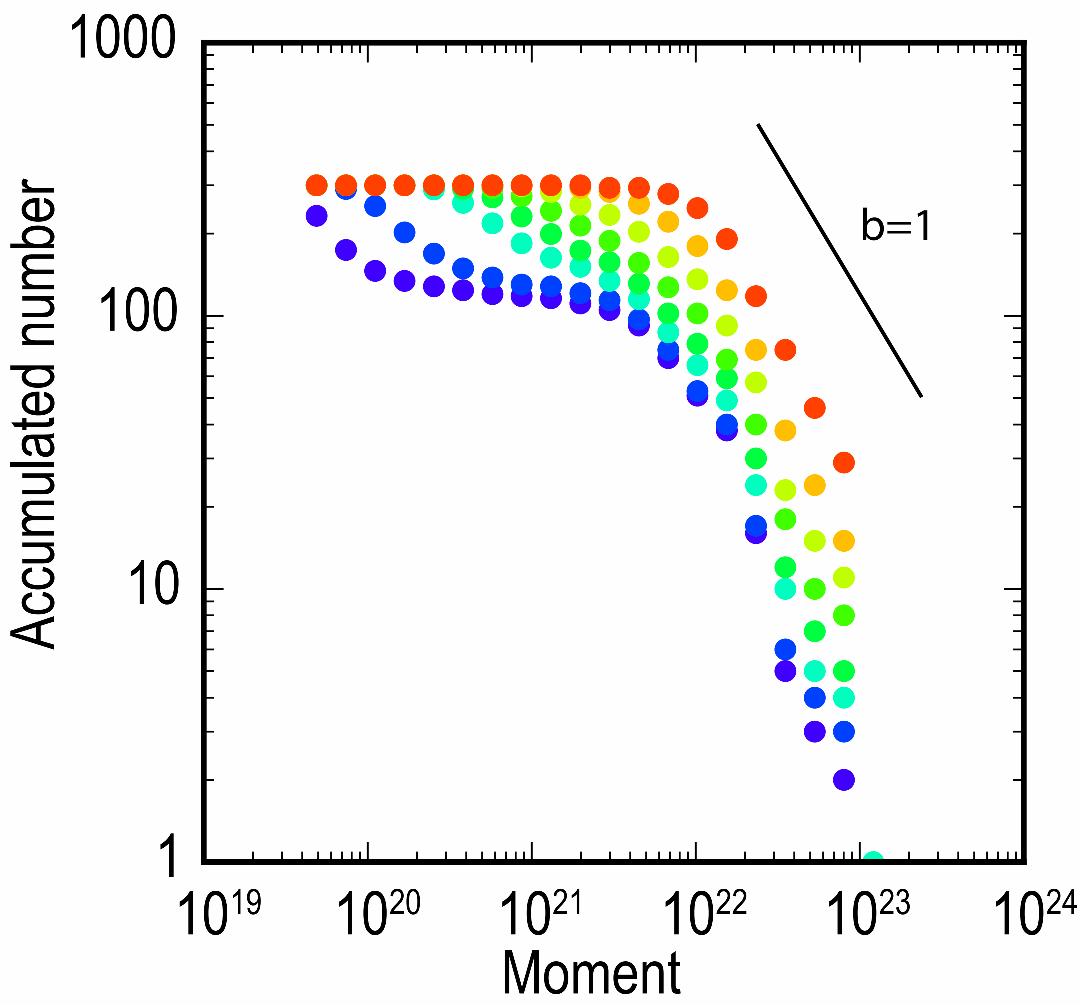
Weng and Ampuero, JGR, in revision

Seismicity frequency-size distribution



Assumption: $G_c/G_0 = B\Delta\tau^{n-2}$

Seismicity frequency-size distribution



Outline

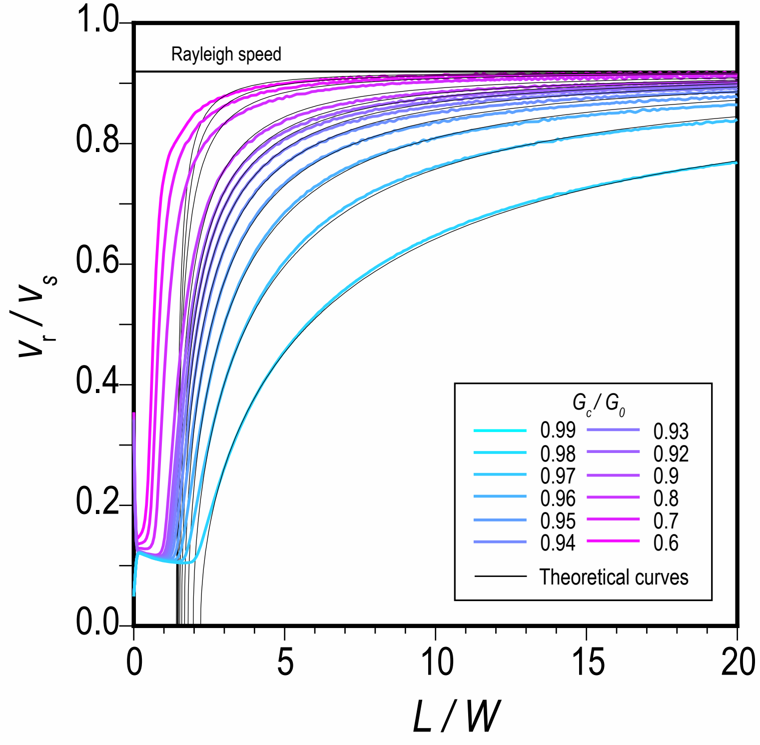
- Motivations
- Model (theory and simulations)
- Implications
- Ongoing work: supershear

