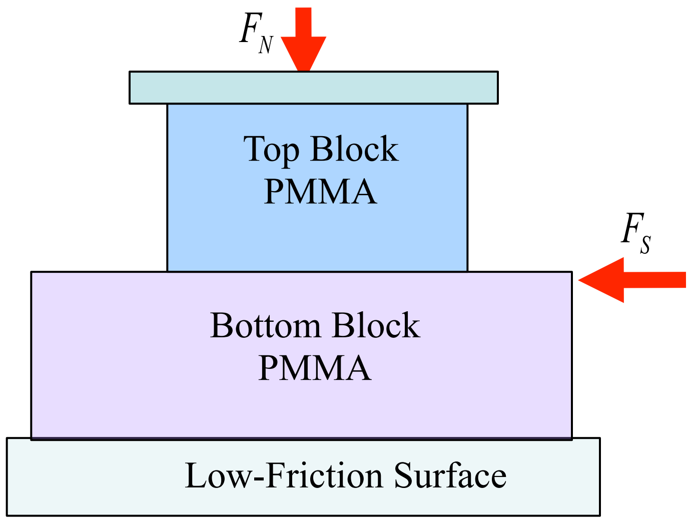
The Onset of Frictional Motion: “Fracture” or “Friction”

Oded Ben-David and Jay Fineberg

The Racah Institute of Physics
The Hebrew University of Jerusalem



O. Ben-David, G. Cohen, J.F., Science **330**, 211 (2010).

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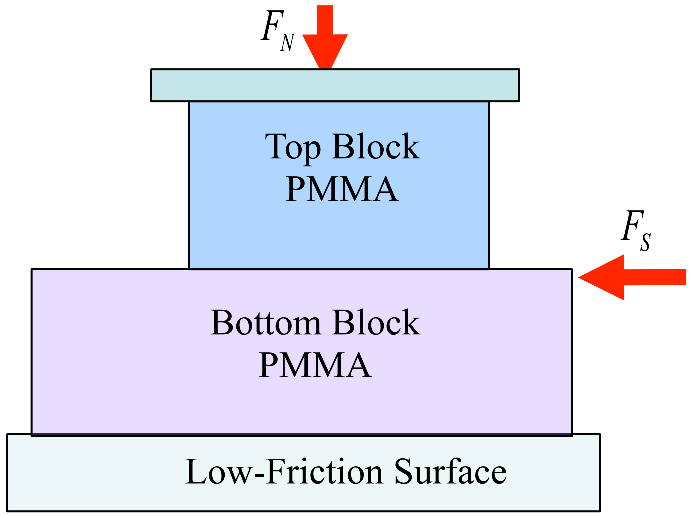

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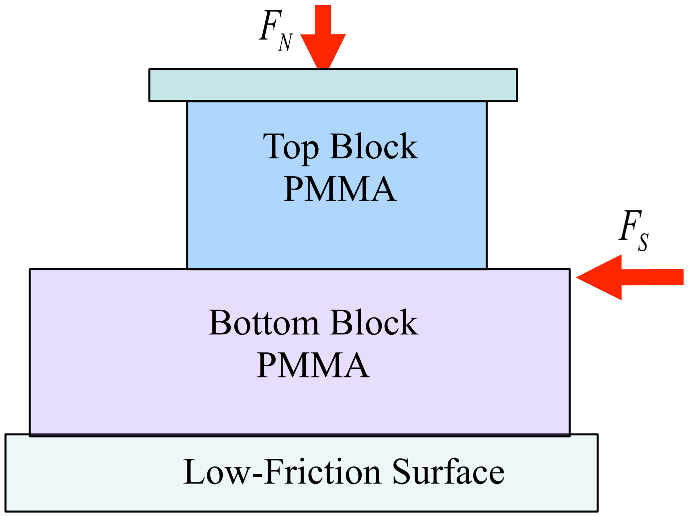

"*Insignificant*" details of loading ➔ *Highly* ***nonuniform*** *stress distributions*

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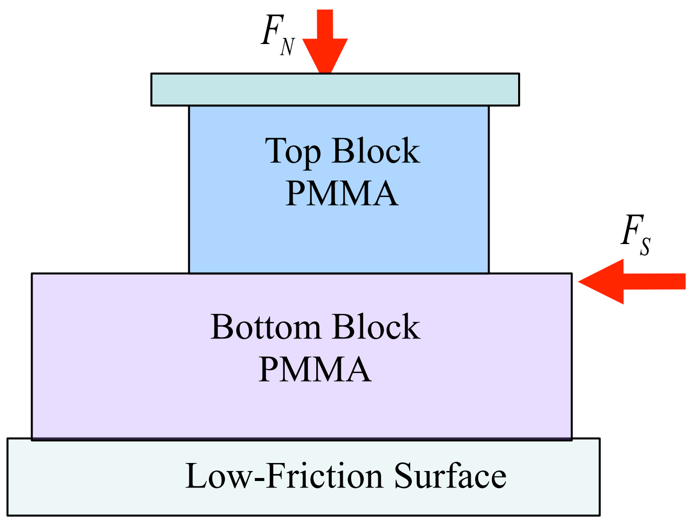


“*Insignificant*” details of loading ➔ *Highly* ***nonuniform*** *stress distributions*

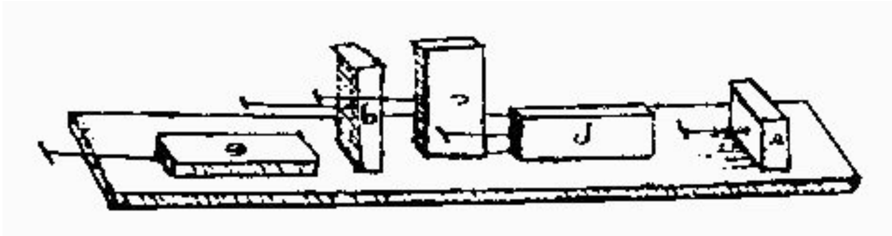
These dictate:

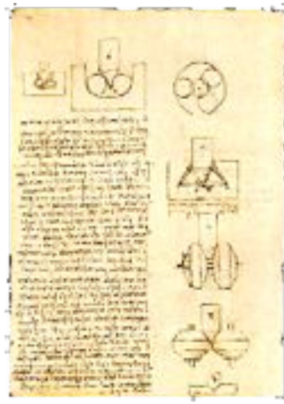
- The ***rupture mode*** that mediates slip onset
- The ***value*** of the static “*friction coefficient*”

O. Ben-David, G. Cohen, J.F., Science **330**, 211 (2010).

The *Classical* View of Friction

Leonardo Da Vinci (1452-1519)



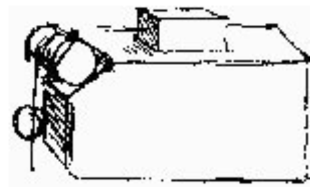


1. The areas in contact have no effect on friction.

- If the load of an object is doubled, its friction will also be doubled.

  ➔ $F_S \propto F_N$

Guillaume Amontons (1663-1705)
Charles August Coulomb (1736-1806)



➔ "Static" and "Dynamic" friction:

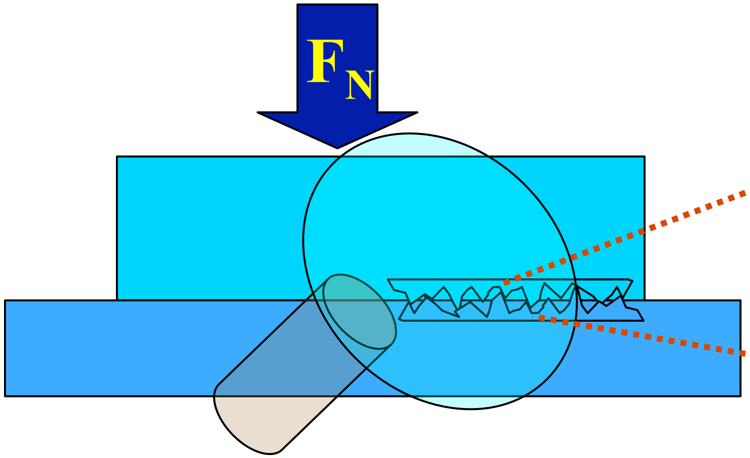
$$F_S = \mu_S F_N \ (v = 0)$$
$$F_S = \mu_D F_N \ (v > 0)$$

μ - Friction Coefficient

The *Classic* View of Friction: $F_S = \mu_S F_N$

F. Philip Bowden and David Tabor (1950)

The *Classic* View of Friction: $F_S = \mu_S F_N$



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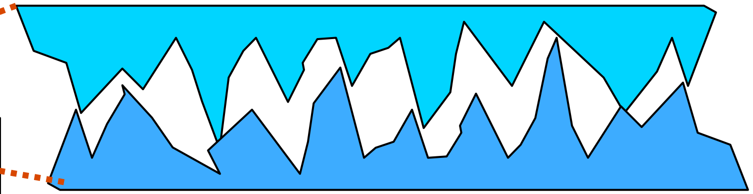

- Net contact area = ***A*** << Nominal contact area

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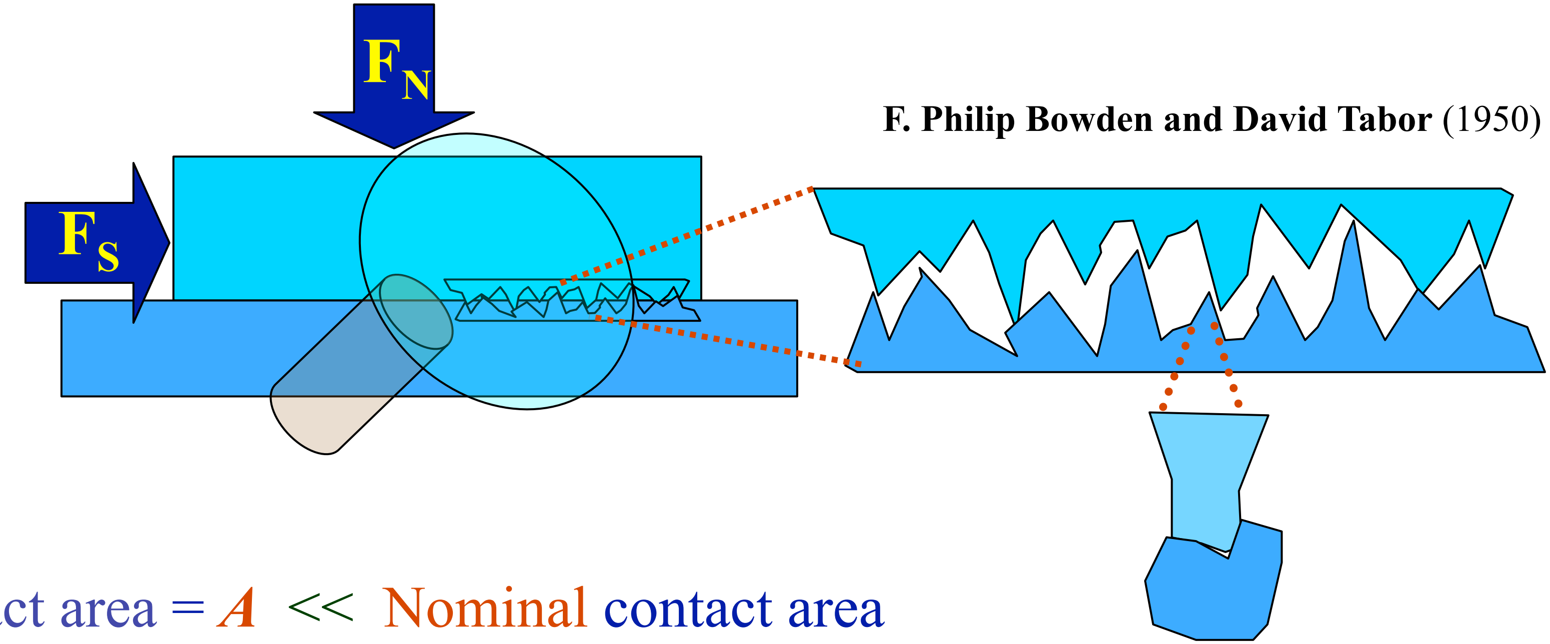

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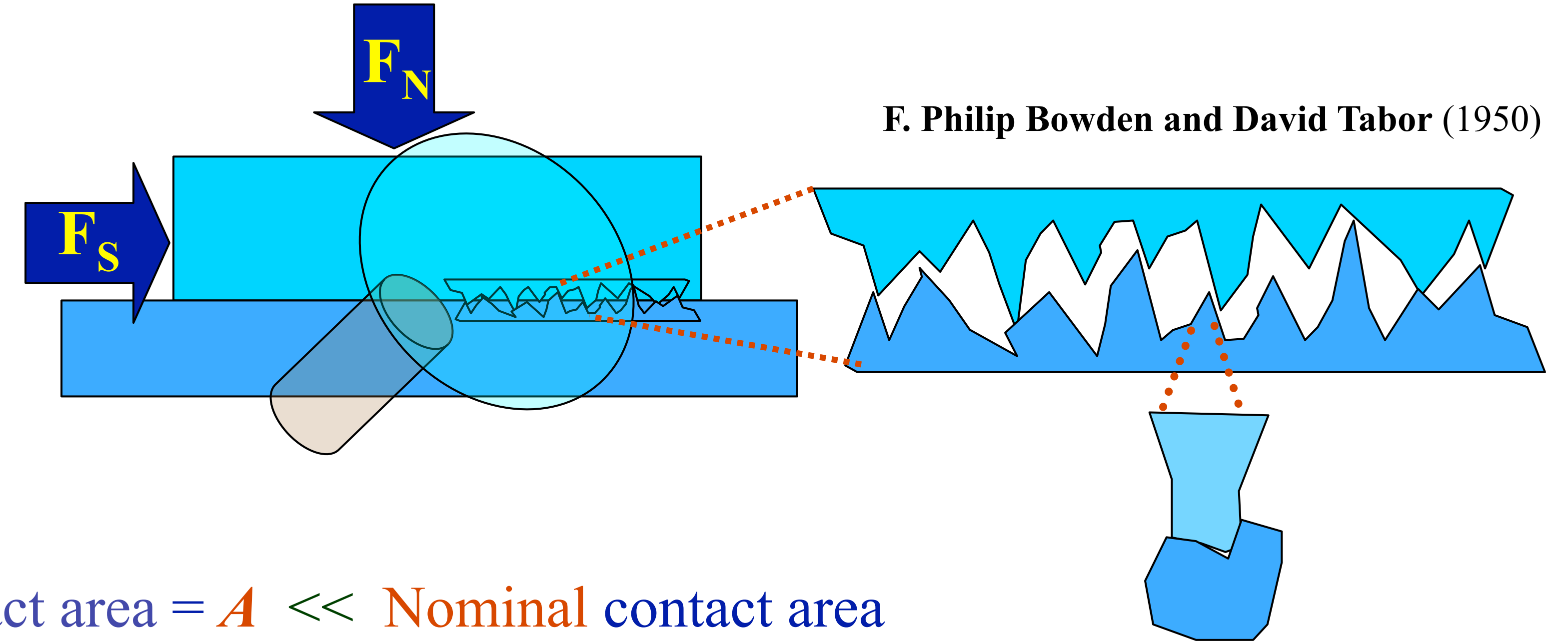

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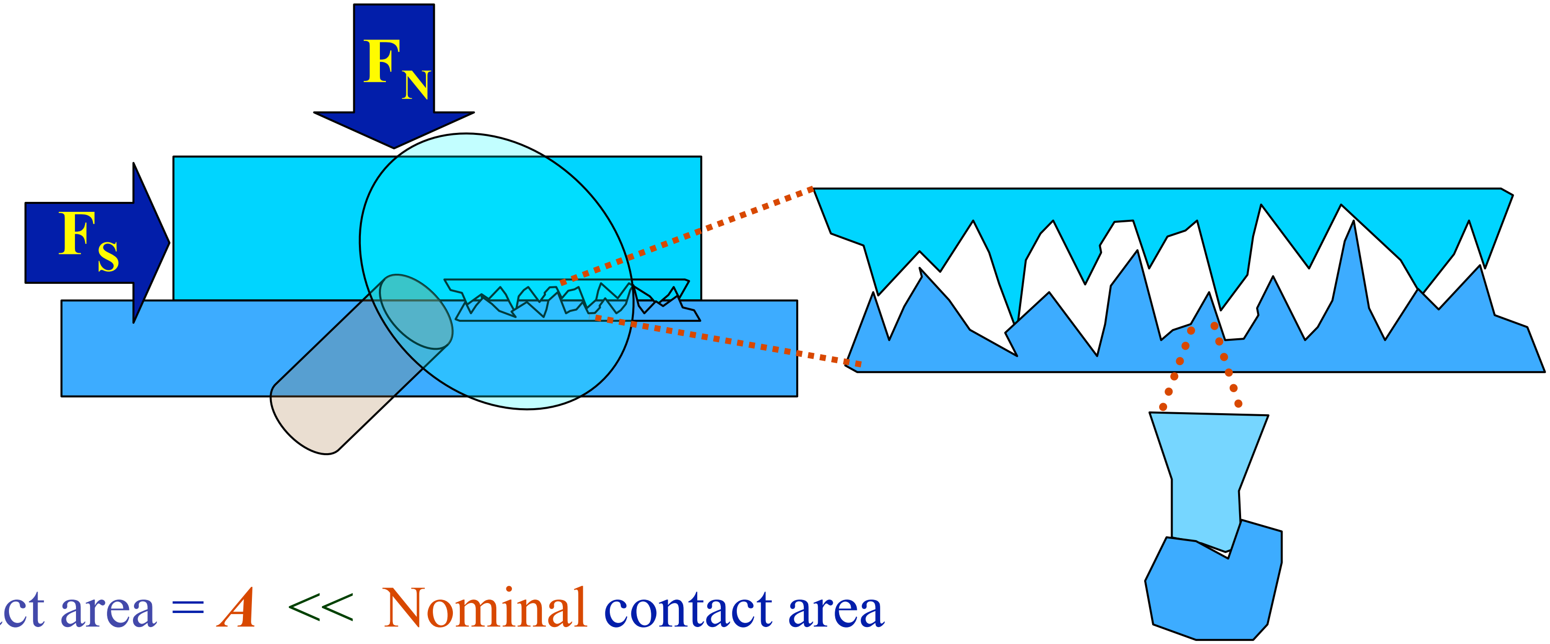

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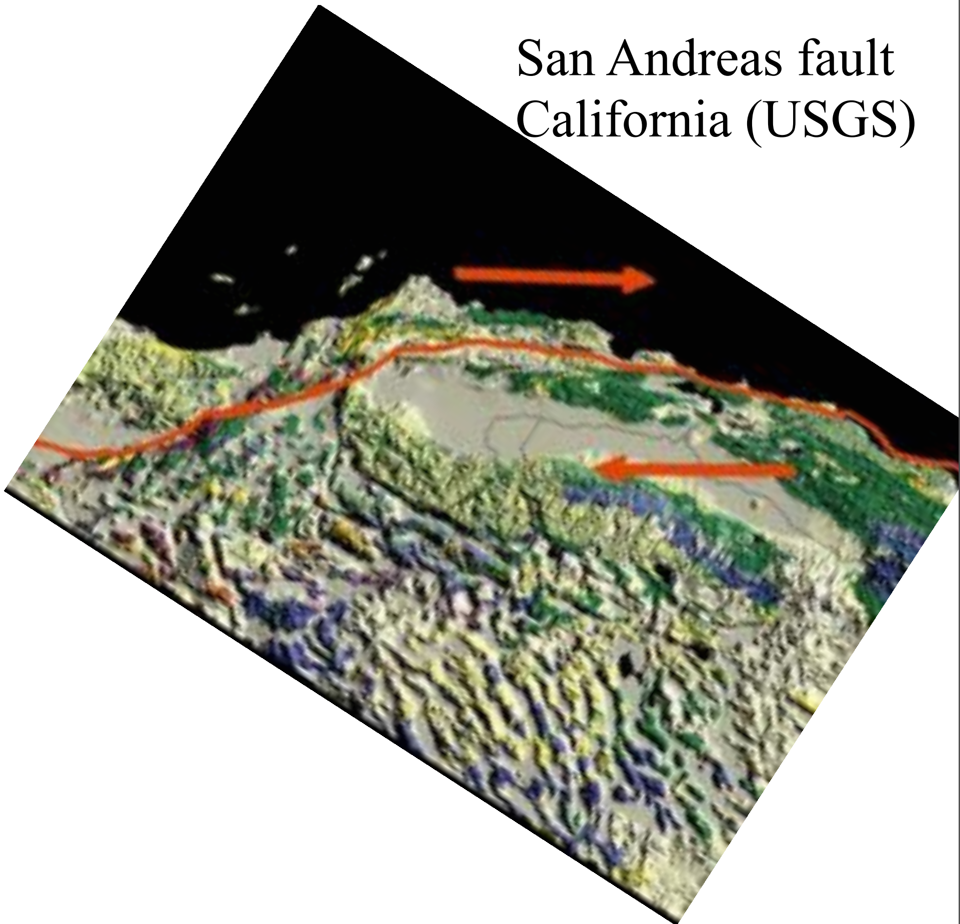
- *A* grows until local pressure = yield strength
- Slip: ***Instantaneous*** Fracture of contacts when F_S=Shear strength ·***A***rea = $\tau_S \cdot A$

- *A* and τ_S govern the **local** contact strength of a rough interface!
- Note: ***Both A*** and τ_S may vary ***spatially*** and ***dynamically***

S. M. Rubinstein, G. Cohen, and J. F., Phys. Rev. Lett. 96, 256103 (2006)
S. M. Rubinstein, G. Cohen, and J. F., Phys. Rev. Lett. 98, 226103 (2007)

Ben-David, Rubinstein and Fineberg, *Nature* 463, 76 (2010)

Earthquakes ***are*** Friction



San Andreas fault
California (USGS)

Earthquakes *are* Friction

but: Earthquakes are mediated by *(rapid)* **fracture fronts**

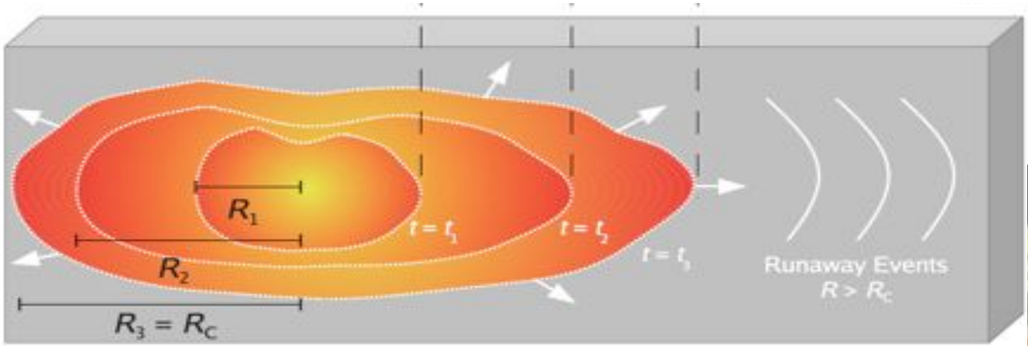
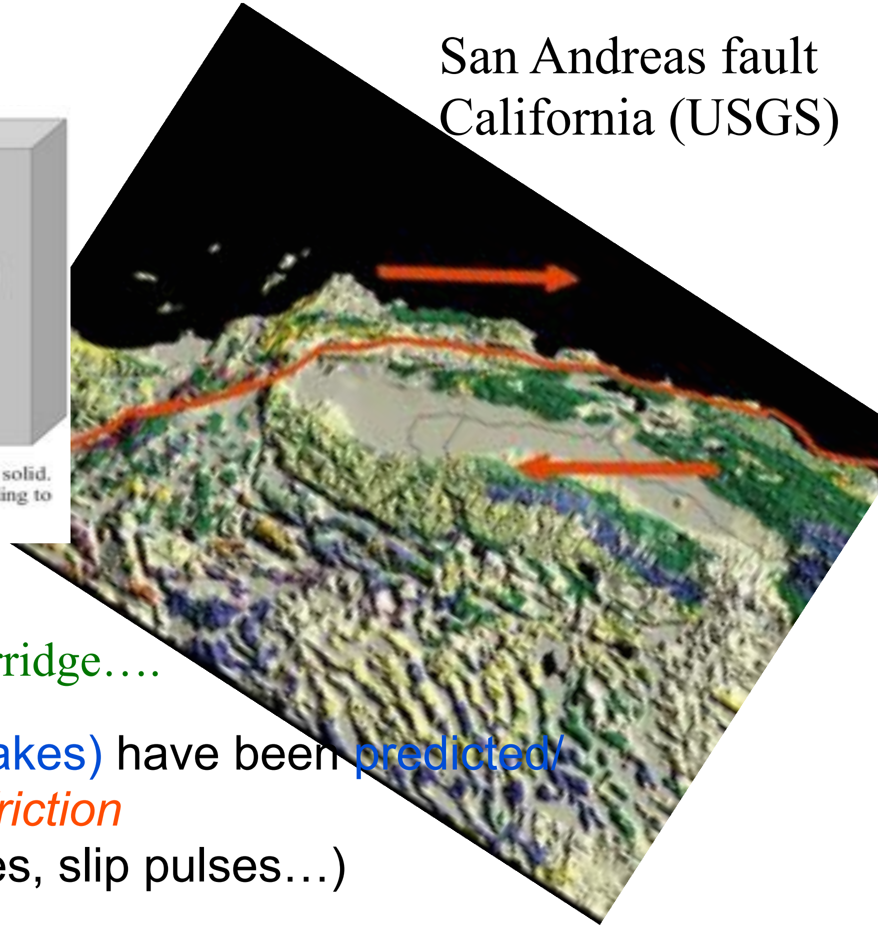


Figure 13. (top) Stress versus distance from the edge of (bottom) ruptures growing in elastic solid. Ruptures with a critical size R_c produce dynamically stress comparable to the static friction τ_s, leading to runaway events.

Y. Benzion (2008)



San Andreas fault California (USGS)

Kostrov, Eshelby, Freund, Rice, Aki, Andrews, Burridge….

A variety of different rupture modes (⇔ earthquakes) have been predicted/observed/deduced… that *mediate the onset of friction*
(e.g slow, sub-Rayleigh, Supershear earthquakes, slip pulses…)

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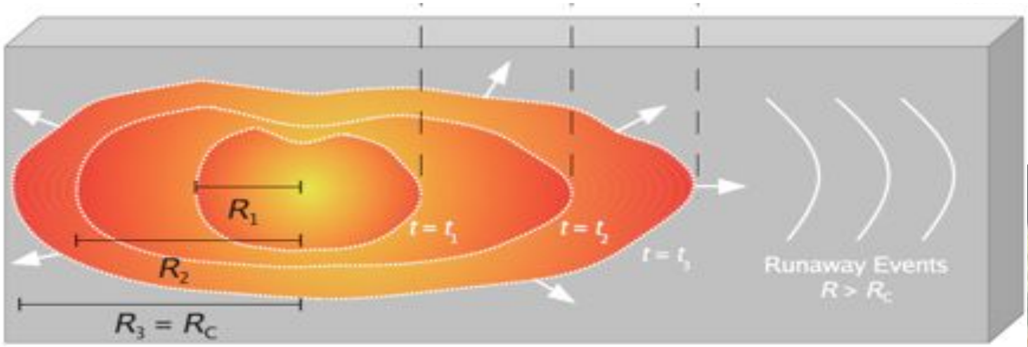

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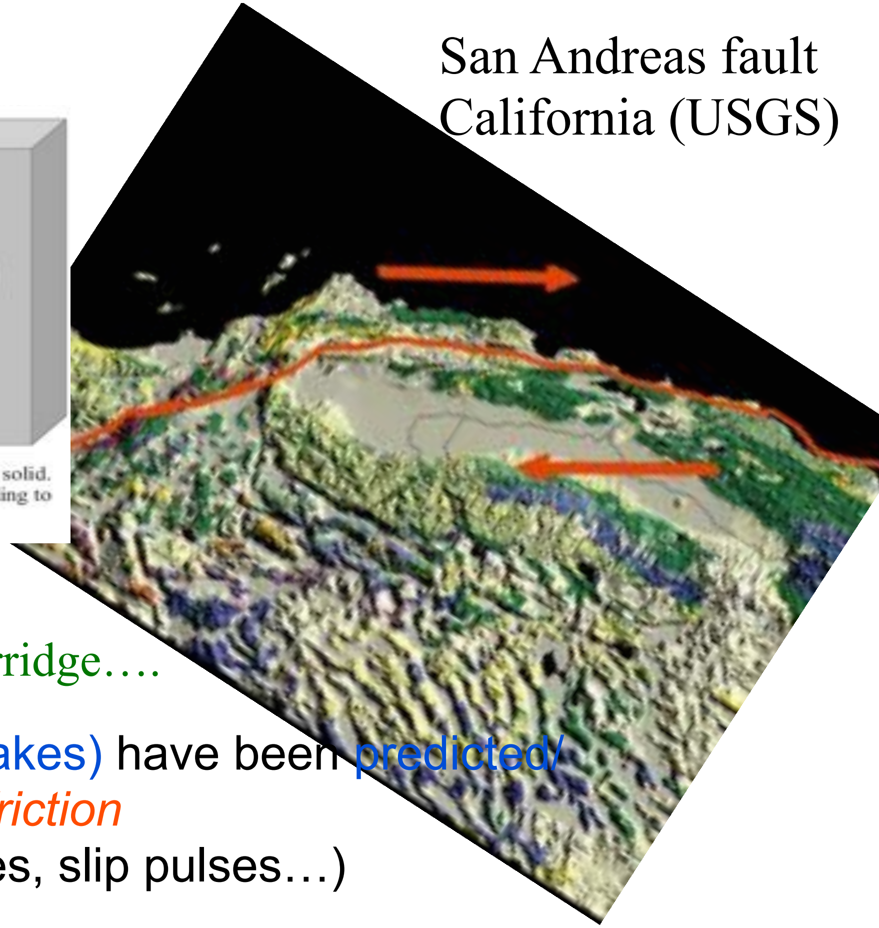

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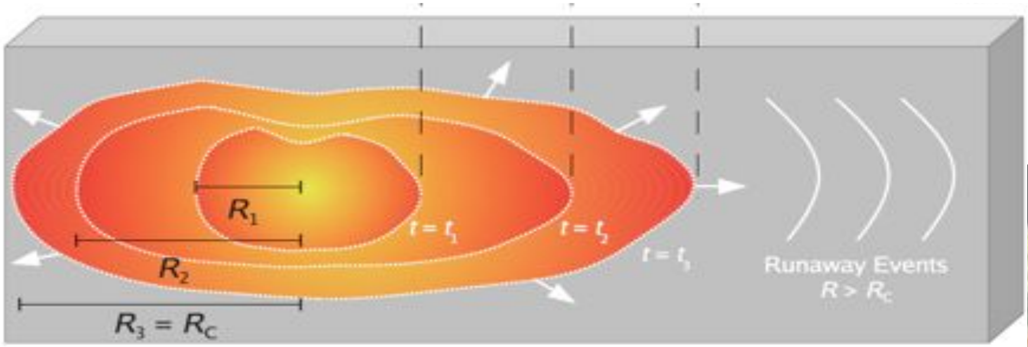

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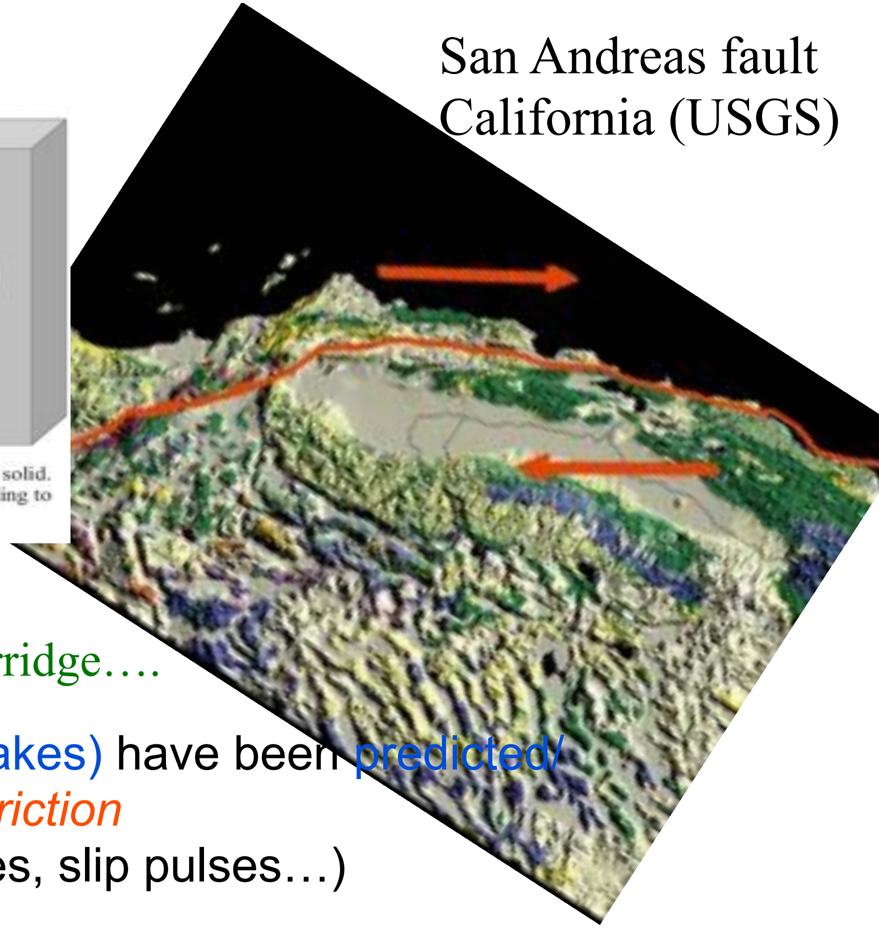

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(e.g slow, sub-Rayleigh, Supershear earthquakes, slip pulses…)

- How can we make "sense" of these different rupture modes?
- Can these different rupture modes conspire to produce a **single** "friction coefficient"**???**
- ***Do they***??

