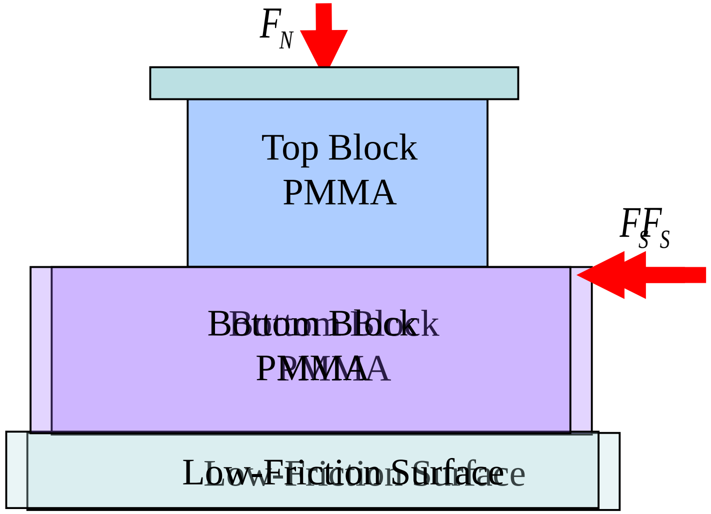
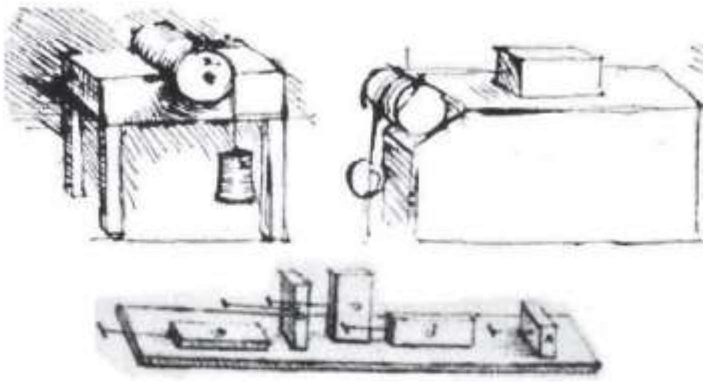
Friction is fracture: Slippery surfaces and frustrated cracks



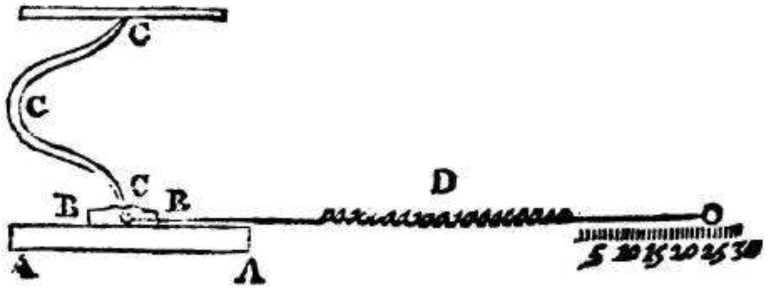
Elsa Bayart, Ilya Svetlizky and Jay Fineberg
The Racah Institute of Physics
The Hebrew University of Jerusalem, Israel

THE LADY DAVIS FELLOWSHIP TRUST
האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM
erc

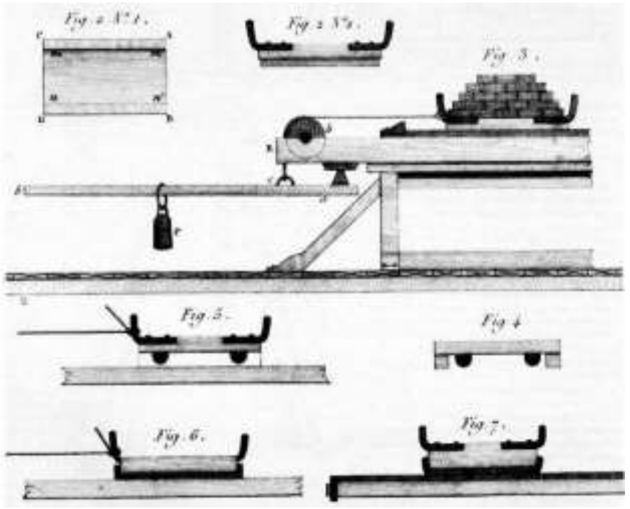
1480 - Da Vinci



1699 - Amontons



1785 - Coulomb



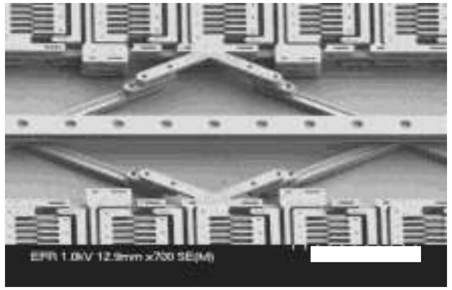
$$F = \mu N$$

F is independent of the area of contact

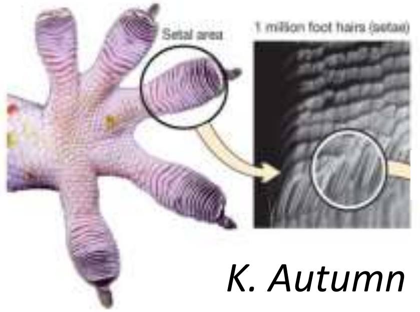
$$\mu_{static} \neq \mu_{dynamic}$$

Small scales: technological challenges

- Reducing friction (MEMS).
- Reducing wearing of surfaces.
- Improving lubricants efficiency and durability.
- Biomimetic approach.



www.memx.com 500 µm

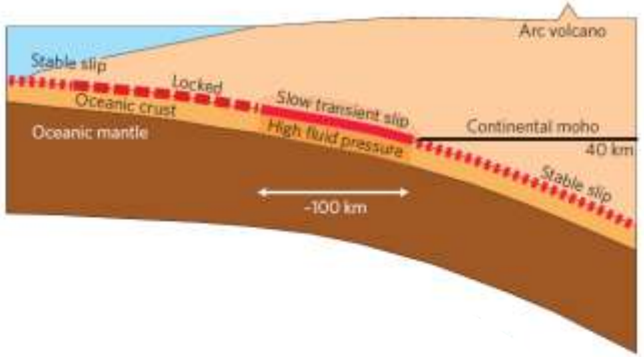


K. Autumn

Large scales: geophysical challenges

- Earthquakes and landslide mechanisms.
- Predictability.
- Effect of heterogeneities of interfaces (water,

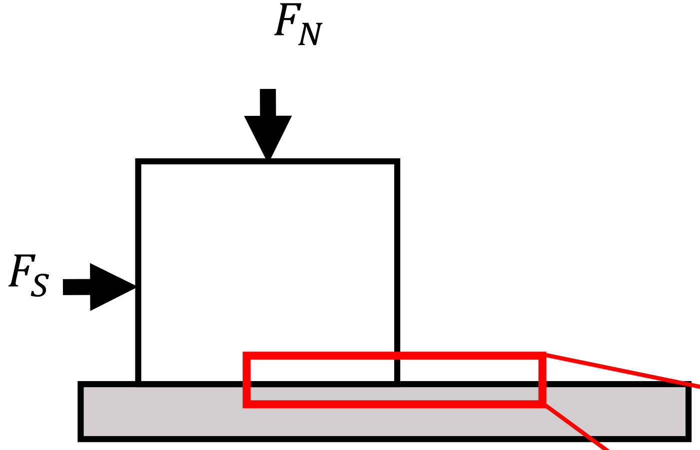
melted rocks, roughness).



Peng and Gomberg,
Nature Geoscience **3**, 599 - 607 (2010)

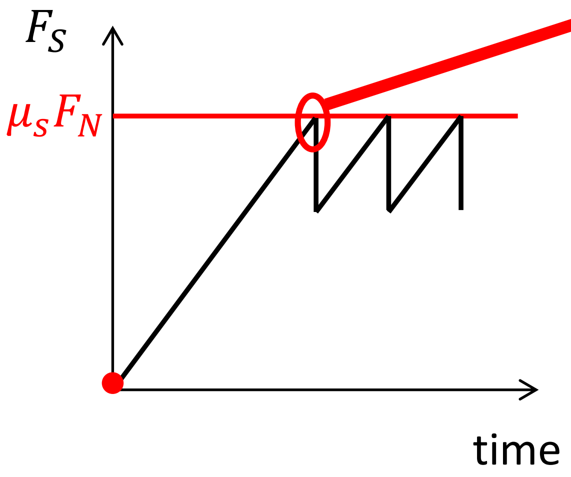
What we usually know about friction

Da Vinci, Amontons, Coulomb



$F_S < \mu_s F_N \Rightarrow$ no motion

$F_S = \mu_s F_N \Rightarrow$ motion



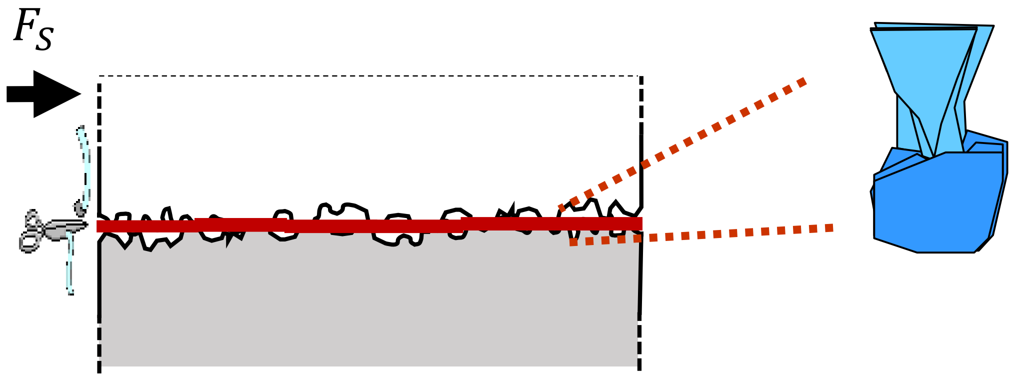
What actually happens at the interface

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

Huge **pressures deform** the contacts

Pressure = yield stress, σ_Y ➔ ***A*** $= F_N / \sigma_Y$

➔ ***A*** is proportional to **the normal load**



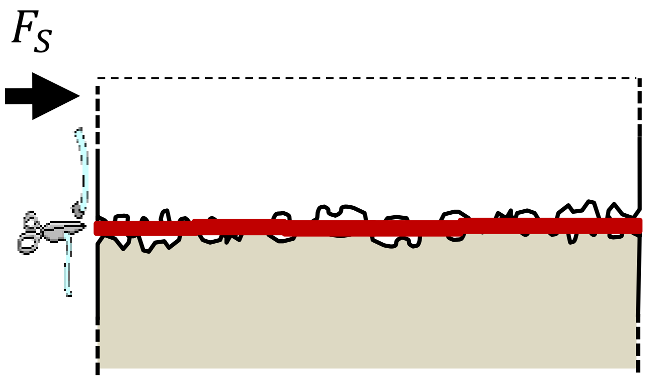
EARTHQUAKE !

The onset of friction

⇔

fracture of the discrete contacts that form the interface

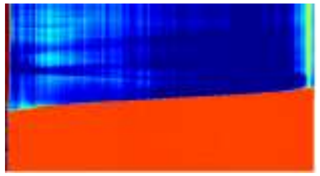
F.P. Bowden and D. Tabor (1950)
S. M. Rubinstein et al (2004)

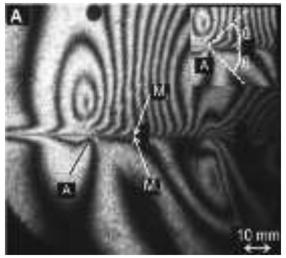


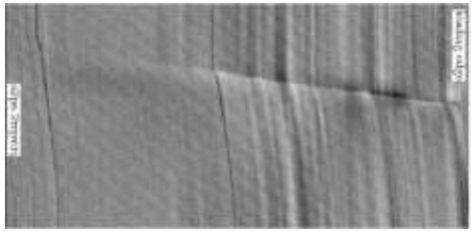
Interface slip is mediated by crack-like rupture fronts

Fronts have been observed experimentally in many different systems:

- **PMMA** : Rubinstein et al (2004)
- **Homalite**: Xia et al (2004)
- **Granite**: Passelègue et al (2013)
- **Gels**: Baumberger et al (2002), Latour (2011)
- **PDMS:** Chateauminois et al (2008) , Prévost et al (2013)







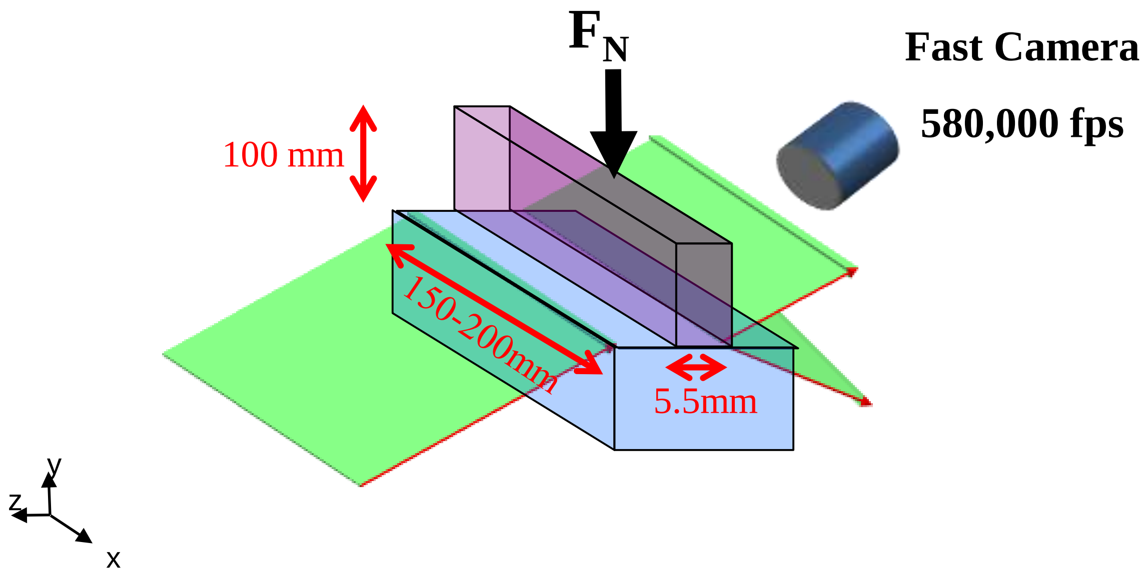
We'll show that: The ***stresses*** driving these fronts are described by ***Fracture Mechanics***

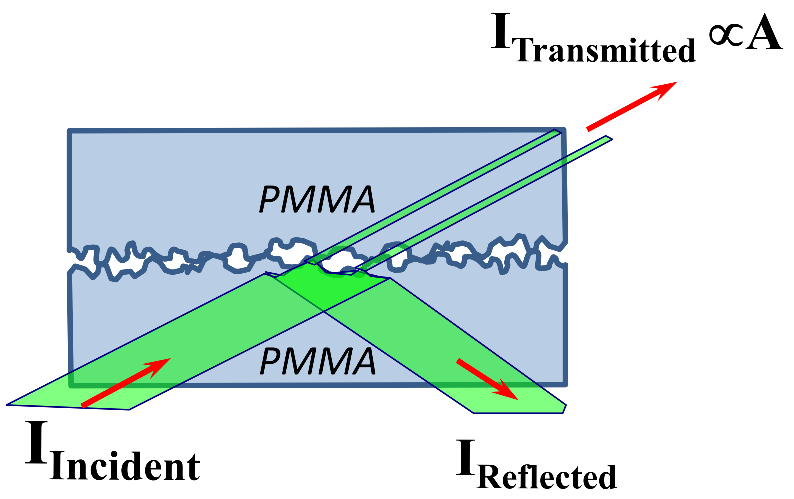
Outlines

1. The experiment
2. Previous work: Friction is fracture, I.Svetlizky and J. Fineberg, Nature, **509** 205–208 (2014)
3. Arrested ruptures: Predictability of “laboratory earthquakes”
4. Lubricated interfaces: Slippery can be tough