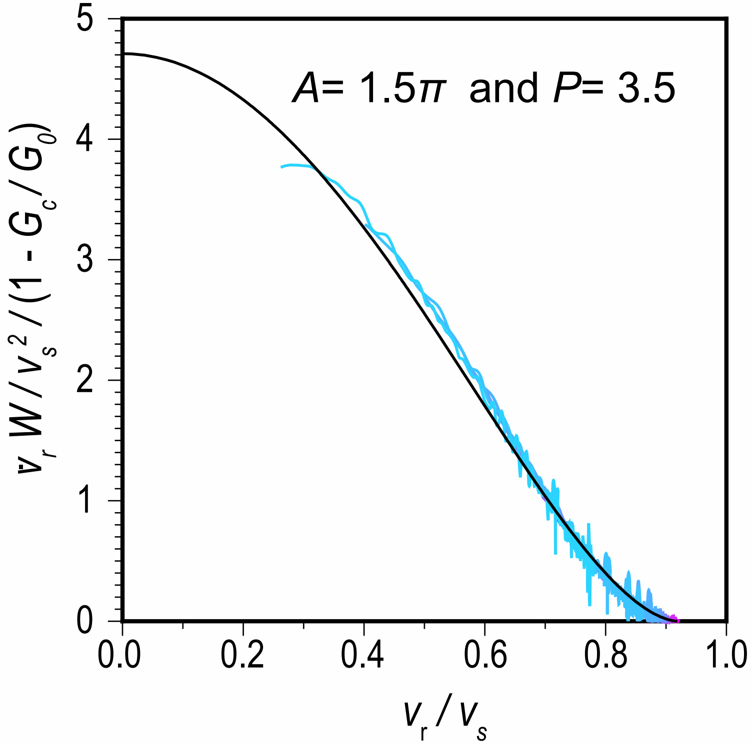
In-plane sub-shear

Theoretical equation:

$$\frac{\dot{v}_r W}{v_s^2(1 - G_c/G_0)} = A\alpha_R^P$$

$$\alpha_R = \sqrt{1 - (v_r/v_R)^2}$$





Weng and Ampuero, In prep.

Dynamics of supershear ruptures

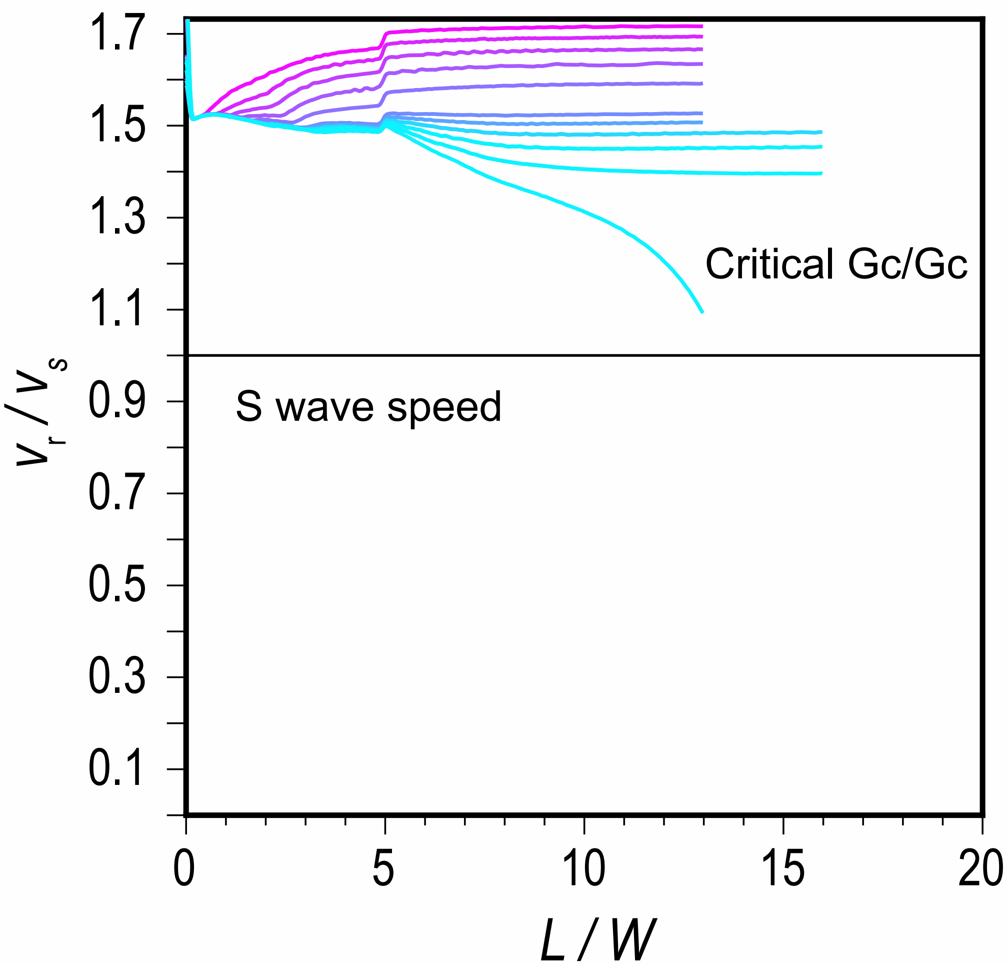
- Steady-state supershear
- G_c/G_0 controls supershear speed
- Critical value of G_c/G_0 for supershear

On-going analytical work:

$$G^{sup} = g(v_r)G_0\left(\frac{\Lambda}{W}\right)^{q(v_r)}$$

Weng and Ampuero, In prep.

