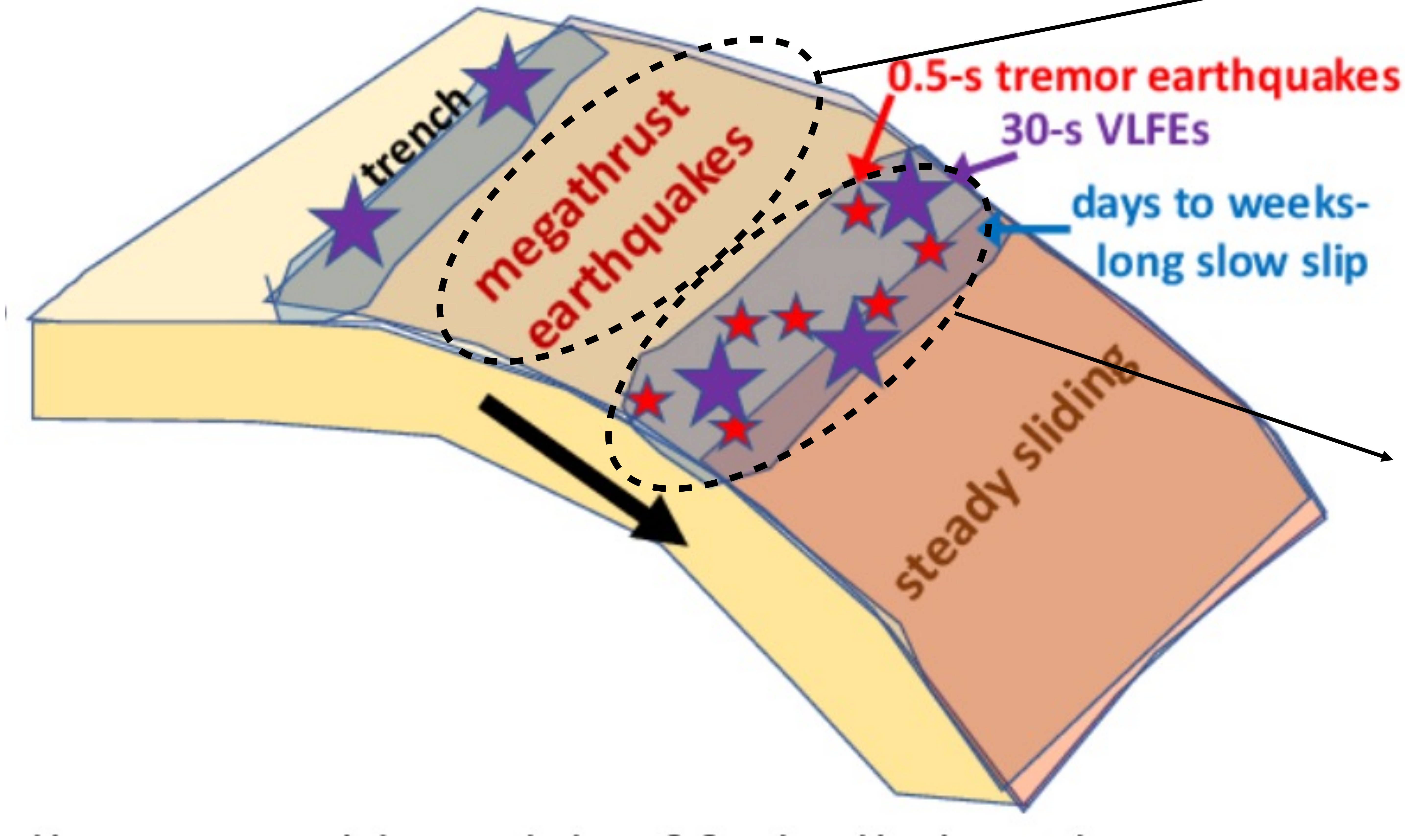
*CIG seminar - 2022*

# Rupture styles and recurrence patterns in seismic cycles linked to physical properties of the fault zone

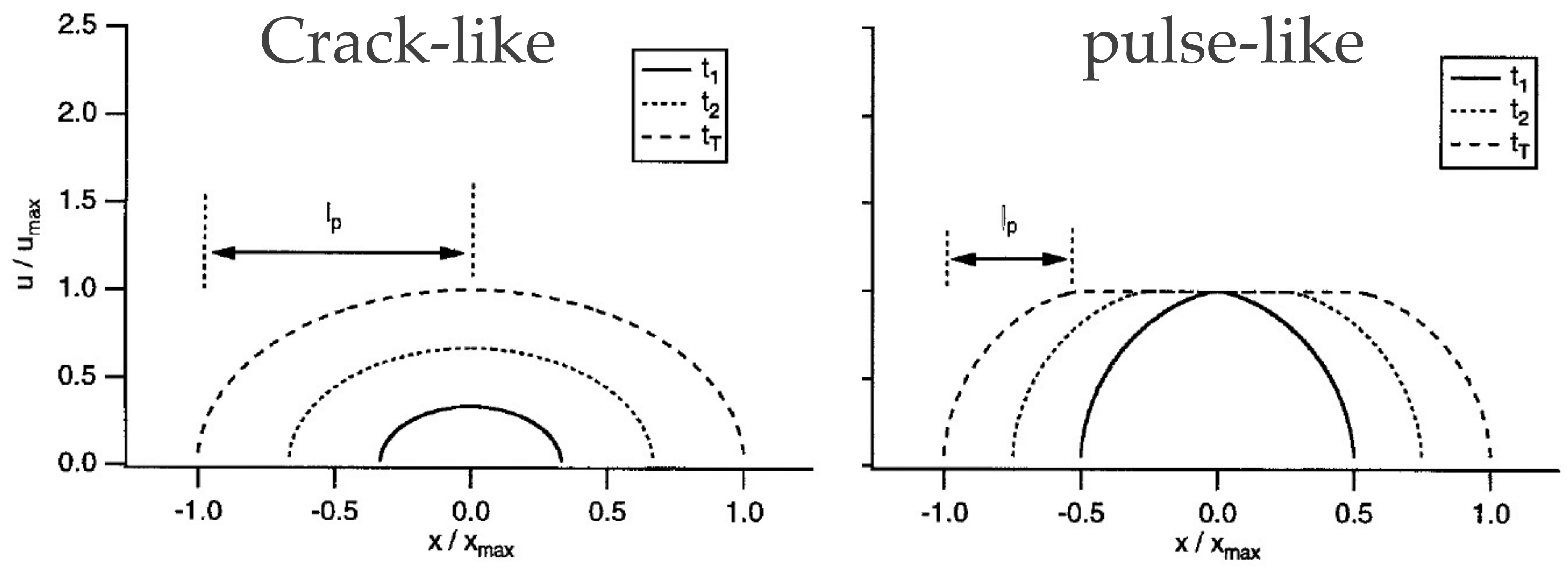
Shiying Nie
Sylvain Barbot
University of Southern California

# A broad range of rupture behaviors

- Rupture events behave in very different ways.




**Earthquakes** are ***seismic*** phenomena



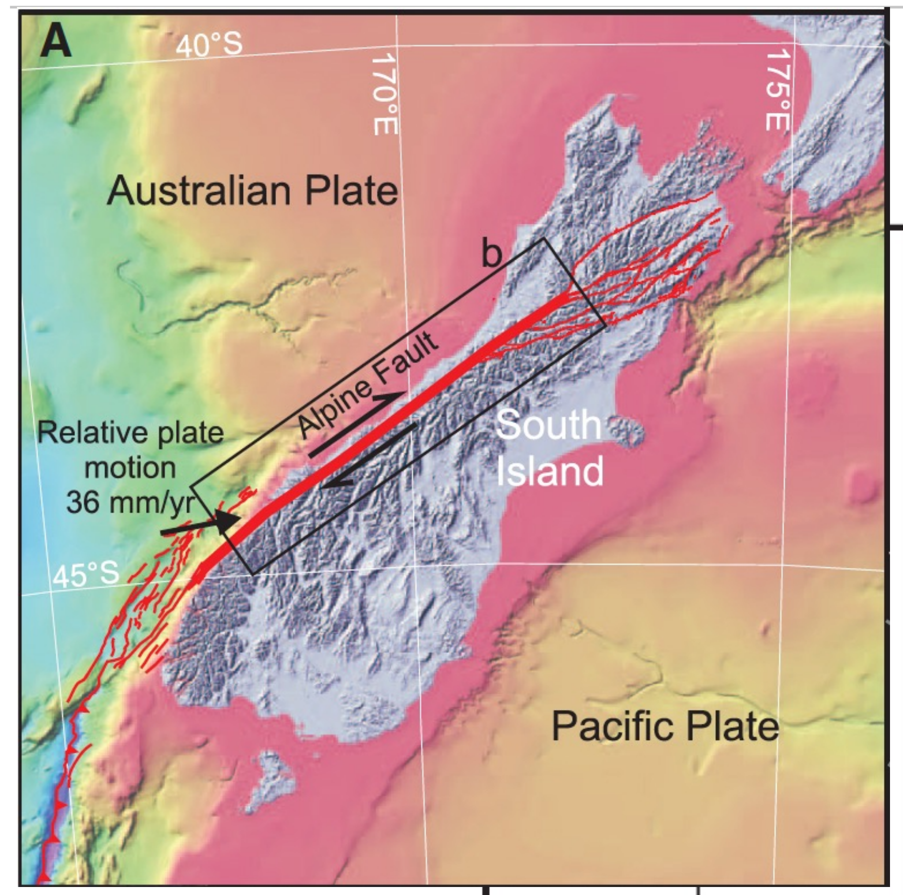

Beeler and Tullis, 1996

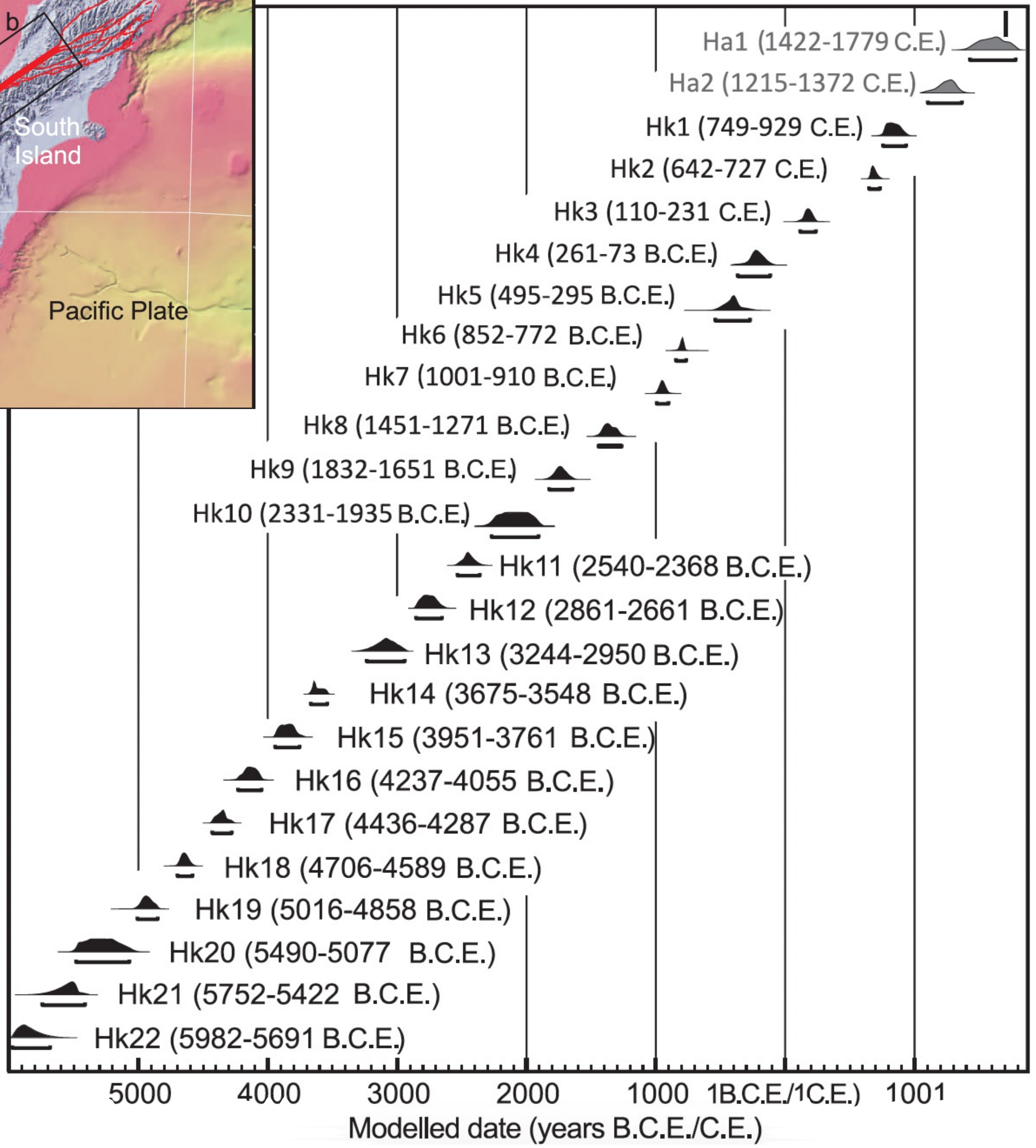
**Slow slip events** (SSEs) are ***GPS*** phenomena

