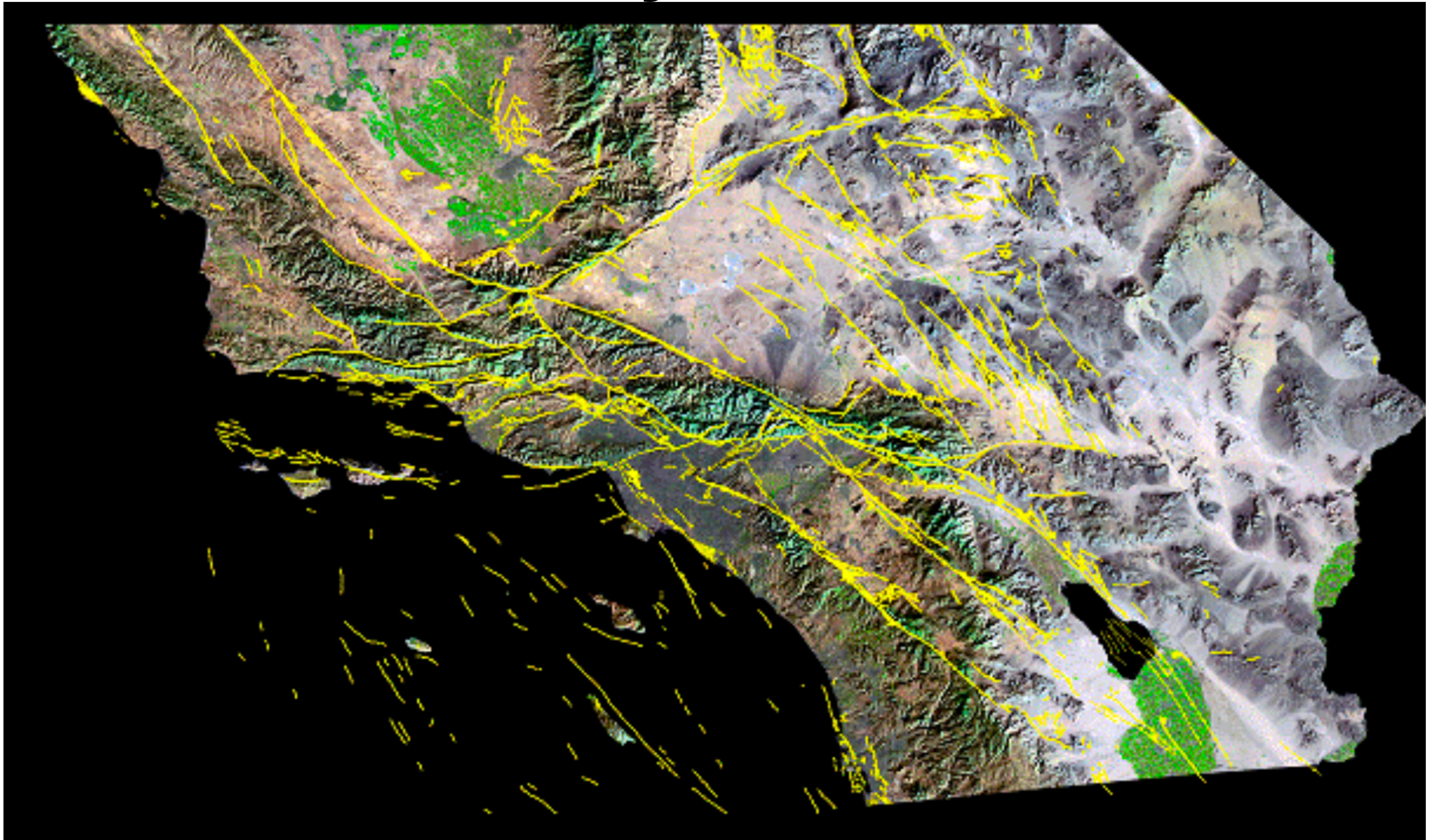
Earthquake Physics and Fault Geometry

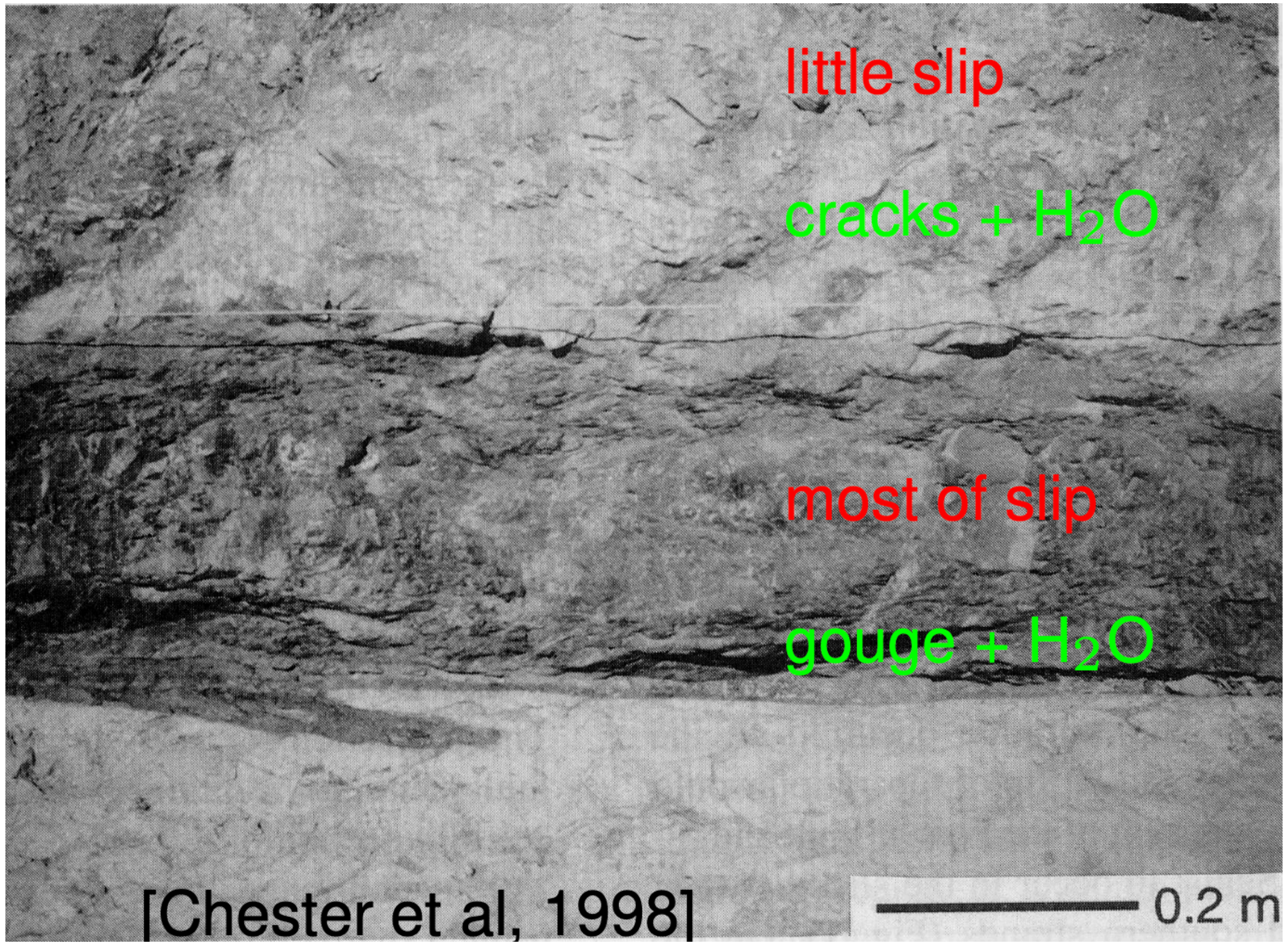
Simple Models and Complex Behavior, Chapter 1.

Bruce E Shaw, Columbia University | ICTP Trieste, October 2023

Fault Systems



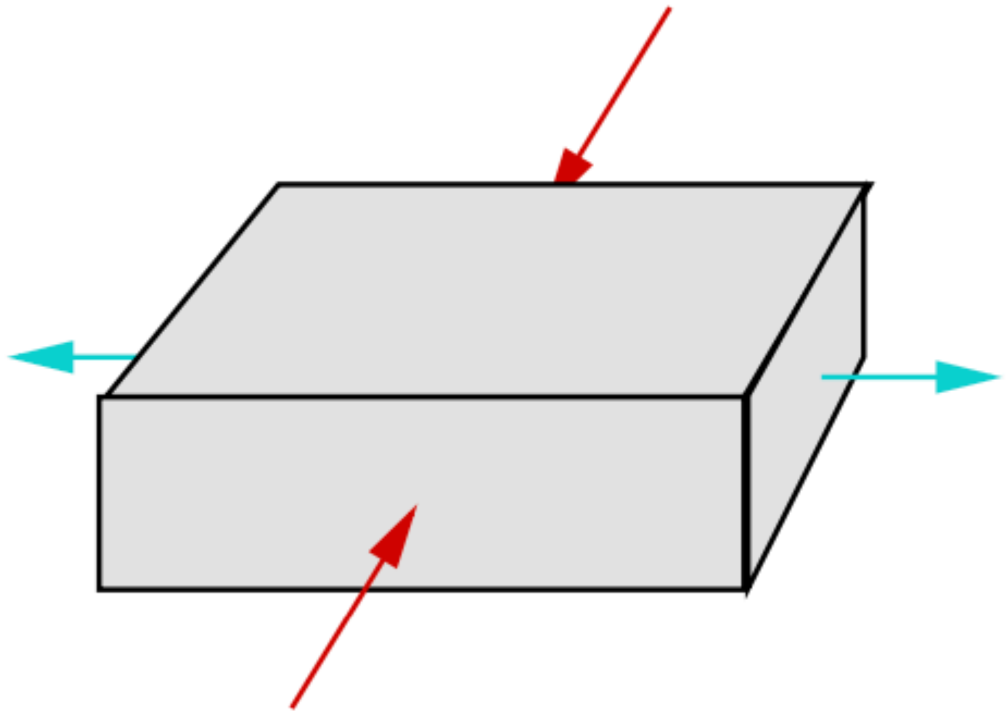
Faults



little slip
cracks + H_2O
most of slip
gouge + H_2O
[Chester et al, 1998]
0.2 m

Equations of Motion

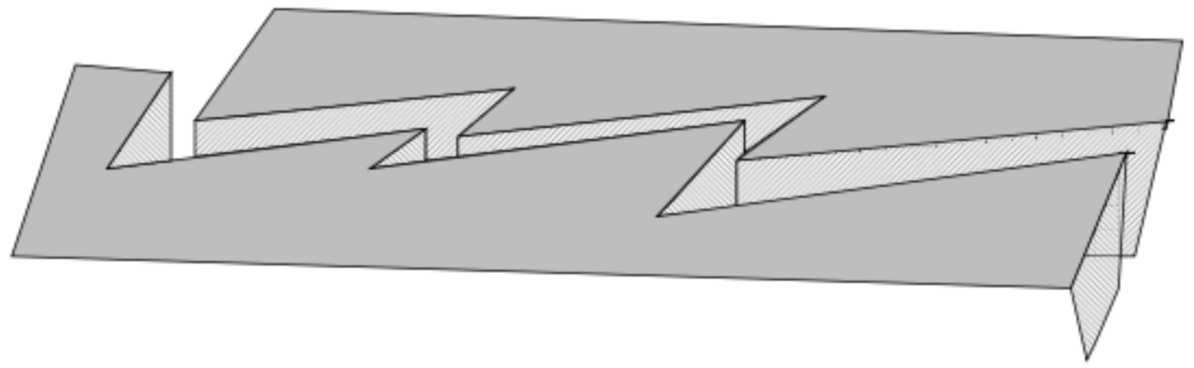
√ Bulk Equations



- Linear Elasticity

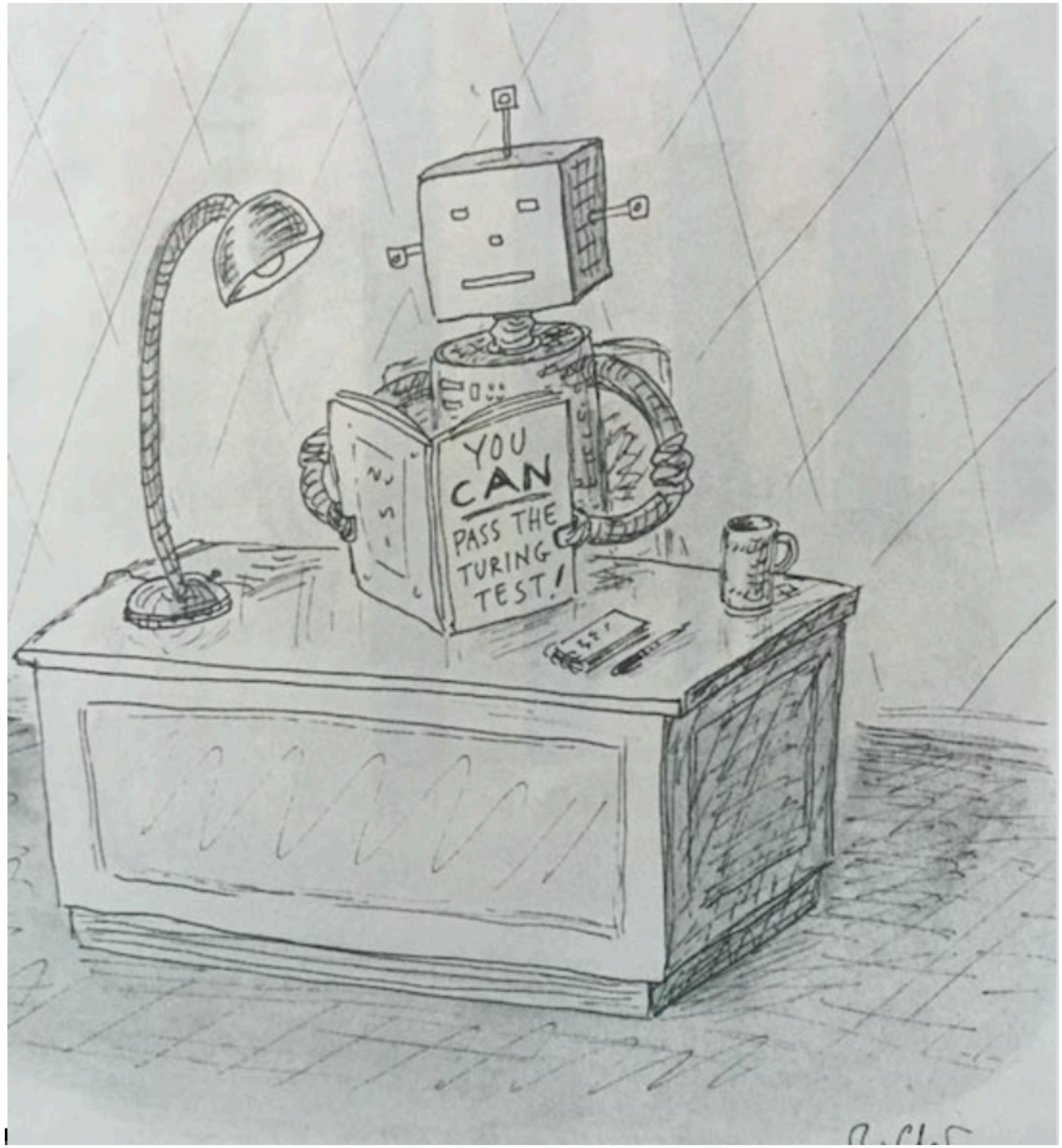
? Boundary Conditions

- Condition on Boundary?

