Physics-Based Ground Motion Simulation

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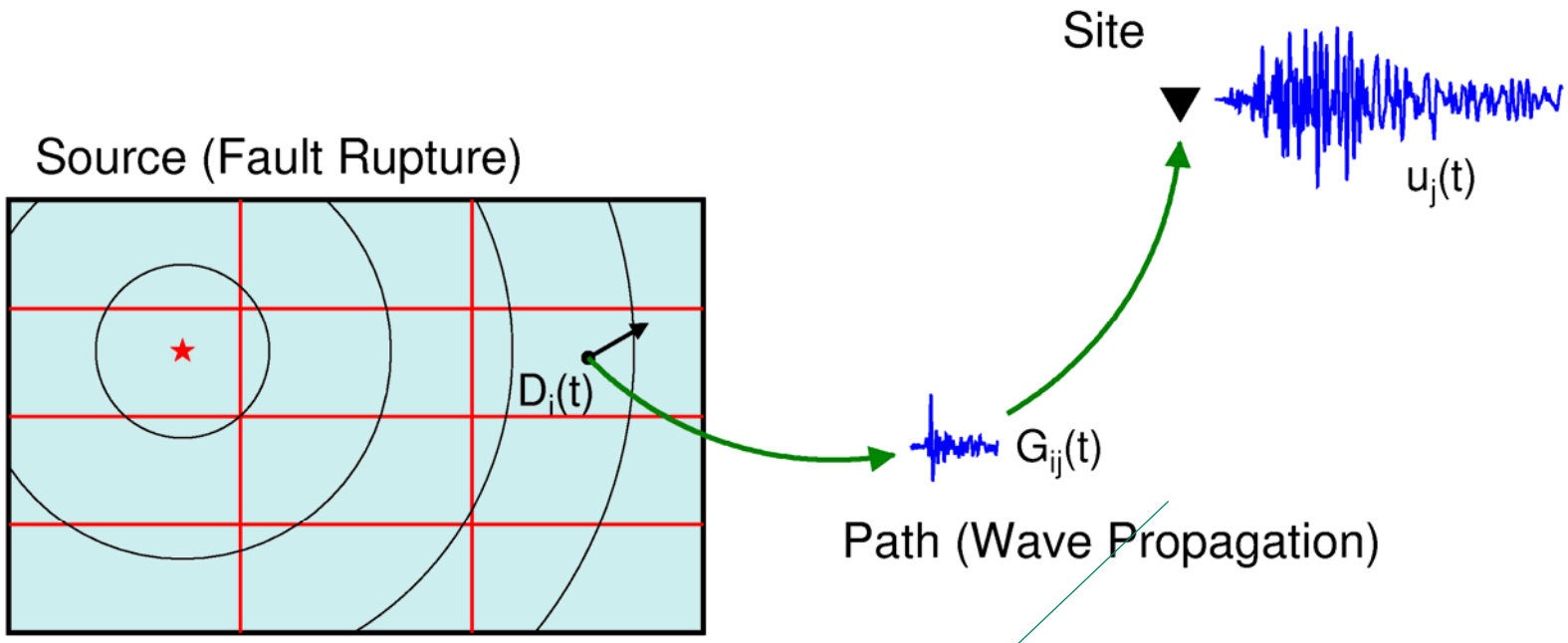
Content

- Introduction to the Graves and Pitarka (2010;2016) hybrid method
- Modeling of key fault rupture and wave propagation effects on strong ground motion
- Validation of ground motion simulation method

Ground Motion Simulation Method

Representation Theorem

$$u_j(t) = \sum G_{ij}(t) * D_i(t)$$



- **Deterministic approach for low frequencies (<1 Hz)**
- **Stochastic approach for high frequencies (>1 Hz)**

Graves &Pitarka (GP2015) Hybrid Method

Earthquake Rupture

Non-Planar fault randomly heterogeneous rupture
GP2015

Planar fault rupture with multiple asperities
IM2011, Japan

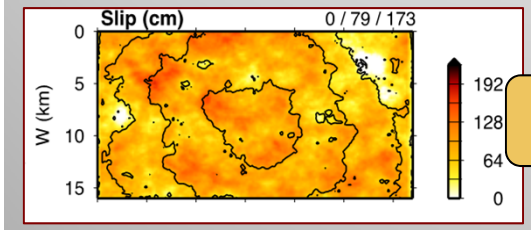
Wave Path

LF: 3D, 1D Linear anelastic simulations
HF: Stochastic GFs

Local Site Effects

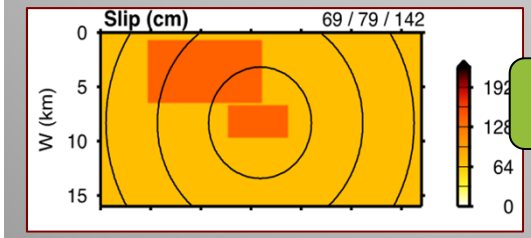
Empirical corrections based on Vs^{30}

Match filter at ~1 Hz BB Acceleration Time History



GP2015

Graves and Pitarka, 2015



IM2011, Japan

Irikura and Miyake, 2011

Hybrid Approach to Broadband Ground Motion Simulations

A) Kinematic Rupture Generator

Parameters guided by rupture dynamics

- **rise time with depth scaling**
- **slip velocity function**
- **rupture speed and spatial variation with depth scaling**
- **rise time with depth scaling**

- ***Parameters that satisfy empirical relationships***
- **Magnitude-fault area**
- **Average rise time**
- **Background rupture speed**
- **Radiation pattern as a function of frequency**
- **Spatial correlation lengths of stochastic slip variability**

B) Wave Path Model

Physics based Green's functions up to 1Hz

- solution of elastic wave equation in 3D heterogenous media
- anelastic wave attenuation

Stochastic Green's functions > 1Hz

- Separate GFs for direct and down-going rays
- Amplitude decays as inverse of ray path length
- Gross impedance effects based on quarter wavelength (Boore and Joyner, 1997)

Semi stochastic velocity model

- Spatially correlated random small-scale perturbations
- Surface topography

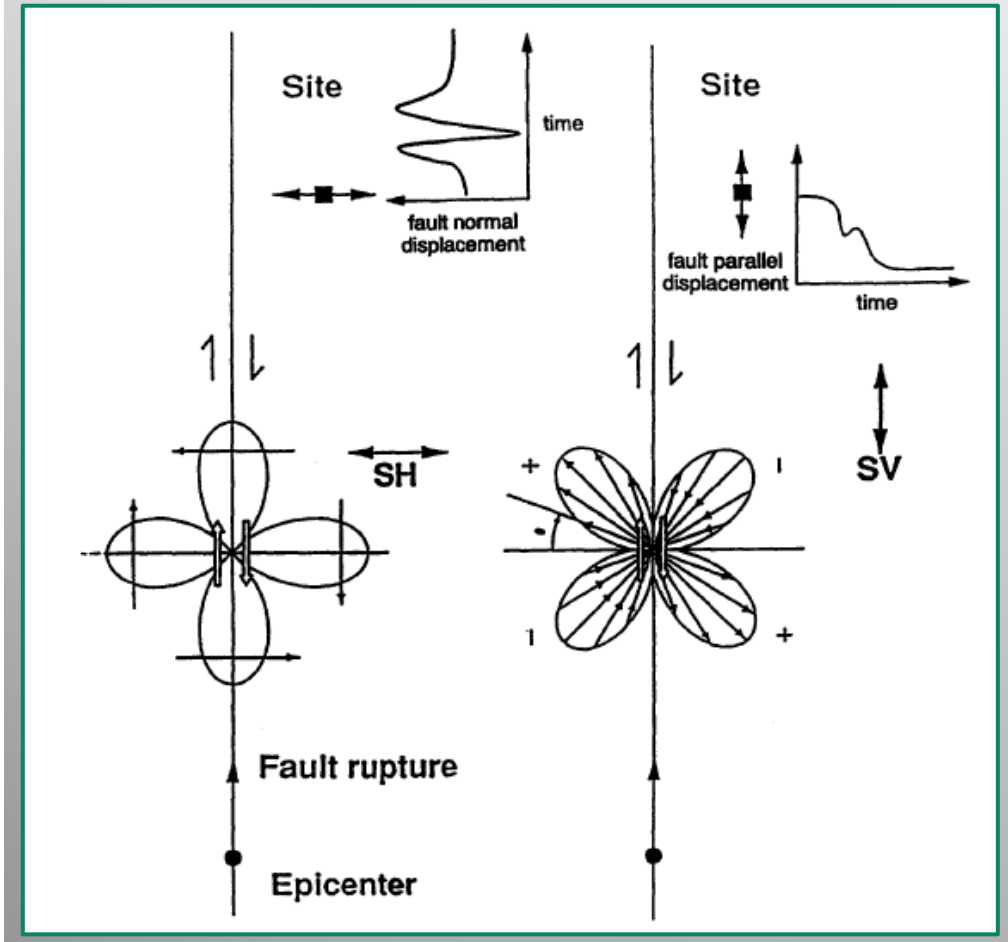
Finite-fault Rupture Effects

Somerville et al. (1997)

