Slow slip events simulated using a friction law with a velocity-weakening to -strengthening transition

Jessica Hawthorne
Allan Rubin

Princeton University

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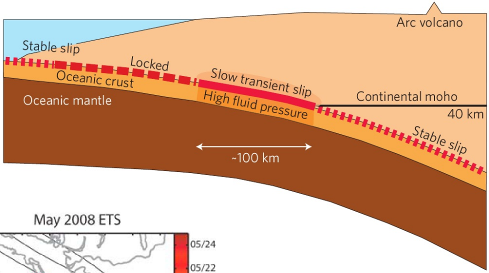
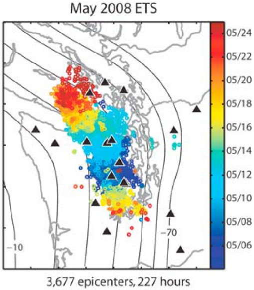
Slow slip events (in Cascadia)

- Every 12-16 months
- 2-3 centimeters of slip
- Last 3-5 weeks
- Slip rates 10-100 times plate rate
- Accompanied by tremor: lots of very small earthquakes on the plate interface
- Propagate several hundred kilometers along strike

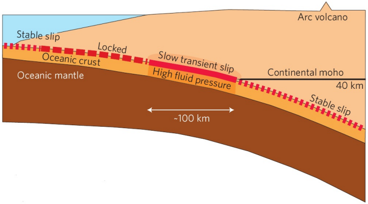
Peng and Gomberg, 2011





Wech et. al., 2009

Outline



Peng and Gomberg, 2011

Which friction law is appropriate?

- Standard velocity-weakening friction with tuned size
- Dilatancy
- Velocity-weakening to -strengthening friction

- All can produce episodic slow slip
- All require tuning
- But can they reproduce all of the observed features of slow slip?

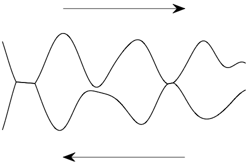
Here: Try to understand slow slip events simulated with a friction law with a velocity-weakening to -strengthening transition.

- Model motivation and setup
- Model predictions
  - Steady propagation
  - Stress drops
  - Gradual modulation due to tidal forcing
  - Back-propagating fronts

Rate and state friction

frictional strength = f(slip rate V, state θ)

$$\mu(V, \theta) = \text{constant} + a \ln\left(\frac{V}{V*}\right) + b \ln\left(\frac{V_c \theta}{D_c}\right)$$



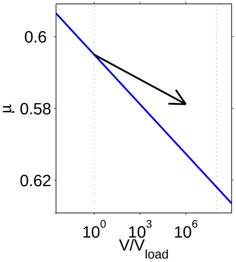
$a \ln\left(\frac{V}{V*}\right)$: direct effect

- accounts for adhesion at individual asperities
- larger for steady slip at higher slip rates

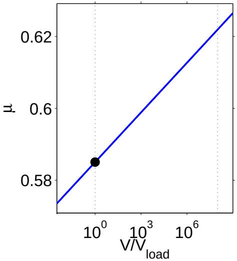
$b \ln\left(\frac{V_c \theta}{D_c}\right)$: evolution effect

- accounts for number and size of asperities
- at larger slip rates, longer asperity lifetime, larger contact area
- smaller for steady slip at higher slip rates

$a < b$, evolution effect dominates, earthquakes



$a > b$, direct effect dominates, steady sliding

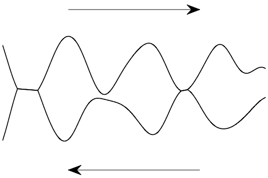


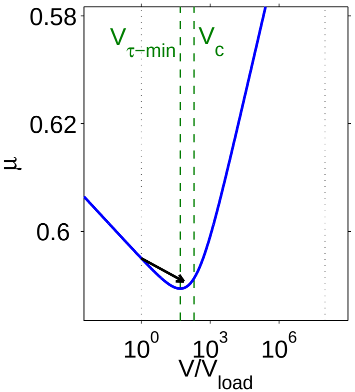
One constitutive law for episodic slow slip

frictional strength = f(slip rate V, state θ)

$$\tau(V,\theta) = \text{constant} + a\sigma \ln\left(\frac{V}{V*}\right) + b\sigma \ln\left(\frac{V_c\theta}{D_c}+1\right)$$