A fracture primer:

Griffith threshold for Fracture initiation

Released elastic energy > Energy to create new surfaces ("Fracture Energy")

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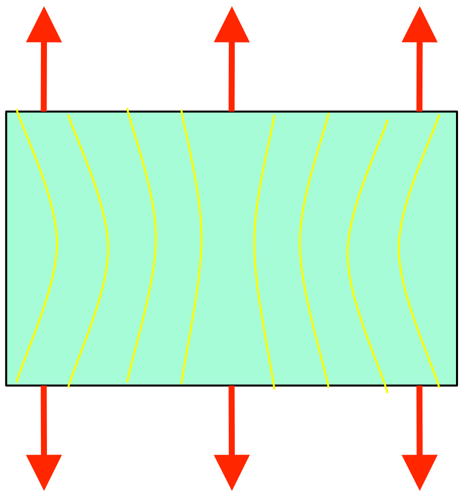

A fracture primer:

Griffith threshold for Fracture initiation

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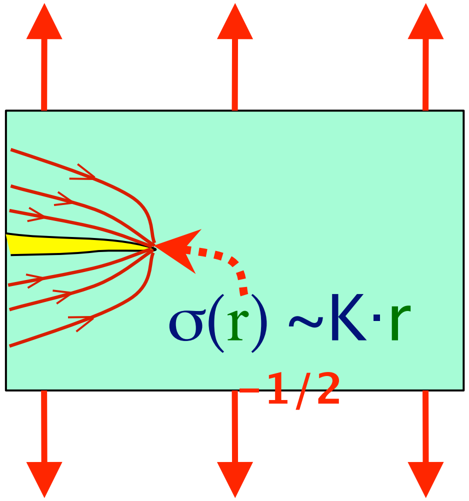
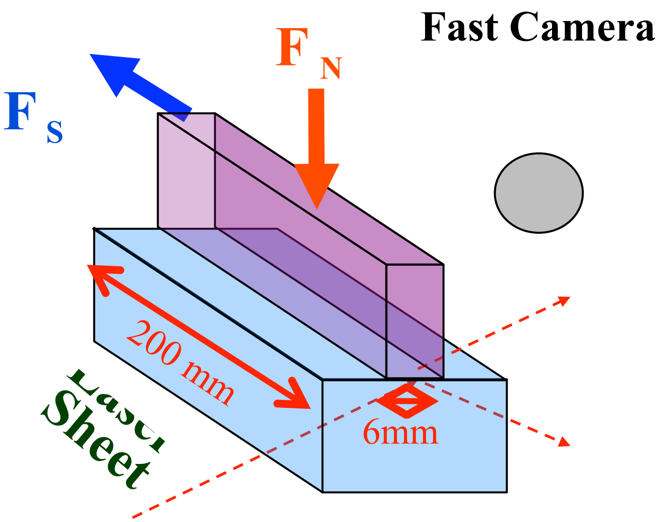


A crack focuses elastic energy into a **stress field singularity** at its tip.

- Material is preferentially ruptured at the tip of a crack
- Failure: Loads << theoretical strength

Real Contact area *A* measurements



S. M. Rubinstein, G. Cohen, and J. F., Nature 430, 1005-1009 (2004)
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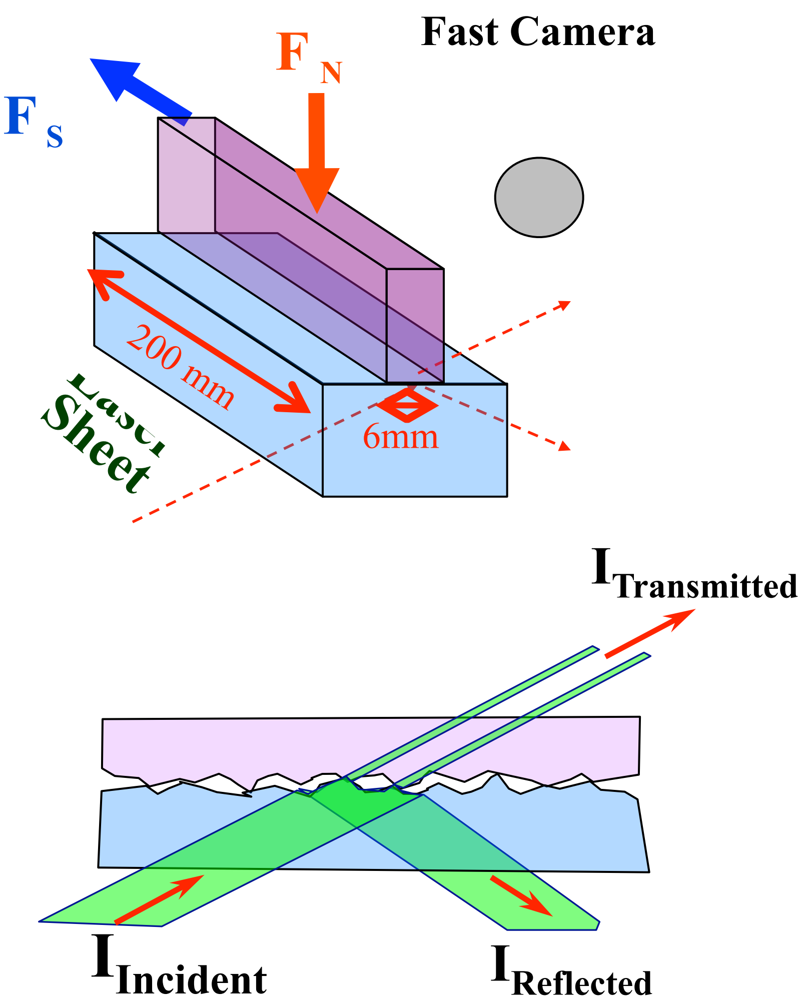

$I_{transmitted} \propto A$

Frame Rate ~ 250,000 Frames/sec

Resolution: 1280 Pixels / 200mm

$$A(x,t) = I(x,t) = \int I(x,y,t)\, dy$$

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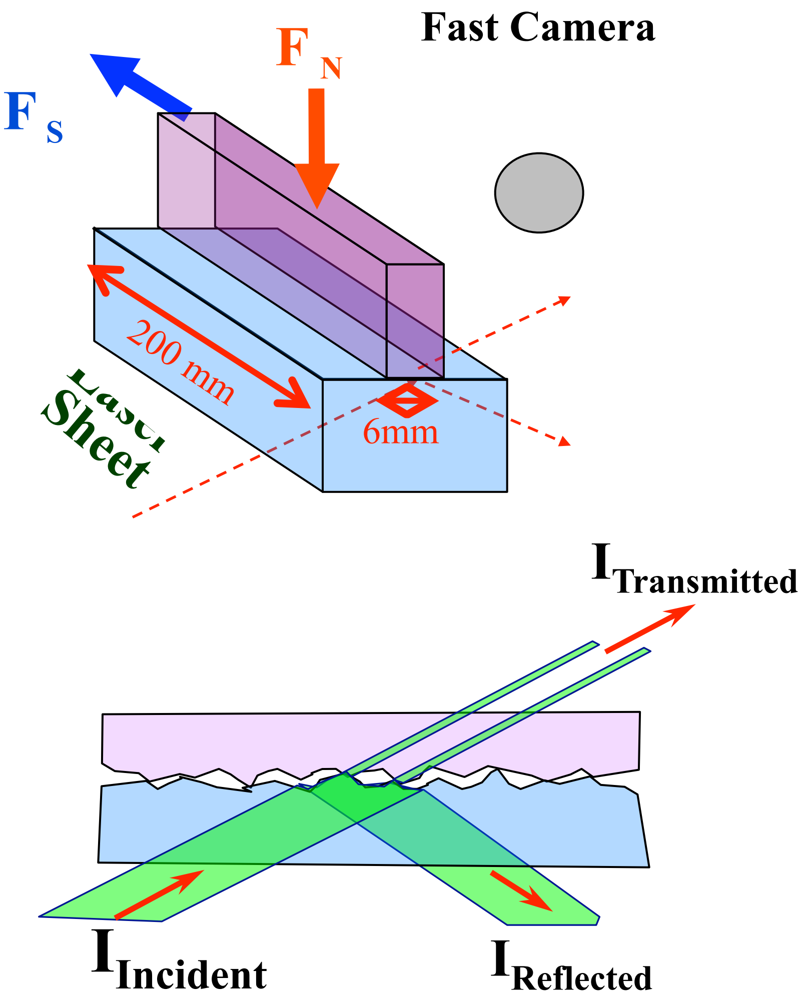

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Non-uniform stresses along the interface

Are introduced/controlled by:

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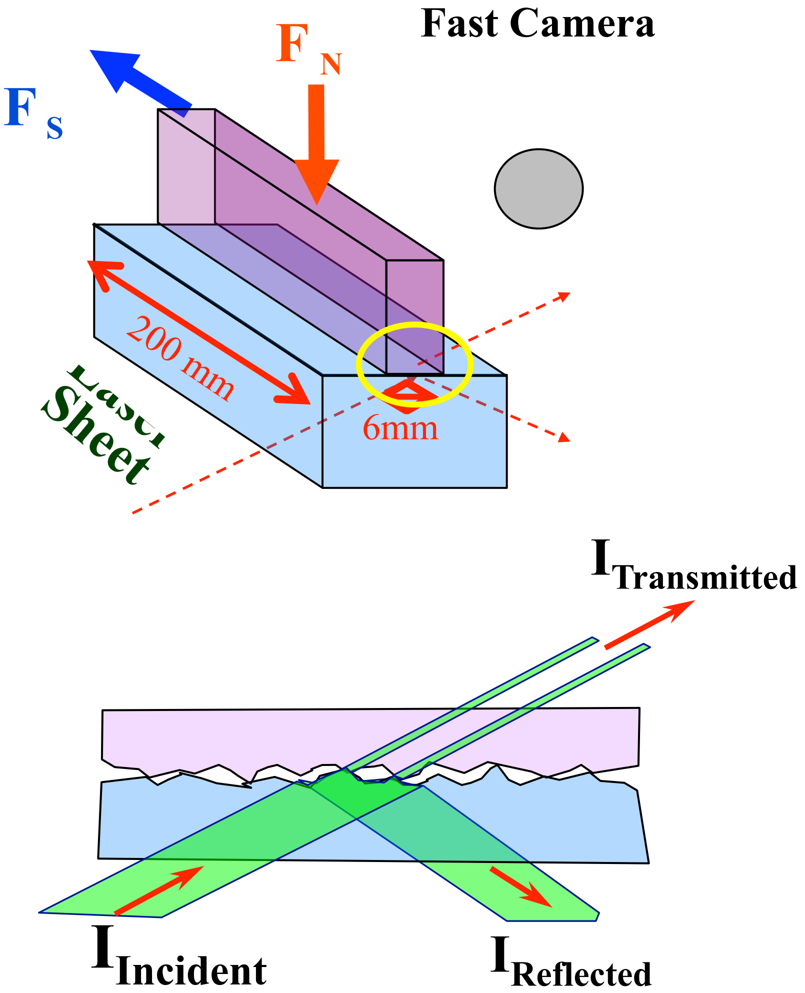

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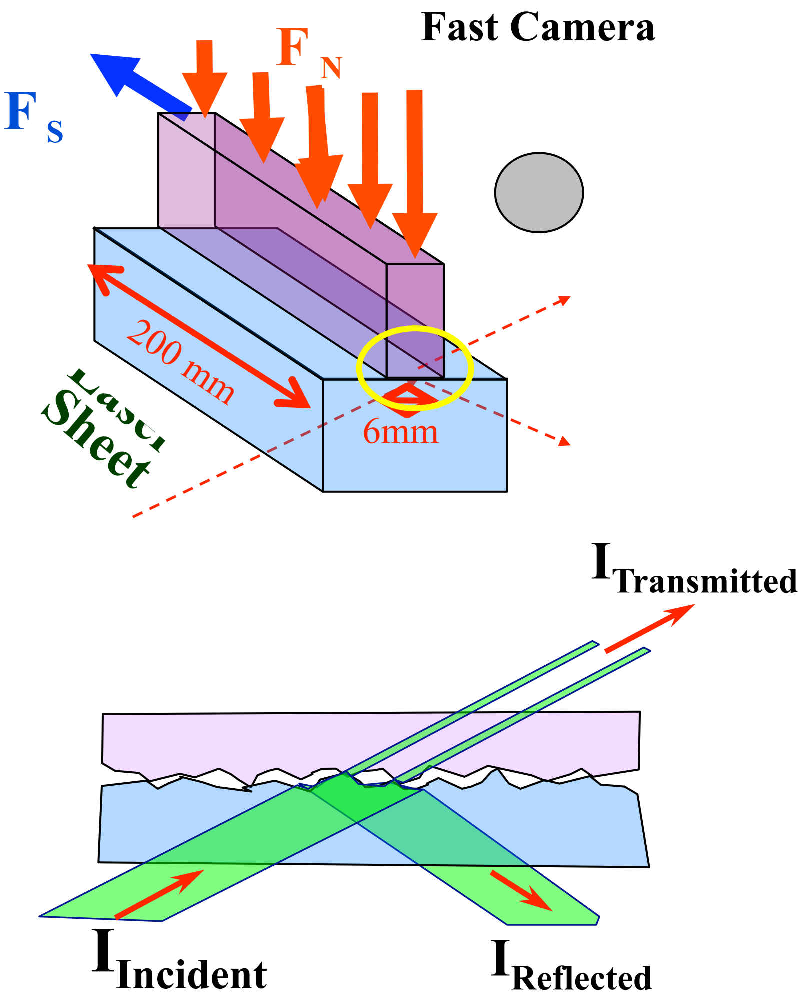

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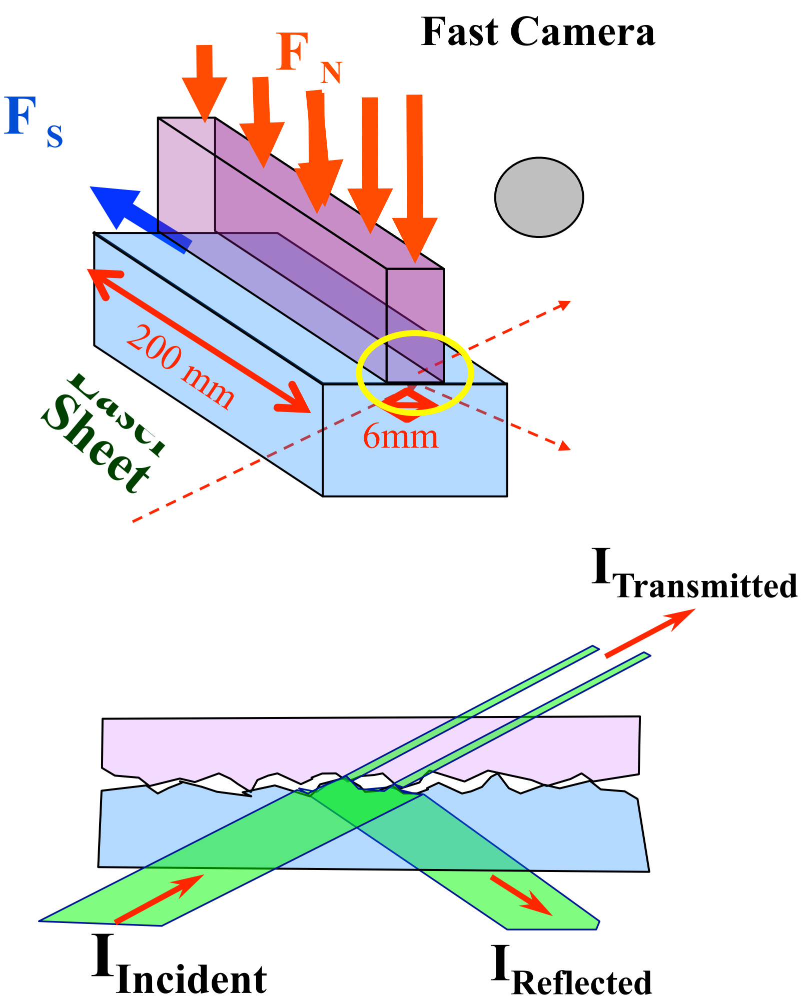

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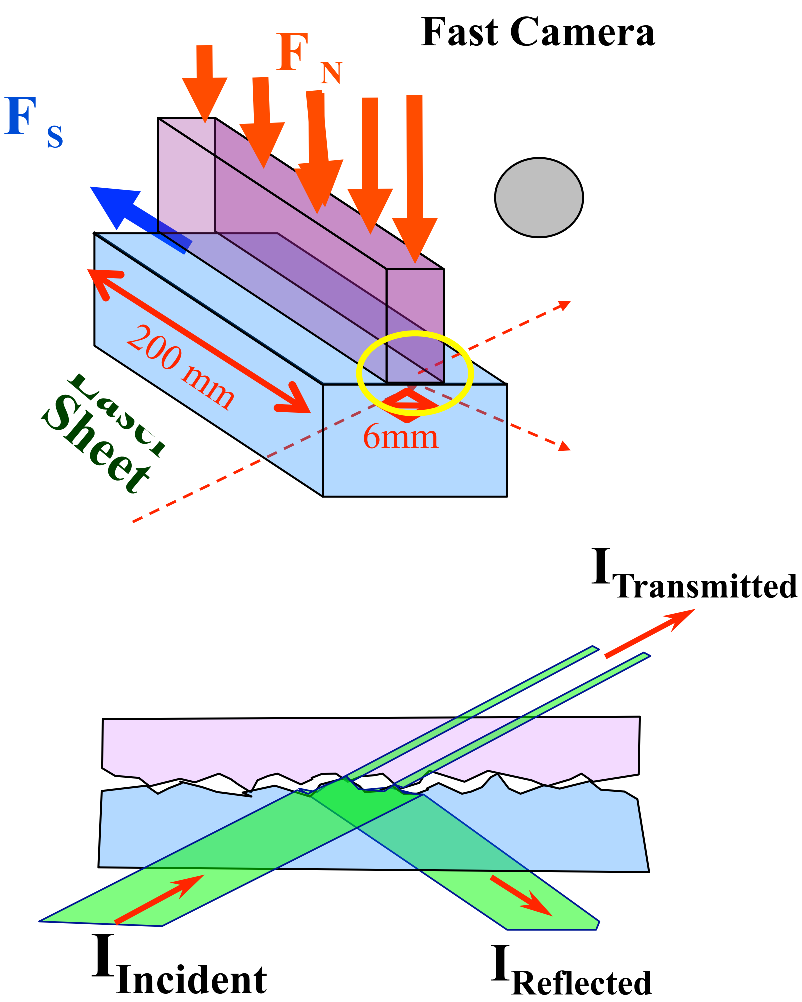

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Non-uniform stresses along the interface

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- ***Dynamically,*** by prior slip events

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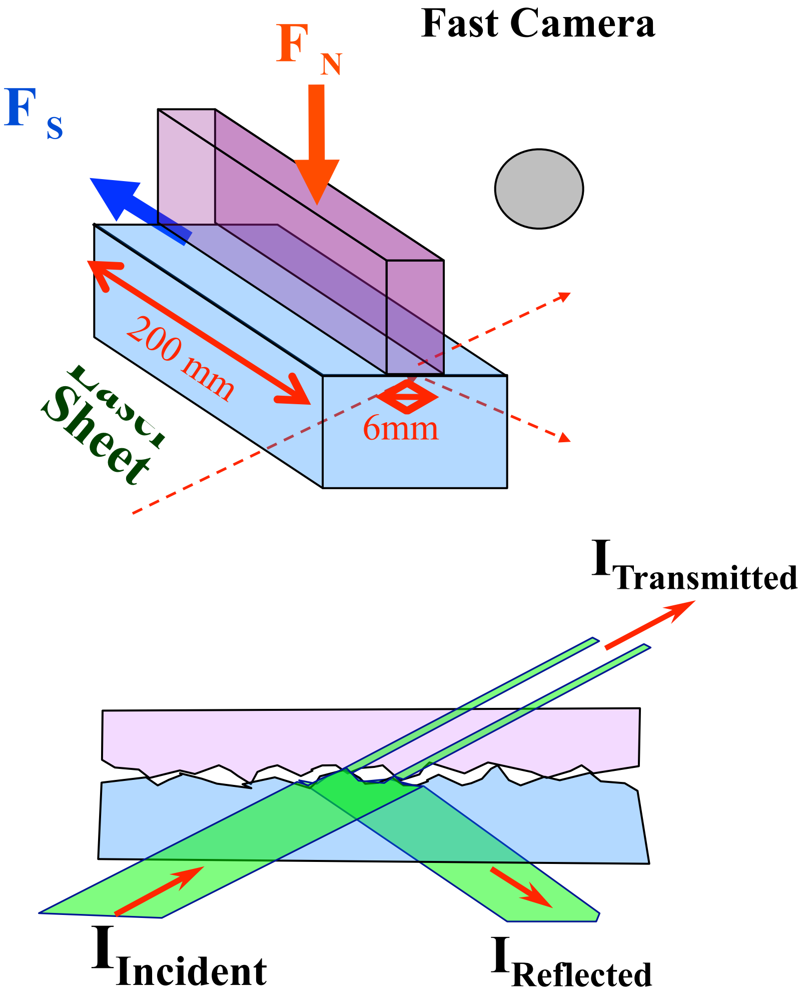

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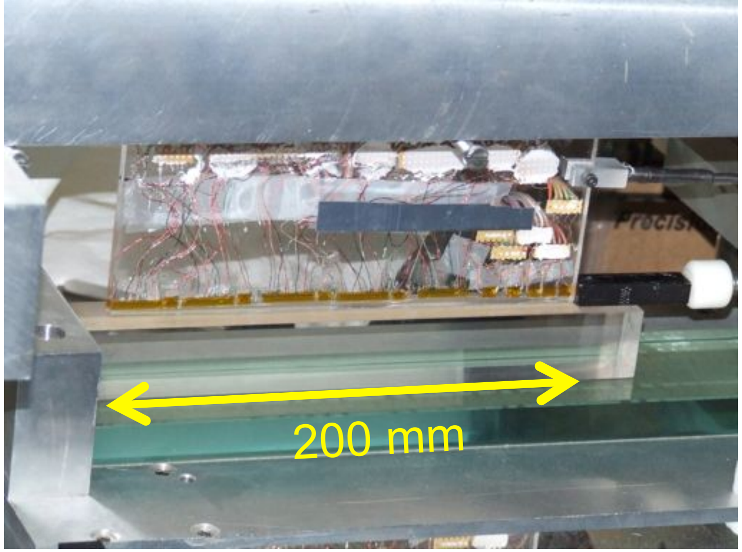
Stress measurements



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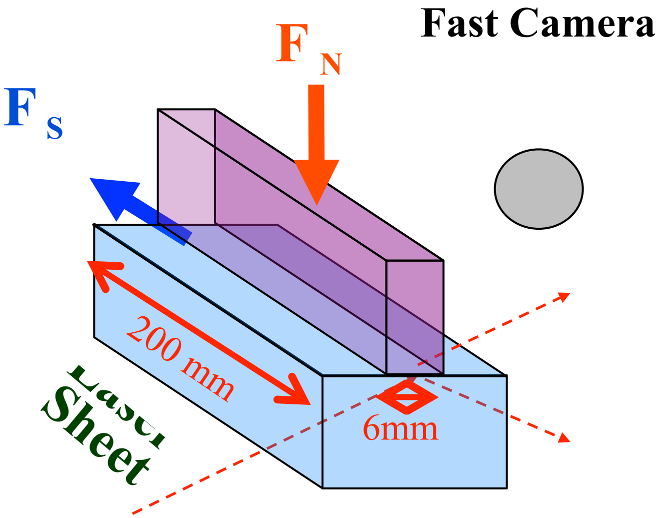

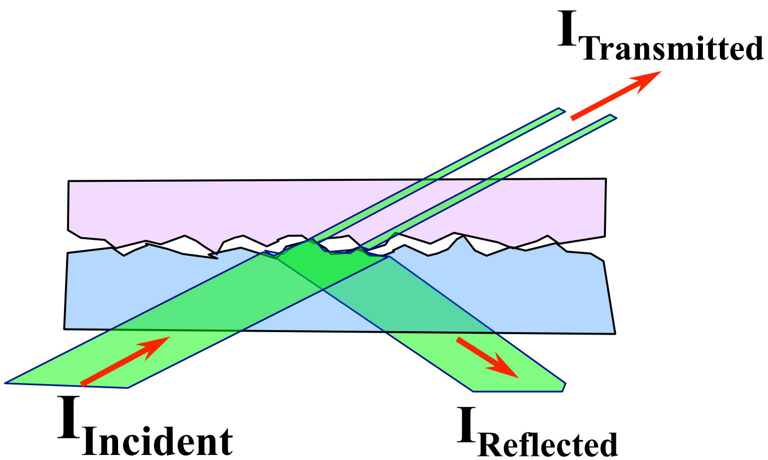

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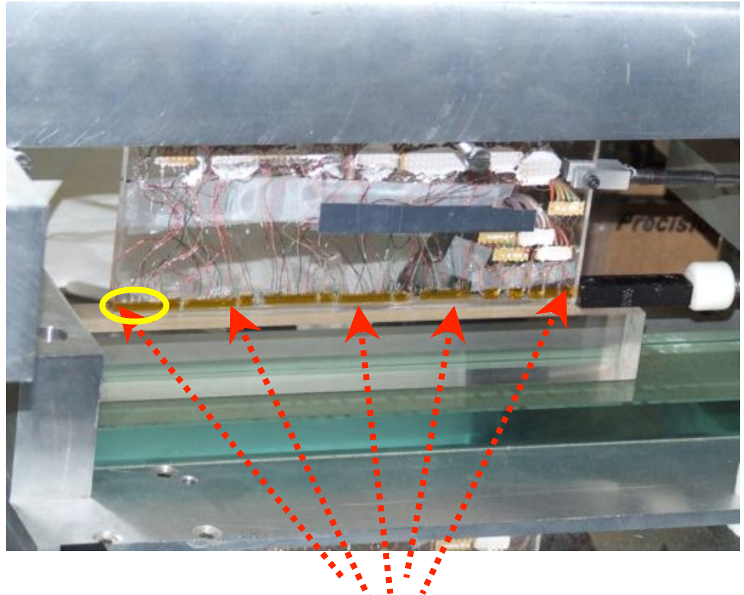
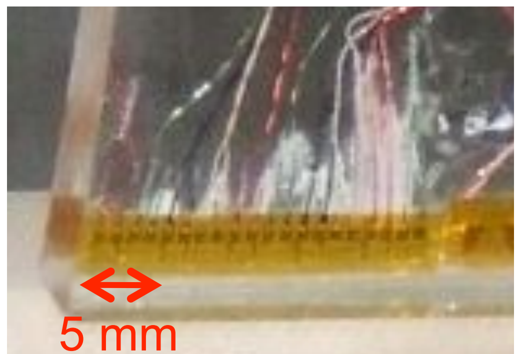


