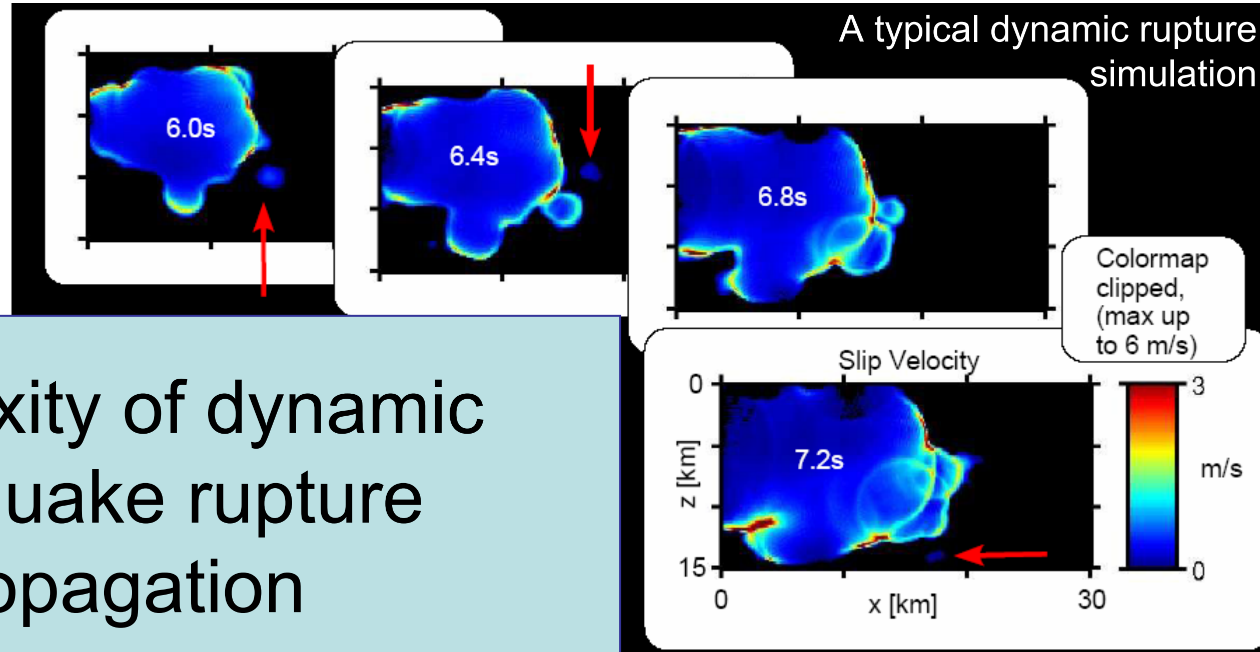
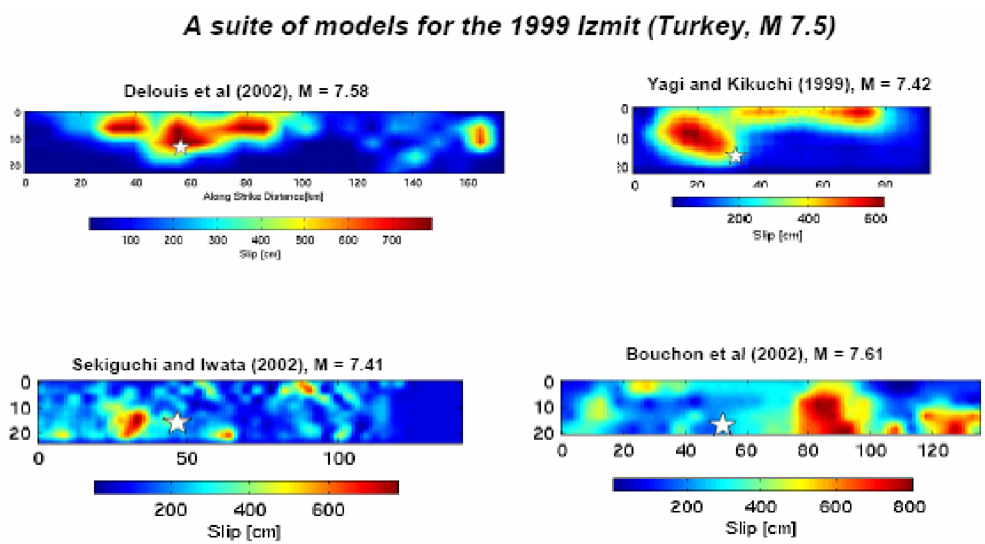
Diversity of rupture styles during earthquake nucleation and dynamic rupture

Jean-Paul Ampuero

Caltech Seismolab



Complexity of dynamic earthquake rupture propagation



Parameters of rupture kinematics usually inferred from seismograms (recorded ground motions):

- rupture speed
- total slip
- rise time
- slip velocity

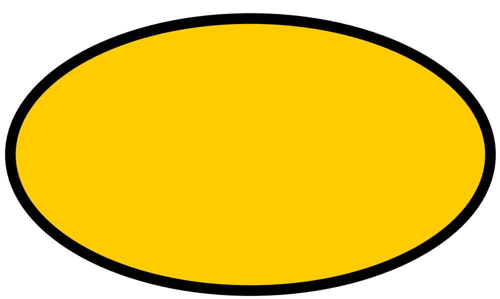
Notorious space-time complexity affects earthquake hazard

… but insight limited by low resolution of source imaging

Cracks vs. pulses (definition)

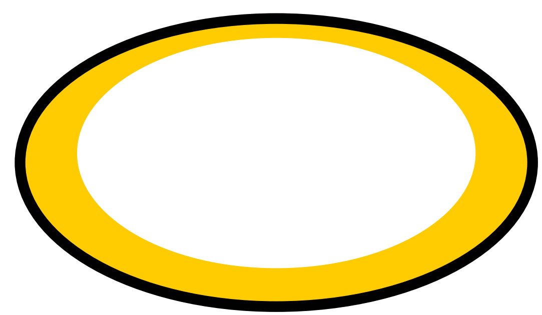
Looking at slip velocity on the fault plane
Thick ellipse = barrier (will stop rupture)
Colored zone = actively slipping region at a given time
Rise time = duration of slip at a given point on the fault

Crack



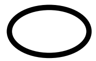
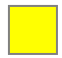
Long rise time
~ final size / rupture speed

Pulse

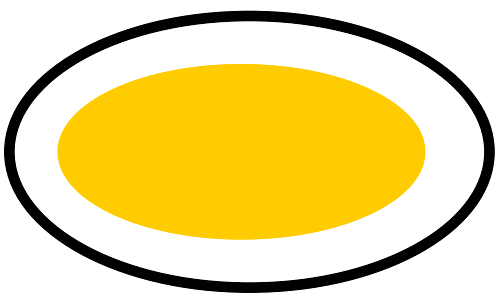


Short rise time

Cracks vs. pulses (definition)

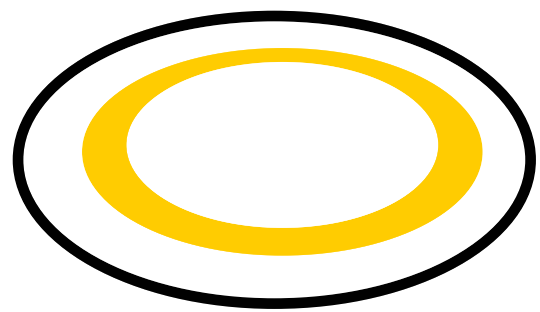
Looking at slip velocity on the fault plane
Thick ellipse  = barrier (will stop rupture)
Colored zone  = actively slipping region at a given time
Rise time = duration of slip at a given point on the fault

Crack



Long rise time
~ final size / rupture speed

Pulse



Short rise time

Summary

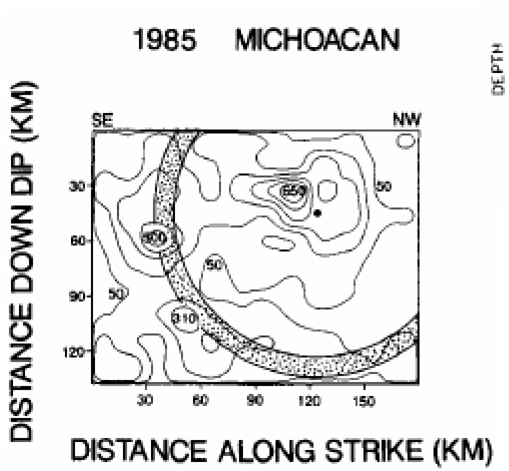
- Overview of rupture styles: cracks and pulses
  - Short rise time inferred from earthquake data
  - Possible origins of pulse-like rupture
  - Implications on earthquake complexity
- Pulse directivity in dynamic rupture on bimaterial faults
  - Pure bimaterial pulses
  - Bimaterial effect on macroscopic pulses
  - Effect of stress heterogeneities
- Earthquake nucleation under rate-and-state friction:
  - Aging law → cracks
  - Slip law → pulses
  - Implications for slow fronts

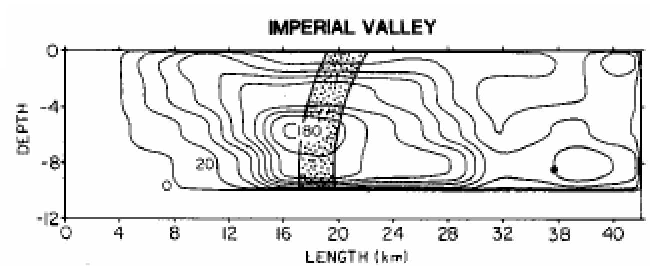
Summary

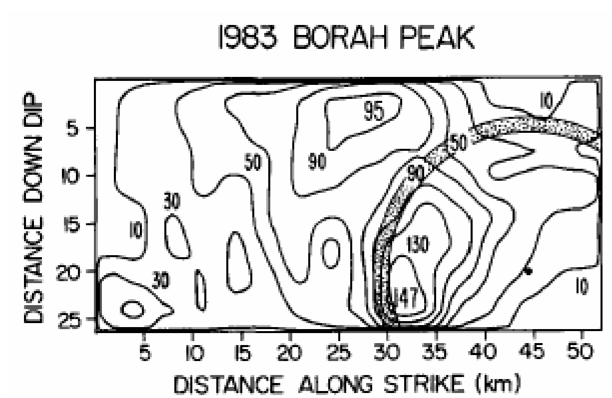
- Overview of rupture styles: cracks and pulses
  – Short rise time inferred from earthquake data
  – Possible origins of pulse-like rupture
  – Implications on earthquake complexity
- Pulse directivity in dynamic rupture on bimaterial faults
  – Pure bimaterial pulses
  – Bimaterial effect on macroscopic pulses
  – Effect of stress heterogeneities
- Earthquake nucleation under rate-and-state friction:
  – Aging law → cracks
  – Slip law → pulses
  – Implications for slow fronts

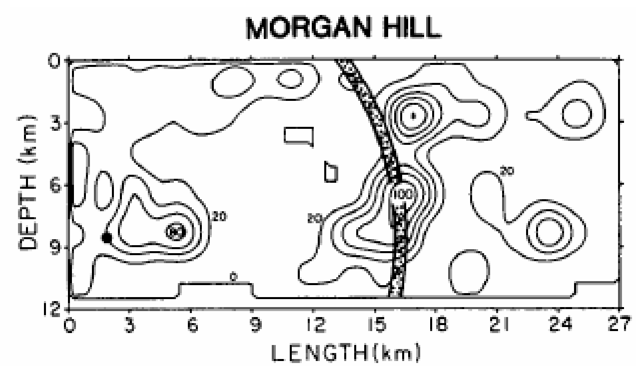
Short rise times inferred from earthquake data

- Rise time = duration of slip at a point on the fault plane
- Heaton (1990): short rise time is common in source images

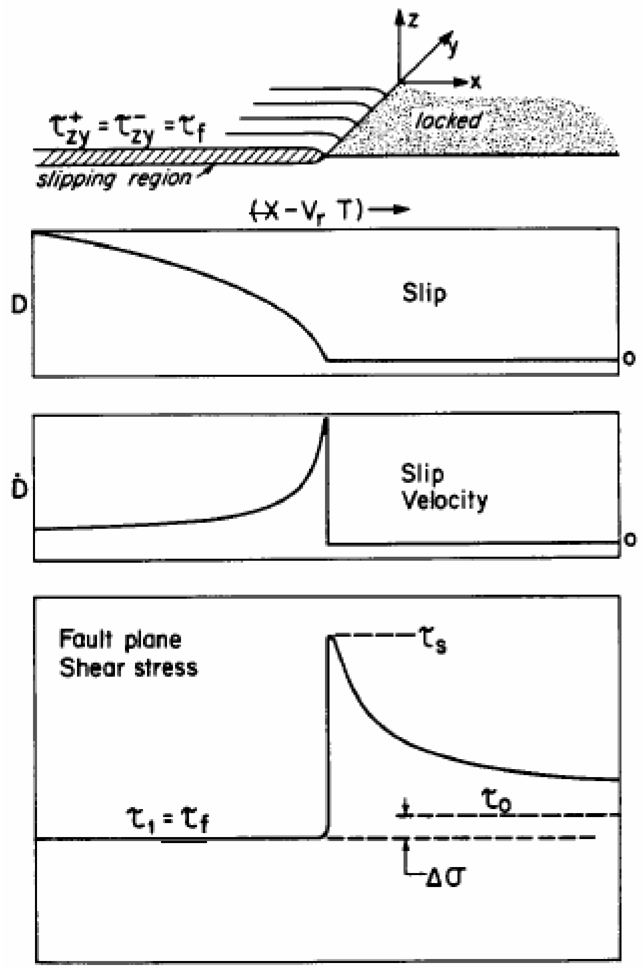


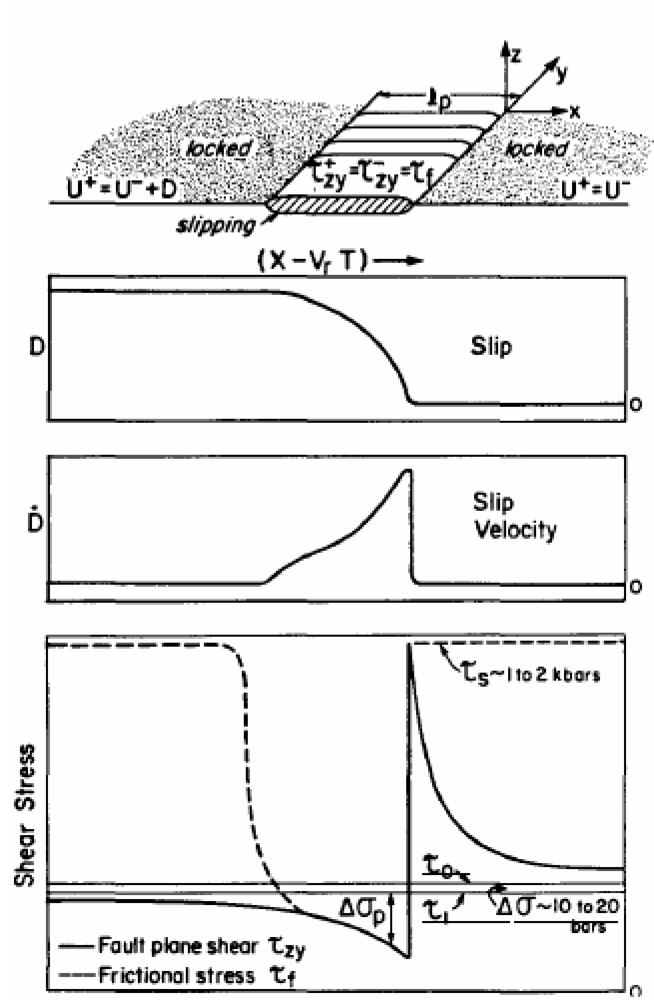






Cracks vs. pulses





Heaton (1990)

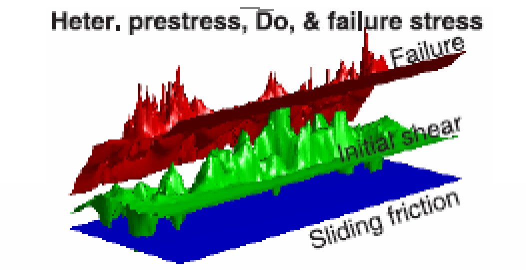
Possible origins

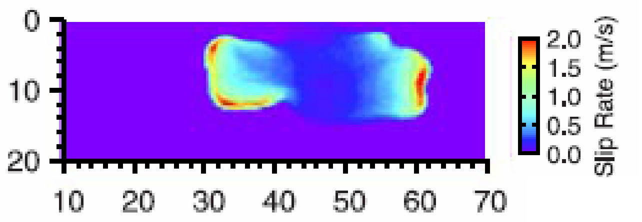
- In homogeneous faults, at low stress, self-healing pulses appear under **velocity-weakening friction** (e.g. thermal weakening)
  Perrin, Rice and Zheng (1995); Zheng and Rice (1998); Nielsen and Carlson (2000)

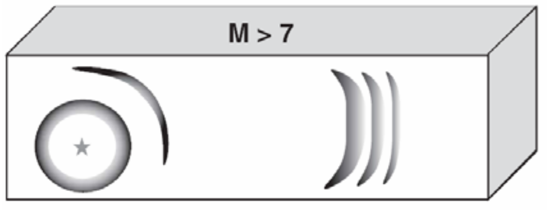
- Pulses (healing fronts) generated by heterogeneities
  Mikumo and Beroza (1994); Oglesby and Day (2002); Aagaard and Heaton (2009)

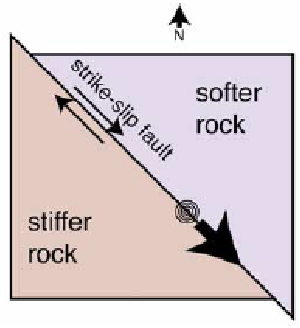
- Pulses controlled by geometry
  Day (1983); Johnson (1992)

- Pulses in bimaterial faults
  Weertman (1980), Adams (1995), Andrews and Ben-Zion (1997), Cochard and Rice (2000)



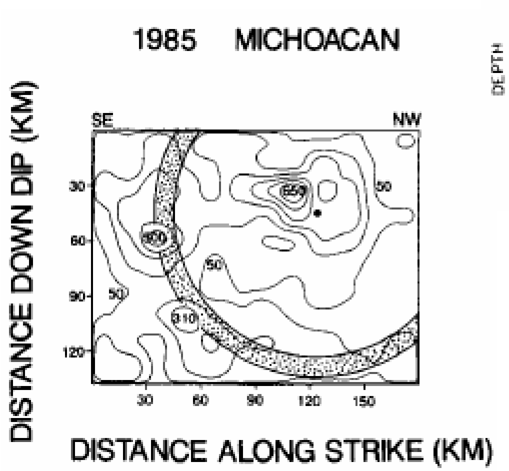


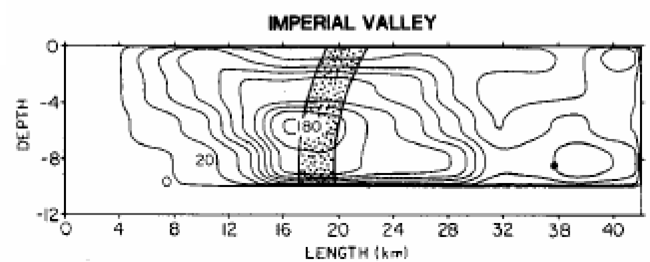


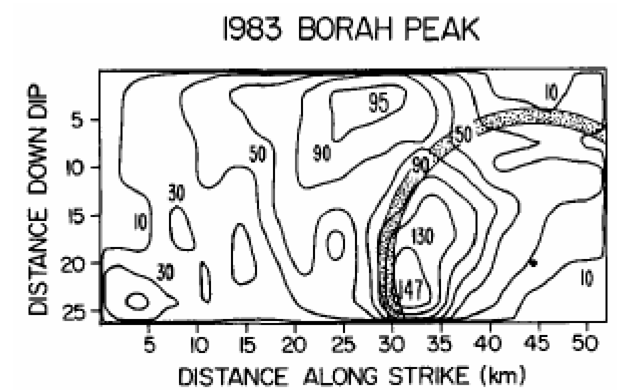


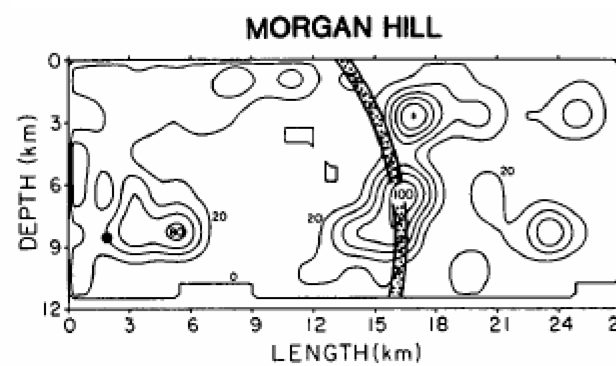
Short rise times inferred from earthquake data

