On the energy balance behind frictional ruptures

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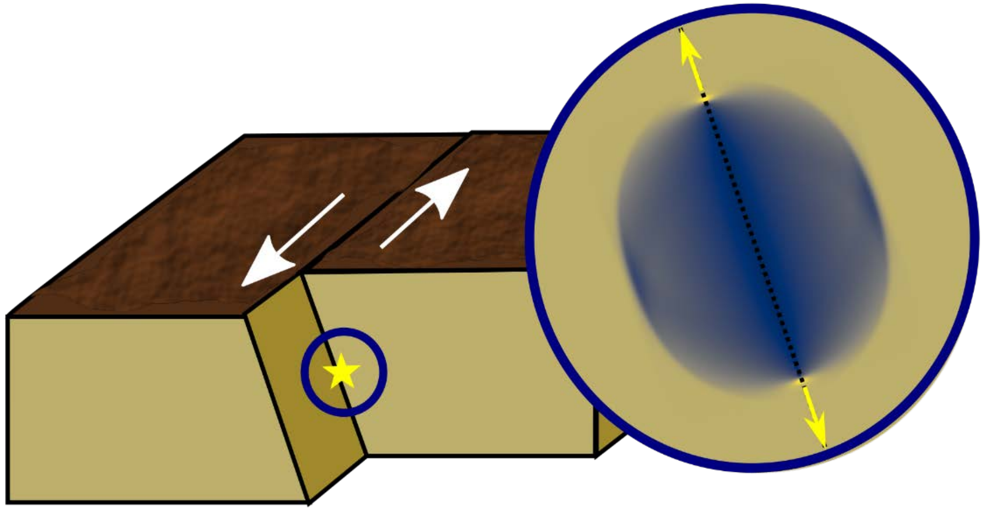
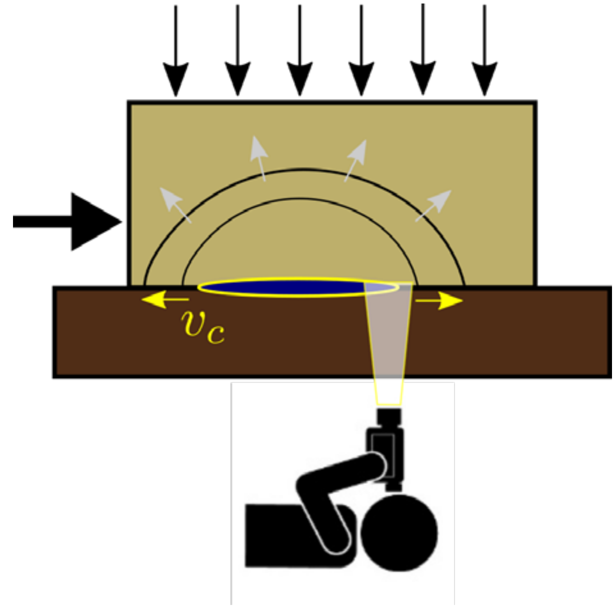
Motivation



