Spatial Correlation Between Kinematic Source Parameters Derived From Dynamic Rupture Modeling

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ICS UCSB INSTITUTE FOR CRUSTAL STUDIES

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Wanted

Kinematic source description

"designed to emulate important characteristics of dynamic rupture"

(Guatteri et al, 2004)

Correlated Source Parameter

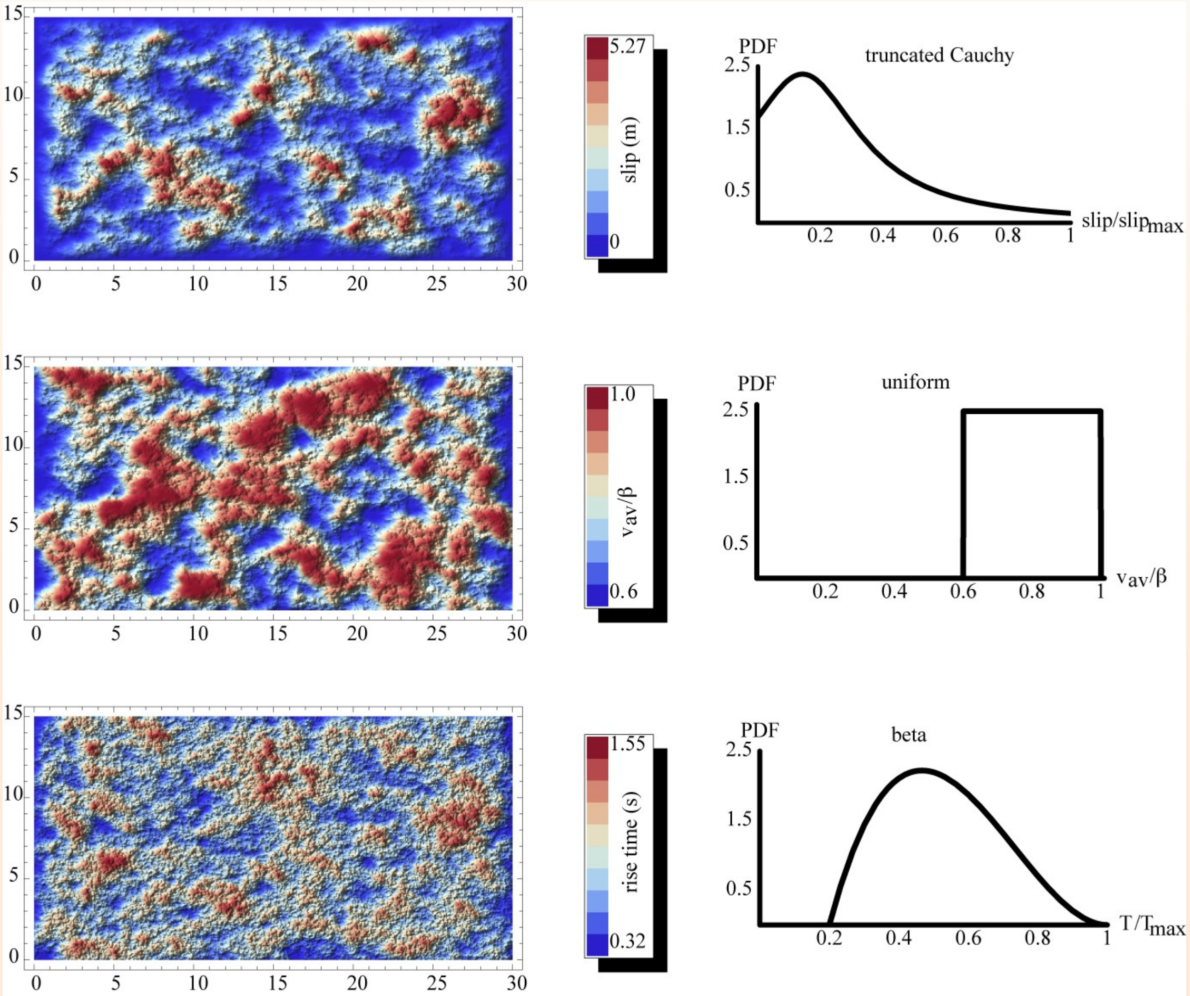
Slip

Spatial correlation 30%

Average rupture velocity

Spatial correlation 60%

Rise time



(Liu, Archuleta, Hartzell, 2006)

Limitations

•Model constructed and correlations calibrated to predict 1994 Northridge strong motion recording
•Amplitude distributions for average rupture velocity and rise time not based on observations or dynamic modeling
•No real basis for using average rupture velocity

Because of limited resolution of kinematic inversions, and trade-offs between the parameters, dynamic rupture modeling necessary to gain understanding of rupture process.

Uncertainties

Aleatoric Uncertainty: Represents natural variability in rupture process (stochastic nature of problem)

Epistemic Uncertainty: Represents our lack of knowledge. In dynamic modeling:
- Initial stress distribution on fault? Some insight from kinematic slip inversions
- Strength distribution on fault?
- Friction law and distribution of friction parameters on fault?
- Correlation between initial parameters?
- …

- Account for aleatoric uncertainty by computing multiple realizations of dynamic ruptures
- Account for epistemic uncertainty by using various approaches from literature to construct stress and strength distributions on the fault

Approach

Compute many spontaneous dynamic ruptures for a variety of initial models

For each rupture compute fault maps of source parameters (slip, peak-sliprate, rupture velocity, rise time,…)

For each rupture and for each parameter pair (for example slip and rise time) compute spatial correlation

Find parameter pairs that show the least variability in correlation given the uncertainties in the input parameters.

Approach

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For each rupture compute fault maps of source parameters (slip, peak-sliprate, rupture velocity, rise time,…)

For each rupture and for each parameter pair (for example slip and rise time) compute spatial correlation

Find parameter pairs that show the least variability in correlation given the uncertainties in the input parameters, that is, find the parameter pairs that show the least dependence from the initial models.

270 'own' + 3 *DynaShake* Models

Rupture dimensions:

30km x 15km, 30km x 20km
60km x 12km, 60 km x 15 km , 60km x 20km
120 km x 15 km
300 kmx 16 km

Free surface to top of rupture:

600m, 0m

Velocity models:

halfspace, 1 layer over halfspace, 1D gradient, *CVM*

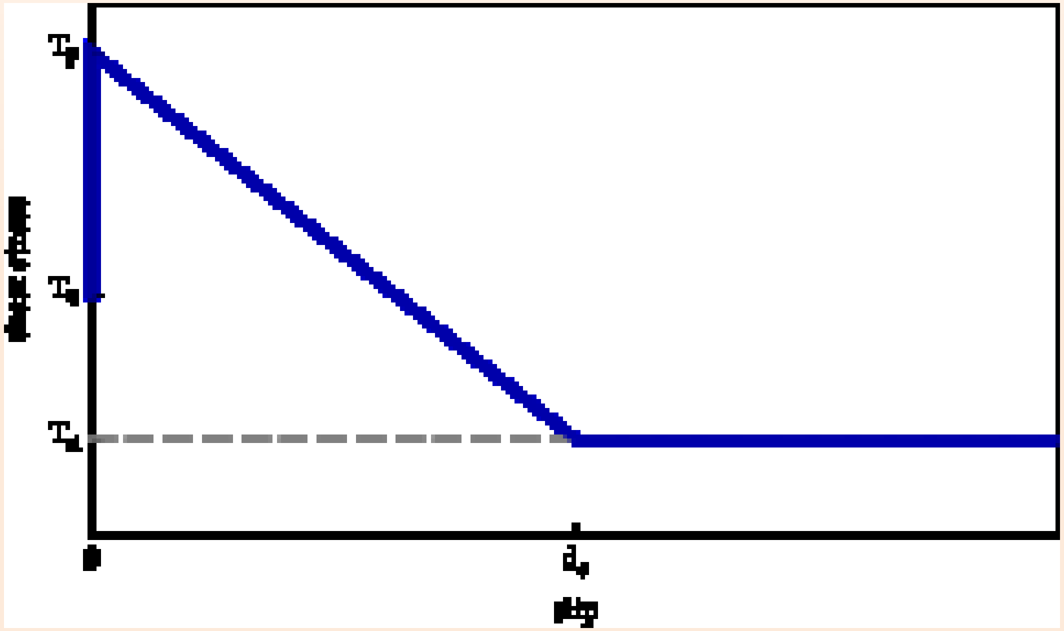
Discretization:

h=200m and dt=0.01s, h=60m and dt=0.011s, h=30m and dt=0.0055

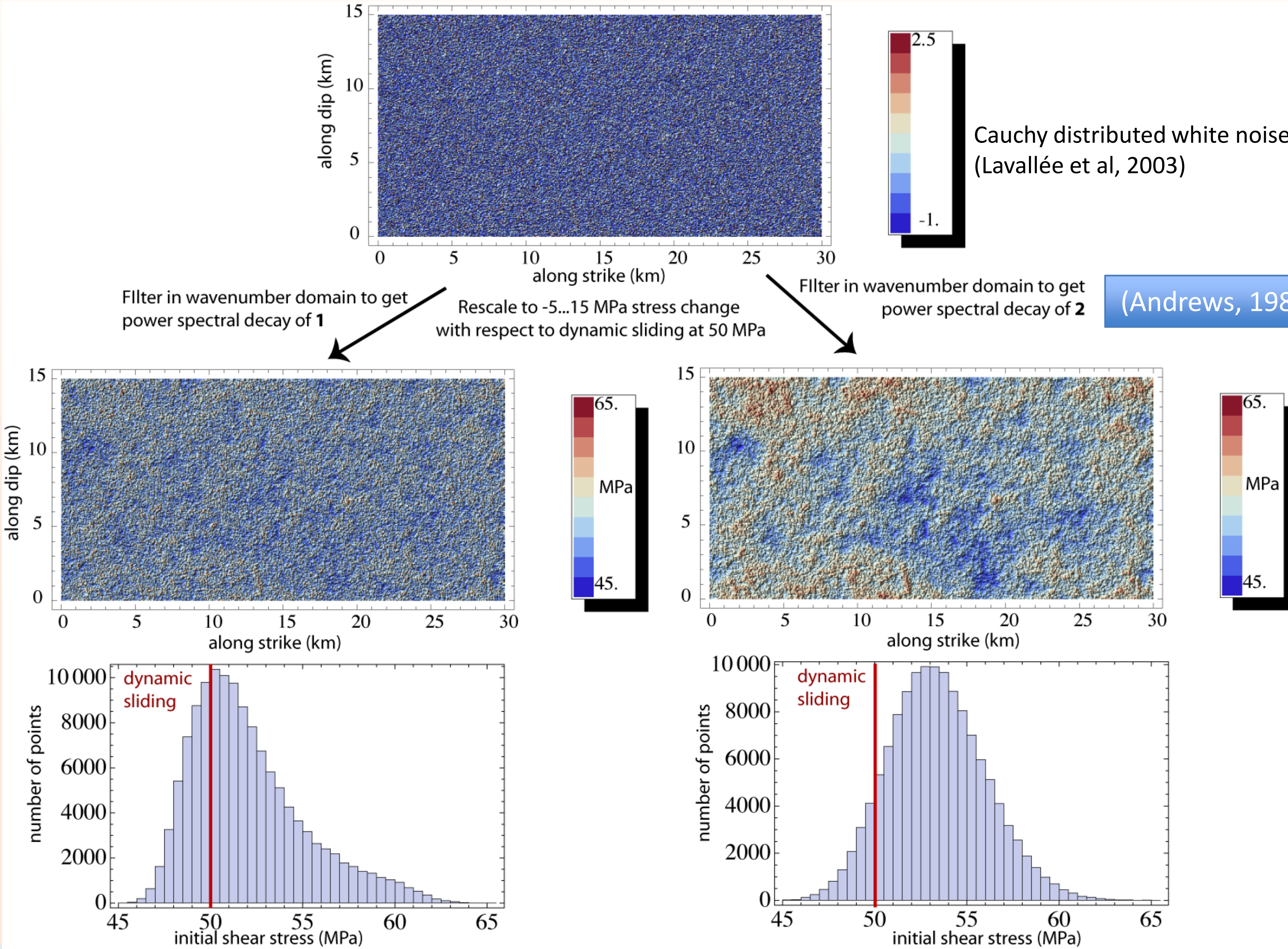
For halfspace 10 grid points per wavelength correspond to **5Hz**

‘Fixed’ ingredients

- Pure strike slip ruptures only
- Unilateral ruptures
- Slip weakening friction
- Normal stress constant
- Dynamic friction coefficient: 0.5 in my calculation, in Dynashake ruptures this coefficient is variable but the initial stress is fixed.

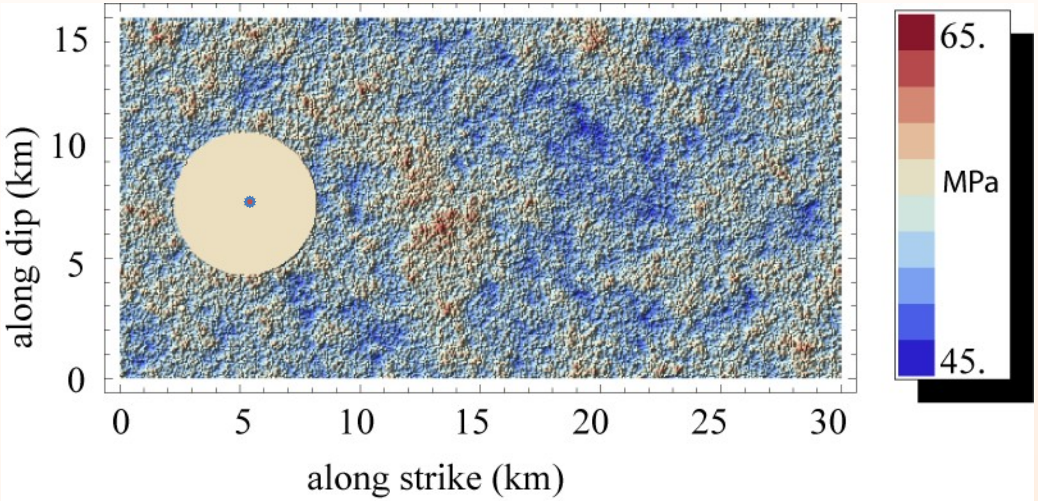


Example: Power-law Initial Shear Stress

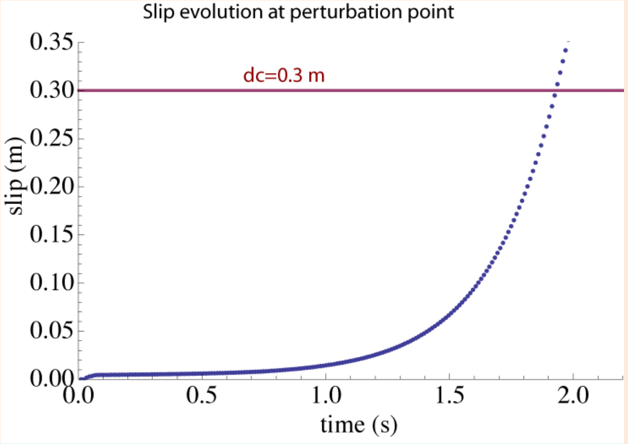


(Andrews, 1980)

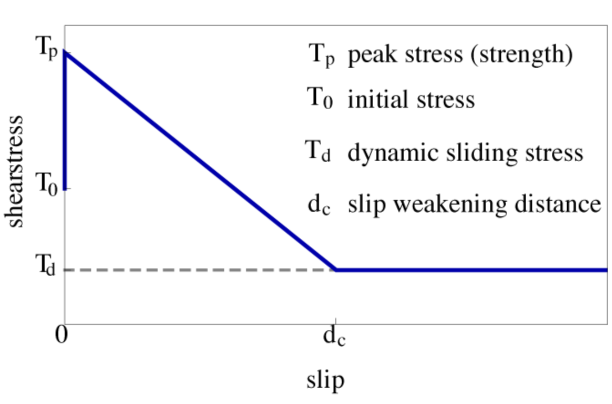
Example: Nucleation



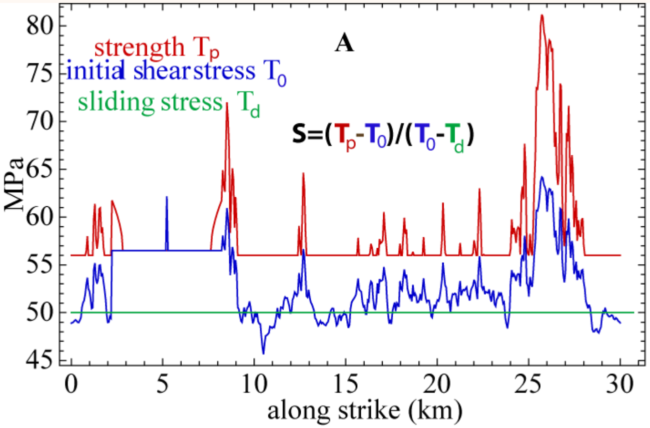
<u>Nucleation</u> by setting a circular region at the strength level and add a small perturbation above the strength in the center. Yields slow nucleation. Motivated by Campillo et al. (2001)



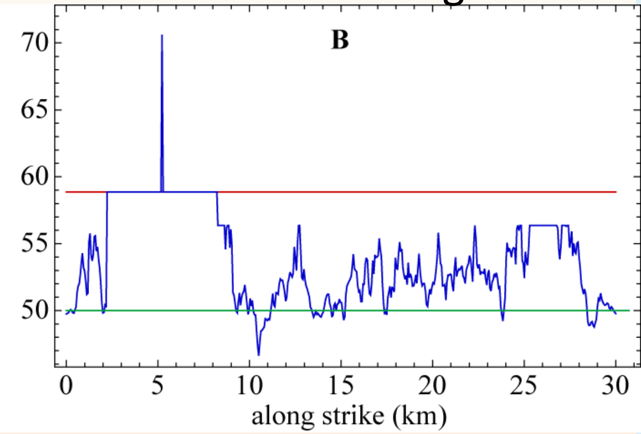
Example: Strength



constant S



constant strength

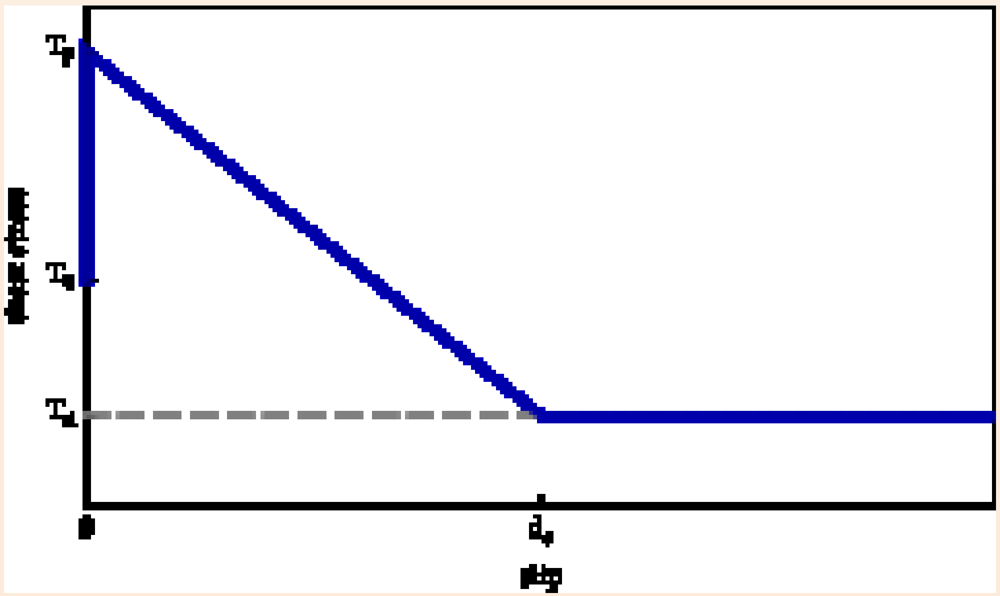


$$S = \frac{T_p - T_0}{T_0 - T_d}$$

- A: Use a constant S-factor to compute distribution of strength on fault. Subshear conditions are for S>1.19 (Dunham, 2007). Strength drops smaller than 6 MPa are not permitted to avoid triggering. In other words we want causal rupture times.
- B: Use constant strength. No strength excess smaller than 2.5 MPa. Note that there are local regions that have S<1.19