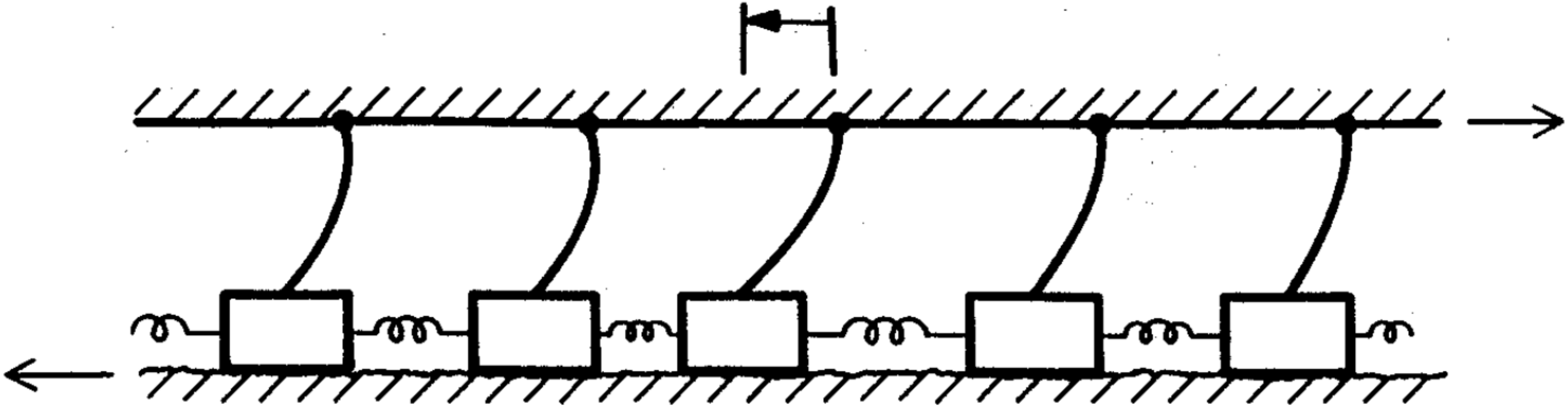


- Shape of Boundary?
- Boundary Layer??

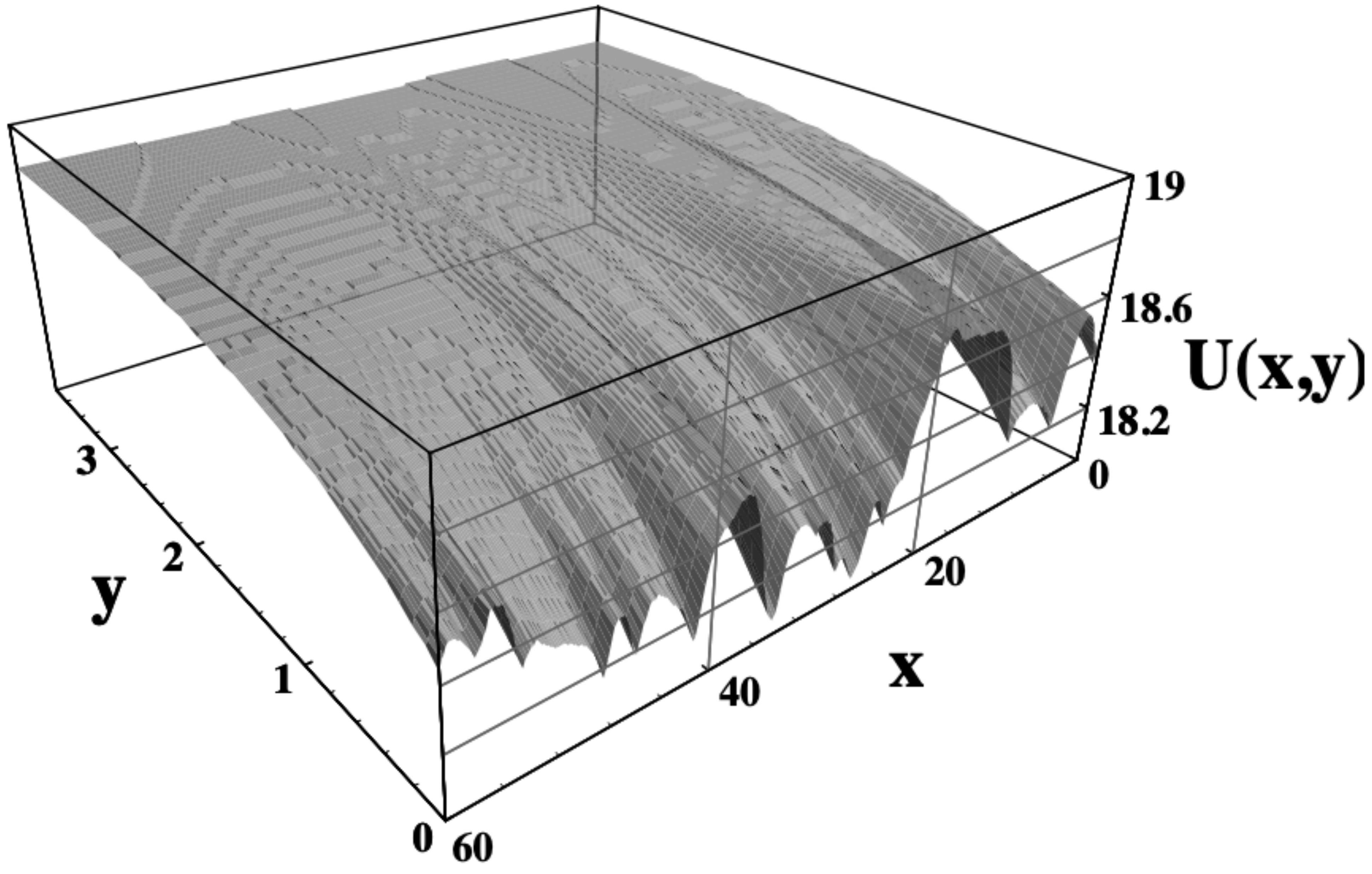
Goal: Develop a model that can pass the Turing Test