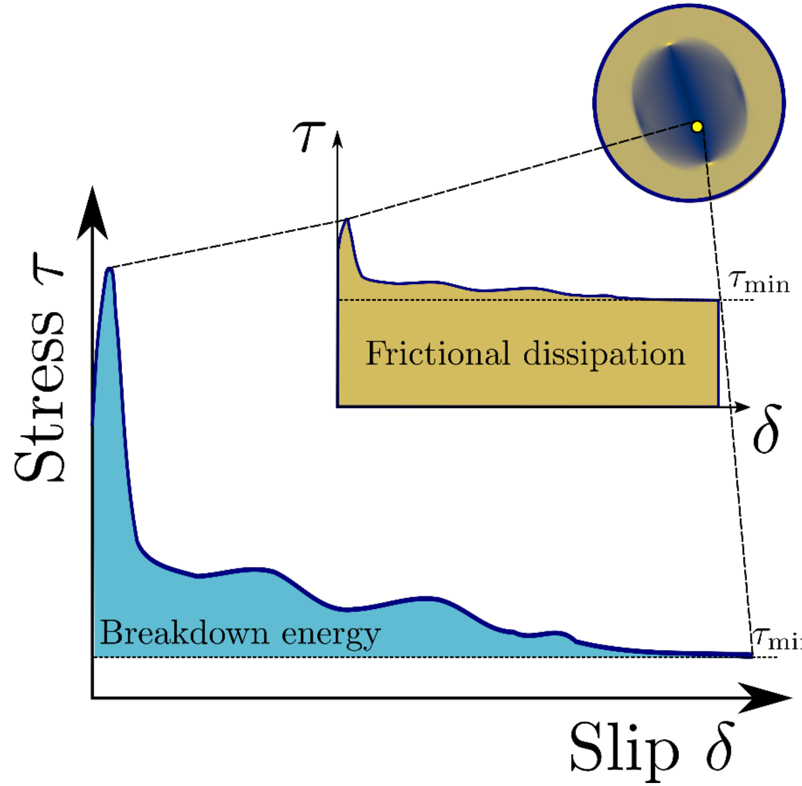


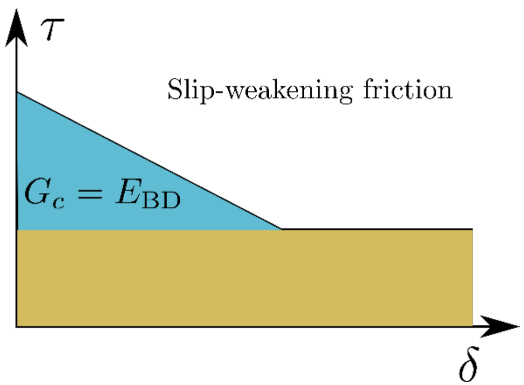
- Earthquake ruptures are driven by the dynamic weakening of frictional strength along crustal faults
- "Lab-earthquake" experiments revealed the crack-like properties of frictional ruptures.
  (e.g Xia *et al.*, Science, 2004
  Passelègue *et al.*, Science, 2013
  Svetlizky *et al.*, Nature, 2014
  Rubino *et al.*, Nature Comm., 2017)

➢ This work investigates the rupture energy controlling the propagation of frictional ruptures by analogy with fracture mechanics

Context

- Shear stress does not drop to zero in the wake of frictional ruptures (unlike shear cracks)
- The energy controlling the rupture dynamics (≡ the **rupture energy** G_c) is only a subpart of the frictional dissipation
- Slip-weakening friction model predicts that G_c corresponds to the **breakdown energy** E_{BD} (≡ excess of frictional dissipation on top of the minimum stress)





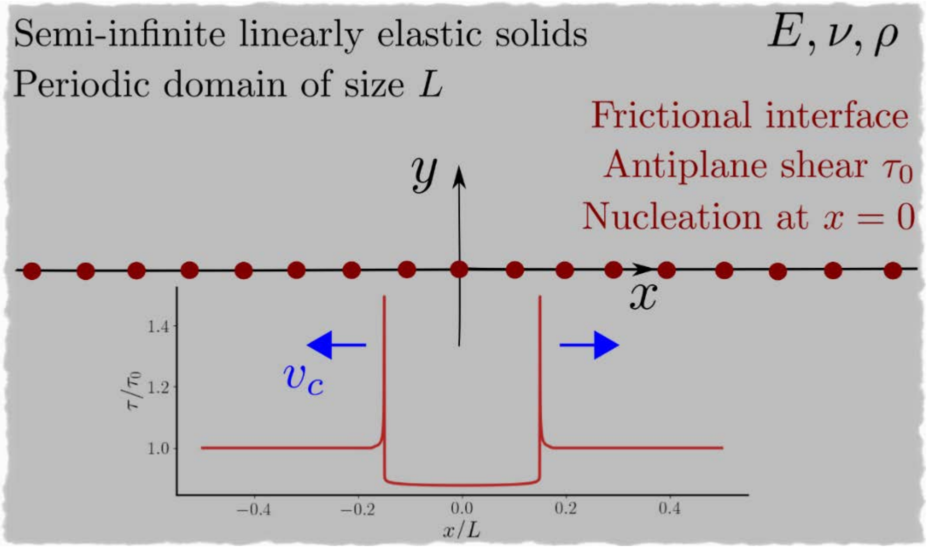
Ida, JGR, 1972
Andrews, JGR, 1976

➢ What is the rupture energy for more sophisticated friction models?

