The effect of roughness on small earthquakes

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Massachusetts Institute of Technology
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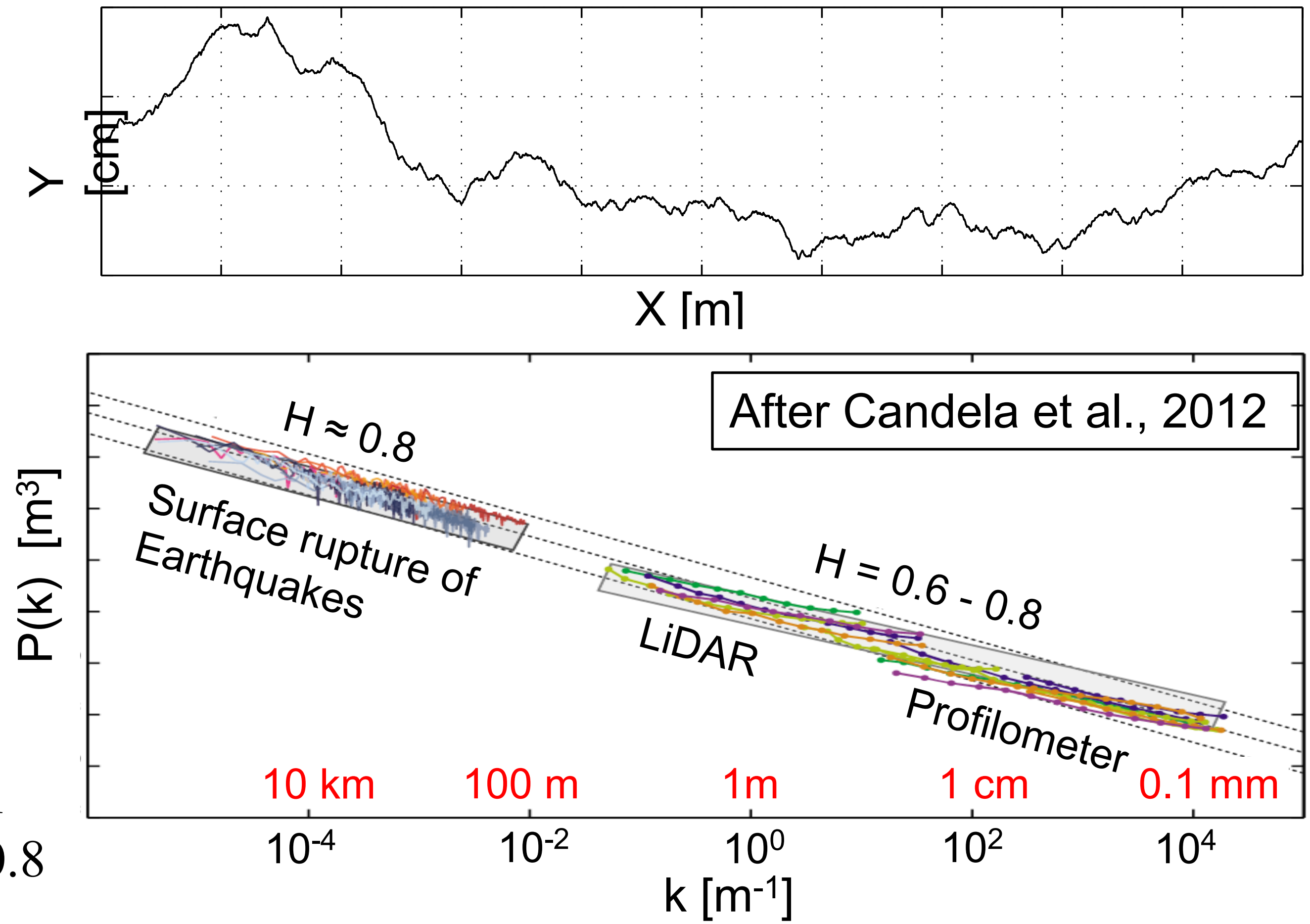
Fault roughness- self-affine fractals

RMS height

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



L - profile length

b_r - pre-factor 0.001 - 0.01

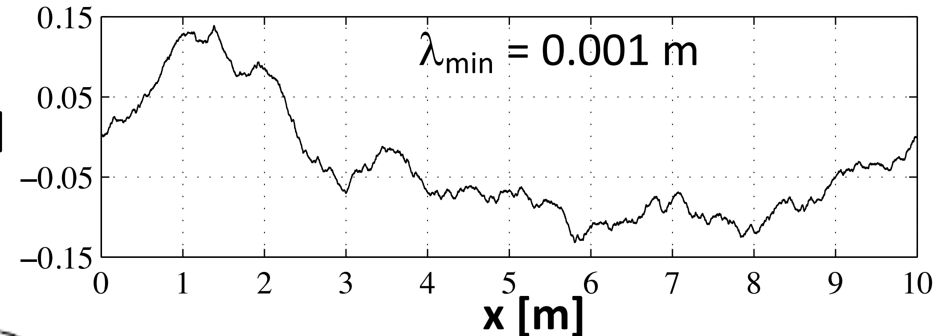
H - Hurst exponent 0.6 - 0.8

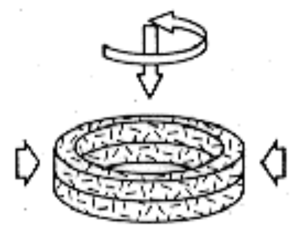
Goal

Study numerically the effect of roughness on small earthquakes:

