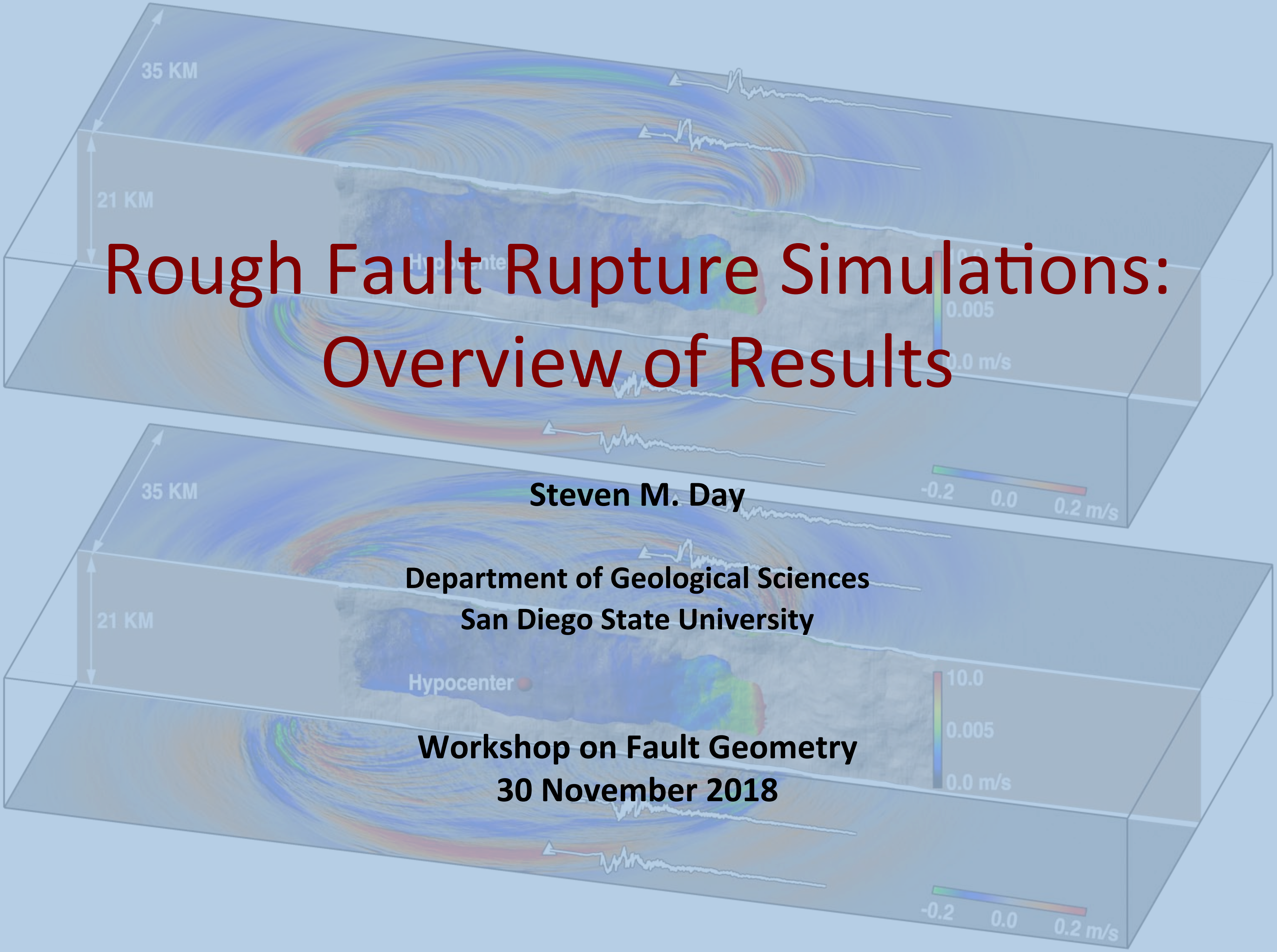

Rough Fault Rupture Simulations: Overview of Results

Steven M. Day

Department of Geological Sciences
San Diego State University

Workshop on Fault Geometry
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DEFINITIONS

- By fault roughness, I mean components of morphology best treated as random field
    - Departures from planarity widely distributed in location and scale
    - Sufficiently complex to merit (require) stochastic representation

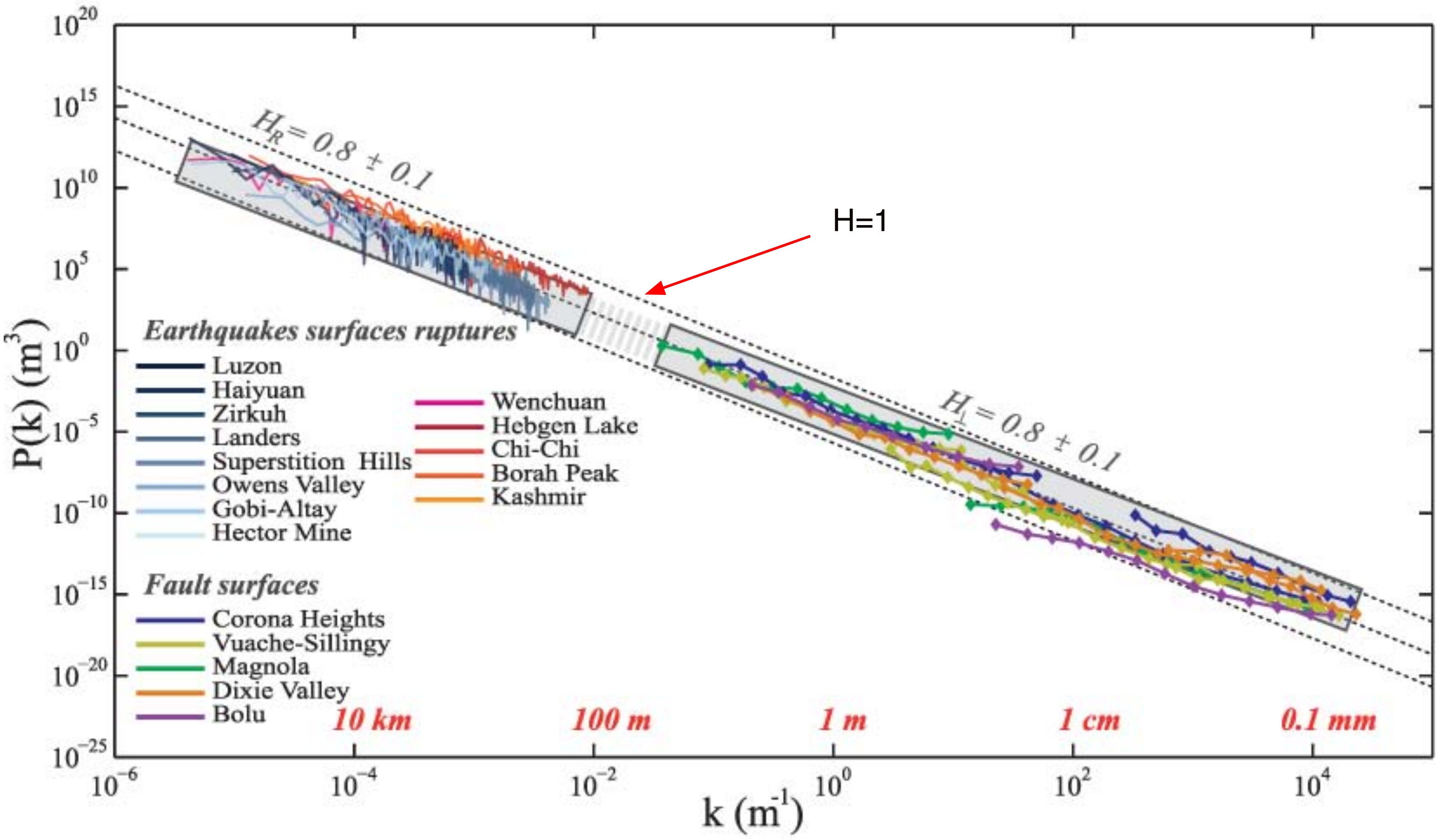
- What I mean by rupture simulation
    - Dynamic models, 2D or 3D, with slip- or rate-weakened friction
    - Neglect geometrical nonlinearity (i.e., minimum roughness scale >> slip)
    - Un-branched fault surfaces
    - Power-law roughness