Experimental setup

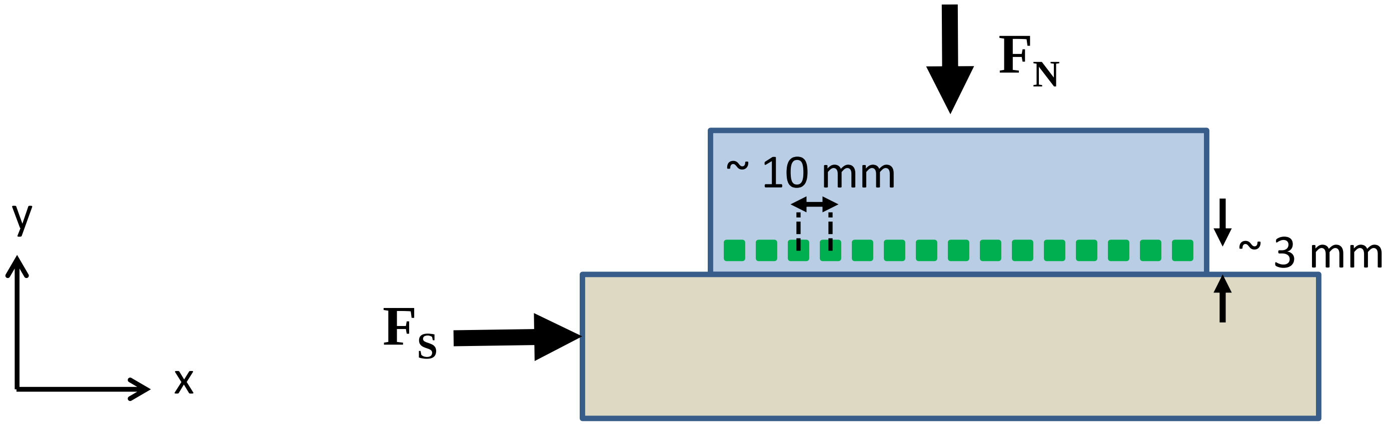
Real contact area measurement

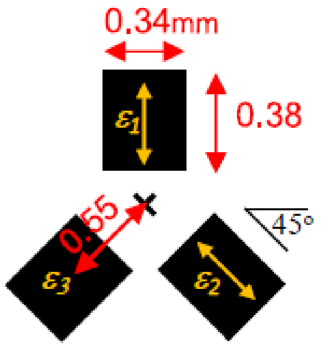




S. M. Rubinstein et al (2004)

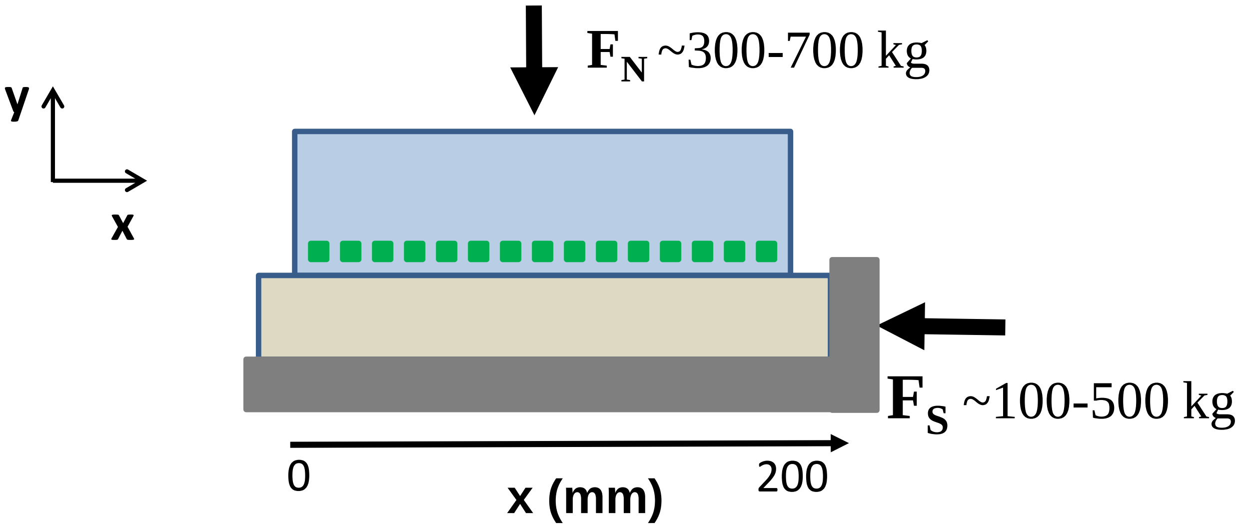
2D-strain tensor measurement at 1 MSamples/s

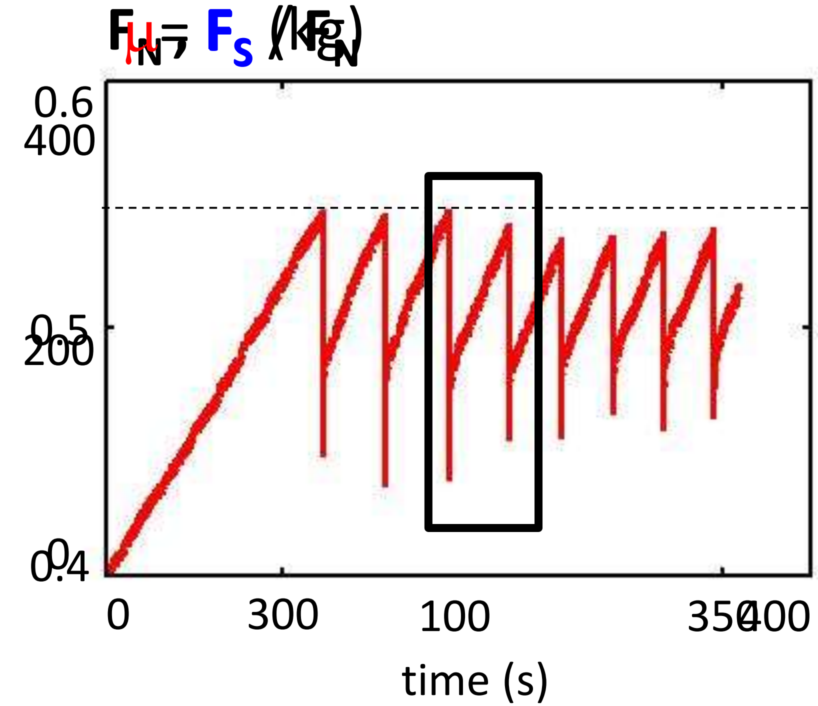


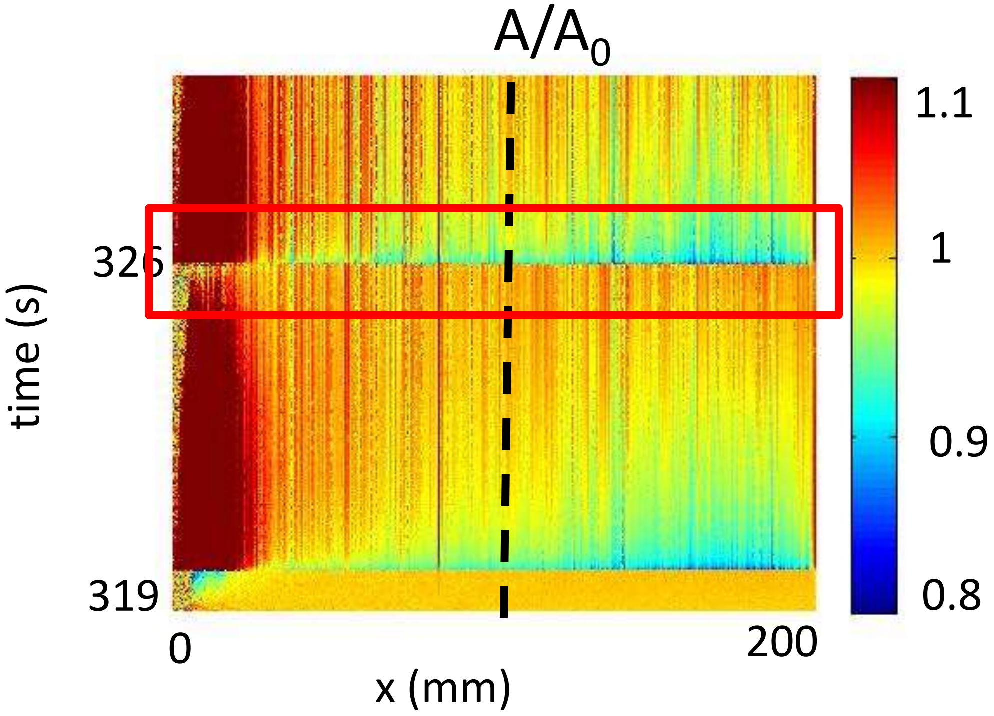


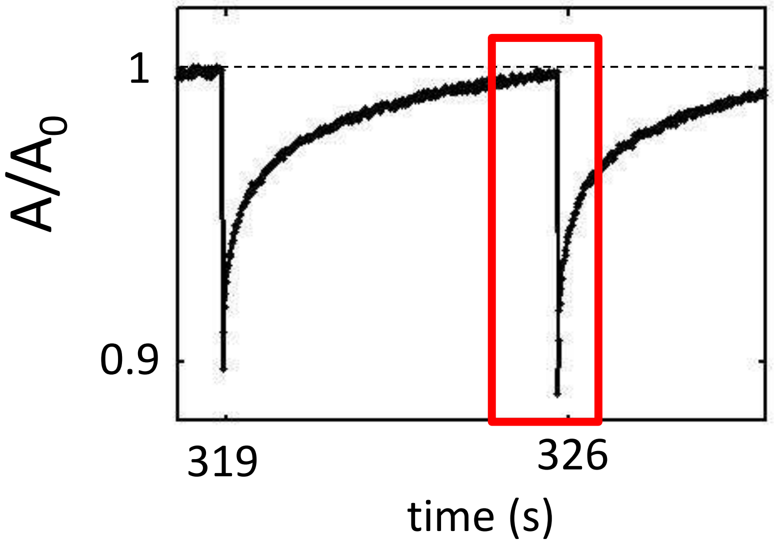
Svetlizky and Fineberg (2014)

A typical experiment

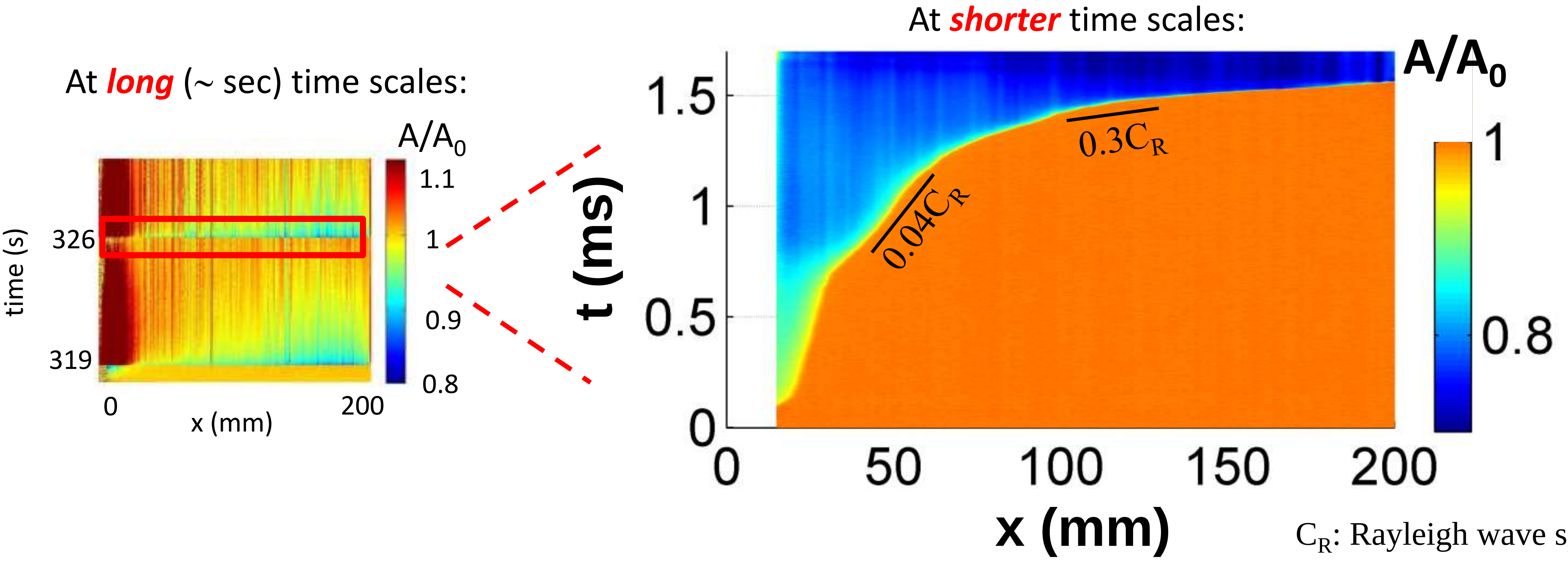






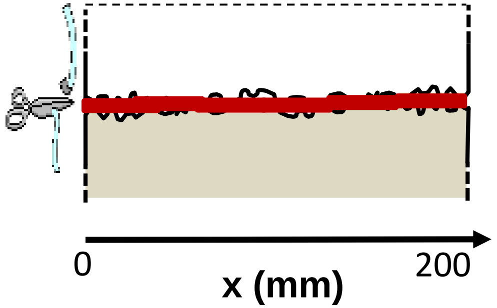


Rupture Fronts



At *long* (~ sec) time scales:

At *shorter* time scales:



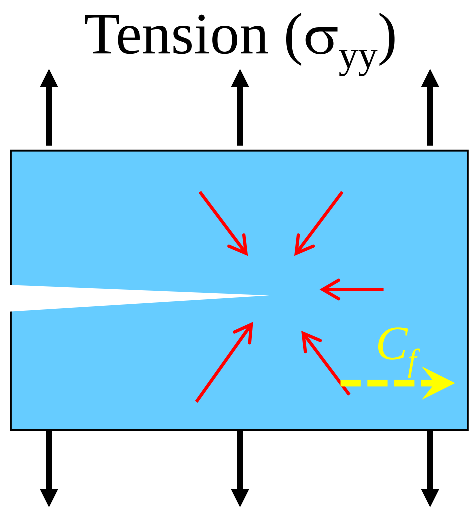
C$_R$: Rayleigh wave speed (1255m/s for PMMA)