- Rise time = duration of slip at a point on the fault plane
- Heaton (1990): short rise time is common in source images





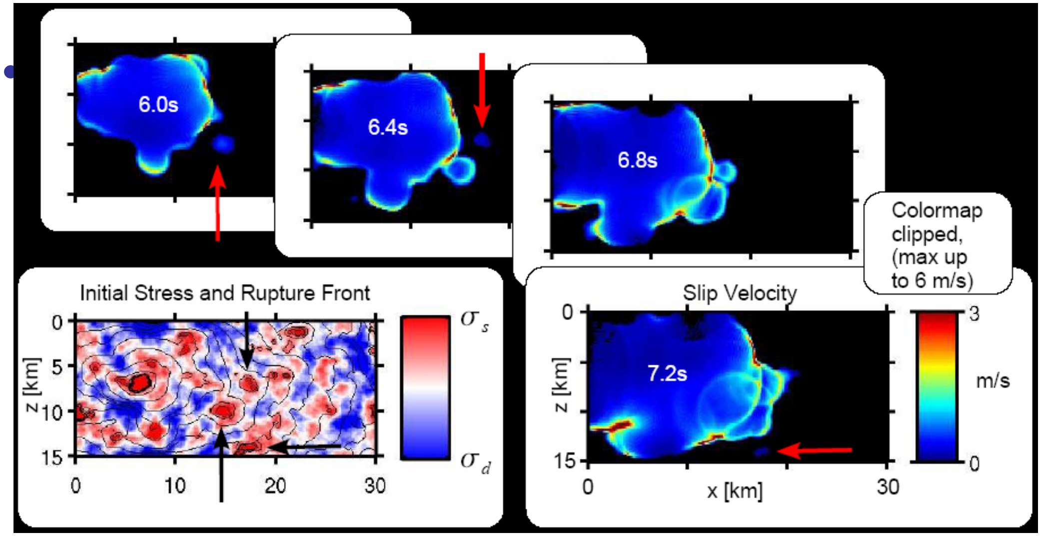




Implications

- Short time scale: complexity of dynamic rupture, the **rupture front geometry is more unstable for pulses** than for cracks

  Pulses are sensitive to fault heterogeneities over a short length scale (the pulse width) whereas cracks average over the whole rupture size

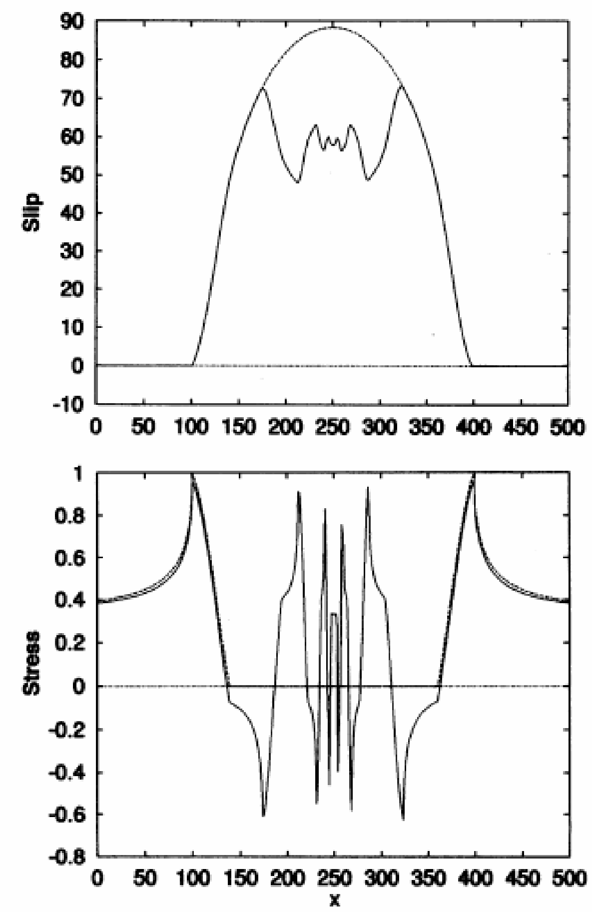


Implications

- Short time scale: complexity of dynamic rupture, the **rupture front geometry is more unstable for pulses** than for cracks

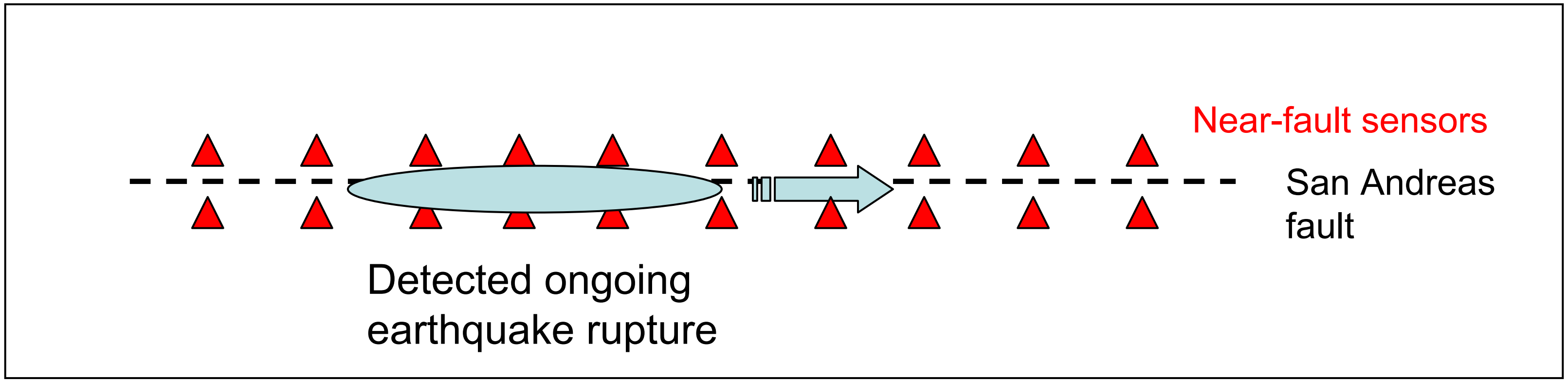
  Pulses are sensitive to fault heterogeneities over a short length scale (the pulse width) whereas cracks average over the whole rupture size

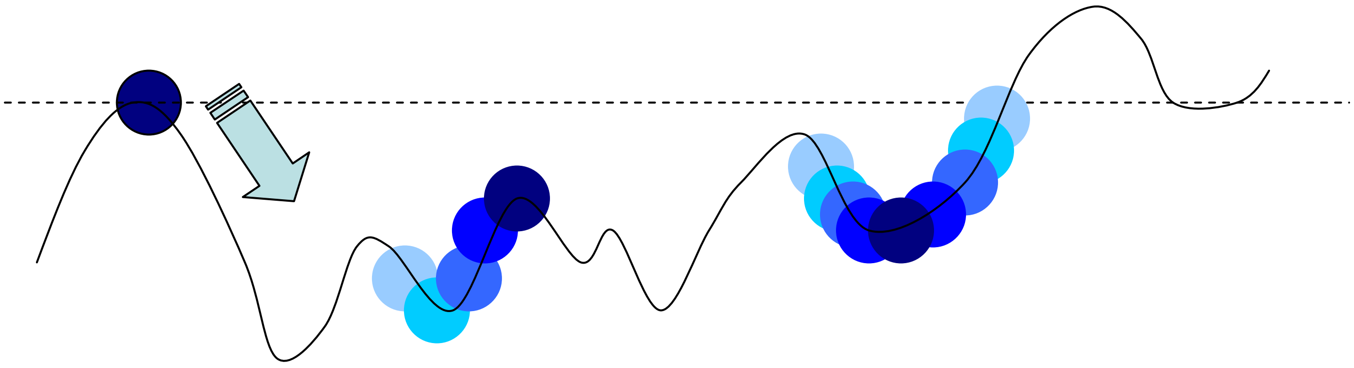
- Long time scale: complexity of seismicity (Gutenberg-Richter, clustering, etc): pulses can leave a heterogeneous residual stress on the fault (cracks can't)



Madariaga and Cochard (1996)

How large the earthquake is going to be? (implication for early warning)



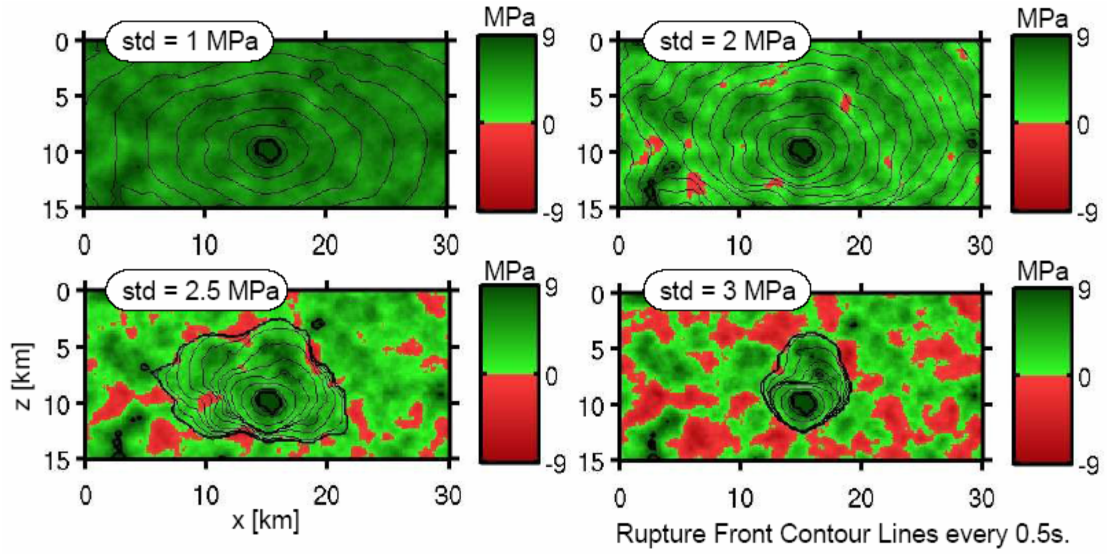


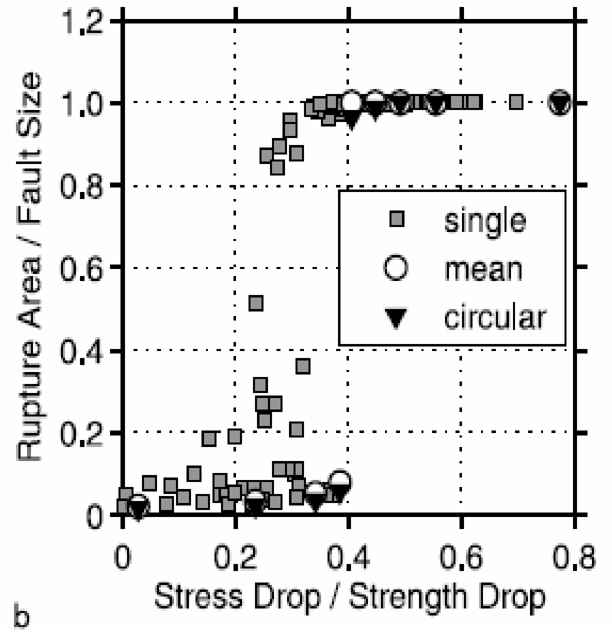
Analogy: pulse with constant width = ball with constant mass

Real problem: the “mass” of a rupture pulse changes in a way that we do not understand yet, probably correlated with the changing landscape

Crack rupture:
First order transitions of final earthquake size controlled by stress heterogeneities

Rupture "percolation" transition



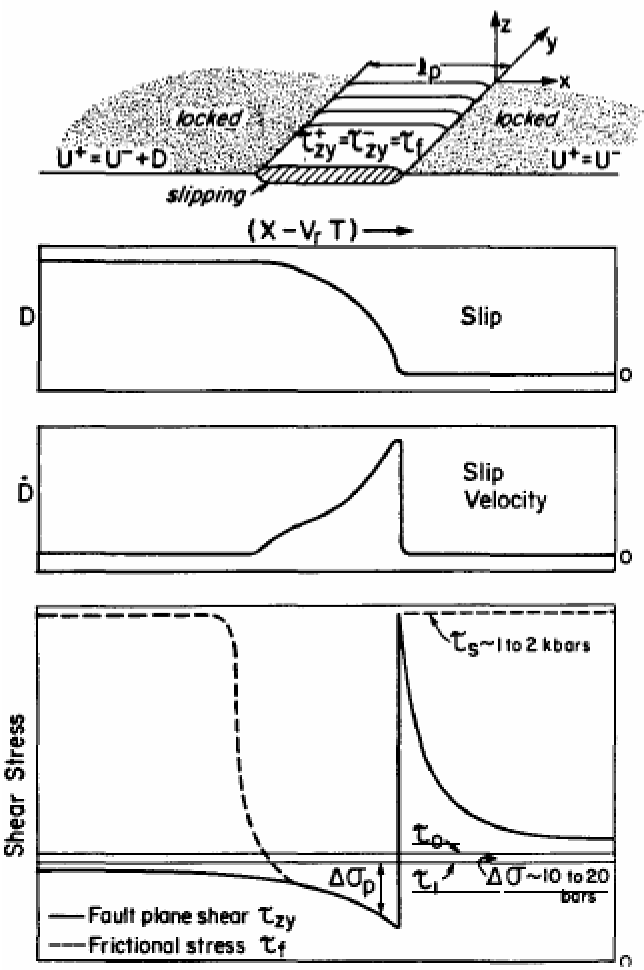


A fundamental open question: what controls the pulse width (rise time) ?

- **Two unknowns**: position of rupture and healing fronts
- Crack tip energy balance provides only **one equation** (the “crack tip equation of motion” of Freund, 1990)
- The healing front is energy neutral (no dissipation)

→ need a complete solution to the problem, beyond basic energy arguments

(computational challenges)



Summary

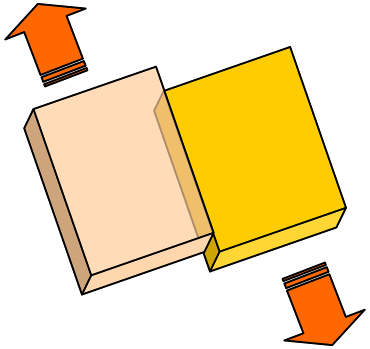
- Overview of rupture styles: cracks and pulses
  - Short rise time inferred from earthquake data
  - Possible origins of pulse-like rupture
  - Implications on earthquake complexity

- Pulse directivity in dynamic rupture on bimaterial faults
  - Pure bimaterial pulses
  - Bimaterial effect on velocity-weakening pulses
  - Effect of stress heterogeneities

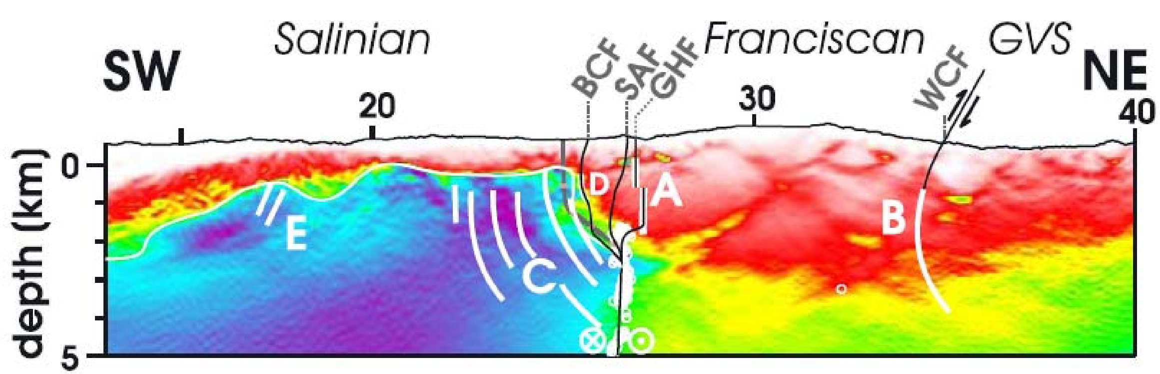
In collaboration with Allan Rubin (Princeton) and Yehuda Ben-Zion (USC)

Rubin and Ampuero (JGR 2007) *Aftershock asymmetry on a bimaterial interface*
Ampuero and Ben-Zion (GJI 2008) *Cracks, pulses and macroscopic asymmetry of dynamic rupture on a bimaterial interface with velocity-weakening friction*

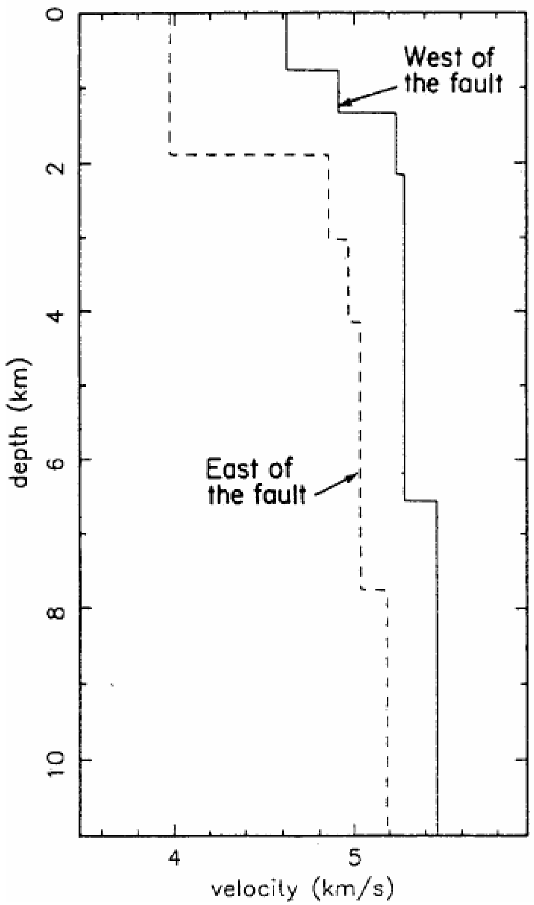
Bimaterial faults



San Andreas Fault at Parkfield, California



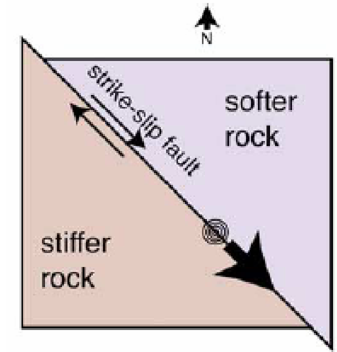
Waveform tomography (Bleibinhaus et al. 2007)

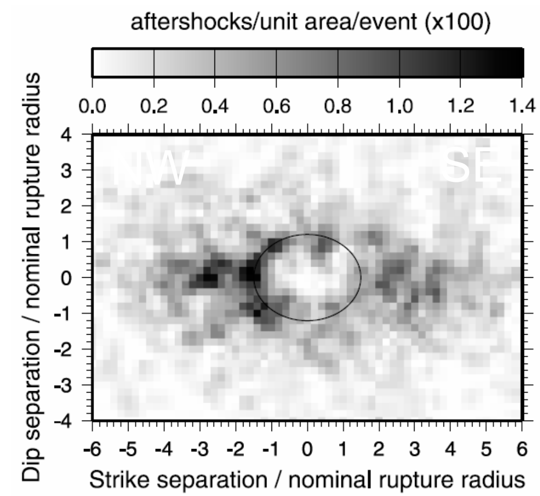


Fault zone head-wave inversion
(Ben-Zion et al. 1992)

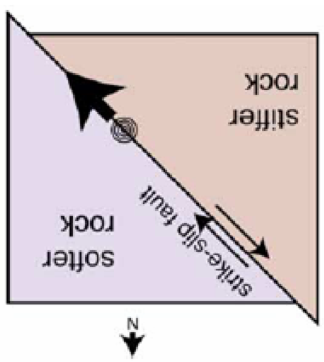
Why do we care about bimaterial faults ?

