Dynamic Modeling: Friction and Stepovers

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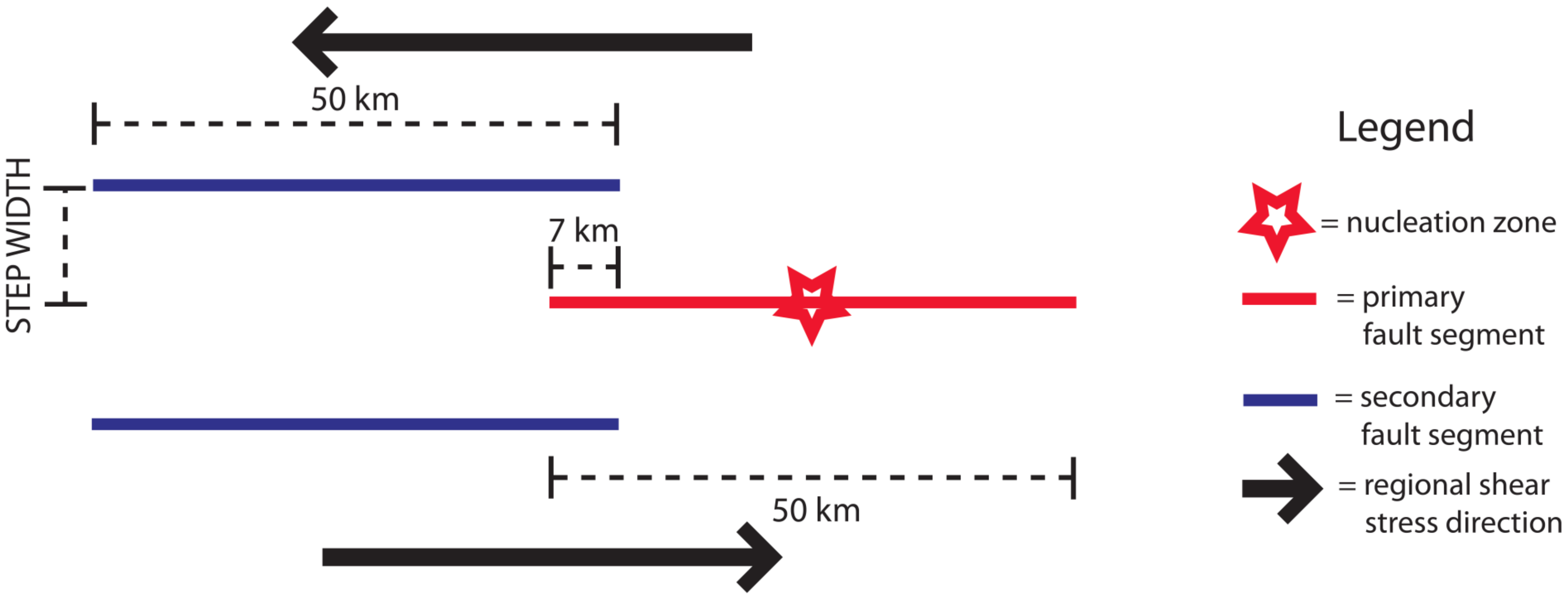
Cartoon Geometry



- 2-D models using dynamic finite element code FaultMod (Barall, 2008, 2009)
- Position of secondary fault segment signifies whether the system is compressional (top) or dilational (bottom)
- Stepover width is variable
- For any given simulation, only one secondary (blue) fault is present

Friction Equations

- Slip-Weakening: $$\mu = \begin{cases} \frac{\mu_{dynamic} - \mu_{static}}{d_o} d\delta + \mu_{static}, & d\delta < d_o \\ \mu_{dynamic}, & d\delta \geq d_o \end{cases}$$

- Rate-State: $$\mu = \operatorname{arcsin} h\left[\frac{V}{2V_o}\exp\left(\frac{\mu_o + \psi}{a}\right)\right] \approx \mu_o + a\ln\left(\frac{V}{V_o}\right) + \psi \qquad \psi = b\ln\left(\frac{\theta}{\theta_o}\right)$$

- Ageing Law: $$\frac{d\psi}{dt} = \frac{-bV_o}{L}\left(\exp\left(\frac{-\psi_{ss}}{V}\right) - \exp\left(\frac{-\psi}{b}\right)\right) \qquad \frac{d\theta}{dt} = \frac{-1}{\theta_{ss}}\left(\theta - \theta_{ss}\right)$$

- Slip Law: $$\frac{d\psi}{dt} = \frac{-V}{L}\left(\psi - \psi_{ss}\right)$$

- Steady State: $$\psi_{ss} = -b\ln\left(\frac{V}{V_o}\right)$$

***Slip-weakening formula from Ida (1972). Formulas for rate-state friction shown are contained within Barall (2008, 2009) and references therein.**

Friction Equations

- Strong Rate-Weakening variation of Slip Law:

$$\frac{d\psi}{dt} = \frac{-V}{L}(\psi - \psi_{ss})$$

- Steady State:

$$\psi_{ss} = a\ln\left(\frac{2V_o}{V}\sinh\left(\frac{\mu_{ss}(V)}{a}\right)\right)$$

$$\mu_{ss}(V) = \mu_w + \left(\mu_{lv}(V) - \mu_w\right)\left(1 + \left(\frac{V}{V_w}\right)^{1/8}\right)^{-1/8}$$

$$\mu_{lv}(V) = \mu_s - (b-a)\ln\left(\frac{V}{V_o}\right)$$

where μ_w is the weak friction coefficient and μ_s is the strong friction coefficient