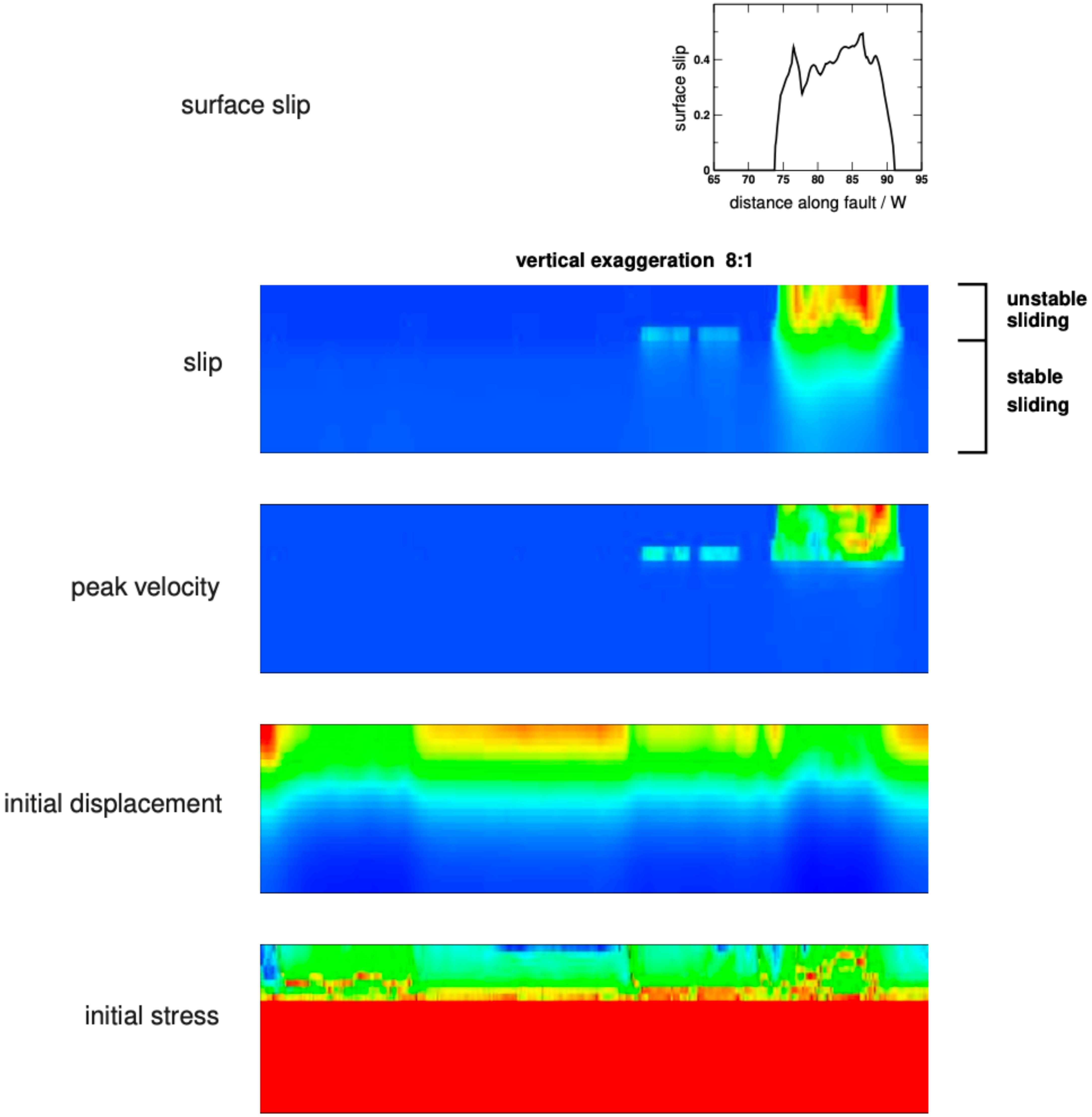


Simplest earthquake model



2D & 3D earthquake model





Equations

$$\frac{\partial^2 U}{\partial t^2} = \nabla^2 U$$

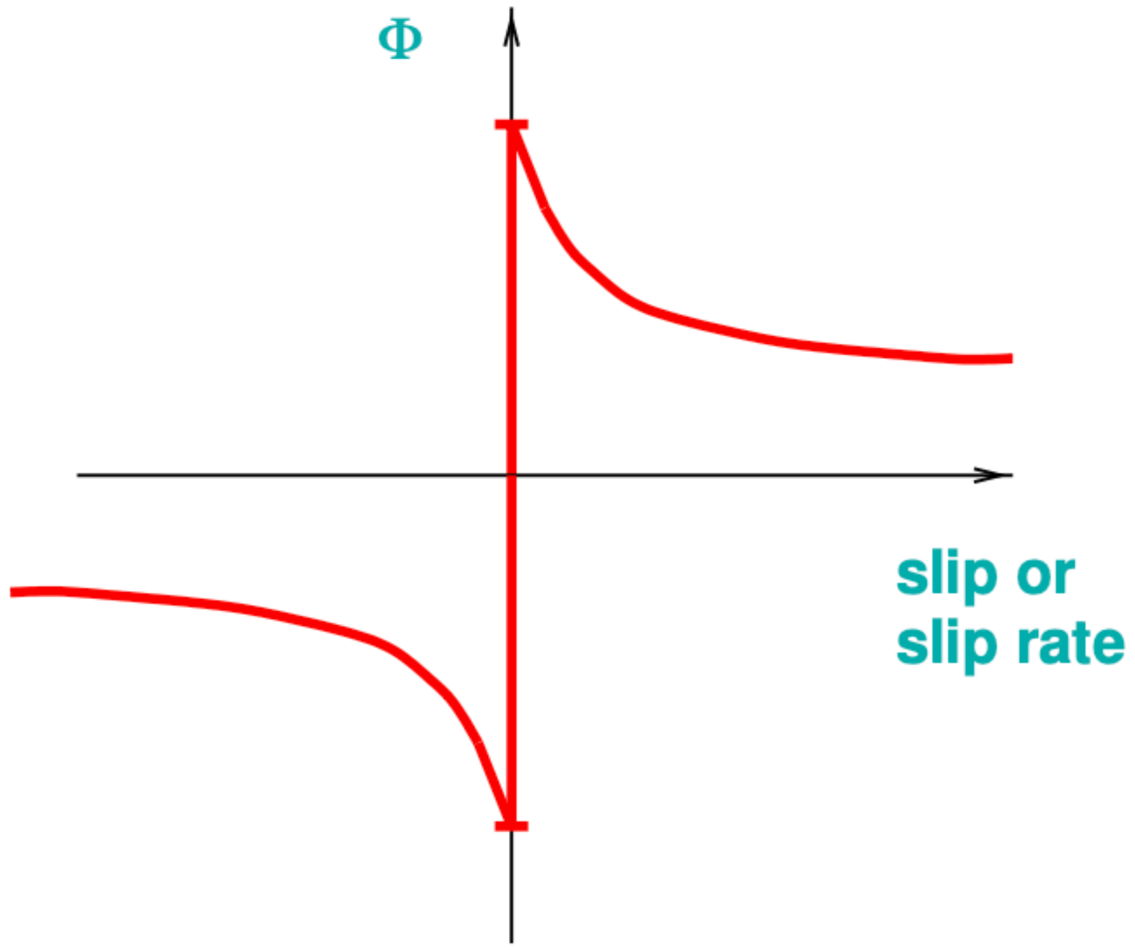
Wave equation Bulk

$$\left.\frac{\partial U}{\partial t}\right|_{\text{loading}} = \nu$$

$\nu \ll 1$ slow uniform loading

$$\left.\frac{\partial U}{\partial n}\right|_{\text{fault}} = \Phi$$

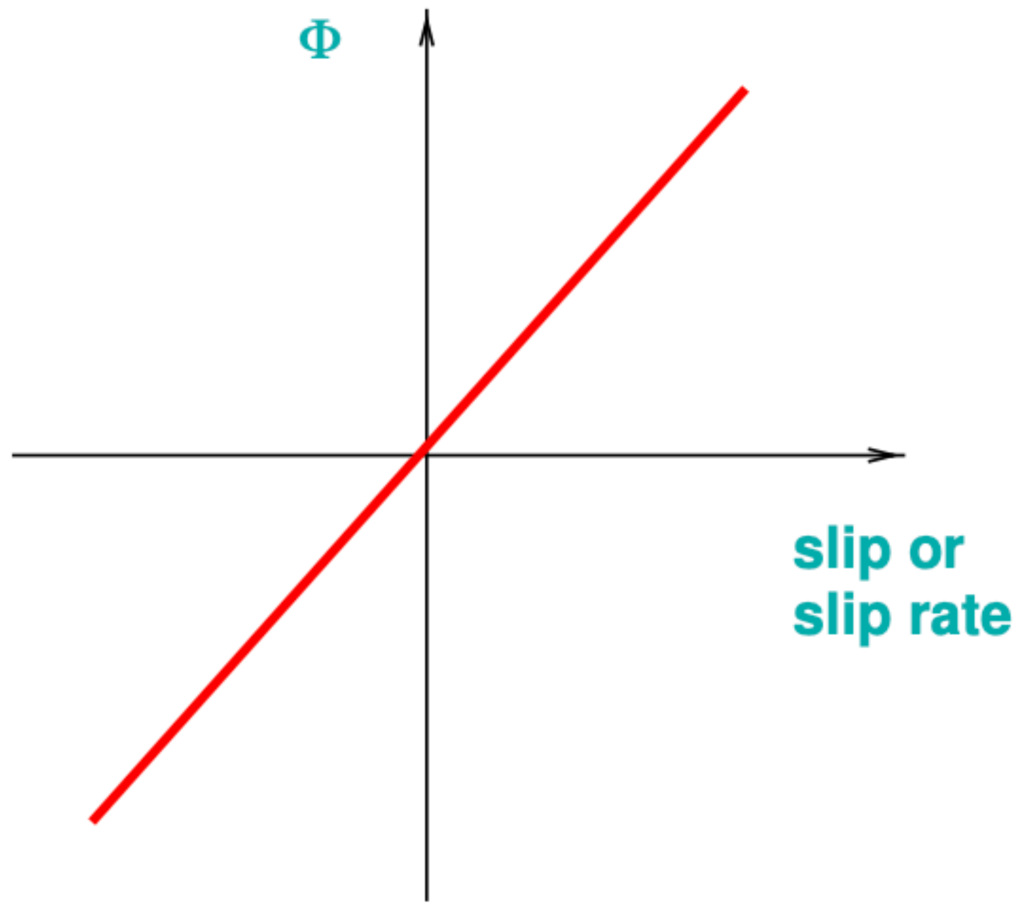
Fault Boundary Condition

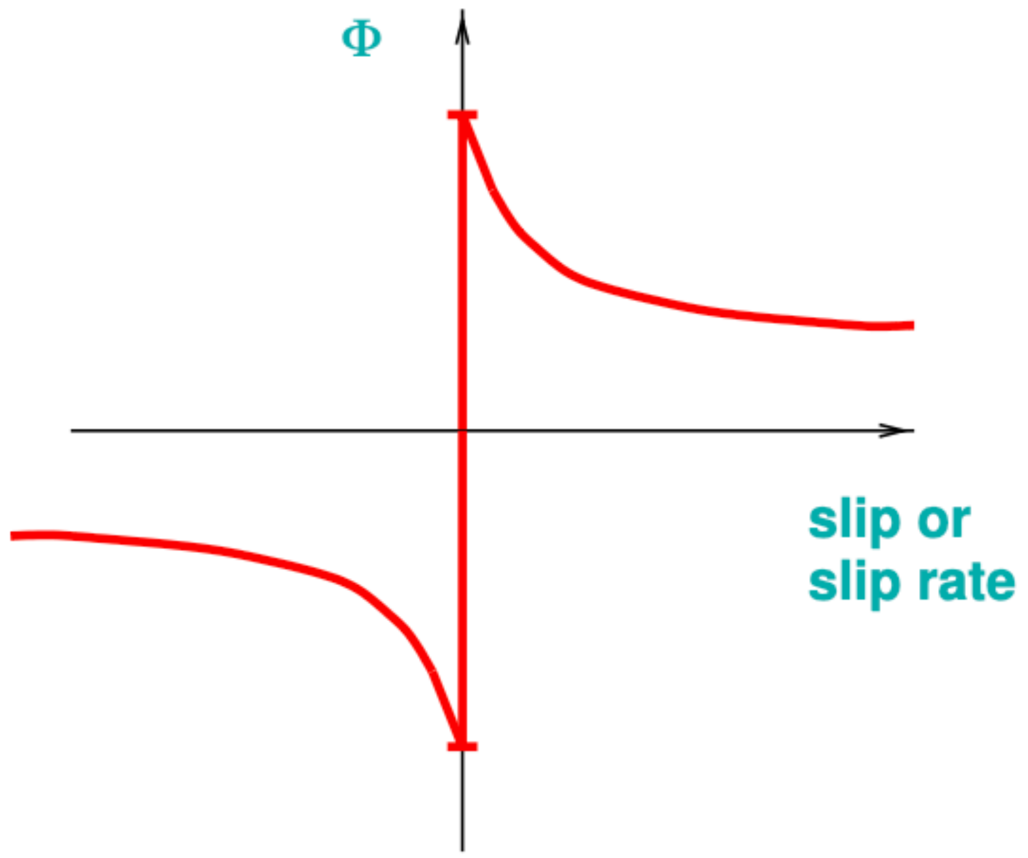


If frictional weakening:

$\Rightarrow$ chaotic slip sequences

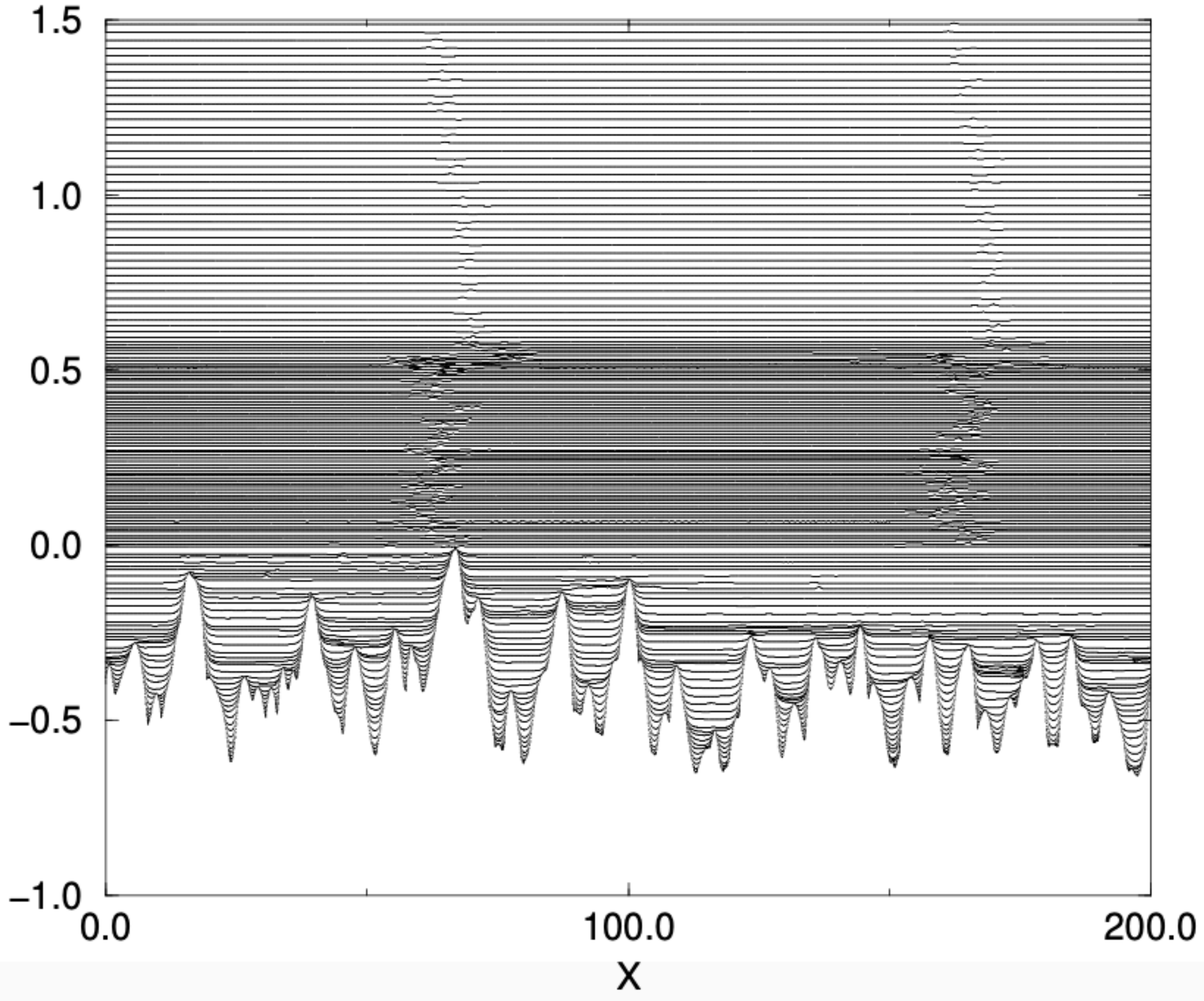
Frictional weakening ⟶ complexity

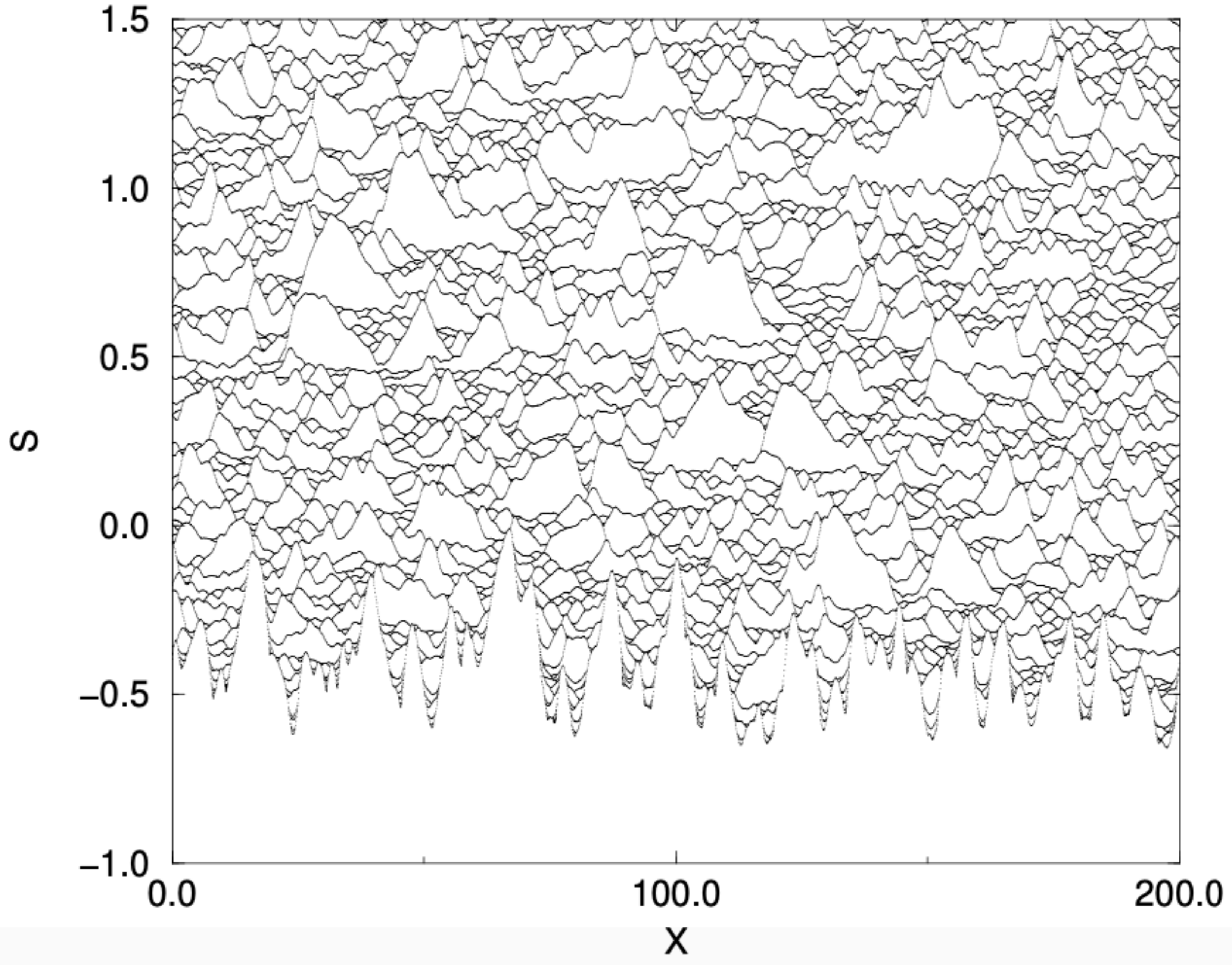




strengthening ⟶ periodic

weakening ⟶ complexity





Frictional weakening from frictional heating

$$\Phi = N\mu$$

$$\mu = \begin{cases} [-\mu_0\ ,\ \mu_0] & \frac{\partial S}{\partial t} = 0; \\ -\mu_0(1-\sigma)\ ,\ \mu_0(1-\sigma) & \frac{\partial S}{\partial t} < 0\ ,\ \frac{\partial S}{\partial t} > 0 \end{cases}$$

$$N = N_0 - \alpha Q$$

$$\frac{\partial Q}{\partial t} = -\gamma Q + \Phi \frac{\partial S}{\partial t}$$

$\gamma \ll 1 \longrightarrow$ slip weakening:

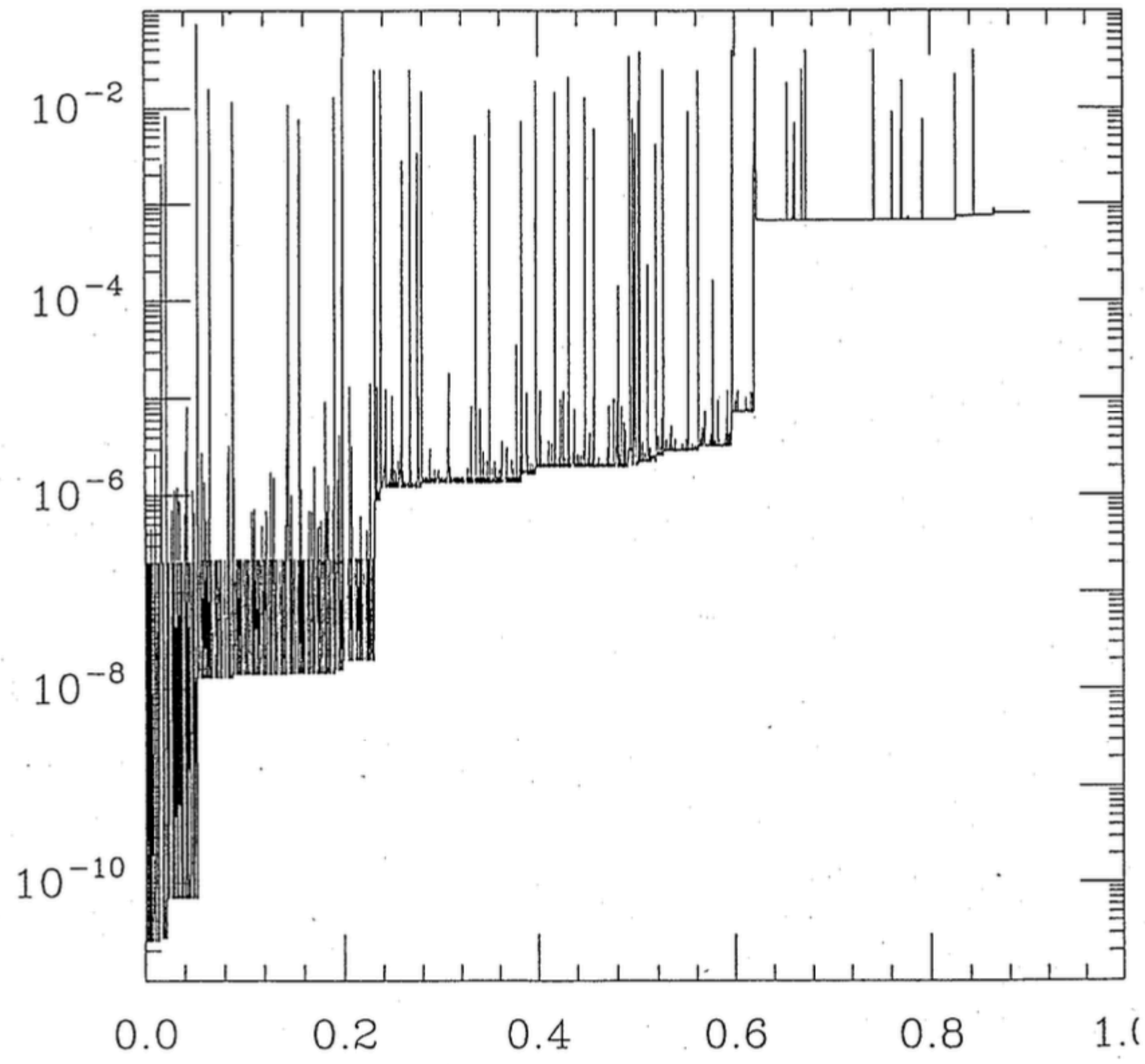
$$\Phi = N_0 \mu e^{-\alpha\mu(S-S_0)}$$

