Heterogeneities and complexity in earthquake dynamics

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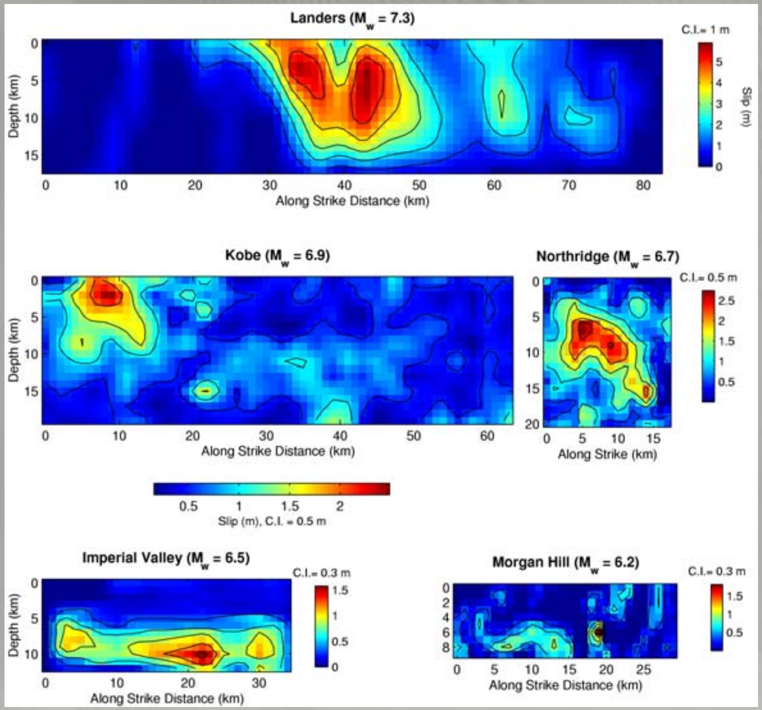
Overview

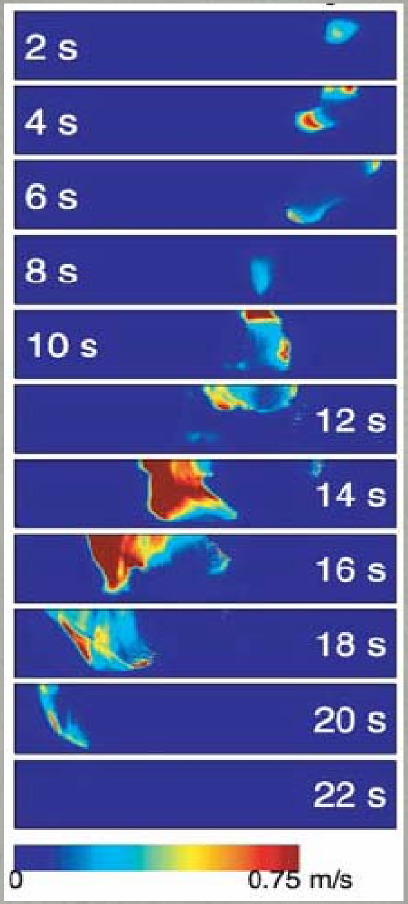
- Evidence of earthquake source complexity and stress heterogeneity
- Impact on dynamic source models for strong ground motion prediction
- Effect on directionality of rupture on bimaterial faults
- Perspectives on complexity in continuum earthquake cycle models

Earthquake complexity revealed by source imaging

Coseismic slip, hence stress drop, are spatially heterogeneous over a broad range of scales. Rupture propagation paths are complicated.

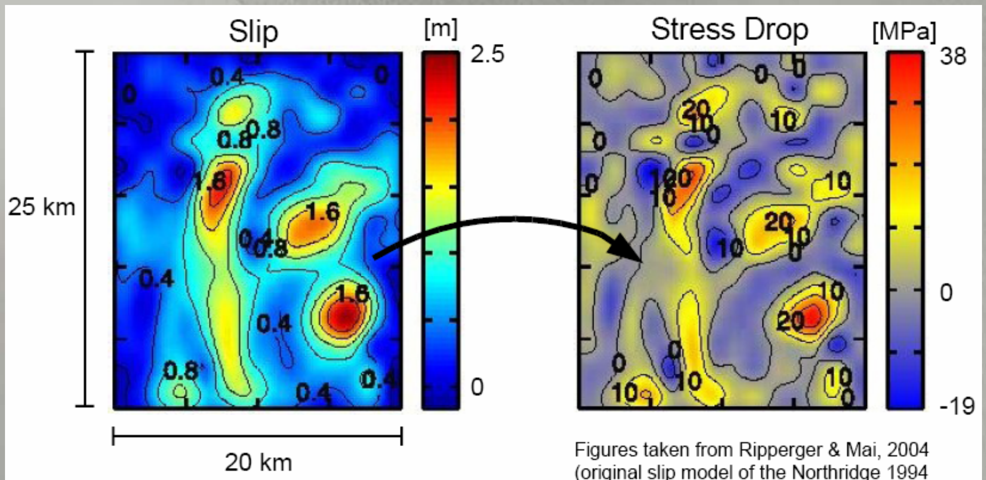


Examples of coseismic slip inferred from seismological and geodetic data (Mai and Beroza 2002)



A dynamic model of the Landers earthquake that matches low-frequency near-field data (Peyrat et al 2004)

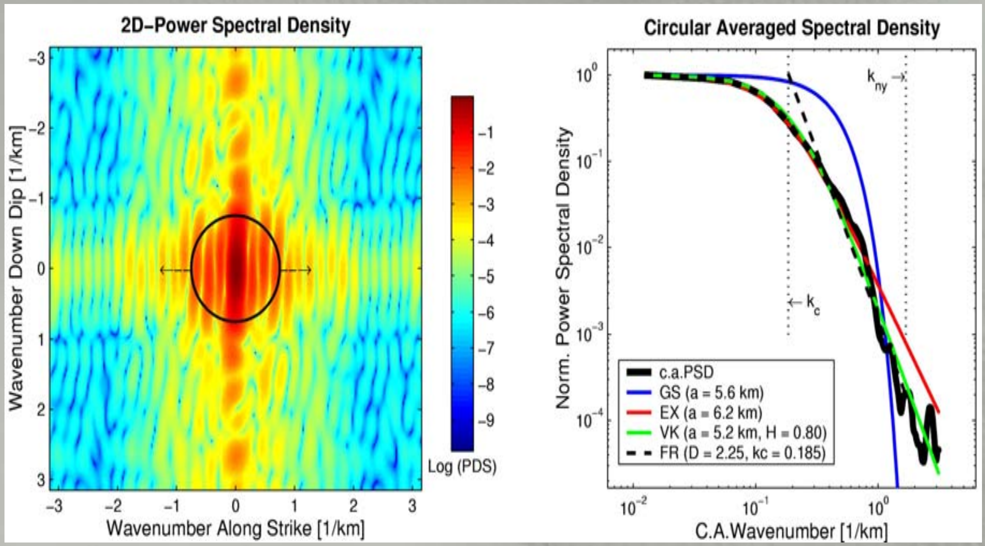
Seismological constraints on stress heterogeneity



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

- Stress heterogeneity over a broad range of length scales
- Power law spectral decay at short length scales

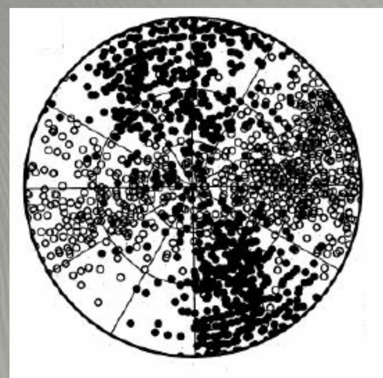
Statistical spectral analysis of stress drop distributions inferred from a catalog of source slip images



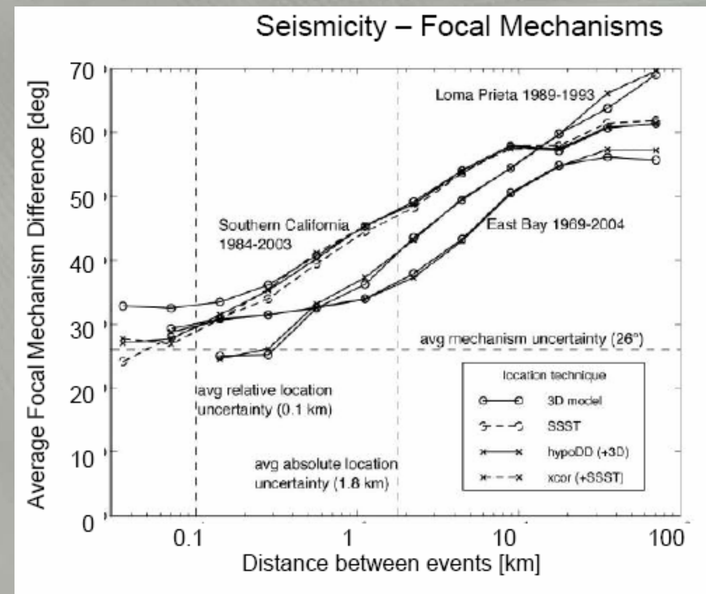
Mai and Beroza (2002)

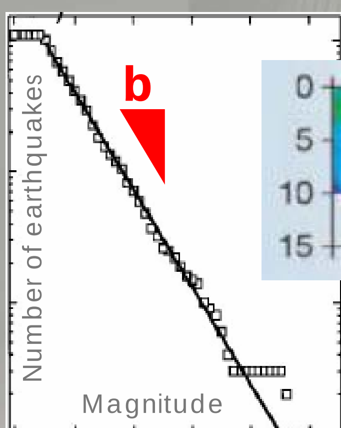
More evidence of stress heterogeneity

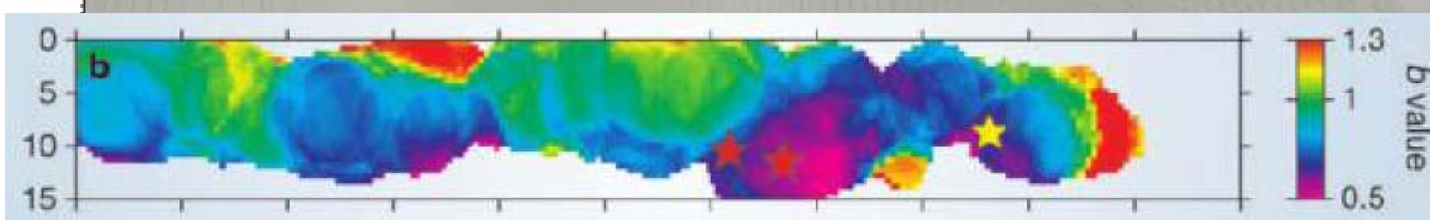
Heterogeneity of focal mechanisms



Hardebeck & Hauksson (2001)



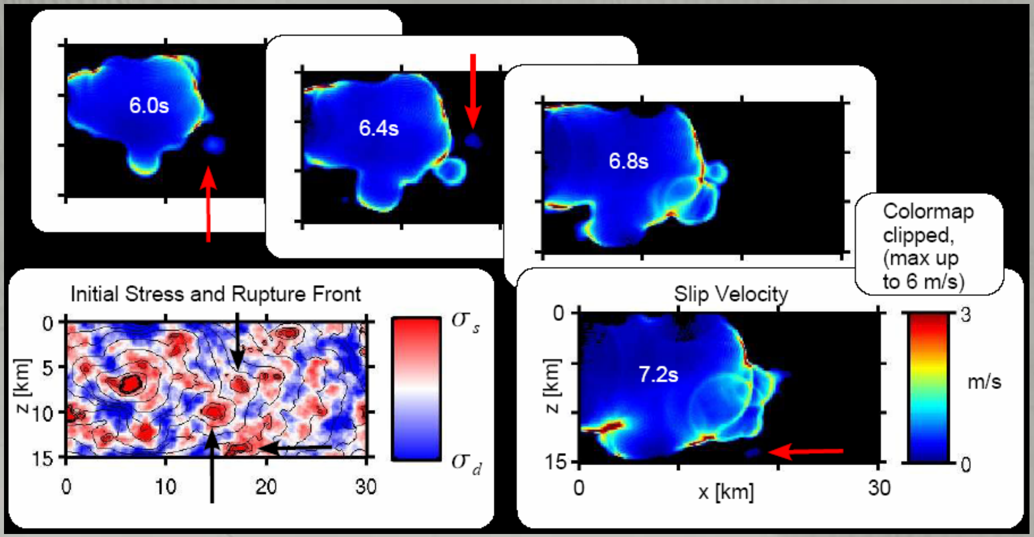




Heterogeneity of b-values (Schorlemmer and Wiemer, 2005)

Possible nature of stress heterogeneity

- Stress concentration at the edge of previous earthquakes on the same fault zone
- Stress transfer from neighboring faults
- Non uniform loading from creeping fault regions
- Non planar fault geometry
- Fluid pressure migration
- Material and frictional heterogeneities



Dynamic rupture on heterogeneous initial stress
(simulation by J. Ripperger)

Dynamic models for ground motion prediction

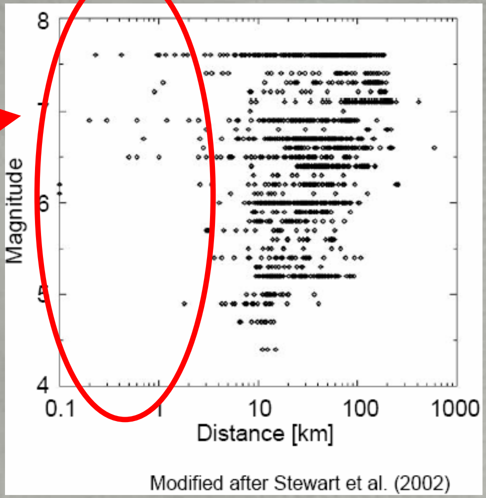
In collaboration with Martin Mai and Johannes Ripperger (ETH Zurich)

Physics based ground motion prediction

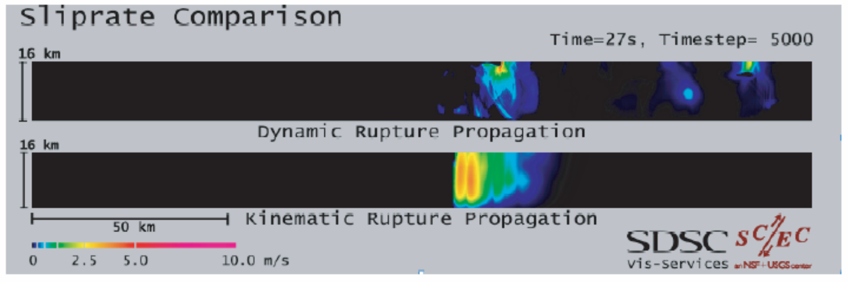
Empirical approaches are limited by the scarcity of strong motion data close to active faults

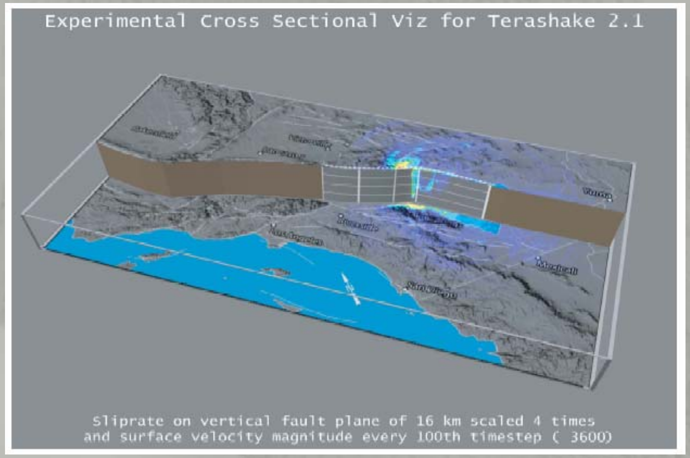
… but that is exactly where the strongest shaking occurs !