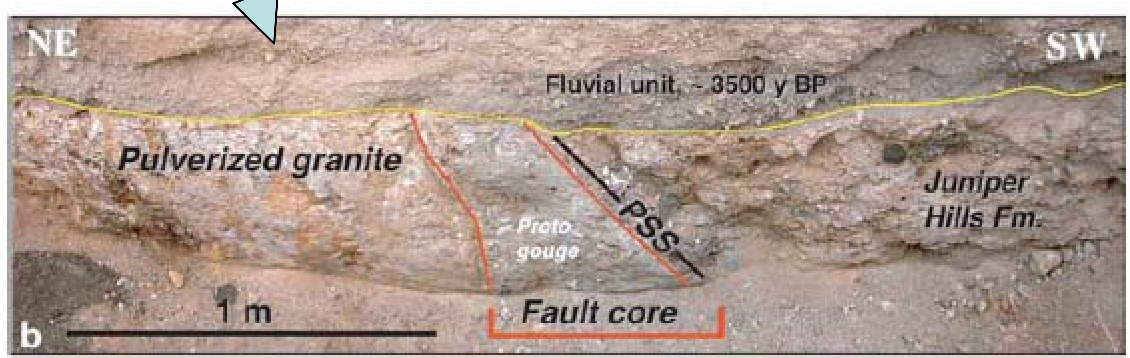
- Bimaterial faults are ubiquitous
- Theory predicts a bimaterial rupture pulse with a preferred rupture direction: the direction of motion of the softer rock
- Indirect observations:
  - Asymmetric distribution of microearthquake aftershocks
  - Asymmetry of off-fault damage patterns





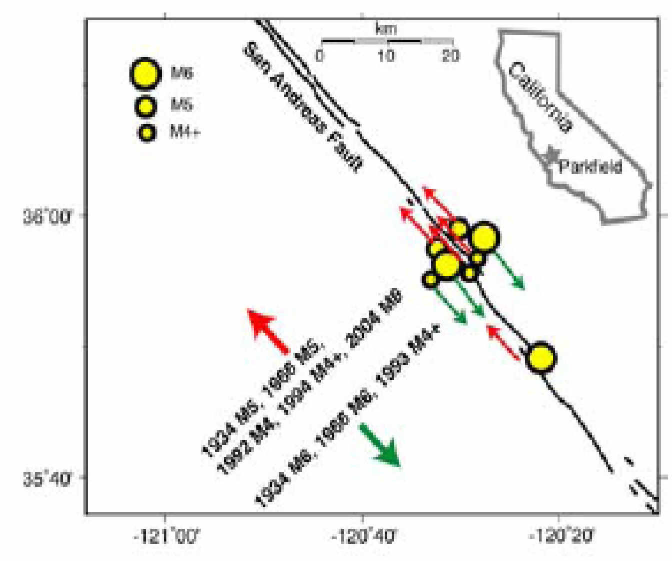
Rubin, 2002

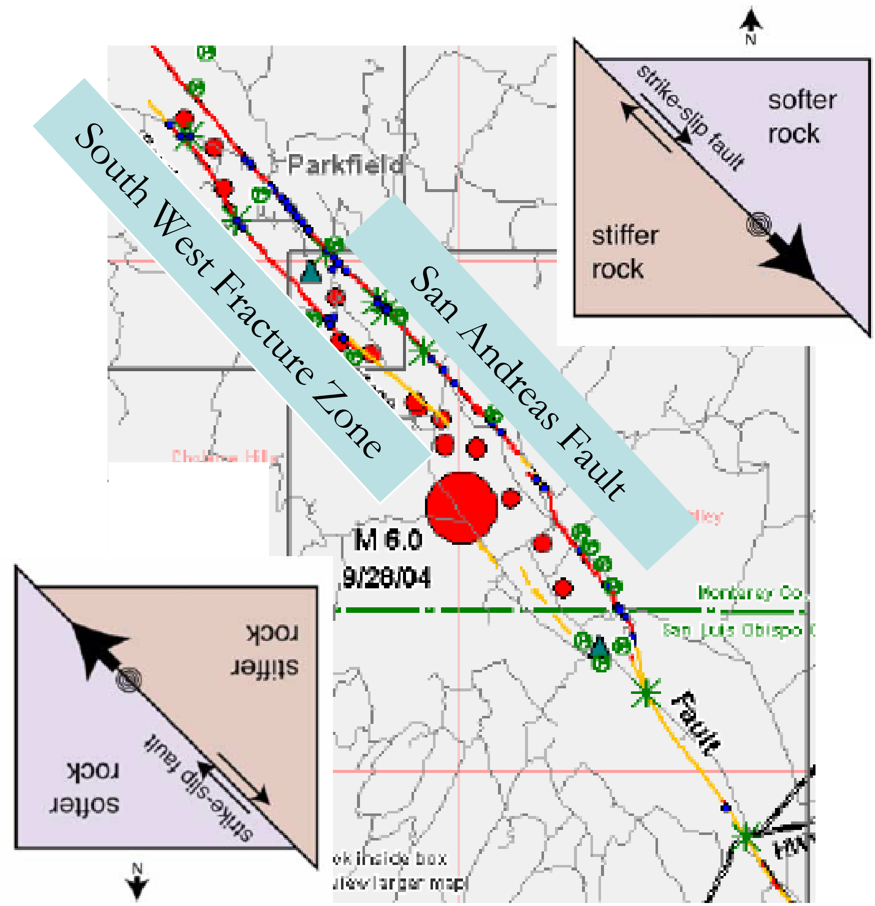




Dor et al., 2006

Dominance of southwards rupture in Parkfield ?

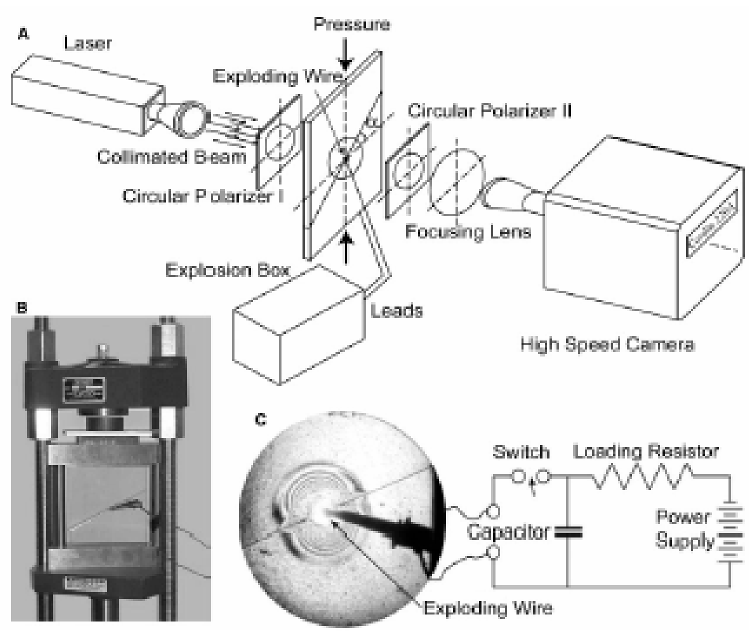


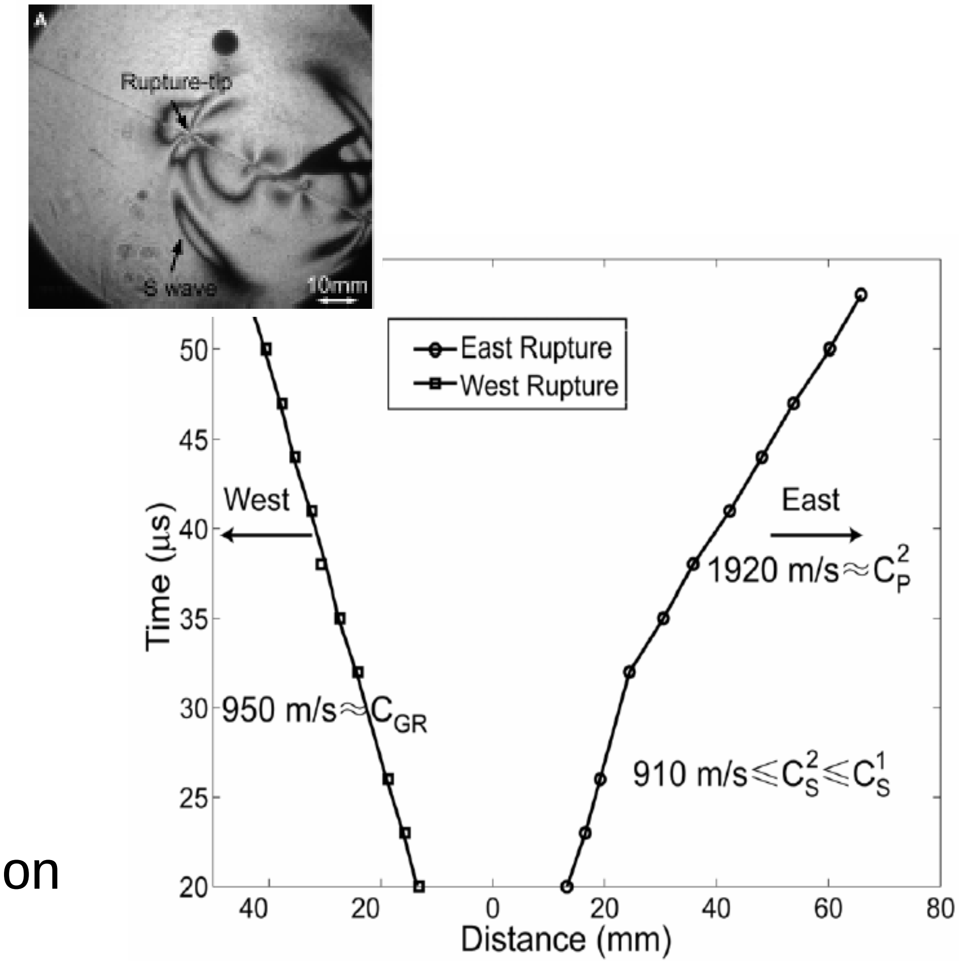


The 1934 and 1966 “repeating earthquakes” (M6) in Parkfield, California, ruptured towards the SE

… but not the 2004 event !

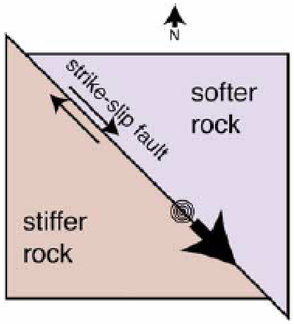
Laboratory experiments of bimaterial rupture (A. Rosakis team, Caltech)





Bilateral ruptures are also common

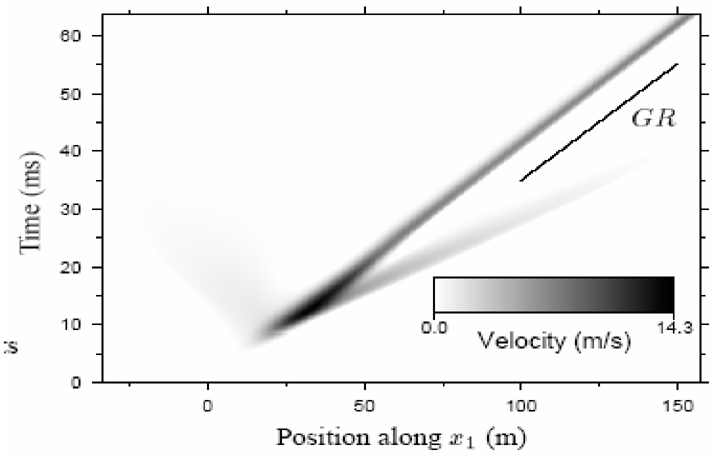
Predicted bimaterial effects on dynamic rupture (theory and simulations)



- The bimaterial effect: coupling between slip and normal stress (stronger at fast rupture speed)

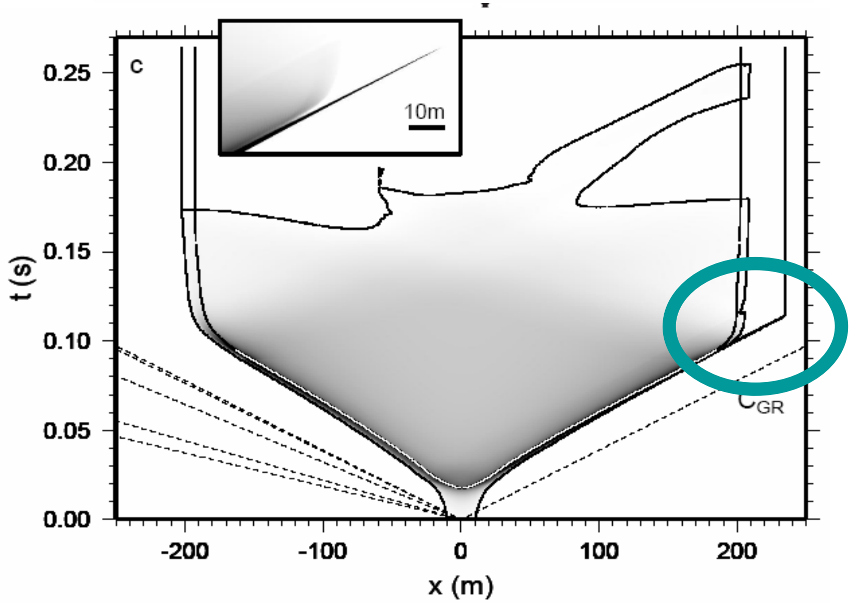
- **Bimaterial pulses running in a "preferred" direction:** the direction of motion of the softer rock
  → is rupture direction determined by the material contrast across the fault ?

  Weertman (1980), Adams (1995), Andrews and Ben-Zion (1997), Cochard and Rice (2000), Harris and Day (2005)

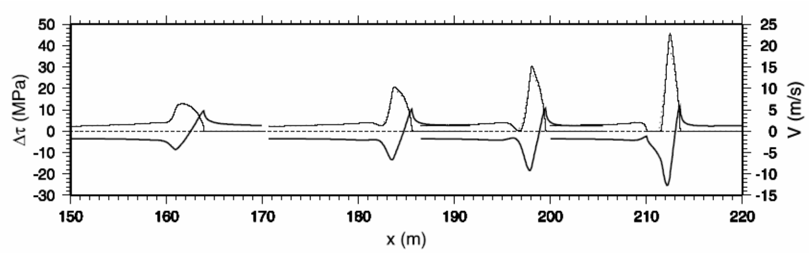


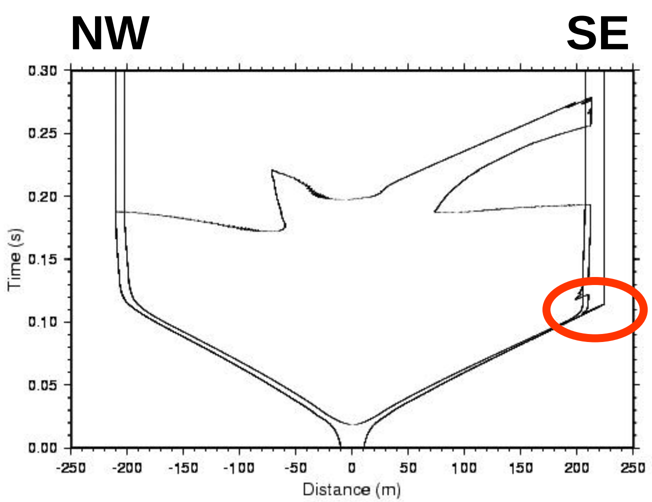
- **Slip-weakening bilateral cracks: a tiny bimaterial pulse detaches from the "preferred" crack front**, spontaneously or upon rupture arrest on abrupt barriers
  → explains various observations without requiring unilateral rupture

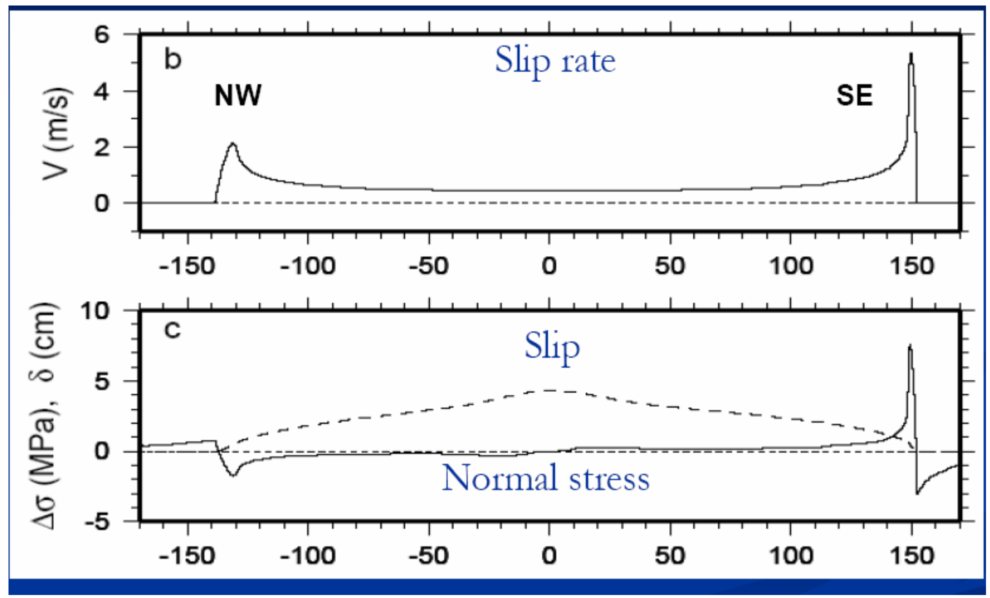
  Harris and Day (1997), Andrews and Harris (2005), Rubin and Ampuero (2007)

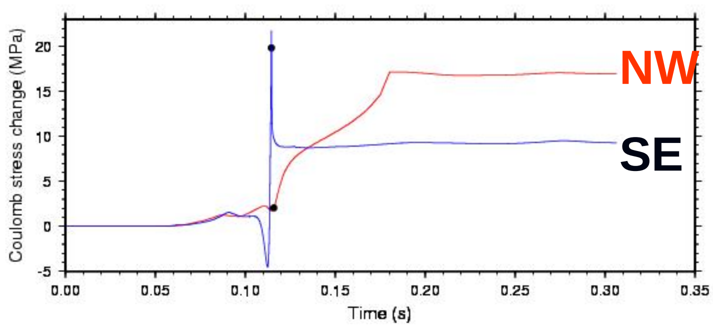


Bimaterial pulse detachment under slip-weakening friction









- The wrinkle pulse is a small scale feature
- No macroscopic slip asymmetry
- But significant slip velocity asymmetry

→ **what if velocity-weakening feedback?**

What if we include velocity-weakening friction at high slip velocity ?

