Dynamic Earthquake Ruptures in the Presence of Material Discontinuities

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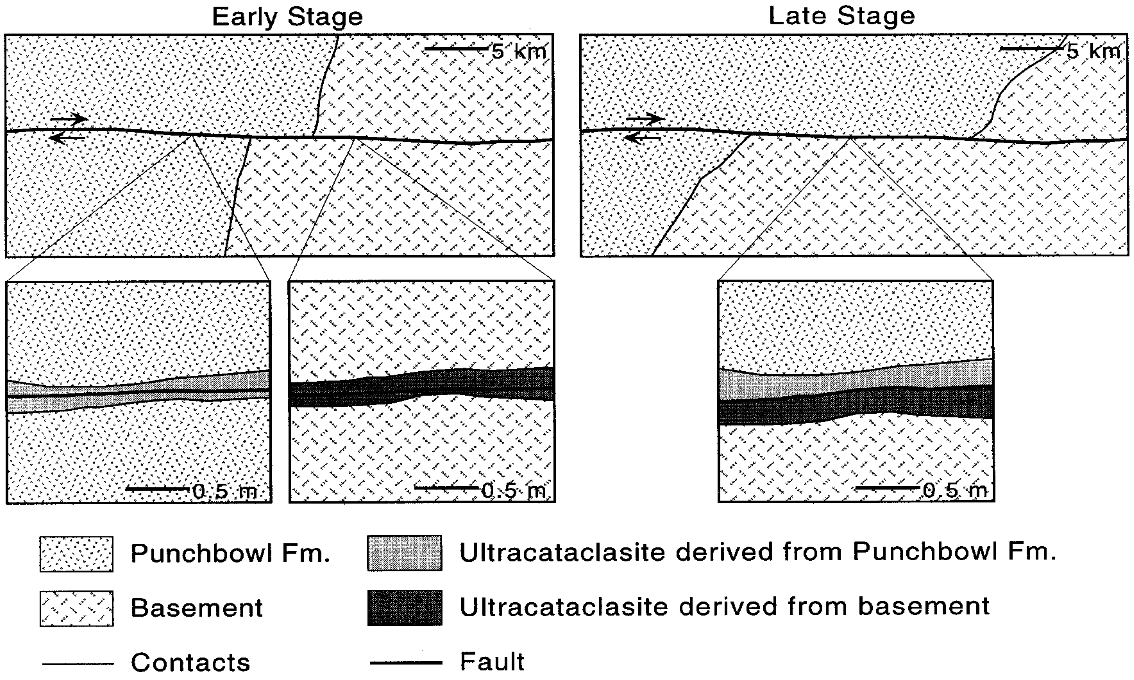
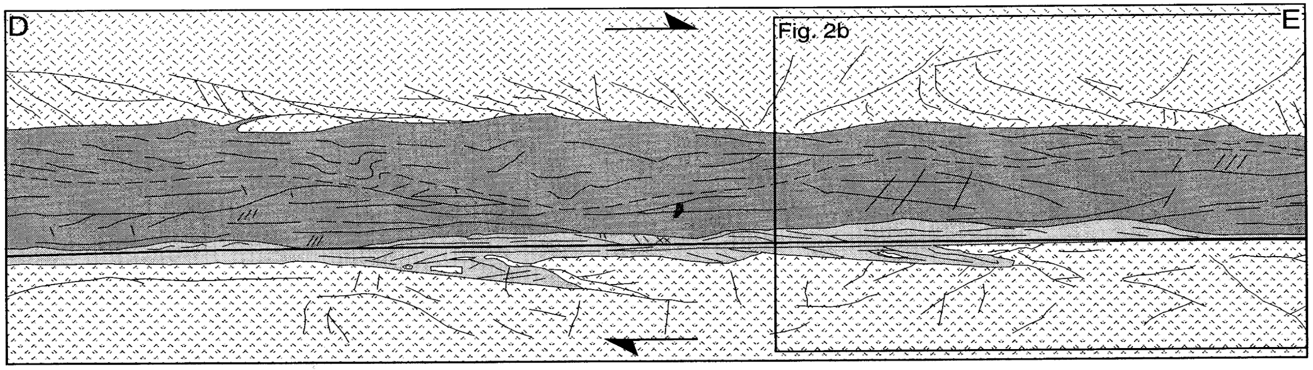
Dynamic Earthquake Ruptures in the Presence of Material Discontinuities

Motivation

- Material contrast at small scale: Punchbowl Fault example

Example 1: Geological mapping at the Punchbowl faut (Chester and Chester 1998)



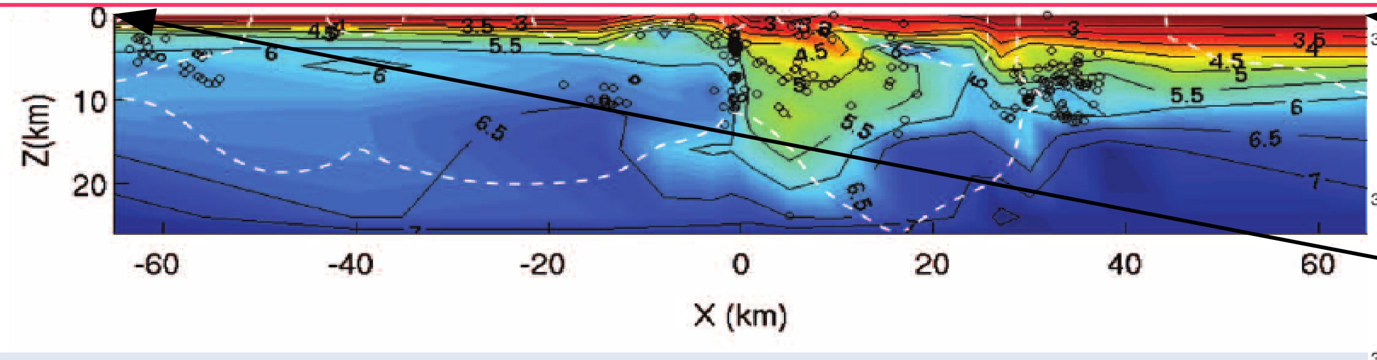


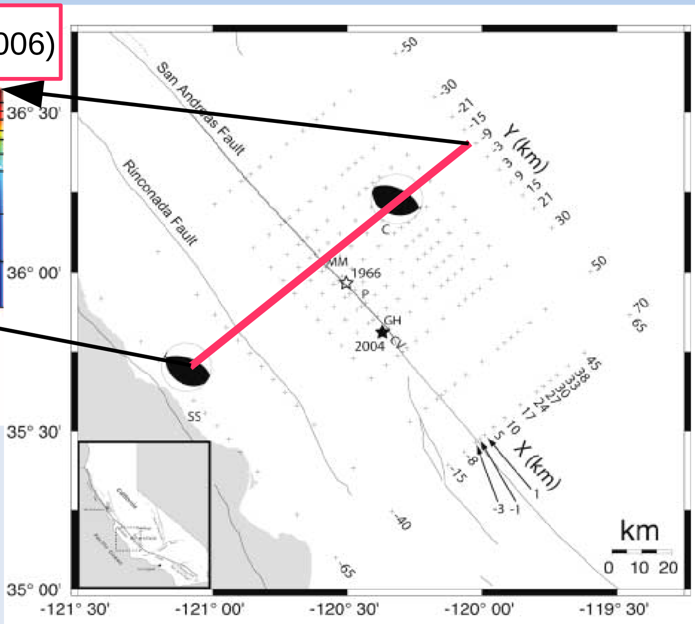
Dynamic Earthquake Ruptures in the Presence of Material Discontinuities

Motivation

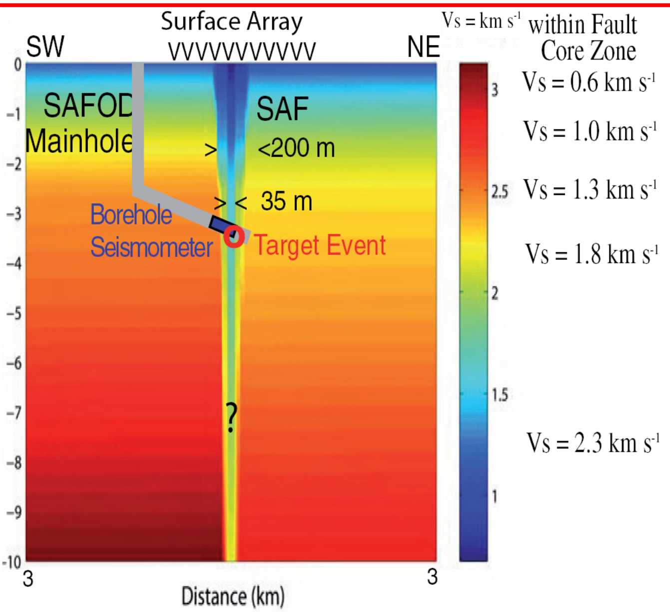
- Material contrast at the San Andreas fault at Parkfield

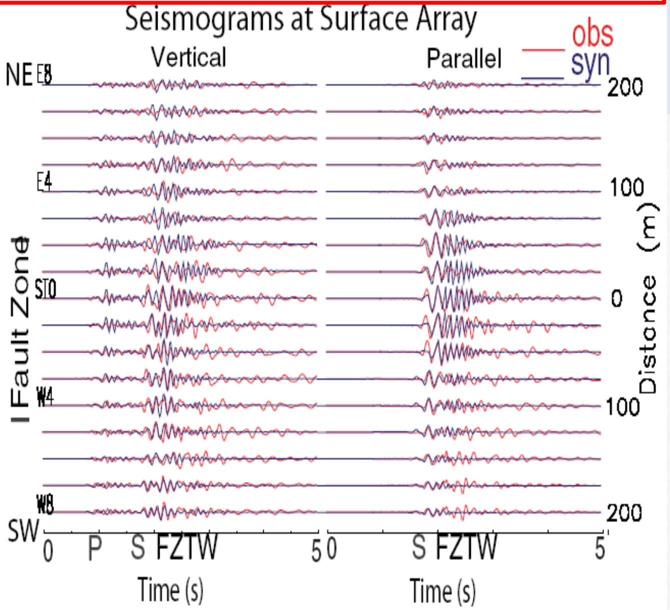
Example 2: Seismic imaging incl. recent seismicity (Thurber et. al. 2006)

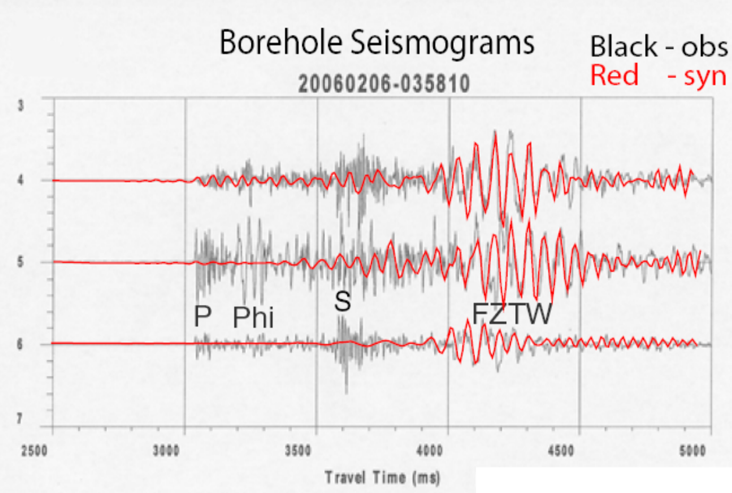




Example 3: Imaging of FZ-trapped waves (Li et. al. 2007)







Dynamic Earthquake Ruptures in the Presence of Material Discontinuities

Outline

- Migration of fault rupture onto material interfaces
- Bimaterial rupture in 3D
- Importance of material contrasts for source dynamics and ground motion

Earthquake Ruptures as Frictional Instability on a Plane

- Governing equations

- Equations of motion:

$$\partial_t \boldsymbol{v} = \frac{1}{\rho} \nabla \boldsymbol{\sigma}$$

$$\partial_t \boldsymbol{\sigma} = \boldsymbol{c}\, \dot{\boldsymbol{\epsilon}}$$

