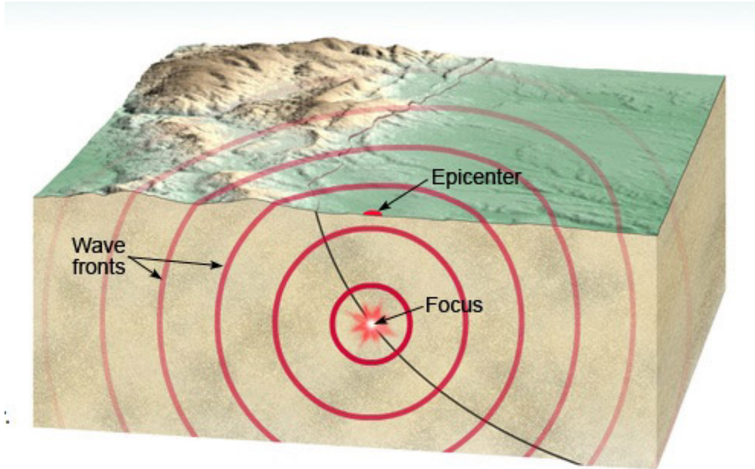
Advanced Workshop on Earthquake Fault Mechanics: Theory, Simulation and Observations

ICTP, Trieste, Sept 2-14 2019

Lecture 4: beyond friction

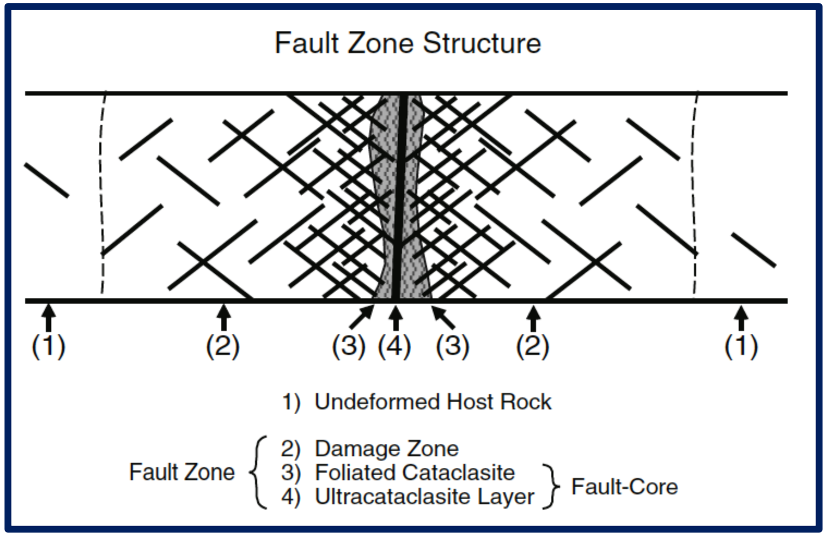
Jean Paul Ampuero (IRD/UCA Geoazur)

Real faults are thick ...



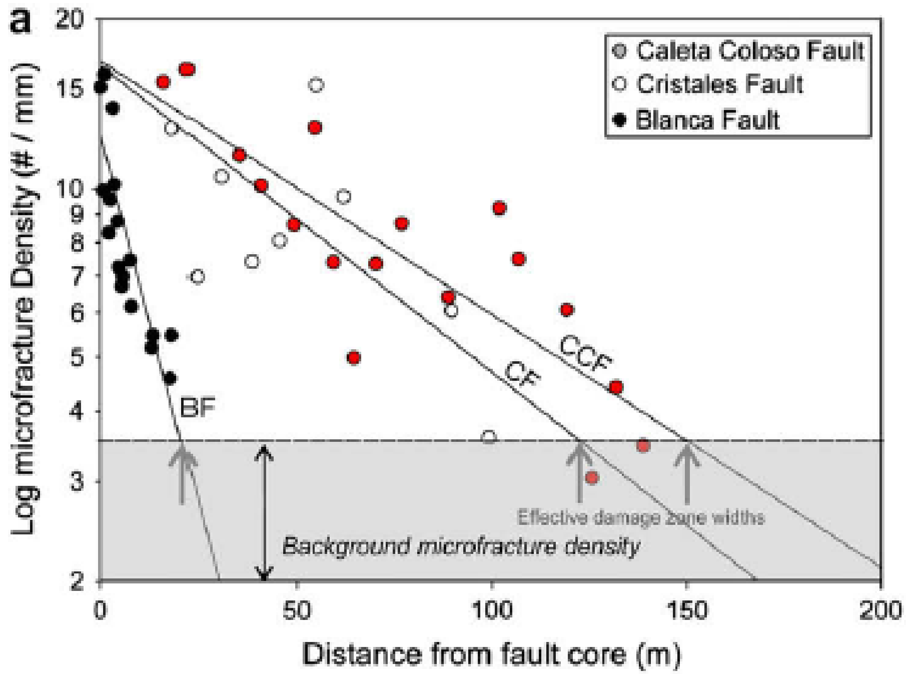
Punchbowl fault, CA
(Chester and Chester, 1998)

Fault zones are damaged

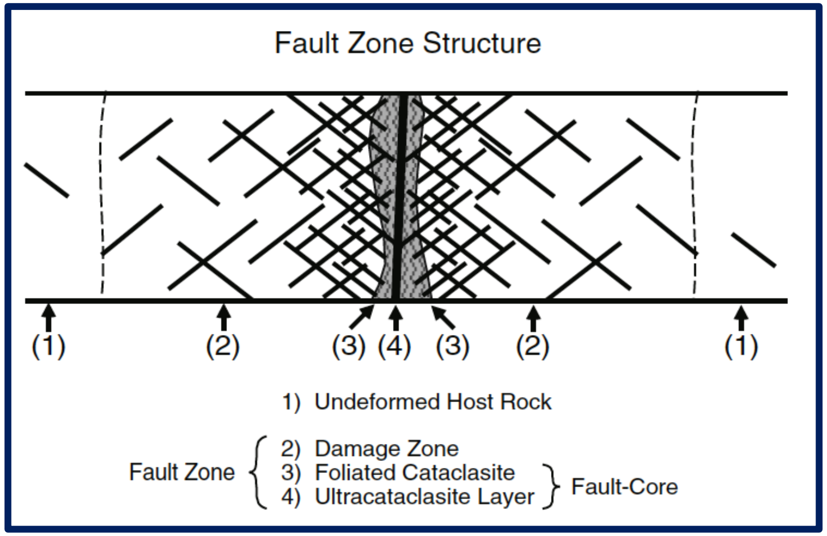


(Chester et al., 2004)

Mitchell and Faulkner (2009)

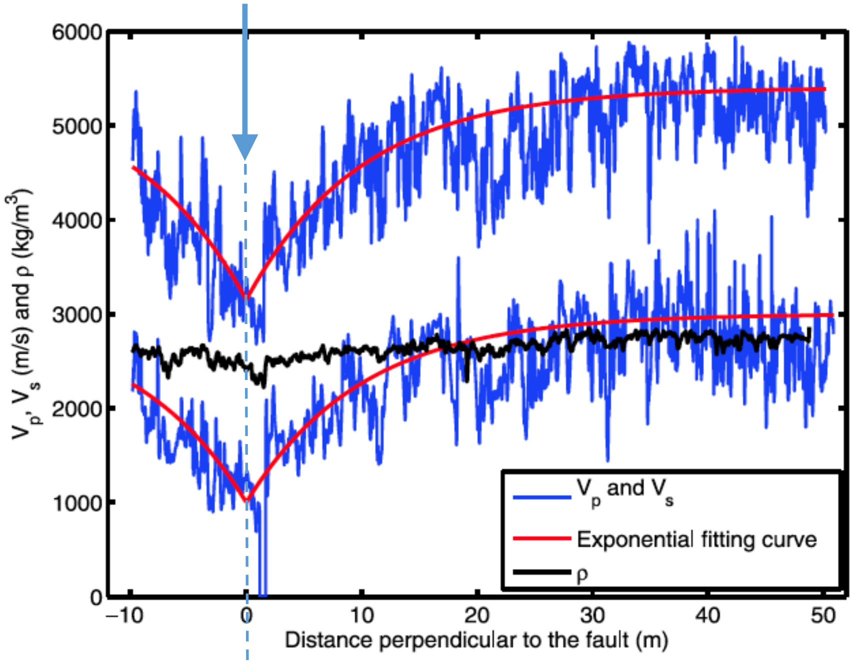


Fault zones are damaged



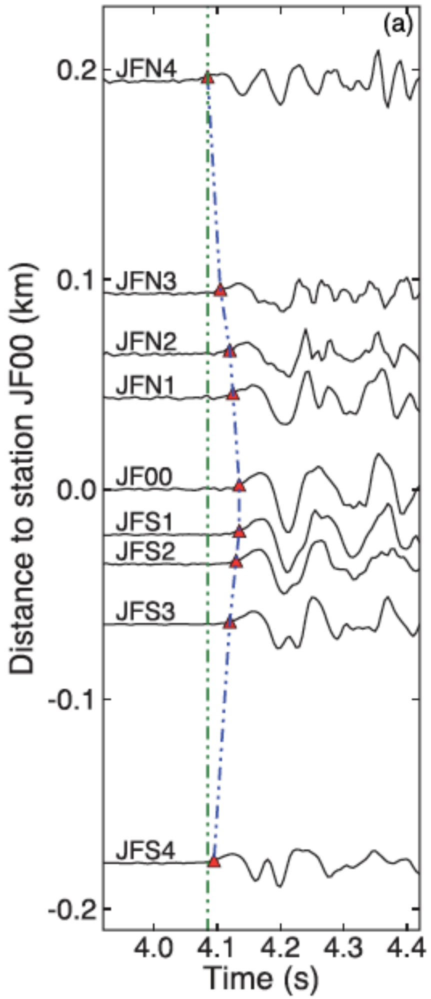
(Chester et al., 2004)

Low wave velocity zone surrounding the Nojima Fault, Kobe, Japan



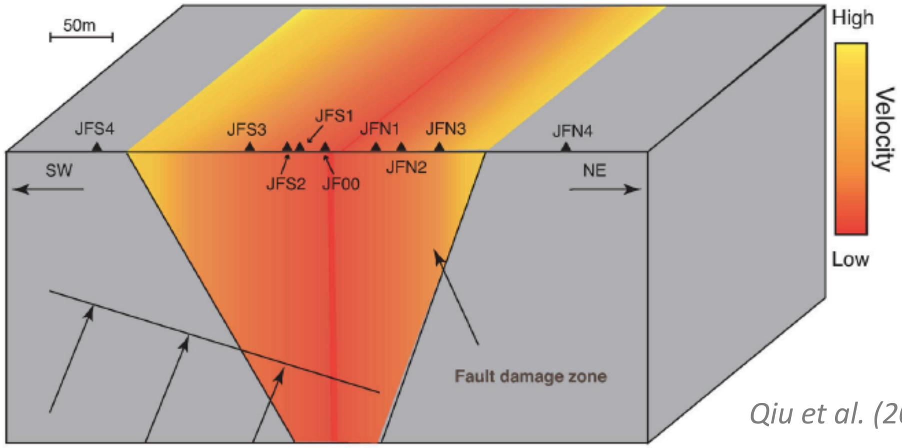
(Huang and Ampuero, 2011; borehole data courtesy of H. Ito)

Low velocity fault zones imaged by trapped waves



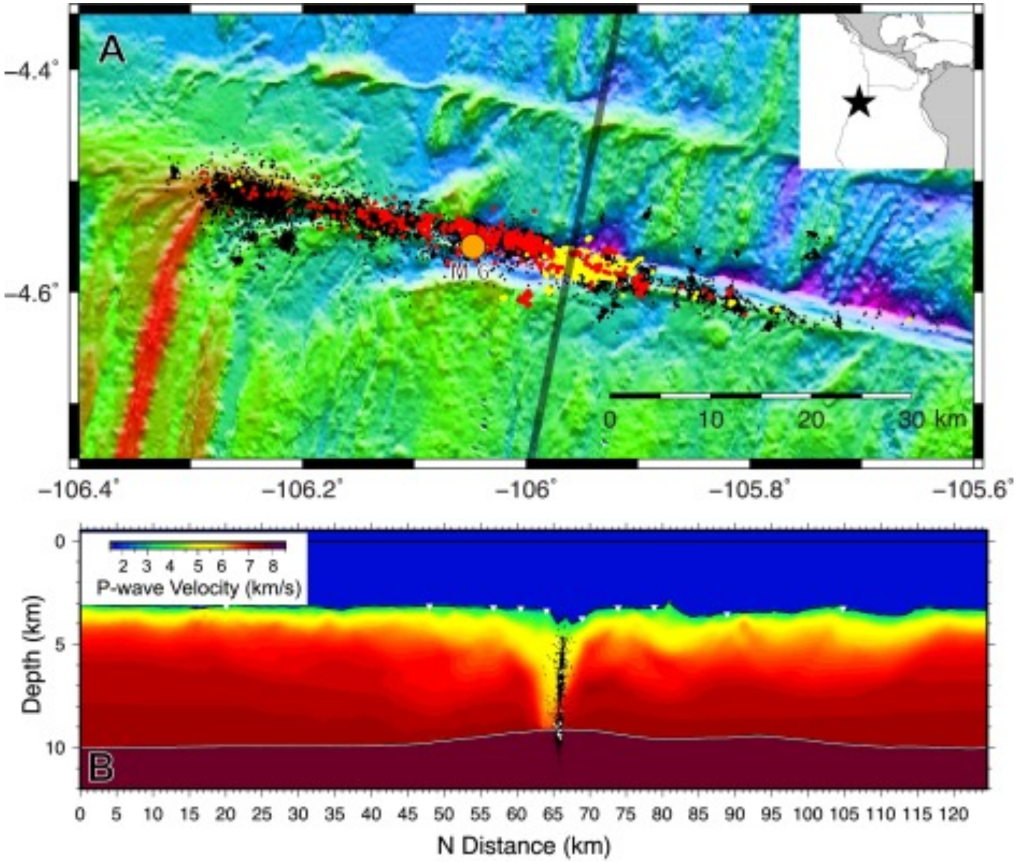
P wave and head wave travel times

Modeling of trapped waves



Qiu et al. (2017)

Fault zones are damaged

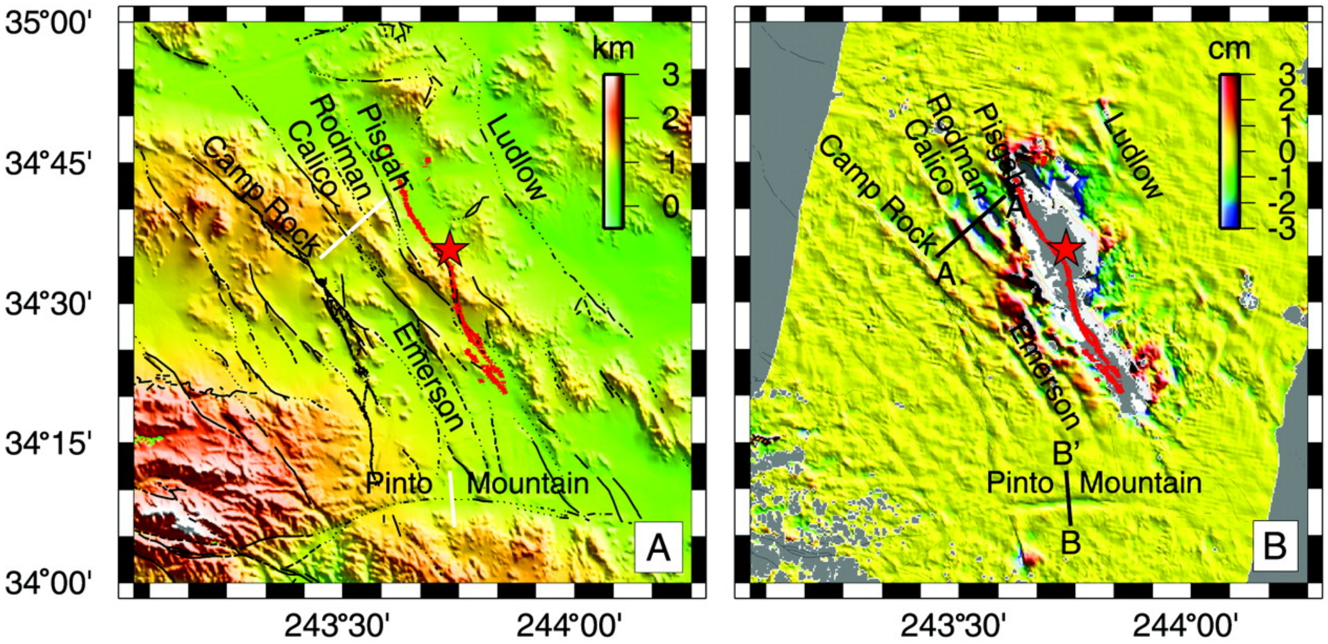


Central section of the Gofar transform fault on the East Pacific Rise

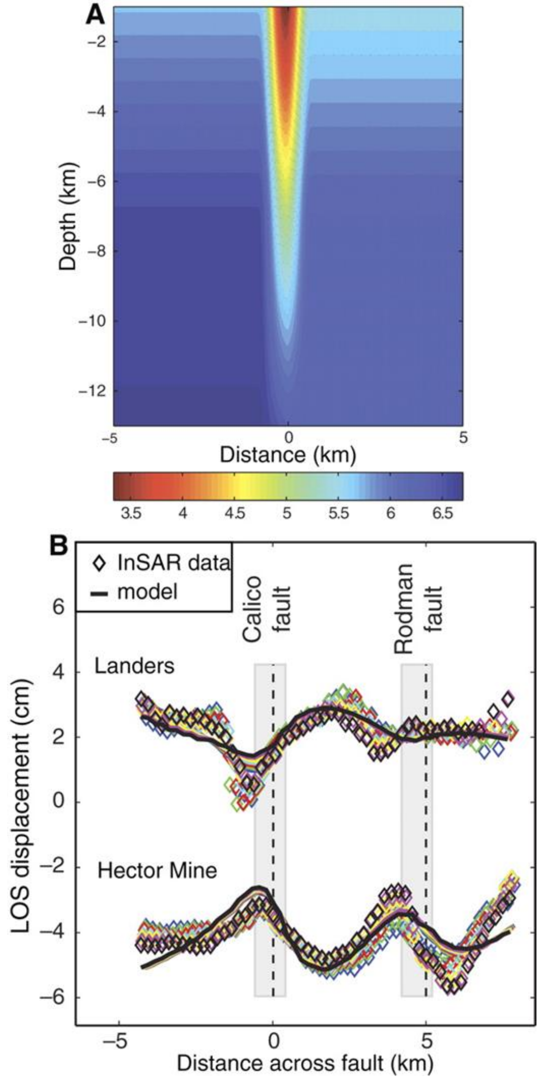
>2-km-wide low-velocity fault zone down to the base of the crust

Roland et al (2012)

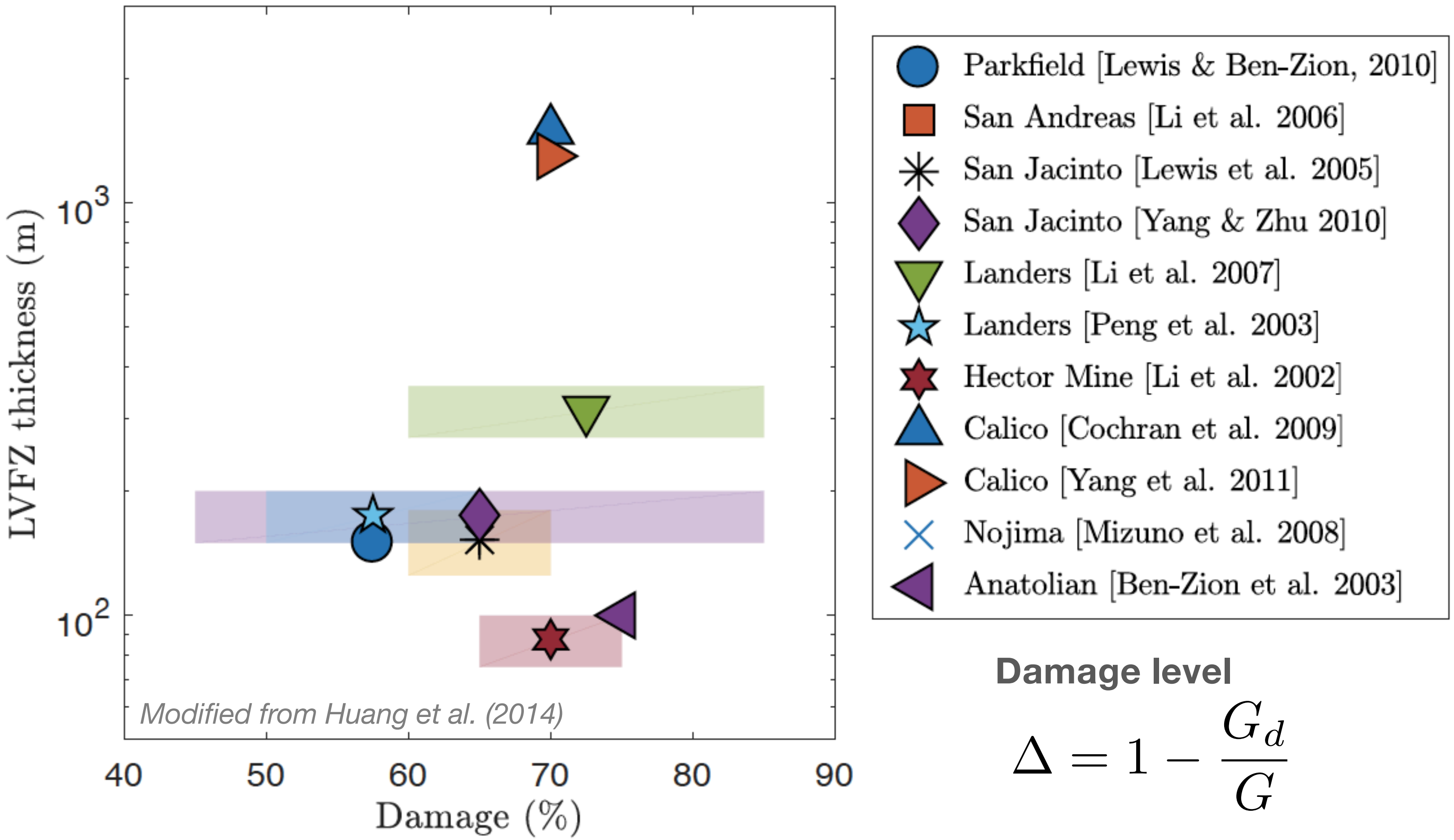
Fault zones are damaged



Fialko et al (2002), Cochran et al (2009)