In theory and experiments, this law results from a lower limit on the size of asperities





velocity-weakening at low slip rates, velocity-strengthening at high slip rates

Need equations for state evolution

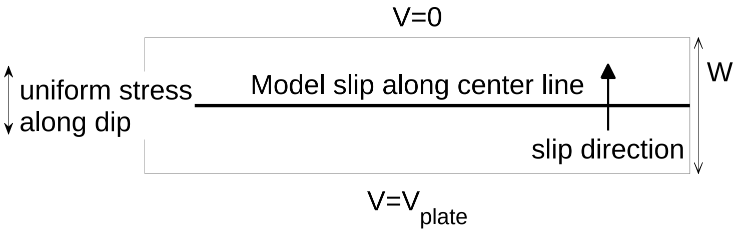
aging law

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

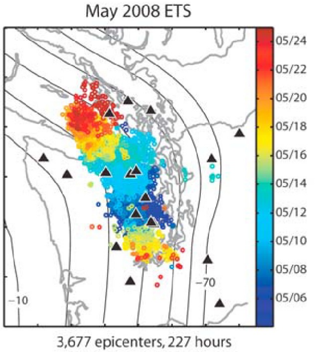
slip law

$$\frac{d\theta}{dt} = -\frac{V\theta}{D_c} \ln\left(\frac{V\theta}{D_c}\right)$$

Model geometry



- Slow slip events often extend farther along strike than along dip
- Use one point per along-strike distance
- Assume stress is uniform along dip

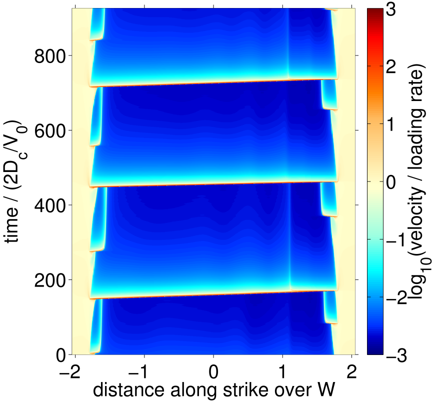


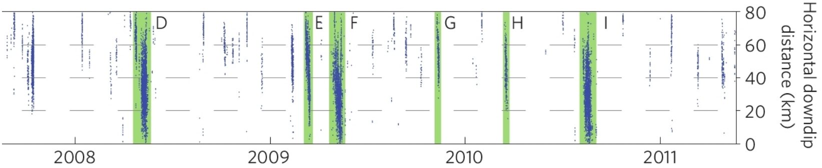
Wech et. al., 2009

Simulated slow slip events

Model does produce episodic slow slip events

- Slip rates around V_c, 100 times plate rate
- Episodic large events with a number of small events between

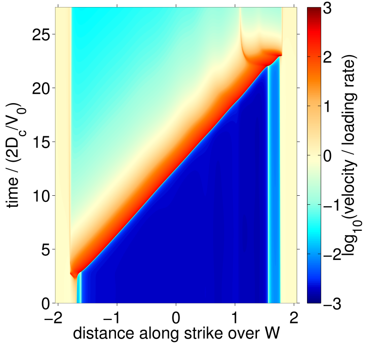




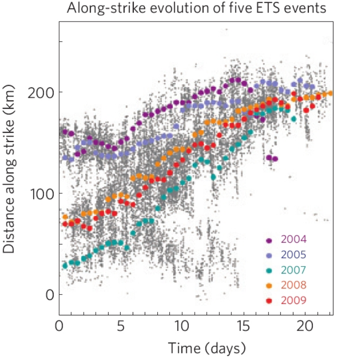
Wech and Creager, 2011

Steady propagation

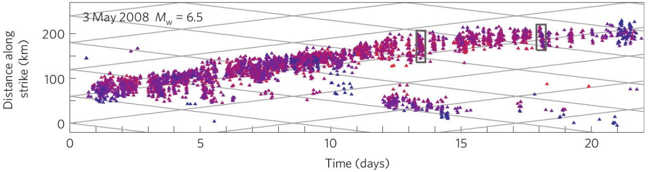
Events propagate steadily along strike



Tremor observations



Houston et. al., 2011



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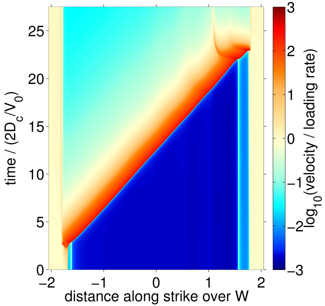
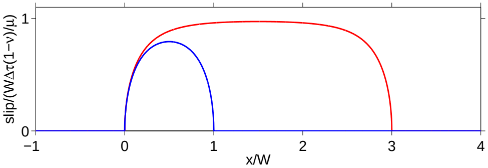
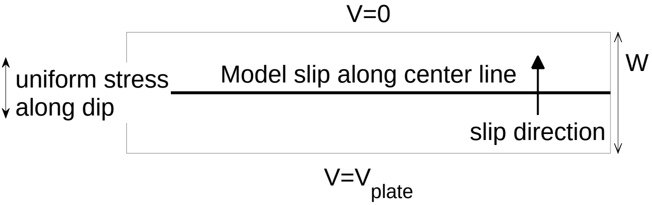