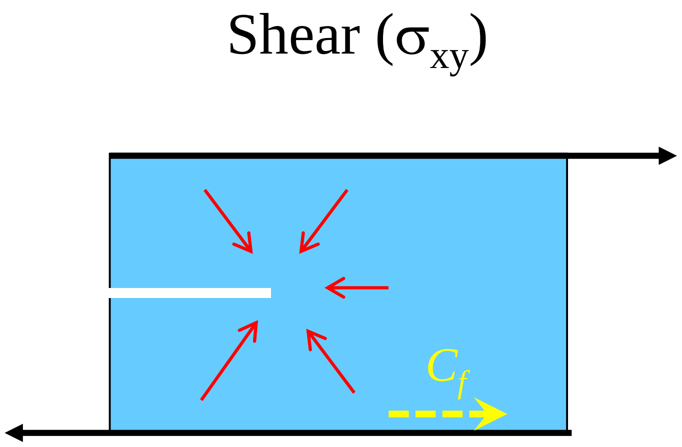
Each line = snapshot of the real area of contact along the entire interface
1.5μsec between lines

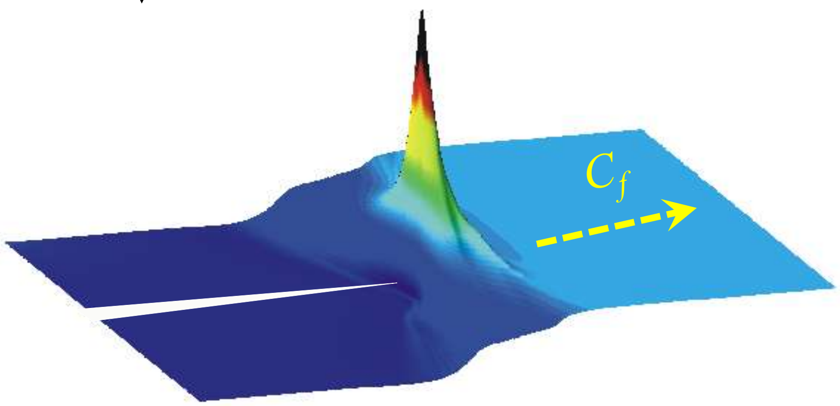
Block detachment is mediated by propagating crack-like fronts

Fracture Mechanics

Linear Elastic Fracture Mechanics (LEFM)



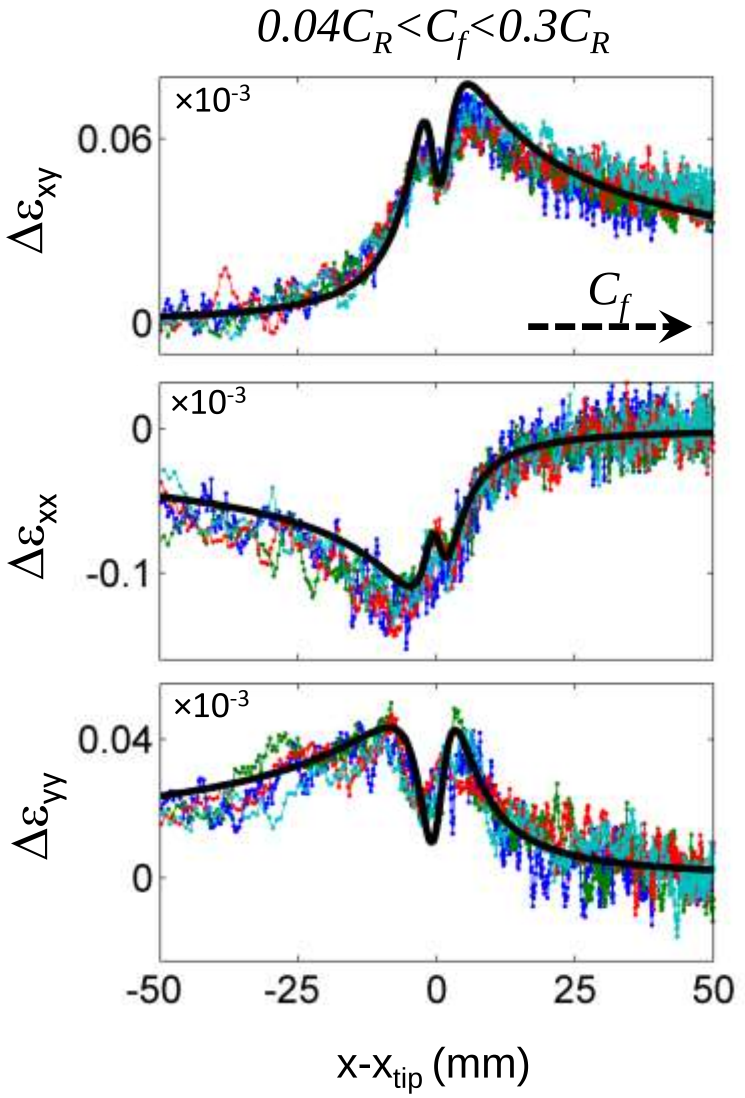




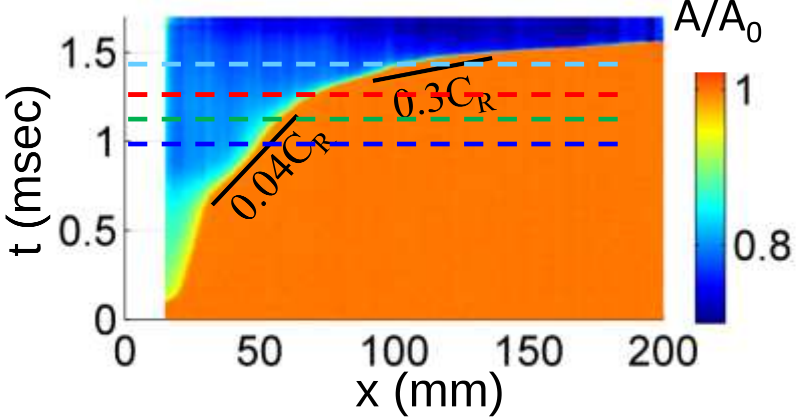
$$\sigma(r) \sim r^{-1/2}$$

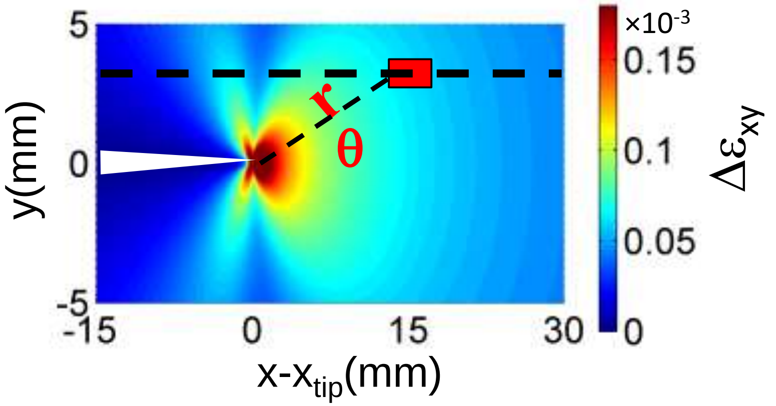
- Linear elasticity → singular stress at a crack's tip
- Energy balance → Dissipation = Energy flux into the crack tip
- Speed limit: C_R ,Rayleigh wave speed (1255m/s for PMMA)

Rupture propagation



— Fracture mechanics solution (LEFM):





Propagation condition $G = \Gamma$

$\Gamma =$ energy to break a unit area of contacts

$$\boxed{K \leftrightarrow \Gamma}$$

$\Gamma \sim 1\ \mathrm{J/m^2}$

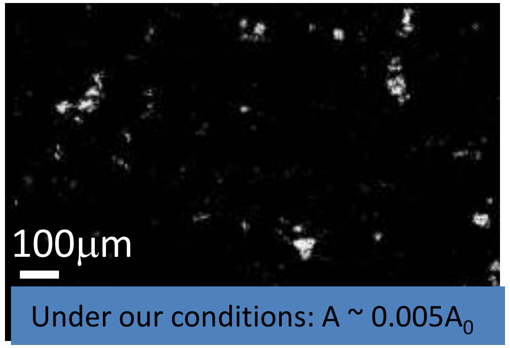
Detachment fronts are shear cracks

Strain field measurements ↔ Γ

Svetlizky and Fineberg, Nature **509**, 205–208 (2014)

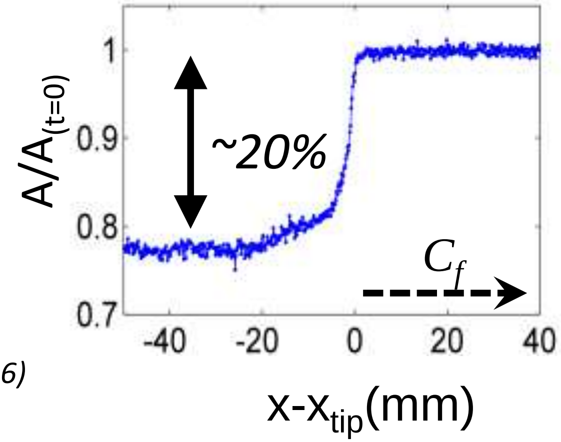
About the value of Γ

Real area of contact - PMMA



Under our conditions: $A \sim 0.005A_0$

J.H. Dieterich, B.D. Kilgore Tectonophysics 256 (1996)

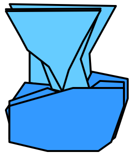


$\Gamma_{bulk} = \Gamma \cdot A_0/\Delta A = 1 / (0.2 \times 0.005) \sim 1000\ J/m^2$

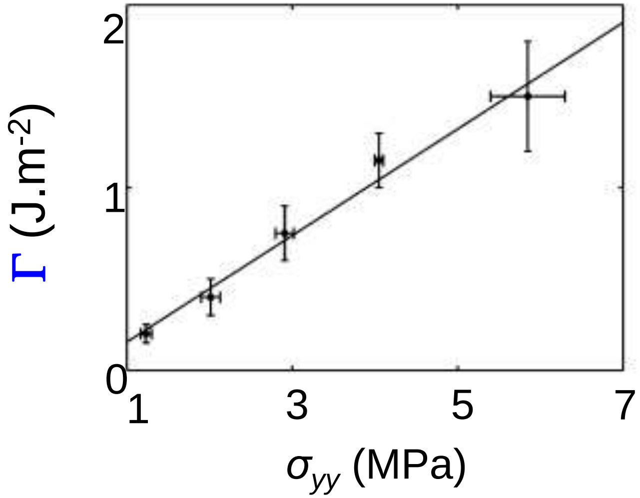
➔ $\Gamma_{bulk} \sim$ the measured bulk fracture energy for PMMA!

➡ Γ is proportional to A

➡ A is proportional to σ_{yy}



➡ Γ is proportional to σ_{yy} ?



➔ Friction rupture fronts are essentially shear cracks
(at least when they are moving)

We will now use this to describe related phenomena/questions

1. **Arrested rupture fronts**

   How far will an earthquake extend ⇔ when will a rupture stop?

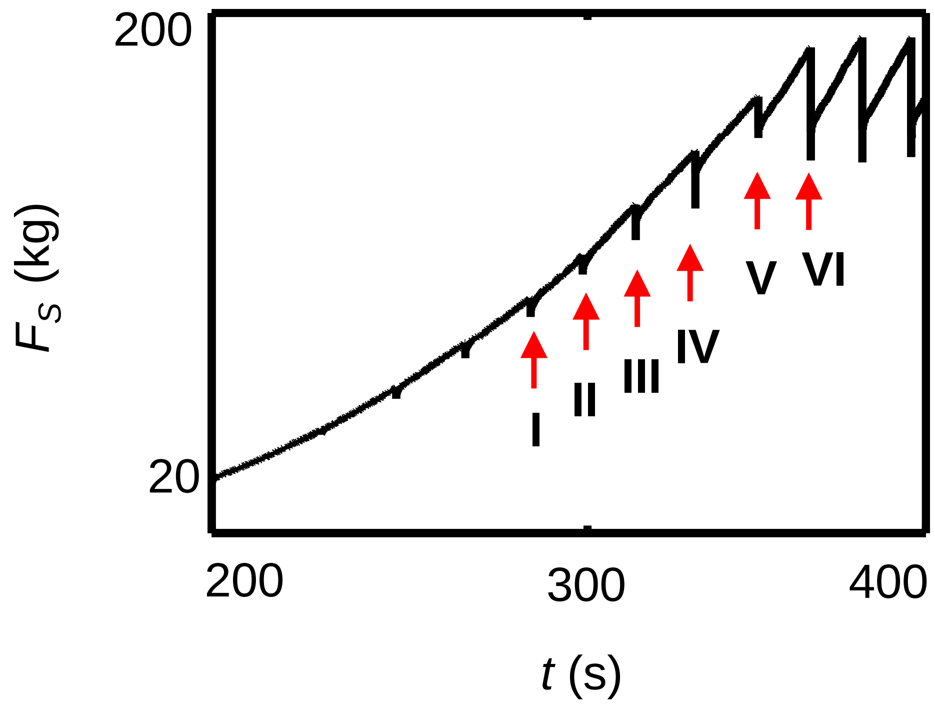
2. **Lubrication of the interface**

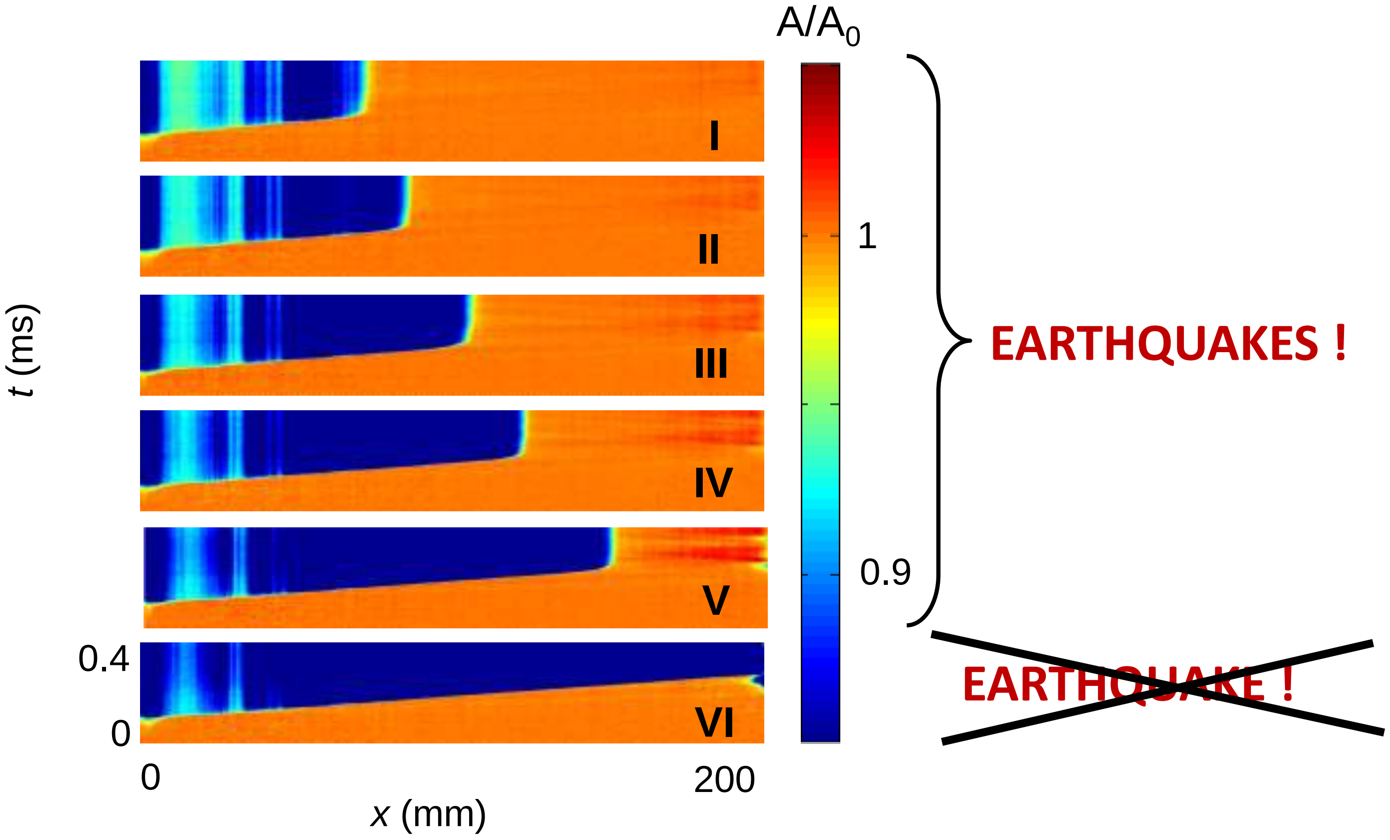
   Is friction still fracture?