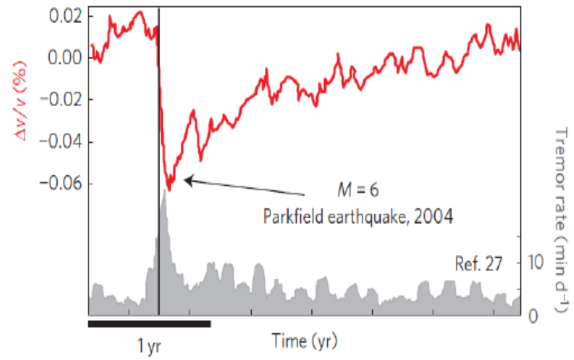
Fault zone properties



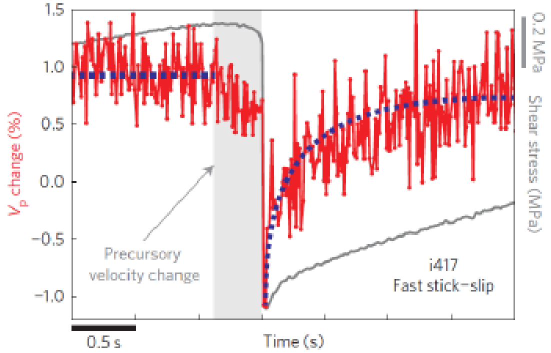
Damage level

$$\Delta = 1 - \frac{G_d}{G}$$

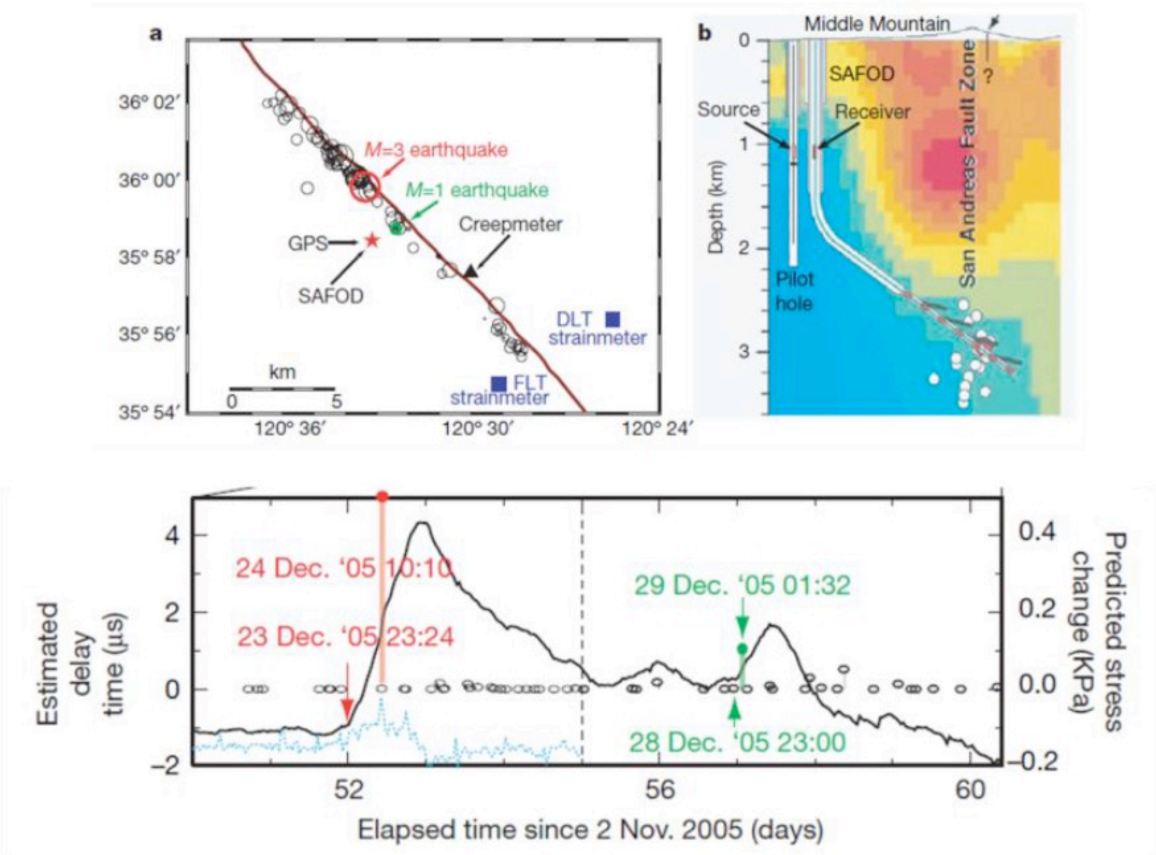
Crustal velocity changes post- and pre-seismic



Brenguier et al (2008)

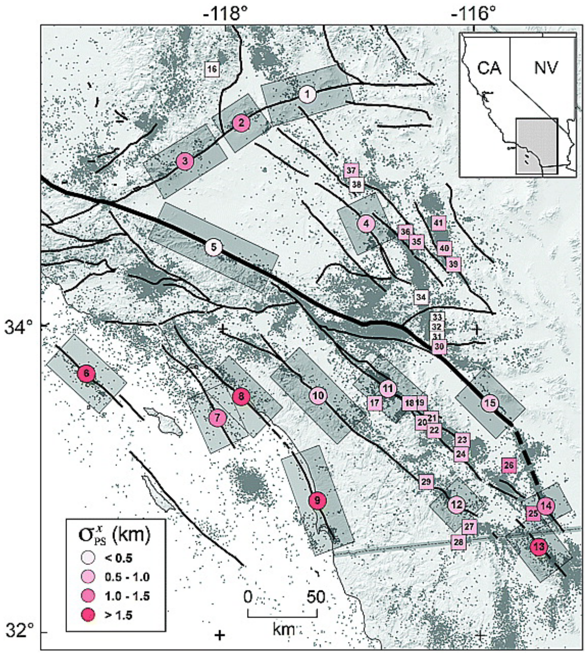


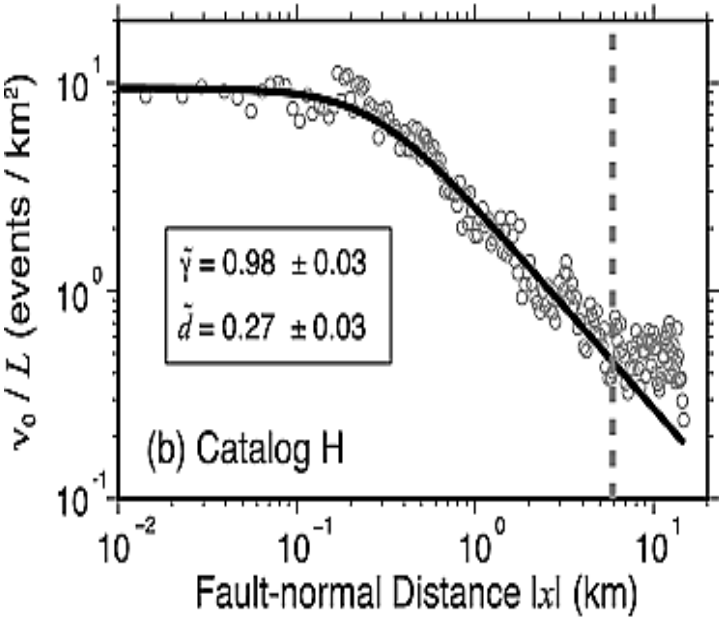
Scuderi et al (2016)

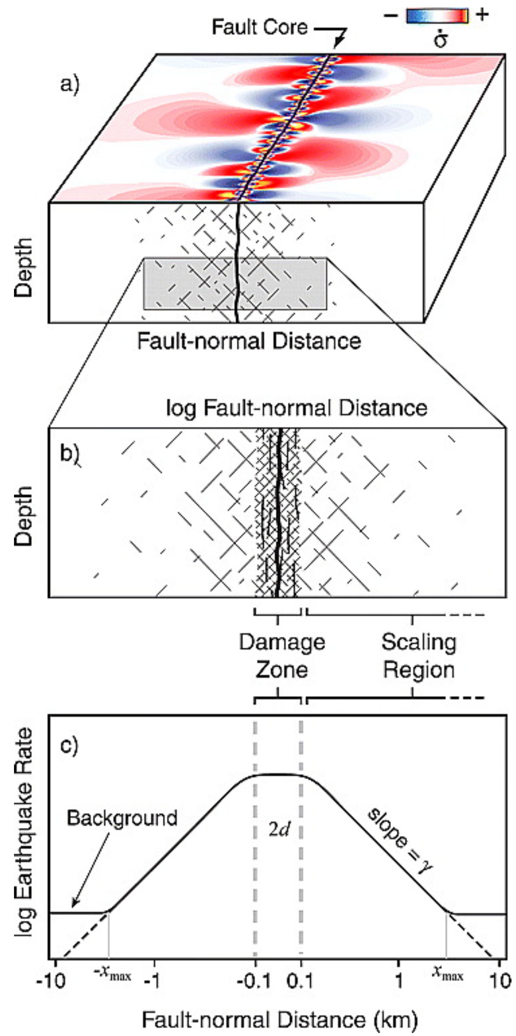


Niu et al (2008)

Fault zones are damaged

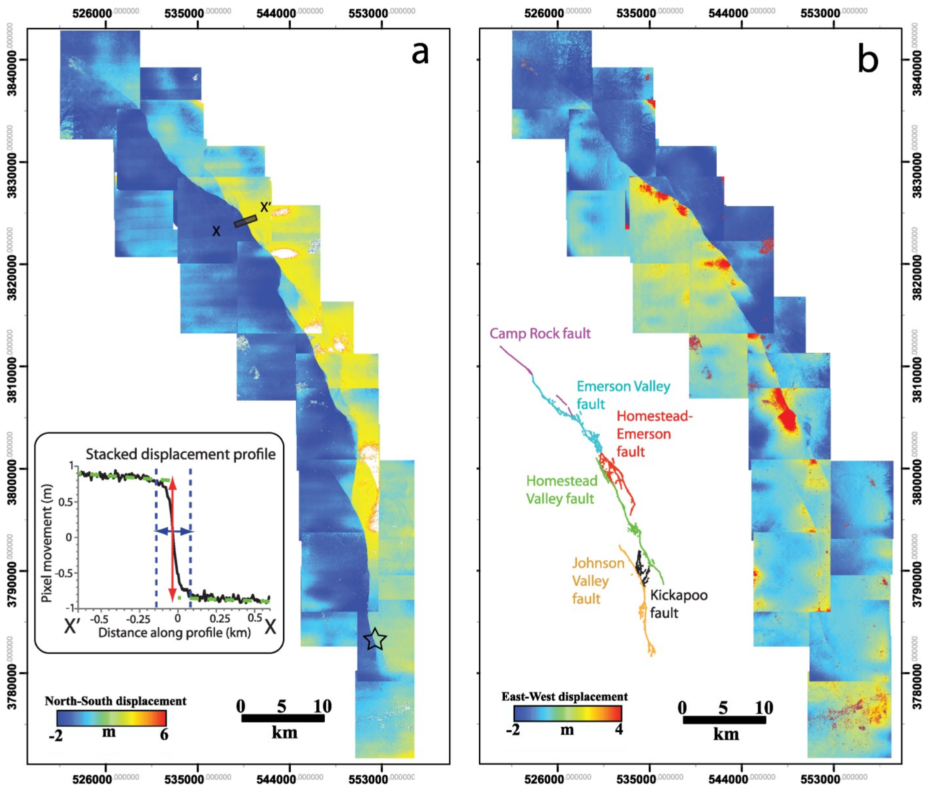


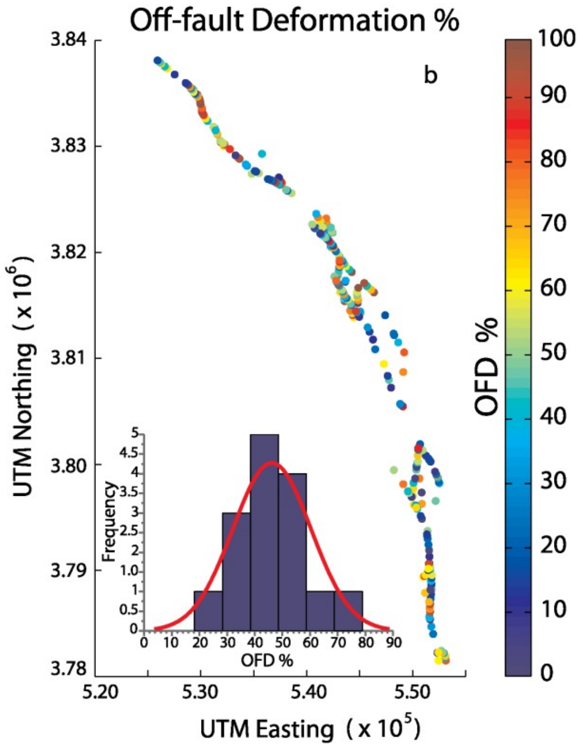




Distribution of seismicity in the vicinity of main faults in California
Powers and Jordan (2010)

Coseismic damage

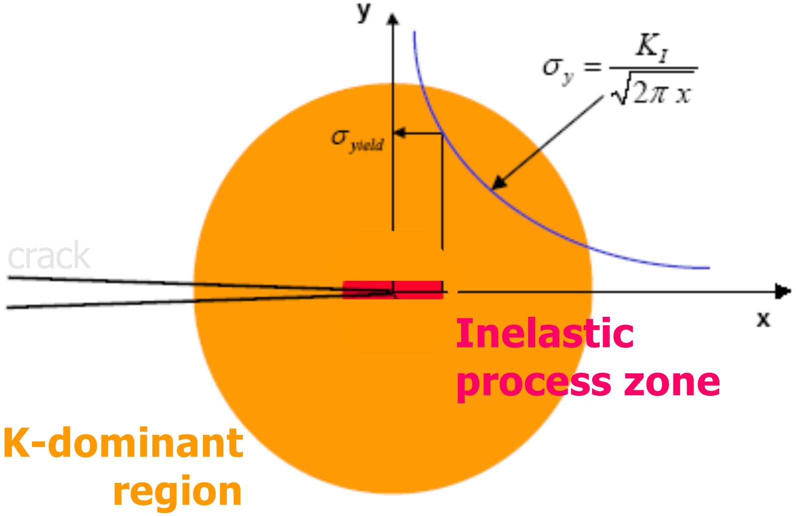


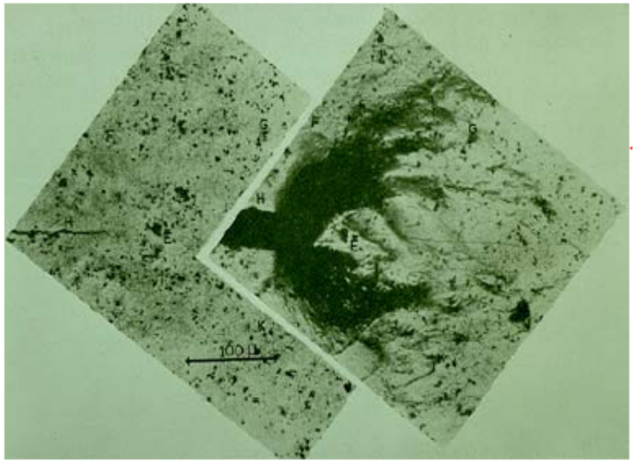


Optical satellite images, Landers earthquake, Milliner et al (2015)

A perspective from fracture mechanics

Linear elastic fracture mechanics (LEFM) predicts
a stress singularity at the rupture front



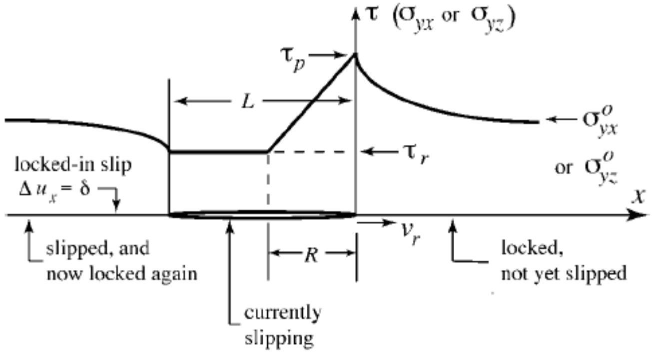


Process zone formation in Al-Cu-Mg alloy, From Broek, Elementary Engineering Fracture Mechanics, 3d Edit, 1982.

The stress concentration must be physically accommodated by nonlinear material behavior (damage, plasticity, micro-fractures)

Kostrov, Freund, Husseini, Kikuchi, Ida, Andrews (60-70s)

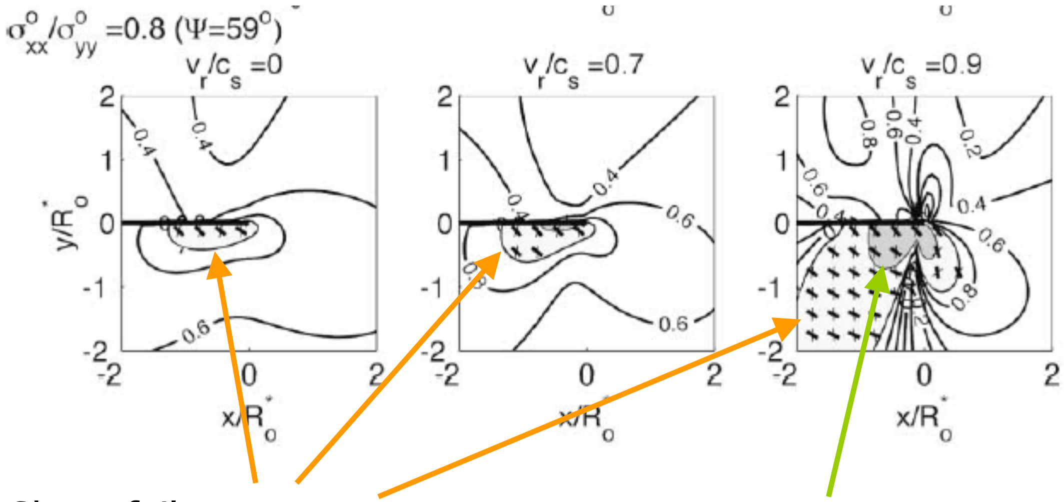
Predictions from a steady pulse rupture model
(Rice, Sammis and Parsons, 2005)



Characteristic size of off-fault damage zone:

$$R_o^* = \frac{9\pi F(0)}{16}\,\frac{\mu G}{(\tau_p - \tau_r)^2} = \frac{9\pi}{16(1-\upsilon)}\,\frac{\mu G}{(\tau_p - \tau_r)^2}$$

Estimates range from 1m to 1km



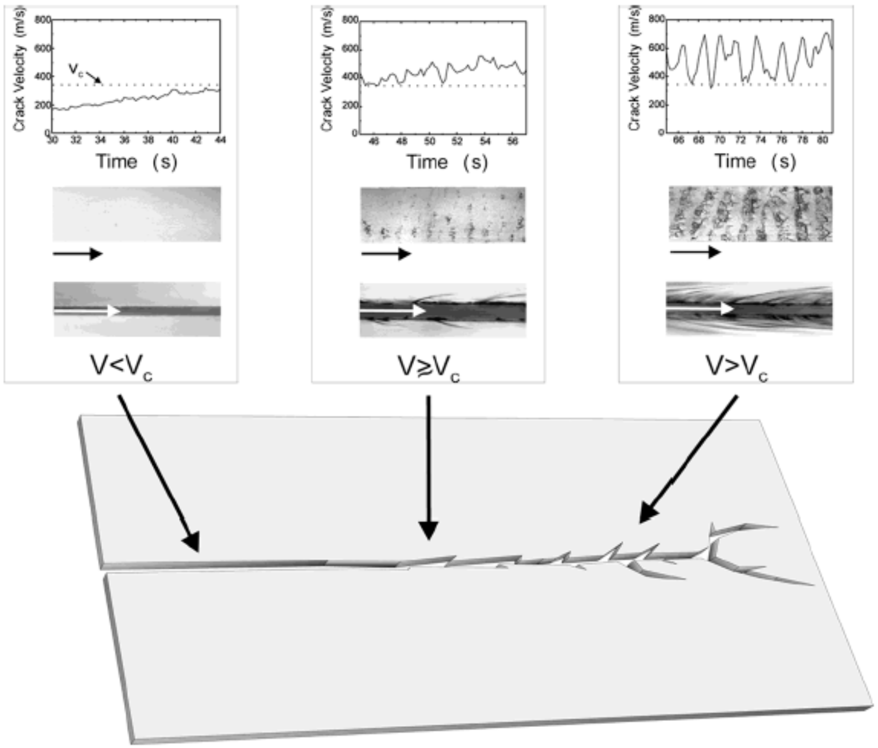
Contours of Coulomb stress outside the fault plane (>1 means failure)