- Boundary conditions on fault-plane:

$$\tau^s - |\boldsymbol{\tau}| \geqslant 0$$

$$\tau^s \boldsymbol{V} - \boldsymbol{\tau} |\boldsymbol{V}| = 0$$

$$\tau^s = \sigma_n f$$

$\boldsymbol{v}$ = velocity

$\boldsymbol{\tau}$ = traction

$\boldsymbol{\sigma}$ = stress tensor

$\boldsymbol{c}$ = elastic tensor

$\dot{\boldsymbol{\epsilon}}$ = strainrate tensor

ρ = density

τ^s = shear strength

f = friction coefficient

σ_n = normal stress

$\boldsymbol{V}$ = slip velocity

Frictional Instability on a Plane and Bimaterial Rupture

Introduction

$$\tau^s(D) = f \cdot \sigma_\mathrm{n}$$

$\tau^s = \text{shear strength}$

$D = \text{slip}$

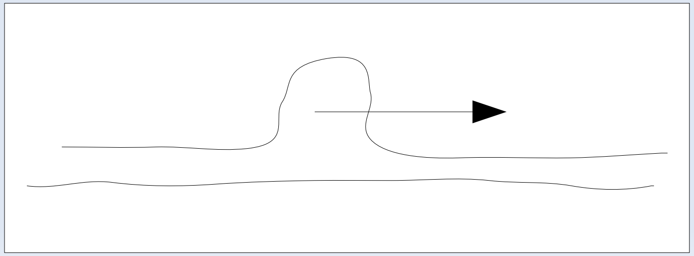
$f = \text{friction coefficient}$

$\sigma_\mathrm{n} = \text{normal stress}$

- Weertman (1980) predicts unstable slip due to normal stress perturbation on bimaterial interfaces with unilateral pulse propagation of rupture:

  => preferred direction of rupture on a bimaterial fault

- Andrews & Ben-Zion (1997) numerically simulate a wrinkle-like rupture pulse in 2D in-plane rupture simulations which they identify as a Weertman-pulse



- How does such a wrinkle-like rupture pulse look like?

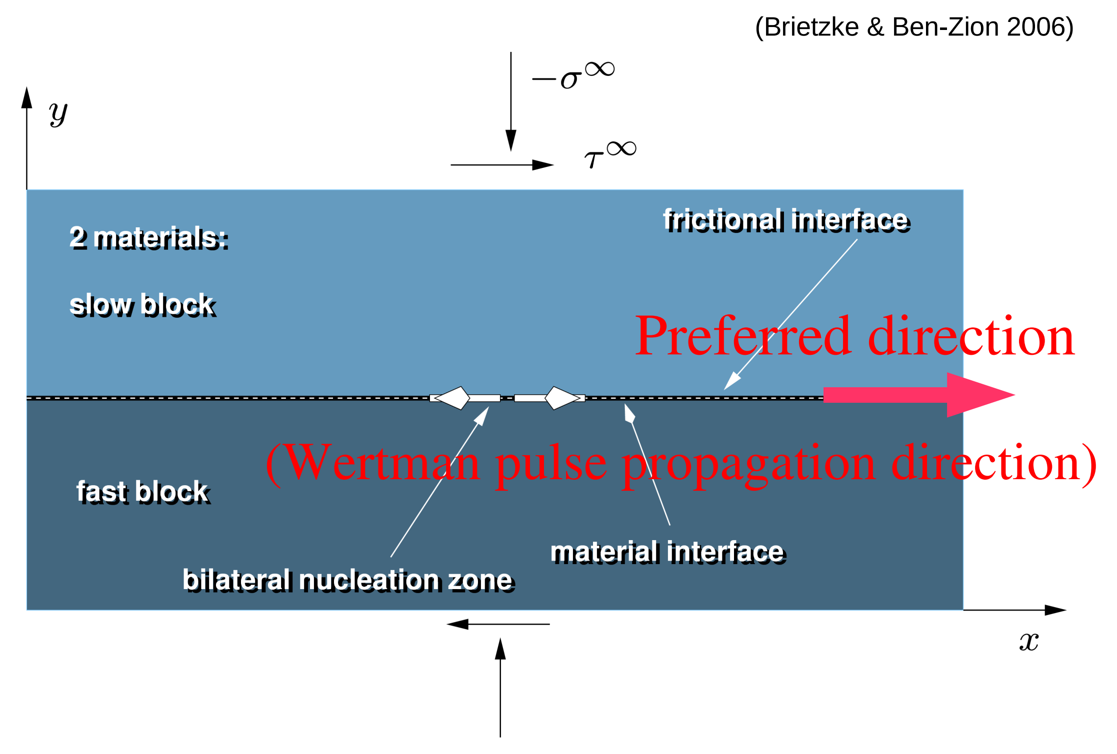
  ... like a moving wrinkle in a carpet

Dynamic Ruptures along a Bimaterial Interface

Simple bimateral setup

- 2D in-plane-model:
  - Discretization by finite-differences
  - Single frictional interface
  - Two different elastic materials
  - Constant friction coefficient

    $\tau^{s} = f \cdot \sigma_{\mathrm{n}} \quad f = \text{constant}$
  - Space-time function pore-pressure for nucleation


(Brietzke & Ben-Zion 2006)

Preferred direction

(Wertman pulse propagation direction)

wrinkle-pulse animation

Dynamic Ruptures Along a Bimaterial Interface

Unstable modes and ill-posedness

Cochard & Rice (2000) and Ranjith and Rice (2001):

2 key outcomes:

- Clarified bimaterial conditions for dynamic instability:
  - the generalized Rayleigh velocity must be defined
  - for realistic cases of elastic contrasts of up to 30%
- Demonstrated the numerical challenge of the problem due to the Adams (1995) instability which may lead to grid dependent results => Prakash & Clifton (1993, 1998) friction provides regularization of the otherwise ill-posed problem

$$\dot{\tau}_s = \frac{-|V| + V^*}{L}\left[\tau_s - f \max(0, -\sigma_n)\right]$$

Dynamic Ruptures Along a Bimaterial Interface

- Fault-zone typical material setup

- Several studies focused on the properties and behavior of 2D-in-plane wrinkle-like rupture on a single interface:
  - Rupture propagation velocity: $v_r = v_{gr}$
  - Amplification: self-sustaining behavior
  - Nucleation behavior: hard to nucleate

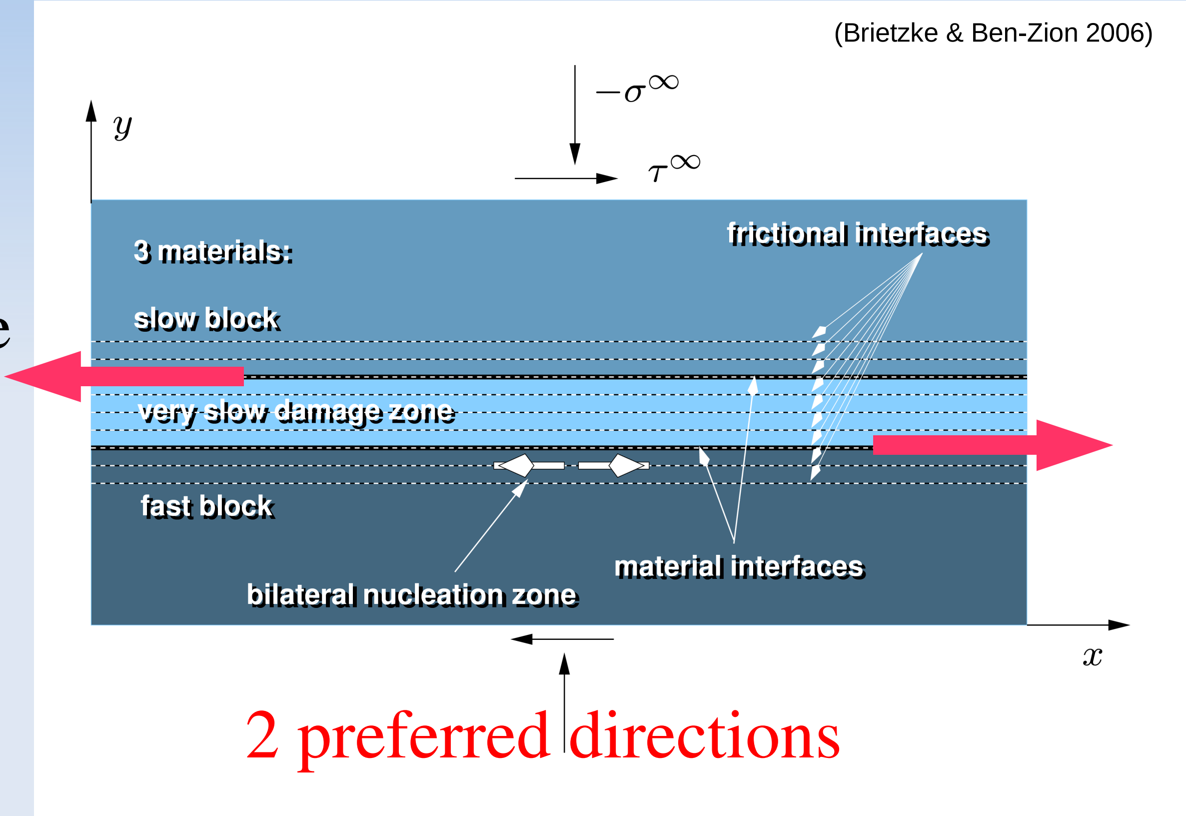
- To motivate the following we pose two questions:
  - Can fault rupture migrate spontaneously onto the material contrast and nucleate wrinkle-like slip-pulses for hypocenters located off the material contrast?
  - Under which conditions is the migration of fault ruptures inhibited?

Migration of Ruptures onto Bimaterial Interfaces

Fault-zone typical material setup

- 2D-in-plane-model:
  - Discretization of equations by finite-differences
  - Multiple frictional interface
  - Three different elastic materials
  - Constant friction coefficient

    $\tau^s = f \cdot \sigma_n \quad f = \text{constant}$
  - Nucleation on all individual faults in separate simulations


(Brietzke & Ben-Zion 2006)

2 preferred directions

Explore parameter space:

fault-separation, velocity contrast, initial shear stress, nucleation location

Migration of Ruptures onto Bimaterial Interfaces

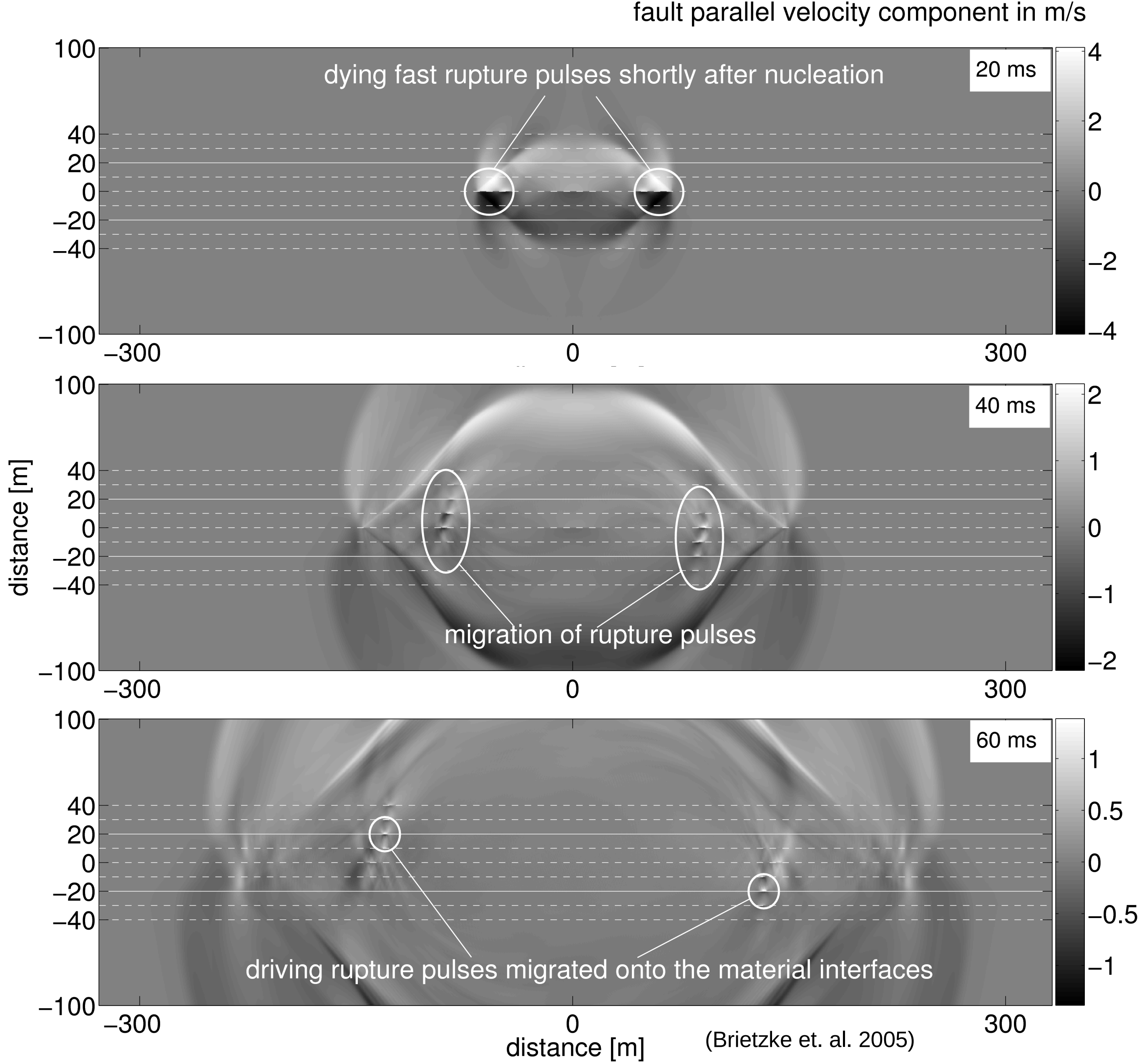
Migration of fault ruptures on parallel faults

Setup:

- 9 parallel faults, nucleation on the central fault
- 3 materials

Result:

- Rupture on central fault dies out
- Wrinkle-like rupture pulse ignited on fault with large material contrast



(Brietzke et. al. 2005)

animation rupture migration

Migration of Ruptures onto Bimaterial Interfaces

Effect of multiple parallel faults

9 faults:

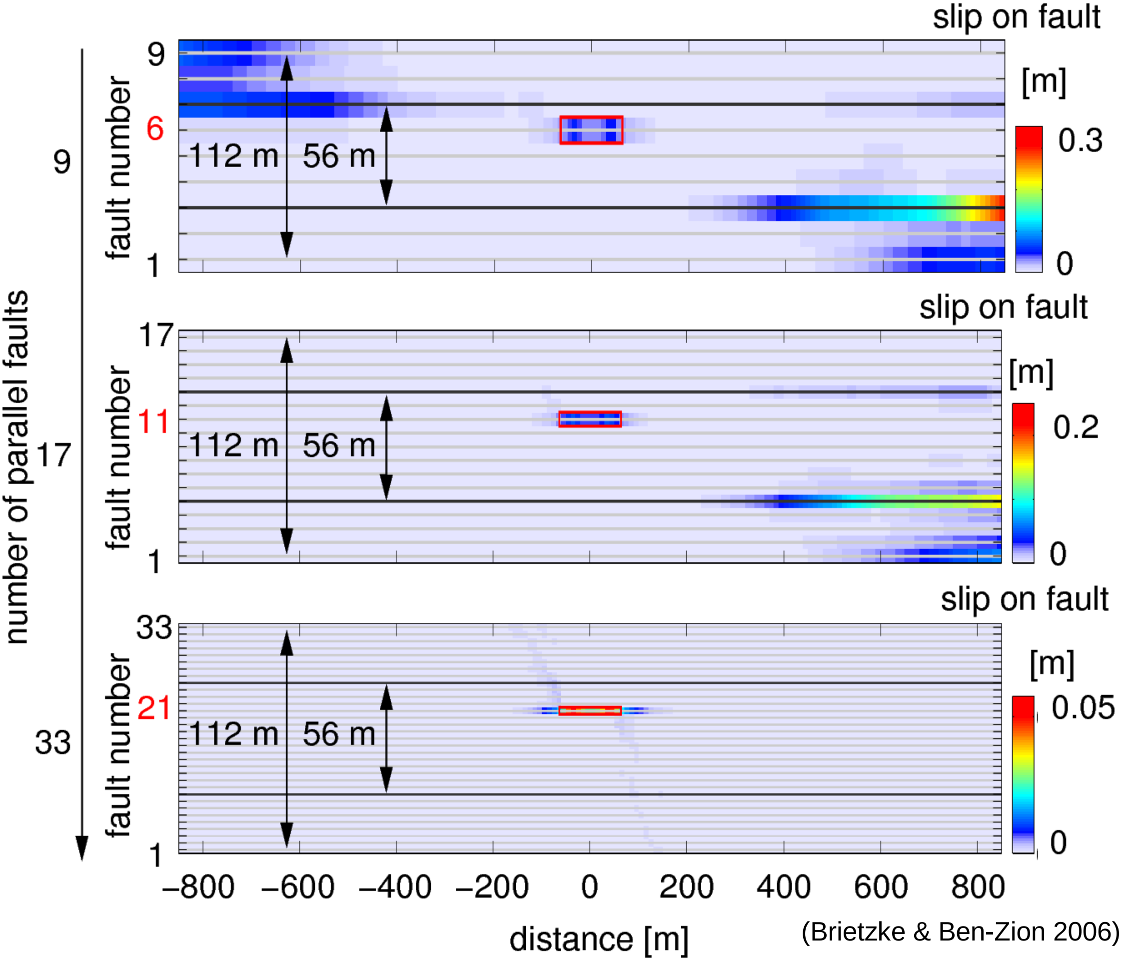
- Rupture on nucleating fault dies out
- Sustaining ruptures pulses ignited on both bimaterial faults

17 faults:

- Rupture on nucleating fault dies out
- Wrinkle-like rupture pulse ignited on fault with larger material contrast only

33 faults:

- No sustaining ruptures ignited on any fault



(Brietzke & Ben-Zion 2006)

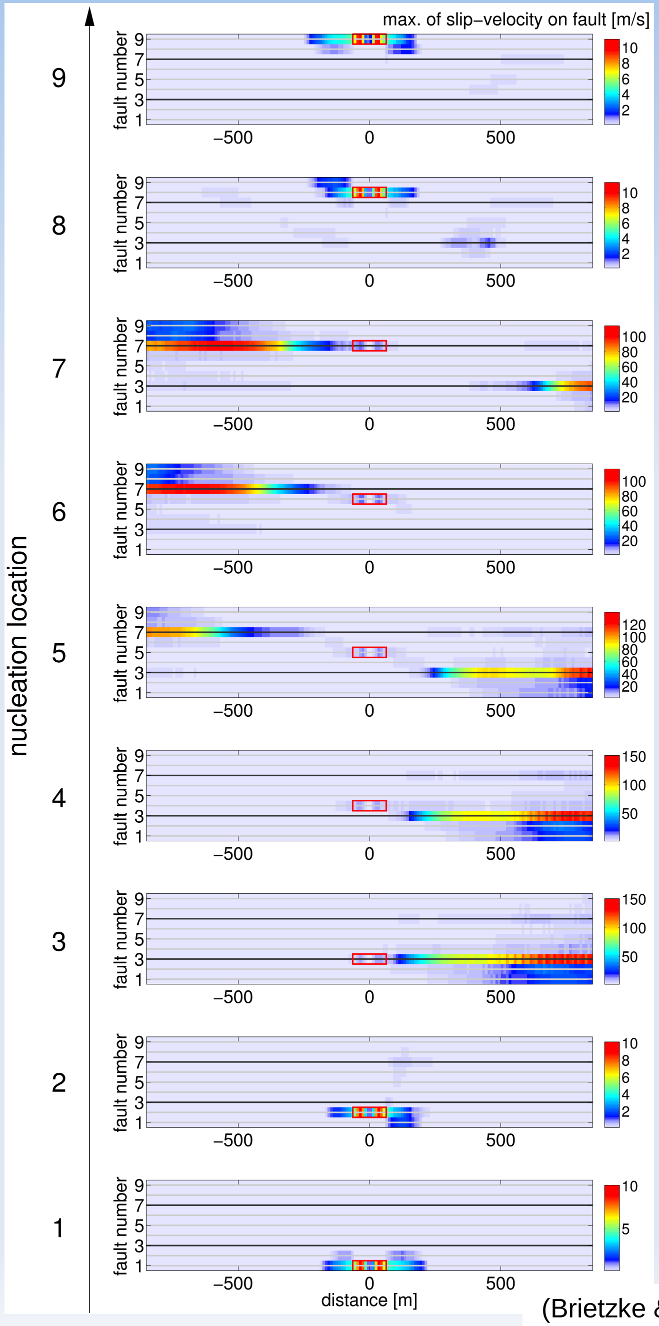
1. Multiple surfaces lead to a macroscopic plastic deformation effect
2. Model needs a limited number of weak planes to allow rupture localization

Migration of Ruptures onto Bimaterial Interfaces

- Examining tendencies of rupture migration

9 simulations with nine different nucleation locations

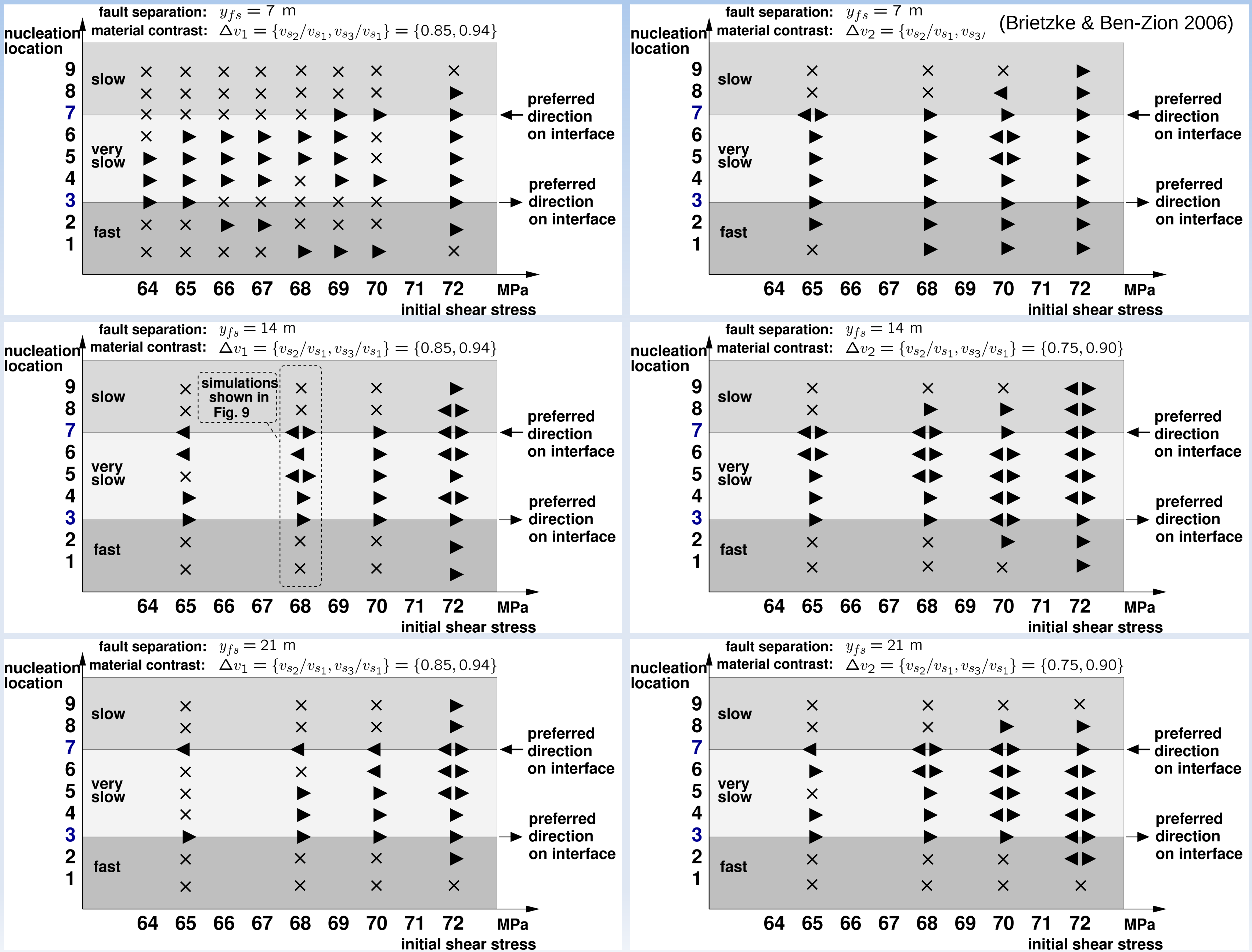
- Rupture migration appears to be stable feature
- Rupture even across low-velocity layer
- Macroscopic bilateral ruptures