74 miniature strain gages



All strain gages monitored continuously at ~2Hz

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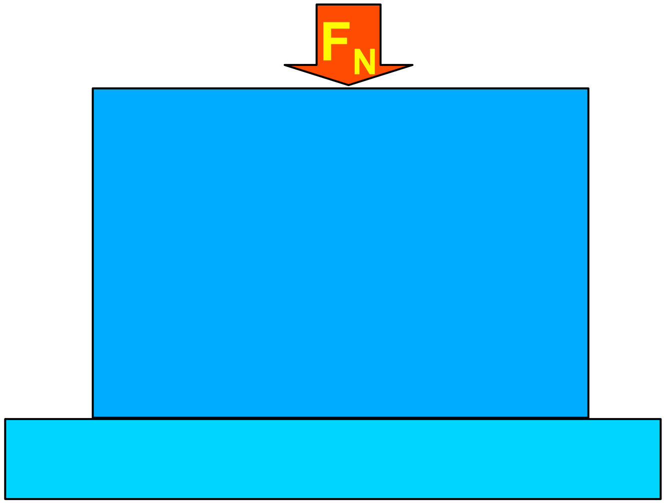
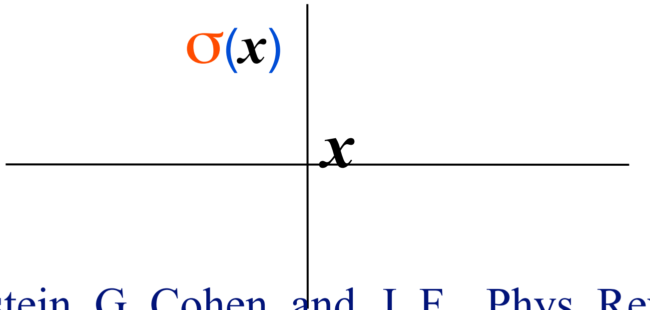
Non-uniform stress profiles are formed naturally - ***prior to motion***





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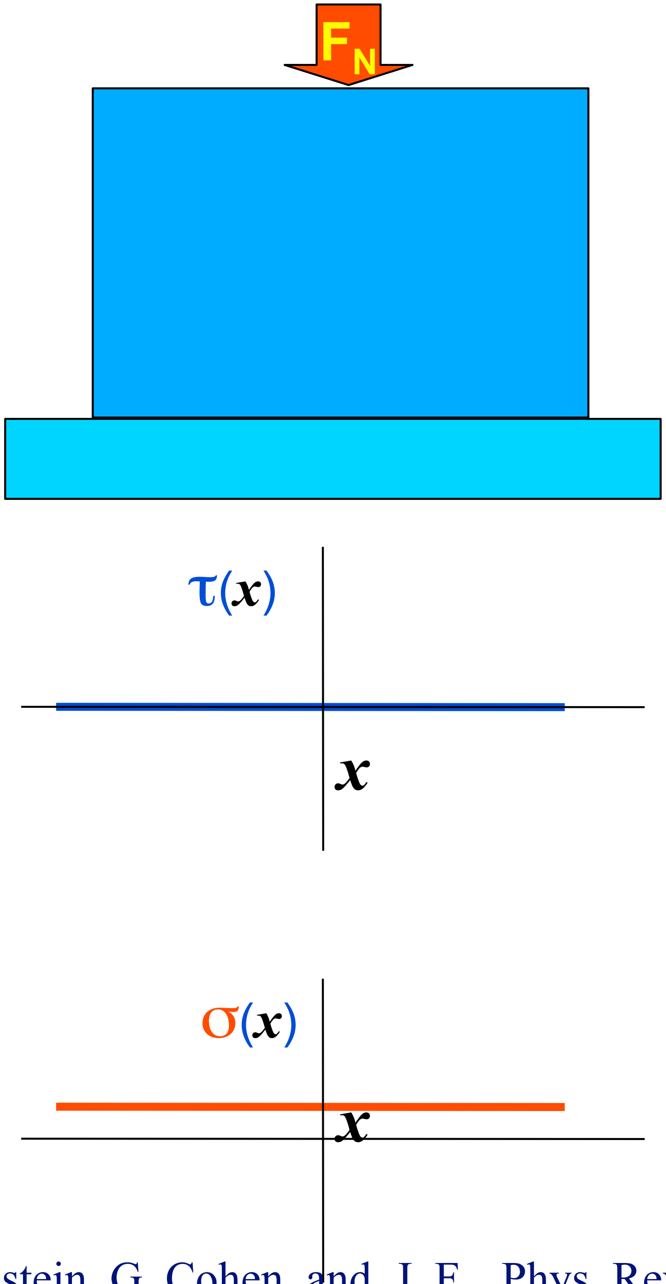

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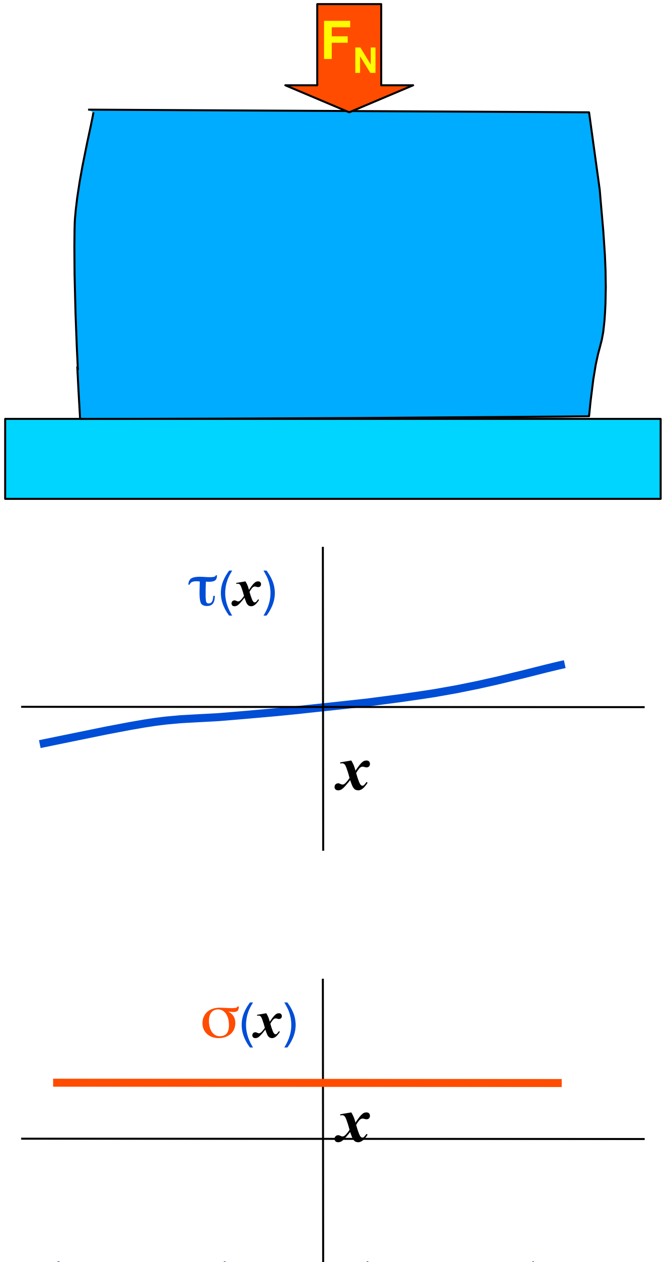

Uniform loading + friction

Frustrated Poisson expansion:

➔ ***Non-uniform*** shear stess, $\tau(x)$

\+ uniform normal stress, $\sigma(x)$

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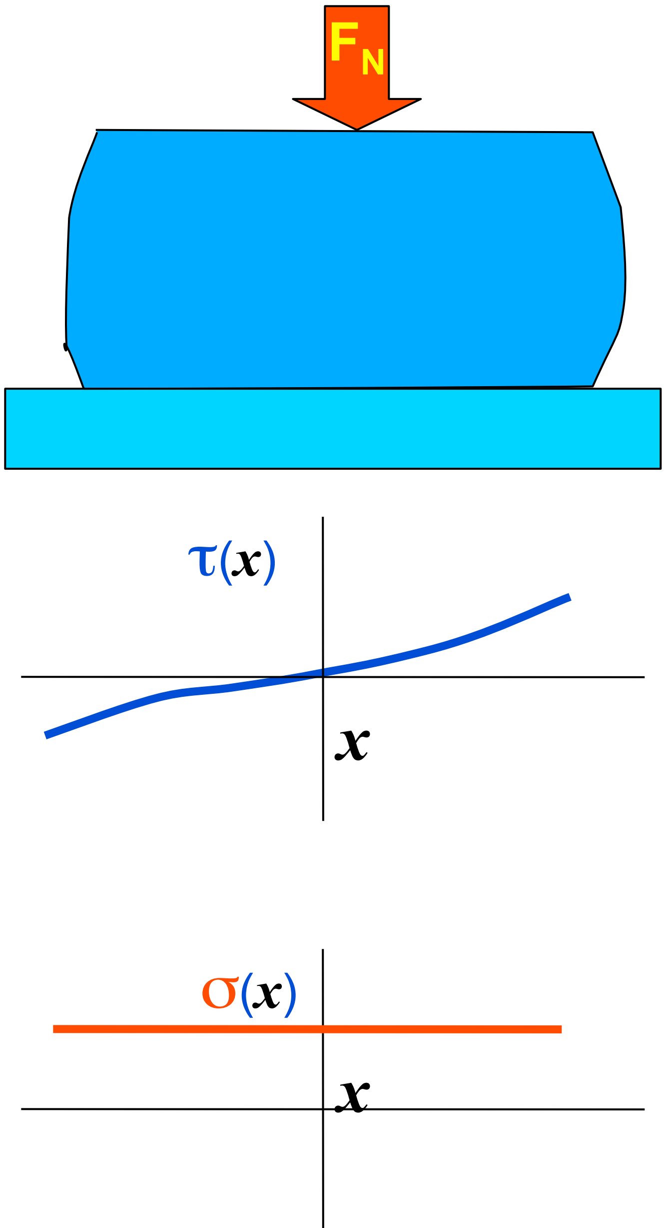

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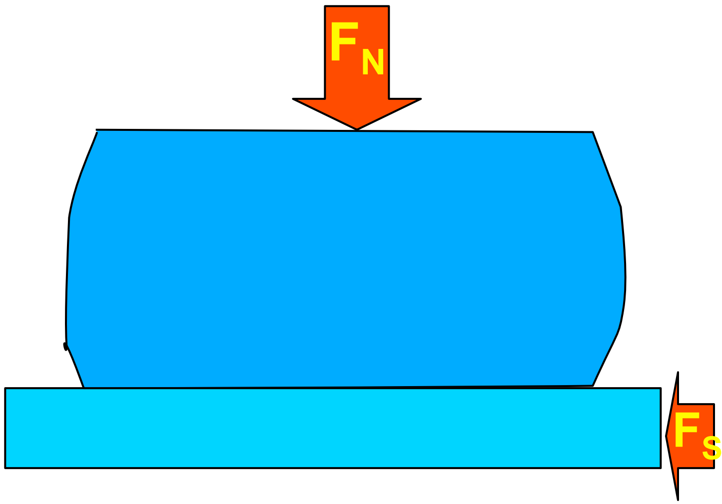

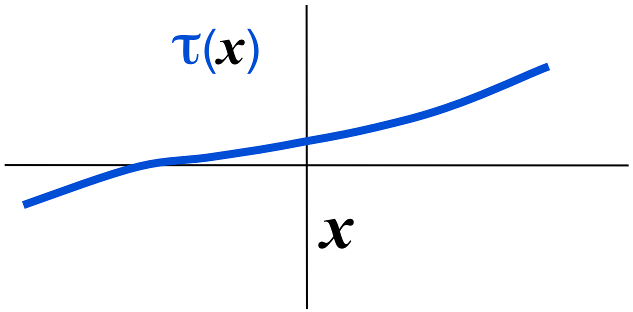

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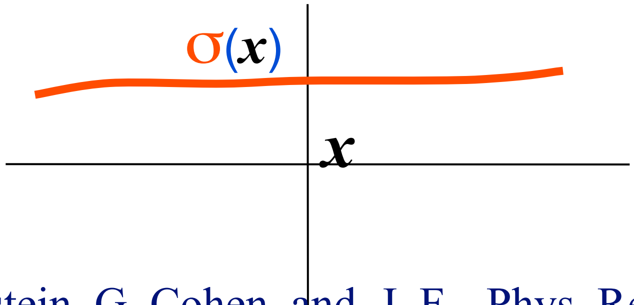

Torque due to applied shear, F_S:

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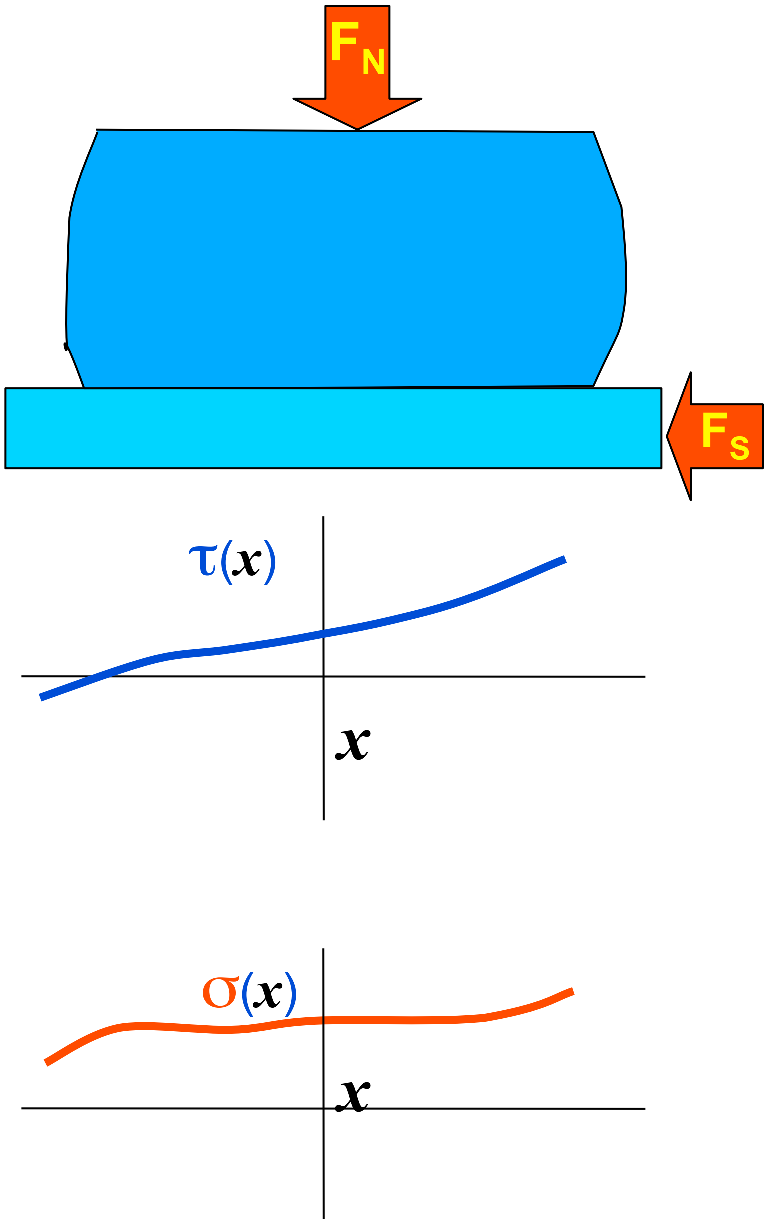

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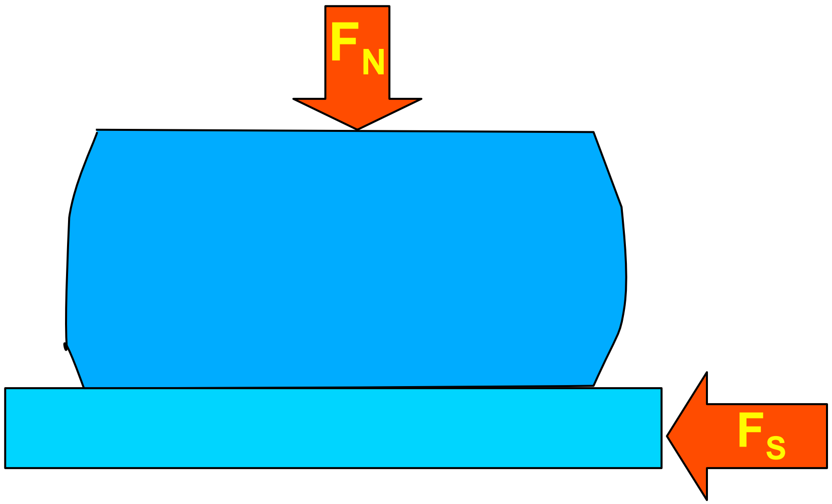
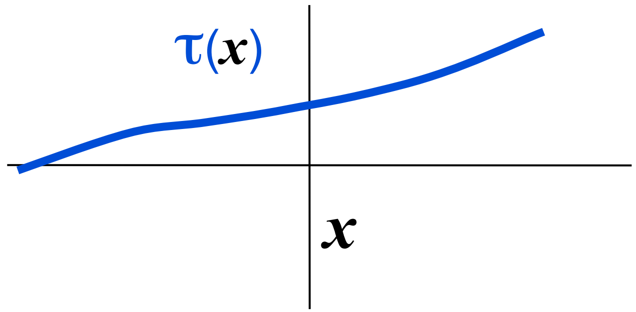


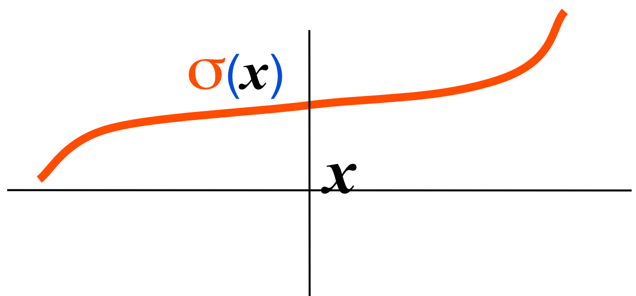


Uniform loading + friction

Frustrated Poisson expansion:

→ ***Non-uniform*** shear stess, $\tau(x)$

+ uniform normal stress, $\sigma(x)$



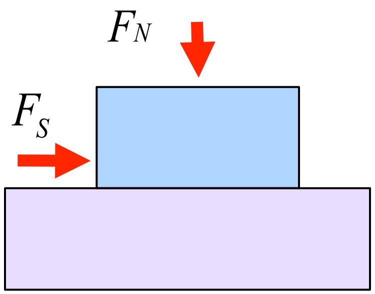
Torque due to applied shear, F_S:

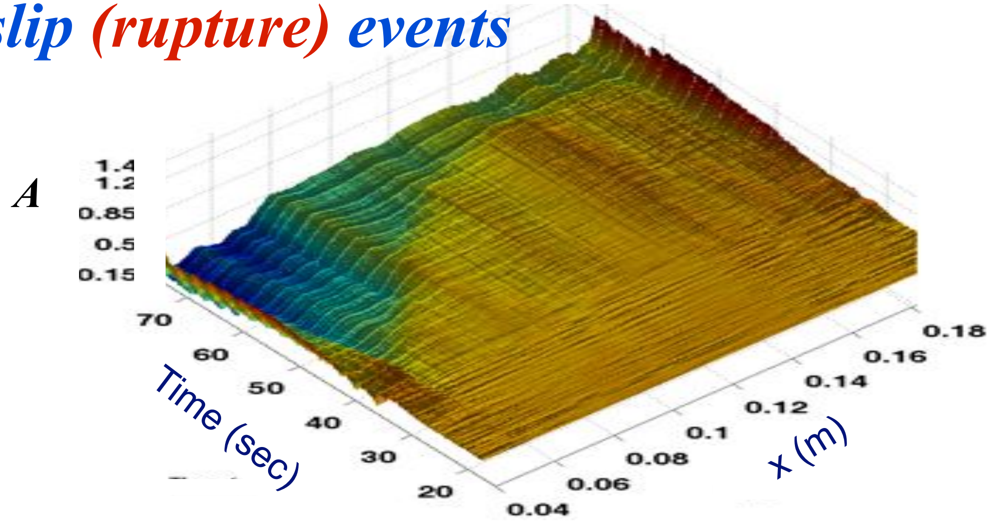
→ ***Uniformly*** increased $\tau(x)$

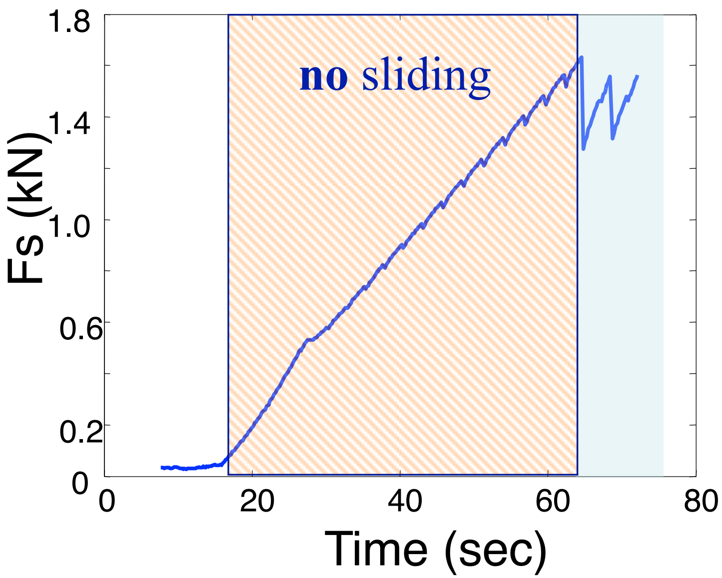
+ ***non-uniform*** $\sigma(x)$

S. M. Rubinstein, G. Cohen, and J. F., Phys. Rev. Lett. 96, 256103 (2006)

The contact-area/stress distribution can also change ***dynamically via arrested precursory slip (rupture) events***







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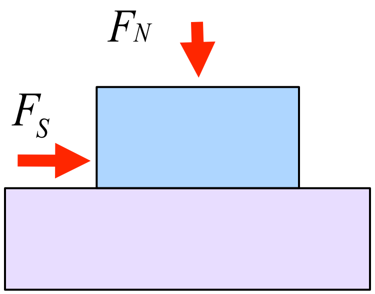

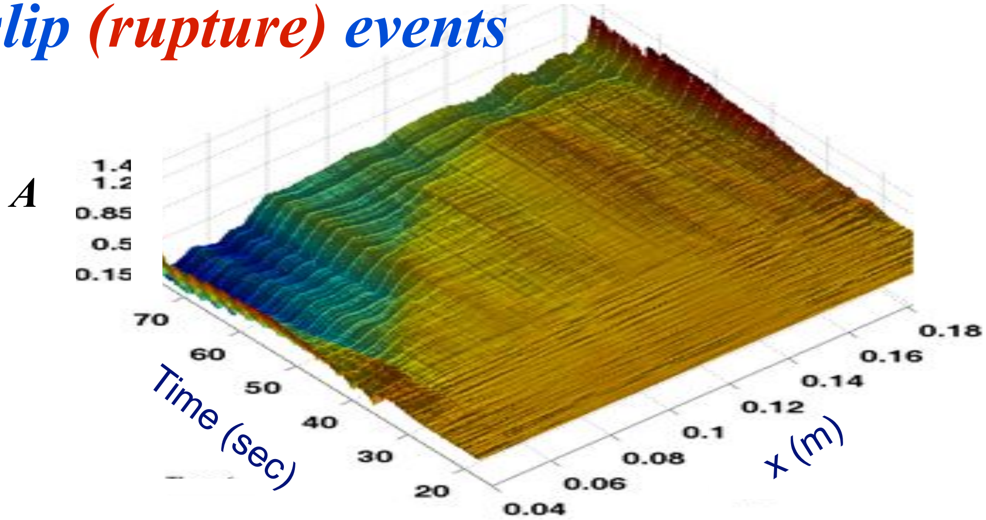

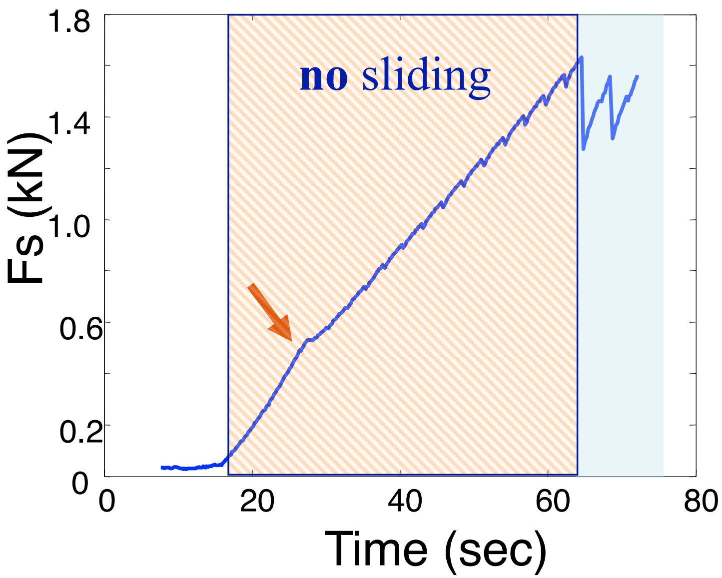

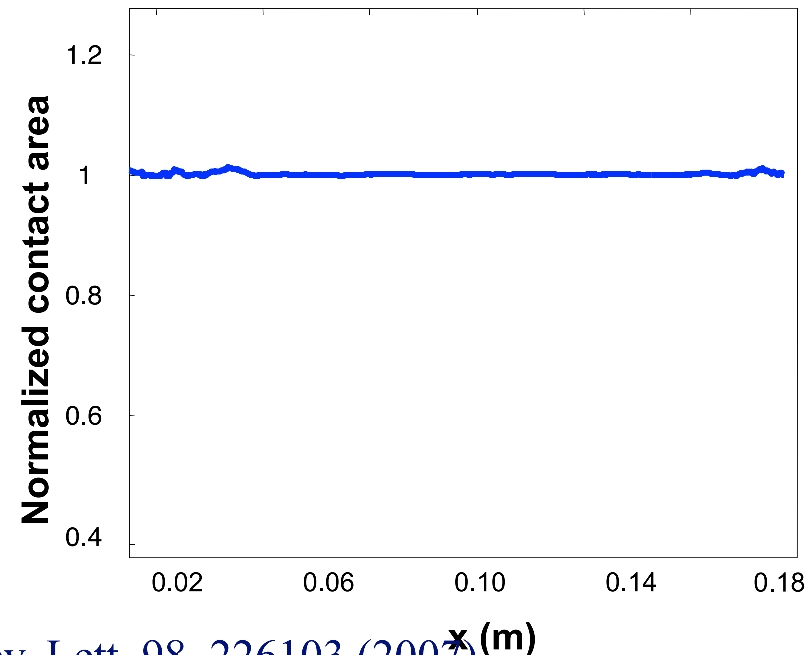

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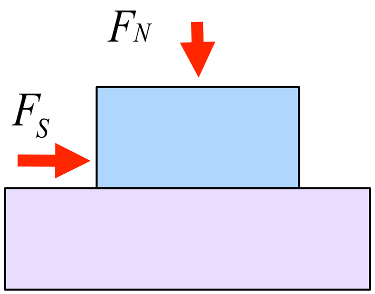

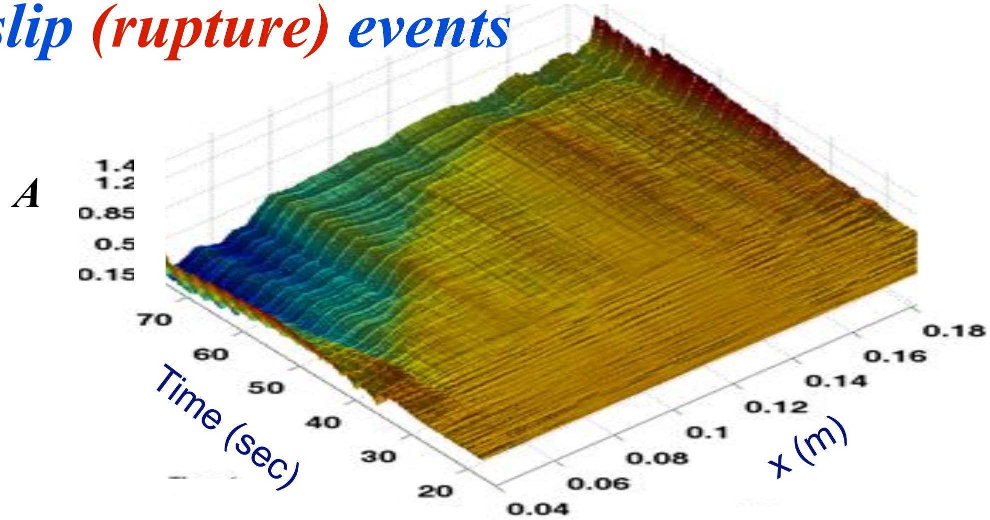

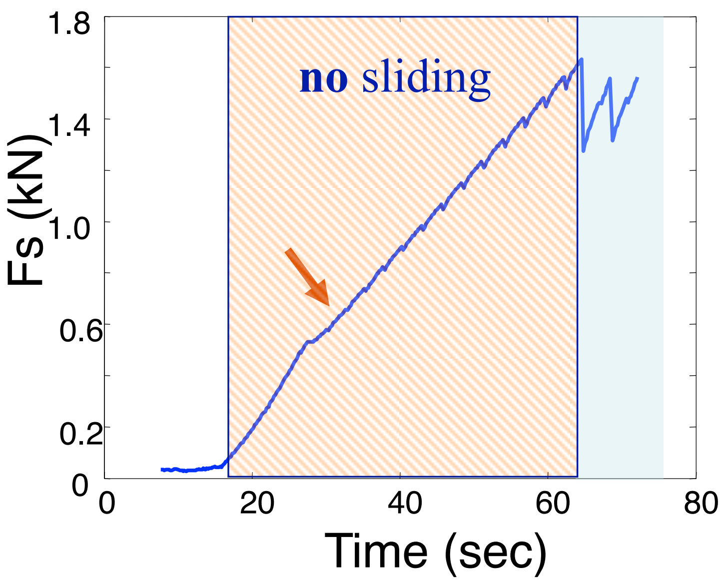

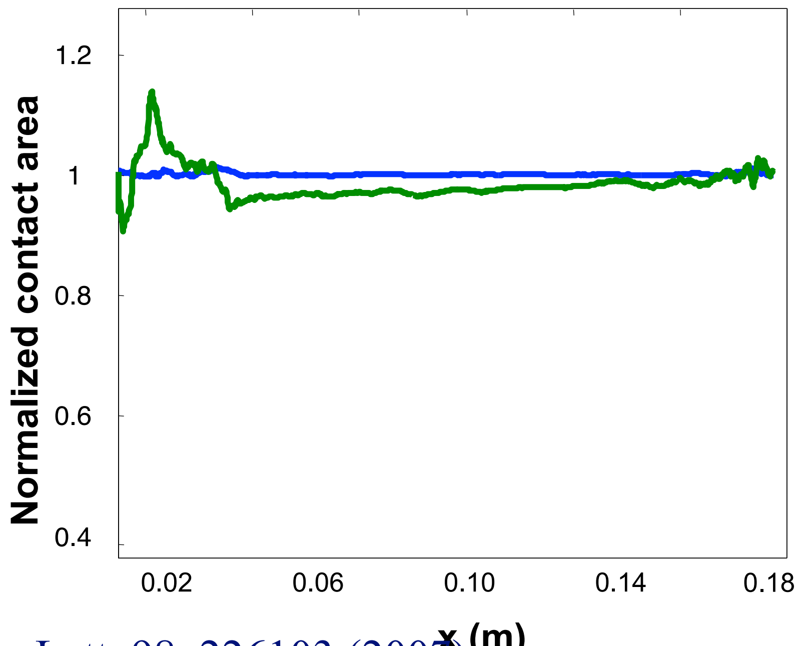

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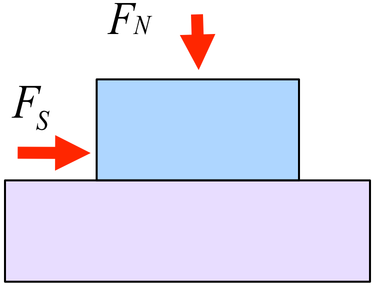