1. **Rupture process**

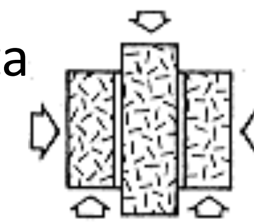
2. **Source parameters**
   - **Static stress drop**
   - **Seismic moment**

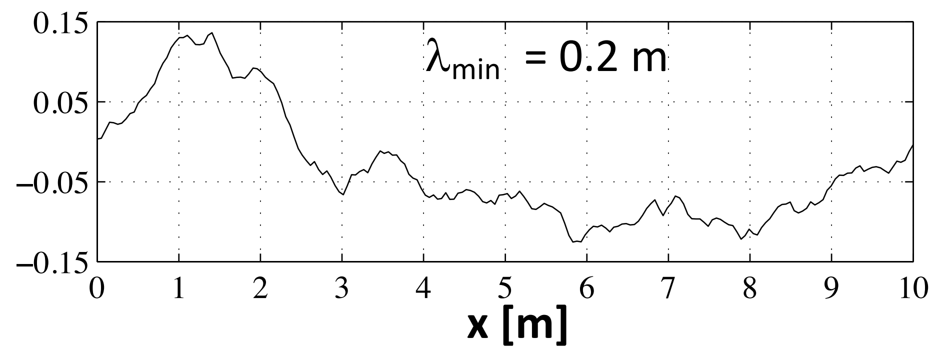




Experimental data

Gouge thickness





Friction law

Rate and state friction (Dieterich, 1979)- $\mu\ (V_{rel}, \theta)$

$$\mu = \mu^{*} + a ln\left(\frac{v_{\mathrm{rel}}}{v^{*}}\right) + b ln\left(\frac{v^{*}\theta}{d_c}\right)$$

v_{rel}- slip velocity, v*- reference velocity

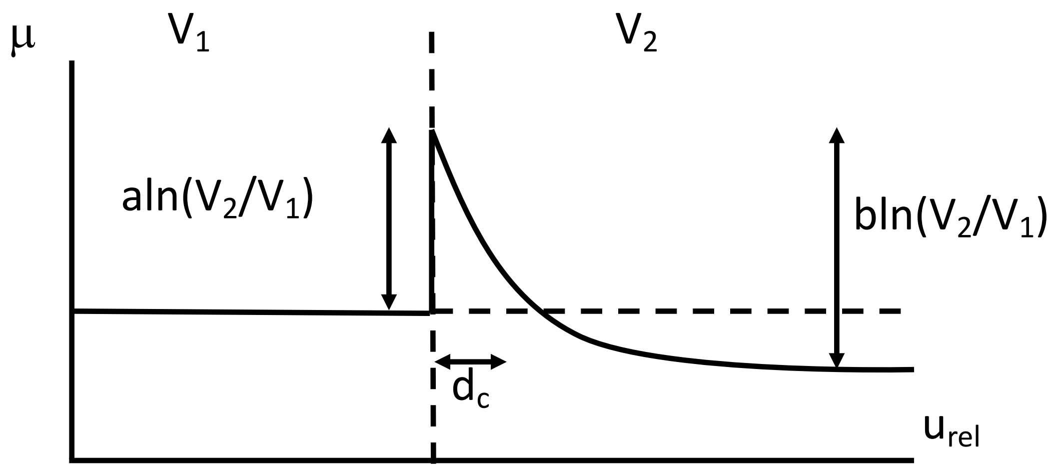
μ*- steady-state friction at $v_{rel} = v^*$

a and b- material dependent empirical constants

d_c- critical slip distance, θ- state variable:

Aging law

$$\dot{\theta} = 1 - \frac{\theta v_{\mathrm{rel}}}{d_c}$$



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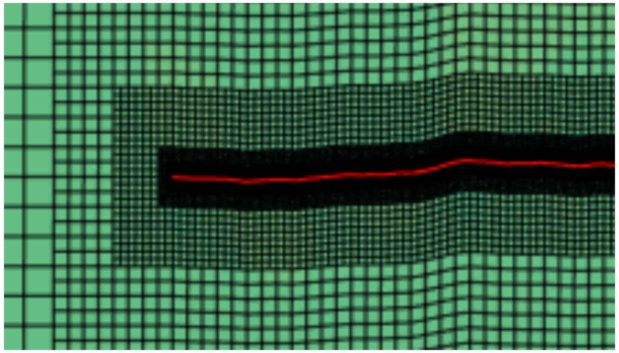
Numerical approach

1. Implementing rate and state friction law into the **Mortar Finite Element Method**

- Enables slip that is large relative to the size of the elements near the fault
- Models accurately the variation of normal stress during slip