Each dot is an available recording



Alternative/complementary physics-based approach: **simulation of earthquake source and wave propagation** (e.g. TeraShake)

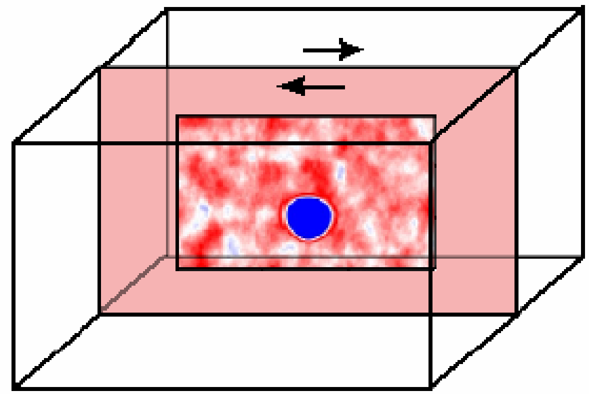


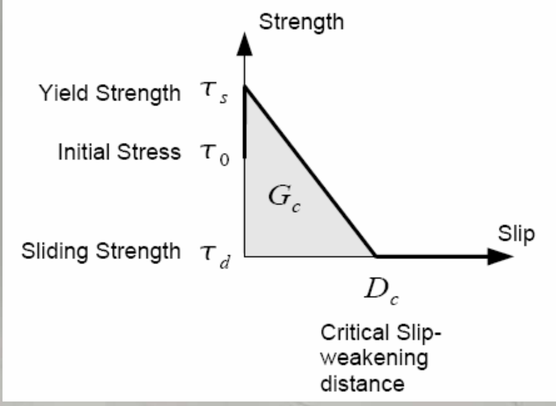


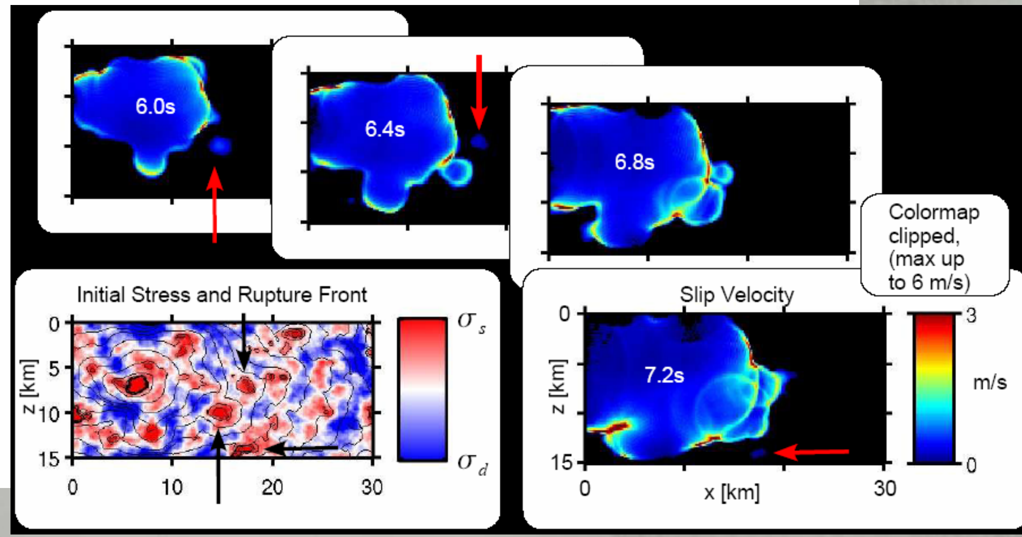
Dynamic Rupture Simulation

Setup:

- Planar fault embedded in homogeneous elastic full space
- Boundary Integral Equation Method (*Dunham, 2005*)







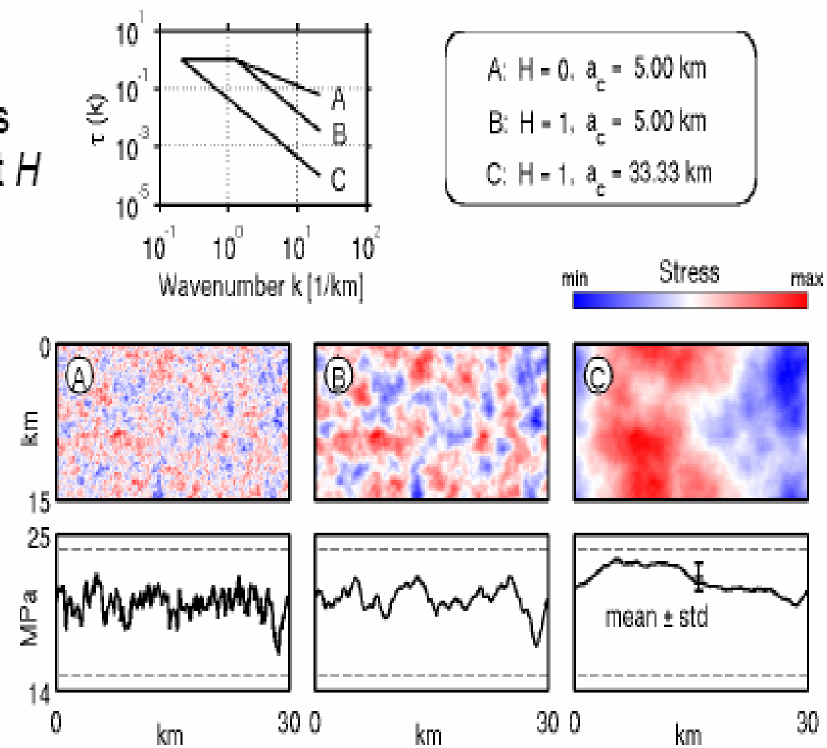
Prescribed stochastic initial stress field

Statistical Quantification of Stress Heterogeneity

Non uniform initial shear stress on the fault plane

Wavenumber spectrum

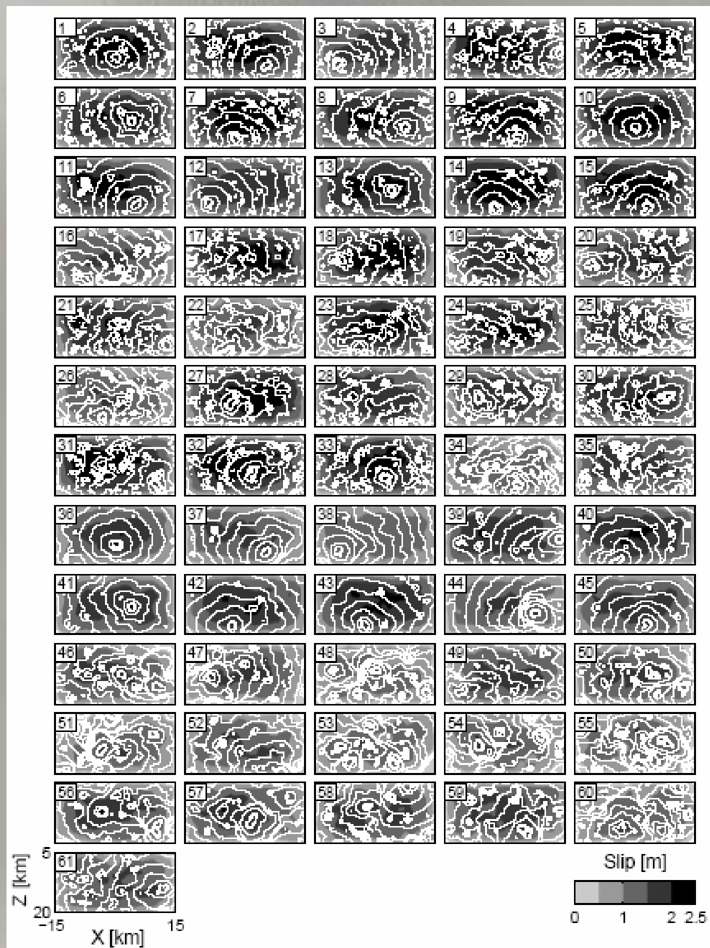
- Decay at high wave numbers controlled by Hurst exponent H
- Correlation length a_c

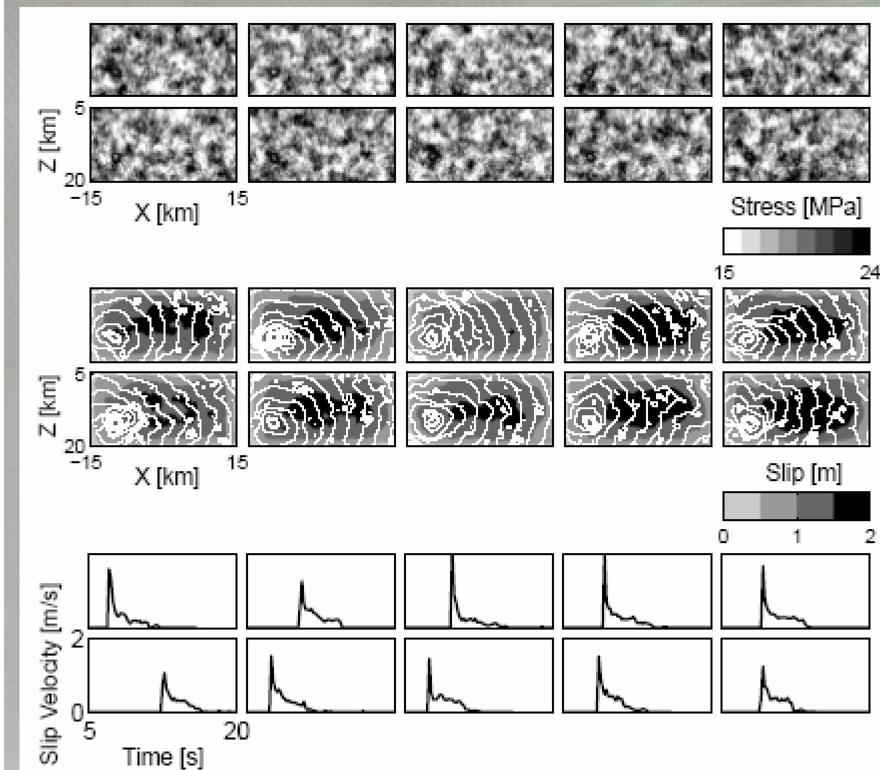


Gaussian Distribution

- Standard deviation

A large collection of dynamic source models

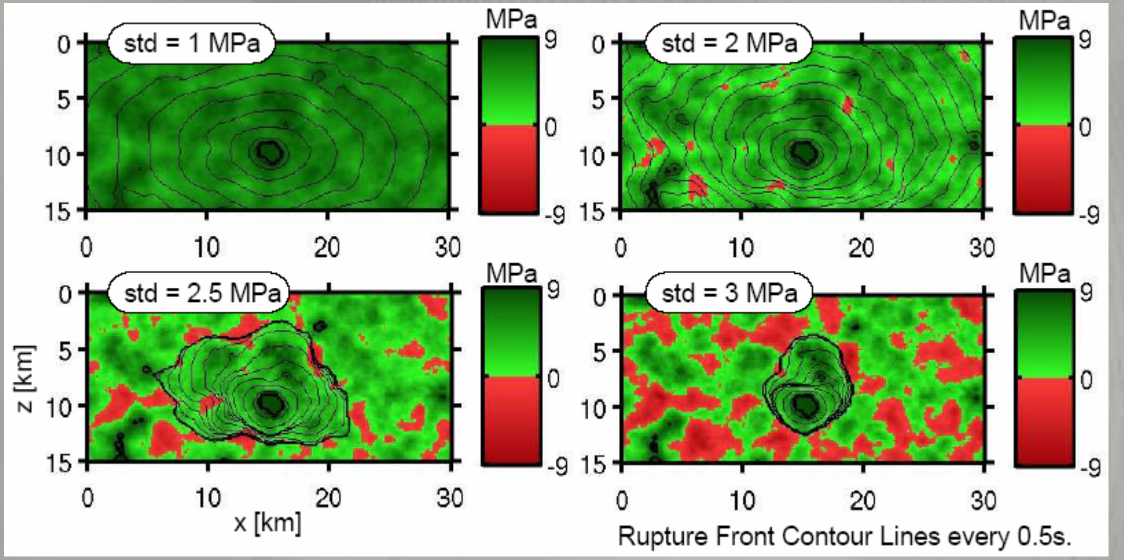


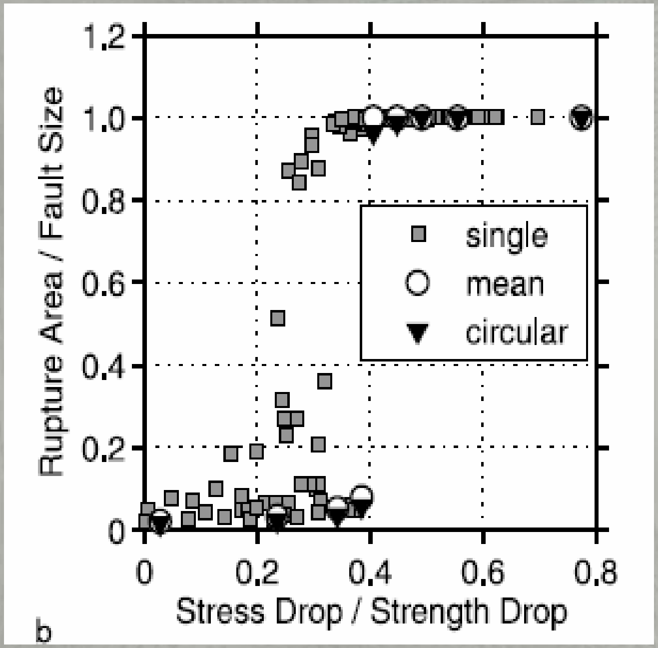


Ripperger et al (2008)