   Effect of lubricants on rupture onset/dissipation…

ARRESTED RUPTURE FRONTS

Bayart, Svetlizky and Fineberg, *Nature Physics* (2016)

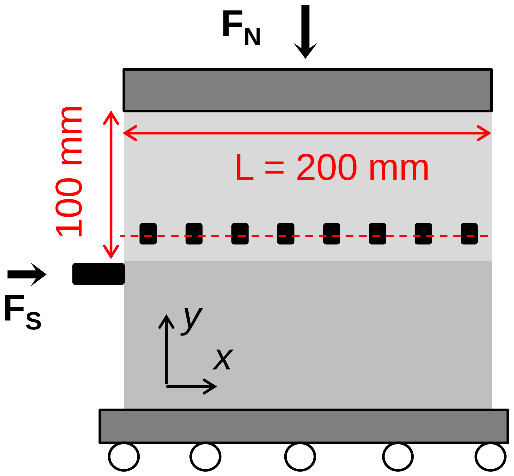


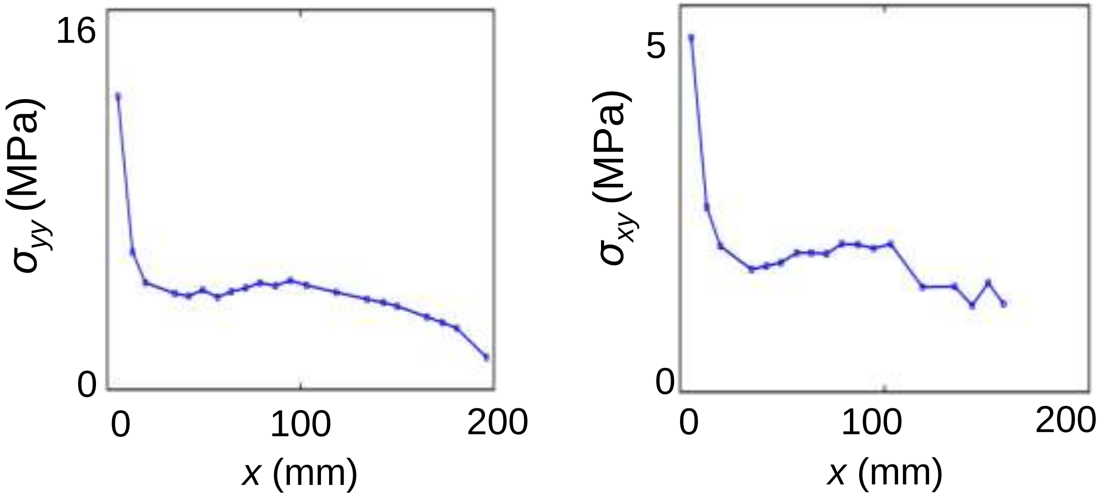


- Transition from stick to slip is mediated by a rupture front
- Partial ruptures occur before the transition: no macroscopic sliding

What controls the arrest of the rupture?

Arrested ruptures can result from inhomogeneous stress distributions





Several **observations** of these partial ruptures: *Rubinstein* 2007, *Maegawa* 2010, *Katano* 2014

Numerical studies of the **existence** of such ruptures:

Braun 2009, *Scheibert* 2010, *Tromborg* 2011, *Taloni* 2015, *Bar-Sinai* 2015

Recent study proposed a **CRACK ARREST CRITERION**

D. S. Kammer, M. Radiguet, J. P. Ampuero, & J. F. Molinari, *Tribology Letters* 57, 23 (2015).

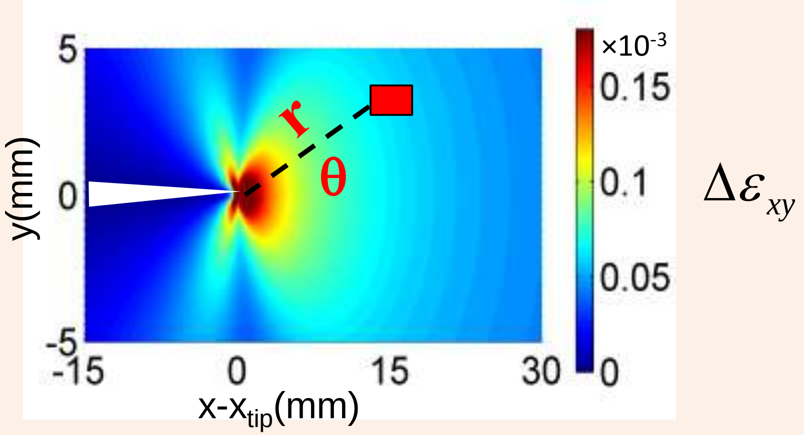
Our work: Experimental verification of the validity of a crack arrest criterion

How can fracture mechanics help?

We have seen that

Stresses are singular at the crack tip

$$\Delta\sigma_{ij} = \frac{K}{r^{1/2}} f(\theta, v)$$



Propagation criterion:

Energy flux = Fracture energy

$$G \sim K^2/E = \Gamma$$

E is the Young's modulus

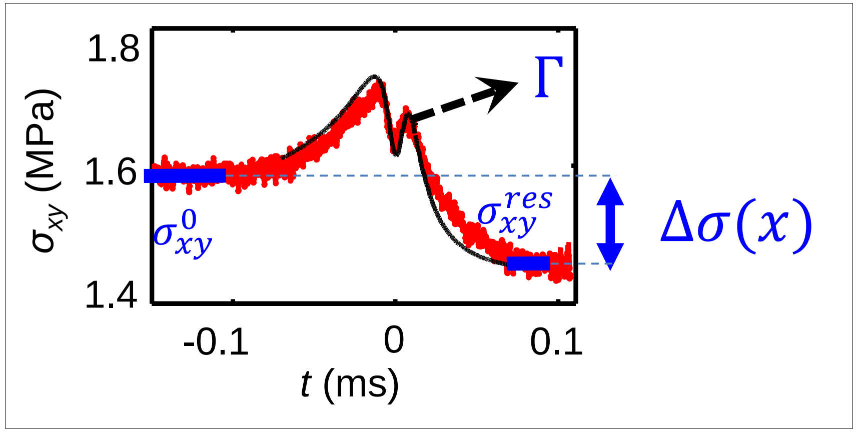
At the arrest: $G(v,l) \xrightarrow[v\to 0]{} G_{stat}(l) = \frac{K_{stat}(l)^2}{E}$

Arrest criterion: $G_{stat} < \Gamma \Rightarrow \boxed{K_{stat} < K_c = \sqrt{\Gamma E}}$ Griffith criterion

Griffith (1920)
Freund (1990)
Kammer et al (2015)

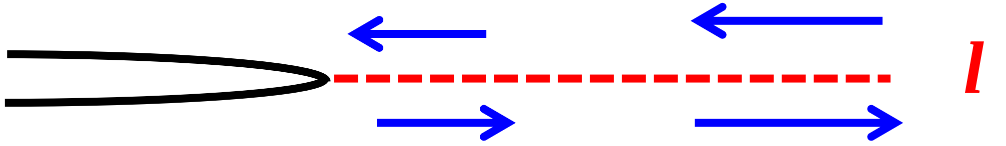
Arrest criterion:

$$\boxed{K_{stat} < K_c = \sqrt{\Gamma E}}$$



- Determination of K_c ➡ We know how to determine Γ
- Calculation of K_{stat}

$\Delta\sigma(x)$ = stored stress *ahead* of the crack



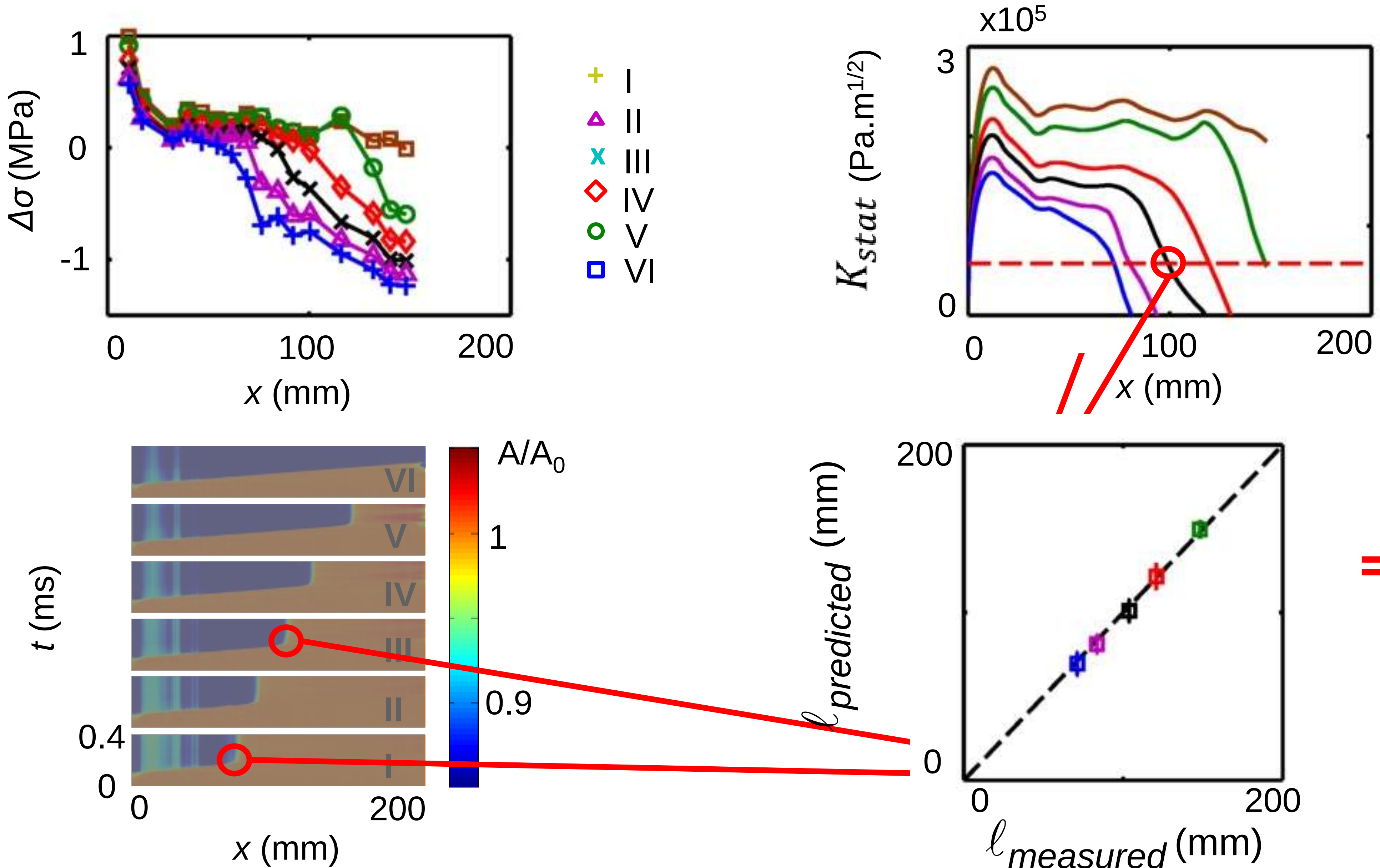
l = **prospective** (predicted) crack length

Fracture Mechanics: K_{stat} is determined by the stress drop $\Delta\sigma(x)$ for all $x < l$

$$K_{stat}(l) = \sqrt{\frac{2}{\pi}} \int_0^{l} \frac{\Delta\sigma(x)}{\sqrt{l - x}}\, dx$$

Can we **predict crack arrest**?

$$K_{stat}(l) = \sqrt{\frac{2}{\pi}}\int_0^l \frac{\Delta\sigma(x)}{\sqrt{l-x}}\,dx$$

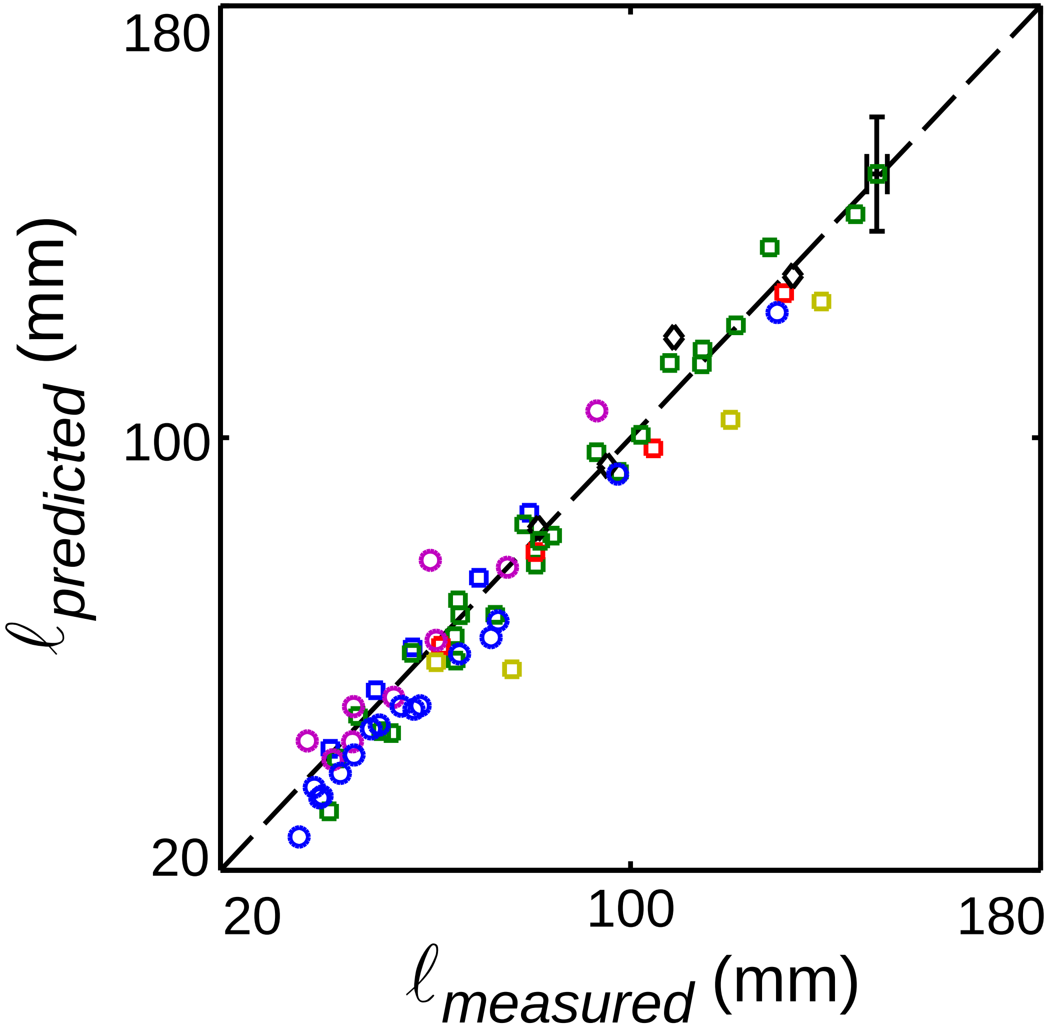


$K_c = \sqrt{\Gamma E}$

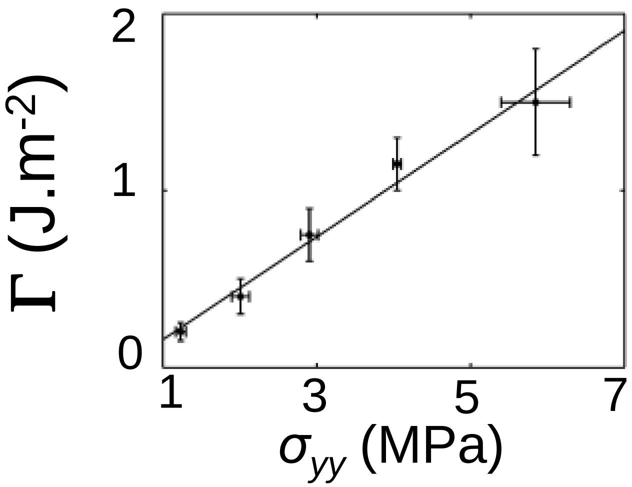
⟹ **SLOPE 1 !**

Excellent agreement!