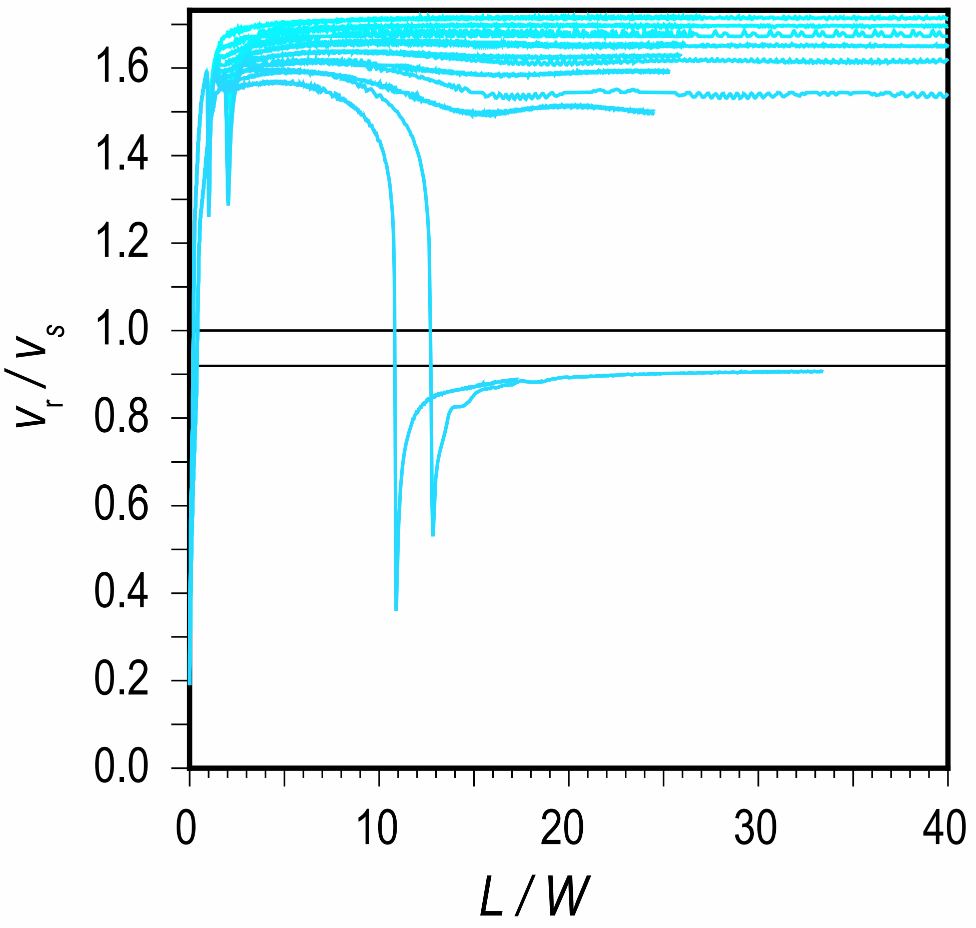
3D numerical simulations



Conclusion

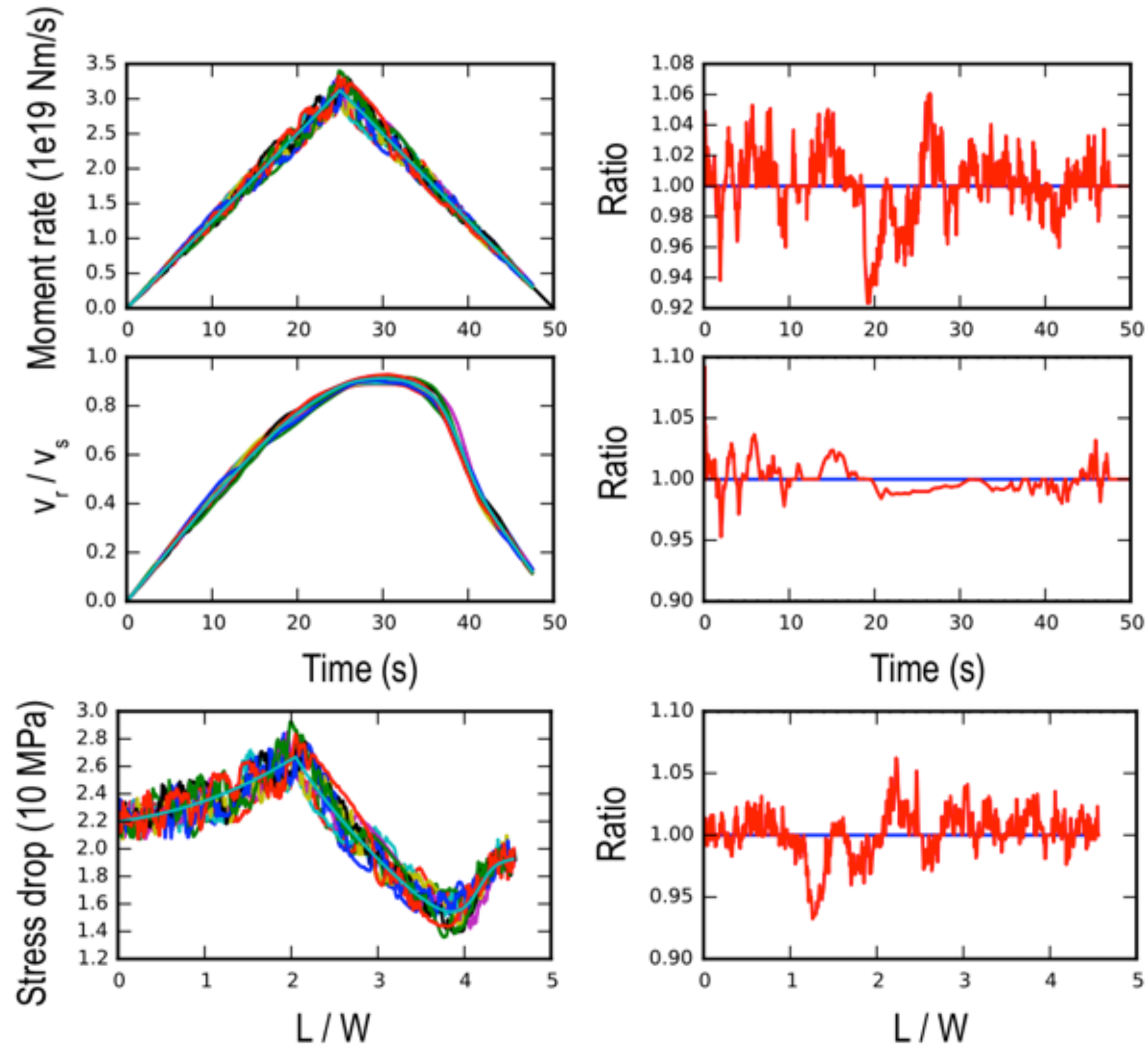
- A new rupture-tip-equation-of-motion for elongated ruptures elucidates how the evolution of rupture speed of large earthquakes (large aspect ratio) depends on fault strength and stress.
- This theoretical equation has important implications for evaluating how final earthquake size depends on fault stress and strength.
- The seismogenic width also plays significant effects on dynamics of supershear ruptures.