Freq. Depend. Radiation Pattern

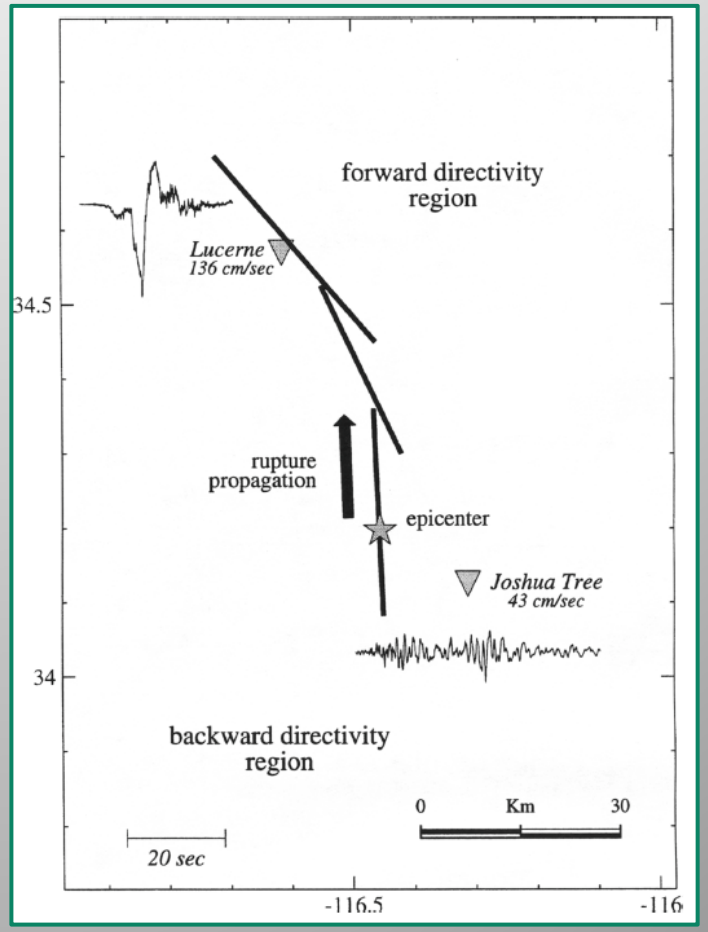
SH motion sums coherently in direction of rupture propagation: **Larger Fault Normal**

SV motion is nodal in direction of rupture propagation: **Smaller Fault Parallel**



Rupture Directivity, Segmentation

Low frequency (f < 1 Hz) motions build up in direction of rupture propagation: **rupture directivity**

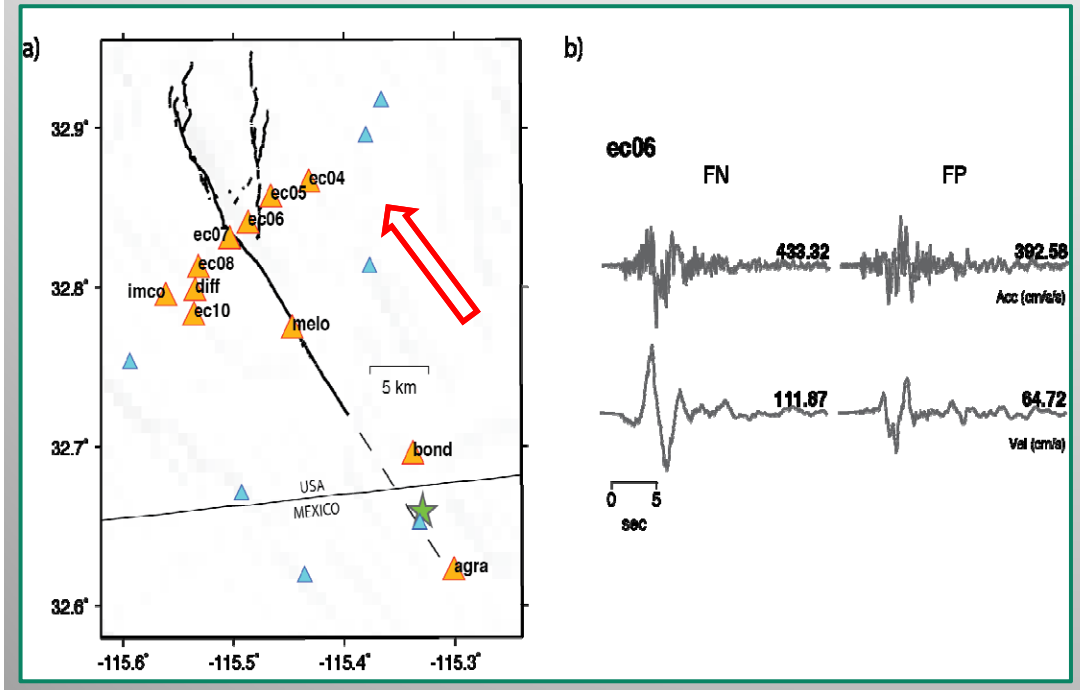


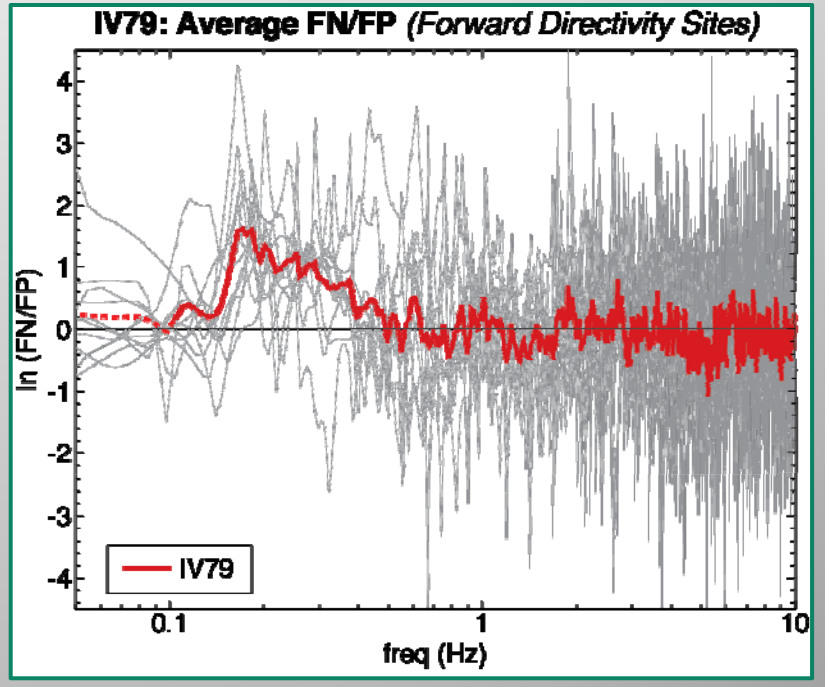
Graves and Pitarka (2016)

Finite-fault Rupture Effects: Rupture Directivity

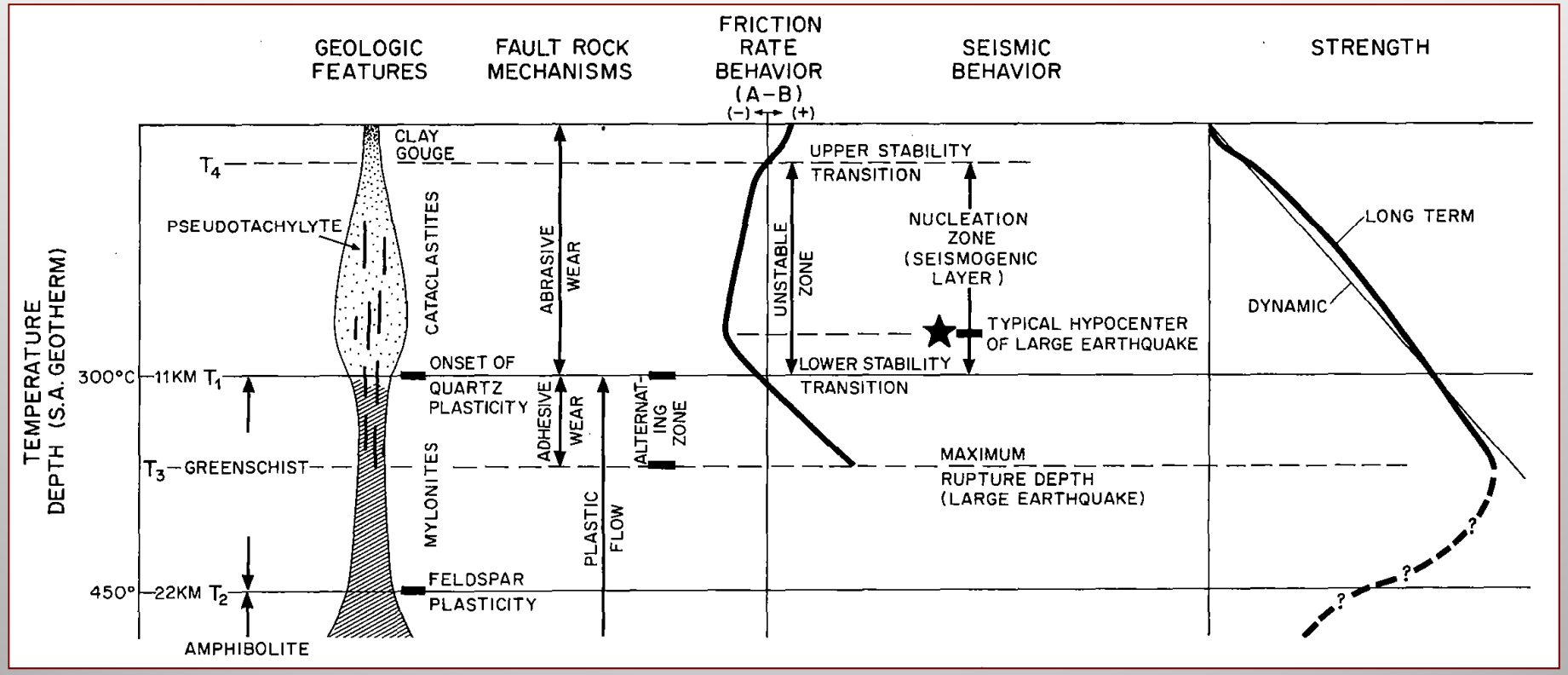
Rupture directivity can lead to strong pulse-like ground velocity motions (periods of 1-10 seconds) in particular onto **Fault Normal** component

