Advanced Workshop on Earthquake Fault Mechanics: Theory, Simulation and Observations

ICTP, Trieste, Sept 2-14 2019

Lecture 5: 3D rupture effects

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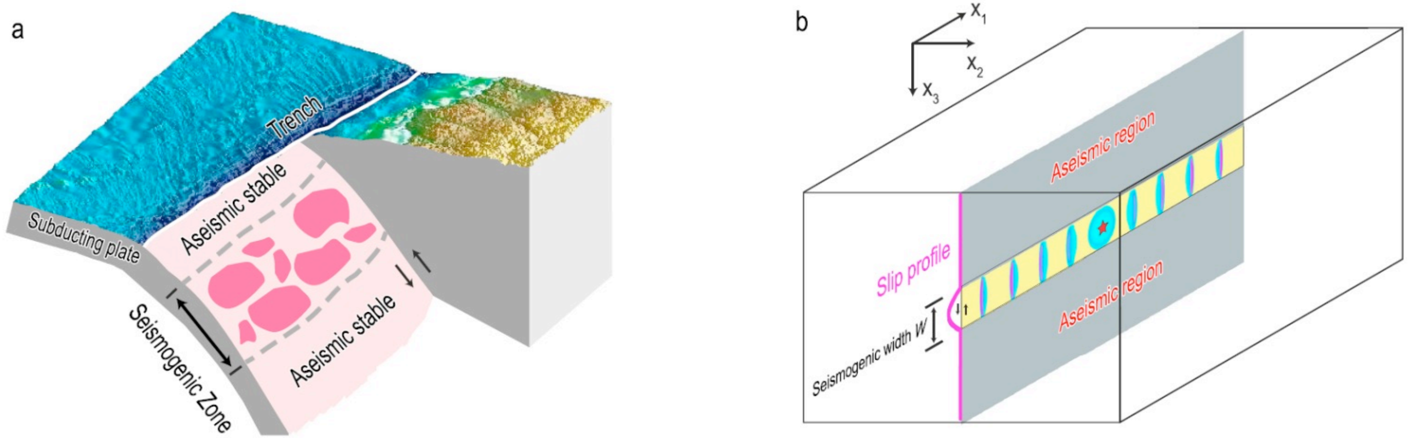
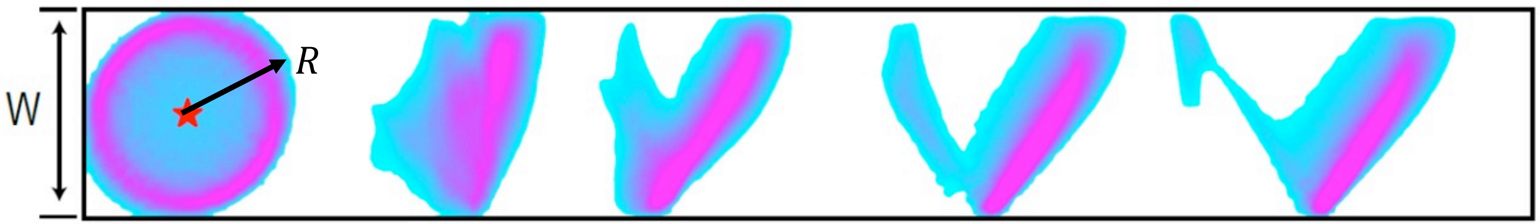
Pulses on faults with finite seismogenic depth



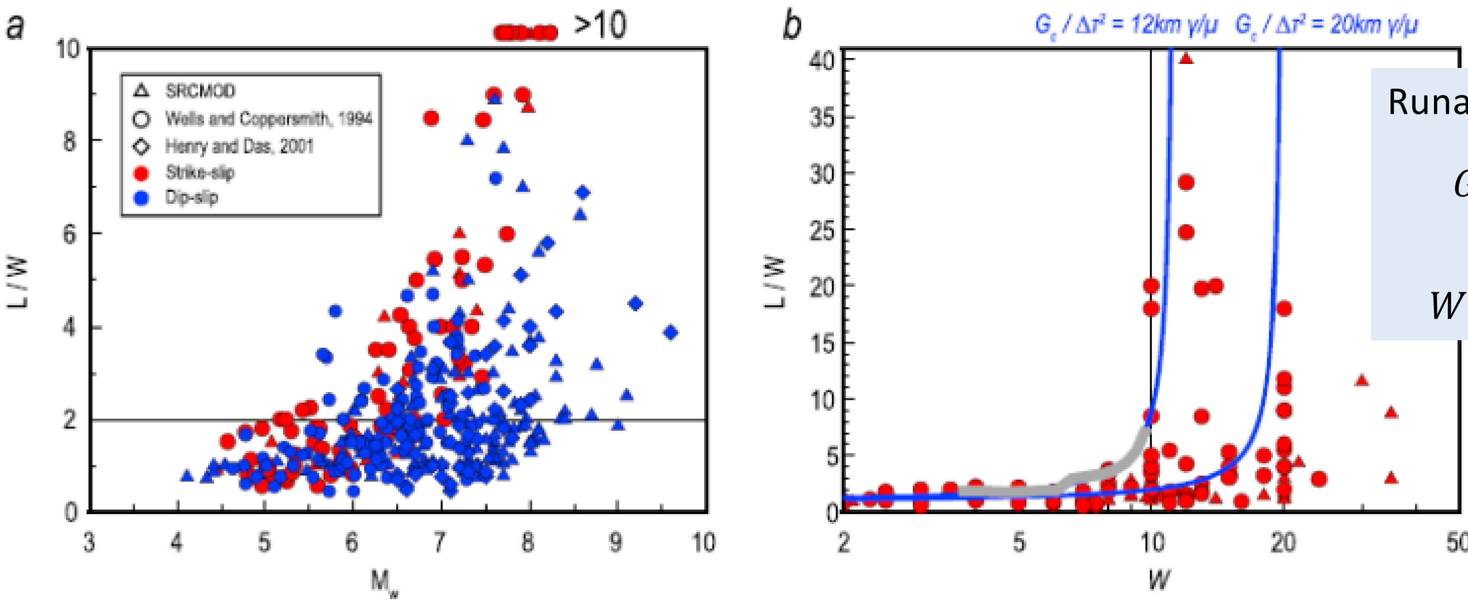


$K \propto \sqrt{R}$
$G \propto R$

$K \propto \sqrt{W}$
$G \propto W$

Arrest of long ruptures

Rupture length/width



Earthquake magnitude

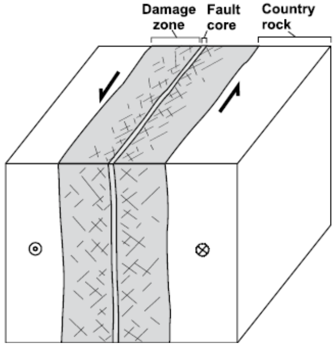
Rupture width

Runaway condition:

$$G_0 = \frac{\gamma \Delta\tau^2 W}{\mu} > G_c$$

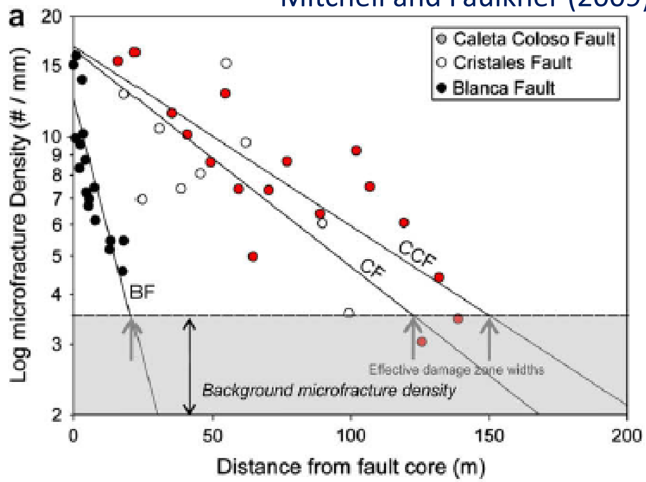
$$W > W_c = \mu G_c / \gamma \Delta\tau^2$$

Weng and Ampuero (2019)

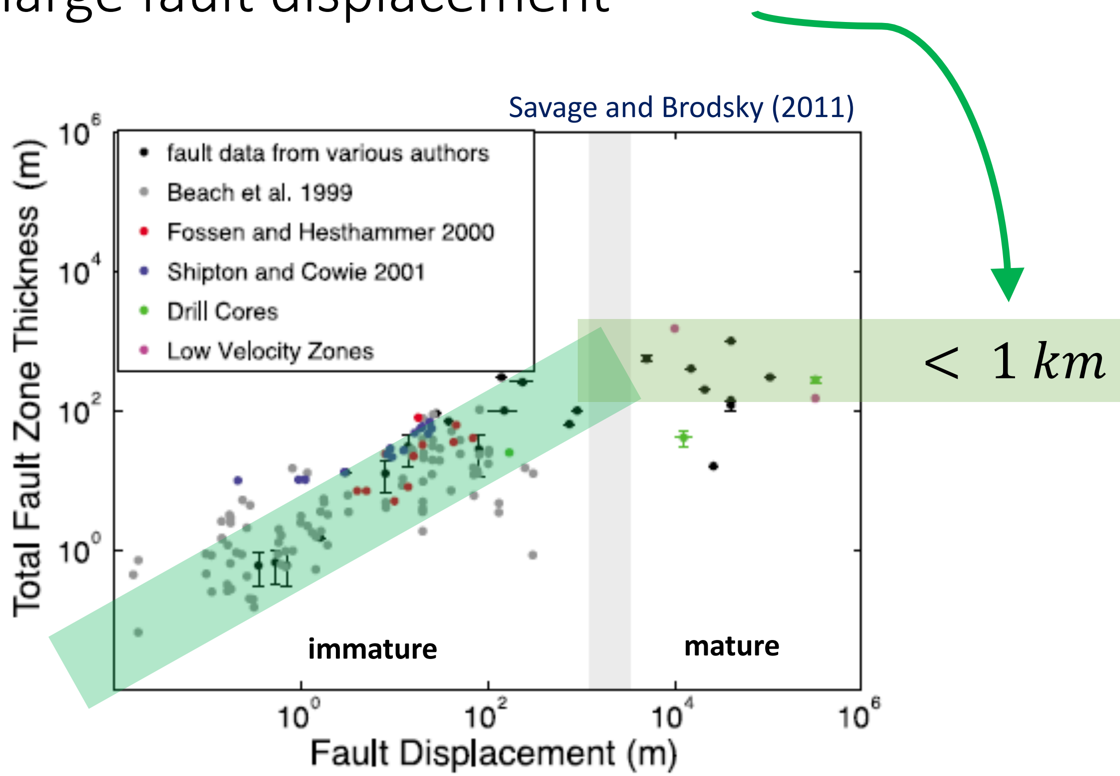


Damage zone thickness saturates at large fault displacement

Mitchell and Faulkner (2009)



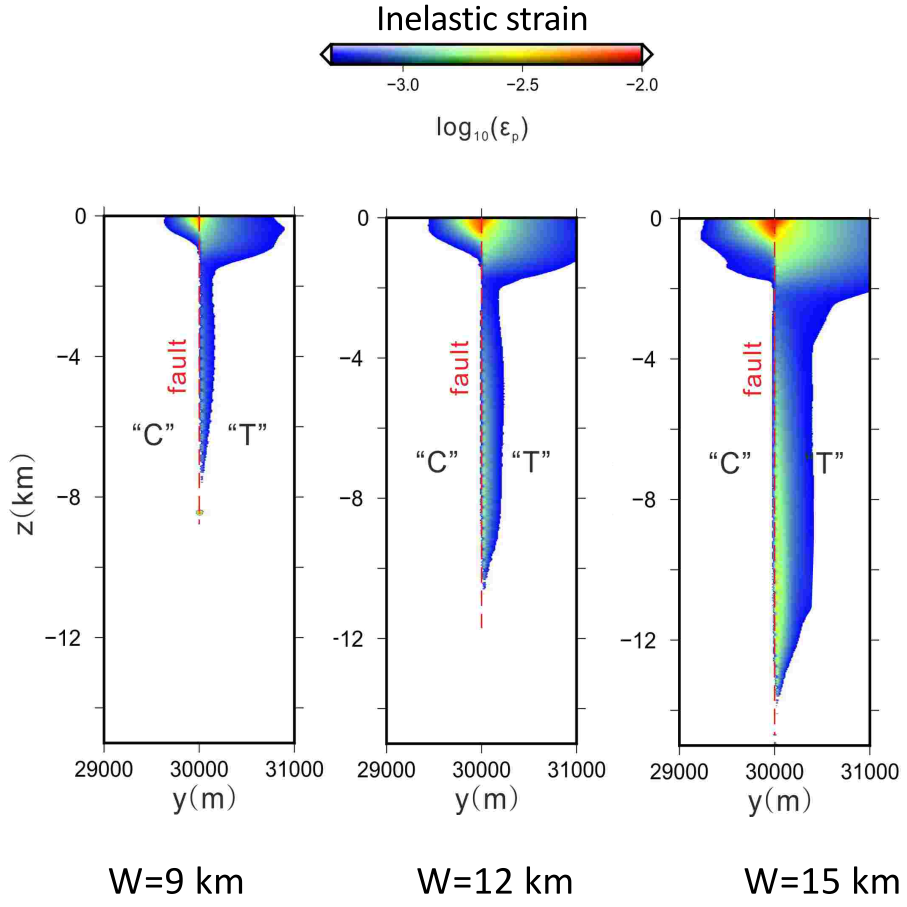
Savage and Brodsky (2011)