The manuscript can be download from EarthArXiv:
eartharxiv.org/9yq8n/



1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
V_r / V_s
0
10
20
30
40
L / W

Information from source time function



Analytical model

$$\sigma_{ij,j} = \rho \ddot{u}_i$$ (3 equations)

Reduce to 1 equation

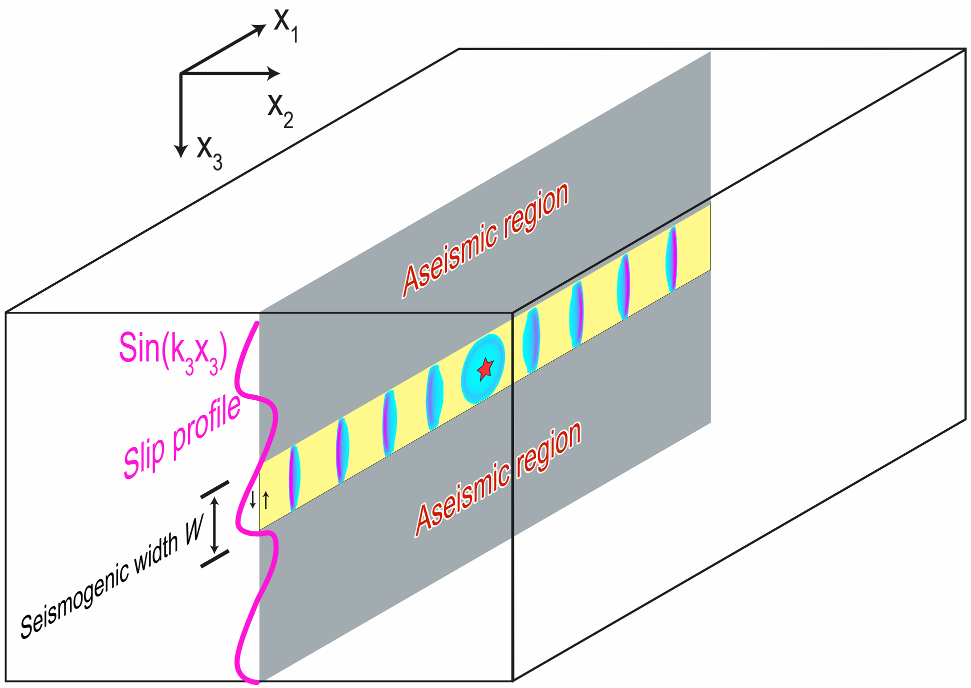
$$\frac{\partial^2 u}{\partial x_1^2} + \frac{\partial^2 u}{\partial x_2^2} + \frac{\partial^2 u}{\partial x_3^2} = \frac{1}{v_s^2}\frac{\partial^2 u}{\partial t^2}$$

Slip approximation

$$u(x_1, x_2, x_3) = u(x_1, x_2, t)e^{ik_3 x_3}$$

$$k_3 = \pi / W$$

$$\frac{\partial^2 u}{\partial x_1^2} + \frac{\partial^2 u}{\partial x_2^2} - {k_3}^2 u = \frac{1}{v_s^2}\frac{\partial^2 u}{\partial t^2}$$

