Ground Motion Simulation and Prediction

Paul Somerville

URS Corporation, Pasadena, California

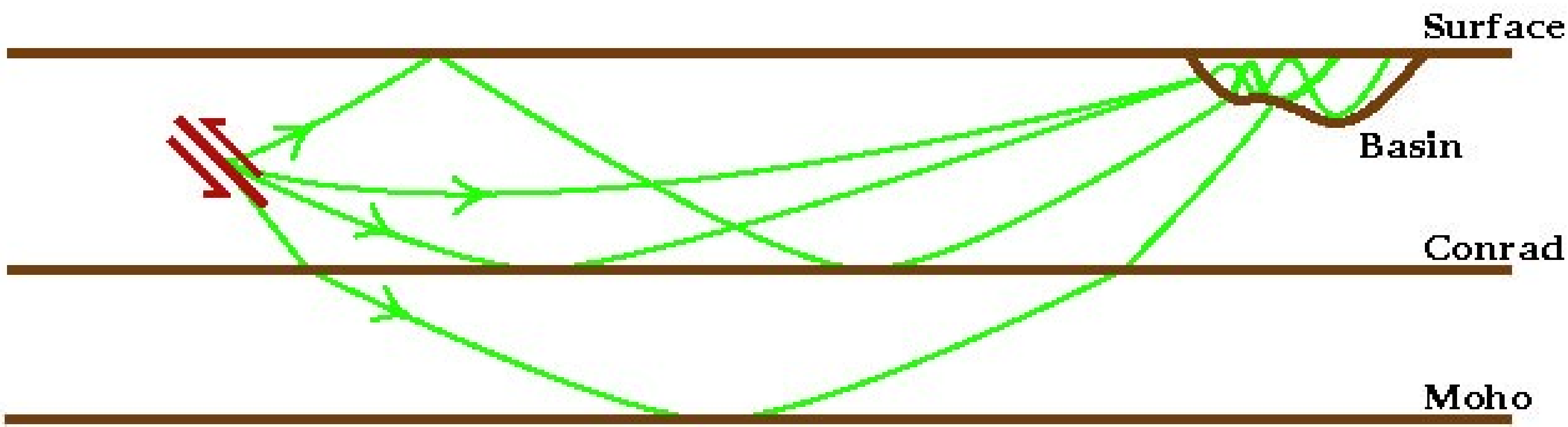
Risk Frontiers, Macquarie University, Sydney

Outline

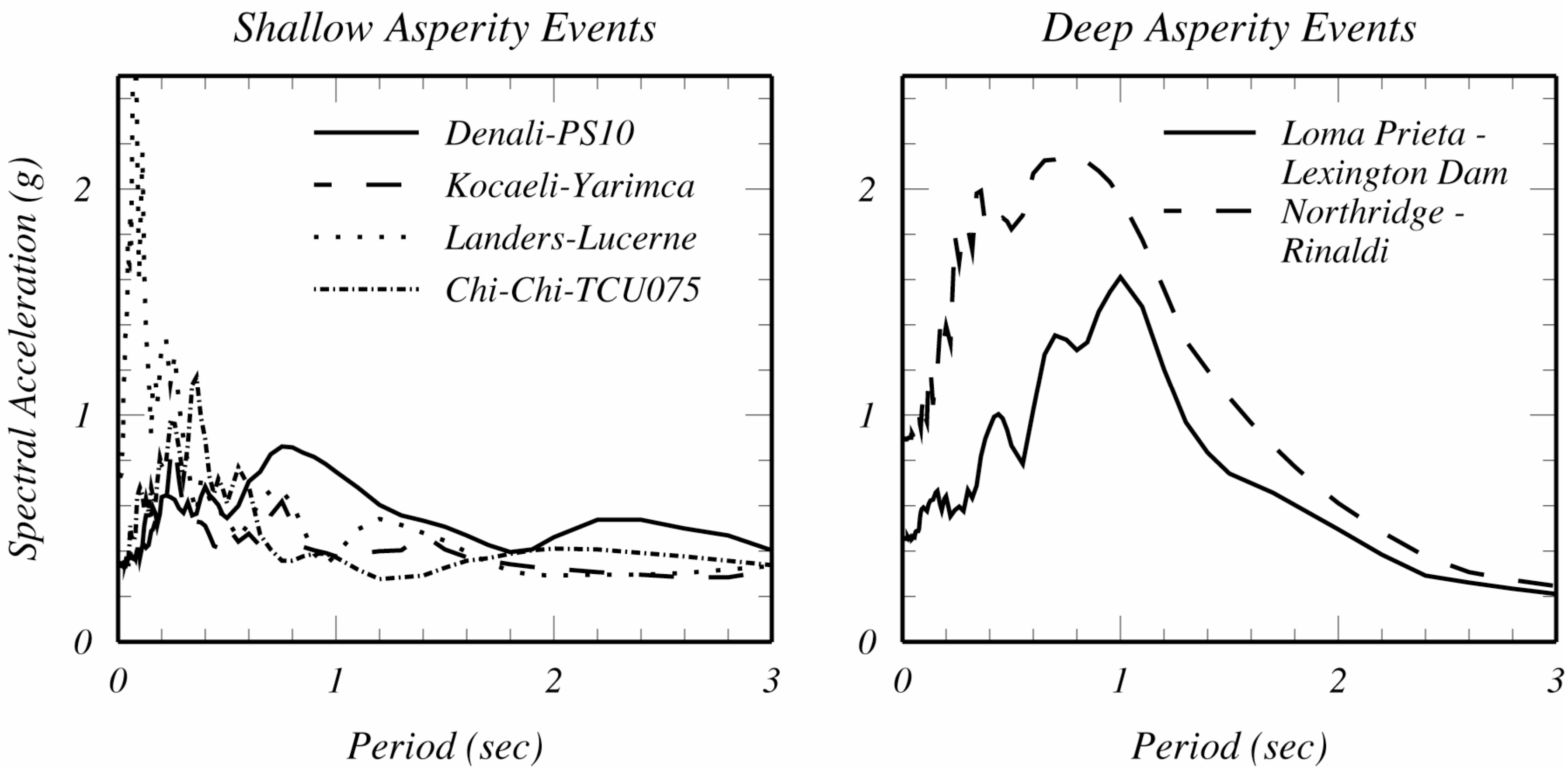
- Ground motion prediction using “empirical” models
- Changes in ground motion models caused by weak ground motions from recent large surface faulting earthquakes
- Physical causes of weak ground motions from large surface faulting earthquakes
- Ground motion prediction using strong motion simulation
- Scenario simulations of basin and directivity effects
- Probabilistic ground motions based on simulations