First order transitions of final earthquake size controlled by stress heterogeneities

Rupture “percolation” transition

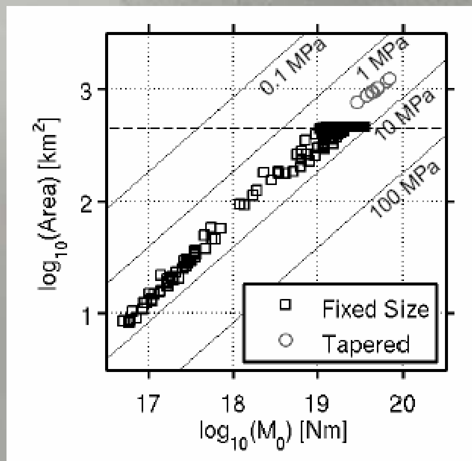


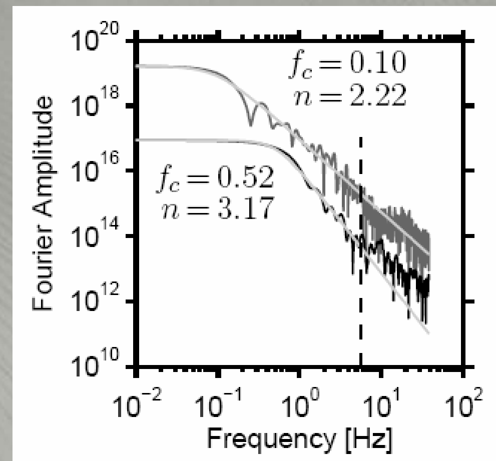


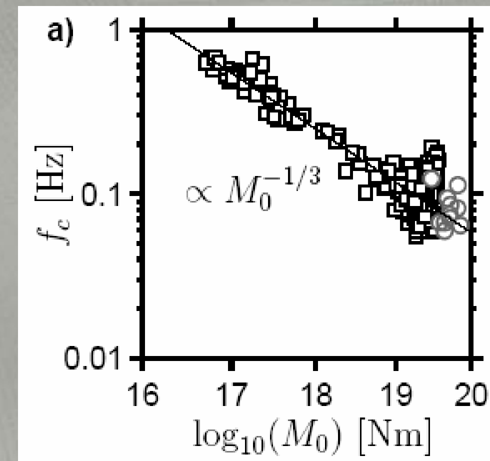
Ampuero et al (2007), Ripperger et al (2007)

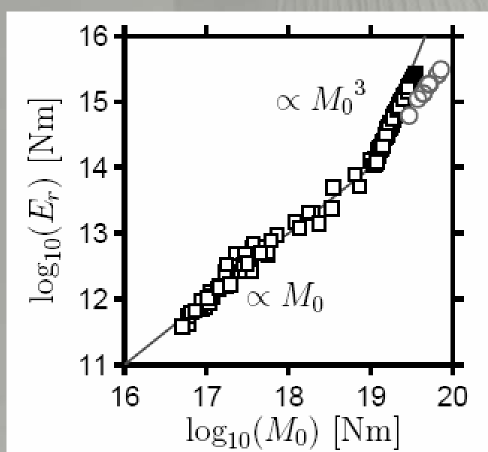
Macroscopic source parameters consistent with seismological observations

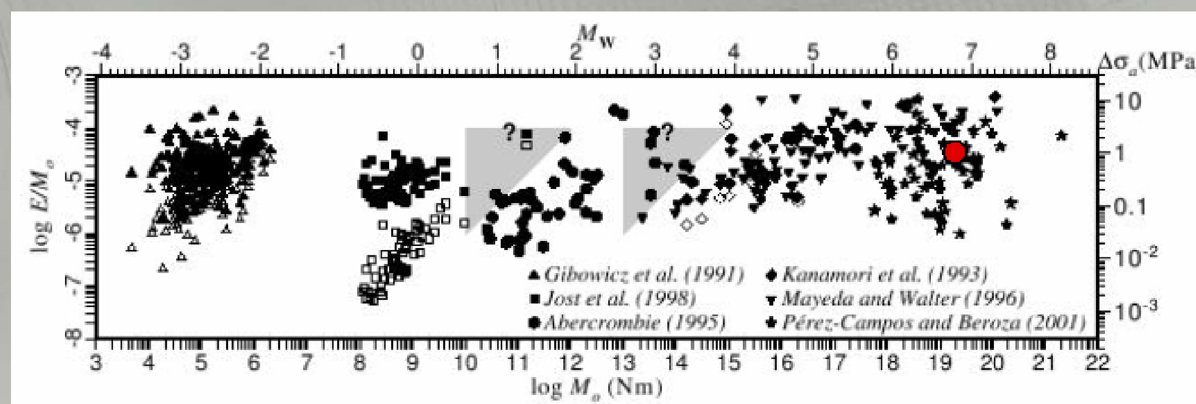
Ripperger et al (2007)





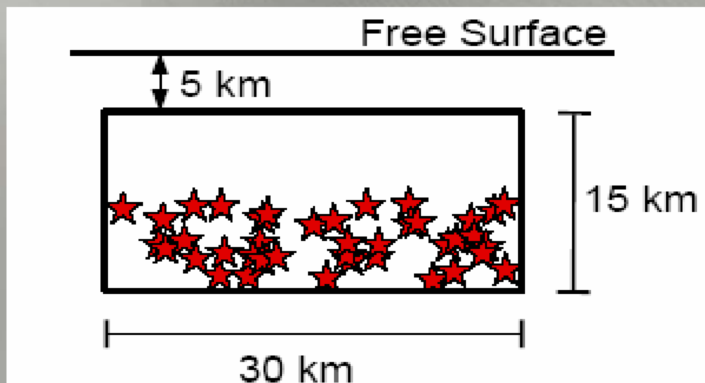


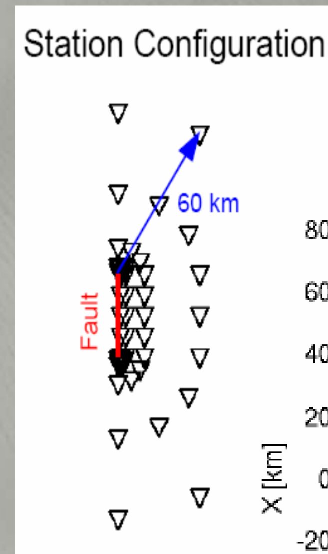


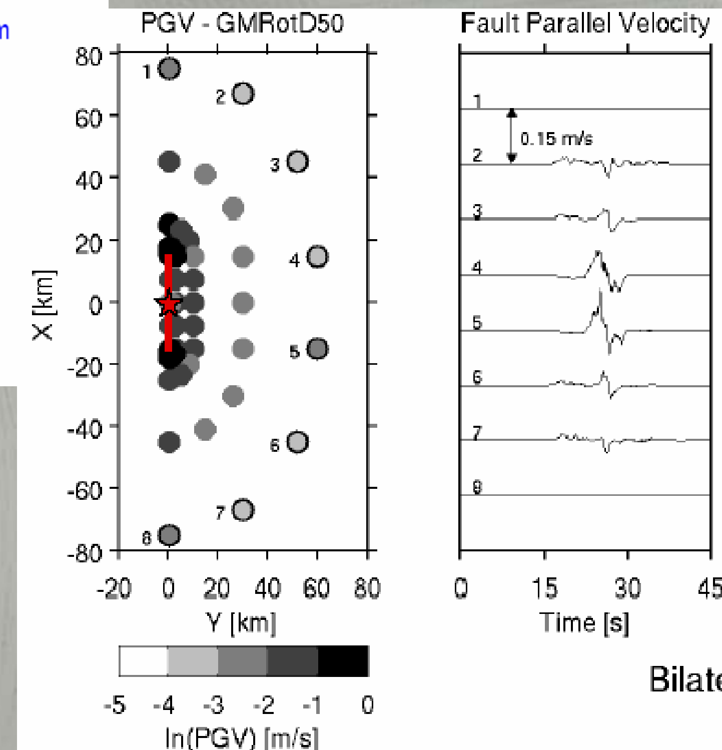


Ide & Beroza (2001)

Computation of Ground Motion







Selection of rupture models:

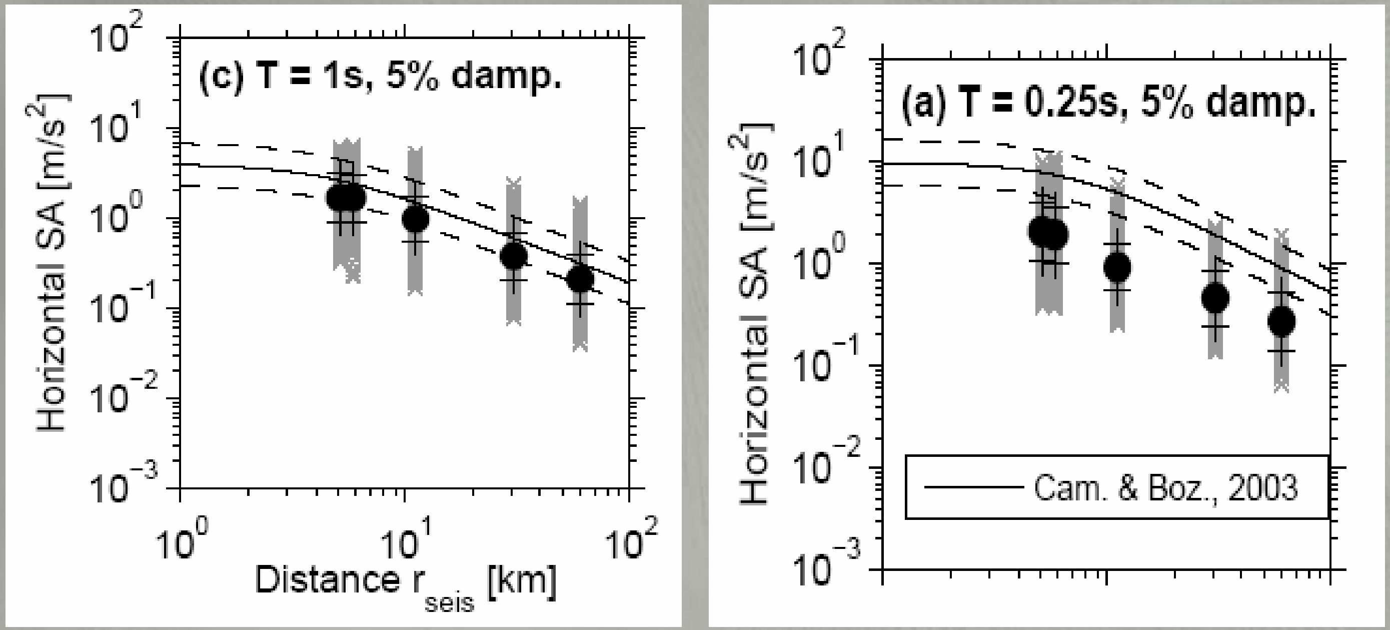
- **average rupture speed <80% Vs**
- **magnitude range Mw 6.7-6.9**
- **hypocenter in lower half of the fault**

→ **Synthetic seismograms (COMPSYN)**

→ **peak ground motion parameters**

Ripperger et al (2008)

Comparison to empirical attenuation laws



Spectral accelerations match well at low frequency (f<1Hz) but are too weak at high frequencies (f>4Hz)

Beyond empirical attenuation laws

The variability of ground motion (at a given source distance) has two contributions:

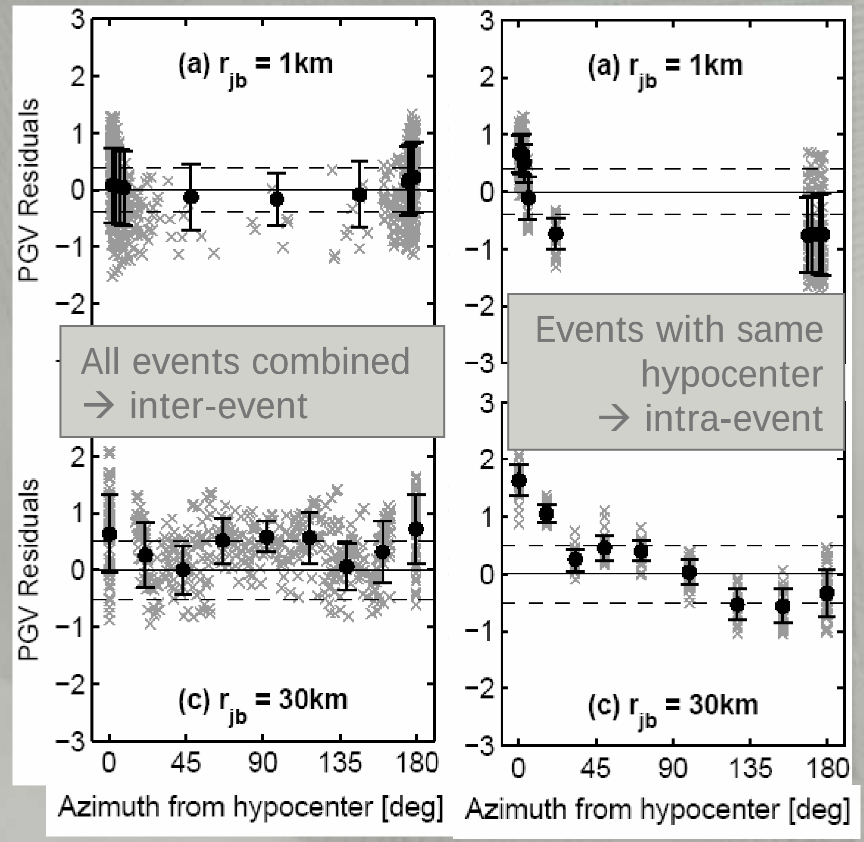
1. **Inter-event** variability at a single station due to many earthquakes
2. **Intra-event** variability among all stations recording the same earthquake