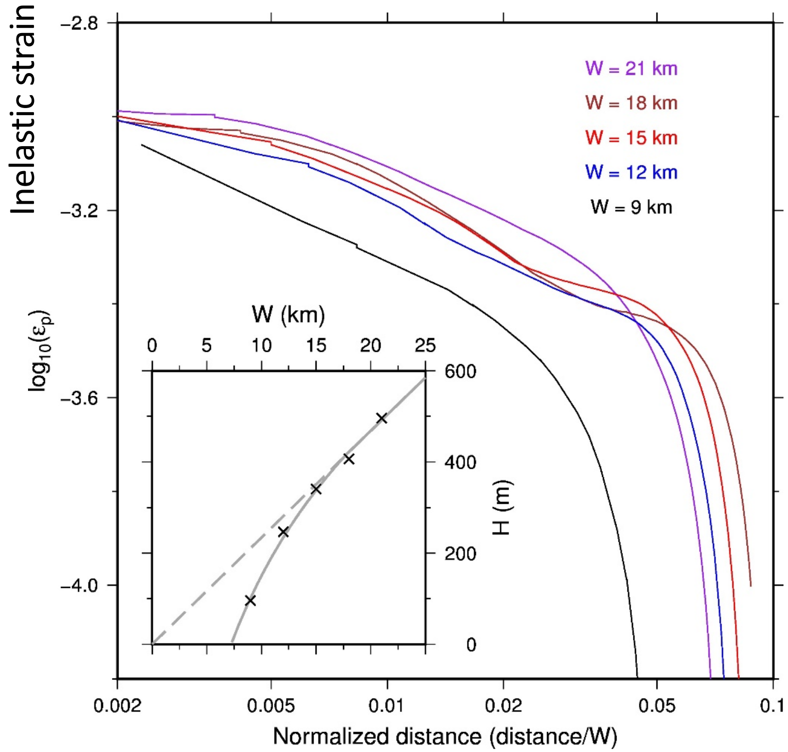


What limits the thickness of damage zones ?

Ampuero and Mao (2017), Upper Limit on Damage Zone Thickness Controlled by Seismogenic Depth

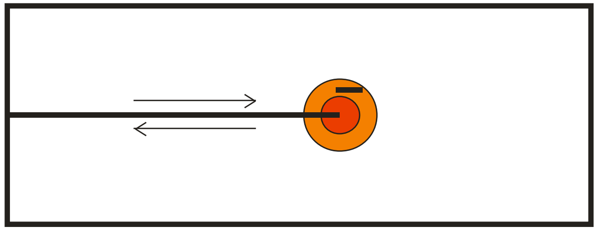
Inner damage zone thickness depends on seismogenic width



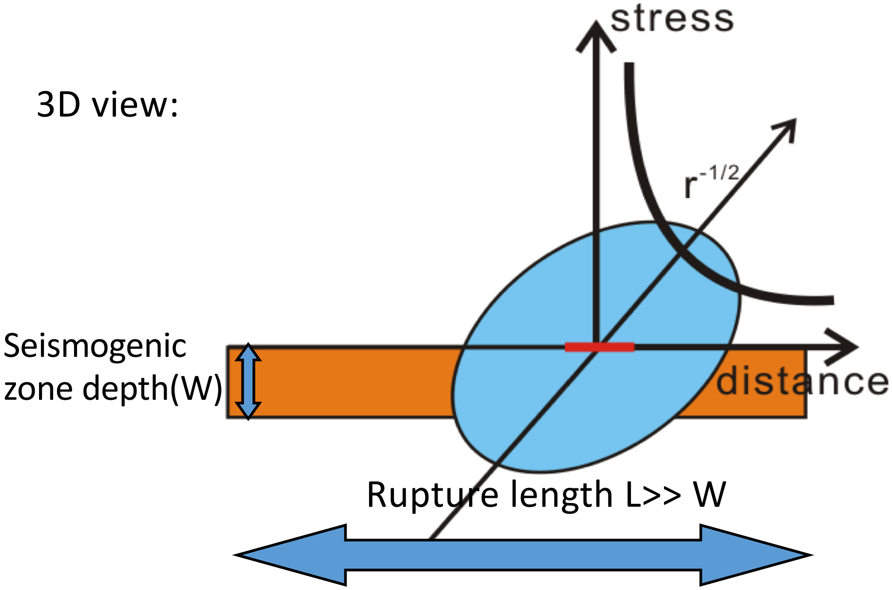


Fracture mechanics theory

Map view:



3D view:



Stress near crack tip: $\tau \approx \frac{K}{\sqrt{r}} + \tau_0$

where K is the stress intensity factor, $K \sim \sqrt{l}\,\Delta\tau$

$\Delta\tau$ is stress drop and l the shortest rupture size:

$l = R$ (radius) for circular ruptures,

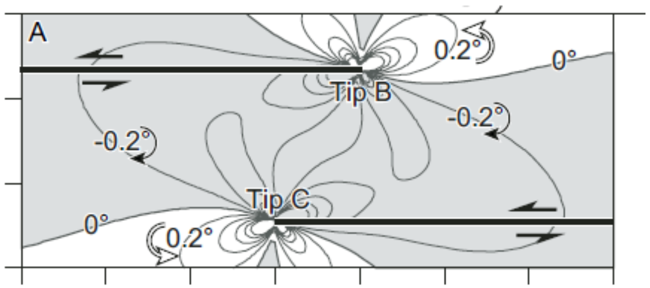
$l = W$ (width) for elongated ruptures ($W \ll L$)