Ground Motion Prediction Models

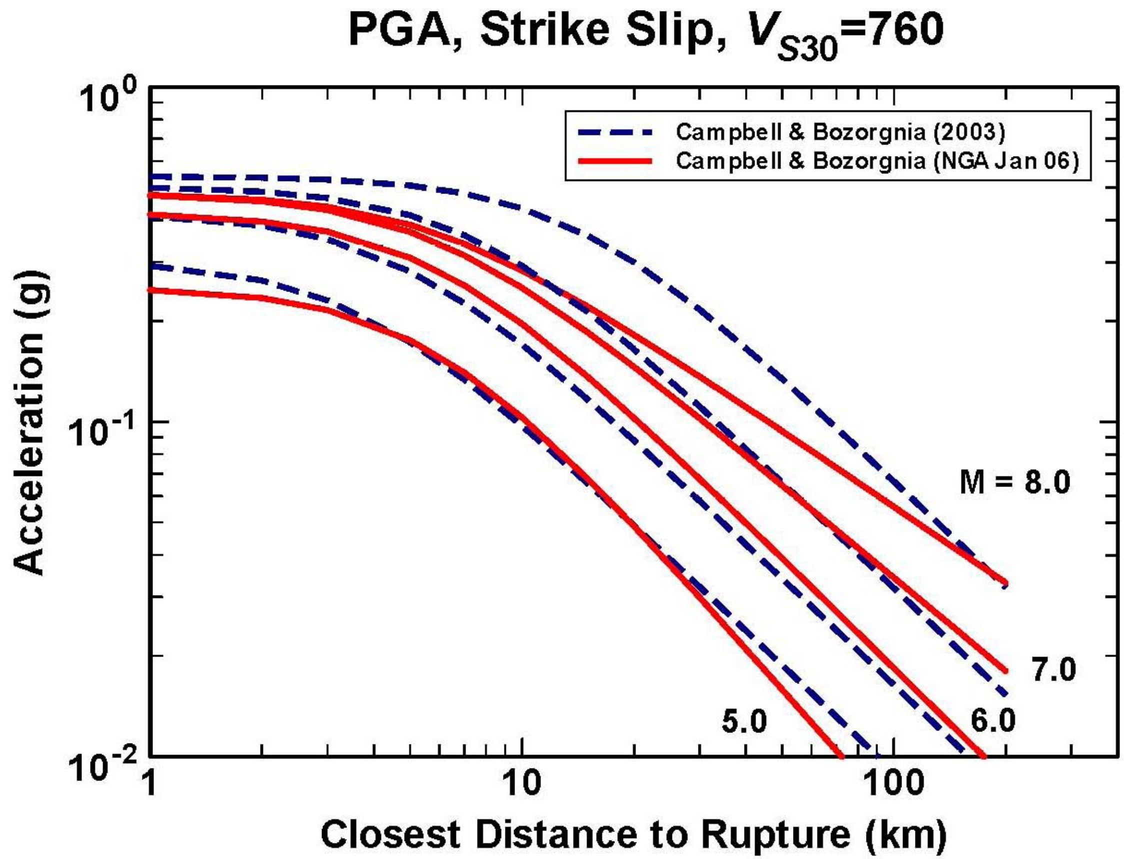
Earthquake Source	Path	Site



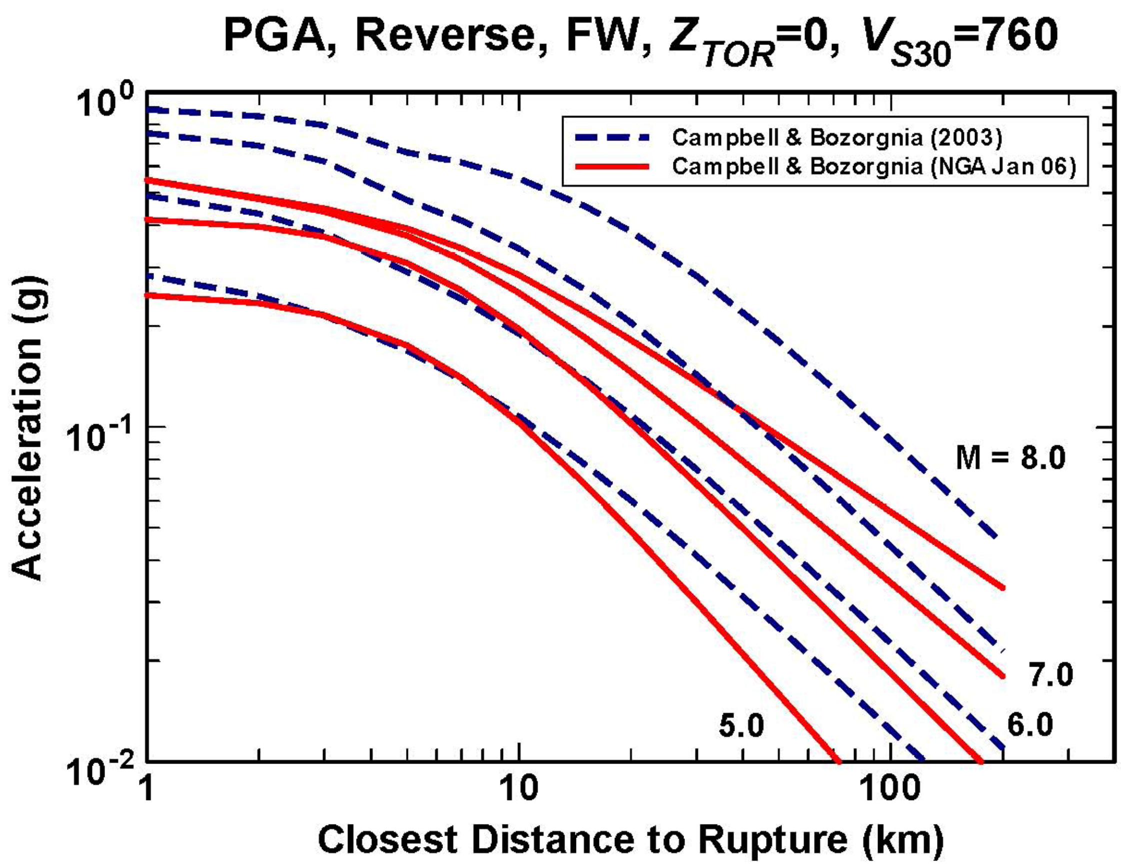
Empirical:	*Magnitude*	*Distance*	*Soil Category*
Seismological:	*Shear Dislocation*	*Crustal Waveguide*	*Complex 3D Structure*

