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Earth Resources Laboratory

Earthquake Rupture Modeling: Fracturing vs. Friction

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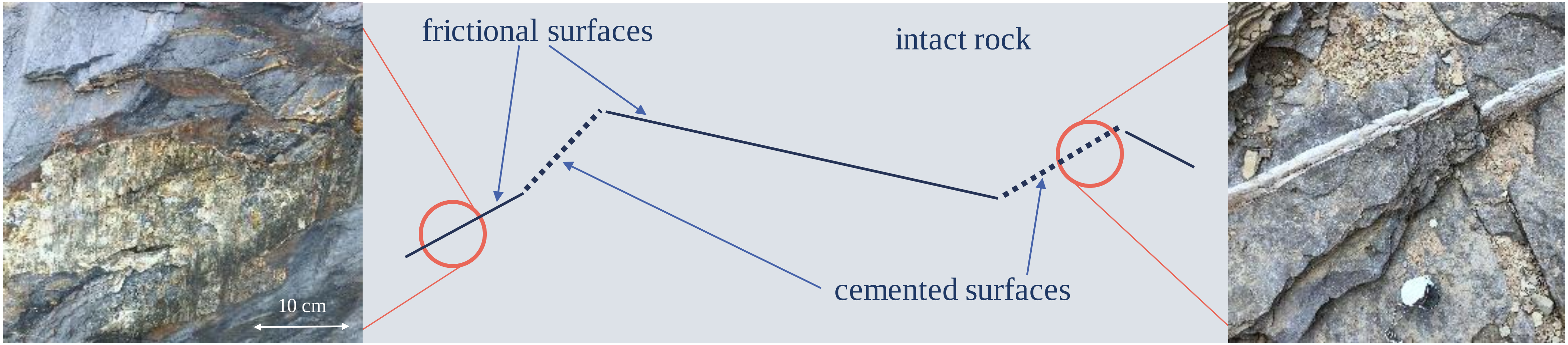
Motivation



Joint theory of friction and fracturing for induced earthquakes:

Mineralization of parts of the fault, slip propagation includes breaking of locked sections (fault jogs and step overs) – fracturing along with frictional sliding on preexisting surfaces.

Computational complexity of rate-and-state and unclear physics behind the fitting parameters:

Can we approximate rate-and-state dynamic rupture propagation results with something simpler: EPFM or slip-weakening friction?