However, the correlated "**slow earthquakes**" (Tremors, low-frequency-earthquakes and very-low-frequency-earthquakes) are ***seismic*** phenomena

# Are major earthquakes periodic and characteristic ?

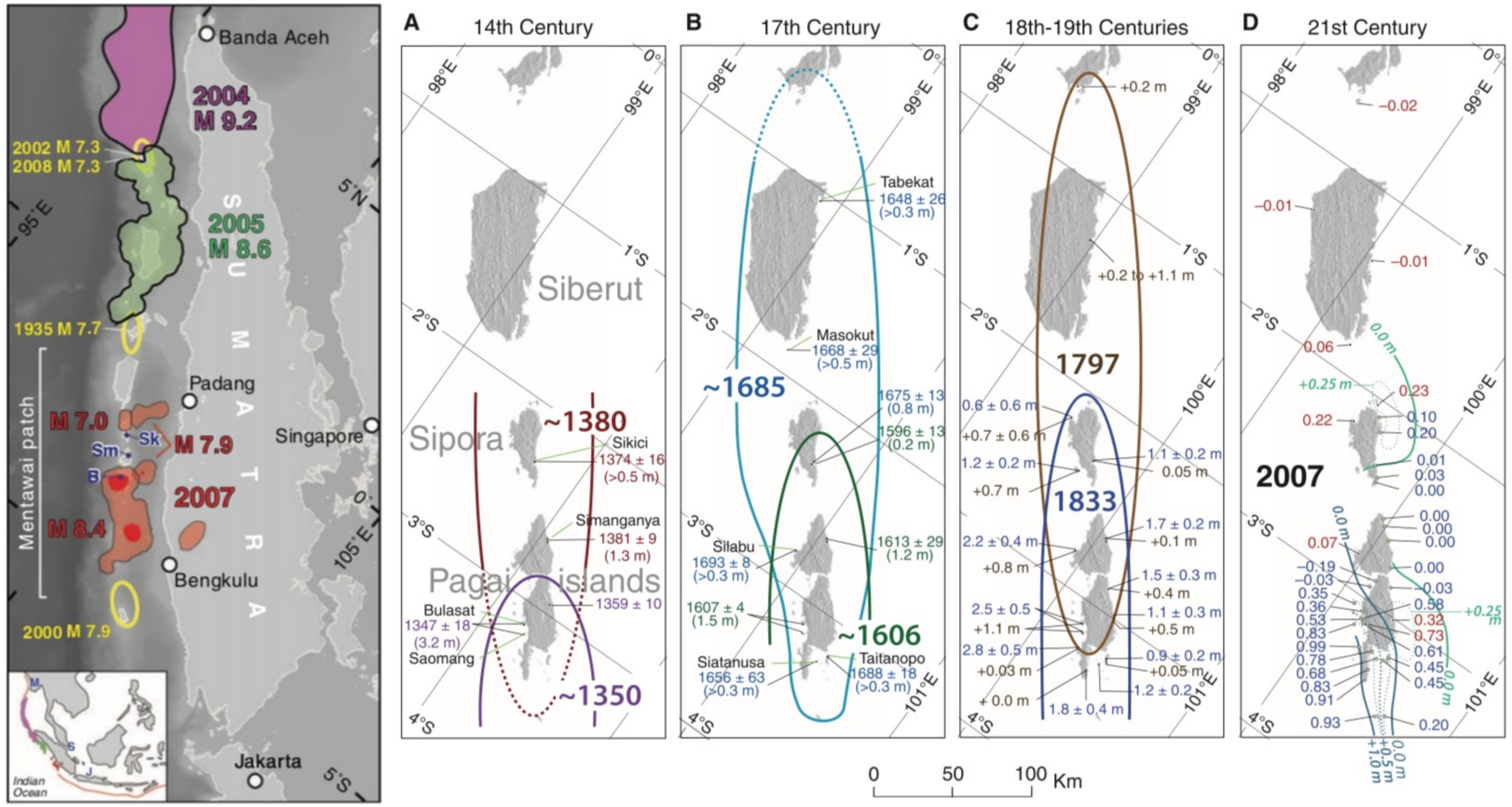
## Periodic (CoV = 0.33)




Berryman et al. (2012)

## Supercycles / aperiodic




West Sumatra Supercycles (Sieh et al. 2008)

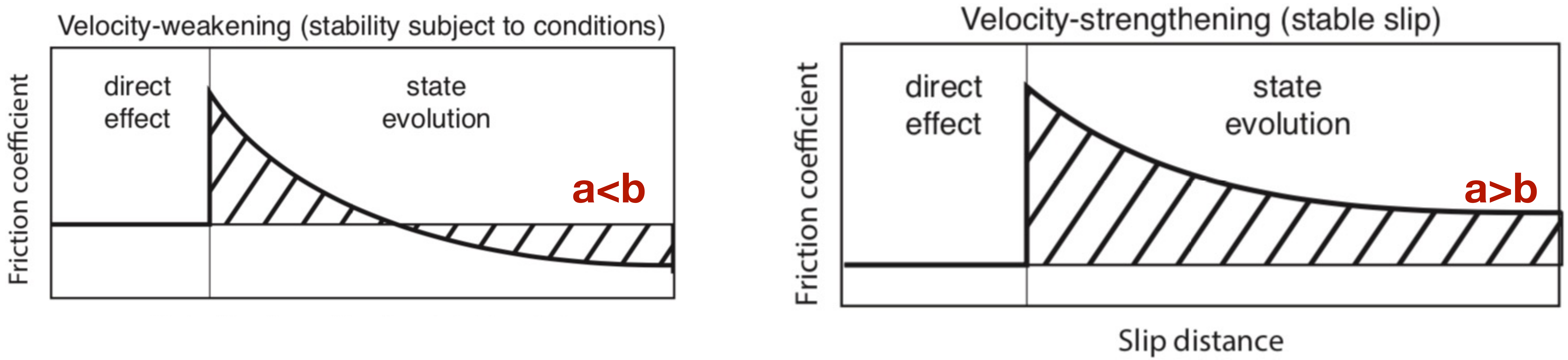
# Frictional framework underlying these phenomenon

- We apply the multiplicative form of a friction law:

$$\tau = \mu_0 \bar{\sigma} \left( \frac{V}{V_0} \right)^{\frac{a}{\mu_0}} \left( \frac{\theta V_0}{L} \right)^{\frac{b}{\mu_0}}$$

- The state variable evolves by aging law:

$$\dot{\theta} = 1 - \frac{V\theta}{L}$$



# Non-dimensional parameters to union the phenomenon

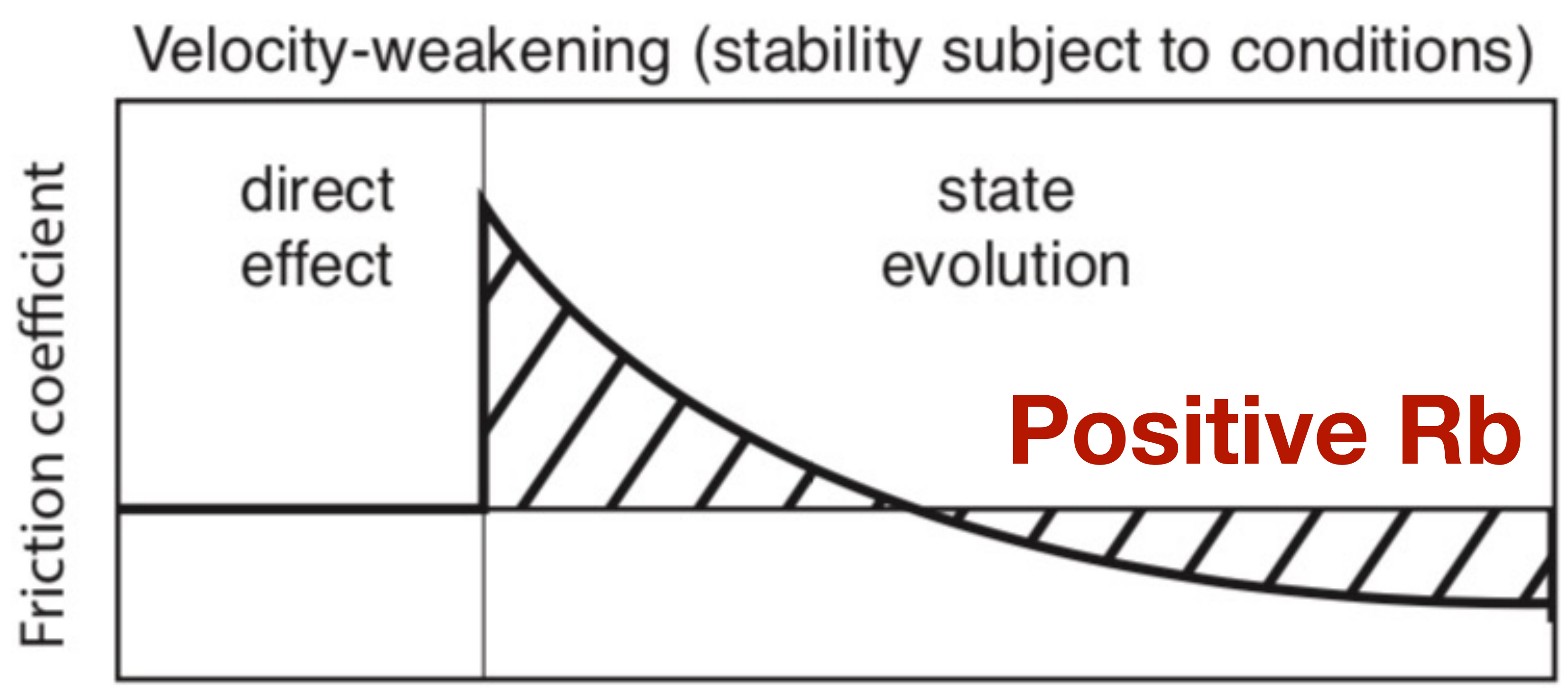
- The Dieterich-Ruina-Rice number:

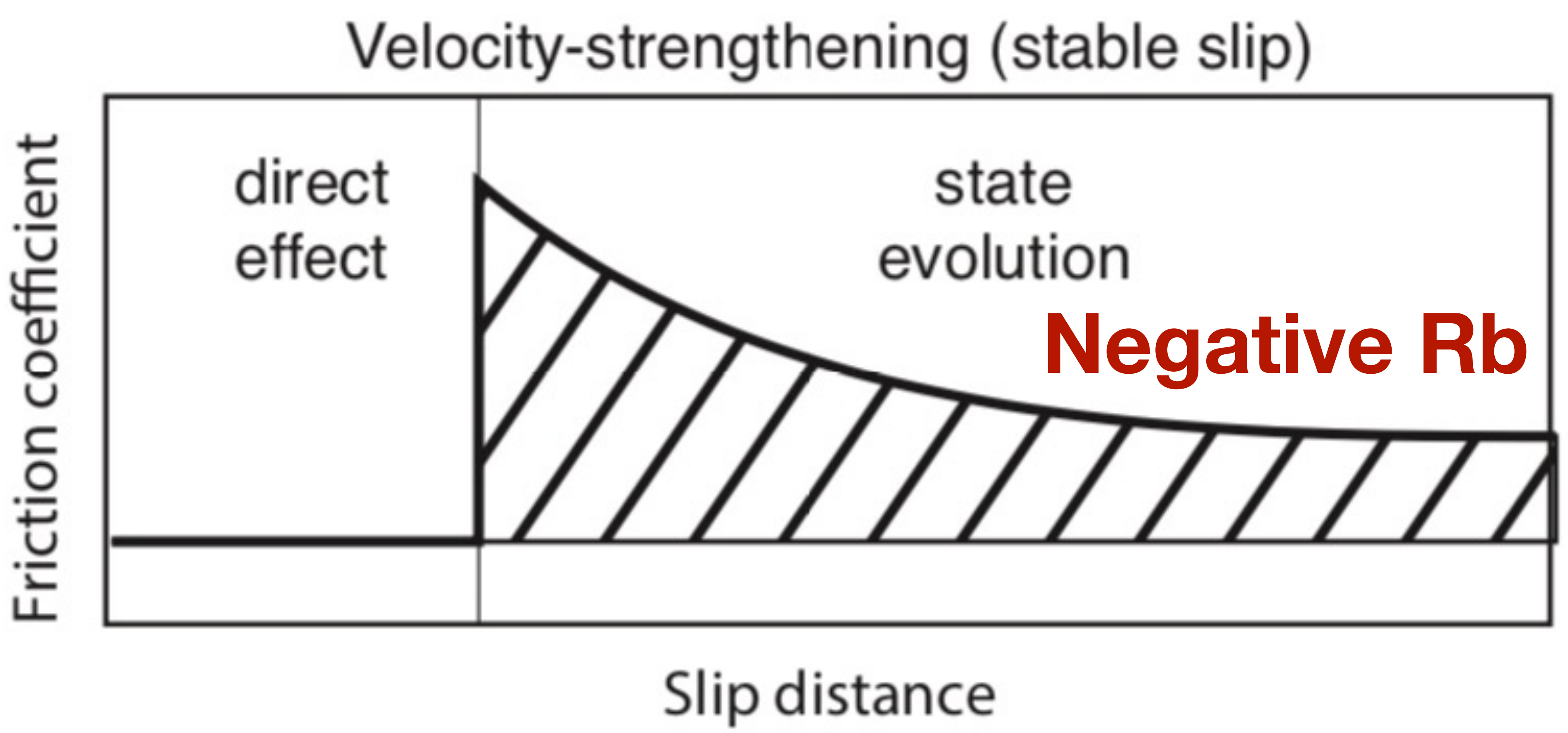
$$R_u = \frac{(b-a)\bar{\sigma}}{G}\frac{W}{L} \quad \sim W/h^*$$

- Which is the ratio between asperity size W and nucleation length h*. It controls the complexity of ruptures

$$R_b = \frac{b-a}{b}$$

- Reflects the velocity dependence;



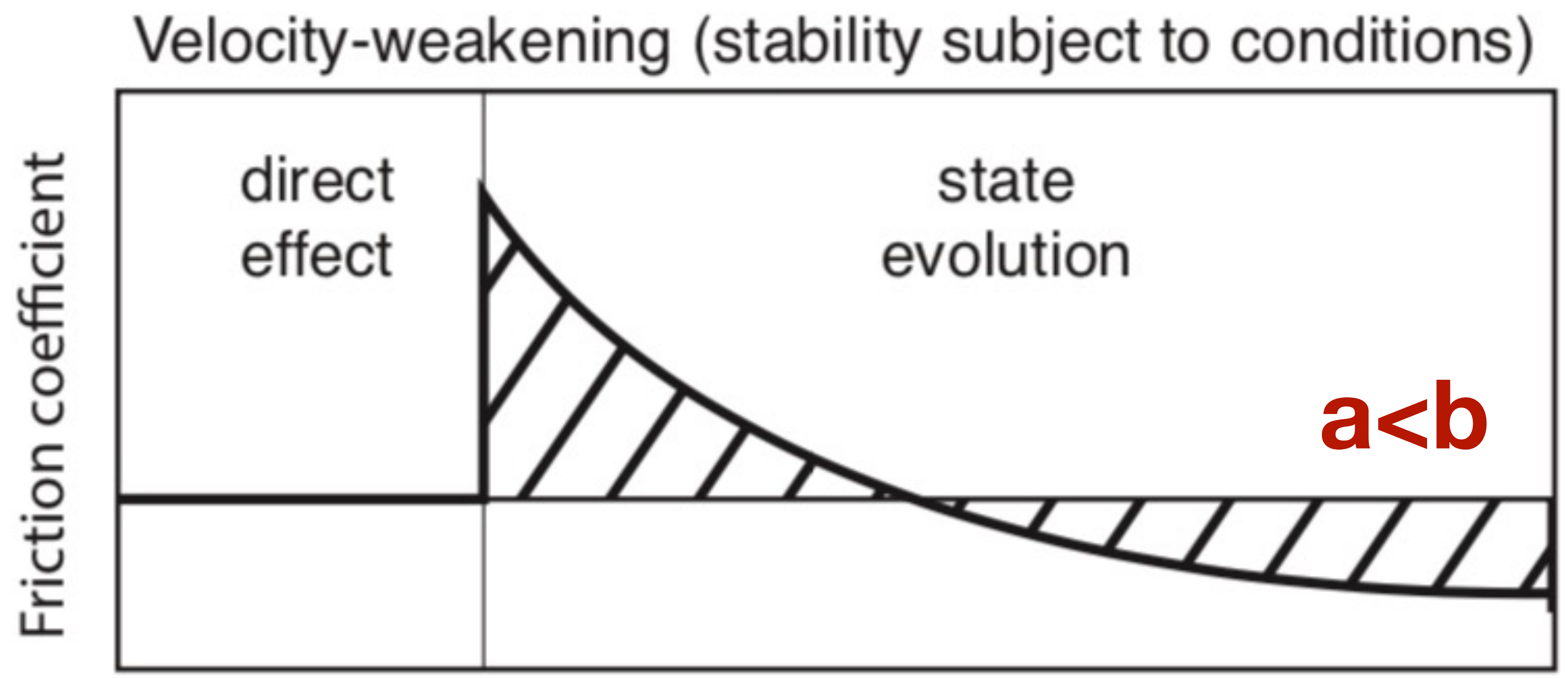
# Non-dimensional parameters to union the phenomenon

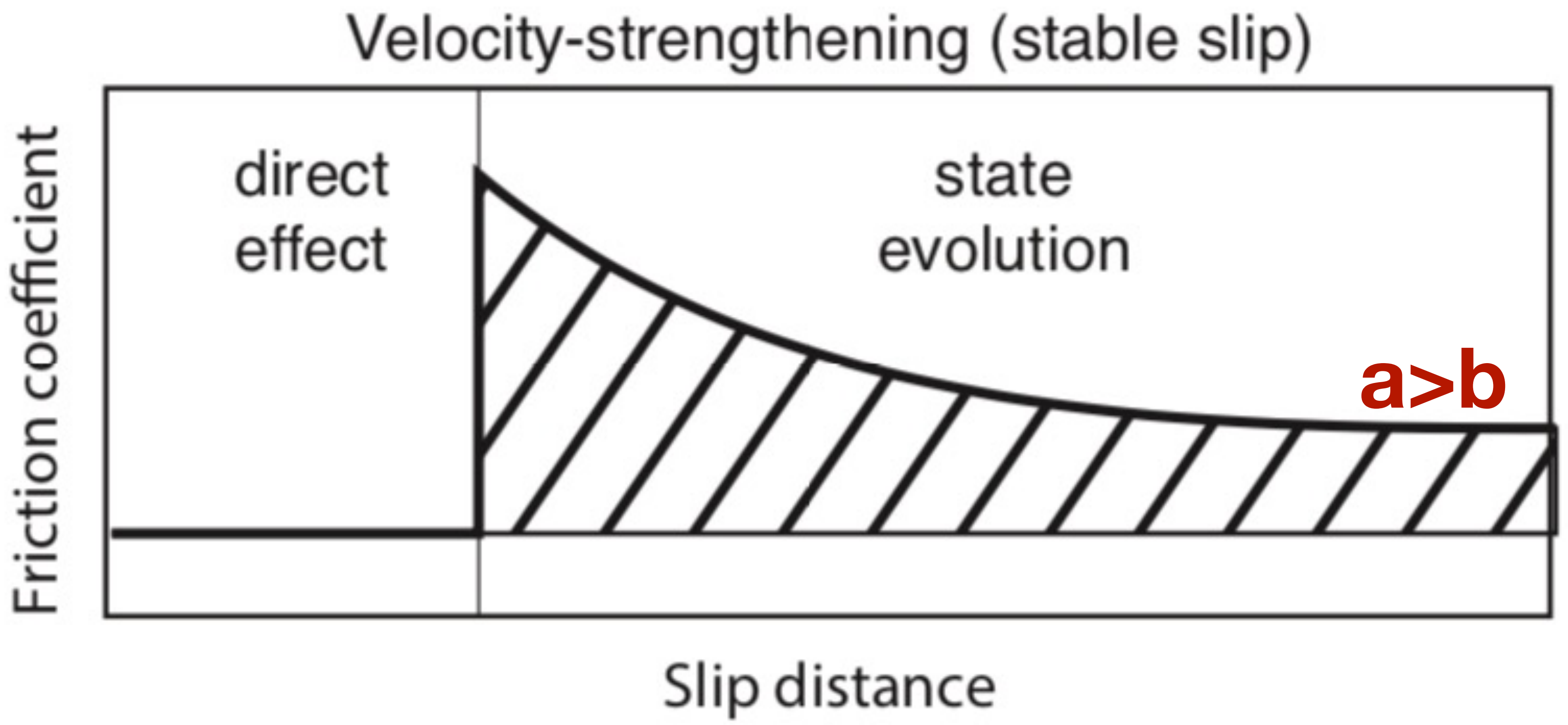
- The Dieterich-Ruina-Rice number:

$$\boxed{R_u = \frac{(b-a)\bar{\sigma}}{G}\frac{W}{L} \quad \textbf{Varied}}$$

- Which is the ratio between asperity size and nucleation length. It controls the complexity of ruptures
- Reflects the velocity dependence;

