Simulations of Thermal Pressurization on Rough Faults: Rupture Dynamics and Temperature Evolution

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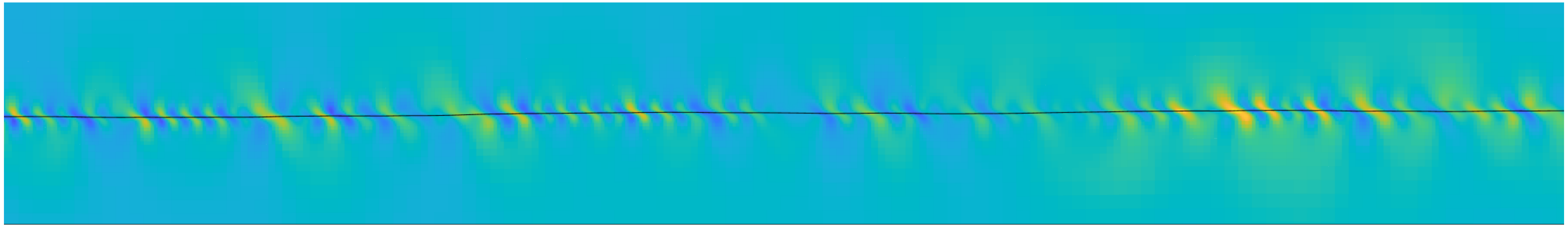
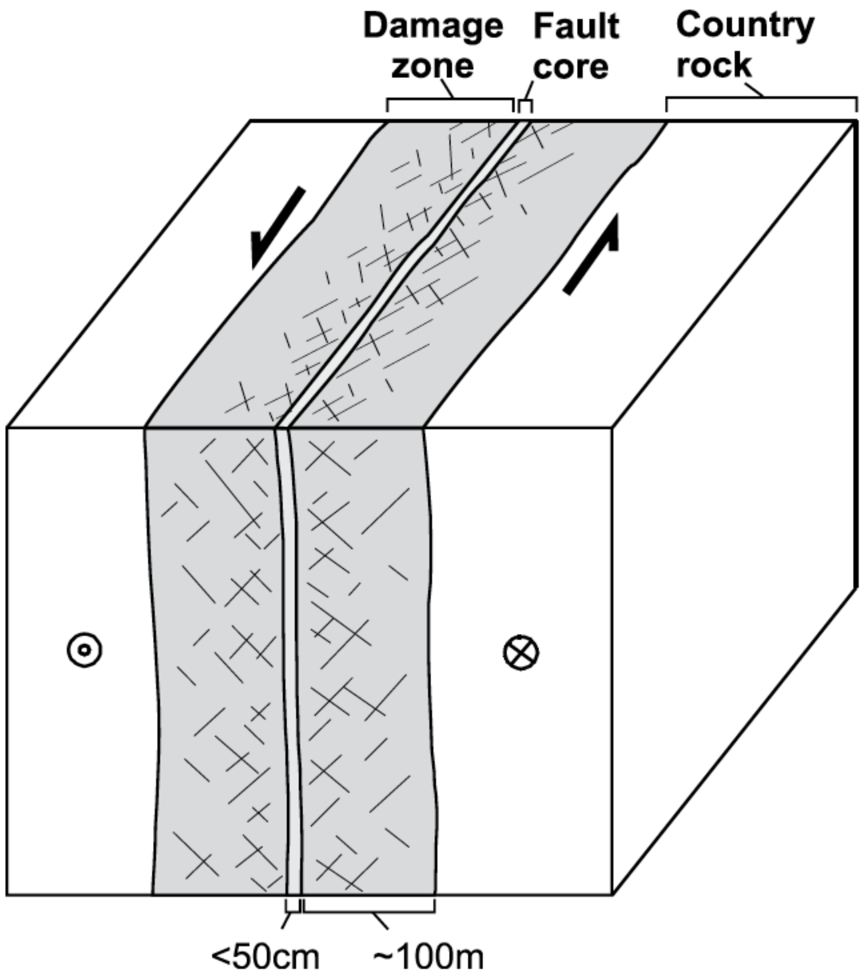
EQMech from Rupture to Structure

Ben-Gurion University of the Negev

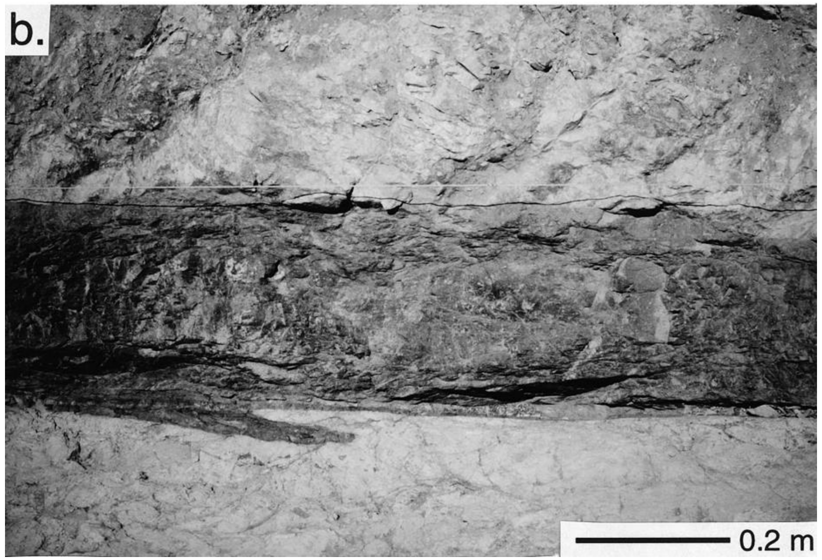
(Badt and Tal, JGR, 2025)

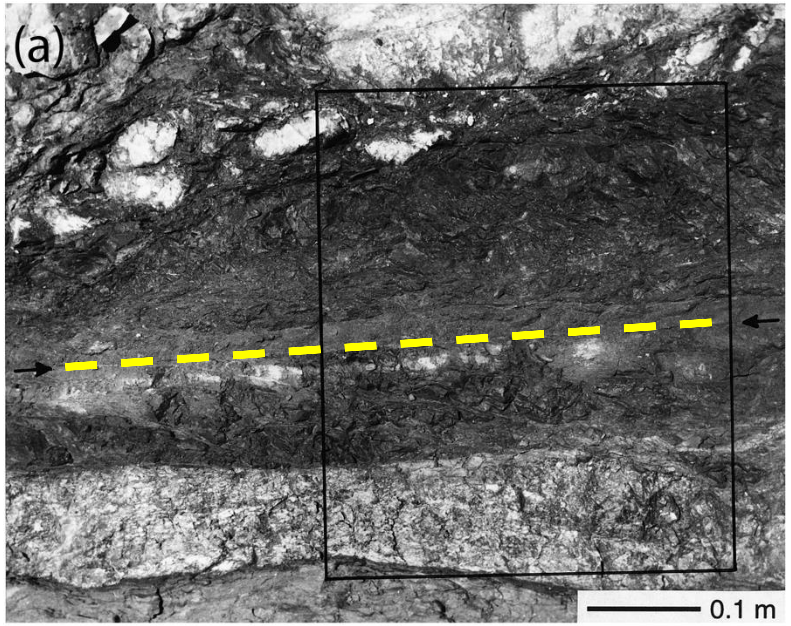


Fault zone structure



Mitchell and Faulkner (2009)