Azimuth dependency: effect of rupture directivity

The variability at 90° and backward-directivity region results mainly from the stress heterogeneity

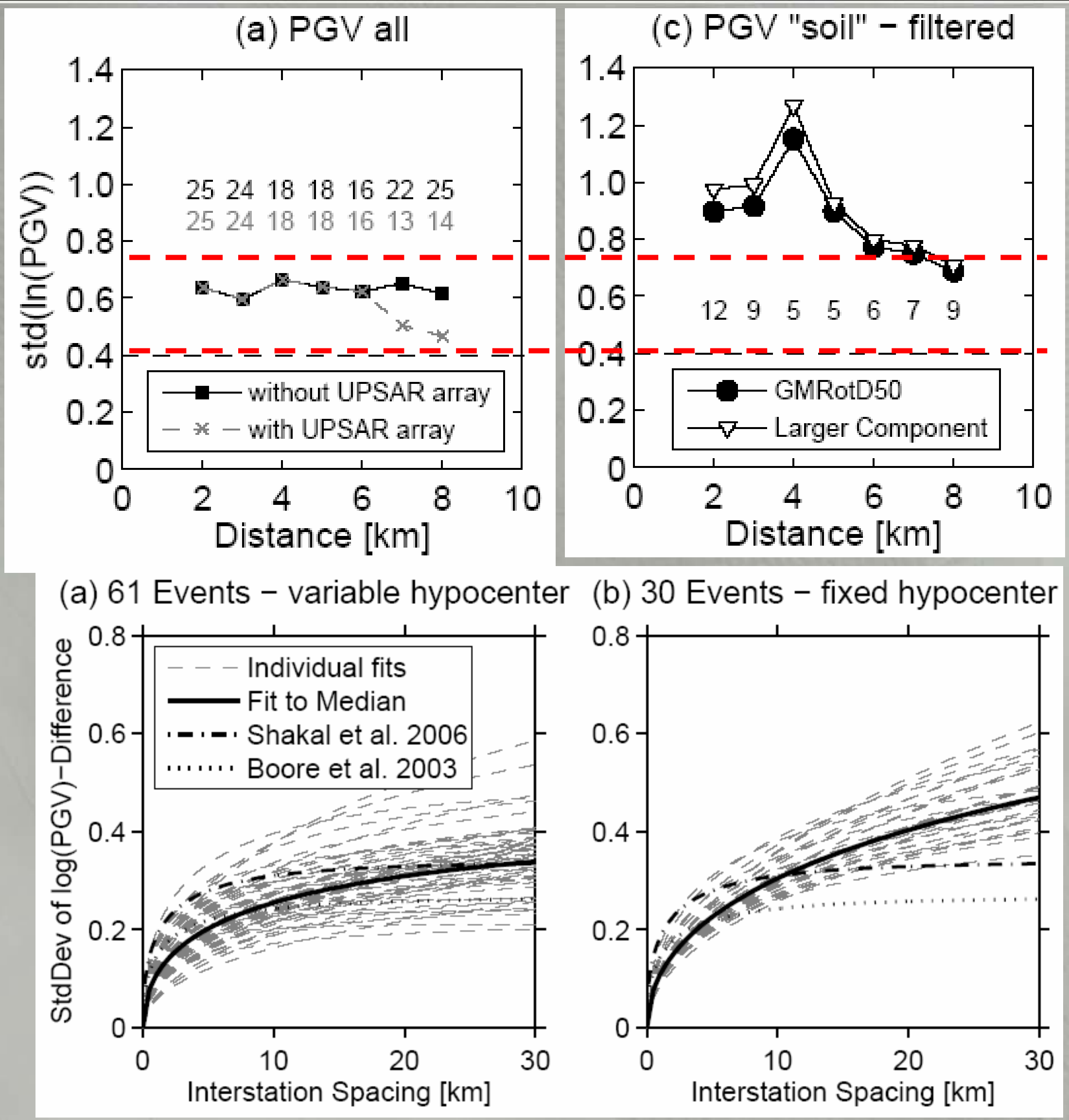
The very near field is most sensitive to intra-event variability

Difference between predicted and empirical PGV



Comparison to ground motions from the 2004 Parkfield earthquake

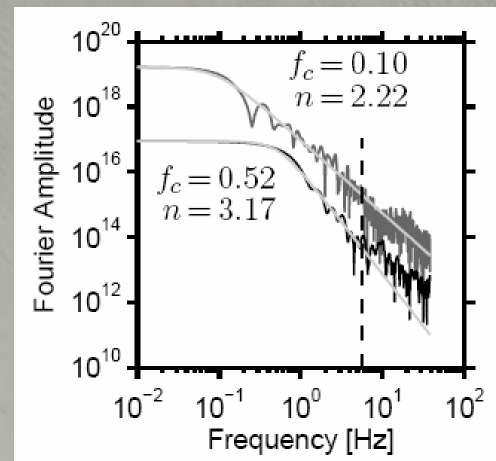
- **Comparable variability (intra-event, unilateral) in the near-fault region**
- **Ground motions are spatially correlated over much longer scales in our models than in observations**
- **Source/site effects ?**

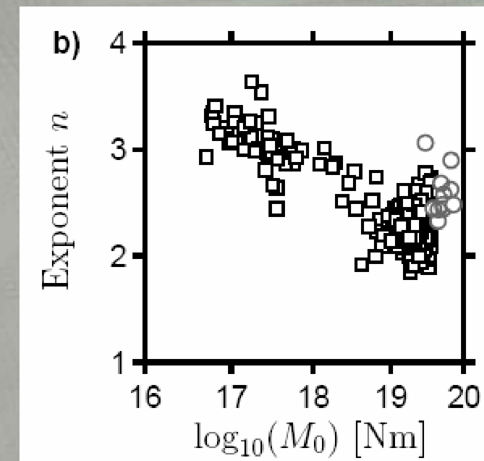


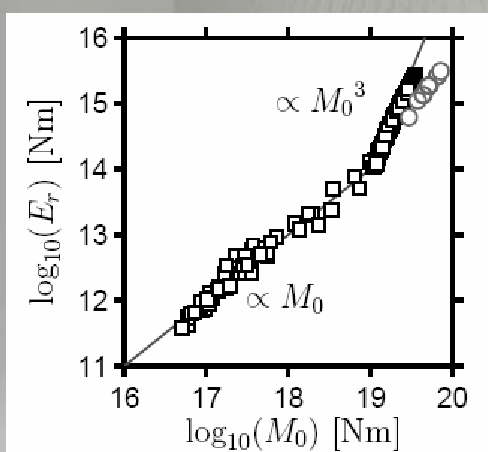
Some weaknesses of our dynamic models

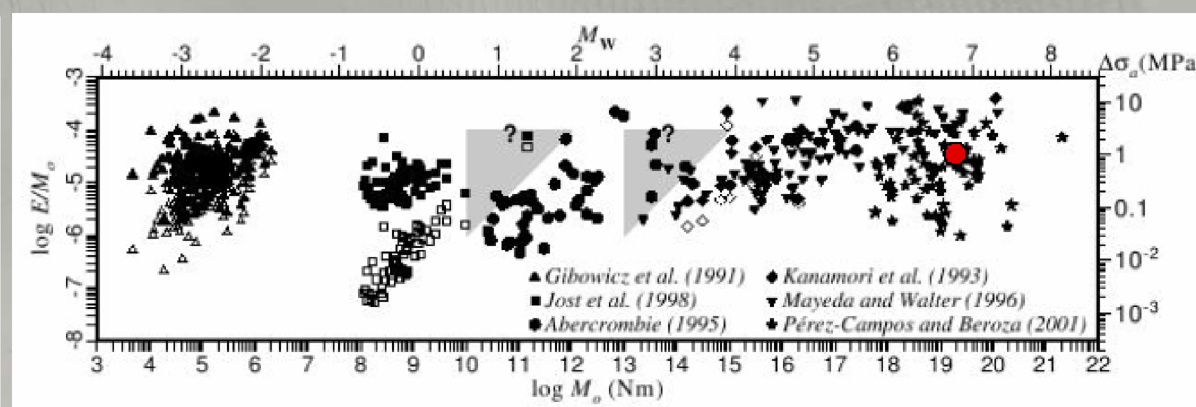
Imperfect source scaling at low magnitude and deficient high frequency generation

Strong high frequency radiation is primarily generated by abrupt rupture arrest on artificial boundaries



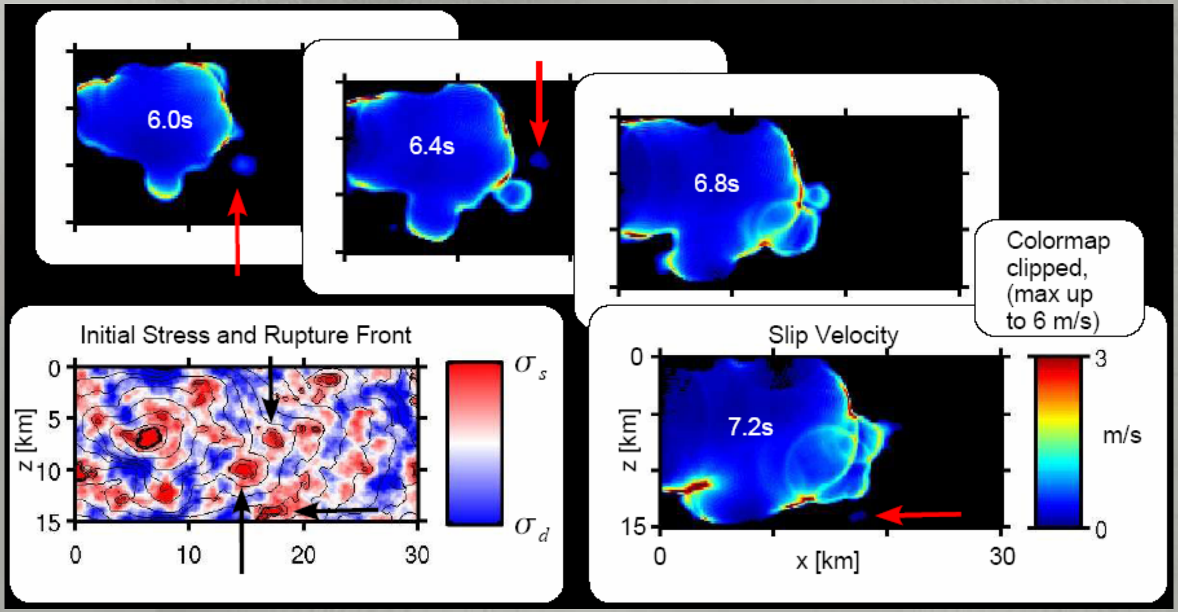


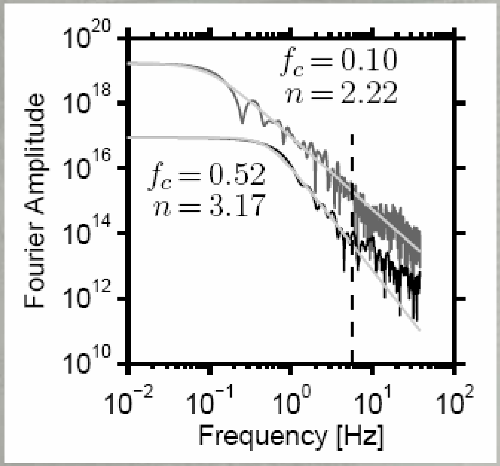


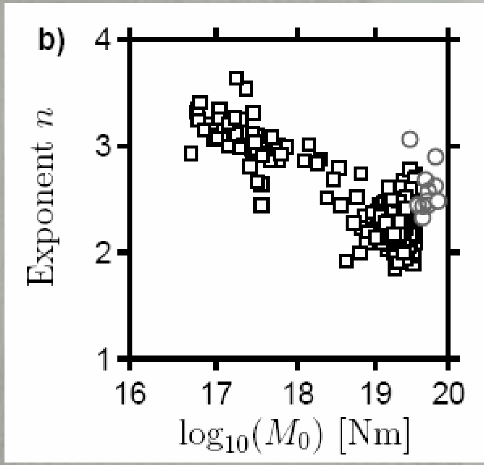


Ide & Beroza (2001)

Some weaknesses of our dynamic models







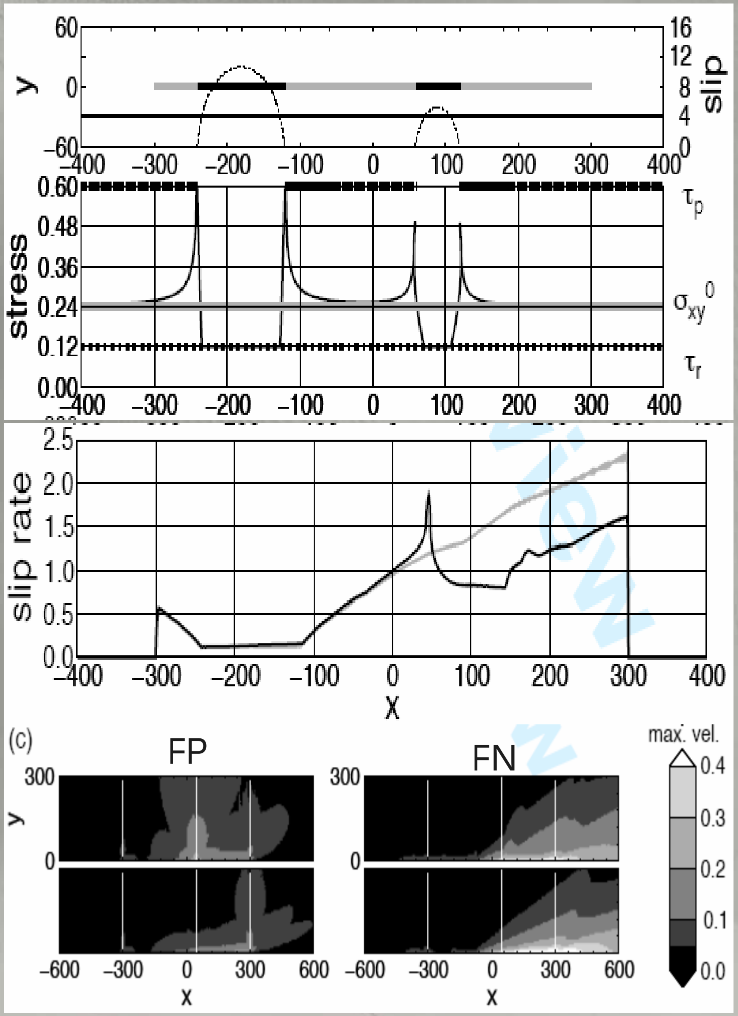
High frequency radiation throughout the rupture can be boosted by jumps in rupture speed:

Abrupt spatial fluctuations of fracture energy

Stress singularities (residual stress concentrations)

Pulse-like ruptures (more reactive to small scale fluctuations)

Effect of stress concentrations on dynamic rupture



Kame and Uchida (2008)

(Madariaga, 1983) When a rupture encounters a stress concentration at the edge of a previous rupture or of a secondary nucleation zone:

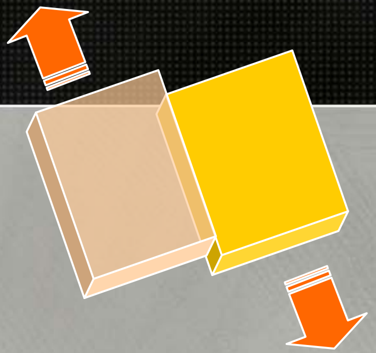
- rupture speed jump
- slip velocity peak
- strong high-frequency radiation

The spatial distribution of stress concentrations should be inherited from previous seismicity

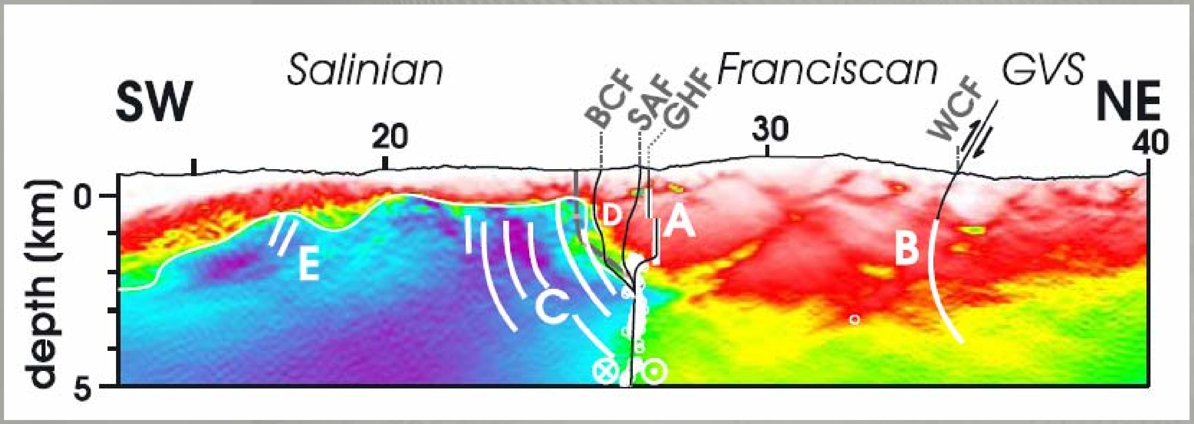
Dynamic rupture on bimaterial faults

In collaboration with Yehuda Ben-Zion (USC)

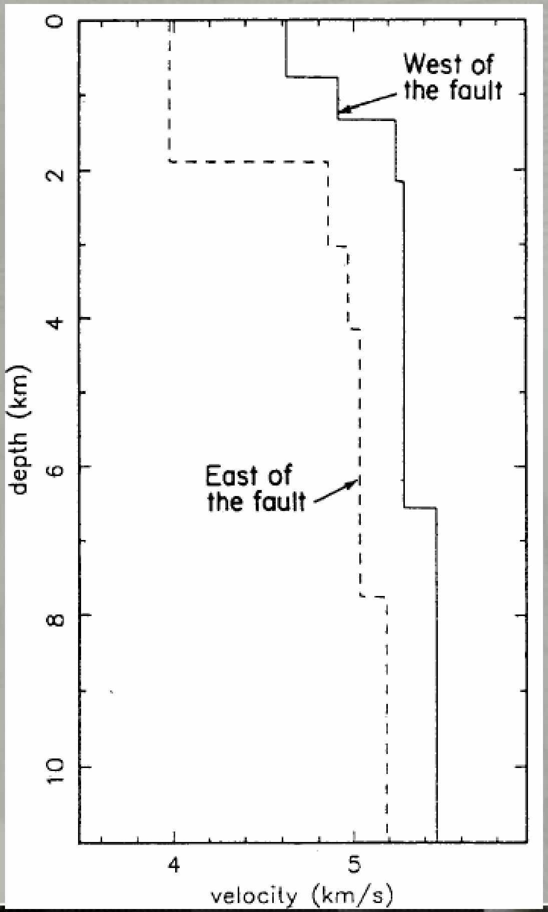
Bimaterial faults



San Andreas Fault at Parkfield, California

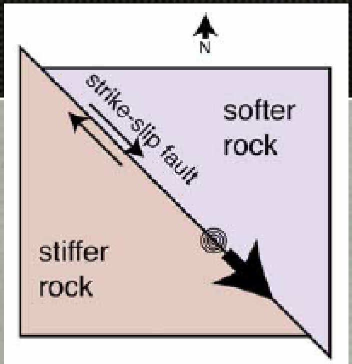


Waveform tomography (Bleibinhaus et al. 2007)

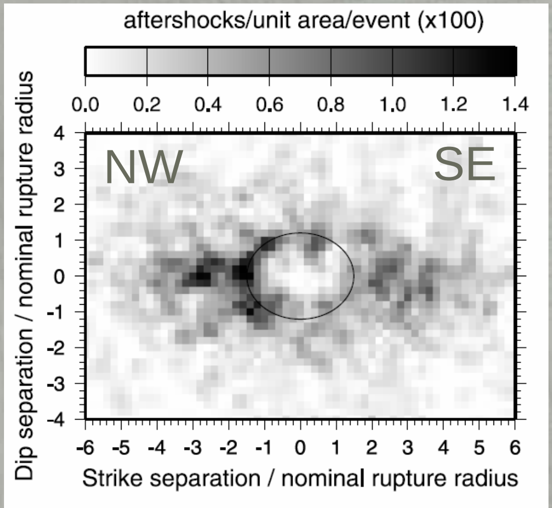


Fault zone head-wave inversion (Ben-Zion et al. 1992)

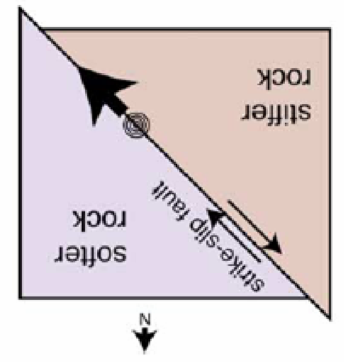
Why care about bimaterial faults ?

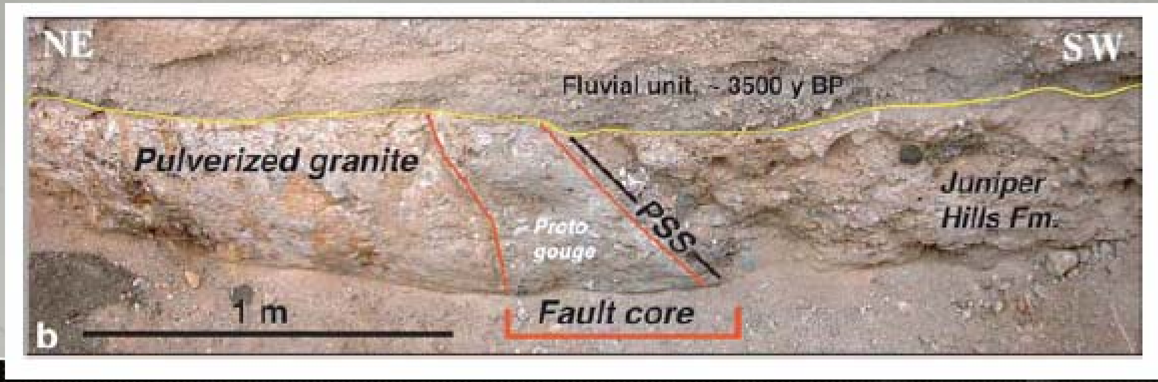


- **They are everywhere**
- **Theory predicts a specific bimaterial rupture mode with a preferred rupture direction, the direction of motion of the softer rock**
- **Indirect observations:**
  - **Asymmetry of microearthquake aftershocks distribution**
  - **Asymmetry of off-fault damage patterns**



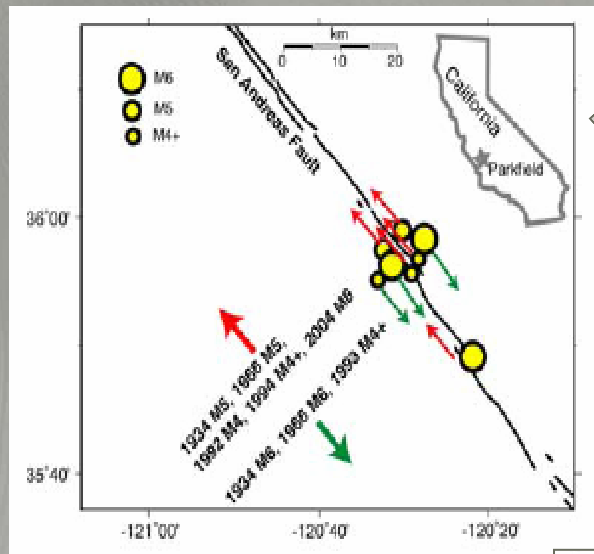
Rubin, 2002

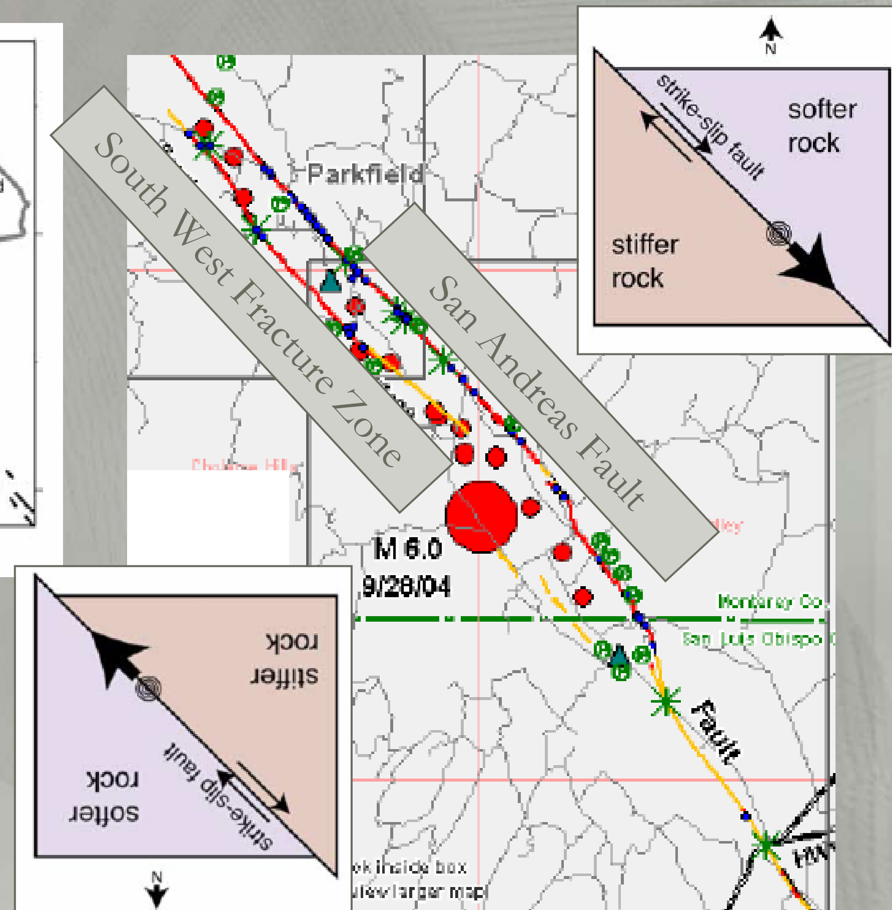




Dor et al., 2006

Dominance of southwards rupture in Parkfield ?