Approach: dynamic simulation of frictional ruptures

- Elastodynamics boundary integral method

Geubelle and Rice, JMPS, 1995
Breitenfeld and Geubelle, IJF, 1998



- Friction law at the interface: two examples (model variables are written in red)

<u>Rate-and-state friction</u>

Dieterich, JGR, 1979 Bar Sinai *et al.*, JGR, 2012
Ruina, JGR, 1983

- $\tau(x) = \left(f_0 + A\ln(1 + \frac{v(x)}{v^*}) + B\ln(1 + \frac{\phi(x)}{\phi^*})\right)\sigma_n$
- ϕ[s] can be related to the microcontacts area (Baumberger and Caroli, Adv. In Phys., 2006)
- Empirical law representative of rock friction experiments

<u>Thermal pressurization across a layer of gouge at the interface</u>

Rice *et al.*, JGR, 2014
Platt *et al.*, JGR, 2014

- $\tau(x) = \left(f_0 + A\ln\frac{\dot{\gamma}(x,y)}{\dot{\gamma}^*}\right)(\sigma_n - p(x,y))$
- $\dot{\gamma}$ strain rate profile through the layer depending on fluid press. p and temp. T
- Mature fault zone with a core filled with fluid-saturated gouge

Approach: dynamic simulation of frictional rupture

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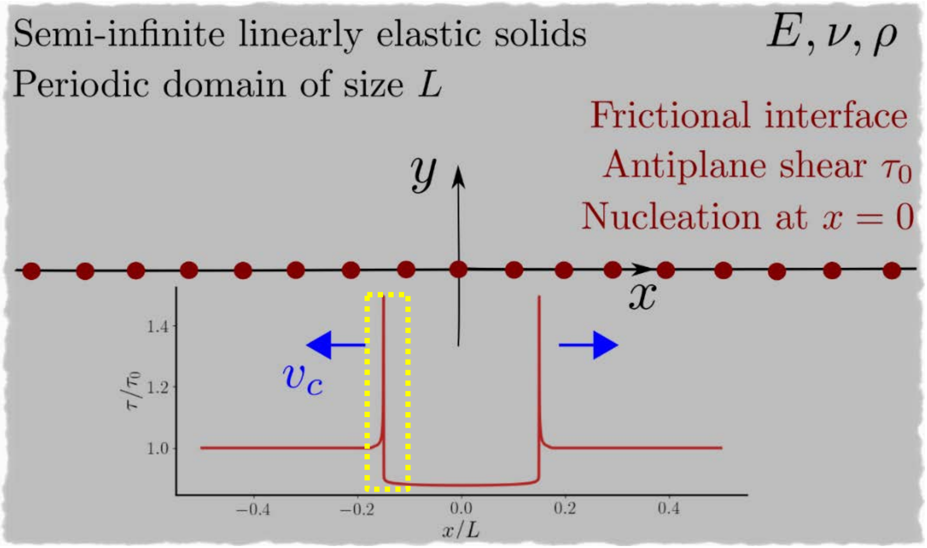


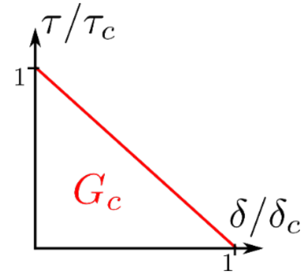
- Friction law at the interface: two examples

- Study the near-tip elastic fields to compute the energy released by the rupture

- Compare it to the energy dissipation at the interface during the rupture

Shear-fracture: a well-defined benchmark

- Demonstrate the approach for a shear crack simulated by slip-weakening cohesive law:



- The near-tip singularity can be studied using fracture mechanics (LEFM) predictions for stress τ and slip velocity v

Freund, *Dynamic Fracture*, 1990

Stress intensity factor (SIF)

$\alpha_s^2 = 1 - v_c^2/c_s^2$

$$\frac{K}{\sqrt{2\pi(x - x_r)}} \cong \tau \cong v \frac{\mu \alpha_s}{2 v_c}$$

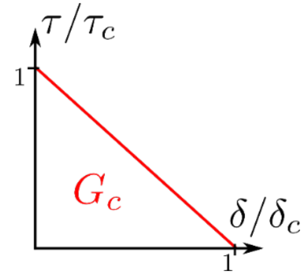
Tip location   Rupture speed   Shear modulus/wave speed

