Friction Law and Leve Matter in Dynamic Ruptures of Earthquake Gates

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The New York Times

'Scarier' Than Hurricane Maria: A Deadly Earthquake Terrifies Puerto Rico

The state of chaos that followed t
Ricans of any belief that their lea
natural disaster.

By Edmy Ayala, Patricia Mazzei, Frances

Jan. 7, 2020

On Tuesday, FEMA said it was in contact with island officials and was considering the governor's request for an emergency declaration.

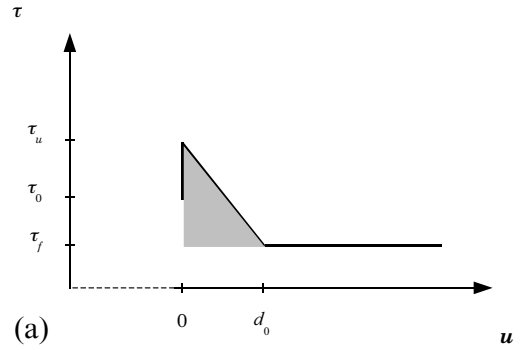
"This is more nerve-racking than Maria because for Maria we were warned, and we were aware of what a hurricane coming through Puerto Rico would be like," said Harold Rosario, a spokesman for the mayor of Guánica. "But Puerto Rico has never experienced an earthquake this big. You never know when the ground will start shaking again, and if it does you don't know if it will be a big earthquake or a small one."

Outline

- Background: Bizzarri et al. (2001 GJI); Cocco & Bizzarri (2002 GRL)
- Friction laws in single-event dynamic ruptures of nonplanar faults: Ryan and Oglesby (2014 JGR); Luo and Duan (2018 JGR)
- Friction laws in multicycle dynamics of EQ gates: Duan et al (2019, Tectonics); Liu and Duan (2019 AGU)
- Concluding Remarks

Background: SW vs. RSF laws

- Slip-weakening friction law (SW)



- Rate- & state-dependent friction laws (RSF)

$$\tau = \left[\mu_* - a\ln\left(\frac{v_*}{v}+1\right) + b\ln\left(\frac{\Phi v_*}{L}+1\right)\right]\sigma_n^{\text{eff}},$$

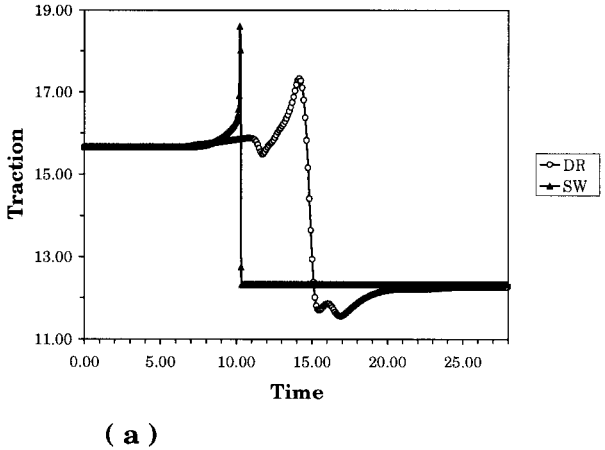
- Others

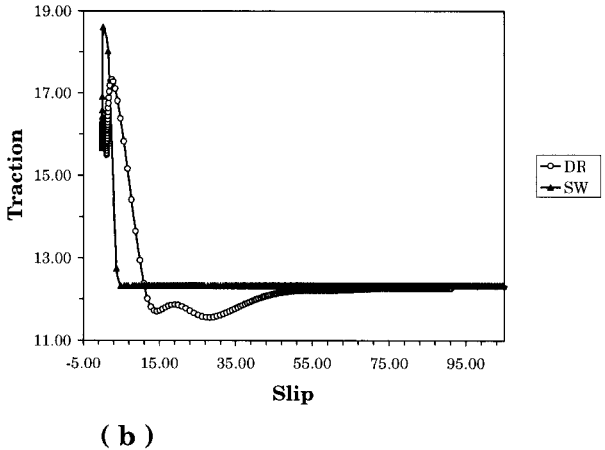
$$\frac{d}{dt}\Phi = 1 - \frac{\Phi v}{L},$$

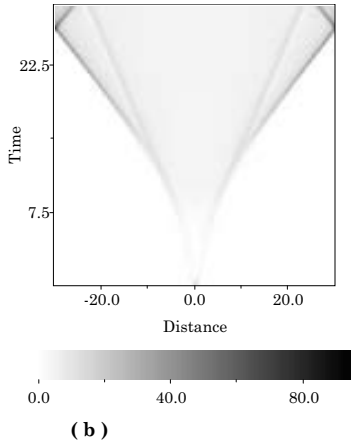
Bizzarri et al (2001)

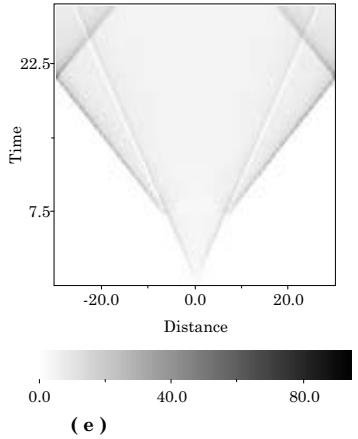
Background: Equivalence of SW & RSF on Planar Faults