Example: dc

- Use constant dc=0.3m (136)
- Use a constant fracture energy and constant S. In this case dc is anti-correlated with strength. Large strength gives small dc. (6)
- Use constant weakening slope in slip weakening law and constant S. In this case dc is correlated with strength (large strength gives large dc). (6)
- Use dc that is correlated with strength and has dc increasing with distance (6)



Initial Models

<u>Stress Drop</u>: Using Andrews (1980) from kinematic slip map (van Karman autocorrelation, Cauchy amplitudes) to stress drop
Power law stress with Cauchy amplitudes
Slip matching technique (Dalguer et al., 2008)

<u>Strength Excess:</u> Use constant S (sub- and supershear)
Use constant strength
Slip matching technique (Dalguer et al., 2008)

<u>Dc:</u> Constant Dc
Constant slip weakening slope
Constant fracture energy
Increasing with distance
1 layer of large Dc at top of fault

<u>Nucleation:</u> Slow using single point perturbation
Forced by *setting initial stress inside circle above strength*
Forced by setting initial stress inside circle above strength + lower DC

Approach

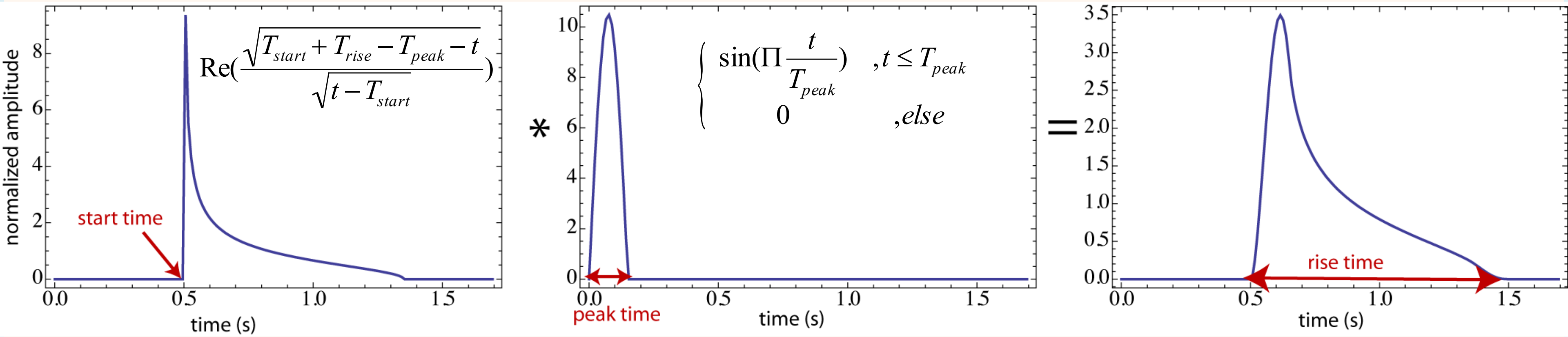
Compute many spontaneous dynamic ruptures for a variety of initial models

For each rupture compute fault maps of source parameters (slip, peak-sliprate, rupture velocity, rise time,…)

For each rupture and for each parameter pair (for example slip and rise time) compute spatial correlation

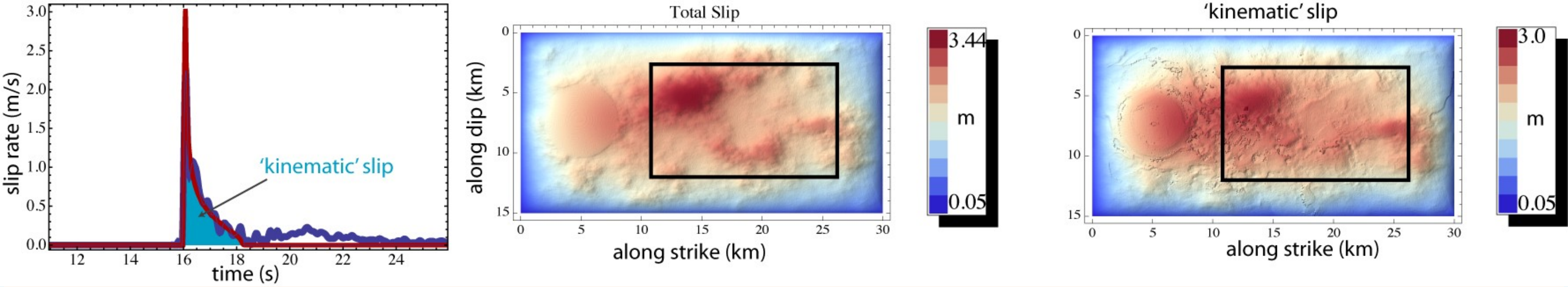
Find parameter pairs that show the least variability in correlation given the uncertainties in the input parameters.

Slip rate function



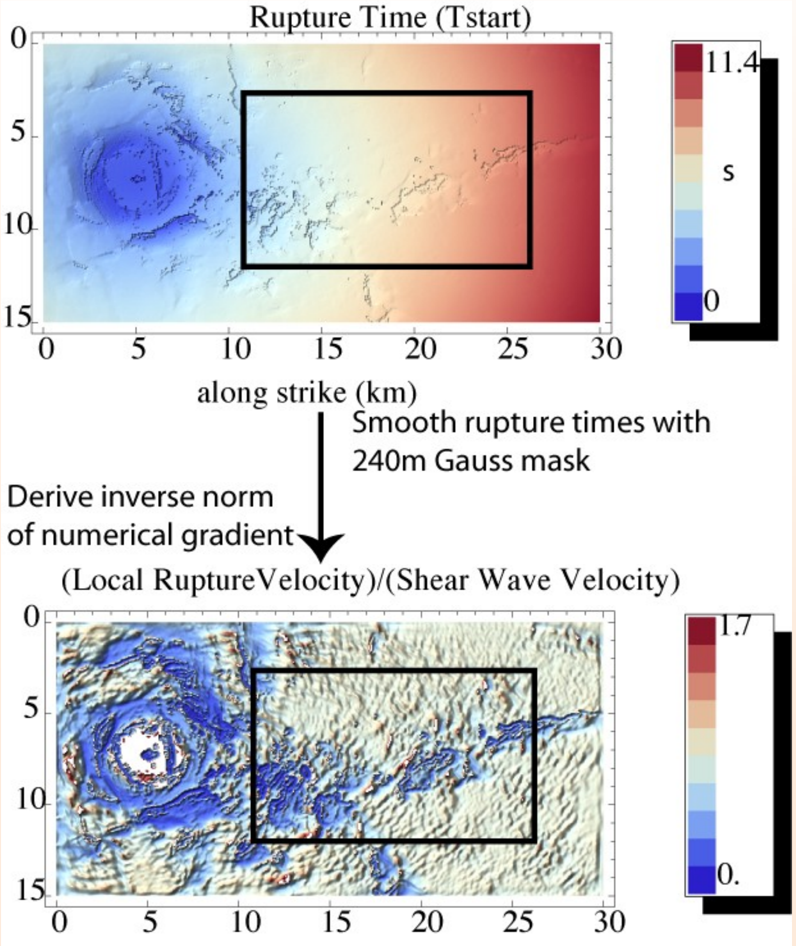
Convolution of sliprate function proposed by Nielsen and Madariaga (2003) with halfsine

Fit slip rate function



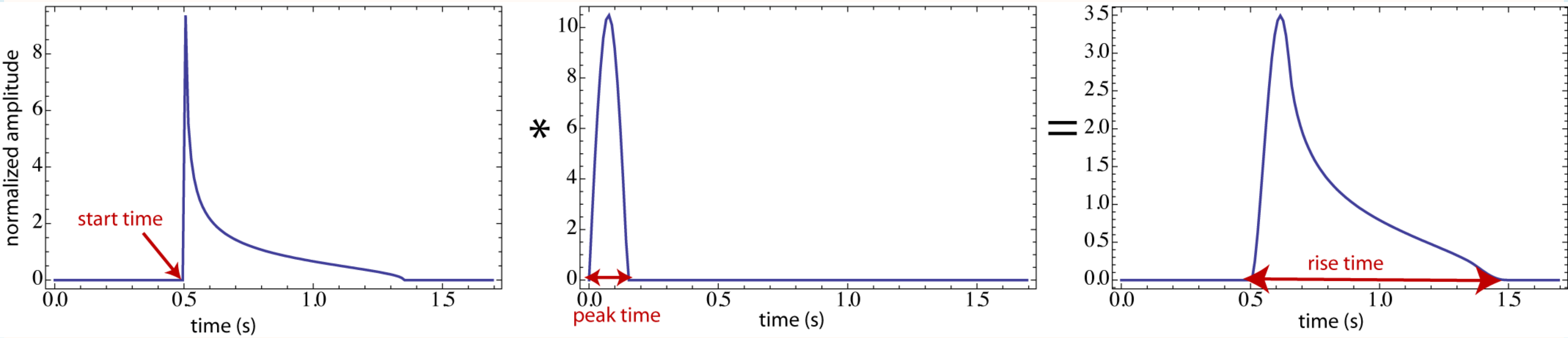
- Fit new slip rate function to 5 Hz filtered computed slip rate functions
- Due to lack of healing there is sliding at low velocities that accumulates significant slip. Thus use slip consistent with the kinematic slip rate function, that is, slip under fitted portion of curve
- Rectangle shows area that will be analyzed for correlations. Exclude boundaries and nucleation zone

Rupture Velocity



Rupture velocity computed as inverse norm of the numerical gradient of rupture times. The gradient is smoothed with a 240m Gauss mask before it is inverted

Computed Parameters



Total slip
Kinematic slip
Peak slip rate
Rupture time t_0
Rise time T
Peak time
Local rupture velocity divided by local shear wave velocity
Average rupture velocity (secant velocity)

