Propagation of Slow Slip Events on a Rough Fault

Yudong Sun[1]; Camilla Cattania[1]

[1]Massachusetts Institute of Technology

Abstract

Recent studies showed that slow slip events (SSEs) in subduction zones can happen at all temporal and spatial scales and propagate at a wide range of velocities. Heterogeneity of fault properties, such as fault roughness, is often invoked to explain this complex behavior, but how roughness affects SSEs is not well understood. Here we use linear elastic fracture models and quasi-dynamic seismic cycle simulations to model slow slip events on a rough fault. Roughness induces heterogeneity in normal stress and causes locked asperities where normal stress is high. We find that SSEs tend to rupture like a pulse rather than a crack when the amplitude of the normal stress perturbation is large and the minimum wavelength is in an appropriate range. In our models, pulse-like ruptures are usually clusters of small subevents and propagate slowly, while crack-like ones are single extensive events and propagate much faster. On a rough fault with a fractal elevation profile, the transition from pulse to crack can also lead to faster re-rupture of SSEs. By treating asperities as spring-sliders rupturing in sequence, we explain the difference in forward and backward propagation velocity. Our study provides a possible mechanism for the complex evolution of SSEs from geophysical observations.

Introduction

Researchers have observed slow slip events (SSE) and non-volcanic tremors in many subduction zones worldwide. Houston et al. (2011) observed rapid tremor reversals (RTR) in Cascadia subduction zones, which occur in previously ruptured regions. The backward propagating velocity is significantly higher than the forward propagating velocity. Geological observations show that the fault is corrugated at all scales, and the distribution is self-affine with a Hurst exponent H (0.4-0.8; Renard and Candela, 2017). We want to determine the effect of normal stress perturbations, as a proxy for roughness, on the complex rupture behaviors.

Two key questions:

- Can fault roughness explain re-rupture and back propagation?
- What controls the back propagation velocity on a rough fault?