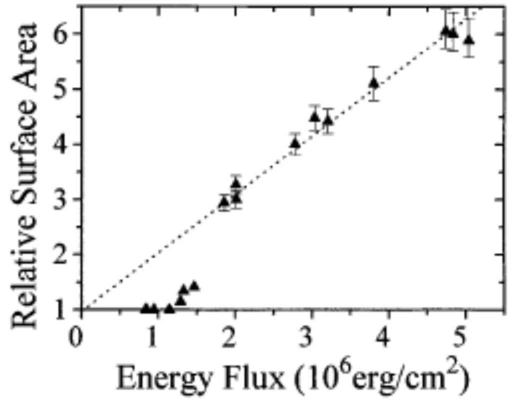
Shear failure zone

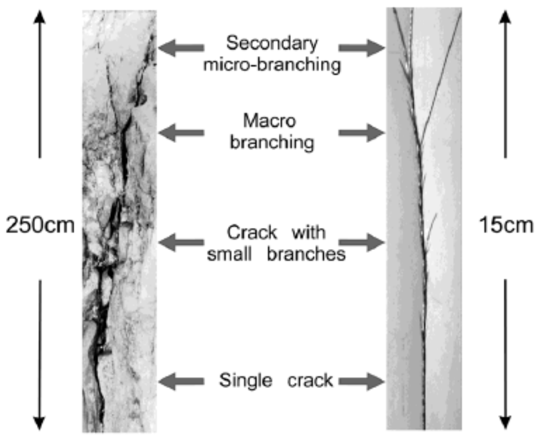
Tensile zone

- Sharon, Gross and Fineberg (PRL, 1996) “Energy dissipation in dynamic fracture”
- Sharon and Fineberg (1999) “The dynamics of fast fracture”

Laboratory mode I rupture (opening) in plexiglas with controlled energy flux



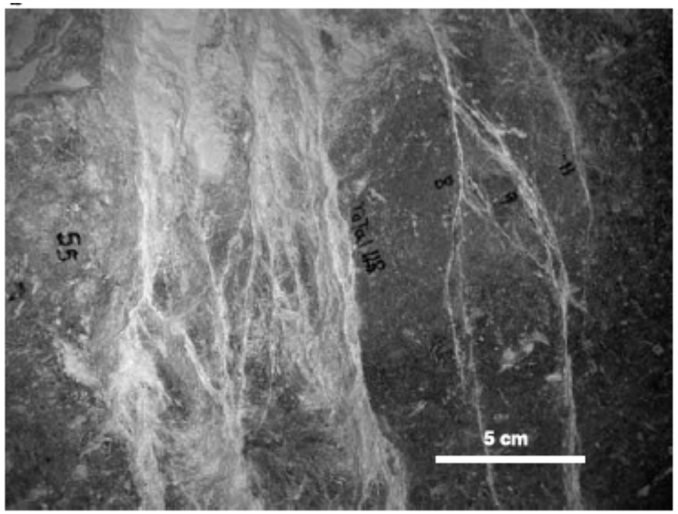


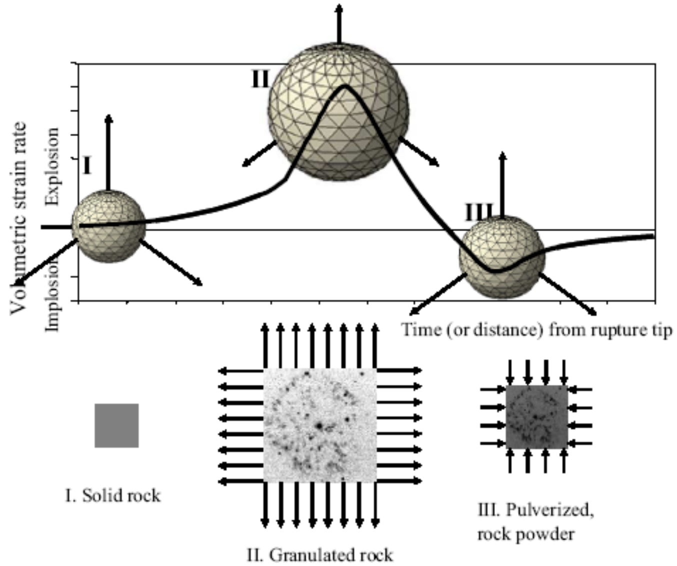


Natural fault vs. Plexiglas

- Wilson et al. (Nature, 2005) “Particle size and energetics of gouge from earthquake rupture zones”
- Reches and Dewers (EPSL, 2005) “Gouge formation by dynamic pulverization during earthquake rupture”

Fracture zone of the Bosman fault, a **new** fault in a deep South African mine (M3.7, max slip 0.4 m): coalescing fractures filled with gouge powder





Measured grain size distribution +multiple fracture branches

→surface energy ~ 2-10 MJ/m^2

Modeling of secondary micro-cracks generated by dynamic ruptures

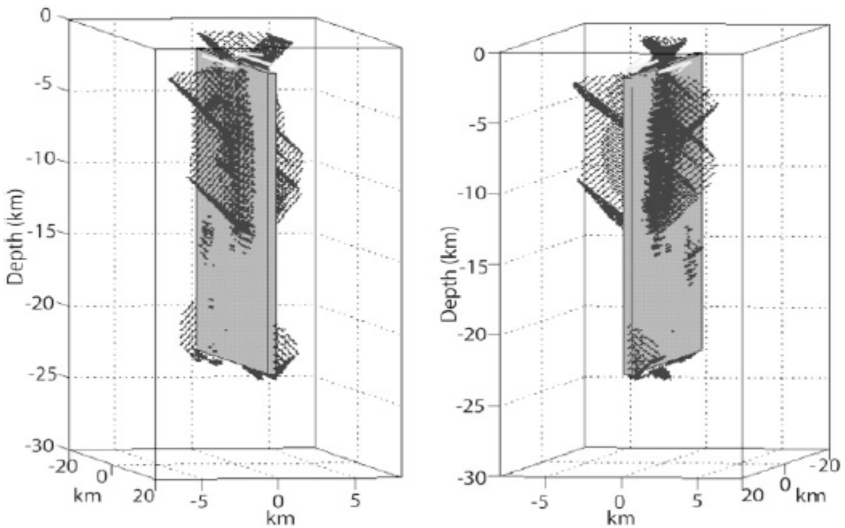
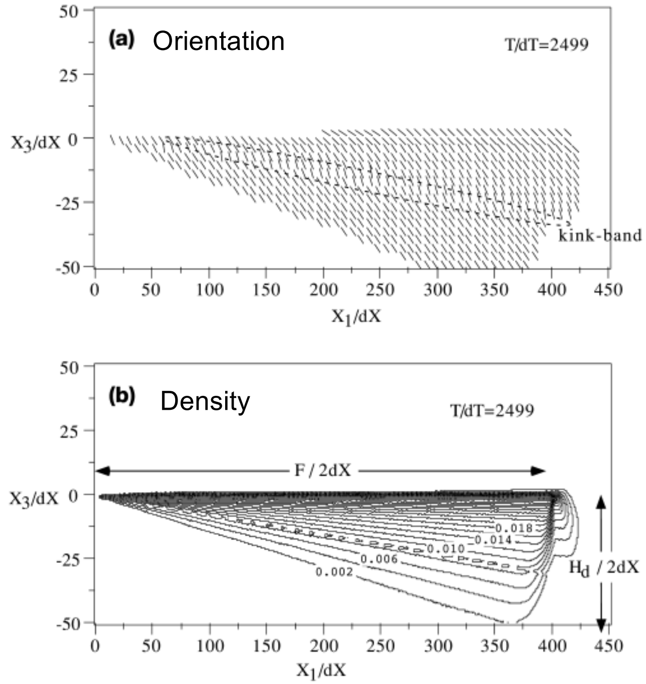


Figure 8. Two perspectives of the final stage of crack evolution for the 2000 Tottori earthquake dynamic simulation. The gray surface represents the shear crack on the pre-existing fault, and the dashed lines represents the tensile cracks.

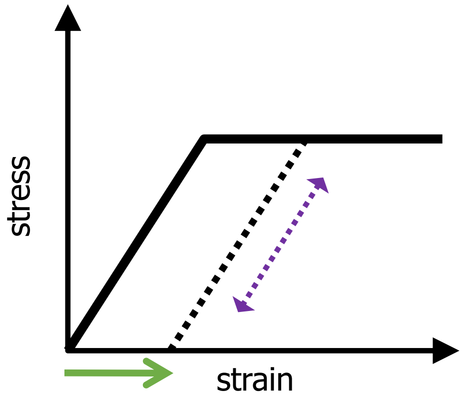
Dalguer et al (2003)



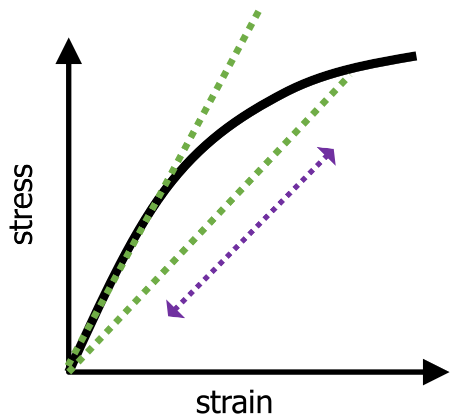
Yamashita (2000)

Continuum damage *vs.* plasticity

Plasticity



Damage



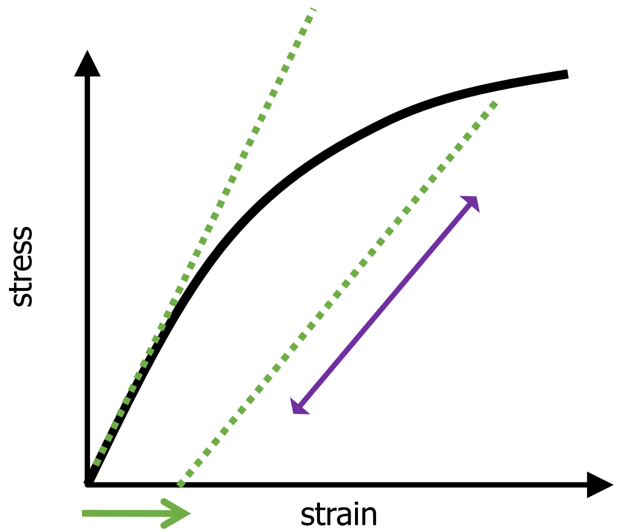
Plasticity describes the **generation of irreversible strains**

Damage describes **changes in elastic moduli** due to microcracking

Continuum damage and plasticity

Both can be combined:
irreversible strain and reduction of elastic moduli

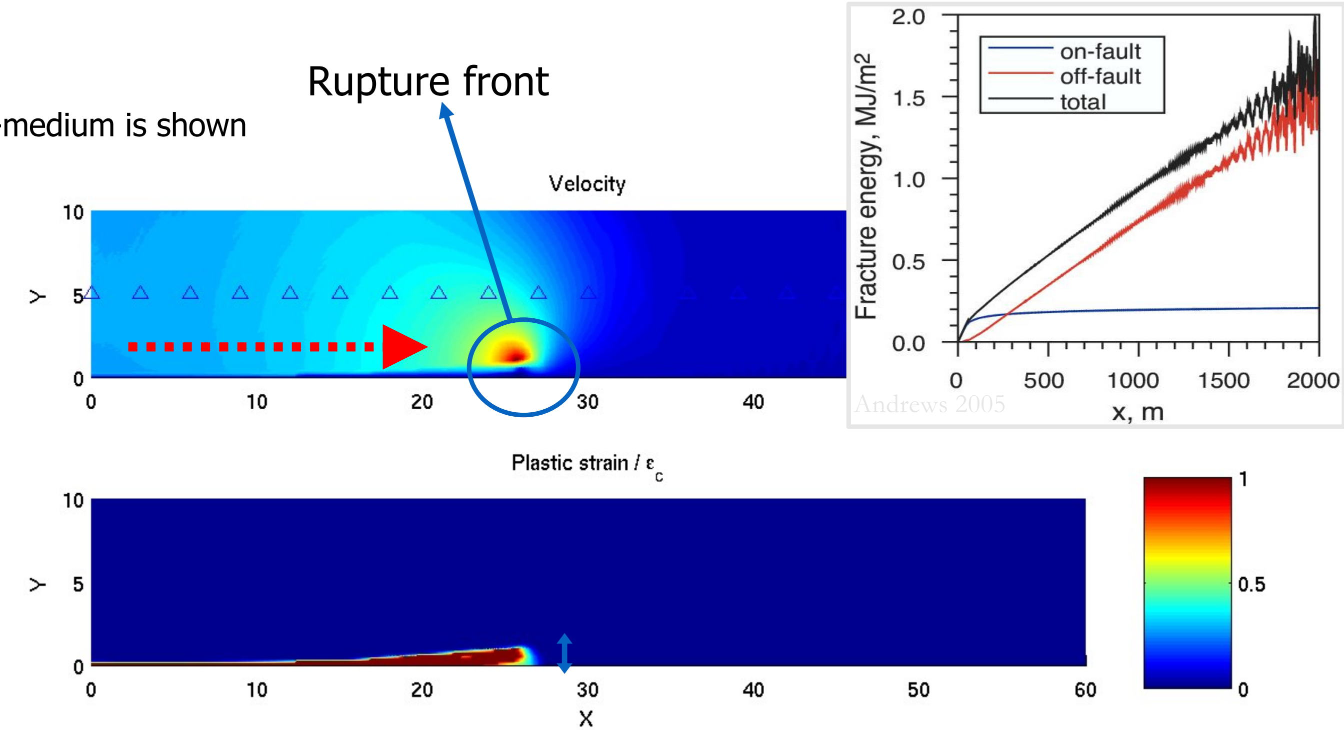
Damage +plasticity



Strain weakening visco-plasticity outside the fault plane

Only ¼-medium is shown

Rupture front



Andrews 2005

The thickness of the dissipation zone increases as the rupture grows

→ the "apparent" fracture energy increases with rupture length

Stable rupture speed and process zone size

Crack tip equation of motion:

$$\boldsymbol{G_c} = \boldsymbol{g}(\boldsymbol{v})\boldsymbol{G_0} = \boldsymbol{g}(\boldsymbol{v})\,\boldsymbol{\pi a}\frac{\boldsymbol{\Delta\tau^2}}{\boldsymbol{2\mu}}$$

Off-fault dissipation → scale-dependent total fracture energy $\boldsymbol{G_c} = \gamma a$

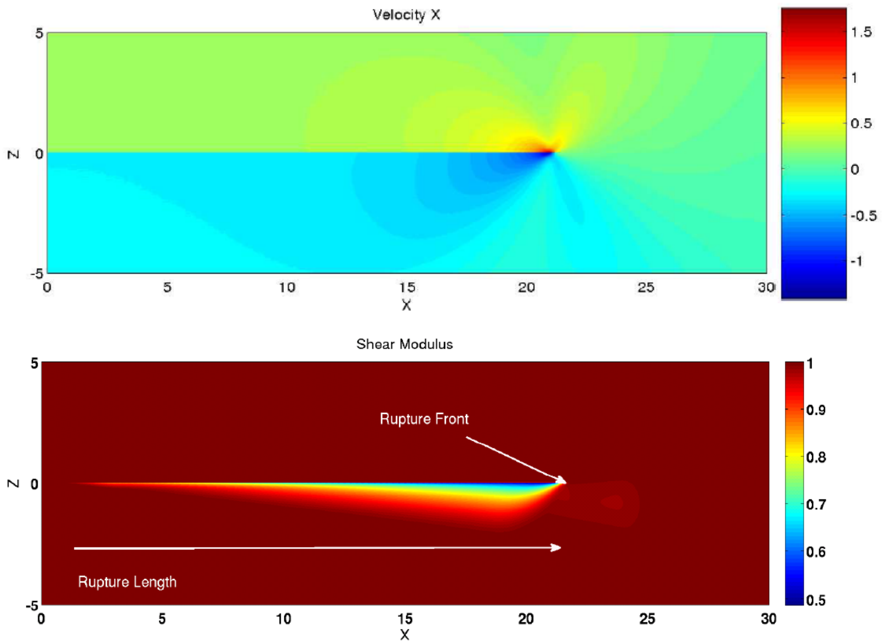
→ Steady rupture speed: $\boldsymbol{v} = \boldsymbol{g}^{-1}\left(\frac{2\gamma\mu}{\pi\Delta\tau^2}\right)$

→ Steady process zone size: $\Lambda = \sqrt{1 - v^2/\beta^2}\,\Lambda_0$

Continuum damage outside the fault

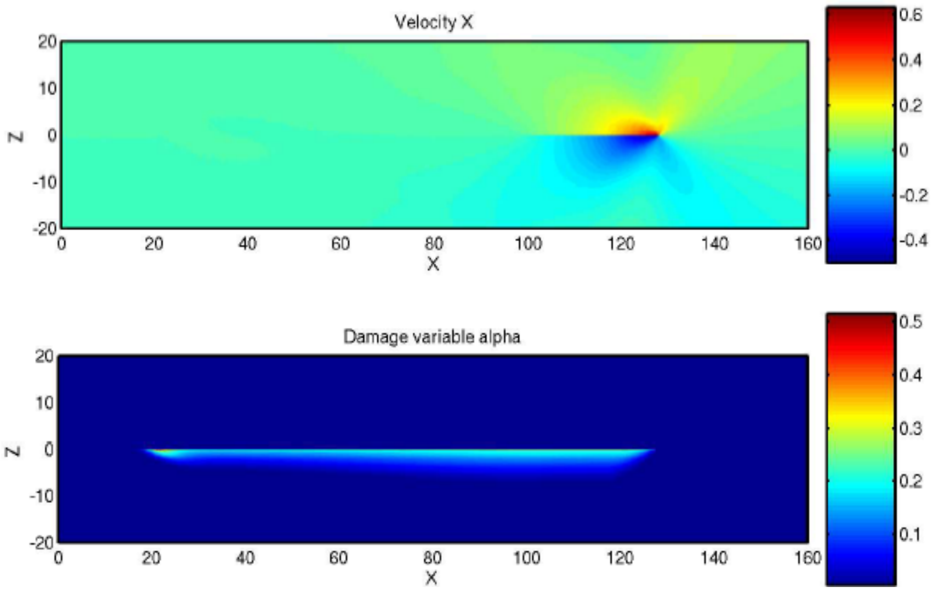
Dynamic simulations with a spectral element code (Ampuero et al, 2008)

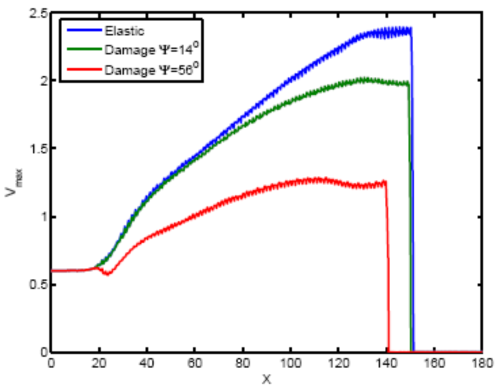
Self-similar crack ruptures develop growing damage zones



Continuum damage outside the fault

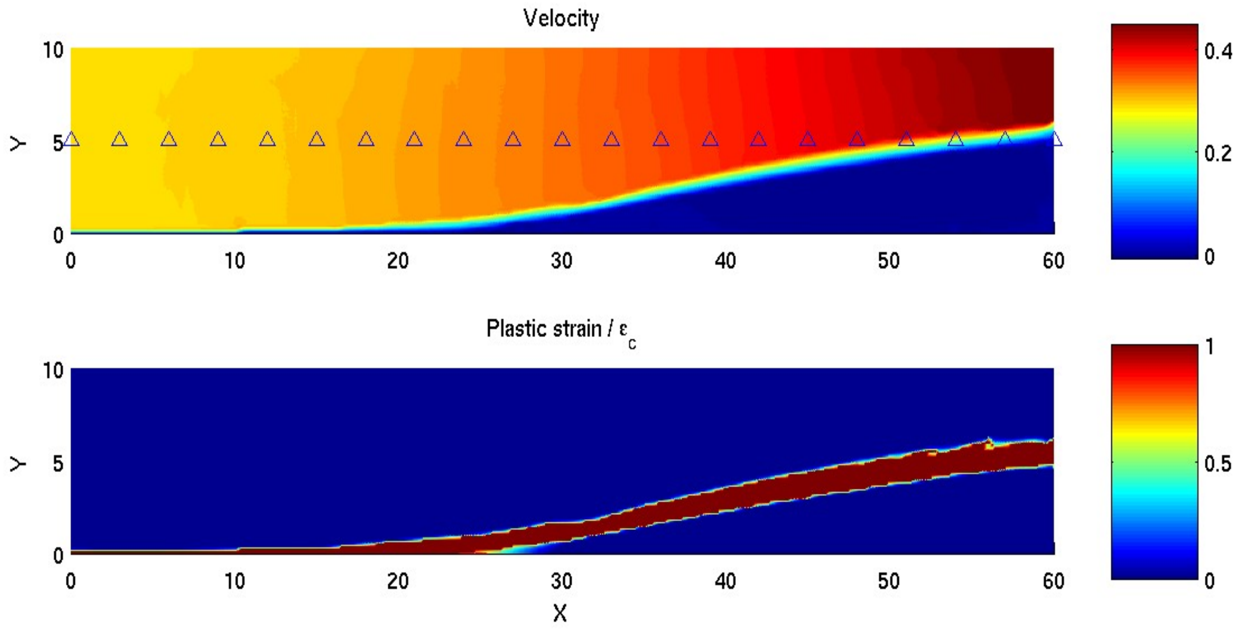
Self-similar pulse-like ruptures show similar features, but thinner damage zones controlled by the pulse width (rise time)





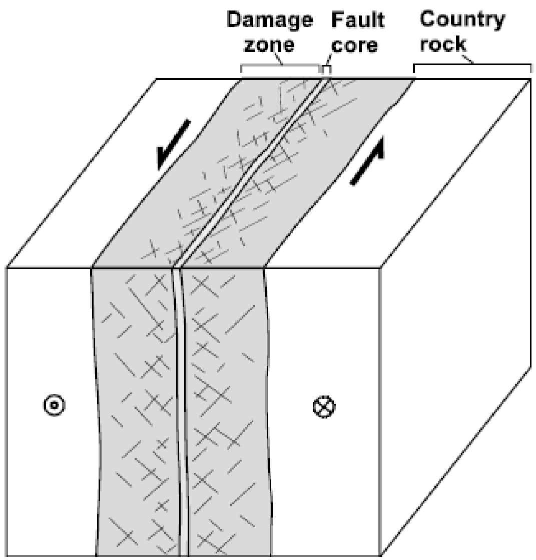
Dynamic off-fault damage reduces peak ground motions (Ampuero et al, 2008)

Strain weakening visco-plasticity outside the fault plane



Interesting problem: rupture branches out spontaneously when not guided by a weak fault plane

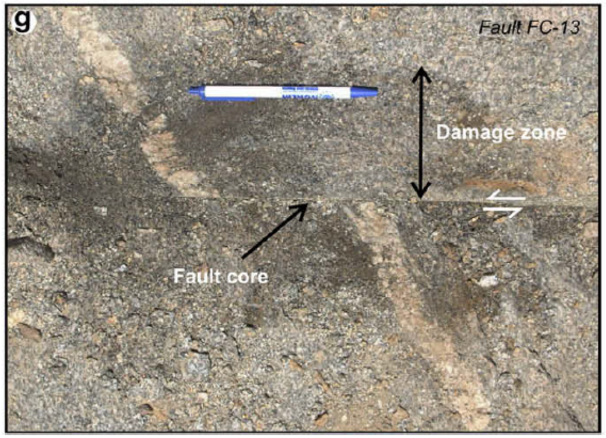
How do ruptures generate fault damage zones?