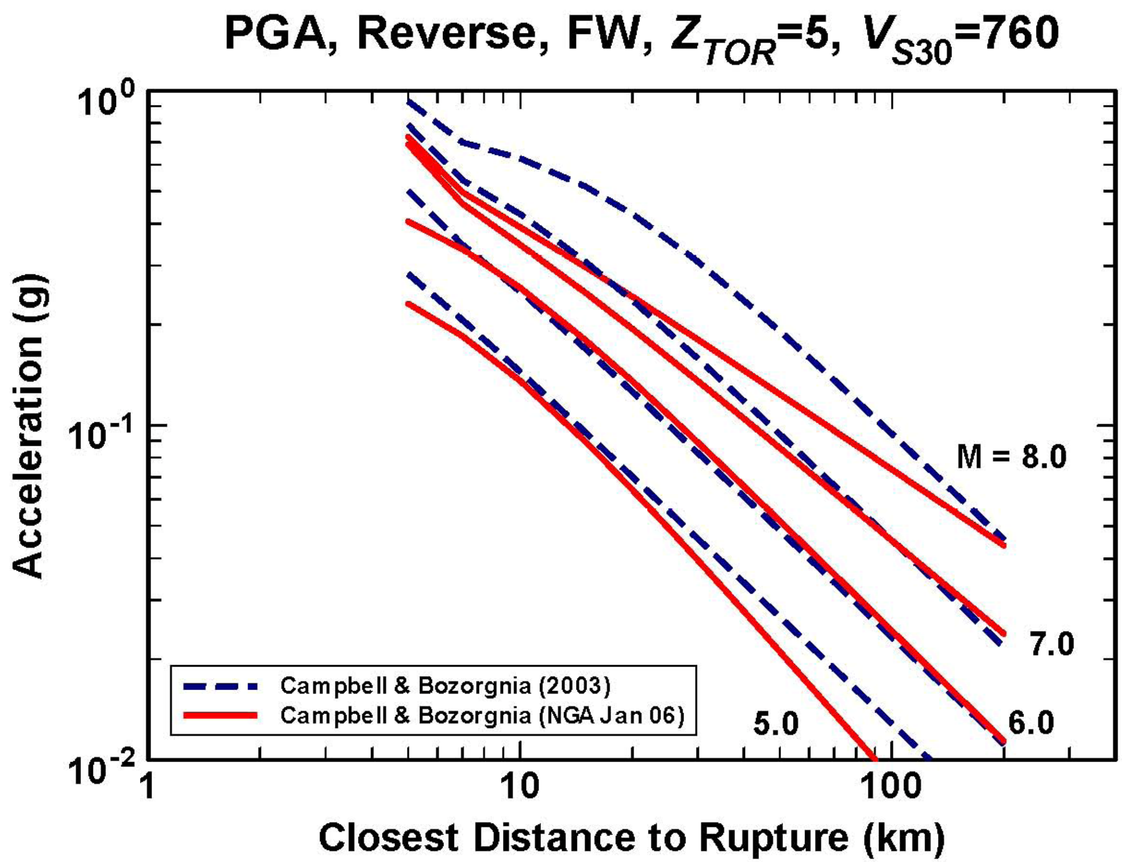


Shallow Asperity Events
Deep Asperity Events
Spectral Acceleration (g)
Denali-PS10
Kocaeli-Yarimca
Landers-Lucerne
Chi-Chi-TCU075
Loma Prieta - Lexington Dam
Northridge - Rinaldi
0
1
2
3
Period (sec)
Period (sec)