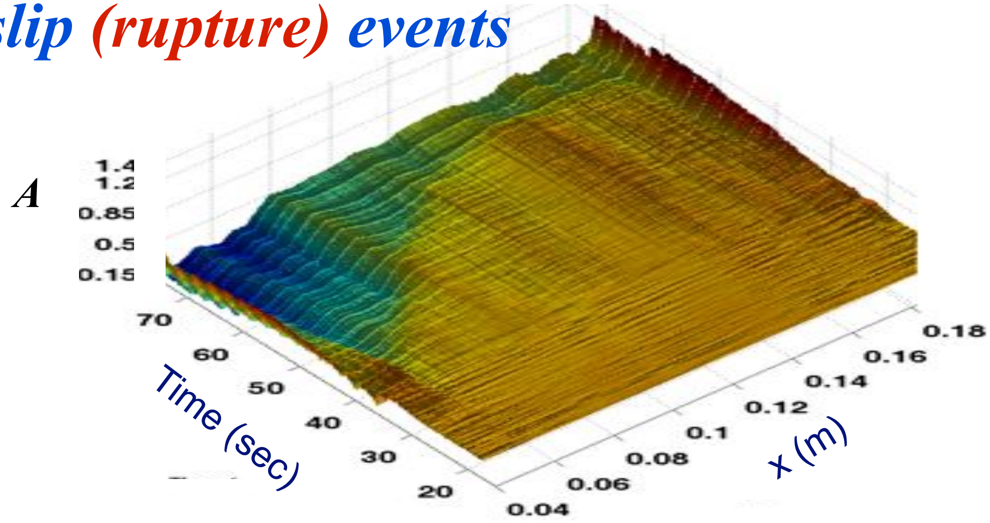

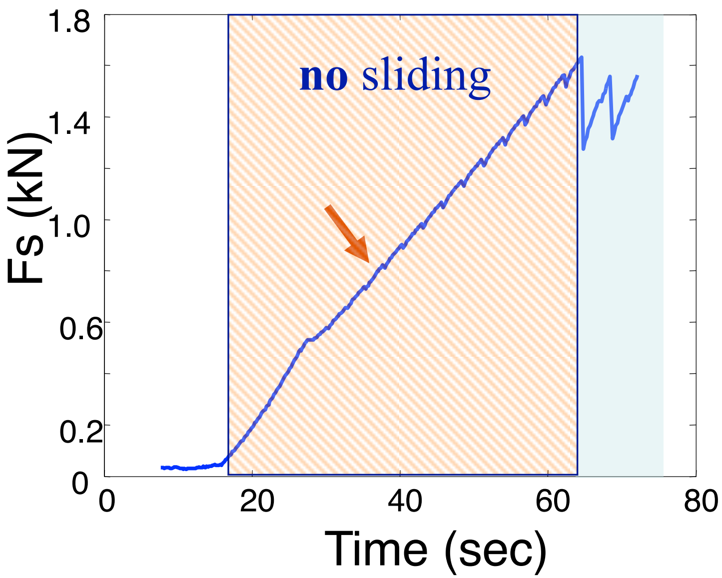

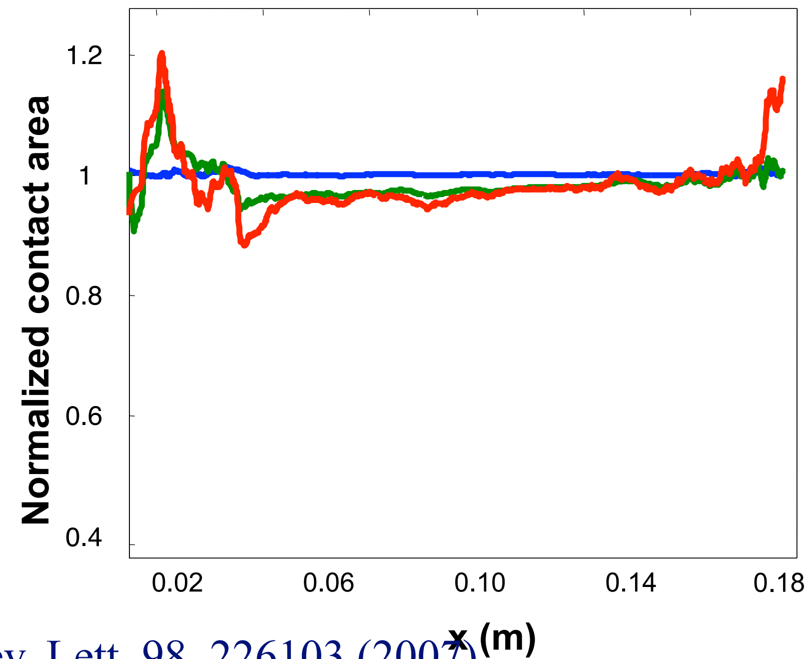

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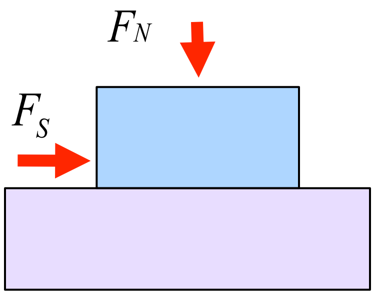

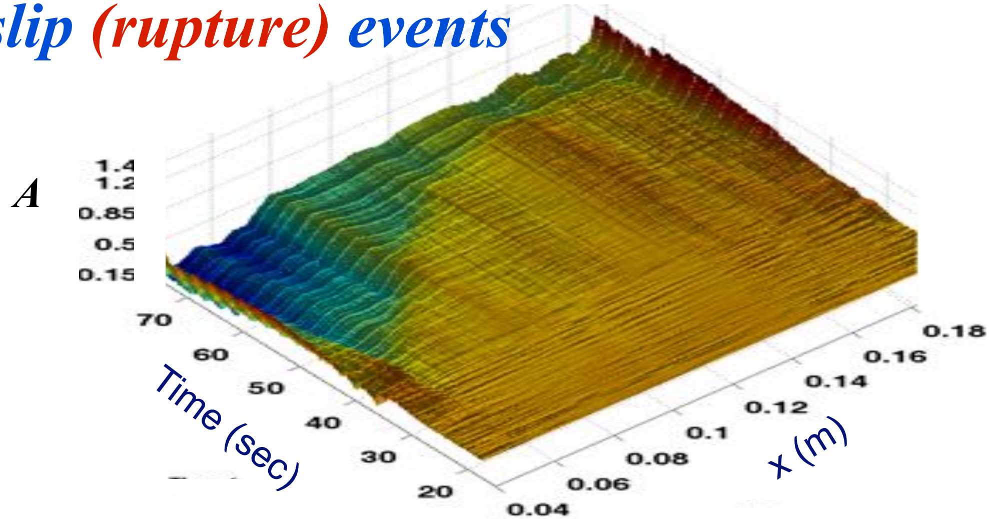

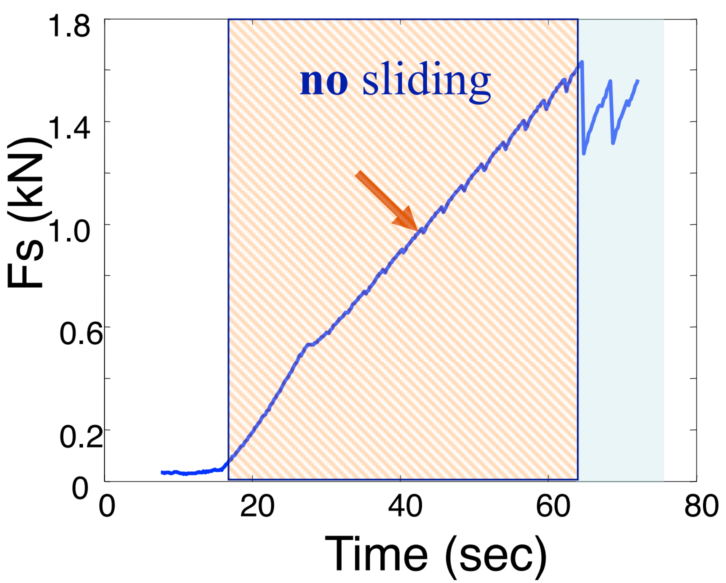

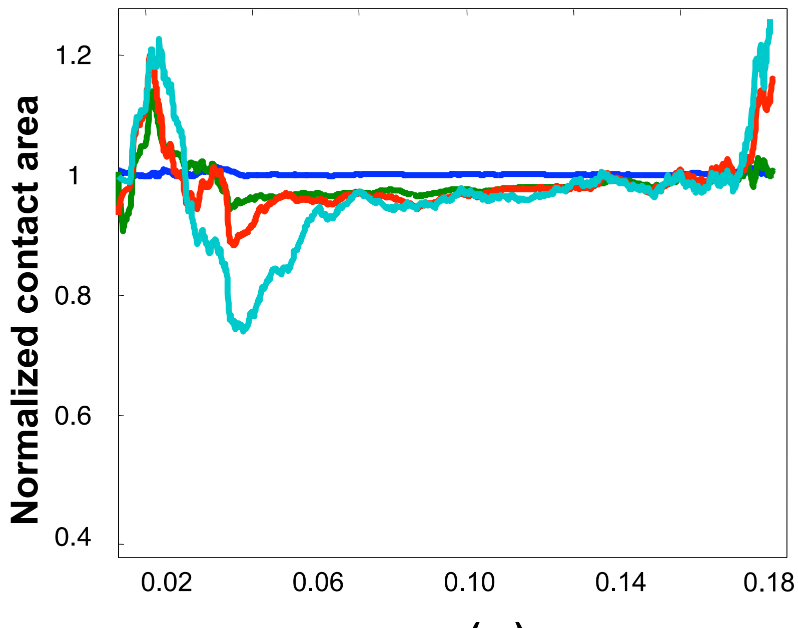

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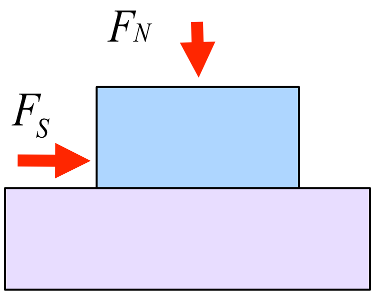

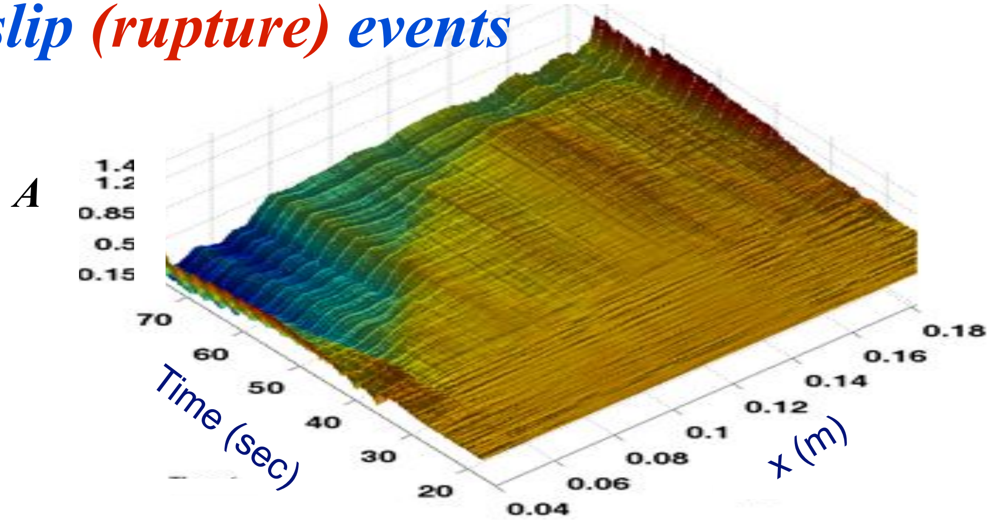

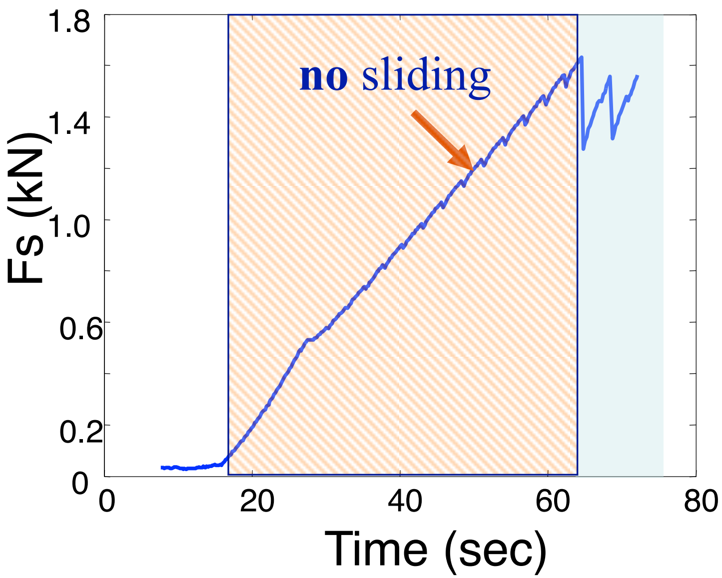

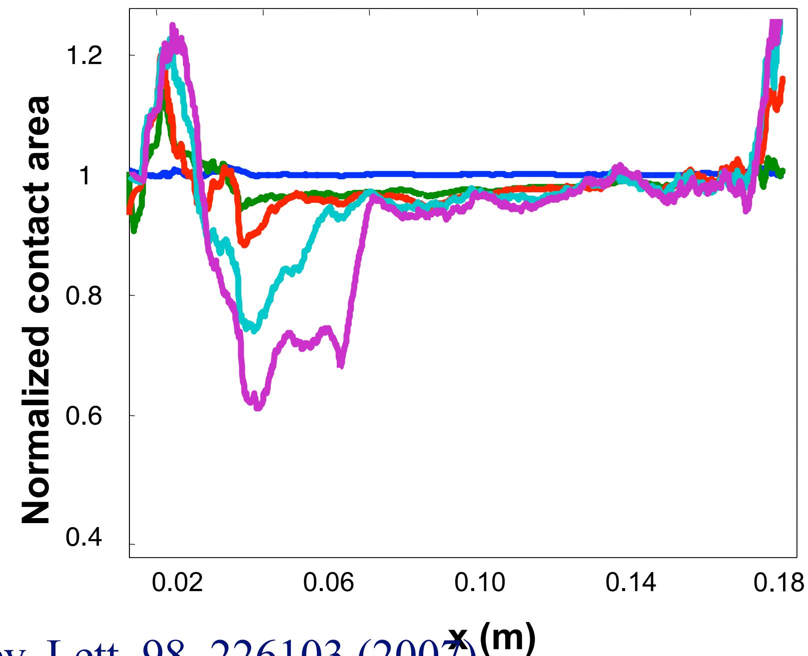

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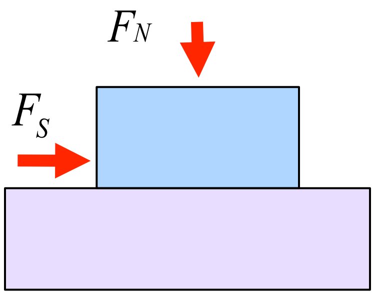

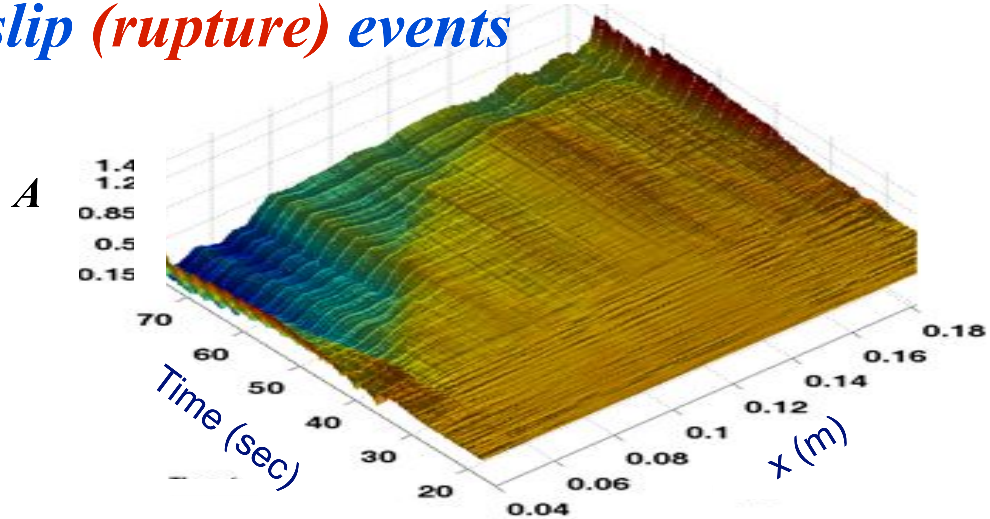

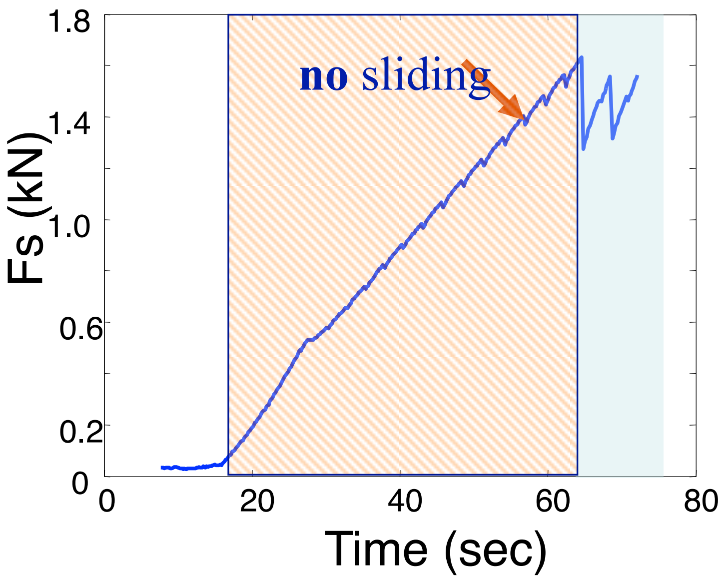

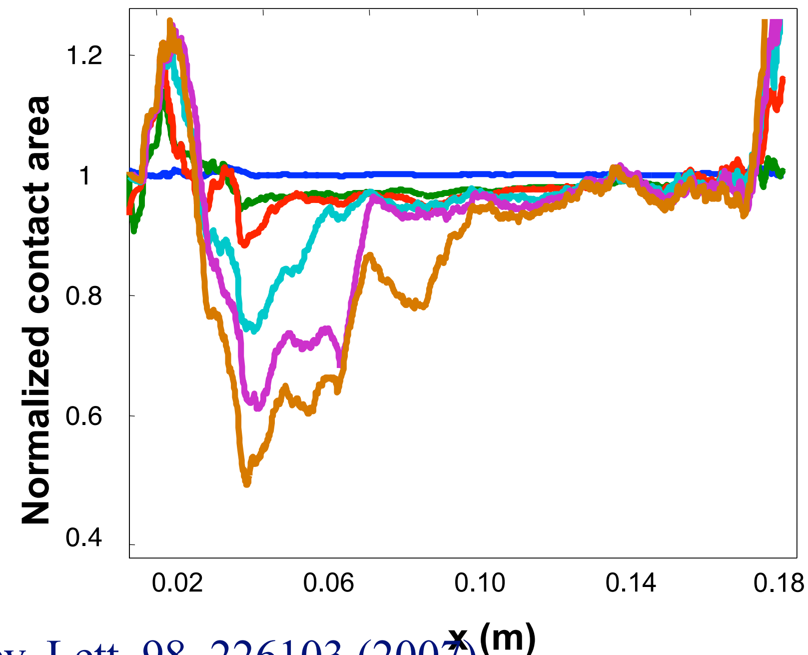

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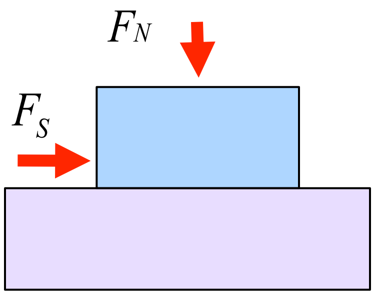

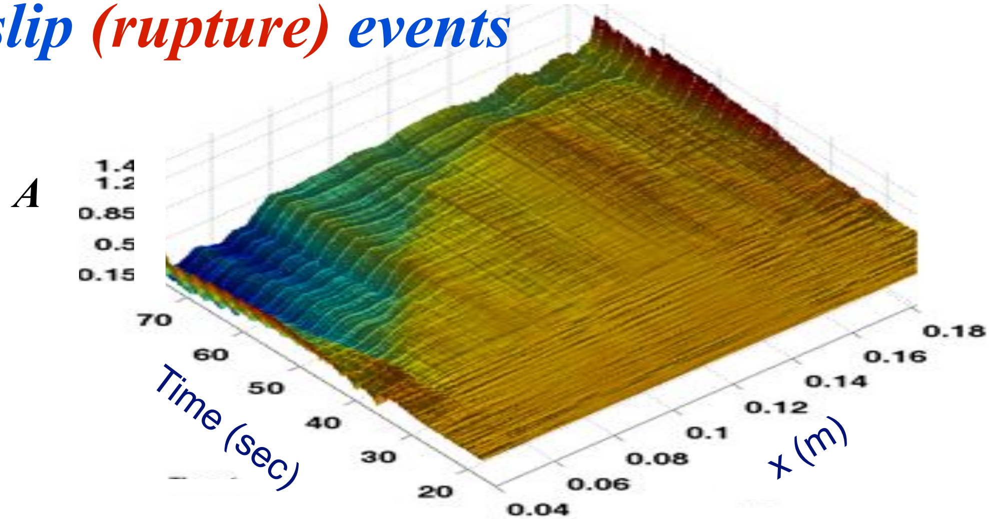

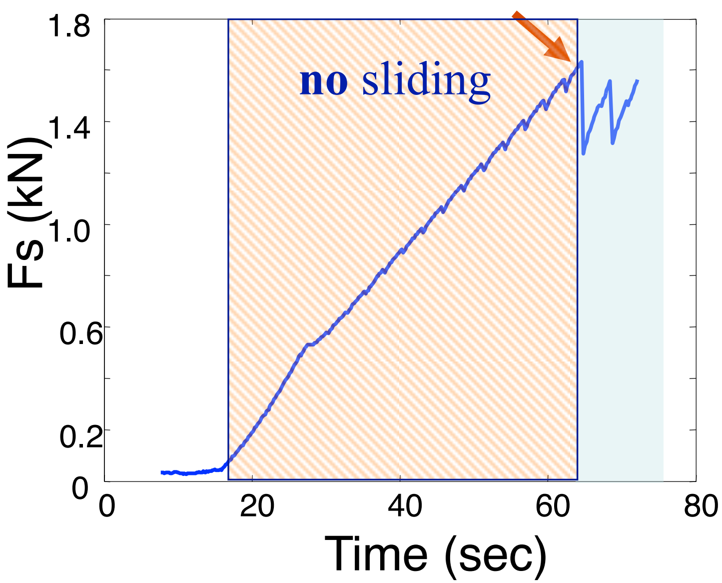

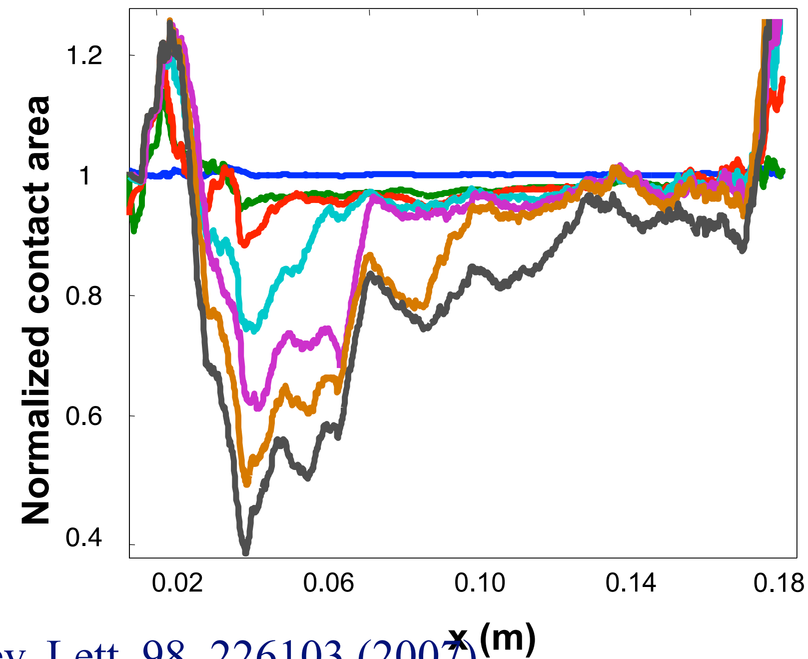

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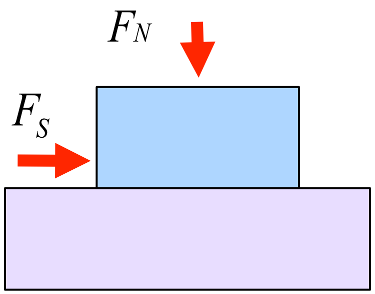