Chester and Chester, 1998

Thermal pressurization (TP)

Thermal pressurization:

Frictional heat

Heat: $$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial y^2} + \frac{Q(v,\tau)}{\rho c}$$

Pressure: $$\frac{\partial p}{\partial t} = \Lambda \frac{\partial T}{\partial t} + \alpha \frac{\partial^2 p}{\partial y^2} - \cancel{\frac{1}{\beta}\frac{\partial \phi}{\partial t}}$$

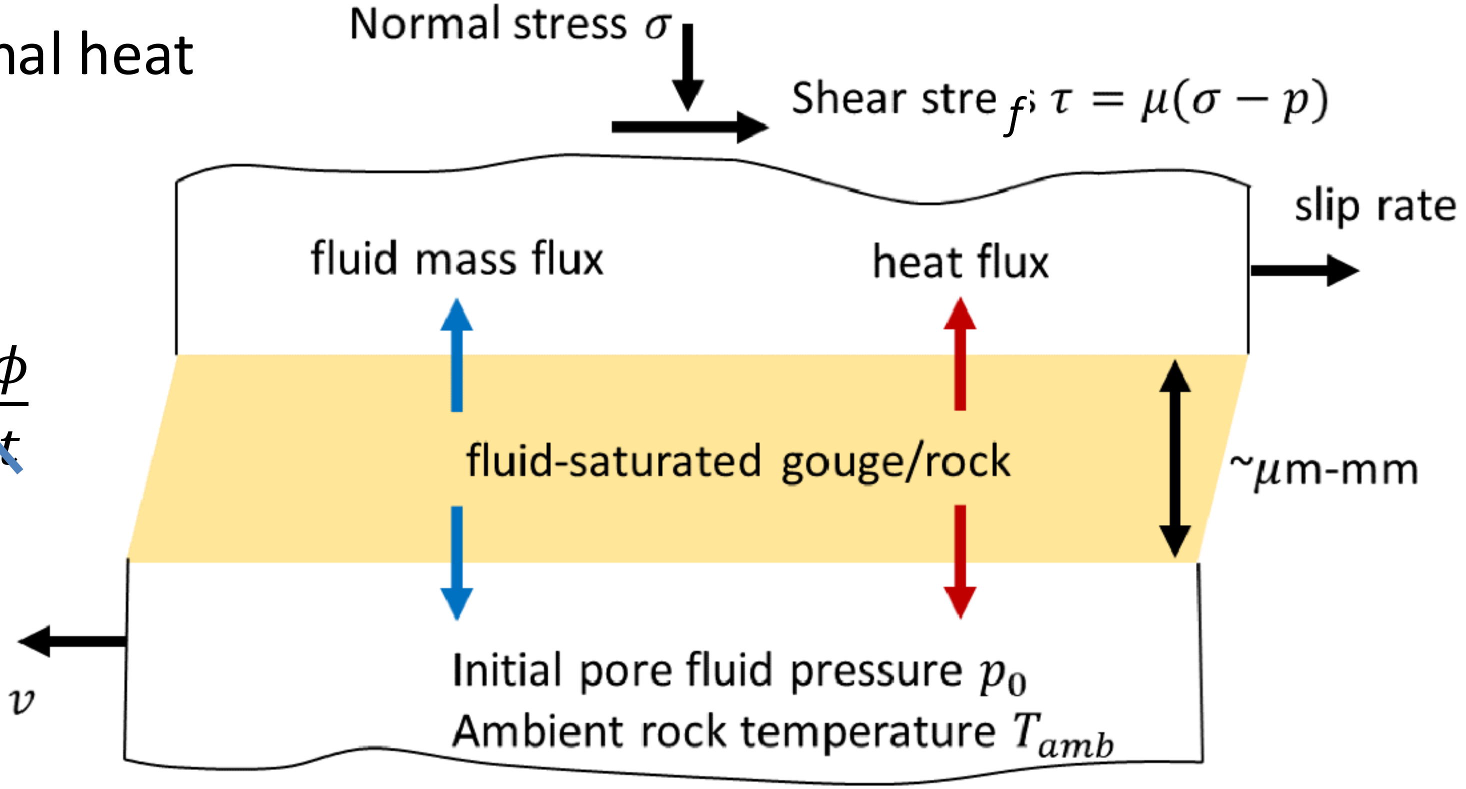
Hydrothermal Parameters:

κ - Thermal diffusivity

α - Hydraulic diffusivity

Λ - Coupling coefficient

ρc - Specific heat



after Rempel & Rice (2006)

Shear resistance on the fault:

$$\tau = f(u, v, \theta)(\sigma - p)$$

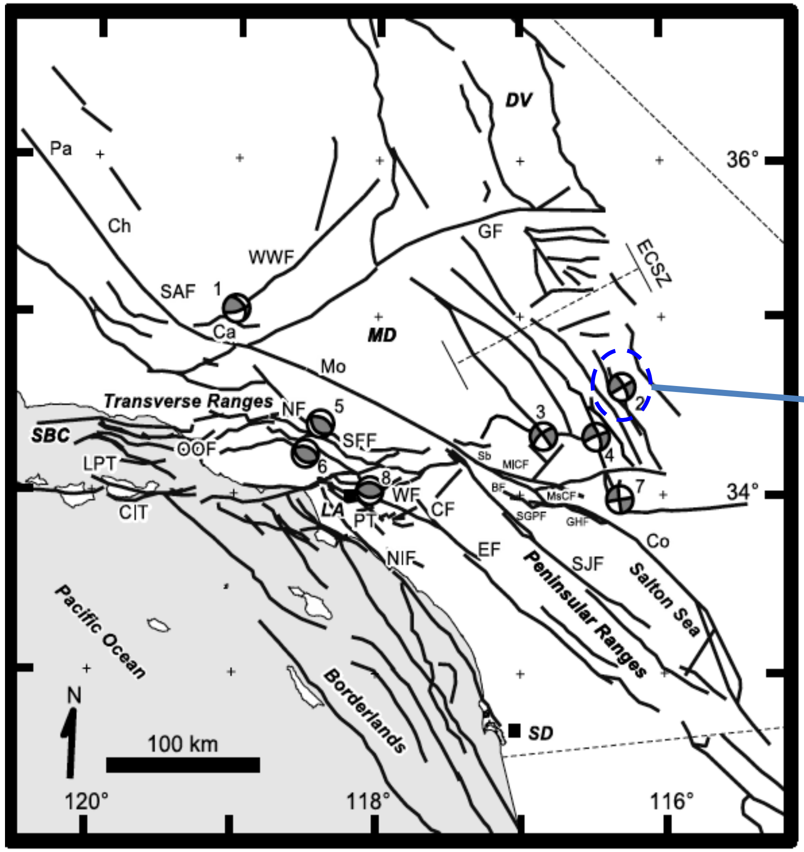
σ - normal stress, p - pore fluid pressure,

f - friction coefficient

Theoretical and numerical studies have examined the effect of TP on earthquake ruptures on **planar** faults (Andrews, 2002; Badt et al., 2023; Bizzarri & Cocco, 2006a; Lambert & Lapusta, 2023; Mase & Smith, 1987; Noda & Lapusta, 2010; Perry et al., 2020; Rice, 2006; Stathas & Stefanou, 2023; Urata et al., 2008, 2012, 2015)