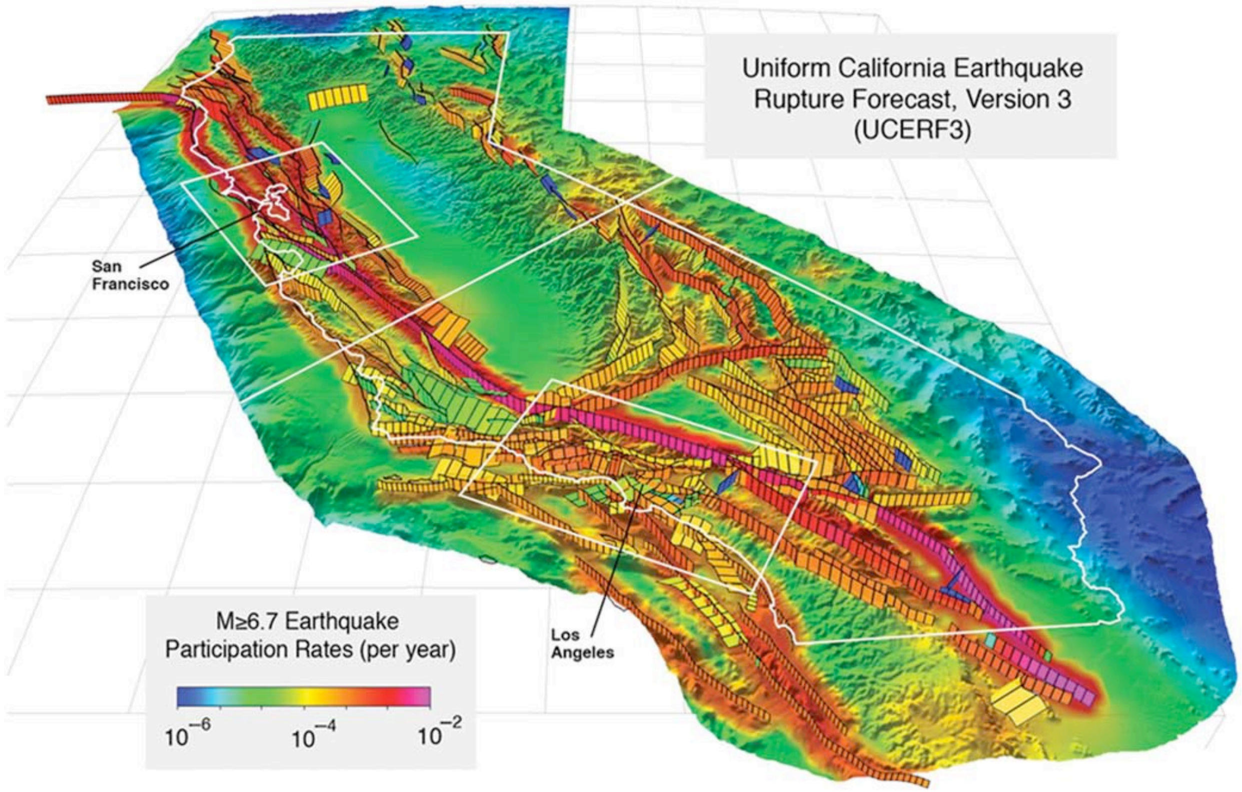
Damage zone size: distance at which $\tau = \tau_s$ (stress=yield strength)

$$r_c \sim \left(\frac{\Delta\tau}{\tau_s - \tau_0}\right)^2 l < \sim 0.01\, W$$

Relative stress drop

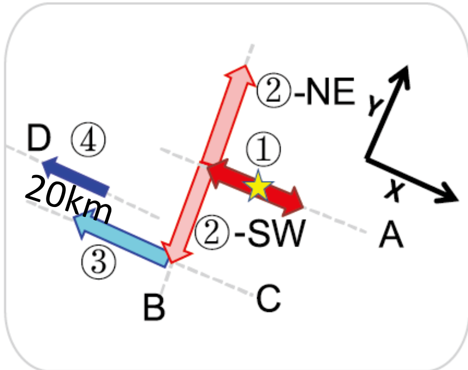
Seismogenic zone depth control on the likelihood of fault stepover jump

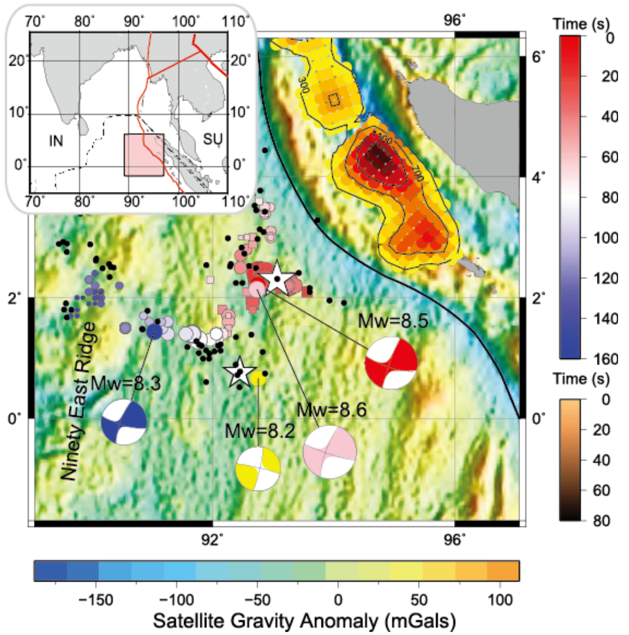




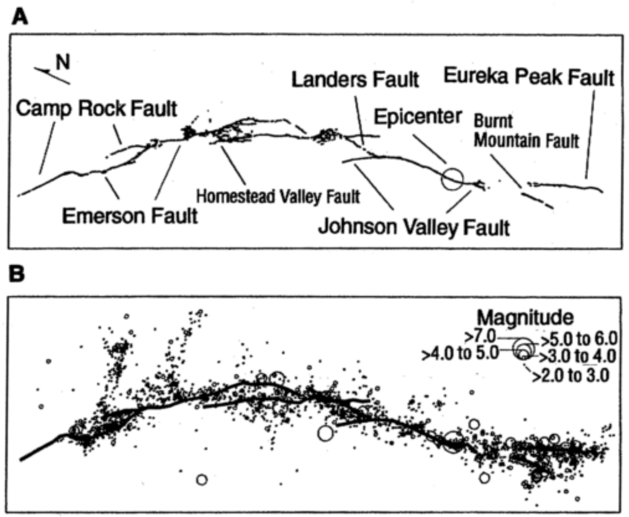
Examples of rupture complexity in large strike slip earth quakes