Most examples (not quite all) have additional simplifications:

Highly simplified initial stress state (stress tensor depth dependent only)
Simple elastic or (pressure-dependent) elastoplastic continuum
Self-similar roughness spectrum (Hurst exponent H=1)

Fault surface roughness

Spectral Model for Fault Geometry
(Candela et al., 2013)



- Self-similar over ~10 orders of magnitude
- Modeled as random field, Hurst exponent ~1
- Max Frequency > 10 Hz → Min scale ~100 m

SUMMARY

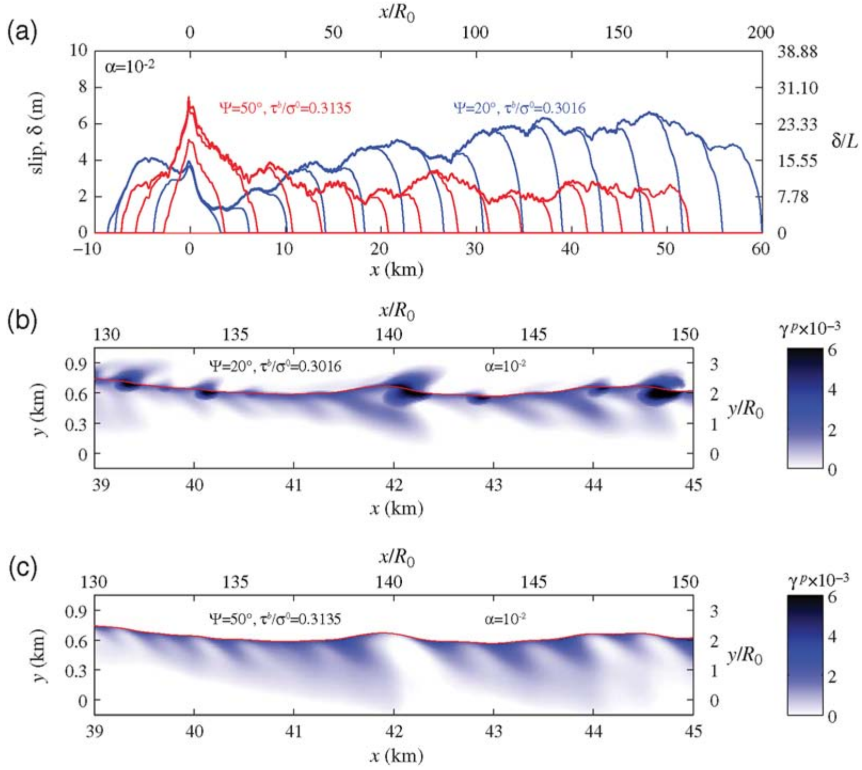
Roughness:

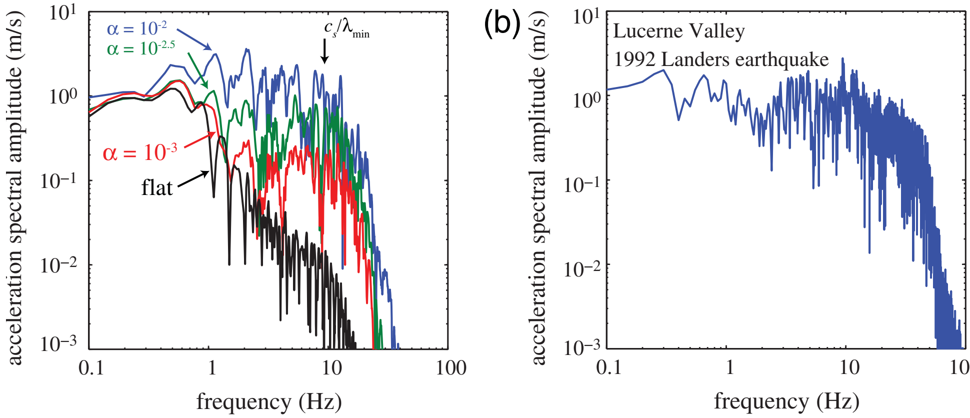
- Contributes to high-frequency GM (may be the principal source)
- Contributes to GM statistical variability
- Modifies kinematic parameter correlations
- <u>Nucleates</u> transient, buried supershear bursts
- <u>Suppresses</u> sustained, shallow SS events
- Creates frequency-dependent radiation patterns
- Produces power-law co-seismic surface slip fluctuations