We have predicted crack arrest once … **is it general?**



	$< \sigma_{yy} >$ (MPa)	Γ (J.m^{-2})
○	8.2-8.5	3.5
○	5.2-5.8	2.5
□	6	1.5
□	3.8-4	1.1
◊	3	0.75
□	2	0.4
□	1.3	0.2



Bayart et al (2016)

We have shown that

The location of a **rupture arrest** is **deterministic.**

can be simply defined with a **crack arrest criterion**.

WHY ARE WE INTERESTED IN ARRESTED RUPTURES ?

- Confirmation of the fracture-paradigm for understanding friction.

Friction coefficient = force balance
Fracture mechanics = energy balance

- Prediction of earthquake’s size

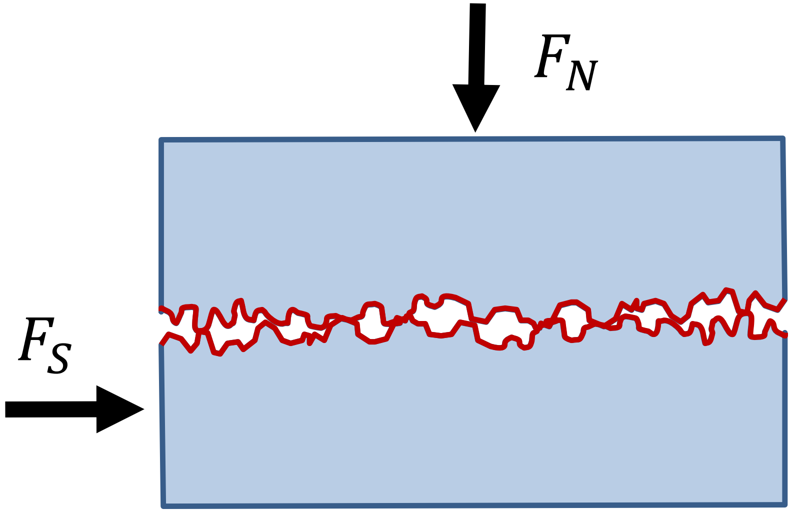
An earthquake is a finite size rupture in an infinite size system

LUBRICATED FRICTION

Bayart, Svetlizky and Fineberg, *arXiv:1602.00085* (2016)

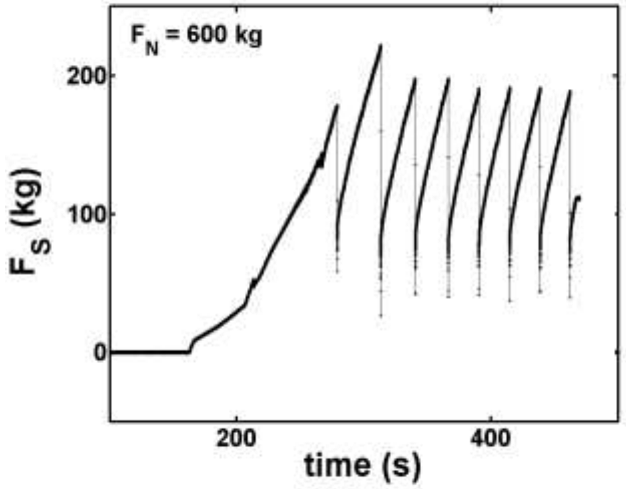
What about lubricated interfaces ?

Coated lubricated interfaces = Interfaces coated with a film of lubricant

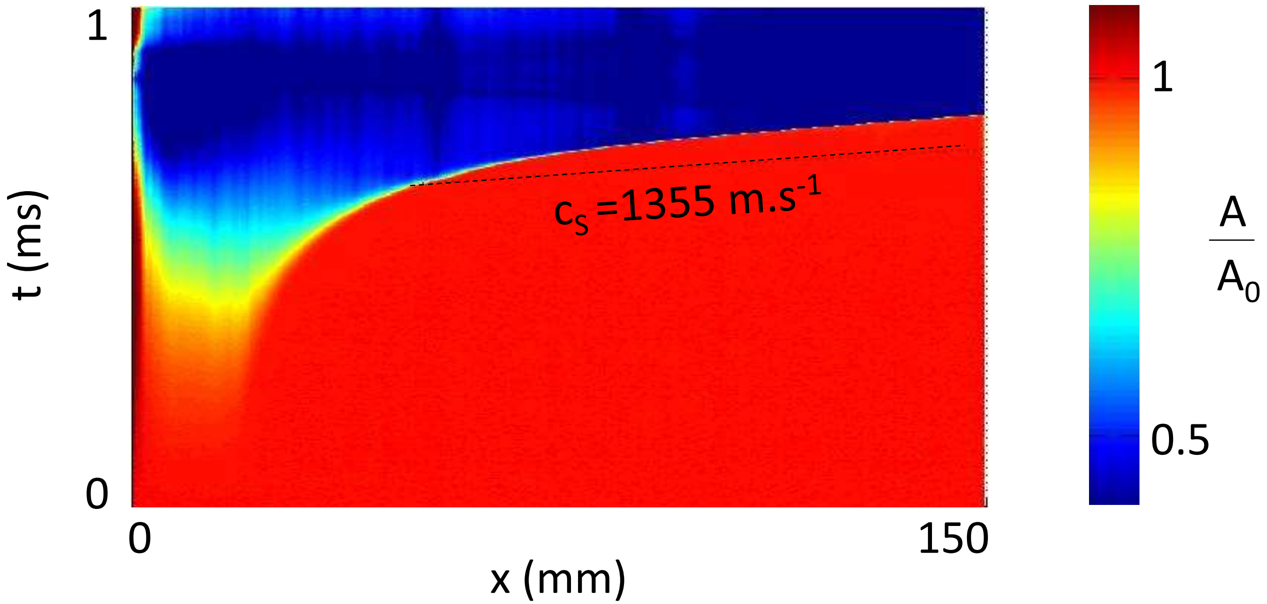


LUBRICANT	KINEMATIC VISCOSITY (cSt)
Silicone oil	5
Silicone oil	100
Silicone oil	10^4
Hydrocarbon oil (TKO-77)	200

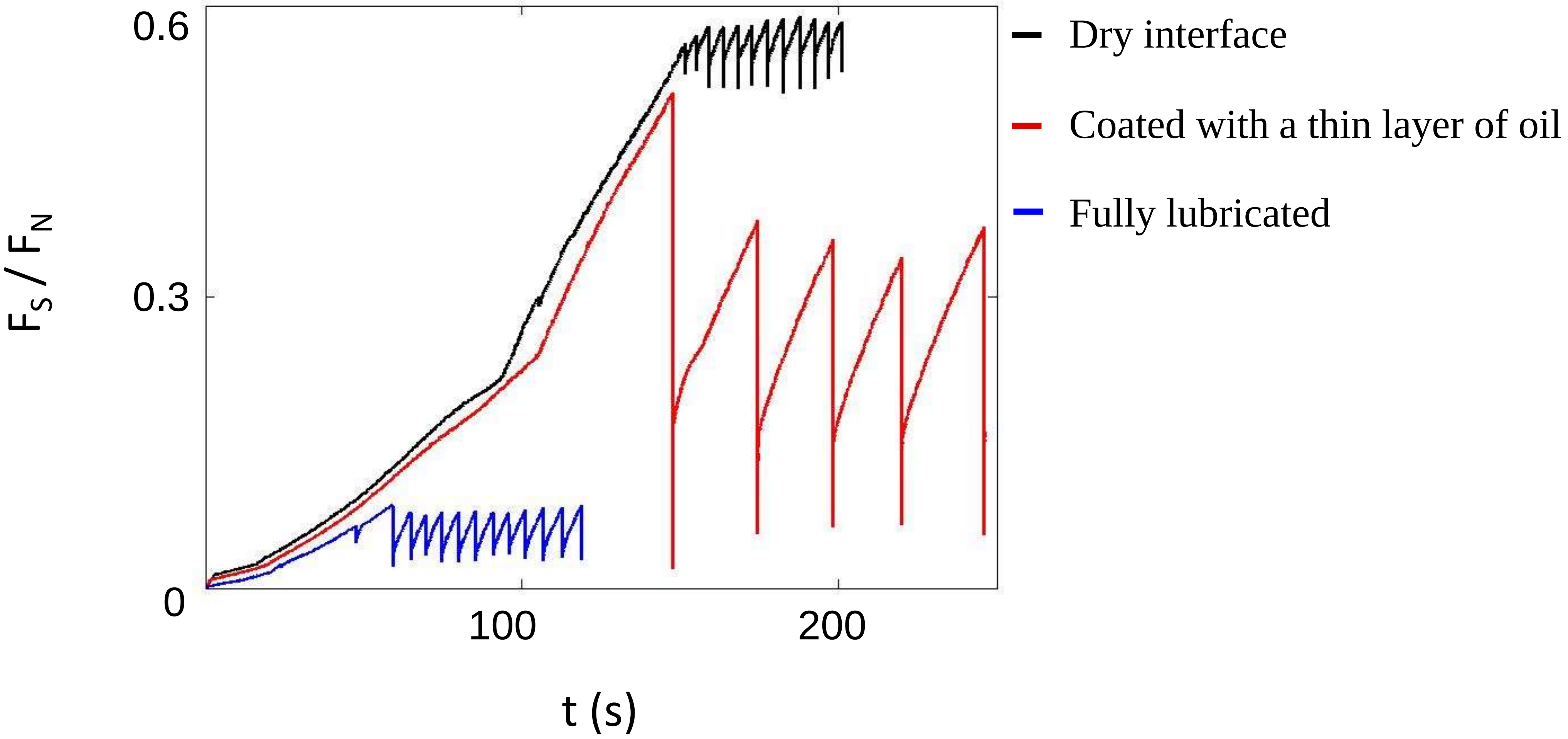
For slippery interfaces, we observe **STICK-SLIP**