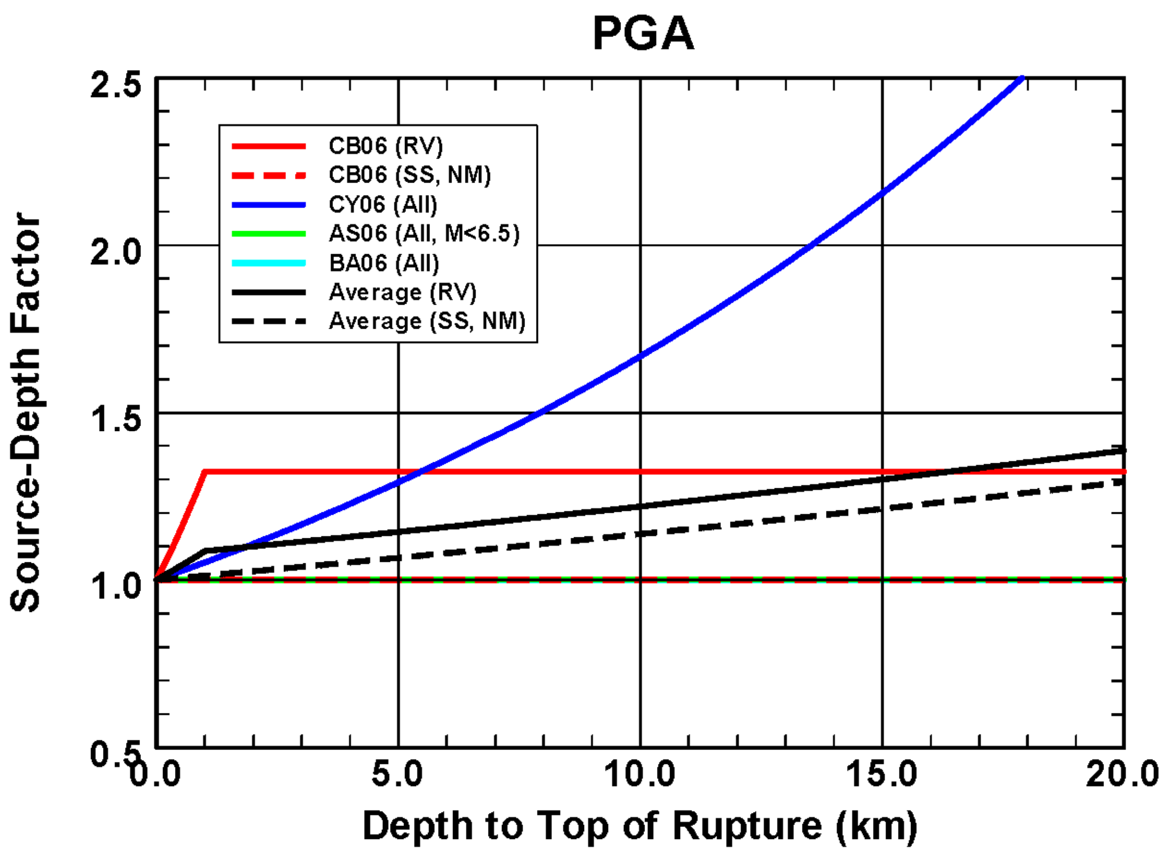


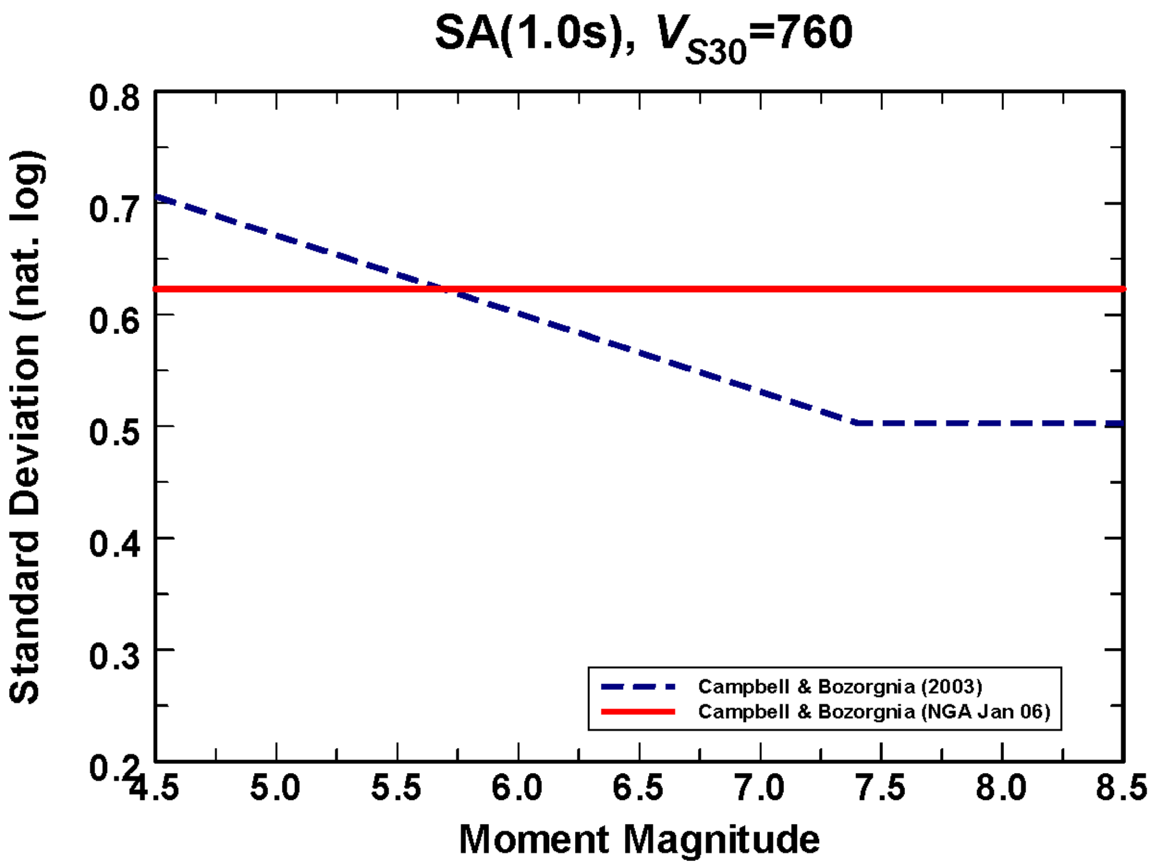
PGA, Strike Slip, V_{S30}=760
Campbell & Bozorgnia (2003)
Campbell & Bozorgnia (NGA Jan 06)
M = 8.0
7.0
6.0
5.0
10^0
10^{-1}
10^{-2}
1
10
100
Acceleration (g)
Closest Distance to Rupture (km)


PGA, Reverse, FW, Z_{TOR}=0, V_{S30}=760
Campbell & Bozorgnia (2003)
Campbell & Bozorgnia (NGA Jan 06)
M = 8.0
7.0
6.0
5.0
Acceleration (g)
Closest Distance to Rupture (km)
10^0
10^{-1}
10^{-2}
1
10
100