- K can be directly related to the energy release by unit crack advance G

$$G = \frac{K^2}{2\mu\alpha_s}$$

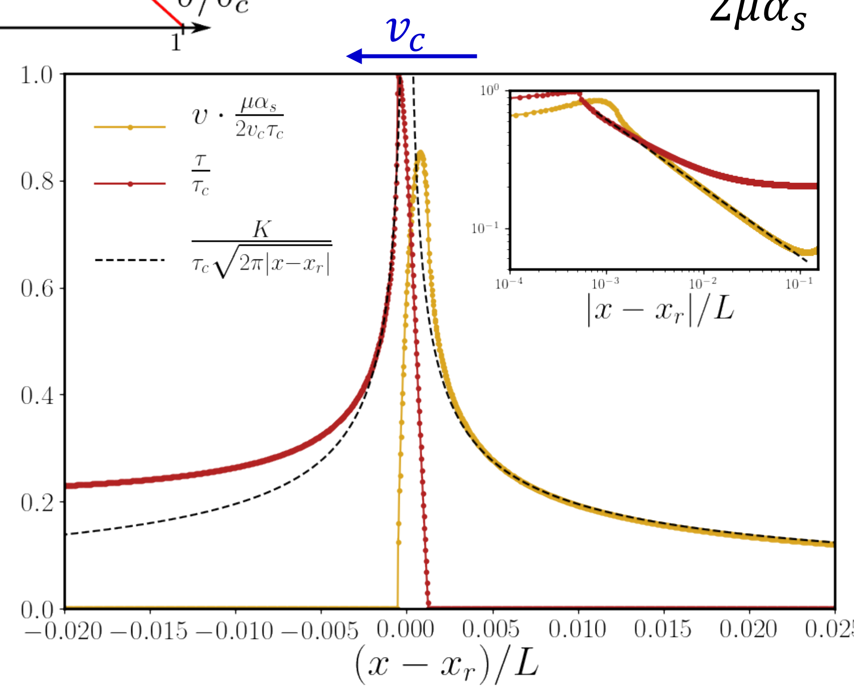
Shear-fracture: a well-defined benchmark

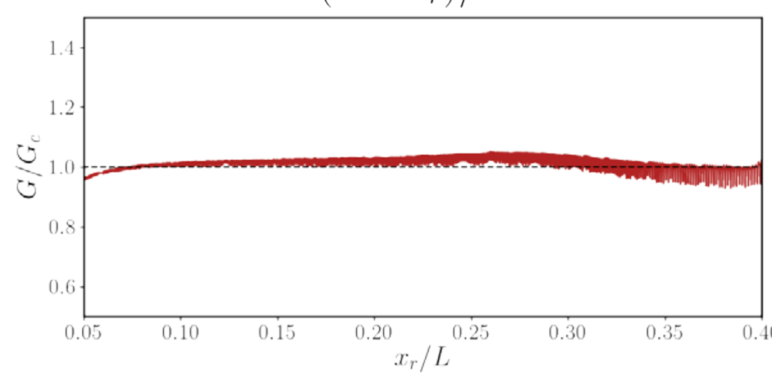
- Demonstrate the approach for a shear crack simulated by slip-weakening cohesive law:
- The near-tip singularity can be studied using fracture mechanics (LEFM) predictions for stress τ and slip velocity v
- K can be directly related to the energy release by unit crack advance G
- The fit of τ and v allows for estimating G
- The rupture energy balance is verified $G = G_c$