GM = “Ground Motion”
SS = “Supershear”

High-Frequency GM: 2D Models

- Fault roughness has essential role in HF ground motion excitation
- At least qualitatively consistent with observed features of ruptures and ground acceleration

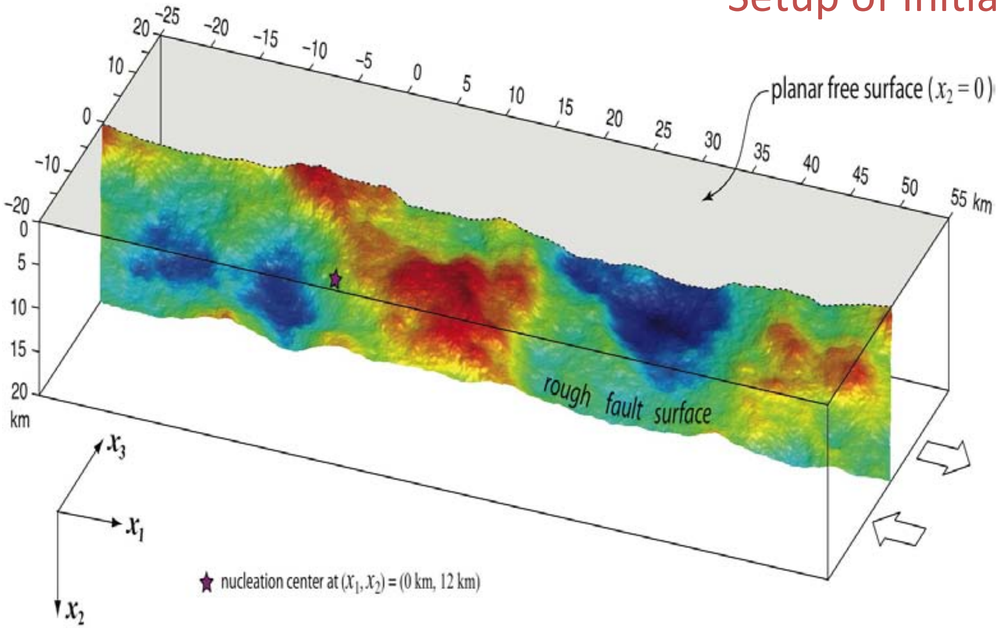




(*Dunham et al., 2011*)

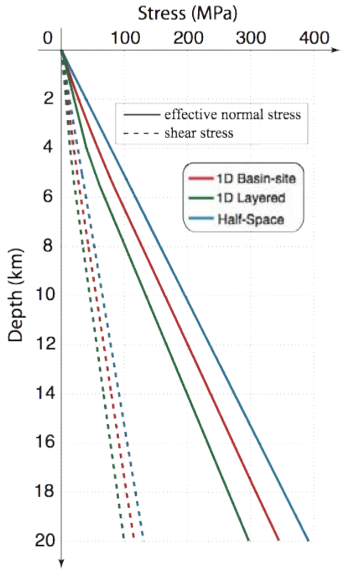
High-Frequency GM: 3D Models

Setup of Initial State



- Self-similar (80 m to 80 km scale range)
- RMS-offset ÷ scale-length = 0.005
- Rate-state with dynamic weakening
- Top 1 km velocity strengthening

- Computational cell 20 m



Lithostatic stress

$$\sigma^0_{11} = \sigma^0_{22} = \sigma^0_{33}$$
$$= -\int (\rho - \rho_w) g dx_2$$

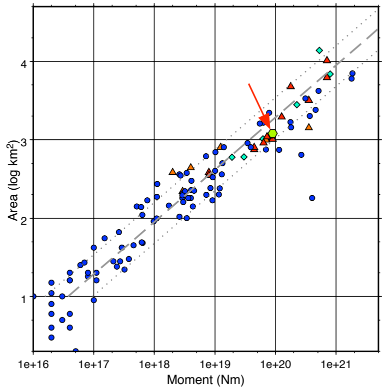
$$|\sigma^0_{31}/\sigma^0_{22}| = const.$$

- Shear/normal stress ratio is minimum permitting system-wide rupture

- Resulting rupture is M 7.25

- Fits empirical magnitude-area relationship

Area vs Moment
Interplate strike-slip case
(Leonard 2010)



Shi and Day, 2013

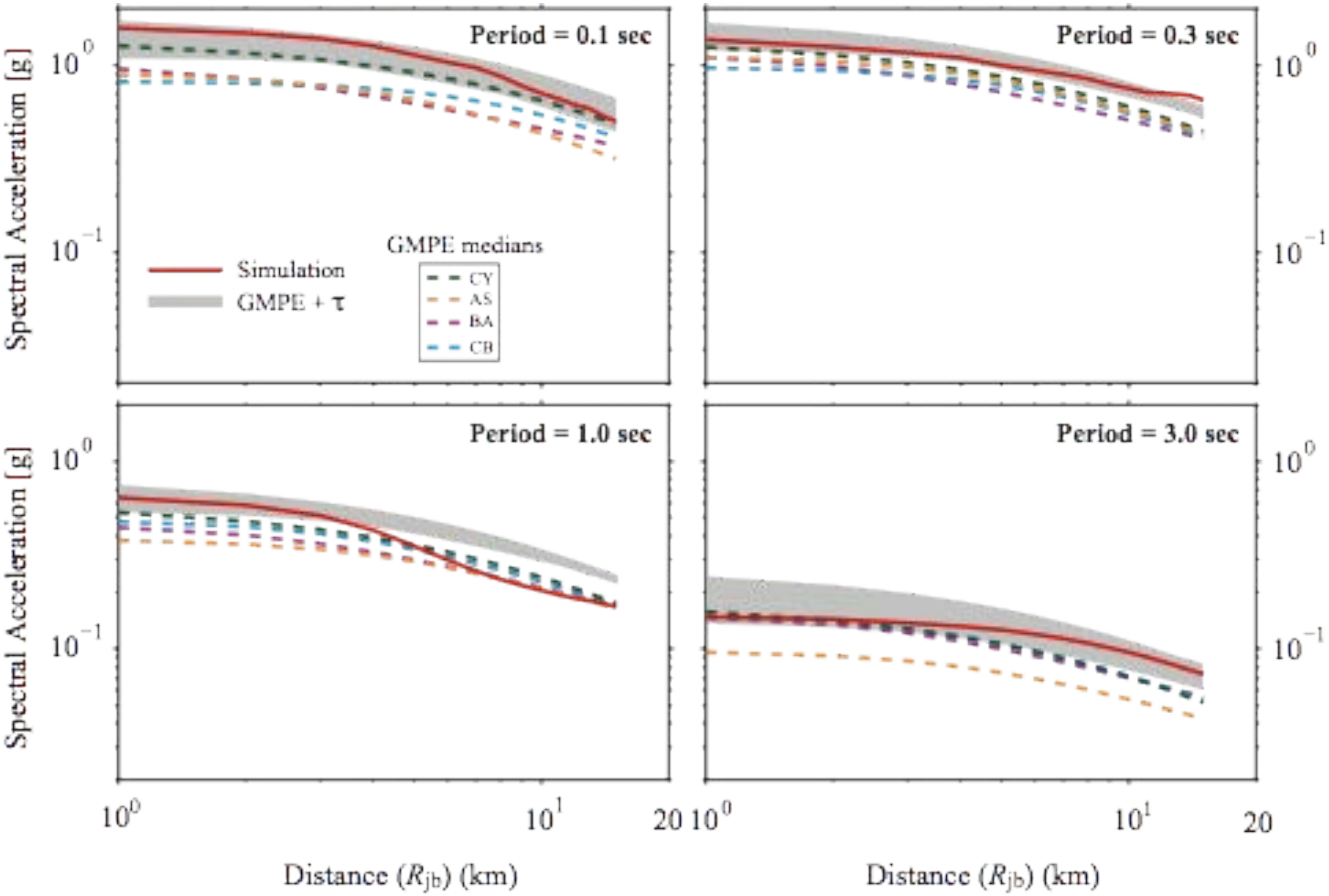
High-Frequency Ground Motion: GMPE Comparison)