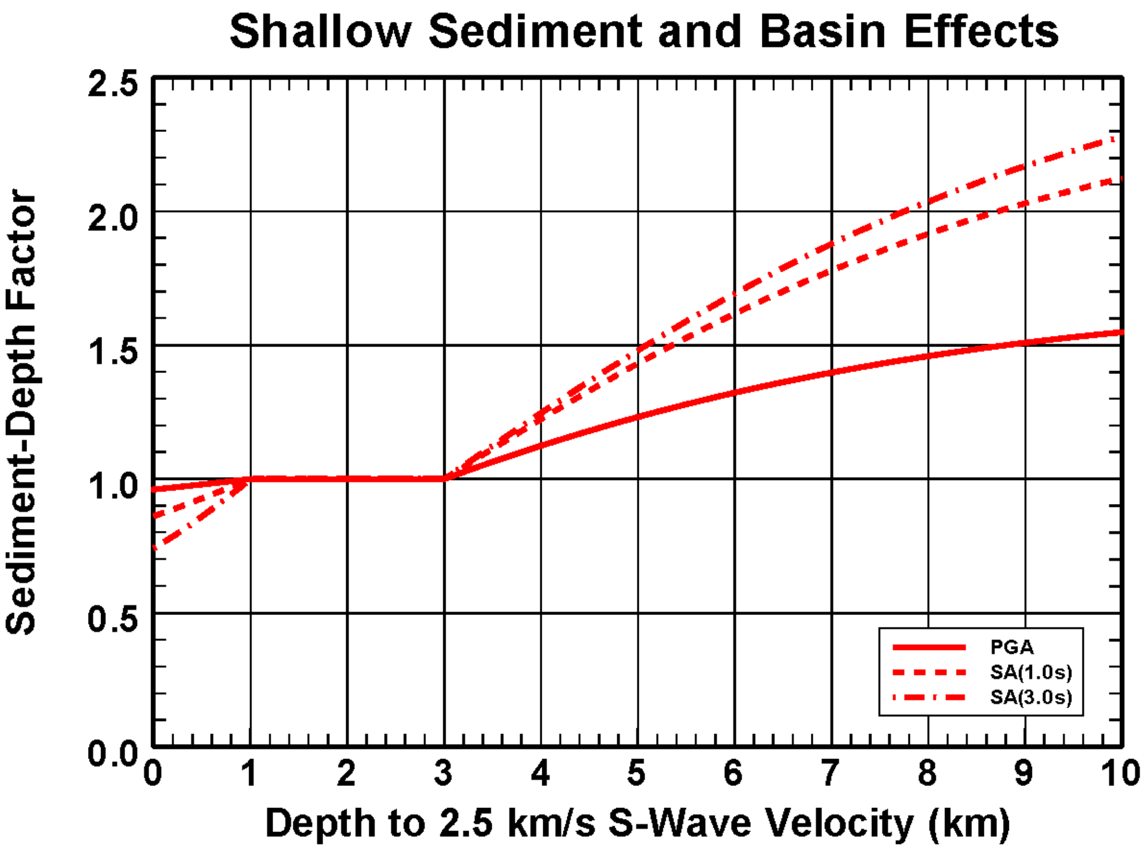


PGA, Reverse, FW, Z_TOR=5, V_S30=760
Acceleration (g)
Closest Distance to Rupture (km)
10^0
10^-1
10^-2
1
10
100
M = 8.0
7.0
6.0
5.0
Campbell & Bozorgnia (2003)
Campbell & Bozorgnia (NGA Jan 06)

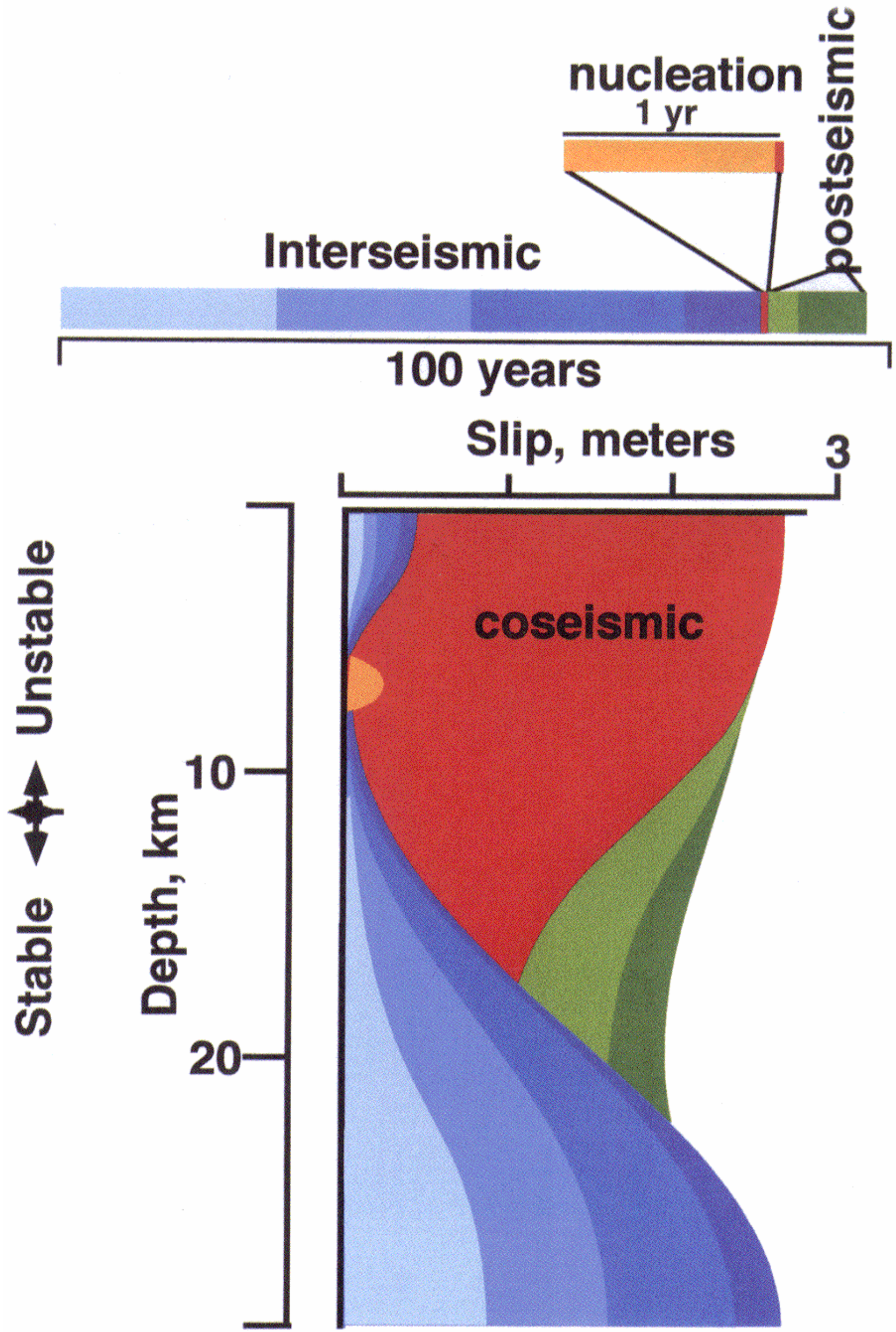

PGA
2.5
2.0
1.5
1.0
0.5
0.0
5.0
10.0
15.0
20.0
Source-Depth Factor
Depth to Top of Rupture (km)
CB06 (RV)
CB06 (SS, NM)
CY06 (All)
AS06 (All, M<6.5)
BA06 (All)
Average (RV)
Average (SS, NM)