$$\frac{K}{\sqrt{2\pi(x-x_r)}} = \tau = v\frac{\mu\alpha_s}{2v_c}$$

$$G = \frac{K^2}{2\mu\alpha_s}$$





Let's now study frictional ruptures

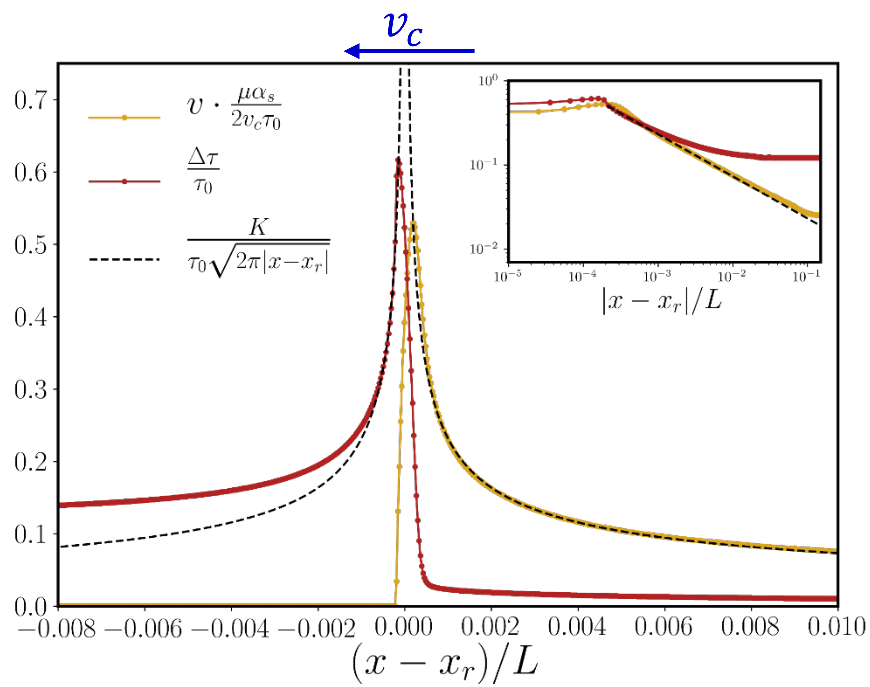
Case 1: Rate-and-state friction

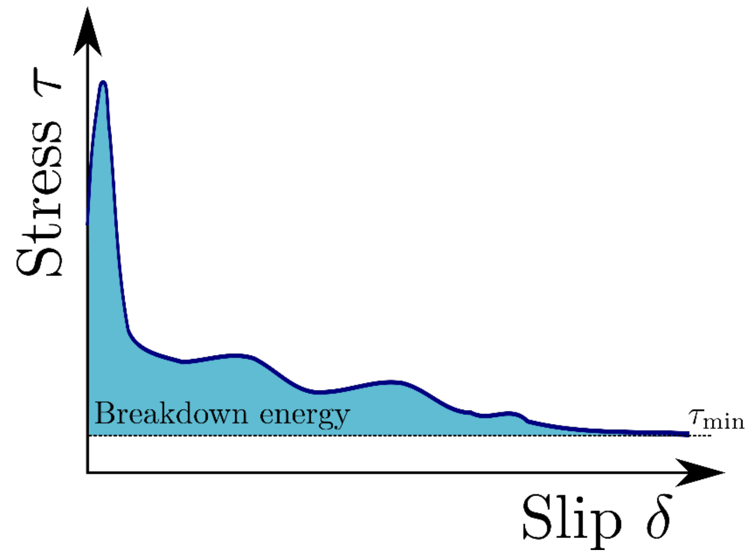
- As τ does not drop to zero, the frictional stress drop $\Delta\tau = \tau - \tau_r$ shall be used in the analogy with LEFM (invoking the linearity of the bulk constitutive law)
  Palmer and Rice, Proc. Roy. Soc., 1973

- Friction reaches a steady value of τ_r which can be predicted theoretically
  Barras *et al.*, PRX, 2019

- The breakdown energy overestimates G !

$$G < E_{BD}(x) = \int (\tau(x) - \tau_{min}) d\delta(x)$$





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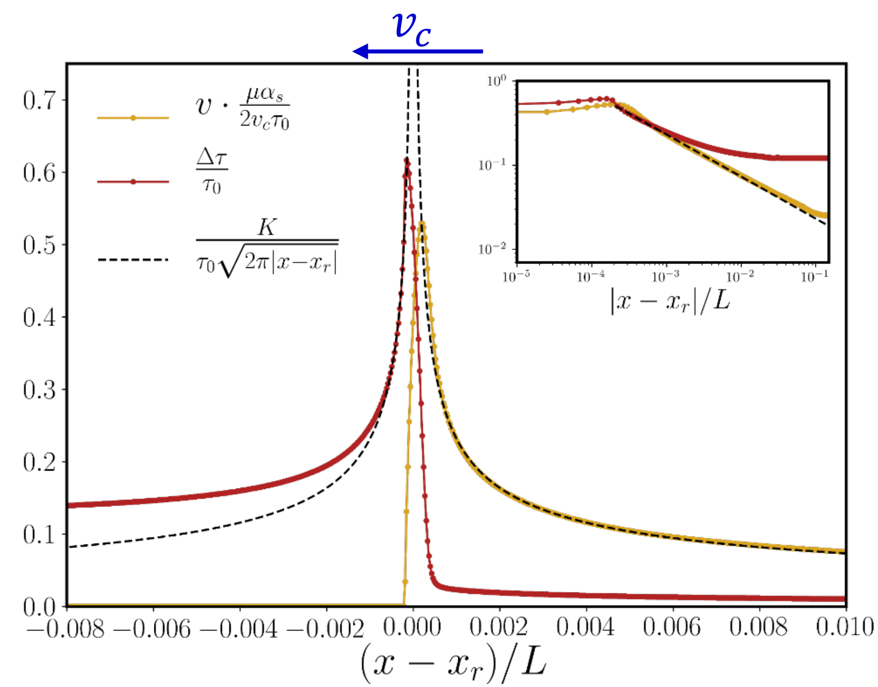
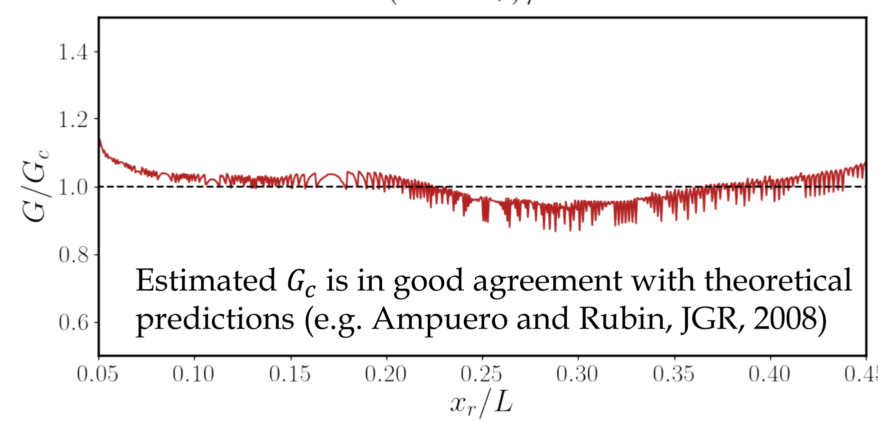
- A better estimate of G_c can be obtained by integrating only the near-tip dissipation