Site-Corrected GMRotD50 Response Spectra Compared to the Next Generation Attenuation (NGA) Curves

Site Amplification: SH plane-wave response of the generic rock structure representative of western North America rock sites [Boore and Joyner, 1997]

Site Attenuation: $e^{-\pi\kappa f}$ with site anelastic loss exponent (defined by Anderson and Hough [1984]) k = 0.04 sec

Half-space Model



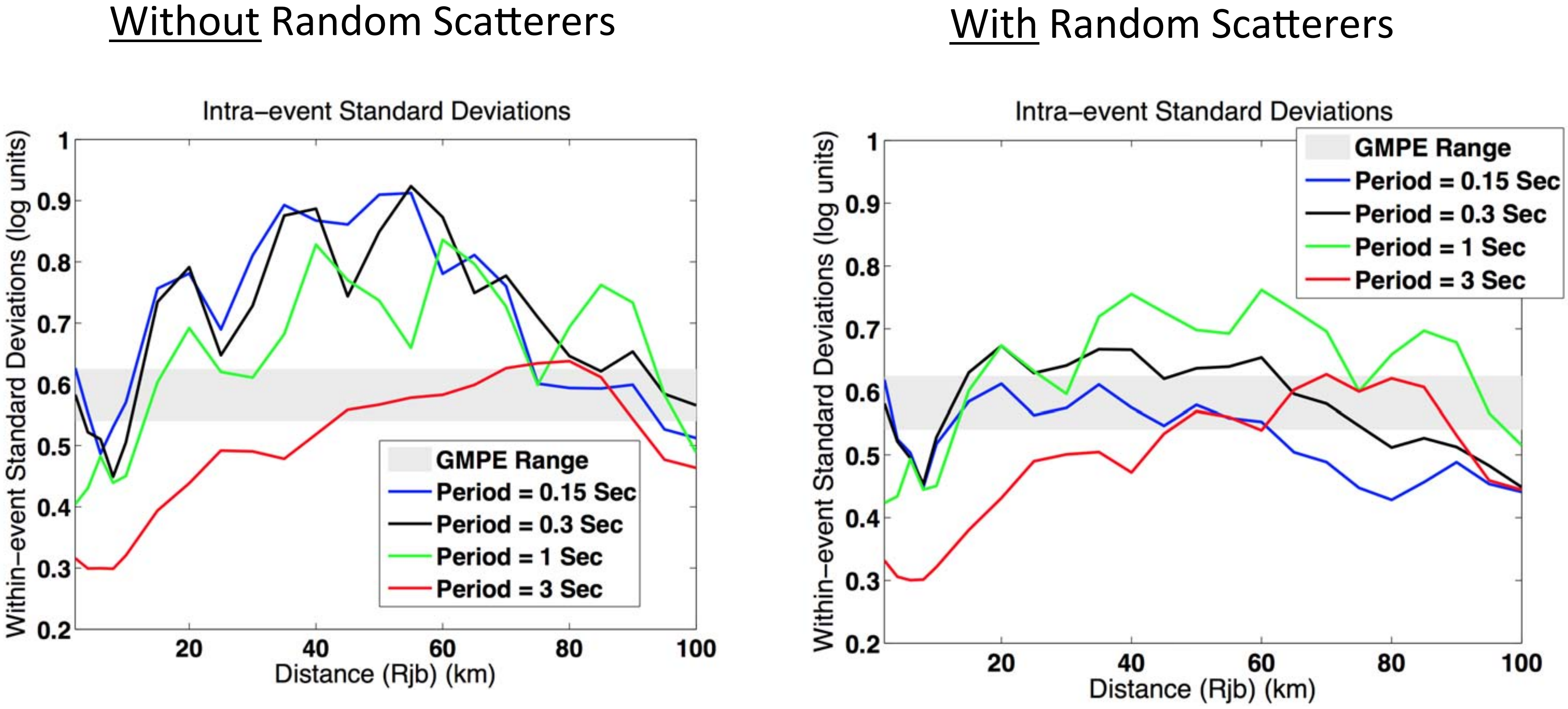
$M_W = 7.23$

CY: Choi and Young (2008)
AS: Abrahamson and Silva (2008)

BA: Boore and Atkinson (2008)
CB: Campbell and Bozorgnia (2008)