***Formulas for rate-state friction shown are contained within Barall (2008, 2009) and references therein.**

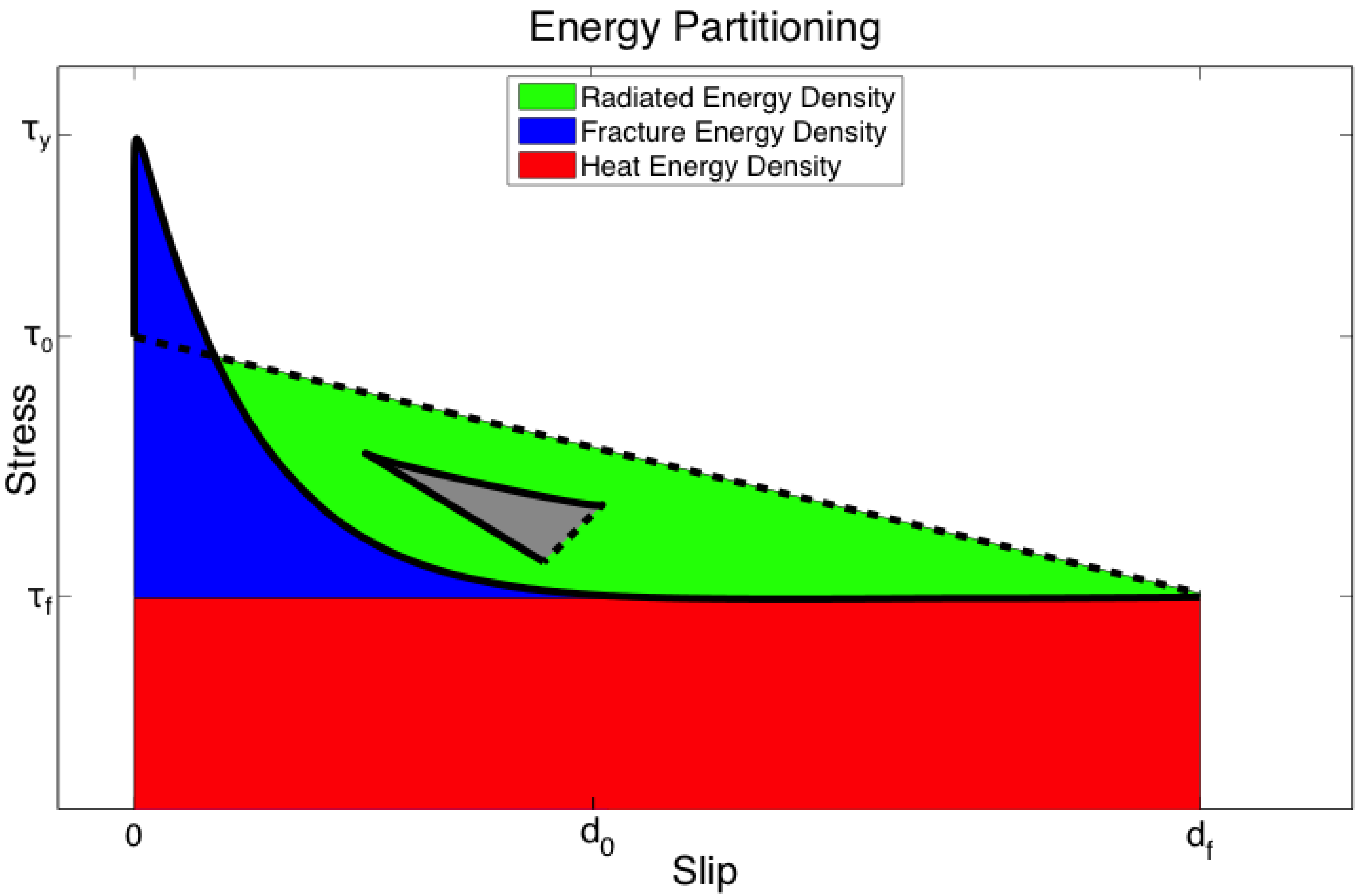
Parameters

Low Stress Models

τ_0	15 MPa
σ_0	24 MPa
τ (nucleation zone)	20 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 m
V_{ini}	1.000e-12 m/s
V_0	1.000e-6 m/s
a	0.008000
b	0.01200
L (aging law)	0.02330 m
L (slip law)	0.1505 m
μ_0	0.6000
μ_s	0.6000
μ_w	0.3000
V_w	0.1000 m/s
μ_{static}	0.8299
$\mu_{dynamic}$	0.5487
d_0	0.6 m

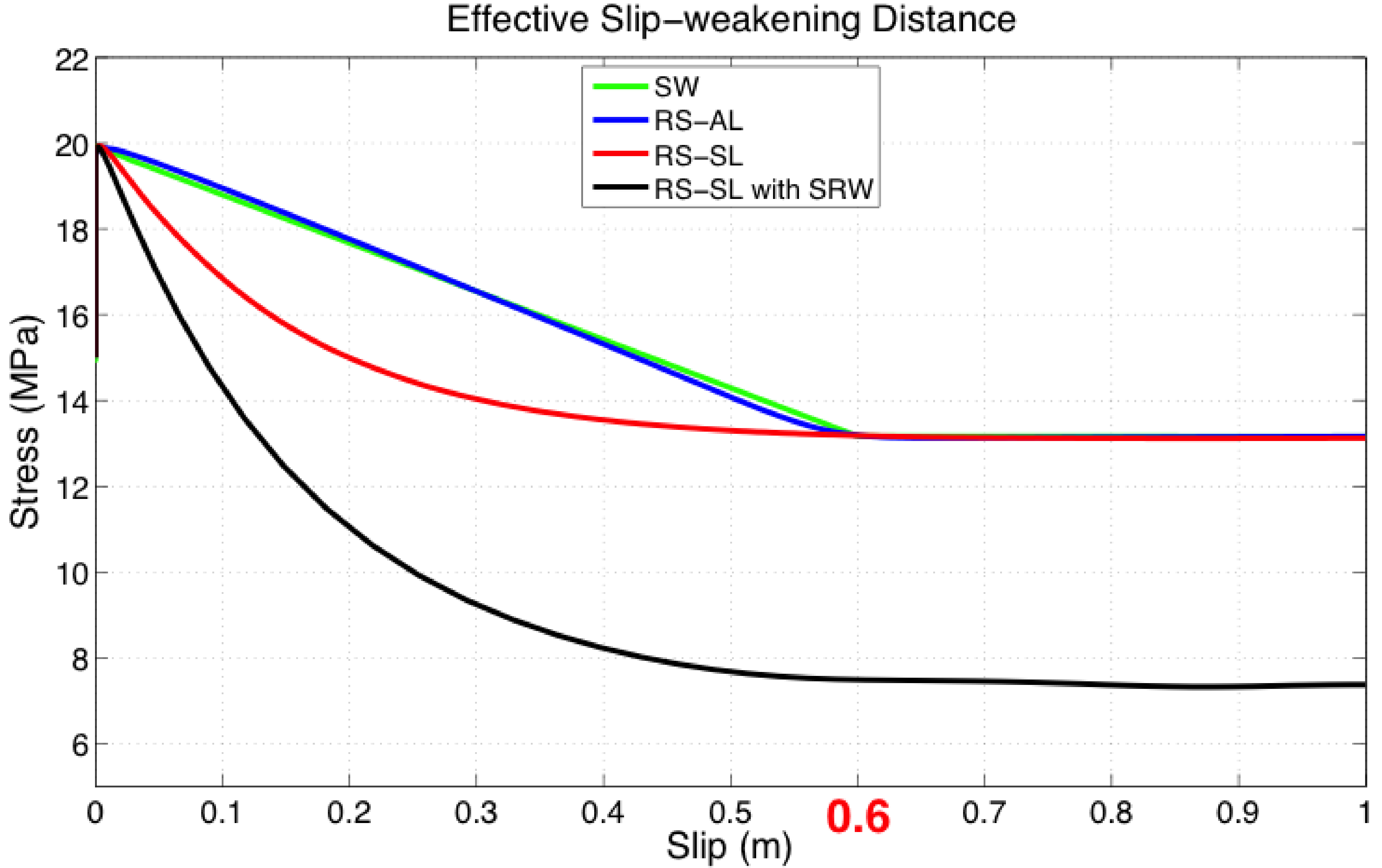
High Stress Models

τ_0	75 MPa
σ_0	120 MPa
τ (nucleation zone)	100 MPa
Density	2670 kg/m^3
S-wave speed	3464 m/s
P-wave speed	6000 m/s
Nucleation Radius	600 m
Nucleation Speed	1750 m/s
Element Size	50 m
V_{ini}	1.000e-12 m/s
V_0	1.000e-6 m/s
a	0.008000
b	0.01200
L (aging law)	0.02015 m
L (slip law)	0.1000 m
μ_0	0.6000
μ_s	0.6000
μ_w	0.3000
V_w	0.1000 m/s
μ_{static}	0.8465
$\mu_{dynamic}$	0.5340
d_0	0.6 m



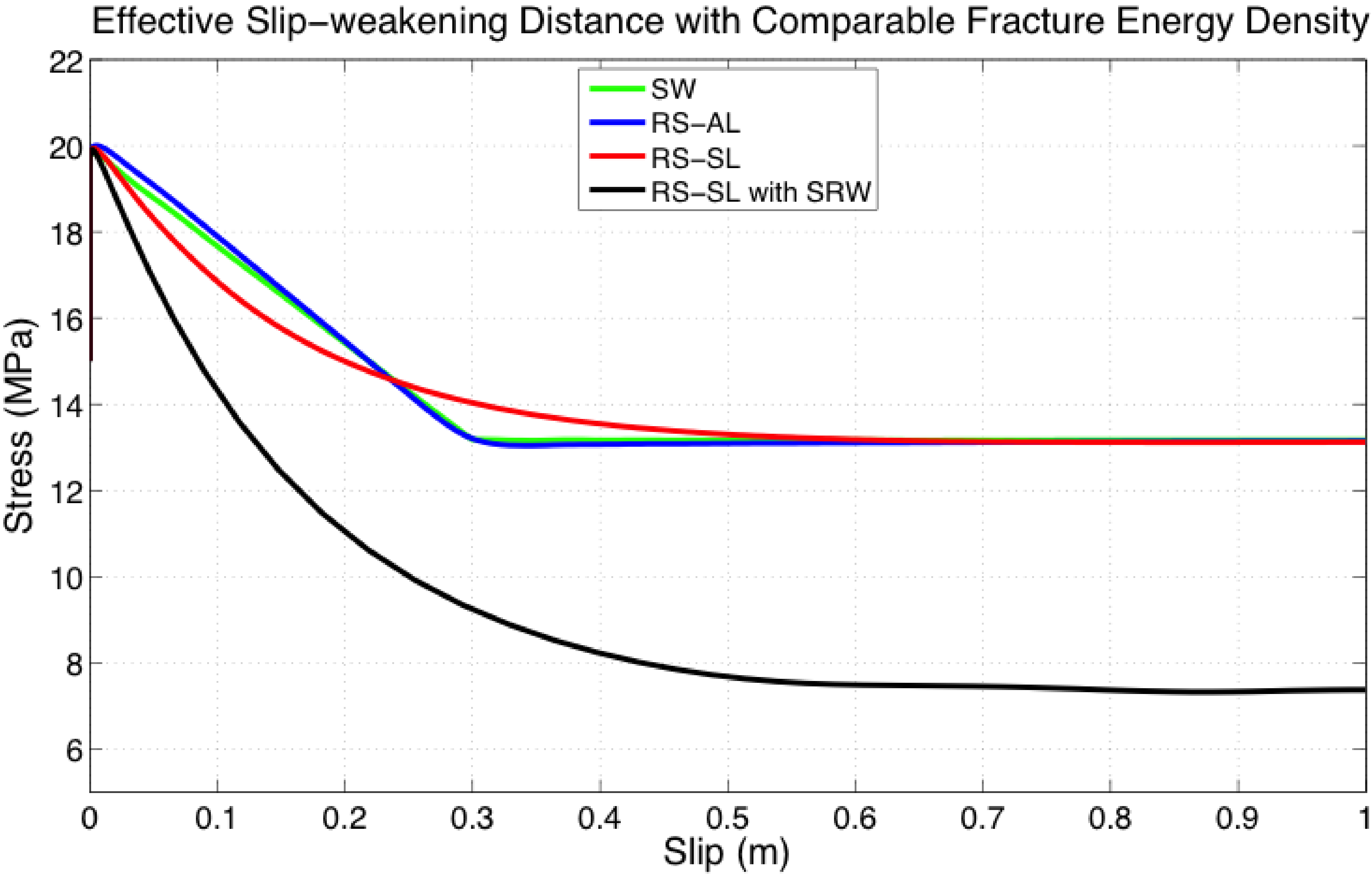
Energy Partitioning
Radiated Energy Density
Fracture Energy Density
Heat Energy Density
τ_y
τ_0
τ_f
Stress
0
d_0
d_f
Slip