Uniform stress drop slip profiles

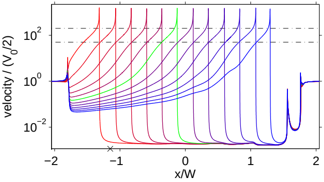


With the strip model geometry, points don't feel slip at locations much more than *W* away.

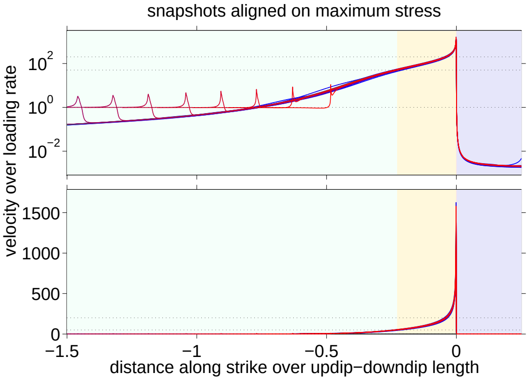
This makes a steady solution possible.



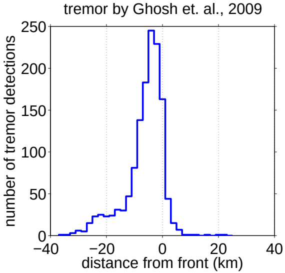
Steady velocity and stress profiles



- Most of the slip accumulates in a region behind the front somewhat smaller than the updip-downdip length *W*
- Velocity profiles resemble asymmetric tremor density

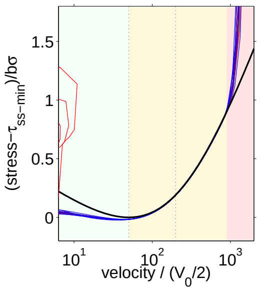


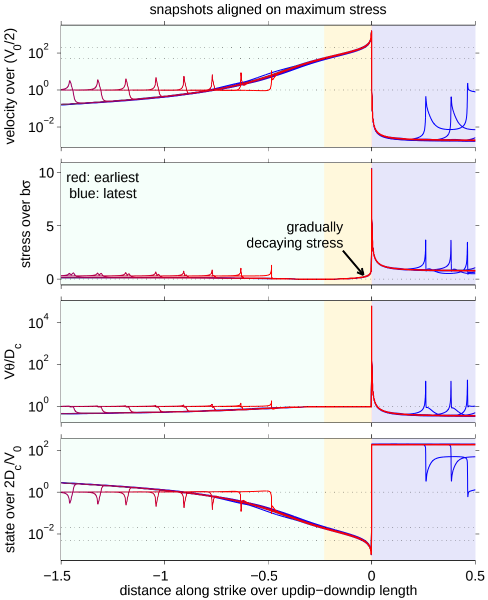
2 days of tremor stacked behind a tremor-defined front



Steady velocity and stress profiles

- purple: unbroken, well-healed
- pink: strongly slip-weakening region, above steady state
- yellow: gradually decaying stress, near steady state
  - Specific to this friction law
  - Know stress-velocity relation in this region
- green: low-stress, below steady state



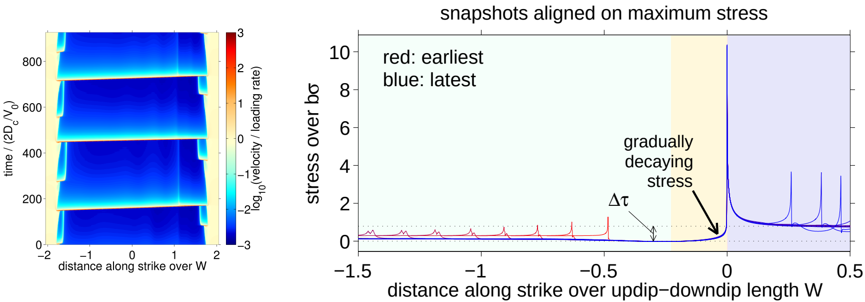


Conclusions to this point

- Simulations exhibit many small events as well as periodic large events
- Large events propagate steadily “along strike” with the strip model