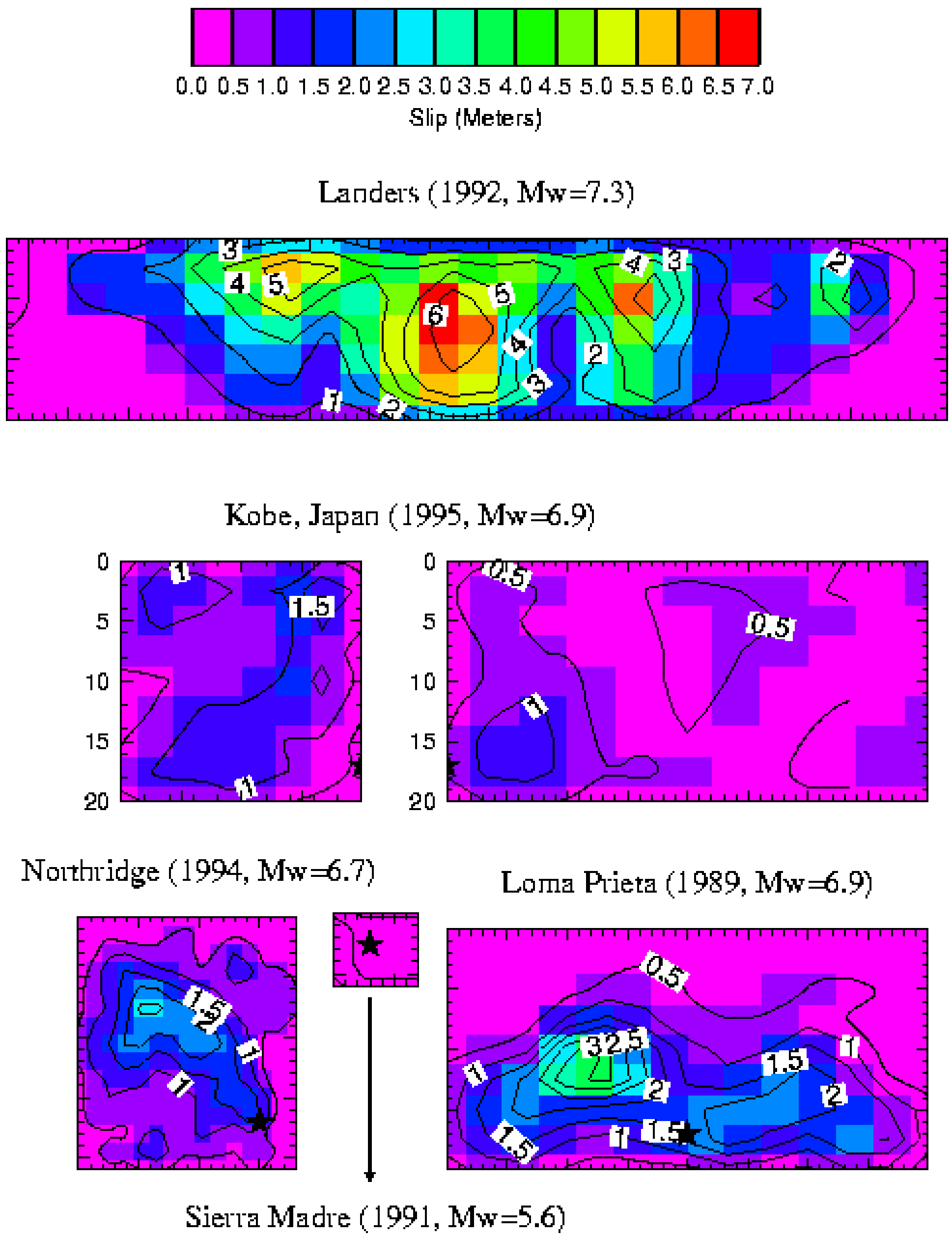


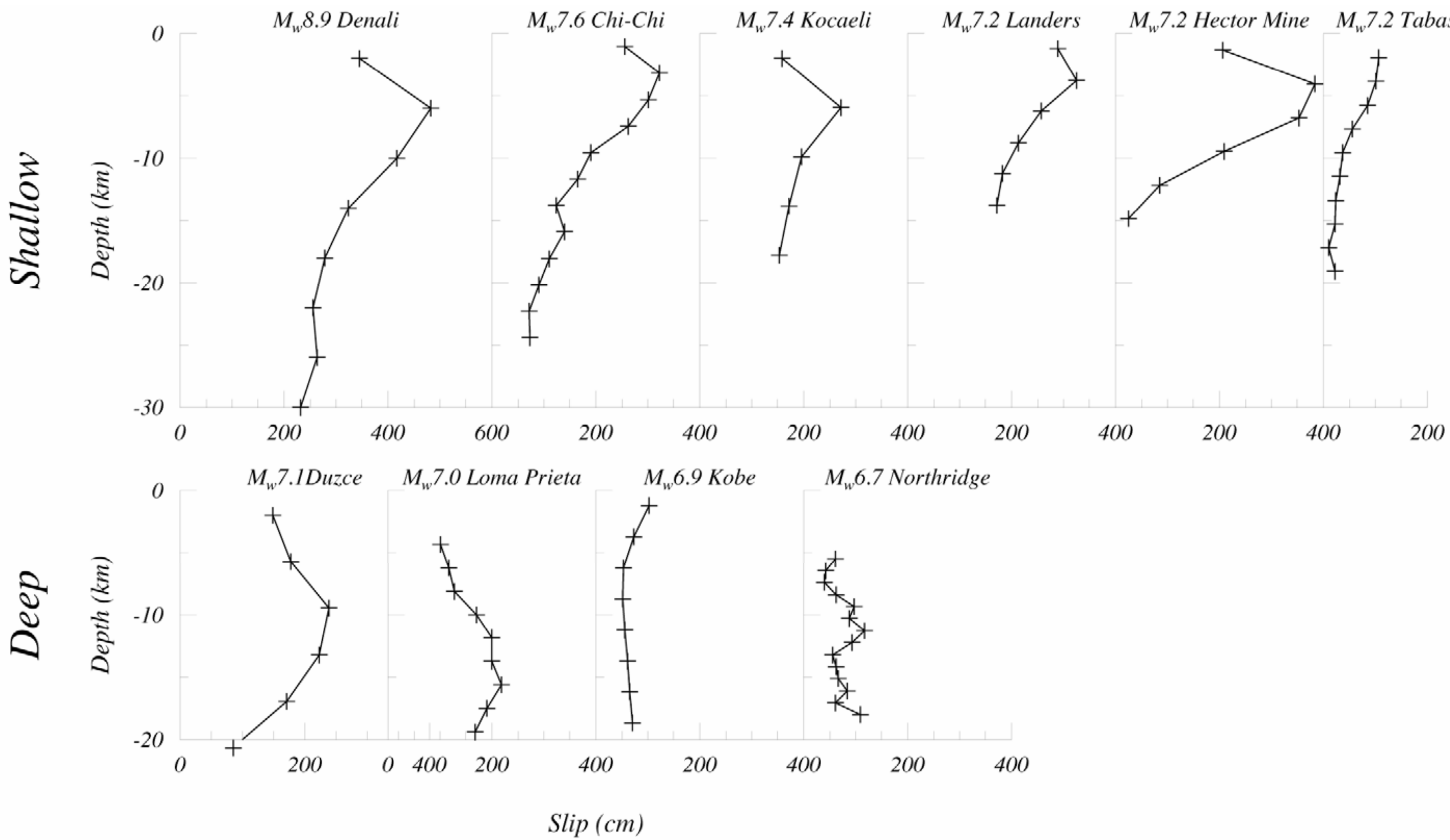
SA(1.0s), V_{S30}=760
0.8
0.7
0.6
0.5
0.4
0.3
0.2
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
Standard Deviation (nat. log)
Moment Magnitude
Campbell & Bozorgnia (2003)
Campbell & Bozorgnia (NGA Jan 06)