- **Strong velocity-weakening** (1/V) at high slip rates as a proxy for thermal weakening processes in the fault zone

- Regularized velocity and state dependent friction law:

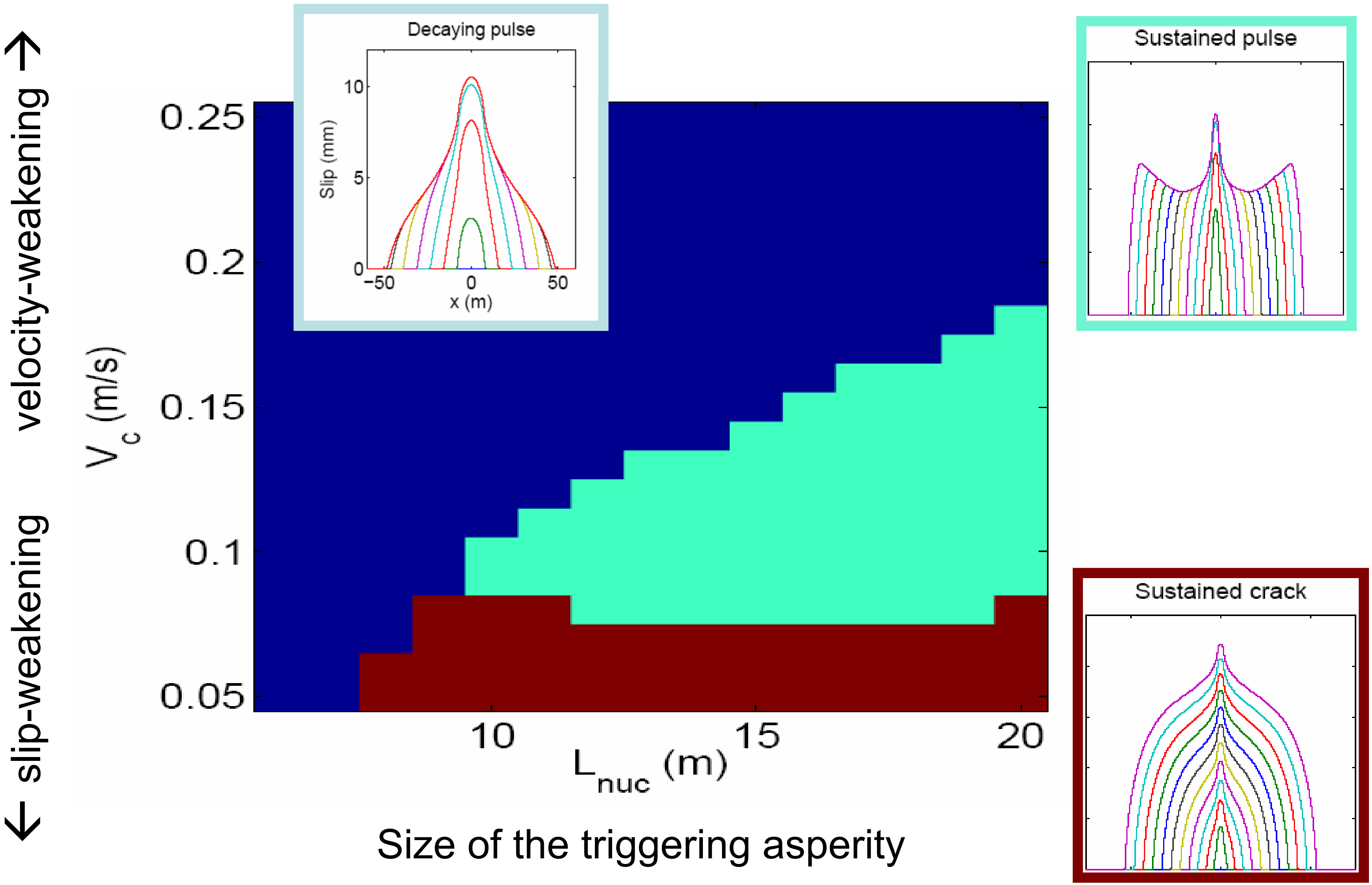
$$\mu_f = \mu_s + \alpha \, \frac{V}{V + V_c} - \beta \, \frac{\theta}{\theta + V_c} \qquad \dot{\theta} = \frac{V - \theta}{\tau_c}$$

- Parameter V_c tunes between slip-weakening (small V_c) and velocity-weakening (large V_c)

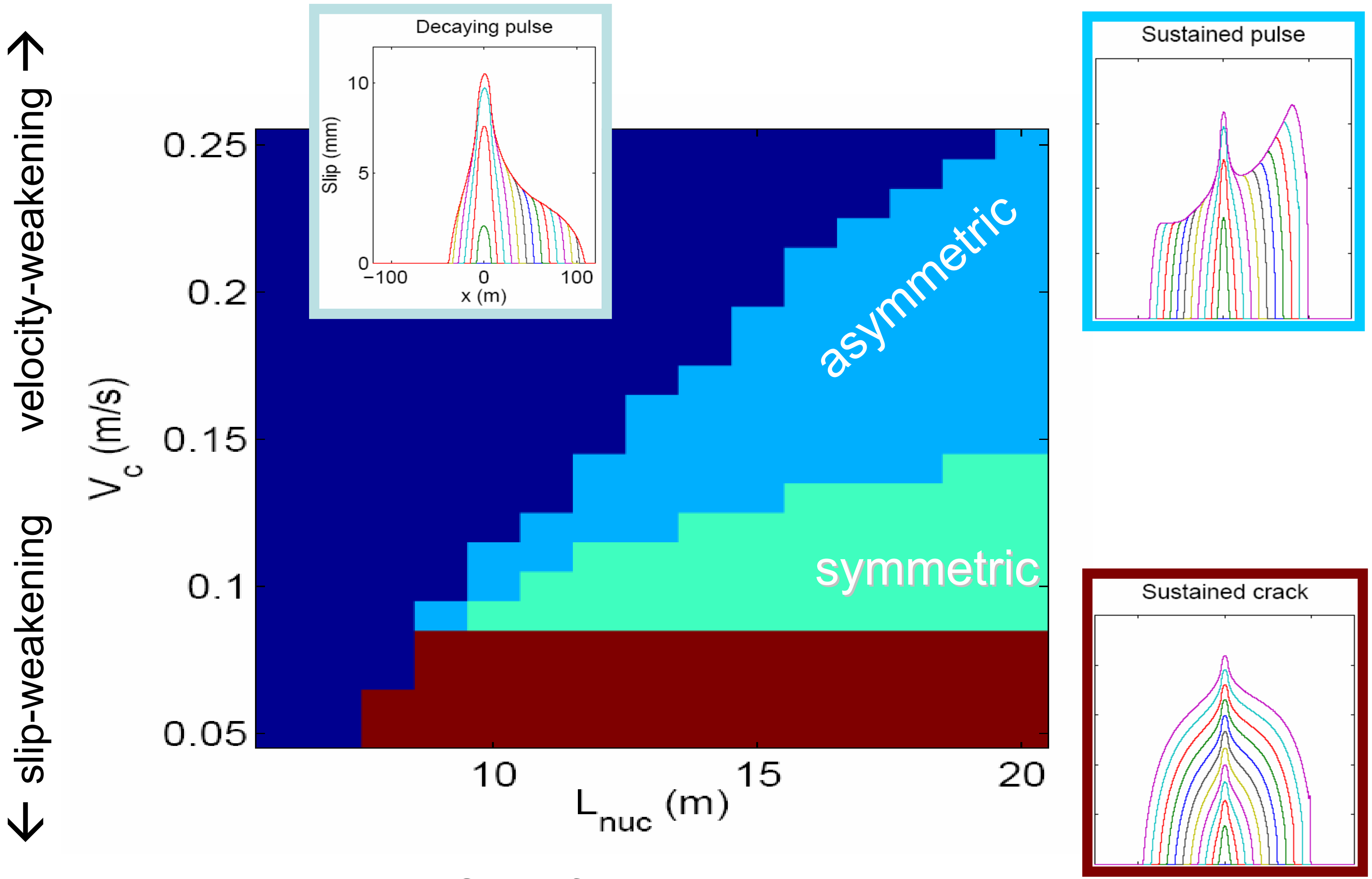
- Regularized normal stress response $\dot{\sigma^*} = \frac{V^*}{\delta_\sigma} (\sigma - \sigma^*)$

- Smooth nucleation, subshear rupture, parameter choice unfavorable for wrinkle-like pulse

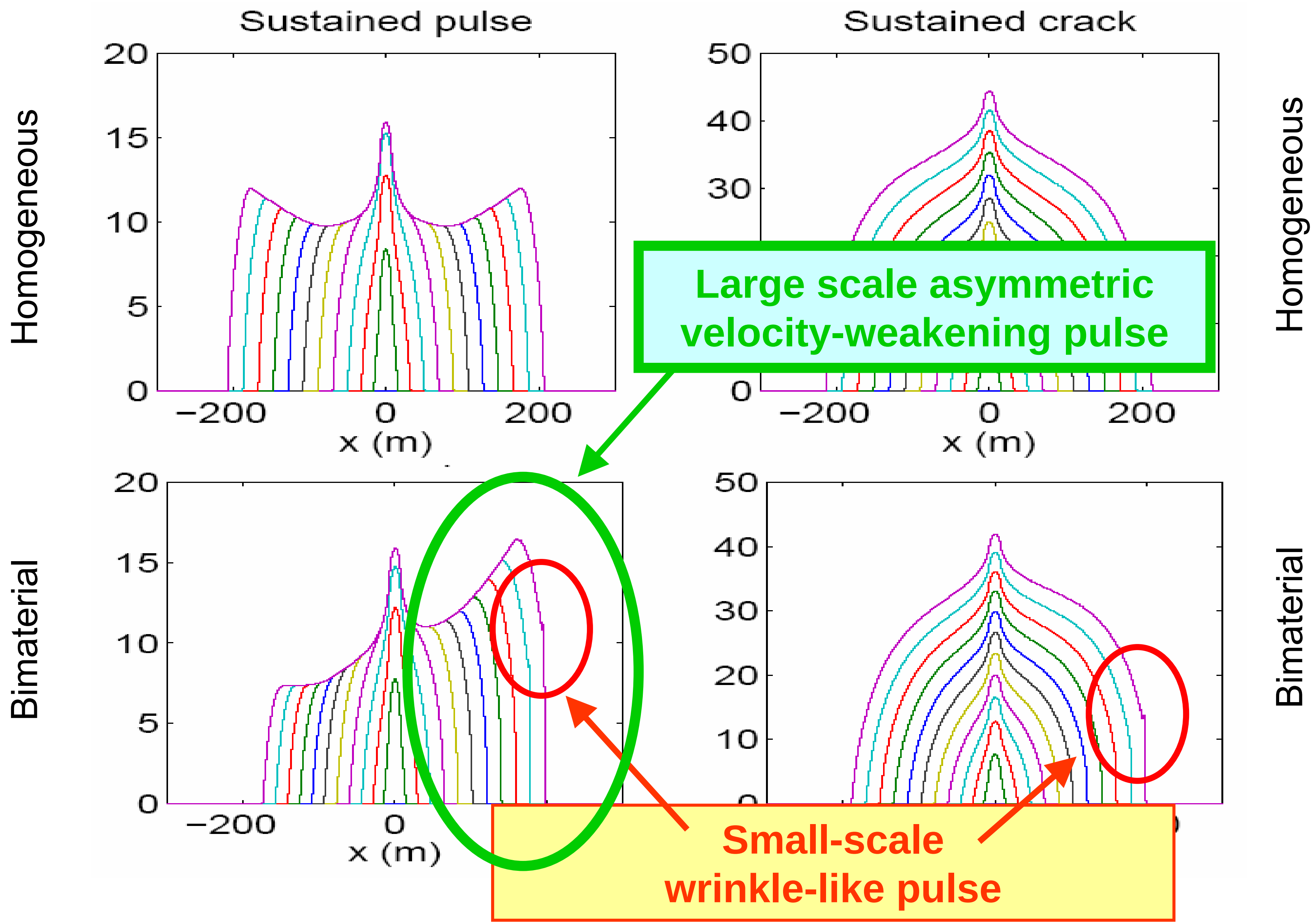
Rupture styles in homogeneous medium



Rupture styles in bimaterial faults

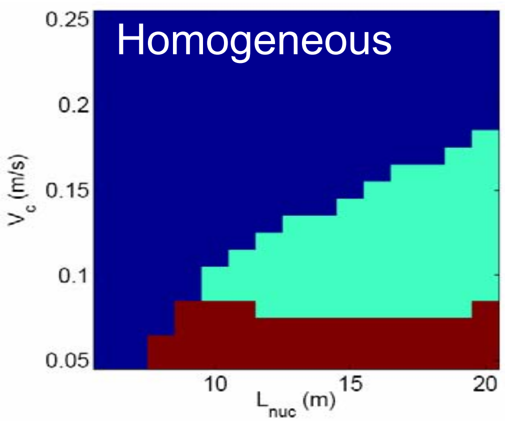


Size of the triggering asperity



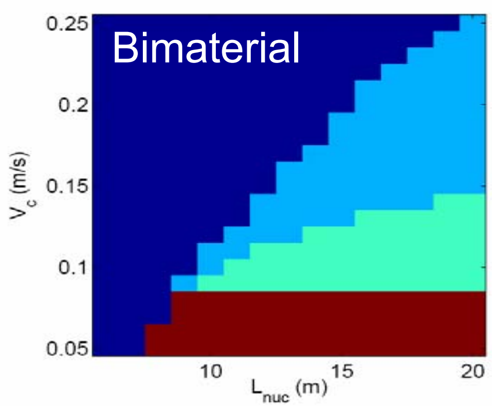
Sustained pulse
Sustained crack
Homogeneous
Bimaterial
x (m)
Large scale asymmetric velocity-weakening pulse
Small-scale wrinkle-like pulse

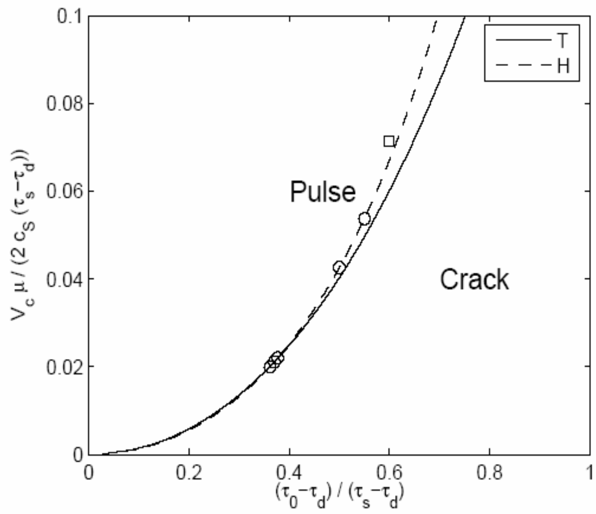
Macroscopic source asymmetry

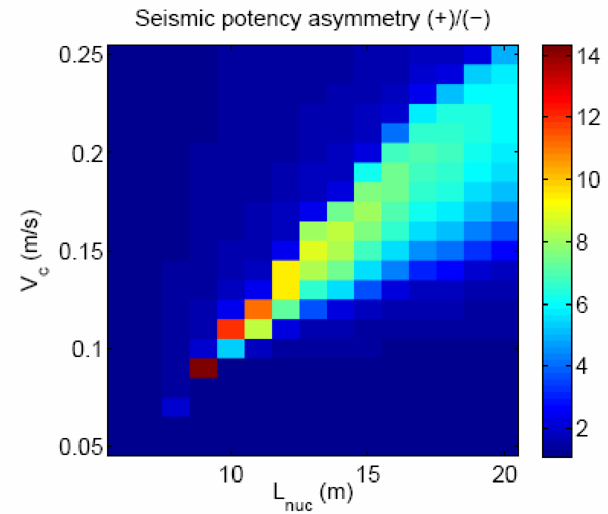


The bimaterial effect destabilizes first the large-scale pulse that propagates in the preferred direction

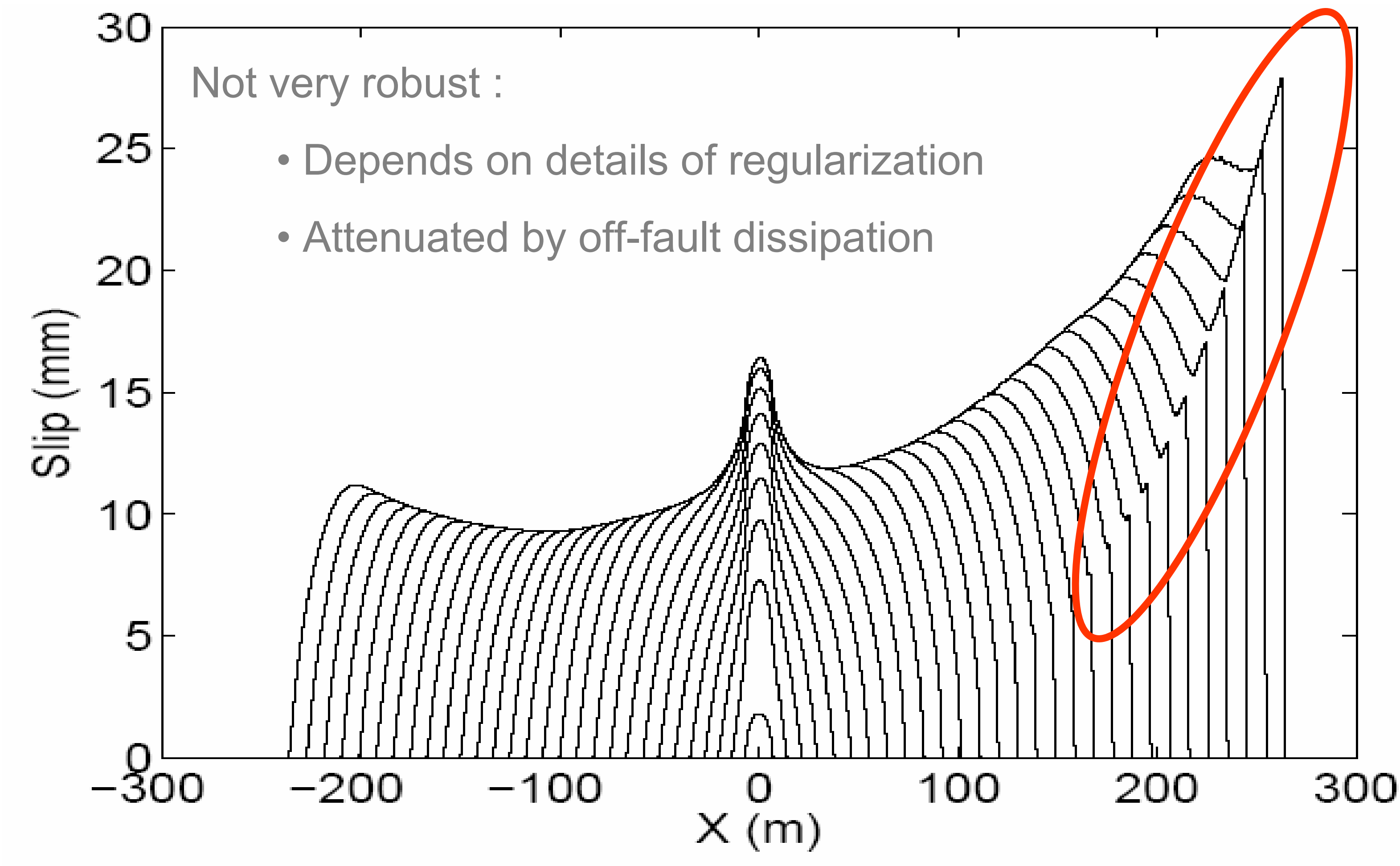
→ larger propagation distance and larger slip in the preferred direction