Problem and solution

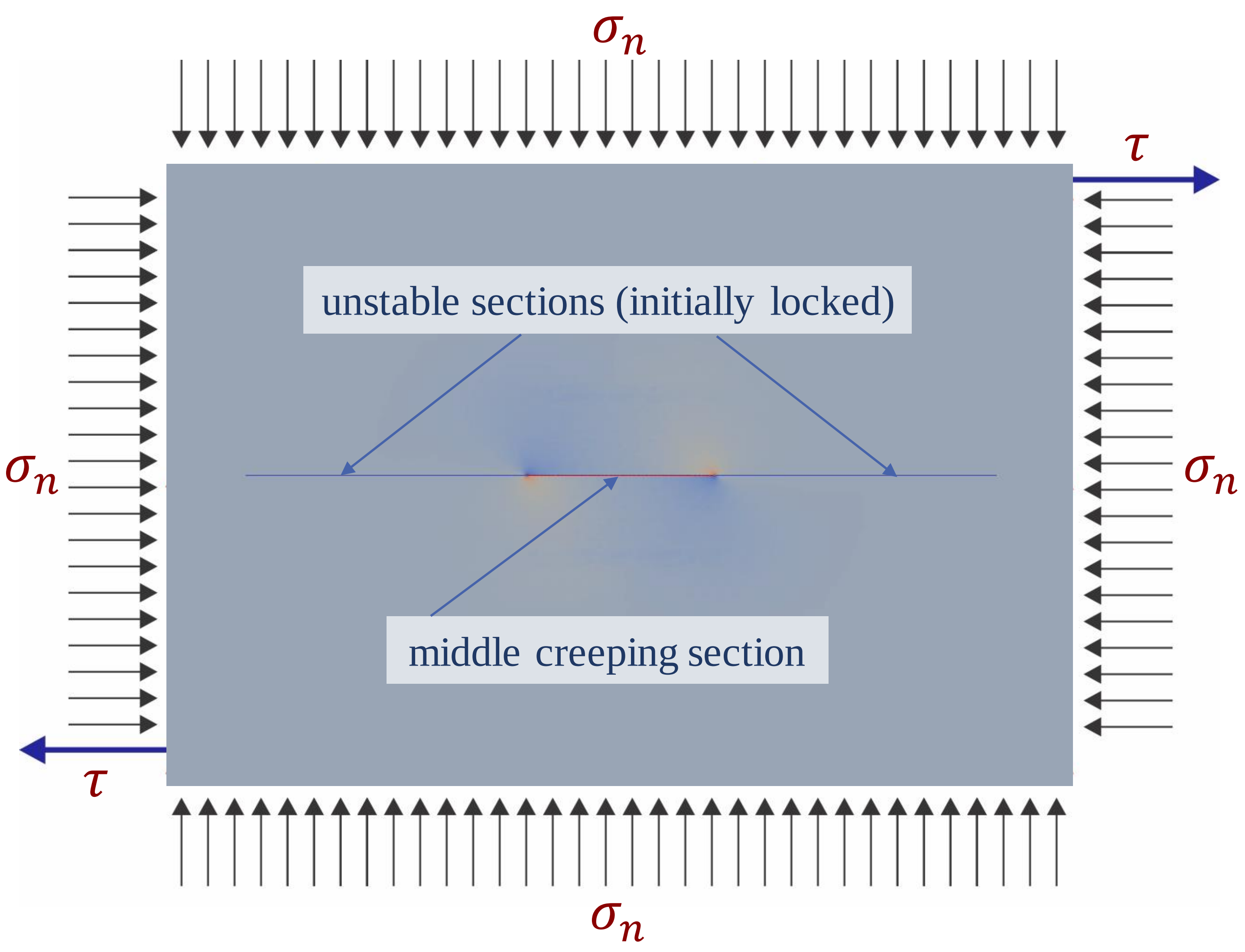
Problem:

Absence of joint theory of fracturing and friction that would be able to describe both brittle cracking and frictional sliding along the fault and delineate where the two are applicable.

Solution:

- Finite element numerical simulations
- Observing similarities and differences in stress, slip, friction coefficient, slip rate etc., trying to link fracture and friction theories
- Comparison with experimental results?

Earthquake cycle model



- 2D, plane strain
- Linear elastic material
- Boundary conditions: lithostatic compression and shear
- 3 fault sections: middle section – static friction $\mu = 0.6$; sides – slip-weakening $\mu_d = 0.6$, $\mu_s = 0.65$
- Time scale: years for quasi-static part, seconds for dynamic part

Figure 3. Model geometry

Quasi-static cycle

- 3 cycles.
- Fault healing is enforced between the cycles.