- Spatial & temporal evolution of slip rate: 2D model
- Time histories of fault quantities







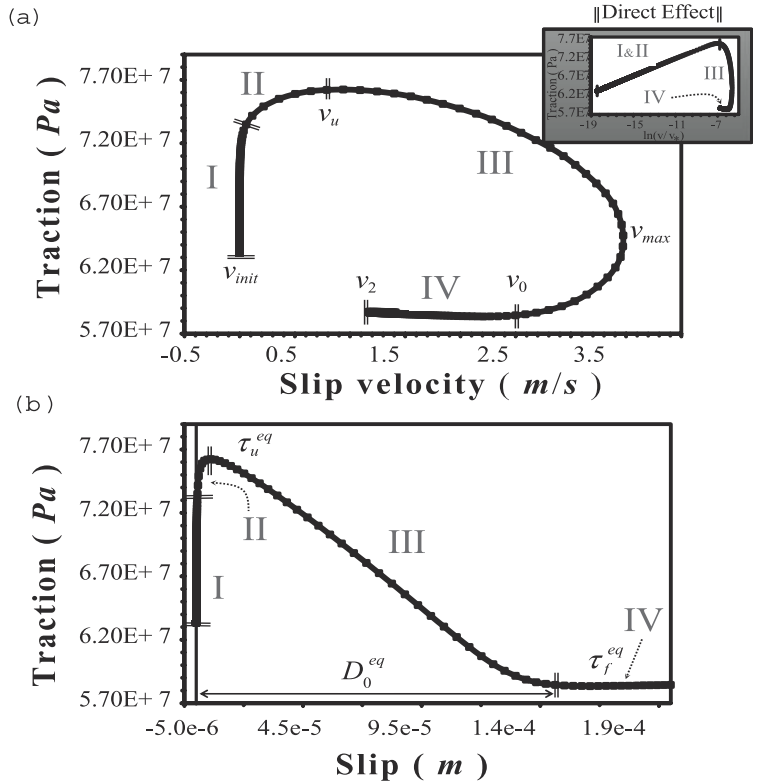


Bizzarri et al (2001)

Background: Slip-weakening behavior of RSF

- Several phases
- Slip-weakening curve:
  - equivalent D0
  - Scaling between D0 and L

$$D_0^{eq} = L \ln\left(\frac{V_0}{V_i}\right) \approx \frac{\tau_u^{eq} - \tau_f^{eq}}{b\sigma_n} L$$

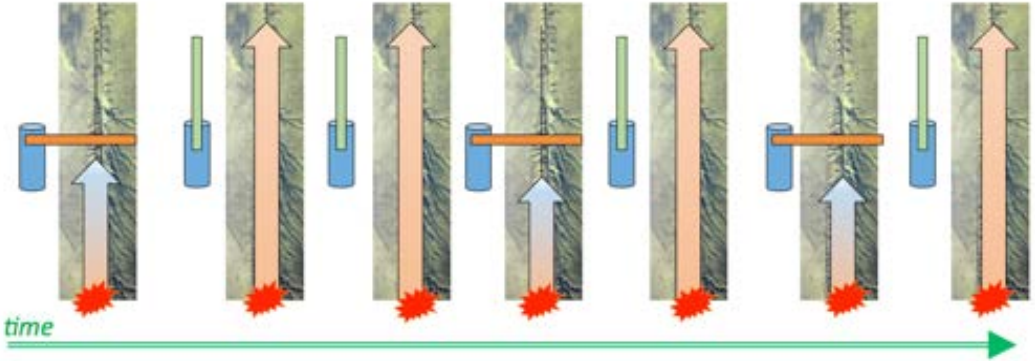


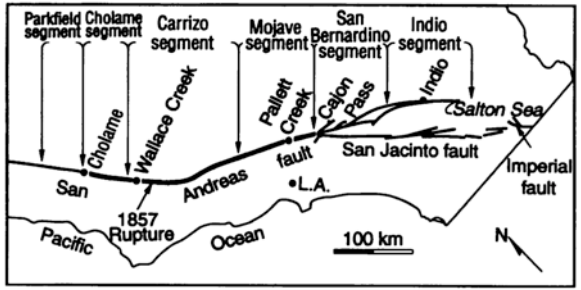
Cocco & Bizzarri (2002)

Background: Non-planar Faults – EQ gates

- Mostly, dynamic models use SW law.
- **Will different friction laws result in different rupture behaviors on non-planar faults? – Main theme of this talk**.
- Earthquake (EQ) gates: at fault geometrical complexities

  Open (rupture breaks through) or close (rupture stops)





Step-over faults & friction laws: Ryan & Oglesby (2014)

- Models: 2-D with FaultMod
- Friction laws:
- Low vs high stress cases:

SW
RS–AL
RS–SL
RS–SL with SRW

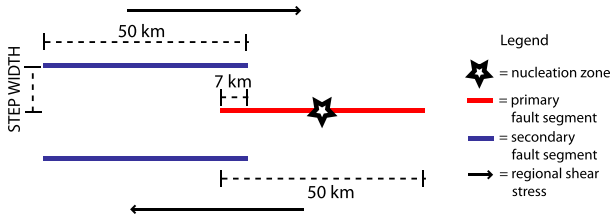


Table 2. High-Stress Models[a]