Recurrence intervals: energy balance

- controlled by the ability of events to propagate, not by nucleation.



strain energy release rate $G =$ energy dissipated by friction (fracture energy G_c)

Recurrence intervals: energy balance

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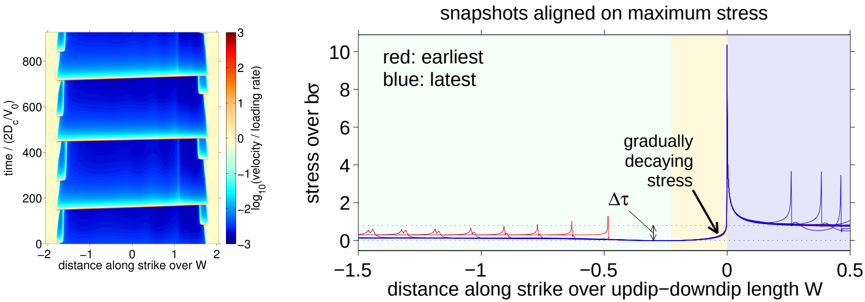


strain energy release rate G = energy dissipated by friction (fracture energy G_c)

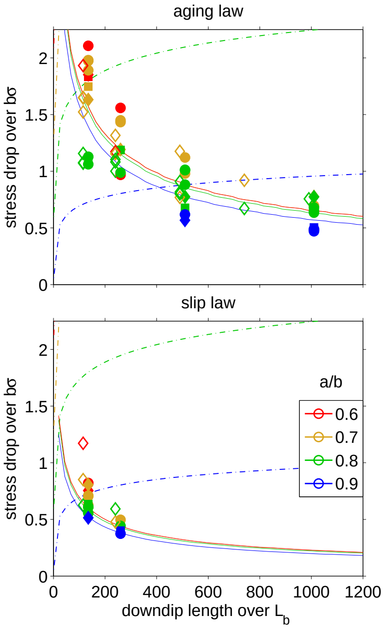
constant × stress drop × slip ≈ near-tip contribution + gradual decay contribution

$$\frac{\psi}{2}\Delta\tau\left(\Delta\tau\frac{W}{\mu}\right)\approx b\sigma D_c \times \text{ evolution-law-dependent constant}$$

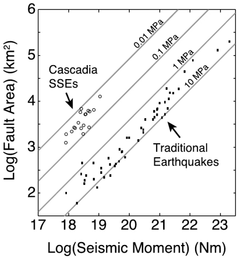
$$\Delta\tau \approx \psi' b\sigma\sqrt{\frac{L_b}{W}} \qquad \text{where } L_b = D_c\frac{\mu}{b\sigma}$$

b = evolution effect coefficient, ψ = geometric factor,
D_c = slip distance for state evolution, μ = shear modulus

Recurrence intervals: simulation results



Schmidt and Gao, 2010



Observed along-dip length W: 50-100 km

Observed stress drops: 10-100 kPa

slip $\times \mu/(1-\nu)/W$ = 2 cm $\times$ 40 GPa / 50 km = 15 kPa

$$\Delta\tau \approx \psi' b\sigma \sqrt{\frac{L_b}{W}} \quad \text{where } L_b = D_c \frac{\mu}{b\sigma}$$

$$b\sigma D_c \approx \frac{\Delta\tau^2 W}{\mu \psi'^2}$$

Required model parameters:

- Slip law: $D_c b\sigma \approx 3 - 200$ Pa-m
- Aging law: $D_c b\sigma \approx 0.3 - 20$ Pa-m

For the slip law, $b = 0.01$

- For $D_c = 10\ \mu$m: $\sigma \approx$ 30 MPa - 1 GPa
- For $D_c = 100\ \mu$m: $\sigma \approx$ 3 MPa - 200 MPa
- For $D_c = 1$ mm: $\sigma \approx$ 0.3 MPa - 20 MPa

Conclusions to this point

- Simulations exhibit many small events as well as periodic large events
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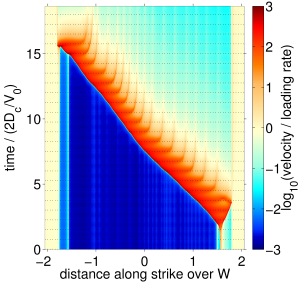
- Stress drops controlled by ability to propagate long distances along strike
  - Understood with an energy balance approach