Lower Stress Models



- Estimated Effective Slip-Weakening Distance = 0.6 m
- For Rate-State Formulations, we estimate it as the distance over which 98% of the stress drop occurs

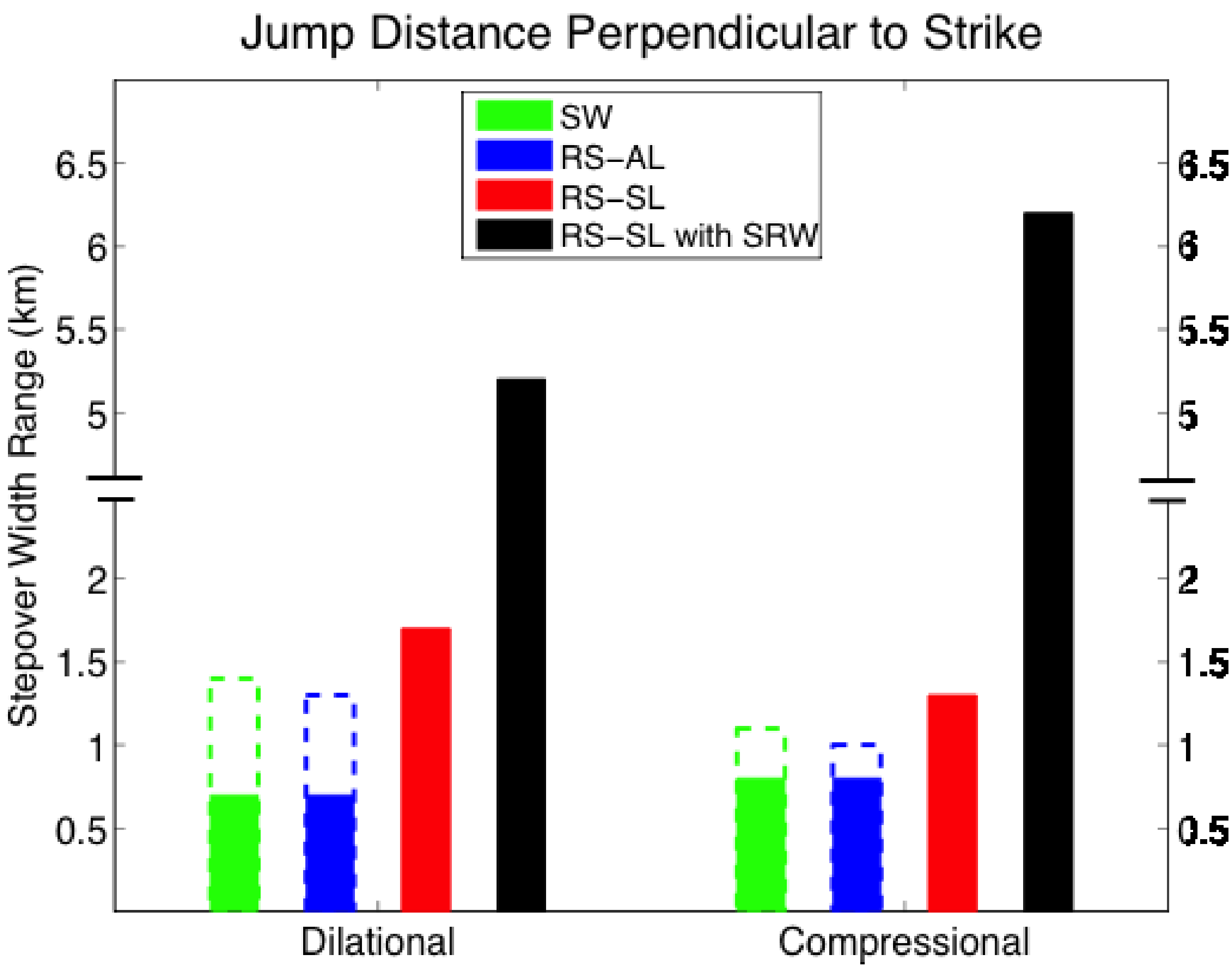
Lower Stress Models



- SW, RS-AL, and RS-SL with approximately the same fracture energy densities

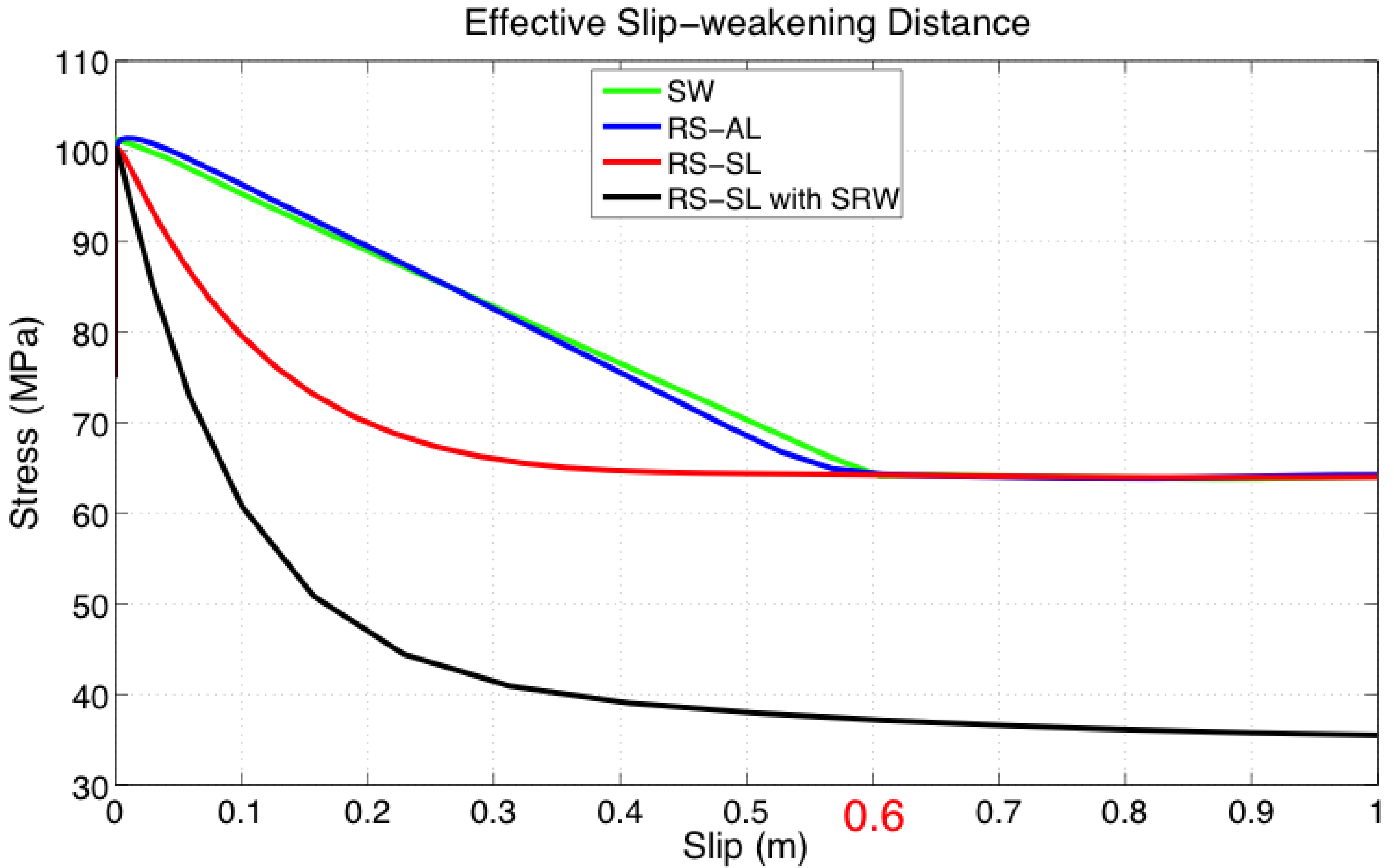
→ The Effective Slip-Weakening Distance are now different