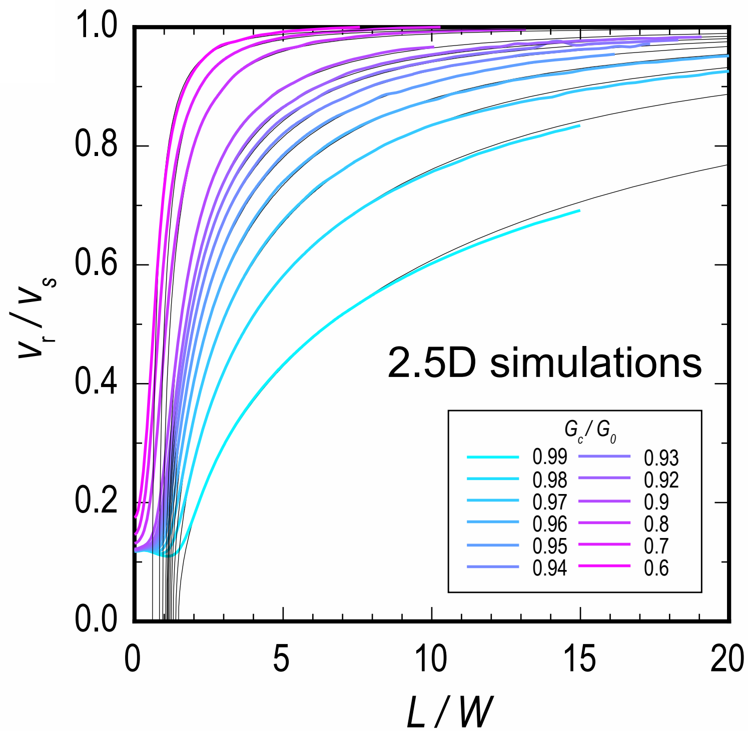


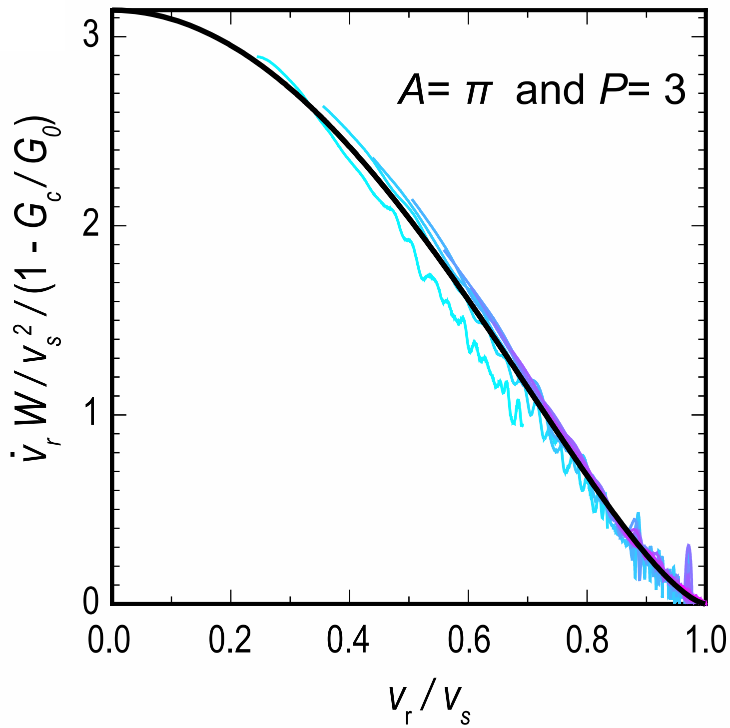
Rupture acceleration

- $G_0 > G_c$ → ruptures accelerate ↑
- G_c/G_0 plays an important role in controlling rupture speed

$$\frac{\dot{v}_r W}{v_s^2(1 - G_c/G_0)} = \pi\alpha_s^3$$

$$\alpha_s = \sqrt{1 - (v_r/v_s)^2}$$



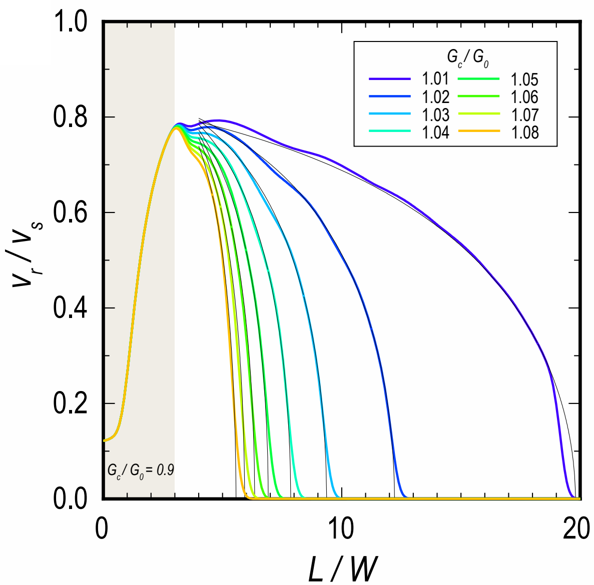


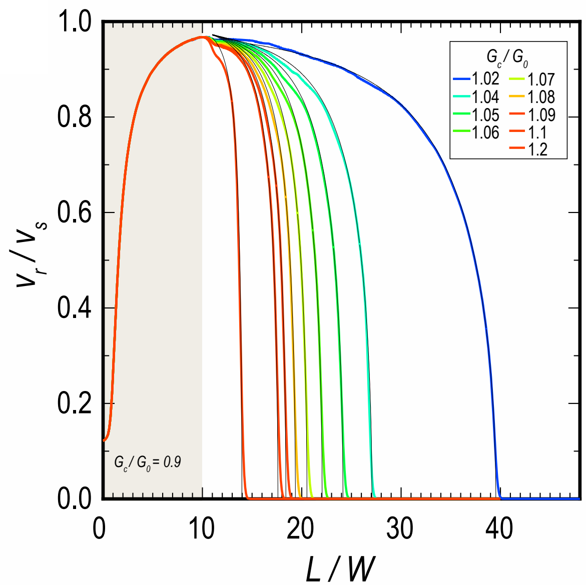
Rupture deceleration

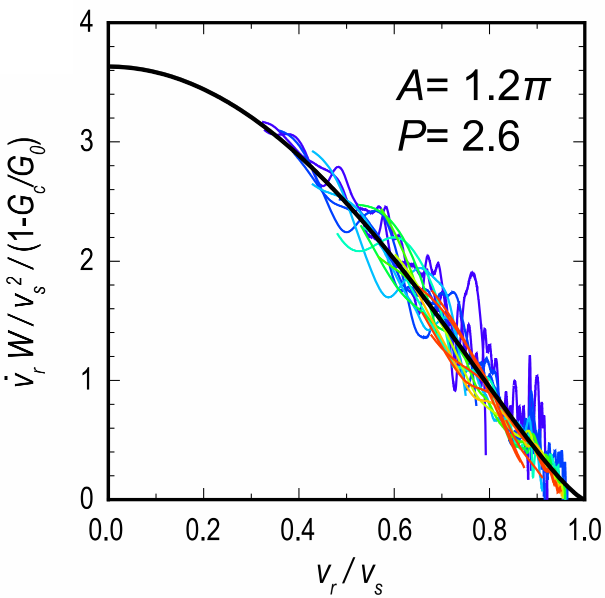
- $G_0 < G_c$ → ruptures decelerate ↓
- Starting speed also plays a role
- Larger rupture speed lead to longer distance