Imperial Valley Earthquake





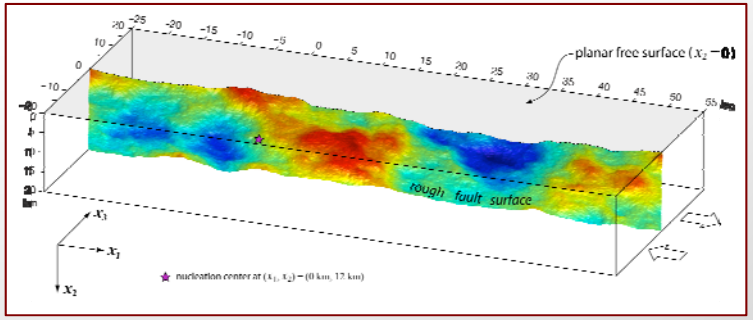
Rupture Extension at Depth: Brittle Ductile Transition below Seismogenic Zone



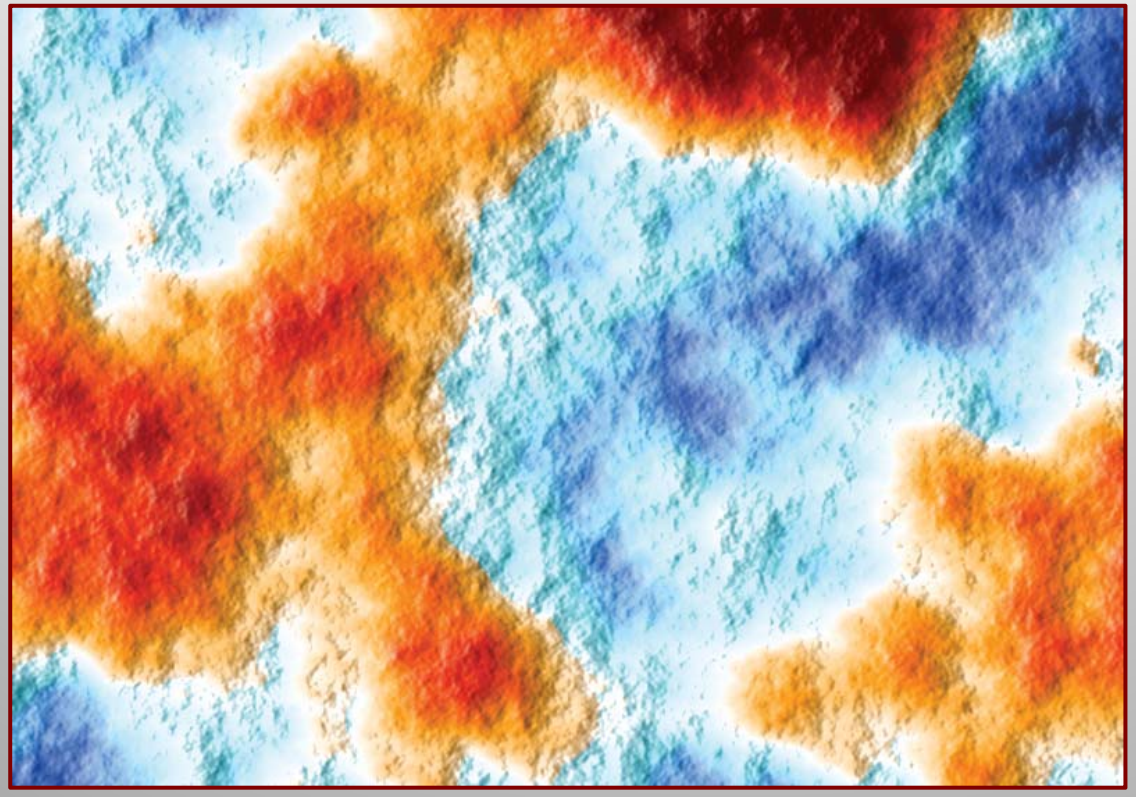
- Addition of deep weak zone between 15-18km (larger fault area) while keeping the seismic moment fixed. Use the magnitude-length and magnitude-area relationships of Leonard (2010).

Rupture Dynamics on Faults with Rough Surface

(Shi and Day,2013)

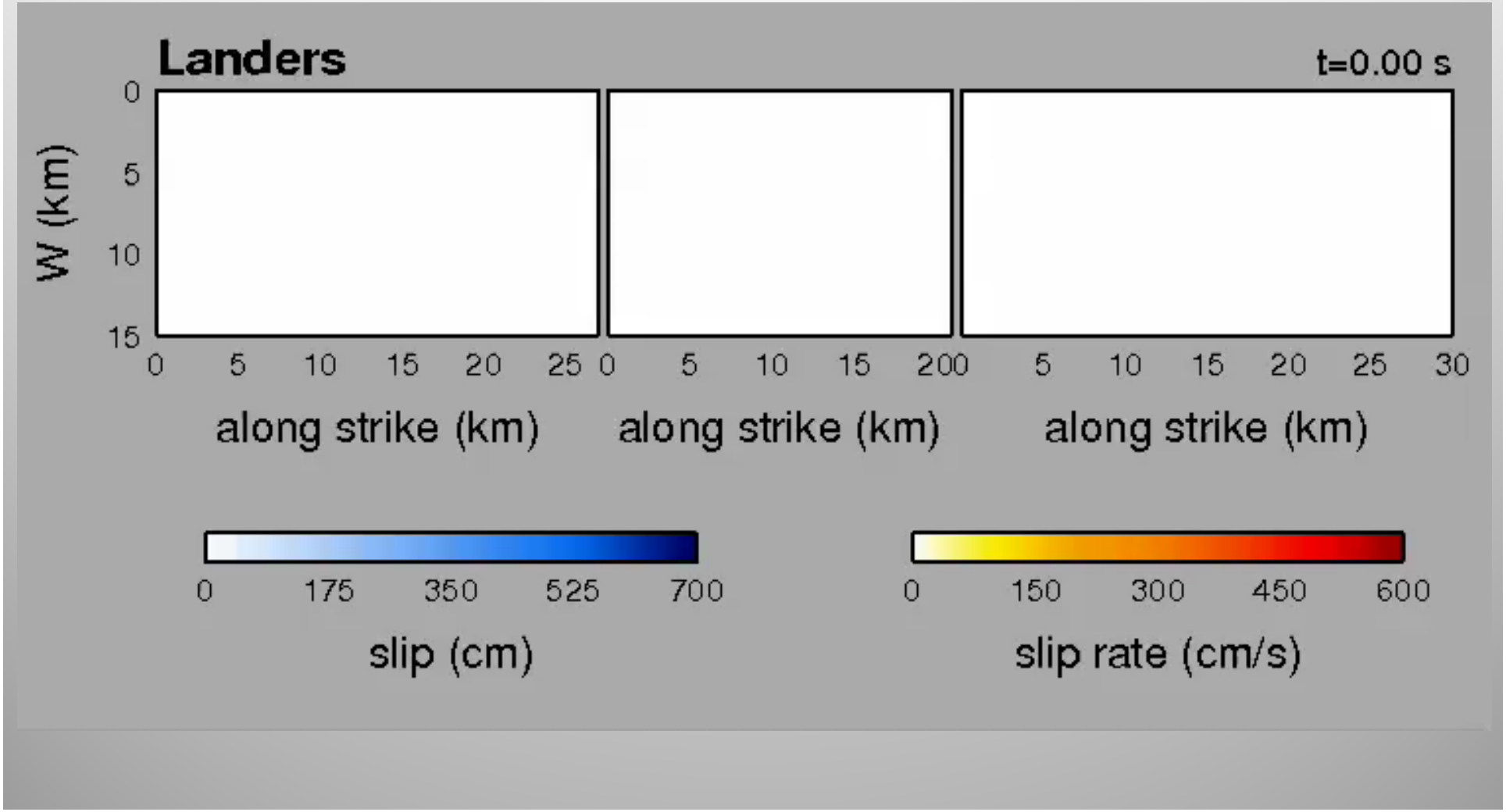


$\alpha = h_{rms} / L$, =0.001-0.01 (Power and Tulis, 1991)