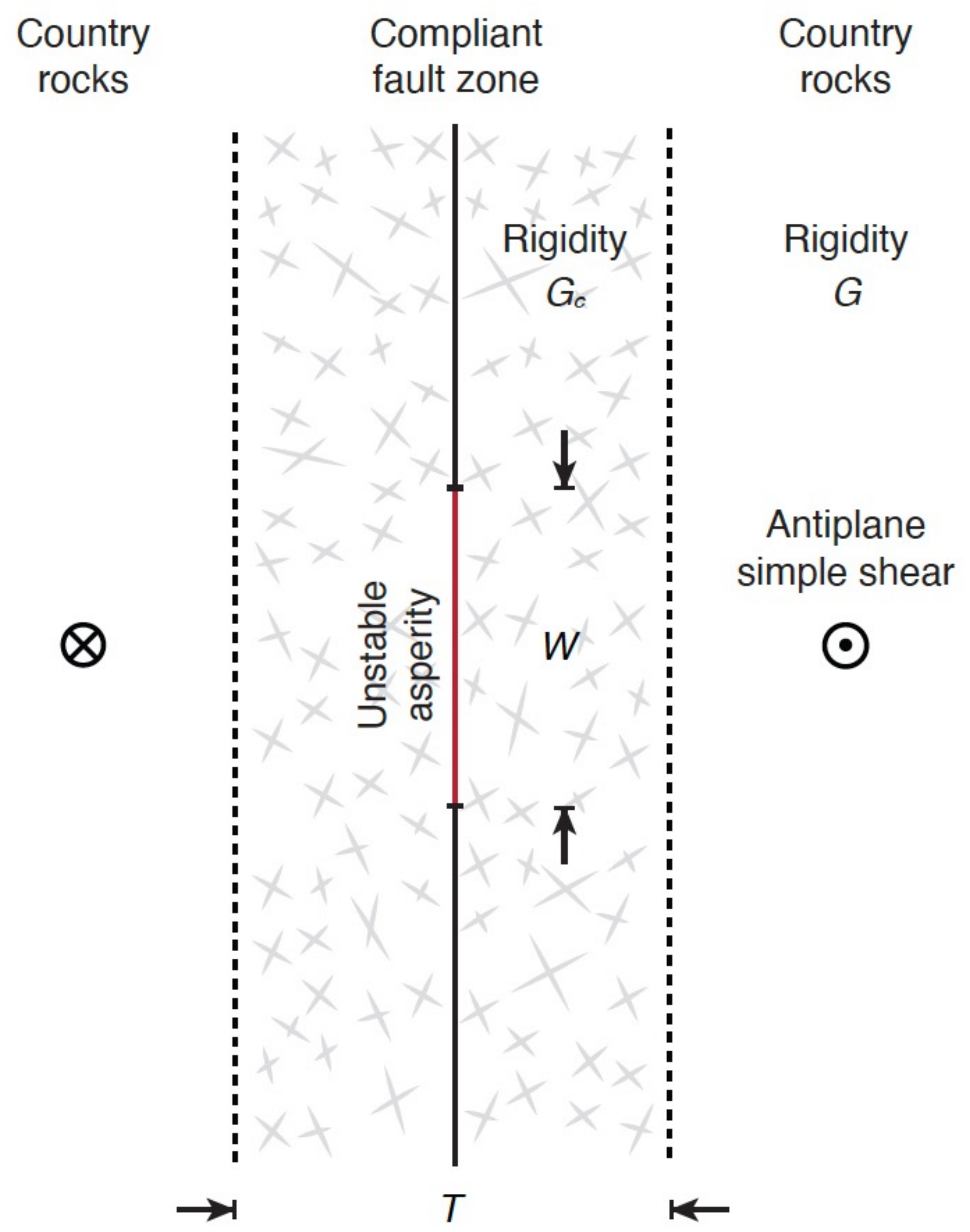
$$\boxed{R_b = \frac{b-a}{b} \sim 0.28}$$

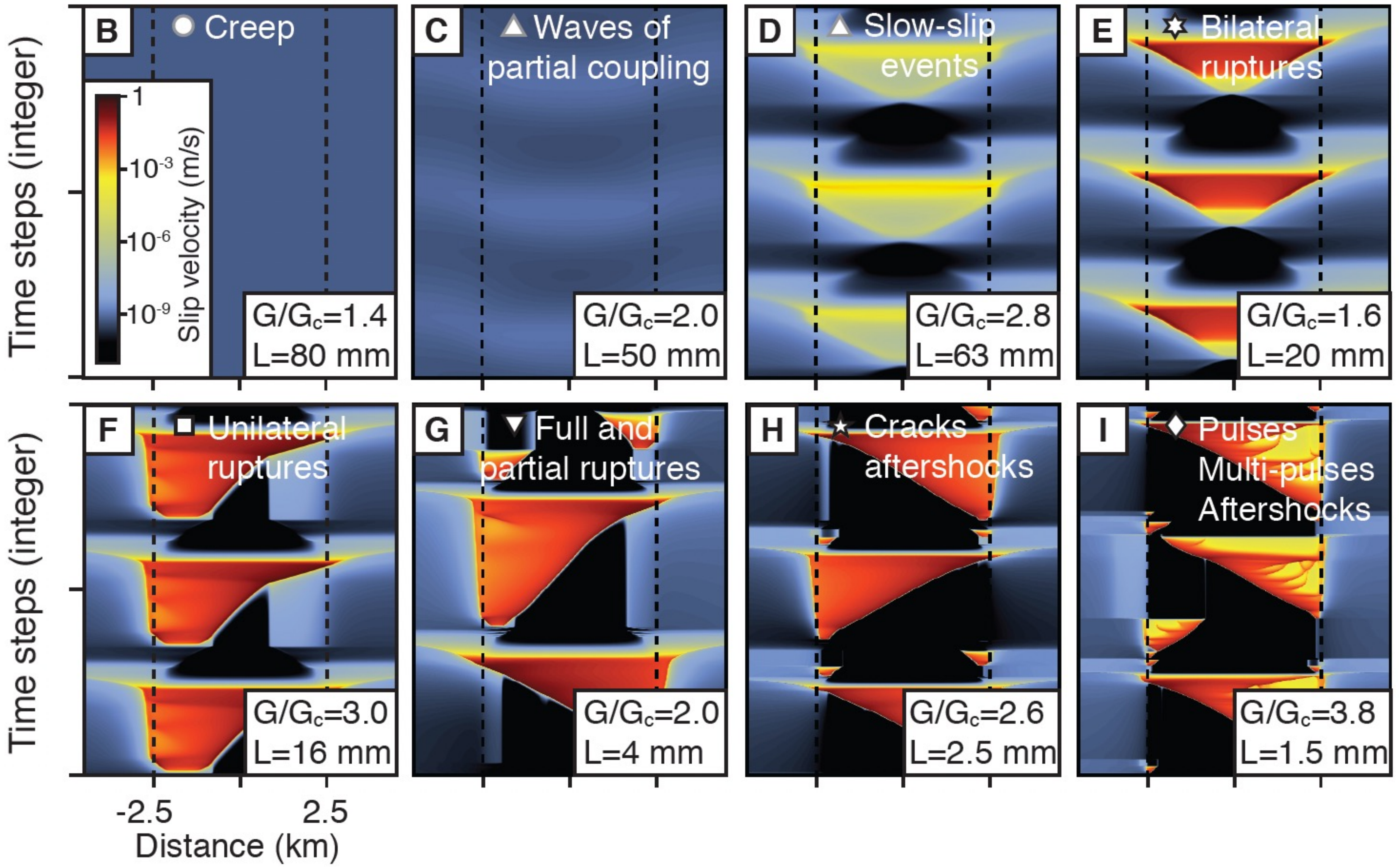


# From slow slip to chaotic sequences

- We consider seismic cycles of a **strike-slip fault** surrounded by a **low-velocity fault zone** in **two-dimensional antiplane** strain.
- we use the **spectral boundary-integral method** for **quasi-dynamic** ruptures (Barbot, 2021)