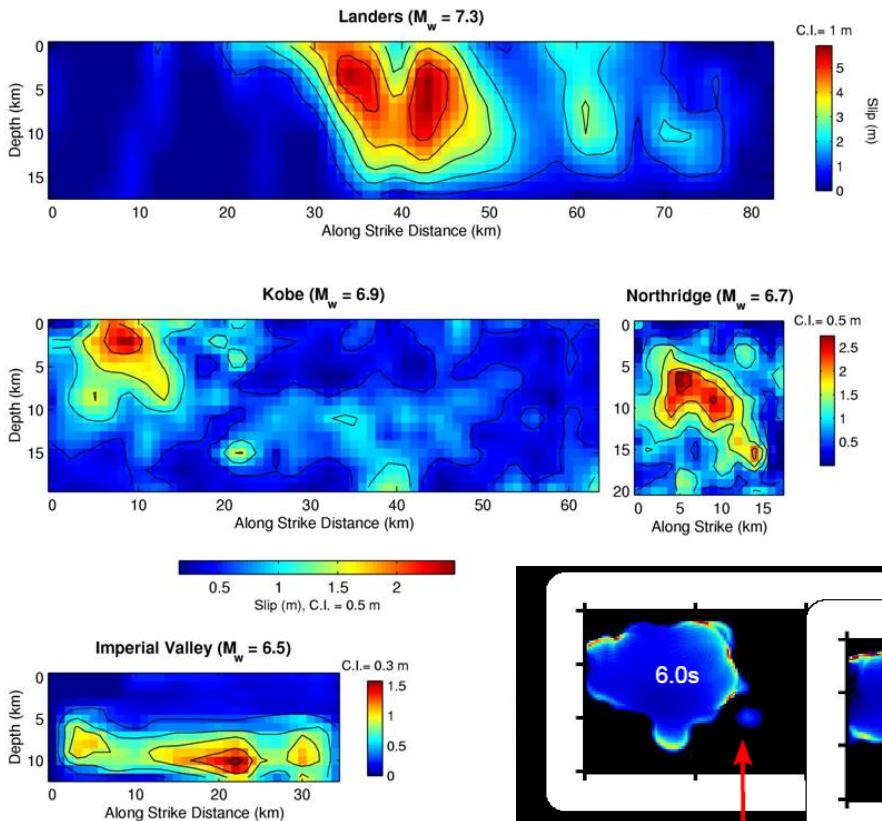




Small-scale, asymmetric bimaterial pulse

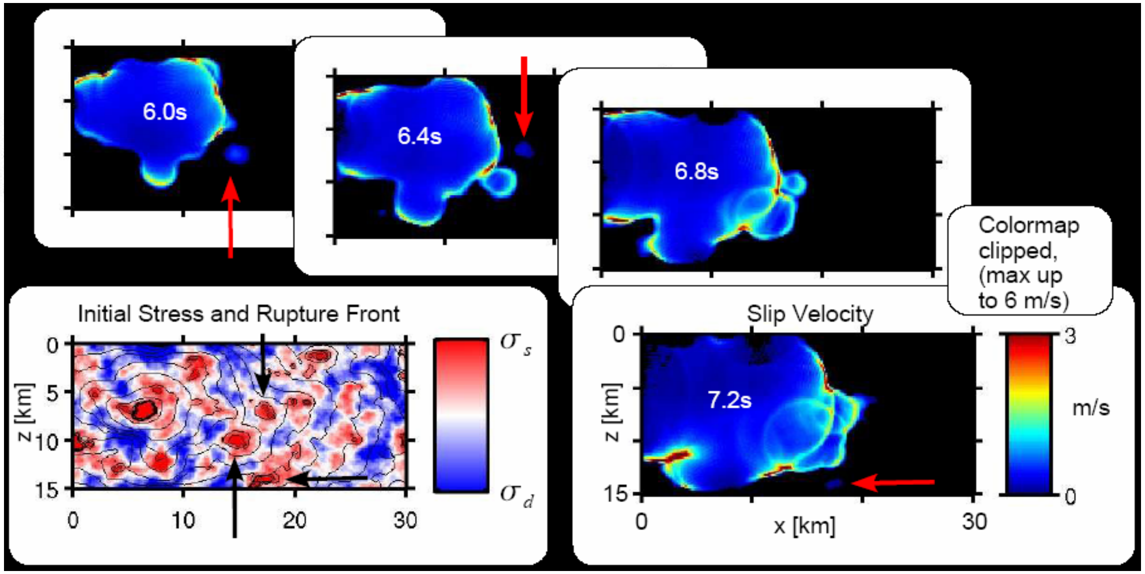


Evidences and origins of stress heterogeneity



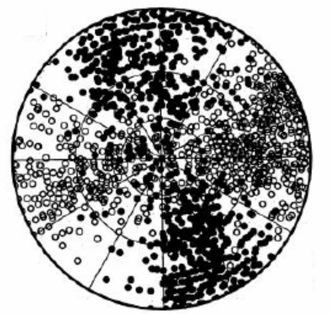
Sources imaged through seismological and geodetic data are notoriously complex

Fault heterogeneities (stress and strength) can generate earthquake complexity

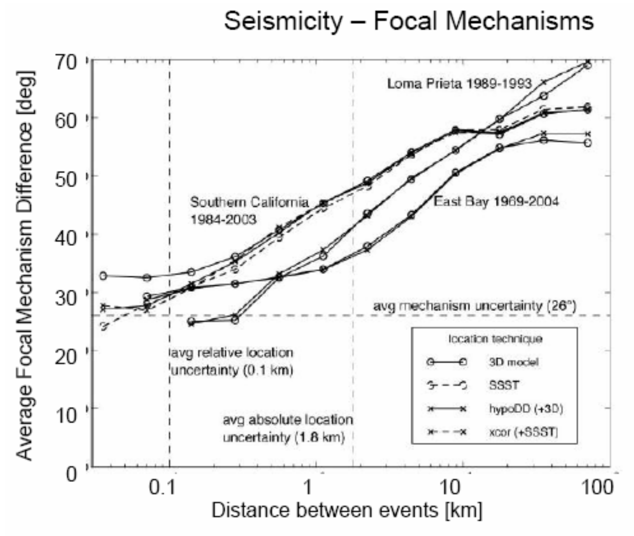


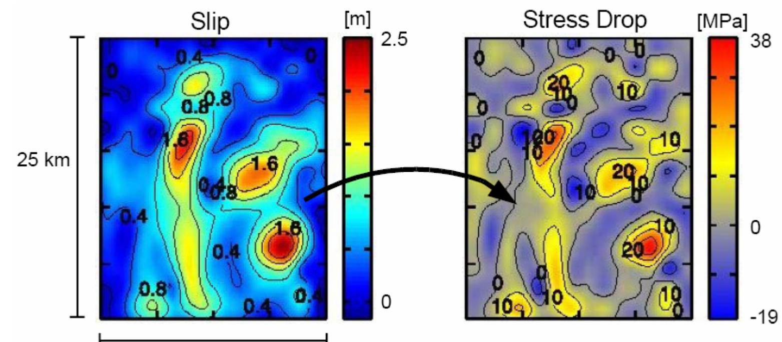
Evidences and origins of stress heterogeneity

Heterogeneity of focal mechanisms



Hardebeck & Hauksson (2001)

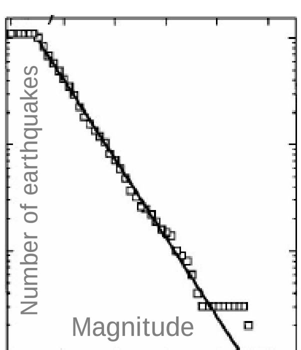




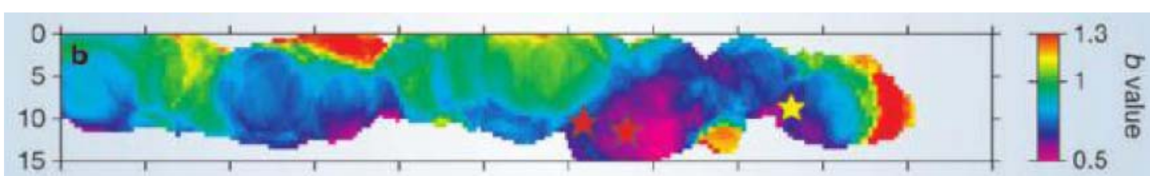
Figures taken from Ripperger & Mai, 2004 (original slip model of the Northridge 1994 event by Hartzell et al., 1996)

Imaged coseismic slip distributions and inferred stress drop

- Stress concentration at the edge of previous earthquakes on the same fault
- Stress transfer from neighboring faults
- Non uniform loading: creeping sections, creep at the bottom
- Non planar fault geometry
- Fluid pressure migration
- Material heterogeneities



Heterogeneity of b-values (Schorlemmer and Wiemer, 2005)



Initial stress heterogeneities

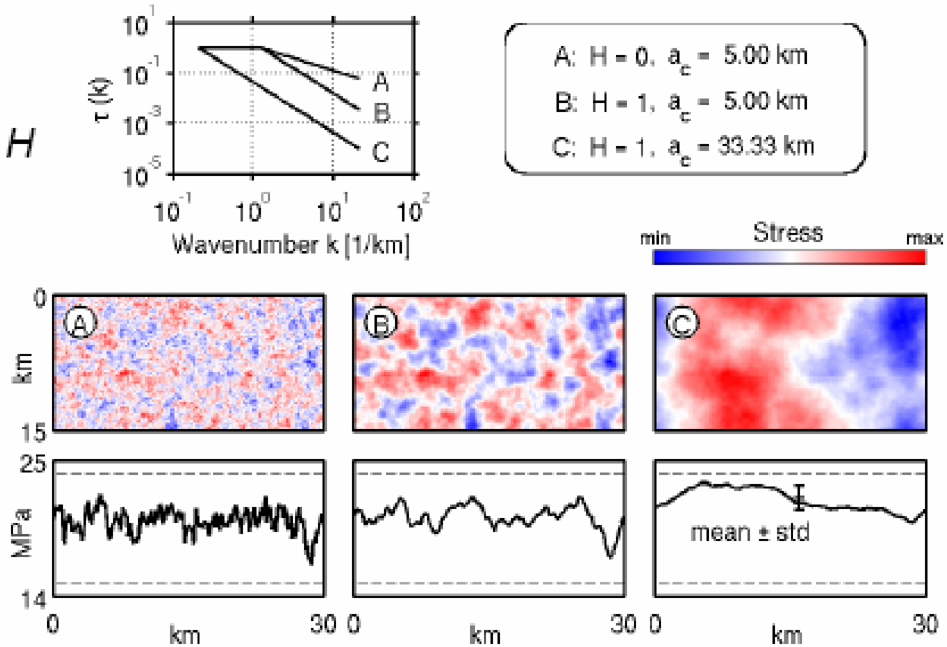
Statistical Quantification of Stress Heterogeneity

Wavenumber spectrum

- Decay at high wave numbers controlled by Hurst exponent H
- Correlation length a_c

Gaussian Distribution

- Standard deviation

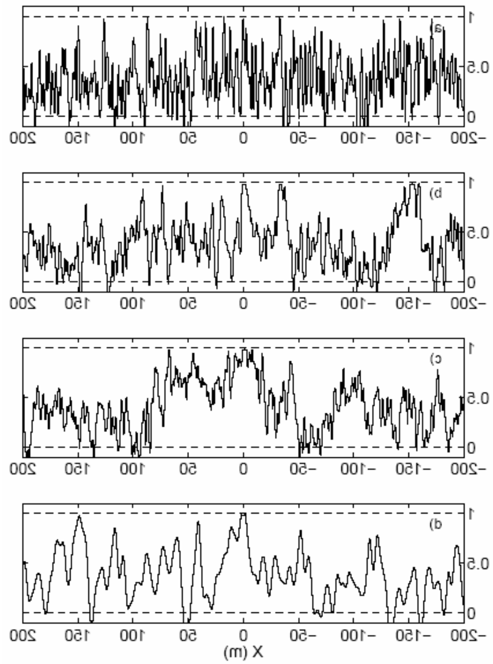


J. Ripperger

Initial stress heterogeneities

Prescribed stress spectrum :

$$|\tau_0(k)|^2 \propto \frac{\exp\left[-(L_2|k|)^2\right]}{\left[1+(L_1|k|)^2\right]^{1/2+H}}$$



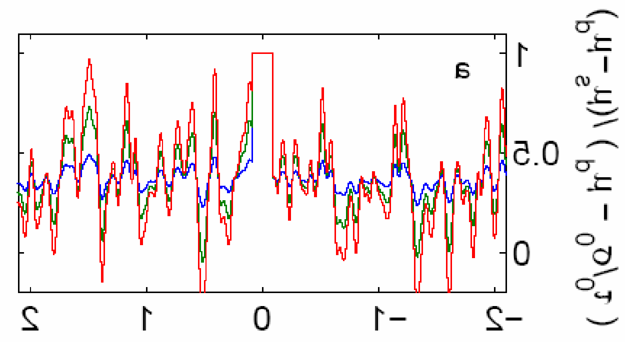
Prescribed amplitude (standard deviation *std*)

4 representative parameter sets :

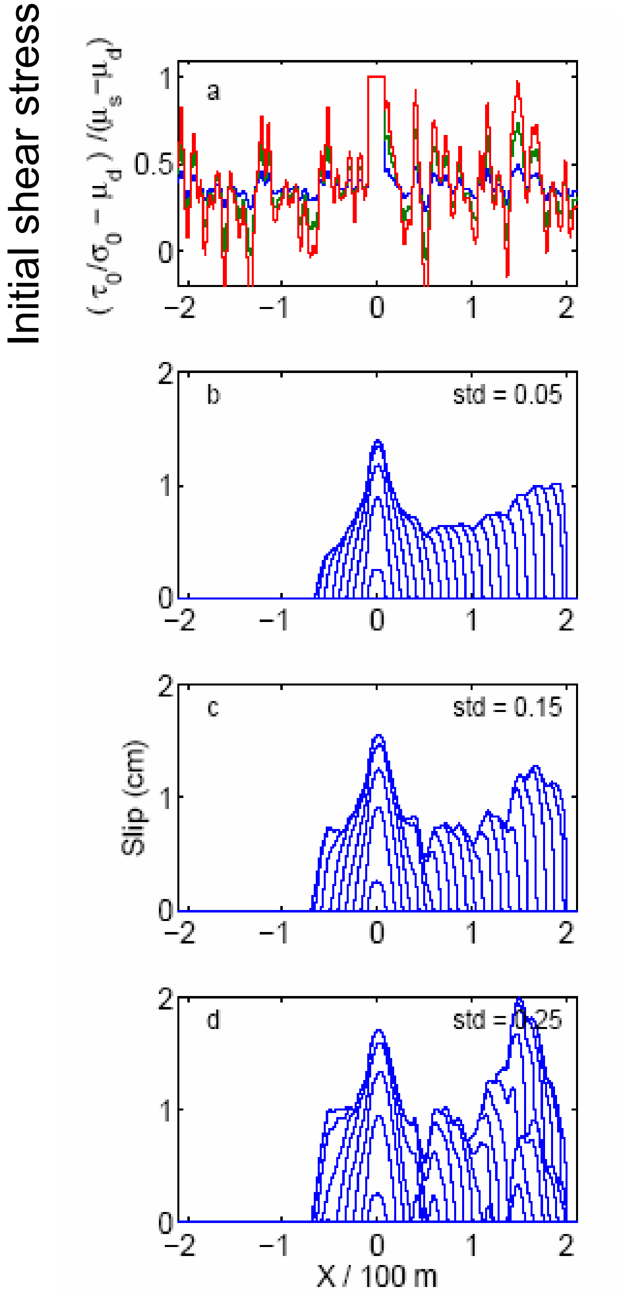
Set	L_1 (m)	L_2 (m)	H
A	0	0.5	0
	$\times$	0.5	-0.5
B	10	0.5	0
C	100	0.5	0
D	$\times$	2	-0.5

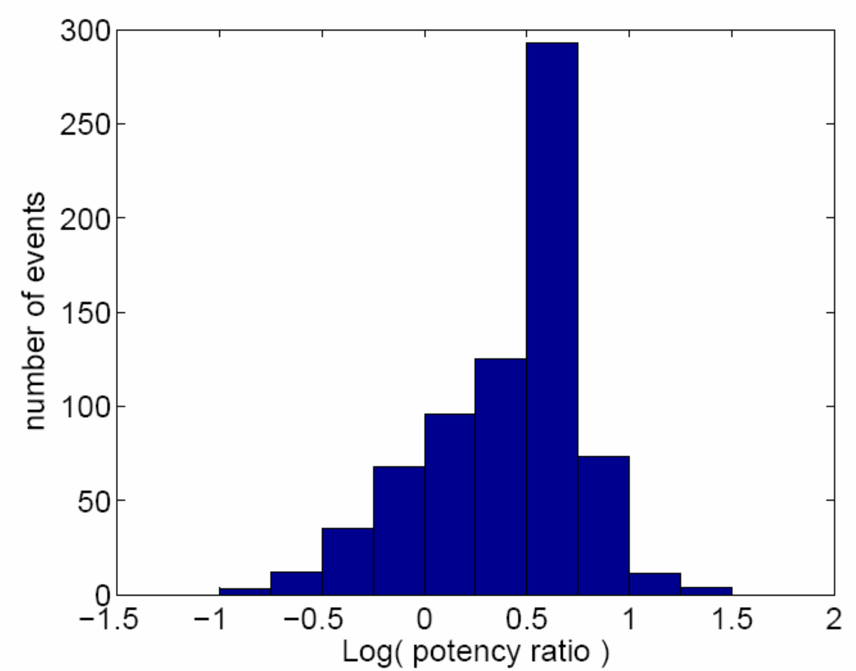
180 simulations for each set :

- 30 noise realizations
- 3 amplitude levels (*std*)
- fixed average
- flipped version