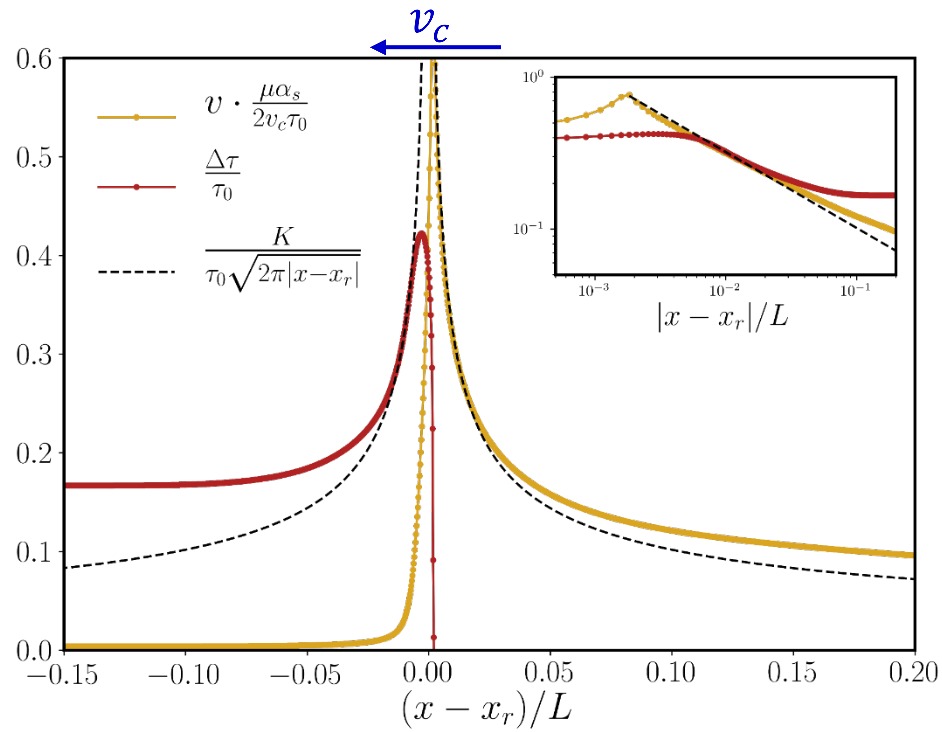


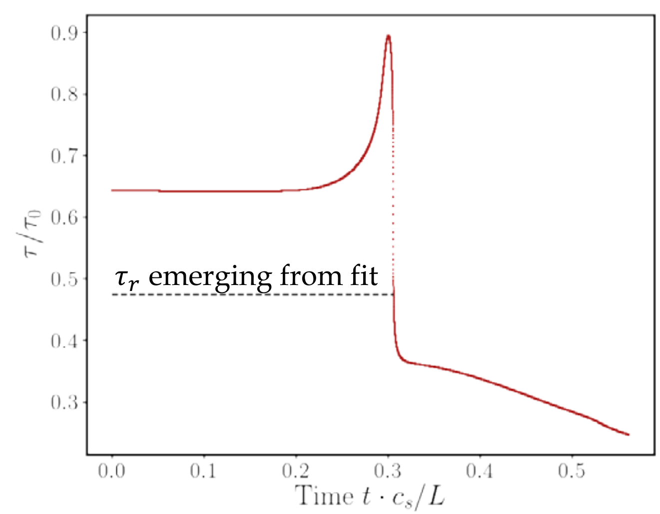
$$G_c = \frac{1}{v_c} \int_{\dot{\phi}<0} (\tau(x) - \tau_r) v(x) dx$$