characteristic weakening distance L ↓; Fault zone rigidity Gc ↓

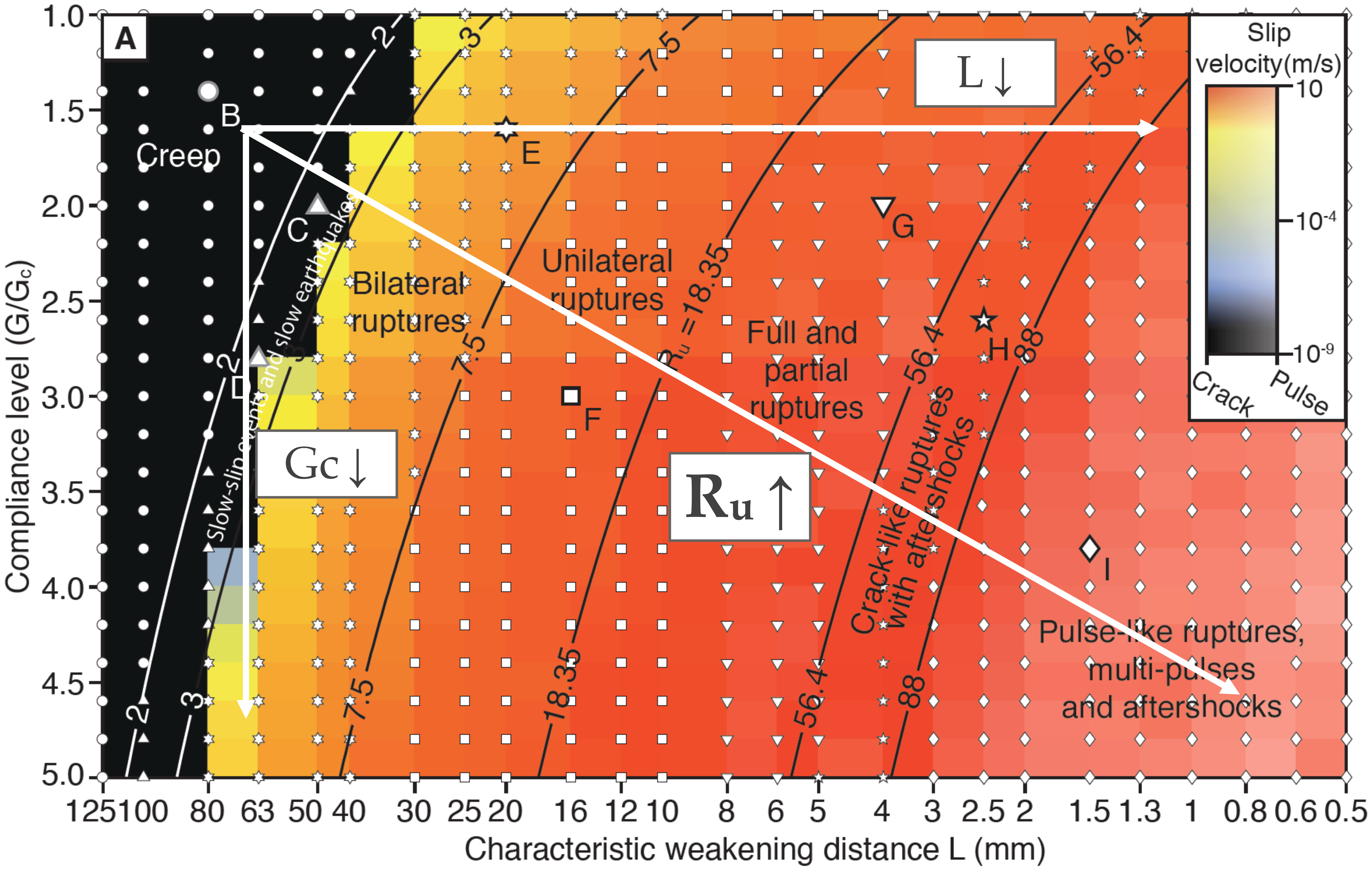
so: $\mathbf{R_u}$ ↑

$$R_u = \frac{(b-a)\bar{\sigma}}{G}\frac{W}{L}$$

Nie and Barbot, *in revision*

# From slow slip to chaotic sequences

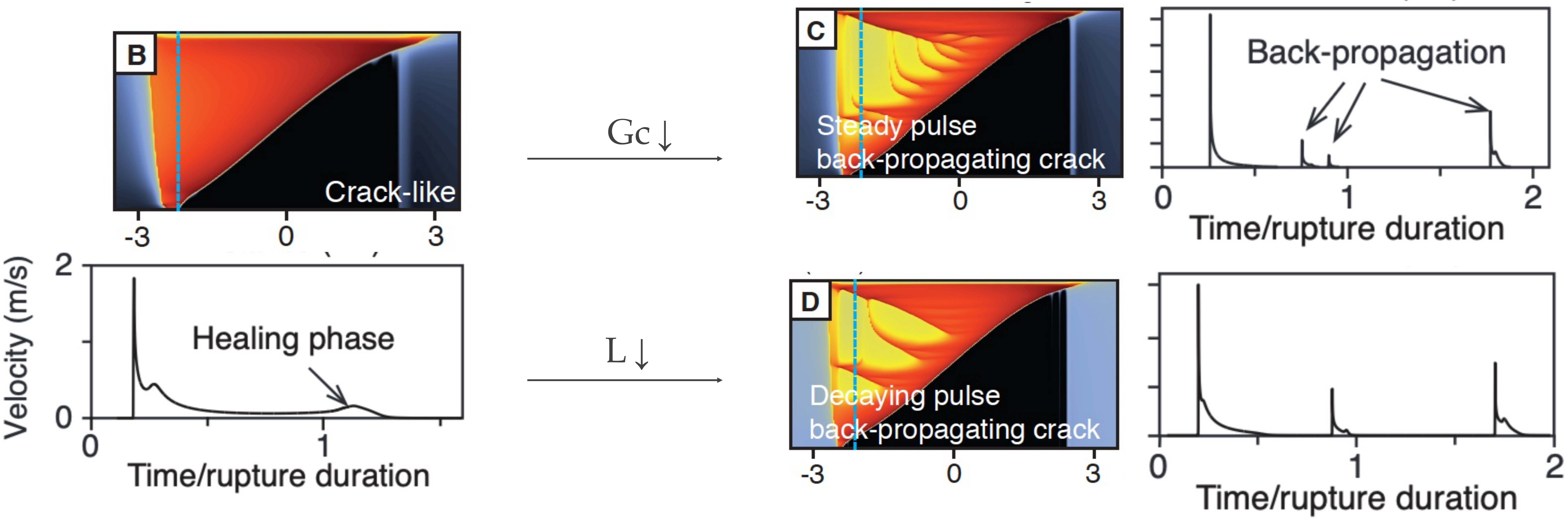
- We use 525 simulations to conduct a phase diagram of **L** and **Gc;**
- The **transition of rupture style phases** follows **$R_u$** contours roughly.




Nie and Barbot, *in revision*

# Transition from crack- to pulse- like ruptures

- **Damaged fault zones** promote **pulse-like** ruptures and **back-propagating** rupture fronts. (Idini and Ampuero, 2020)
- The transition from **crack-like** to **pulse-like** ruptures can be obtained by **increased $R_u$,** either obtained by decreased characteristic weakening distance L or fault zone rigidity $G_c$.



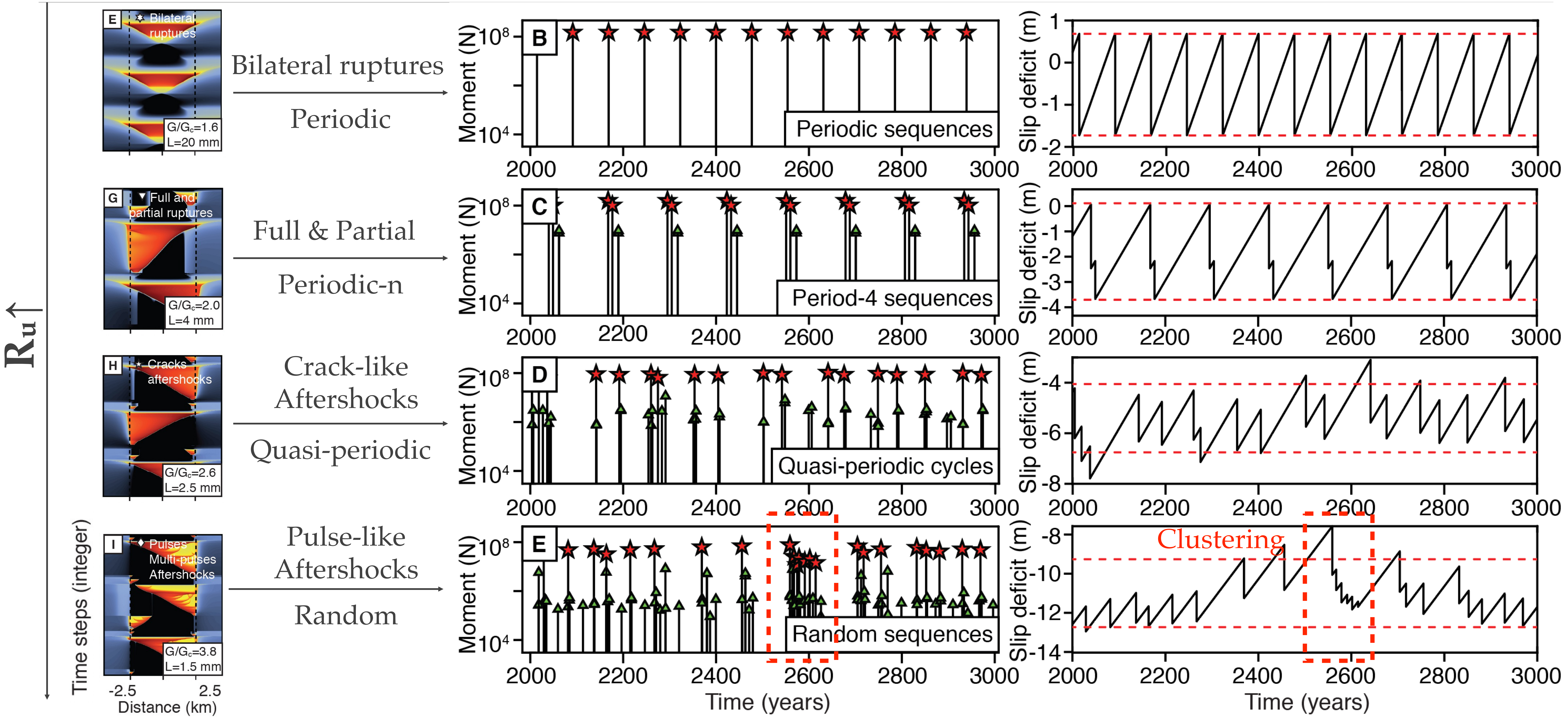
# Conflating fault zone behaviors by $R_u$

- The faulting behavior of models with **similar $R_u$** is mostly **analogous**, even with **different physical properties**, including thickness and compliance level of fault zones, and the characteristic weakening distance (L).
- No particular rupture styles for fault zone models.

$$R_u = W/h^*(\text{Thickness}, Gc, L, a, b\ldots)$$


Nie and Barbot, *in revision*

# Rupture styles linked to temporal recurrence



# Rupture styles linked to spatial recurrence


**Ru↑**

Characteristic → Dissimilar slip

Nie and Barbot, *in revision*

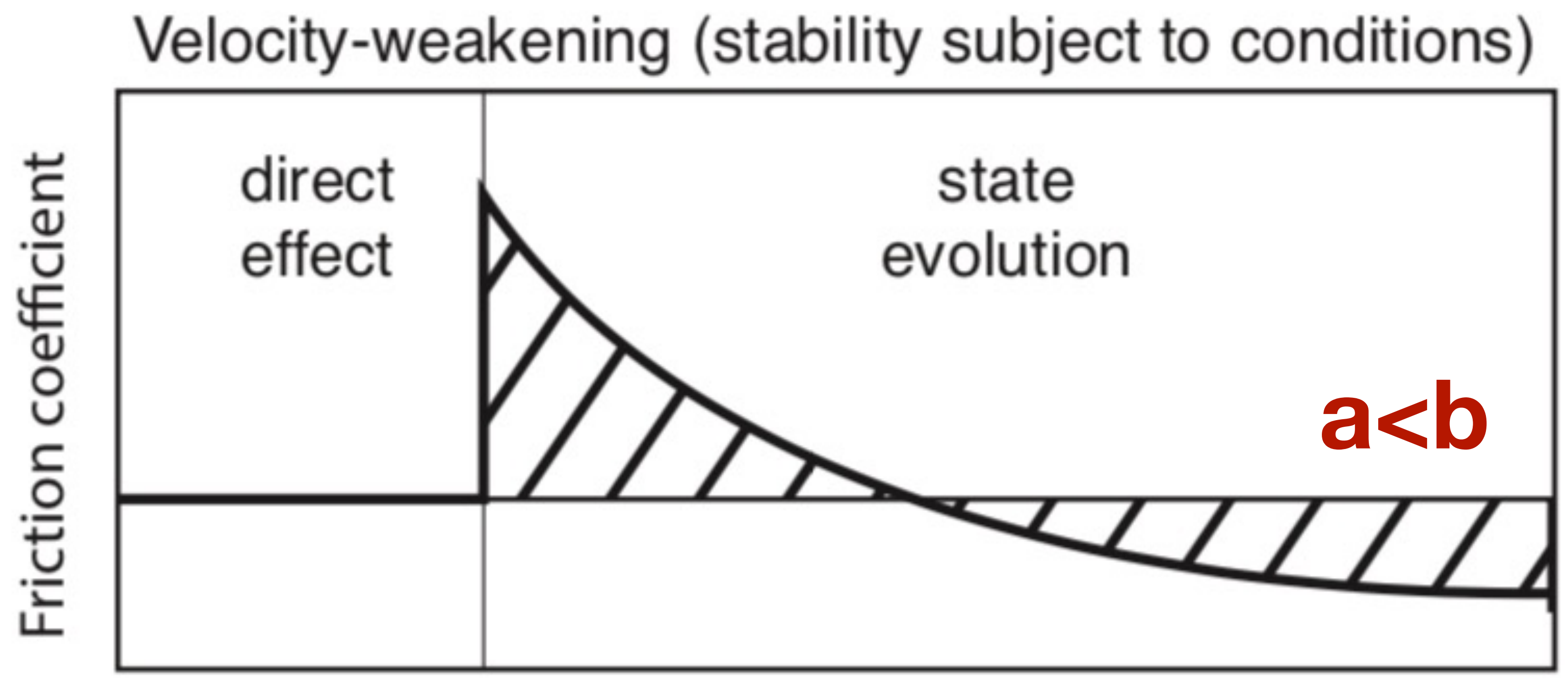
# Non-dimensional parameters to union the phenomenon