Lower Stress Models

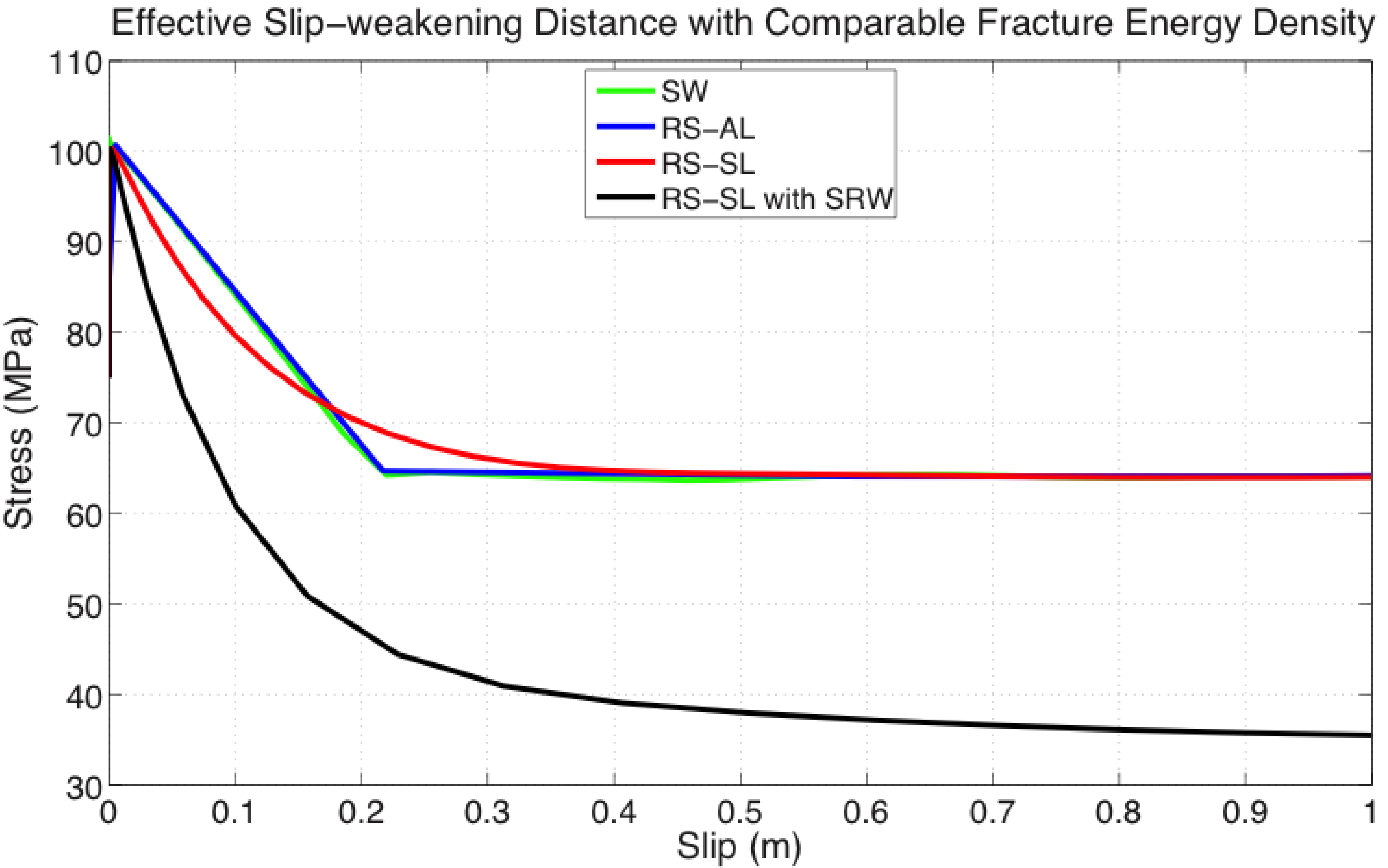


- Range of rupture jumps for low stress models
- Solid bars represent range for comparable effective slip-weakening distances
- Dashed lines denote range for comparable fracture energy densities within SW, RS-AL, and RS-SL models