Approach

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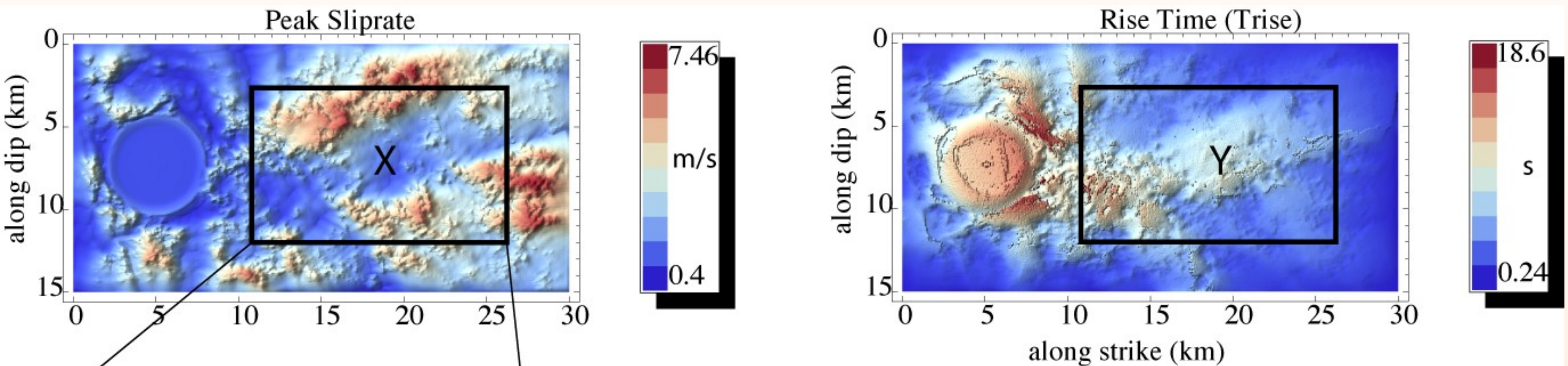
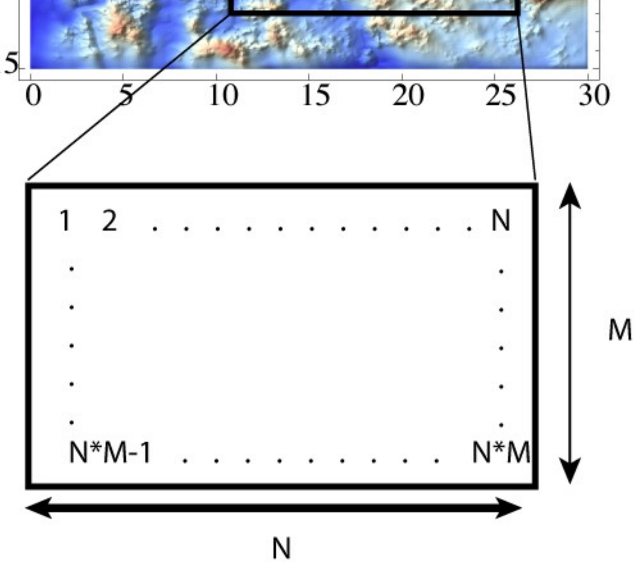
Find parameter pairs that show the least variability in correlation given the uncertainties in the input parameters.

Correlations





$$correlation = \sum_{i=1}^{1=N*M} \frac{(x_i - \bar{x})(y_i - \bar{y})}{(NM-1)std(x)std(y)}$$

$$\bar{x} = \frac{1}{NM}\sum_{i=1}^{NM} x_i \qquad std(x) = \sqrt{\frac{\sum_{i=1}^{NM}(x_i - \bar{x})^2}{NM-1}}$$

For each of N ruptures and each parameter pair compute the point to point correlation. This yields N point to point correlations for each parameter pair.

Approach

Compute many spontaneous dynamic ruptures for a variety of initial models

For each rupture compute fault maps of source parameters (slip, peak-sliprate, rupture velocity, rise time,…)

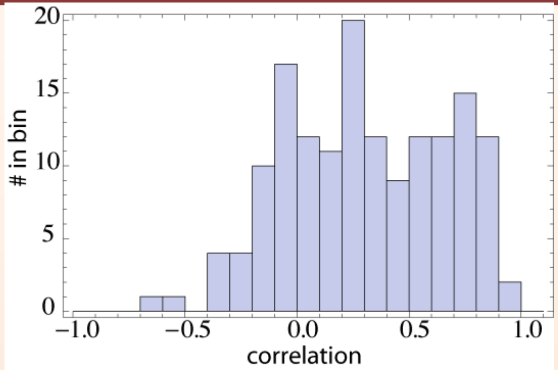
For each rupture and for each parameter pair (for example slip and rise time) compute spatial correlation

Find parameter pairs that show the least variability in correlation given the uncertainties in the input parameters.

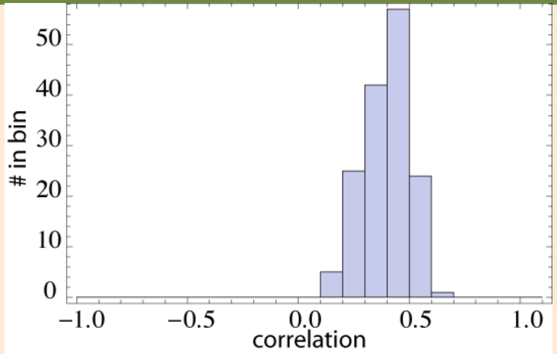
What is a useful parameter pair?

We want to find the parameter pairs that have a correlation that shows the least variability given the epistemic and aleatoric uncertainty in our initial models.

Not useful because: large variability



Useful because: small variability

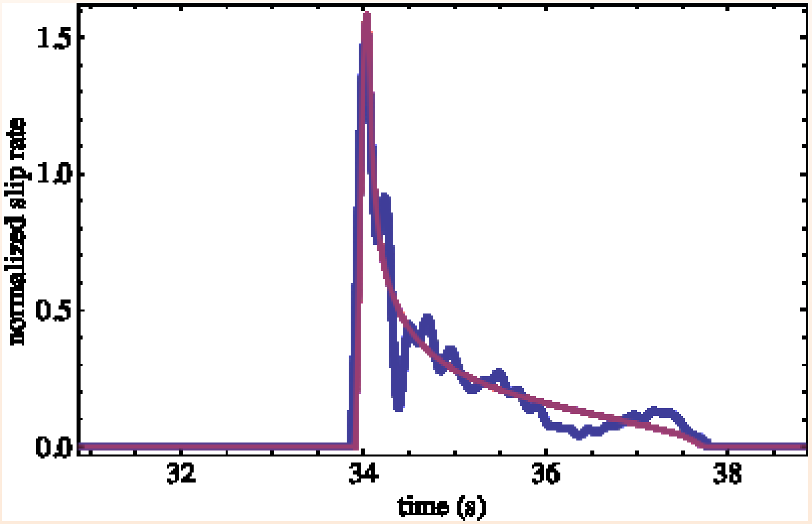


Wish list for modelers

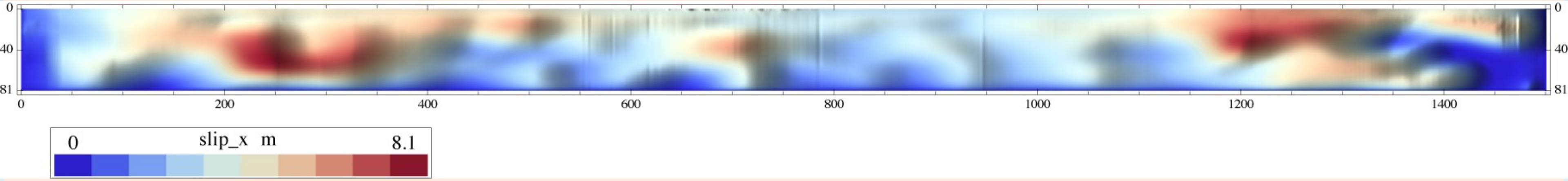
- Full spatio-temporal slip rate history on fault, dx and dt
- Piece of code that explains how to read the slip rate file(s)
- Input: Stress, Strength, Dc (or other friction law parameter), Geometry
- Local shear v

Example: Dynashake model

Provided: slip rate snapshots on fault and code to read it

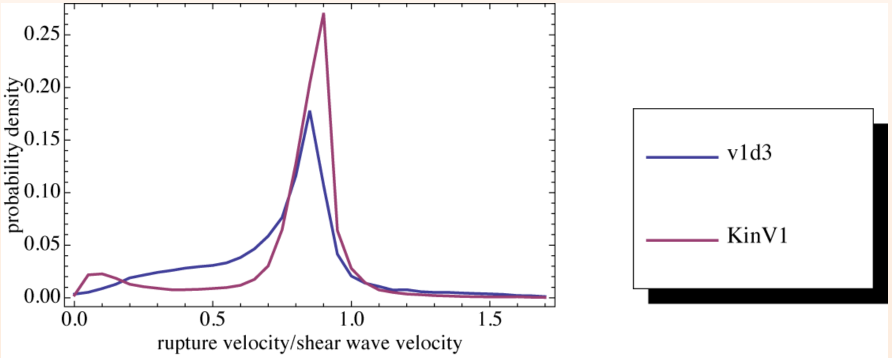


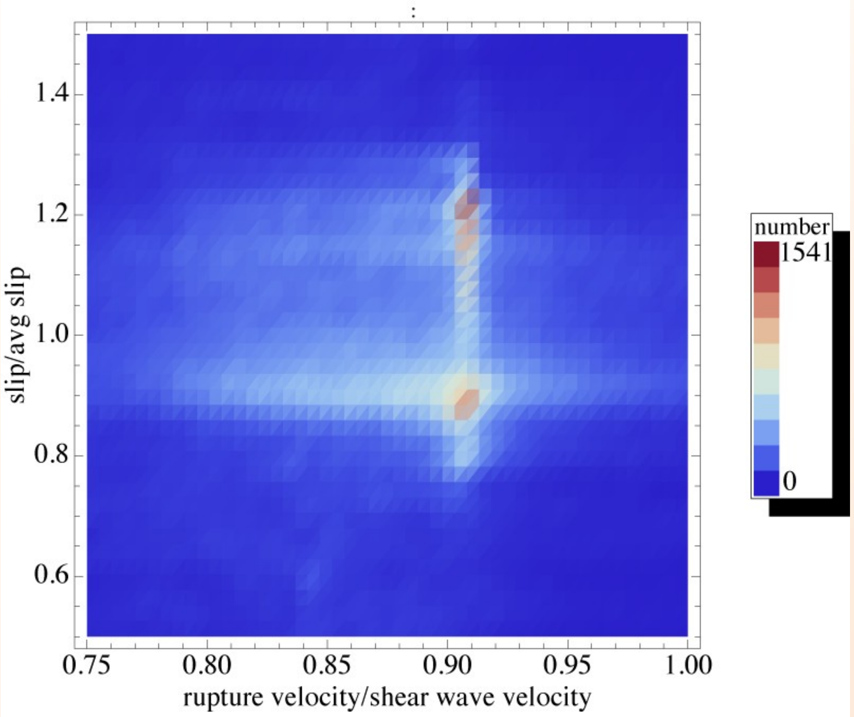
Fit slip rate function, extract kinematic parameter