Let's now study frictional ruptures

Case 2: Thermal pressurization

- Crack-like rupture fronts emerge from intense shear-localization across the gouge layer
- The computed energy release rate G is also much smaller than E_{BD}.
- No obvious value for τ_r as friction keeps weakening after the rupture due to pressurization. Its value is also determined during the fit before computing $\Delta\tau = \tau - \tau_r$



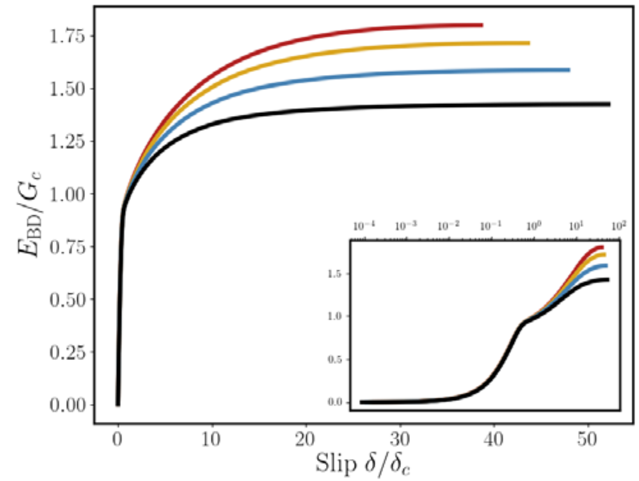


Different friction laws, but generic observations

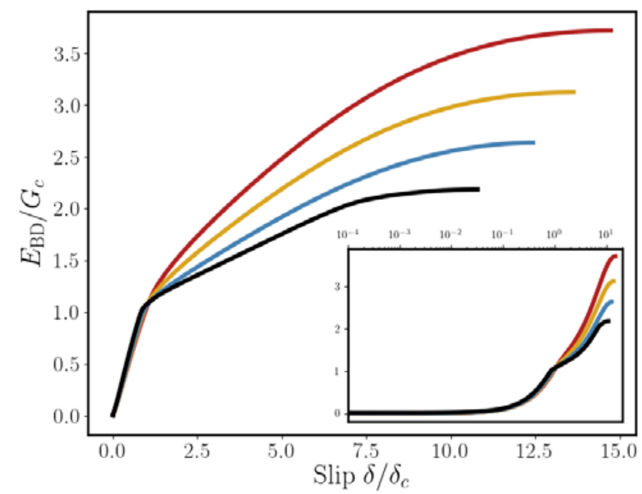
- Rupture energy ($G_c = G$) is only a fraction of E_{BD}
- Rupture energy is associated to the rapid weakening of friction immediately in the wake of the rupture
- The subsequent long-term evolution of friction after the rupture does not enter the rupture energy budget and significantly differs along the interface
- A critical displacement δ_c can be associated to this transition

Evolution of E_{BD} during the rupture integrated at different locations along the interface