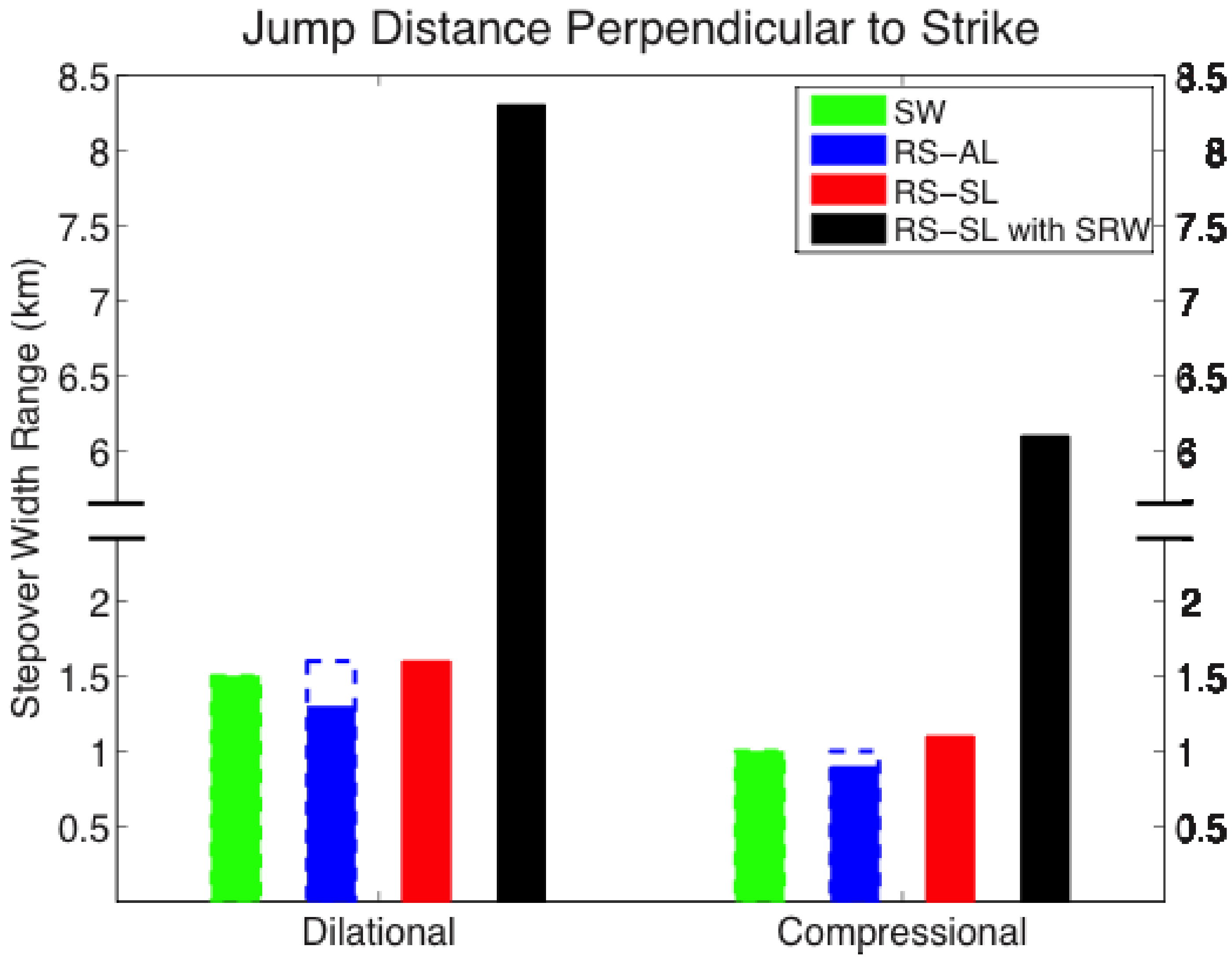
Higher Stress Models



Higher Stress Models



Higher Stress Models

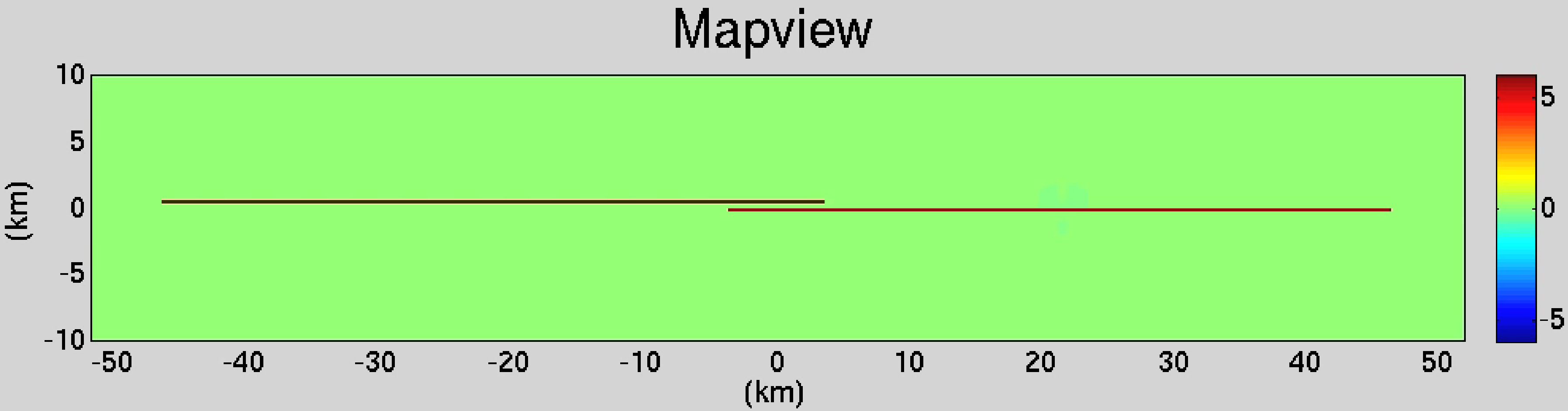


- Solid bars represent range for comparable effective slip-weakening distances
- Dashed lines denote range for comparable fracture energy densities within SW, RS-AL, and RS-SL models

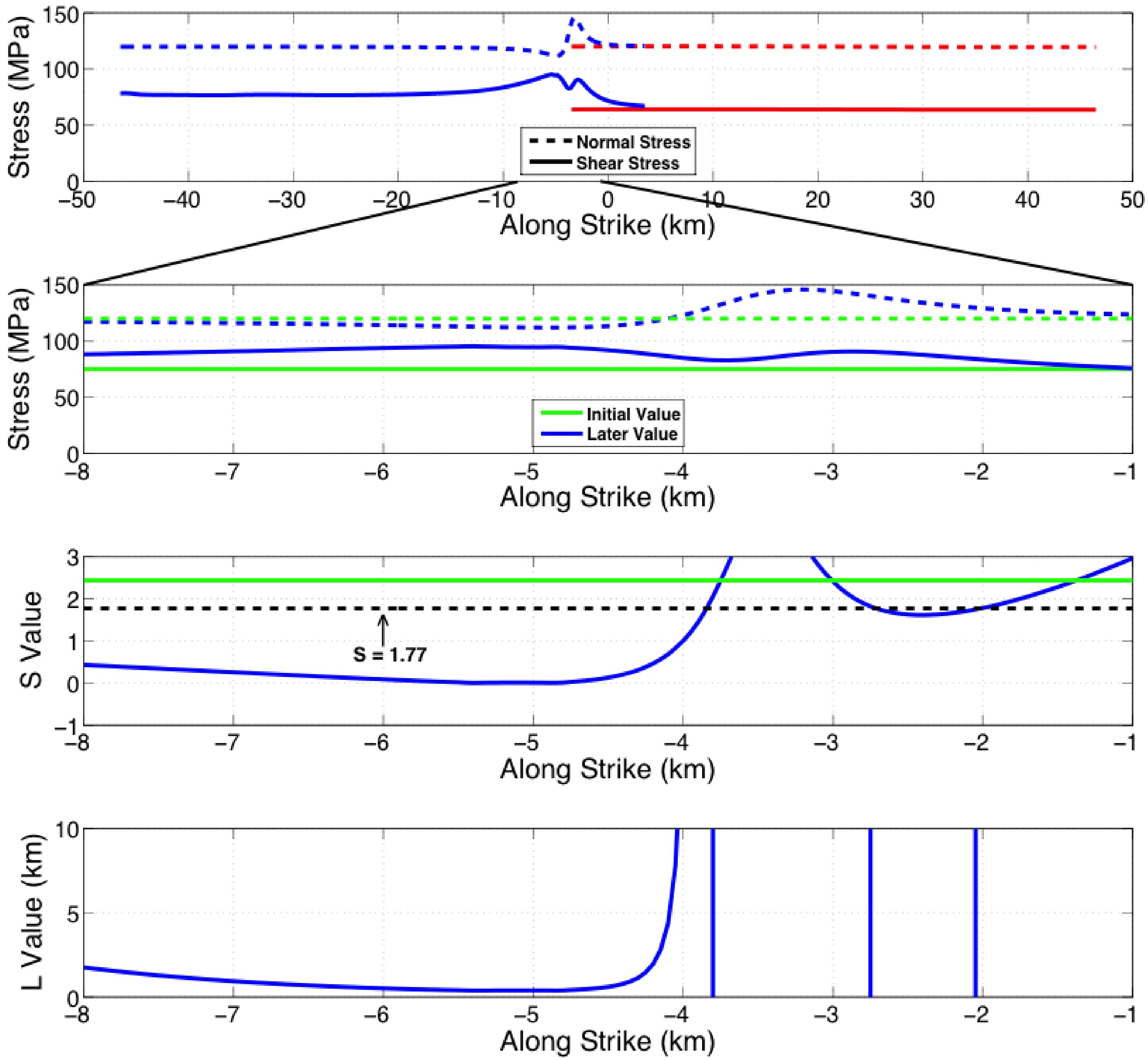
Supershear Rupture Speed on Higher Stress Models

- An S ratio of 2.4 would normally preclude supershear rupture speeds
- Rupture speed reaches supershear on secondary fault segment, after seismic energy from the primary fault segment has altered the stress field
- Occurs at some minimum stepover width for compressional systems
- Occurs for dilational systems as well, but with a less obvious pattern