(Brietzke & Ben-Zion 2006)

Migration of Ruptures onto Bimaterial Interfaces

- Examining tendencies of rupture migration


(Brietzke & Ben-Zion 2006)

Migration of Ruptures onto Bimaterial Interfaces

- Examining tendencies of rupture migration

Conclusions:

- Rupture migration stable feature
- Apparent bilateral rupture due to low-velocity layer

  (for not too thin low-velocity layers)
- Eventual rupture plane not necessarily with larger contrast
  - ➔ low resolution perspective: against preference overall contrast
- Many parallel faults act as macroscopically “effective volume deformation”

  (larger dissipation of elastic strain energy)
- Normally larger stress => easier rupture propagation

  but! when low-velocity layer is thin and fault separation is small this might fail

Migration of Ruptures onto Bimaterial Interfaces

- Examining tendencies of rupture migration

Future study:

The model presented is limited to in-plain strain, slip-independent friction to focus on effects associated with structure and dynamic normal stress changes

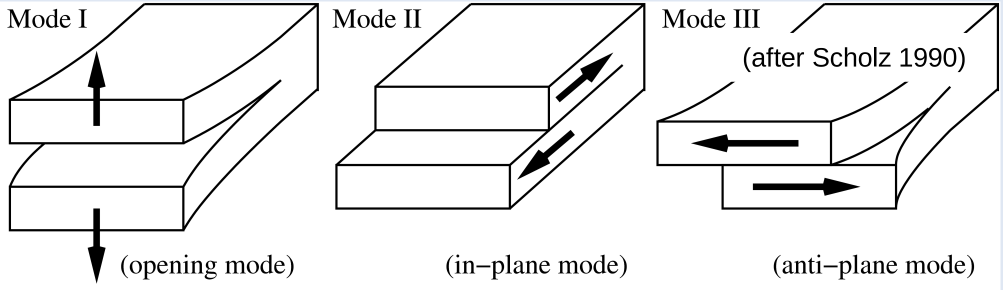
➔ Generality of the results should be tested by incorporating additional levels of realism (e.g, dimensionality, rheology, geometrical complexity)

Bimaterial Ruptures in 3D

From 2D in-plane to 3D

Bimaterial mechanism allowing for instable slip
under classically stable conditions
exists for the 2D in-plane case only

There is no such effect active for the 2D anti-plane case



(after Scholz 1990)

Question:

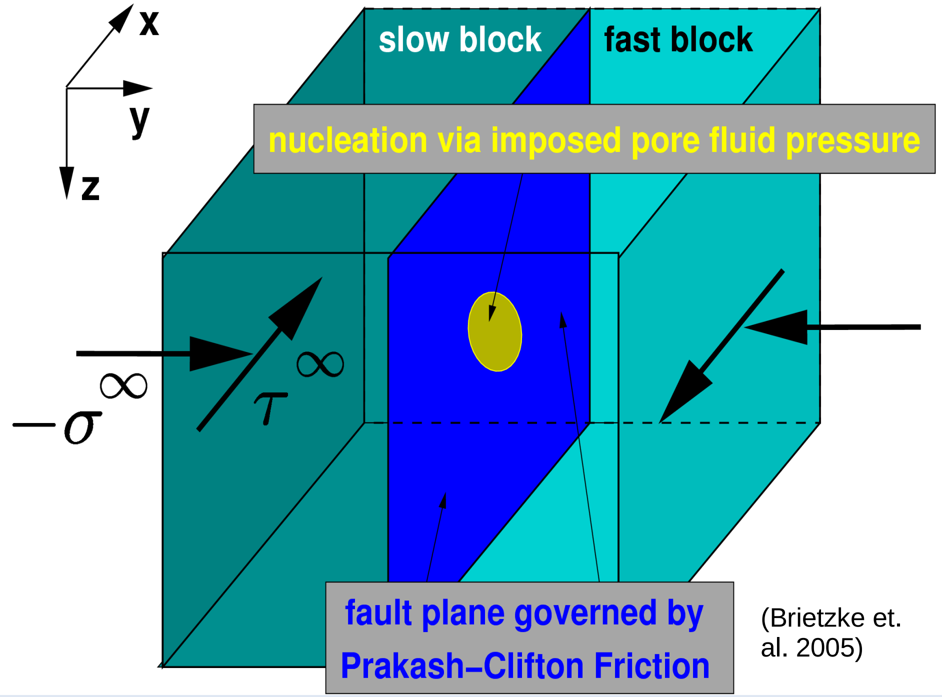
- Can a wrinkle-like pulse be nucleated in the general 3D case? (where there is a mixing of modes)

Bimaterial Ruptures in 3D

3D model

3D Model Setup:

- Finite-difference approx.
- 2 materials (20% contrast of elastic constants)
- Unbounded planar fault
- Regularized Coulomb friction (Prakash-Clifton friction)
- Circular-symmetric nucleation
- Homogeneous initial stress condition



(Brietzke et. al. 2005)

Convergence of numerical results in 3D is challenging:

=> parallel implementation of the algorithms is required

LRZ Munich Supercomputing Center

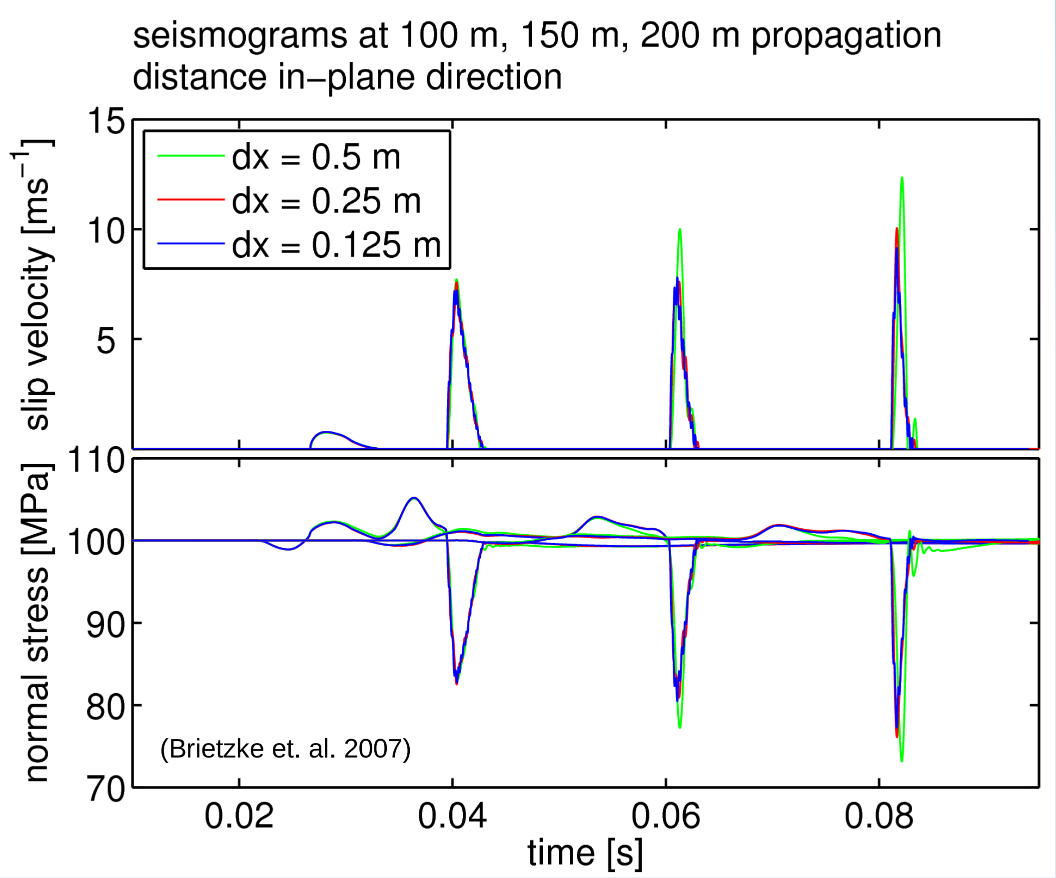
Bimaterial Ruptures in 3D

Convergence tests

- Convergence of numerical results for unstable problem is challenging, especially in the 3D case!

➔ We do a convergence test of our numerical model

✔ Result: The finite-difference implementation converges with grid refinement!

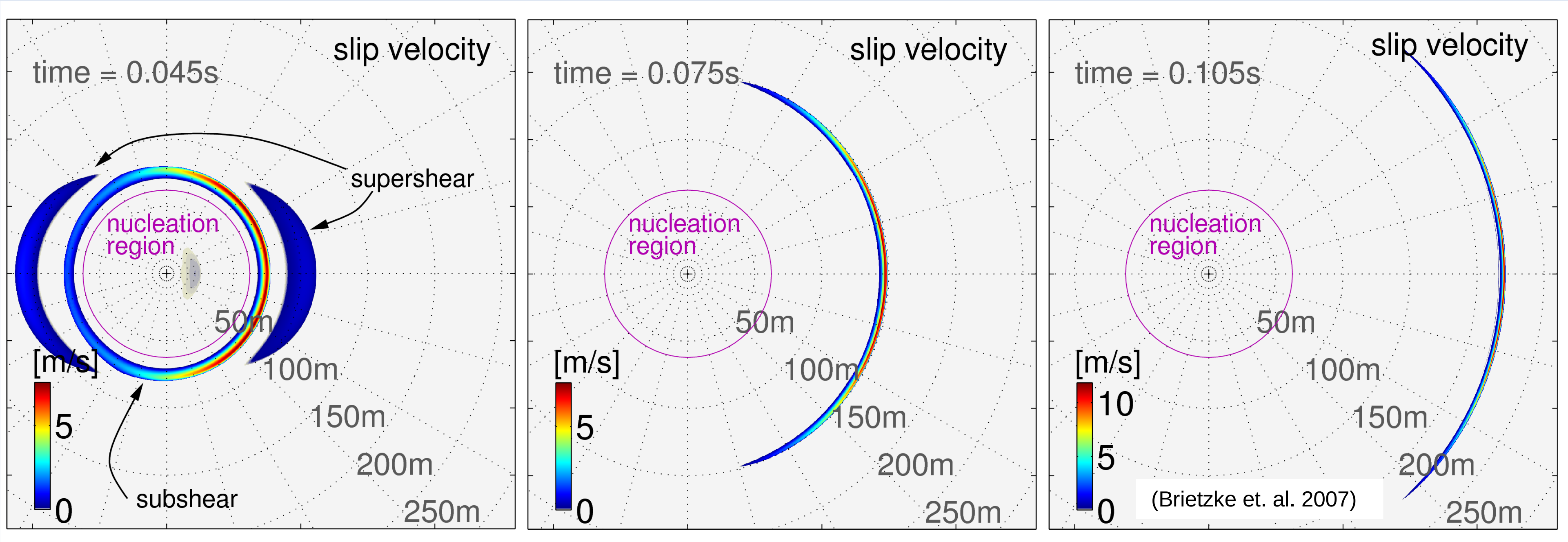


(Brietzke et. al. 2007)