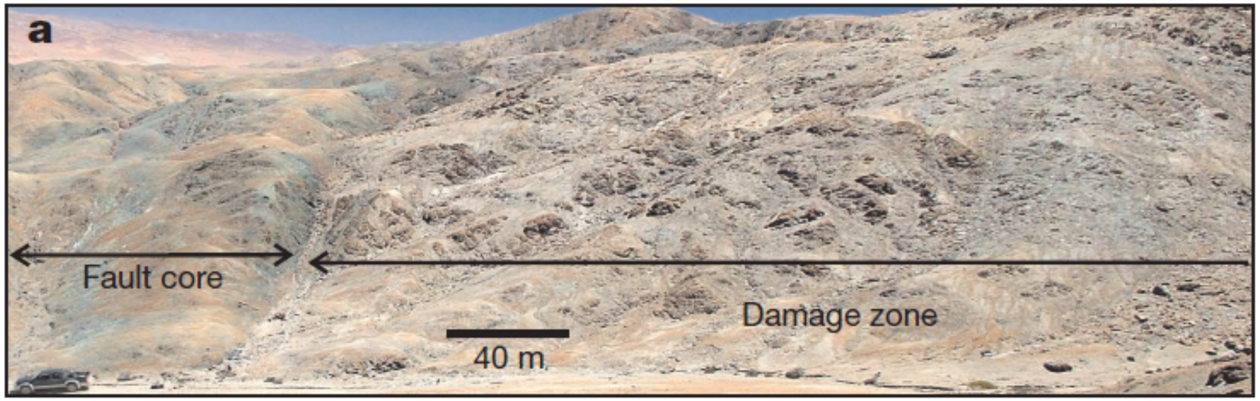


fault zone

Mitchell and Faulkner (2009)

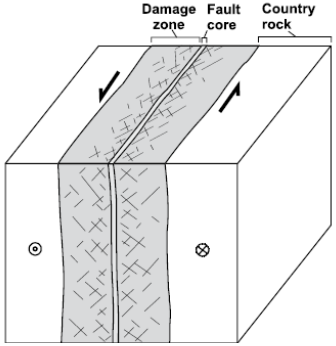
Damage zone thickness varies from a few centimeters to several hundred meters.



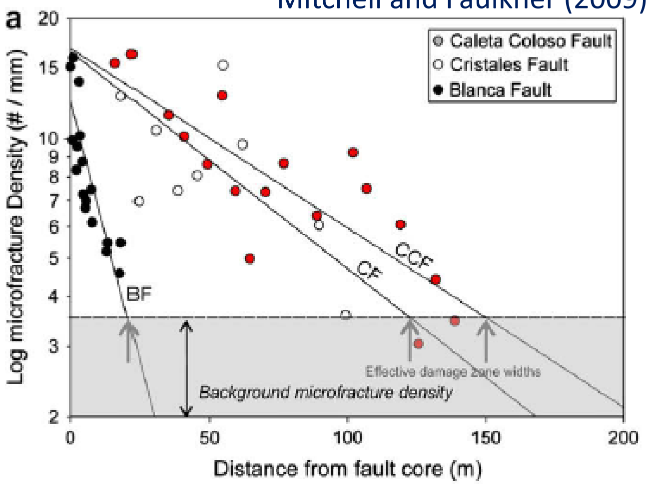


Faulkner et al. (2006)

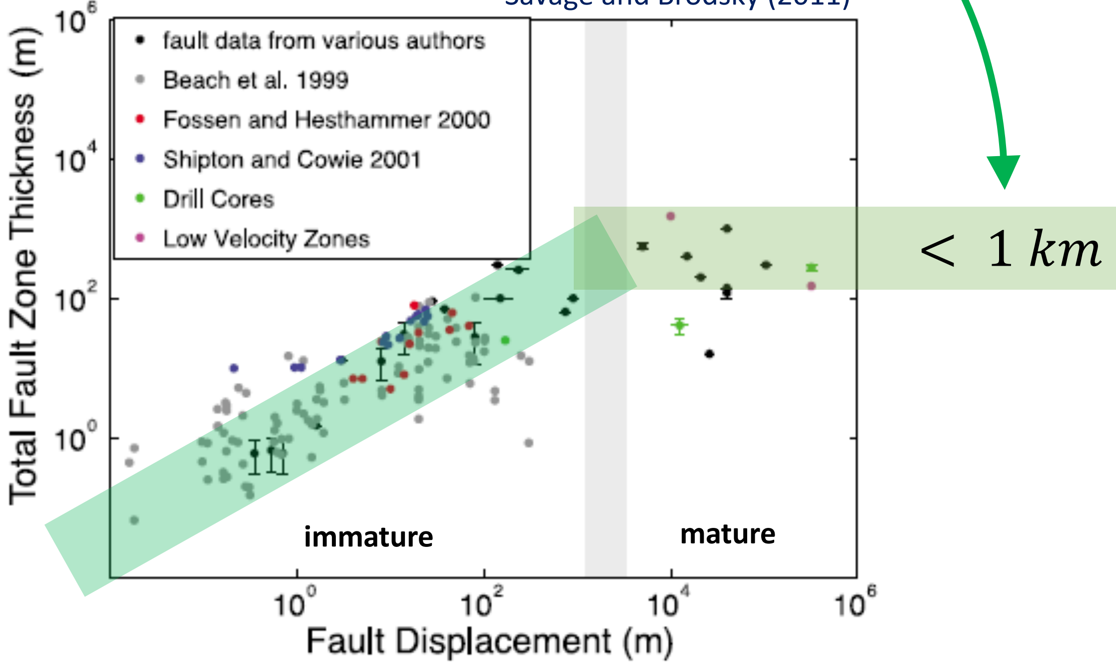
Damage zone thickness saturates at large fault displacement



Mitchell and Faulkner (2009)



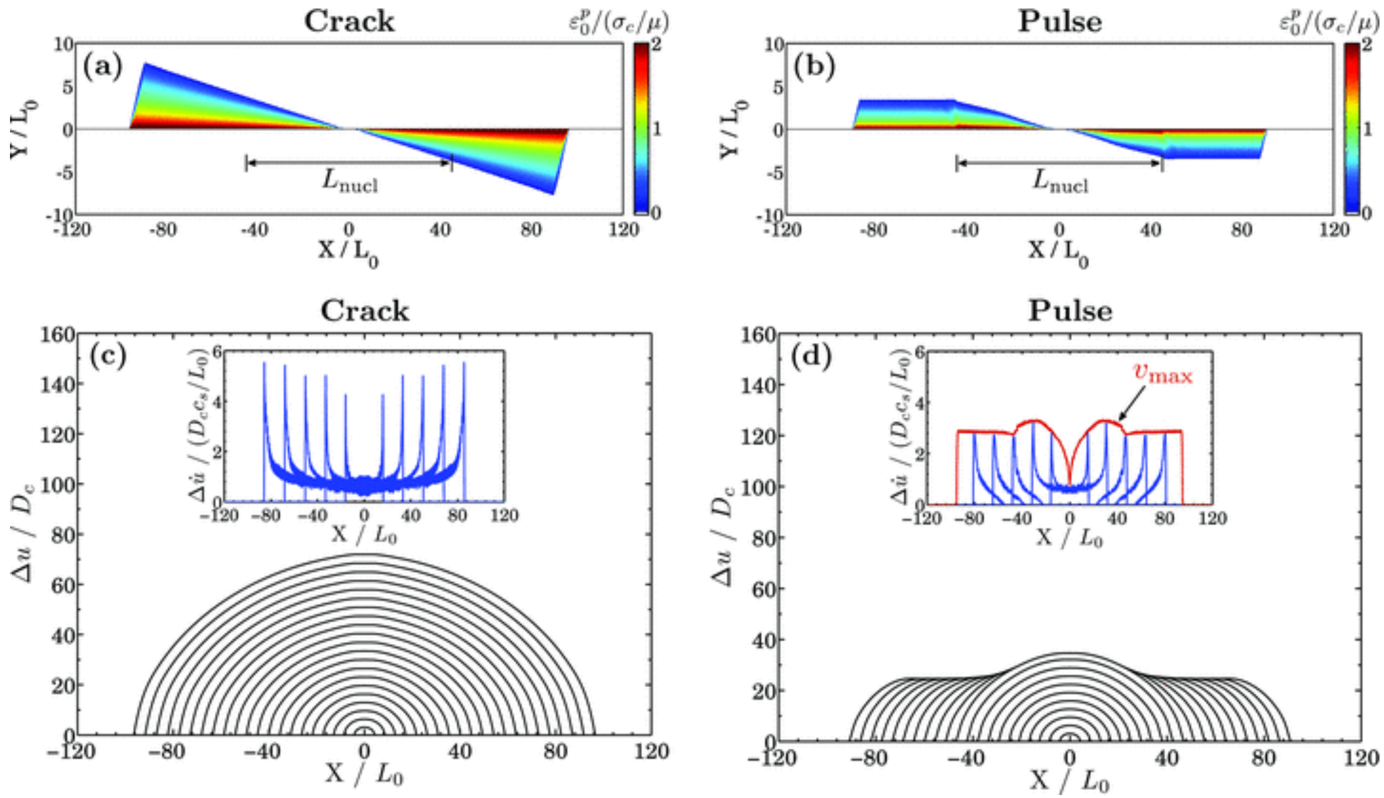
Savage and Brodsky (2011)



What limits the thickness of damage zones ?

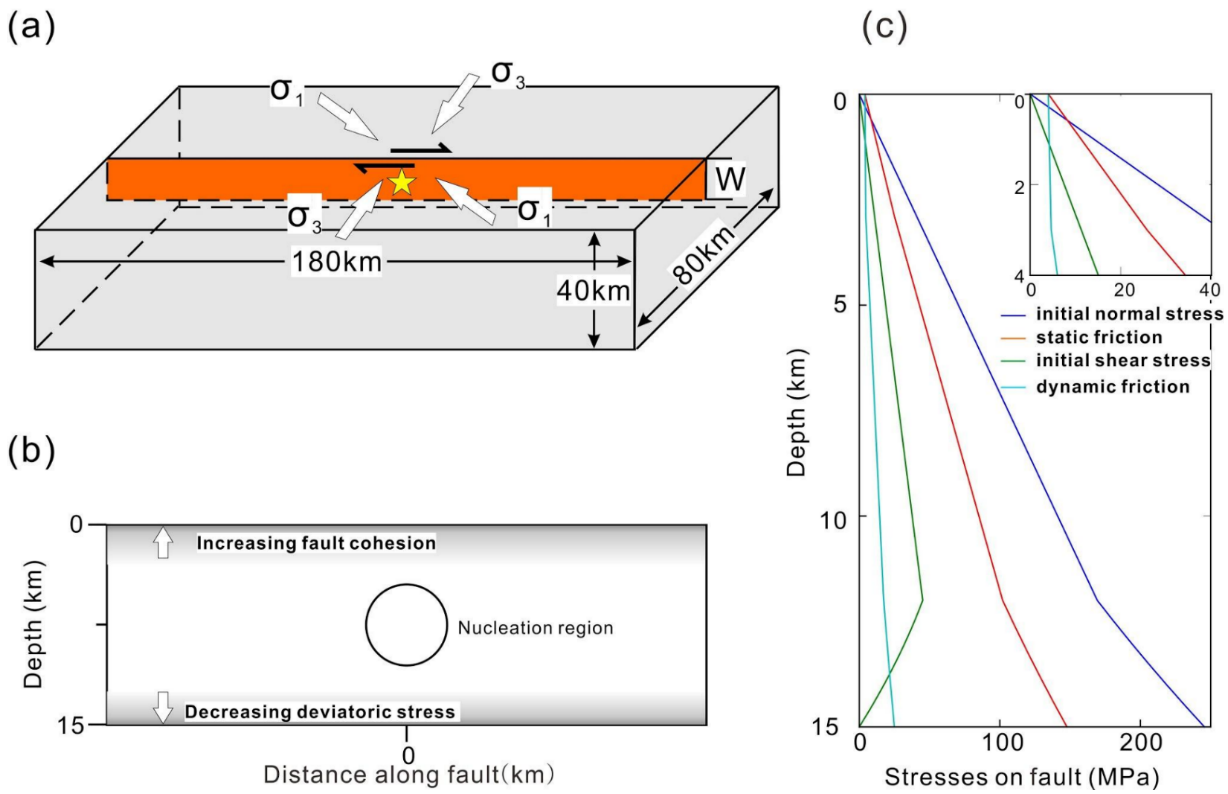
Ampuero and Mao (2017), Upper Limit on Damage Zone Thickness Controlled by Seismogenic Depth

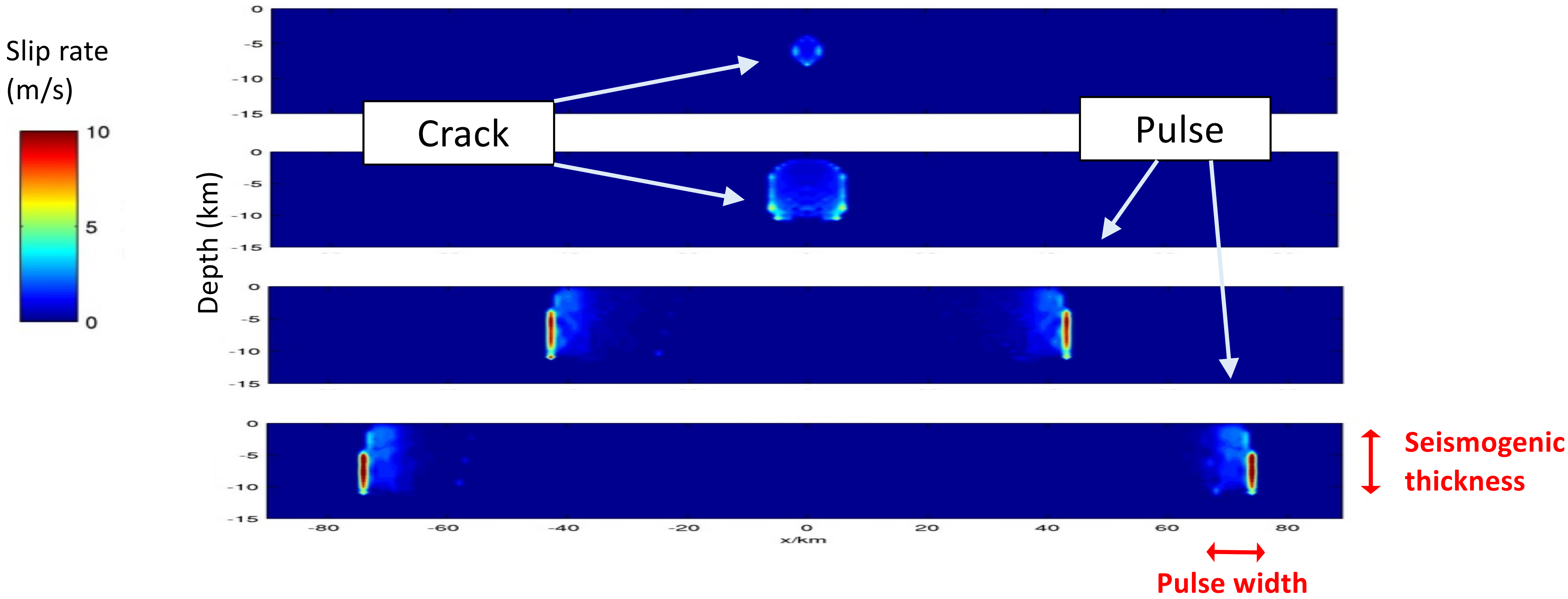
Coseismic off-fault inelastic deformation



Xu, Ben-Zion and Ampuero (2014)

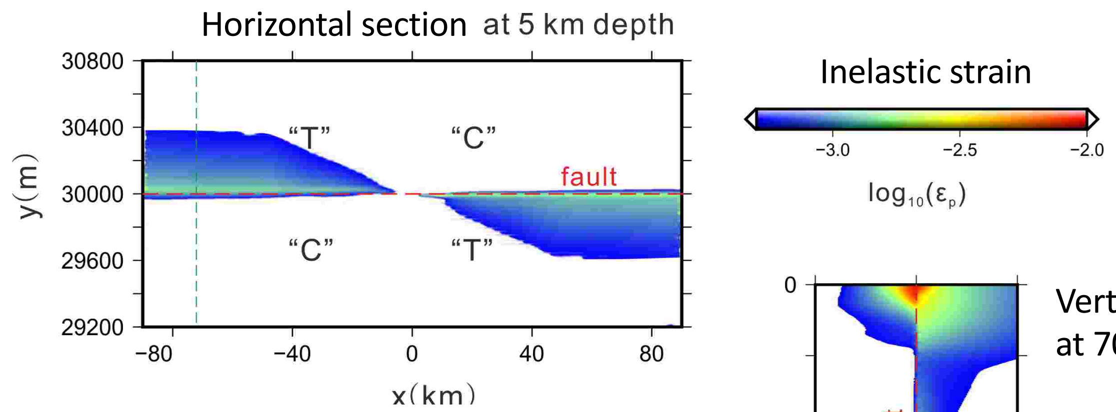
Dynamic rupture models with coseismic off-fault damage

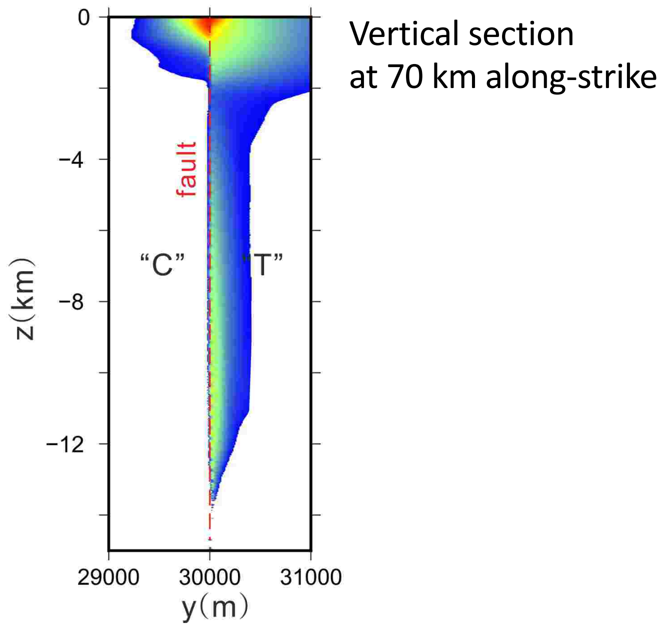


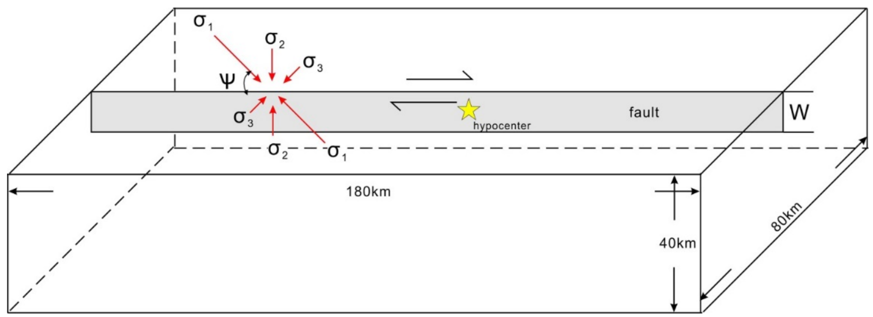


Slip rate
(m/s)
10
5
0
Depth (km)
Crack
Pulse
0
-5
-10
-15
-80
-60
-40
-20
0
20
40
60
80
x/km
Seismogenic
thickness
Pulse width