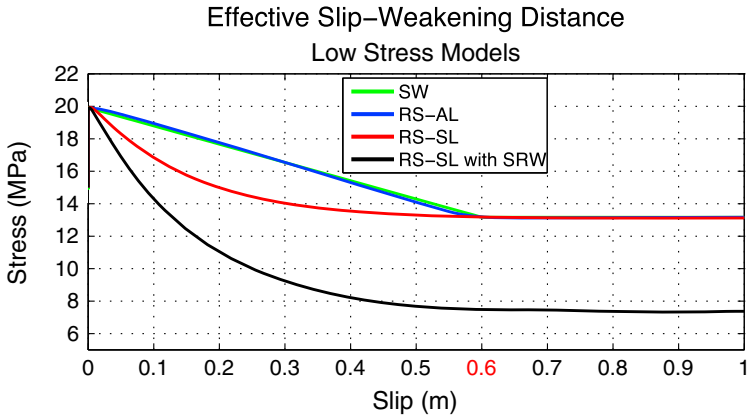
	Values
τ_o	75.00 MPa
σ_o	120.0 MPa
τ_o (nucleation zone)	100.0 MPa
Density	2670 kg/m^3
S wave speed	3464 m/s
P wave speed	6000 m/s
Nucleation radius	600.0 m
Nucleation speed	1750 m/s
Element size	50.00 m

Table 1. Low-Stress Models[a]

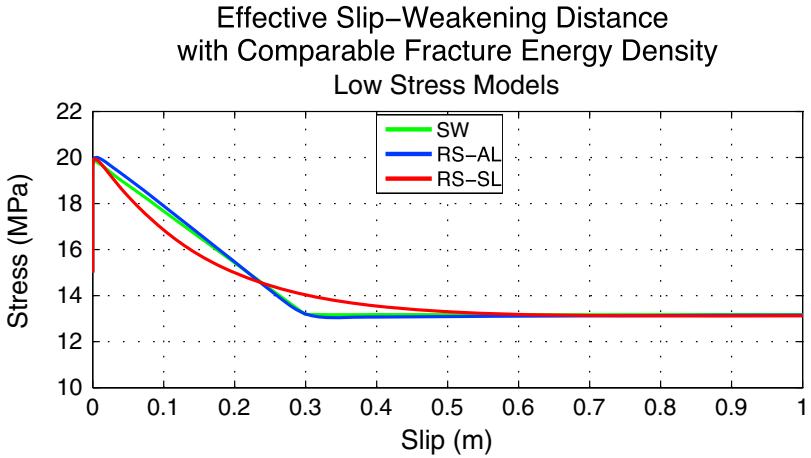
	Values
τ_o	15.00 MPa
σ_o	24.00 MPa
τ_o (nucleation zone)	20.00 MPa
Density	2670 kg/m^3
S wave speed	3464 m/s
P wave speed	6000 m/s
Nucleation radius	3000 m
Nucleation speed	1750 m/s
Element size	100.0 m
V_{ini}	1.000E−12 m/s
V_o	1.000E−6 m/s
a	0.008000
b	0.01200
L (aging law)	0.02330 m
L (slip law)	0.1505 m
μ_o	0.6000
μ_{lv}	0.6000
μ_w	0.3000
V_w	0.1000 m/s
μ_{static}	0.8299
$\mu_{dynamic}$	0.5487
d_0	≈0.3–0.6 m

Make friction laws comparable

- Similar d0



- Similar fracture energy: no SRW here

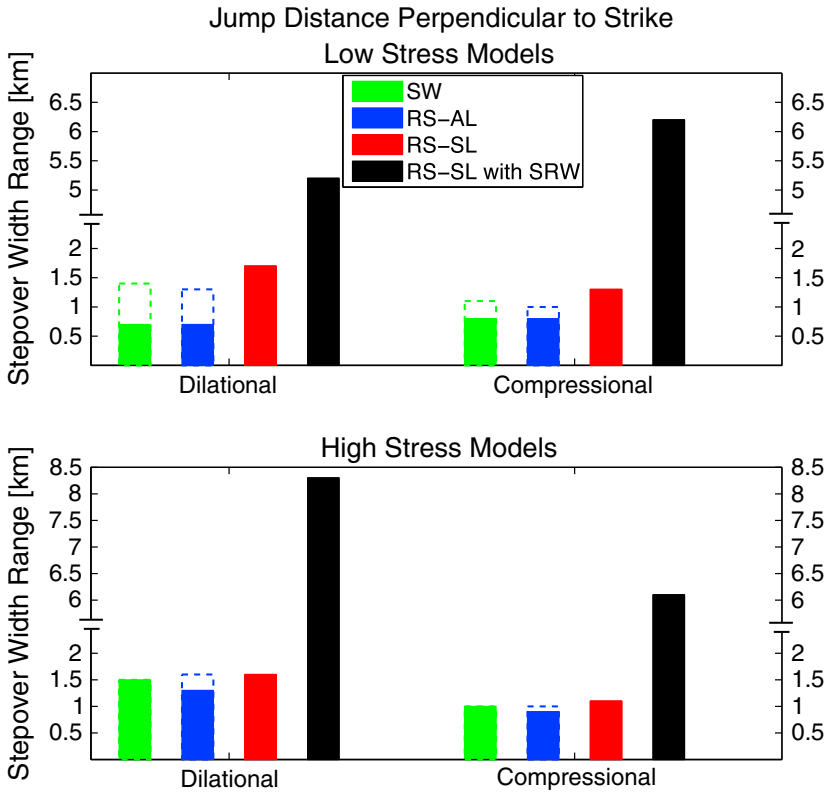


Ryan & Oglesby (2014)