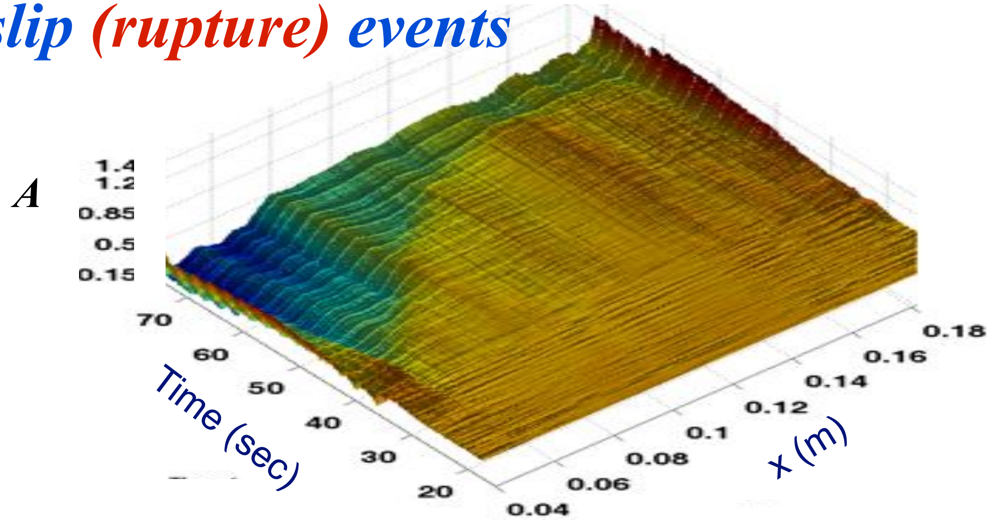

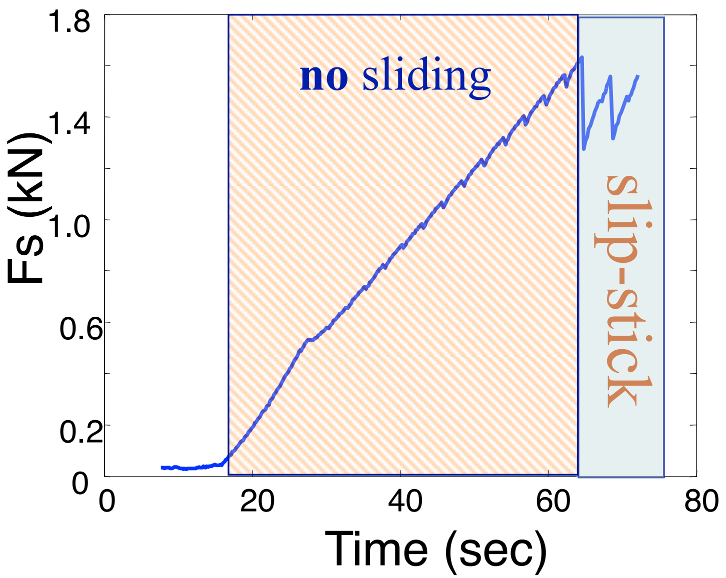

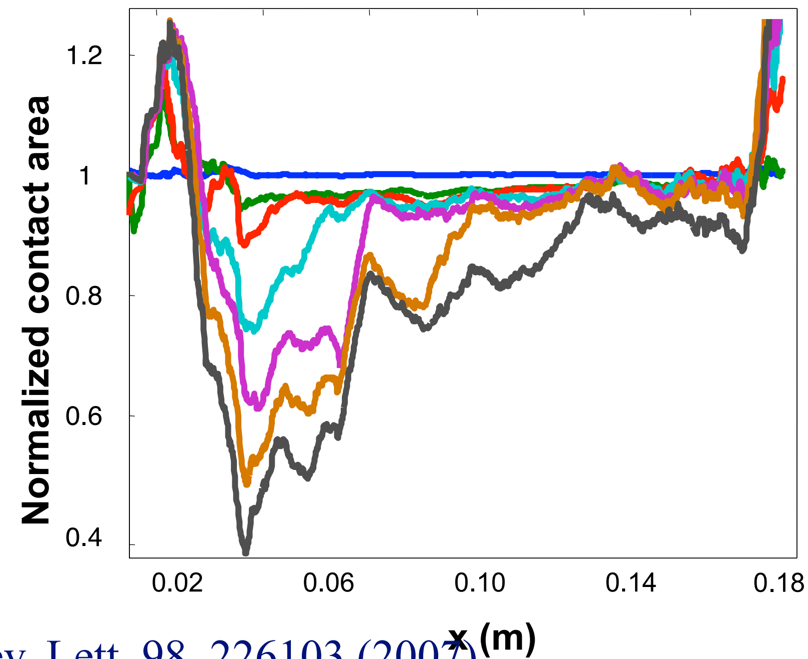

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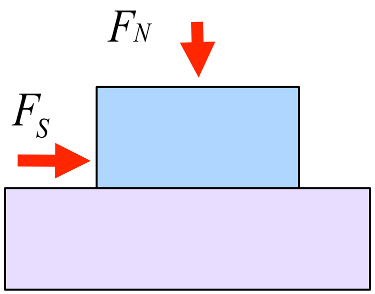
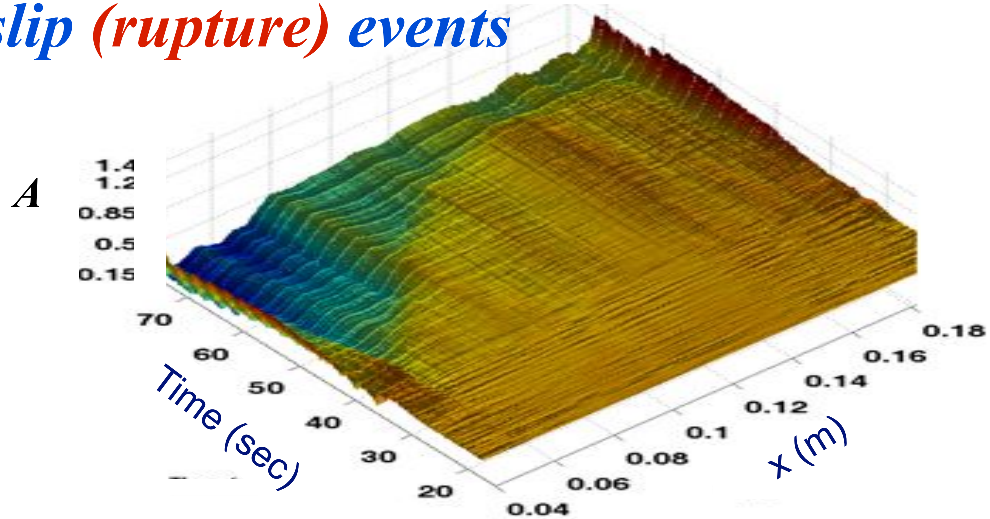
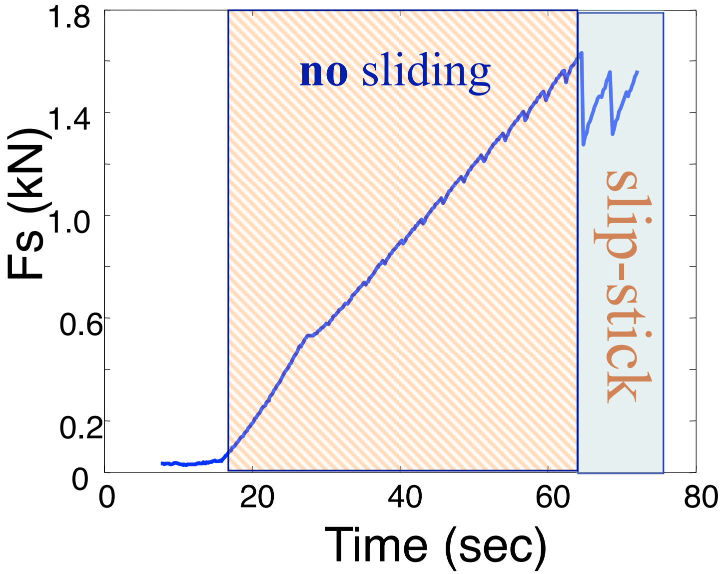
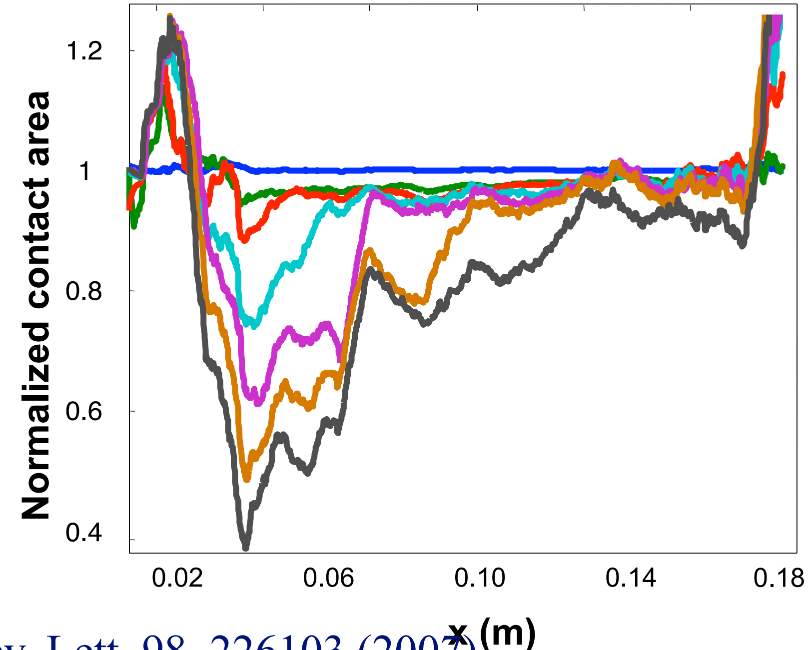




• Precursors create highly non-uniform $A(x)$





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Monday, November 1, 2010

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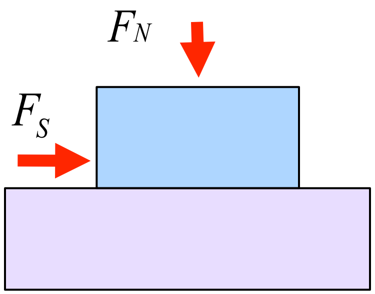
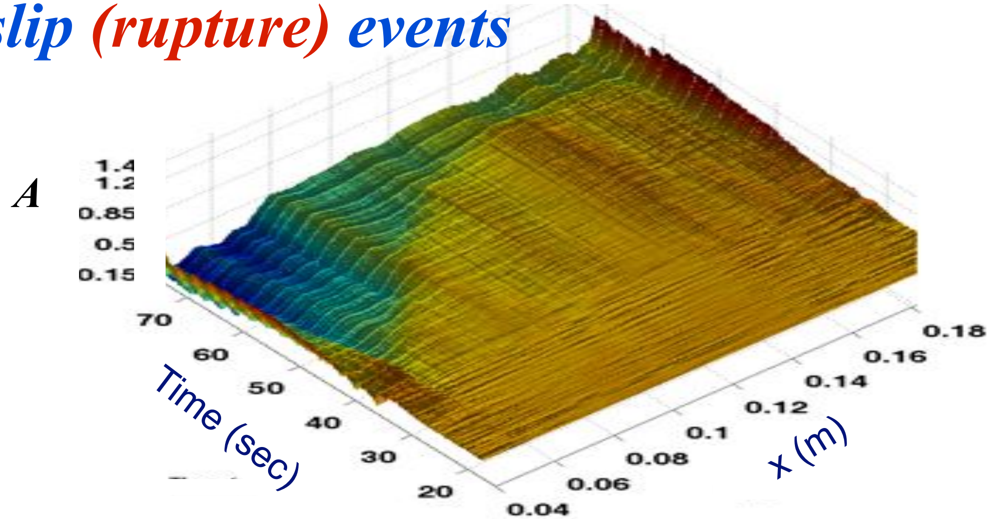
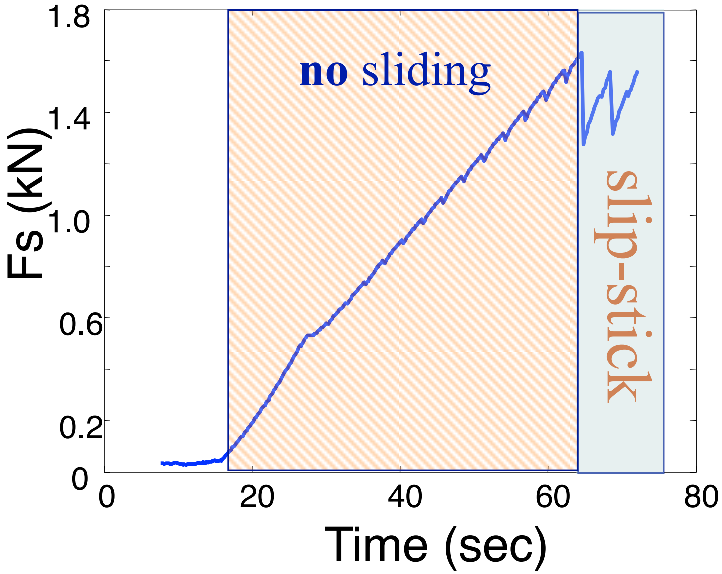
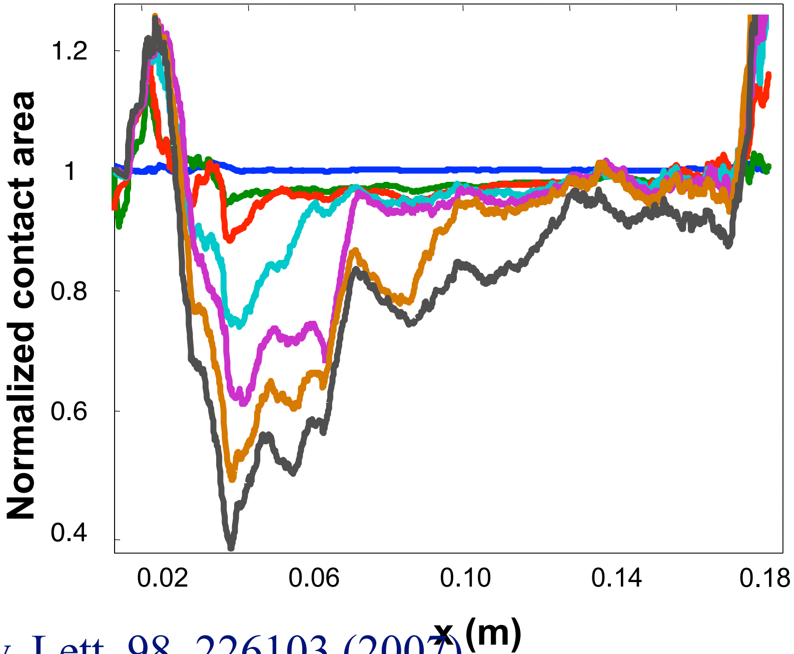




- Precursors create highly non-uniform $A(x)$
- $A(x)$ profile $\propto$ $\sigma(x)$ (normal stress)





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What types of rupture events occur upon slip initiation?

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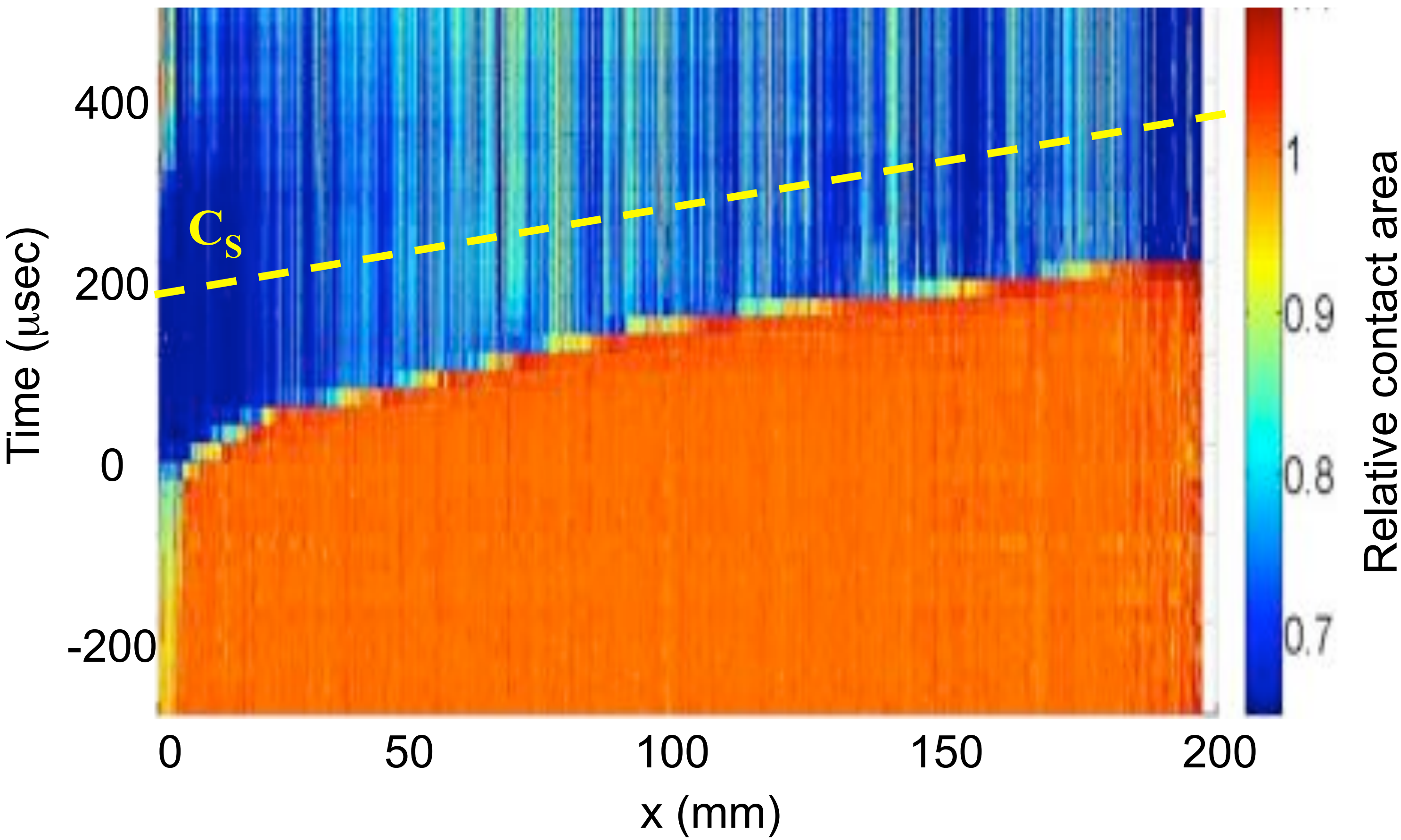
"Garden variety" rupture ($v < C_S$)



Horizontal lines are A(x) over the entire interface separated in time by 2-20μs

What types of rupture events occur upon slip initiation?

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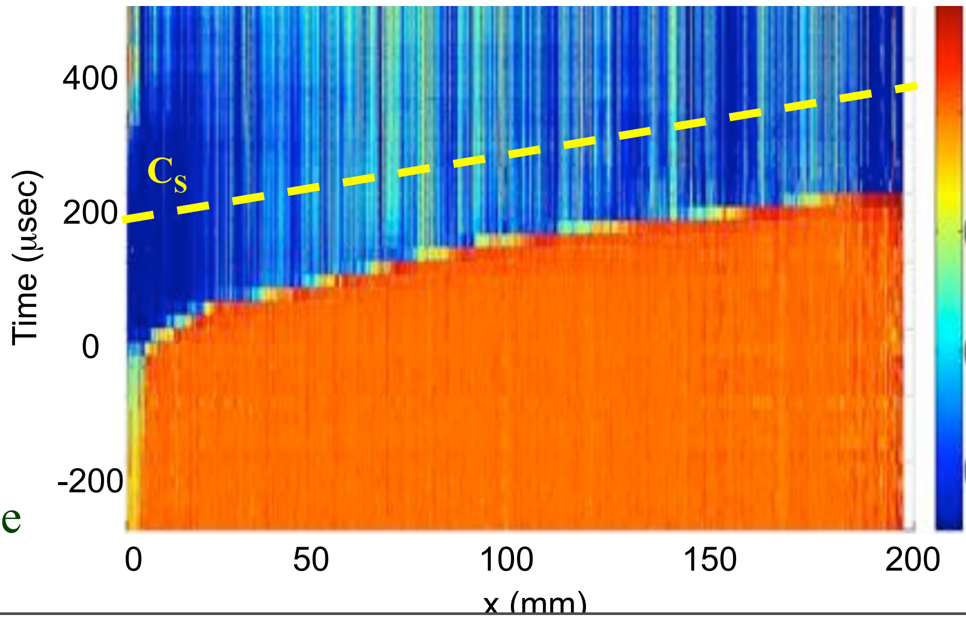

Horizontal lines are *A*(x) over the entire interface separated in time by 2-20µs

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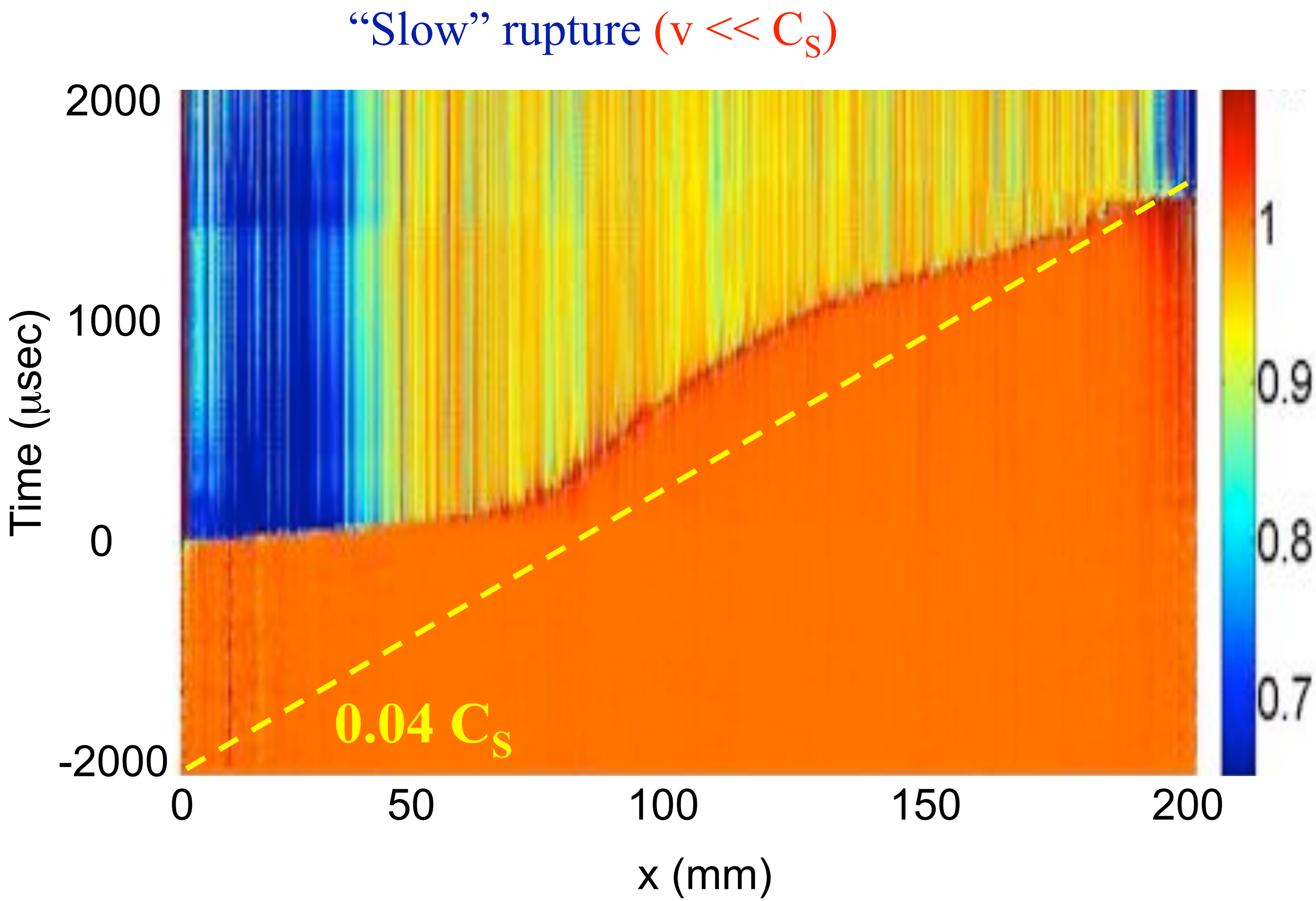
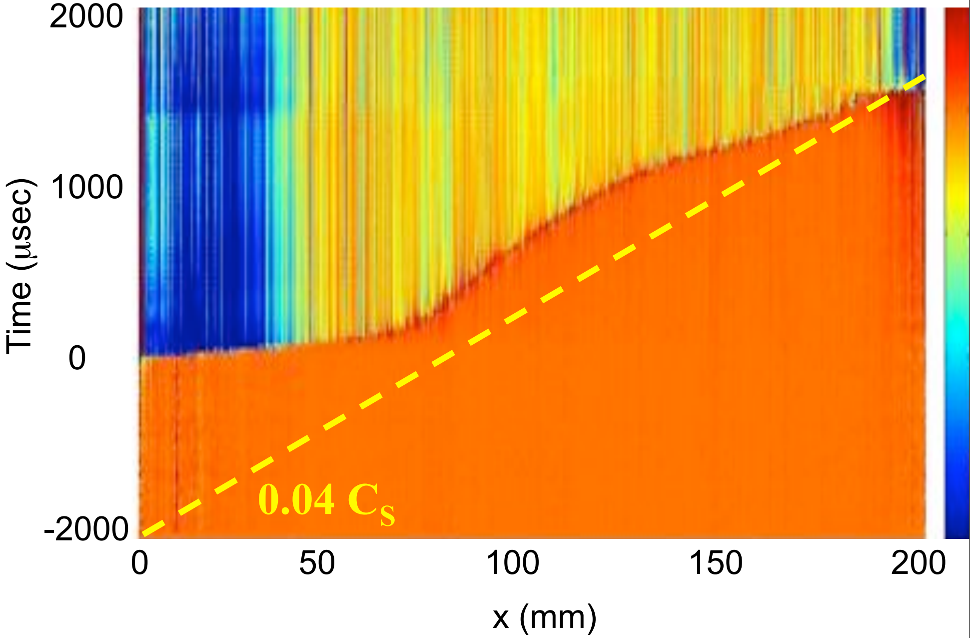


Horizontal lines are *A*(x) over the entire interface separated in time by 2-20μs

What types of rupture events occur upon slip initiation?

"Slow" rupture (v << C_S)



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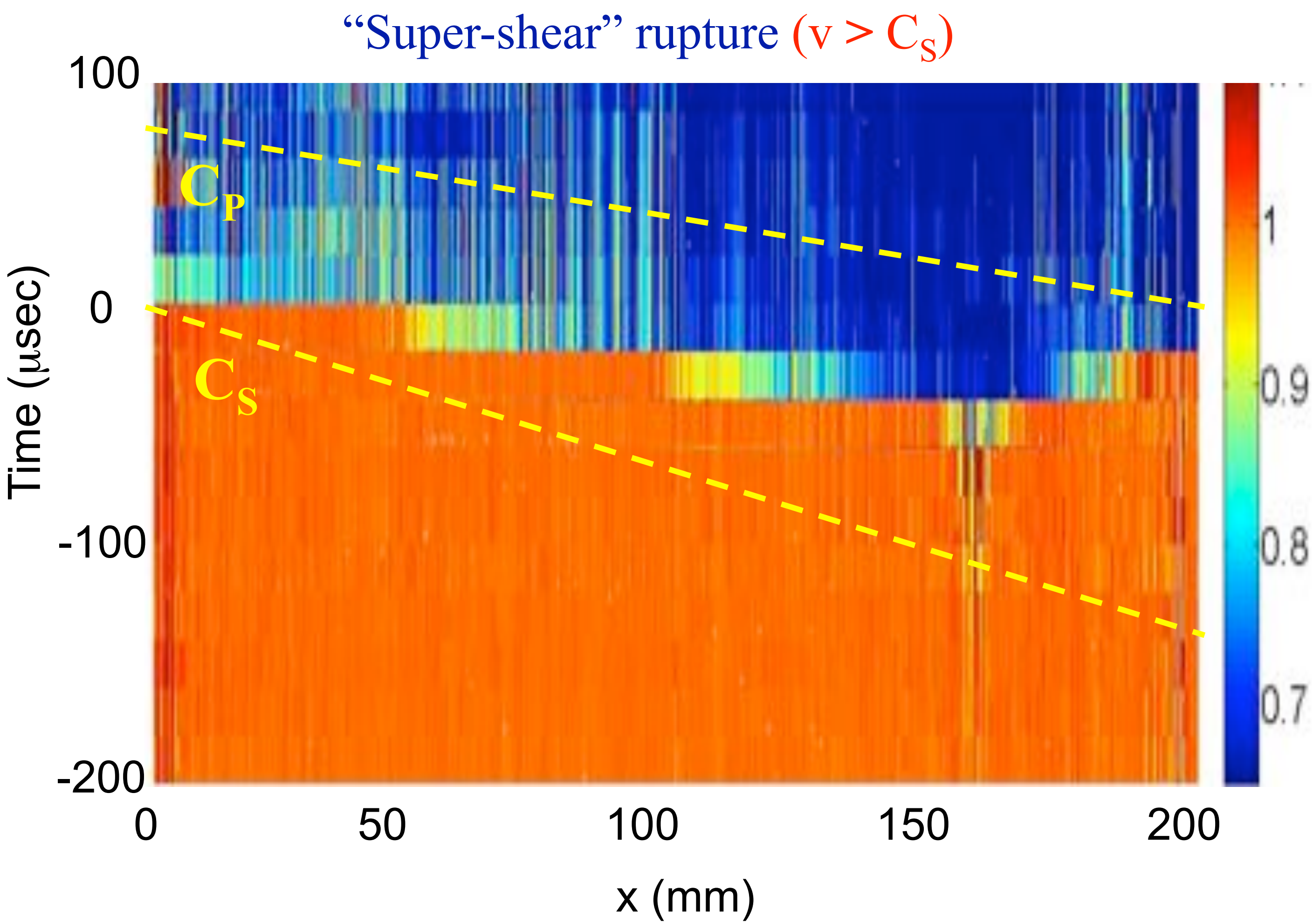

Horizontal lines are *A*(x) over the entire interface
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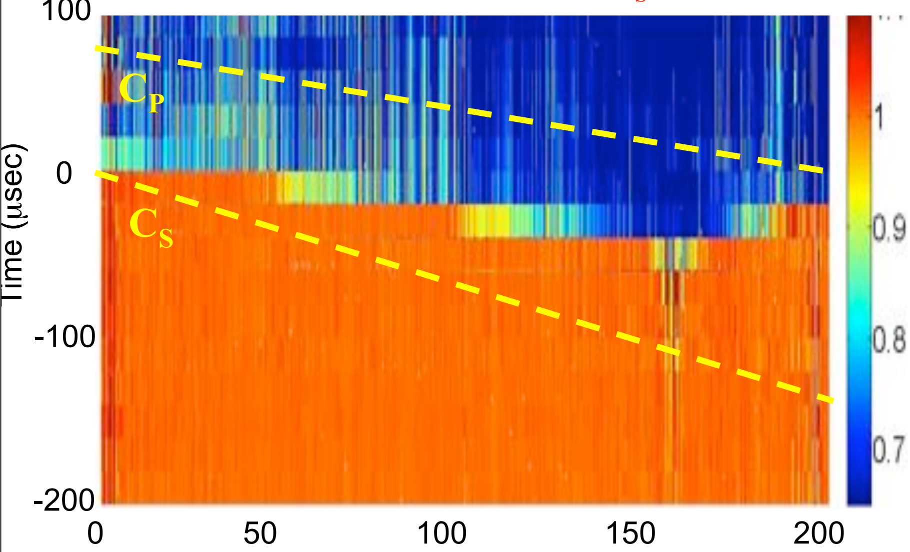
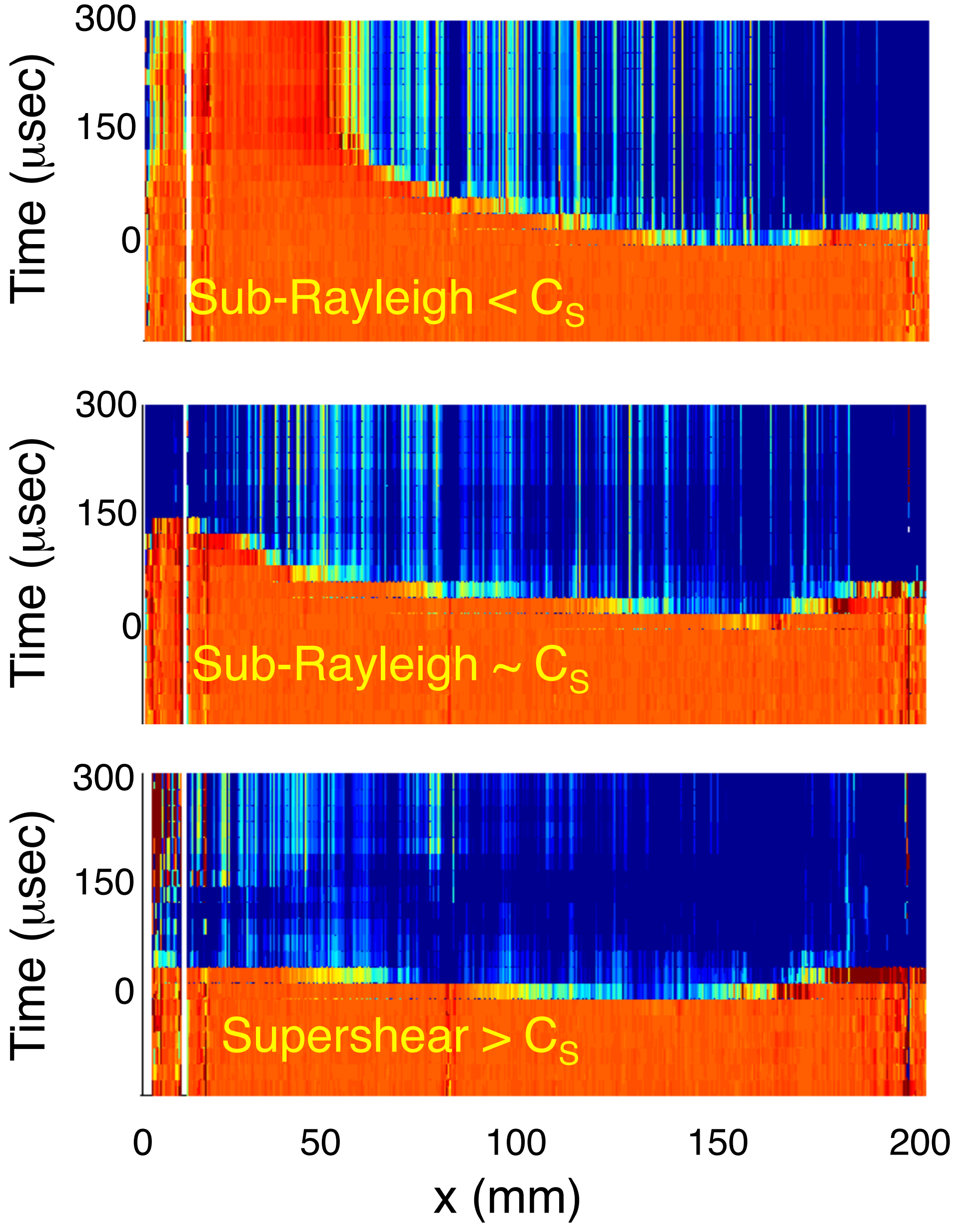
What types of rupture events occur upon slip initiation?