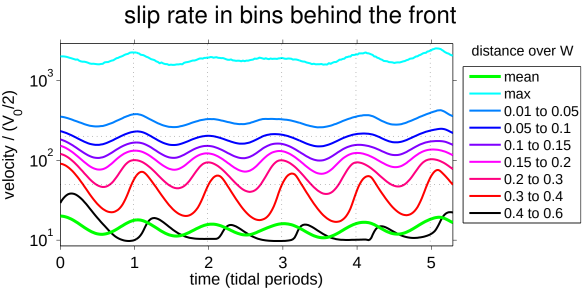
Effect of a tidal forcing

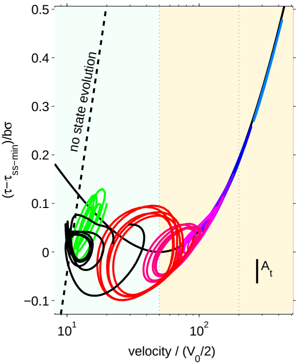


Tides introduce a gradual modulation of the slip rate.

Larger tidal stress = faster slip, with some complications from the friction law

- More modulation in shallower portions of the steady state curve, at lower slip rates
- More modulation when there is enough slip in each period for state evolution, at higher slip rates





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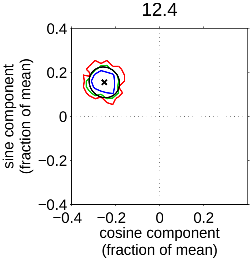
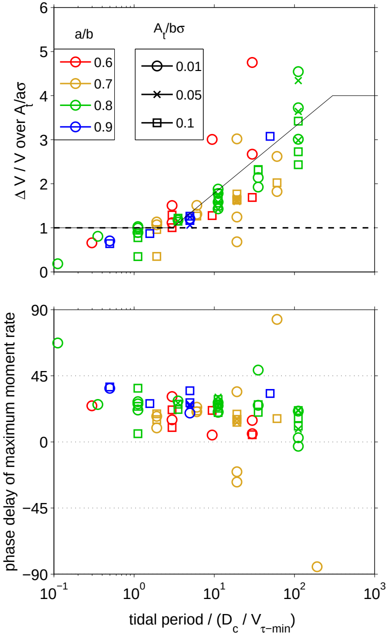


Hawthorne and Rubin, 2010



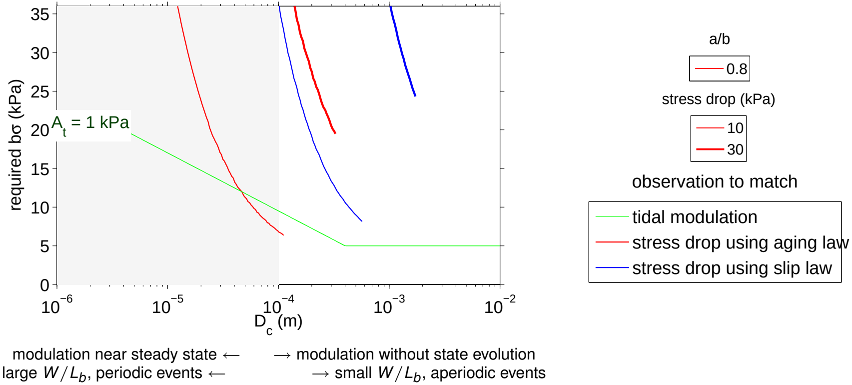
- Modulation of slip in Cascadia A_t: $\pm$ 30%
- Tidal stress on the interface: $\pm$0.5 to 1.5 kPa

$$\frac{\Delta V}{V} = 1\text{-}4\ \frac{A_t}{a\sigma}$$

$$0.3 = 1\text{-}4\ \frac{1\text{ kPa}}{a\sigma}$$

Implies $a\sigma \approx 1 - 20$ kPa
For $a \approx 0.01$, $\sigma \approx 0.1 - 2$ MPa

Matching tidal forcing and recurrence interval simultaneously?