Example: Dynashake Model

Provided: Local shear wave velocity on fault

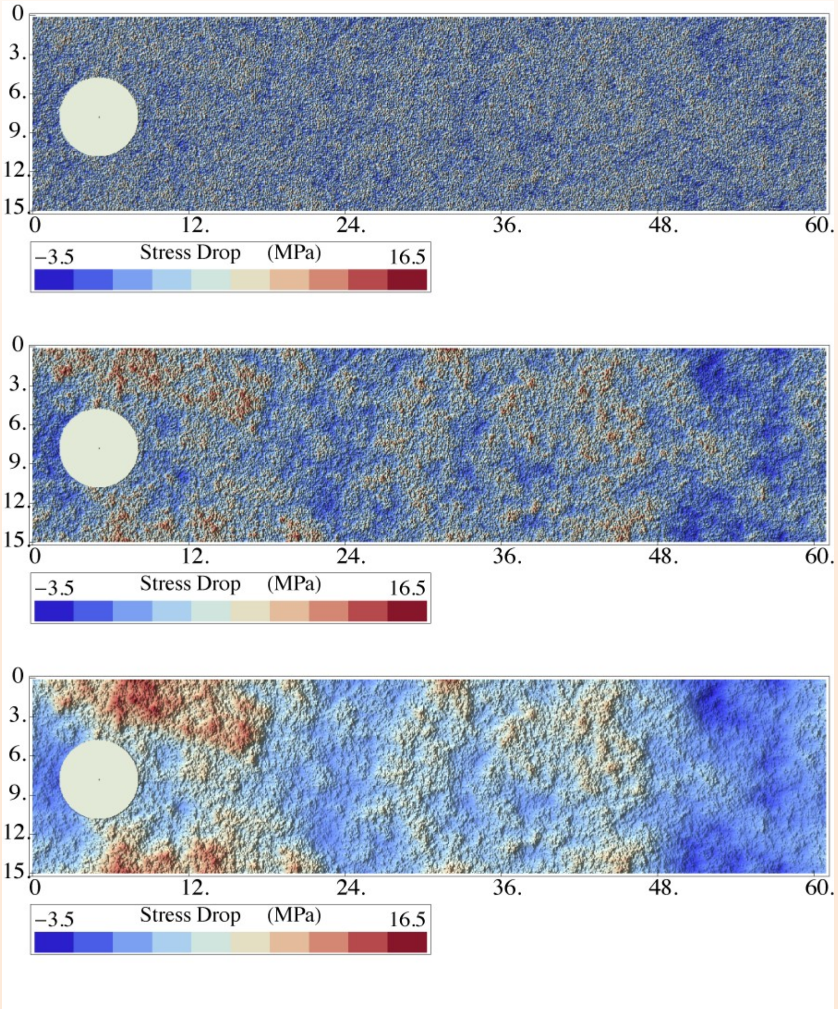




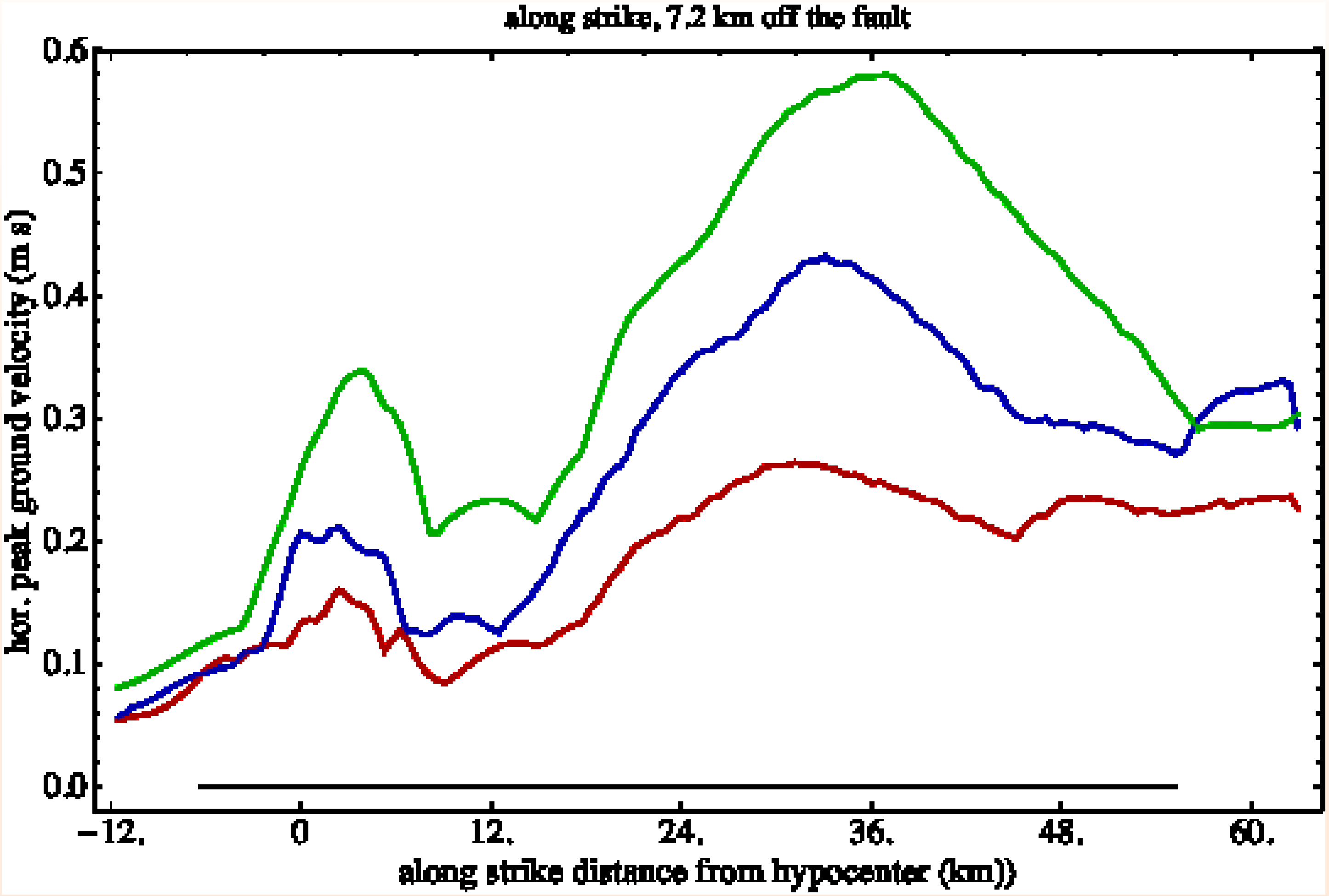
Enables comparison and joint analysis of rupture velocity for ruptures in different velocity structures

Autocorrelation and Ground Motion

Compare ground motion for stress models with power spectral decays of 1,2 and 3 and identical amplitude distributions