Mw 8.6 Indian Ocean earthquake





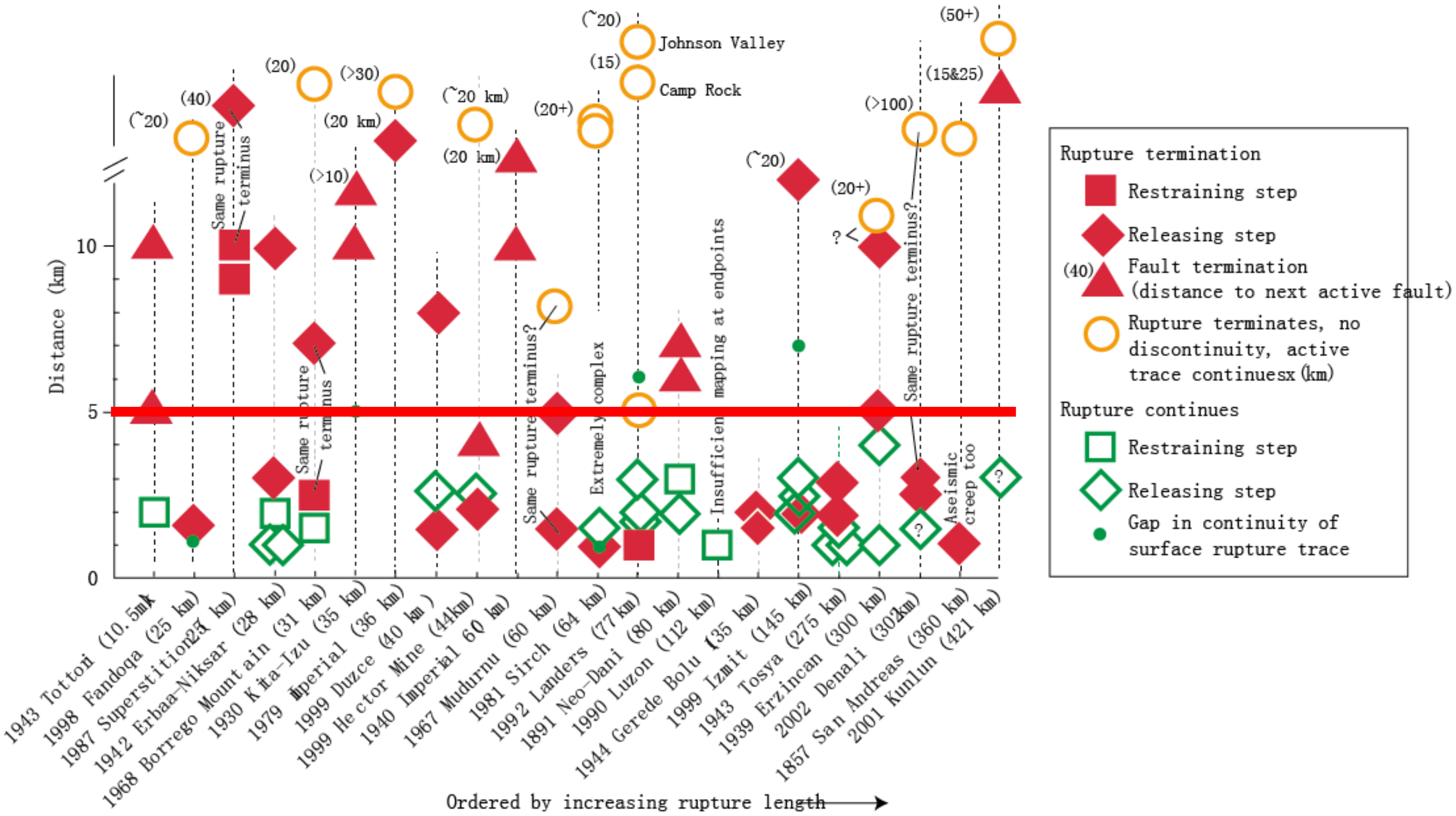
Meng et. al 2012



Mw7.3 Landers Earthquake

Sieh et. al 1993

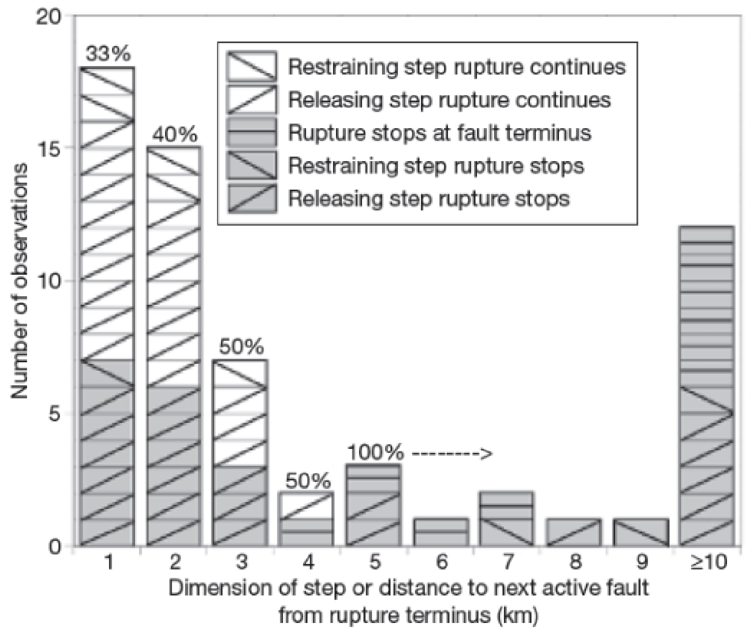
Stepover jumps in past earthquakes



(Wesnousky 2006)

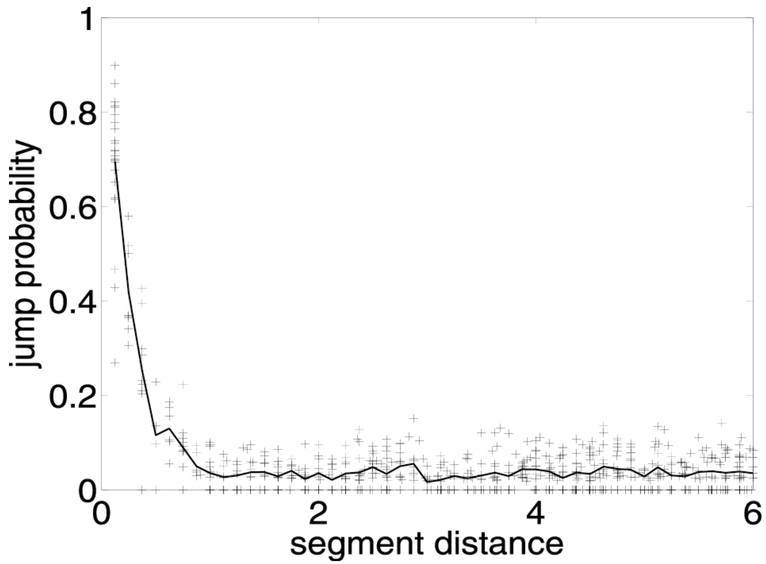
Critical stepover distance ≈ 5 km

Observations



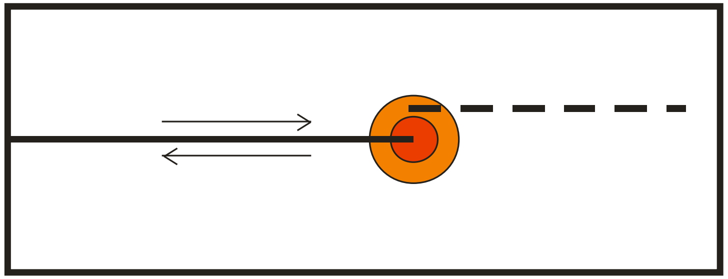
(Wesnousky 2006)