$\gamma \gg 1 \longrightarrow$ velocity weakening:

$$\Phi = \frac{N_0\mu}{1+\frac{\alpha}{\gamma}\mu\frac{\partial S}{\partial t}}$$

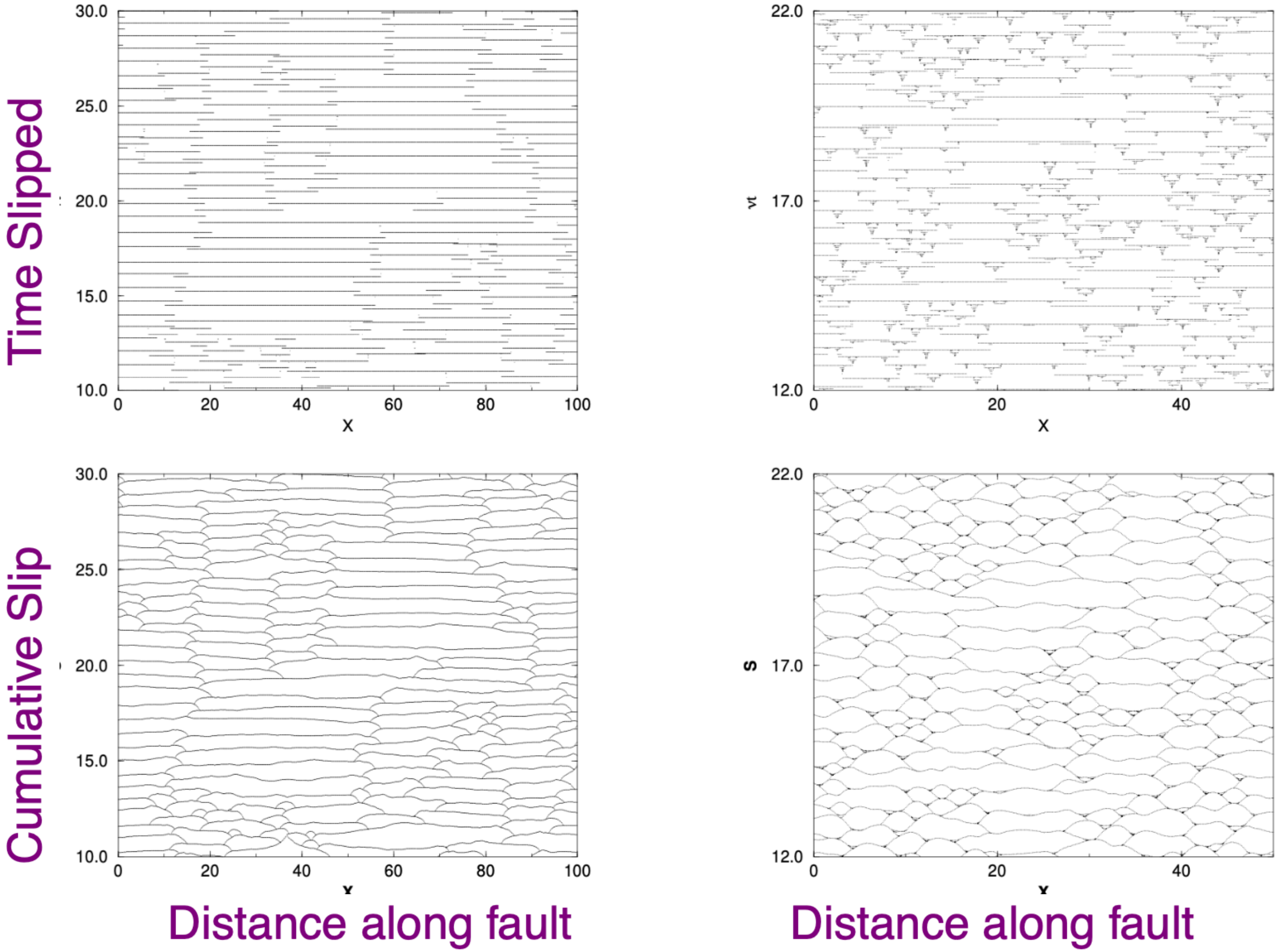
[Shaw, 1995]

Chaos



- Exponential divergence
- Huge Lyopunov exponents
- Divergence happens during large events
- Rules out predicting *past* next large event, but not next large event