2. Hanging nodes

- Represent the geometry of the fault accurately



3. Variable time steps with quasi-static and fully dynamic implicit schemes

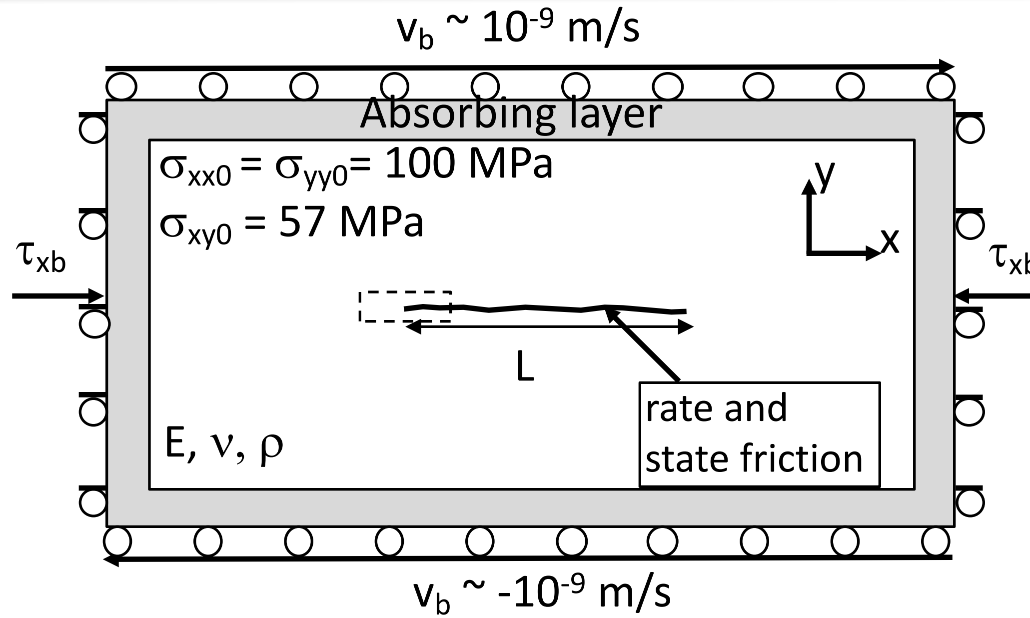
- Model the whole seismic cycle

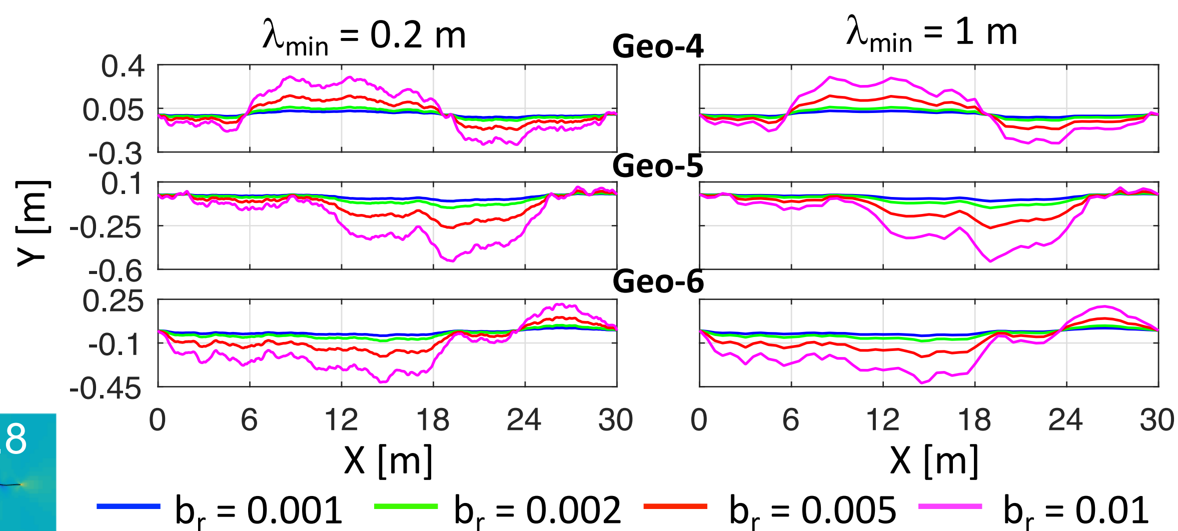
Model

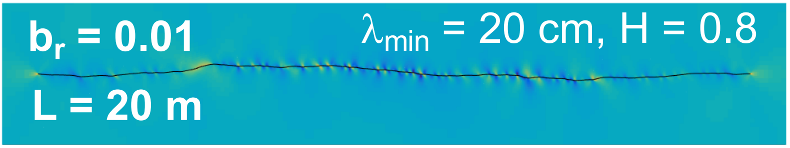
75 simulations with different fault geometries