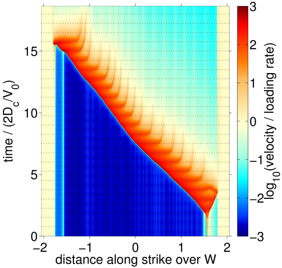


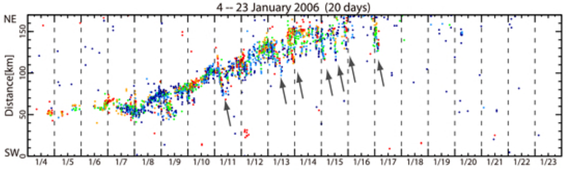
- Possible to match 10 kPa stress drop and 30% modulation with the aging law
- But not 30 kPa stress drop and 30% modulation
- More difficult to match the observations with the slip law
  - Slip law preferred by experiments for frictional energy dissipation estimates—for our stress drop estimates
- Lines terminate when they leave the regime that allows for periodic steadily propagating events

Conclusions to this point

- Simulations exhibit many small events as well as periodic large events
- Large events propagate steadily “along strike” with the strip model
- Stress drops controlled by ability to propagate long distances along strike
    - Understood with an energy balance approach
- Tidal forcing results in a gradual modulation of the slip rate behind the propagating front
- Difficult to match the observed stress drops and tidal modulation with the slip law

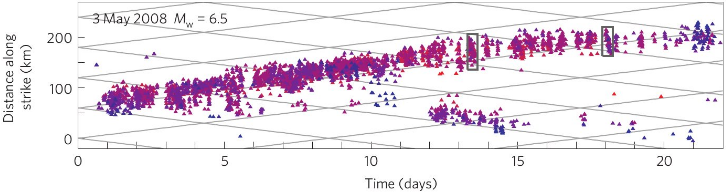
Back-Propagating Fronts





Obara et. al., 2012

Regions of high slip rate propagating back through the region that has already slipped



Houston et. al., 2011

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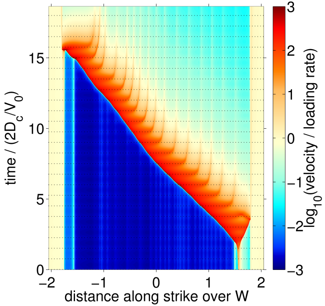
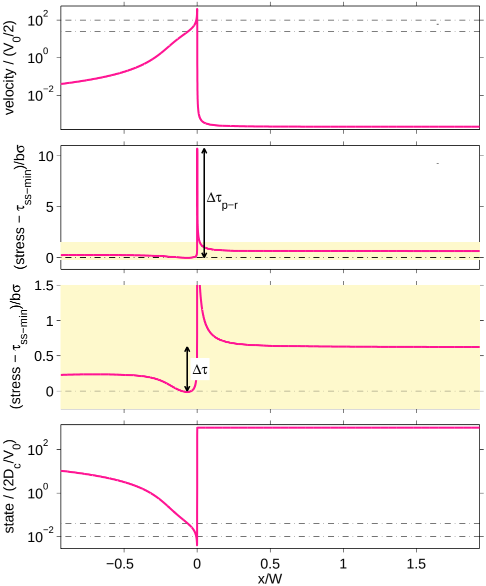


Driven by available stress drop

- From tidal forcing
- From naturally arising stress recovery

Similar to forward-propagating fronts, but with smaller stress drop and smaller initial state



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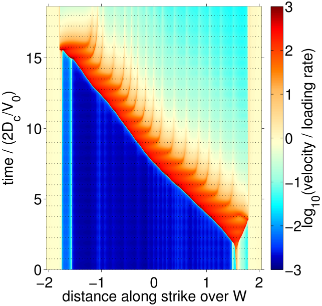

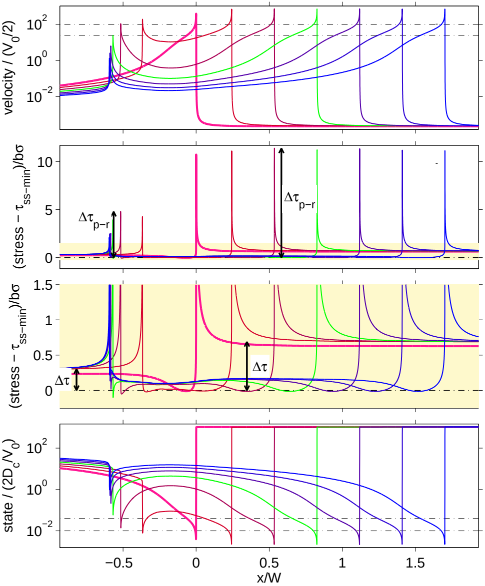

Driven by available stress drop

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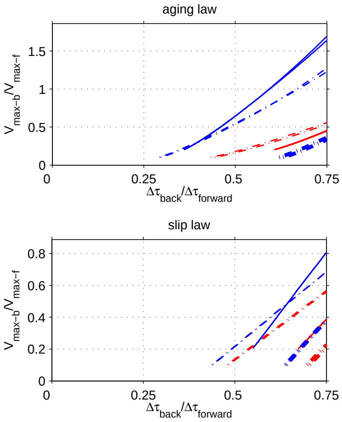
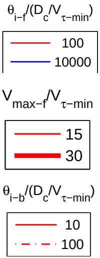
Similar to forward-propagating fronts, but with smaller stress drop and smaller initial state