“Super-shear” rupture (v > C_S)



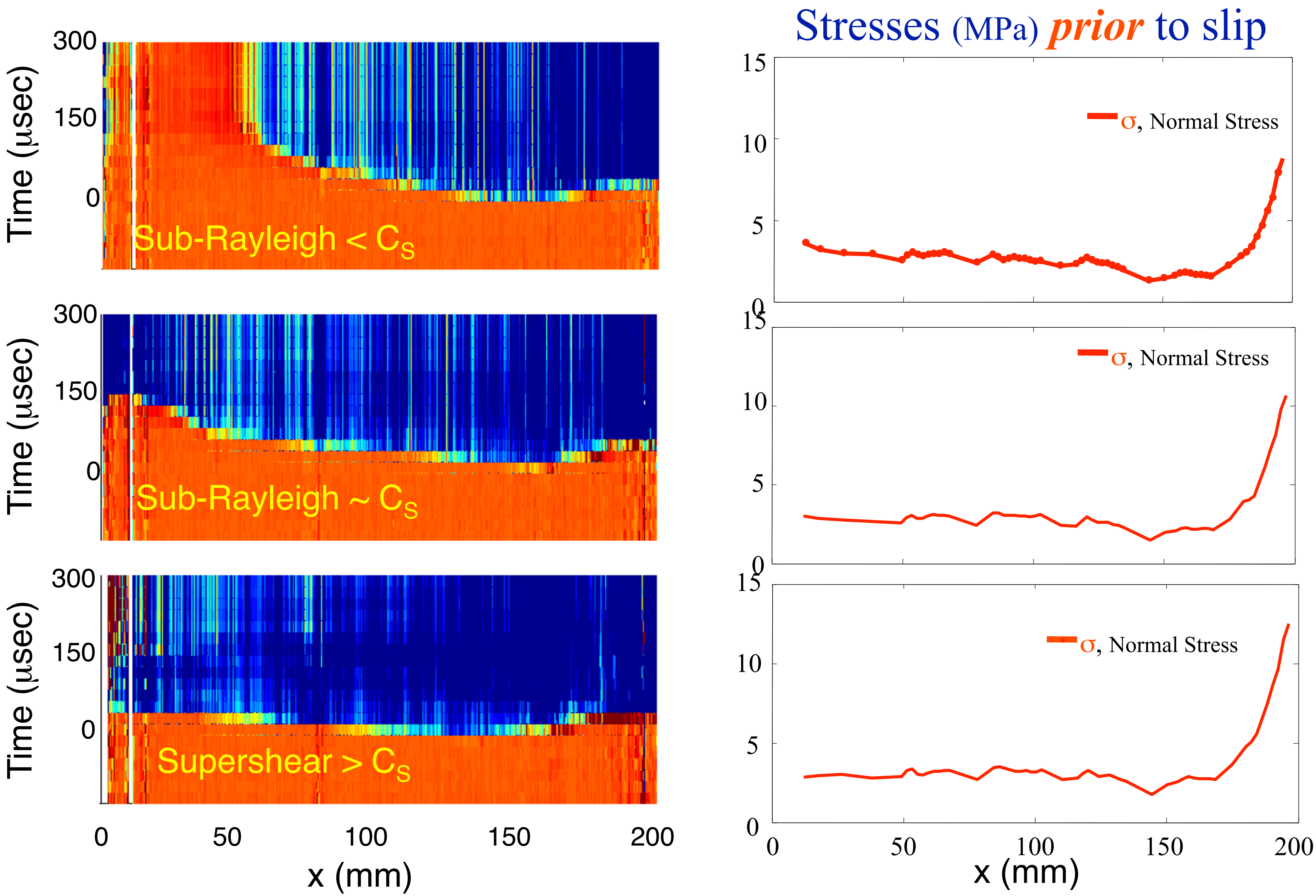
- Why do we see three ***different*** classes of “crack-like” behaviors?
- ***When*** do we see them?
- Can we ***predict*** which of the different types of ruptures will occur?



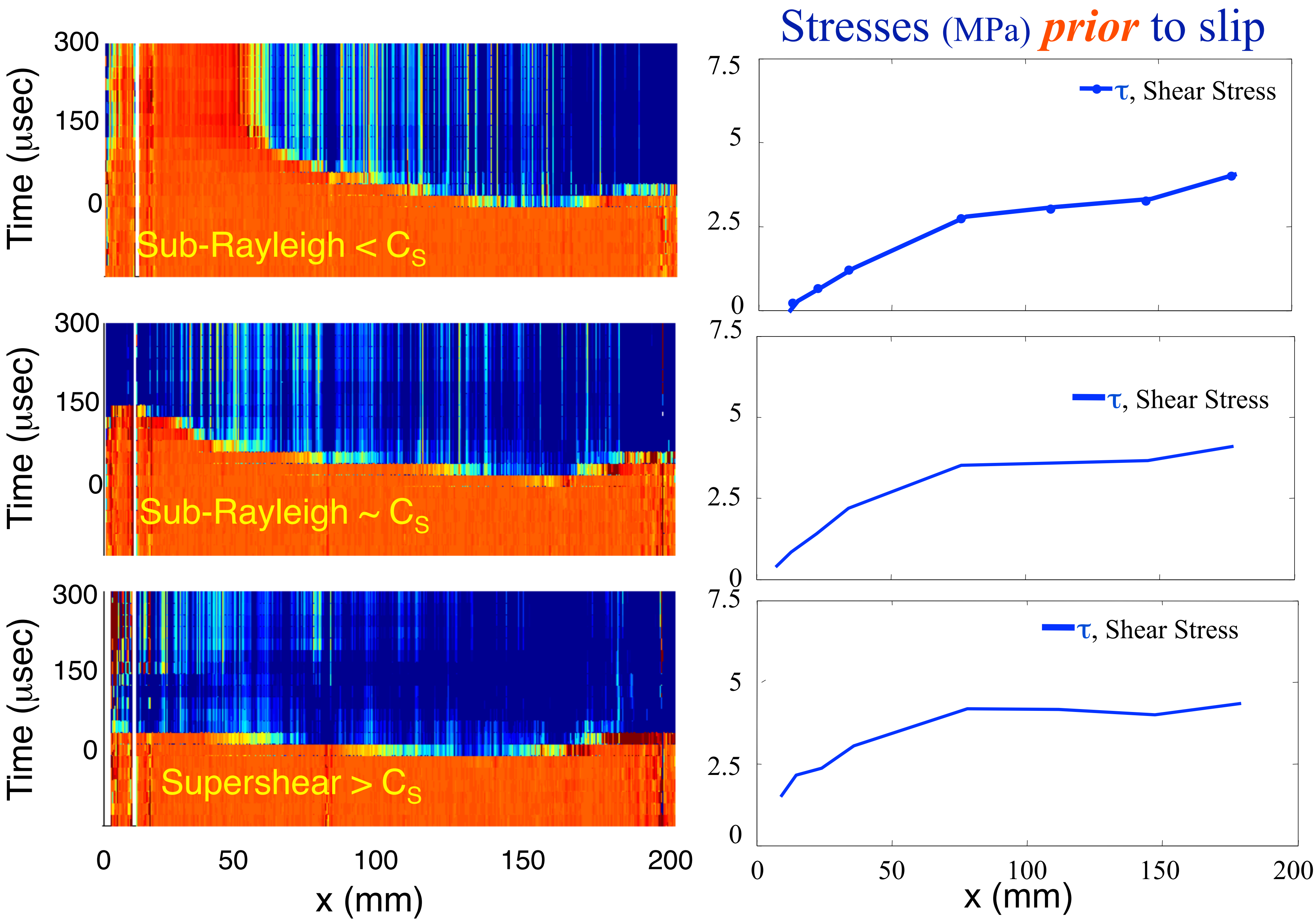
Three successive slip events driven under *ostensibly* the ***same external*** loading conditions:

Let's look at the ***measured*** stress distributions…

• Normal stress distributions are nearly identical!

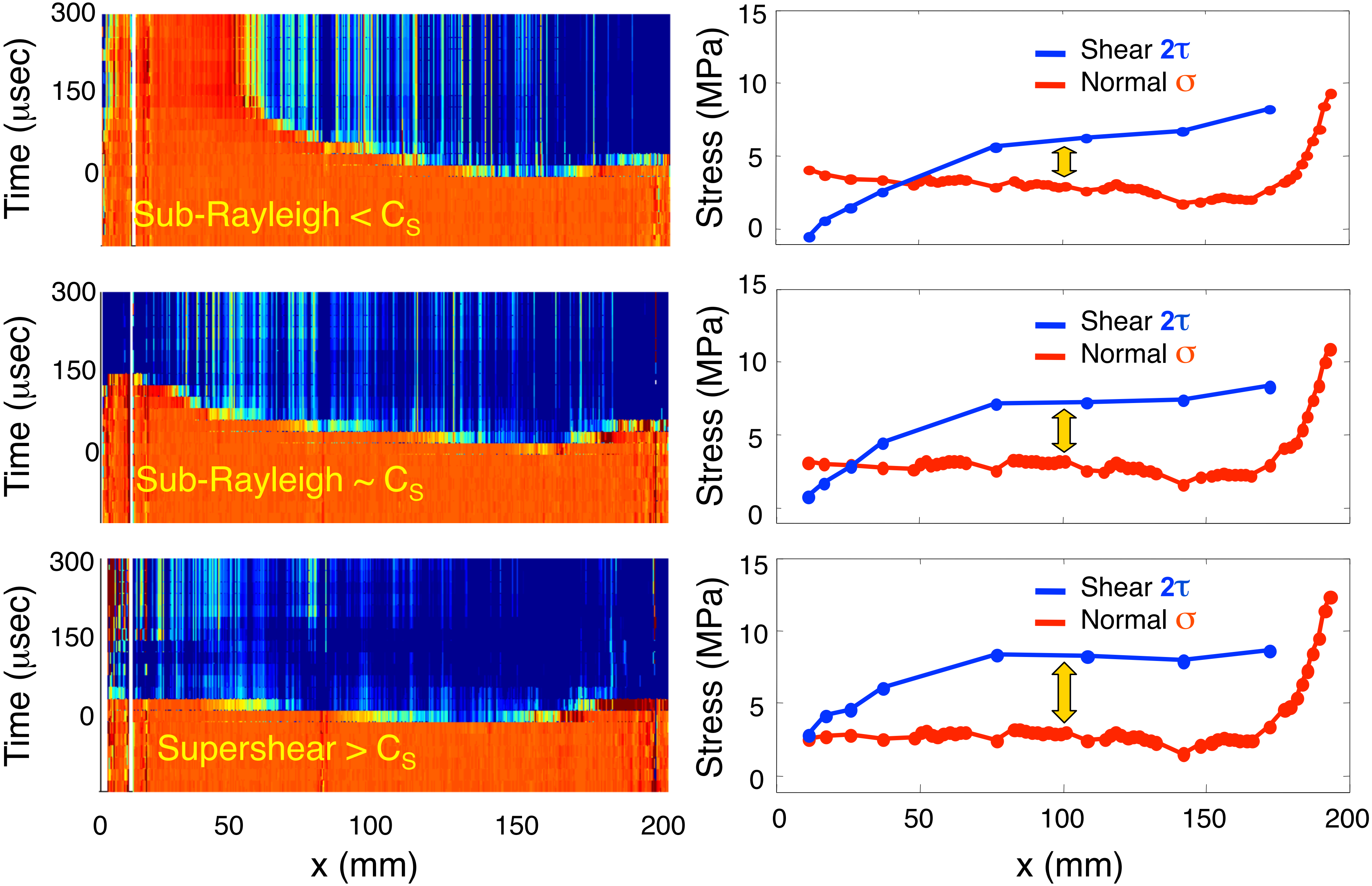


• Shear stress distributions are very similar! – What's going on?

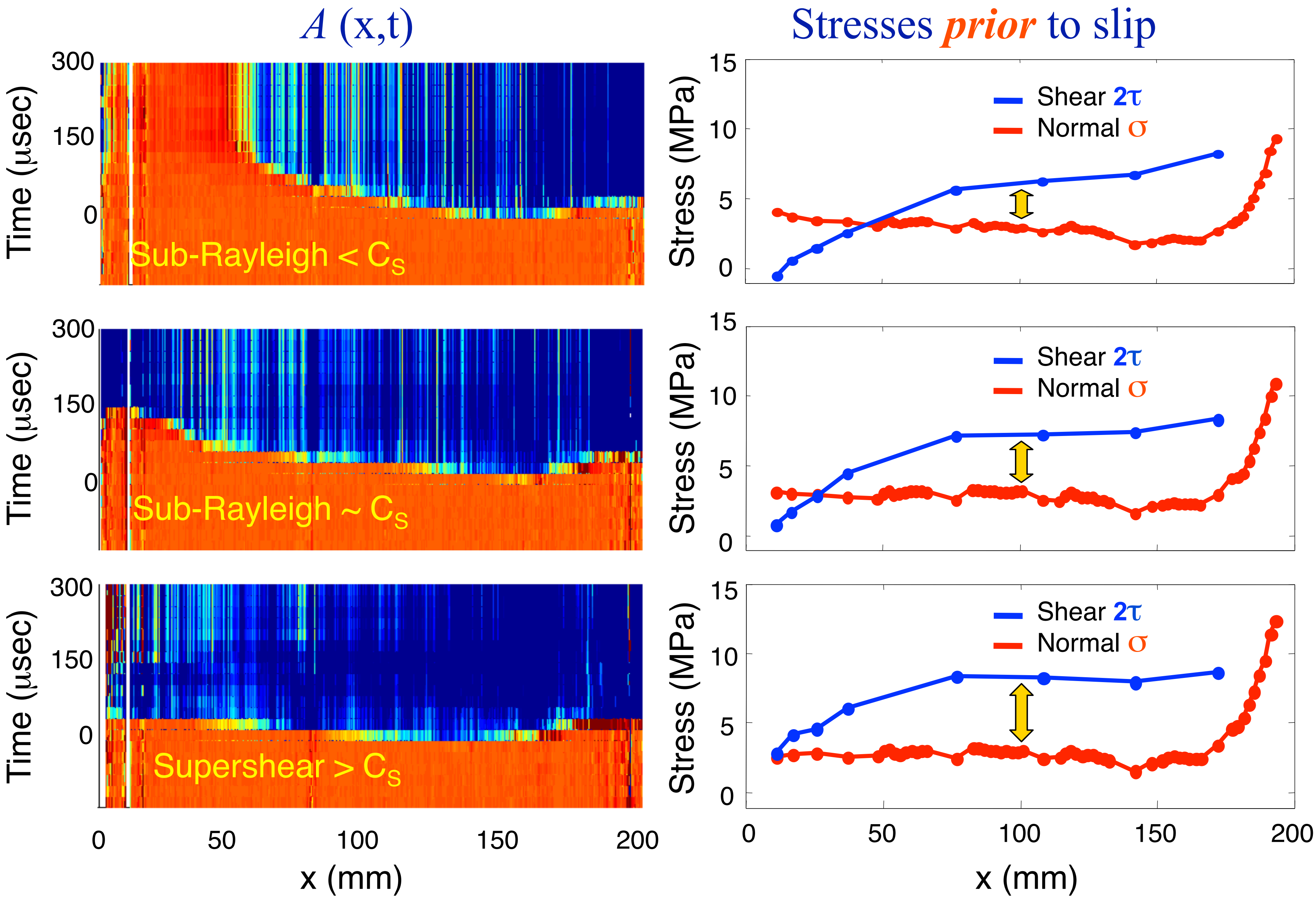


A (x,t)

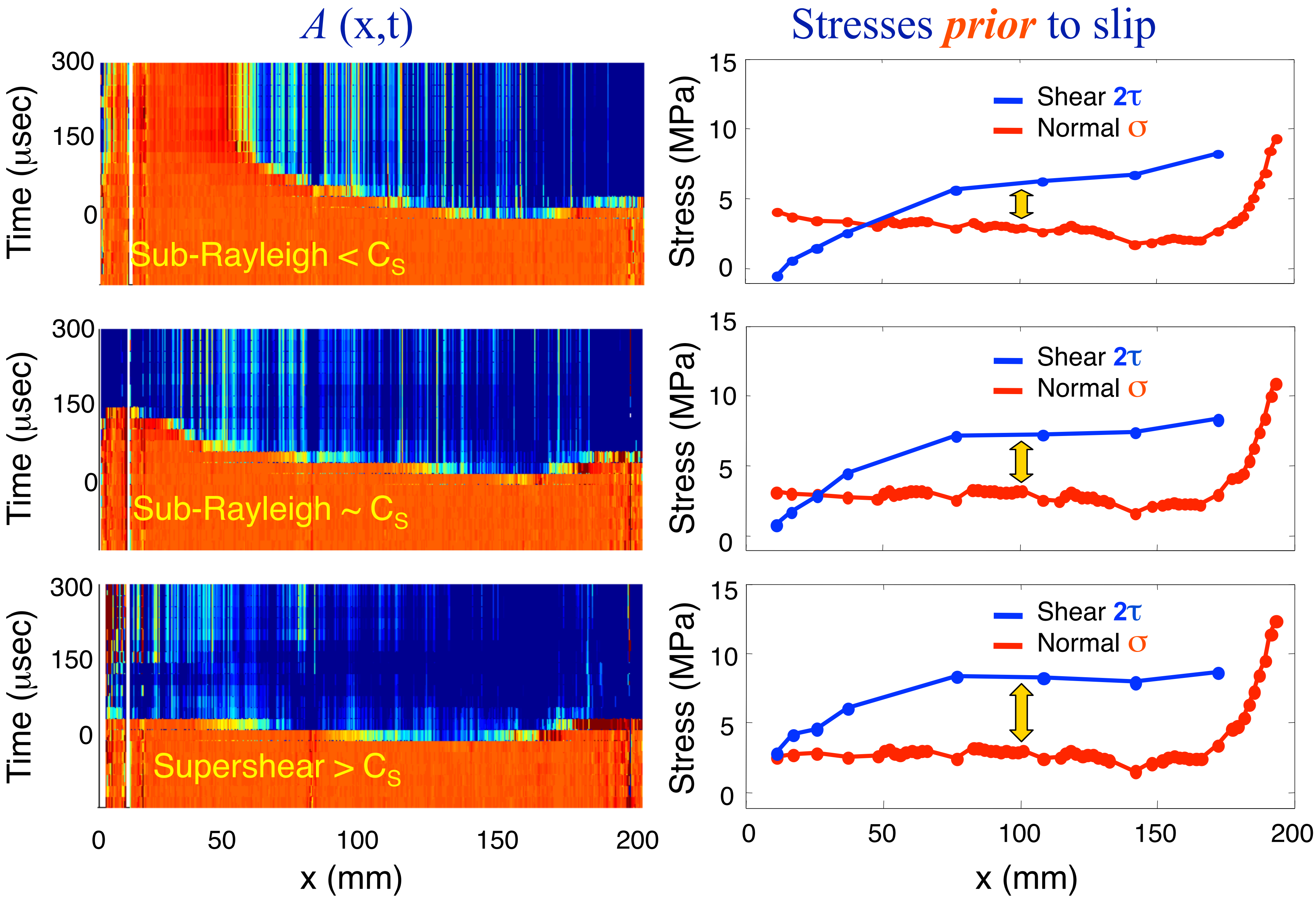
Stresses *prior* to slip



• A hint is given by looking at the ***local*** stress ***differences***!



Local stress *differences* predict the *different* local dynamics



Does this hold for all types of rupture process?

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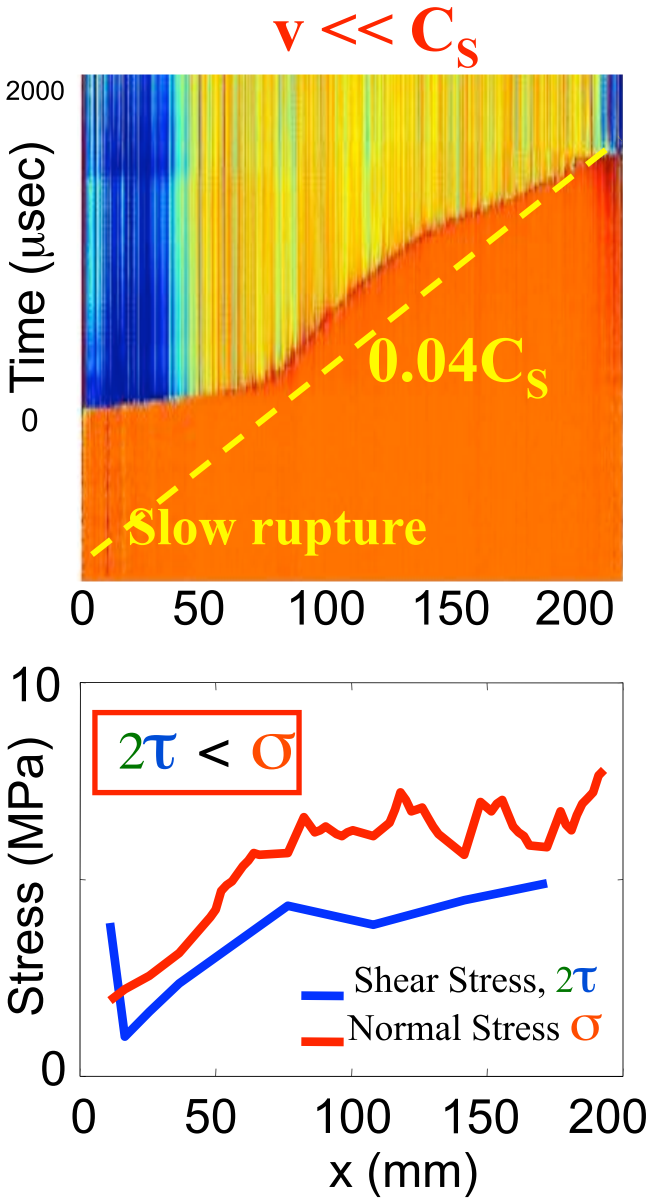

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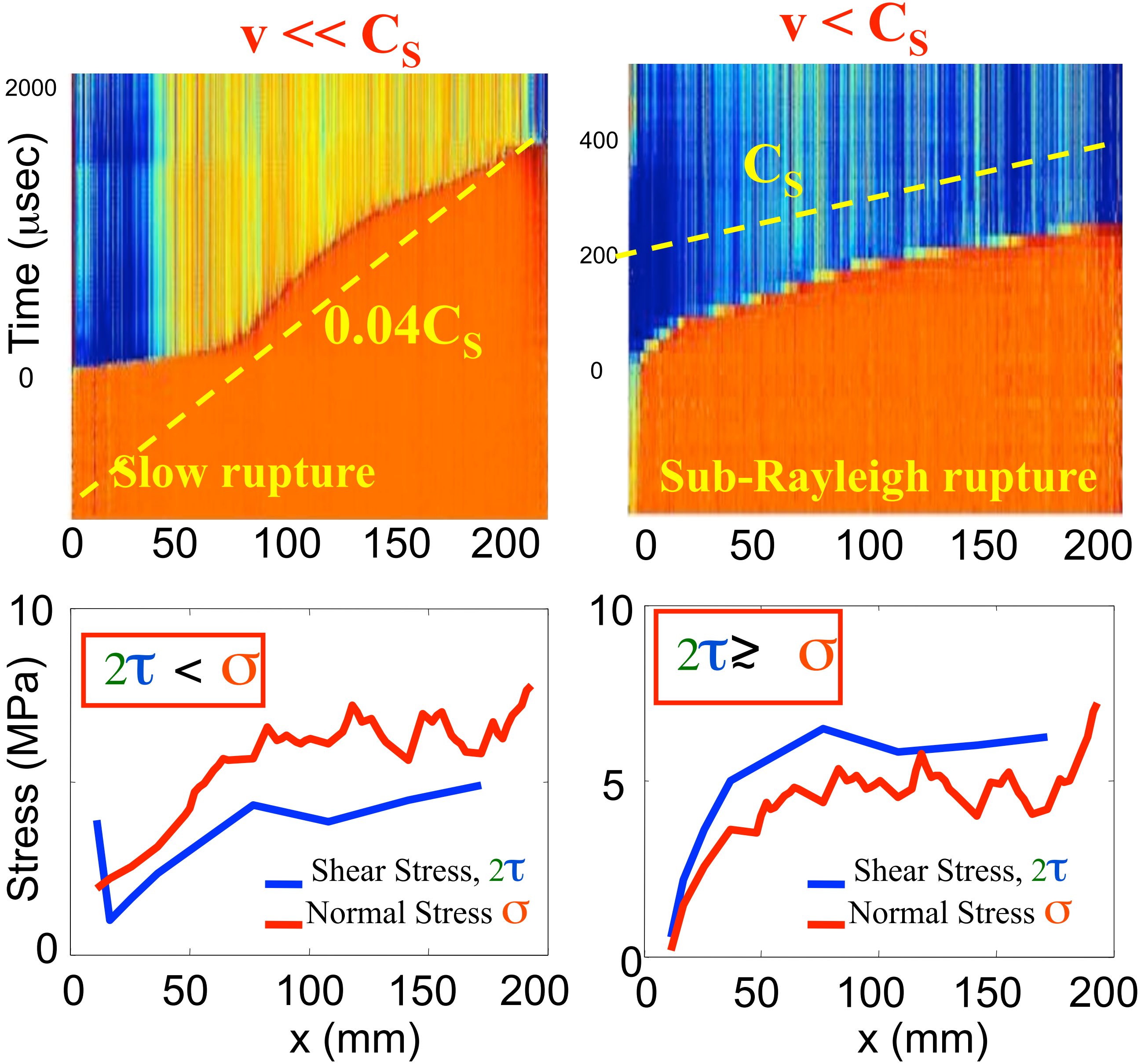

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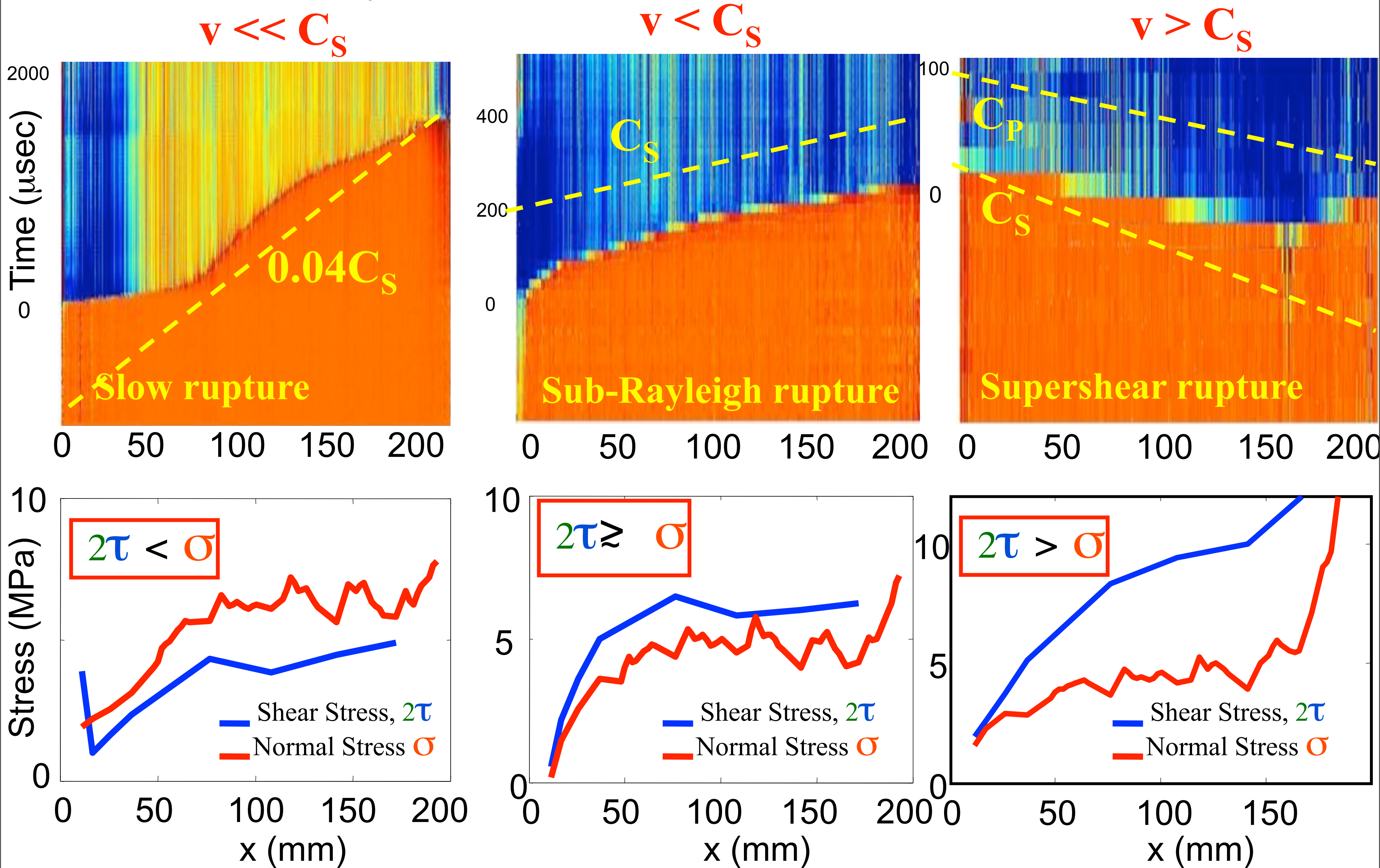
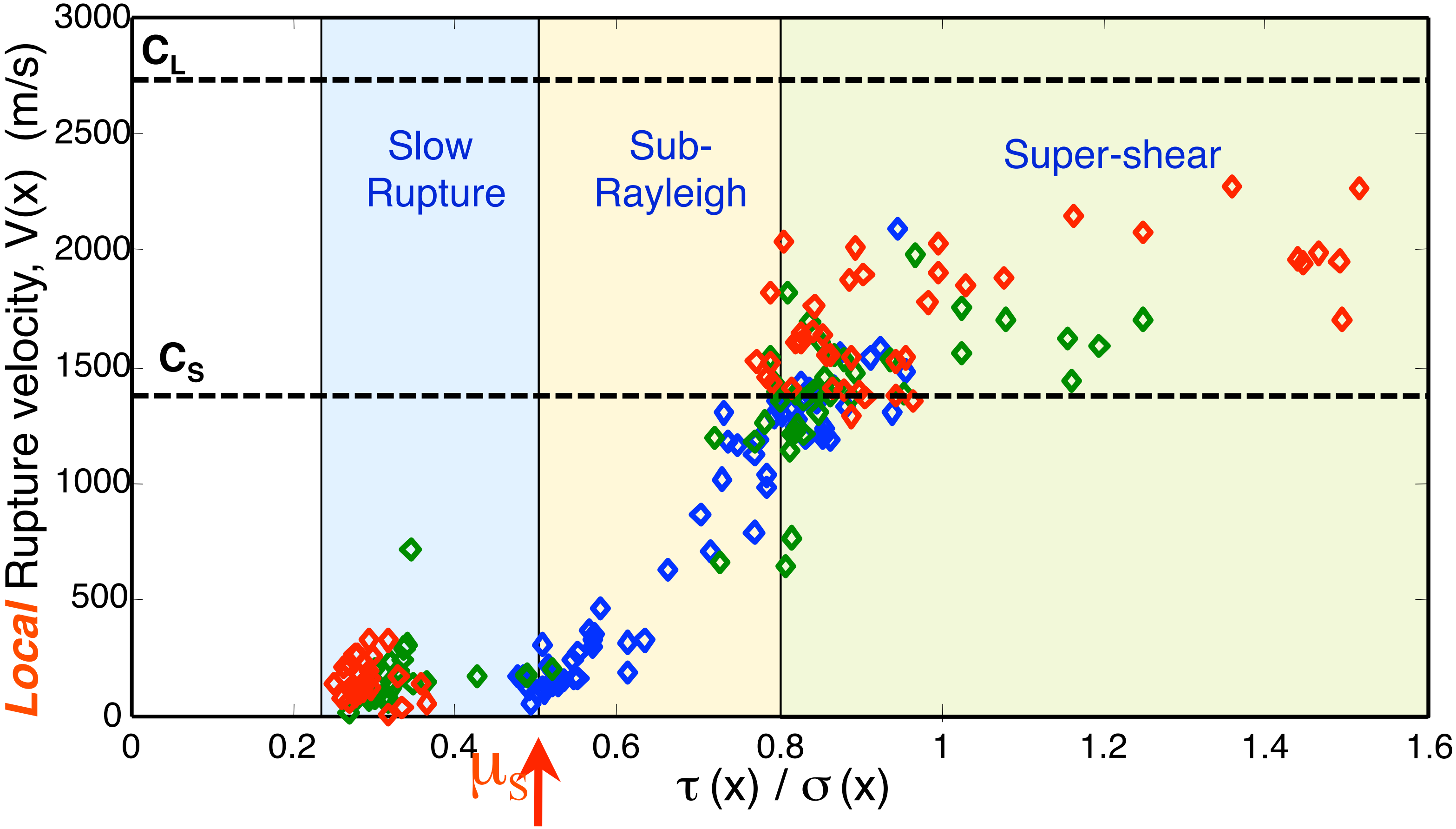
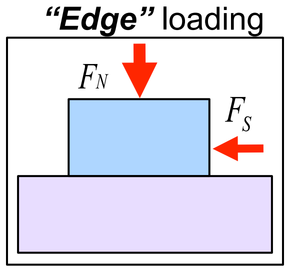


We can now understand the ***local dynamics*** in terms of $\tau(x)/\sigma(x)$!