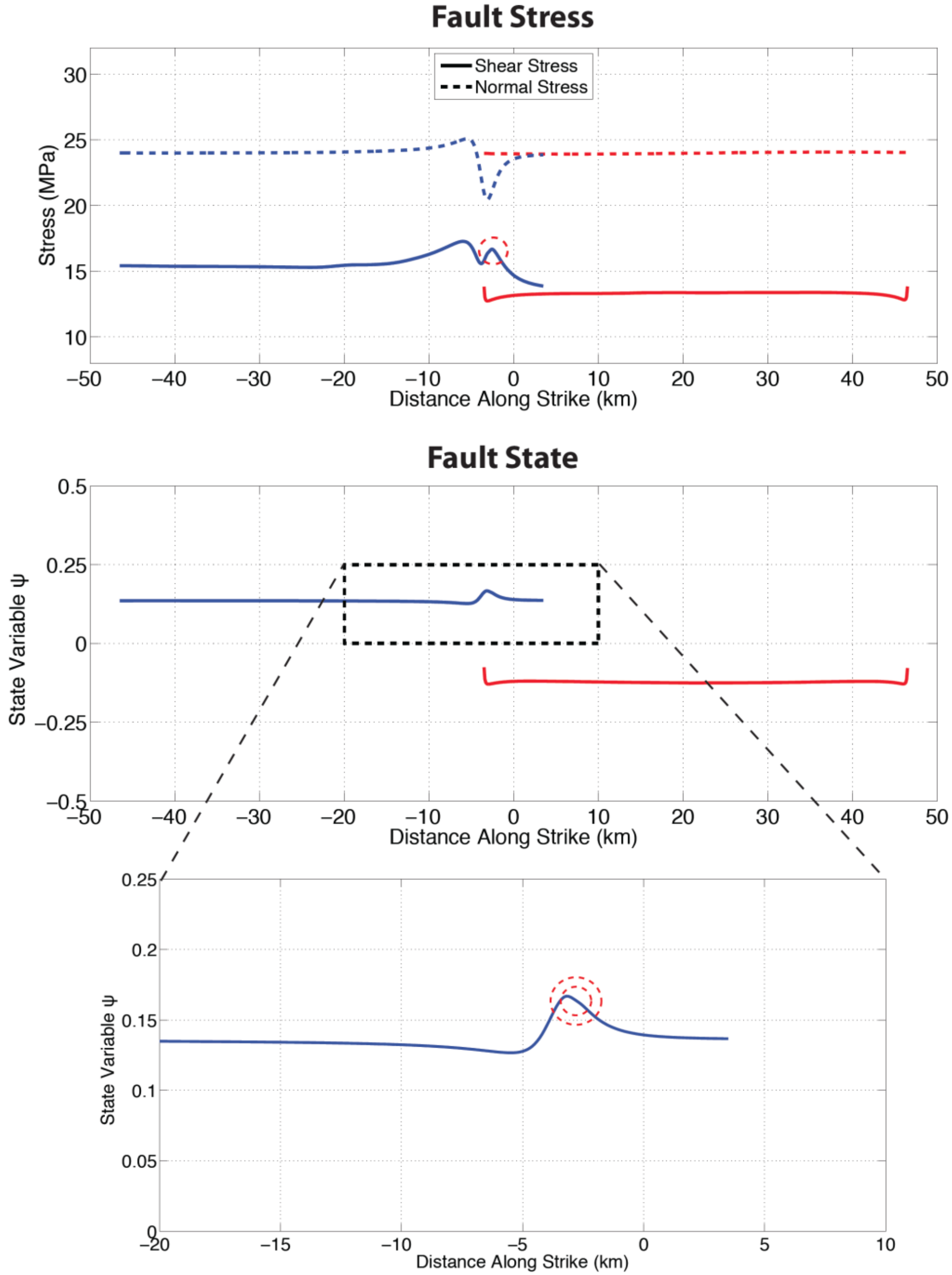
Supershear Rupture
Velocity Parallel to Strike (m/s)



Compressional 1000 meter Stepover with Slip−Weakening Friction
Immediately Before Re−nucleation