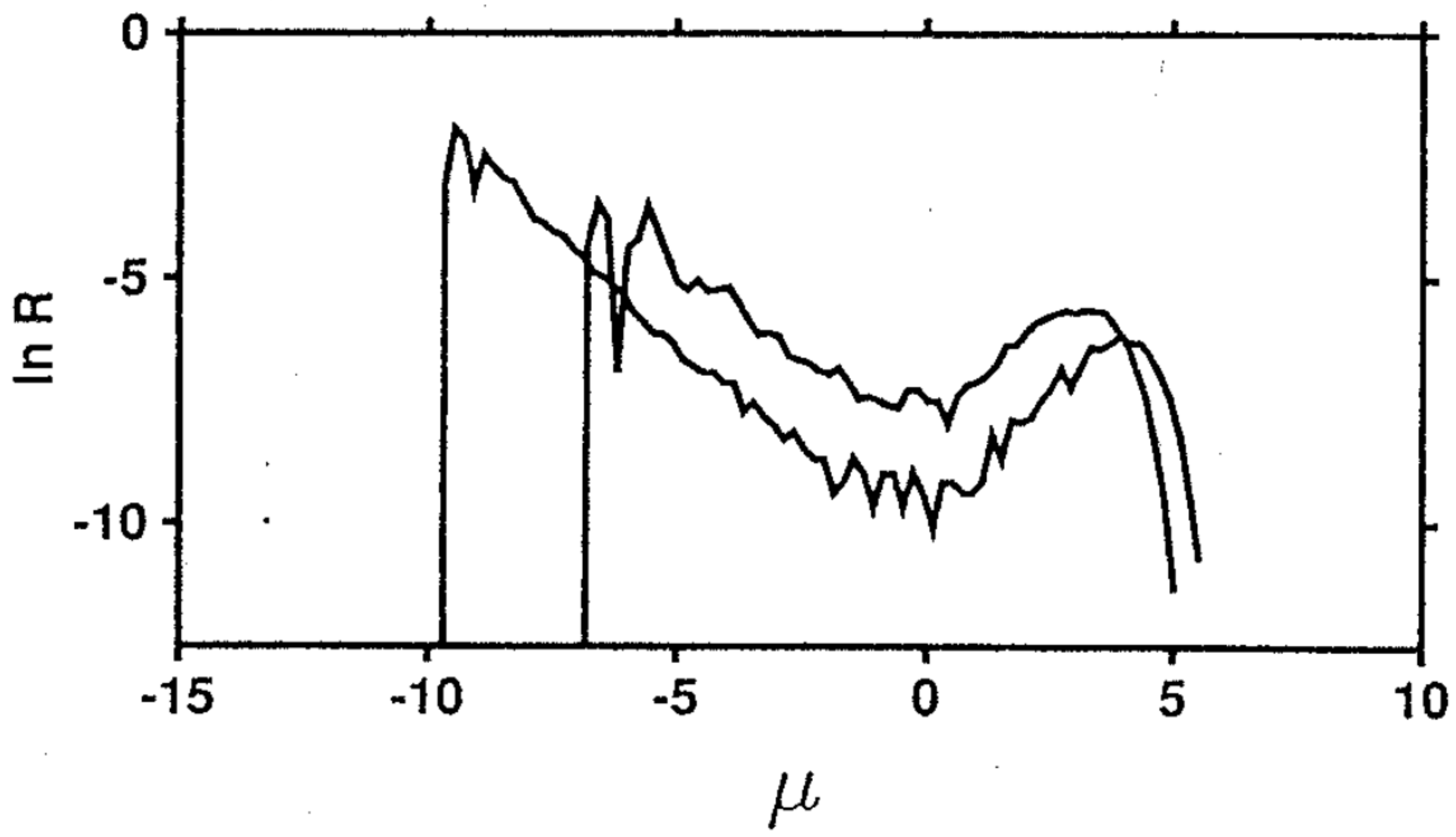
Self-Organized Slip Complexity



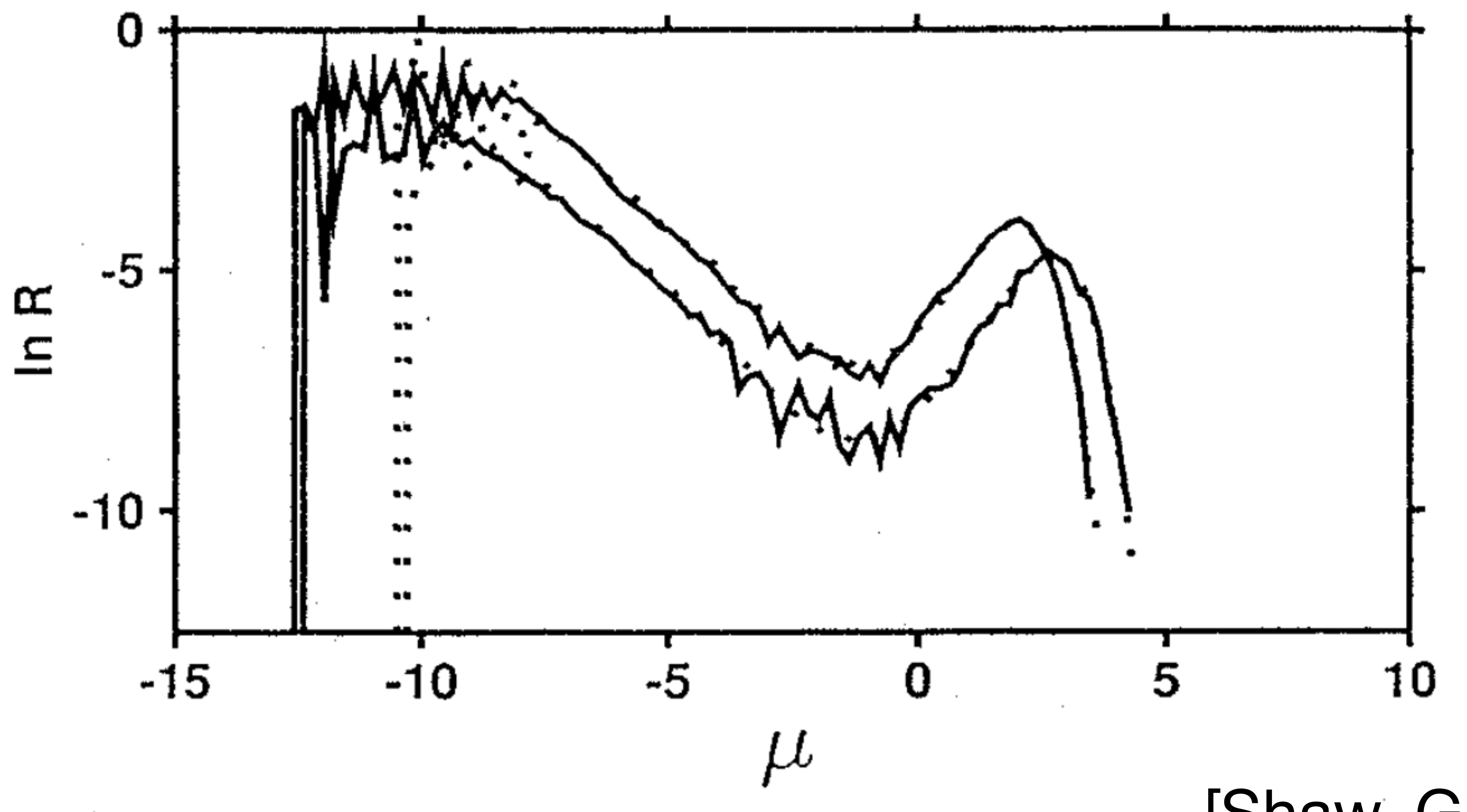
Large event complexity
Generic

Small + large events near
Critical value

Complexity and the continuum



Discrete block cutoff

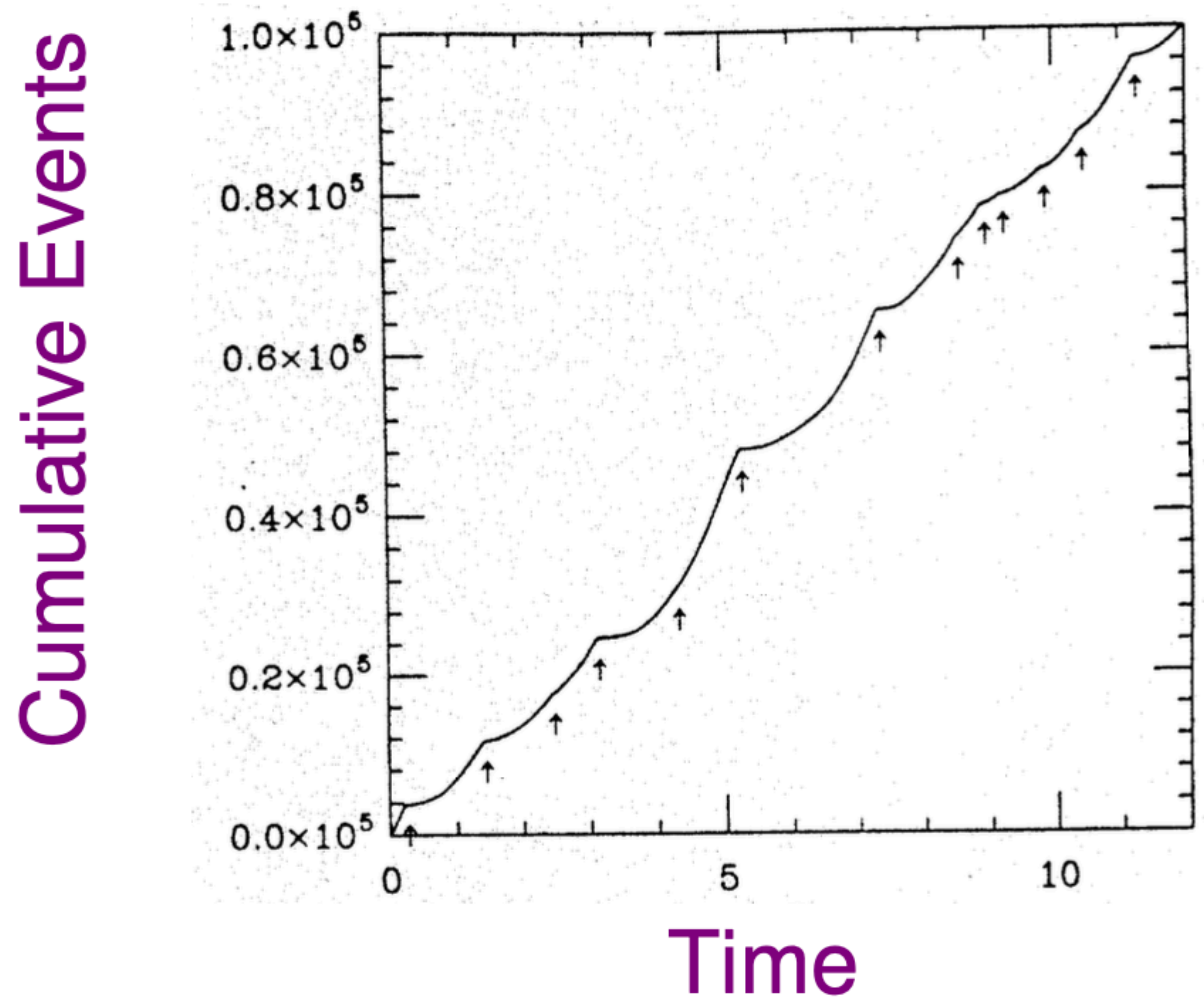


[Shaw, GRL, 1994]

Continuum viscous cutoff

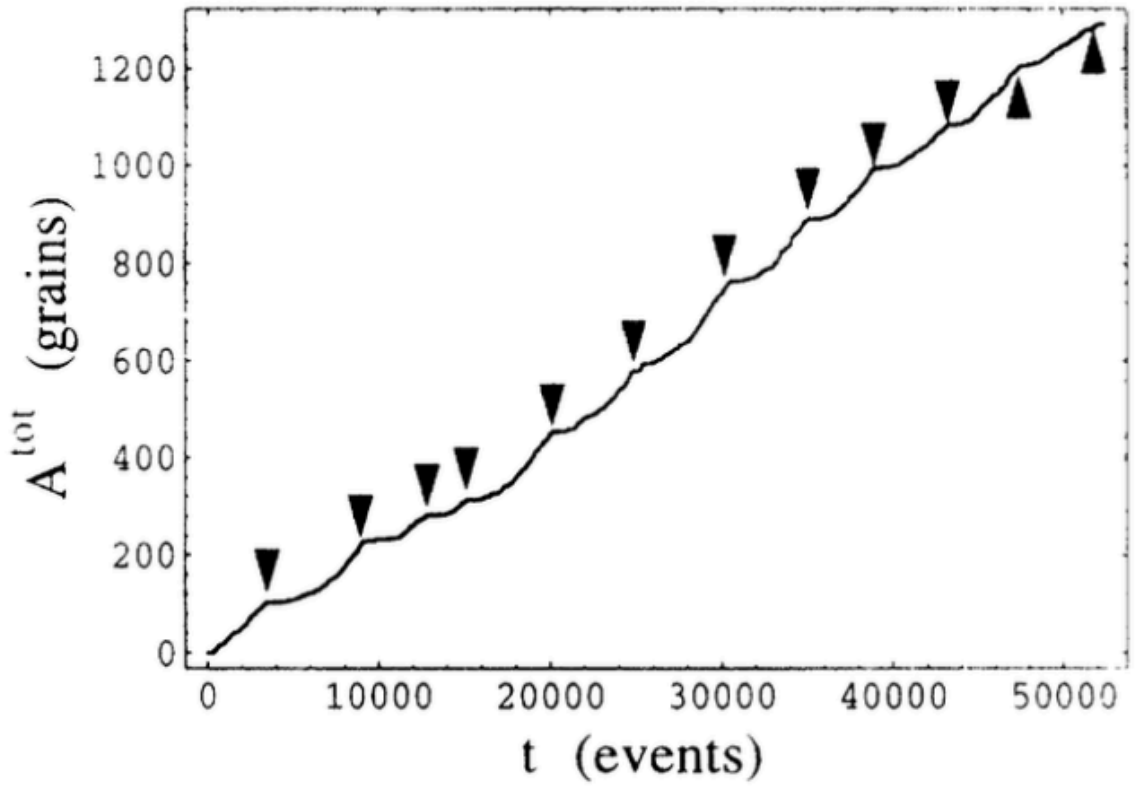
- Distribution of magnitudes depends on small cutoff scale.
- Scale of small cutoff matters at small and large scales.
- But whether discrete or continuum process at cutoff get similar behavior.

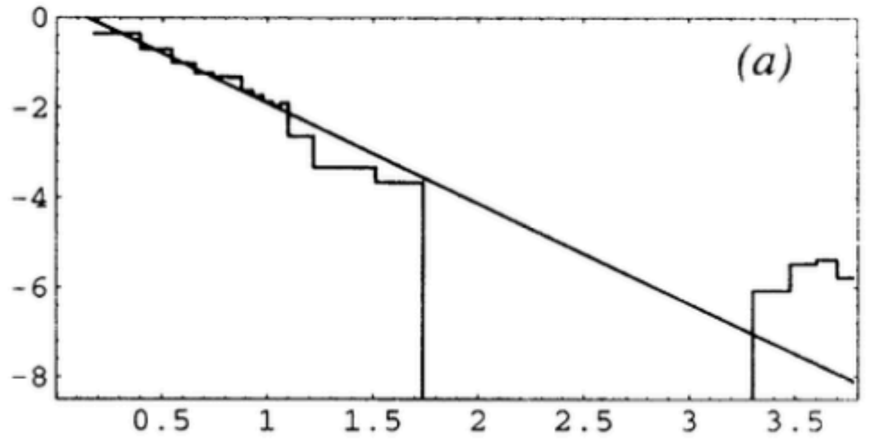
Buildup of small events before the big one



[Shaw et al, 1992]

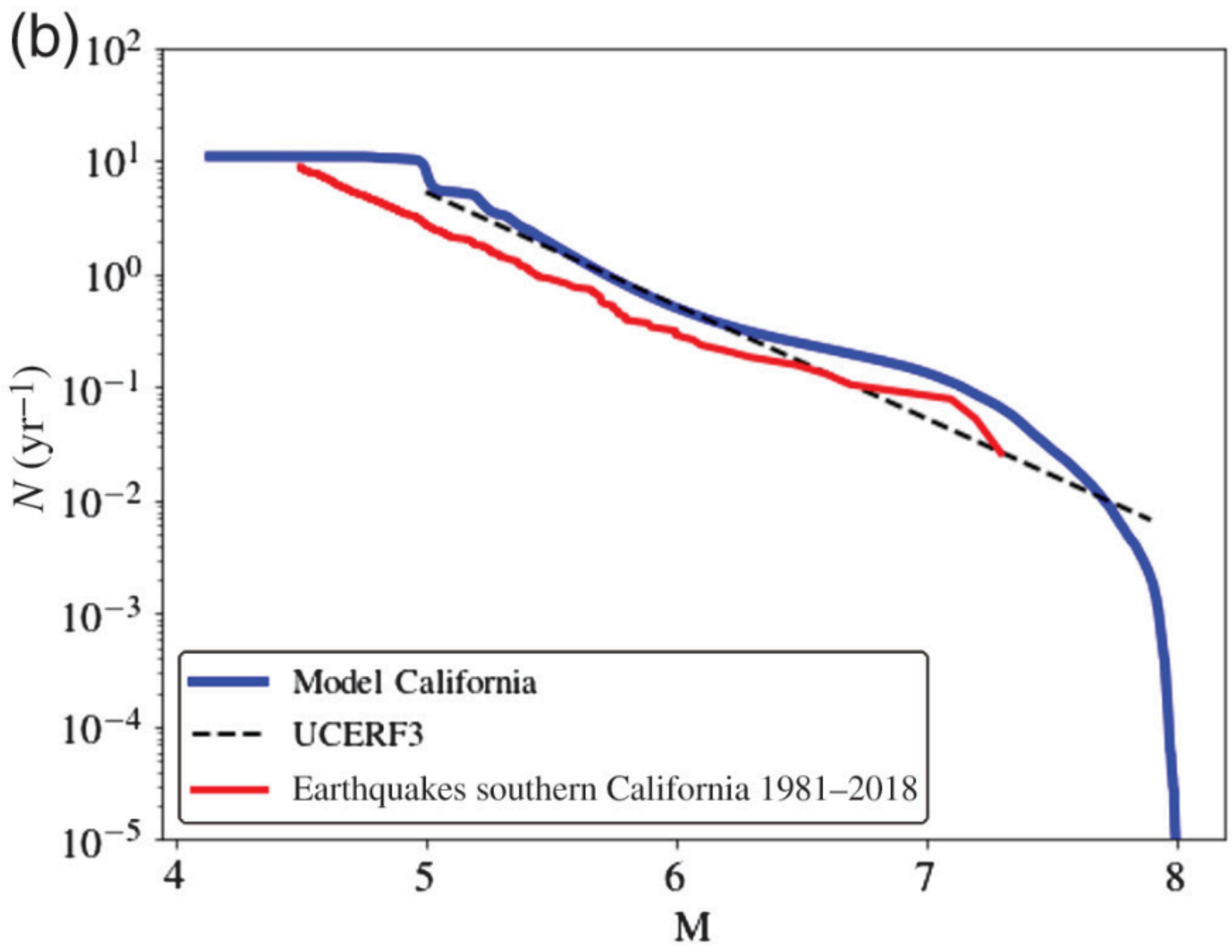
Avalanches in Sand:





[Rosendahl et al, 1994]

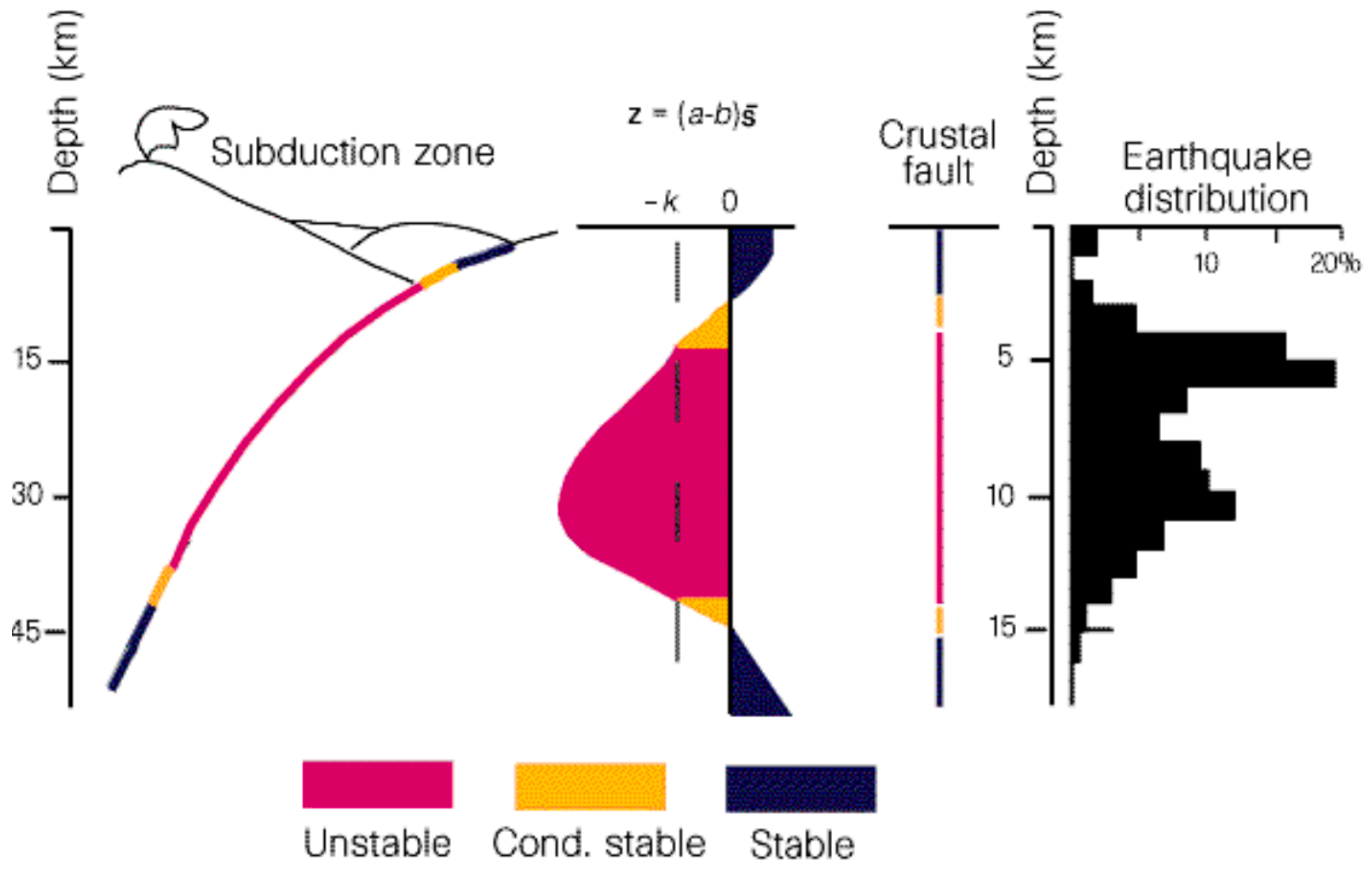
Distribution of sizes



- Excess of large events above extrapolated small event rate
- See this in 1D, 2D, 3D

How Deep Below the Seismogenic Zone do Large Earthquakes Rupture?