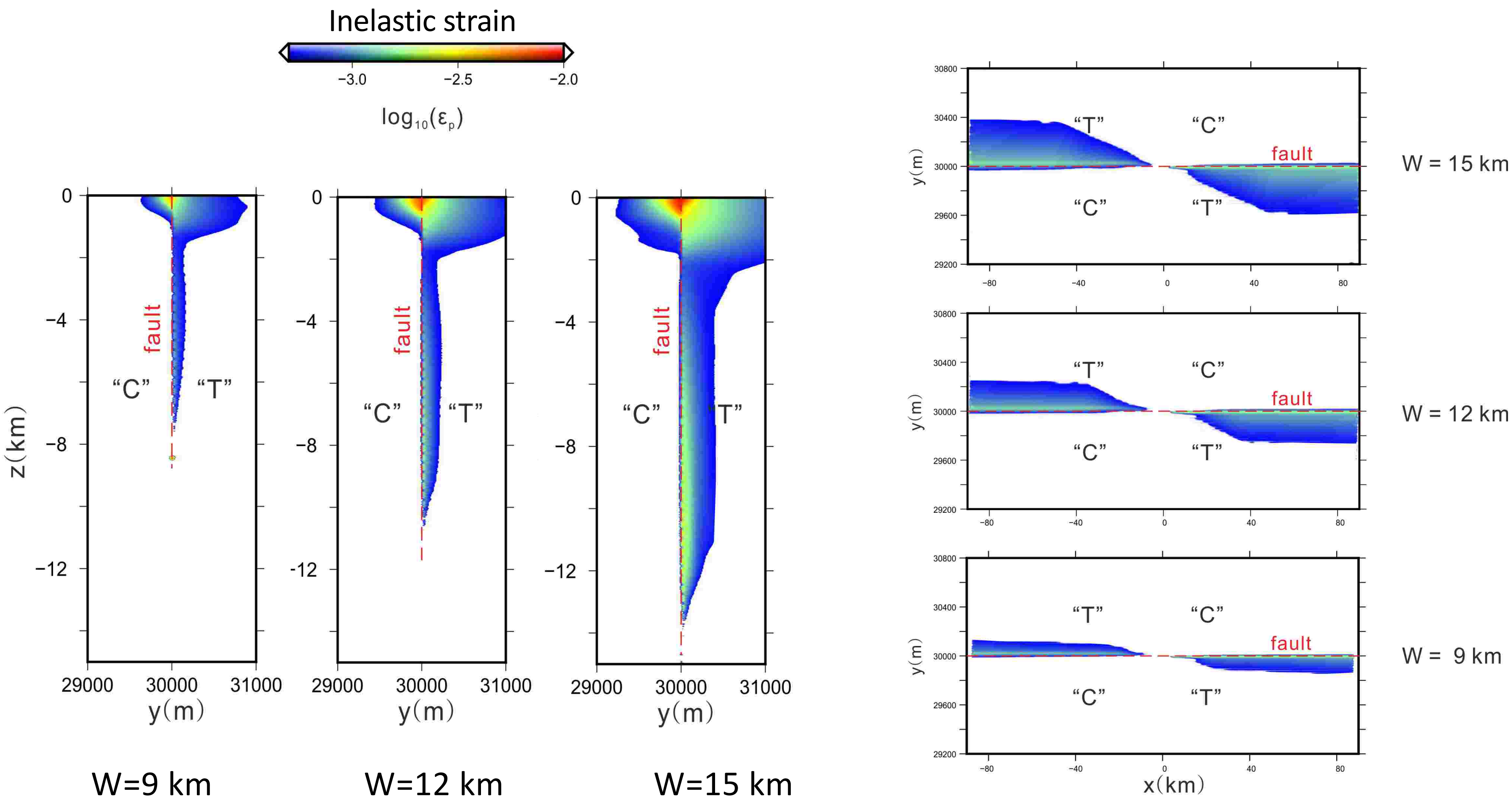
Plastic strain distribution (W=15 km)



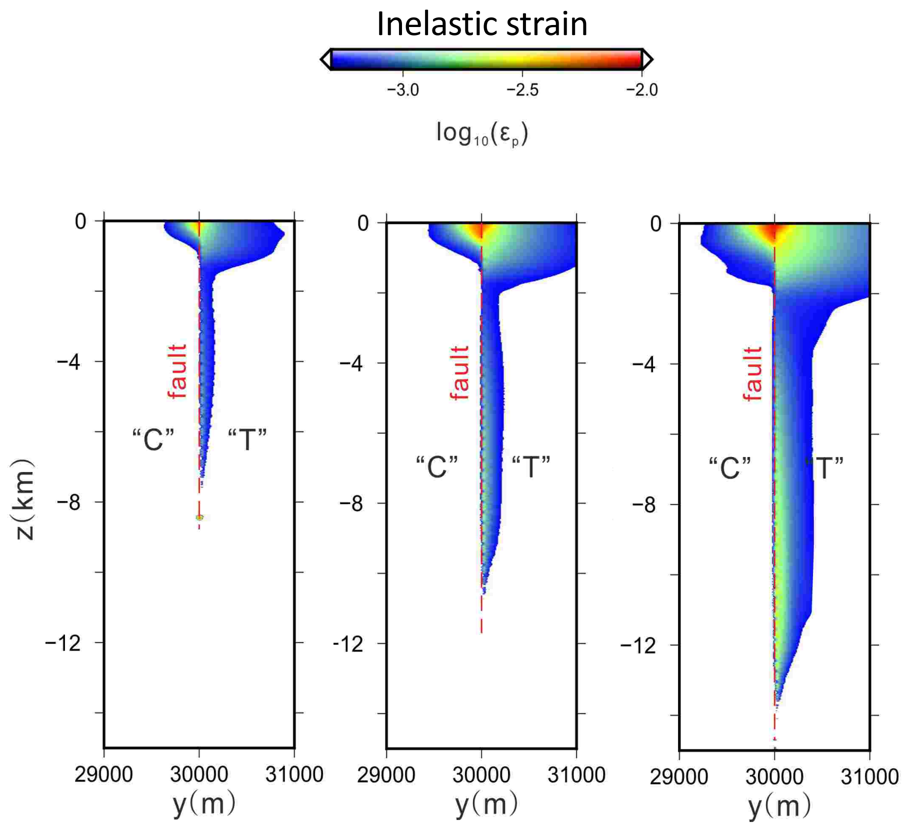




Inner damage zone thickness depends on seismogenic width



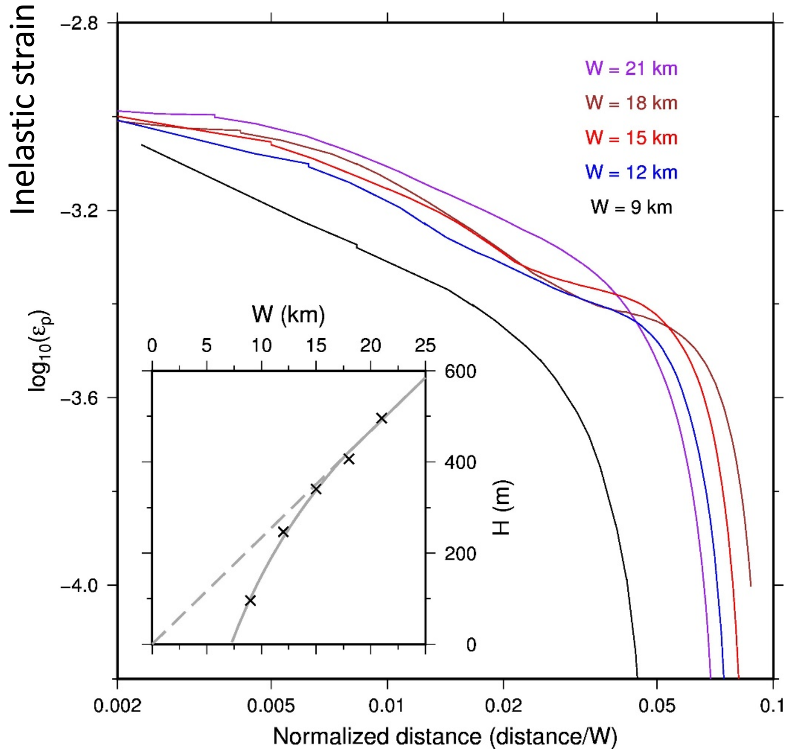
Inner damage zone thickness depends on seismogenic width



W=9 km

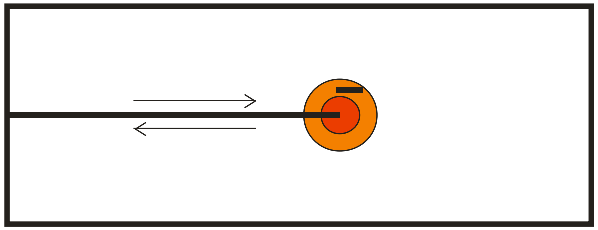
W=12 km

W=15 km

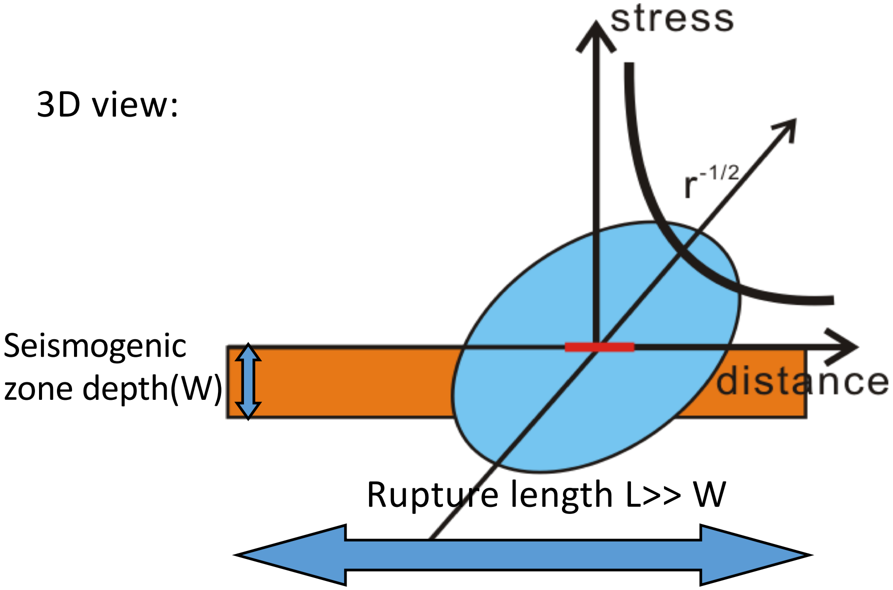


Fracture mechanics theory

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 ($W \ll L$)

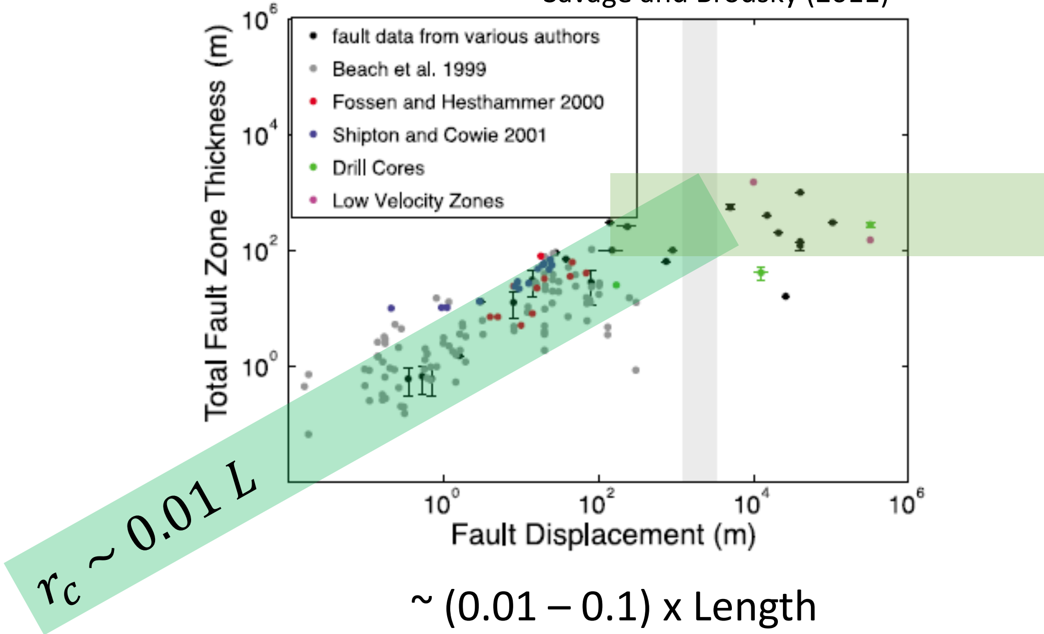
Damage zone size: distance at which $\tau = \tau_s$ (stress=yield strength)

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

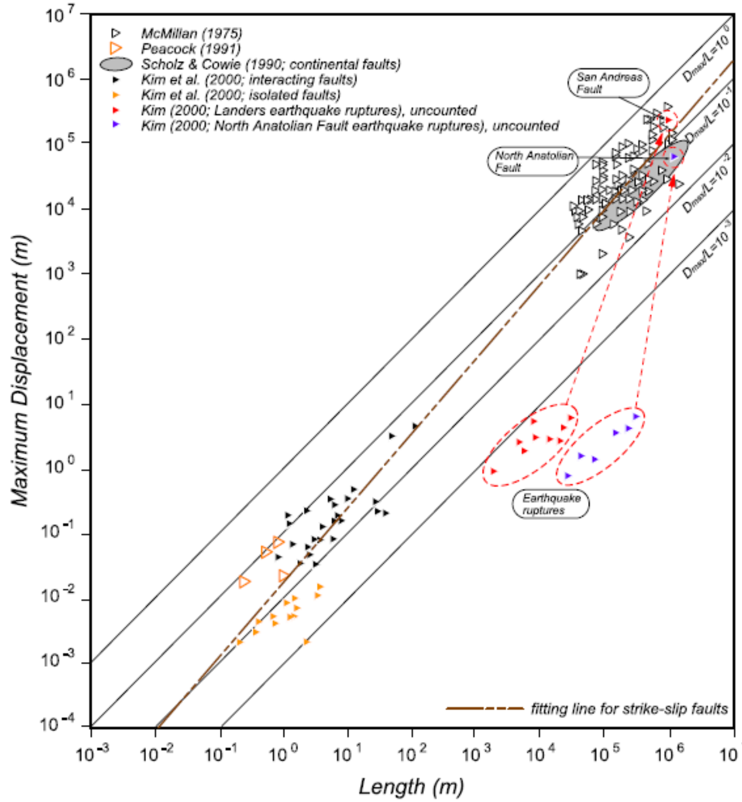
Relative stress drop

Inner damage zone thickness

Savage and Brodsky (2011)

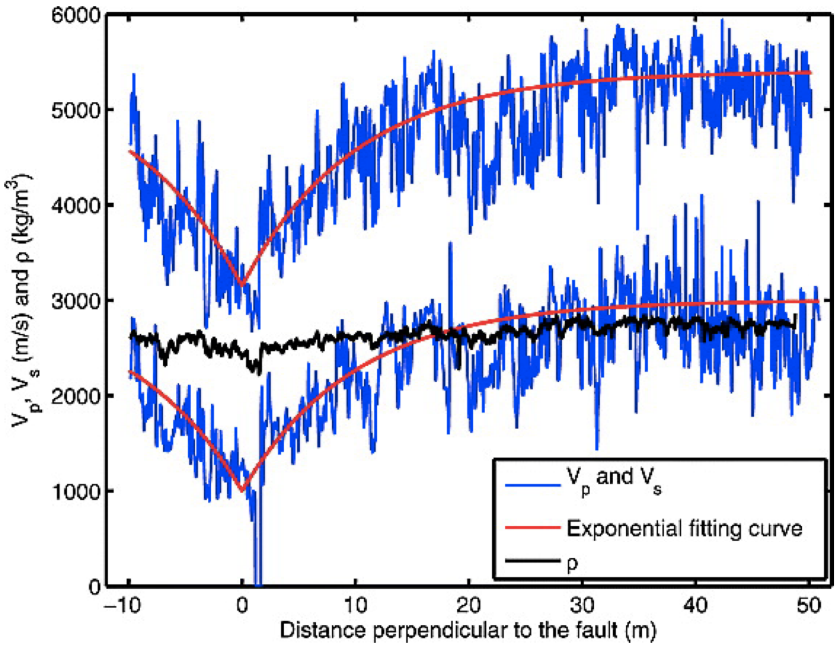


~ (0.01 – 0.1) x Length

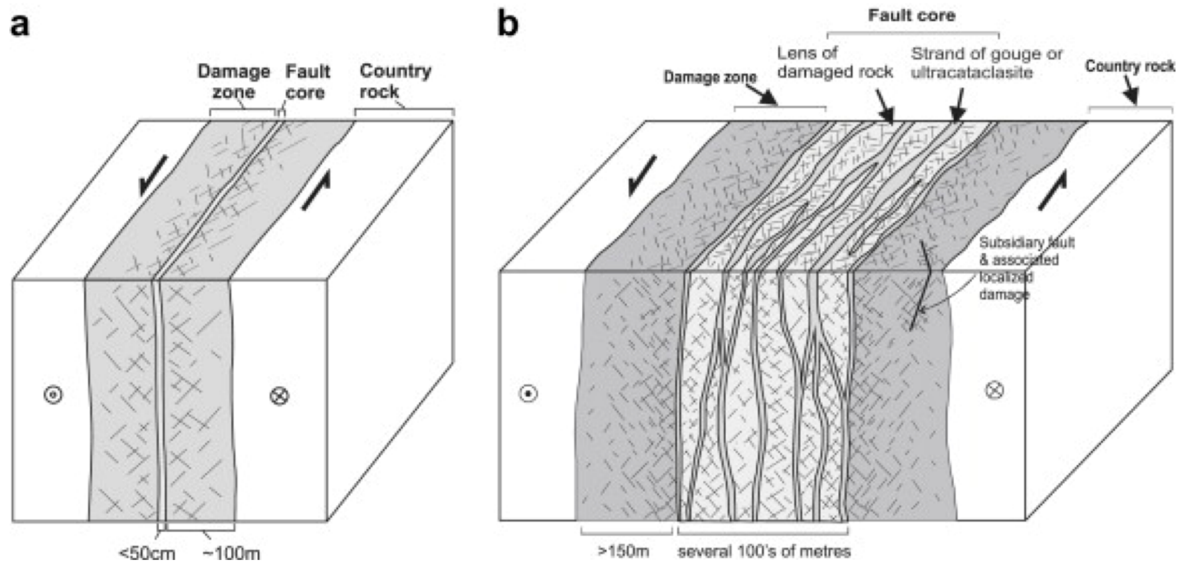


How does pre-existing damage affect ruptures?