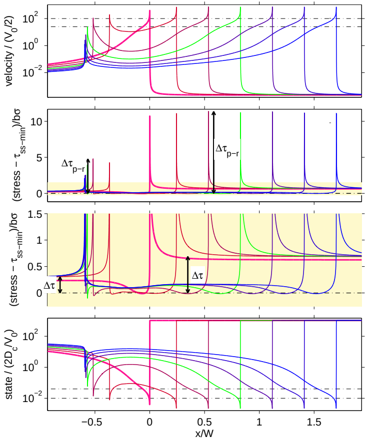
Back-Propagating Fronts: Maximum Slip Rates

strain energy release rate G = energy dissipated by friction (fracture energy G_c)

$$\underbrace{\text{constant} \times \text{stress drop} \times \text{slip}}_{\substack{\text{depends on } \Delta\tau \\ \text{not } V_{\max} \text{ or } \theta_i}} \approx \underbrace{\text{near-tip contribution}}_{\substack{\text{depends on } V_{\max}, \theta_i, \\ \text{not } \Delta\tau}} + \underbrace{\text{gradual decay contribution}}_{\substack{\text{depends on } V_{\max}, \\ \text{not } \theta_i \text{ or } \Delta\tau}}$$





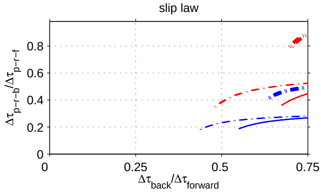


Back-propagating fronts have smaller $\Delta\tau$, but also smaller θ_i

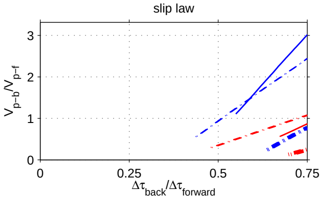
Back-Propagating Fronts: Propagation Rates

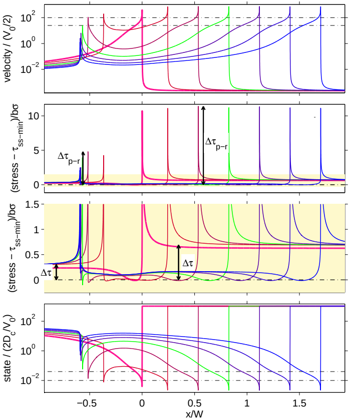
$$V_{\text{prop}} = (0.5 \text{ to } 0.65)\, V_{\text{max}} \frac{\text{shear modulus } \mu}{\Delta\tau_{p-r}}$$

$\Delta\tau_{p-r}$ is smaller for the back-propagating fronts:

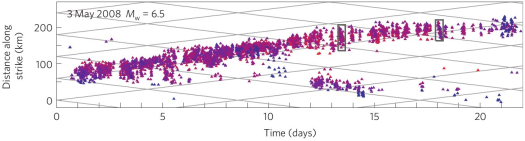


But not by enough to match the observations:





Observed propagation around 10 times forward rate.



Houston et. al., 2011

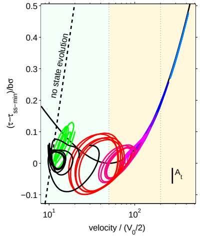
Conclusions 1

- Simulations exhibit many small events as well as periodic large events
- Large events propagate steadily "along strike" with the strip model
- Stress drops controlled by ability to propagate long distances along strike
  - Understood with an energy balance approach
- Tidal forcing results in a gradual modulation of the slip rate behind the propagating front
- Difficult to match the observed stress drops and tidal modulation with the slip law
- Heterogeneity in moment rate smaller than in observed events
- Back-propagating fronts arise
  - Can understand their maximum and propagation velocities with an energy balance approach
  - Propagate too slowly to match the observed fronts

Conclusions 2: Shortcomings of the model

Can we throw out this constitutive law as an explanation for slow slip?

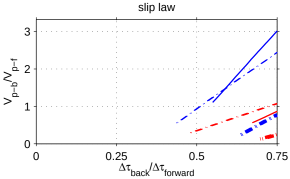
Problem 1: Matching amplitude of modulation and stress drops



Modulation depends strongly on steady state stress: choose a different curve?