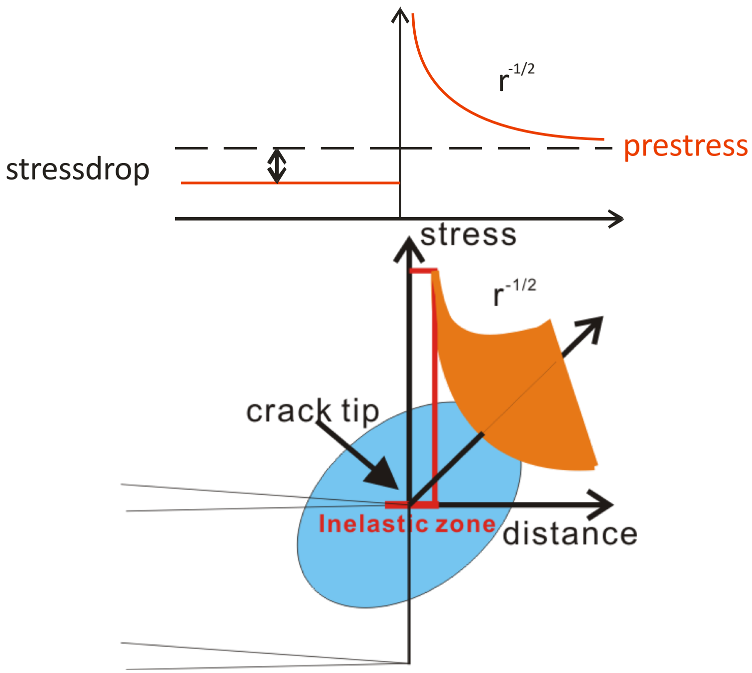
Simulations



Shaw and Dieterich (2009)

Critical stepover distance from static stress analysis





$$\sigma_{ij} = \frac{K_{II}}{\sqrt{2\pi r}}\Sigma_{ij}(\theta) + \sigma_0 + O(\sqrt{r})$$

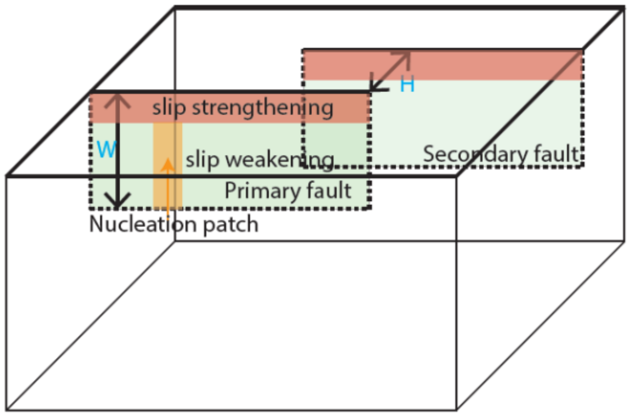
$$K_{II} \propto \sqrt{W} \cdot \Delta\sigma$$

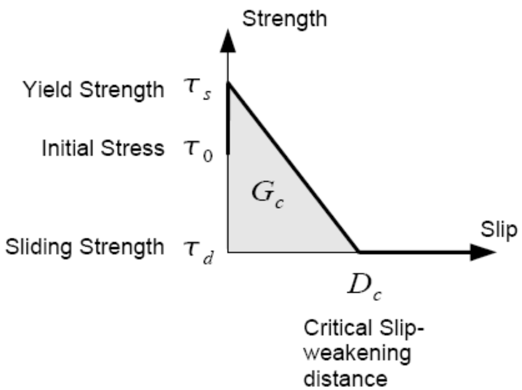
$$H_c \propto W\left(\frac{\Delta\sigma}{\sigma_{yield} - \sigma_0}\right)^2$$

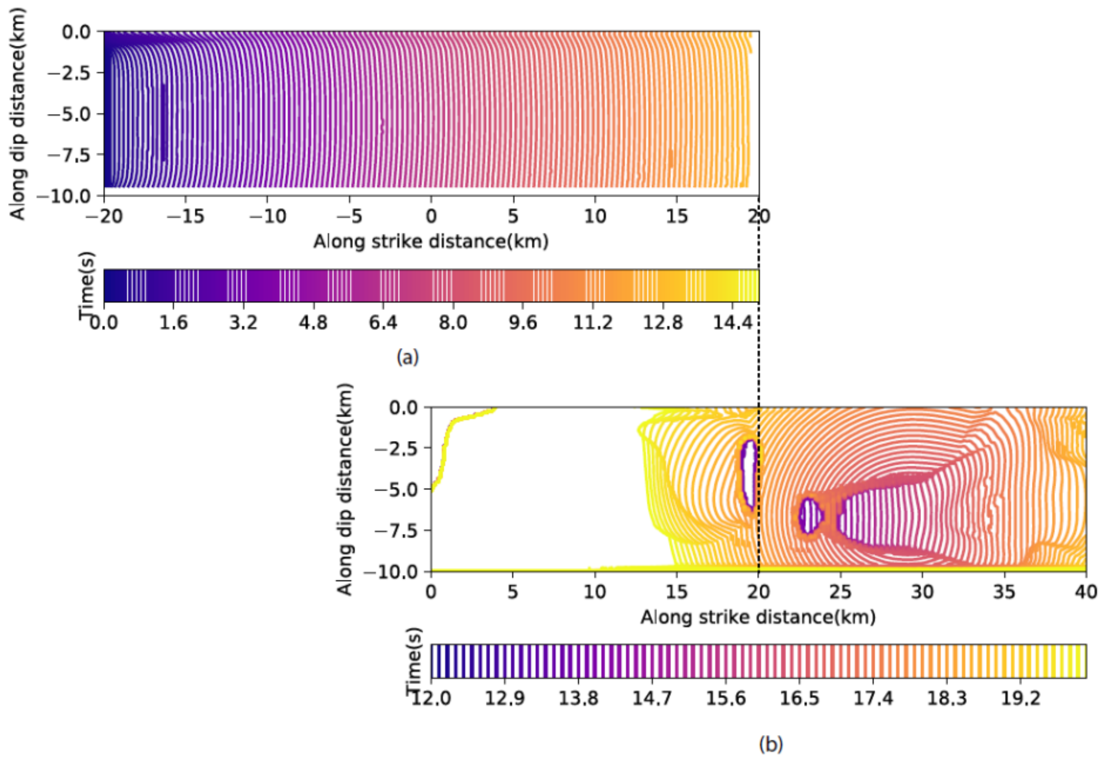
Critical stepover distance
proportional to seismogenic depth

Bai and Ampuero (2017)