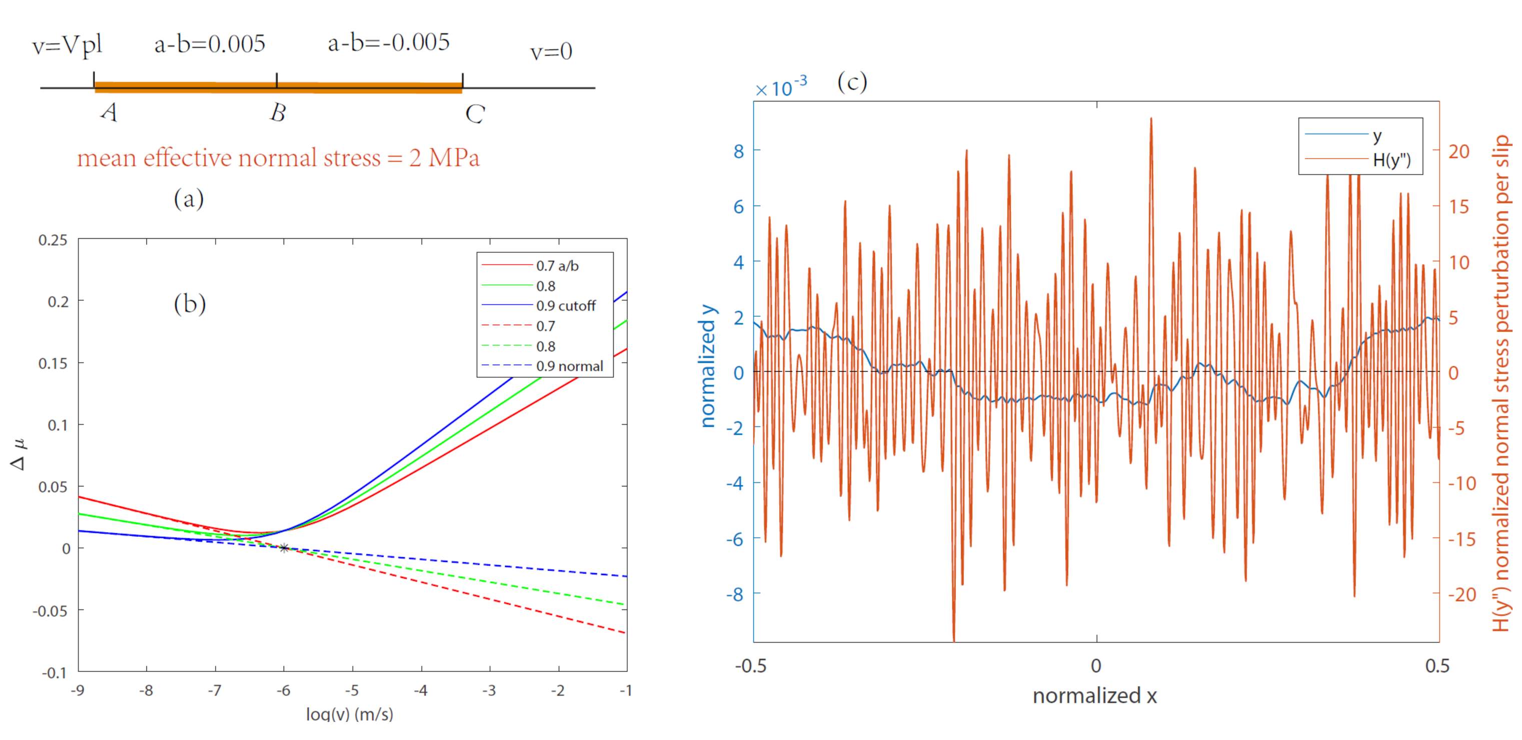

Figure 1: (a) Model geometry. (b) Steady-state friction coefficient of the original rate-and-state friction (dashed line) and velocity cutoff model (solid line, Hawthorne and Rubin, 2013). (c) Normalized elevation of a rough fault and perturbation of the normal stress.

Model Setup

We use a 2D quasi-dynamic boundary element model (FDRA, Segall and Bradley, 2012) to simulate the SSEs on a rough fault. The fault is divided into two regions (Figure 1a, velocity-weakening region BC and velocity strengthening region AB. The characteristic state-evolution distance Dc is set 4×10^{-5} m (Marone, 1998).

We choose to use the velocity-cutoff model to simulate slow slip events (Figure 1b). The fault slip is governed by:

$$\tau_{el} = \tau_f + \frac{\mu}{2c_s} v$$

Where τ_{el} is the shear stress due to remote loading and interaction with other elements, and the frictional resistance τ_f is given by:

$$\tau_f = \sigma\left(\mu_1 - a\ln(\frac{V_1}{V}+1) + b\ln(\frac{\theta V_c}{D_c}+1)\right)$$

State evolution is governed by the ageing law (Ruina, 1983):

$$\frac{d\theta}{dt} = 1 - \frac{\theta V}{D_c}$$

For AC, the average normal stress is 2 MPa (Liu and Rice, 2007). We include a perturbation of normal stress consistent with that induced by a rough fault (Figure 1c). We use the amplitude-to-wavelength ratio α to define the roughness of the fault as $y_{RMS}=\alpha\ \lambda^{H}_{max}$. We use the following analytical expression to relate normal stress perturbations to fault topography (Cattania and Segall, 2021, Fang and Dunham 2013):

$$\Delta\sigma(x) = \frac{\mu' S}{2} H(y'') = \frac{\mu' S}{2}\int_{-\infty}^{\infty}\frac{y''(\xi)}{x-\xi}d\xi$$

Results

Re-rupture: Pulse-like to Crack-like

There are two kinds of rupture behaviors, crack-like and pulse-like. The slip profile of crack-like rupture is elliptic if assuming a constant stress drop. The pulse-like one is similar to the movement of an inchworm, the rise time of one location is much shorter than the duration of the slip events.

In Figure 2, pulse-like ruptures are usually clusters of small subevents and propagate slowly, while crack-like ones are single extensive events and propagate much faster. On a rough fault with a fractal elevation profile, the transition from pulse to crack can also lead to faster re-rupture of SSEs. We also observe some even faster 'streaks' propagating backward in the simulations.

The corrugation of the real fault is fractal over an extensive range of wavelengths. So the perturbation is more likely to be randomly distributed, and the amplitude varies from place to place along the fault. We use a case with a walnut-like normal stress perturbation (Figure 3) to study the influence of the local amplitude of the perturbation on the direction of propagation.