Rate-and-state



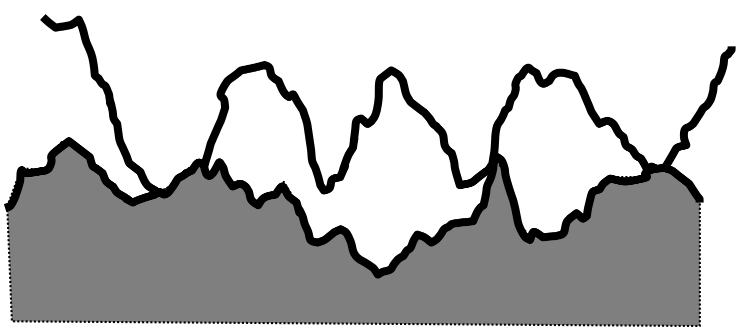
Thermal pressurization



δ_c can be rationalized from the physics behind the two friction laws

<u>Rate-and-state</u>

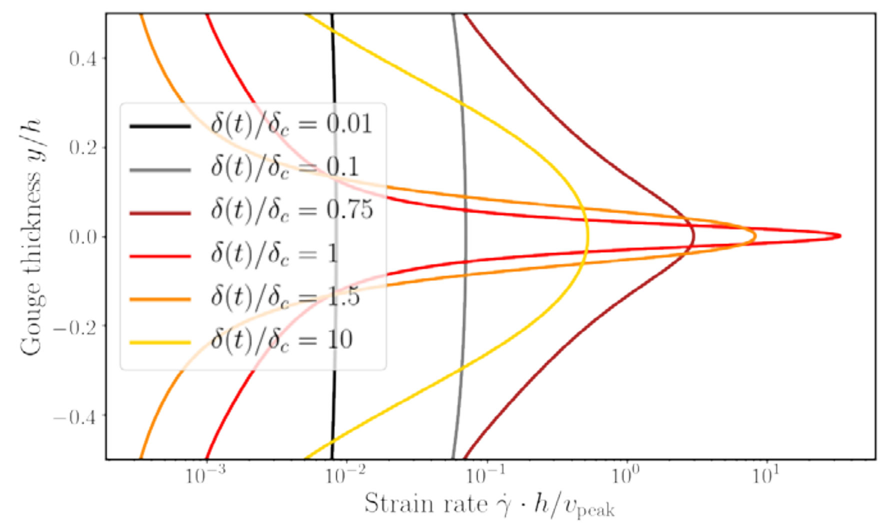
δ_c arises when ϕ reaches its minimum, i.e. when the area of underlying microcontact reaches a minimum value after the rupture



<u>Thermal pressurization</u>

δ_c arises when the most intense shear-localization is observed within the gouge

Strain rate evolution across the gouge during the rupture



Summary and outlook

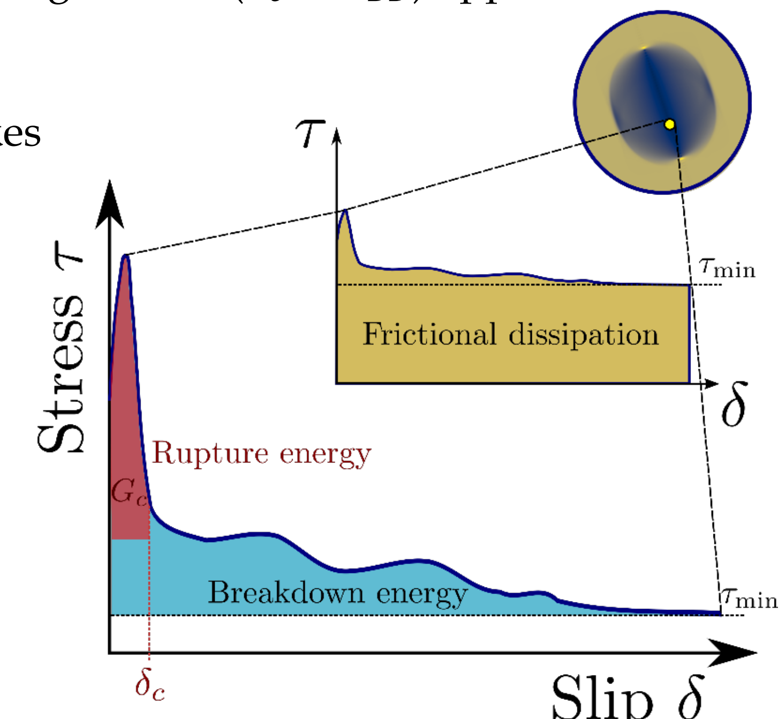
- The energy balance driving the propagation of frictional rupture is studied for two different types of frictional interface:
  - Rate-and-state interface (rock friction experiments)
  - Fluid-saturated granular layer (representative of fault cores filled with gouge)

- The rupture energy G_c is a small fraction of the total breakdown energy observed during the rupture
- G_c corresponds to the near-tip dissipation associated with the rapid drop of frictional stress, whose extend is rationalized using the physics behind each friction law

- The energy partition inherited from slip-weakening friction ($G_c = E_{BD}$) appears to be the exception rather than the rule

- Implications for the energy budget of earthquakes

Tinti *et al.*, JGR, 2005
Chester *et al.*, Nature, 2005
Abercombie and Rice, JGI, 2005
Nielsen *et al.*, GRL, 2016



Thank you!

Collaborators during this work

- Jean-François Molinari, Thibault Roch (EPFL Lausanne)
- Eran Bouchbinder, Michael Aldam (Weizmann Institute of Science)
- Efim A. Brener (Forschungszentrum Jülich)

- Nicolas Brantut (UCL, London)

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