Compare Max Jump Distance w/ Different Laws

- Solid – similar d0 case: friction laws matter
- Dashed – similar fracture energy case: not much (excluding SRW)
- Low stress (more significant) vs high stress (less obvious) cases.
- **Friction laws matter a lot under similar d0 & low-stress situation, particular SRW law.**

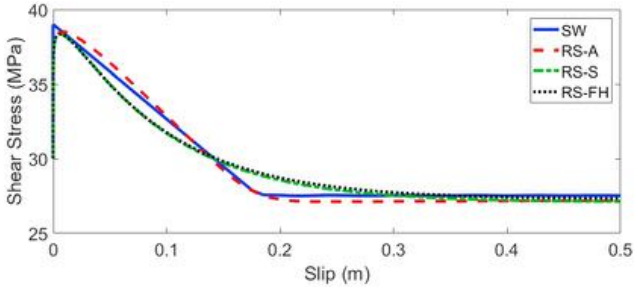
Ryan & Oglesby (2014)

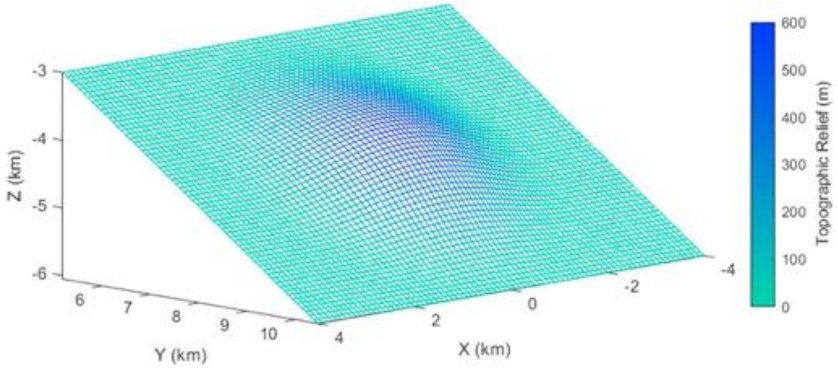


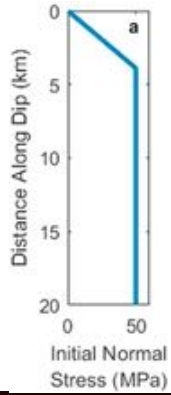
Non-planar faults & Friction Laws: Luo and Duan (2018)

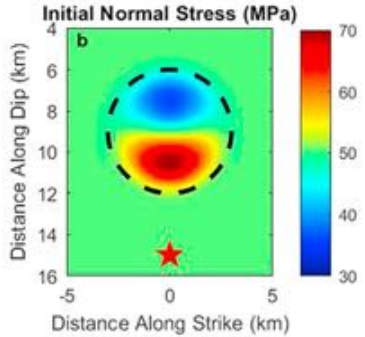
- A bump on a thrust fault
- Initial fault stress from principal stresses
- Various friction laws:

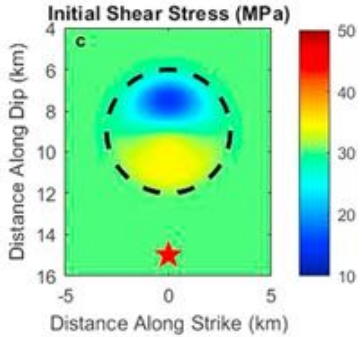
  comparable fracture energy





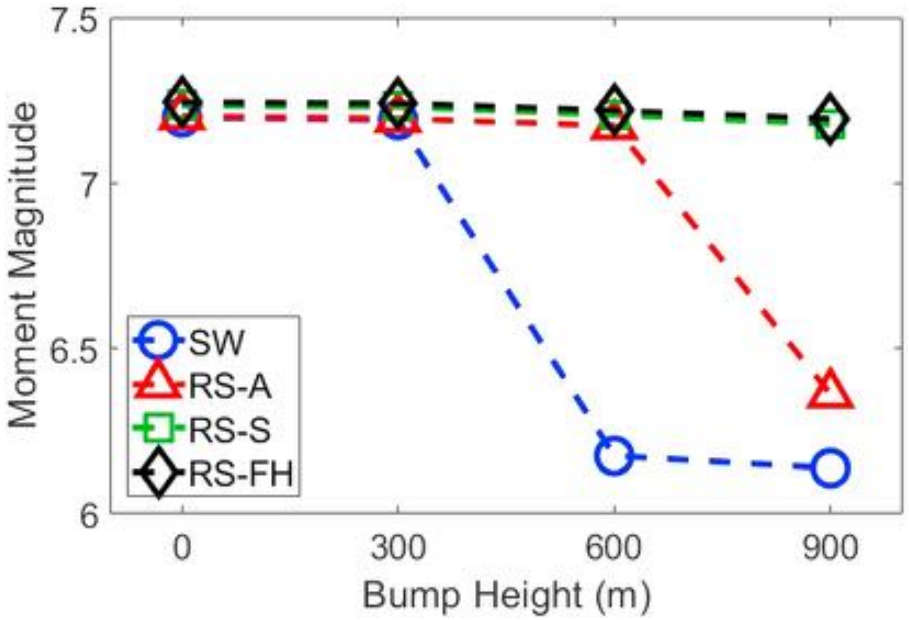






Friction law effects w/ various bump heights

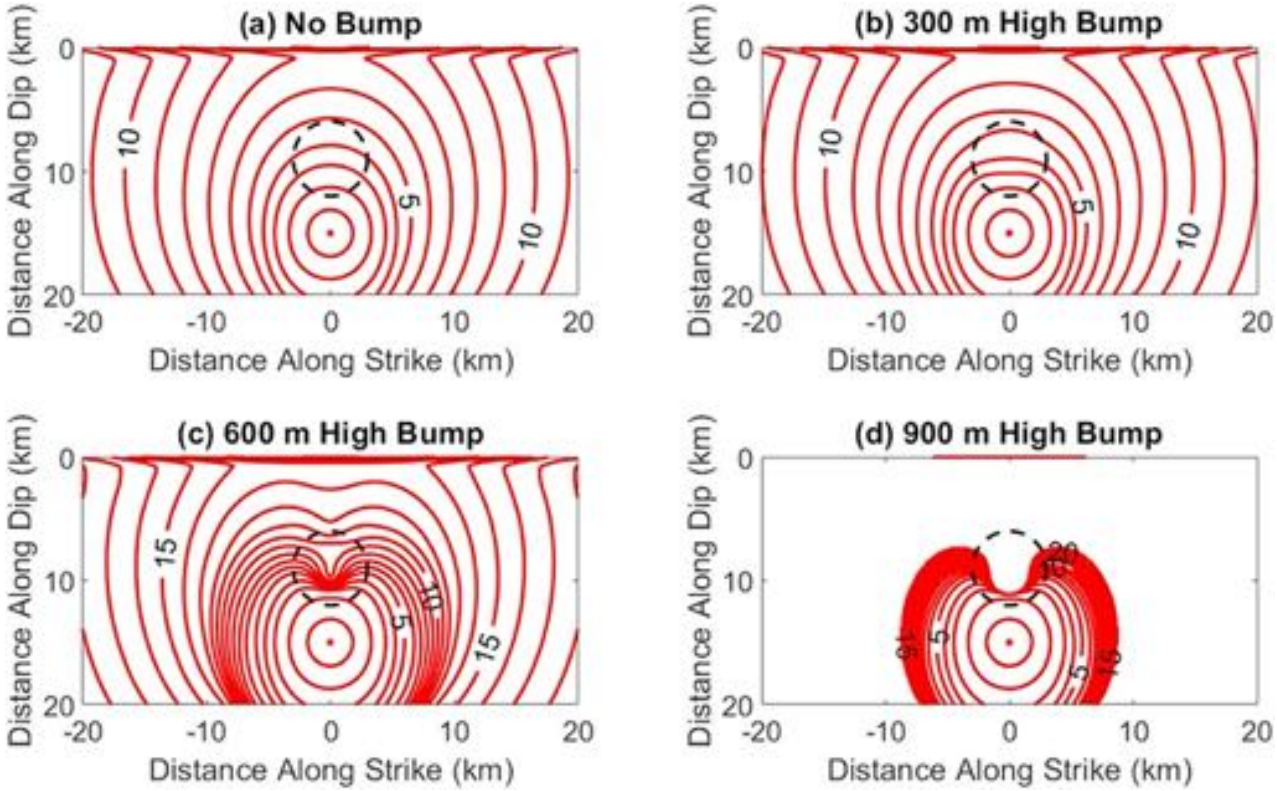
- Friction laws matter a lot for high bumps: rupture stops or not
  - Rupture w/ SW stops starting from 600 m height
  - Rupture w/ RS-A stops by 900 m height
  - Rupture does not stop w/ RS-S & RS-FH up to 900 m height
  - Why?



Luo & Duan (2018)

With a basal diameter of 6 km

rupture time contours of dynamic rupture simulations governed by the RS-A law



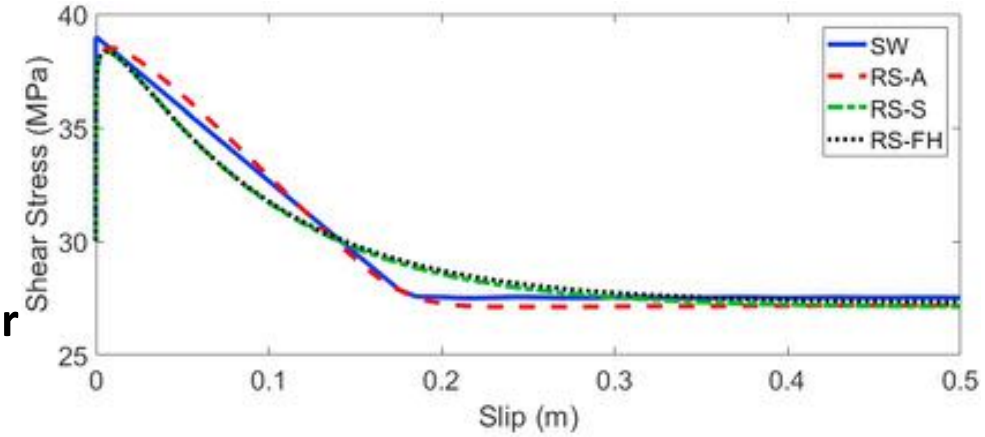
Luo & Duan (2018)

Why are the above effects?