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

L = 20, 30, and 40 m
b_r = 0 – 0.01
λ_{min} = 0.2 and 1 m
H = 0.8



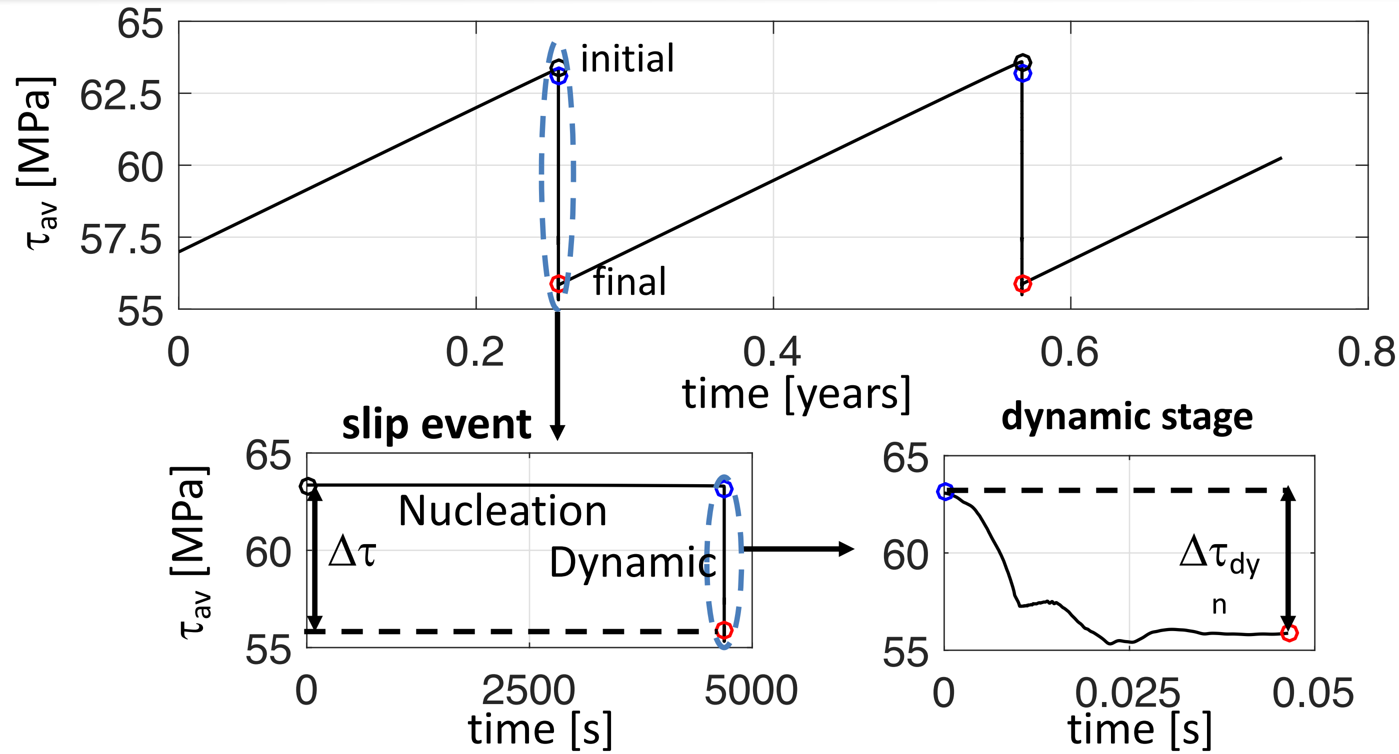


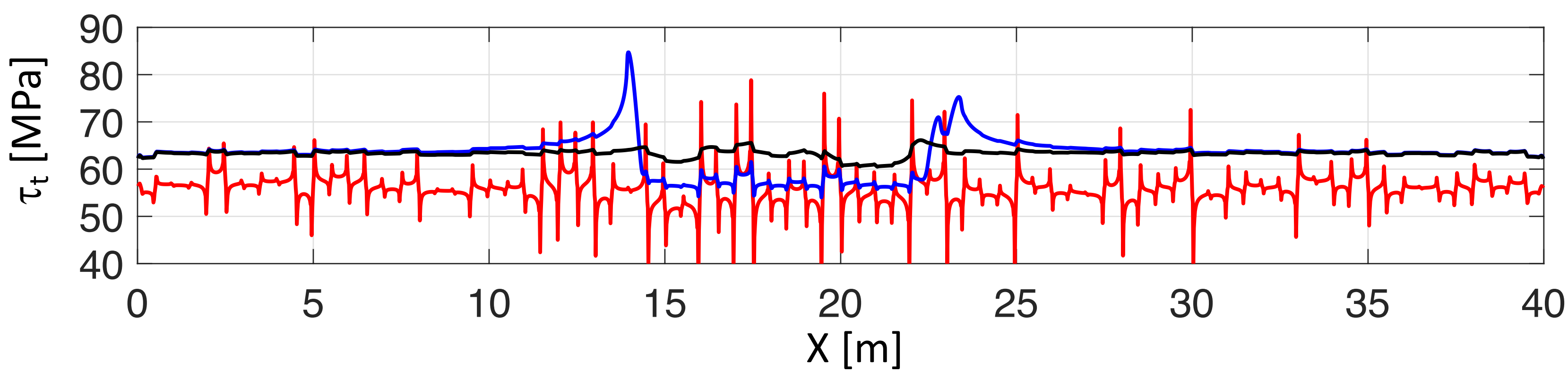


Evolution shear stress

$L = 40$ m
$b_r = 0.001$
$\lambda_{min} = 1$ m

* The dynamic stage begins when the rupture velocity is larger than a threshold value