Bimaterial Ruptures in 3D

Sustaining pulse in 3D

- ✔ The wrinkle-like rupture pulse specific to bimaterial 2D in-plane rupture can be nucleated also in the general 3D case.
  - ➔ The possible existence of such pulses has to be taken into account when interpreting observations and simulations of EQR
- ✔ It propagates with in a horn-shaped region around the favored in-plane axis.
- ✗ A sharpening and amplifying behavior exists



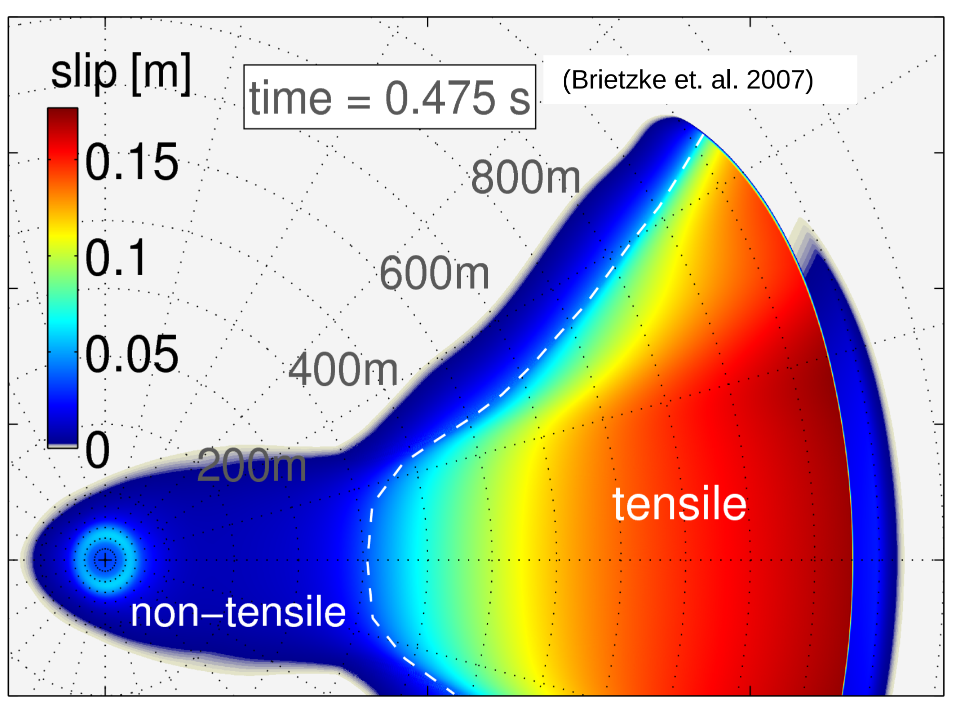
(Brietzke et. al. 2007)

Bimaterial Ruptures in 3D

Amplifying pulse in 3D

- ✓ The results show that after a certain propagation distance the rupture tends to promote tensile normal stress.
  - ➔ It has been shown that additional ingredients of realism (e.g. off-fault plastic deformation) would damp the tensile behavior when amplitudes become too large (Shi & Ben-Zion, 2006)

- ➔ The effects of opening and/or off-fault damage should be tested in future 3D studies of the wrinkle-like pulse.



(Brietzke et. al. 2007)

Bimaterial Dynamics in EQ Source Dynamics and Ground Motion

Is the bimaterial mechanism important in realistic earthquakes

- The question 'whether or not bimaterial effects in natural earthquakes are important' invoked considerable controversy recently

  1. Until recently many studies dealt with the properties of the wrinkle-like pulse (without other sources of frictional instability)
     (e.g., Weertman 1980, Andrews & Ben-Zion 1997/1998, Cochard & Rice 2000, Ben-Zion & Huang 2002, Ben-Zion & Shi 2005, Brietzke & Ben-Zion 2006, Brietzke et al. 2007).

  2. Until recently only few dealt with the combination of weakening effects (e.g., Harris & Day 1997, Andrews & Harris 2005, Harris & Day 2005)

- Since earthquakes are known to happen also in cases of essentially homogeneous material conditions the question is of course valid!

Bimaterial Dynamics in EQ Source Dynamics and Ground Motion

- Is the bimaterial mechanism important in realistic earthquakes

- Andrews and Harris (2005): bold statement:

  “The wrinkle-like slip pulse is not important in earthquake dynamics”

  Unfortunately the study is weak in two aspects:

  - Present results of two 3D and one 2D simulations only
  - 3D simulations too coarse to resolve wrinkle-pulse

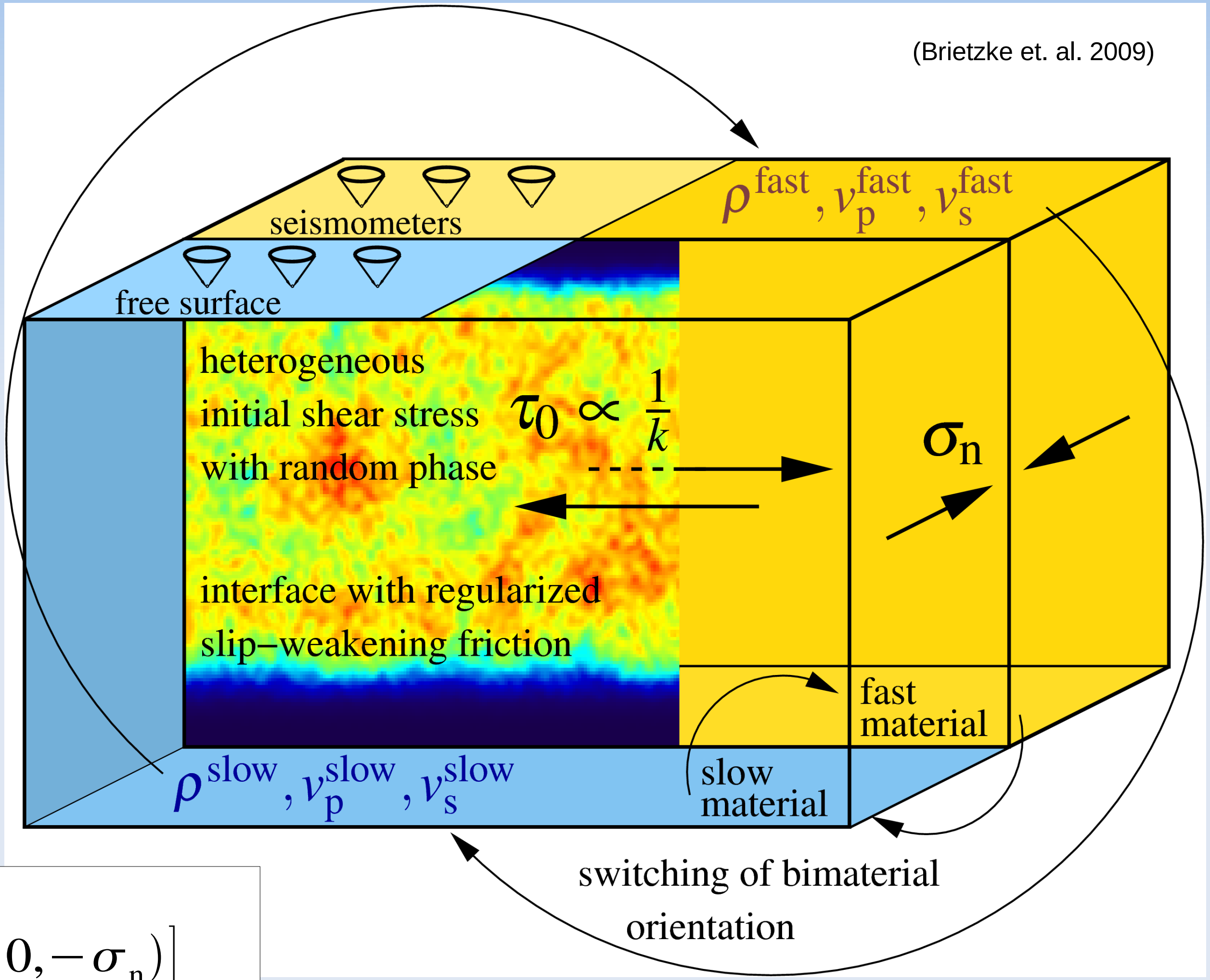
- Andrews and Harris (2005) propose that the wrinkle-like pulse might have effects on the radiated ground motion

We extend the parameter range in a model similar to the one by AH05

Bimaterial Dynamics in EQ Source Dynamics and Ground Motion

3D Model with slip-weakening and heterogeneous stress

- Initial stress with random phase and 1/k Amplitude
- Free surface
- Regularized slip-weakening friction
- Each parameter case simulated twice with reversed orientation



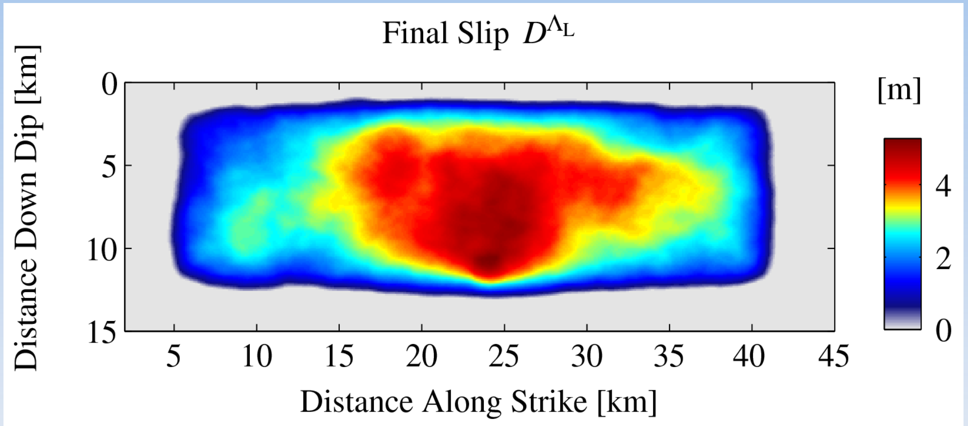
$$\dot{\tau}_s = \frac{-|V| + V^*}{L}\left[\tau_s - f_{sw}\max(0, -\sigma_n)\right]$$

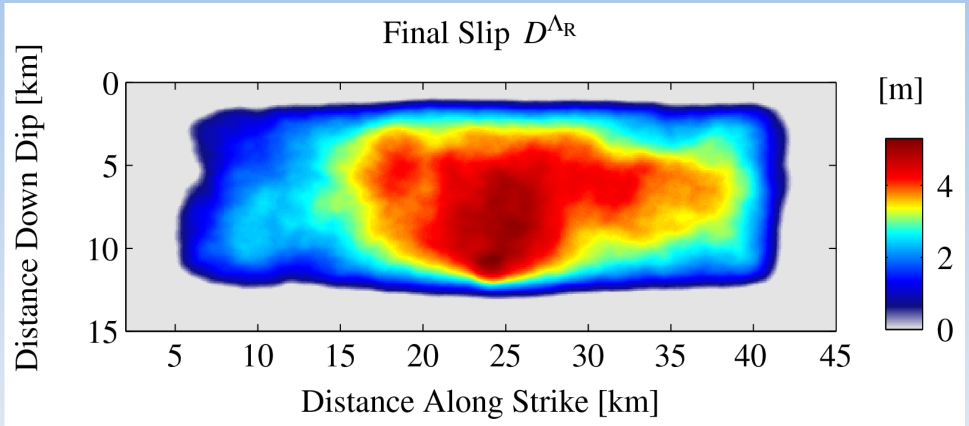
$$f_{sw} = \begin{cases} f_s - D/D_c(f_s - f_d) & \text{for } D < D_c \\ f_d & \text{for } D \geqslant D_c \end{cases}$$

Setup similar to Andrews & Harris (2005)