The pulse-to-crack transition can explain the re-ruptures in the 'walnut' case (Figure 3), in which the SSE propagate from high roughness to low roughness areas. It slips like a pulse in the region (x = ~1.25 km) with a larger amplitude of perturbation and slips like a crack in the region (x = ~0 km) with nearly constant normal stress. So the re-rupture may be due to the deficit between crack and pulse-like slip profiles, as suggested by Idini and Ampuero (2020) for the fault surrounded by damage zone.

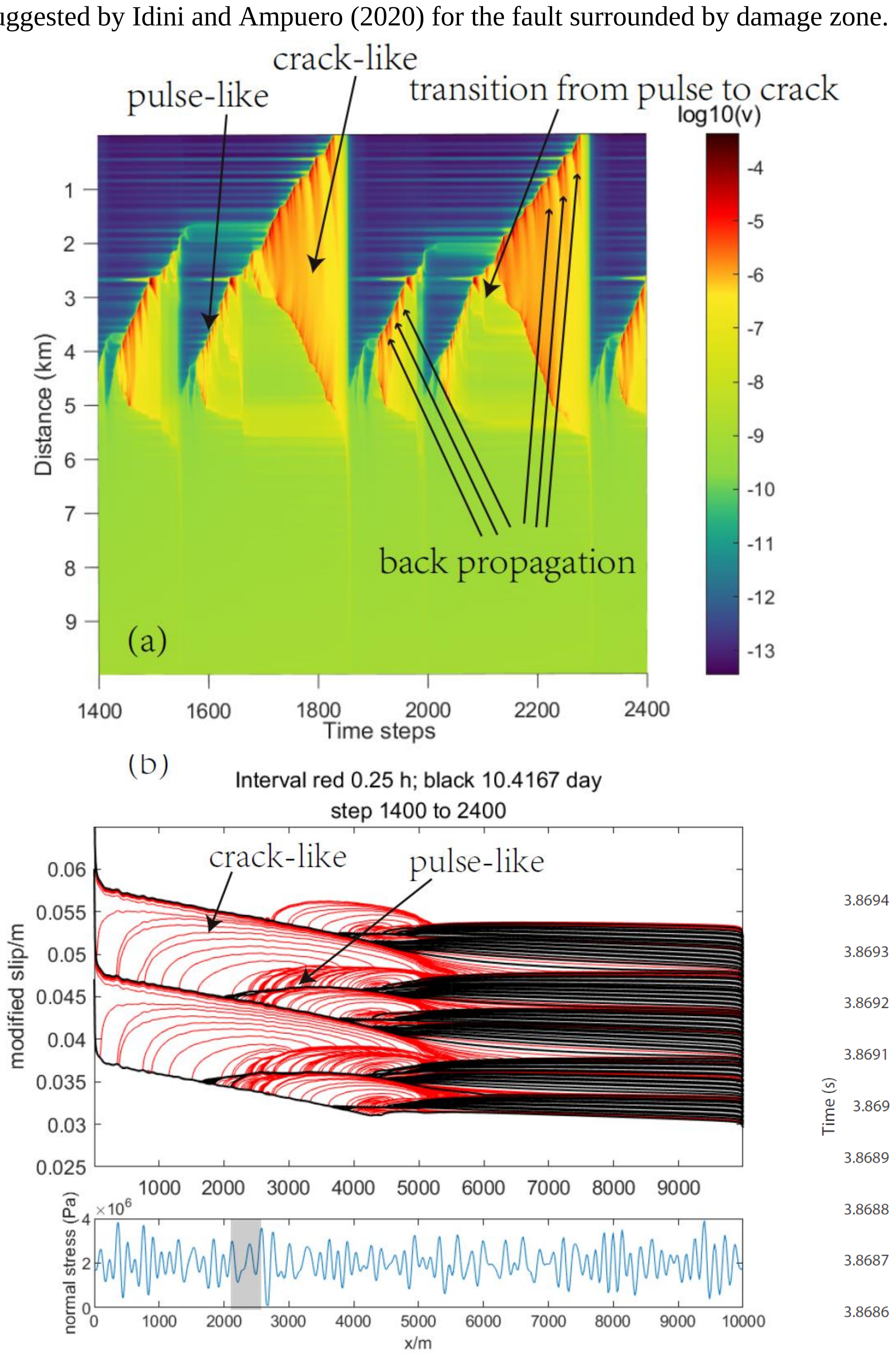

Figure 2: Slip behaviors on a fractal rough fault. (a) Slip rate for each time steps. (b) Top: modified accumulated slip along the fault during several earthquake cycles, which is the slip S divided by $\pi/2+\arcsin\frac{x-W/2}{W/2}$ (analytical expression for a zero stress drop crack driven by end-point displacement, Figure 1a). Bottom: distribution of the normal stress. Grey box denotes where the transition happens.