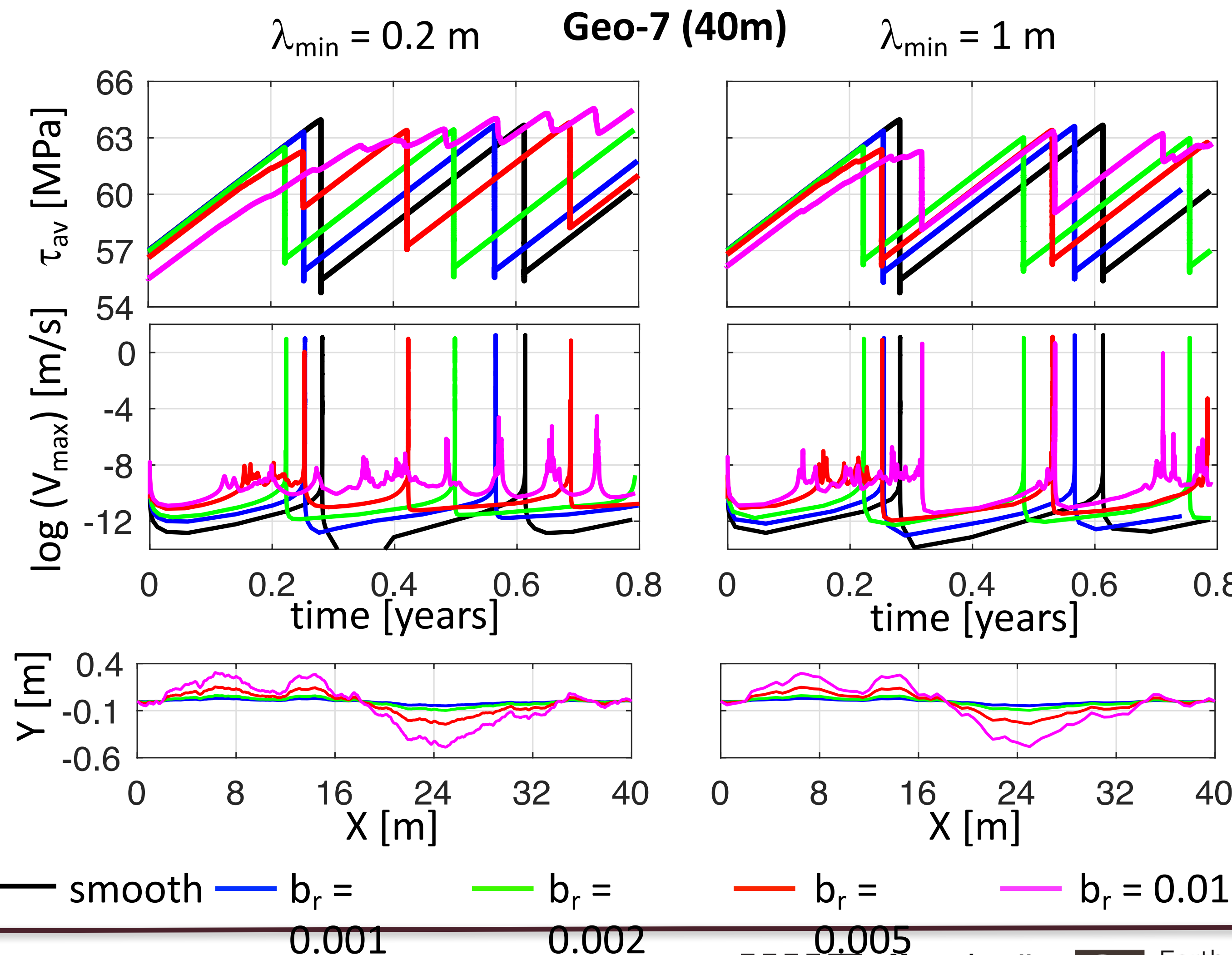


Slip rate and shear stress on the fault

b_r increases =>

More slip events

Lower slip rates stress drops

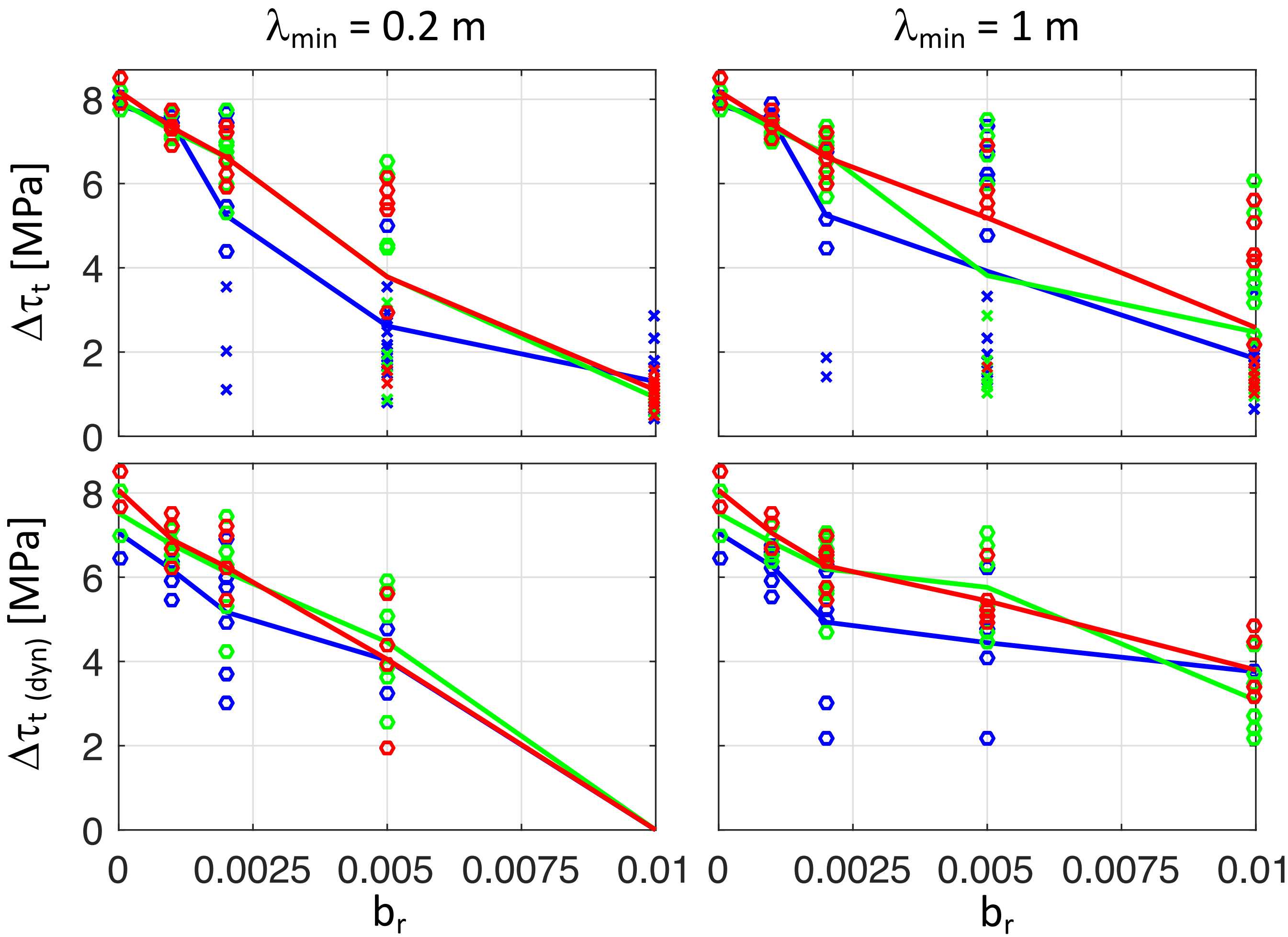


Stress drop

b_r increases
λ_{min} decreases

=> The stress drop decrease

The effect of L is consistent only for smooth fault



- L_f = 20 m, fast
- L_f = 20 m, slow
- L_f = 30 m, fast
- L_f = 30 m, slow
- L_f = 40 m, fast
- L_f = 40 m, slow