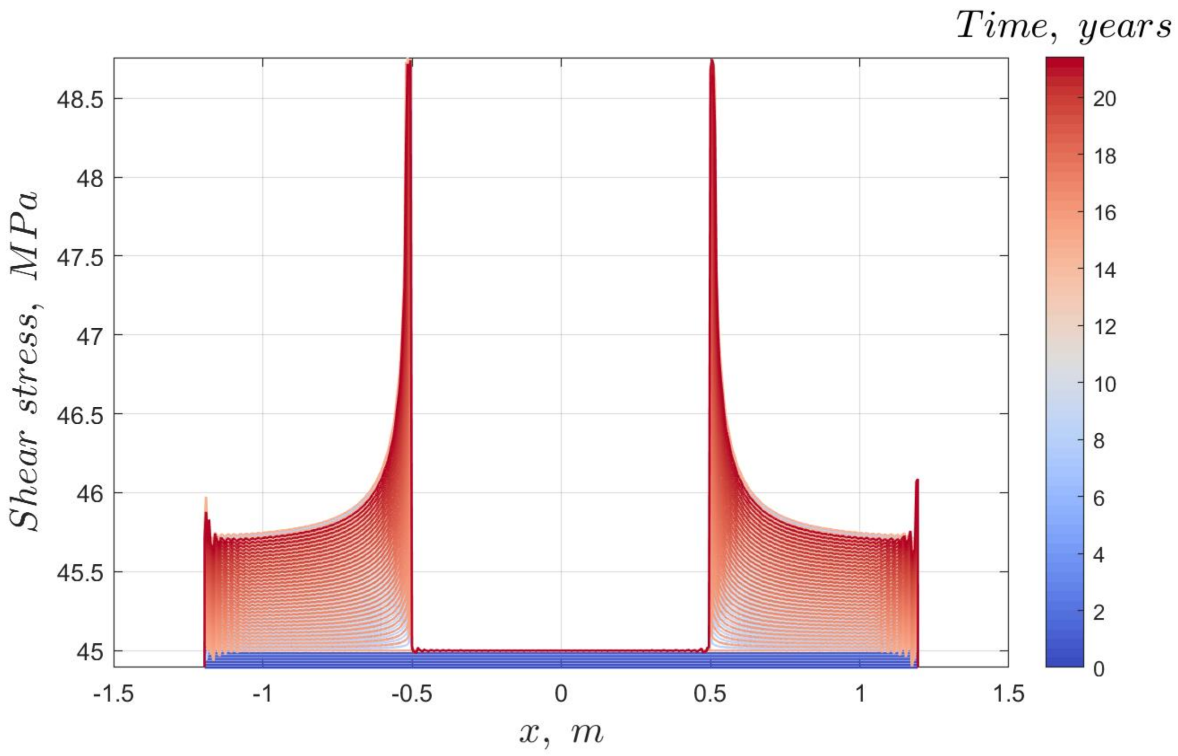


Figure 4. Shear stress on the fault

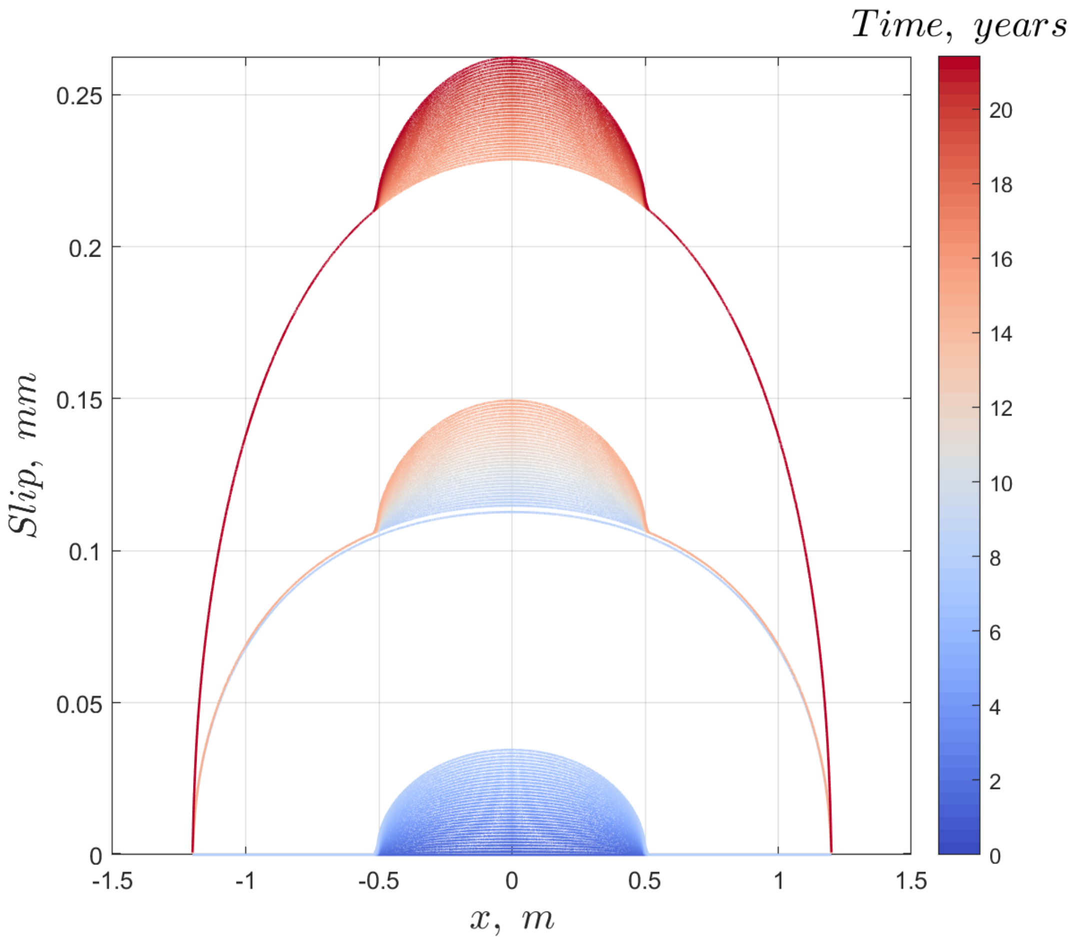
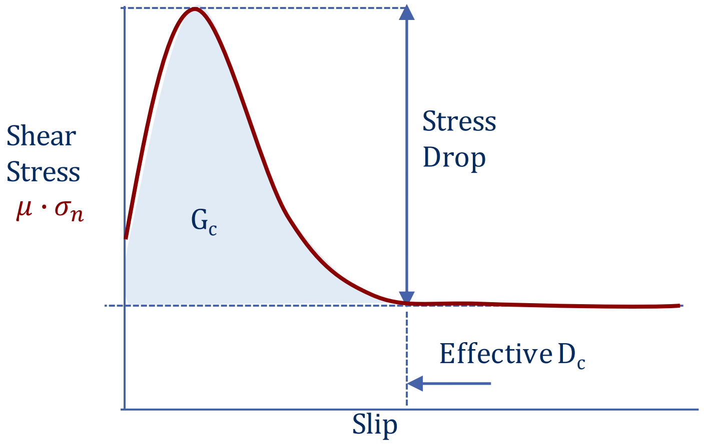


Figure 5. Slip on the fault

Slip-weakening friction vs. fracturing

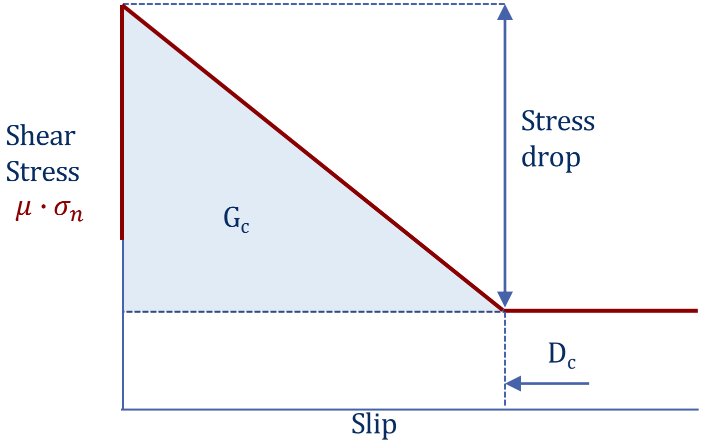
Fracture?