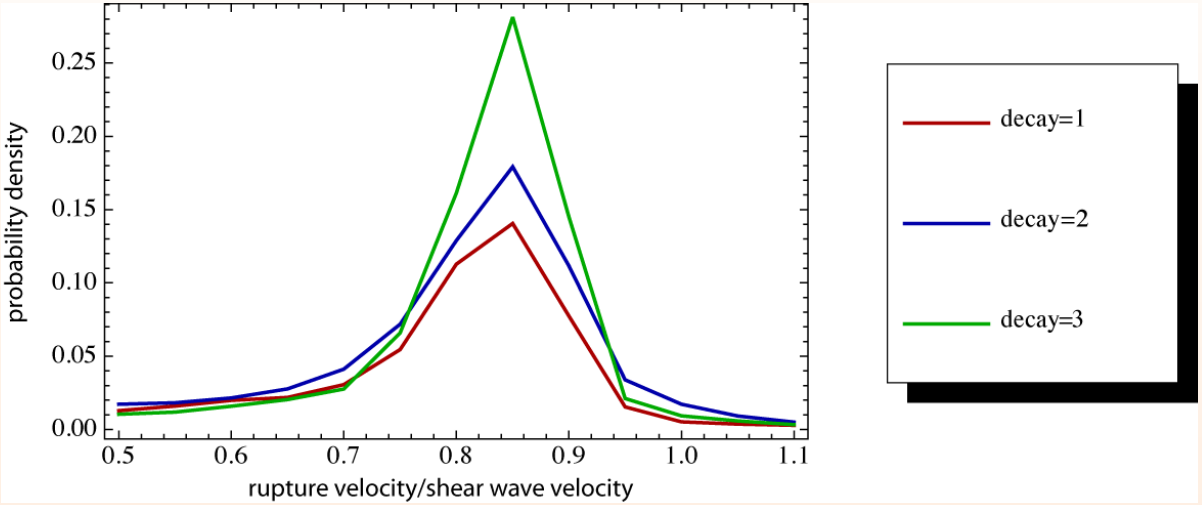


Autocorrelation and ground motion



Huge difference in ground motion

More about smoothness

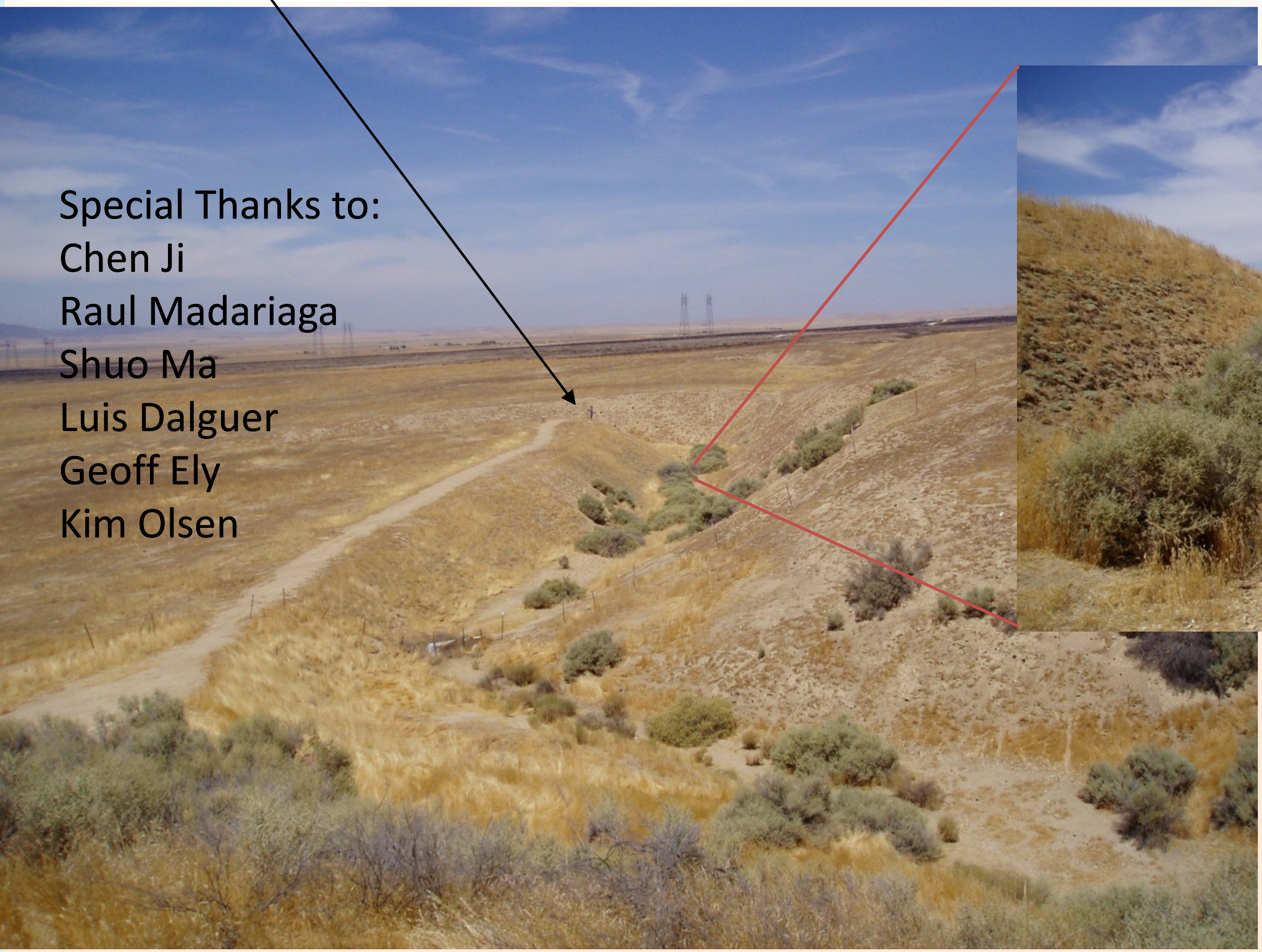


Rupture gets faster with increasing smoothness
Rise times get shorter with increasing smoothness
Larger maximum slip for smoother rupture
average slip (hence magnitude) about the same for all three ruptures

Smoothness of rupture strongly affects dynamics of rupture

Thank You!

Raul Madariaga for scale



Special Thanks to:
Chen Ji
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Shuo Ma
Luis Dalguer
Geoff Ely
Kim Olsen

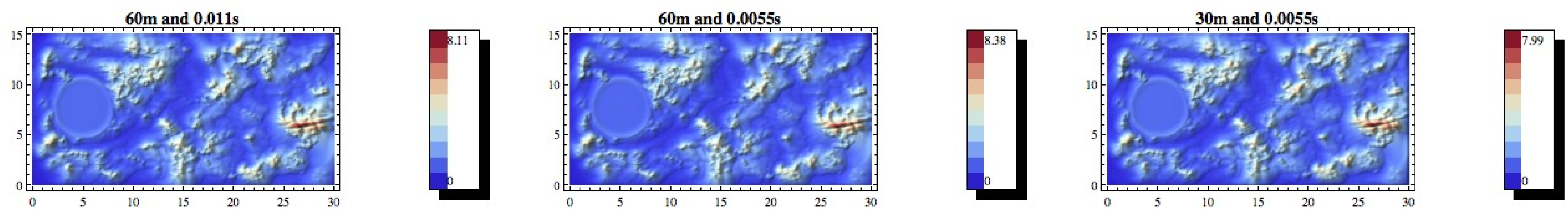
Ralph Archuleta and Raul Madariaga

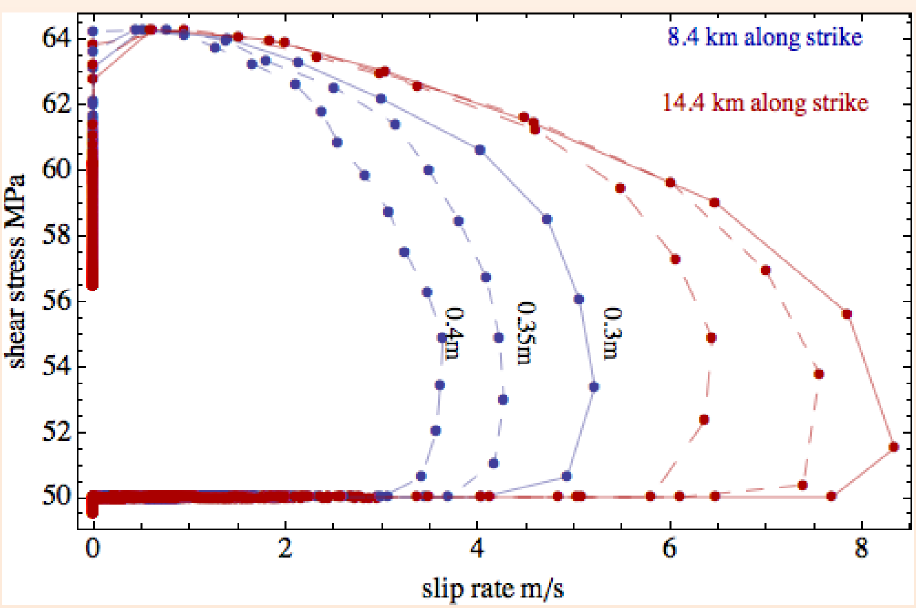
Summer 2006, Wallace Creek

Stability

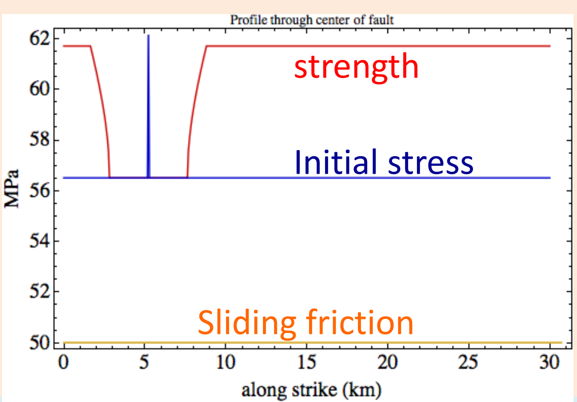
Compute same model with smaller time stepping and smaller grid spacing (interpolated):

Peak Slip Rate (m/s)

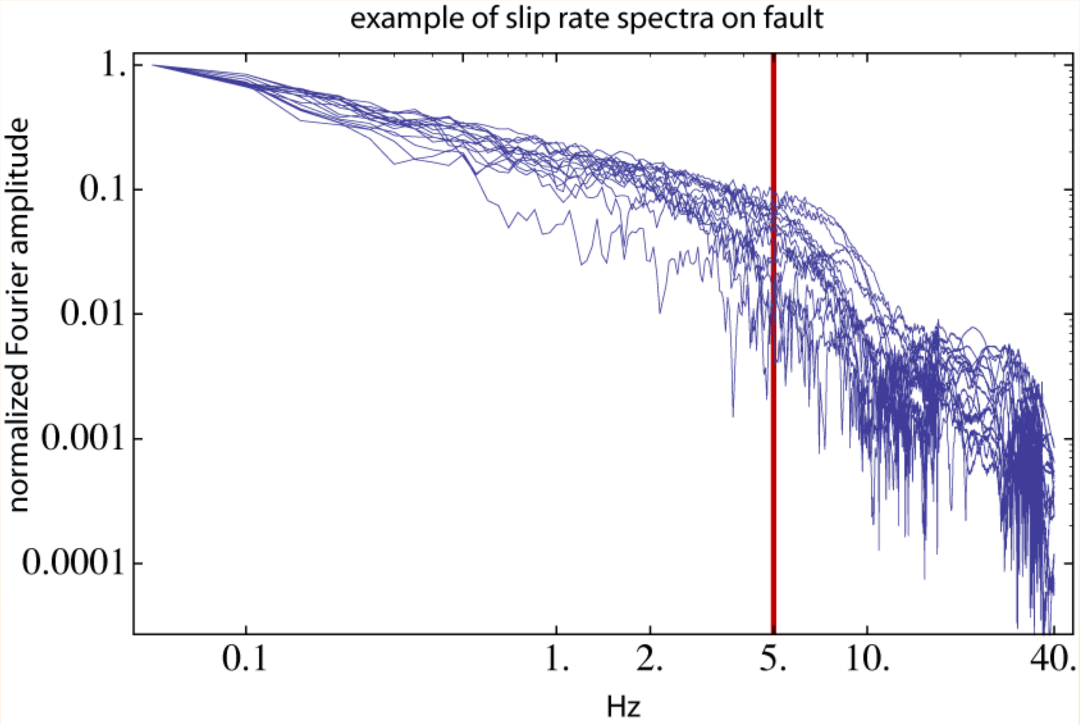




Homogeneous stress and strength model with S=1.2. Plot shows influence of dc (different curve style) and of distance along strike (different colors)