- Yield stress in RSF vs. SW
- Differences in functional forms of laws in slip-weakening curve: two groups
  - Linear weakening:
    SW, RSF-A
  - Exponential weakening:
    RSF-S, RSF-FH

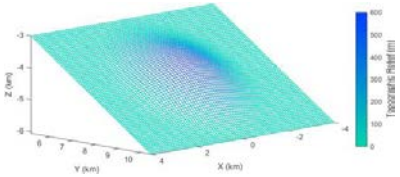
  Steeper initial slope =>

  energy release faster and earlier
- Dynamic friction in RSF



Luo & Duan (2018)

- Yield stress in SW vs. RSF: rupture stop or not



– SW:

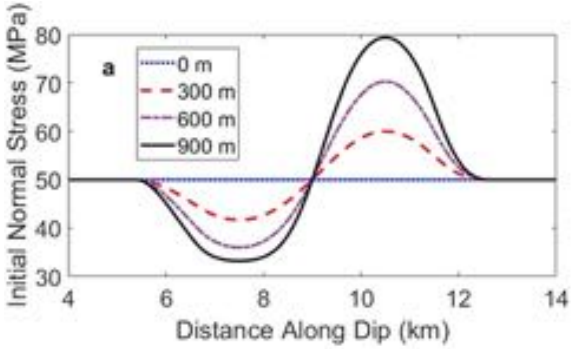
~ directly

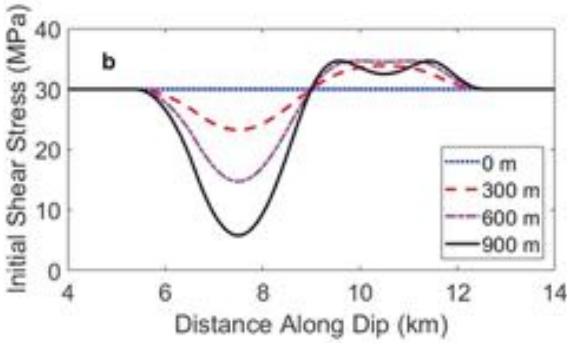
normal stress

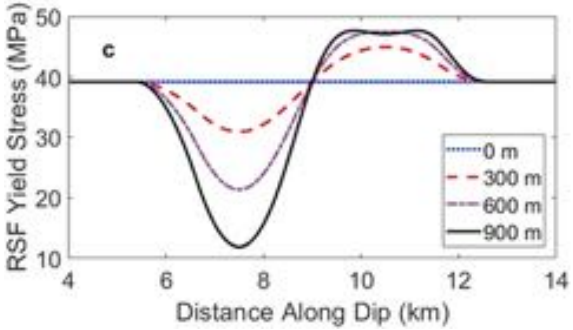
$$\tau_u = \mu_s \sigma_n .$$

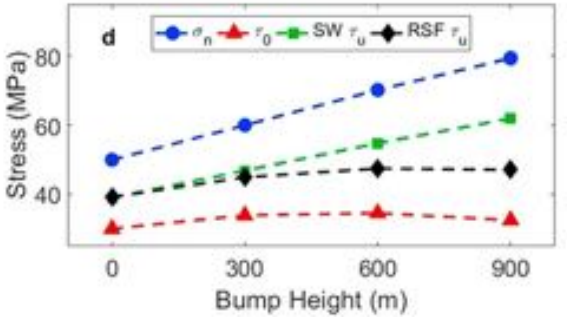
– RSF: ~ shear stress

$$\tau_u = \tau_0 + \Delta\tau \approx \tau_0 + a\sigma_n \ln \frac{V_{dyn}}{V_{ini}}$$









Luo & Duan (2018)

- Dynamic friction in SW vs. RSF:
  - SW: constant
  - RSF:
    - ✓lower at front
    - ✓Higher behind (healing)