Seismic moment $M_0 = GAD$

$M_w = \log_{10}(M_0)/1.5 - 6.07$

b_r increases

λ_{min} decreases => The seismic moment decrease

L decreases

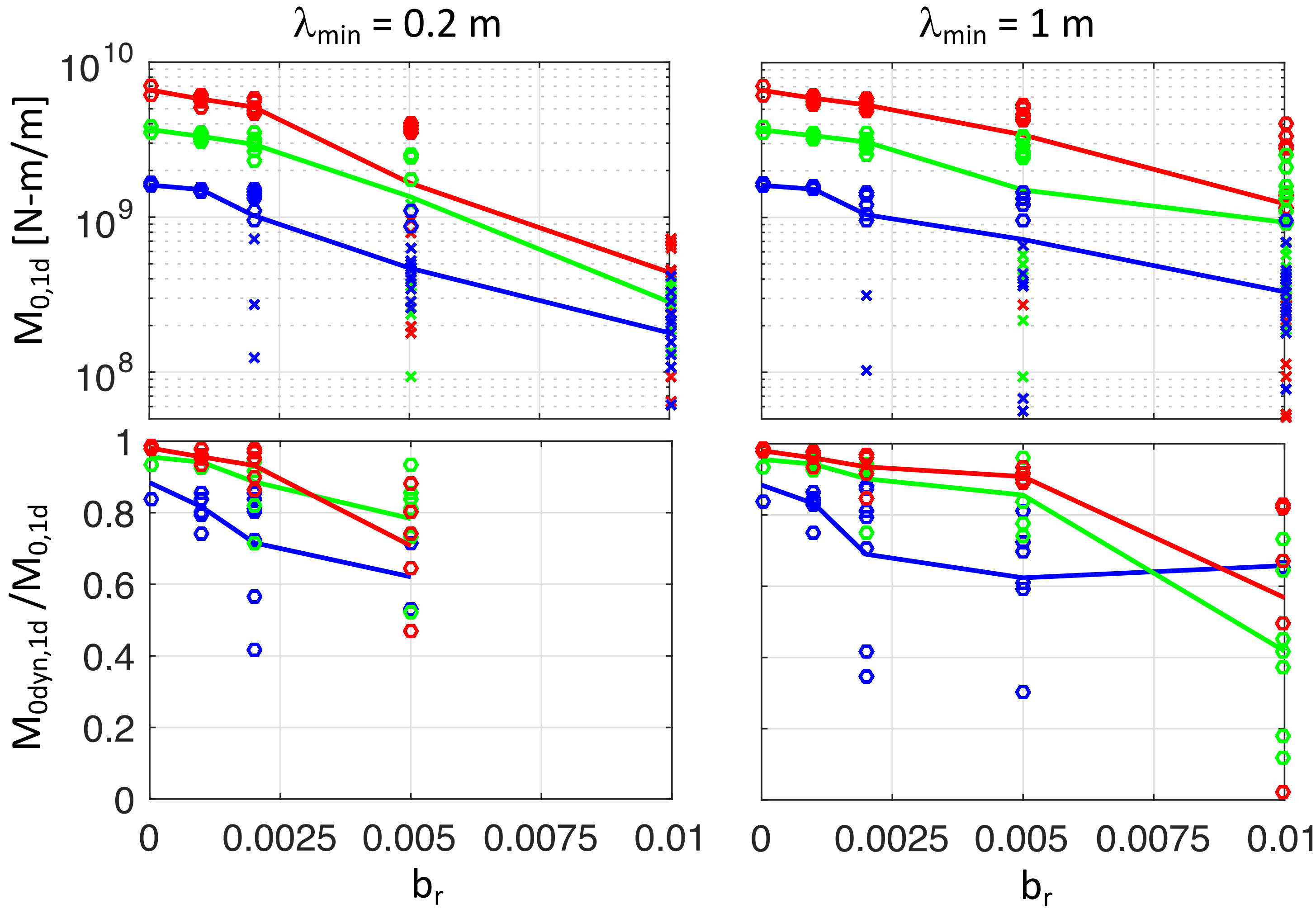
1-D moment

$M_{0,1d} = GLD$

A- rupture area

G- shear modulus

D- average slip



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