$$\frac{\dot{v}_r W}{v_s^2 (1 - G_c/G_0)} = 1.2\pi \alpha_s^{2.6}$$

$$\alpha_s = \sqrt{1 - (v_r/v_s)^2}$$

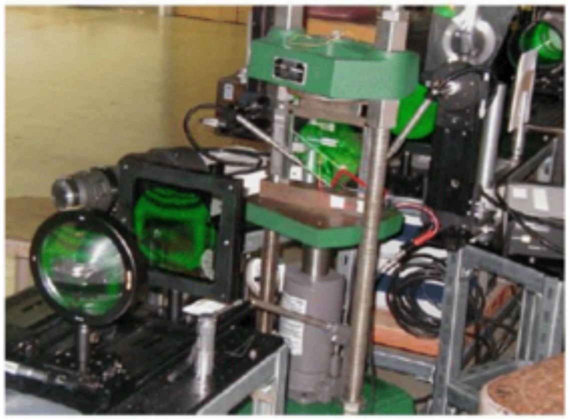




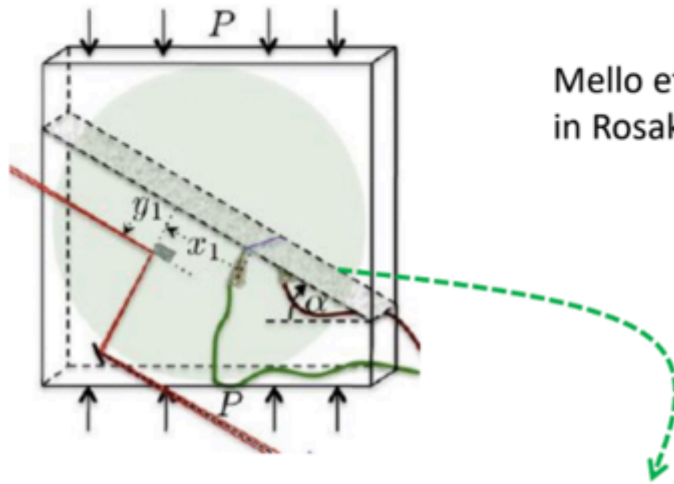


2.5D simulations

Elongated ruptures in the lab



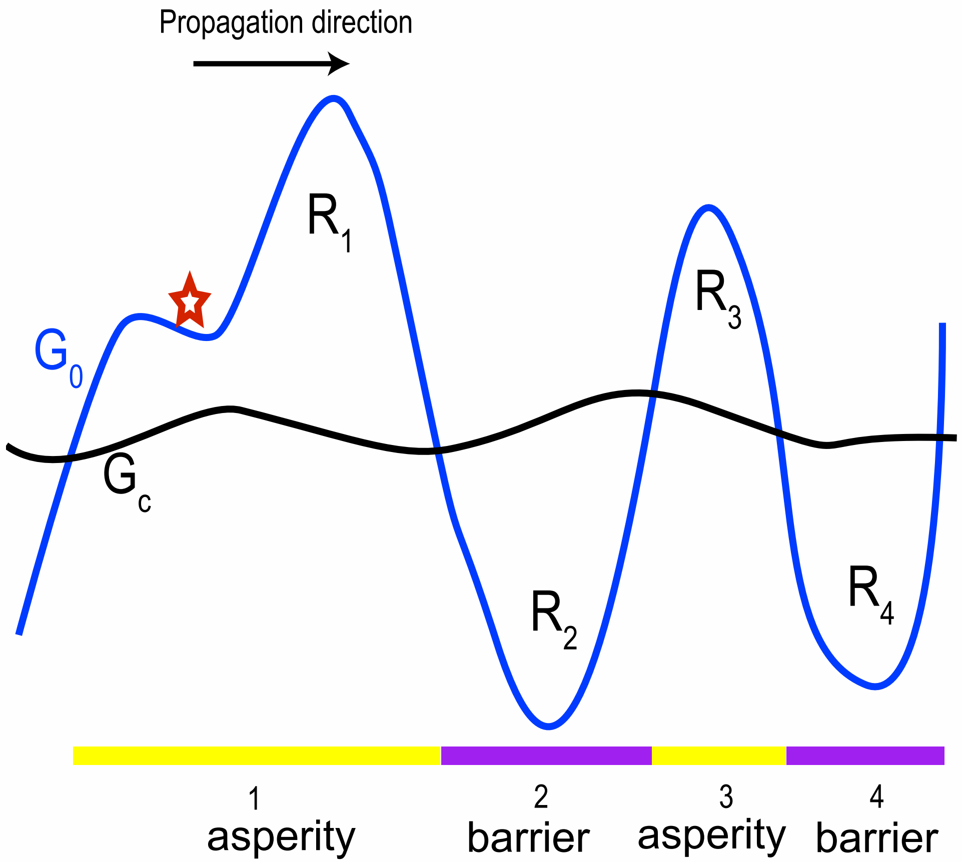
Laboratory earthquake experiment



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

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

Rupture potential



$$\frac{\dot{v}_r W}{v_s^2(1 - G_c/G_0)} = A\alpha_s^P$$

↓

$$\frac{v_r dv_r}{v_s^2 \alpha_s^P} = A(1 - G_c/G_0)dx/W$$

"Kinetic" energy? ↓ "Potential" energy?

$$\frac{1}{P-2}(\alpha_s^{2-P} - 1)\Big|_{v_{r1}}^{v_{r2}} = \int_{L_1}^{L_2} A(1 - G_c/G_0)dx/W$$