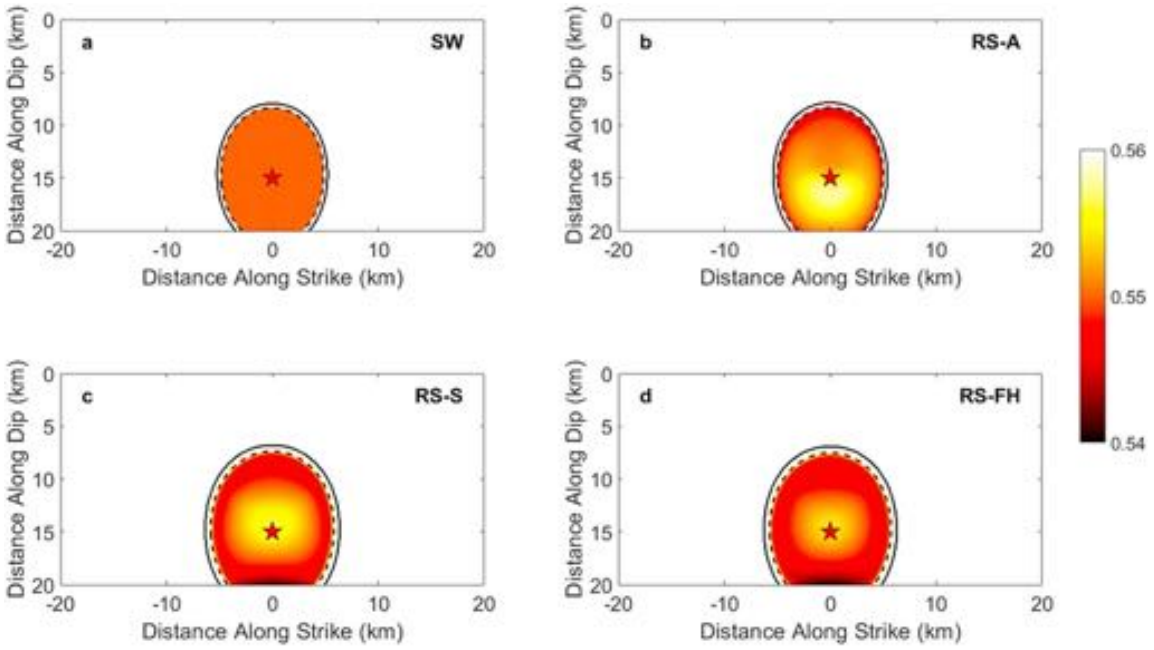
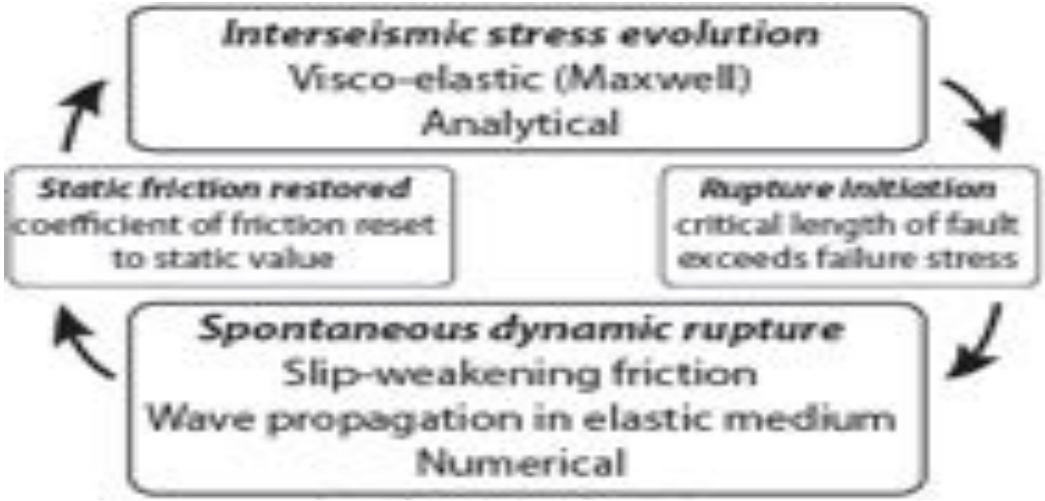


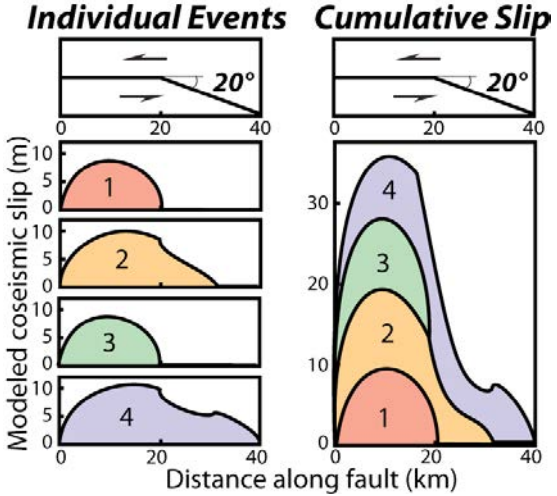
Figure 5. Spatial distributions of the dynamic friction coefficient in various friction laws at 4 s. The solid and dashed lines denote the leading and trailing edges of the propagating rupture front, respectively. The area within the dashed line has

Luo & Duan (2018)

Friction law effects on multicycle dynamics of EQ gates:
Duan et al. (2019)