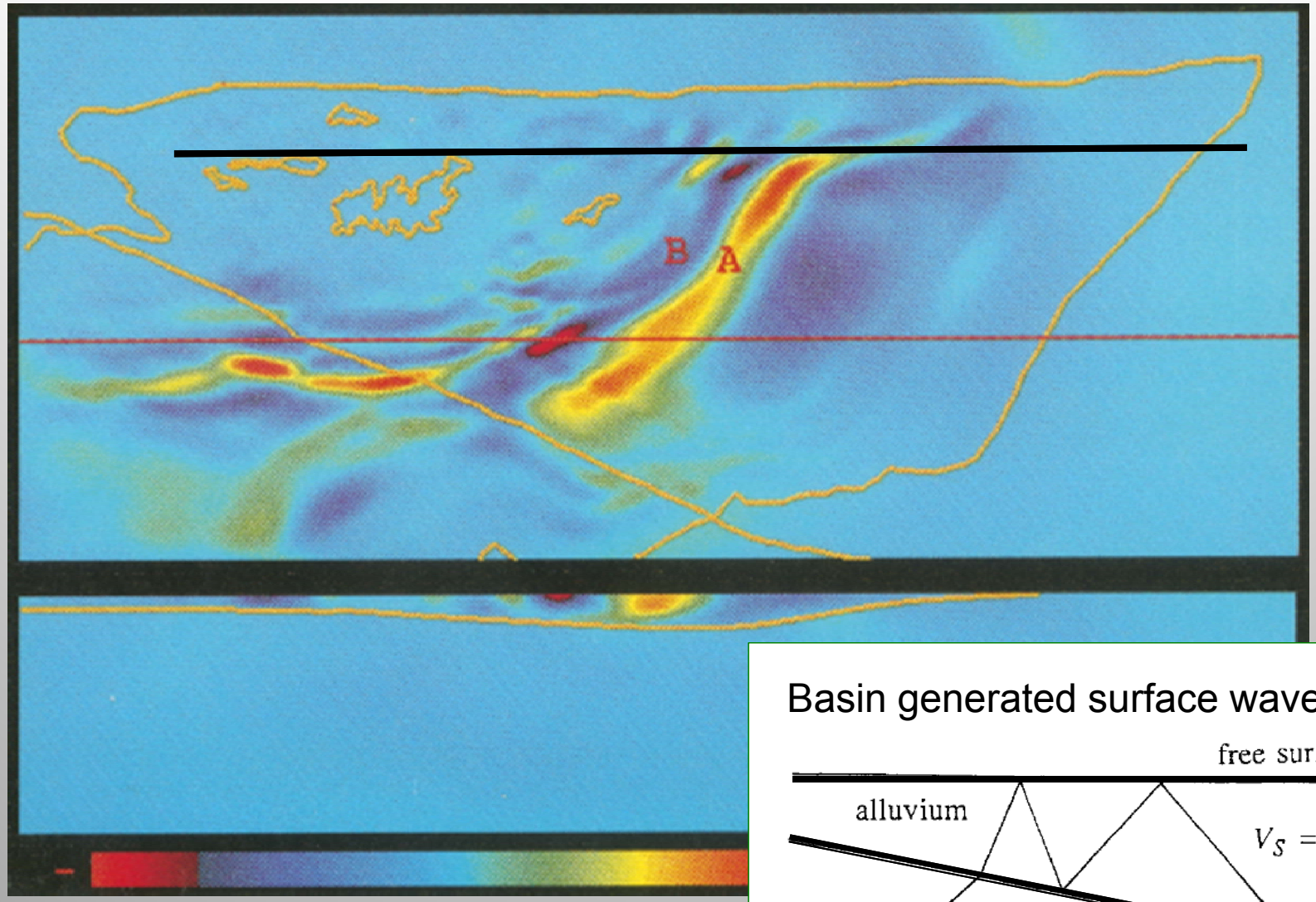
Example of Simulated Earthquake Rupture : 1992 Landers EQ

- Multi-segment jumps (rupture delay)
- Shallow rupture effects

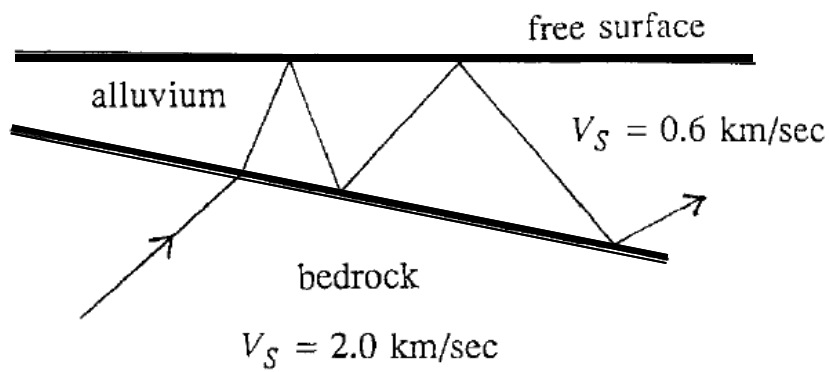


Deterministic 3D Wave Propagation Effects

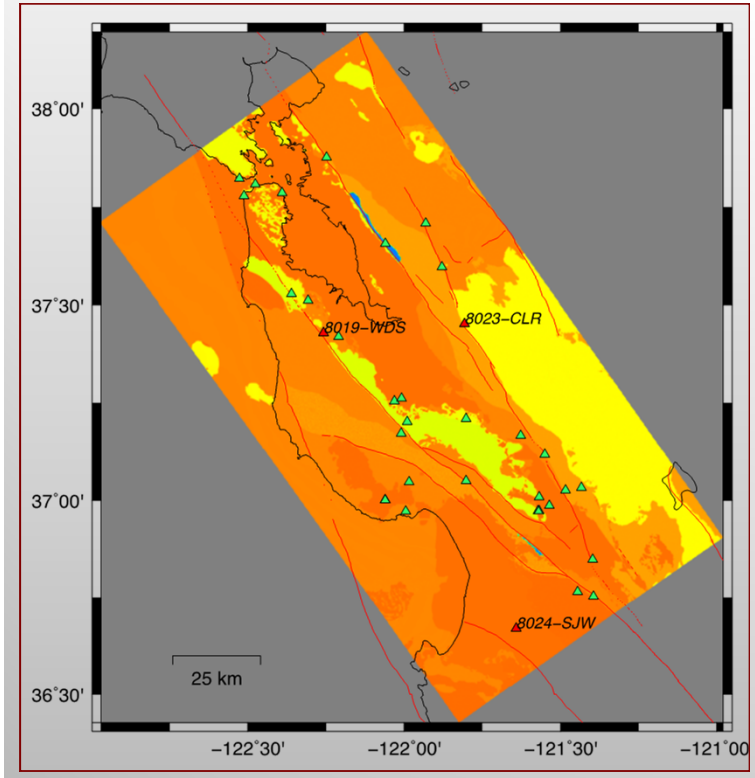
Frankel (1993)