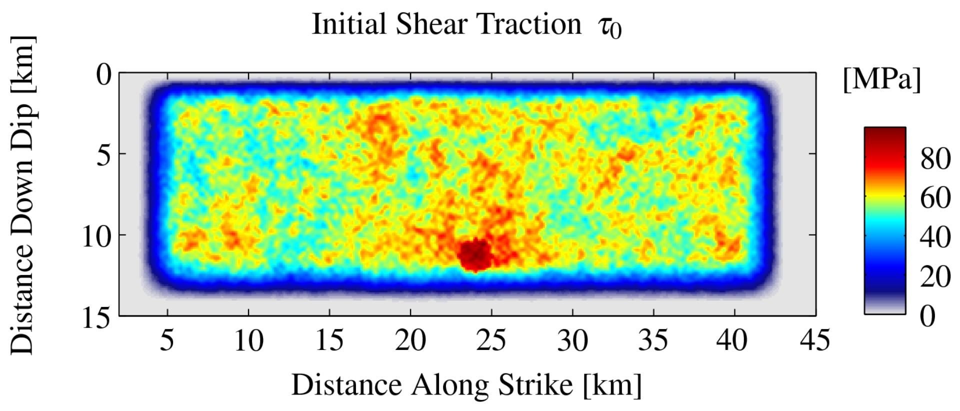
Bimaterial Dynamics in EQ Source Dynamics and Ground Motion

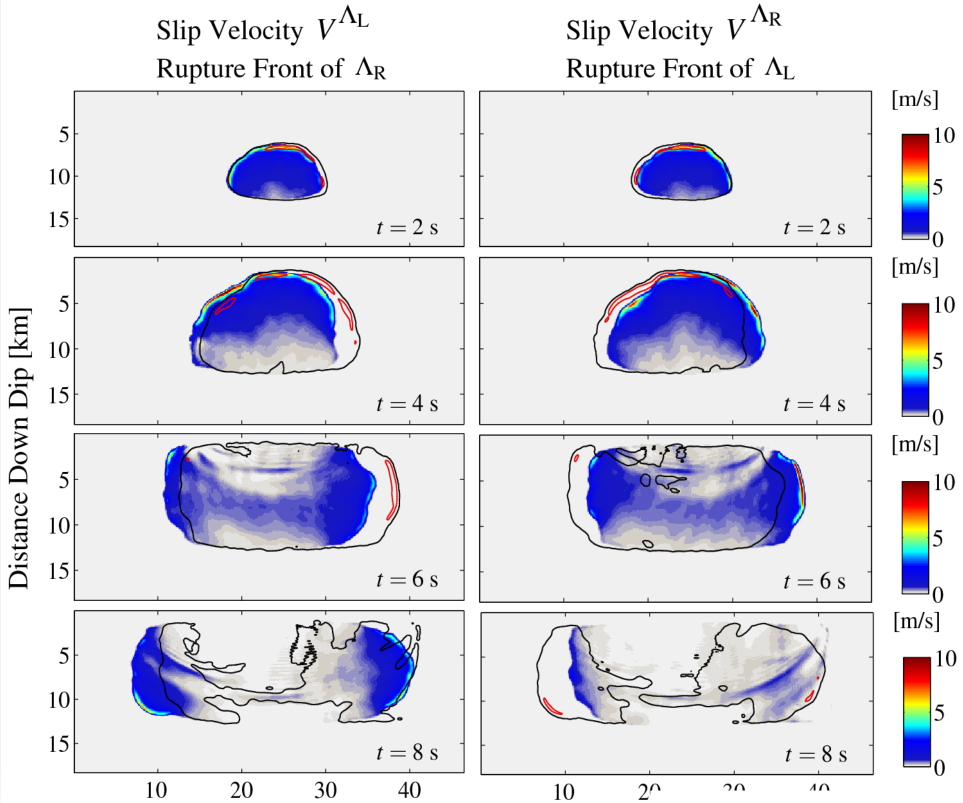
Example 1: slip-similar


Final Slip D^{Λ_L}


Final Slip D^{Λ_R}

- Initial stress same
- Slip similar
- Slip-history considerably different


Initial Shear Traction τ_0


Slip Velocity V^{Λ_L} Rupture Front of Λ_R

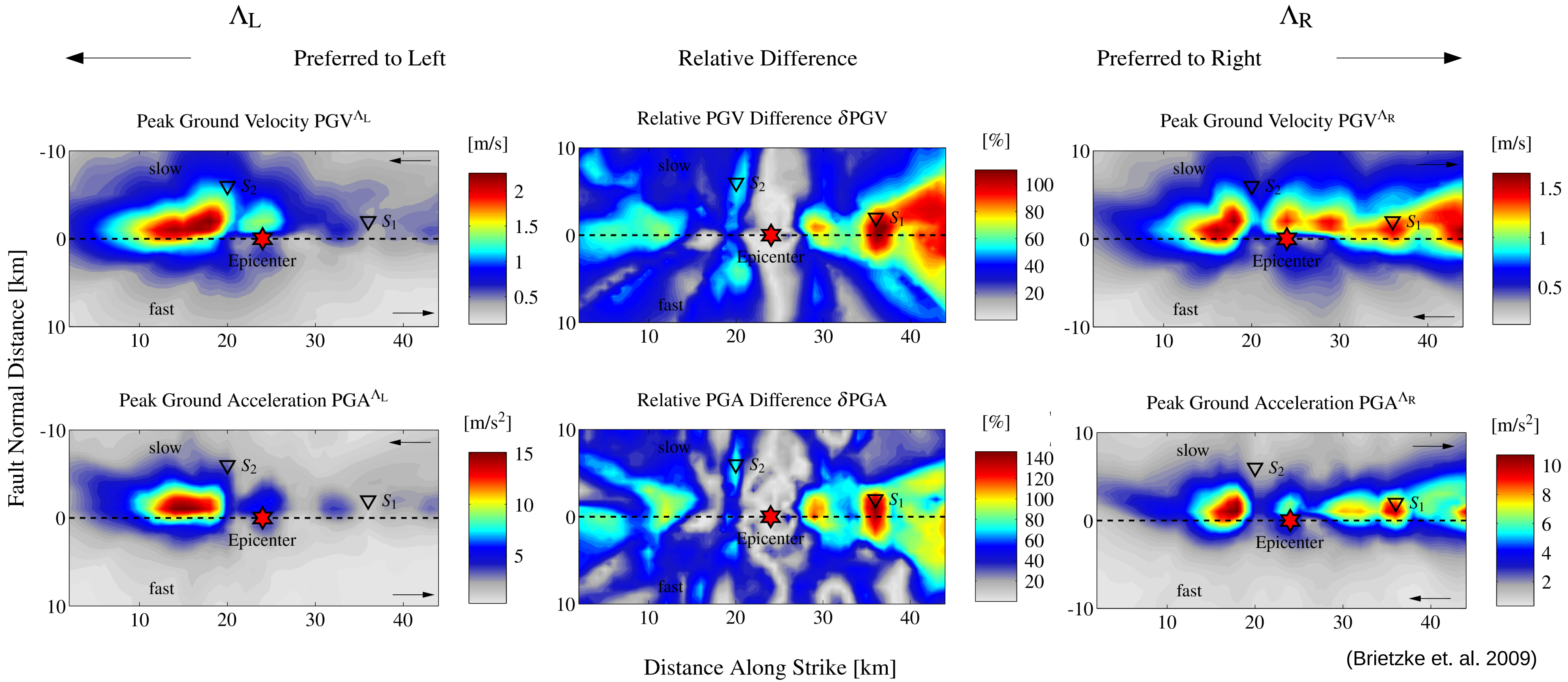
Slip Velocity V^{Λ_R} Rupture Front of Λ_L

(Brietzke et. al. 2009)

How about ground motion?

Bimaterial Dynamics in EQ Source Dynamics and Ground Motion

Example 1: slip-similar



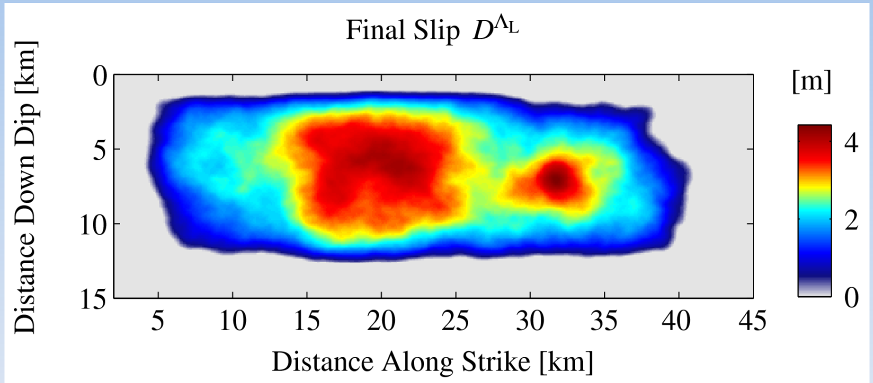
(Brietzke et. al. 2009)

- Initial stress same
- **Slip similar!**
- **Ground motion considerable different!**
- Slip-history considerable different

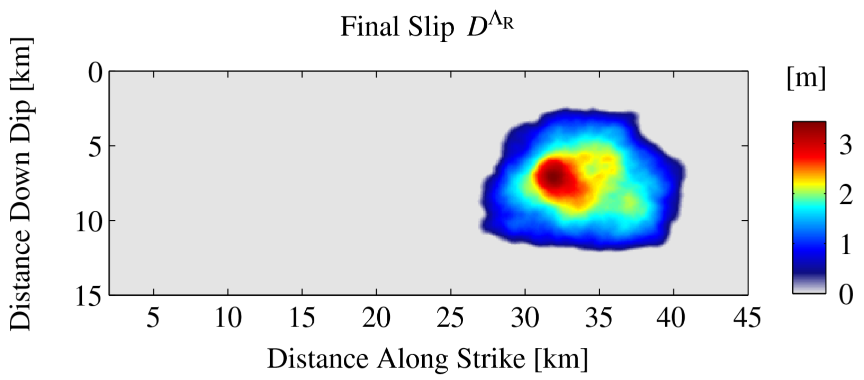
visual inspection

Bimaterial Dynamics in EQ Source Dynamics and Ground Motion

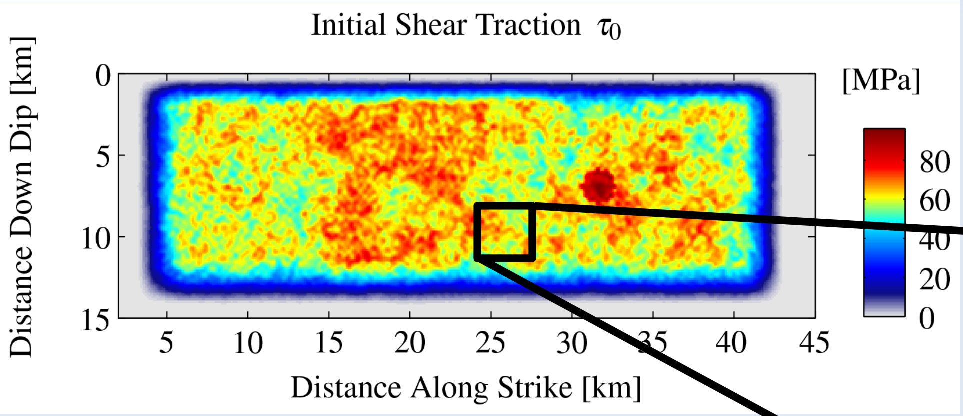
Example 2: slip very different



Final Slip D^{Λ_L}

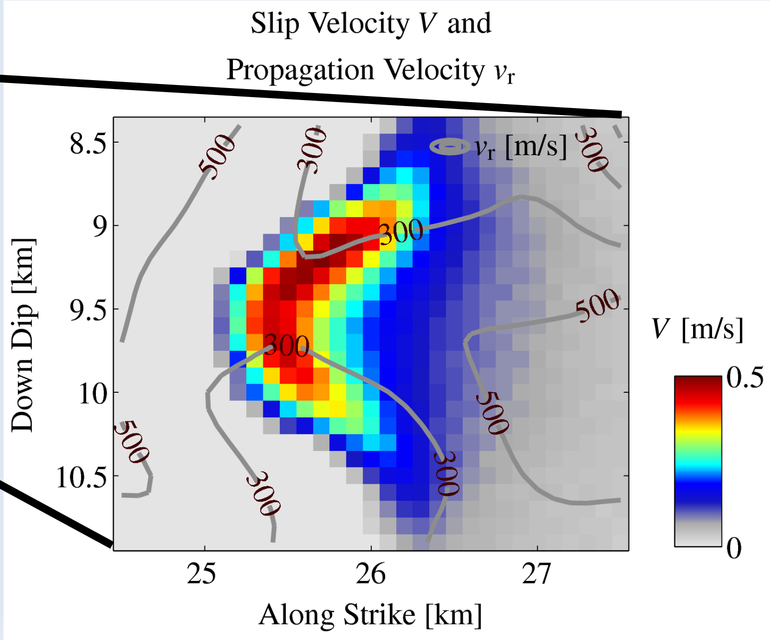


Final Slip D^{Λ_R}



Initial Shear Traction τ_0

- Rupture 'creeps through Bottleneck'