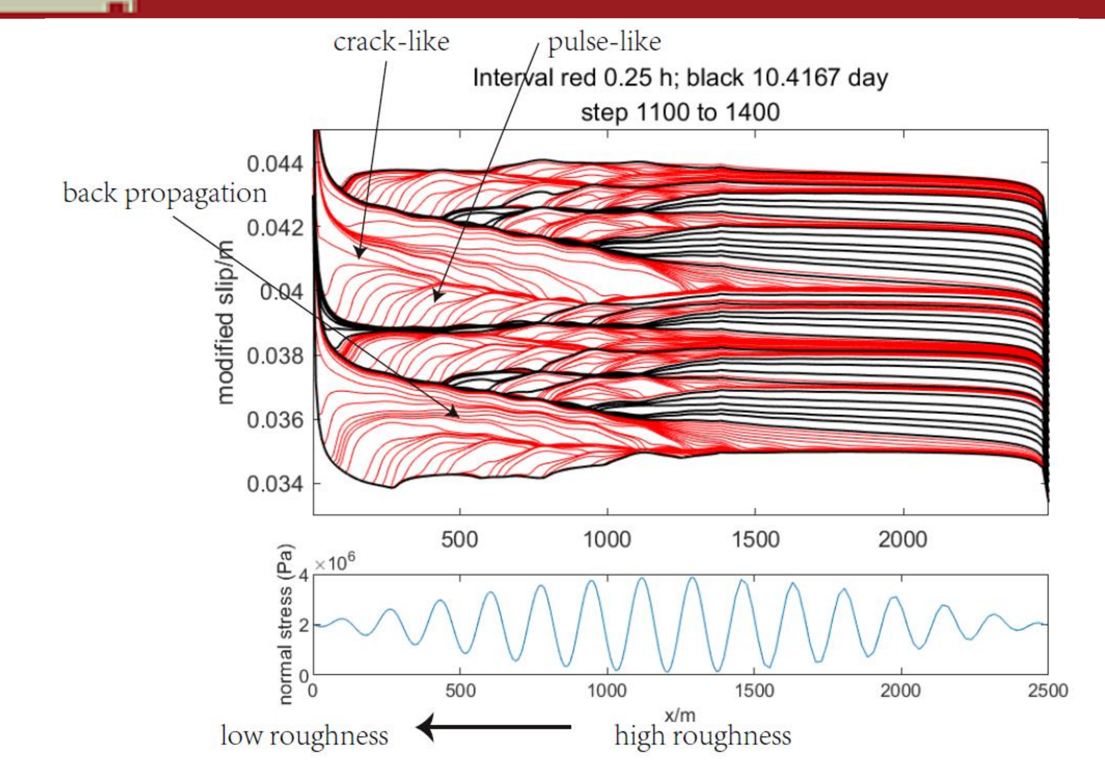

Figure 3: Accumulated slip and the normal stress for 'walnut' case. It shows the re-rupture in the full-rupture event which propagate from high to low roughness regions.

Back Propagating Velocity

To account for the spatial variations in normal stress we use a spring-slider model to study back propagation, regarding the fault patches with higher normal stress as sliders. A rupture propagates through progressive failure of asperities (Figure 4), each of them increasing stresses behind the rupture front causing back propagation. After an event, the time before another event on the patches nearby tells how fast it propagates. For example, it propagates back more quickly if the fault patch behind ruptures again shortly after. While it propagates forward more slowly if it takes a longer time for the patch in the front to rupture (Figure 4).