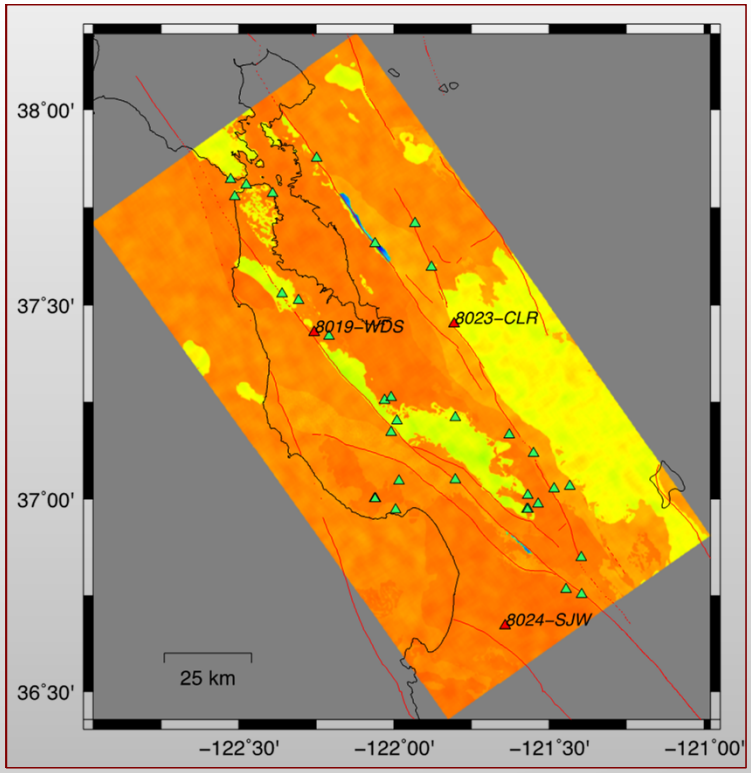


Basin generated surface wave



Stochastic Wave Propagation 3D Velocity Models with Random Perturbations

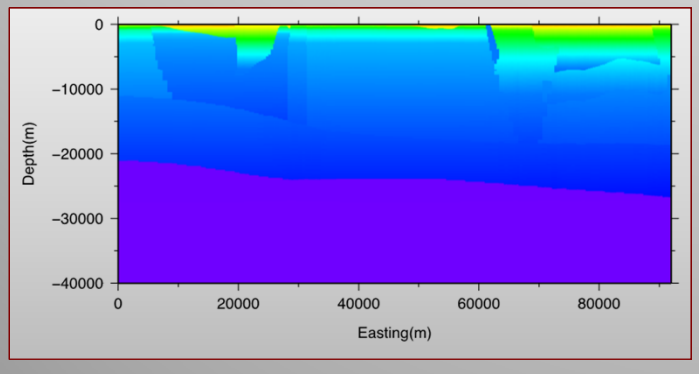




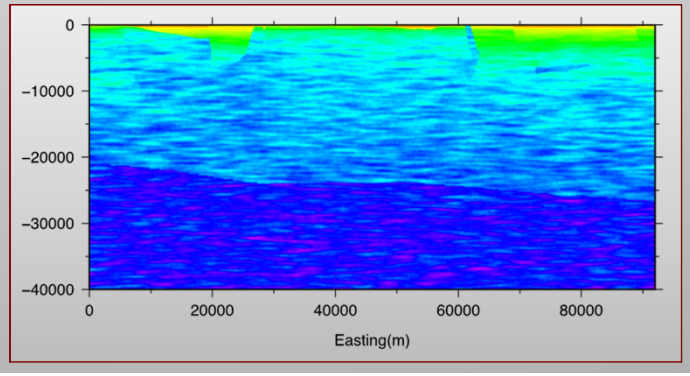
Random Velocity Perturbations (Pitarka et. al., 2009)

L_h=2000m
L_z=200m
Perturb=30%
V_{smin}=400m/s

SW NE



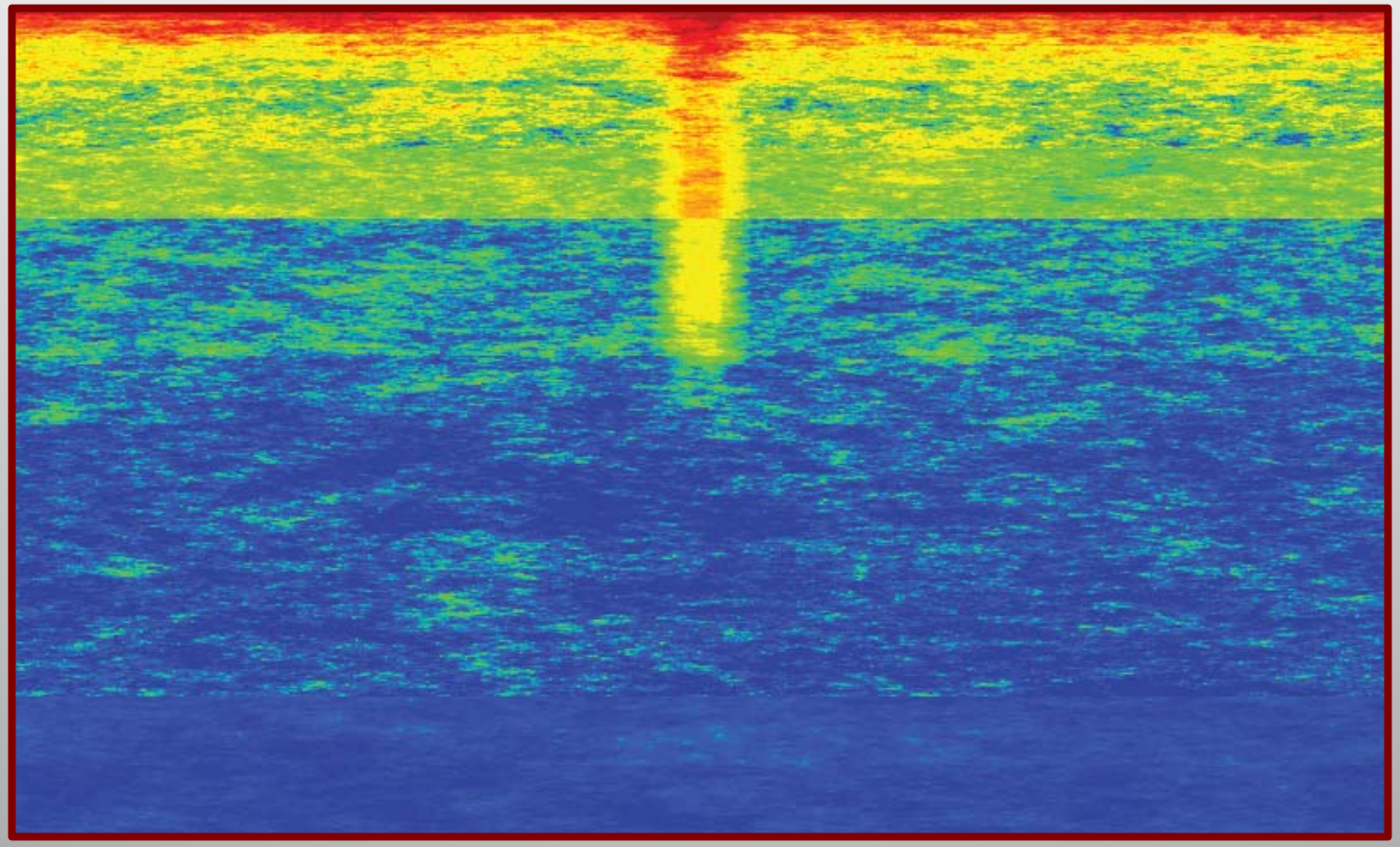
SW NE



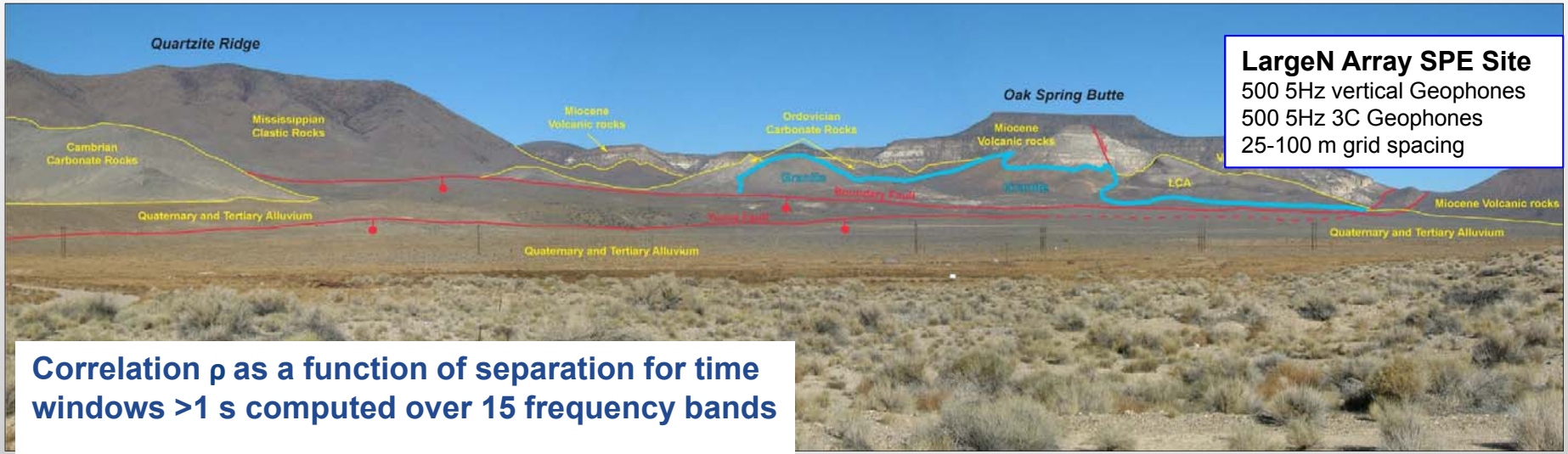
Random Perturbations to the Velocity Model Including Fault Zone