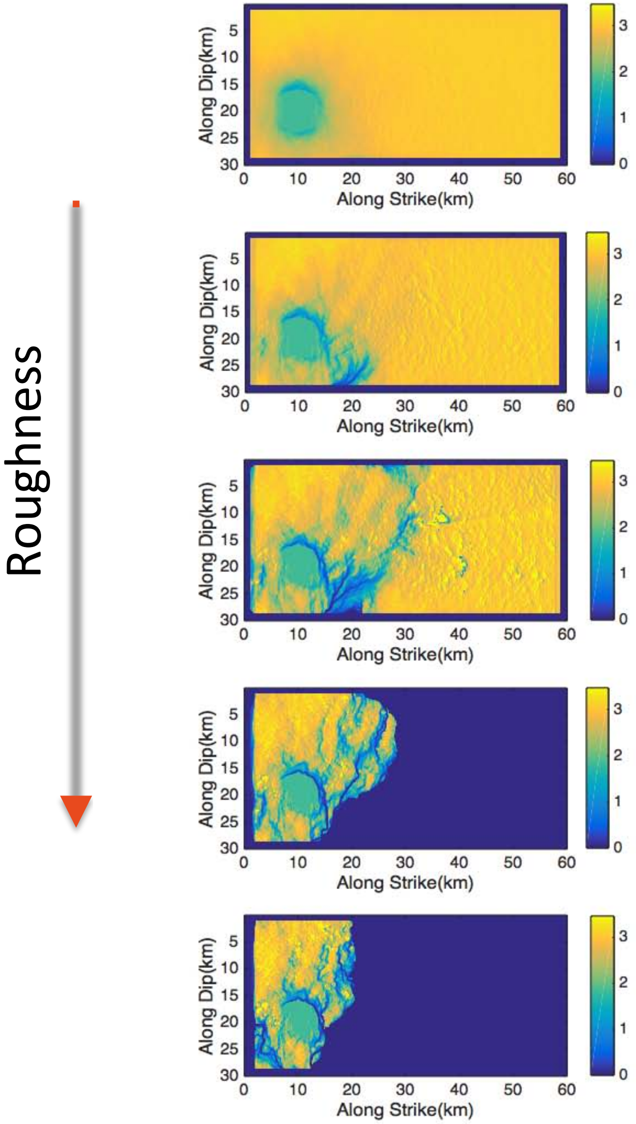
Ground Motion Variability: Within-EQ Sigma

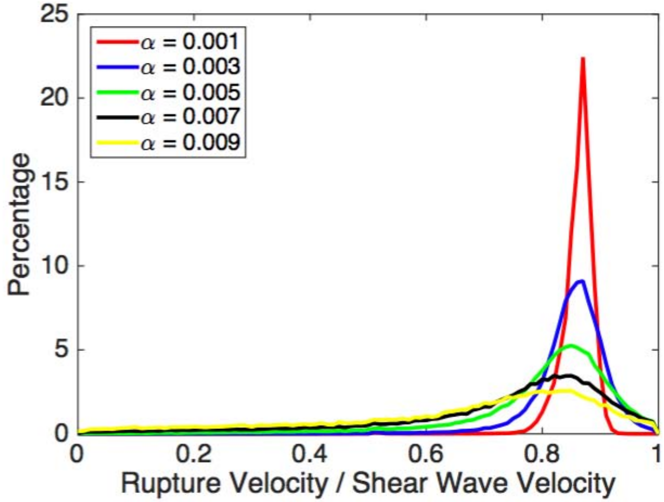
- Roughness is strong source of GM variability (sigma)
- Random-field heterogeneities moderate sigma



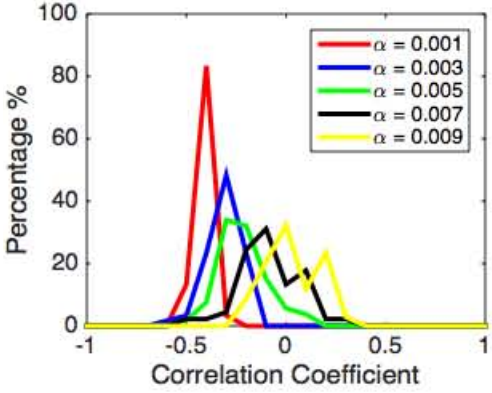
Withers et al. (2015)

Kinematic Parameter Correlations: Rupture Velocity Example





Increased roughness
→increased spread of RV distribution (reduced rupture coherence, diminished directivity)



Increased roughness
→Rise time <u>decorrelates</u> with rupture velocity

Yao, 2017 (SDSU PhD Thesis)

Supershear Rupture

2D simulations (Bruhat et al., 2016):

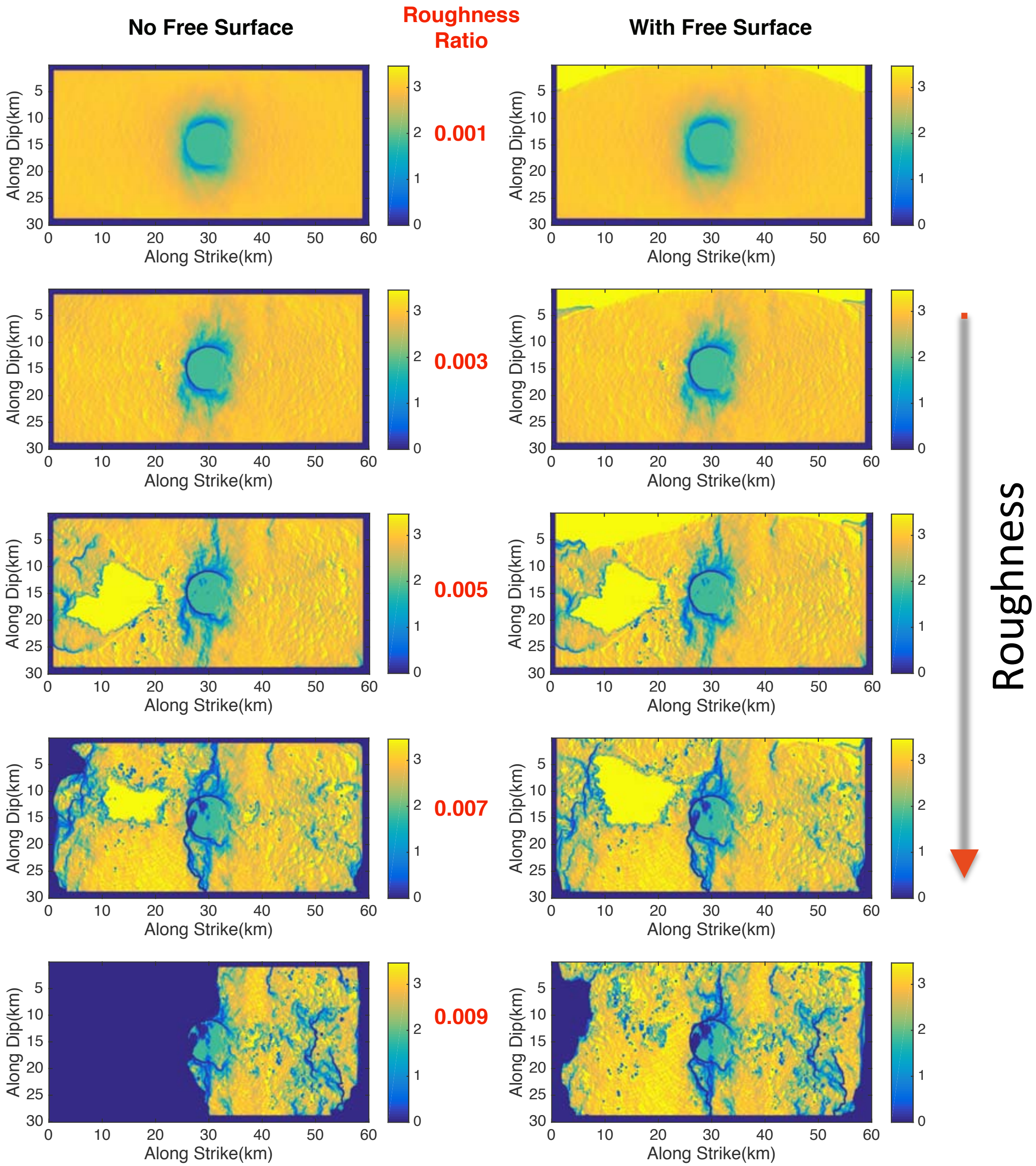
Overall roughness favors *nucleation* of SS transients