We run simulations with a sinusoidal normal stress perturbation with different wavelength. We measure the back propagation velocity (Figure 4b) and compare with two analytical models. The back propagating velocity of streaks is $v_{re} = \lambda/t$, where λ is the wavelength. Assuming far above steady state, the time t before the failure is as follows (Dieterich, 1994)

$$t = \frac{a\sigma}{\dot{\tau}}\ln\left(1+\frac{\dot{\tau}}{H\sigma v_i}\right)$$

Where H and $\dot{\tau}$ are $\frac{b}{D_c}-\frac{k}{\sigma}$ and loading stressing rate. The initial slip rate v_i is elevated from v_0 by the stress change $\Delta\tau$ as $v_i = v_0\exp(-\frac{\Delta\tau}{a\sigma})$

We use two analytical models for propagating velocity with different v_0 (Figure 4b). For models with different λ, the blue model uses a constant v_0 but the red model uses a variable v_0 accounting for the evolution of slip velocity since the previous rupture, as derived as (Rubin and Ampuero, 2005, Equation A10, assuming below steady state):

$$v_0 = v_{dyn}\left(\frac{\theta_{dyn}+t_f}{\theta_{dyn}}\right)^{-b/a}\exp(\frac{\dot{\tau}t_f}{a\sigma})$$

The time t_f is λ/v_{prop}, v_{prop} is the forward propagating velocity.
We write the expressions for two models (blue and red curves) as

$$V_{re} = \frac{\lambda\dot{\tau}}{a\sigma\ln\left(1+\frac{\dot{\tau}}{H\sigma v_0}\exp(-\frac{\Delta\tau}{a\sigma})\right)} \qquad V_{re} = \frac{\lambda\dot{\tau}}{a\sigma\ln\left(1+\frac{\dot{\tau}}{H\sigma v_{dyn}}\left(\frac{\theta_{dyn}+\lambda/v_{prop}}{\theta_{dyn}}\right)^{b/a}\exp(-\frac{\dot{\tau}\lambda/v_{prop}+\Delta\tau}{a\sigma})\right)}$$

In Figure 4b, red curve grows more slowly with λ than the blue curve. The trend of the red curve fits better with the measured propagating velocity.