> 100 different events/experiments under a broad range of local conditions:
(only regions *away* from pushing considered)





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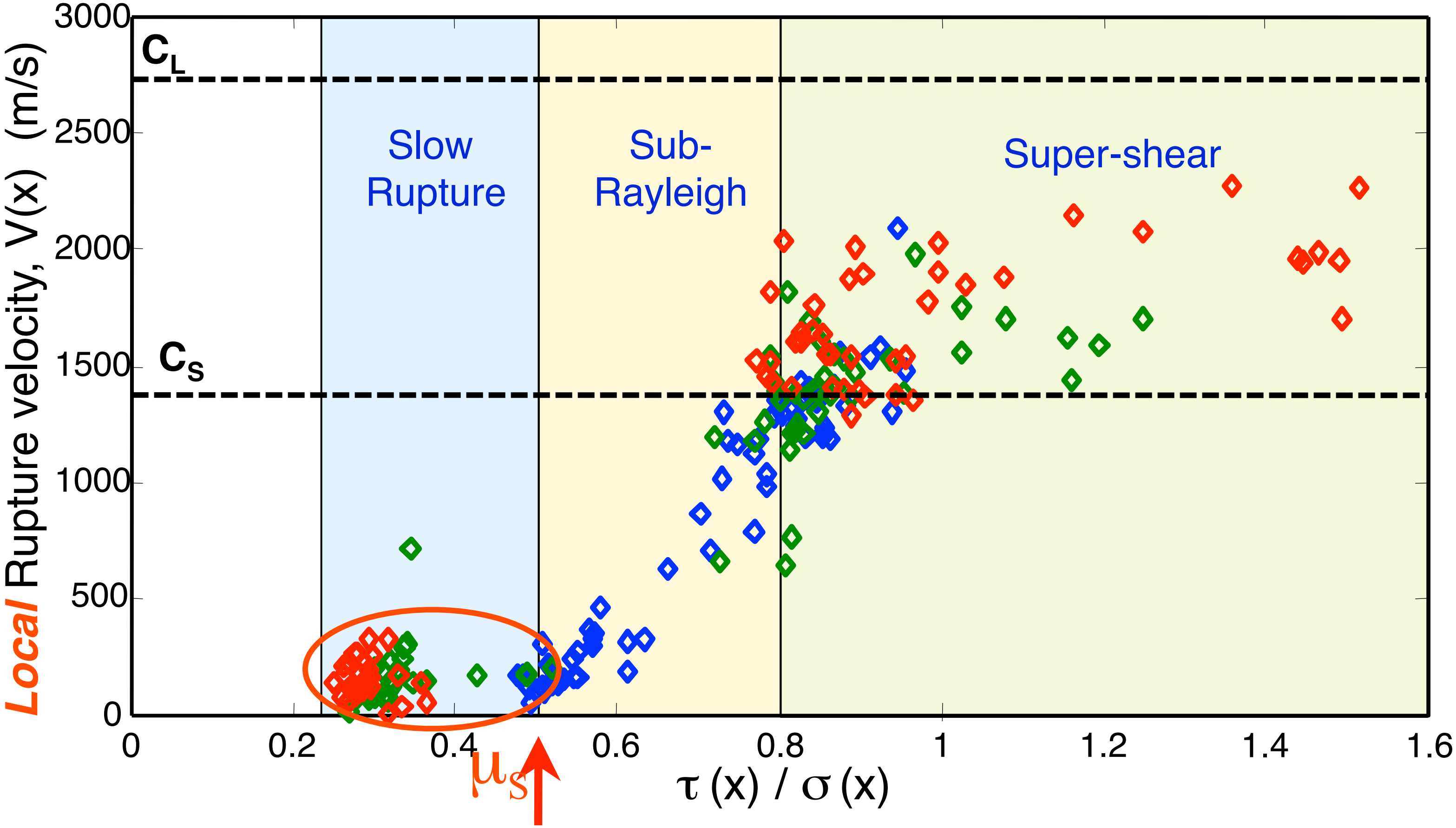

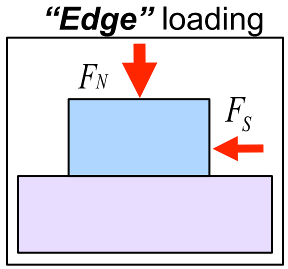

Slow Rupture $\tau/\sigma \lesssim 0.5$

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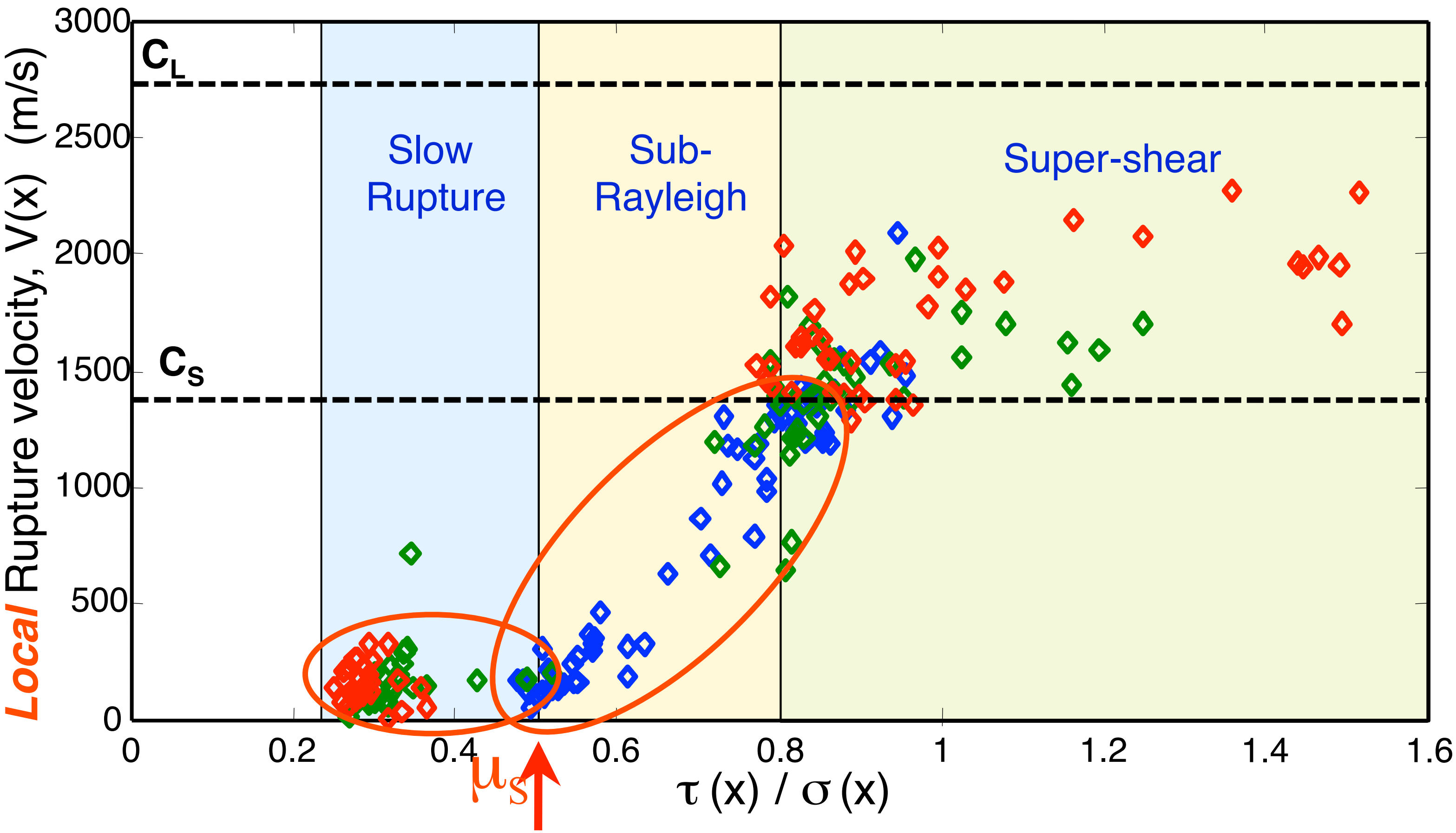

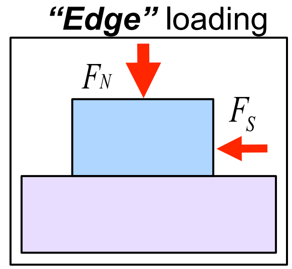

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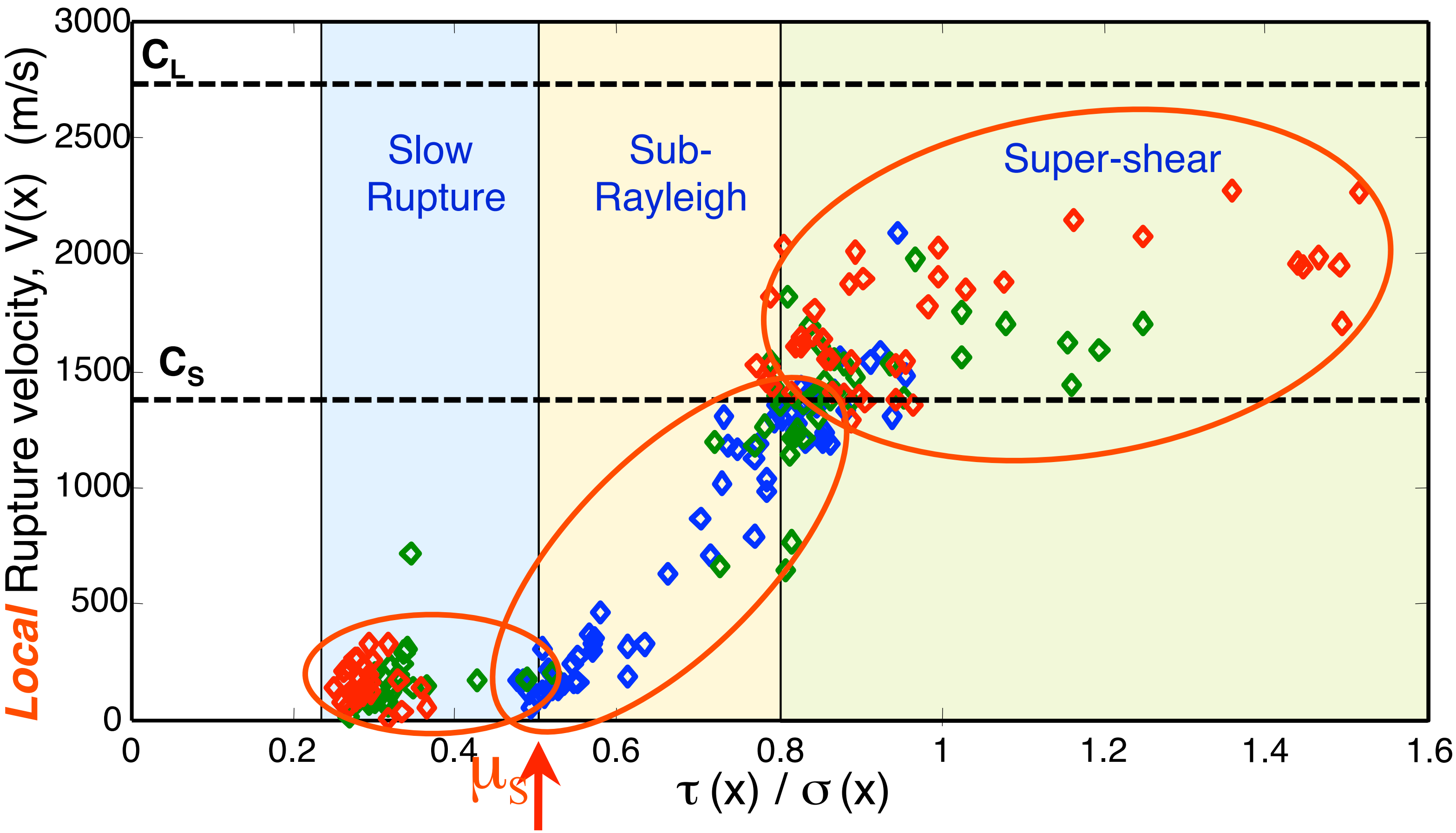

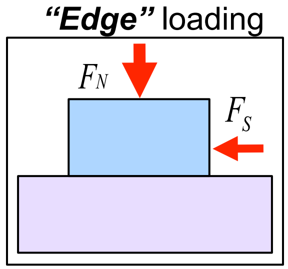

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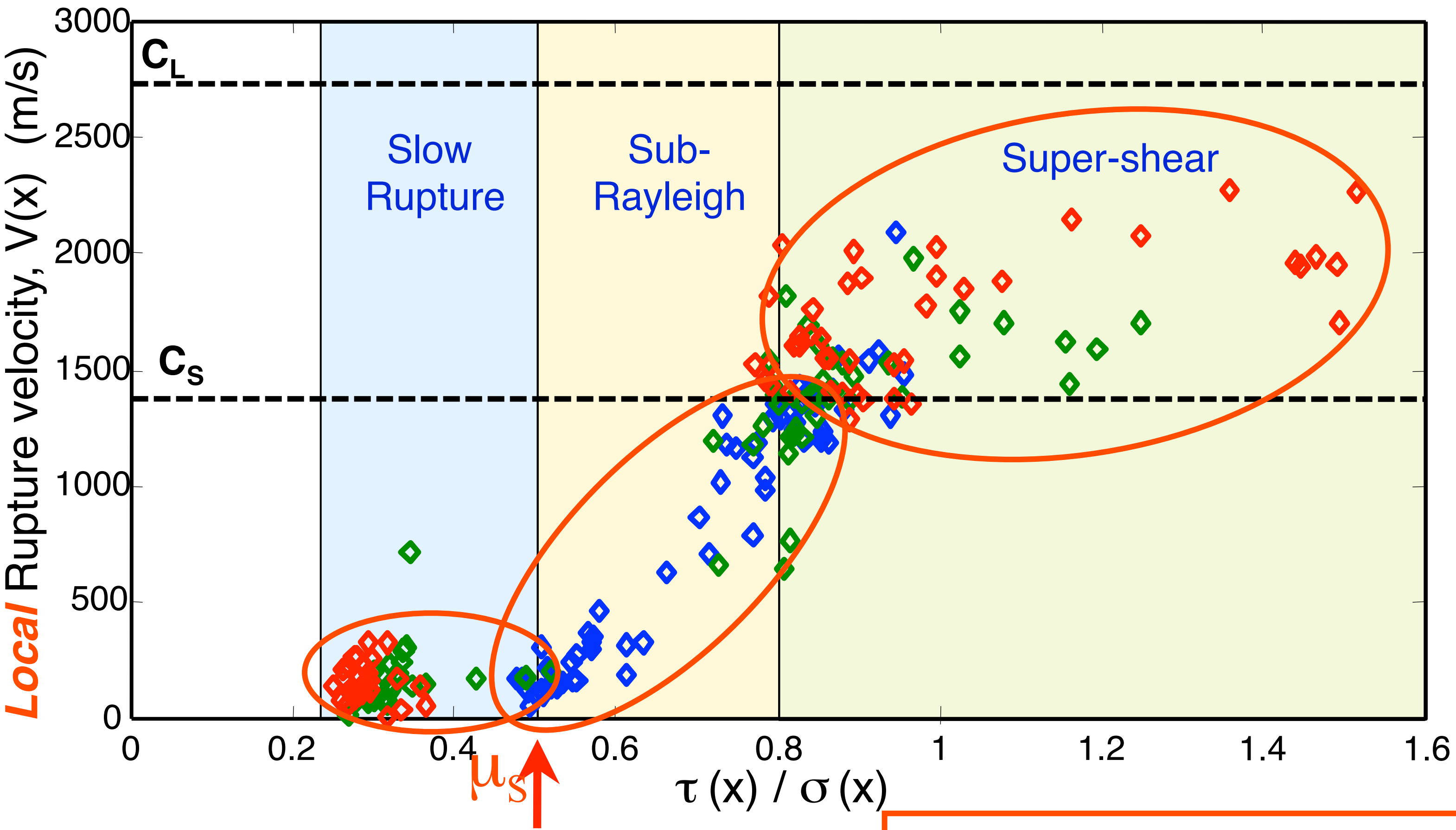

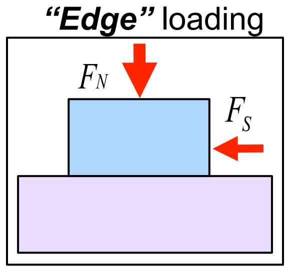

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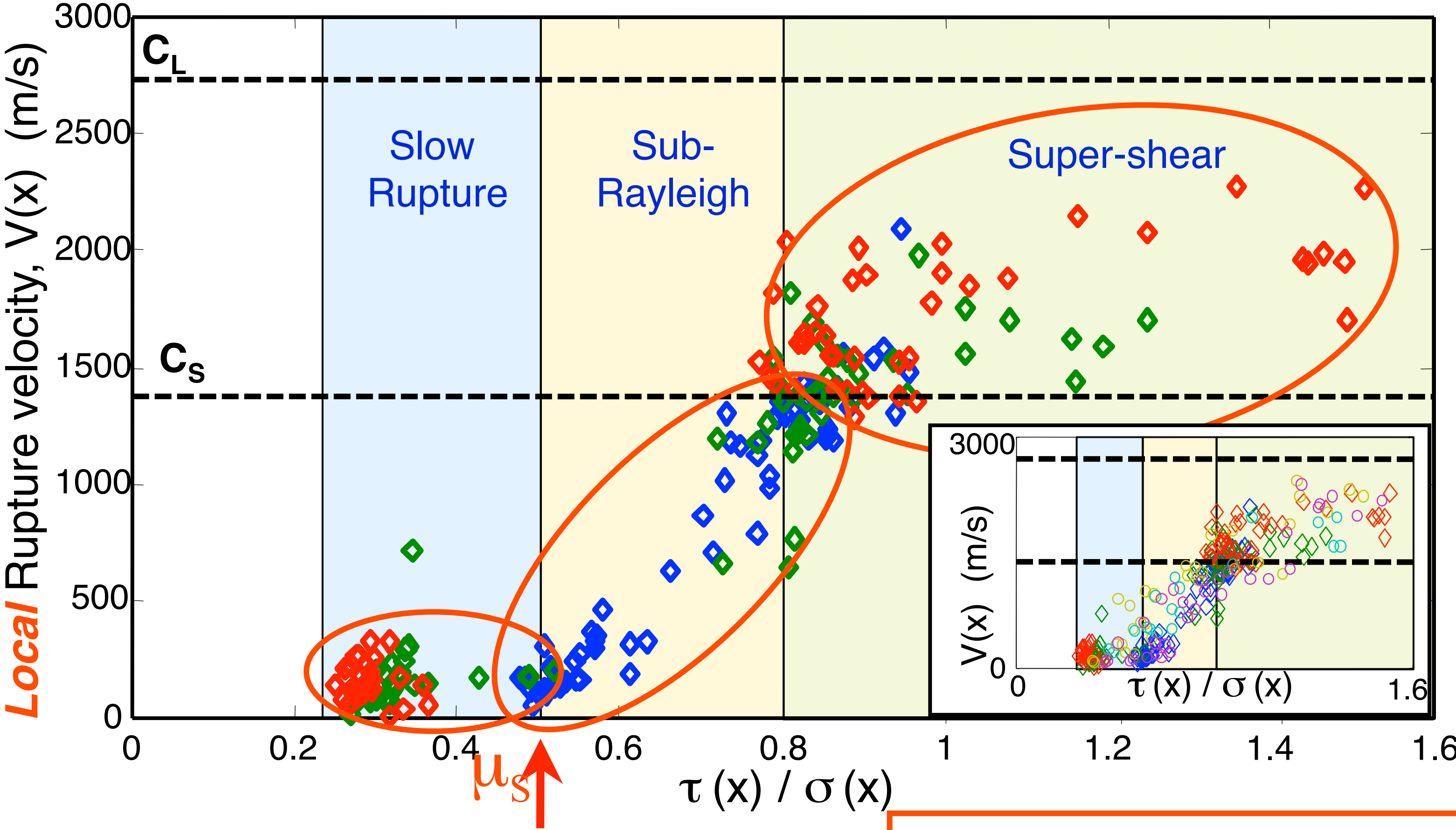

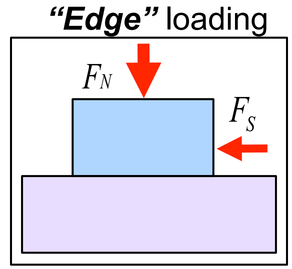

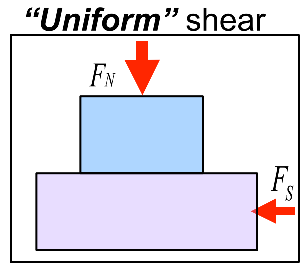

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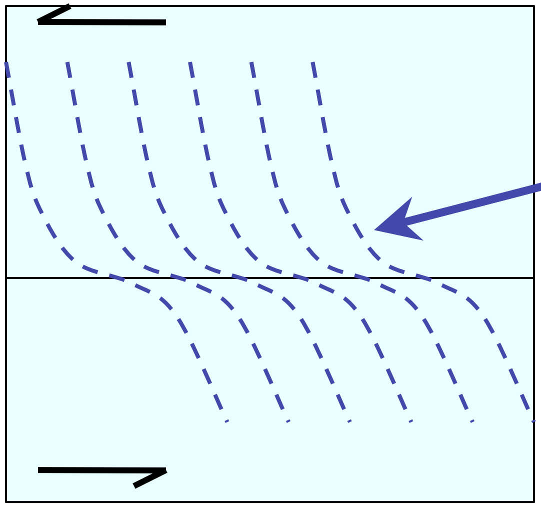

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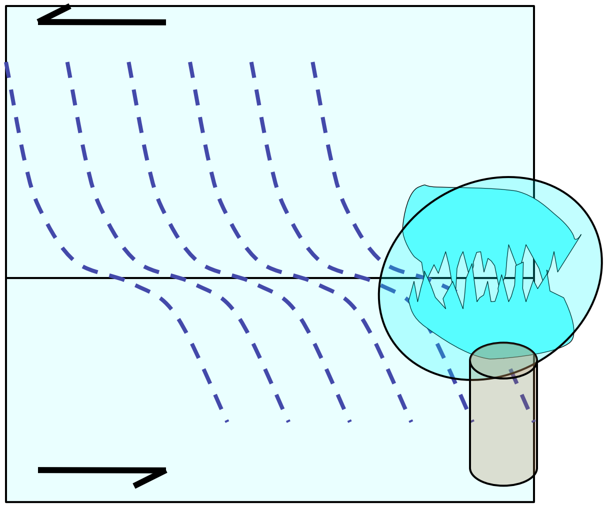

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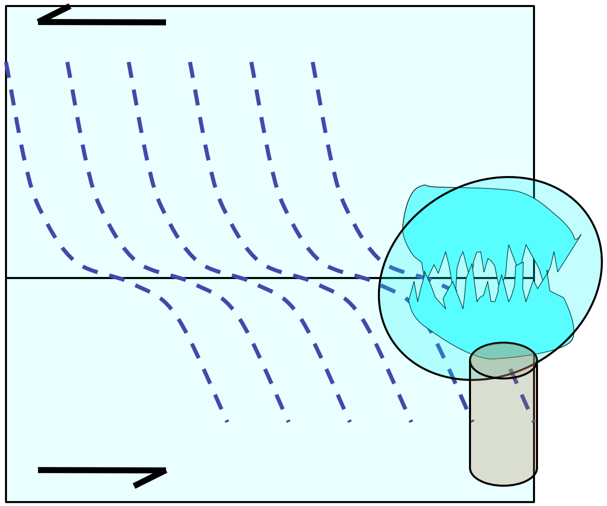

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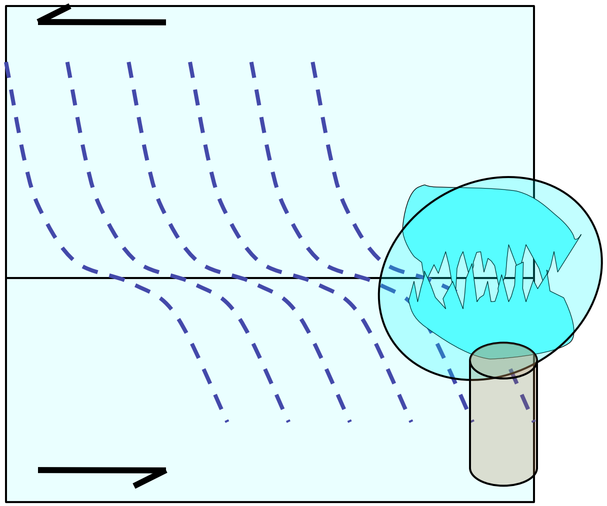

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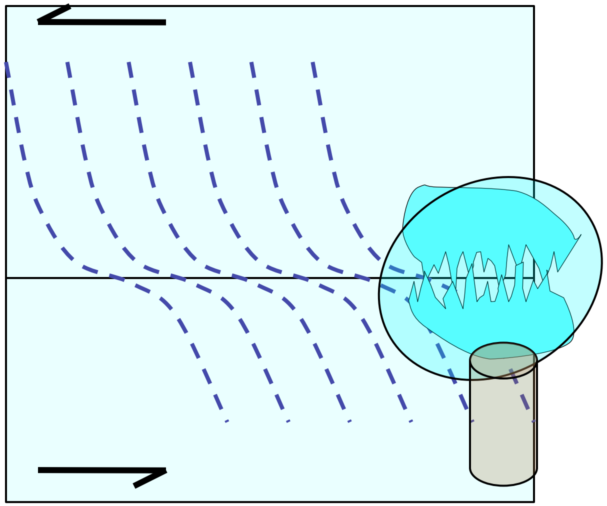

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+ A key difference with ***pure*** fracture:

Slip surface resistance ⬄ ***frictional resistance*** of the "free" crack faces

ASK ME ABOUT: **O. Ben-David, S. M. Rubinstein and J. F., *Nature* 463, 76 (2010)**

Why are there different rupture modes (a hand-waving explanation)?