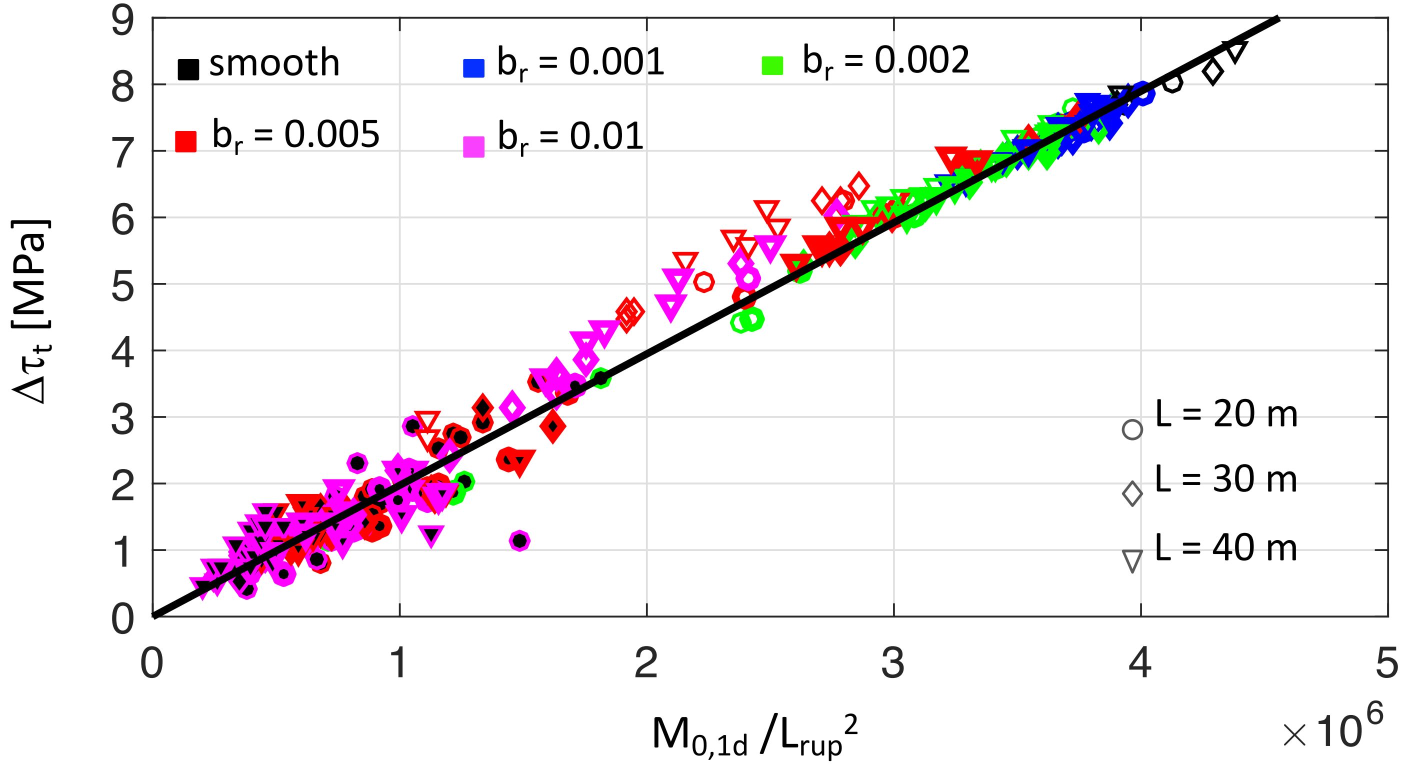
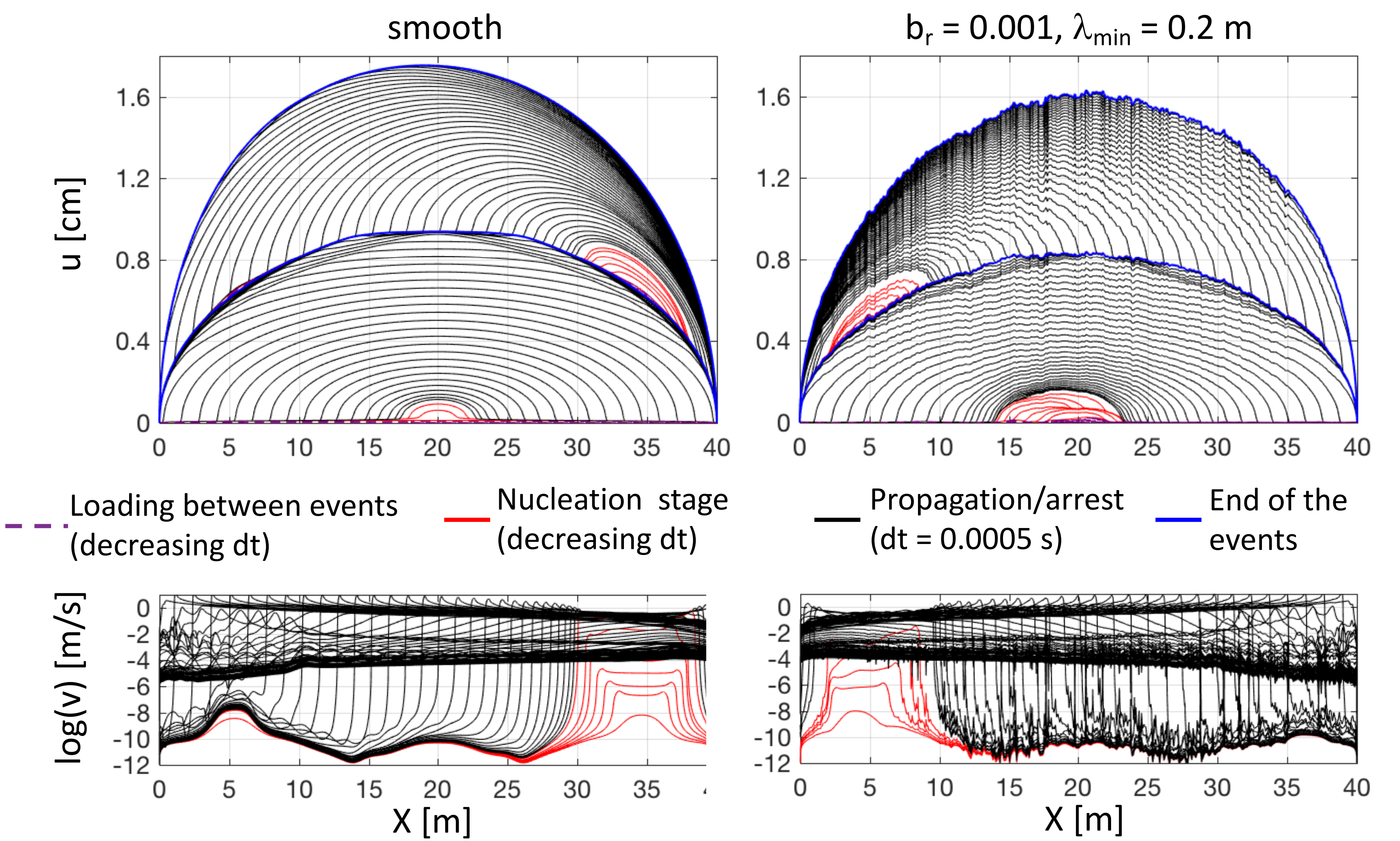
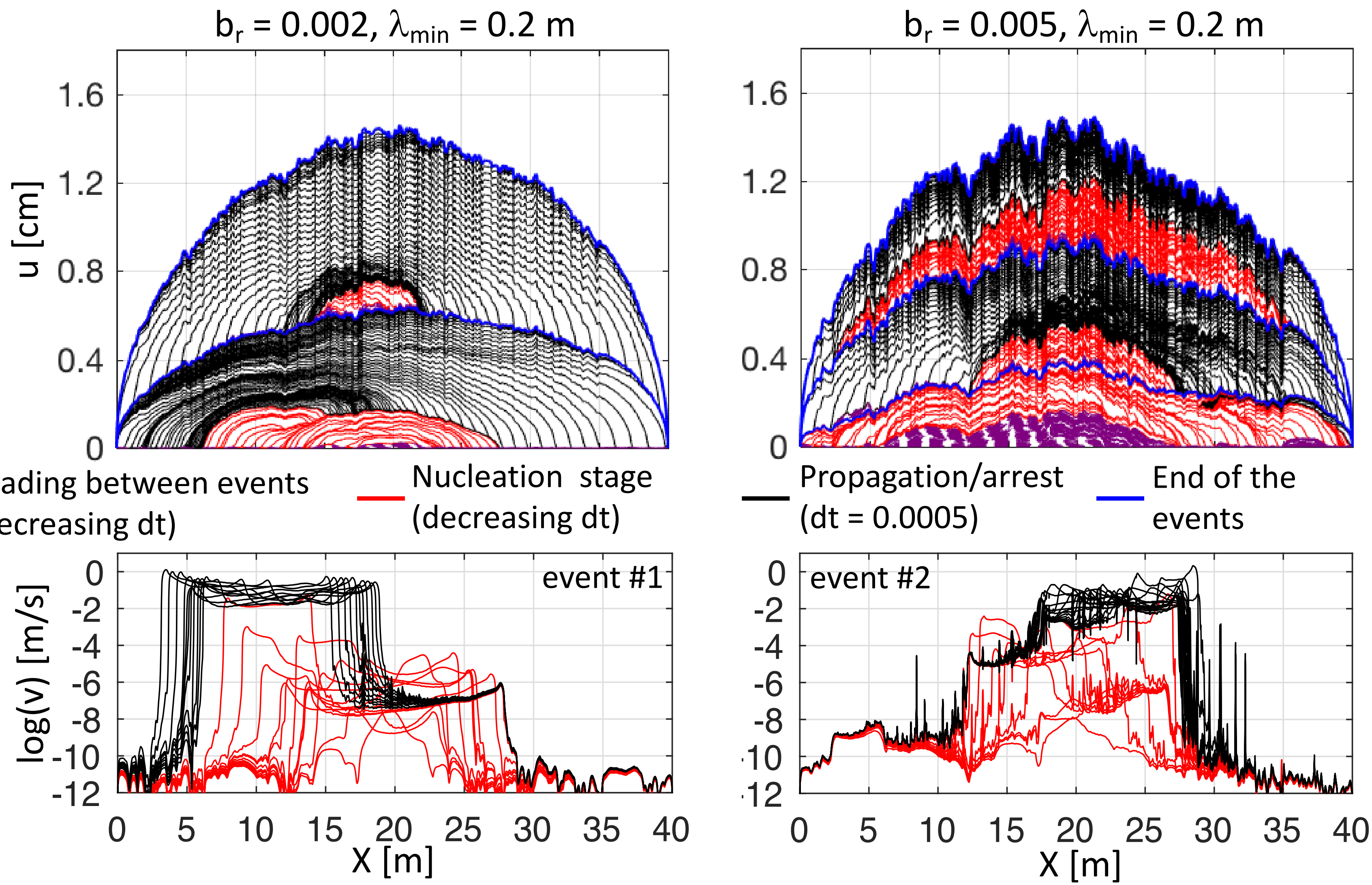
Scaling relations



Rupture process



Rupture process



Conclusions

- The roughness introduces local barriers that complicate the rupture process and result in asymmetric expansion of the rupture, multiple slip pulses, and larger nucleation length.

- As the roughness amplitude increases there is a transition from seismic slip behavior to aseismic slip behavior, in which the load on the fault is released by more slip events but with lower slip rate, seismic moment, and static stress drop.