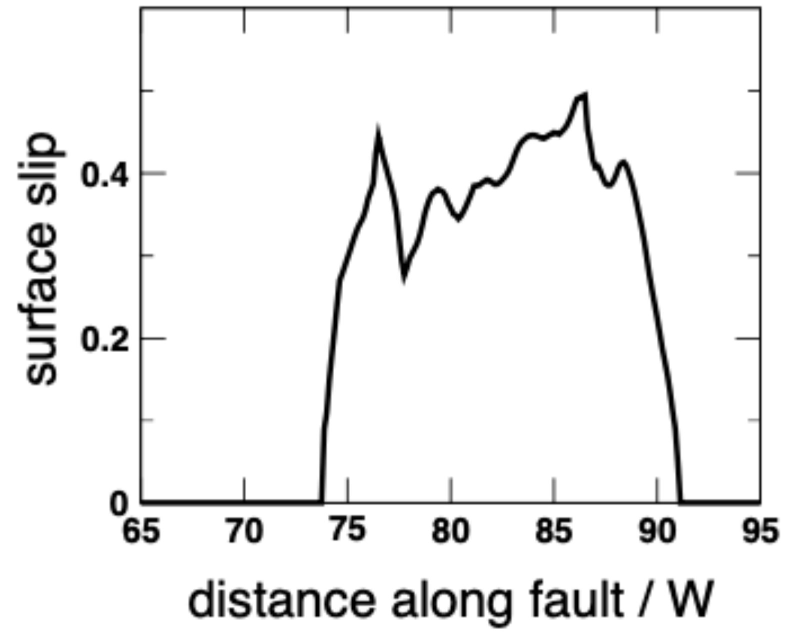
Faults and Stability of Sliding



[Scholz, 1998]

3D Model

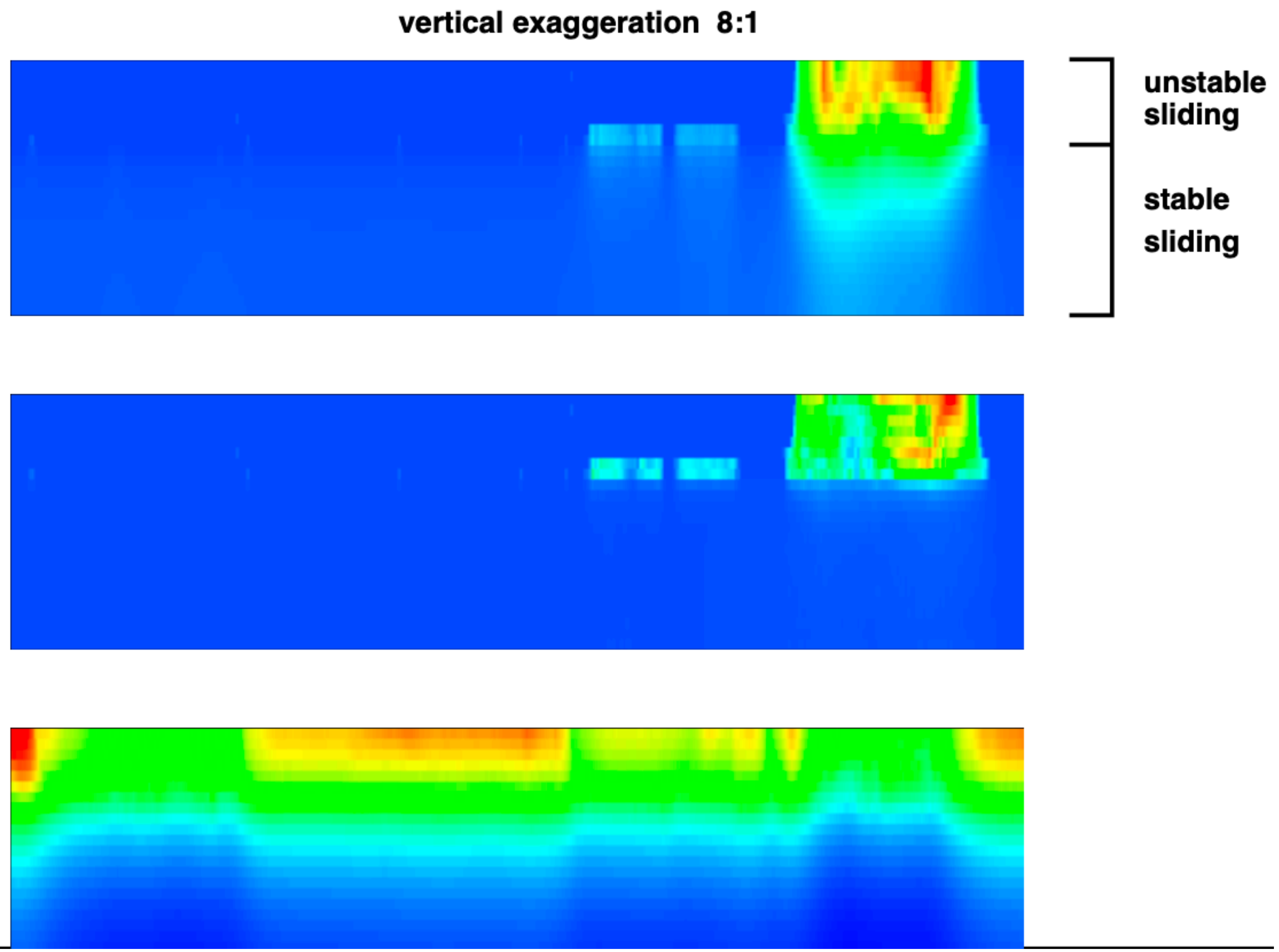
surface slip



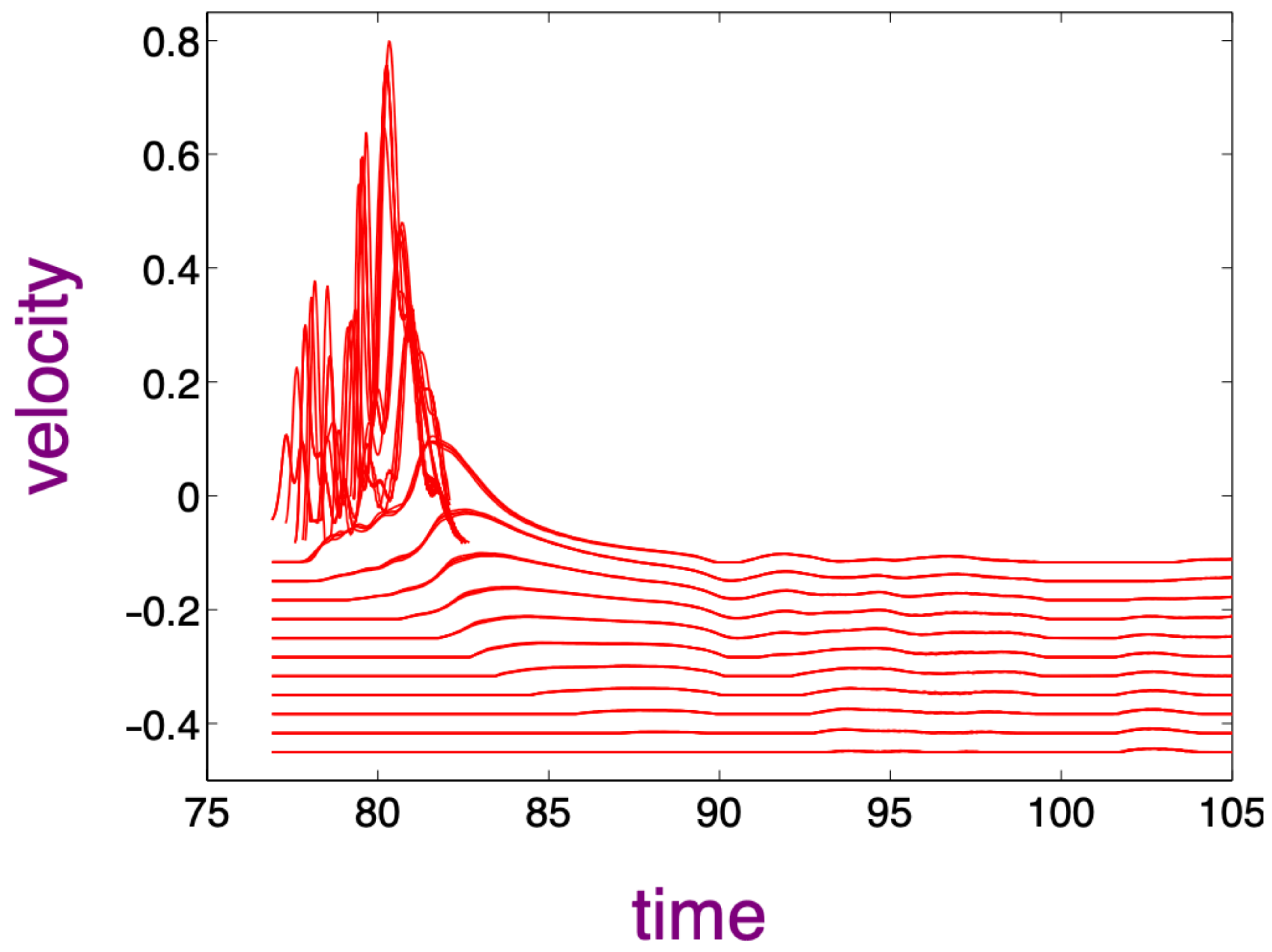
slip

peak velocity

initial displacement

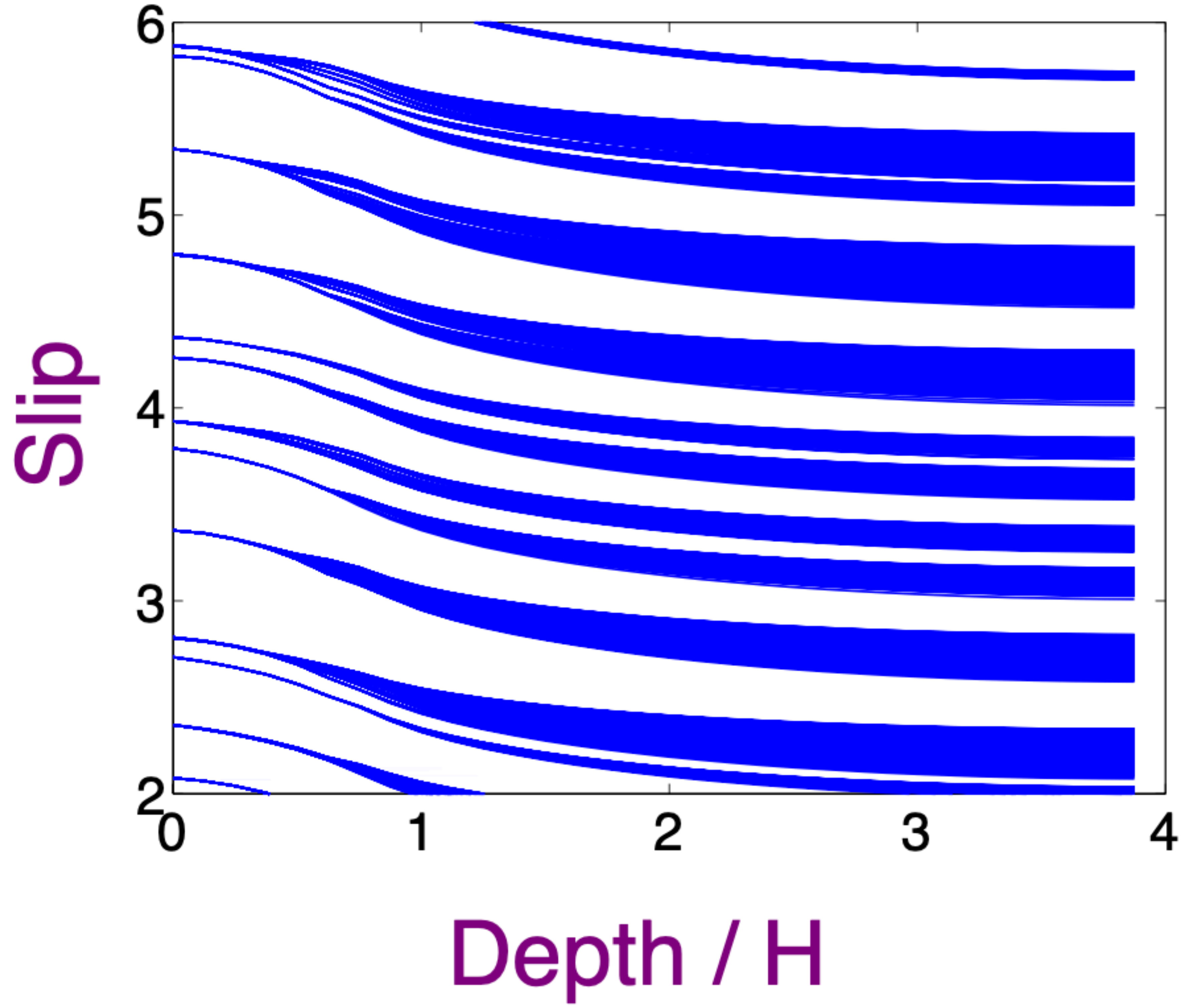


Velocities During Slip Events

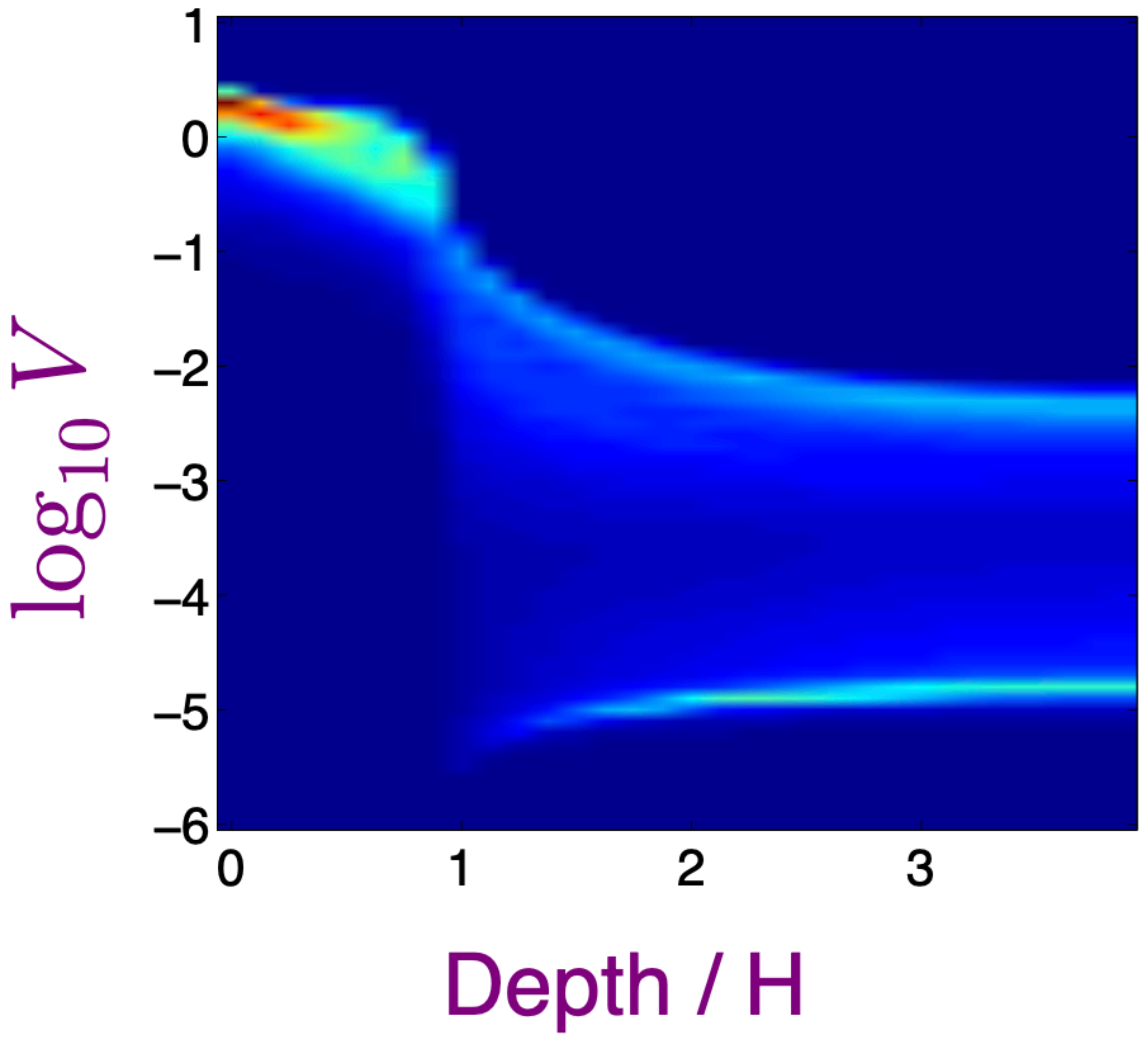


- High and low frequencies at seismogenic depths
- Only low frequencies below seismogenic depths
- *Coseismic* slip at depth