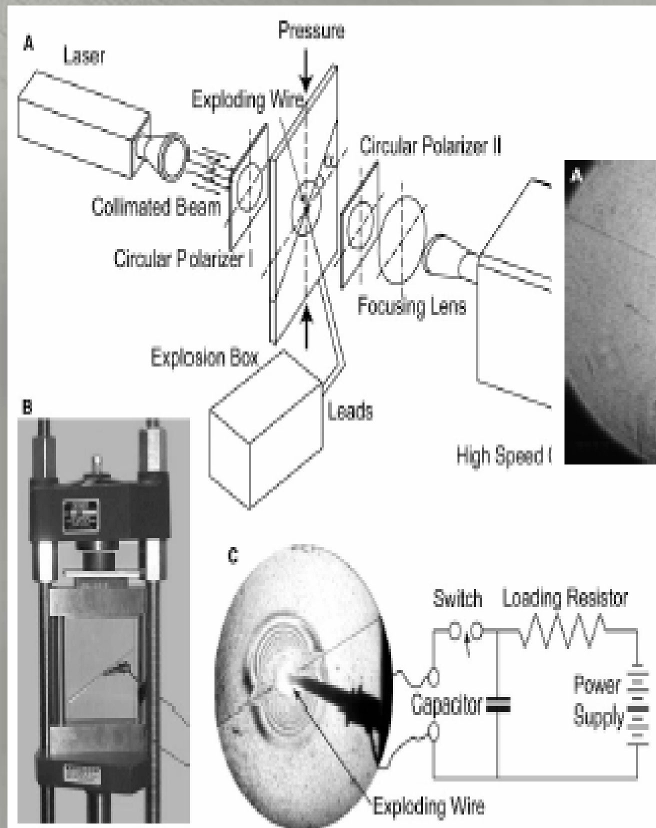


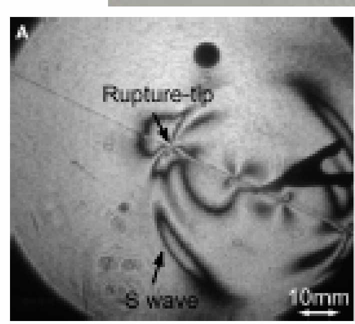


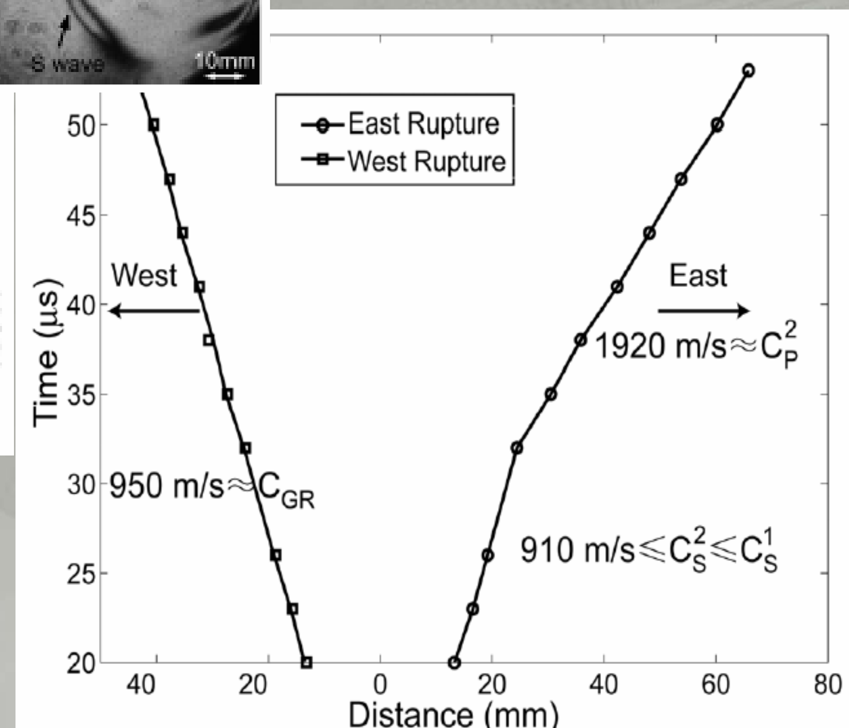
The M6 1934 and 1966 repeating Parkfield earthquakes ruptured towards the SE

… but not the 2004 event !

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







Bilateral ruptures are also common

Earlier views of bimaterial effects on dynamic rupture

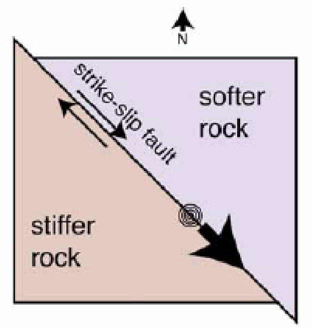
- **The bimaterial effect: coupling between slip and normal stress (stronger at fast rupture speed)**

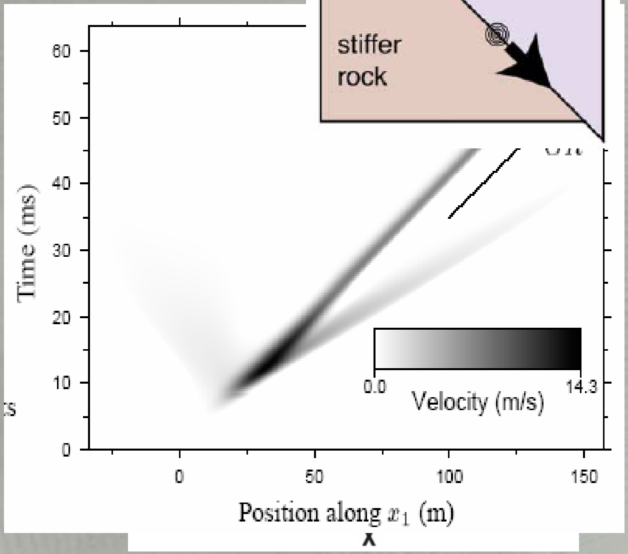
- Unilateral wrinkle-like pulses running in a "preferred" direction **(= the direction of motion of the softer rock)**
  → is rupture direction determined by the material contrast across the fault ?

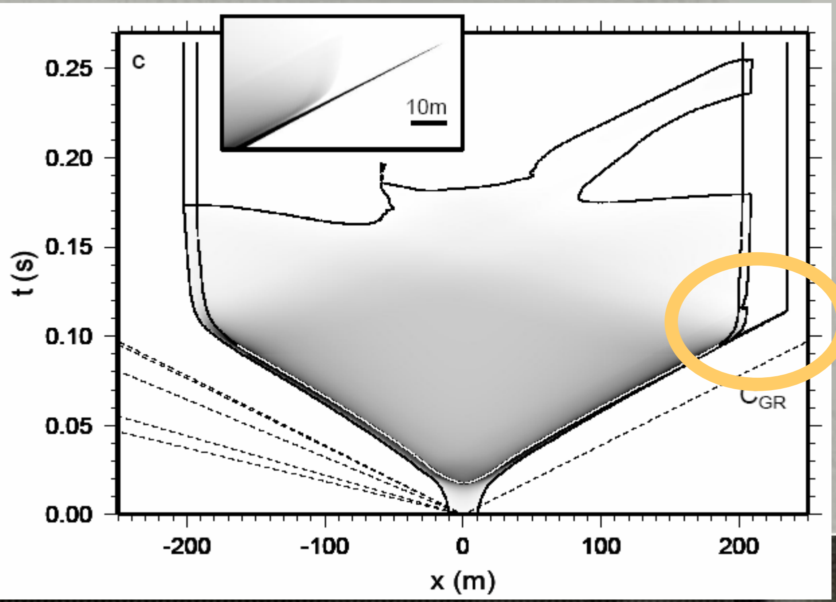
  Weertman (1980), Adams (1995), Andrews and Ben-Zion (1997), Cochard and Rice (2000), Harris and Day (2005)

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

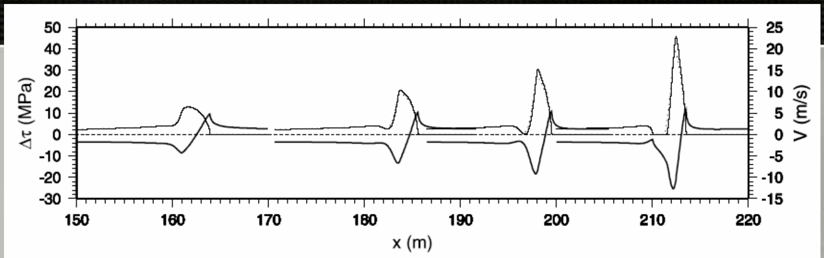
  Harris and Day (1997), Andrews and Harris (2005), Rubin and Ampuero (2007)

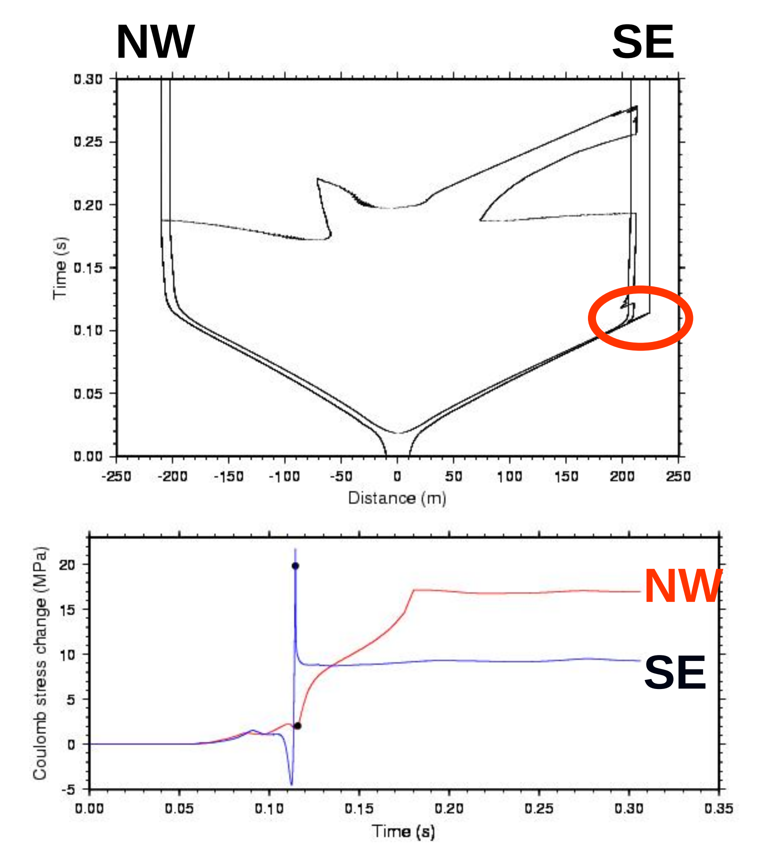




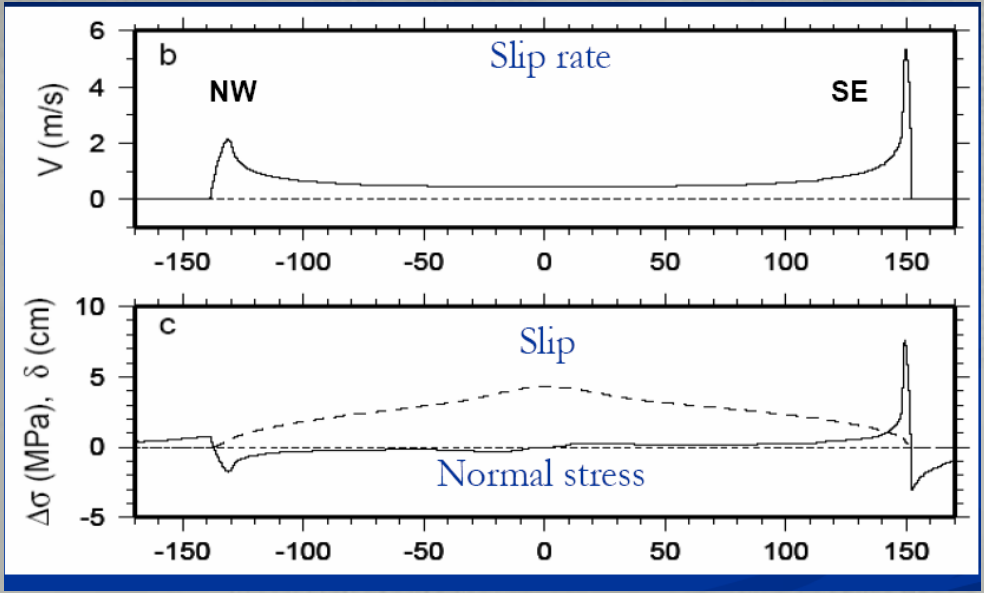


Wrinkle-like pulse detachment in slip-weakening bimaterial faults





Rubin and Ampuero (2007)



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

→ what if velocity-weakening feedback?

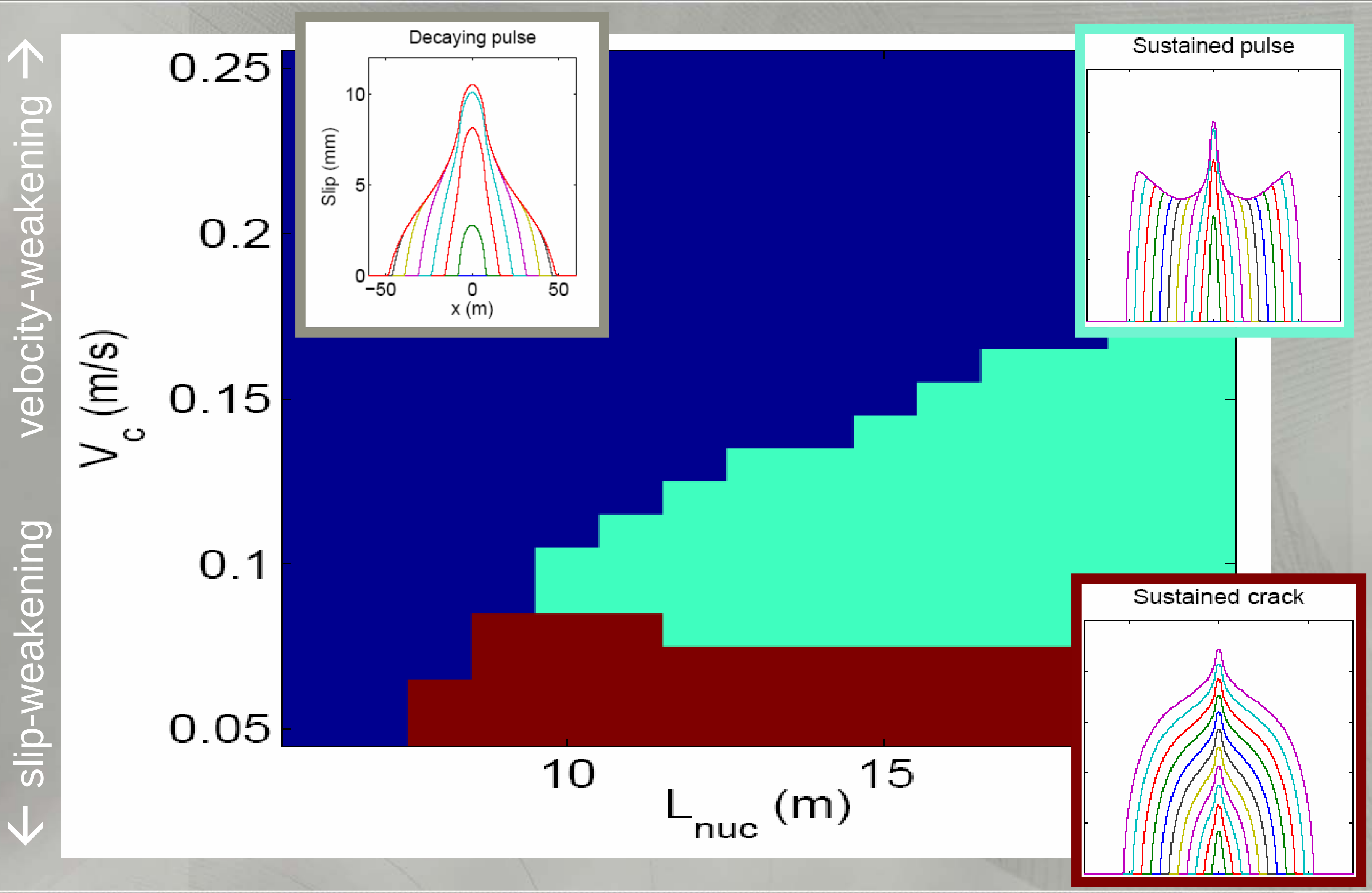
What if we include fast velocity-weakening friction ?