Local smoothness favors *sustained* SS rupture

3D (Yao, 2017):

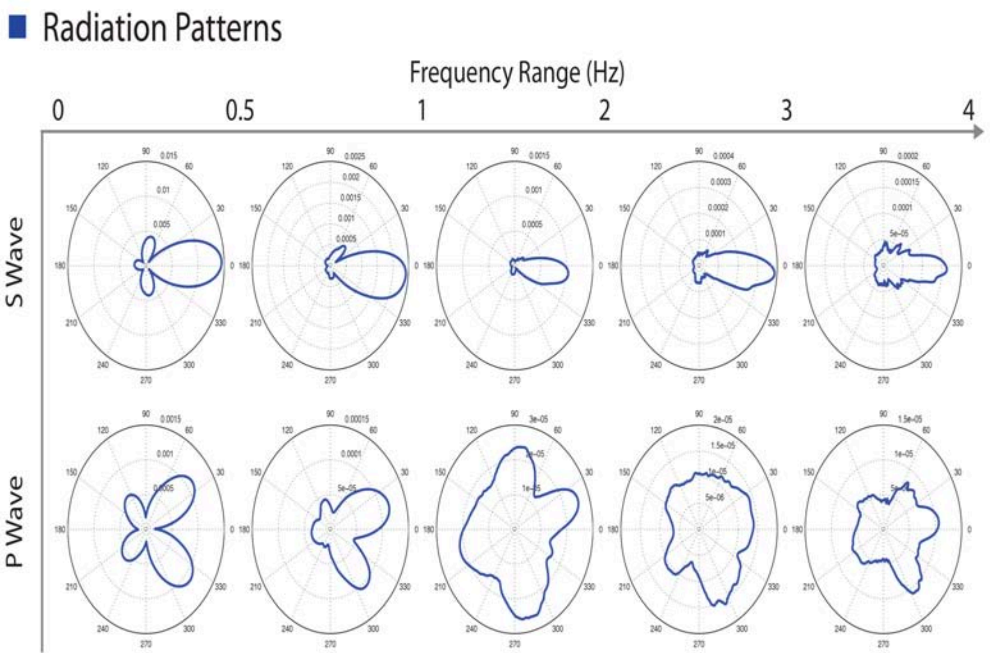
Roughness favors buried SS transients

Smoothness favors shallow, sustained SS ruptures



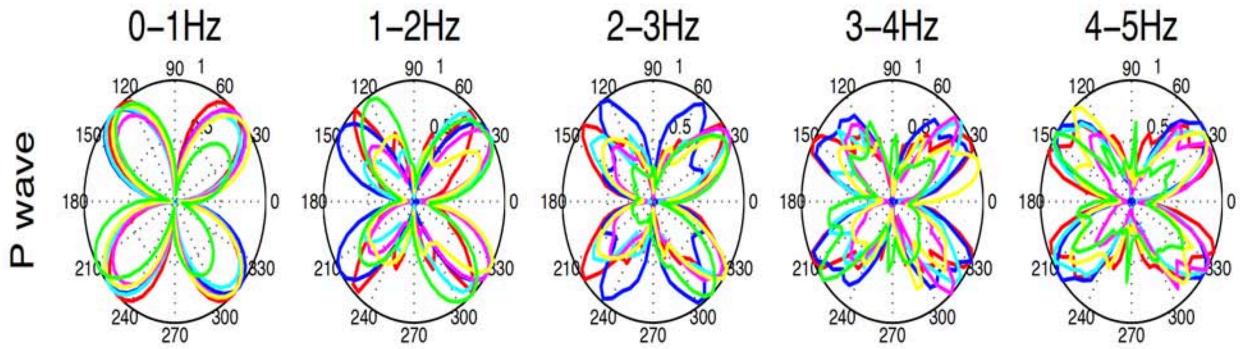
Yao, 2017 (SDSU PhD Thesis)