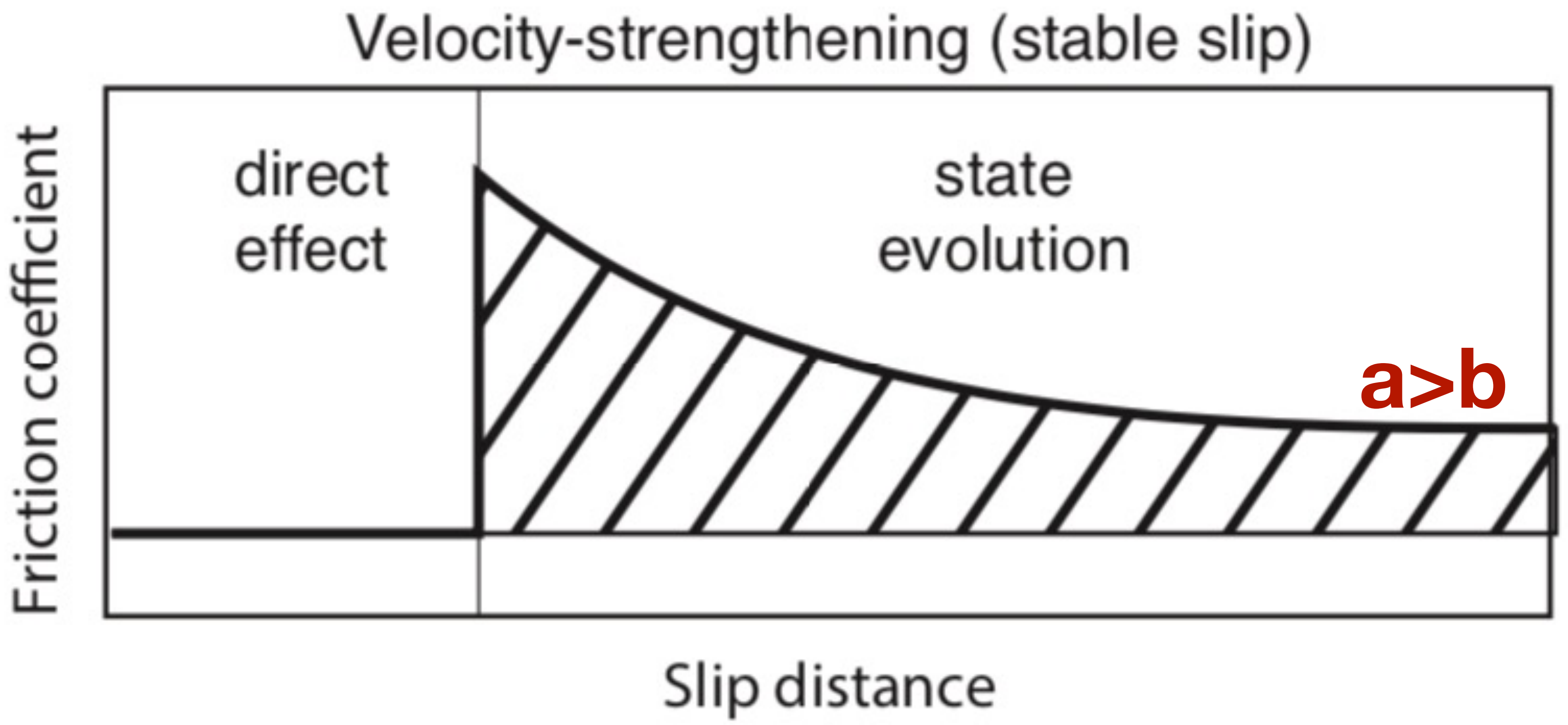
- The Dieterich-Ruina-Rice number:

$$R_u = \frac{(b-a)\bar{\sigma}}{G}\frac{W}{L}$$

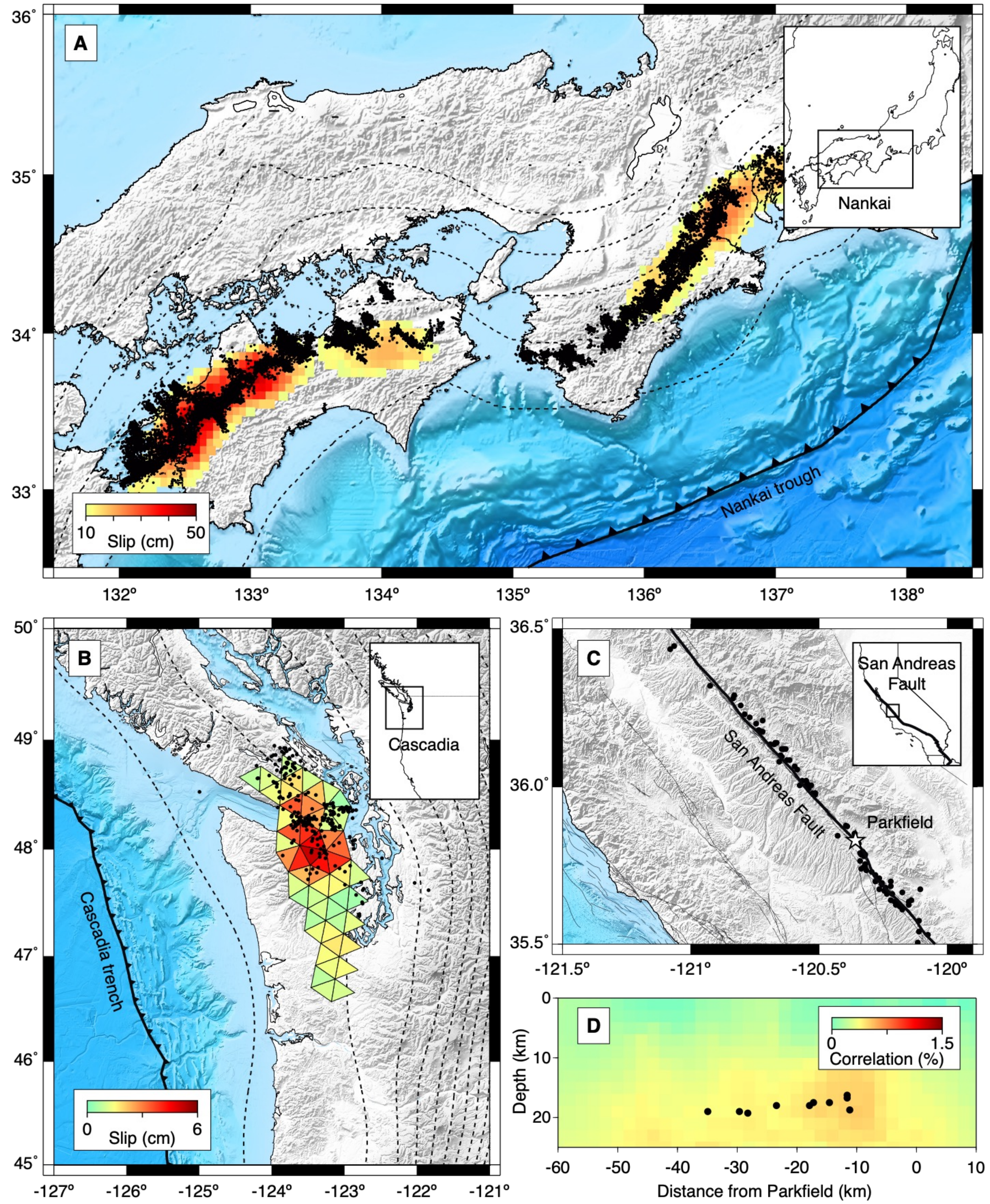
- Which is the ratio between asperity size and nucleation length. It controls the complexity of ruptures

- Reflects the velocity dependence; $\boxed{R_b = \frac{b-a}{b} \quad \textbf{Varied}}$