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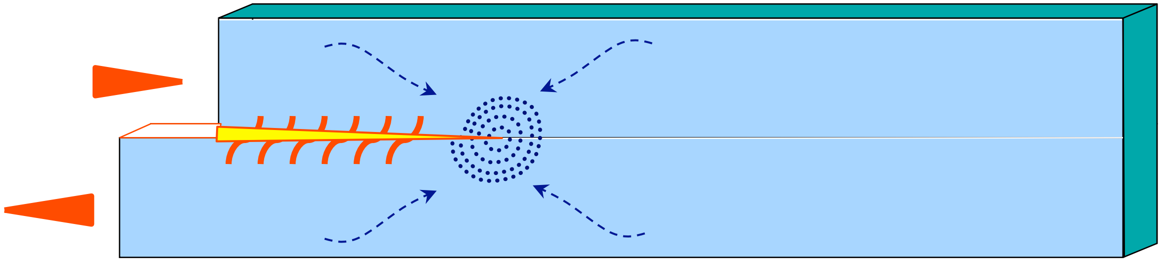

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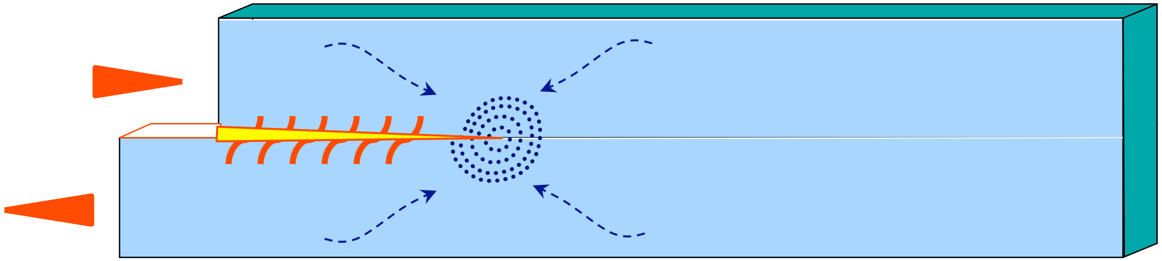

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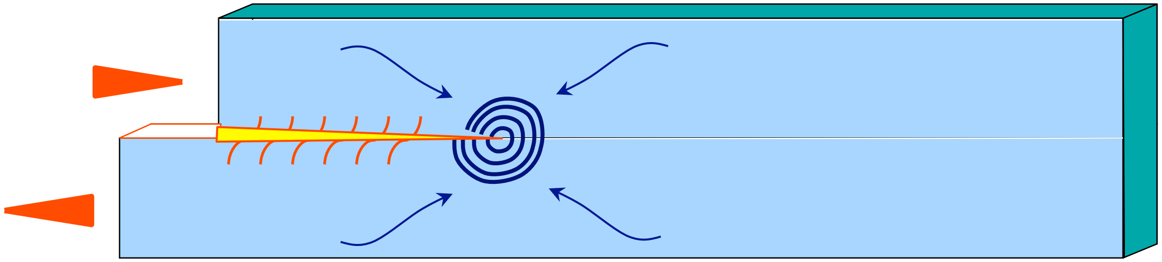
Sub-Rayleigh	remote elastic fields	singular rupture tip ***dominant***

(**V *limited* by V_R**)



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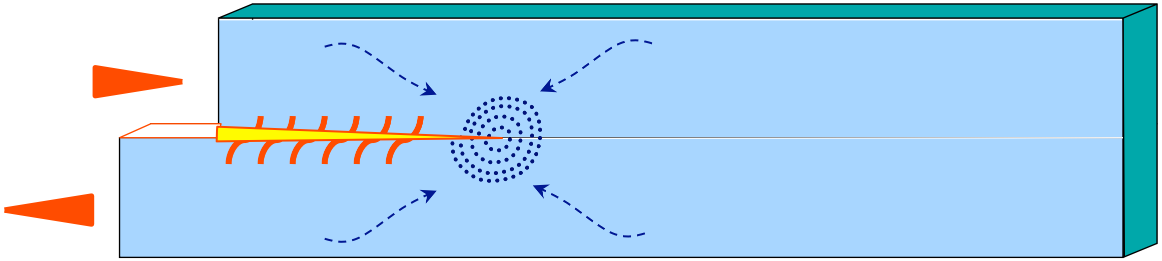

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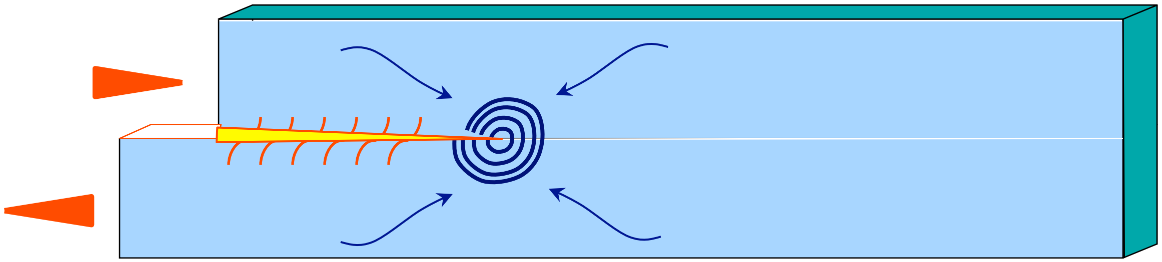

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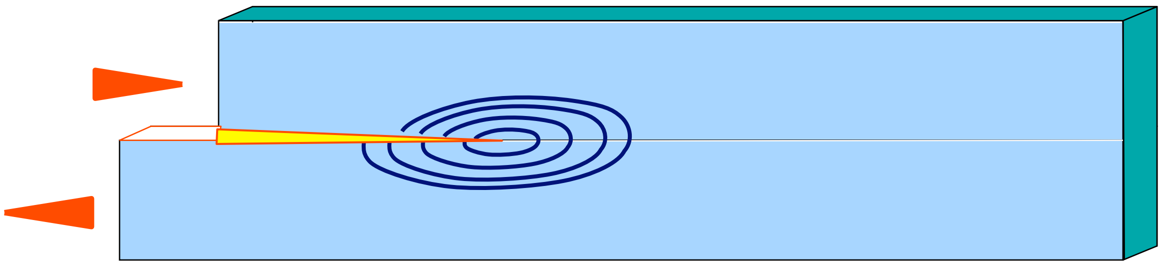
Super-shear — ***LOCAL*** elastic fields — singular rupture tip ***dominant***

(**V** ***unlimited*** **by** $\mathbf{V_R}$ ⇔ no energy transport from remote locations)



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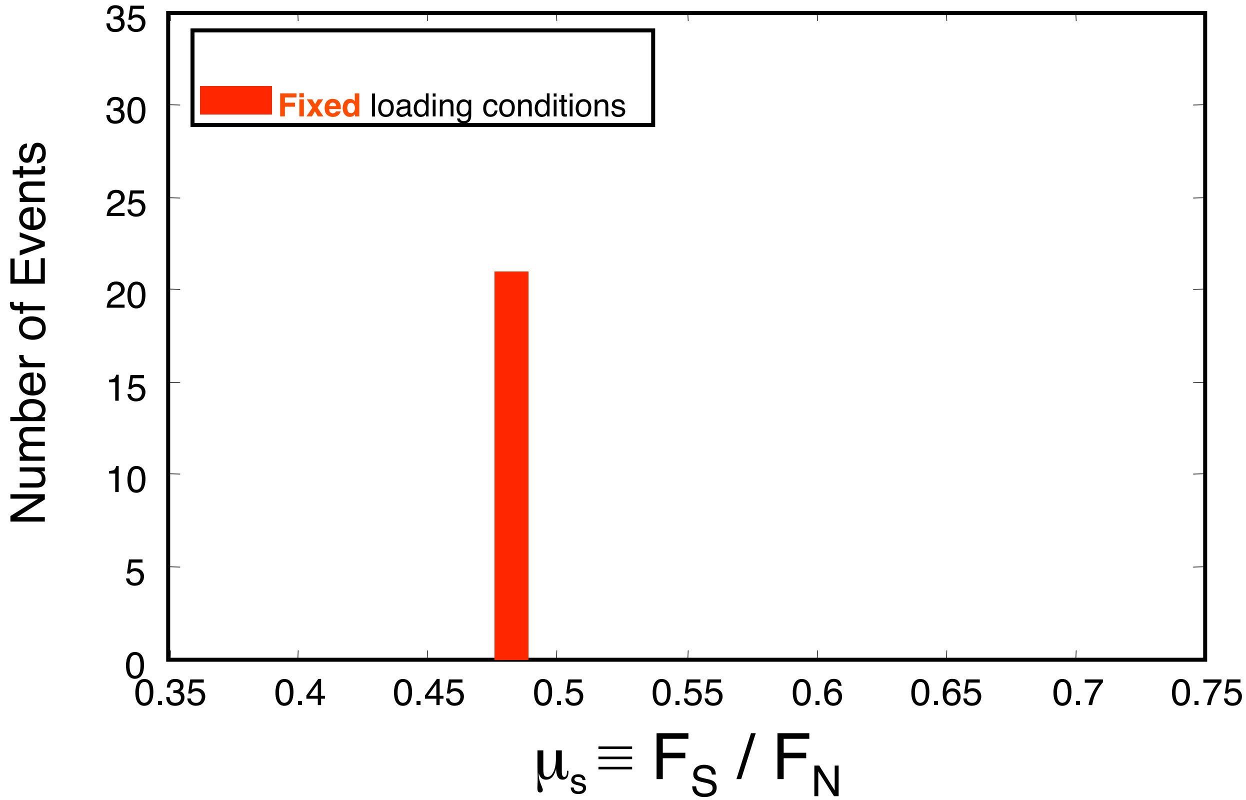

For ***given loading conditions*** μ_S is ***entirely reproducible***

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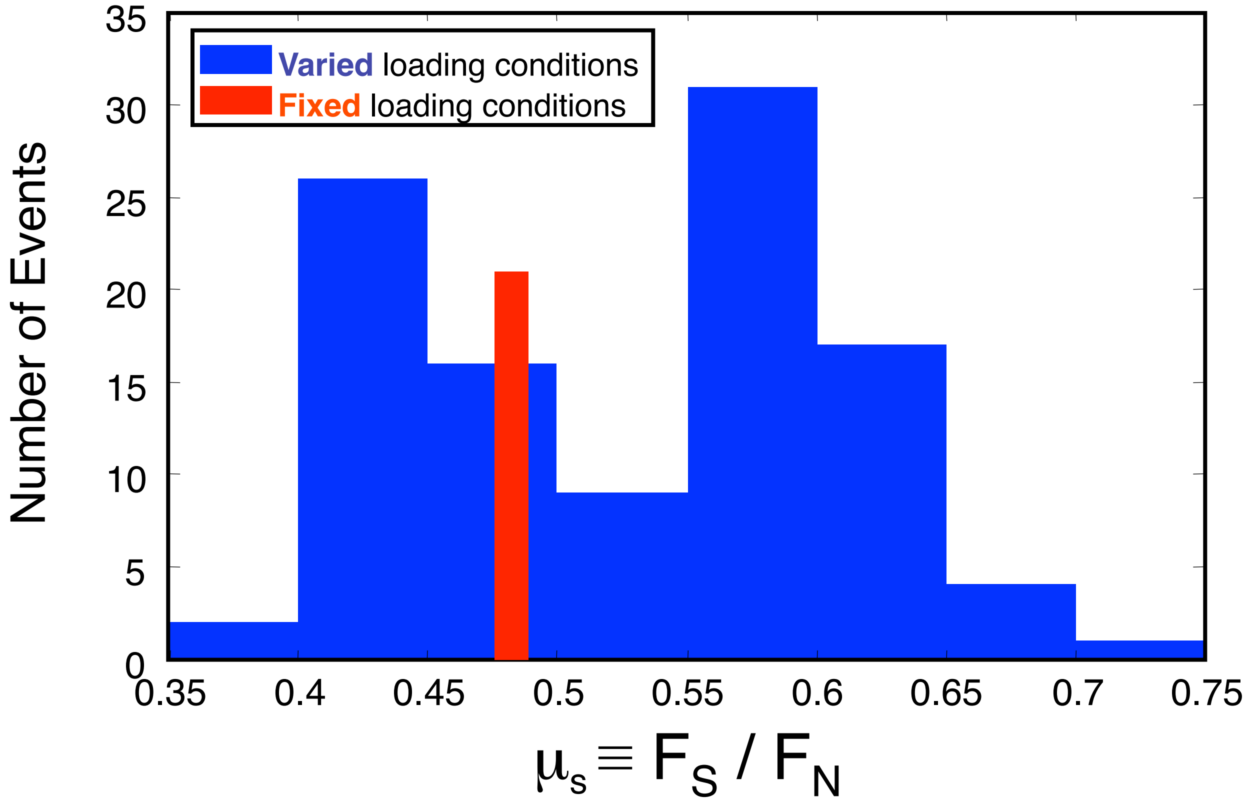

For ***different* loading conditions** μ_S is ***widely scattered***

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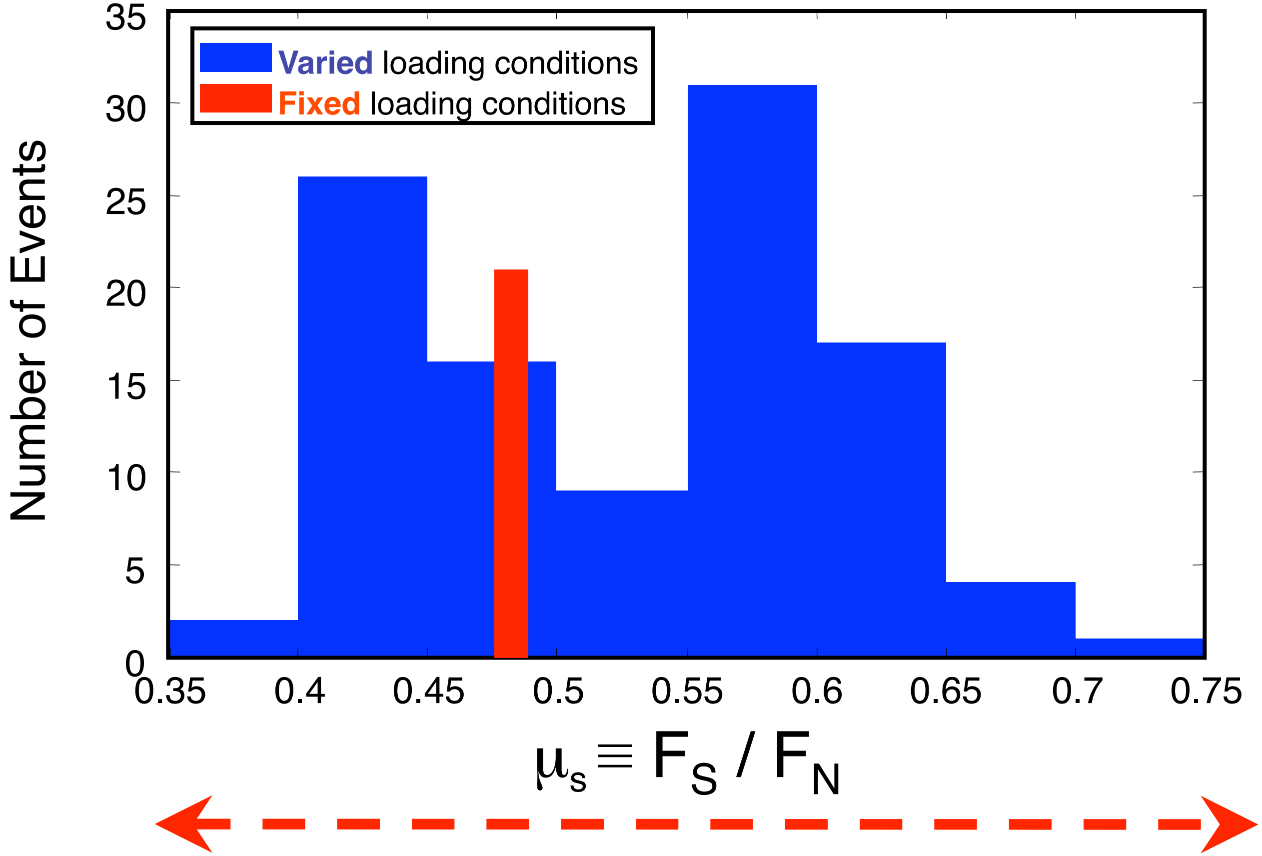

μ_S varies by over a ***factor of 2*** with the (pre-slip) stress distribution

➔ μ_S is far from a *constant* (and in fact is ill-defined)!

μ_S is ***not*** **a** ***material constant***

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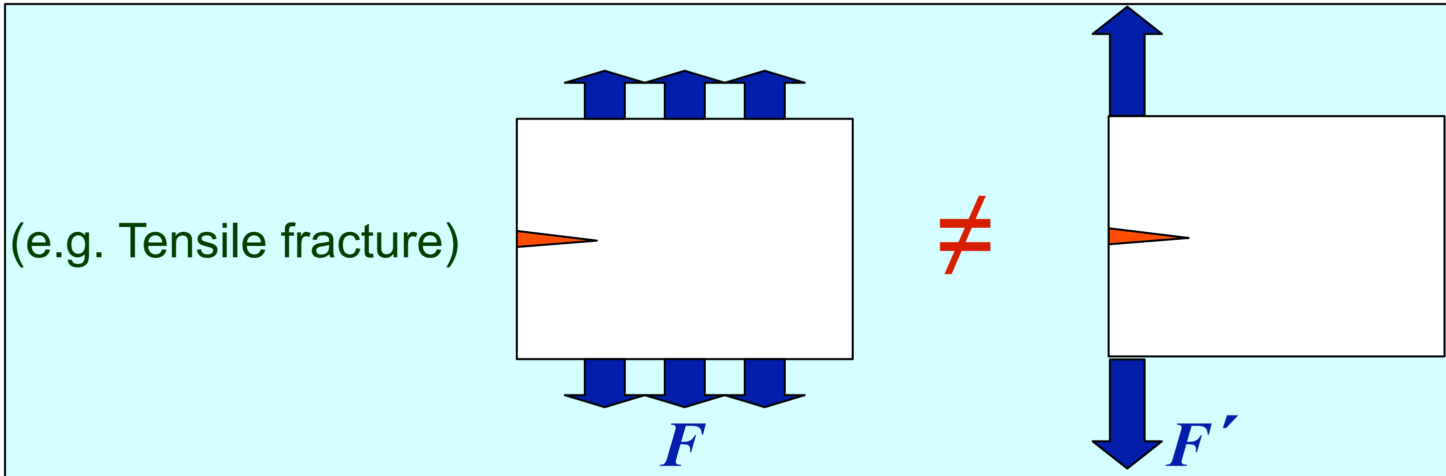

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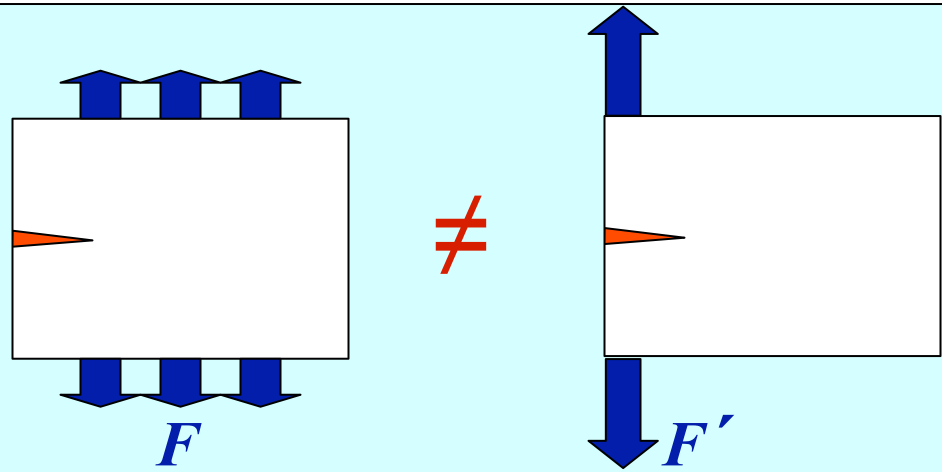

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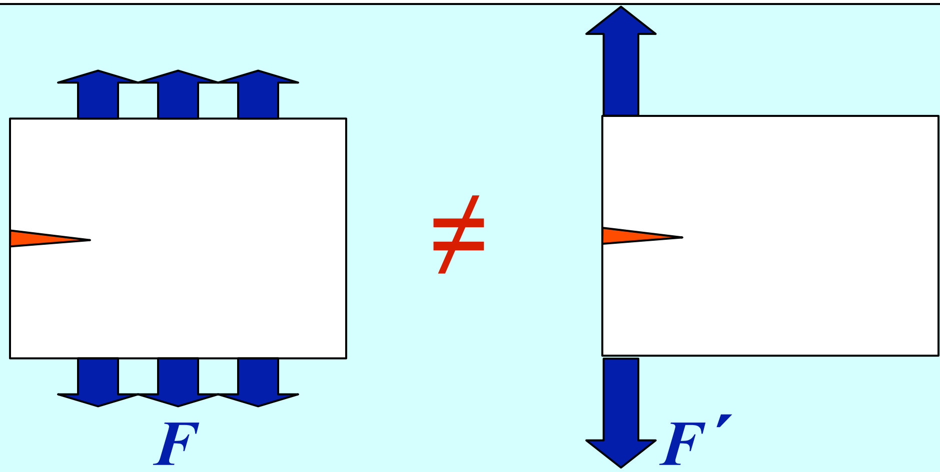

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➔ μ_S is a characteristic scale of the overall stored/fracture energy

Summary: The effects of nonuniform stresses and interface strength

Inhomogeneous stresses ***always exist*** – even under “uniformly” applied loads

Inhomogeneities result from:

- Interface *geometry* or *material contrasts* (e.g. asperities)
- *Non-uniform loading* (internal stresses or externally applied)
- *Dynamically generated* (by previous slip events)

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Inhomogeneities control the amount of energy stored ***prior*** to slip initiation

(Locally, a system can be well beyond the global threshold, μ_S, for static friction!)

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"Standard" (sub-Rayleigh) cracks

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- Laboratory earthquake "prediction" can be performed by comparing the stored/fracture energy distribution prior to earthquake nucleation.
- A spatially *local* "Friction Coefficient" is not a useful concept
- *Big Question*: What is the *proper* theoretical framework for predicting the onset of frictional motion???

Relevance to earthquakes: The dynamics of fault nucleation

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Sub-Rayleigh fronts ⇔ "Standard" earthquakes ($0.2V_R < V < 0.9V_R$)

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Slow detachment fronts ⇔ ???

Slow earthquakes[2] = slow detachment fronts?

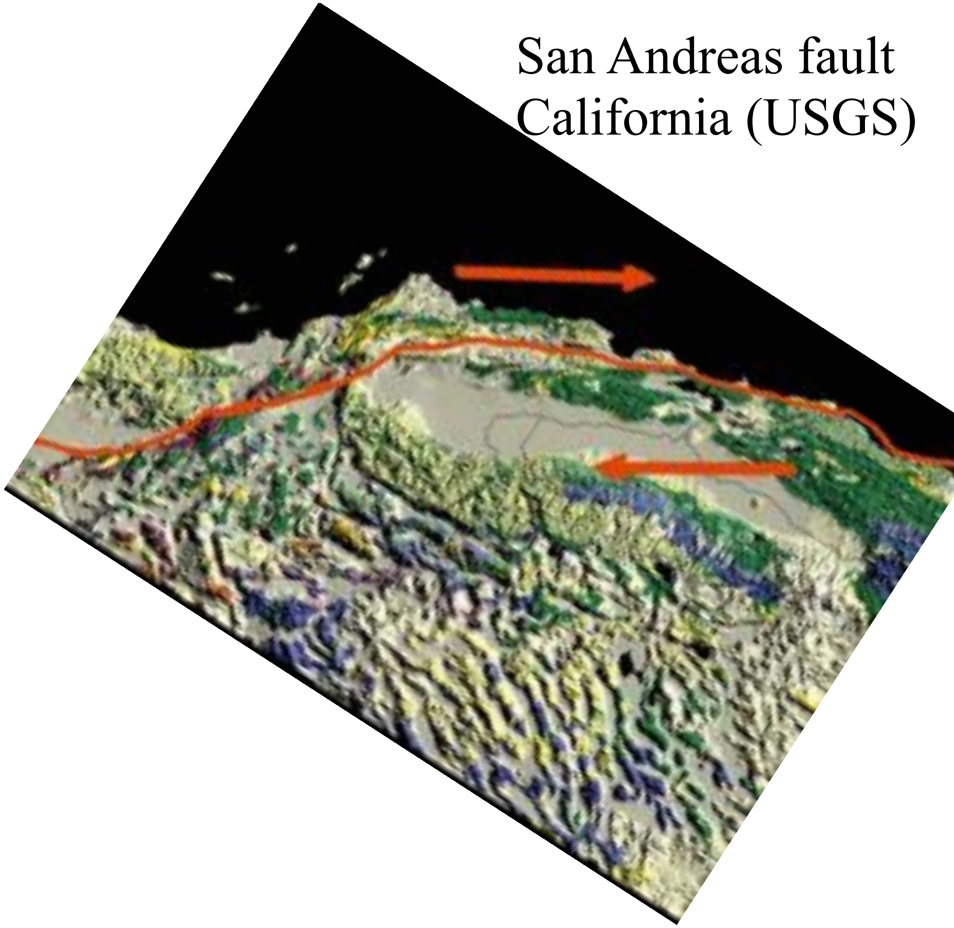
Characteristics of "slow" fronts:

- May occur frequently
- Significant slip/strain release
- "Silent" – having a weak atypical acoustic (seismic) signature.

[1] Bouchon, M. et al. Geophys. Res. Lett. **28**, 2723-2726 (2001).

[2] Crescentini, L., Amoruso, A. & Scarpa, R. Science **286**, 2132-2134 (1999);
Linde, A. T. & Sacks, I. S. Earth and Planetary Science Letters **203**, 265-275 (2002).
Rogers, G. & Dragert, H. Science **300**, 1942-1943 (2003).

Earthquakes ***are*** Friction



San Andreas fault
California (USGS)

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Friction *is* mediated by **rupture fronts**

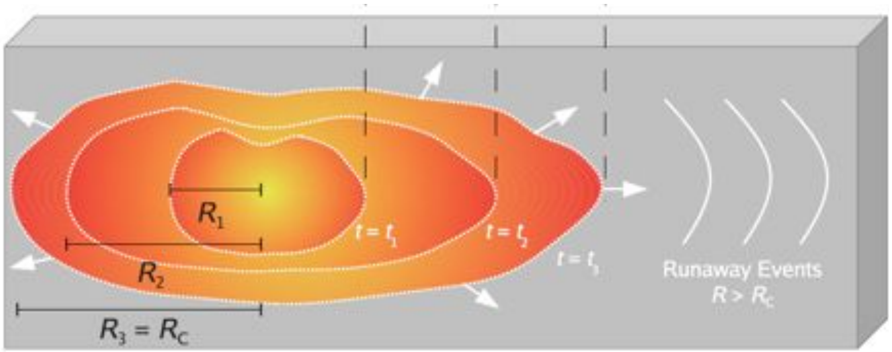
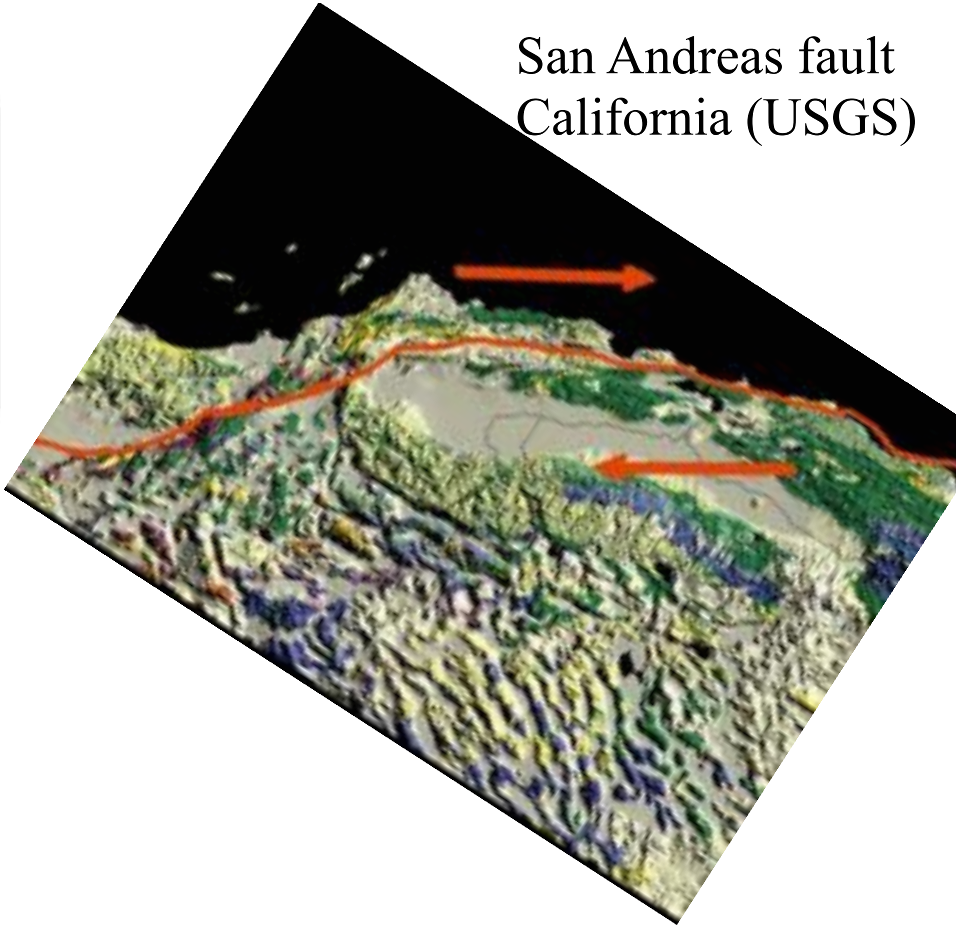


Figure 13. (top) Stress versus distance from the edge of (bottom) ruptures growing in elastic solid. Ruptures with a critical size R_c produce dynamically stress comparable to the static friction τ_s, leading to runaway events.

Y. Benzion (2008)



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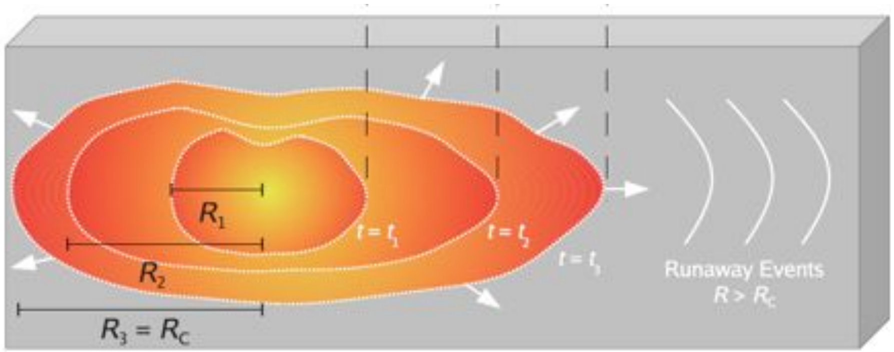

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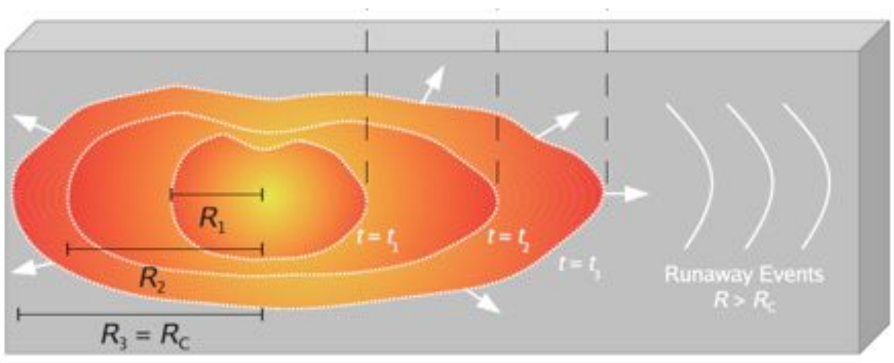

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Thank you!