Radiation Pattern



2D *Cho and Dunham, 2010 (AGU annual meeting)*

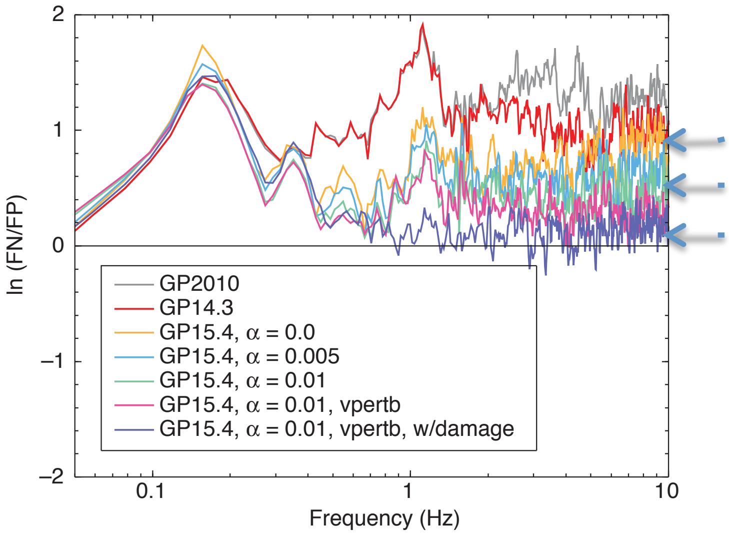
3D *Wang, Day and Shearer, 2014 (AGU annual meeting)*



flat_b	Locked boundary and sharp stopping phase exists	rough 2	$\alpha=10^{-2.5}$
flat_s	Spontaneous stopping no sharp stopping phase	rough 3	$\alpha=10^{-2.3}$
rough 1	Based on flat_s, $\alpha=10^{-3.0}$	rough 4	$\alpha=10^{-2.0}$

Radiation Pattern: Effect on Strong Motion

Fault normal/parallel GM ratios vs frequency in kinematic simulations of *Graves and Pitarka (2016)*

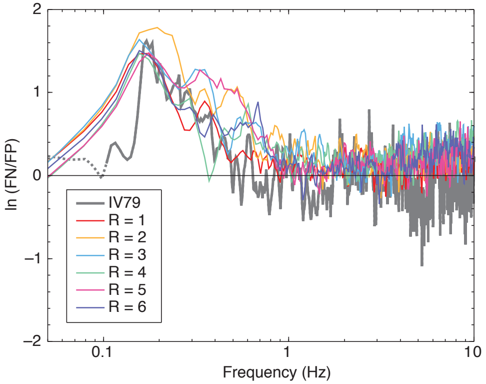


smooth

rough

rough +
scattering medium

Graves/Pitarka model reproduces Imperial Valley (1979) FN/FP ratios



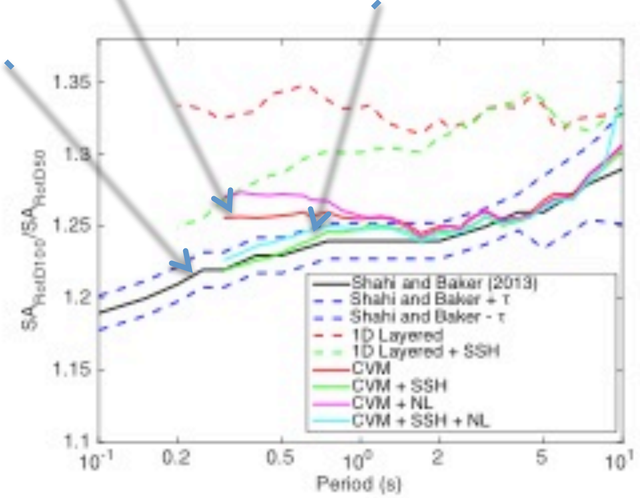
RotD100/RotD50 Ratios vs Period

(Withers et al., 2018)

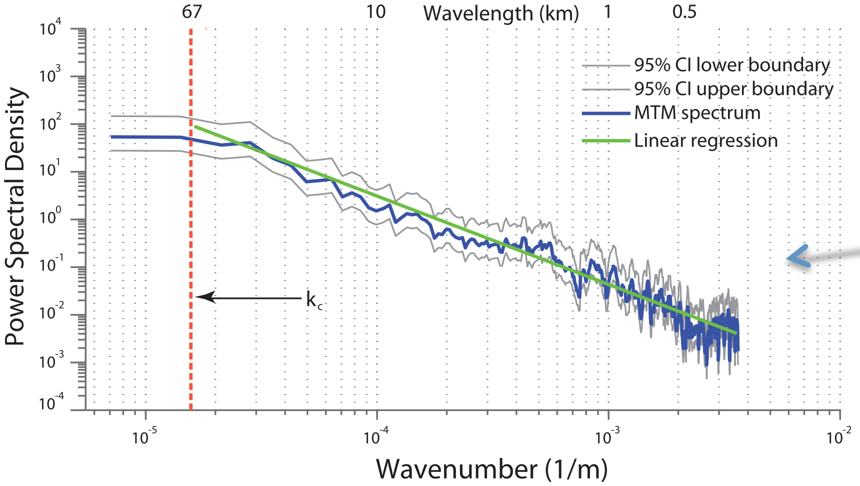
Rough fault + CVM

Rough fault + CVM + scattering

Empirical
(Shahi & Baker)