- Fast velocity-weakening **(1/V) at high slip rates as a proxy for thermal processes, etc. in the fault zone**
- **Regularized velocity and state dependent friction law:**

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

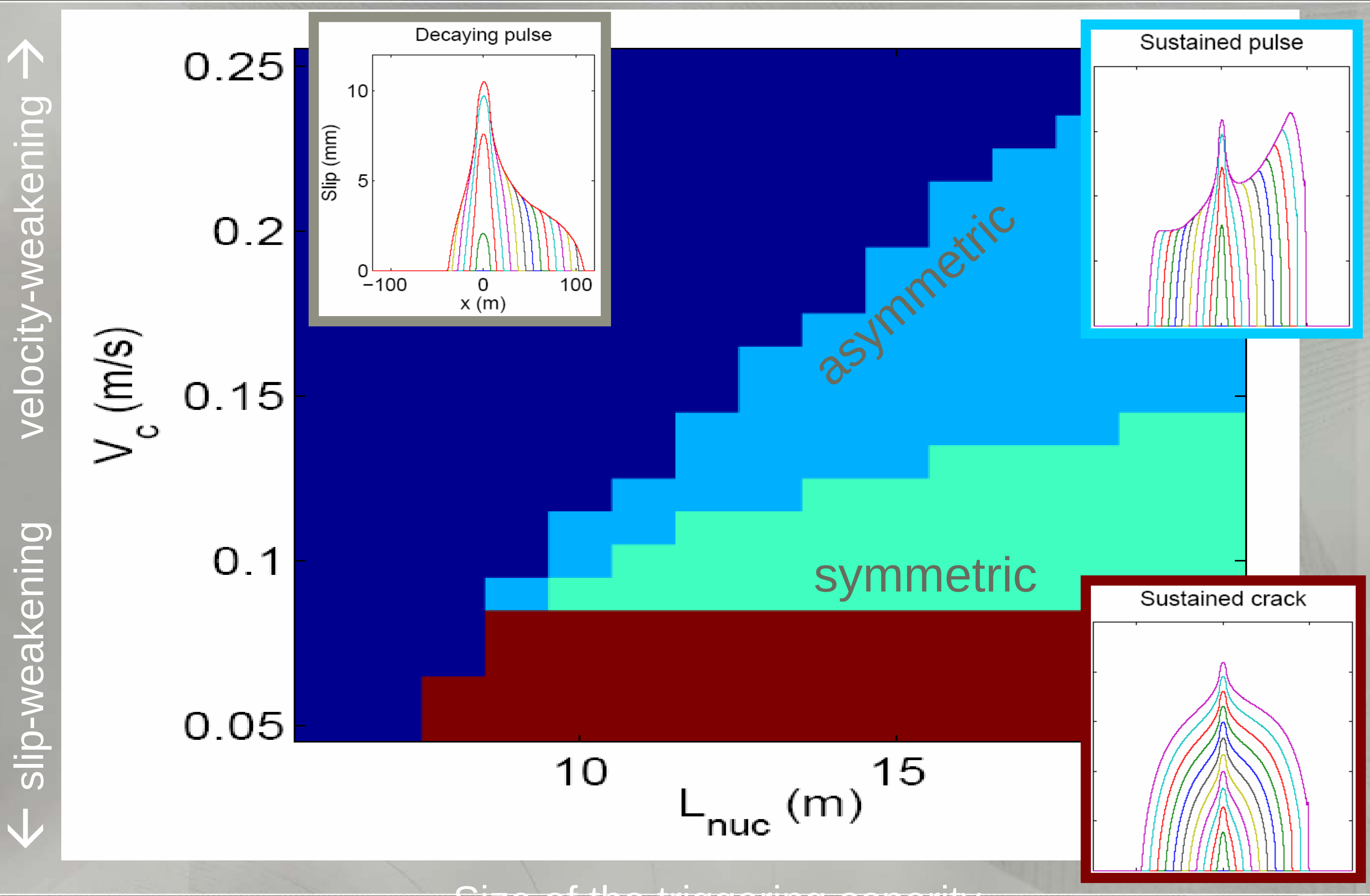
- **Parameter V_c tunes between slip-weakening (small V_c) and velocity-weakening (large V_c)**
- **Regularized normal stress response** $$\dot{\sigma^*} = \frac{V^*}{\delta_\sigma} (\sigma - \sigma^*)$$
- **Smooth nucleation, subshear rupture, parameter choice unfavorable for wrinkle-like pulse**

Rupture styles in homogeneous medium

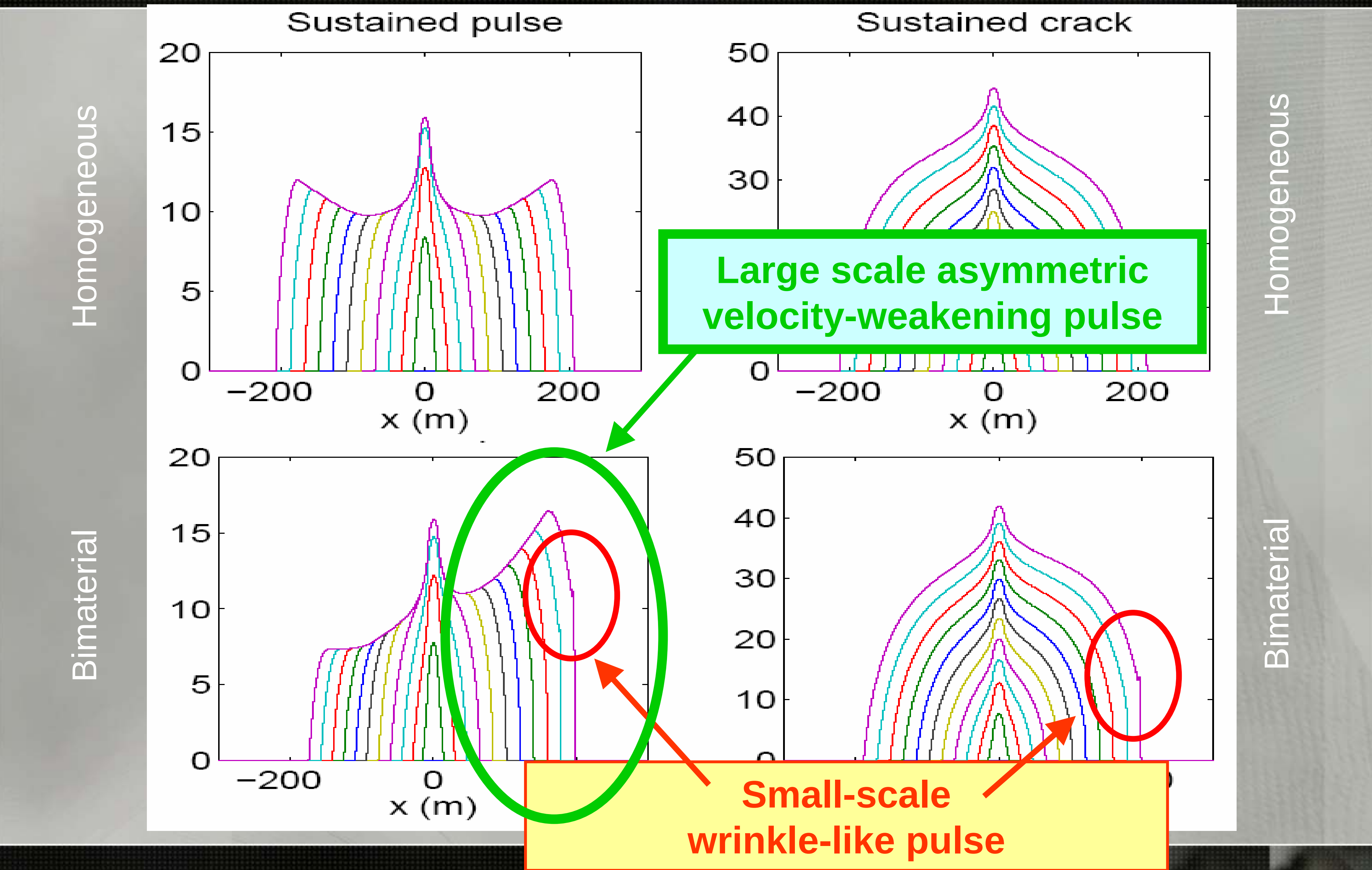


Size of the triggering asperity

Rupture styles in bimaterial faults

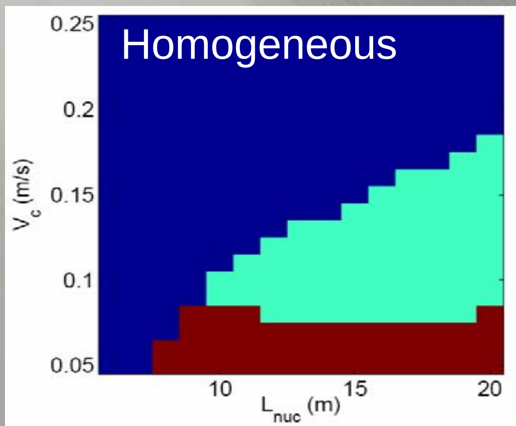


Size of the triggering asperity

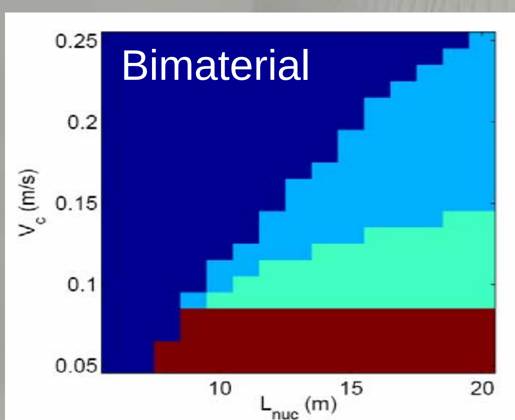


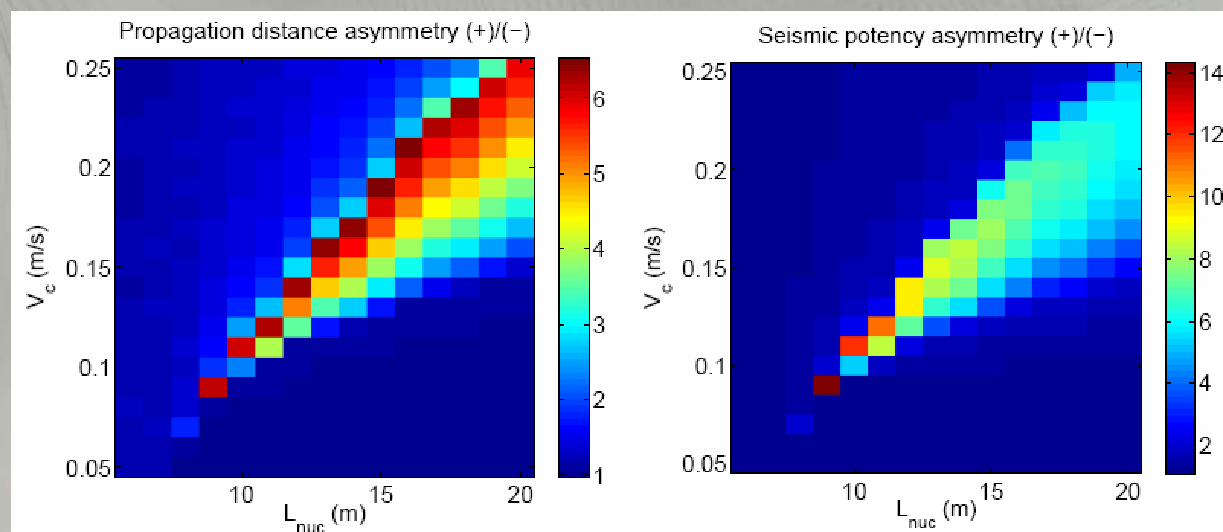
Sustained pulse
Sustained crack
Homogeneous
Homogeneous
Bimaterial
Bimaterial
x (m)
x (m)
x (m)
Large scale asymmetric velocity-weakening pulse
Small-scale wrinkle-like pulse