Low velocity fault zones in nature

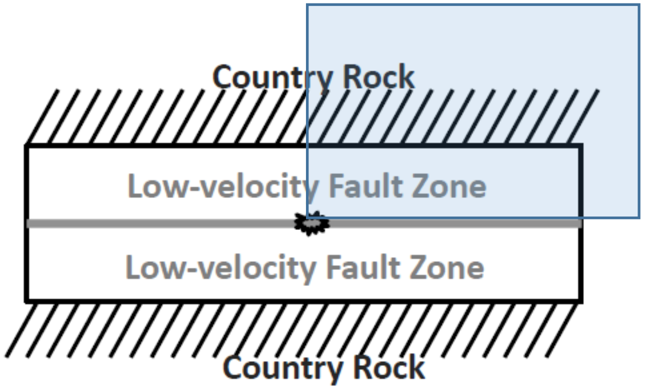


Huang & Ampuero 2011



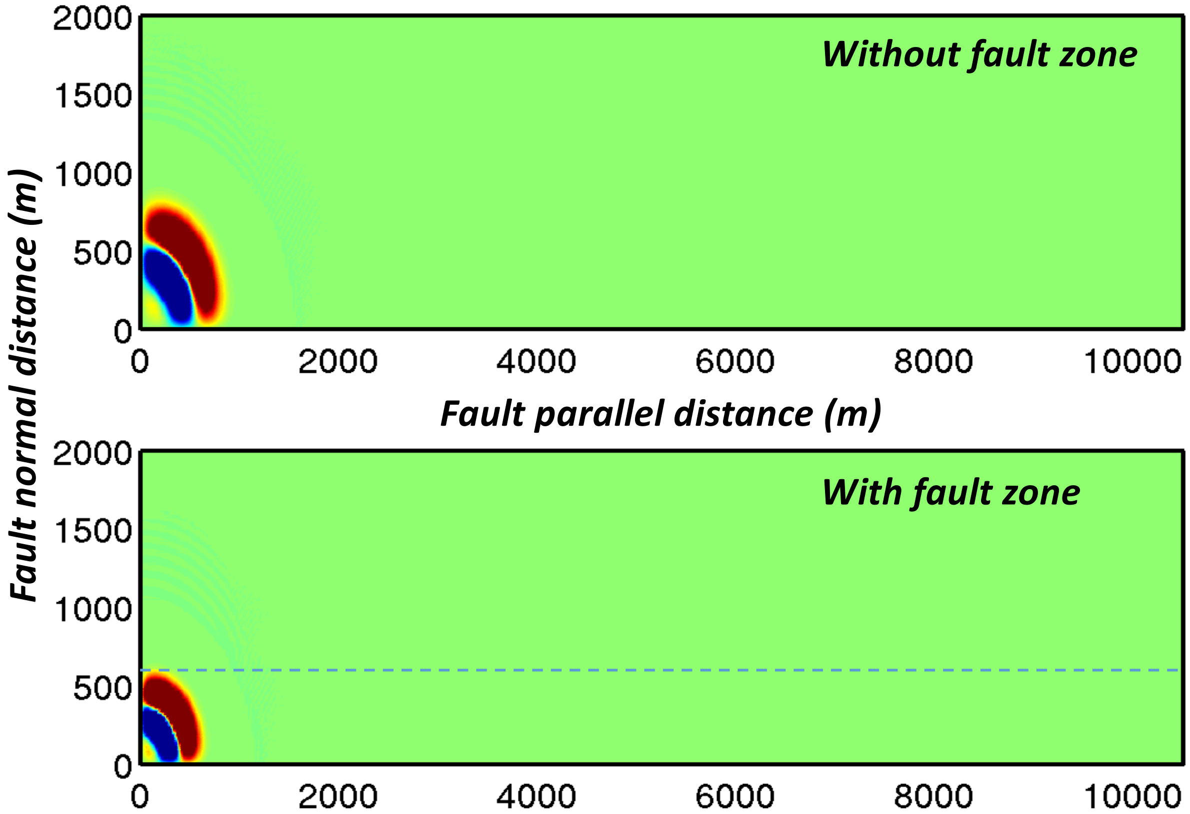
Mitchell & Faulkner 2009

Fault zone damage affects dynamic rupture

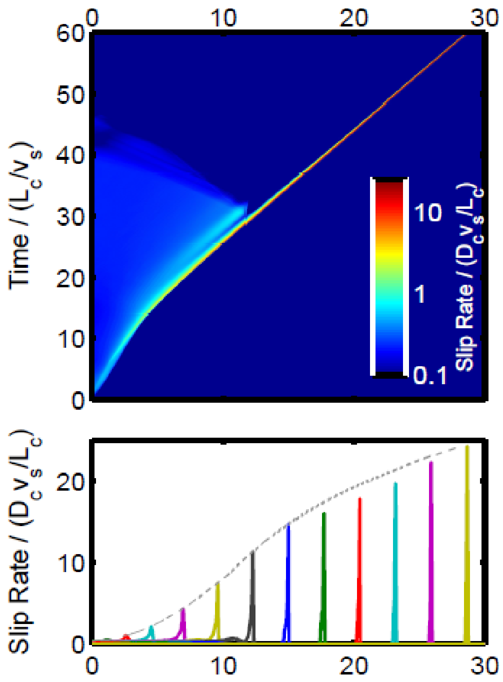


Dynamic rupture simulations on faults bisecting a damaged (low velocity) zone

Huang and Ampuero (2011)
Huang, Ampuero and Helmberger (2014, 2015)

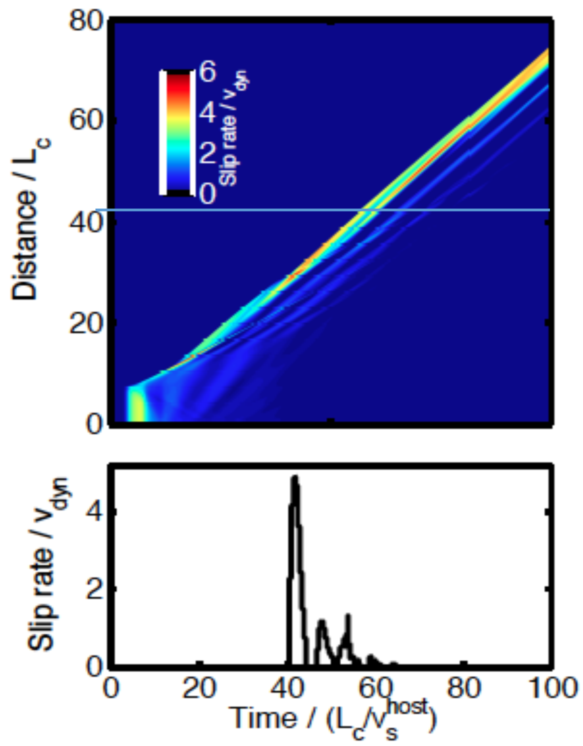


Fault zone damage affects dynamic rupture



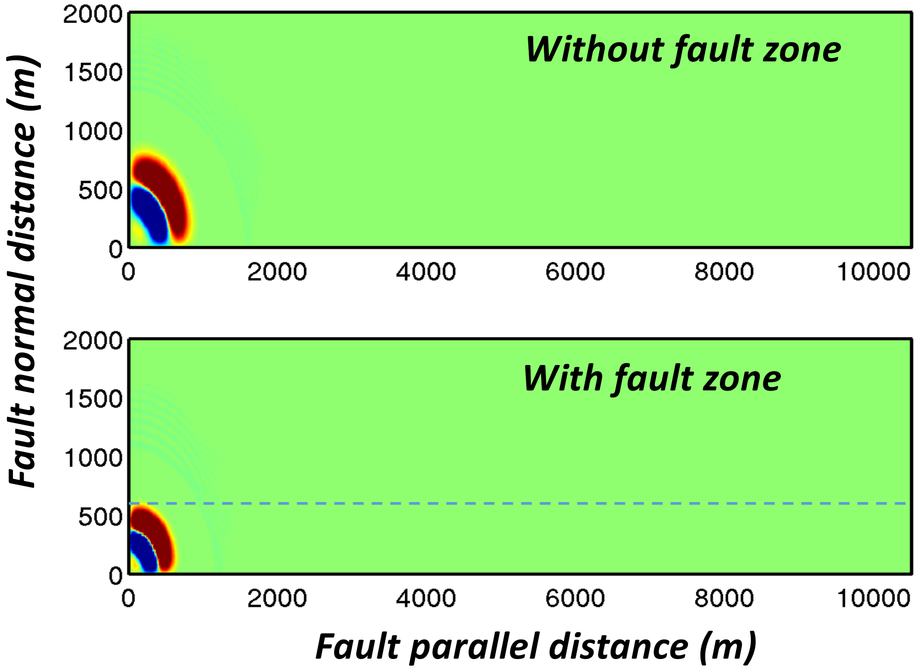
Fault zone effects:

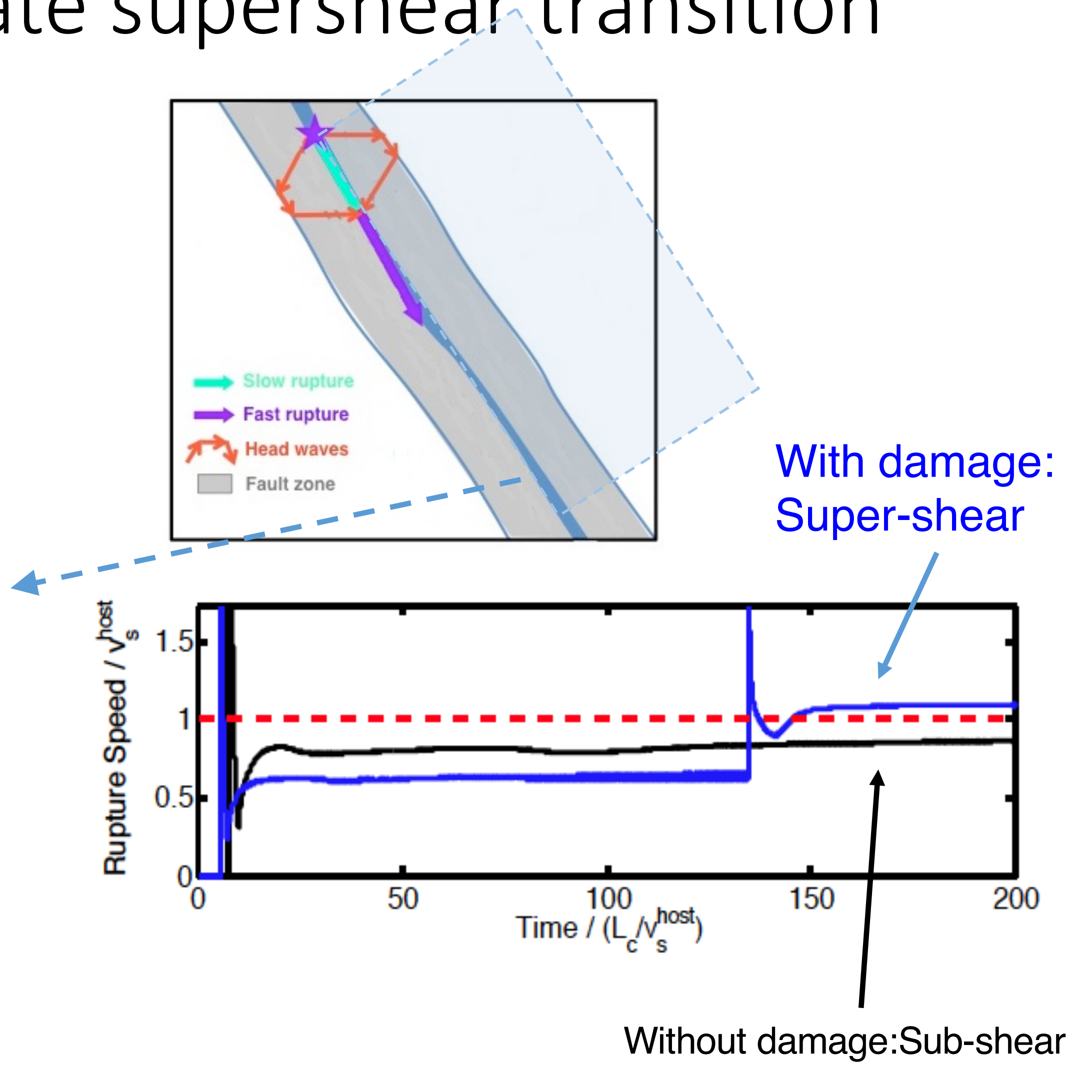
- Short rise time (slip pulses)
- Oscillatory slip rate (multiple pulses)
- Oscillatory rupture speed
- Supershear transition at low stress
- **Rupture at unexpected speeds**
- Spatially periodic off-fault damage patterns
- **Holes in radiated spectra**



Huang and Ampuero (2011)
Huang, Ampuero and Helmberger (2014)

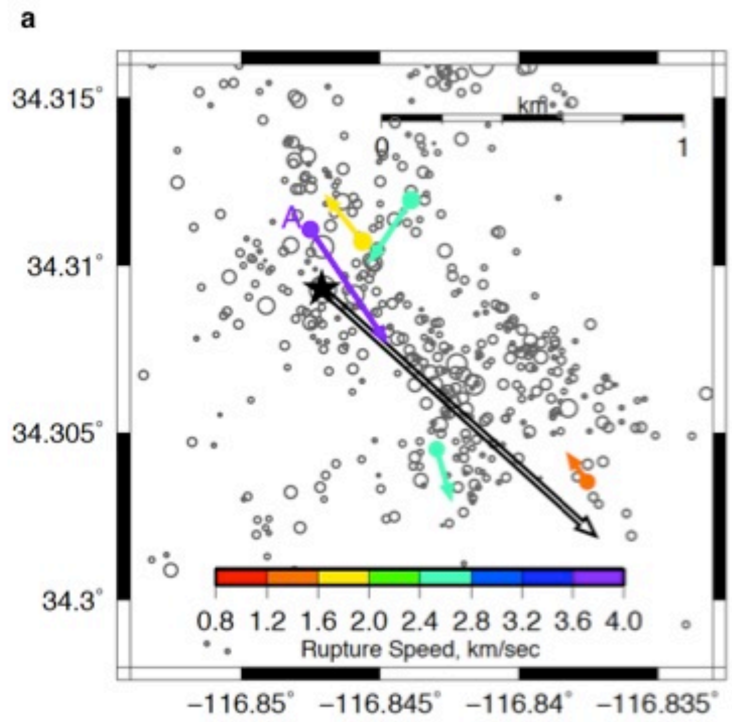
Fault zone waves facilitate supershear transition

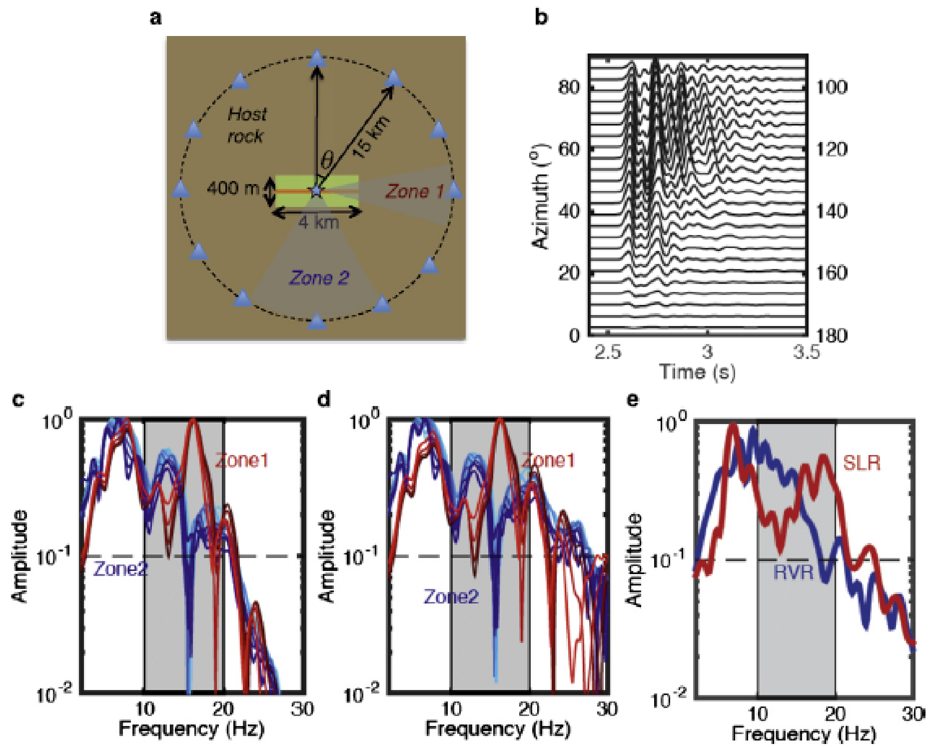




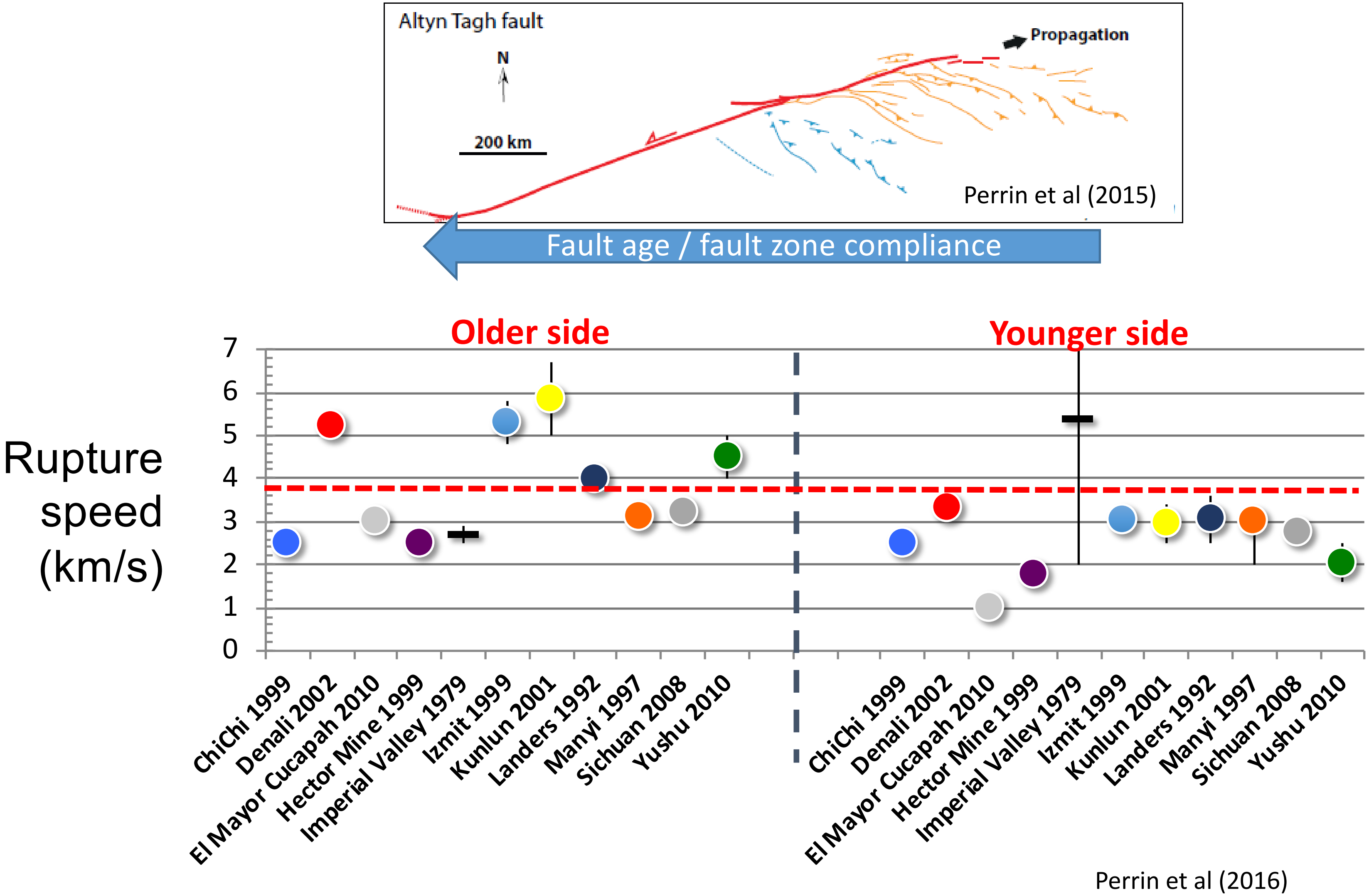
Huang and Ampuero (2011)
Huang, Ampuero and Helmberger (2014, 2015)

Evidence of rupture speed enhanced by fault zones in **microearthquakes**



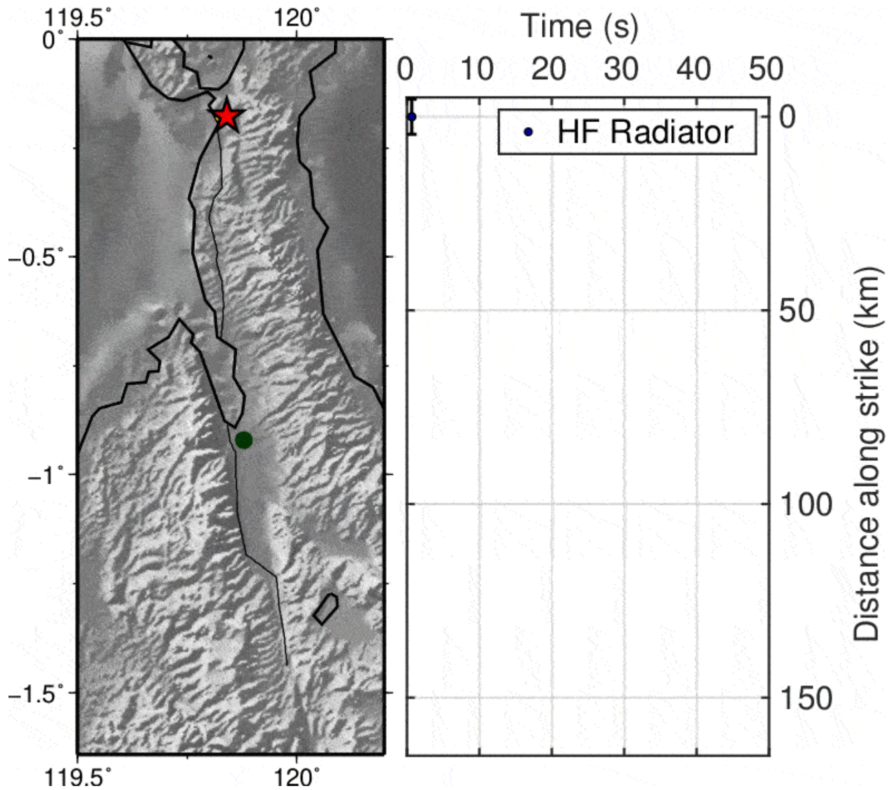


Huang, Ampuero and Helmberger (2015)



Altyn Tagh fault
N
200 km
Propagation
Perrin et al (2015)
Fault age / fault zone compliance
Older side
Younger side
Rupture speed (km/s)
7
6
5
4
3
2
1
0
ChiChi 1999
Denali 2002
El Mayor Cucapah 2010
Hector Mine 1999
Imperial Valley 1979
Izmit 1999
Kunlun 2001
Landers 1992
Manyi 1997
Sichuan 2008
Yushu 2010
Perrin et al (2016)