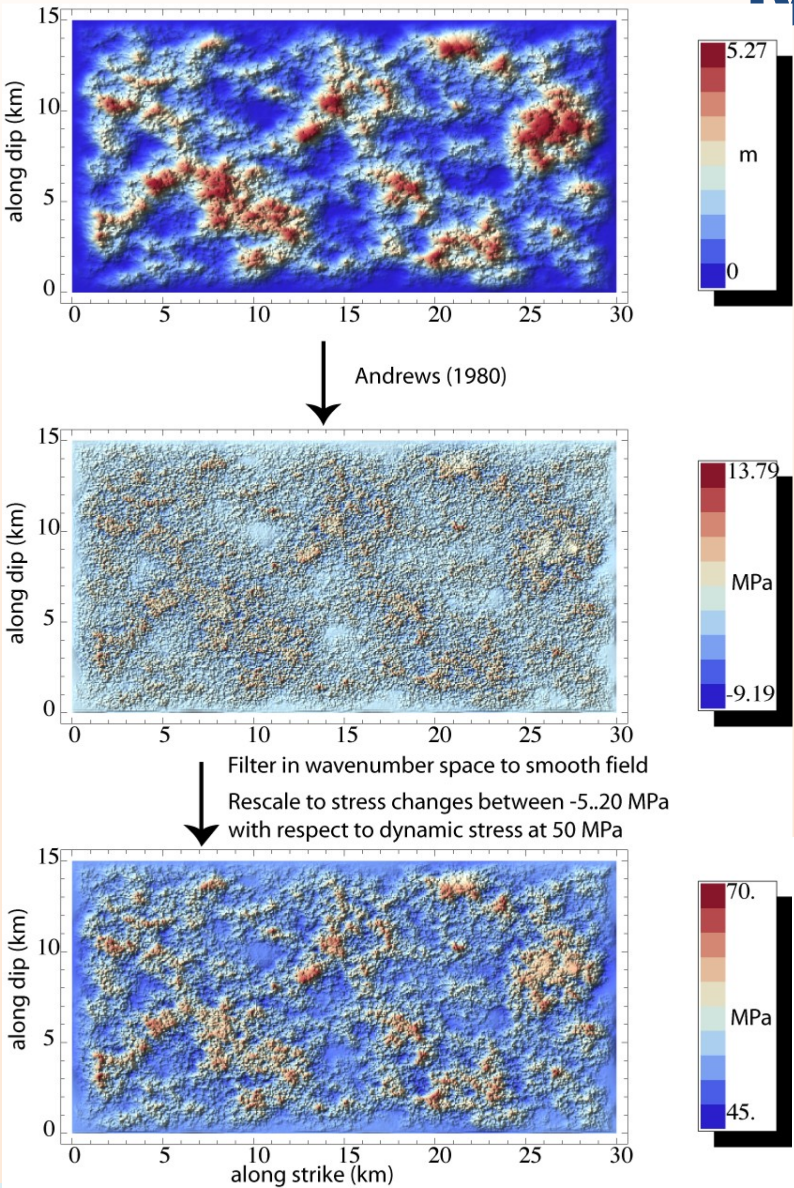


Frequency



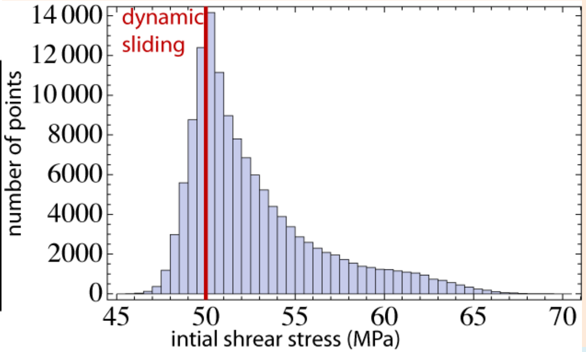
Lowpass filter slip rates to 5 Hz (10 wavelength in halfspace model) in the following analysis

Initial Shear Stress Based on Slip Maps



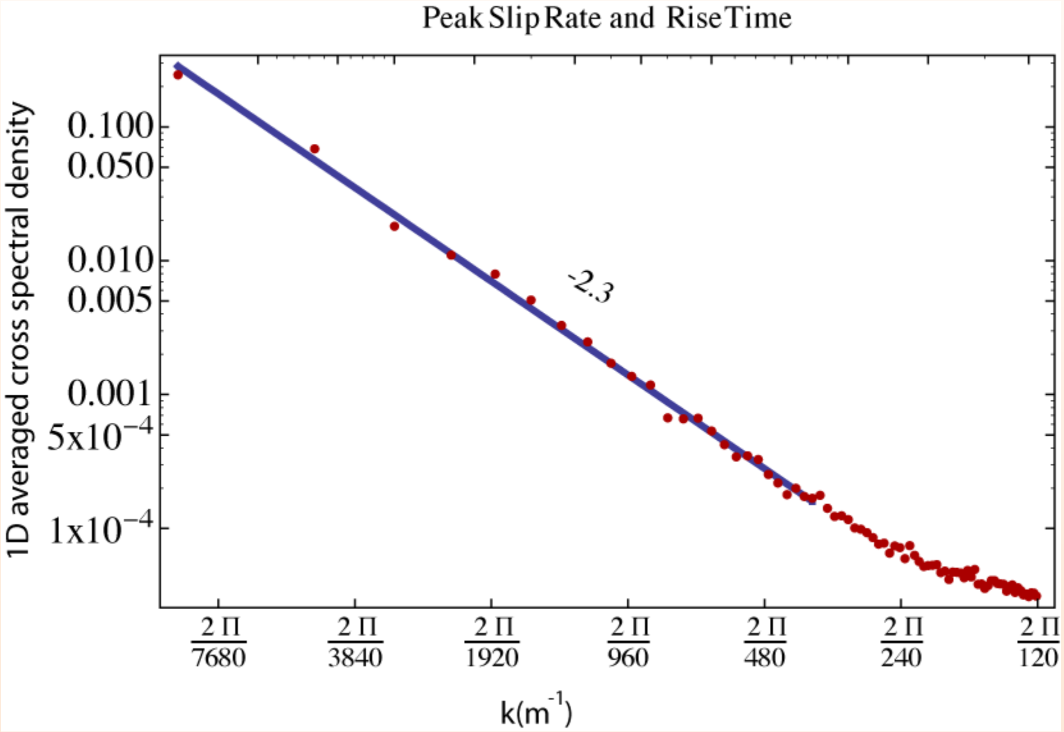
Slip map created using Liu et al (2006)

Static stress drop computed using Andrews (1980)



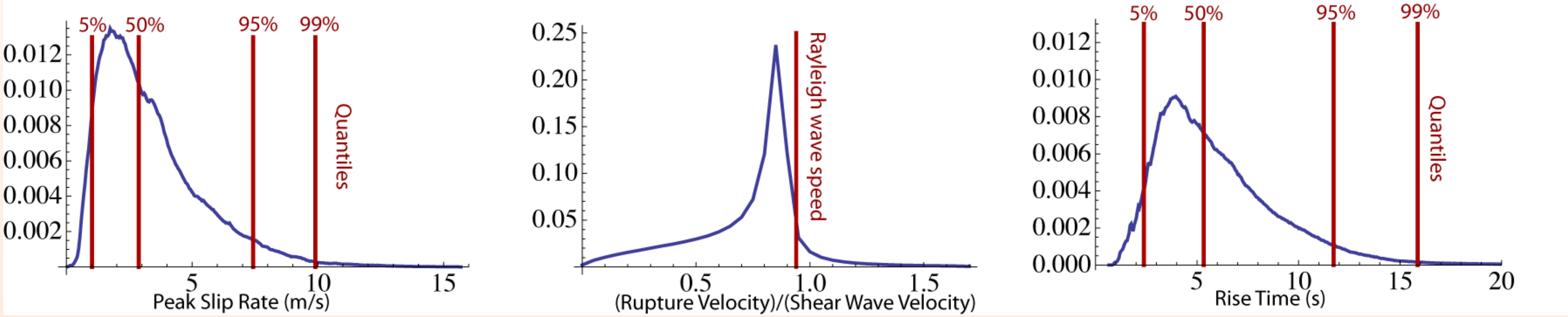
Initial shear stress field after smoothing and rescaling the amplitudes