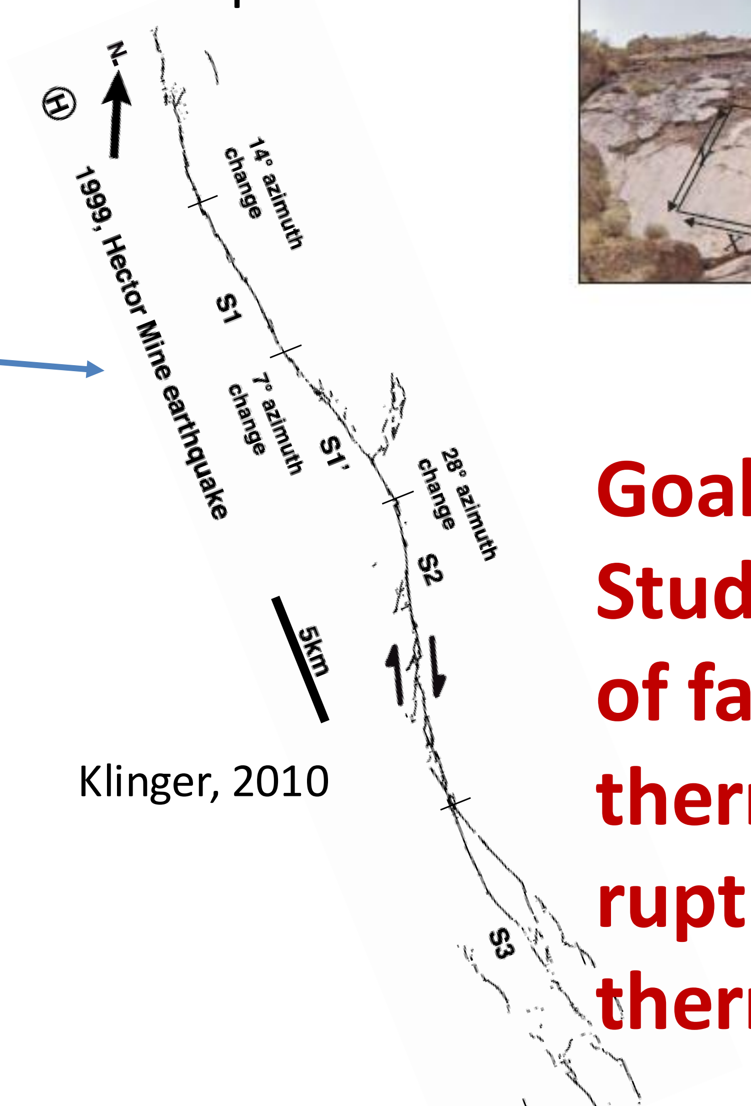
Nonplanar fault geometry

Southern California faults



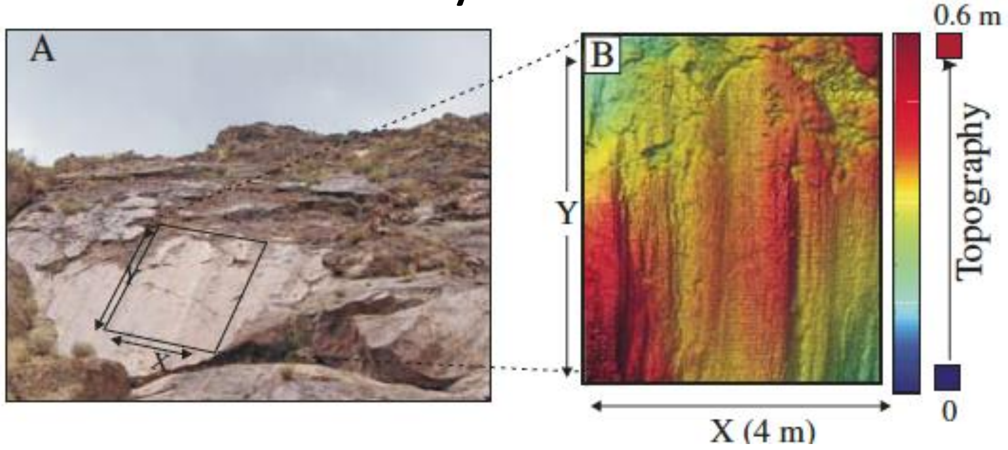
Plesch et al., 2007

1999, Hector Mine earthquake surface rupture



Klinger, 2010

Dixie Valley fault



Sagy et al., 2007

Fault roughness leads to a heterogeneous stress field

Goal:
Study the combined effect of fault roughness and thermal pressurization on rupture dynamics and thermal evolution

Model

The local shear resistance on the fault:

$$\tau = f(v,\theta)(\sigma - p)$$

σ - normal stress

p - pore fluid pressure

Rate and state (RS) friction $f(v,\theta)$:

$$f = f^* + a\ln\left(\frac{v}{v^*}\right) + b\ln\left(\frac{v^*\theta}{D_{RS}}\right)$$

with aging state evolution law:

$$\dot{\theta} = 1 - \frac{\theta V}{D_{RS}}$$

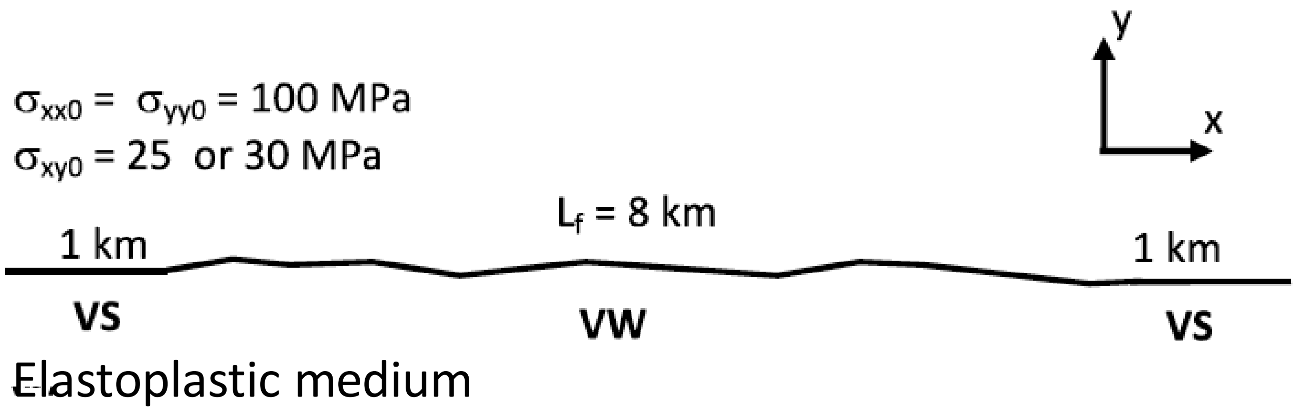
Frictional parameters

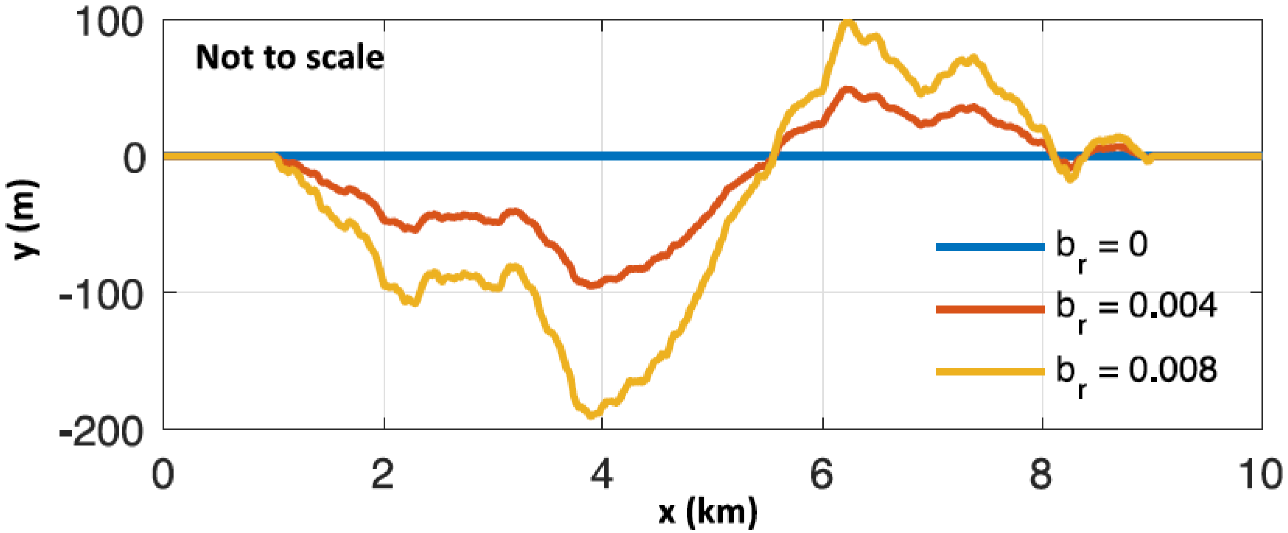
RS parameter

- a = 0.01 (VW), 0.05 (VS),
- b = 0.015 (VW), 0.005 (VS)

Characteristic sliding distance

- D_{RS} = 5 mm





Roughness: $h(L) = b_r L^H$

Roughness prefactor: b_r = 0 (planar), 0.004, 0.008

Hurst exponent: H = 1 (self-similar)

Minimum wavelength: λ_{min} = 20 m

Model

The local shear resistance on the fault:

$$\tau = f(v,\theta)(\sigma - p)$$

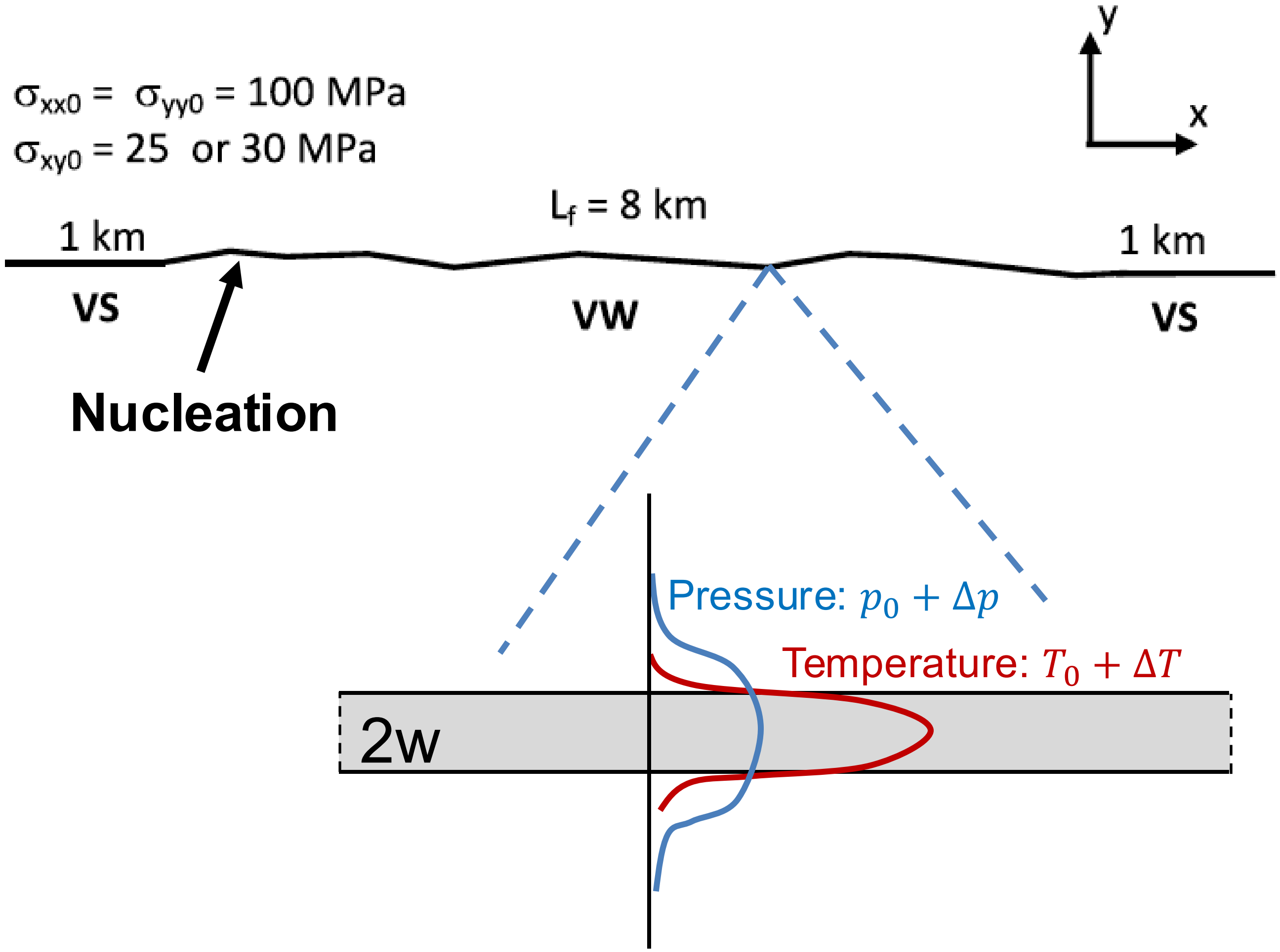
Thermal pressurization:

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial y'^2} + \frac{Q(v,\tau)}{\rho c}$$

$$\frac{\partial p}{\partial t} = \Lambda \frac{\partial T}{\partial t} + \alpha \frac{\partial^2 p}{\partial y'^2}$$

The shear heating Q is distributed over a Gaussian shear layer of half-width w:

$$Q(v,\tau) = \tau v \frac{e^{-y'^2/2w^2}}{w\sqrt{2\pi}}$$



Hydrothermal Properties

Thermal diffusivity
κ = 1x10^{-6} m^2/s

Hydraulic diffusivity
α = 1x10^{-5}, 1x10^{-4} m^2/s

Coupling coefficient
Λ = 1 MPa/^{o}C

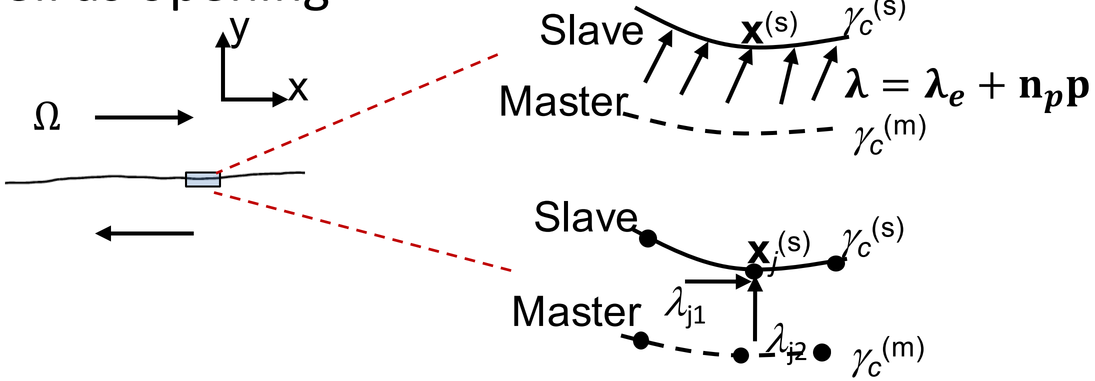
Shear layer half-width
w = 5, 10, 20 mm

We model a **single** dynamic rupture in each simulation

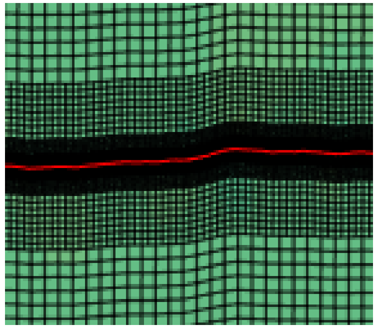
Numerical method (Tal and Hager, 2018; Tal, 2023)

1. Implementing friction laws into the **Mortar Finite Element Method**

- Enables slip that is comparable to the minimum roughness wavelength
- Models the variations of normal stresses during slip, as well as opening



2. Hanging nodes



- Represent the geometry of the interface accurately

3. Variable time steps with quasi-static and **fully dynamic (Newmark)** implicit schemes

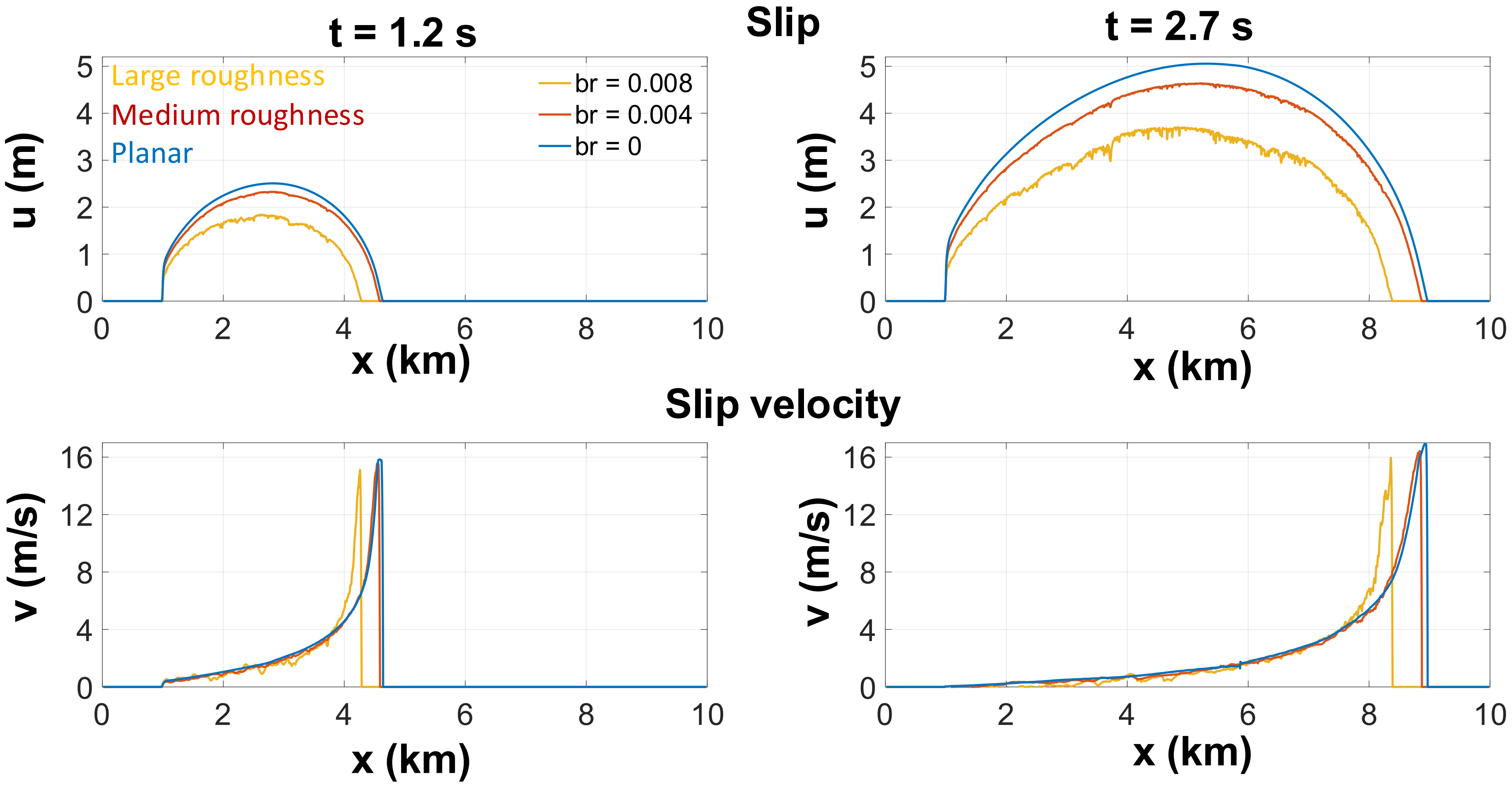
4. Inelastic deformation: **Drucker–Prager plasticity**, Viscoelasticity

5. Various friction laws: Slip weakening, **Rate and state friction**, Flash heating, Wear

6. **Thermal pressurization**: Integrating the temperature and pore pressure in time at a given location x on the fault with the spectral method of Noda and Lapusta (2010) and coupling it to the Mortar FEM method. Benchmarked with SCEC Code Validation problem TPV105.