Slip Velocity V and

Propagation Velocity v_r

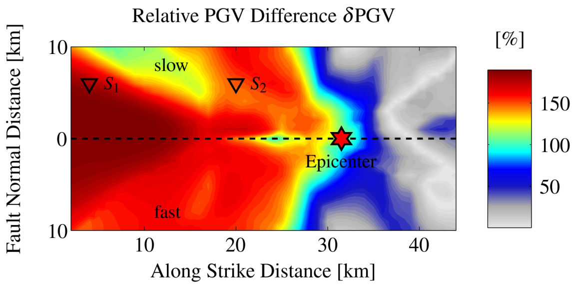
animation

- Initial stress same
- **Slip different!**
- **Rupture slowly overcomes low stress barrier when propagation in favored direction!**

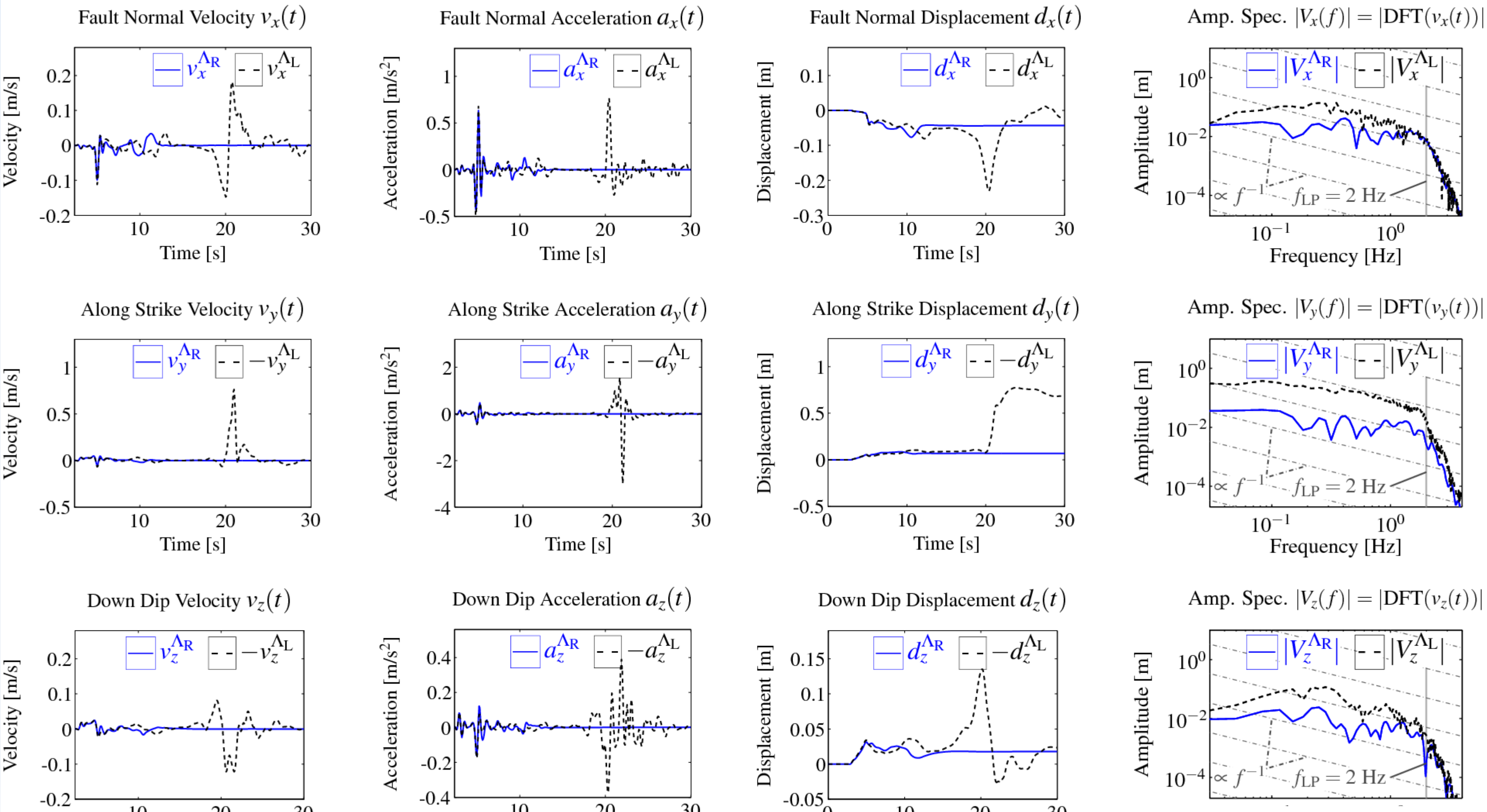
(Brietzke et. al. 2009)

Bimaterial Dynamics in EQ Source Dynamics and Ground Motion

Example 2: slip very different



- Seismograms reveal the huge difference in ground motion
- The amplitude spectra exhibit expected frequency decay

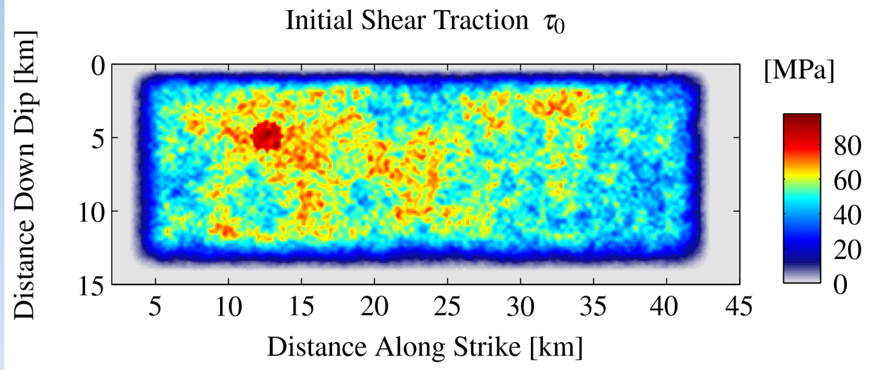


(Brietzke et. al. 2009)

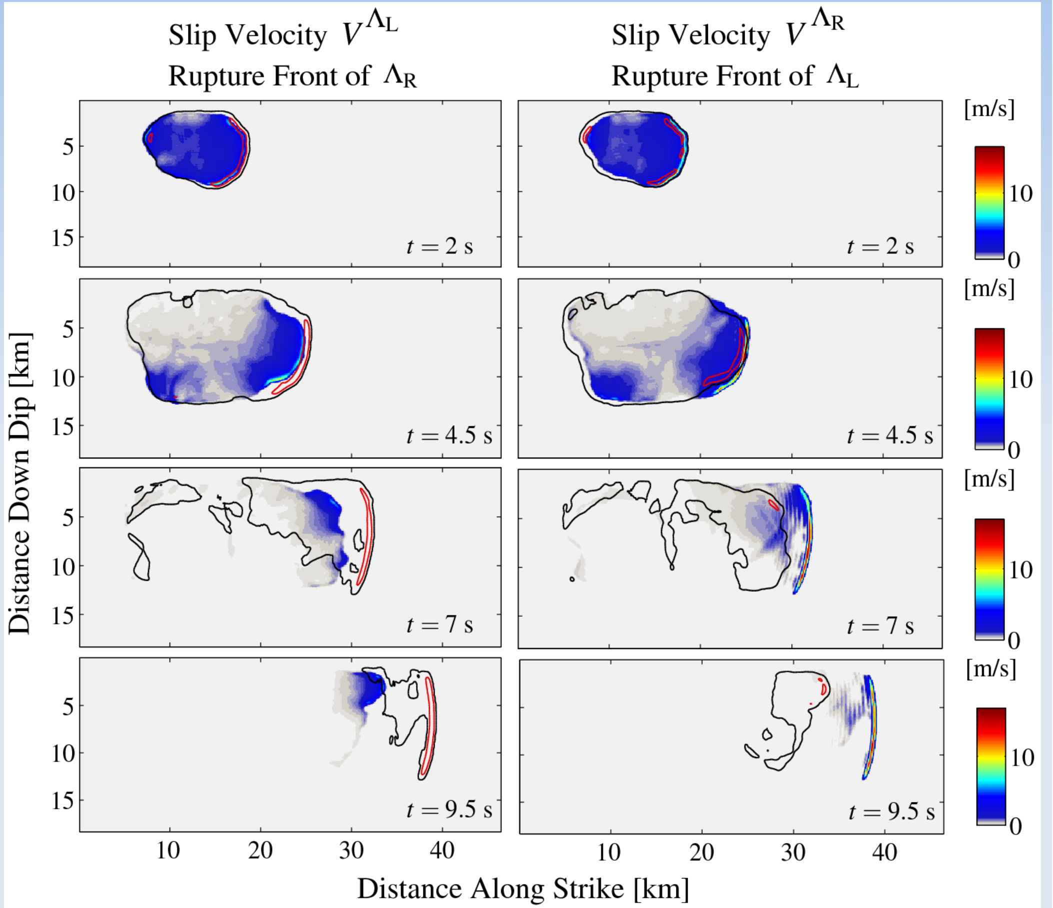
visual inspection

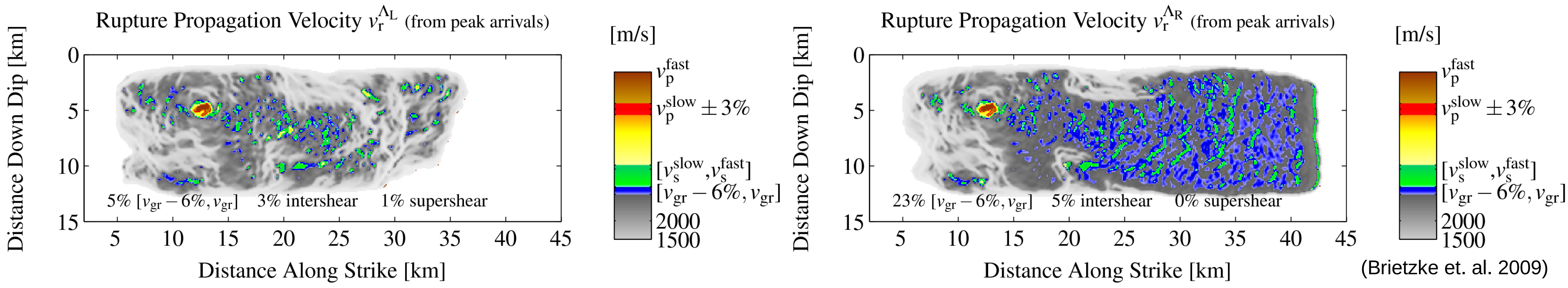
Bimaterial Dynamics in EQ Source Dynamics and Ground Motion

- Example 3: wrinkle-pulse nucleates from initially crack-like rupture



- Initial stress same
- Slip not similar
- Wrinkle-like rupture mode shows up!