Scale dependency



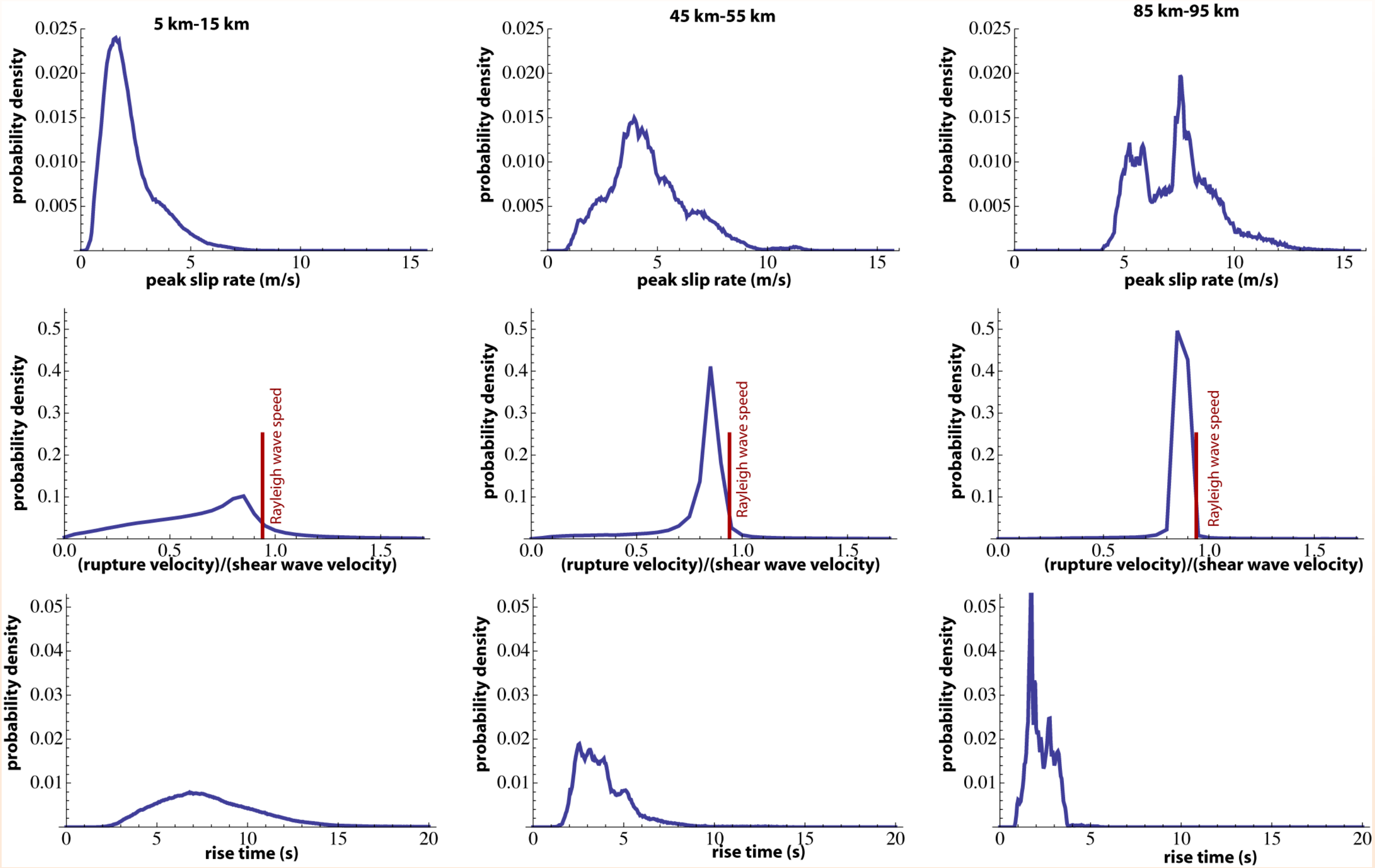
Correlation also at larger Scales

Amplitude distributions



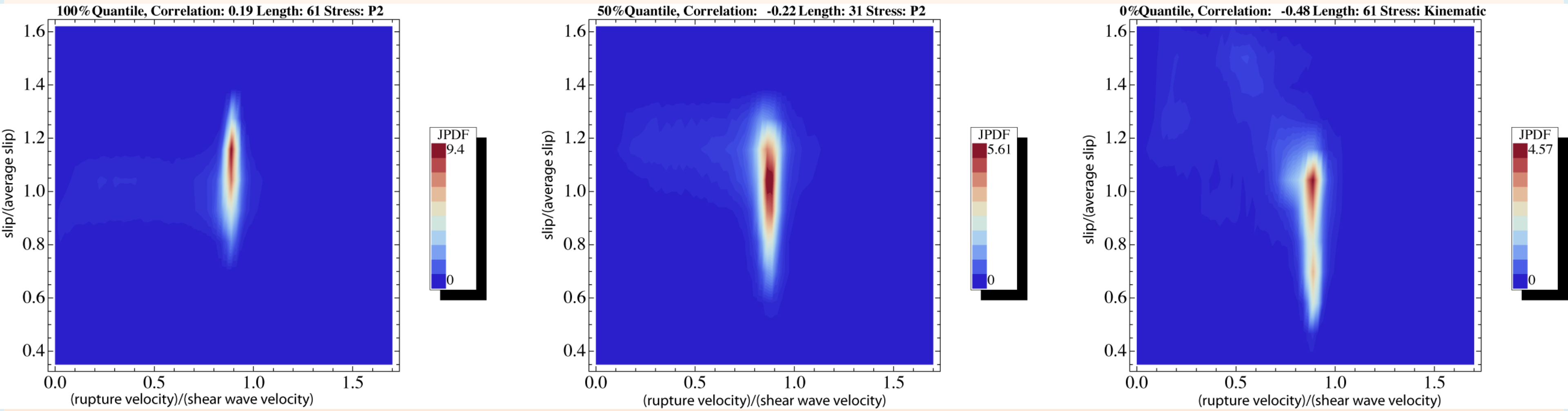
Using 154 models, resulting in about 8.4 Mio points total

Distance dependency



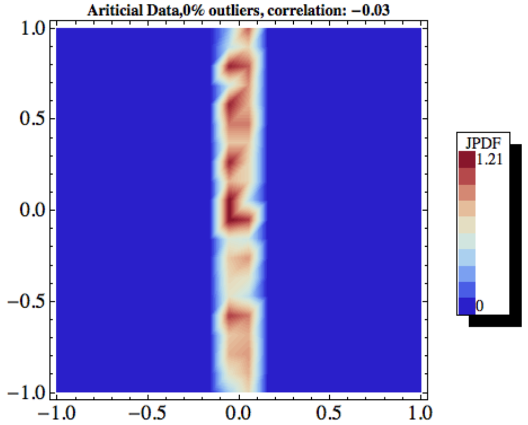
PDFs are distance dependent! Larger peak slip rates; more stabilized rupture speed; and shorter rise times with increasing distance from nucleation zone

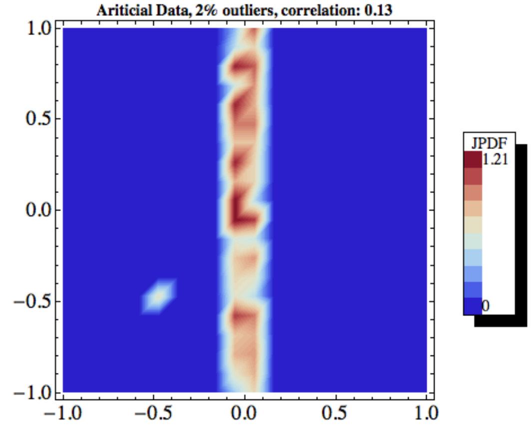
Another View: Joint PDFs



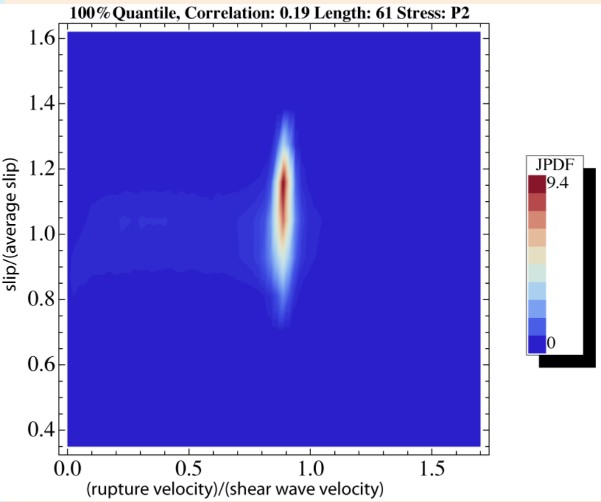
$$p(x,y) = \frac{n_{x,y}}{N \cdot M \cdot (dx \cdot dy)}$$

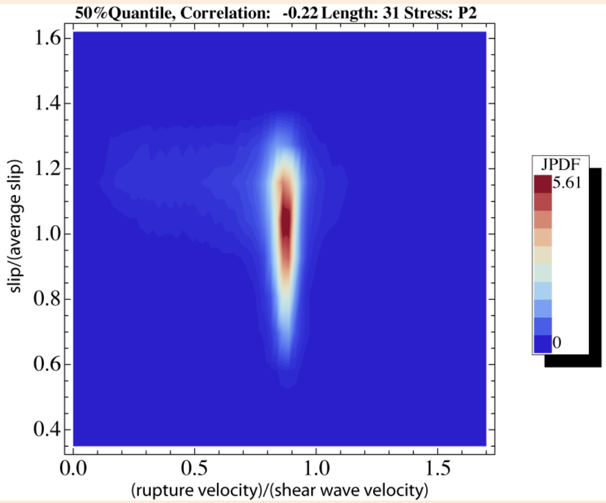
Correlation and 'Outlier'

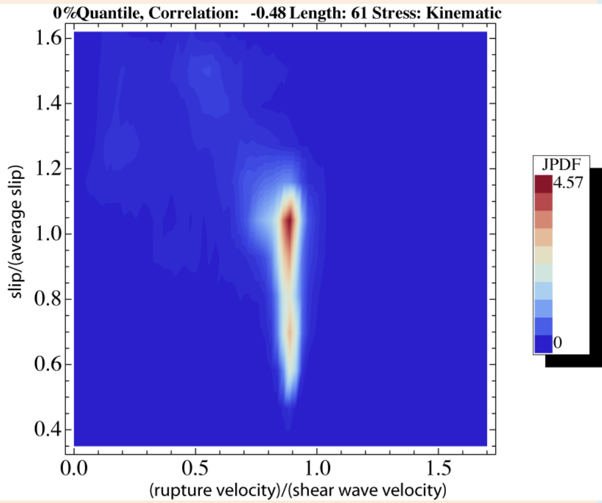




By introducing 2% outlier correlation goes from -0.03 to 0.13!



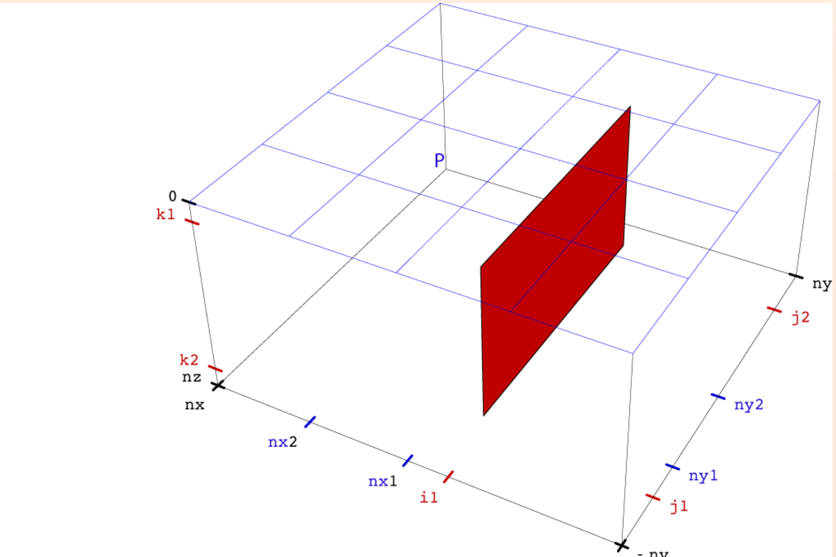




Dynamic Modeling

- Explicit finite element with staggered grid and one point integration
- Slip weakening friction
- Bilinear regular elements

(Shuo Ma, 2006. Dissertation UCSB)



rupture plane and rupture plane indices i1, j1, j2, k1, k2
2D mesh partition and indices nx1, nx2, ny1, ny2 for processor p

- Parallelized using MPI to be able to run many models
- Use 2D processor layout