Slip behavior

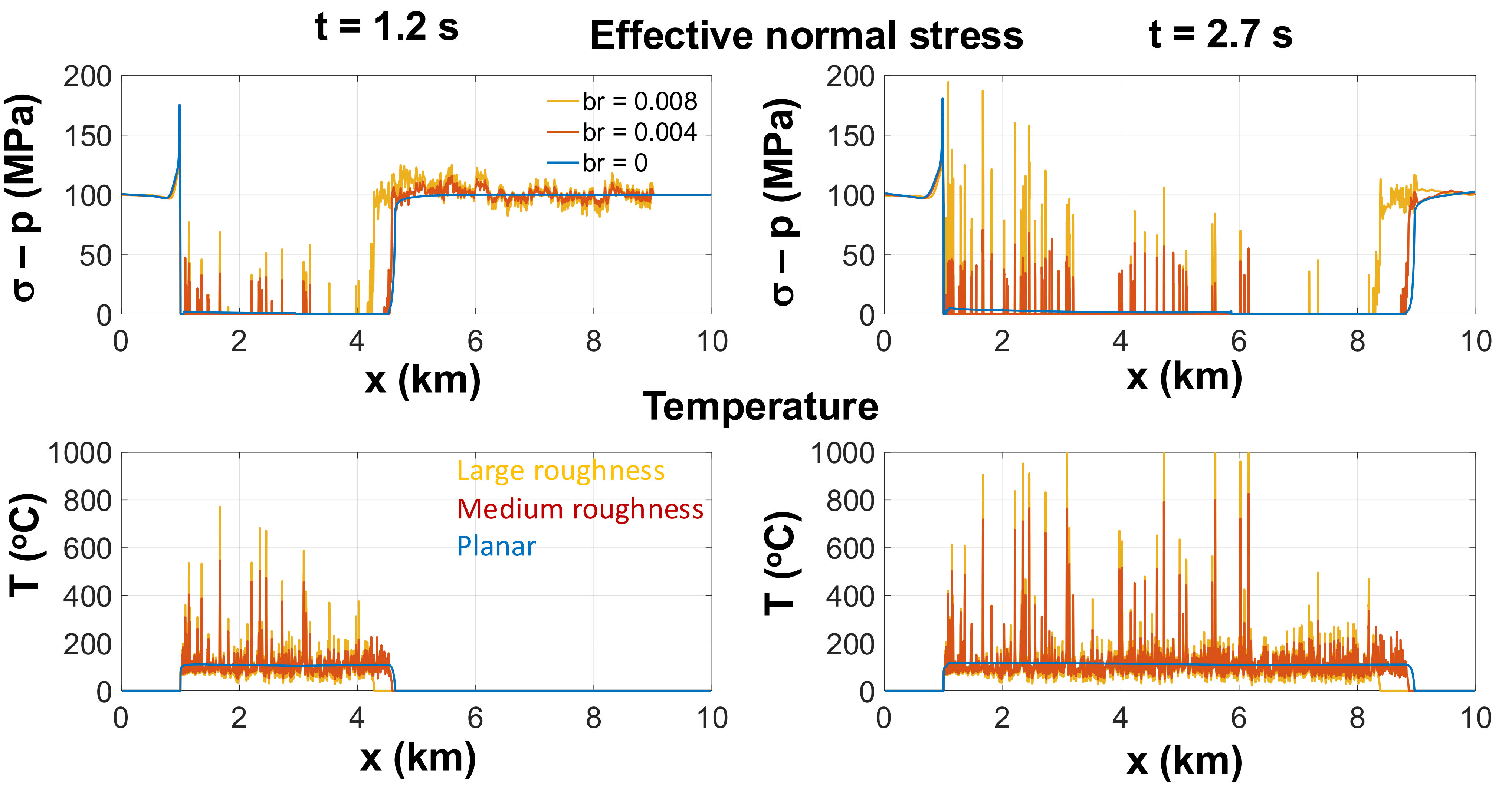
- The intensity of the ruptures slightly decreases with increasing roughness level, resulting in smaller rupture speeds and final slips



Coupling coefficient
Λ = **1** MPa/°C
Thermal diffusivity
κ = **1x10^{-6}** m^2/s
Hydraulic diffusivity
α = **1x10^{-5}**, 1x10^{-4} m^2/s
Shear layer half-width
w = 5, **10**, 20 mm

Temperature and effective stresses

Large heterogeneities in normal effective stress lead to highly heterogeneous temperature profiles on rough faults, locally exceeding the melting point (~800 °C under wet conditions).