Exponential cohesive zone



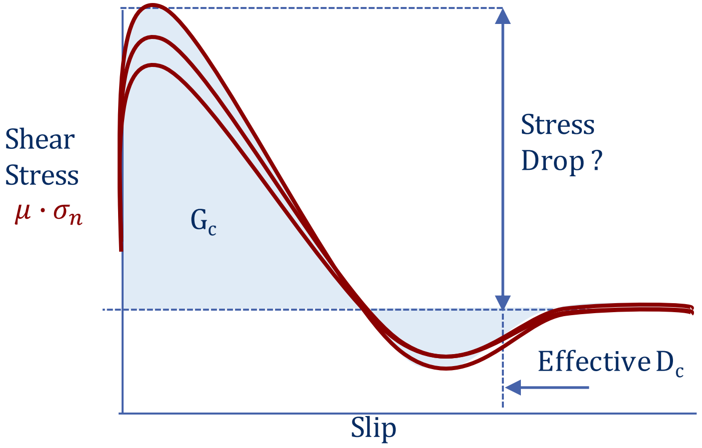
$$\mu = \mu_d + \\ + (\mu_s - \mu_d)\frac{(D + D_1)}{D_2} e^{1 - \frac{(D+D_1)}{D_2}}$$

Slip-weakening



$$\mu = \begin{cases} \mu_s - (\mu_s - \mu_d)\dfrac{D}{D_c} & D \leq D_c \\ \mu_d & D > D_c \end{cases}$$

Rate-and-state



$$\mu = \mu_0 + a ln\left(\frac{V}{V_0}\right) + b ln\left(\frac{V_0 \theta}{L}\right)$$