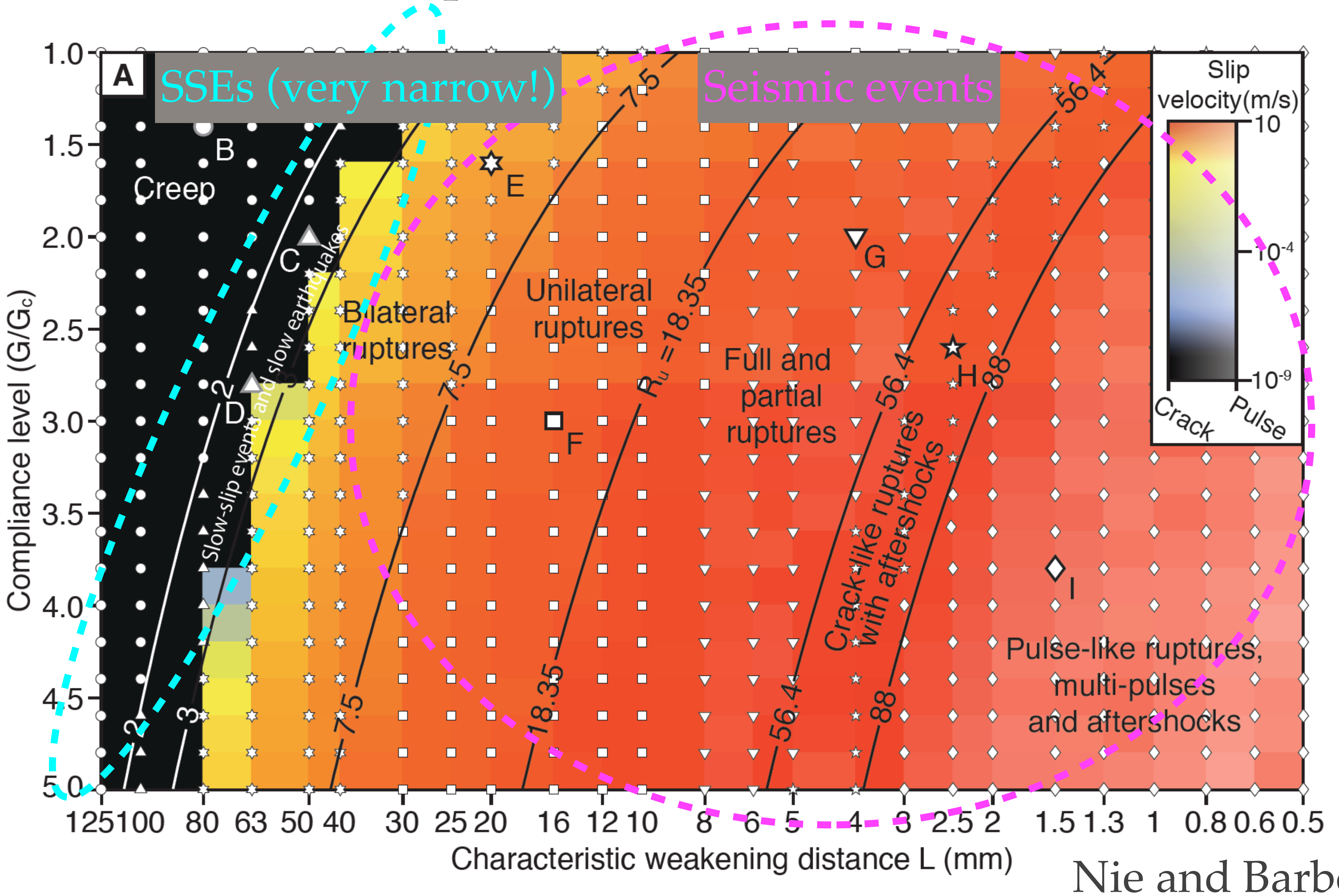


# Concurrent SSEs and slow earthquakes

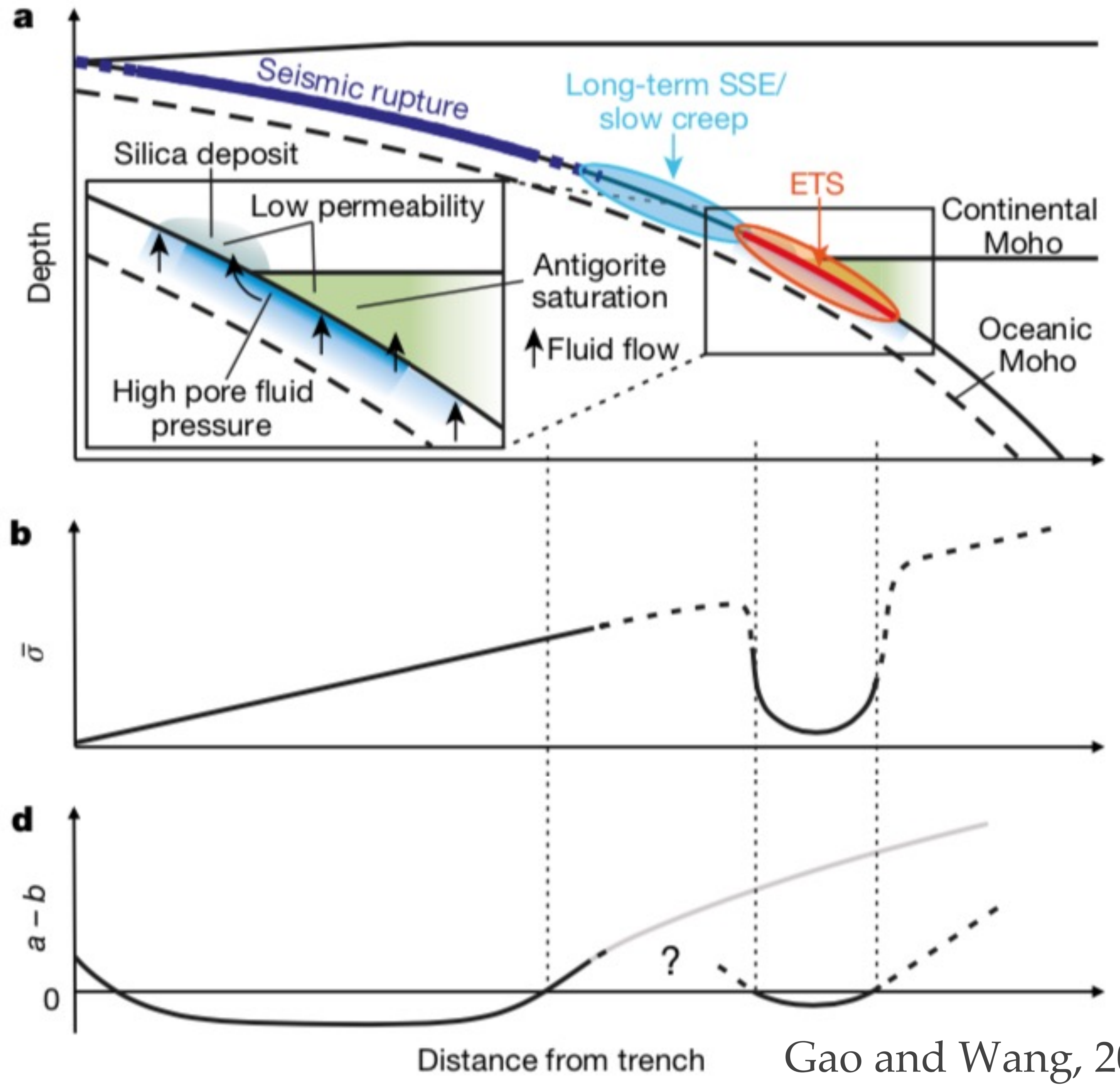



- SSEs and slow earthquakes are **mechanically coupled**, as they are ***temporal*** and ***spatial*** correlated;
- But SSEs and seismic ruptures are **mutually exclusive** based on current experiments.




Nie and Barbot, 2021

# Physical model of the concurrent SSEs and slow earthquakes




Gao and Wang, 2017

- Inspired by where this concurrent behavior takes place: **transition** between **velocity weakening** (seismogenic zone) to **velocity strengthening** (creep area), we propose a ***near-neutral*** mechanism:

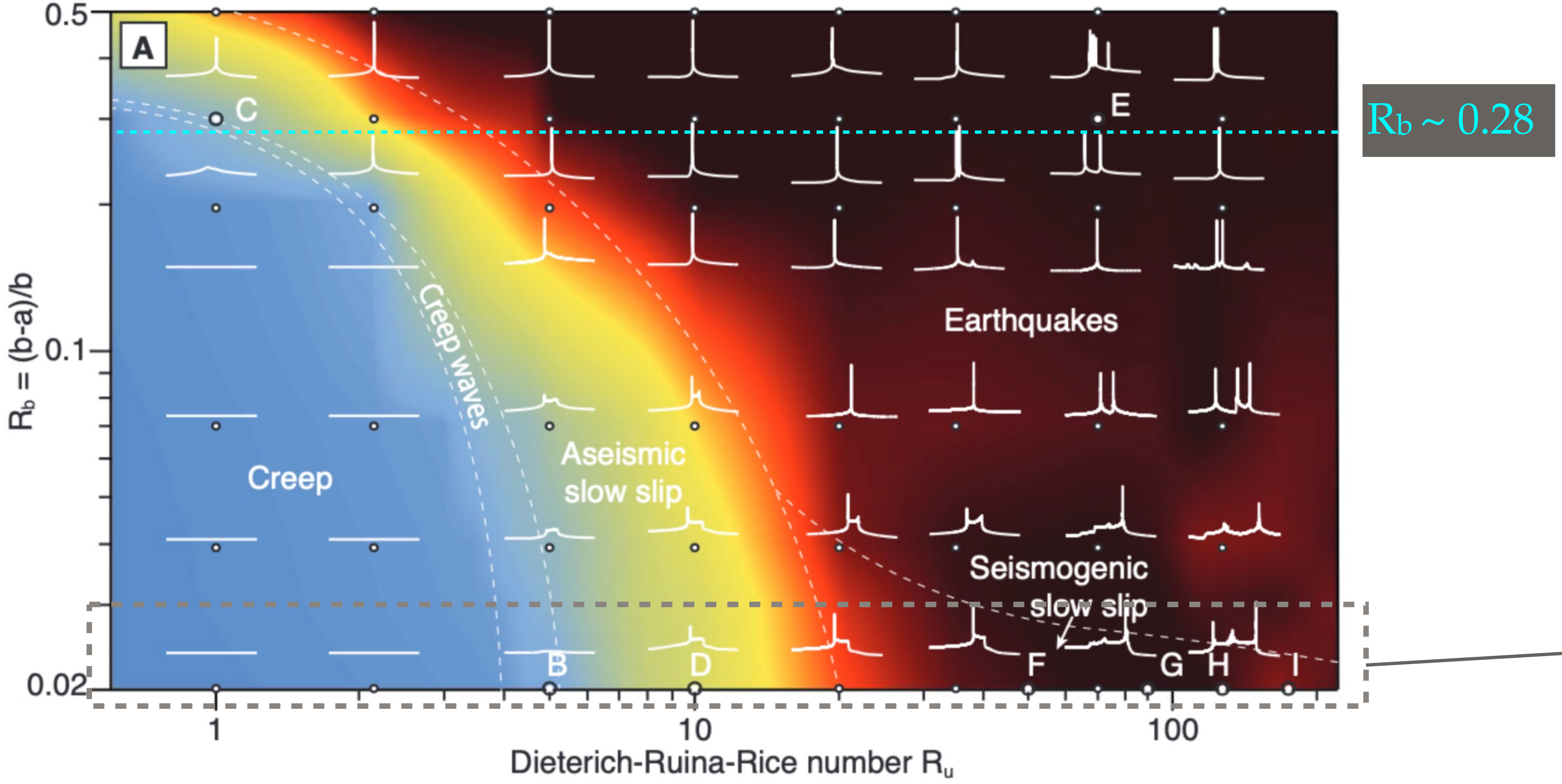
$$R_b = \frac{b-a}{b} \to 0$$

- **High pore pressure** results in decreased effective normal stress:

$$\bar{\sigma} = \sigma - p_f$$

# Phase diagram of $R_u$ and $R_b$

**2-D** homogeneous model; The fault is **20 km** long, including **5 km velocity weakening** area;




$$R_b = \frac{b-a}{b} \quad \rightarrow 0$$

Nie and Barbot, 2021

# Phase diagram of $R_u$ and $R_b$

- Four phase domains:
  1. Creep and creep waves;   2. Earthquakes


Nie and Barbot, 2021

# Phase diagram of $R_u$ and $R_b$

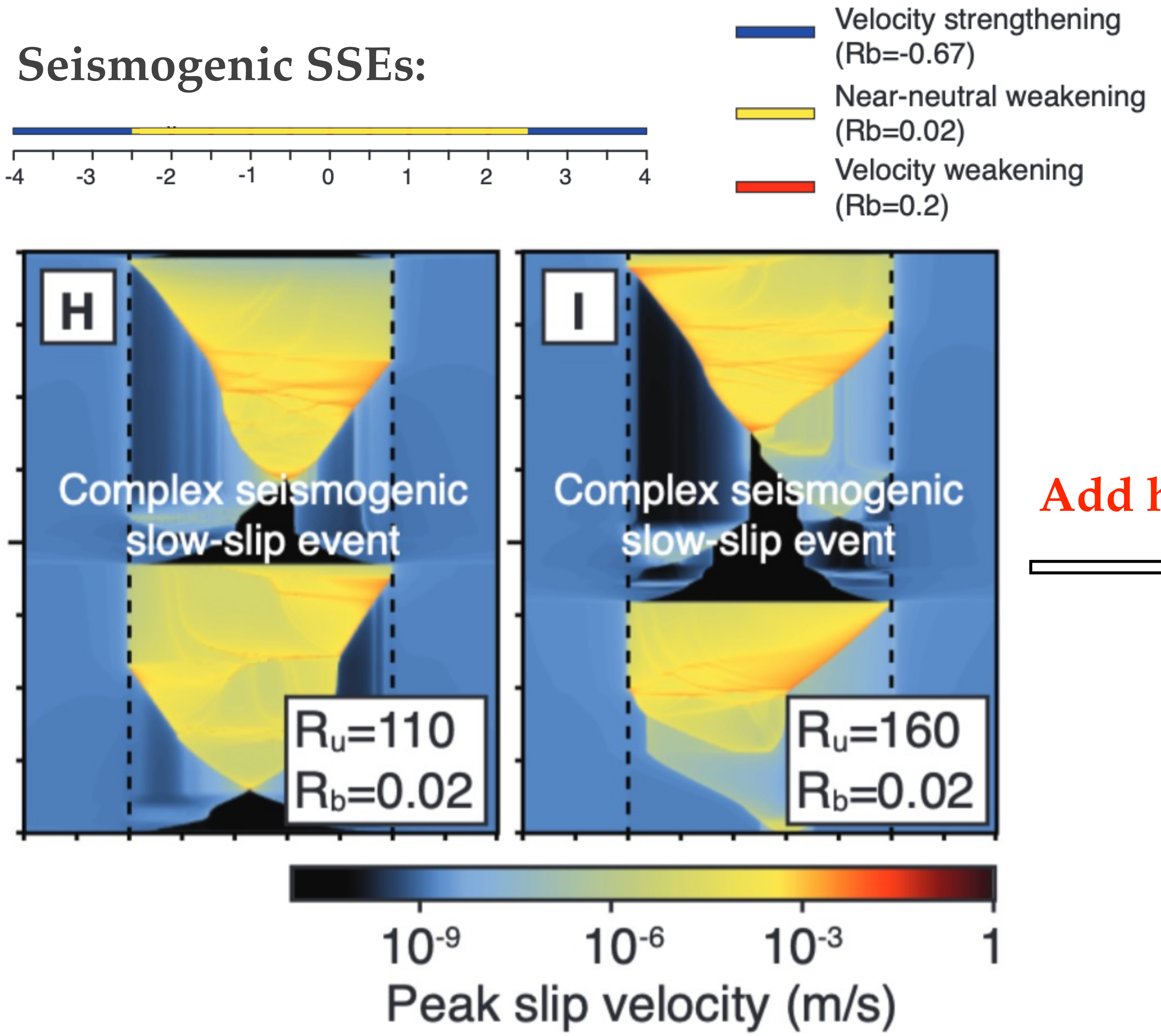
- Two phase diagram of **SSEs**:
  **1.** Aseismic SSEs (any $R_b$, low $R_u$); **2.** Seismogenic SSEs (low $R_b$, large range $R_u$).