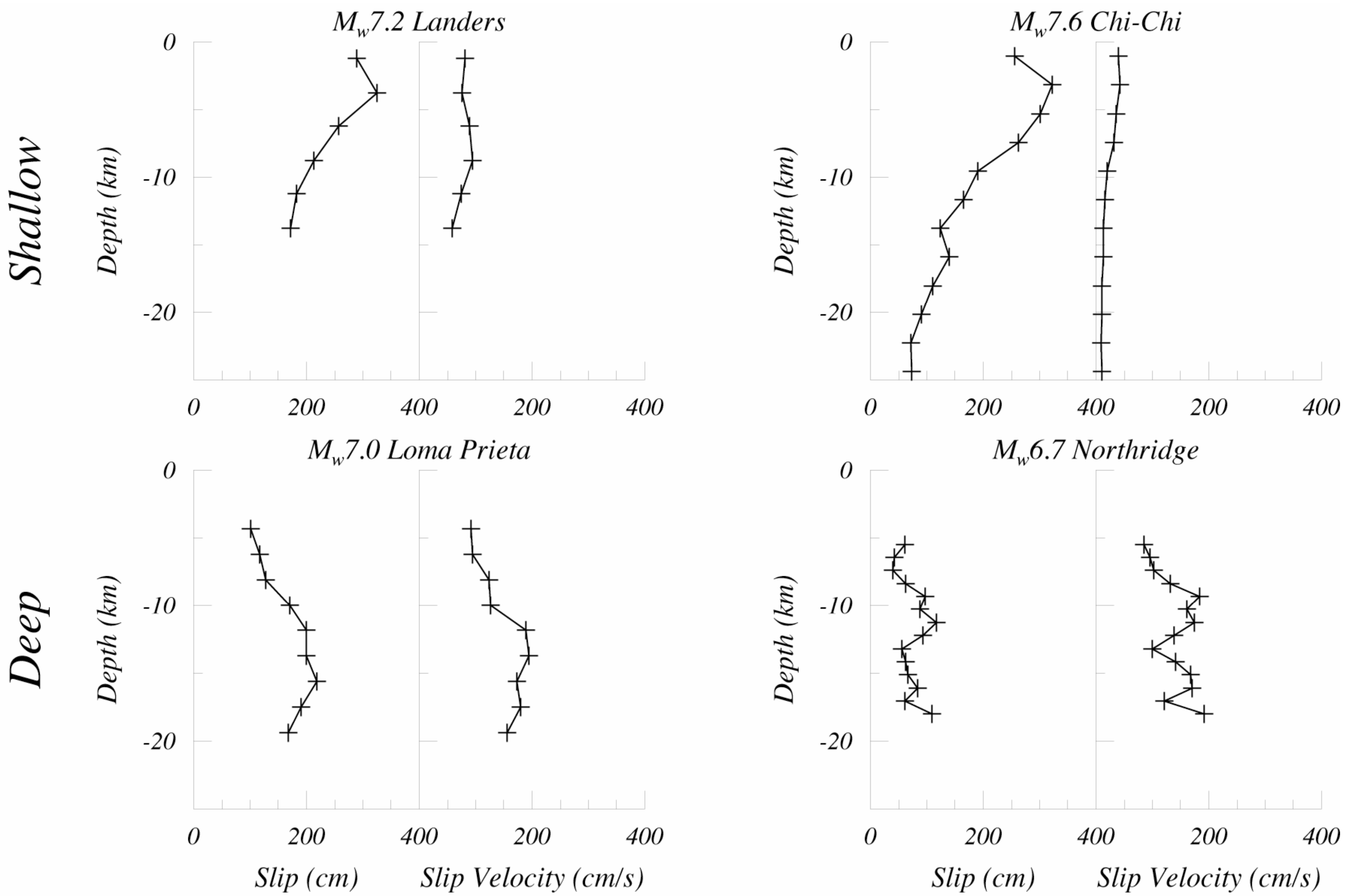
Shallow Sediment and Basin Effects
Sediment-Depth Factor
Depth to 2.5 km/s S-Wave Velocity (km)
0.0
0.5
1.0
1.5
2.0
2.5
0
1
2
3
4
5
6
7
8
9
10
PGA
SA(1.0s)
SA(3.0s)


nucleation
1 yr
postseismic
Interseismic
100 years
Slip, meters
3
coseismic
Stable
Unstable
Depth, km
10
20


0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0
Slip (Meters)
Landers (1992, Mw=7.3)
Kobe, Japan (1995, Mw=6.9)
Northridge (1994, Mw=6.7)
Loma Prieta (1989, Mw=6.9)
Sierra Madre (1991, Mw=5.6)