Fast rupture of the 2018 Mw 7.5 Palu earthquake



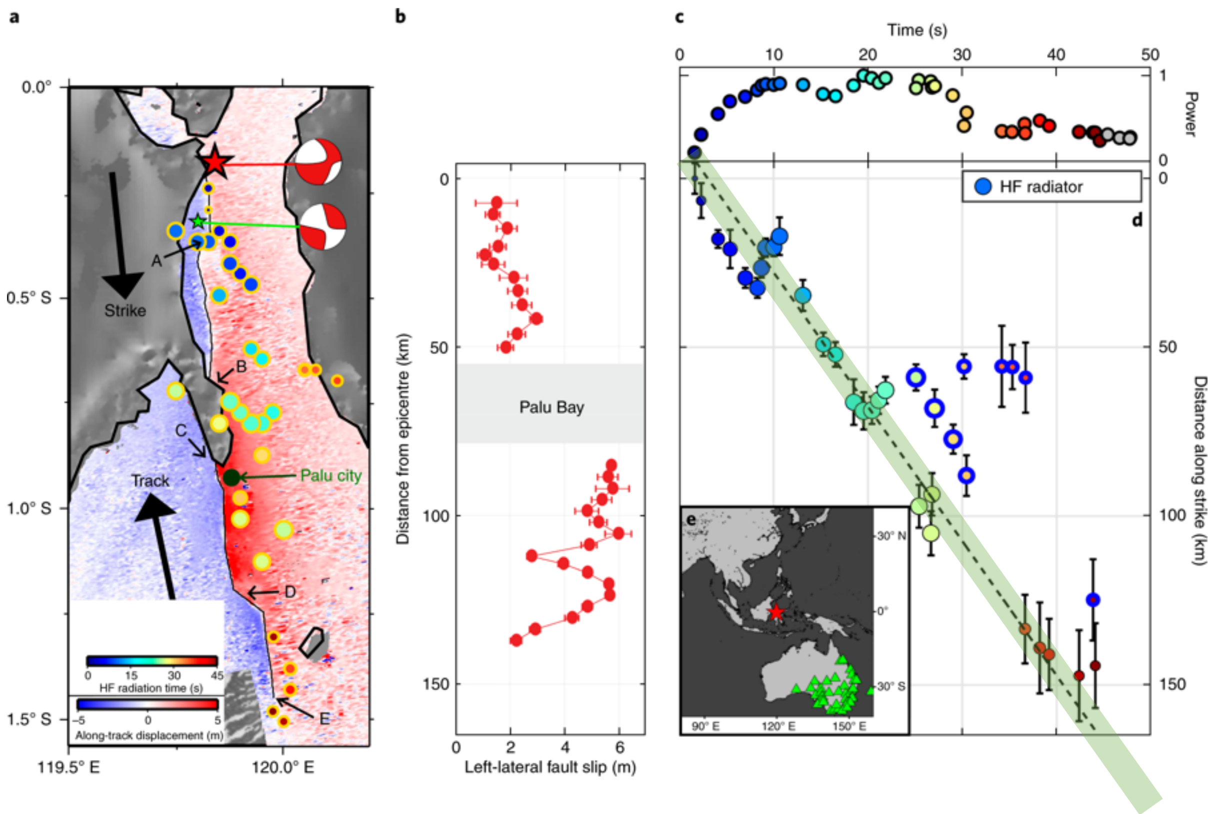
Teleseismic observations of rupture speed by back-projection rupture imaging

Southward rupture length ~150 km

A **supershear** earthquake:
Rupture speed faster than S waves

Steady and fast rupture despite large fault bends

Teleseismic observations of rupture speed



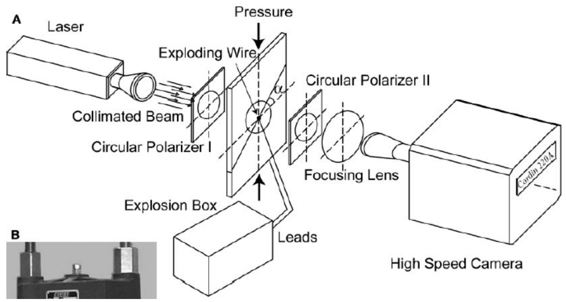
Rupture speed ≈ 4.1 km/s

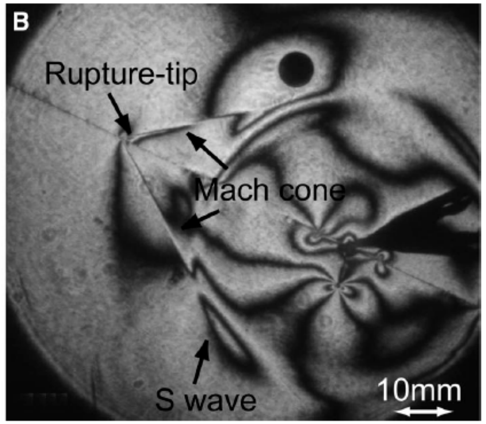
Fast speed from early on

Steady despite fault bends

Teleseismic observations of rupture speed
2. Surface wave Mach cone

Sonic boom of a super-sonic jet plane

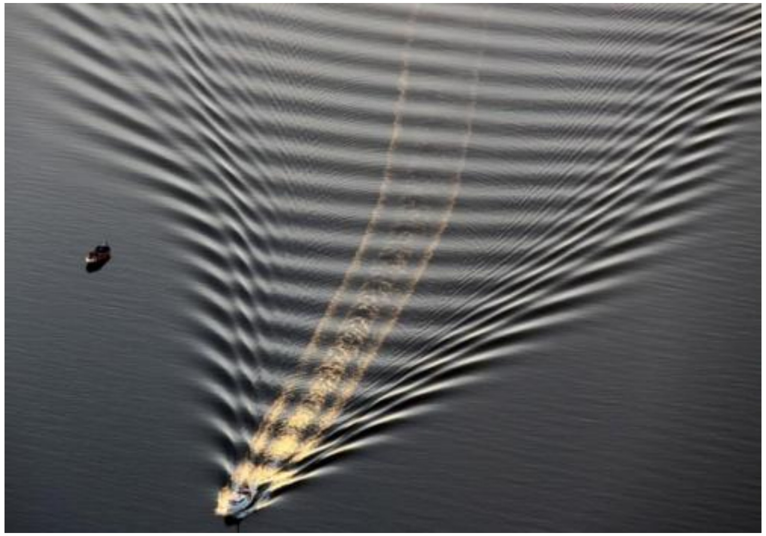




Supershear laboratory earthquake experiments in Ares Rosakis group (Caltech) (Xia *et al*, 2004)

Teleseismic observations of rupture speed
2. Surface wave Mach cone

Sonic boom of a super-sonic jet plane
(body wave analogy)



Wake of a fast boat
(surface wave analogy – dispersive)

See "Ship Wakes: Kelvin or Mach Angle?"
Rabaud & Moisy (PRL 2013)

Teleseismic observations of rupture speed
2. Surface wave Mach cone

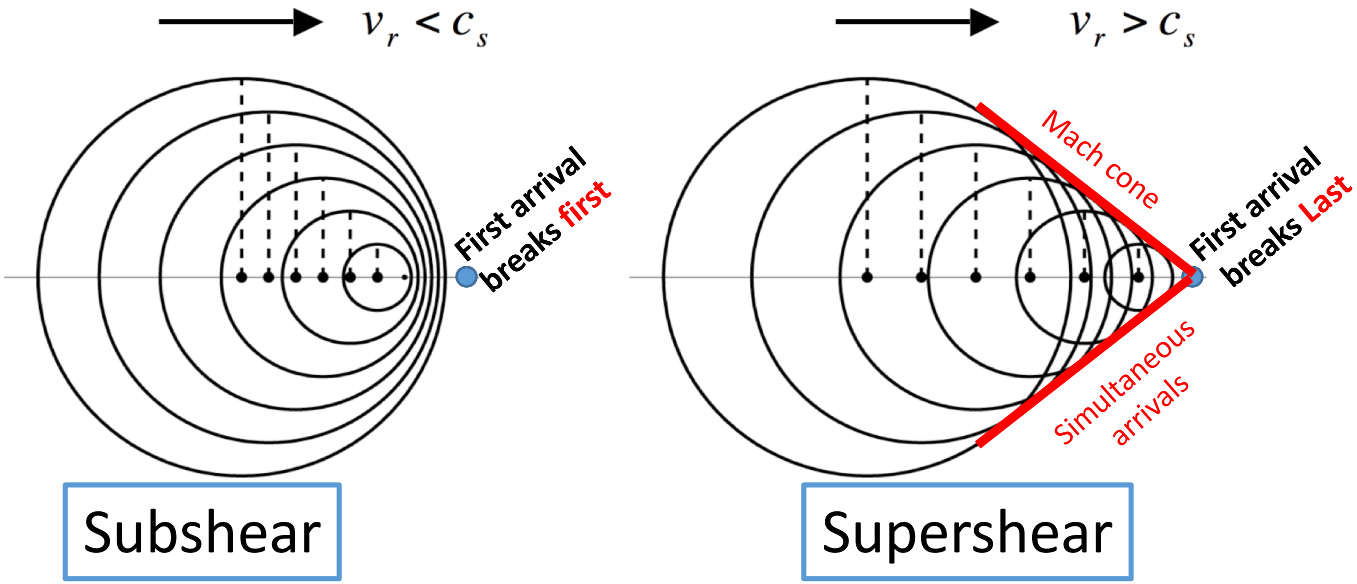
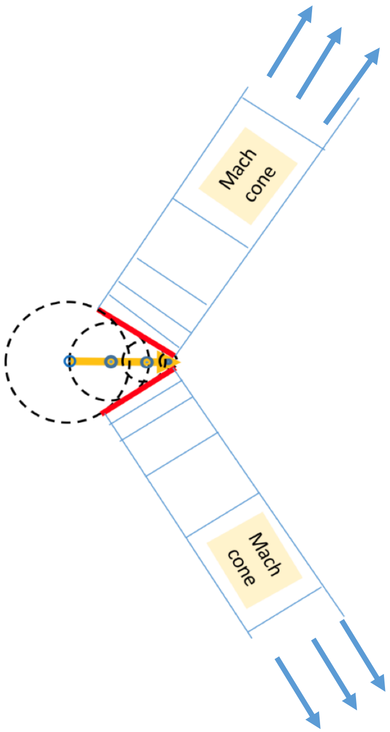
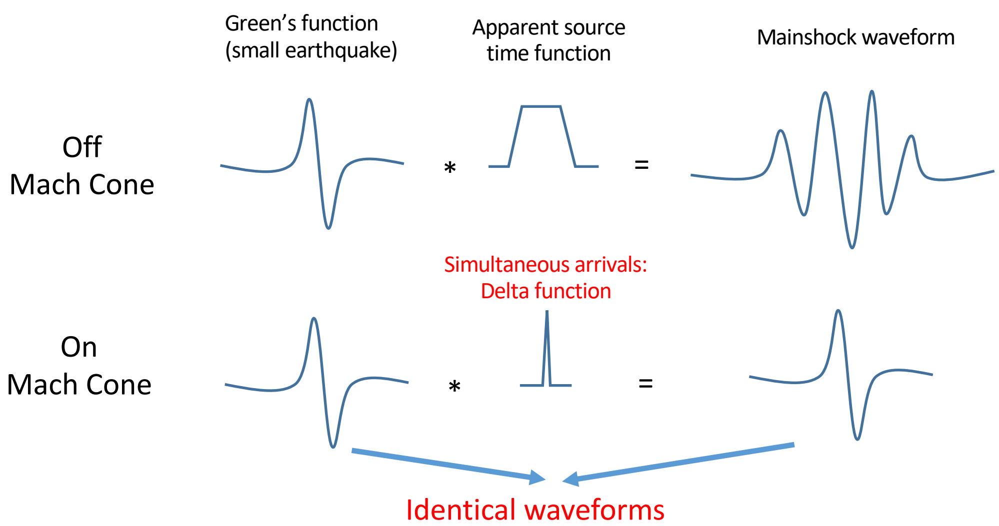


Figure modified from Eric Dunham's website

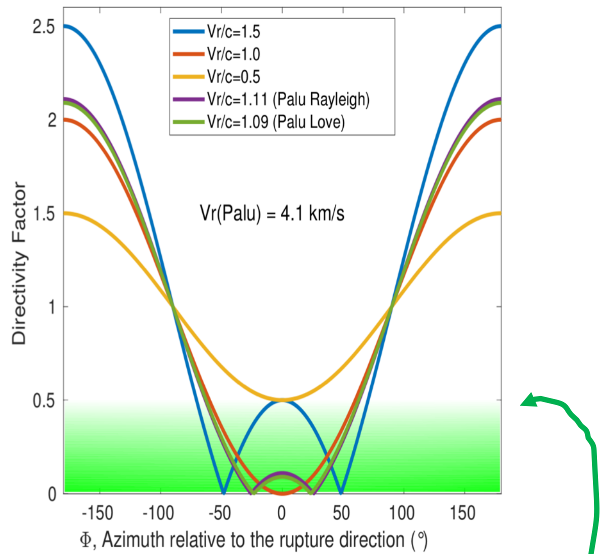
Teleseismic observations of rupture speed
2. Surface wave Mach cone



WAVEFORM SIMILARITY OF SURFACE WAVE



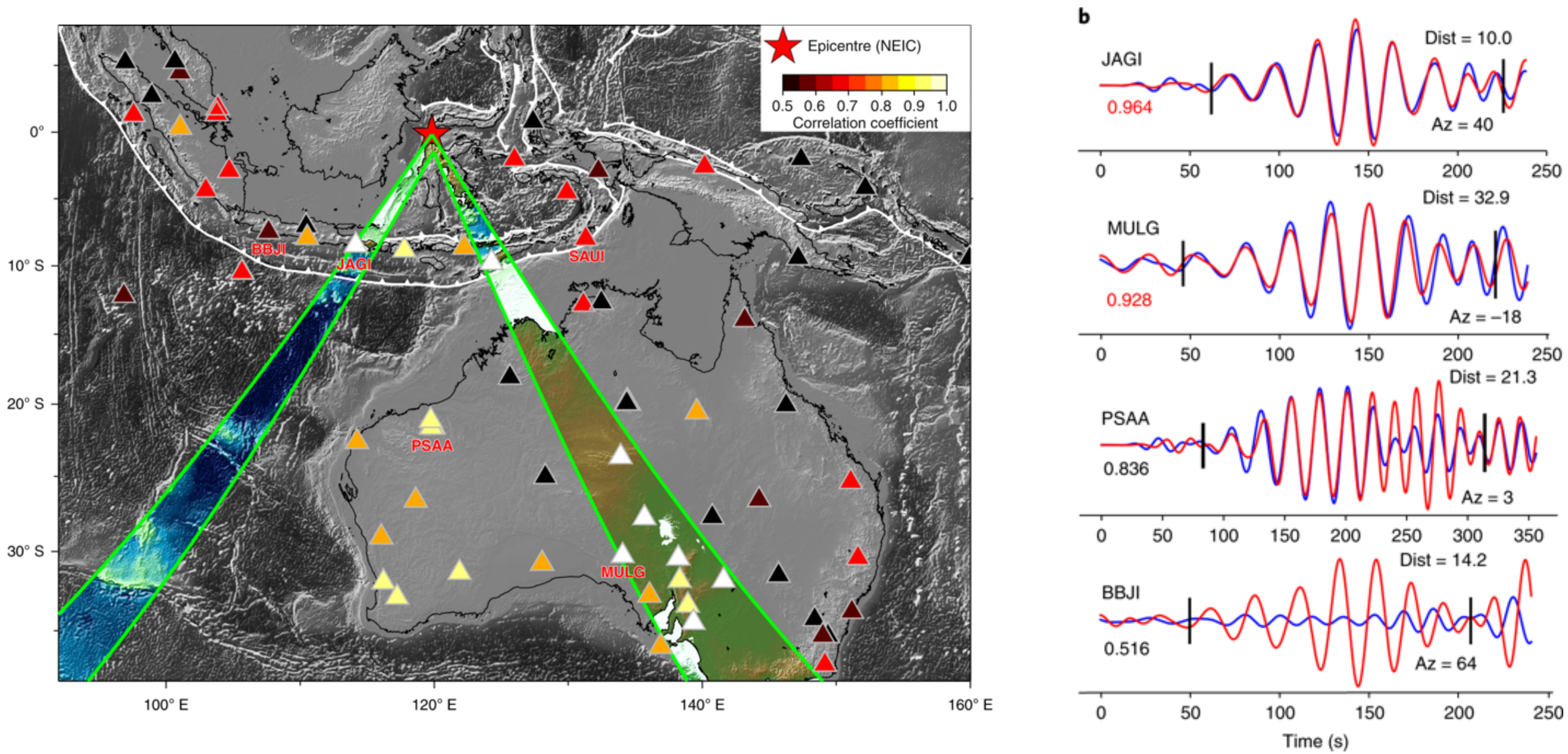
$$\frac{\textit{apparent duration}}{\textit{real duration}}$$



$$\frac{\textit{wave period}}{\textit{rupture duration}}$$

Following Vallée and Dunham, 2012

Teleseismic observations of rupture speed
2. Surface wave Mach cone



In the Mach cone

Off the Mach cone

Supershear earthquakes

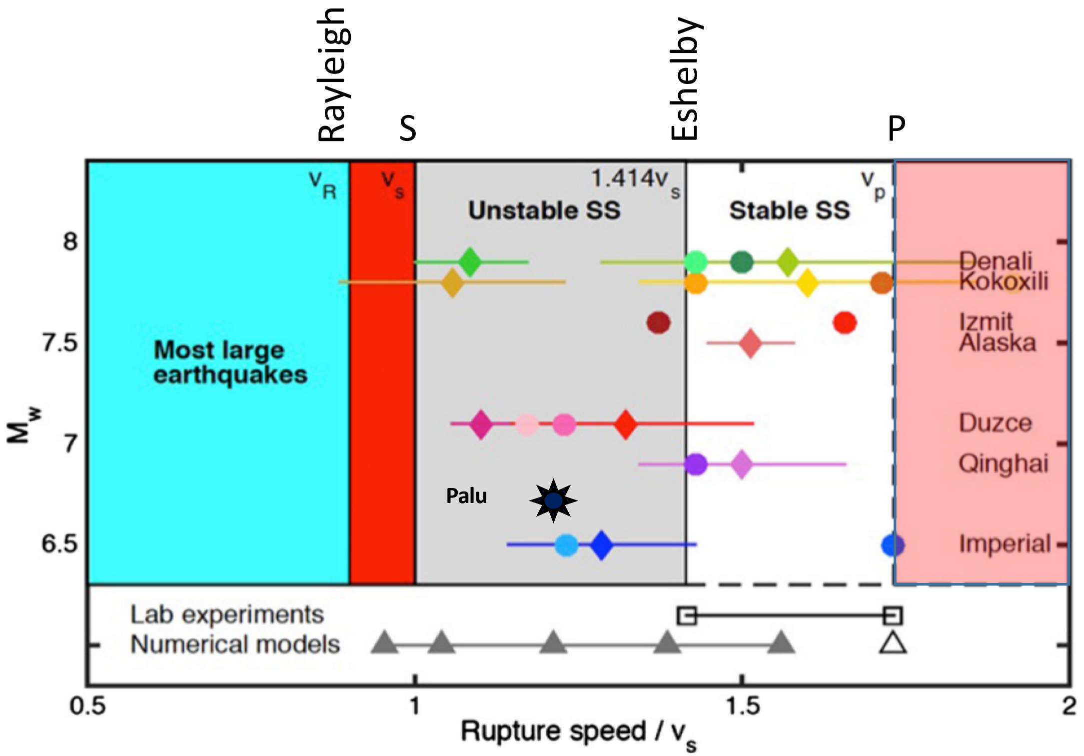
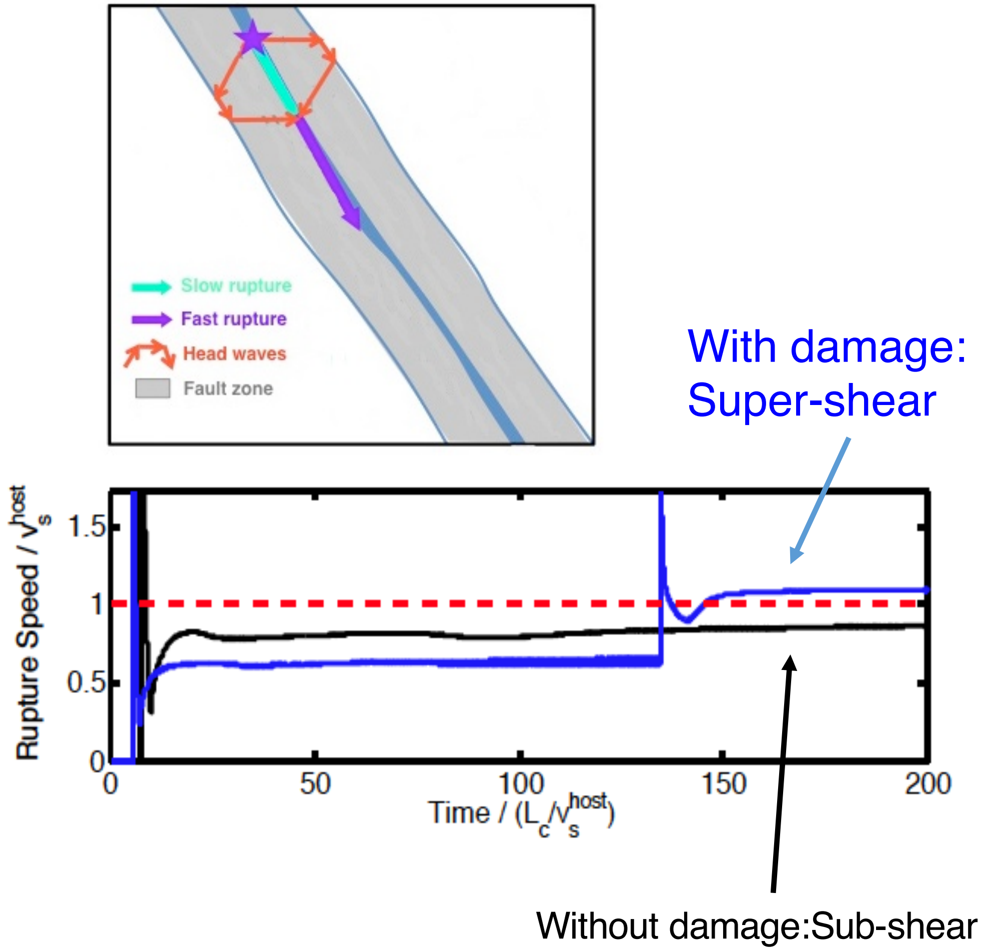