Effect of initial stress heterogeneities

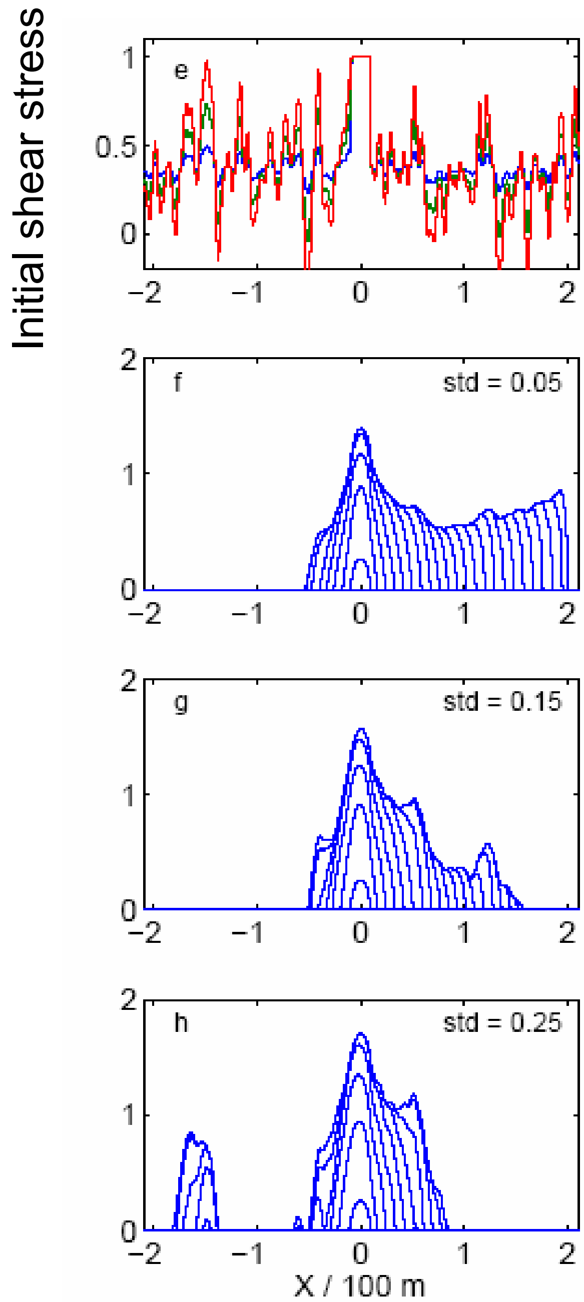


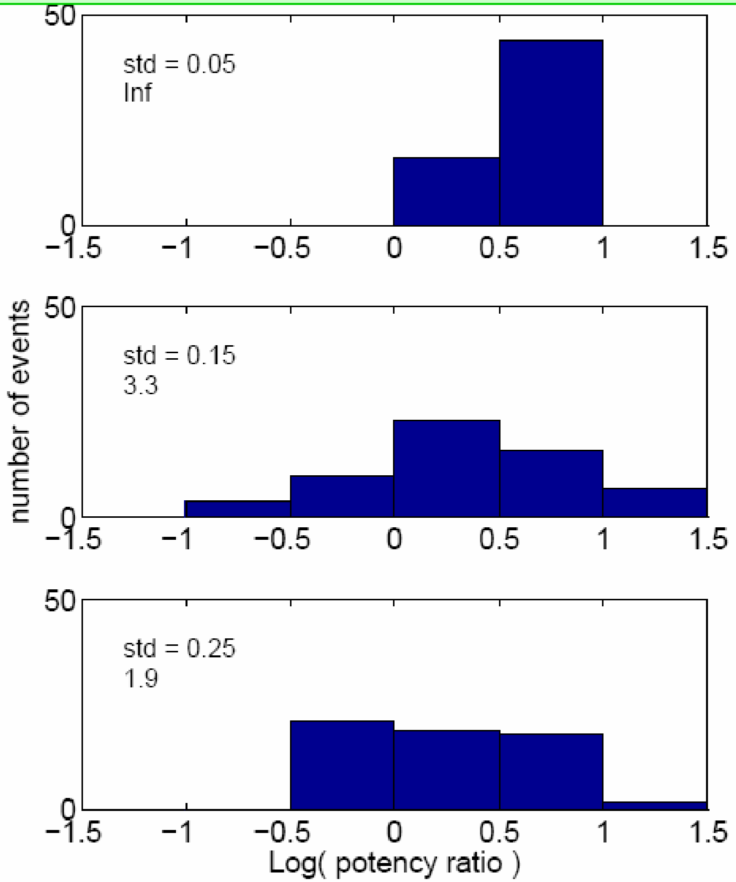


Seismic potency is skewed towards the "preferred" direction

Effect of initial stress heterogeneities

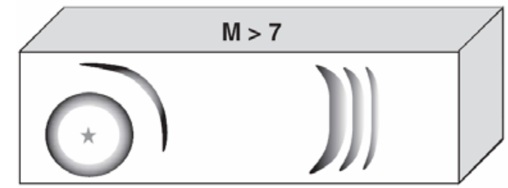
Effect of heterogeneity amplitude: shuffles the asymmetry





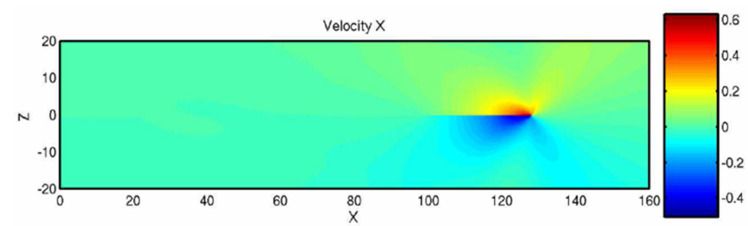
Conclusions on bimaterial rupture

Velocity-weakening bimaterial faults generate large-scale rupture pulses with strong, robust asymmetry towards the “preferred” direction … on average

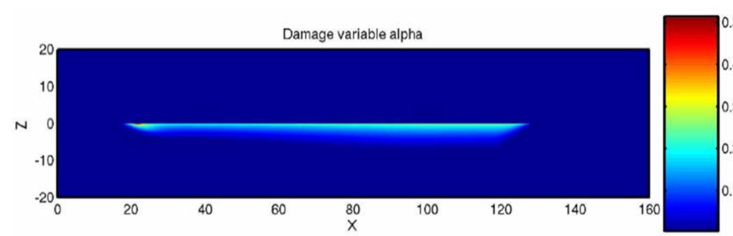


Pulses are more asymmetric than cracks
→ implications on 3D rupture

The “bimaterial pulse” is a small-scale superimposed feature, less robust, but important for aftershock triggering asymmetry



Statistical asymmetry persists for initial stress heterogeneity of moderate amplitude, but can be suppressed by very strong heterogeneities



Open questions (work in progress):

- Competing physical processes: off-fault dissipation by dynamic damage
- Earthquake cycle + micro-seismicity simulations

Summary

- Overview of rupture styles: cracks and pulses

In collaboration with Allan Rubin (Princeton) and Hugo Perfettini (IRD)

Rubin and Ampuero (JGR 2006) *Earthquake nucleation on (aging) rate-and-state faults*

Ampuero and Rubin (JGR 2008) *Earthquake nucleation on rate-and-state faults : aging and slip laws*

Perfettini and Ampuero (JGR 2008) *Dynamics of a velocity strenghtening region: implications for slow earthquakes and postseismic slip*

Rubin and Ampuero (JGR 2009) *Self-similar slip pulses during rate-and-state earthquake nucleation*

  - Effect of stress heterogeneities

- **Earthquake nucleation under rate-and-state friction:**
  - **Aging law → cracks**
  - **Slip law → pulses**
  - **Implications for slow fronts**

Earthquake nucleation

Issue: precursory signals before large earthquake ?

Status: Laboratory experiments and modeling predict stable slip before dynamic rupture

… but evidence on natural faults has remained elusive!

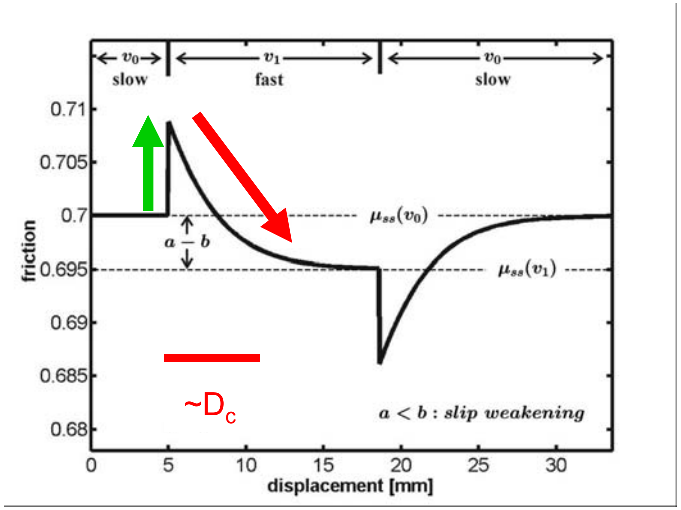
Does that invalidate the view of earthquake nucleation that emerged from decades of laboratory experiments?

Our goal: better understand predictions of rate-and-state friction models

Further impact: seismicity rate evolution, slow slip processes (silent earthquakes)

Rate-and-state friction

Typical evolution of friction
in velocity step experiments



Rate-and-state dependent friction coefficient:

$$\frac{\tau}{\sigma} = f^* + \boxed{a \ln \frac{V}{V^*}} + \boxed{b \ln \frac{V^*\theta}{D_c}}$$

State evolution law:

$$\dot{\theta} = 1 - \frac{V\theta}{D_c}.$$

or

$$\dot{\theta} = -\frac{V\theta}{D_c} \ln \frac{V\theta}{D_c}$$

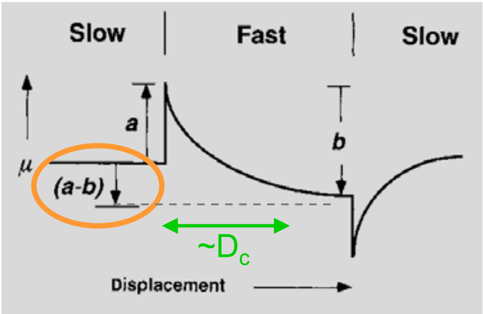
"Aging" law

"Slip" law

- Laboratory-based friction law introduced by Dieterich and Ruina in the early 1980s
- Essential components:
  - non-linear viscosity
  - evolution effect
- Stability of slip depends on the sign of (a-b):
  - a-b>0 : velocity strengthening, stable
  - a-b<0 : velocity weakening, unstable
- Nucleation style depends on a/b

- Open questions:
  - Appropriate state evolution law ?
  - Experiments at high P and T ?
  - Effect of fluids ?

Stability of a rate-and-state fault



- a-b<0 : weakening fault region, unstable if larger than

$$L_c \doteq \frac{\mu D_c}{(b-a)\sigma}$$

- a-b>0 : strengthening fault, stable …but can produce transients if triggered

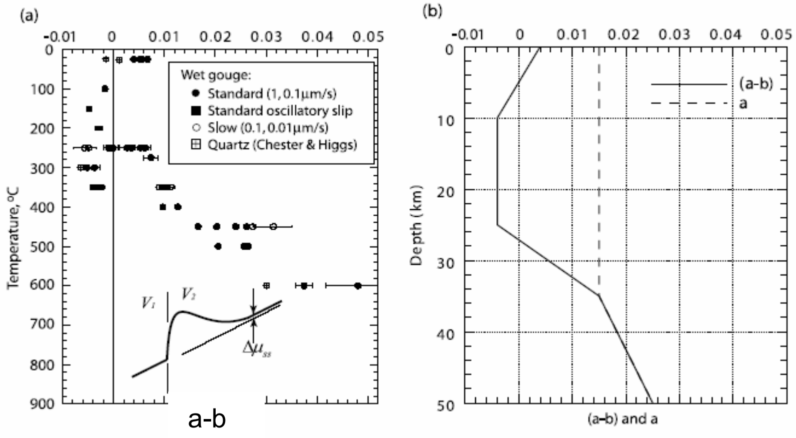
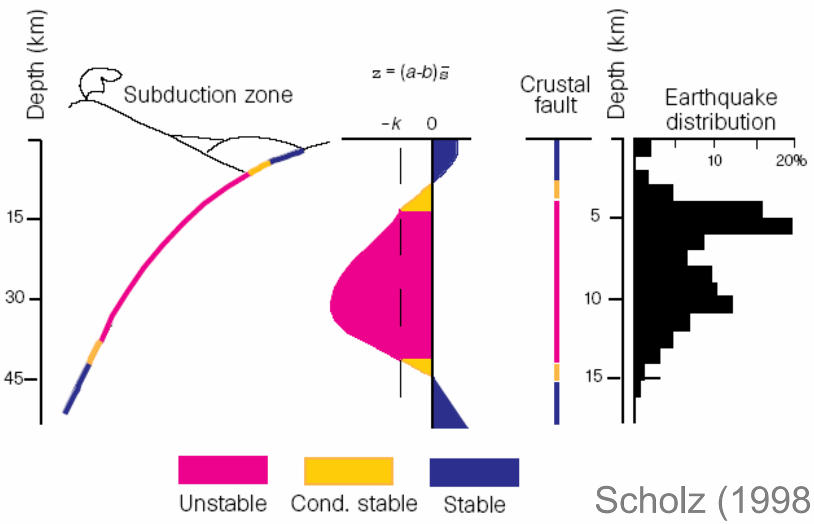


Figure 3. (a) Laboratory data, granite under hydrothermal conditions, on velocity weakening/strengthening at various temperatures (modified after *Blanpied et al.* [1995]). (b) Depth distribution of parameters *a* and $(a - b)$, transformed from temperature-dependent experimental data, using the thermal structure model of southwest Japan subduction zone of *Peacock and Wang* [1999].

Liu and Rice (2005)



Scholz (1998)

Nucleation on a rate-and-state fault with the "aging" law

$$\dot{\theta} = 1 - \frac{V\theta}{D_c}.$$

Dieterich (1992), Rubin and Ampuero (2005)

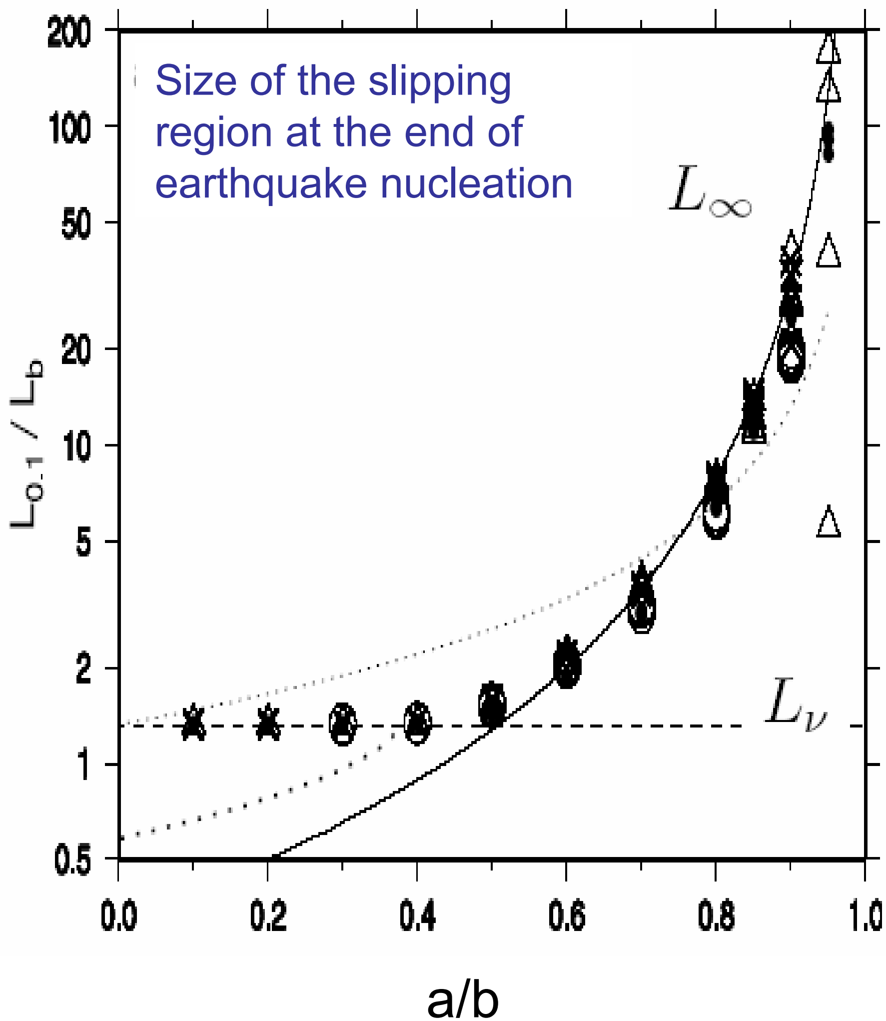
Stages :

- slip localization down to size

$$L_b \doteq \frac{\mu D_c}{b\sigma}$$

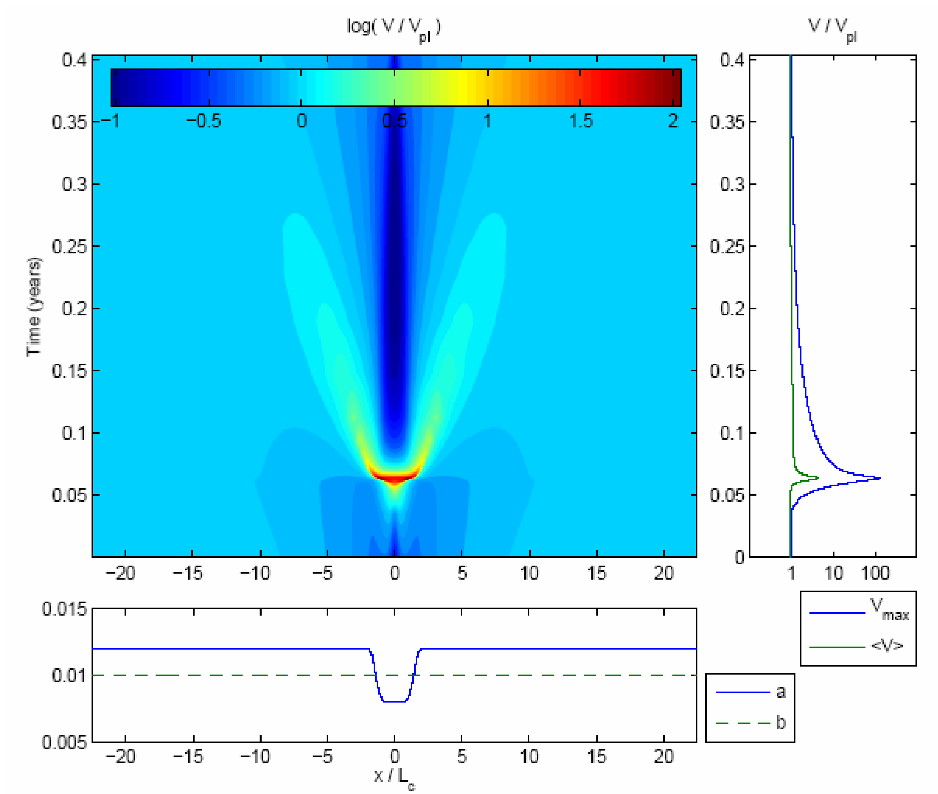
- slip acceleration on an area of fixed size L_b
- **if a/b>0.4**: quasistatic crack growth up to size

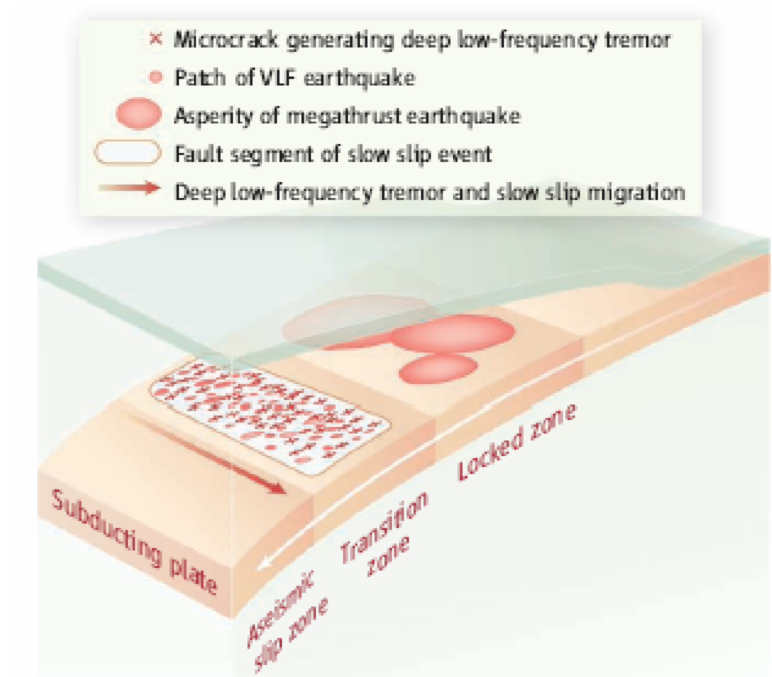
$$L_\infty = \frac{1}{\pi}\left(\frac{b}{b-a}\right)^2 L_b$$



Rubin and Ampuero (2005)