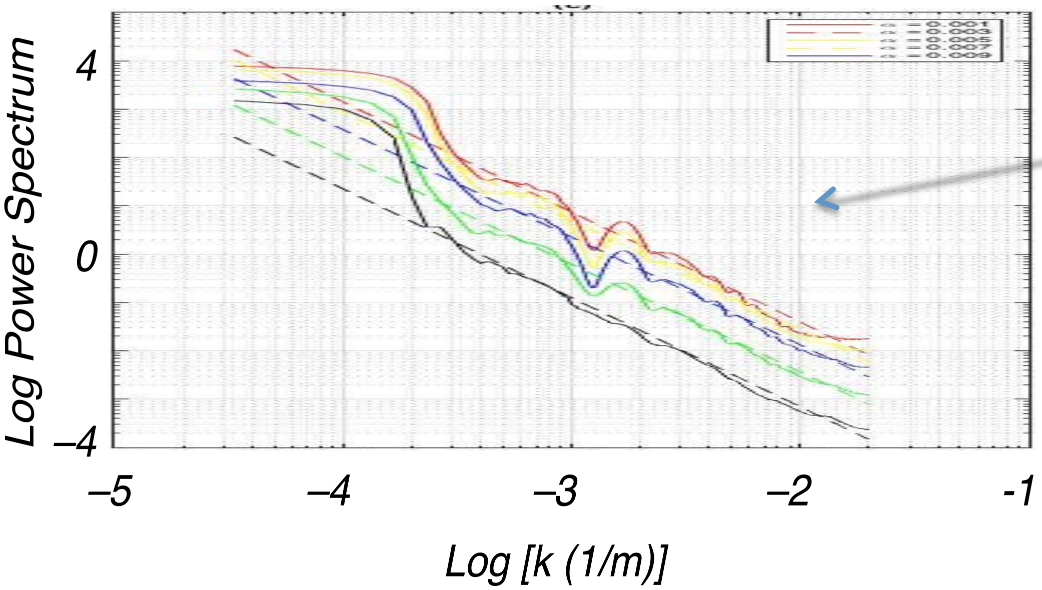


Co-seismic Surface Slip



1992 Landers Rupture
(Milliner et al. 2015)

H ~0.44

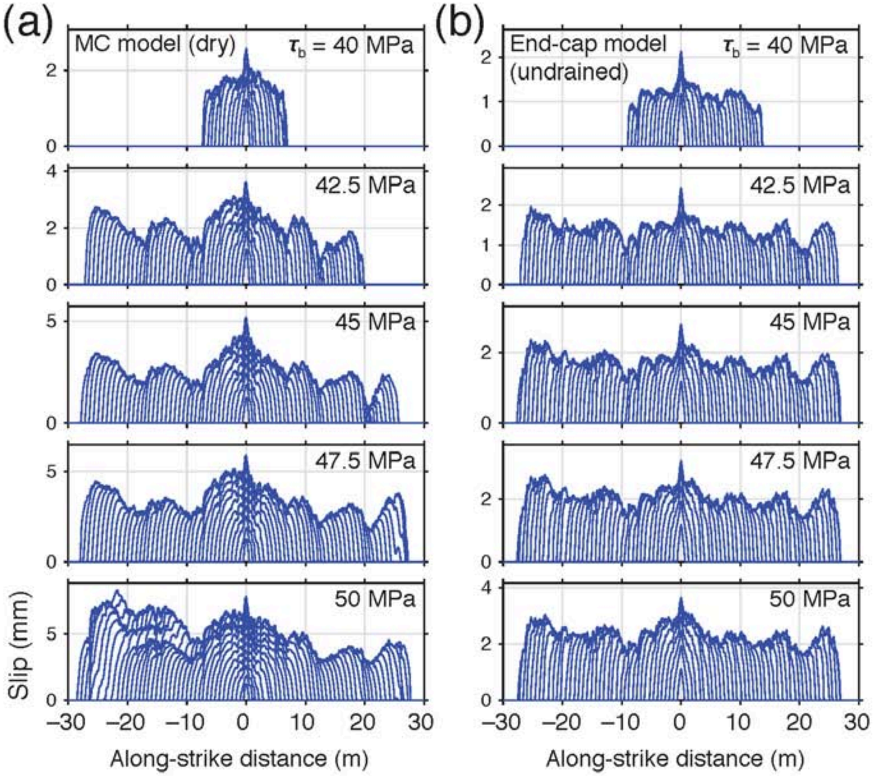


Surface-rupturing Rough-fault simulations
(*Yao, 2017*)

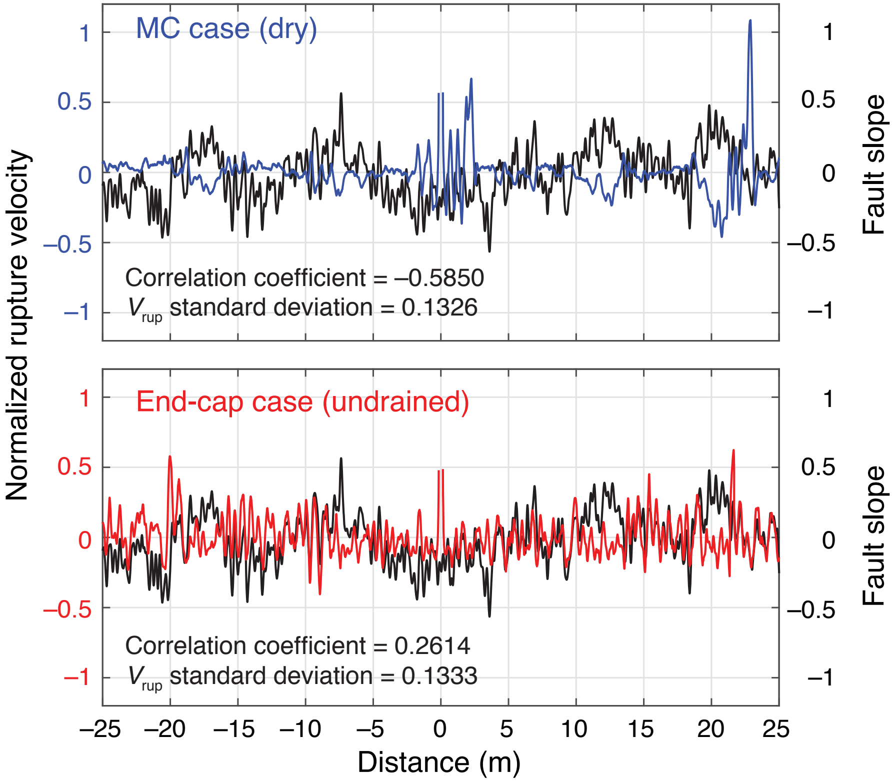
H ~0.6 (ensemble range 0.5-0.8)

Effect of Undrained Gouge Deformation

- Moderates rupture complexity



- Roles of “releasing” and “restraining” orientations are reversed (as in Harris & Day, 1993)
- Rupture velocity fluctuations very similar to constant- pore-pressure case



Hirakawa & Ma (2018)

SUMMARY

- Contributes to high-frequency GM (may be the principal source)
  ~10 Hz @ ~100 km is now calculable
- Contributes to GM statistical variability
  But random heterogeneities are at least equally important
- Modifies kinematic parameter correlations
  Reduces rupture coherence
- <u>Promotes</u> transient, buried supershear bursts
  Most are small and and probably undetectable
- <u>Suppresses</u> sustained, shallow SS events
  Consistent with observed association of SS with smooth fault segments
- Creates frequency-dependent radiation patterns
  Fills nodes at frequencies > ~3 Hz and improves FN/FP ratio predictions
- Produces power-law co-seismic surface-slip fluctuations
  May be partial (but incomplete) explanation of coseismic slip maps
- Model with undrained gouge compaction has <u>mostly</u> similar GM implications
  Roles of restraining and releasing features are reversed.
  Would have big effect on prediction of, e.g., rupture termination points.