- A 2D multicycle dynamic model

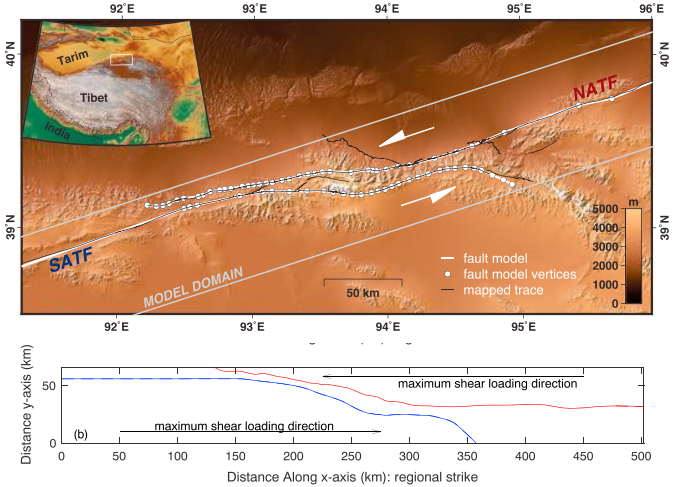


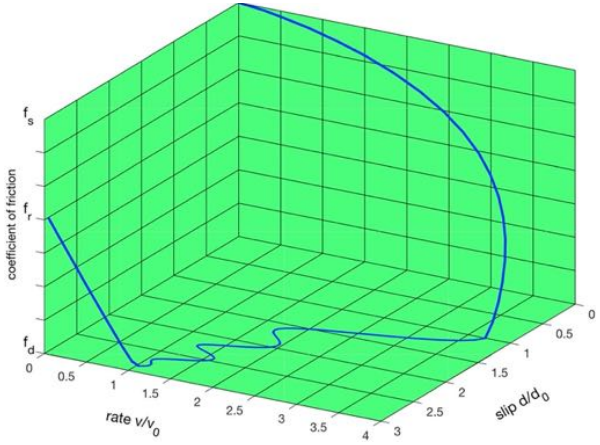


Duan & Oglesby (2005, JGR)

Aksay Bend along the Altyn Tagh Fault (ATF)

- A double restraining bend: 2 strands overlap ~200 km long
- As an EQ gate: Can it be open (rupture through)? How often?
- Slip-weakening law vs. **slip- & rate-weakening law (w/ healing)**



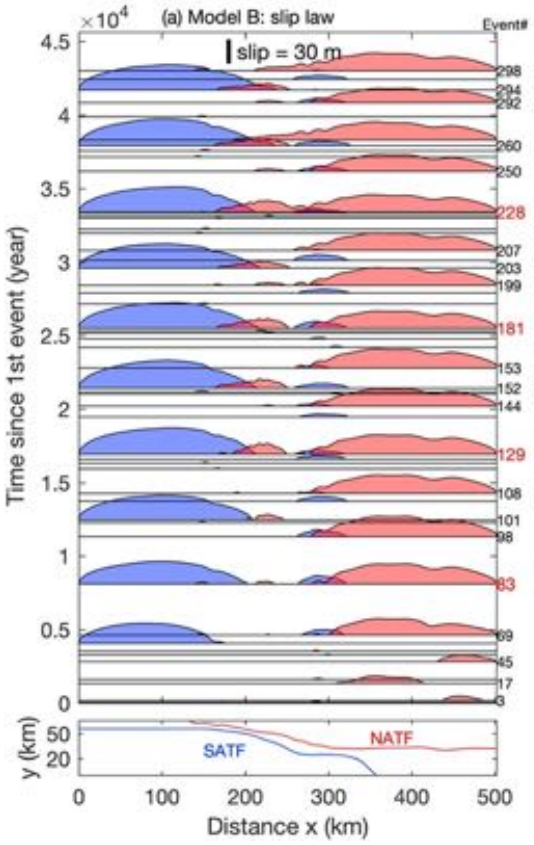


Duan et al (2019)

Slip-weakening vs Slip-&Rate-weakening

- Slip-weakening: no healing ~ larger jumping probability

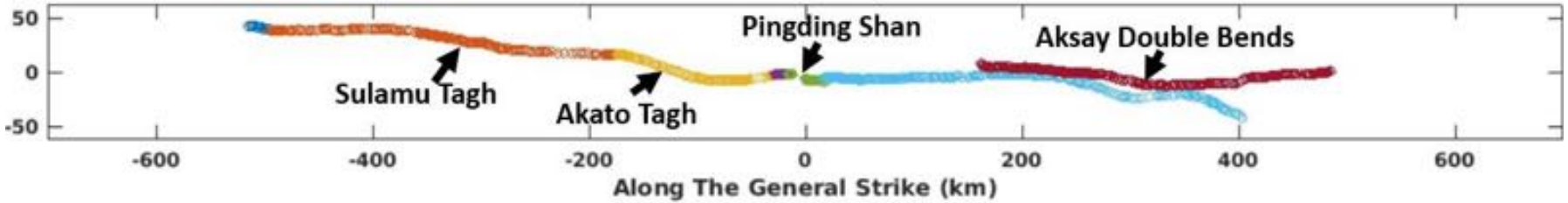
Model/parameters, results	Friction law	# of jumping events	# of large and jumping events	% of jumping events
A	Slip and rate	5	63	7.94
B	Slip only	4	19	21.05



Duan et al (2019)

Multiple EQ gates along ATF: Liu & Duan, 2019 AGU

- Friction level matters:
  - ✓High static friction 0.7: occasionally super-large ruptures (open of multiple EQ gates)
  - ✓Low static friction 0.3: many super-large ruptures
  - ✓**low static friction effectively diminishes geometrical effects ~ EQ gates open easily, but may not be real (too many super-large events)!**



Concluding Remarks

- **Equivalence** of friction laws in single-event dynamic ruptures of planar faults **may not hold for geometrically complex faults**.
- **Equivalent slip-weakening distance** w/ different fracture energy could result in **different jump width for stepover faults**.
- Even with comparable fracture energy, different yield stress evolution, different slip-weakening slope & dynamic friction could result in **different barrier effects of non-planarity**.
- **Over multiple earthquake cycles**, friction laws **can obviously affect EQ gate behavior**.
- **Low static friction effectively diminishes geometrical effects**, making ruptures on geometrically complex faults much easier, which **may be unrealistic**.

Thank You !