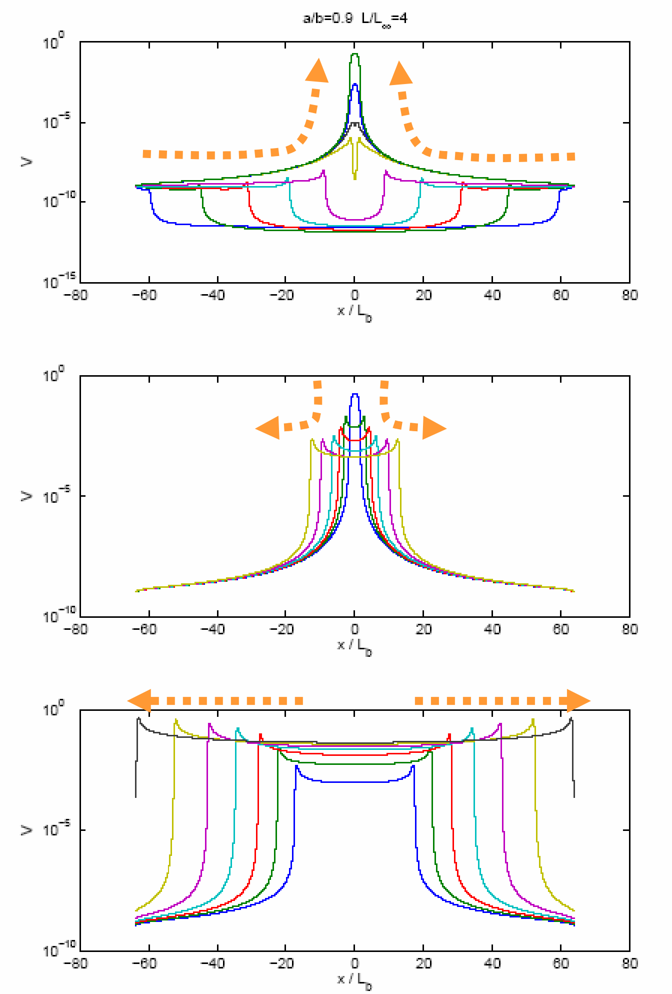
Behavior of a brittle asperity isolated in a creeping fault zone



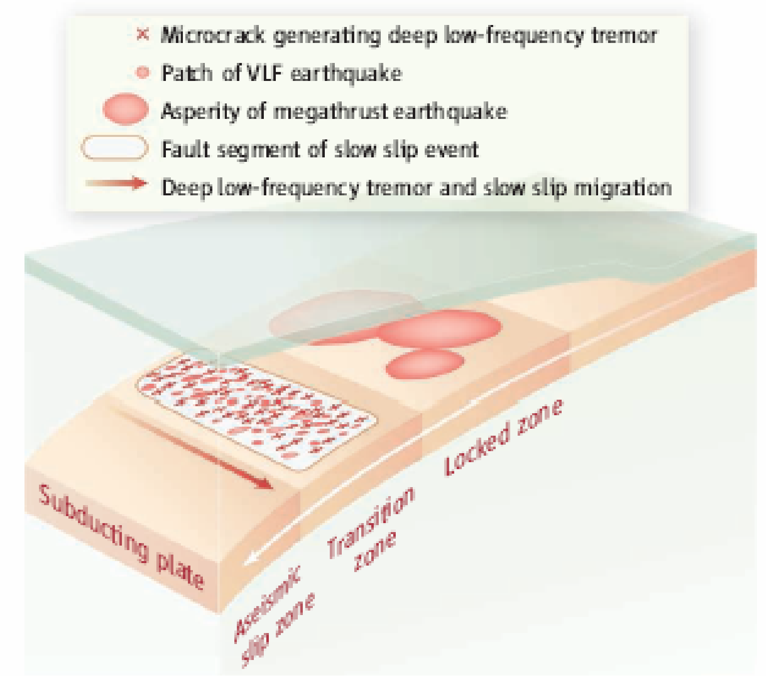


Behavior of a brittle asperity isolated in a creeping fault zone

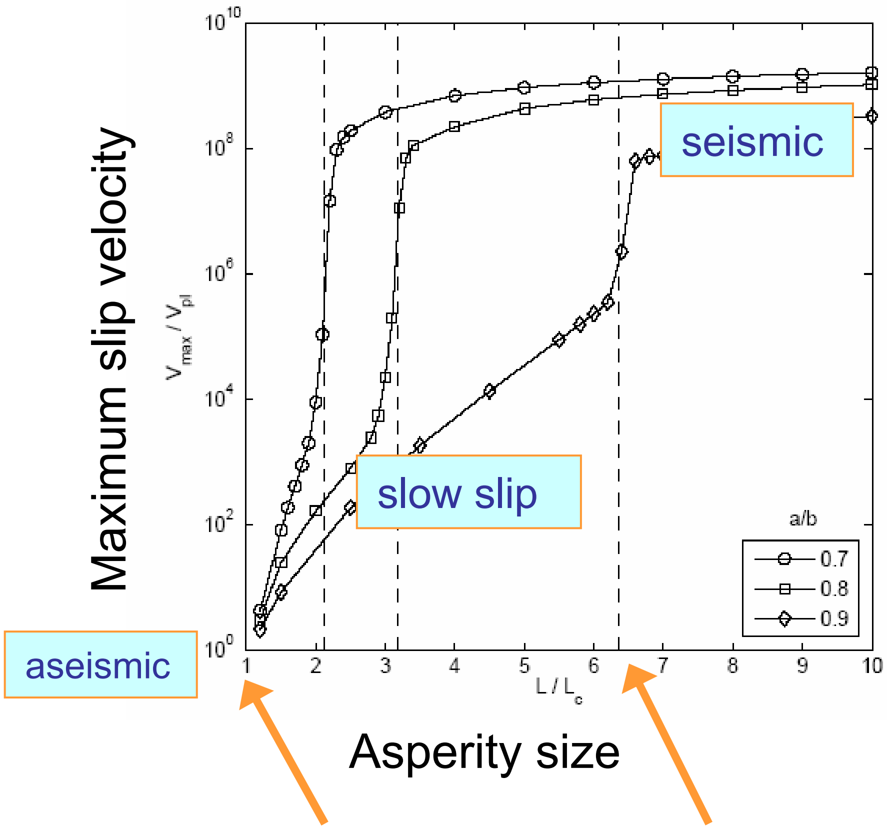
Log slip velocity



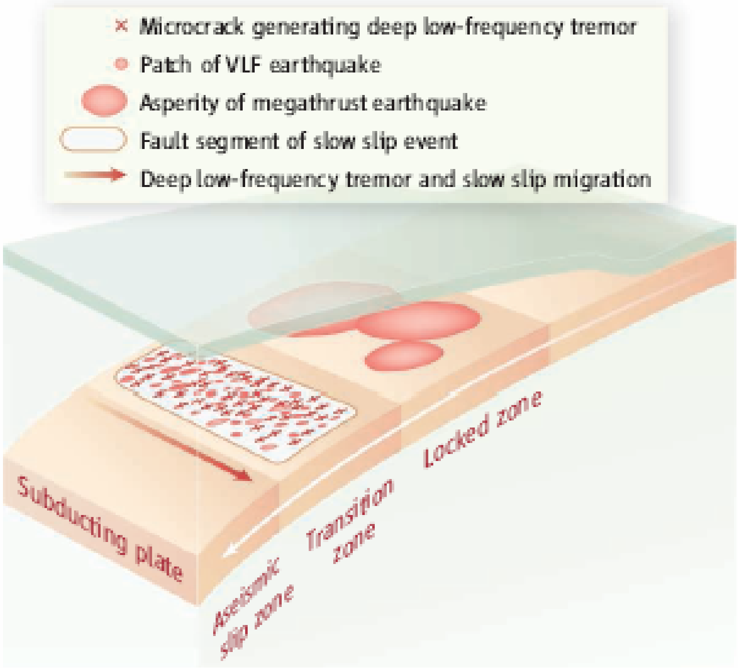
Position inside asperity



Behavior of a brittle asperity isolated in a creeping fault zone



$$L_b \doteq \frac{\mu D_c}{b\sigma} \qquad L_c \doteq \frac{\mu D_c}{(b-a)\sigma} \qquad L_\infty = \frac{1}{\pi}\left(\frac{b}{b-a}\right)^2 L_b$$



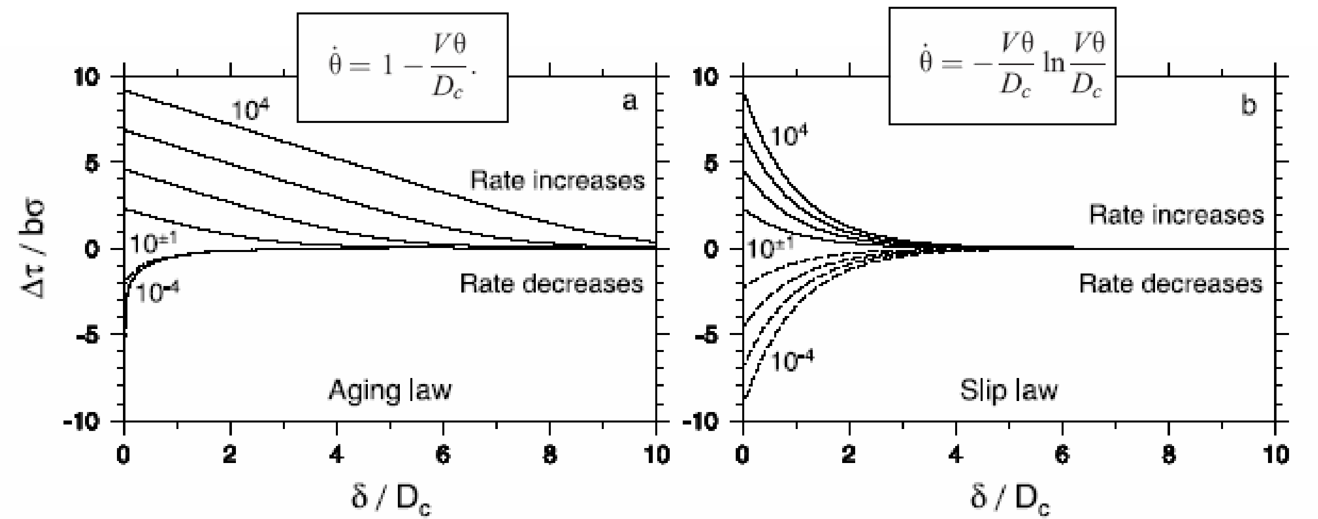
Periodic slow events are possible for large a/b on asperities of intermediate size between L_b and L_∞

Nucleation on a rate-and-state fault with the "slip" law $\dot{\theta} = -\frac{V\theta}{D_c} \ln \frac{V\theta}{D_c}$

Ampuero and Rubin (2008), Rubin and Ampuero (2009)

The two evolution laws for θ predict different slip weakening distance

→ different scaling of fracture energy ("breakdown work")



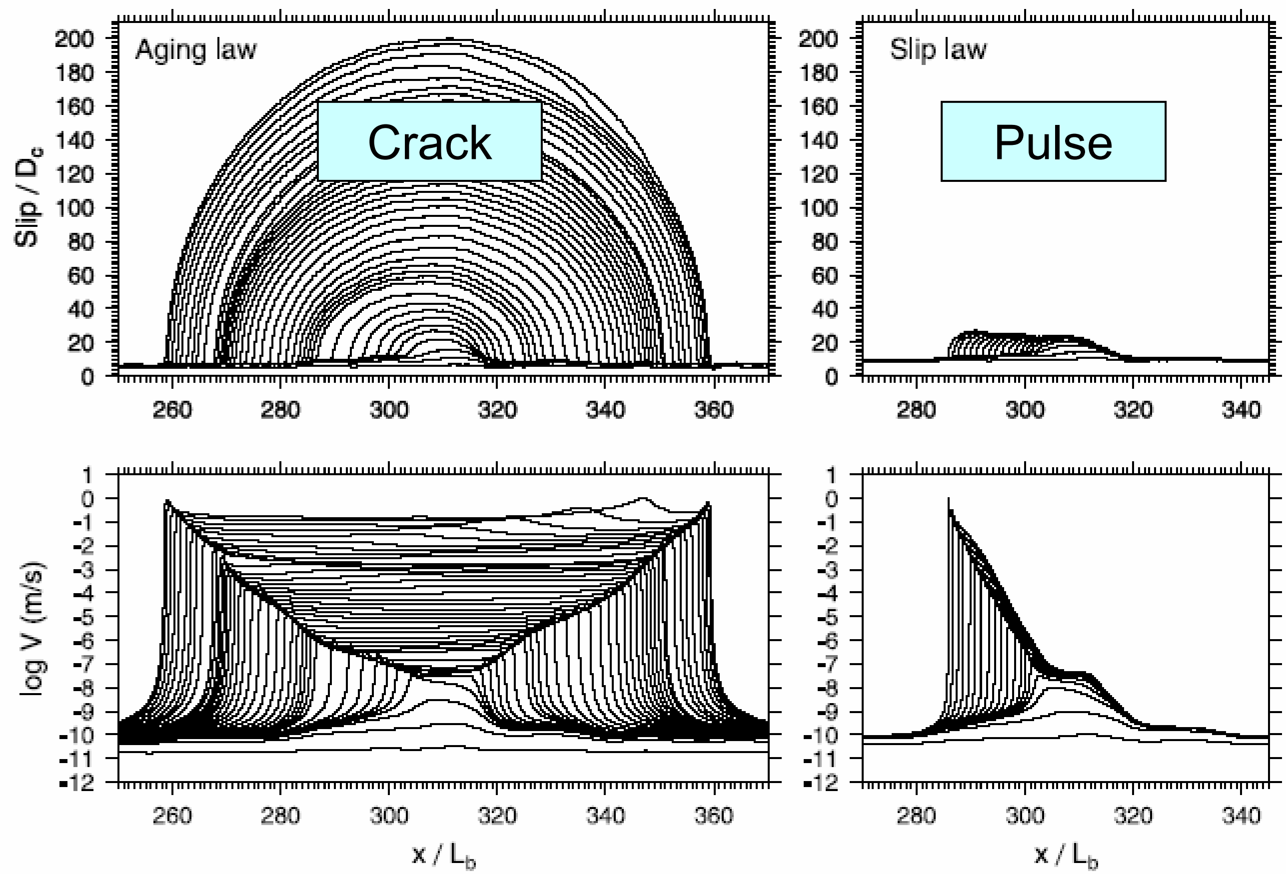
Slip weakening distance:	$\sim D_c \log(V)$	$\sim D_c$
Fracture energy: G_c	$\sim b\sigma\, D_c \log(V)^2$	$\sim b\sigma\, D_c \log(V)$

Energy release rate of a crack of size L: $G \sim [(b-a)\sigma \log(V)]^2\, L$

Energy balance implies:	$L \to L_\infty$	no solution with growing L

Nucleation on a rate-and-state fault with the “slip” law $\dot{\theta} = -\frac{V\theta}{D_c} \ln \frac{V\theta}{D_c}$

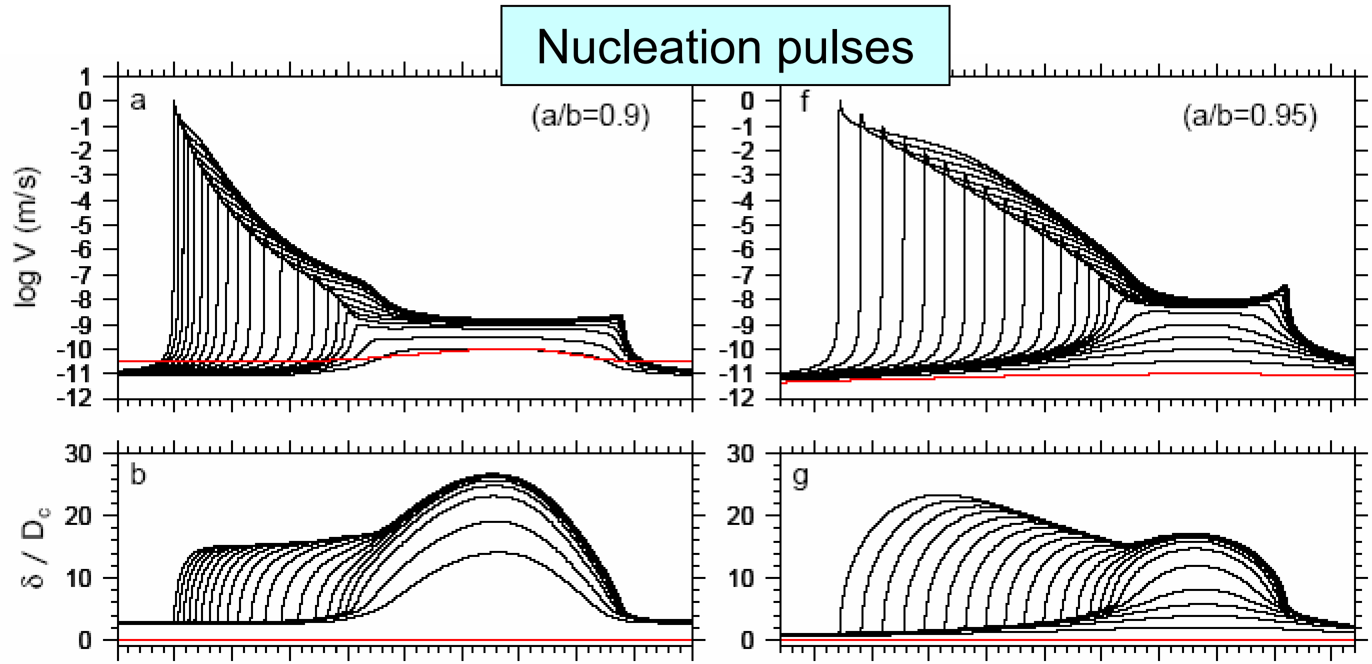
Ampuero and Rubin (2008), Rubin and Ampuero (2009)



Nucleation on a rate-and-state fault with the "slip" law

$$\dot{\theta} = -\frac{V\theta}{D_c}\ln\frac{V\theta}{D_c}$$

Ampuero and Rubin (2008), Rubin and Ampuero (2009)



A range of self-similar solutions:
Growth exponent p = 0, 0.5 or 1

$$\frac{\delta}{D_c} = \Psi_0^p f(X)\ , \quad X \equiv \frac{x'}{L_b}\Psi_0^{(1-2p)}\ ; \quad \Psi_0 \equiv \ln(V_{max}\theta_{bg}/D_c)$$

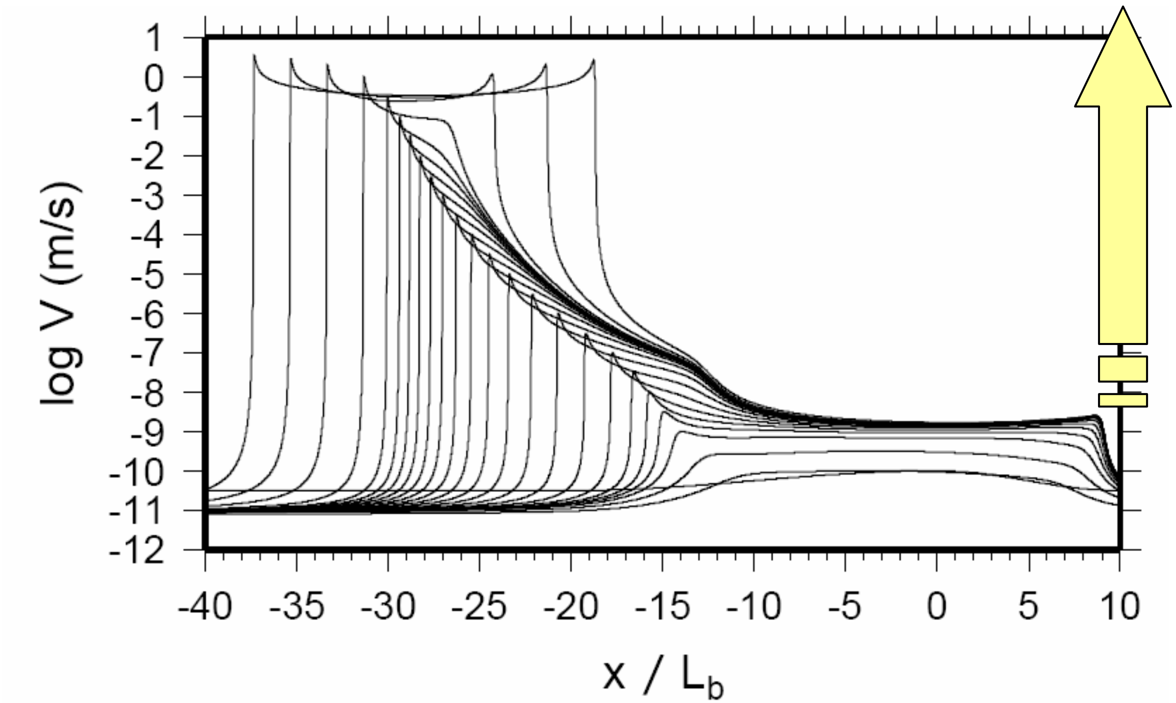
$$\frac{V}{V_{max}} = \Psi_0^{-p} h(X)\ .$$

Nucleation on a rate-and-state fault with the "slip" law $\dot{\theta} = -\frac{V\theta}{D_c} \ln \frac{V\theta}{D_c}$

Ampuero and Rubin (2008), Rubin and Ampuero (2009)

What happens later?