Graves and Pitarka (2016)

Lx=Ly; Lz=Lx/10

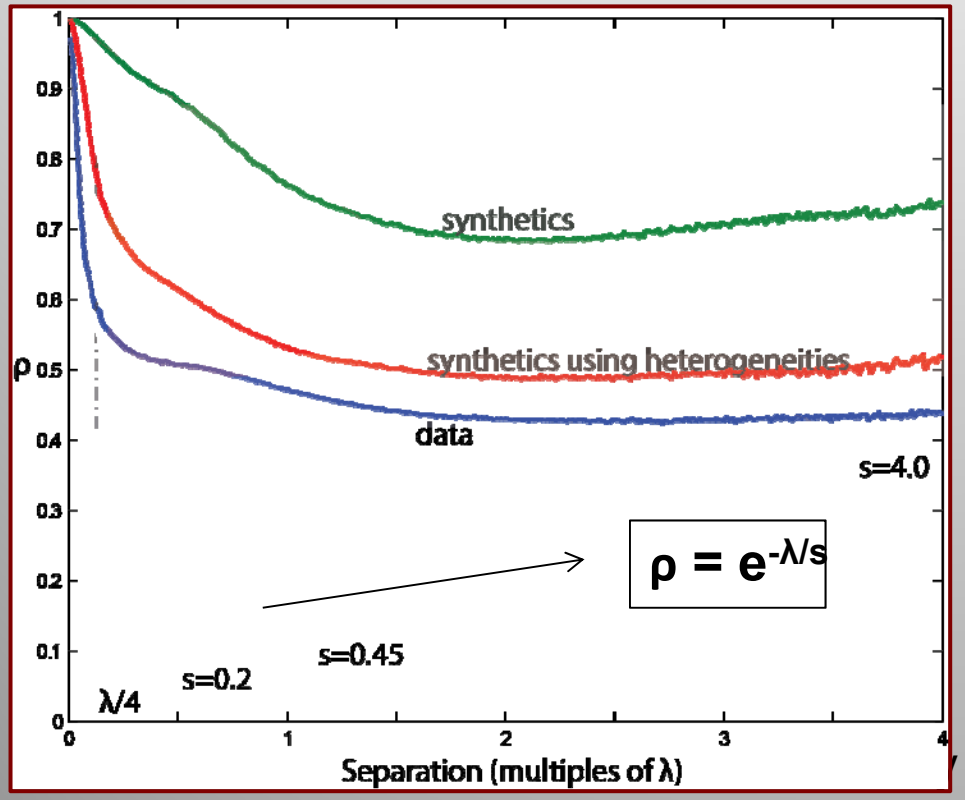


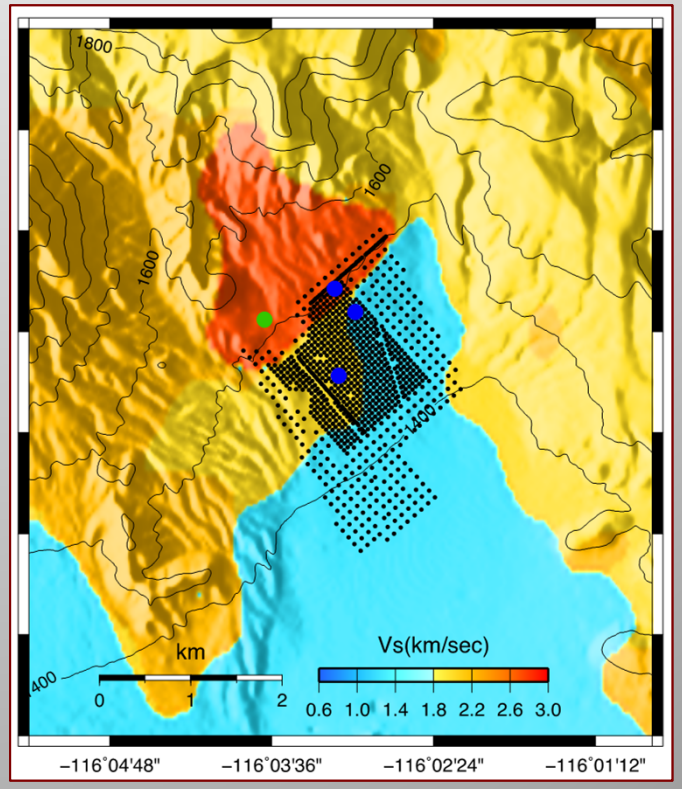
Estimation of stochastic variability parameters using LargeN array data



LargeN Array SPE Site
500 5Hz vertical Geophones
500 5Hz 3C Geophones
25-100 m grid spacing

Correlation ρ as a function of separation for time windows >1 s computed over 15 frequency bands





SCEC Broadband Platform (BBP)

http://scec.usc.edu/scecpedia/Broadband_Platform

Goulet et al., 2015

BBP is an open-source distribution

Broadband 0.1-20+ Hz

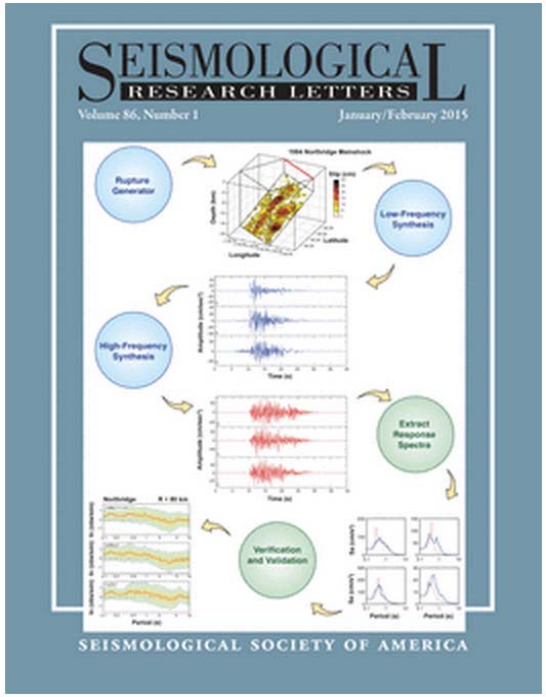
S*imple* source and path (1D)

5 alternative simulation codes

Fully validated for spectral response

- **1.5 year project**
- **Multiple rounds of validation/improvements**
- **Independent review panel**

Used for large ground motion characterization projects



SRL Special Focus on BBP Validation – 9 papers - Jan. 2015

Validation of BB Ground Motion Methods on SCEC BB Platform (Dreger and Jordan,2015)

Goulet et al., 2015

PSA evaluation – using 50 source realizations

- ***PART A: validation against recorded events***
  - Evaluation of bias [ln(data)/ln(model)] using various approaches
  - 13 events completed, ~40 stations/event
- ***PART B: validation against existing GMMs*** in ranges where they are well constrained by data