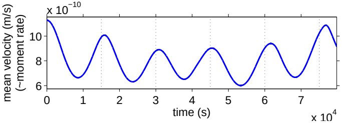
- Probably acceptable for experiments
- This curve has theoretical support
- A flatter curve could mean large changes in propagation velocity

Problem 2: Lack of large variation in moment rate, slow back-propagating fronts

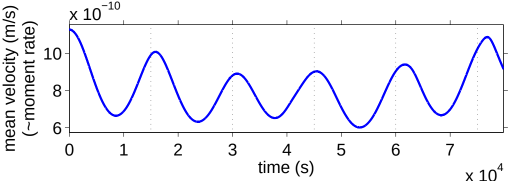


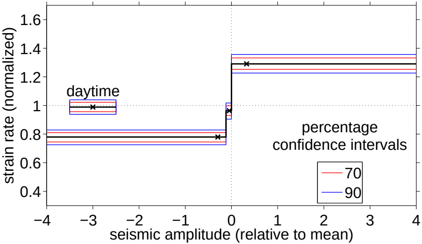
Include heterogeneity in friction parameters, normal stress?

- Need to preserve constant along-strike propagation
- Would likely influence tidal modulation
- Fast back-propagating fronts require stress drops comparable to the overall stress drop



Matching heterogeneity



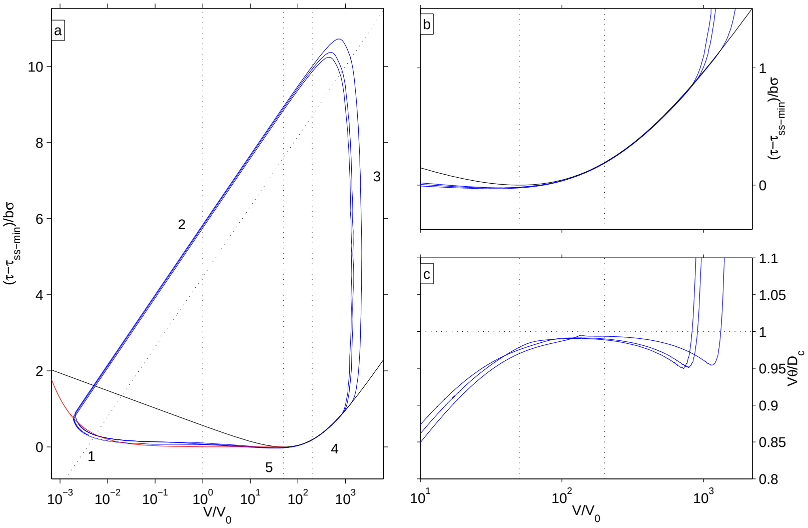


Models don't have enough variability on non-tidal timescales.

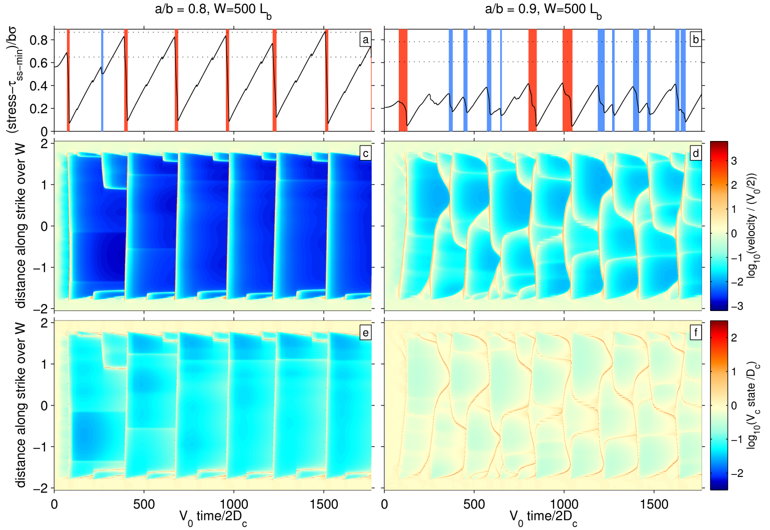
- Need heterogeneity?
- Or the friction law is incorrect?

- at least $\pm$ 30% variation in moment rate at a range of periods shorter than 4 hours
- from correlations between tremor and strain rate

Evolution of stress and velocity



Evolution of stress and velocity



Effect of a tidal forcing

- More modulation in shallower portions of the steady state curve, at lower slip rates
- More modulation when there is enough slip in each period for state evolution, at higher slip rates