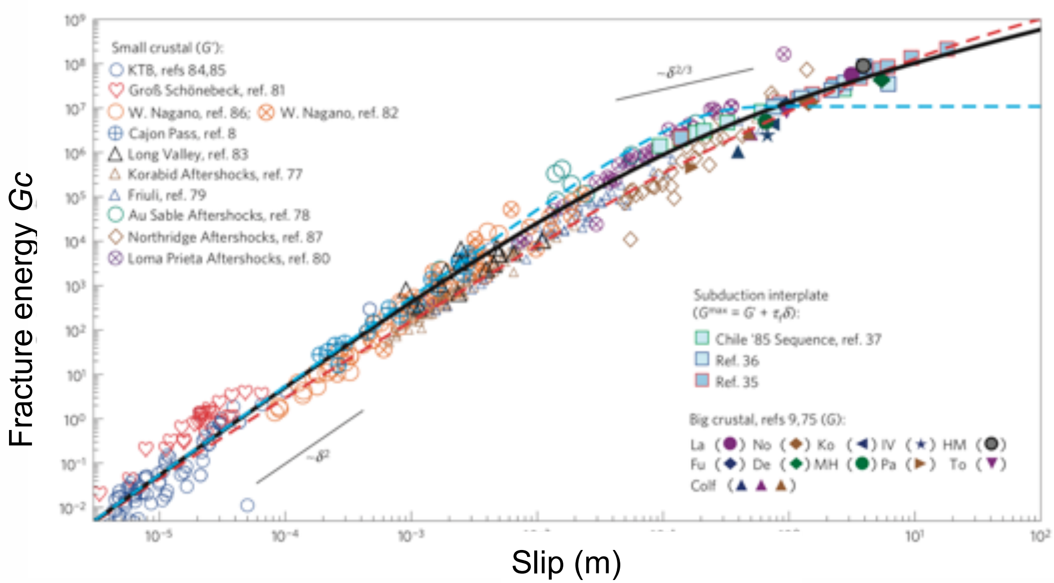
↓ Rupture potential

$$\varphi(L) = \int_0^L A(1 - G_c/G_0)dx/W$$

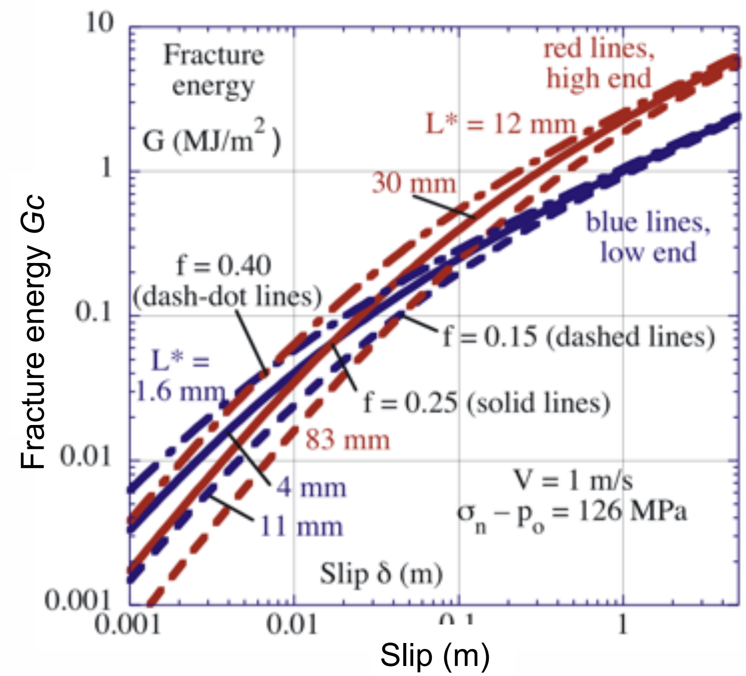
Fracture energy on fault

Fracture energy is a function of final slip $D(x)$?

For bounded fault $D(x) = \gamma \widehat{W} \Delta\tau(x)/\mu$ then $G_c \propto \Delta\tau^n$?