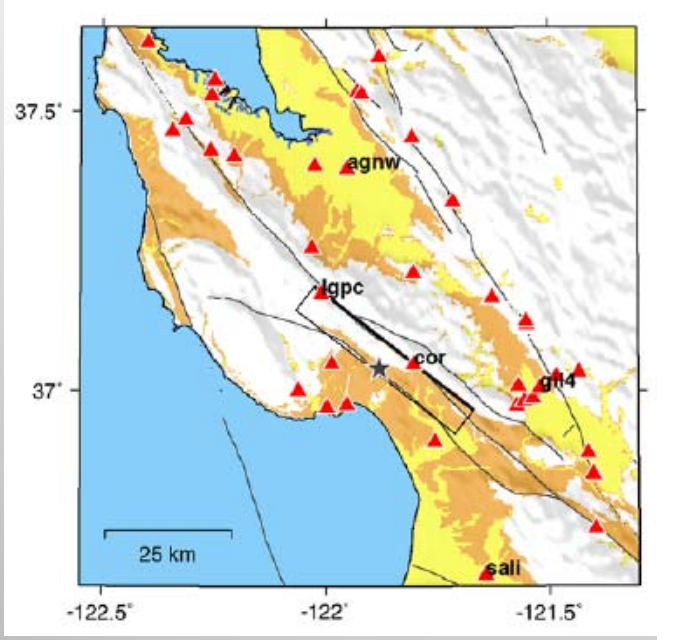
List of Earthquakes Used in Validations

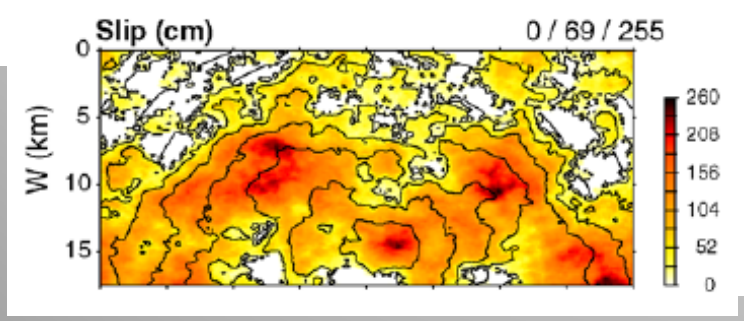
Goulet et al., 2015

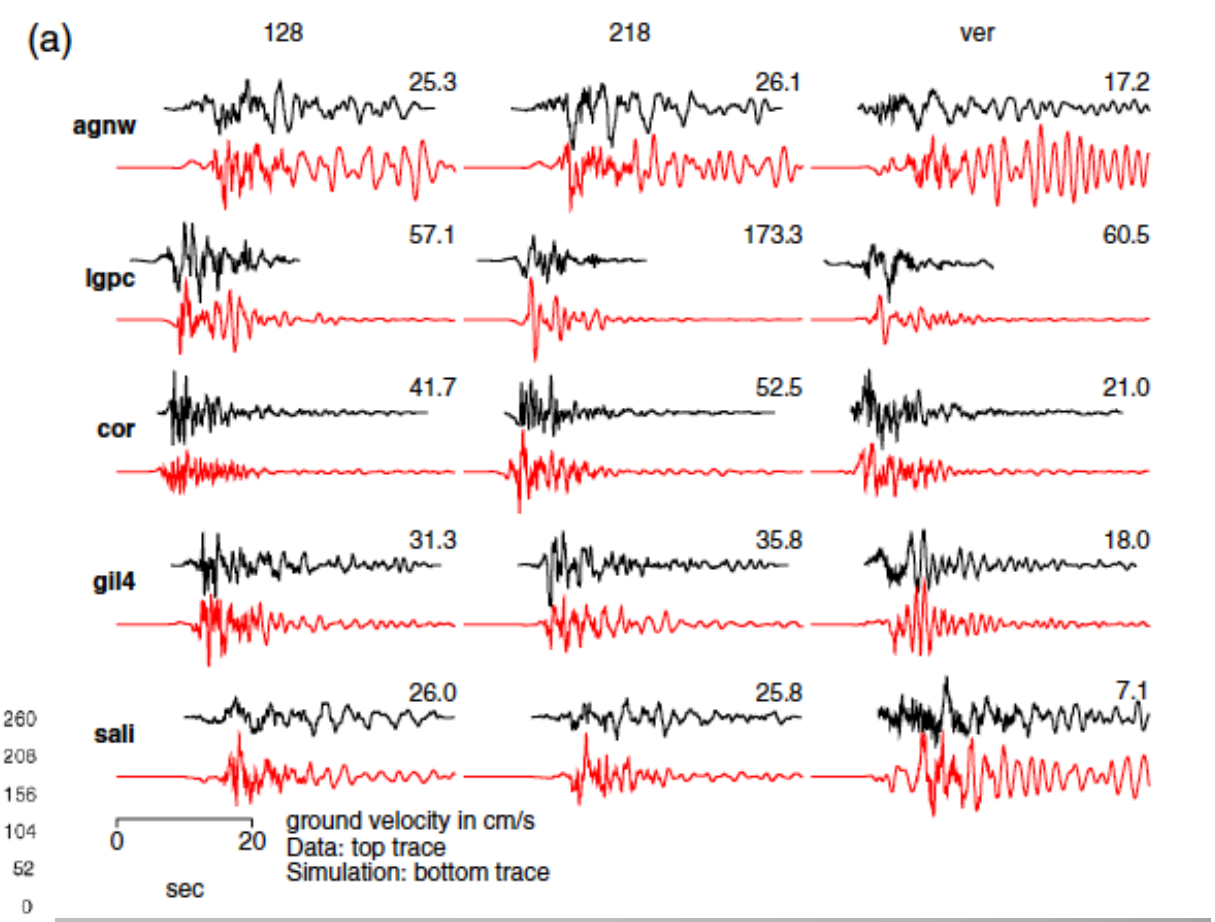
Region	Event Name	Year	Mw	# Records < 200 km
WUS	**Loma Prieta**	1989	6.94	59
WUS	**Northridge**	1994	6.73	124
WUS	**Landers**	1992	7.22	69
WUS	**Whittier Narrows**	1987	5.89	95
WUS	**North Palm Springs**	1986	6.12	32
JAPAN	**Tottori**	2000	6.59	171
JAPAN	**Niigata**	2004	6.65	246
WUS	**Alum Rock**	2007	5.45	40
WUS	**Chino Hills**	2008	5.39	40
CENA	**Saguenay**	1988	5.81	11
CENA	**Riviere-du-Loup**	2005	4.60	21
CENA	**Mineral, VA**	2011	5.68	10
WUS	El Mayor Cucapah	2010	7.20	134
WUS	Hector Mine	1999	7.13	103
WUS	Big Bear	1992	6.46	42
WUS	Parkfield	2004	6.50	78
WUS	Coalinga	1983	6.36	27
WUS	San Simeon	2003	6.50	21
JAPAN	Chuetsu-Oki	2007	6.80	286
JAPAN	Iwate	2008	6.90	186
TURKEY	Kocaeli	1999	7.51	14
TAIWAN	Chi-Chi	1999	7.62	257
ITALY	L' Aquila	2009	6.30	40
NEW ZEALAND	Christchurch	2011	6.20	26
NEW ZEALAND	Darfield	2010	7.00	24

- **Large dataset (25 eqs)**
- Many regions & tectonic environments
- Span wide magnitude range **(Mw 4.6 to 7.62)**
- Variety of mechanisms
- Well-recorded (16 EQs with> 40 records within 200 km)
- Select large subset of stations (~40) that are consistent with mean and standard deviation PSa of the full dataset.