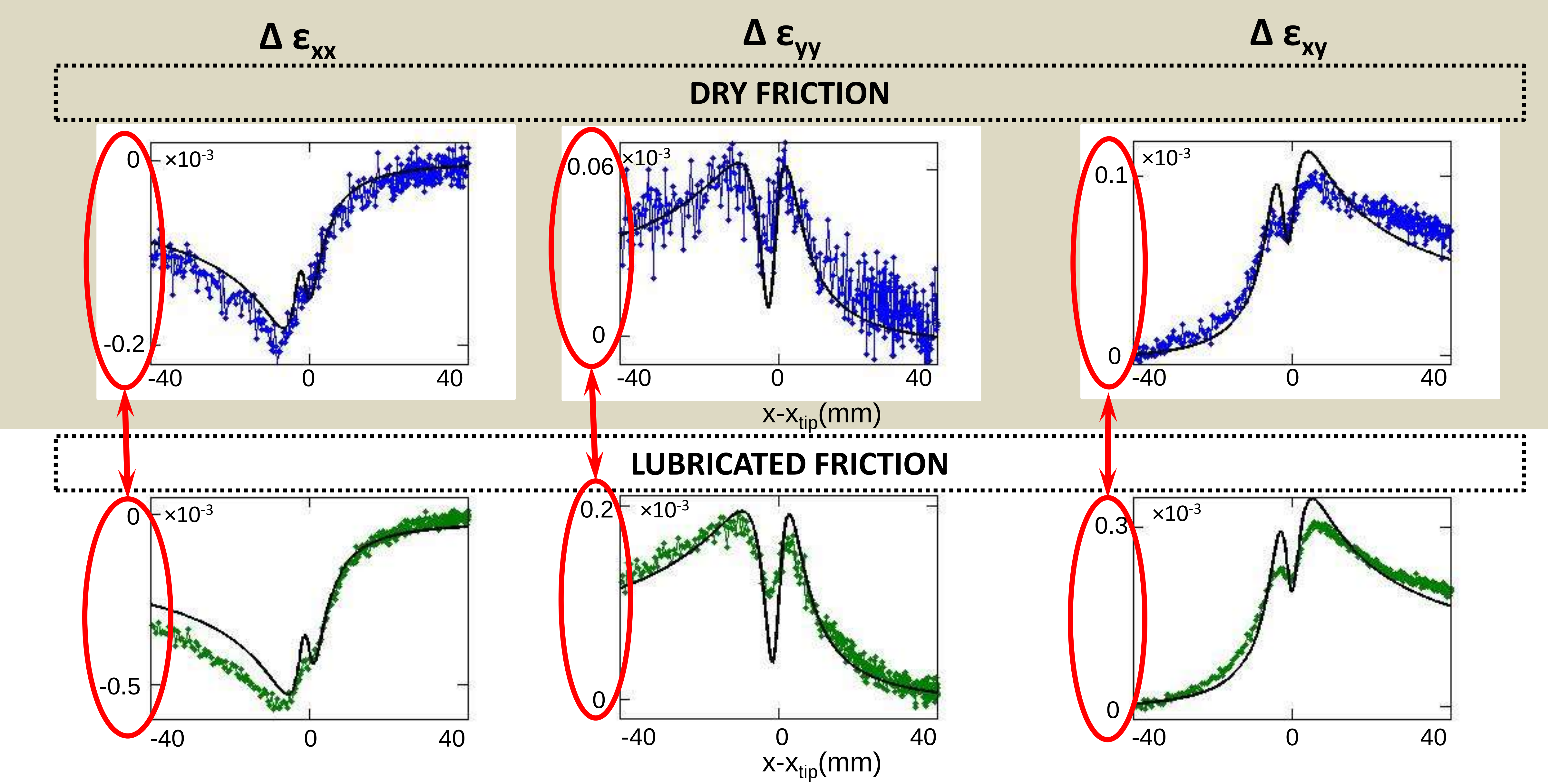
and propagating **RUPTURE FRONTS !**



It is more slippery …

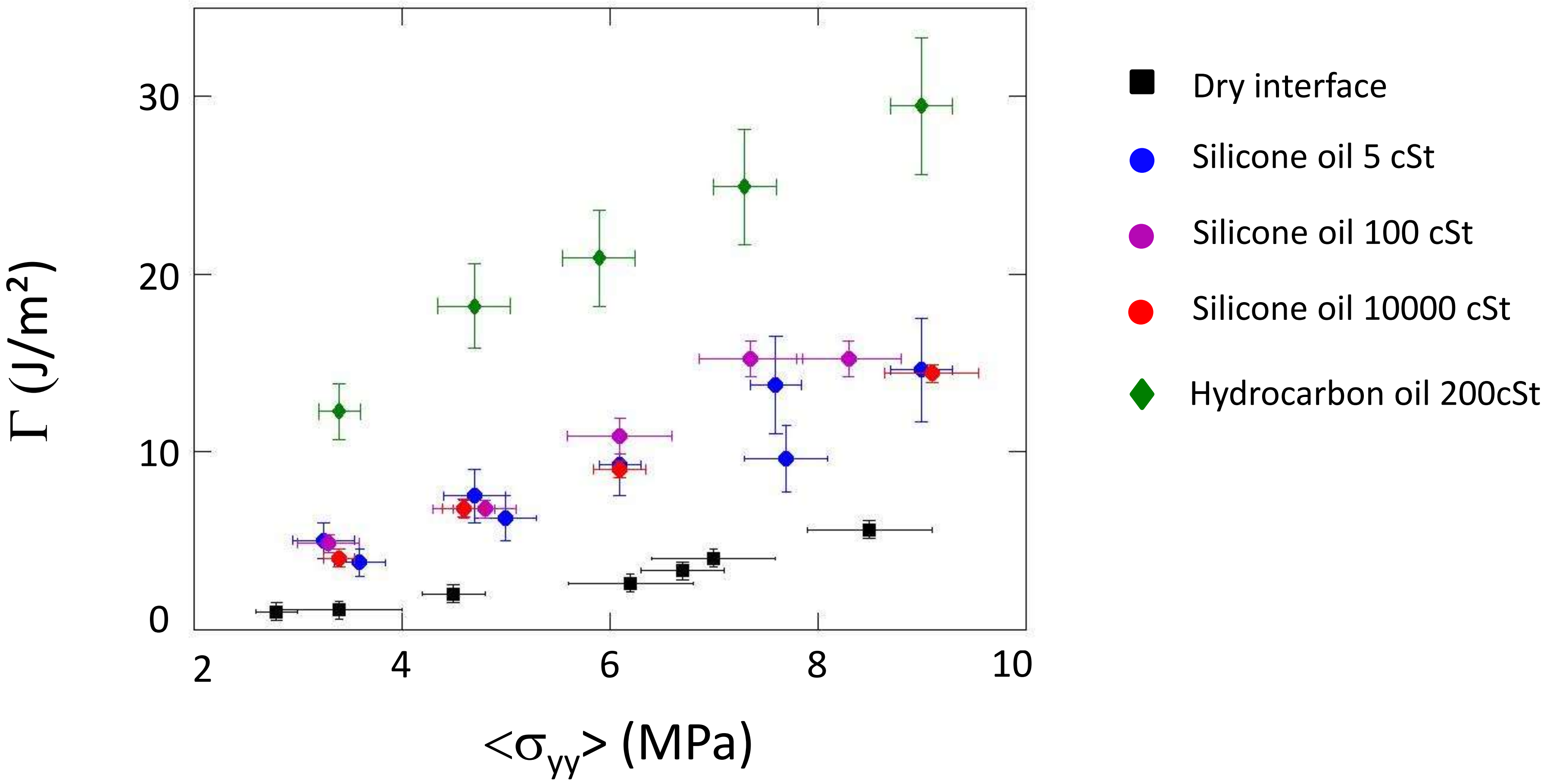


… BUT



$\Gamma_{lubricated} = 23\ J/m^2 \gg \Gamma_{dry} = 2.6\ J/m^2$!!

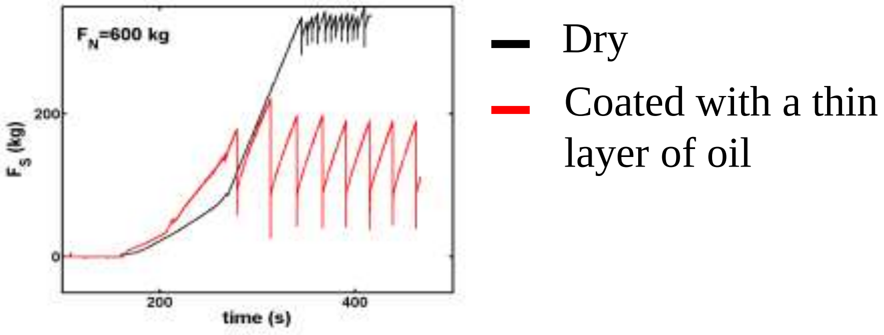
Fracture energy vs normal stress



- Γ is always proportional to normal stress
- Different lubricants have different influence on Γ
- Viscosity does not affect Γ…

Coated lubrication

A **WEAKER** interface – smaller friction coefficient



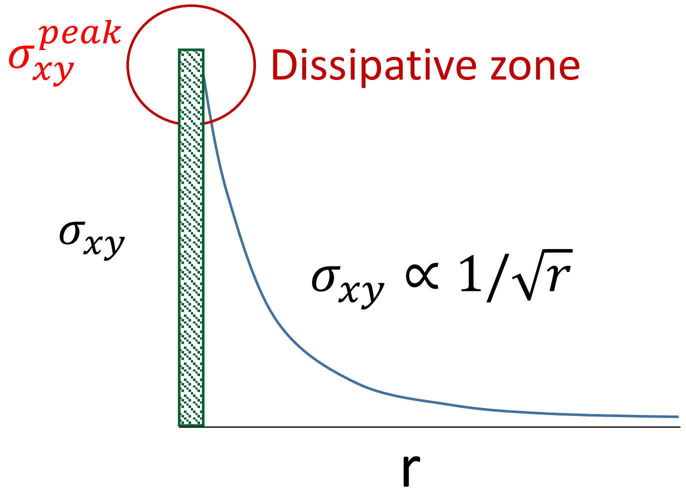
A **STRONGER** interface – higher fracture energy

$\Gamma_{lub} \sim 23\ J/m^2 >> \Gamma_{dry} \sim 3\ J/m^2$ **!!**

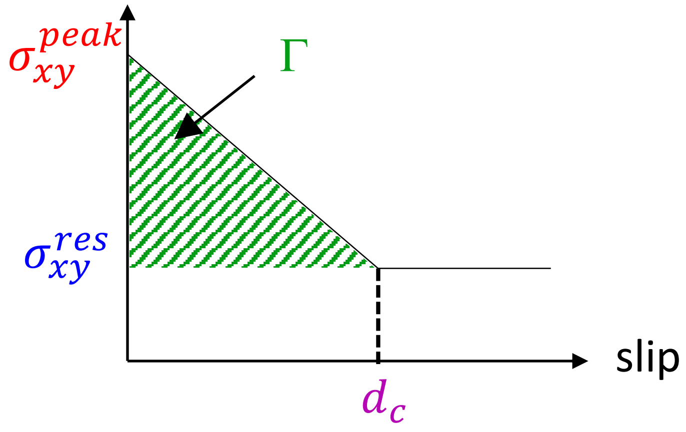
?

How to explain a high fracture energy Γ ?

LEFM: intermediate scale
Small scale: dissipative zone



Frictional crack – Linear slip-weakening model
Palmer and Rice 1973



d_c : slip distance over which stresses are reduced (asperity size)

$$\Gamma = \frac{1}{2}\left(\sigma_{xy}^{peak} - \sigma_{xy}^{res}\right) d_c$$

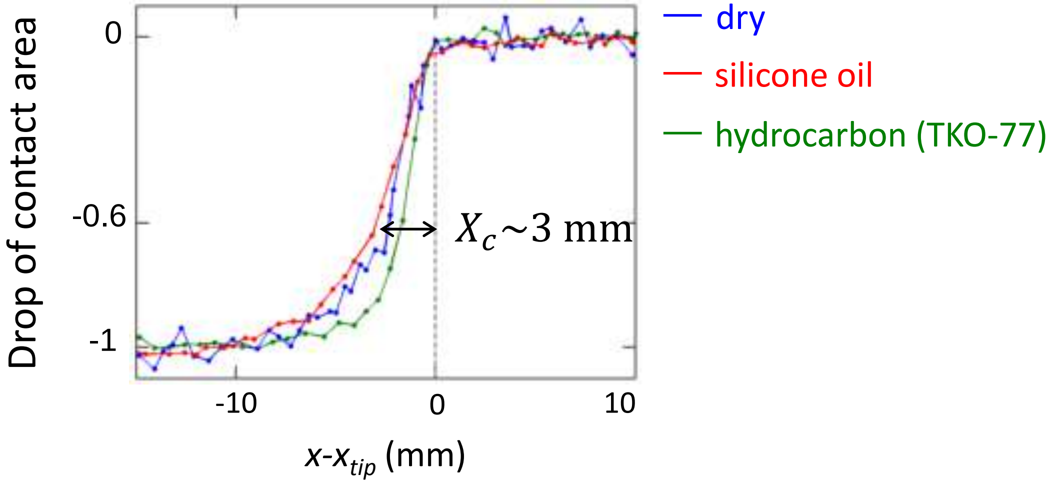
Increase of Γ:

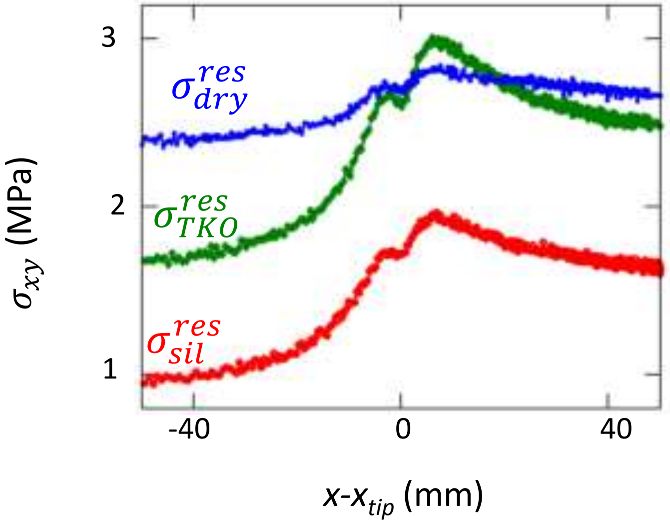
- increase of σ_{xy}^{peak} → not measured
- increase of d_c → not measured
- decrease of σ_{xy}^{res} → measured

Linear slip-weakening model relates σ_{xy}^{peak} to the dissipative zone size X_c:

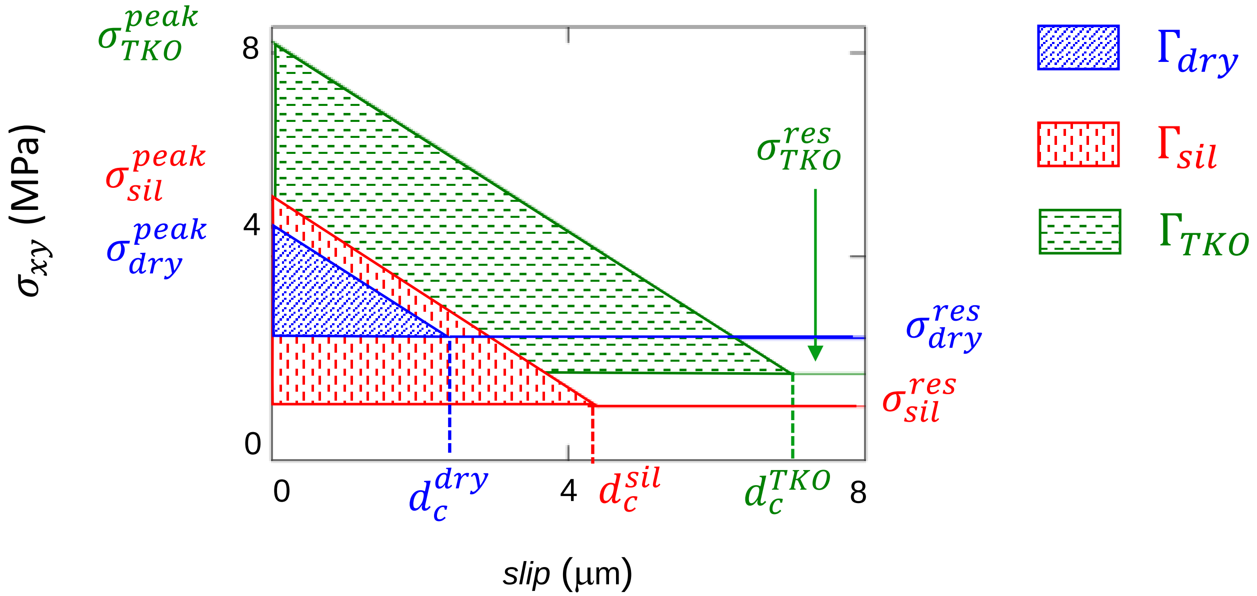
$$\sigma_{xy}^{peak} = \sigma_{xy}^{res} + \sqrt{\frac{9\pi}{32}\frac{\Gamma E}{(1-\nu^2)X_c}}$$

X_c is the distance behind the crack tip over which contact are broken





$$\Gamma = \frac{1}{2}\left(\sigma_{xy}^{peak} - \sigma_{xy}^{res}\right) d_c$$



Increase of Γ:

- increase of σ_{xy}^{peak} → YES
- increase of d_c → YES
- decrease of σ_{xy}^{res} → YES

Coated lubrication: ***Some questions…***

Peak stress **is not** reduced, even increased:

Possibly: Huge pressures at the contacts cause…

Layering transition of the highly compressed liquid *(e.g. layering -Israelachvili, Klein, Granick…) ?*

Residual strength **is** significantly lower.

Possibly: Once motion initiates…

Lubrication of contacts? ➔ Lubricant recovers a liquid behavior

Solidification followed by melting could be the answer

NO PARADOX between a **low static friction coefficient** and a **high fracture energy**

friction coefficient = nucleation process

fracture energy = interface property, related to propagation

Questions do remain:

Why doesn’t fluid viscosity matter?

Why does lubricant composition matter so much?

High fracture energy = high dissipation ➔ high wear of lubricated machine parts at the onset of motion

SUMMARY

At the onset of motion, **RUPTURE FRONTS** propagate along the frictional interface

They are ruled by **FRACTURE MECHANICS** while propagating and at the **ARREST**

Along a **LUBRICATED** interface, fracture mechanics provide a way to observe the complex dynamics of the lubricant layer

NOT A CLOSED PROBLEM

Nucleation = crack initiation ?

probably not

What about more complex interfaces ?