$$\dot{\theta} = 1 - \frac{V\theta}{L}$$

Friction vs. fracture

- Slip distribution for dynamic rupture propagation

Fracture

$G_{IIC} = 46.85$

Slip-weakening

$\mu_s = 0.65, \mu_d = 0.6, D_c = 2.5e-5$

Rate-and-state

$a = 0.0029, b = 0.0043,$

$D_c = 0.2047e-5, \mu_0 = 0.6145$

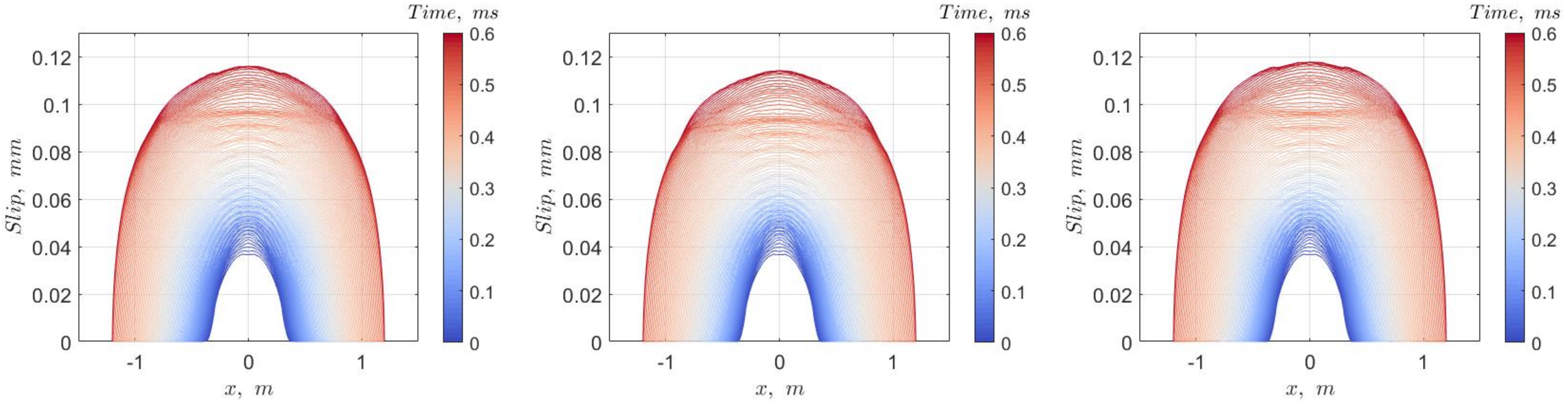


Figure 6. Slip on the fault

Friction vs. fracture

- Slip rate distribution for dynamic rupture propagation

Fracture

$G_{IIC} = 46.85$

Slip-weakening

$\mu_s = 0.65, \mu_d = 0.6, D_c = 2.5e - 5$

Rate-and-state

$a = 0.0029, b = 0.0043,$

$D_c = 0.2047e - 5, \mu_0 = 0.6145$

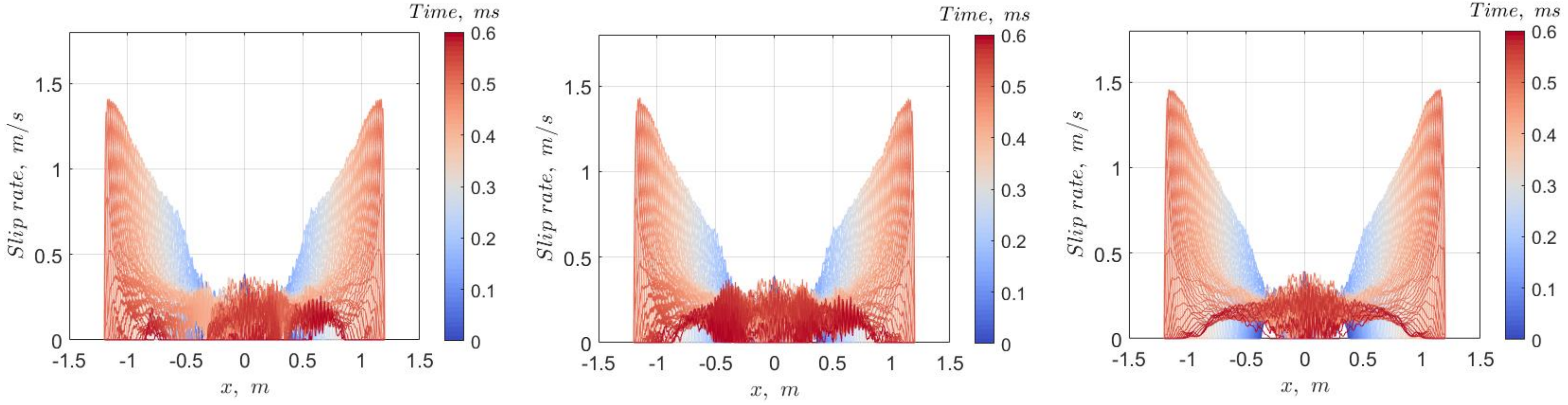


Figure 7. Slip rate on the fault

Friction vs. fracture