Macroscopic source asymmetry



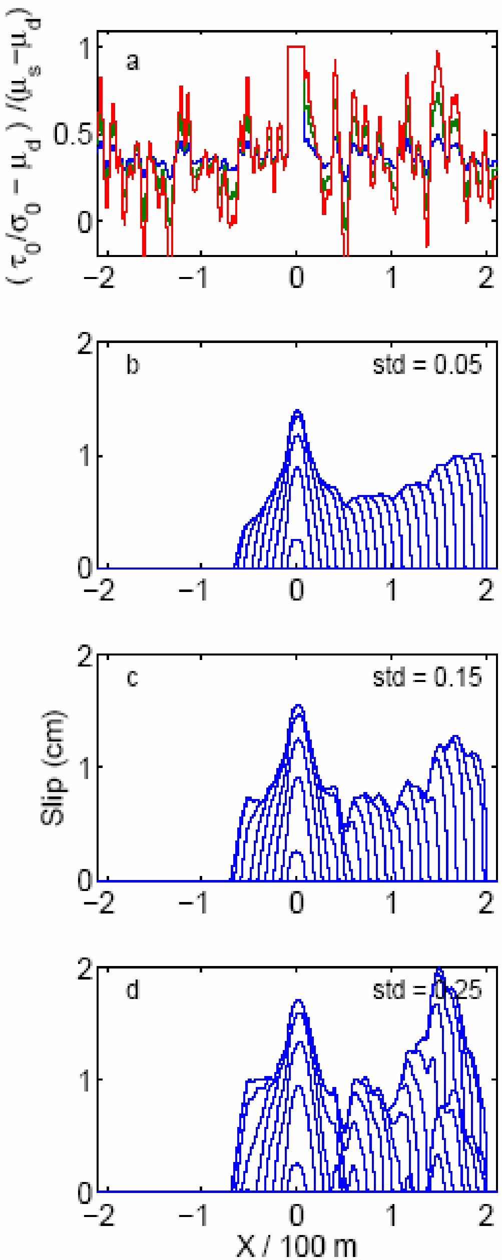
The bimaterial effect destabilizes first the large-scale pulse that propagates in the preferred direction

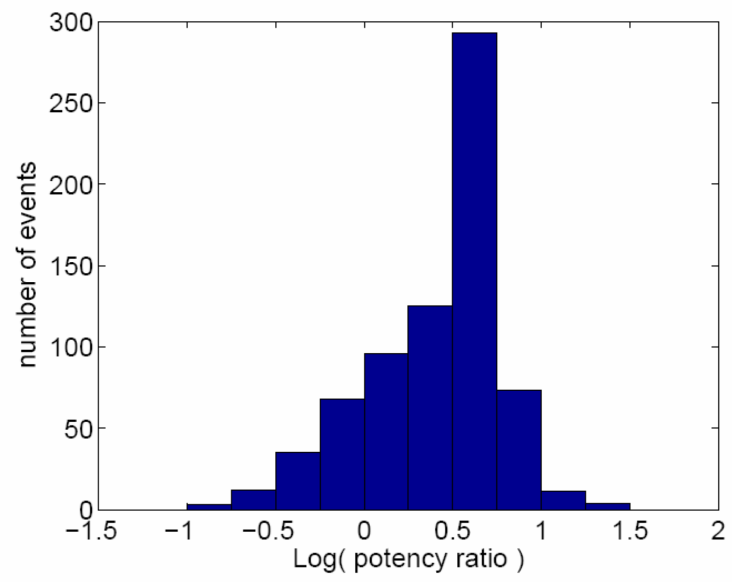




Effect of stress heterogeneities

Initial shear stress

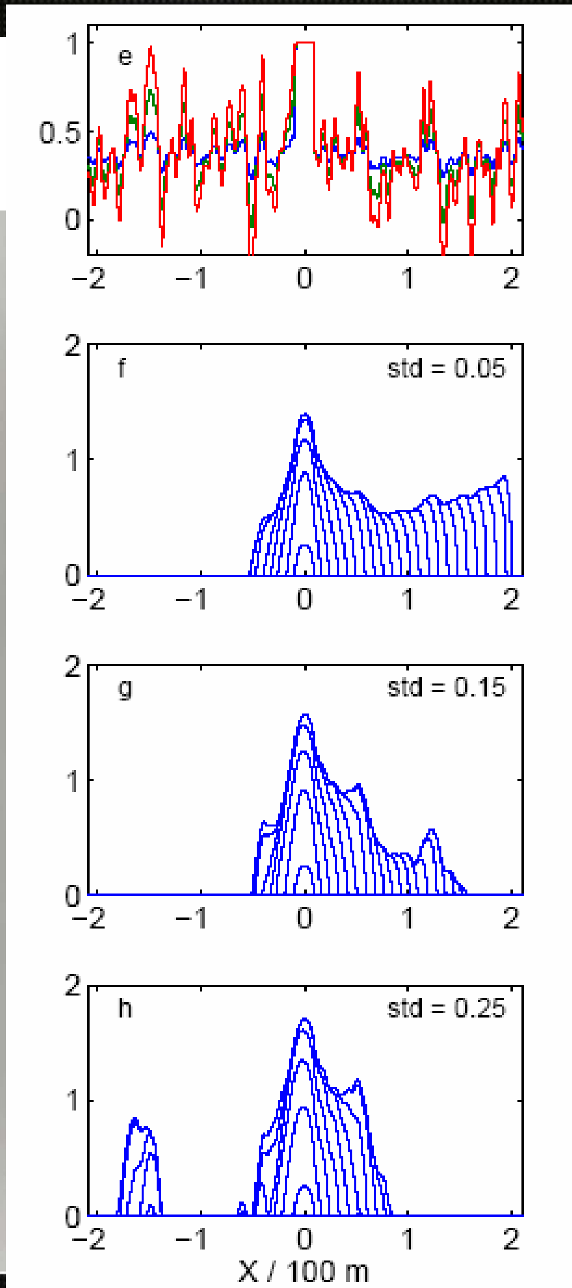


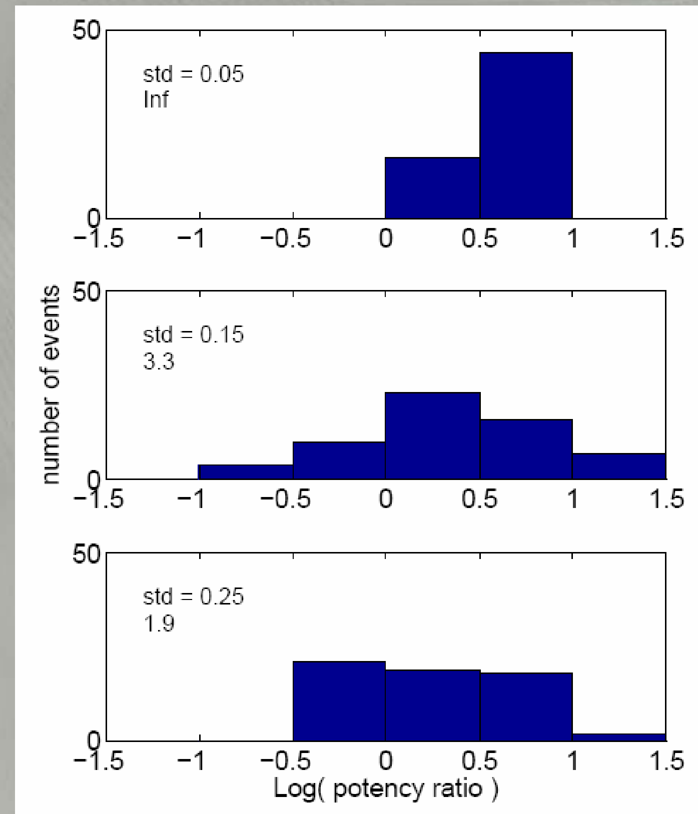


Seismic potency is skewed towards the "preferred" direction

Effect of stress heterogeneities

Initial shear stress





Effect of heterogeneity amplitude: shuffles the asymmetry

Summary and perspectives

Summary

Some statistical properties of fault stress heterogeneities are important for earthquake dynamics:

- **The distribution of stress concentrations affects high-frequency ground motion**
- **Large stress heterogeneities can prevent preferred pulse rupture direction on bimaterial faults**

How do heterogeneities emerge from the longer term evolution of faults (earthquake cycle) ?

Earthquake complexity in continuum models of seismicity

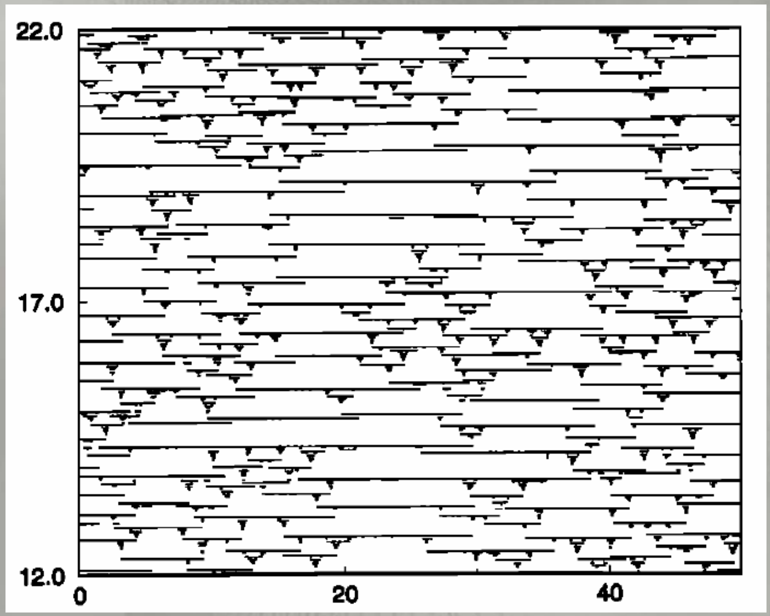
- In principle, seismicity models (multiple earthquake cycles) can provide clues about the statistical properties of stress heterogeneity

- Two types of models (Rice, 1993):
  - "**Continuum models**" have a finite nucleation size L_c, computationally well resolved (numerical results are mesh-independent)
  - The opposite: "**inherently discrete**" models (Burridge-Knopoff spring-block models, cellular automata, etc)

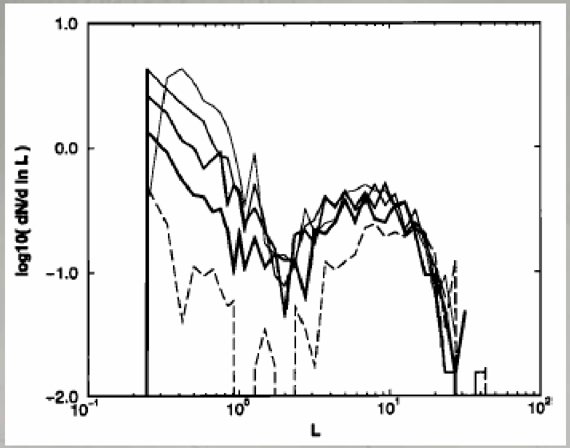
- Inherently discrete models generally produce seismicity with power-law frequency-magnitude statistics, but have no clear connection to continuum dynamic models

- Continuum models produce large event complexity quite generally, but small event complexity emerges only for finely tuned parameters (Shaw and Rice, 2000)

Earthquake complexity in continuum models of seismicity



Shaw and Rice (2000)



- Small scale seismicity clustered at edges of previous event
- Small scale activity does not affect significantly the large scale statistics (although it might affect radiation)

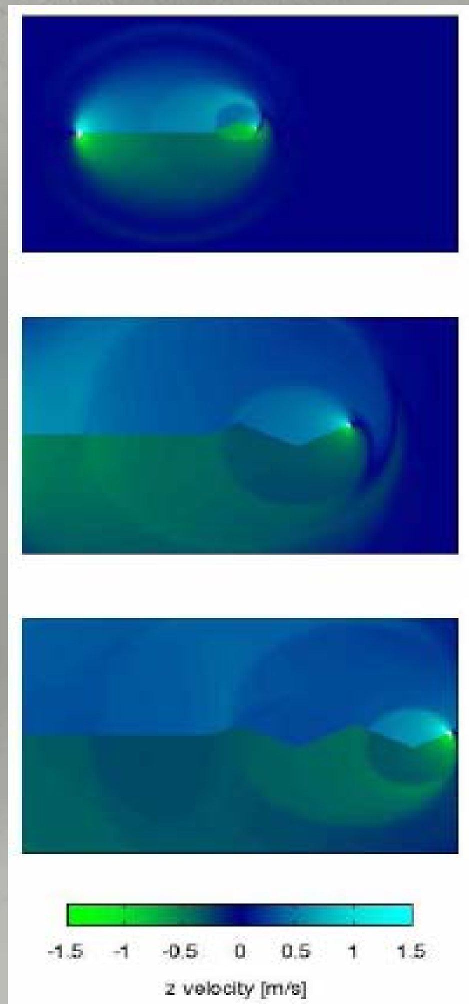
Missing:

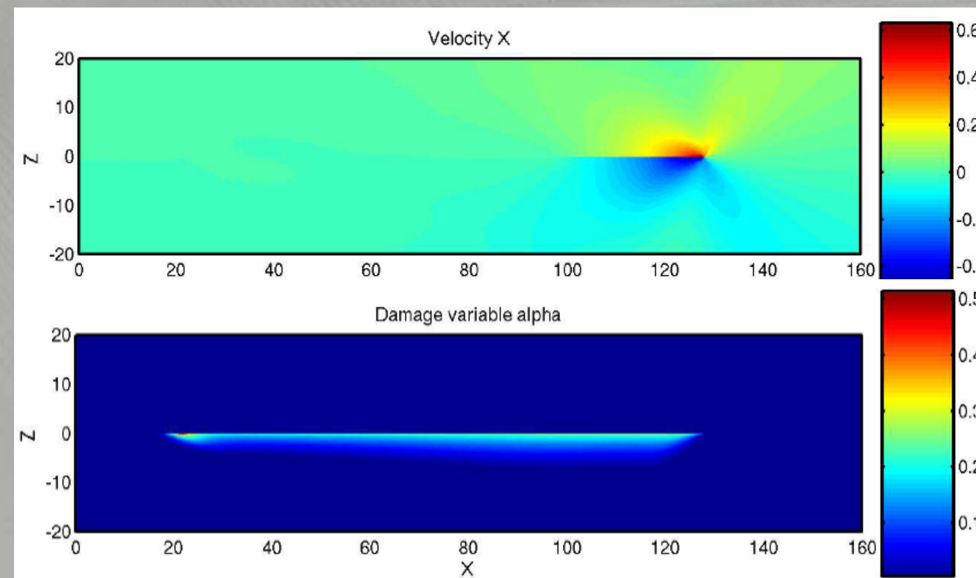
- Generic continuum model (no tuning)
- Statistical characterization of stress: standard deviation, spectral fall-off, correlation length

Computational challenges on earthquake cycle + dynamic simulations

Spectral element simulation of dynamic rupture on a multiply-kinked fault

(Madariaga et al 2007)





SEM simulation of dynamic rupture with off-fault damage (Ampuero et al 2008)

- **3D + multiple time-scales**
- **Fast velocity-weakening**
- **Non-linear off-fault rheologies**
- **Geometrical fault roughness**