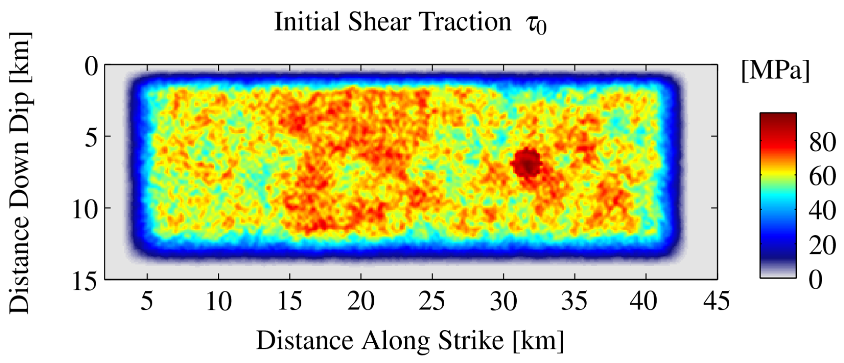




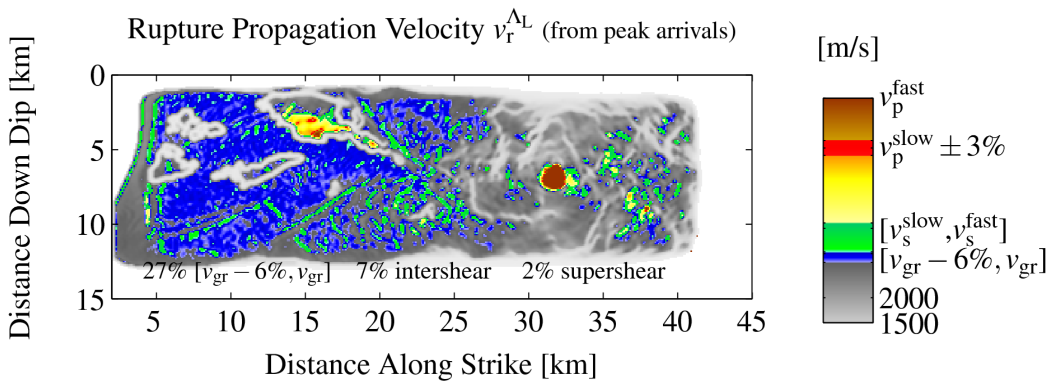
(Brietzke et. al. 2009)

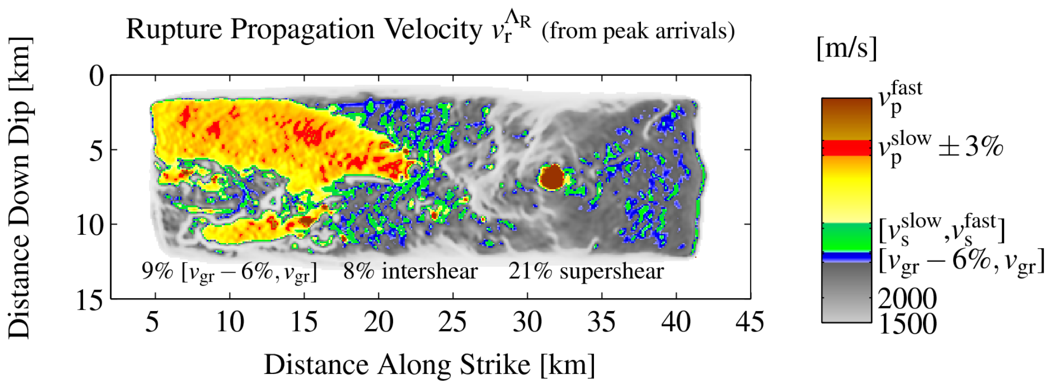
Bimaterial Dynamics in EQ Source Dynamics and Ground Motion

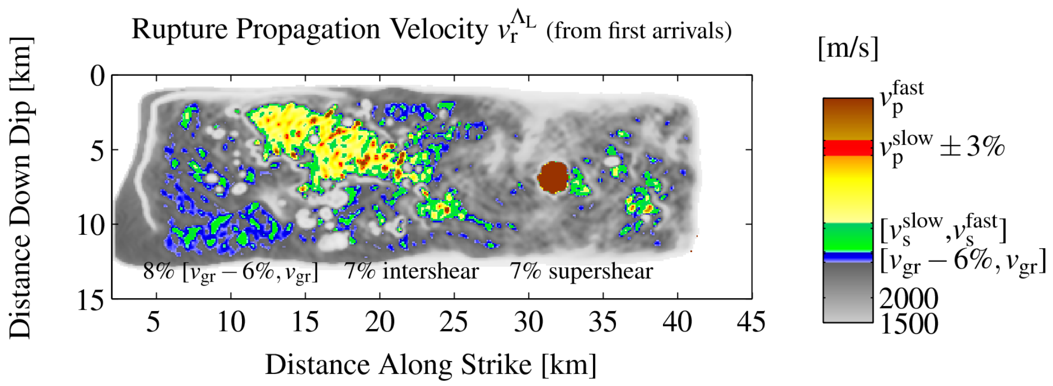
Example 4: supershear promotion/prevention

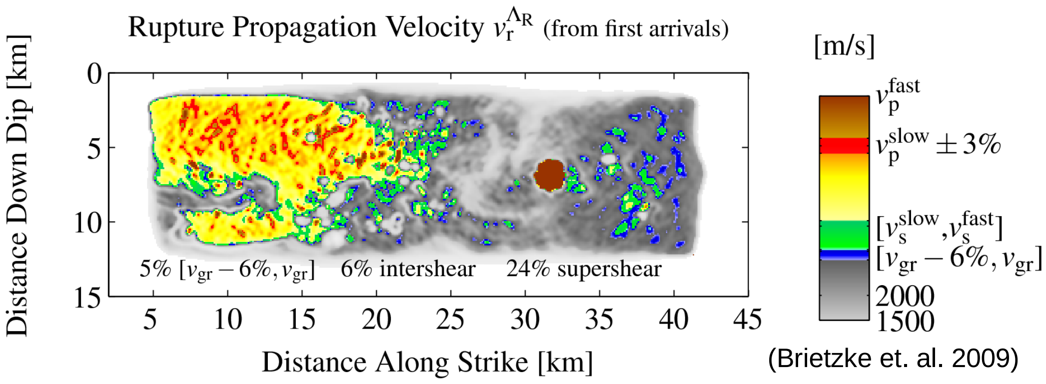


- Supershear promoted in unfavored direction
- Supershear prevention for unfavored direction
- Peak slip velocity slower behind rupture front









(Brietzke et. al. 2009)

visual inspection

Bimaterial Dynamics in EQ Source Dynamics and Ground Motion

- Examining results of about 300 simulation pairs

- Strength excess:

$$S = \frac{\tau_s - \tau_0^{av}}{\tau_0^{av} - \tau_d}$$

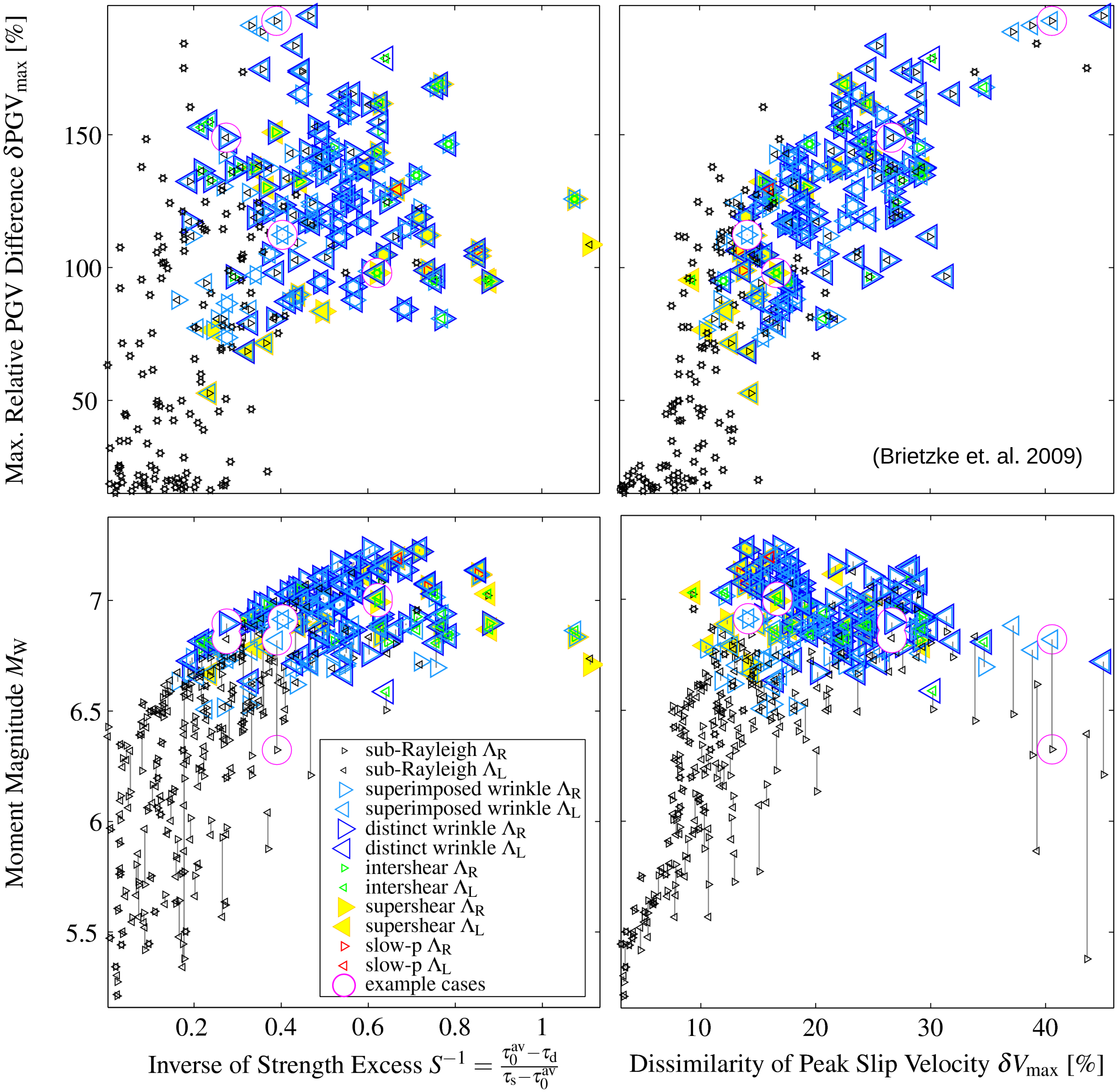
- Dissimilarity of peak slip velocity:

$$\delta V_{max} = \frac{\sum_{i=1}^{N} |V_{max_i}^{\lambda_R} - V_{max_i}^{\lambda_L}|}{\sum_{i=1}^{N} V_{max_i}^{\lambda_R} + \sum_{i=1}^{N} V_{max_i}^{\lambda_L}}$$

- Max. relative difference in peak ground velocity:

$$\delta PGV_{max} = \max(\delta PGV_j)$$

$$\delta PGV_j = \frac{|PGV_j^{\lambda_R} - PGV_j^{\lambda_L}|}{\frac{1}{2}(PGV_j^{\lambda_R} + PGV_j^{\lambda_L})}$$



(Brietzke et. al. 2009)

Bimaterial Dynamics in EQ Source Dynamics and Ground Motion

- Examining results of about 300 simulation pairs

Summary of Results:

- Bimaterial induced diversification:
  - ➔ Large zoo of ruptures:
    - ✓ Classical cracks
    - ✓ Wrinkle-like pulses
    - ✓ Supershear events
    - ✓ Secondary events after slow barriers
- Ground Motion:
  - ➔ Small to huge differences possible!
  - ➔ Often large directivity

Bimaterial Dynamics in EQ Source Dynamics and Ground Motion

Conclusion

١. Bimaterial influence on slip may be small – effect on surface ground motion & earthquake hazard may be substantial.

٢. results contradict the conclusion of previous studies:

   ✗ for ranges of parameters wrinkle-mode is attractive propagation mode

   ✗ wrinkle-like pulses can strongly influence earthquake source dynamics -> effect on ground motion may be very large.

٣. wrinkle-pulse not needed to alter slip history.

   ✗ bimaterial mechanism in heterogeneous setup can affect rupture dynamics for a wide range of propagation velocity

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Future Work

١. Robustness test by including additional physical ingredients, e.g.:

  - off-fault deformation
  - poro-elasticity
  - fluid pressurization
  - melting and gel-formation

٢. With increased complexity parameter space becomes large

  - → larger number of simulations
  - → large synthetic data sets explored by statistical methods

٣. Need for new theoretical concepts and new experiments to reduce the uncertainties in parameters.

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- Acknowledgment

Thanks for your attention!!!