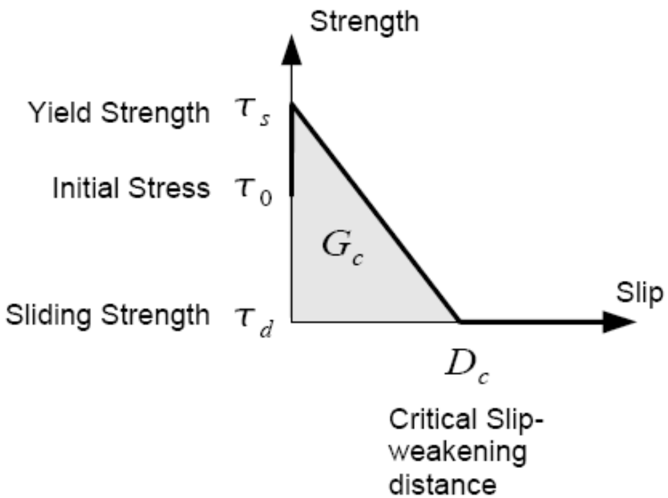
Dynamic rupture simulation
Evolution of the rupture front







Bai and Ampuero (2017)



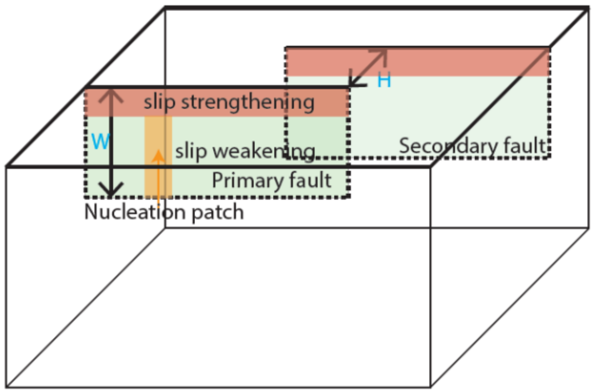
Relative stress ratio:

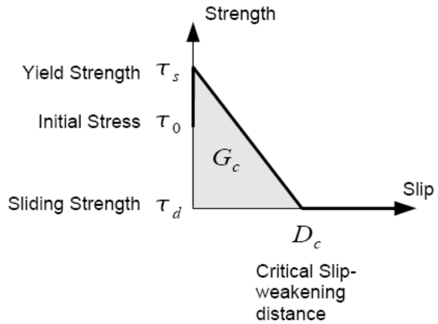
$$S = (\tau_s - \tau_0)/(\tau_0 - \tau_d)$$

= (strength excess) / (stress drop)

High S = low initial stress

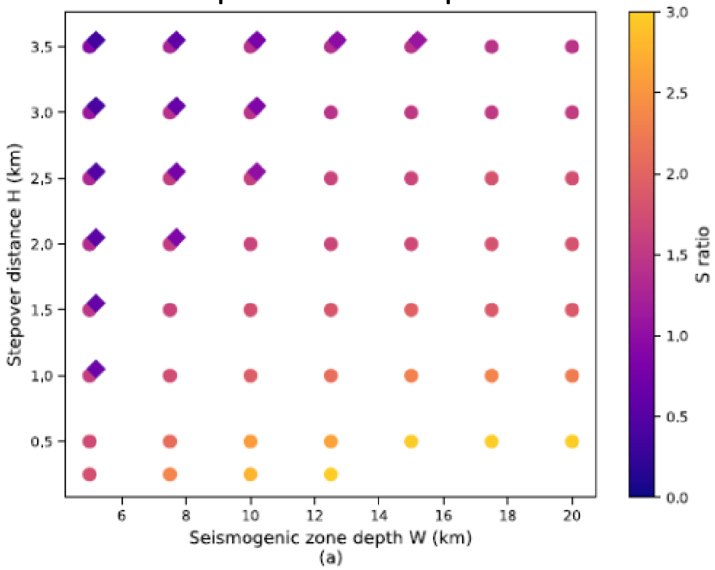
Bai and Ampuero (2017)



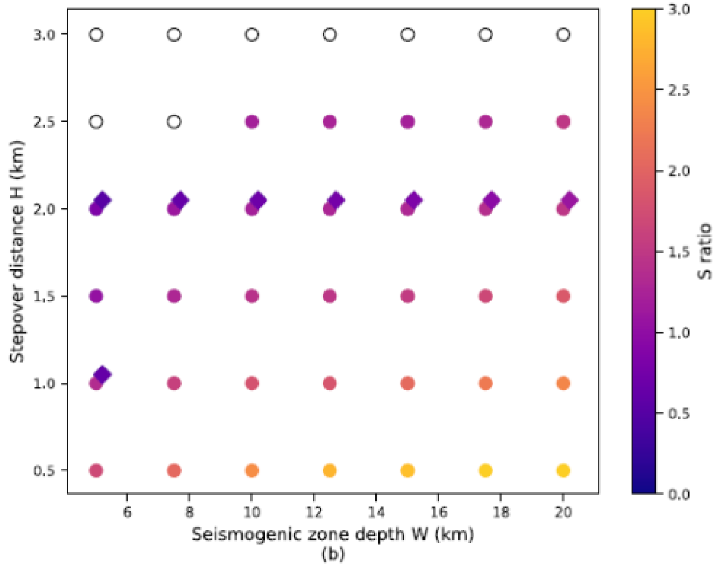


$$S = (\tau_s - \tau_0)/(\tau_0 - \tau_d)$$

Compressional stepovers

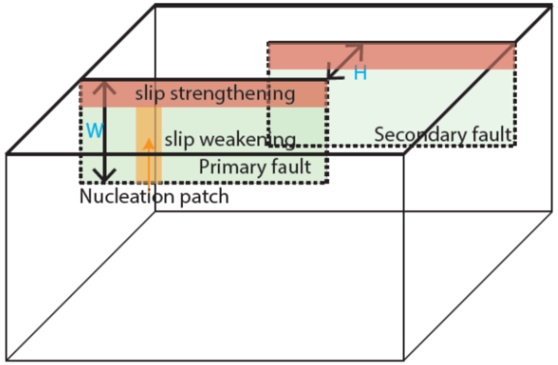


Dilatational stepovers



← Critical initial stress

Bai and Ampuero (2017)