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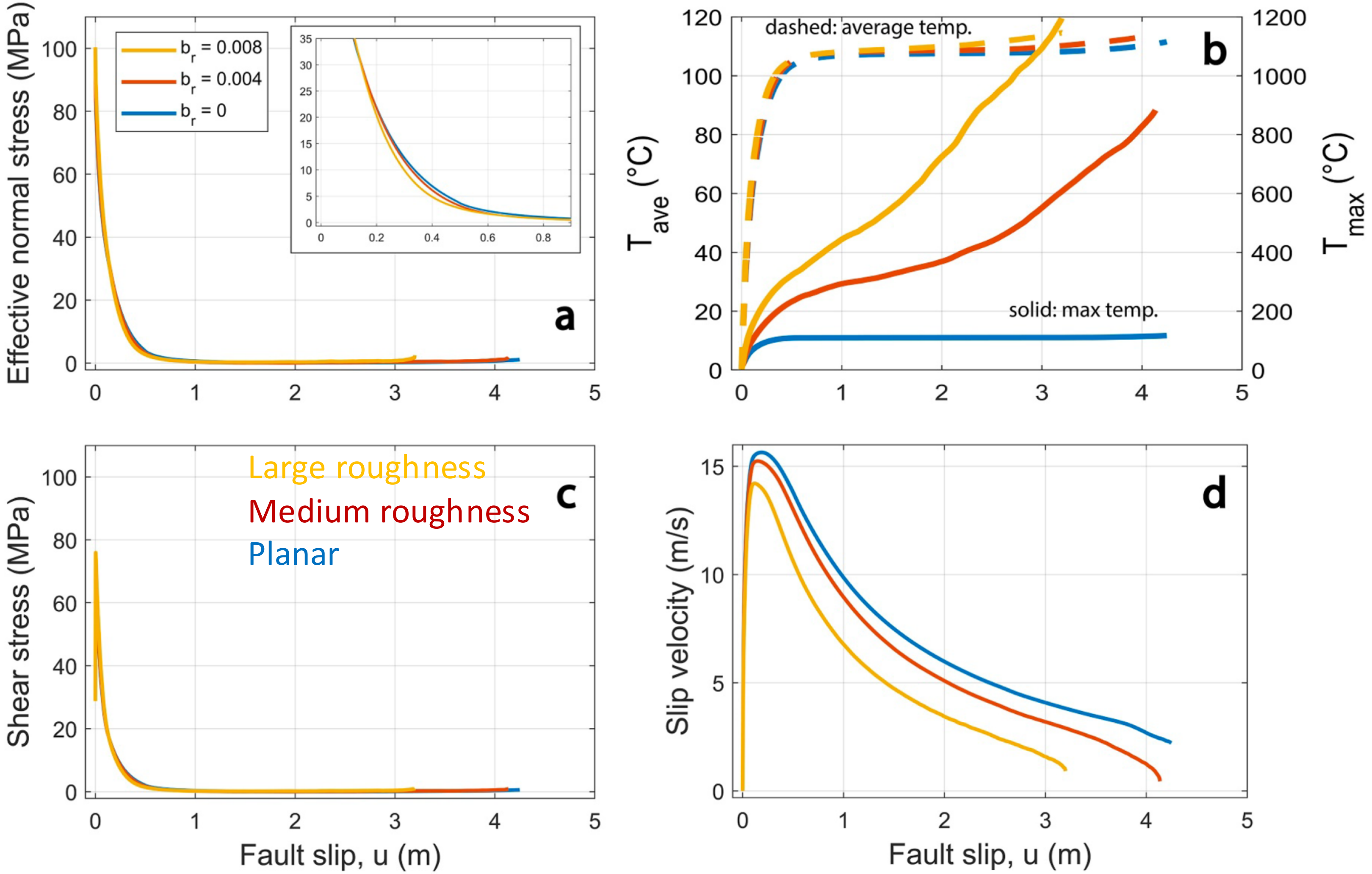
Average behavior

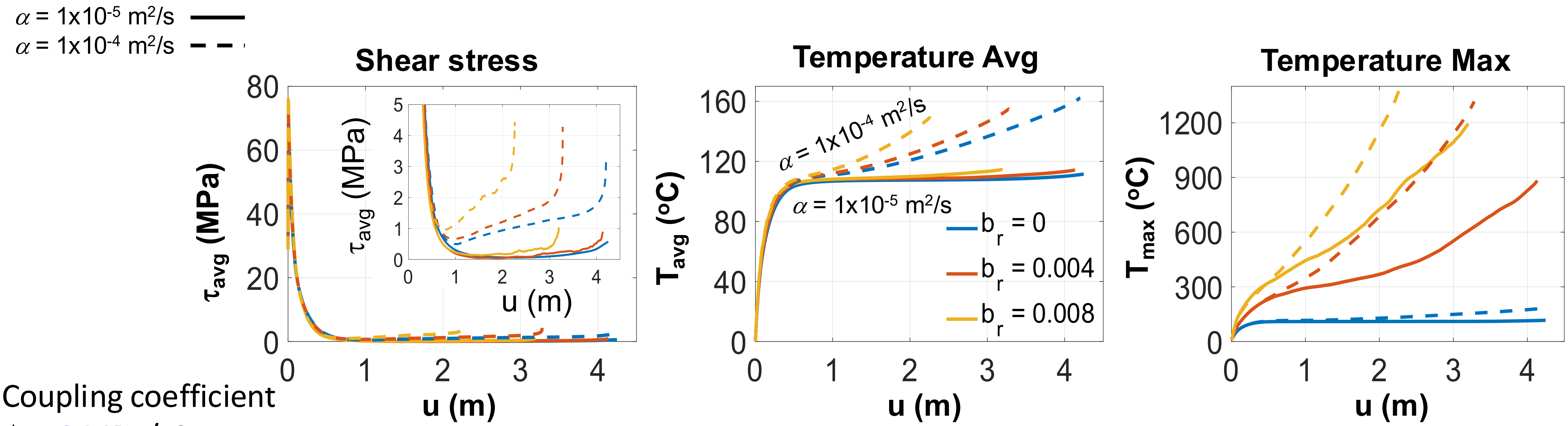
- Similar evolutions of **average** effective normal stress, temperature, and shear stress, with slip for rough and planar faults.
- The high fluid pressurization rates lead to a near-total reduction in average fault strength in the early stages of slip.
- Large maximum temperature for rough fault.



* The average and maximum values are calculated using the energy-based averaging method of Noda and Lapusta (2012), which captures the prevailing features of the local evolution of the variables with slip.

TP in rough faults with "damaged" wall-rocks

- We represent damage by lowering the hydraulic diffusivity α
- The temperature increases for "damaged" wall-rocks, while slip decreases.



Coupling coefficient

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Thermal diffusivity

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Hydraulic diffusivity

α = **1x10^{-5}**, **1x10^{-4}** m^2/s

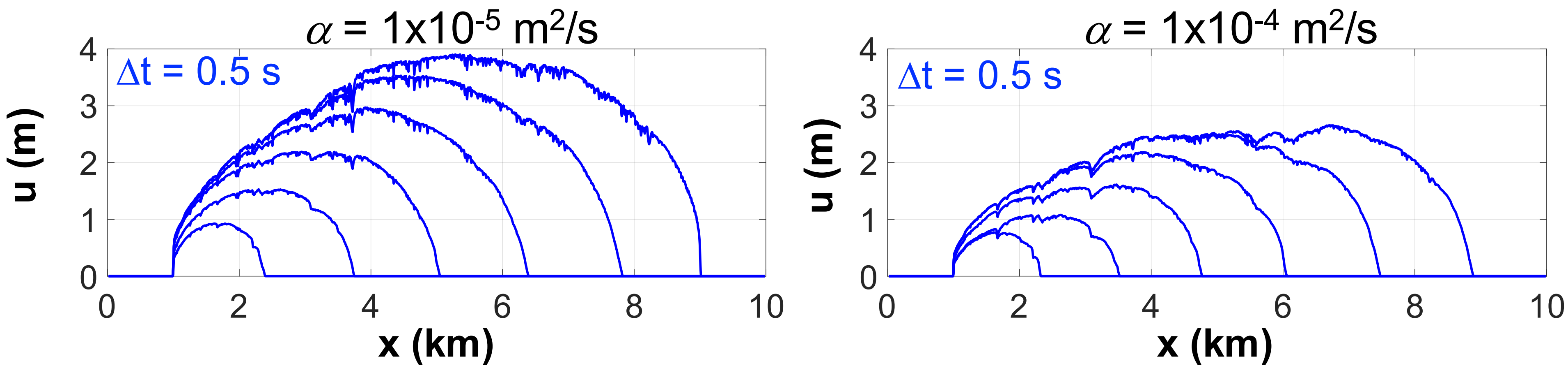
Shear layer half-width

w = 5, **10**, 20 mm

TP in rough faults with "damaged" wall-rocks

- We represent damage by lowering the hydraulic diffusivity α
- For the roughest fault, the lower hydraulic diffusivity leads to a transition from a crack-like to a pulse-like rupture