Aseismic SSEs

# From seismogenic to tremorgenic

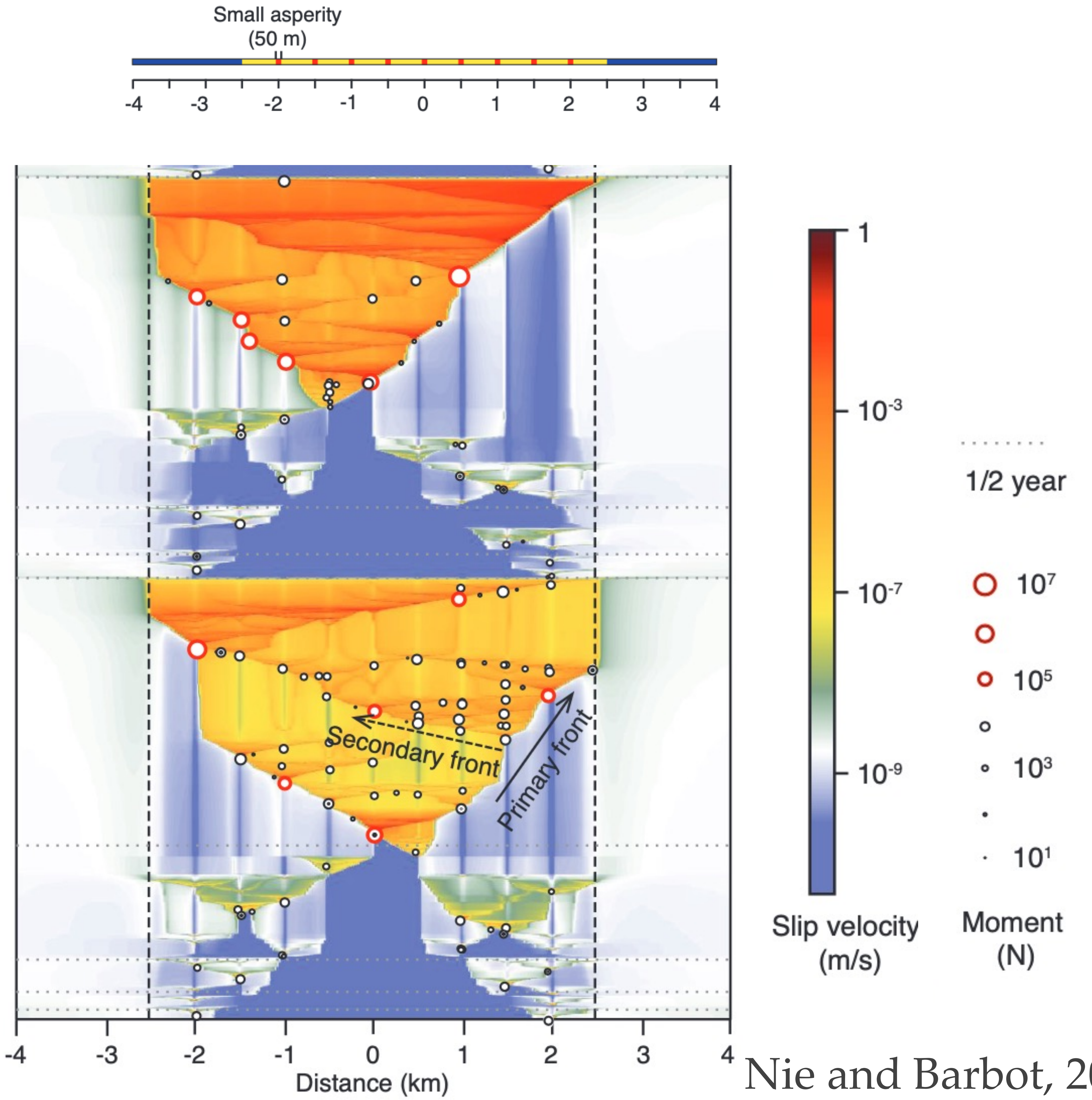
- **Tremors** represent the **chatter** from tiny, distributed sources. (Peng and Gomberg, 2010)

Seismogenic SSEs:



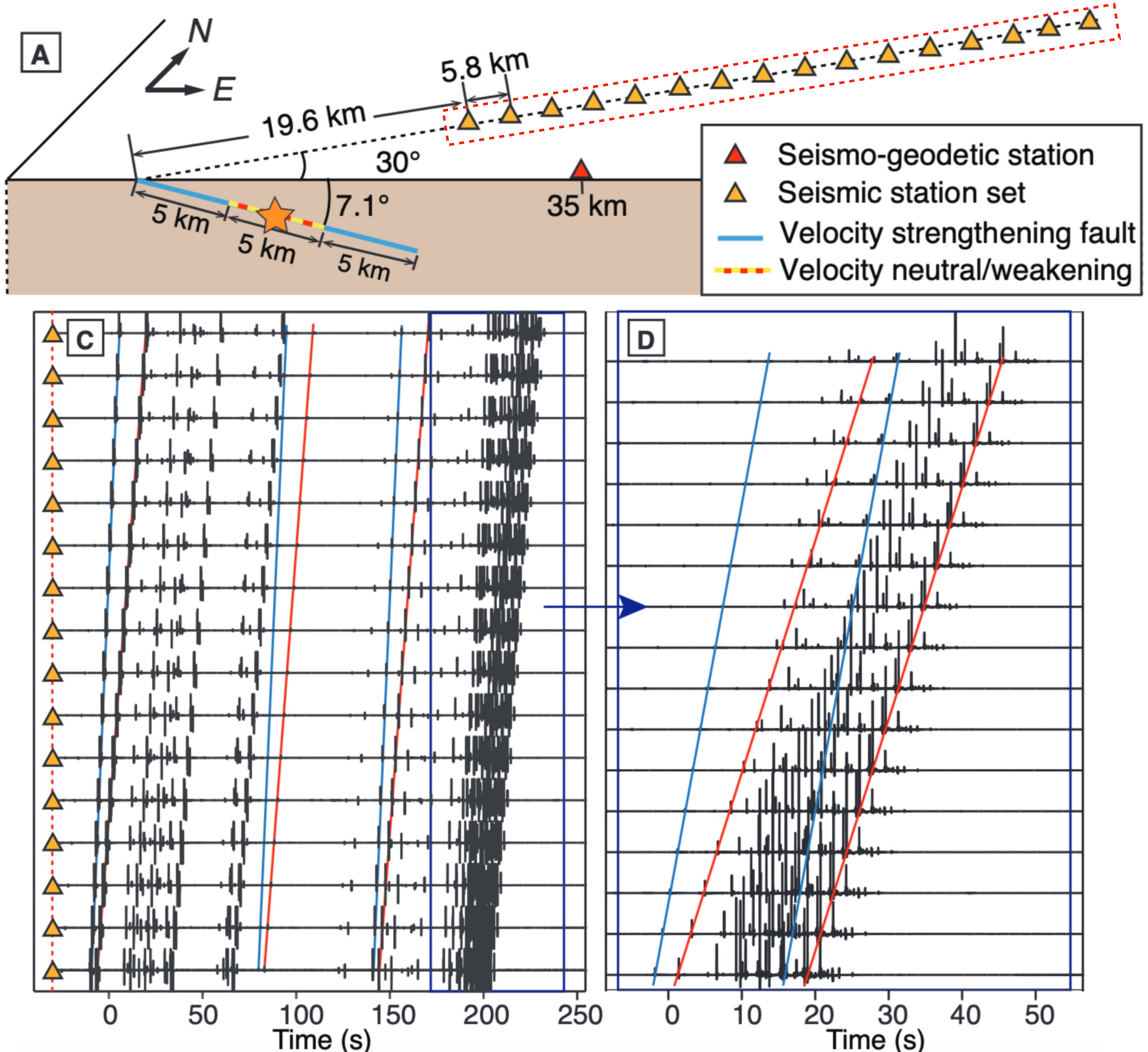

Add heterogeneity

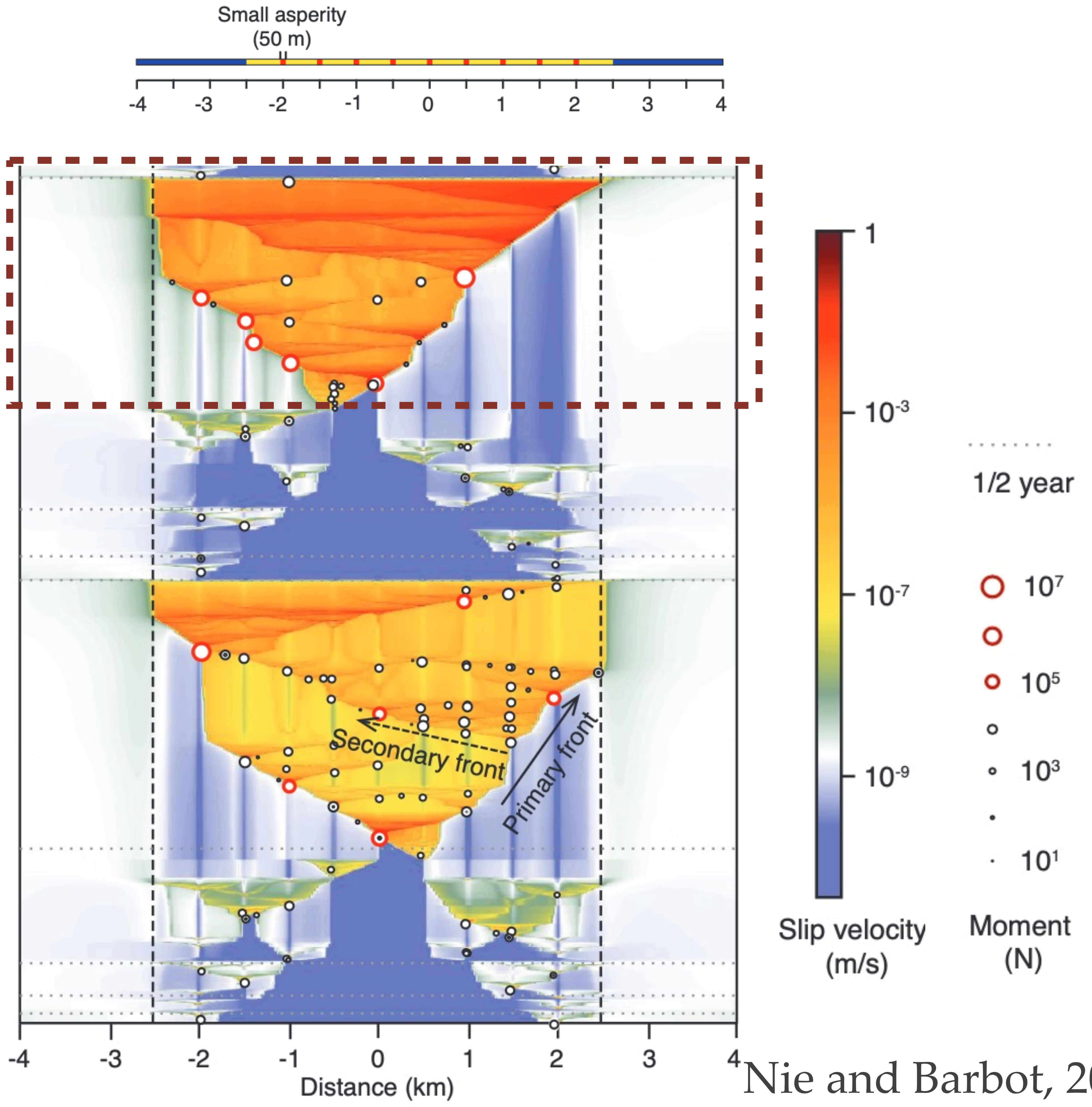
Tremorgenic SSEs:




Nie and Barbot, 2021

# From seismogenic to tremorgenic




Nie and Barbot, 2021

# Take home messages

- The non-dimensional parameters **$R_u$** and **$R_b$** control the **rupture styles** jointly;
- Accompanying a **change of rupture style**, the recurrence patterns evolve from **periodic and characteristic** to apparently **chaotic cycles**.
- The effect of compliant **fault zone** in quasi-dynamic simulations can be approximated by a **larger $R_u$ number**.
- The **velocity-neutral** frictional conditions found near the **boundary of the seismogenic zone** naturally generate **SSEs** and corresponding **slow earthquakes** for a wide range of frictional properties.
- The hypocenter of "**slow earthquakes**" **clusters** both in **space and time**, and is located at the rupture **front of the SSEs**.

USC University of Southern California

# Thank you

## For your attention!

Any questions?