- Shear stress on the fault for dynamic rupture propagation

Fracture

$G_{IIC} = 46.85$

Slip-weakening

$\mu_s = 0.65,\ \mu_d = 0.6,\ D_c = 2.5e-5$

Rate-and-state

$a = 0.0029, b = 0.0043,$

$D_c = 0.2047e-5,\ \mu_0 = 0.6145$

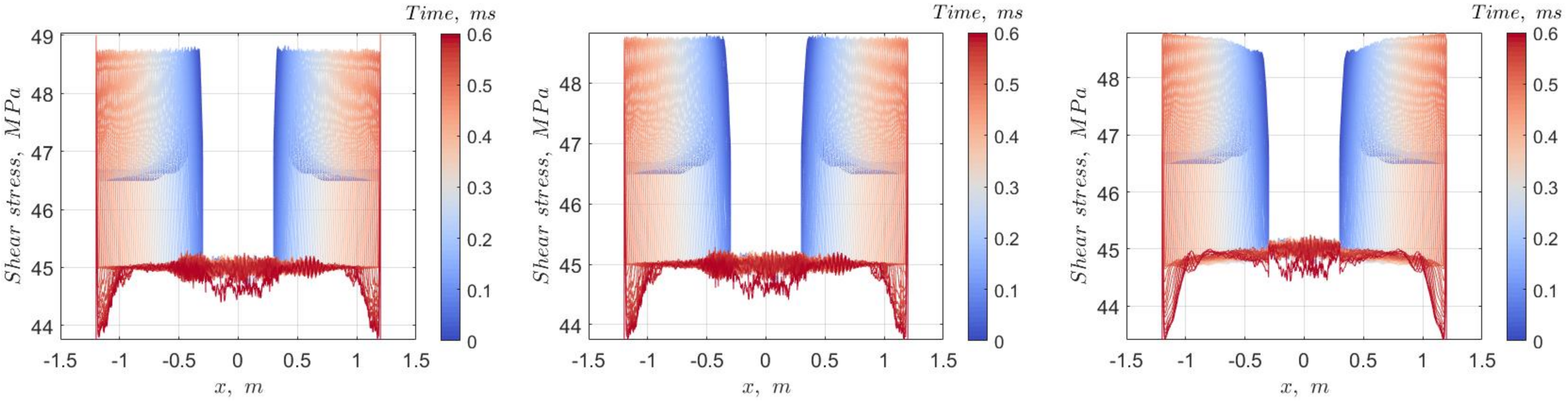


Figure 8. Shear stress on the fault

Friction vs. fracture

- Rupture velocity and tip location for dynamic rupture propagation

Fracture

$G_{IIC} = 46.85$

Slip-weakening

$\mu_s = 0.65,\ \mu_d = 0.6,\ D_c = 2.5e-5$

Rate-and-state

$a = 0.0029, b = 0.0043,$

$D_c = 0.2047e-5,\ \mu_0 = 0.6145$

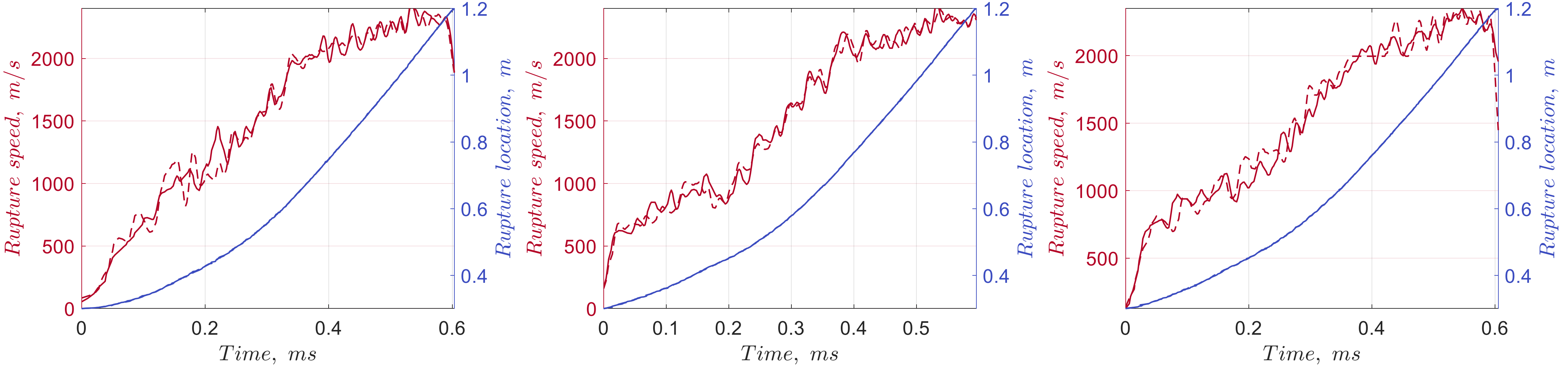


Figure 9. Rupture tip velocity and location

Quantitative comparison - energy

- Energy determined as the area under the stress vs. slip curve:

Fracture | **Slip-weakening** | **Rate-and-state**

$$\int_0^{D_{total}} (\tau - \tau_d)\,dD = \frac{1}{2}(\tau_s - \tau_d)\,D_c = \int_0^{D_{total}} (\tau - \tau_{ref})\,dD$$

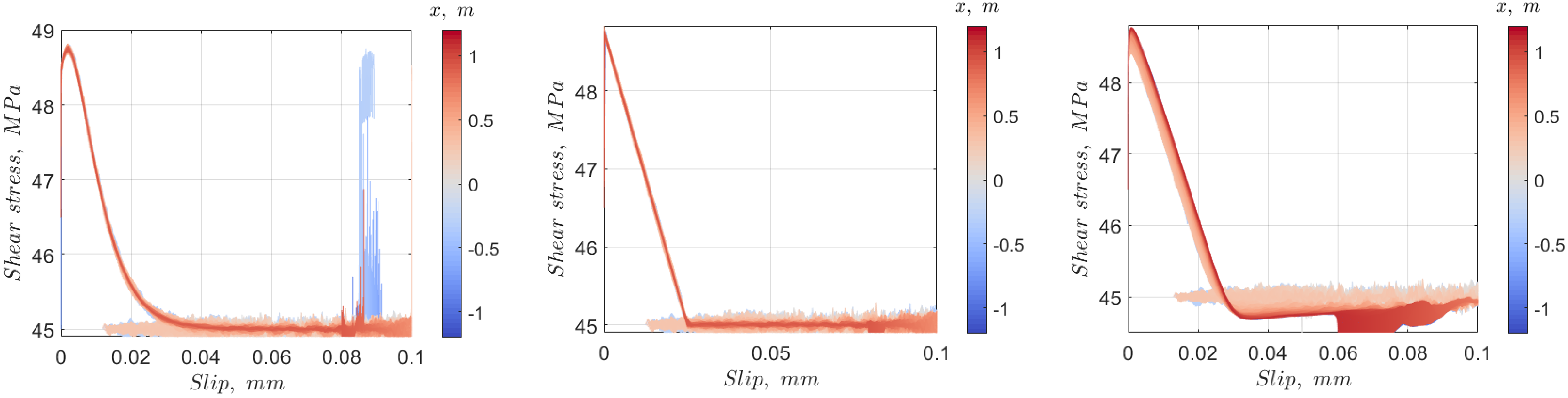


Figure 10. Fracture energy

Progress

- Quasi-static models of earthquake cycle (slip-weakening instability) with fault healing between the cycles
- Dynamic part of the cycle modeled with Pylith slip-weakening subroutine; Pylith rate-and-state subroutine and a custom exponential cohesive zone model (fracture?)
- Exponential cohesive zone vs. slip-weakening vs. rate-and-state dynamic part:
  - Far field: very similar (virtually indistinguishable) observations for the specific case of equal fracture energies
  - Near field: minor differences in stress profiles, slip rates and slip distributions. Resolvable with experiments?
- These models can yield very different results if we don't actively fit parameters to obtain the same fracture energy

Work in progress

- Parametric studies: which model better reproduces specific earthquake / experimental observations? Are parameters used for fitting within physical range?

- Analytical expression for rate-and-state “fracture energy”

$$G_c = \frac{\sigma b D_c}{2}\left[\ln\left(\frac{V\theta_i}{D_c\Omega}\right)\right]^2 \qquad \Omega \equiv \frac{V\theta}{D_c}$$

- Experiments on glued polycarbonate

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Questions?

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