Transition to dynamic rupture: pulse splits



Stages:

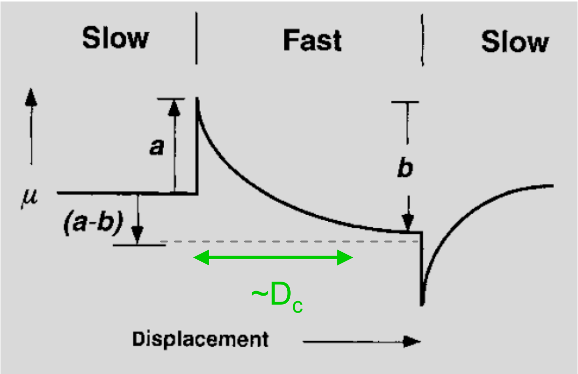
III : bilateral dynamic crack growth

II : nucleation pulse propagation

I : slip localization

Slow fronts in rate-and-state earthquake models

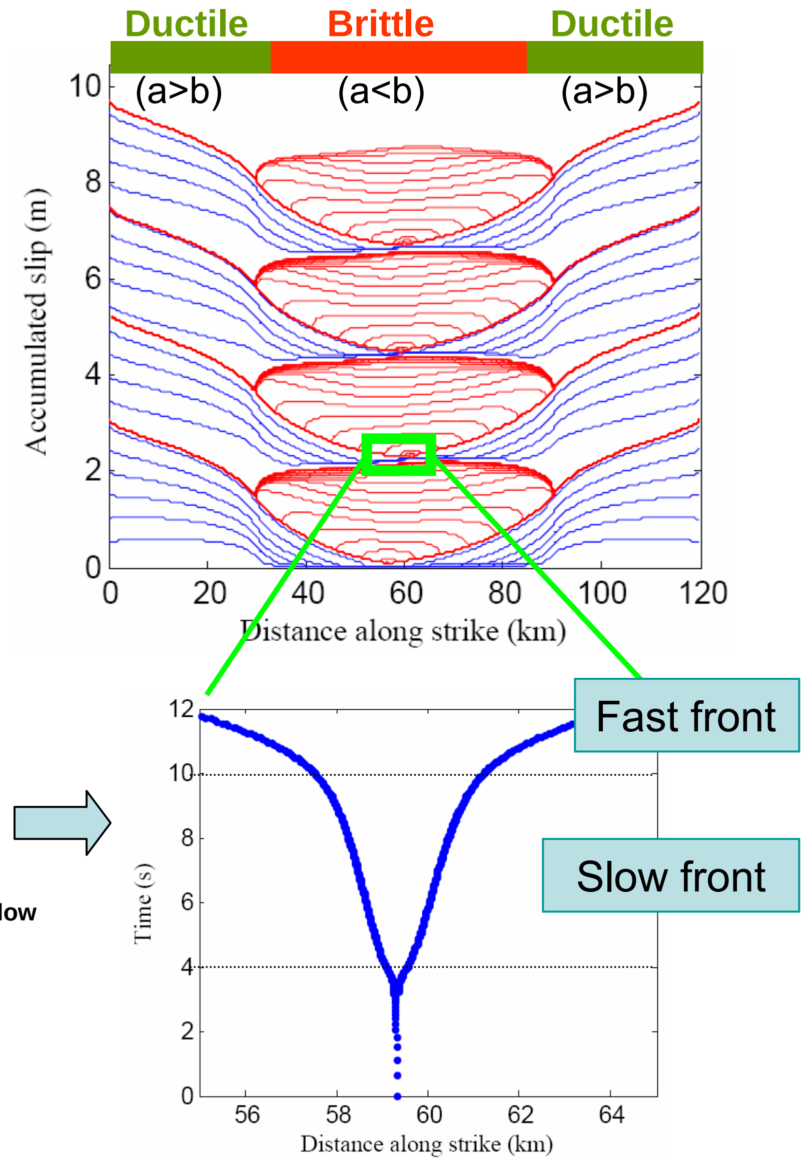
(Kaneko and Ampuero, in progress)



Rate-and-state (V,θ) dependent friction coefficient:

$$\frac{\tau}{\sigma} = f^* + a \ln \frac{V}{V^*} + b \ln \frac{V^* \theta}{D_c}$$

State evolution law ("slip law"): $$\dot{\theta} = -\frac{V\theta}{D_c} \ln \frac{V\theta}{D_c}$$



Position of the rupture front as a function of time during the transition from quasi-static to dynamic rupture

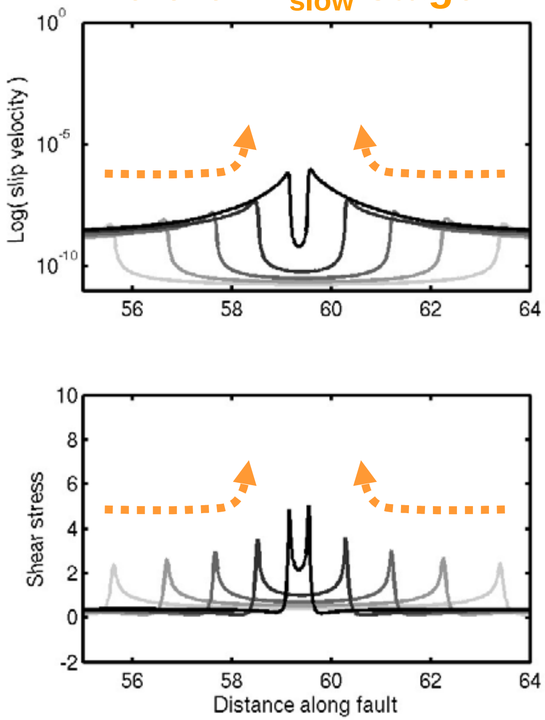
A slow rupture front develops with propagation speed V_{slow} of order 1/20th of the S wave speed

Only found (so far) under the "slip" evolution law and for high a/b >0.8, with some dependence on boundary conditions (size of brittle zone)

Slow fronts in rate-and-state earthquake models

(Kaneko and Ampuero, in progress)

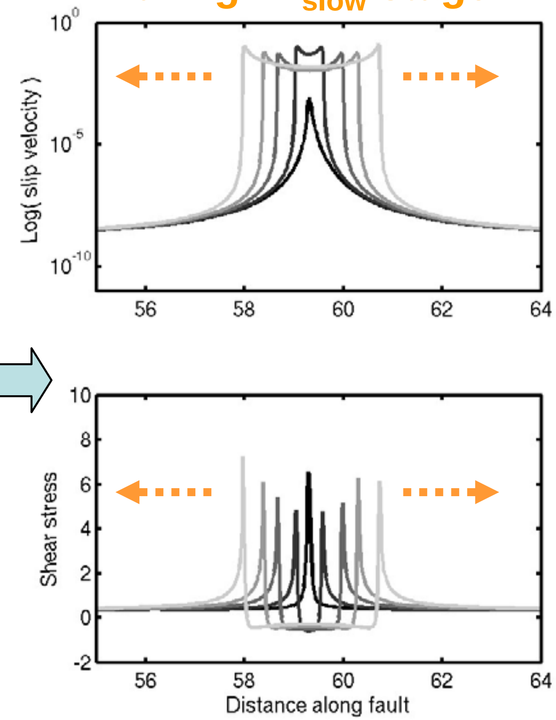
Before "V_{slow} stage"



Before the V_{slow} stage (interseismic stage): inward propagation of two very slow creep fronts

The V_{slow} stage starts on a **stress concentration** inherited from the coalescence of the creep fronts

During "V_{slow} stage"



Consider a stress concentration (=F×length) over a background stress drop ($\Delta\tau$).
The static **energy release rate** as function of distance to the stress concentration (a) **reaches a minimum at some distance.**
This implies a roughly constant rupture speed (V_{slow}).

$$G_0 \doteq \frac{K_0^2}{2\mu}$$

$$\overline{K}_0(a) \approx \sqrt{\pi a}\left(\Delta\overline{\tau} + \frac{2}{\pi}\frac{F}{a}\right)$$

… It remains to elucidate how this nucleation process leads so generally to a V_{slow} speed of order 1/20th of the S wave speed …

Slow fronts in rate-and-state earthquake models

(Kaneko and Ampuero, in progress)

Rupture propagation speed V_{prop} and peak slip velocity V_{max} are related by (Ampuero and Rubin, 2008)

$$\frac{V_{prop}}{V_{max}} \approx 0.75 \frac{\mu'}{b\sigma} \left(\ln \frac{V_{max}\theta_i}{D_c} \right)^{-1}$$

Or

$$\frac{V_{prop}/c_s}{V_{max}/V_{dyn}} \approx \frac{a}{b} \left(\ln \frac{V_{max}\theta_i}{D_c} \right)^{-1}$$

where $V_{dyn} = 2a\sigma\, c_s/\mu$ is a typical slip velocity at the transition to elasto-dynamics (when direct effect and radiation damping become comparable)

The log term above is typically ~ 20 (slip velocity jump ~ 10^9)

If a~b, at the transition to dynamics when $V_{max} = V_{dyn}$,

$$\boxed{V_{prop} \sim c_s /20}$$

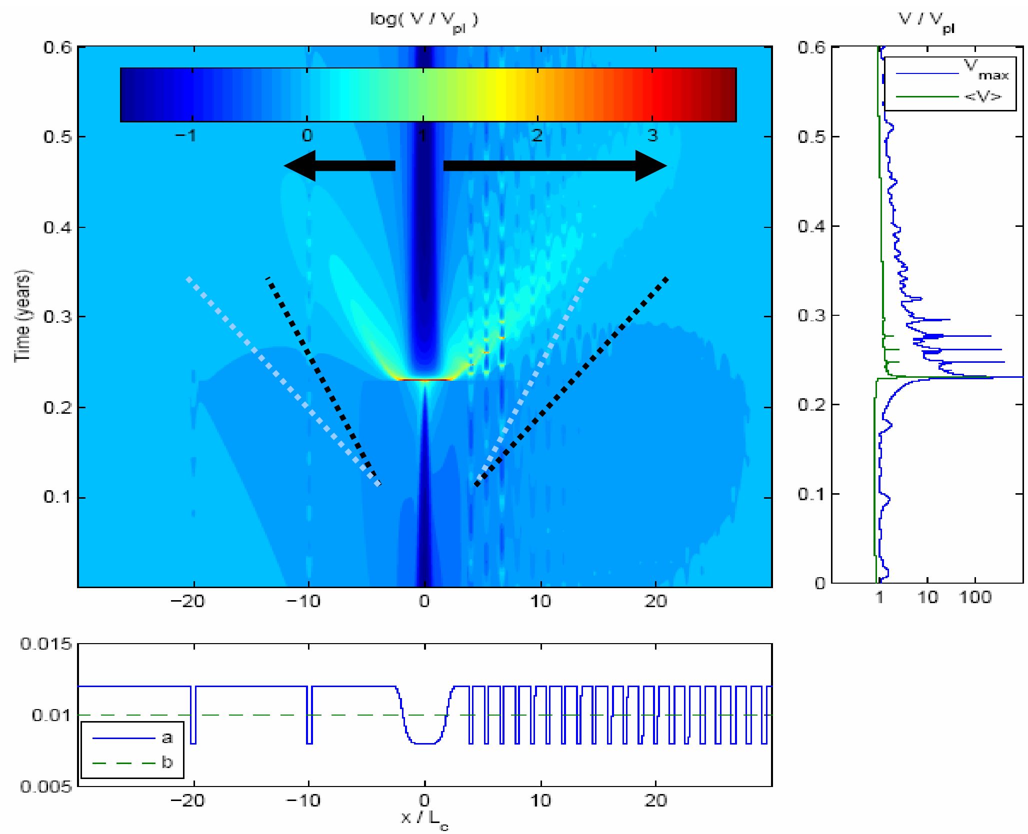
Perfettini and Ampuero (2008)

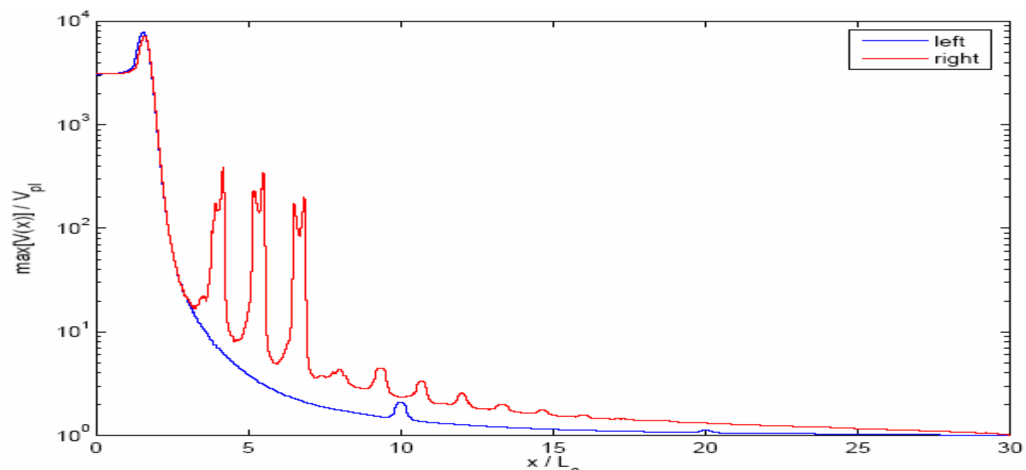
Conclusions on earthquake nucleation under rate-and-state friction

- The slip behavior during nucleation is more complicated than previously recognized: new length scales, cracks vs. pulses, range of pulse styles

- A proper evolution equation for the state variable is crucial: scaling of fracture energy with slip velocity

- Remains to be explored: impact of this complexity on seismicity rate formulations (Dieterich, 1994; based on earlier views of the nucleation process)





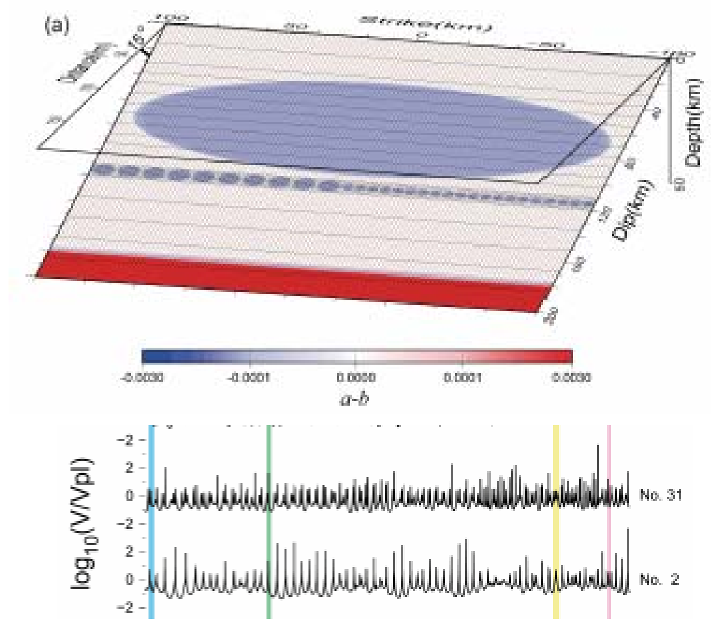
Feedback between slow slip and “tremor asperities”

Macroscopic effects:

- Longer propagation distance
- Faster apparent propagation speed
- Larger moment rate

Efficiency of feedback depends on asperity density

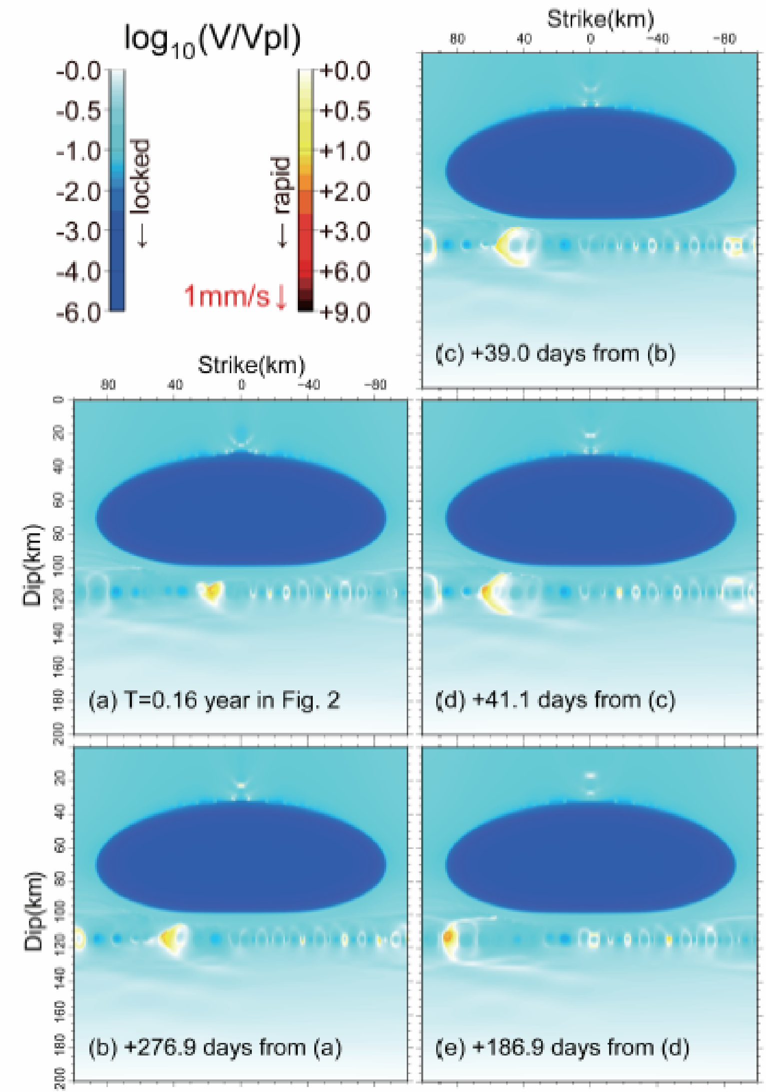
Computational challenges in 3D modeling



Wide range of space-time scales involved in coupled tremor and slow slip phenomena

Multi-scale approach: asperity scale solved by local axisymmetric code, creep propagation solved on a coarse grid

Homogeneization approach: derive constitutive equations for a representative volume of tremor sources and account for their feedback with larger scale slip



Quasi-dynamic 3D simulations by K. Ariyoshi on the Earth Simulator (JAMSTEC)