Part A Validation: 1989 M6.9 Loma Prieta Earthquake



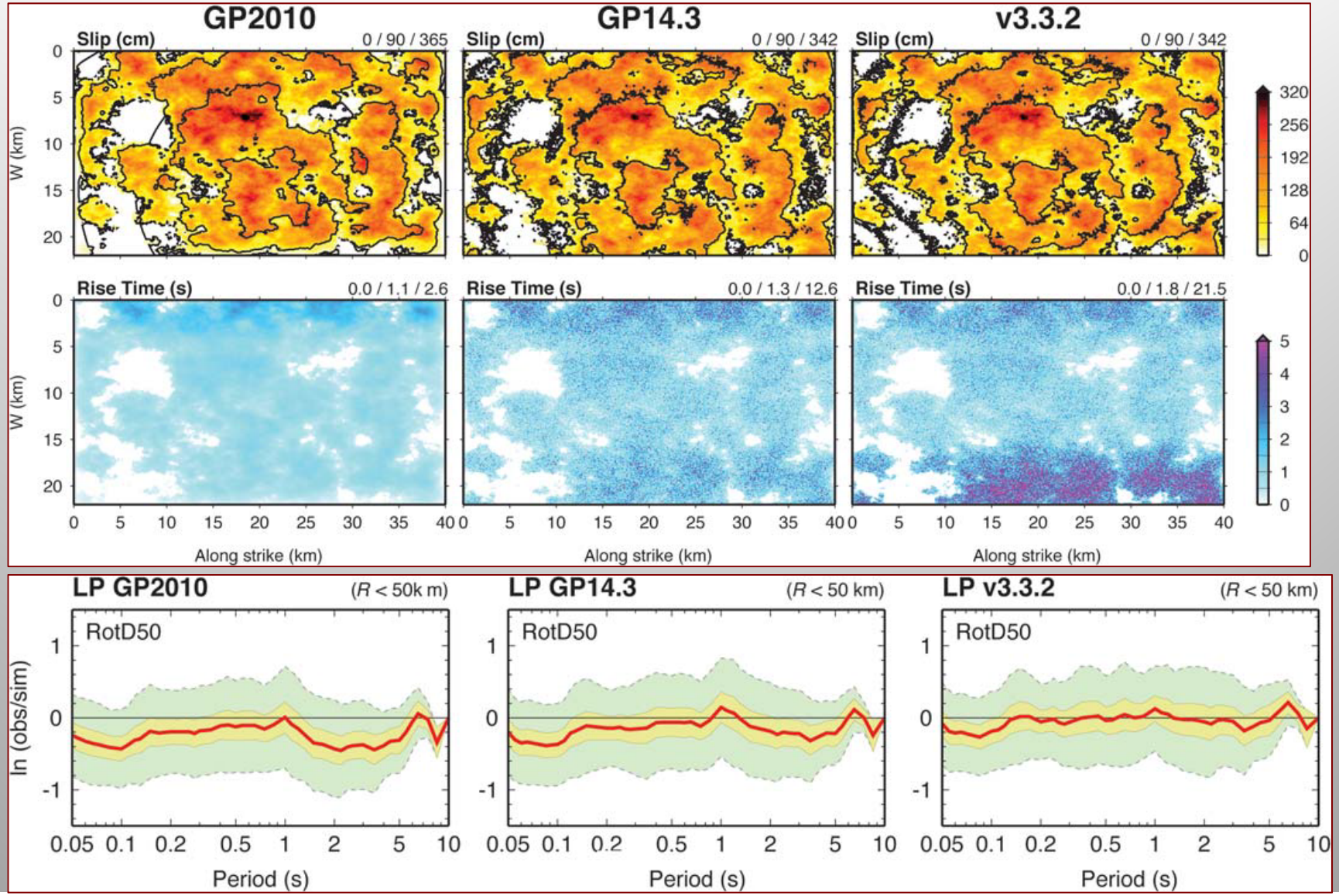




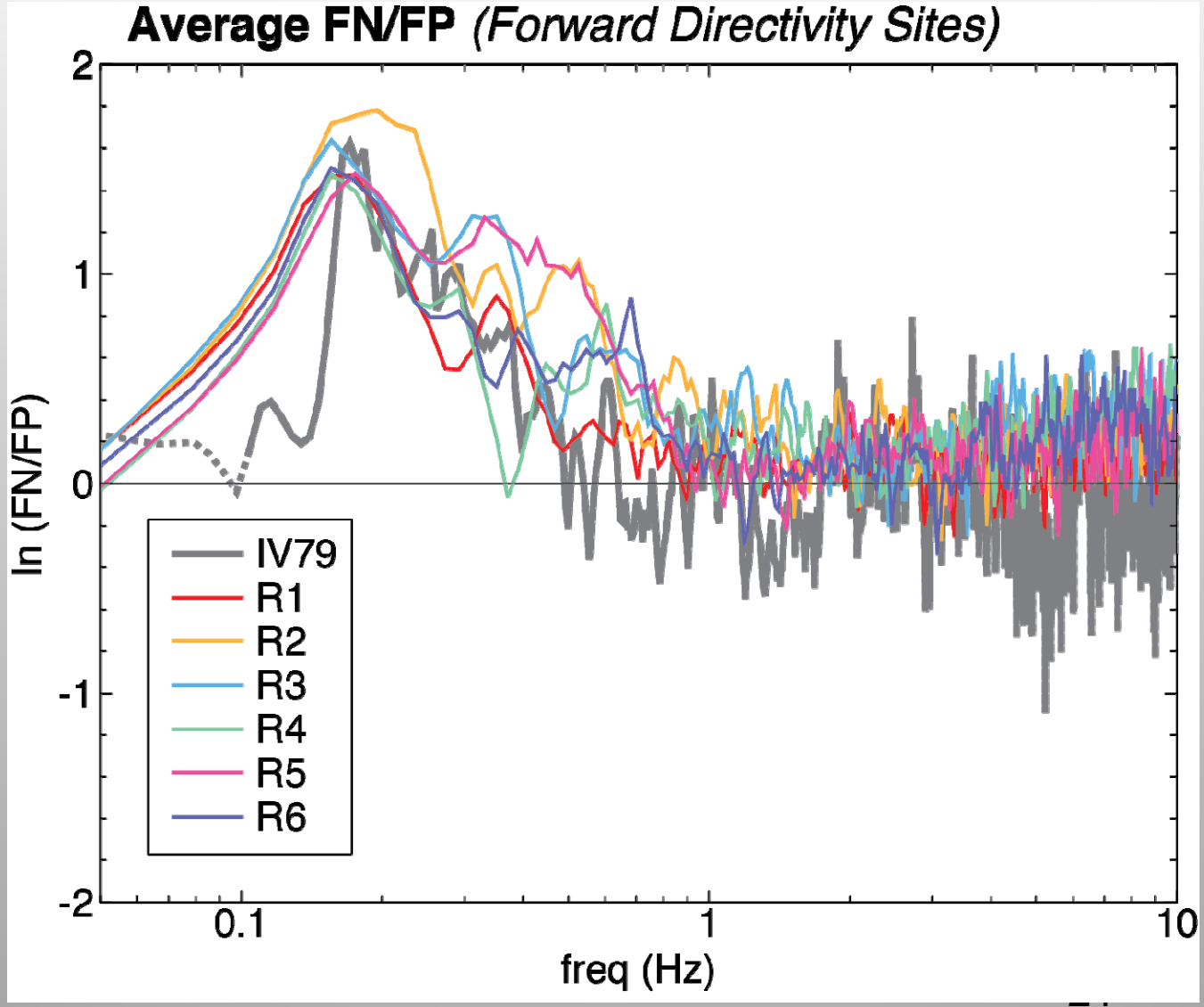
Graves and Pitarka (2010)

Part A: Validation Using Loma Prieta Earthquake Data

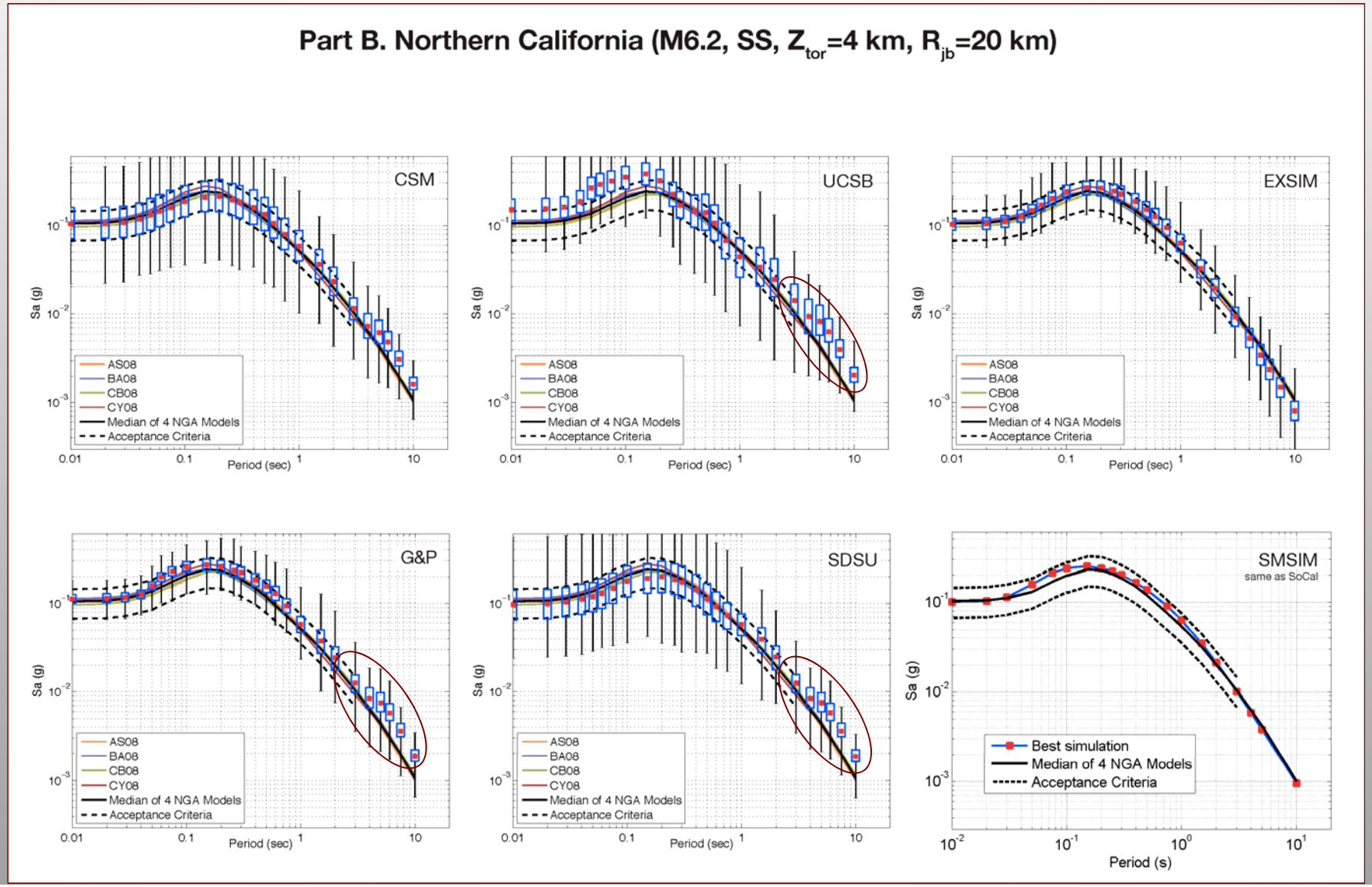
Graves and Pitarka (SRL, 2015)



Multiple realizations nicely replicate observed rupture directivity effects during Imperial Valley earthquake



Part B: Comparisons with GMPEs



Future Improvements

- Improve parameterization of small-scale heterogeneity in 3D velocity models
- Use of high performance computing and stochastic velocity models to extend the application of deterministic approach to higher frequencies (up to 5Hz)
- Sensitivity analysis for non-linear/linear 3D wave propagation modeling
- Inclusion of surface topography in high frequency ground motion simulations

Acknowledgments

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