Dilational System Immediately Before Re-nucleation

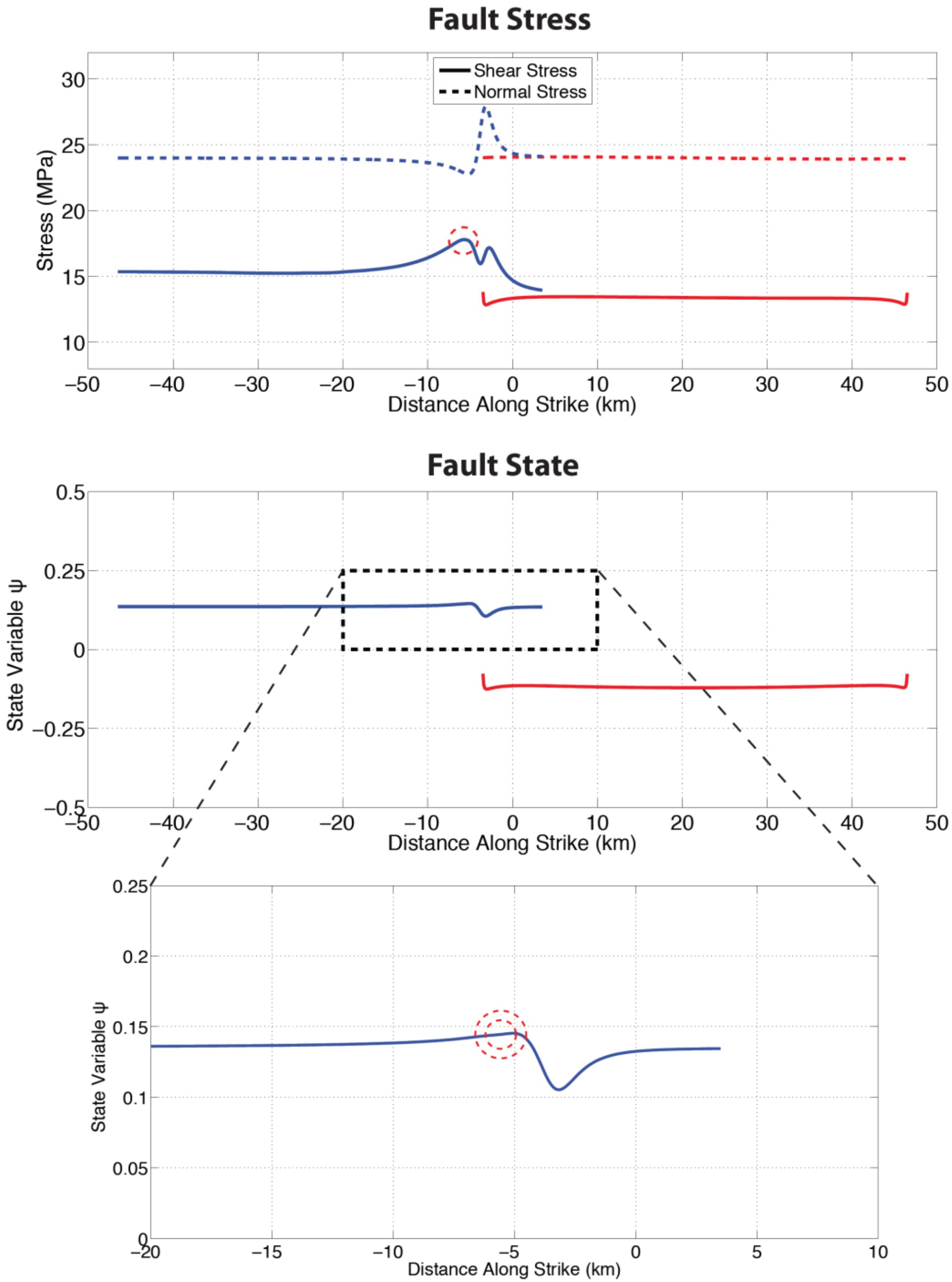


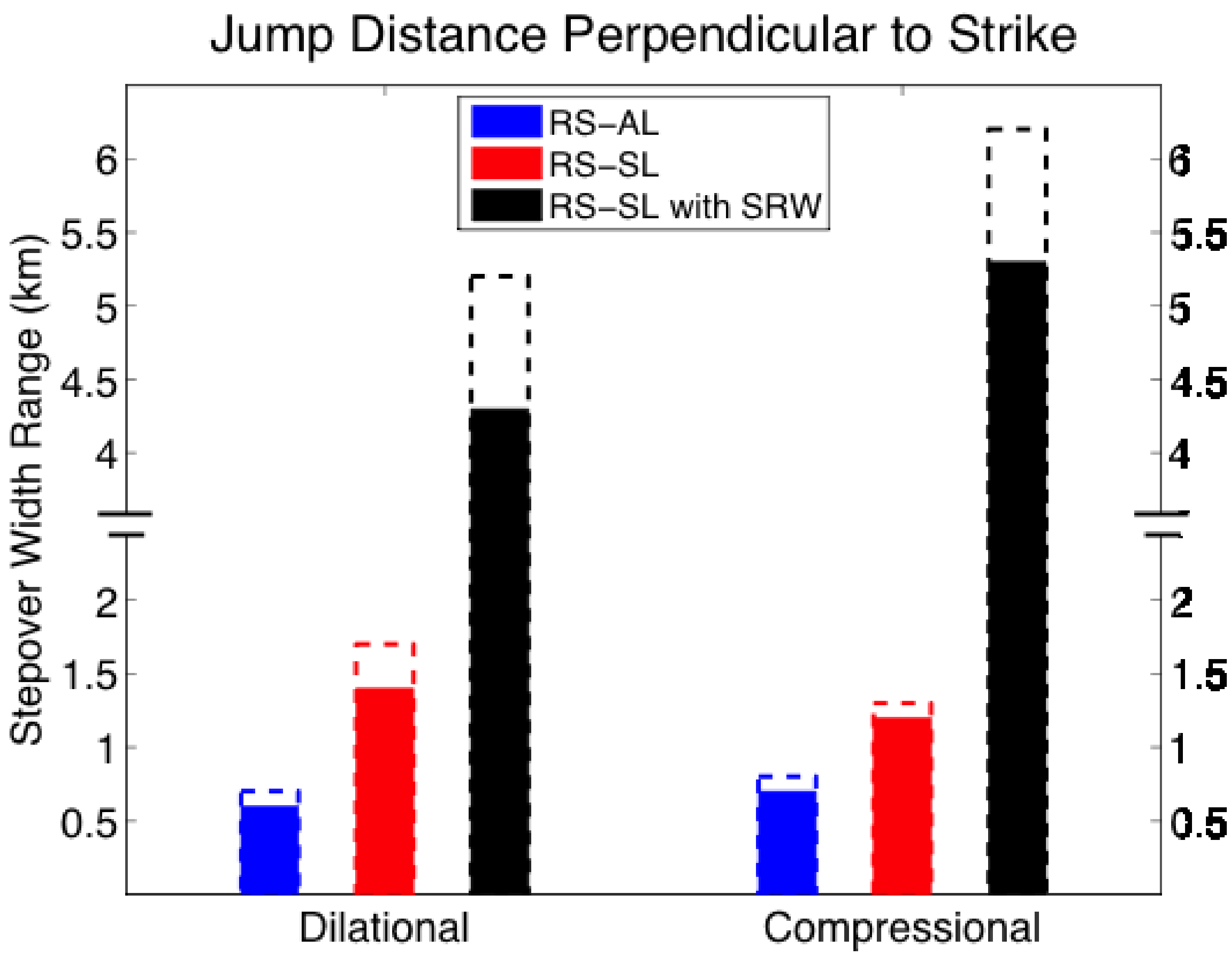
$$\frac{d\psi}{dt} = -\frac{\alpha}{\sigma + \sigma_{off}} \frac{d\sigma}{dt}$$

= primary fault segment

= secondary fault segment

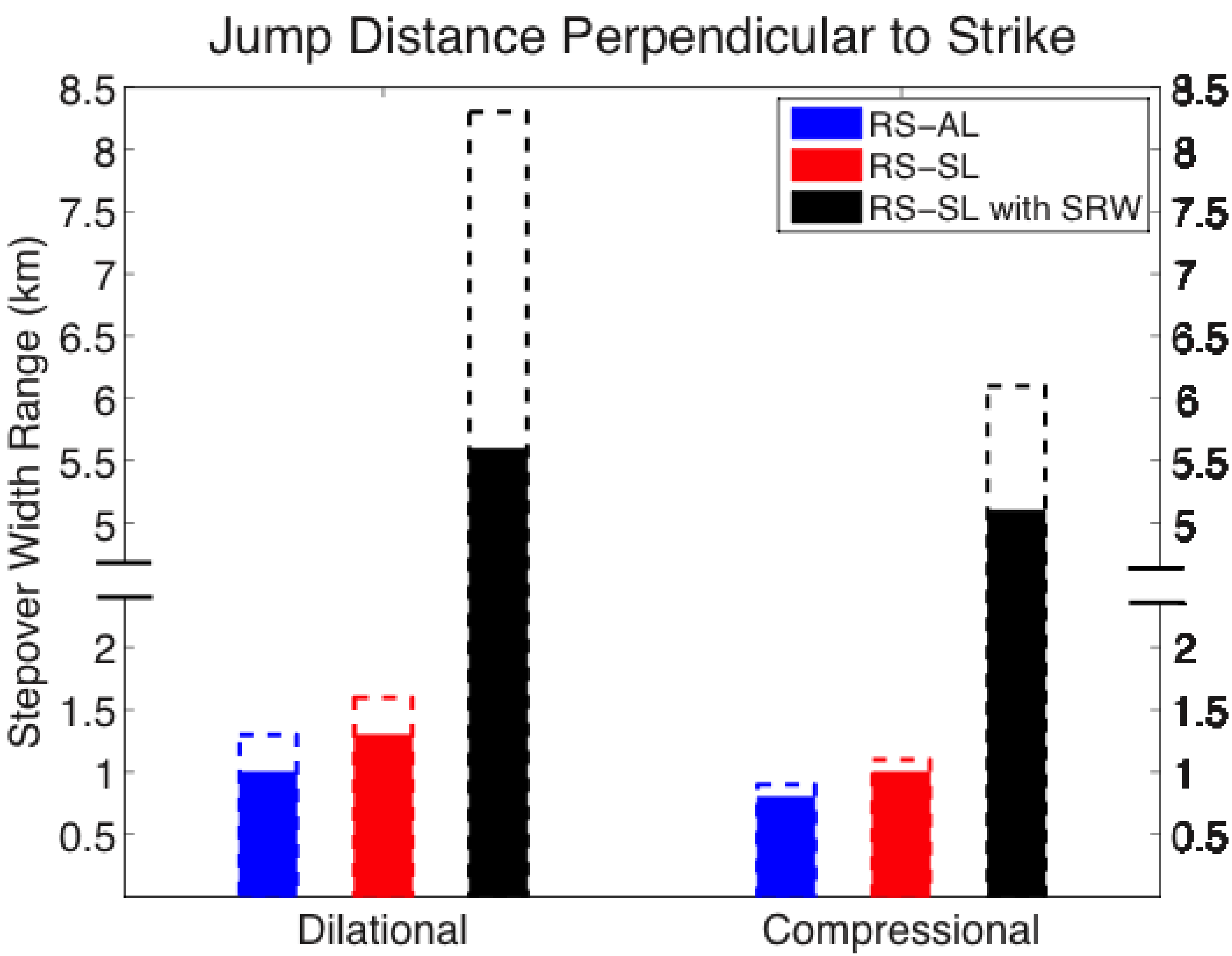
Compressional System Immediately Before Re-nucleation