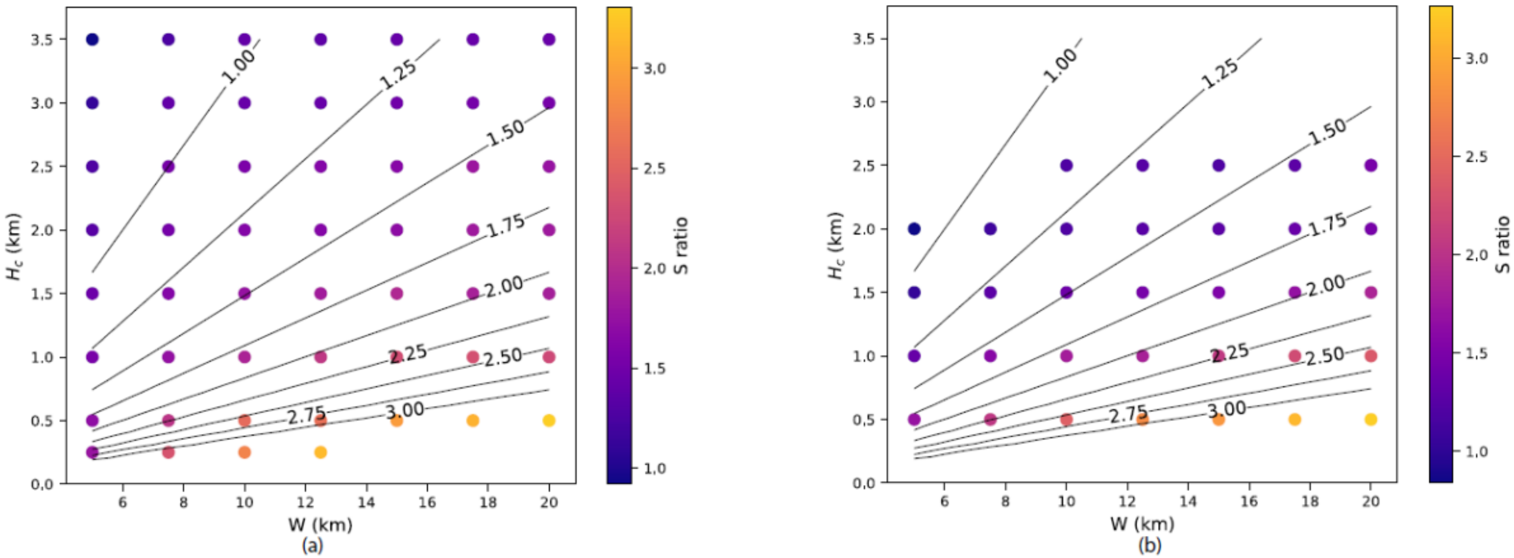


$$H_c/W = 0.3/S^2$$

Compressional stepovers

Dilatational stepovers

$$S = (\tau_s - \tau_0)/(\tau_0 - \tau_d)$$

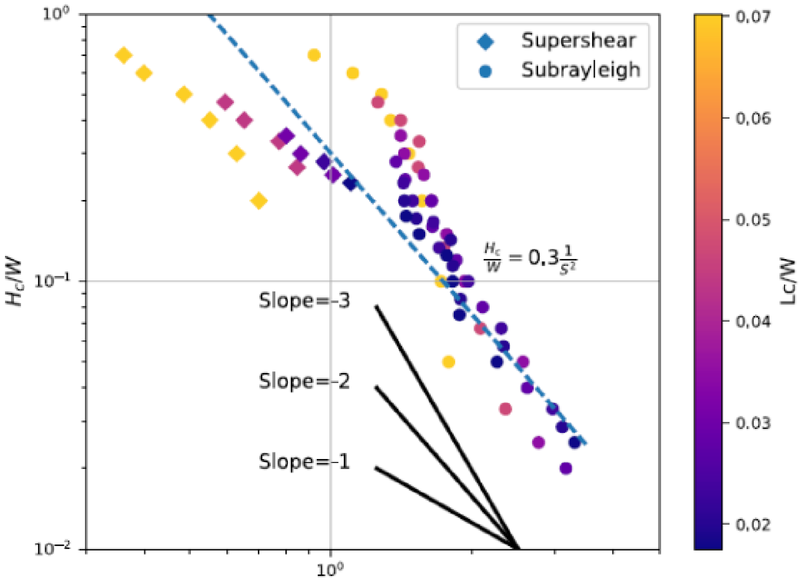


← Critical initial stress

Bai and Ampuero (2017)

Compressional stepovers

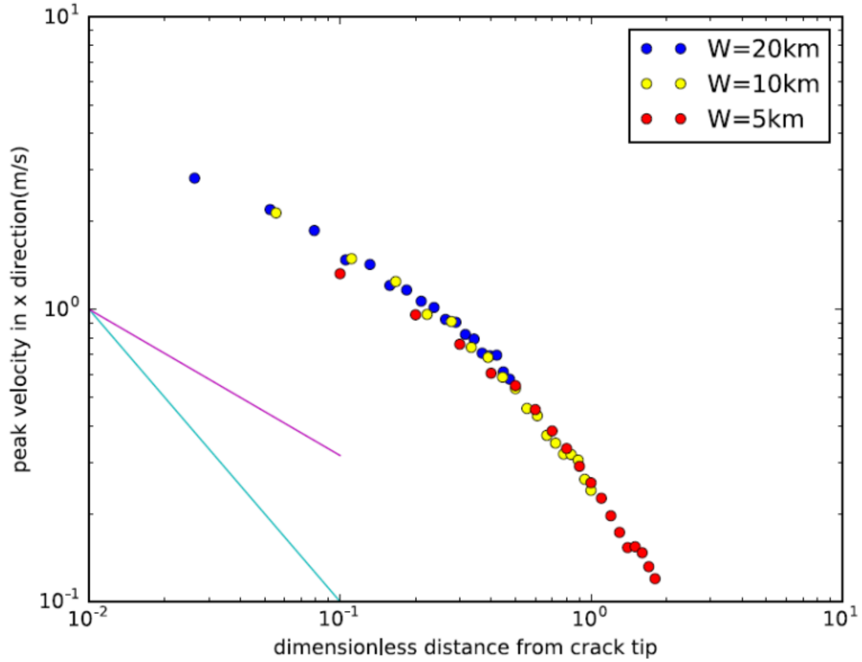
Critical stepover distance



$S = (\tau_s - \tau_0)/(\tau_0 - \tau_d)$

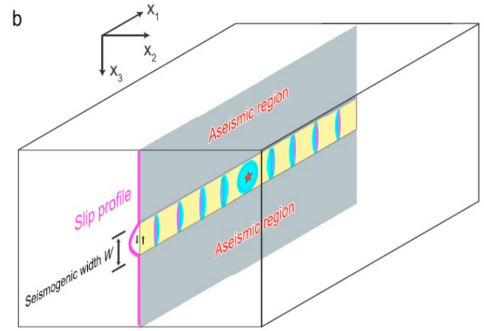
← Initial stress

$$H_c/W = 0.3/S^2$$



$$H_c \propto W/S^n$$

Summary



Effects of seismogenic width W:

- Pulse-like rupture
- Changes the energy balance: limits the energy flux, introduces rupture inertia
  → implications on rupture arrest size
- Limits the thickness of damage zones
- Limits the stepover distance that ruptures can jump
- Allows for rupture at “unstable” and “forbidden” speeds