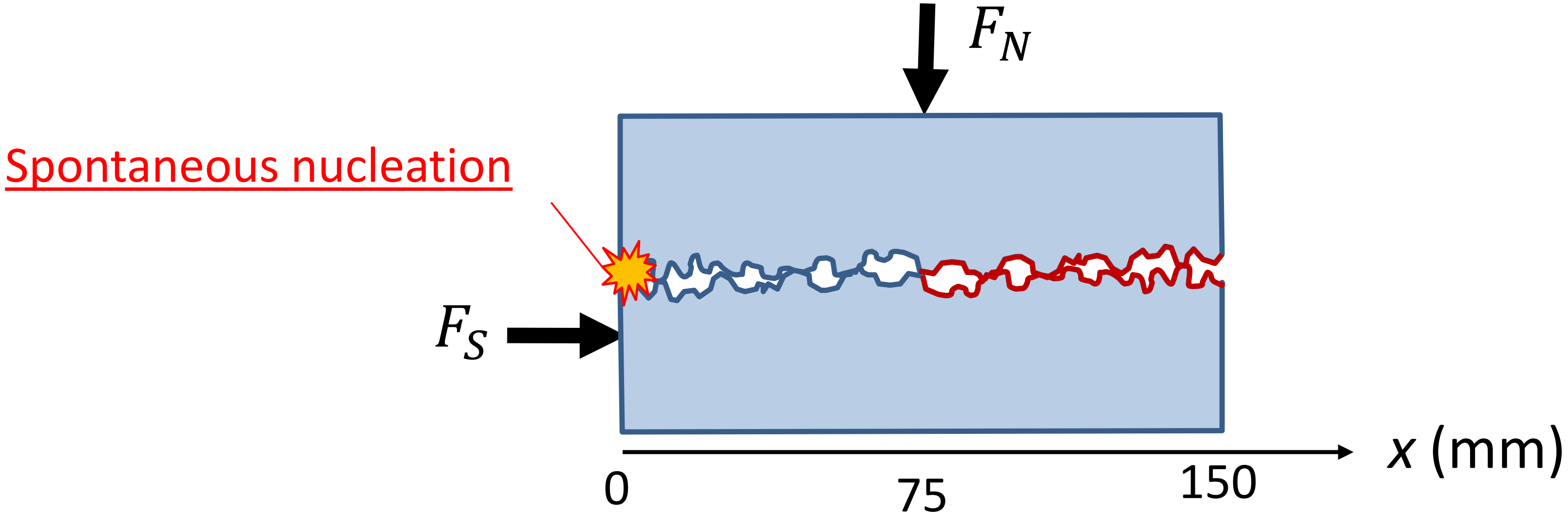
non-cohesive interfaces, textured

What about sliding ?

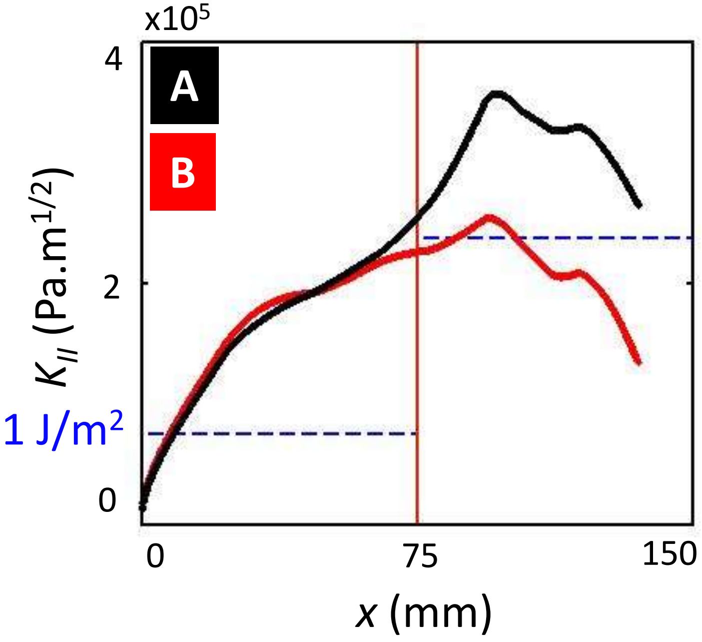
APPLICATION

Can be a rupture arrested by a local increase of the fracture energy ?

- 0 < x < 75mm : non-lubricated surface
- 75mm < x < 150mm: surfaces coated with hydrocarbon oil (TKO-77).
- $<\sigma_{yy}>= 4\text{MPa}$

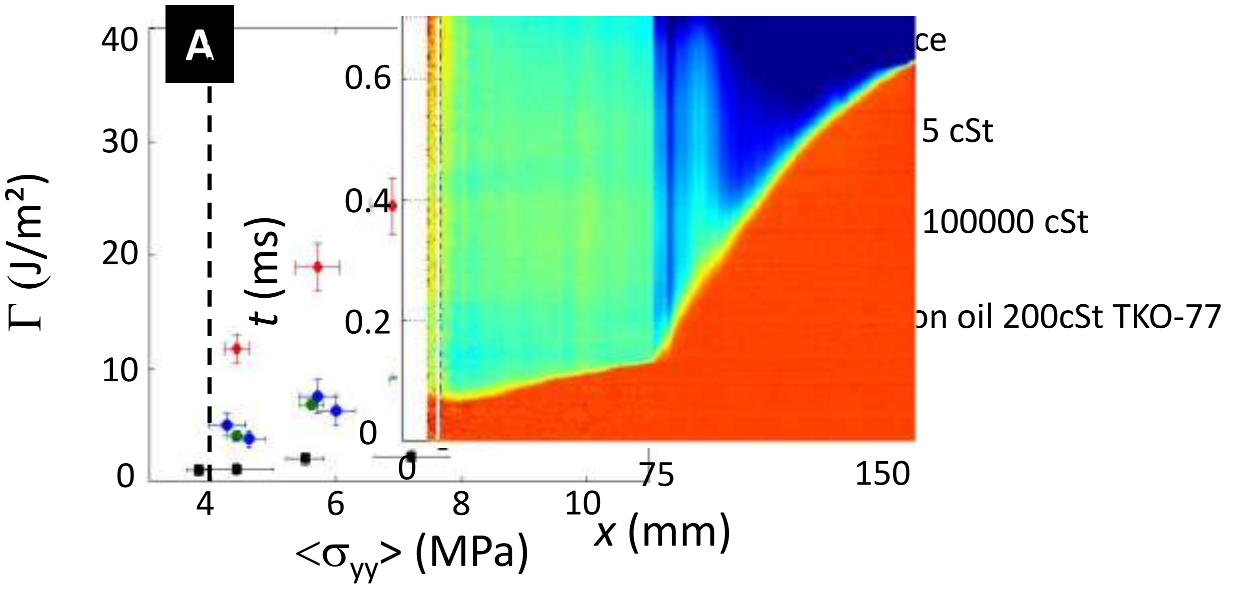


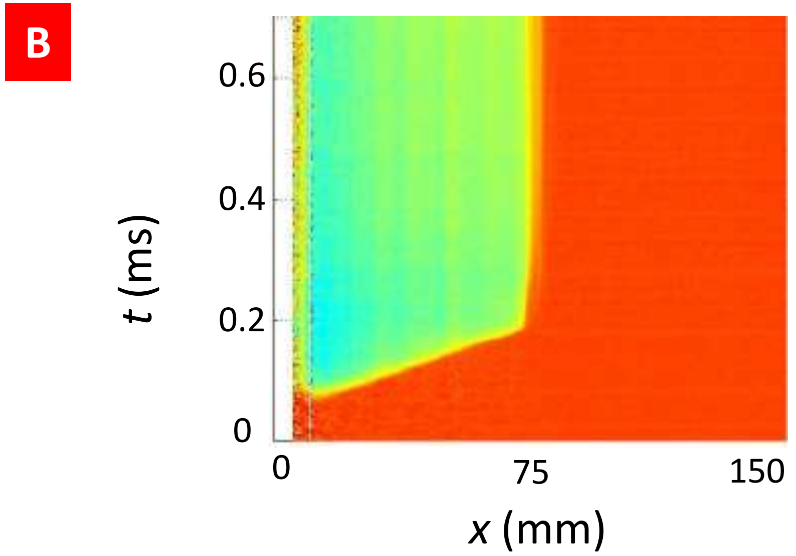
What will happen to the propagating rupture while entering in the lubricated part ?



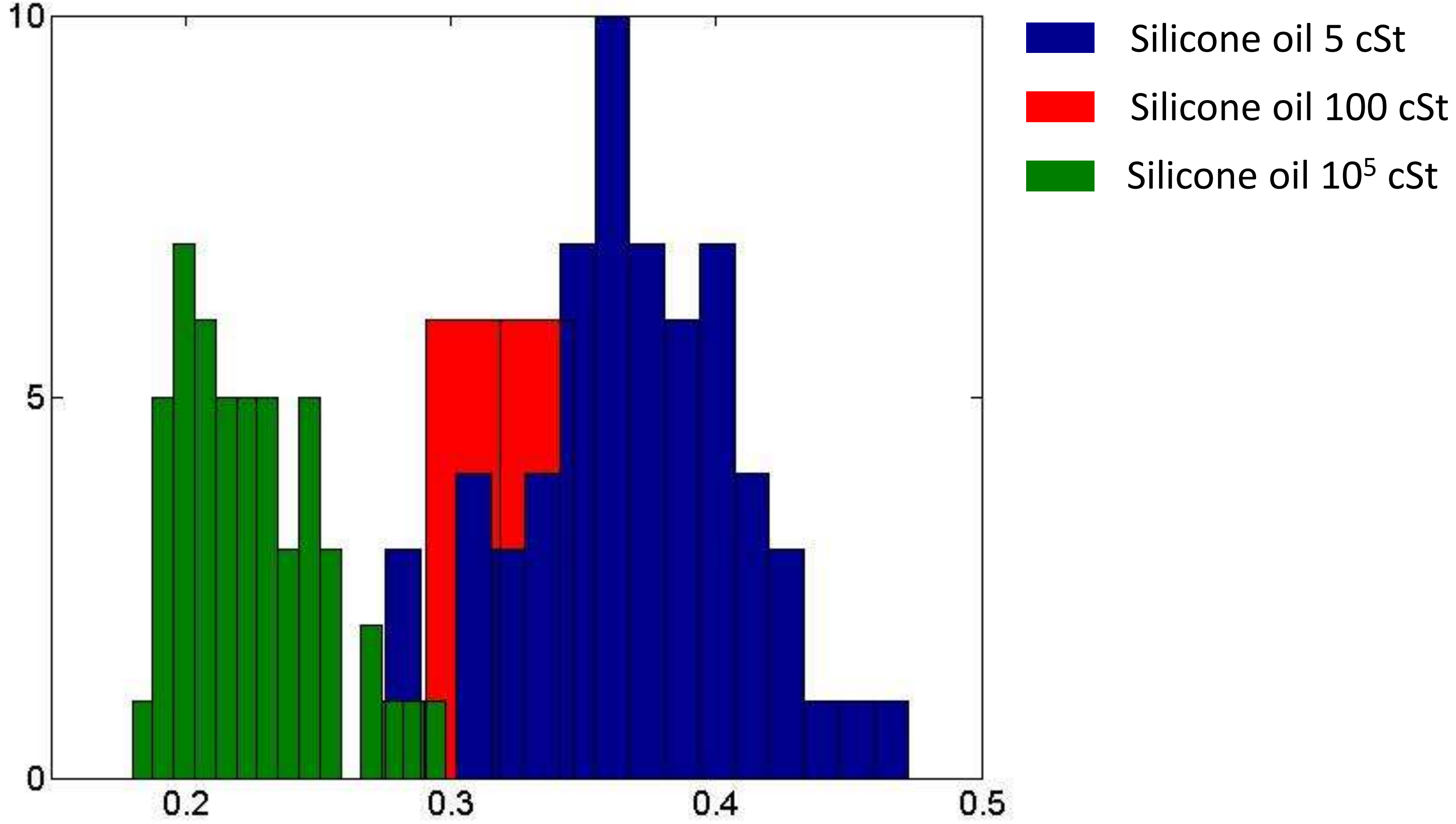
Γ_{TKO-77} ($\langle\sigma_{yy}\rangle$= 4MPa) = 10 J/m^2

Γ_{DRY} ($\langle\sigma_{yy}\rangle$= 4MPa) = 1 J/m^2





THANK YOU


10
5
0
0.2
0.3
0.4
0.5
Silicone oil 5 cSt
Silicone oil 100 cSt
Silicone oil 10^5 cSt

$$\mu = \frac{F_S}{F_N}$$

Summary

- **Rupture fronts** mediating the onset of sliding are **shear cracks**
- **Spontaneously arrested ruptures**: arrest location is defined by a **crack arrest criterion**
- **Lubricated interfaces**: the interface **fracture energy** is increased.

Can we use it?

- Could we deduce Γ along a fault by recording the **displacement field** during a rupture propagation ?

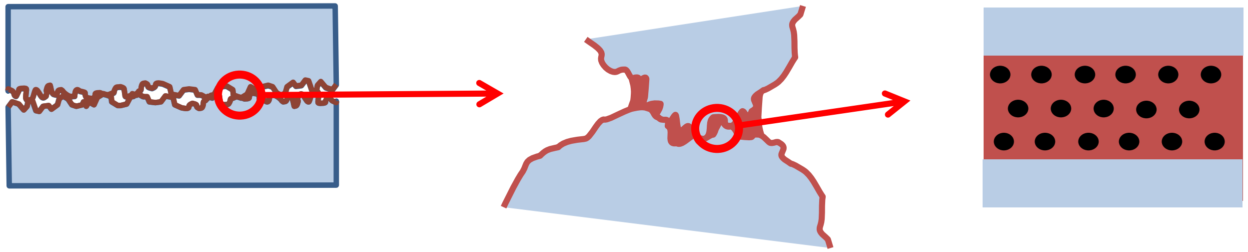
  Comparison of the measured value with the estimation by the drop of stress and the event size ?
- Rupture arrest: knowing the **averaged drop of stress for small earthquakes** along a fault, could this criterion used to evaluate **local** Γ along a fault?
- Increased of Γ by lubrication: increase of the **wear of the material**?

Coated lubrication

Why a Stronger interface?

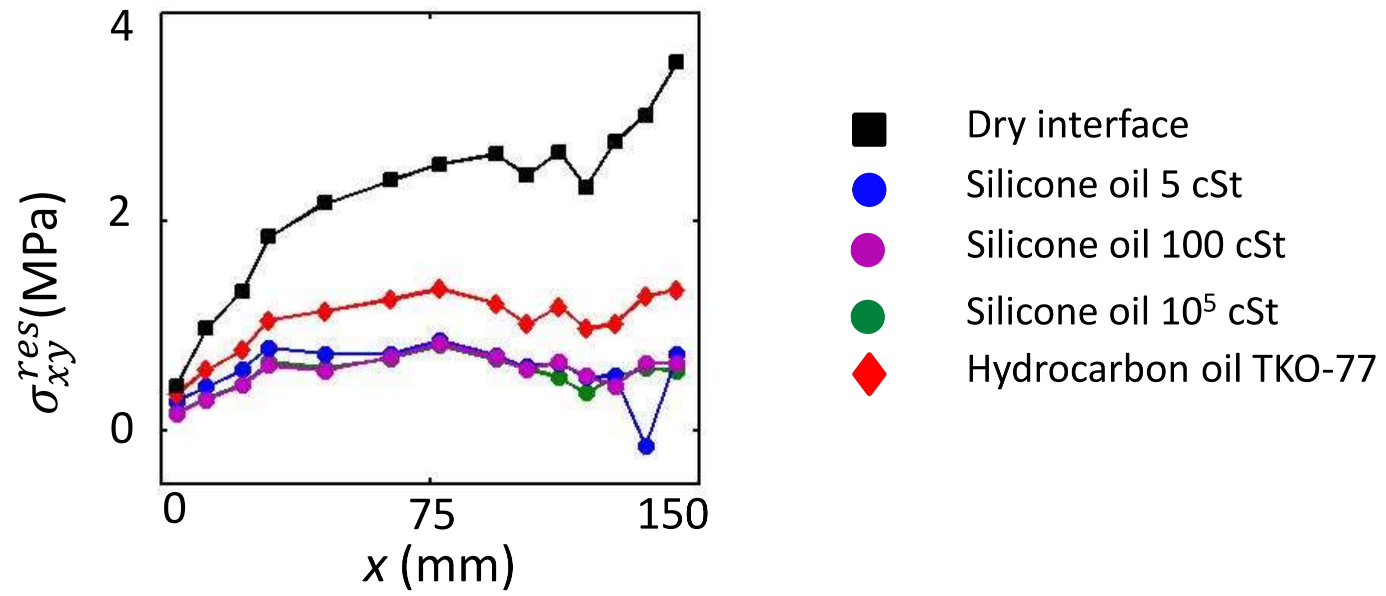
List of propositions including ideas of GRC participants:

- **Layering transition** of the highly compressed liquid *(e.g. layering -Israelachvili, Klein, Granick…)*
- **Piezoviscosity** (increase of the viscosity with the pressure and shear rate)



- **Suction** of the liquid at the onset of motion (negative pressure due to capillary bridges)
- **Effect of the pore pressure** on the residual stress
- **Viscous disspation** in the cohesive zone

$$\Gamma_{\text{interface}} = \frac{\text{real area of contact}}{\text{apparent area of contact}} \times \frac{\text{number of broken contacts}}{\text{total number of contacts}} \times \Gamma_{\text{bulk}}$$

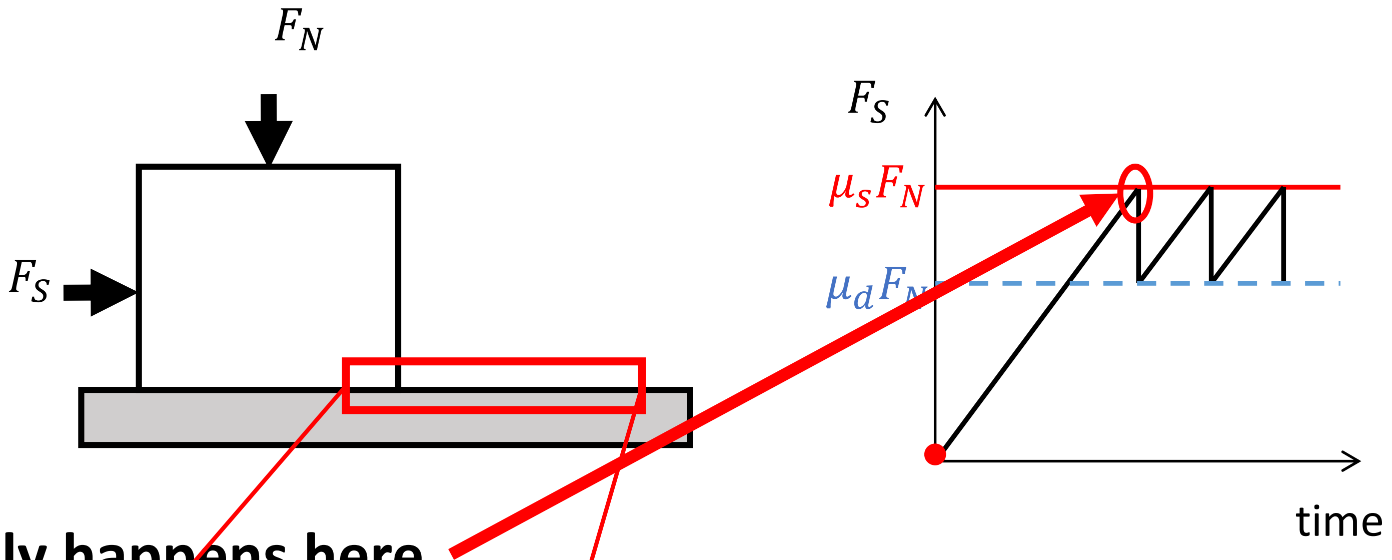


NO PARADOX between a **low static friction coefficient** and a **high fracture energy**

friction coefficient = nucleation process

fracture energy = interface property, related to propagation

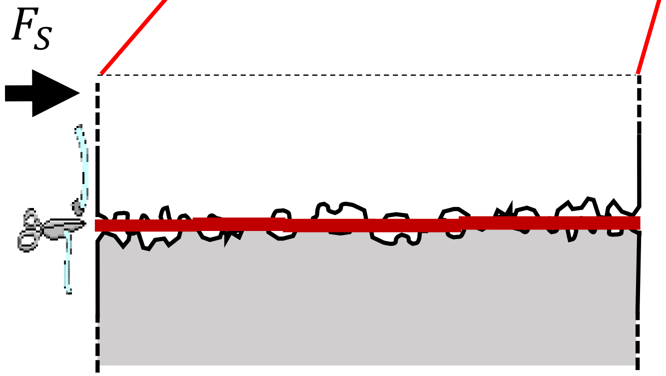
What we usually know about friction



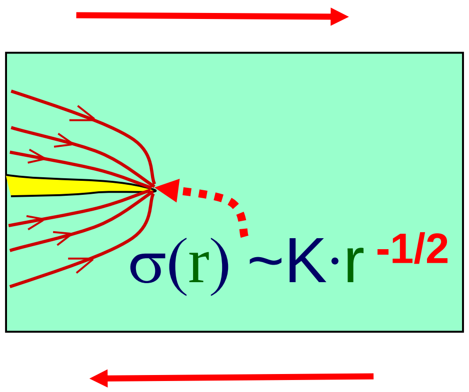
$$F_S < \mu_s F_N \Rightarrow \text{no motion}$$

$$F_S = \mu_s F_N \Rightarrow \text{motion}$$

What actually happens here



EARTHQUAKE !



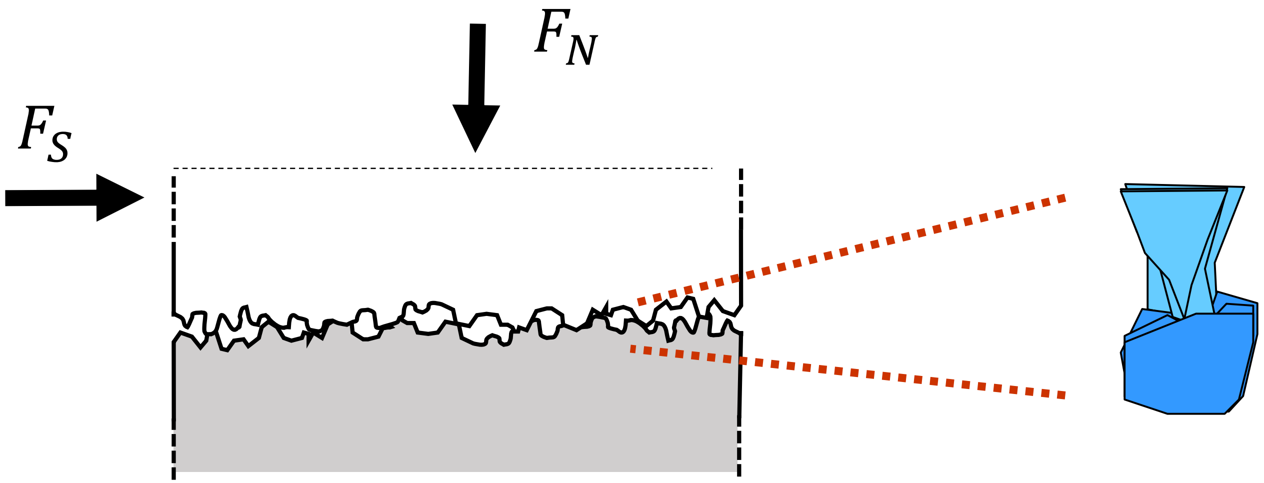
The onset of friction

⇔

fracture of the discrete contacts that form the interface

Svetlizky and Fineberg, Nature **509**, 205–208 (2014)

About the area of contact



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

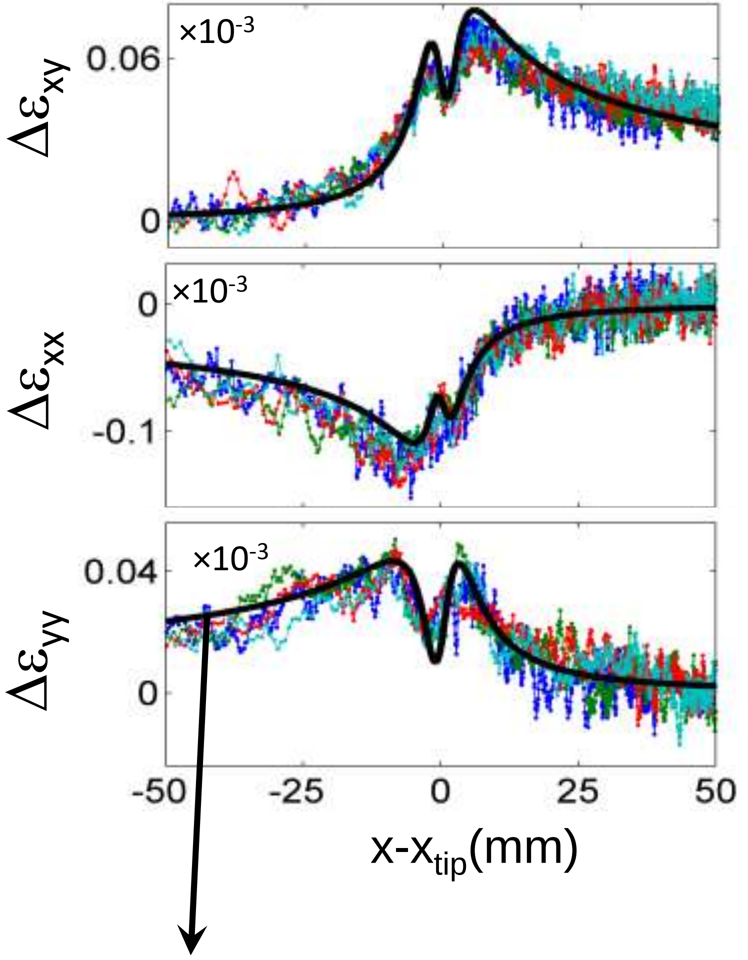
Huge pressures at the contact points **deform the contacts**

Pressure = yield stress, σ_Y ➔ $A = F_N / \sigma_Y$

➔ ***A*** is proportional to **the normal load**

F. Philip Bowden and David Tabor (1950)

Rupture propagation



LEFM solution at the measurement point (3 mm above the interface)

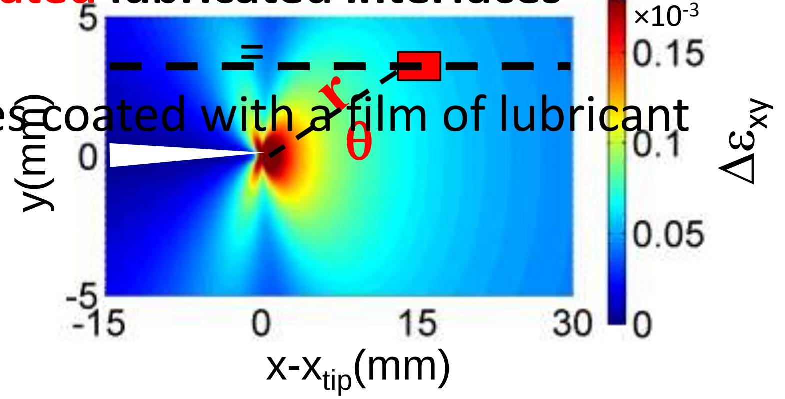
— Fracture mechanics solution (LEFM):

$$\Delta\varepsilon_{ij} = \frac{K}{r^{1/2}} f(\theta, v)$$

$K \leftrightarrow$ energy flux G

Coated lubricated interfaces

Interfaces coated with a film of lubricant



Propagation condition $G = \Gamma$

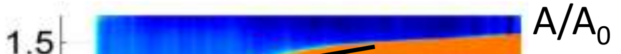
$\Gamma =$ energy to break a unit area of contacts

$$\boxed{K \leftrightarrow \Gamma}$$

$\Gamma \sim 1\ \mathrm{J/m^2}$

Detachment fronts are shear cracks

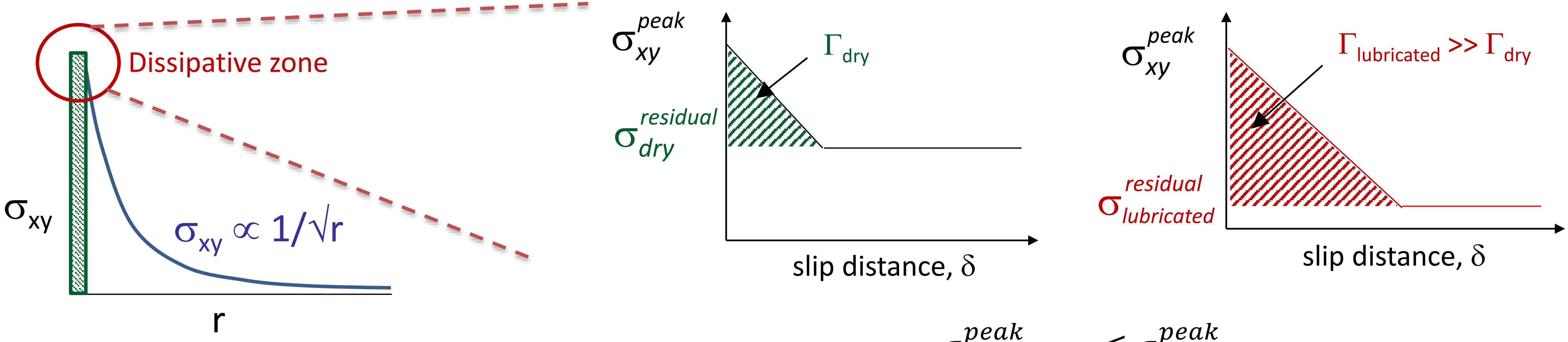
Strain field measurements $\leftrightarrow$ Γ



Svetlizky and Fineberg, Nature **509**, 205–208 (2014)

Coated lubrication: ***Why a Stronger*** interface?

An interpretation of the role of the lubricant:



Palmer and Rice (1973)

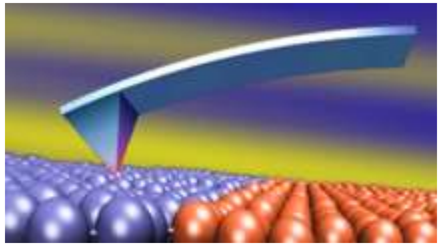
$$\sigma_{lubricated}^{peak} \leq \sigma_{dry}^{peak}$$

$$\sigma_{lubricated}^{residual} \ll \sigma_{dry}^{residual}$$

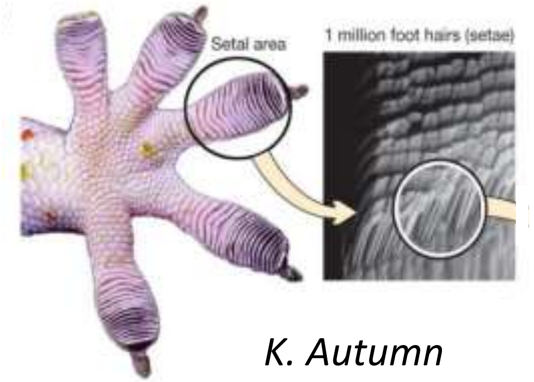
$$\Rightarrow \Gamma_{lubricated} \sim \Delta\sigma \cdot \delta \gg \Gamma_{dry}$$

On a coated surface: $\sigma_{lubricated}^{residual}$ is lower resulting in longer slip, δ

Large improvements this last two decades

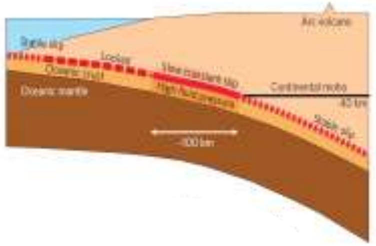


Development of AFM and SFA: measurements for one single contact *(Israelachvili, Klein,…)*



K. Autumn

Biomimetic approach for both dry and lubricated friction



Peng and Gomberg

Development of high-sensitivity seismic captors allowing detection of a large range of types of events (silent to supershear earthquakes)