Depth Dependent Slip Rate Distributions



Cumulative Slip



Distribution of Slip Rates

- Increasing creep fraction with depth; but coseismic still nonzero

GPS Inversion Ambiguity

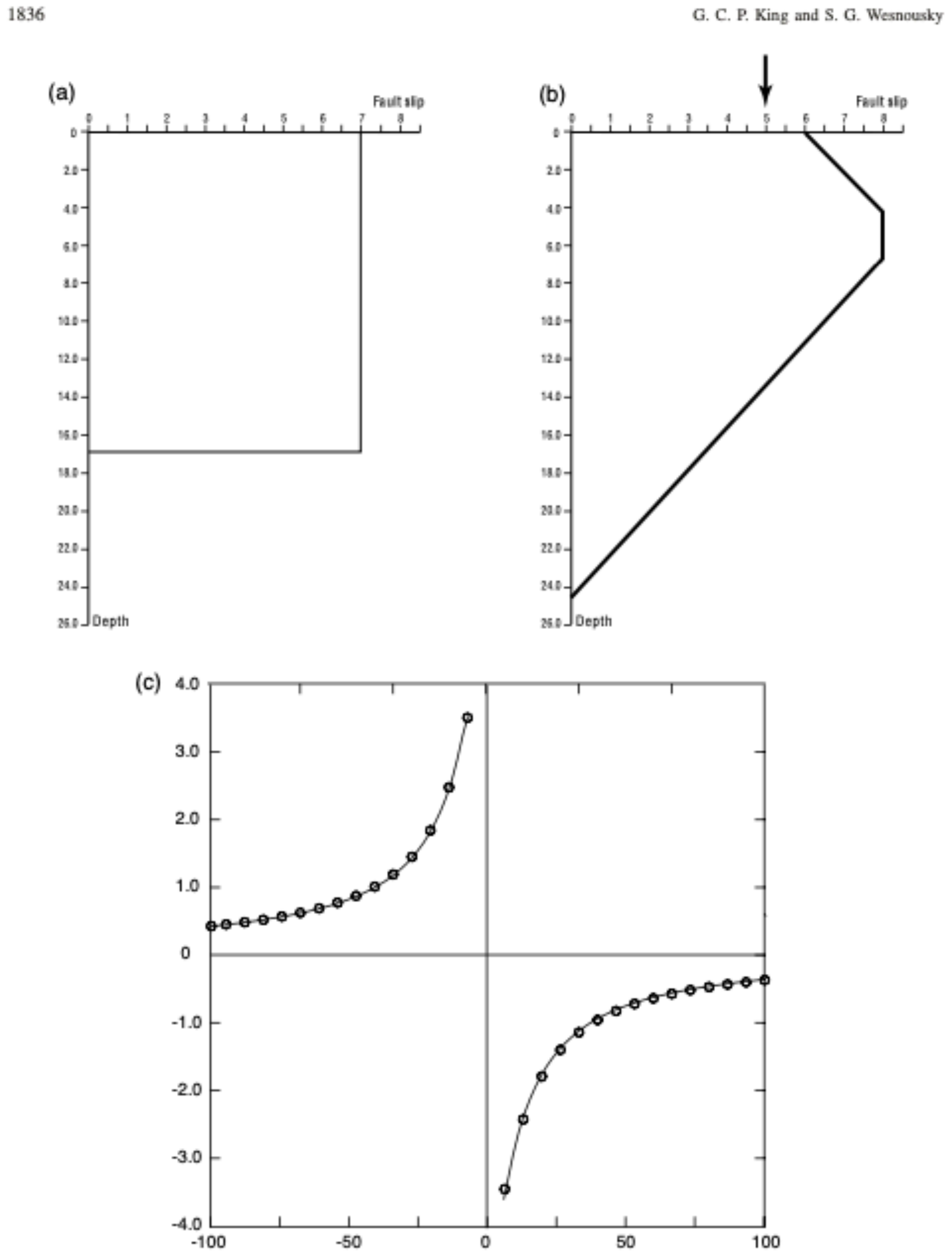
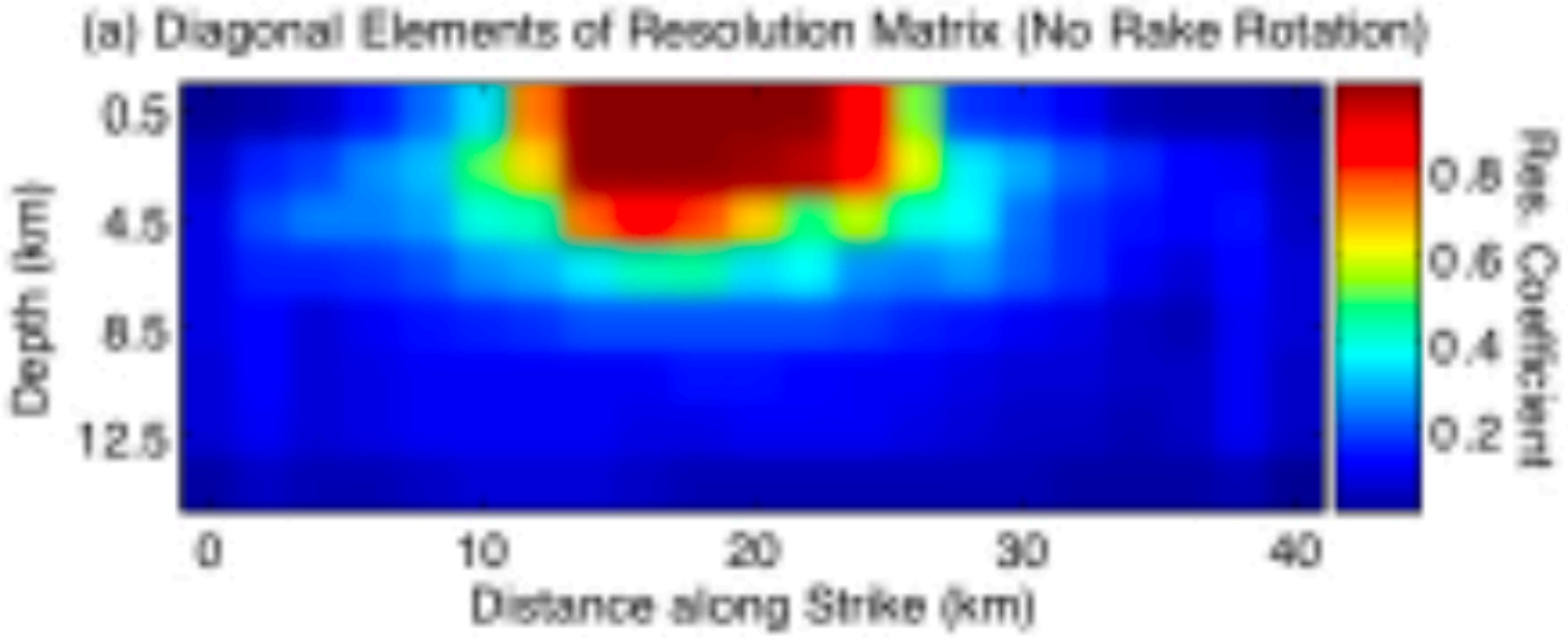


Figure 5. The (a) box and (b) tapered displacement functions produce (c) the same deformation field (circles and lines) at the earth's surface. The vertical axis is meters of surface displacement, and the horizontal axis is distance in kilometers from the fault. The downward pointing arrow indicates the average value of slip for the tapered function.



[King and Wesnousky, 2007]

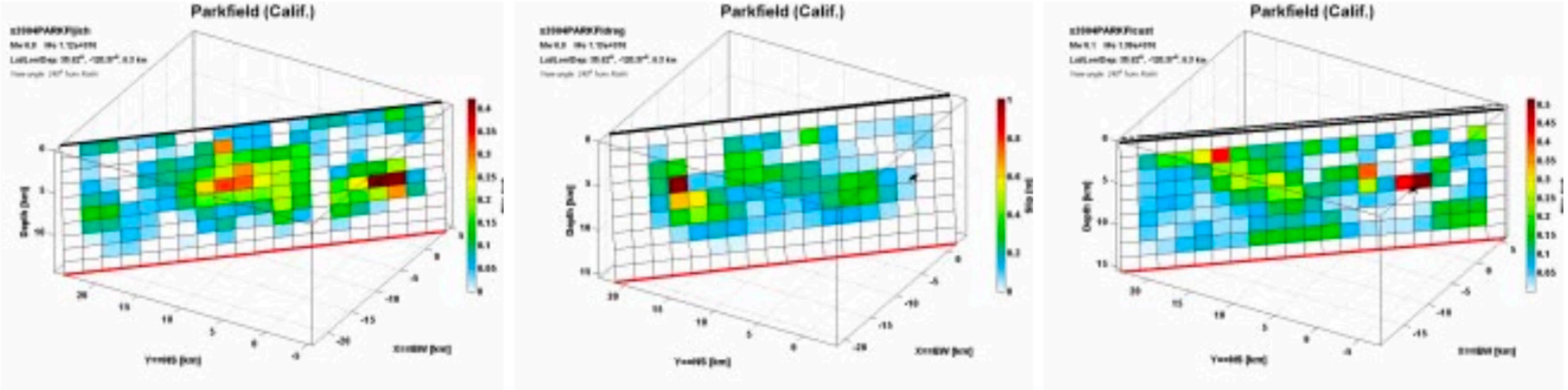
[Page et al, 2008]

Ambiguous depth resolution

Poor resolution for Parkfield

Seismic Inversion Ambiguity

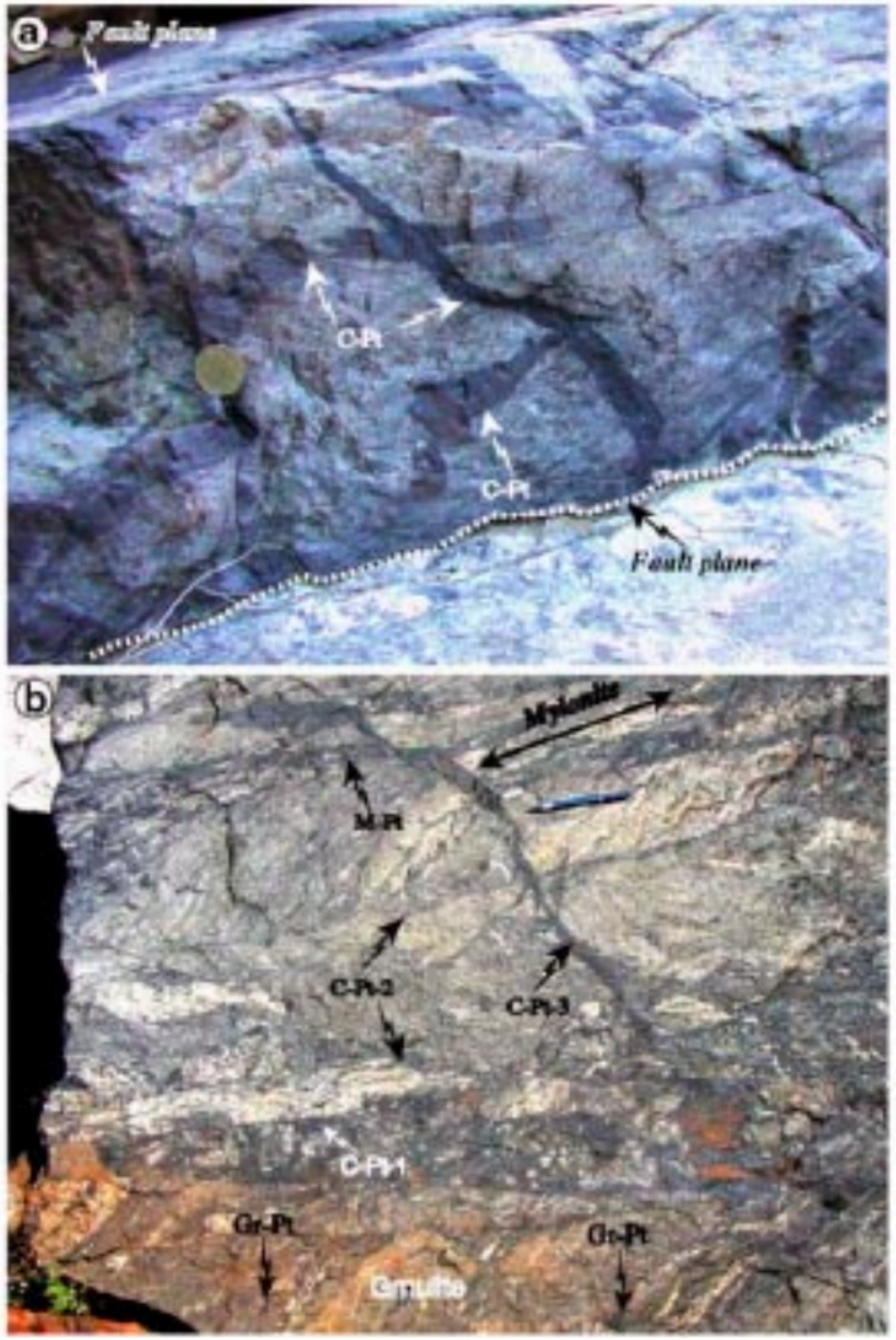
Inversions for slip in 2004 M6.0 Parkfield earthquake
(images from [Mai, 2007] database)