Slip along the fault: b_r = 0.008 (high roughness)

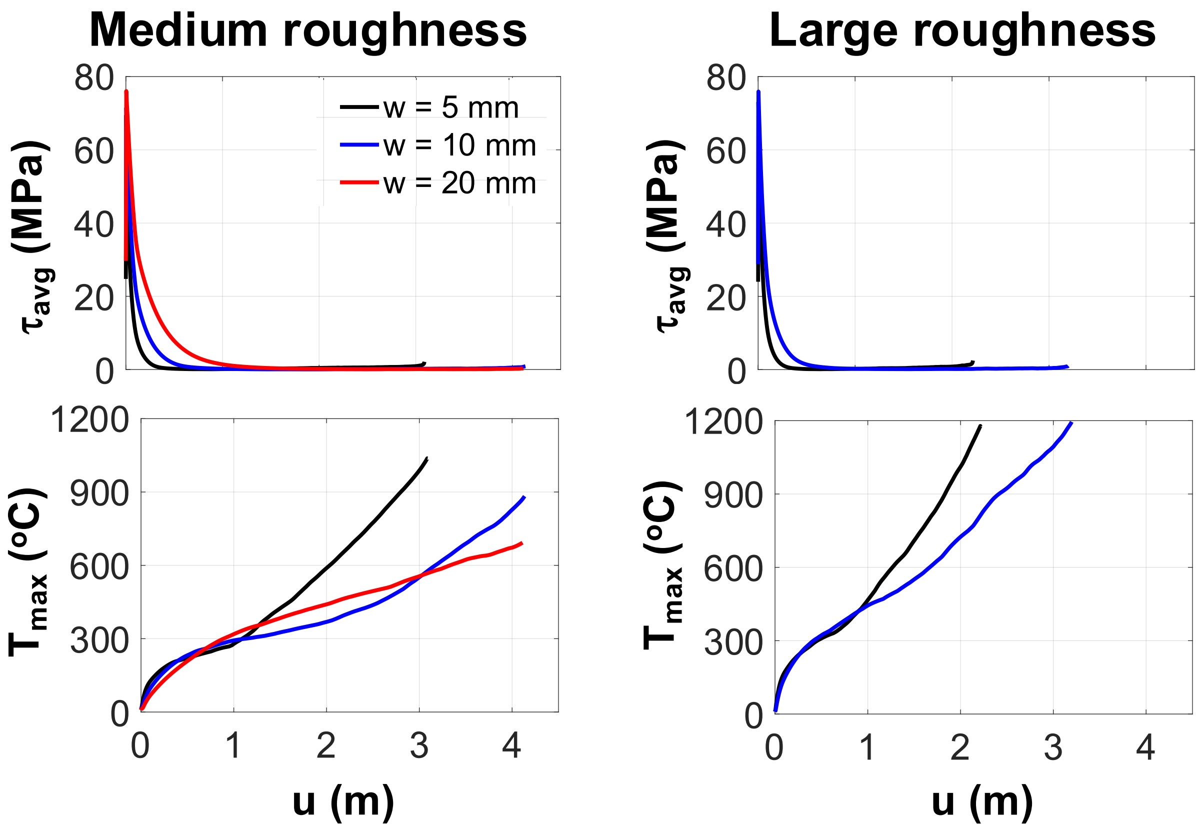


Coupling coefficient
Λ = **1** MPa/^{o}C
Thermal diffusivity
κ = **$1\text{x}10^{-6}$** m^2/s
Hydraulic diffusivity
α = **$1\text{x}10^{-5}$**, **$1\text{x}10^{-4}$** m^2/s
Shear layer half-width
w = 5, **10**, 20 mm

The effect of shear layer width (w)

- As *w* increases, the thermal pressurization is less efficient, leading to smaller temperature increases and larger effective weakening distances.

- Fault with *w* = 20 mm and b_r = 0.008 shows early rupture arrest on a geometrical barrier due to the less efficient TP.



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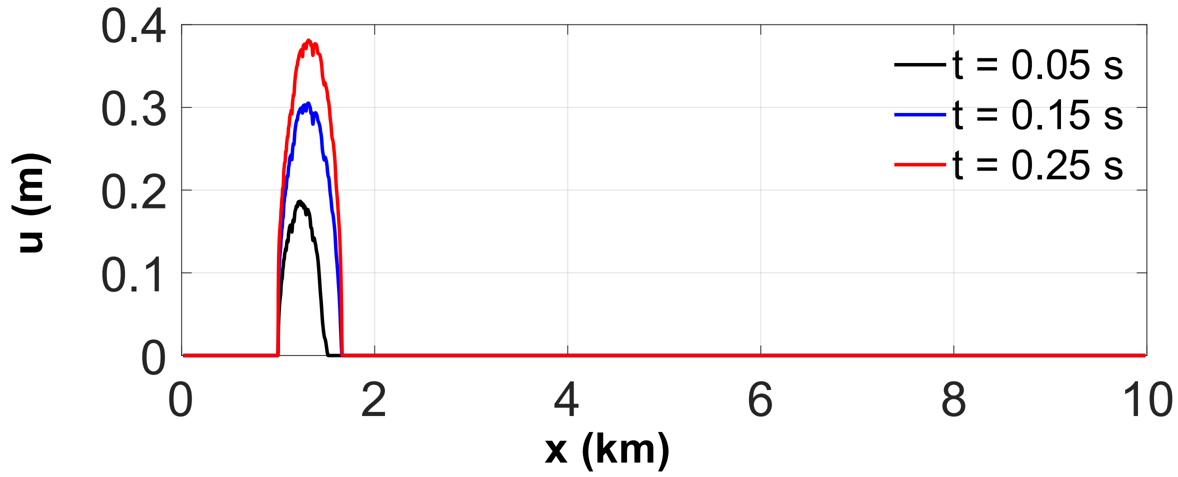

Summary

- Rough and planar faults subjected to thermal pressurization show a similar average temperature and stress evolution during coseismic slip.
- Stress heterogeneities on rough faults can lead to local melting at regions of elevated effective stress, even when thermal pressurization is highly effective.
- Higher hydraulic diffusivity results in a larger temperature increase and can drive a transition to pulse-like rupture.
- For a wide shear layer with low shear heating, fault roughness can arrest the rupture in the early stages of slip.