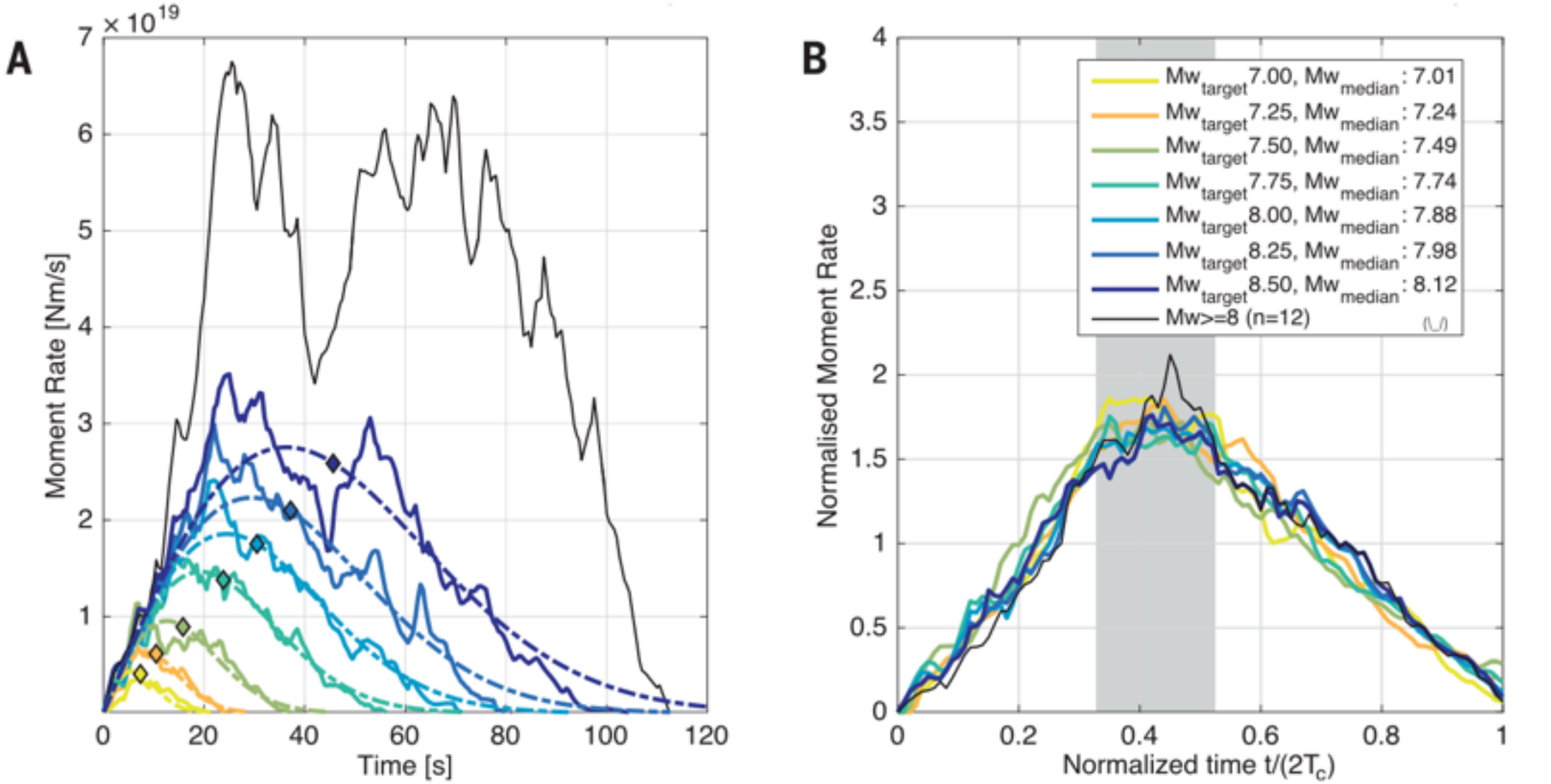


Viesca and Garagash (2015)



Rice (2006)

Source time function of earthquakes



General pattern of earthquake – triangular

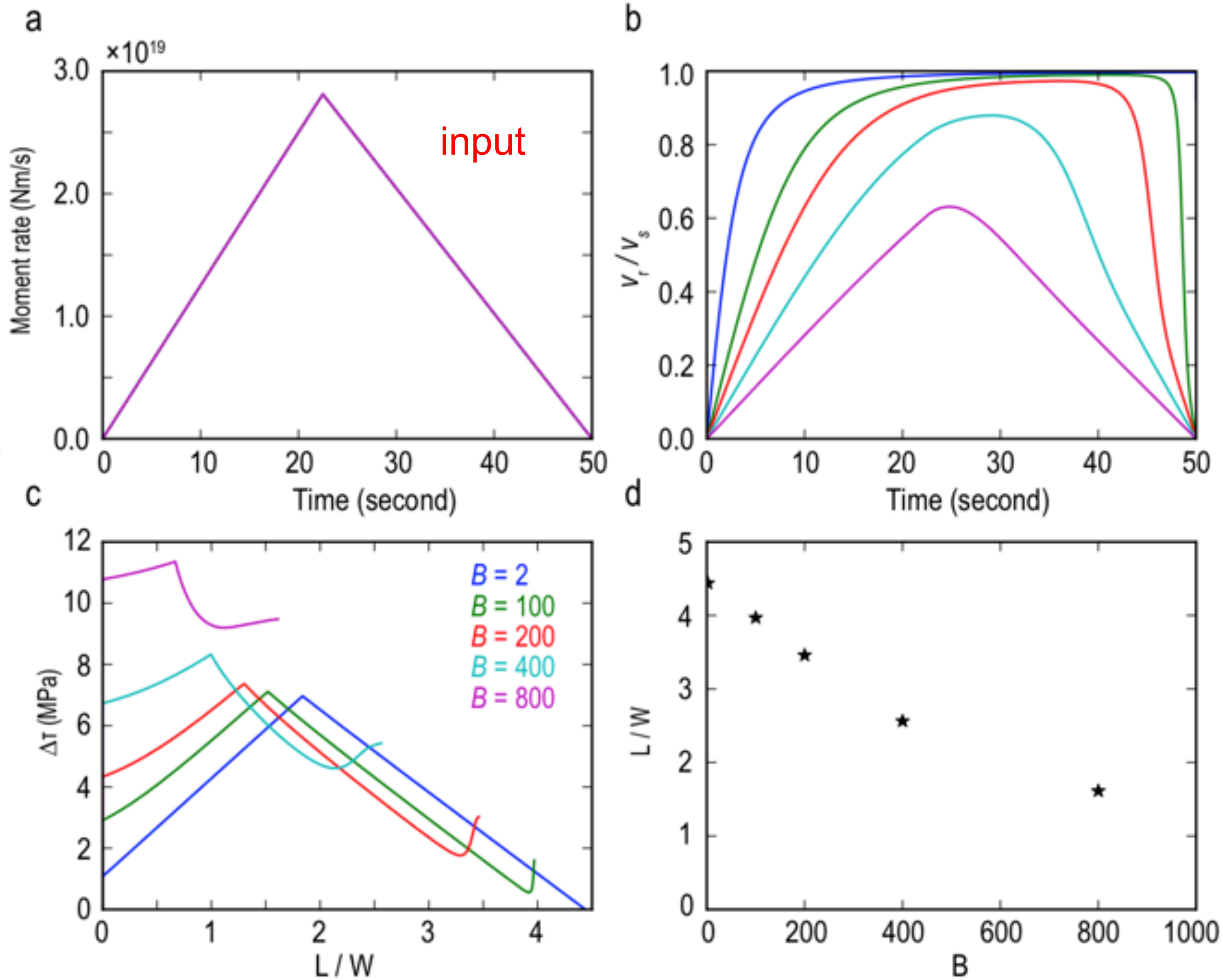
Meier et al 2017

What is the intrinsic physics？

Constrains from STF

$G_c = B\Delta\tau^{2/3}$

$v_{r0}=0$



Assuming n=2/3, γ=1, and $v_r(0)=0$