- Big differences even in extremely well networked event

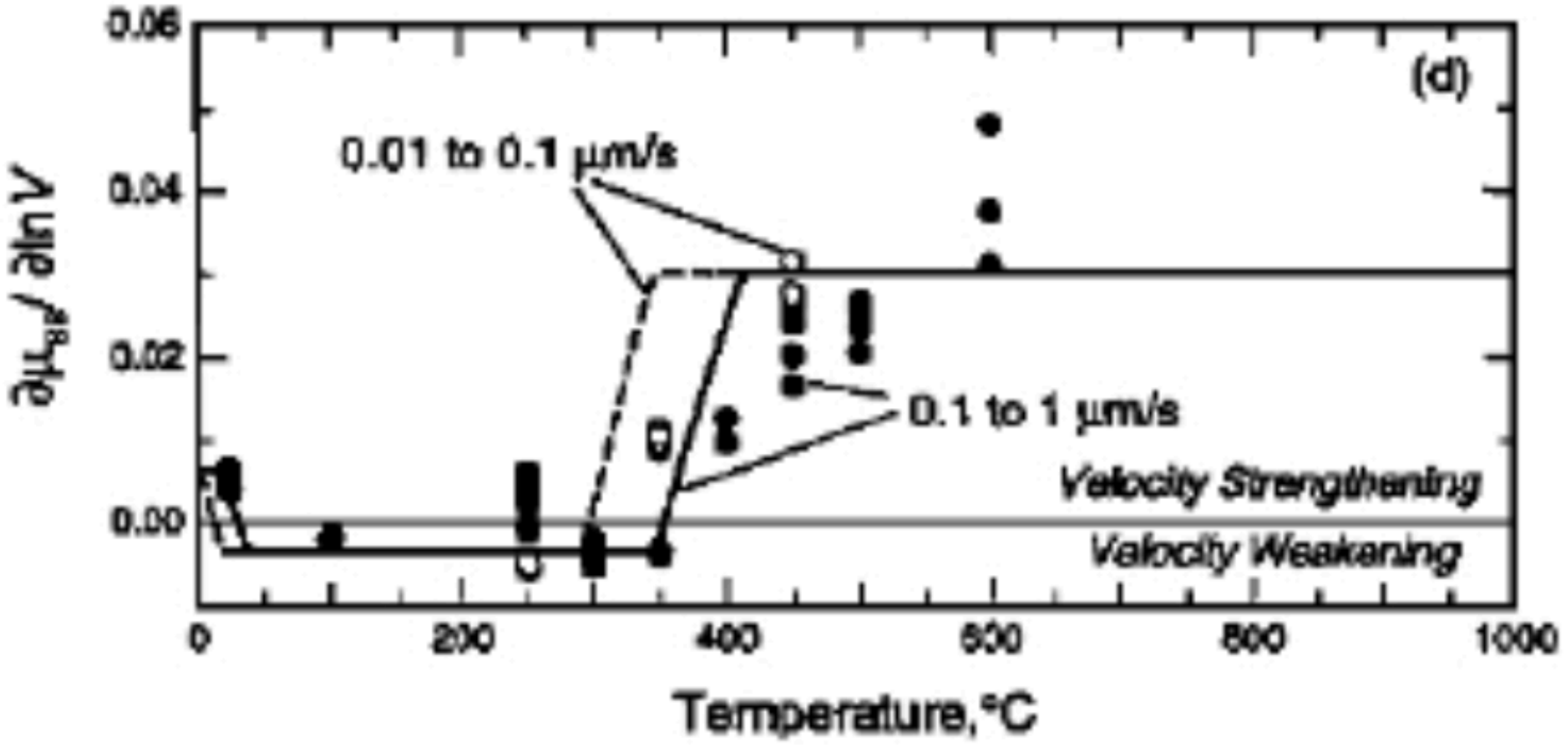
Exhumed Rocks: Fast Deep Slip

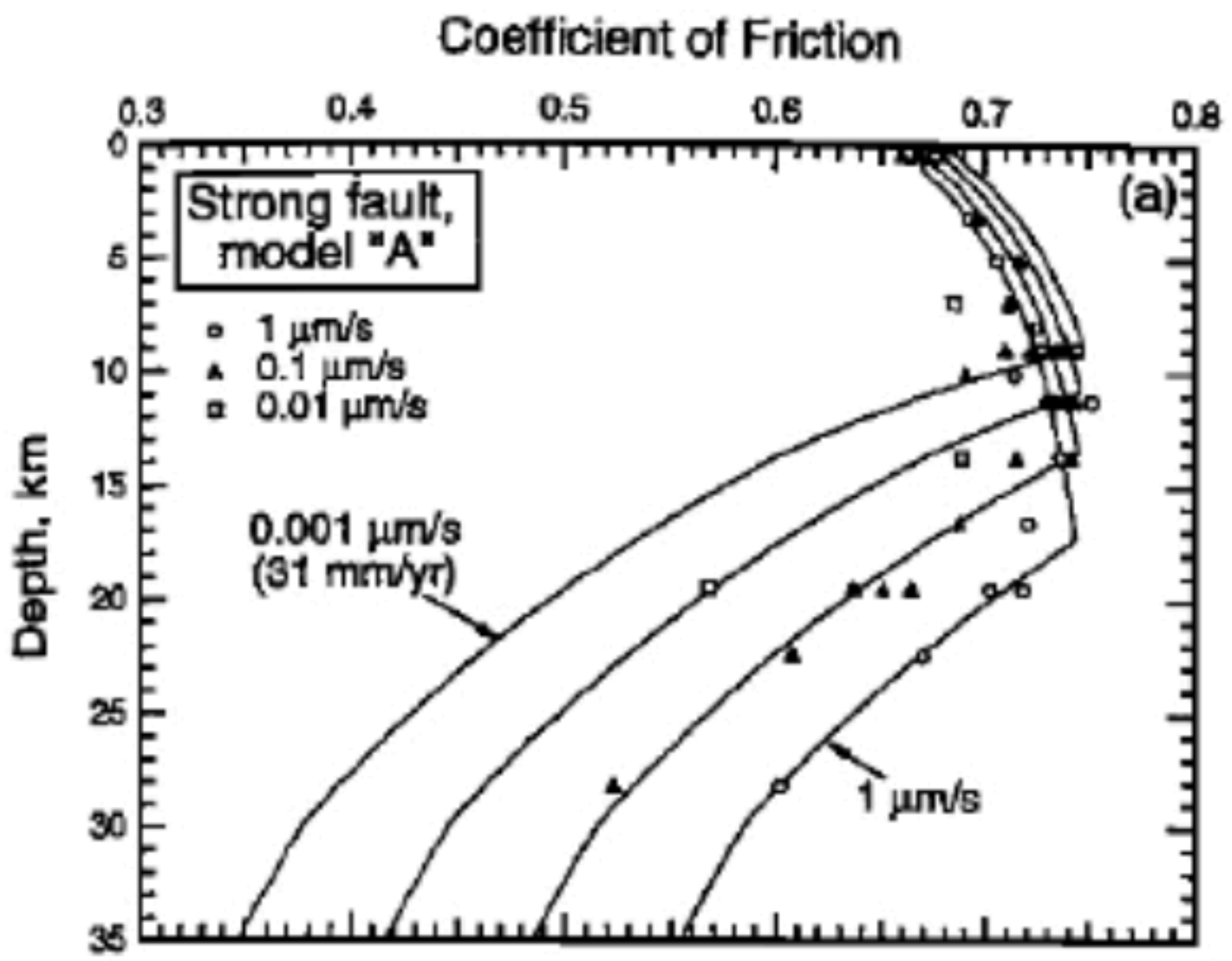
from Pseudotachylytes Crosscutting Mylonites



[Lin, 2008]

Sliding Rate Effect on Lab Friction

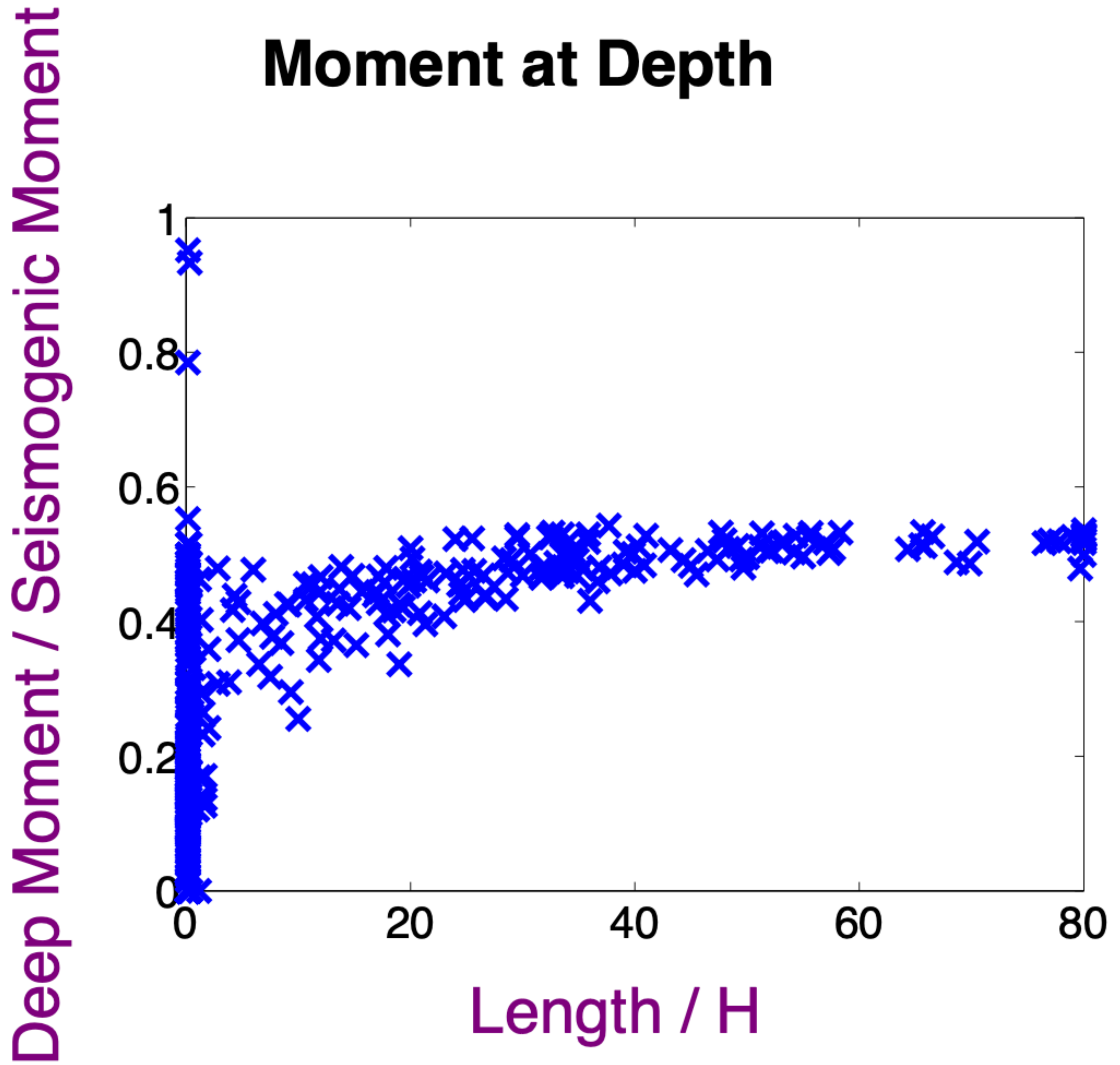




[Blanpied et al, 1995]

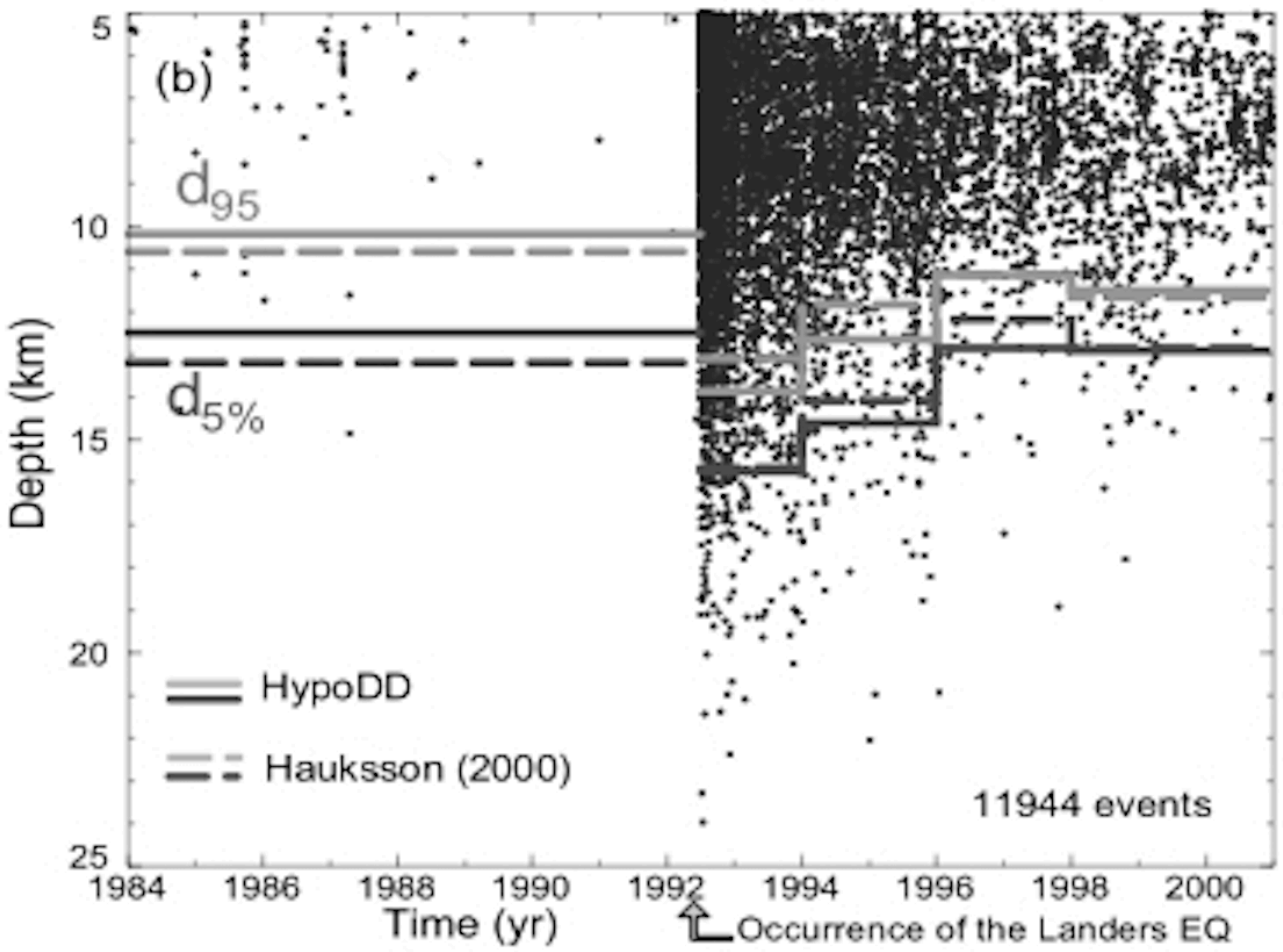
- Unstable sliding deepens at faster sliding rates
- Potentially big effect

3D Model shows significant fraction of slip below seismogenic layer



- Half of seismogenic moment, or $1/3$ total moment at depth

Deepening of aftershocks following large events



[Rolandone, et al., 2004]

Has implications for scaling relations we will see later