Figure modified from Huang et al., 2016

Fault zone waves facilitate supershear rupture

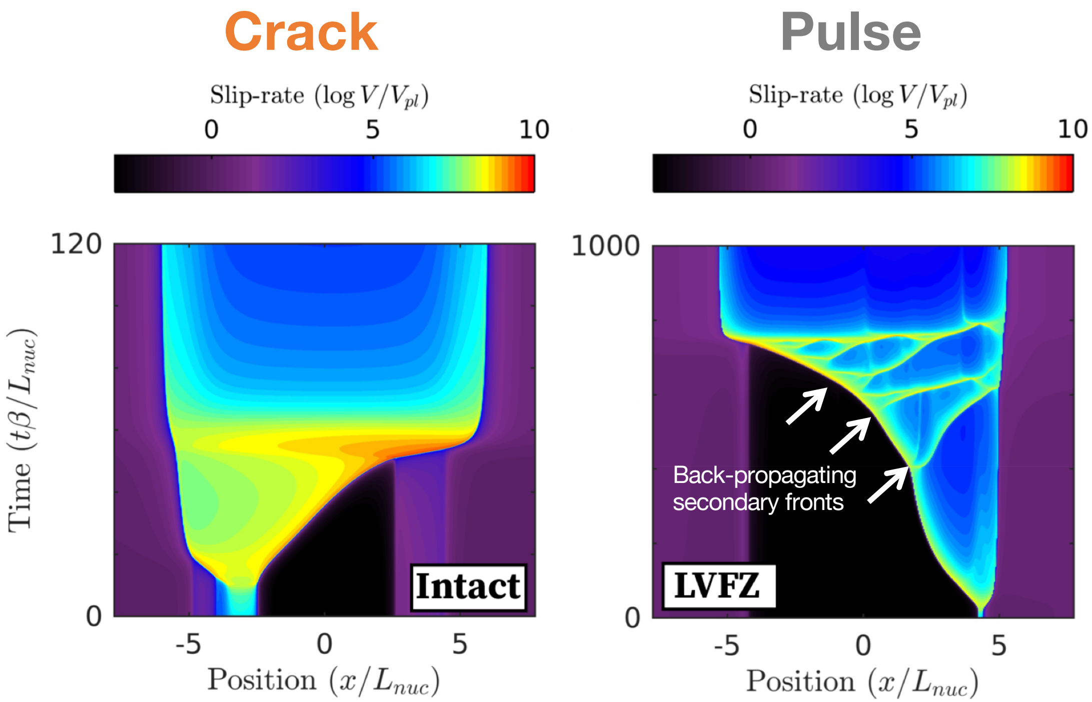
From dynamic rupture models:

The presence of a damaged fault zone facilitates supershear rupture
→ it can happen sooner and at lower stress than in intact rock

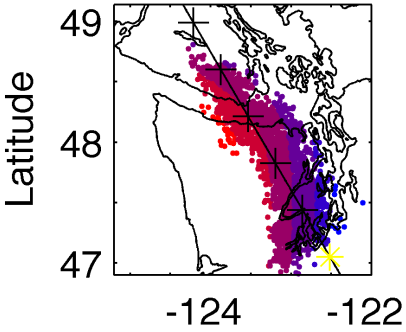


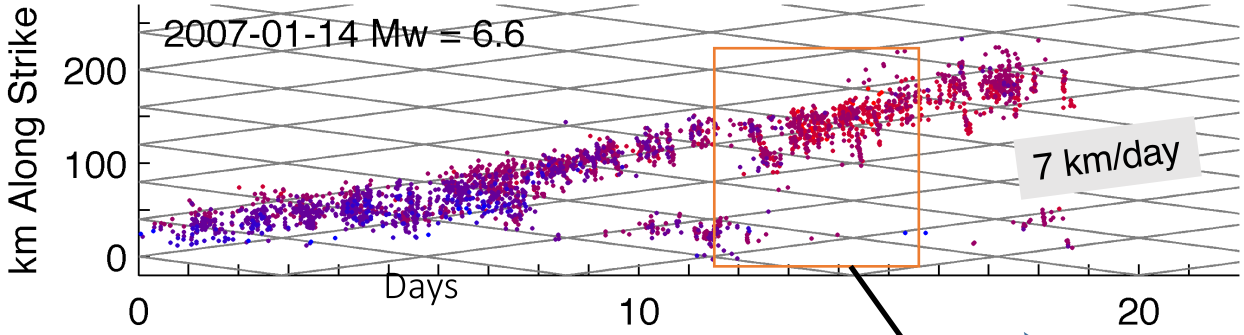
Huang and Ampuero (2011)
Huang, Ampuero and Helmberger (2014, 2015)

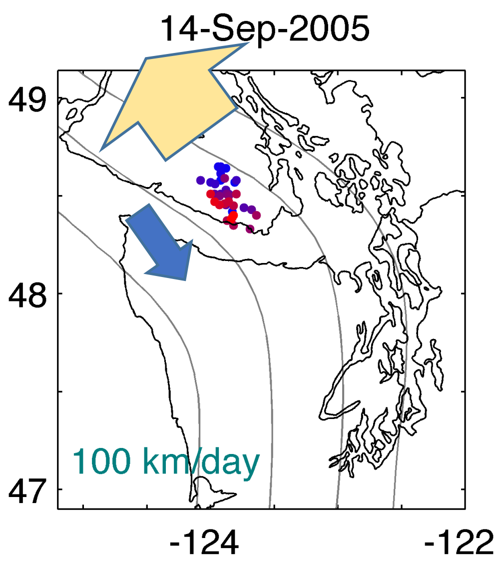
Back-propagating rupture pulses



Rapid tremor reversals

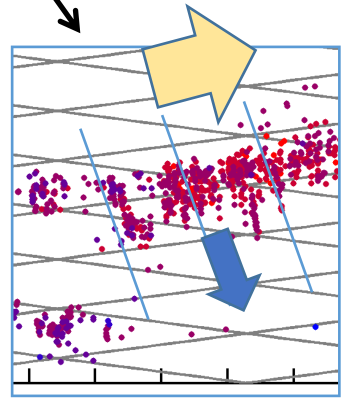






Non-volcanic tremor migration patterns in Cascadia, USA

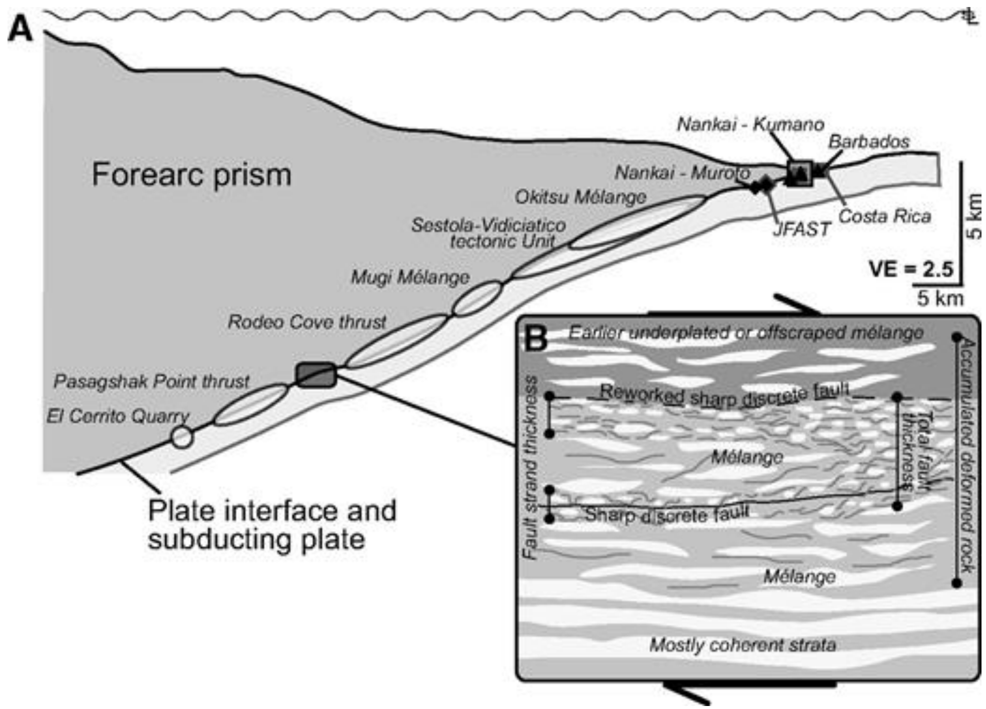
Tremor migrates slowly along strike (~10 km/day) tracking the front of the slow slip event

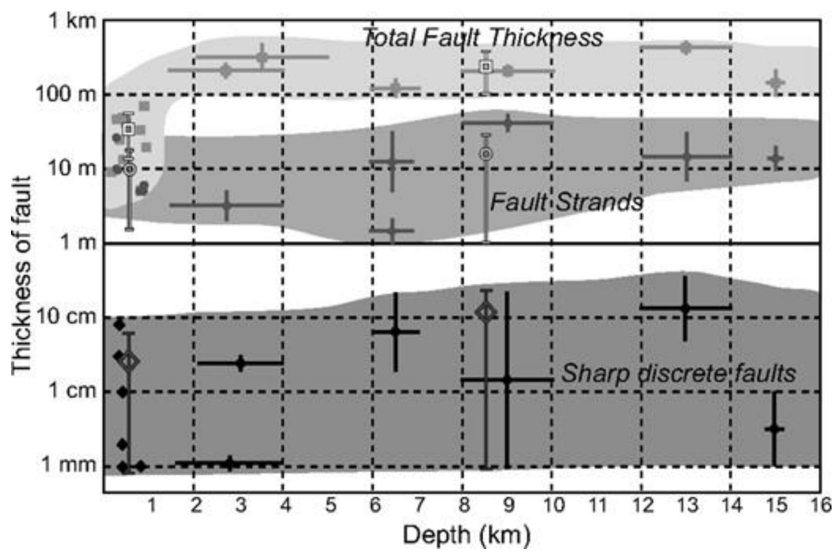


Houston et al (2010)

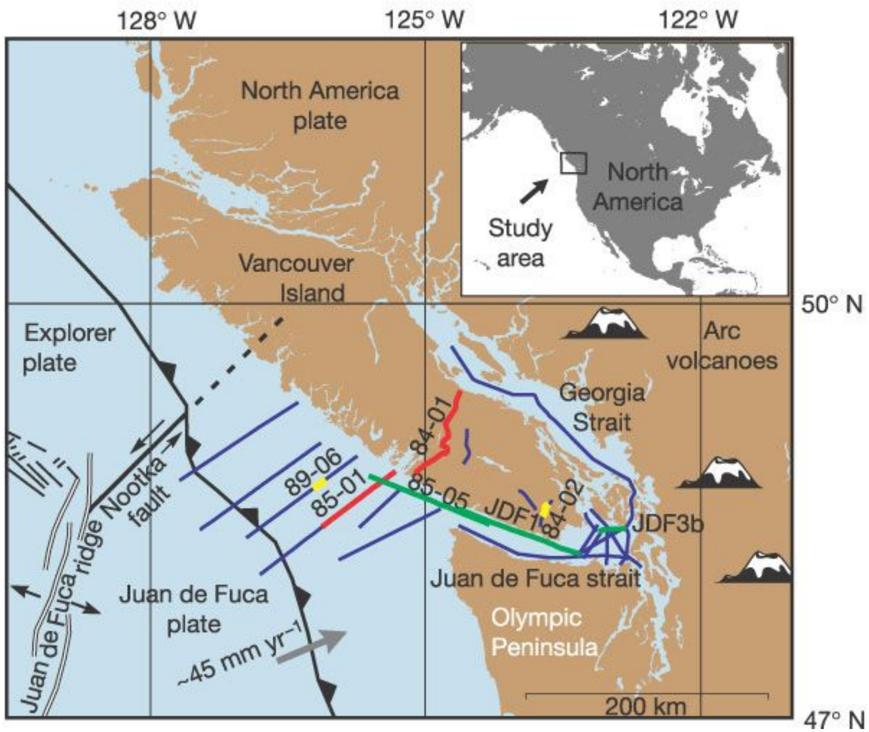
Low velocity zones in subduction megathrusts

Rowe et al (2013)

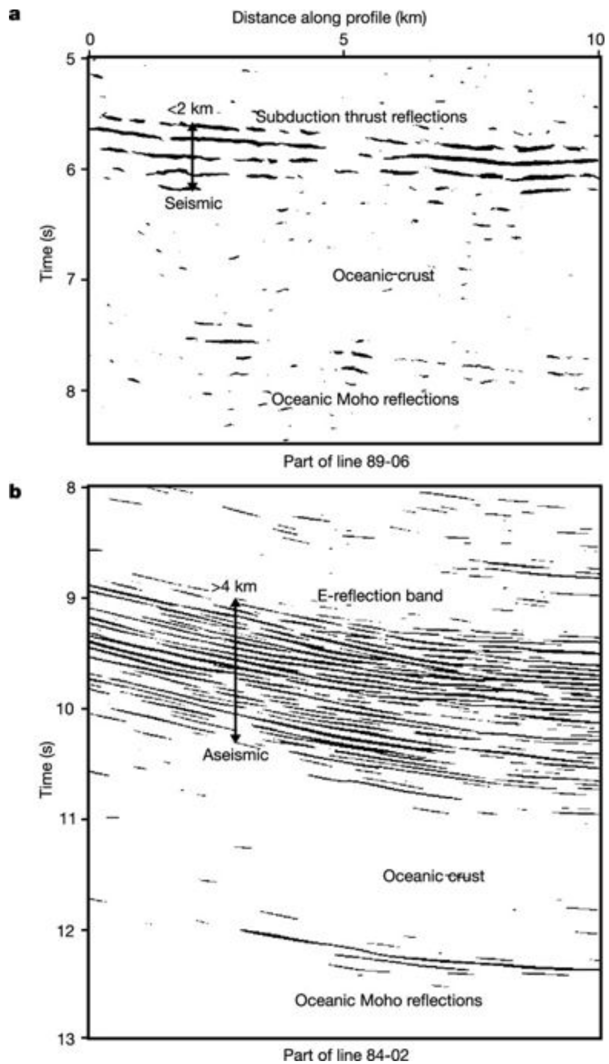




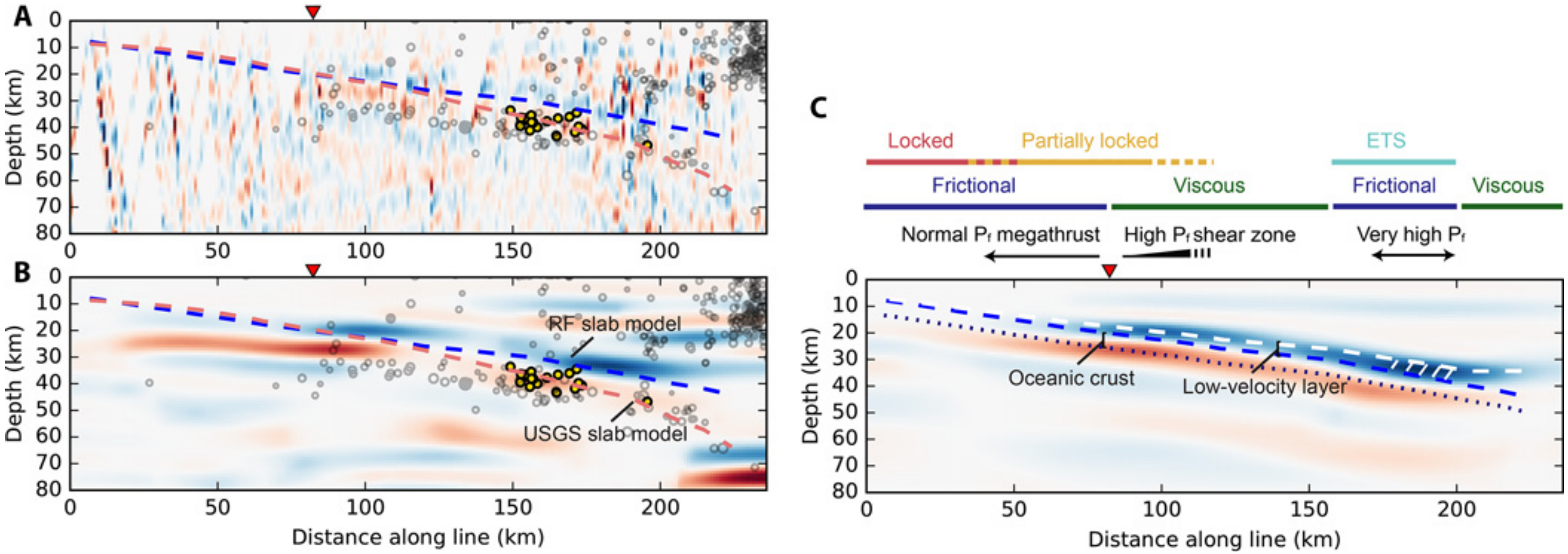
Low velocity zones in subduction megathrusts



Nemidovic et al (2003)

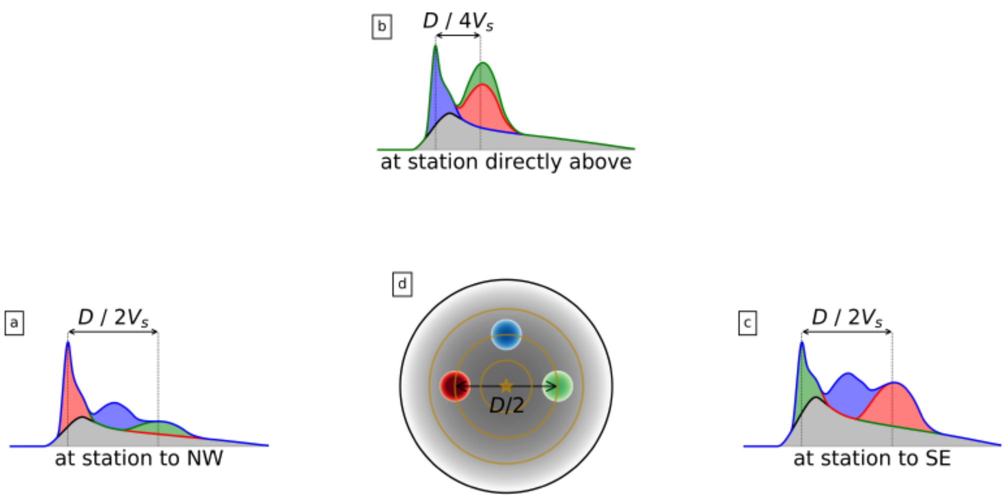


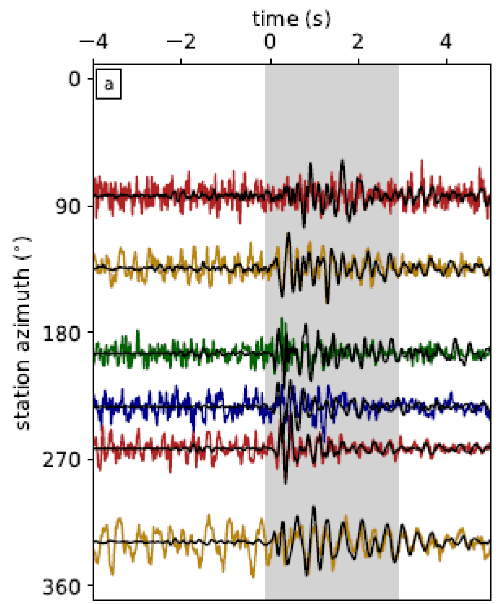
Low velocity zones in subduction megathrusts



Receiver function imaging of low velocity zones at tremor and SSE depths in Cascadia (Audet and Schaeffer 2017)

New constraints on LFE rupture speed
(Hawthorne, Thomas and Ampuero 2018)

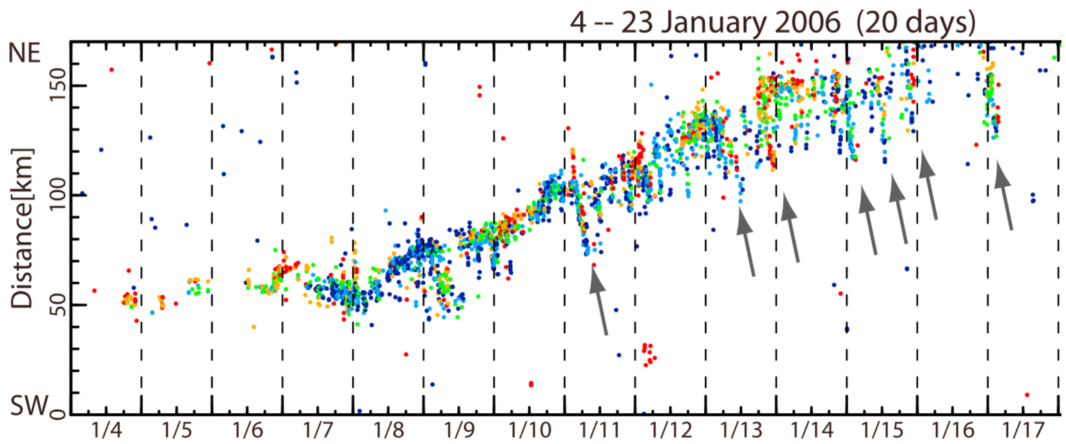




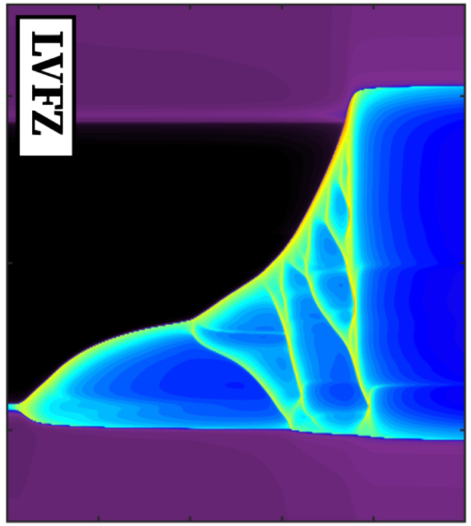
LFE rupture speed <40% Vs of host rock

Back-propagating in slow slip model

Episodic tremor events in Nankai, Japan



Modified from Obara et al. (2012)



A potential candidate to explain rapid tremor reversals during SSE.