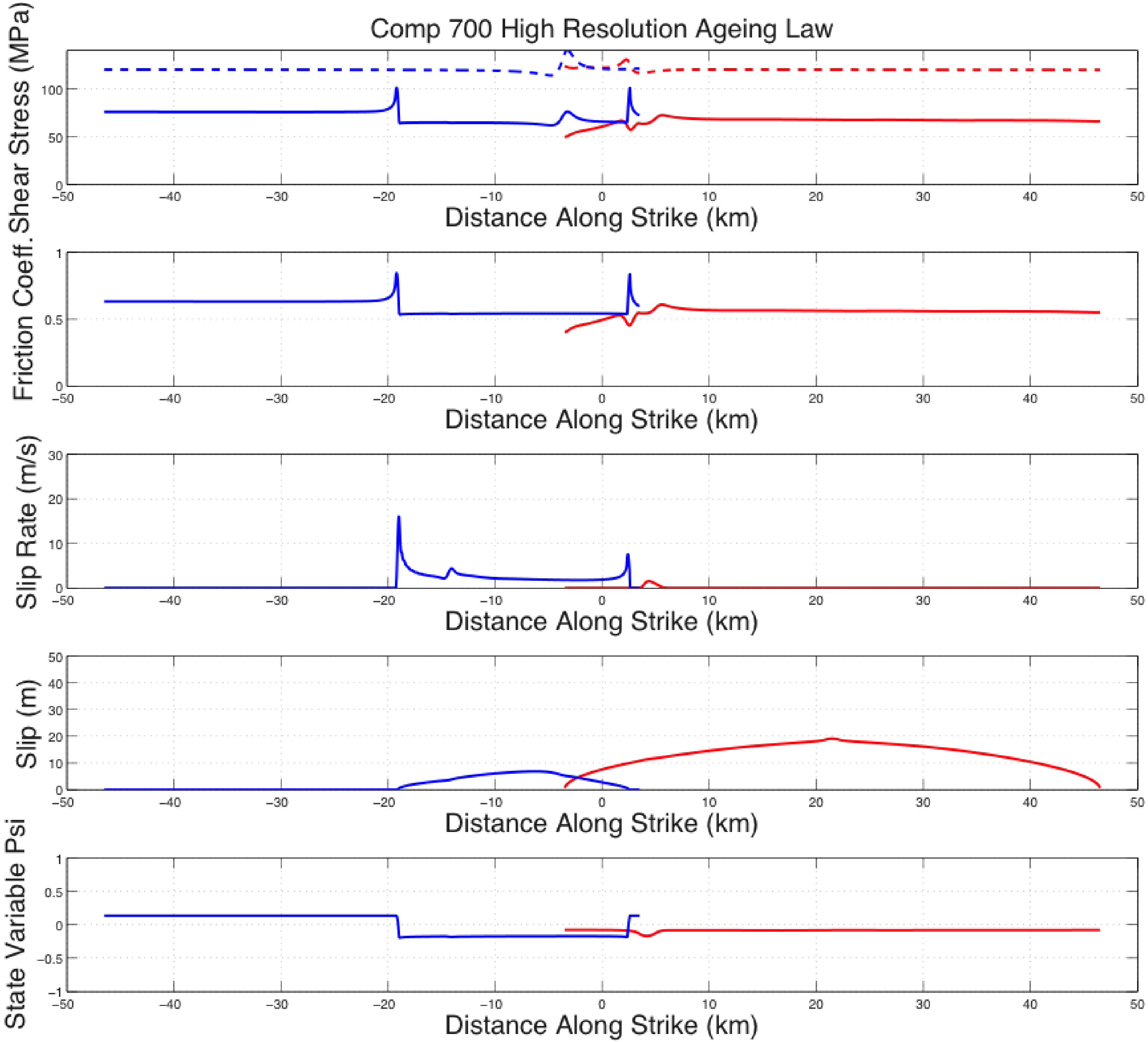

Jump Distance Perpendicular to Strike
RS–AL
RS–SL
RS–SL with SRW
Stepover Width Range (km)
6
5.5
5
4.5
4
2
1.5
1
0.5
Dilational
Compressional

Thank you to:

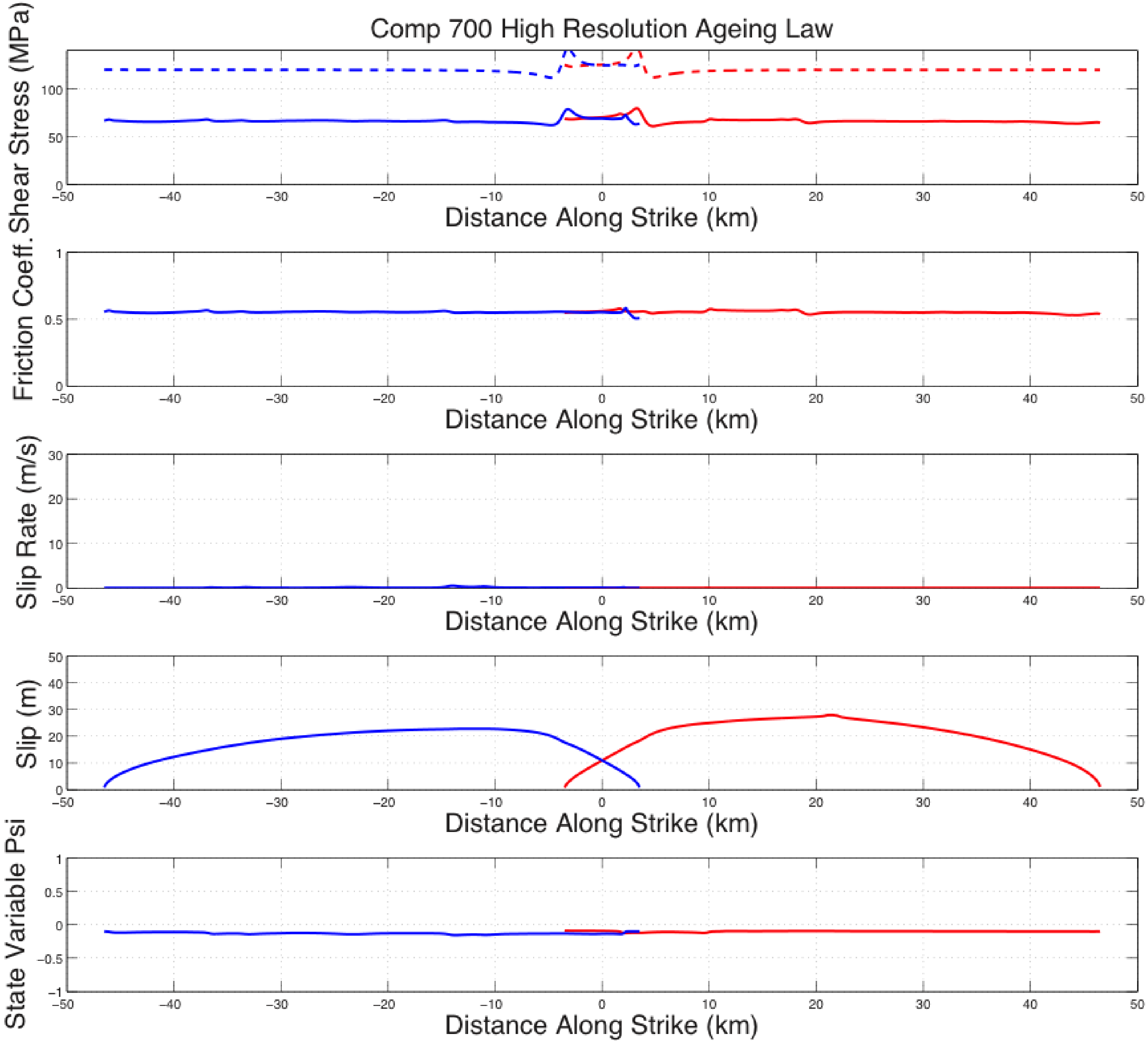
- David Oglesby
- Michael Barall
- Ruth Harris
- Joe Andrews



- **Dashed bars represent range without normal-stress dependent state**
- **Solid bars represent range with normal-stress dependent state**



Comp 700 High Resolution Ageing Law
Shear Stress (MPa)
Friction Coeff.
Slip Rate (m/s)
Slip (m)
State Variable Psi
Distance Along Strike (km)



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Slip Rate (m/s)
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State Variable Psi
Distance Along Strike (km)
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Distance Along Strike (km)

Supershear Stepover Transition

- Smaller Primary Fault Segment (30 km)
- Both Dilational and Compressional Systems
- With and without a normal-stress dependent state

Resolution

- Resolution checked with equations from Bizzarri and Cocco (2003)
- RS-SRW models with 25 meter elements do not show a very different rupture velocity along the primary fault segment (< 1% difference)

FaultMod Grid Doubling

- 6 small elements around the fault segments
- Grid doubling beyond that
- 15 km of elements around fault segments
- Viscous and algorithmic damping (Day, Dalguer, Hughes)

S & L Equations

The Seismic S-factor:

$$S = \frac{\tau_y - \tau_o}{\tau_o - \tau_f} \qquad f(S) = \frac{9.8}{(1.77 - S)^3}$$

The Supershear L-factor:

$$L(S) = f(S) \cdot \left[\frac{(1+\nu)}{\pi}\right] \cdot \left[\frac{(\tau_y - \tau_f)}{(\tau_o - \tau_f)^2}\right] \cdot G \cdot d_o$$