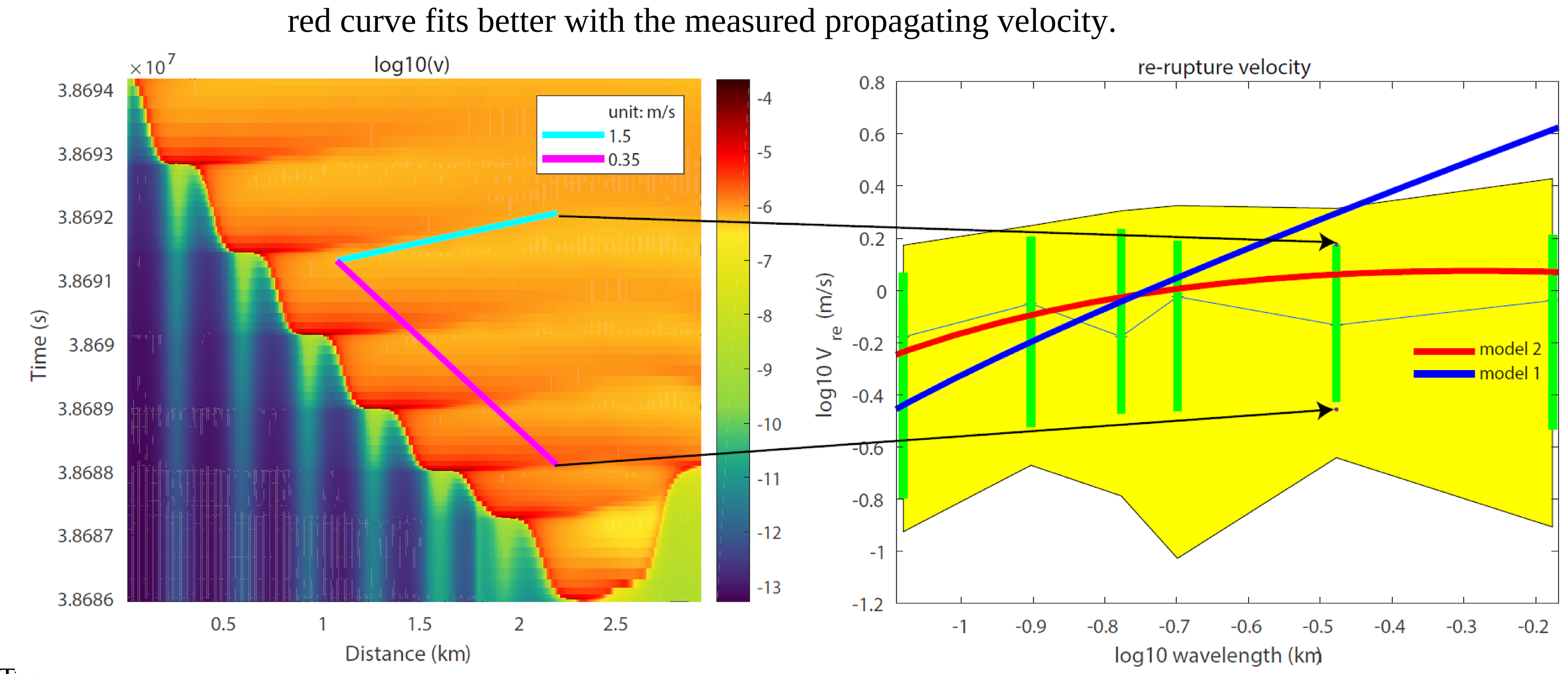

Figure 4: (a) Slip rate during one SSE. Magenta and cyan lines show the forward and backward propagating velocity. (b) Back propagation velocity from simulations with different wavelength of sinusoidal normal stress perturbation. The amplitude-to-average ratio of normal stress is 0.5. The blue and red line represent the back propagation velocity in two analytical models. The blue curve denotes the median of velocities, and the yellow patches and green bars denote the ranges from maximum to minimum velocity and 5% to 95%.

References

1. Houston, Heidi, et al. "Rapid tremor reversals in Cascadia generated by a weakened plate interface." *Nature Geoscience* 4.6 (2011): 404-409.
2. Renard, François, and Thibault Candela. "Scaling of fault roughness and implications for earthquake mechanics." *Fault zone dynamic processes: Evolution of fault properties during seismic rupture* 227 (2017): 197-216.
3. Hawthorne, J. C., & Rubin, A. M. (2013). Laterally propagating slow slip events in a rate and state friction model with a velocity-weakening to velocity-strengthening transition. *Journal of Geophysical Research: Solid Earth*, *118*(7), 3785-3808.
4. Segall, Paul, and Andrew M. Bradley. "Slow-slip evolves into megathrust earthquakes in 2D numerical simulations." *Geophysical Research Letters* 39.18 (2012).
5. Marone, Chris. "Laboratory-derived friction laws and their application to seismic faulting." *Annual Review of Earth and Planetary Sciences* 26.1 (1998): 643-696.
6. Ruina, Andy. "Slip instability and state variable friction laws." *Journal of Geophysical Research: Solid Earth* 88.B12 (1983): 10359-10370.
7. Liu, Yajing, and James R. Rice. "Spontaneous and triggered aseismic deformation transients in a subduction fault model." *Journal of Geophysical Research: Solid Earth* 112.B9 (2007).
8. Cattania, Camilla, and Paul Segall. "Precursory slow slip and foreshocks on rough faults." *Journal of Geophysical Research: Solid Earth* 126.4 (2021): e2020JB020430.
9. Fang, Zijun, and Eric M. Dunham. "Additional shear resistance from fault roughness and stress levels on geometrically complex faults." *Journal of Geophysical Research: Solid Earth* 118.7 (2013): 3642-3654.
10. Idini, B., and J-P. Ampuero. "Fault-zone damage promotes pulse-like rupture and back-propagating fronts via quasi-static effects." *Geophysical Research Letters* 47.23 (2020): e2020GL090736.
11. Rubin, Allan M. "Episodic slow slip events and rate-and-state friction." *Journal of Geophysical Research: Solid Earth* 113.B11 (2008).
12. Dieterich, James. "A constitutive law for rate of earthquake production and its application to earthquake clustering." *Journal of Geophysical Research: Solid Earth* 99.B2 (1994): 2601-2618.

Conclusions

- On a rough fault with a fractal elevation profile, SSEs tend to rupture like a pulse rather than a crack when roughness is high and the amplitude of the normal stress perturbation is large.
- The transition from pulse to crack can also lead to faster re-rupture of SSEs.
- We explain how the back propagating velocity varies with the wavelength of sinusoidal normal stress perturbation.

Future Work

- We will study the combined influence of frequency content and amplitude of normal stress perturbation on the propagating and arresting of SSEs.
- We will derive the expressions for the velocity of forward and backward propagation with spring-slider model and study why they are different.
- We will compare the propagation velocity to observations and determine which parameters are consistent with observations.