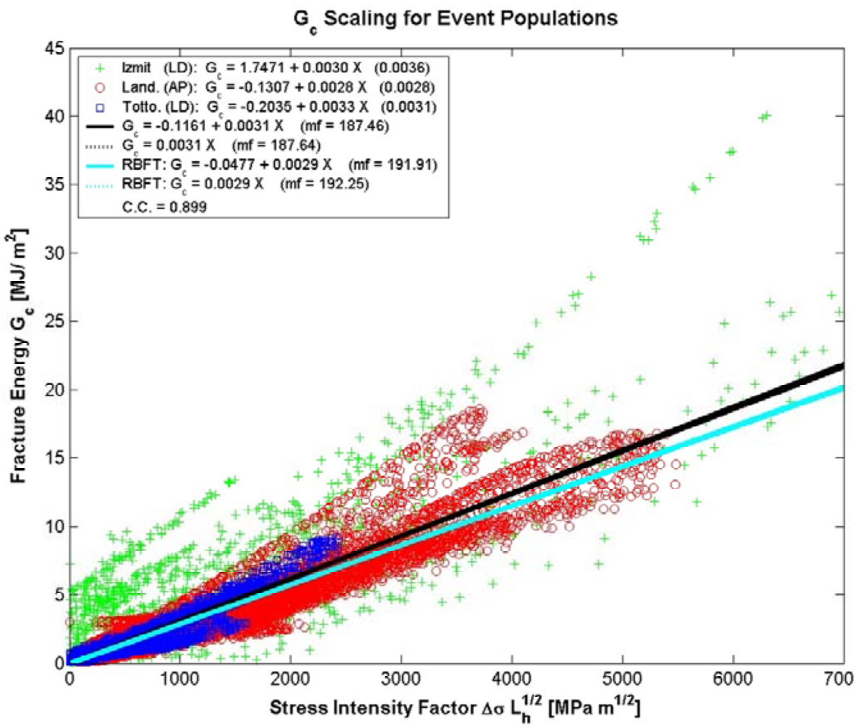
Shallow
Deep
Depth (km)
Depth (km)
M_w8.9 Denali
M_w7.6 Chi-Chi
M_w7.4 Kocaeli
M_w7.2 Landers
M_w7.2 Hector Mine
M_w7.2 Tabas
M_w7.1Duzce
M_w7.0 Loma Prieta
M_w6.9 Kobe
M_w6.7 Northridge
0
-10
-20
-30
0 200 400 600 200 400 200 400 200 400 200 400 200
0 200 0 400 200 400 200 400 200 400
Slip (cm)



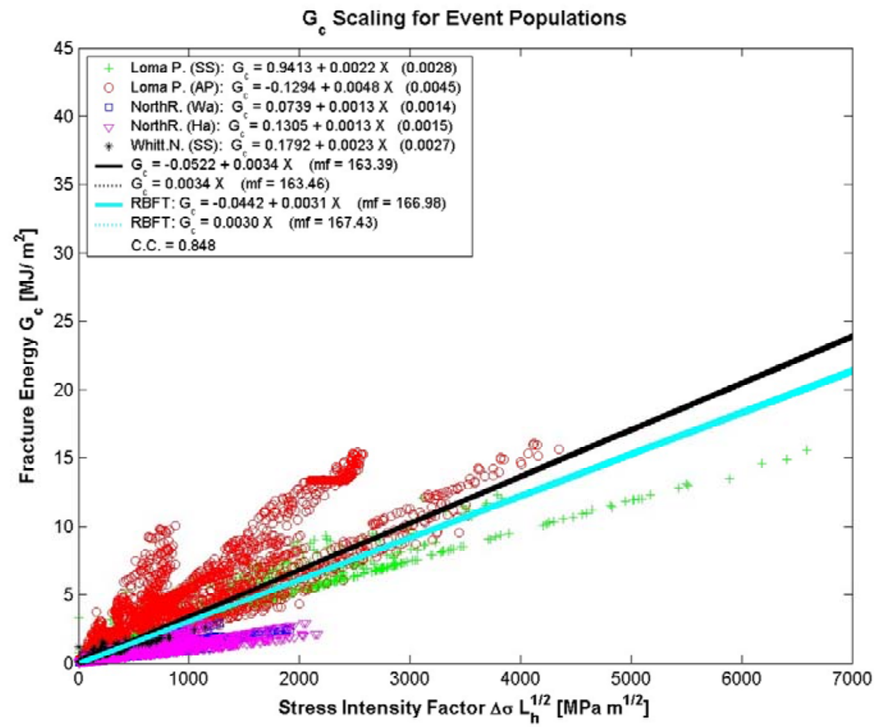
Shallow
Deep
M_w7.2 Landers
M_w7.6 Chi-Chi
M_w7.0 Loma Prieta
M_w6.7 Northridge
Depth (km)
0
-10
-20
0
200
400
200
400
Slip (cm)
Slip Velocity (cm/s)

Depth Dependent Characteristics of Kinematic Rupture Models

- In shallow faulting, fault slip displacement may be large but slip velocity may be small
- In buried faulting, fault slip displacement may be small but slip velocity may be large



G_c Scaling for Event Populations
Izmit (LD): G_c = 1.7471 + 0.0030 X (0.0036)
Land. (AP): G_c = -0.1307 + 0.0028 X (0.0028)
Totto. (LD): G_c = -0.2035 + 0.0033 X (0.0031)
G_c = -0.1161 + 0.0031 X (mf = 187.46)
G_c = 0.0031 X (mf = 187.64)
RBFT: G_c = -0.0477 + 0.0029 X (mf = 191.91)
RBFT: G_c = 0.0029 X (mf = 192.25)
C.C. = 0.899
Fracture Energy G_c [MJ/ m^2]
Stress Intensity Factor Δσ L_h^1/2 [MPa m^1/2]



G_c Scaling for Event Populations
Loma P. (SS): G_c = 0.9413 + 0.0022 X (0.0028)
Loma P. (AP): G_c = -0.1294 + 0.0048 X (0.0045)
NorthR. (Wa): G_c = 0.0739 + 0.0013 X (0.0014)
NorthR. (Ha): G_c = 0.1305 + 0.0013 X (0.0015)
Whitt.N. (SS): G_c = 0.1792 + 0.0023 X (0.0027)
G_c = -0.0522 + 0.0034 X (mf = 163.39)
G_c = 0.0034 X (mf = 163.46)
RBFT: G_c = -0.0442 + 0.0031 X (mf = 166.98)
RBFT: G_c = 0.0030 X (mf = 167.43)
C.C. = 0.848
Fracture Energy G_c [MJ/ m^2]
Stress Intensity Factor Δσ L_h^1/2 [MPa m^1/2]

Fracture Energy and Stress Intensity Factor

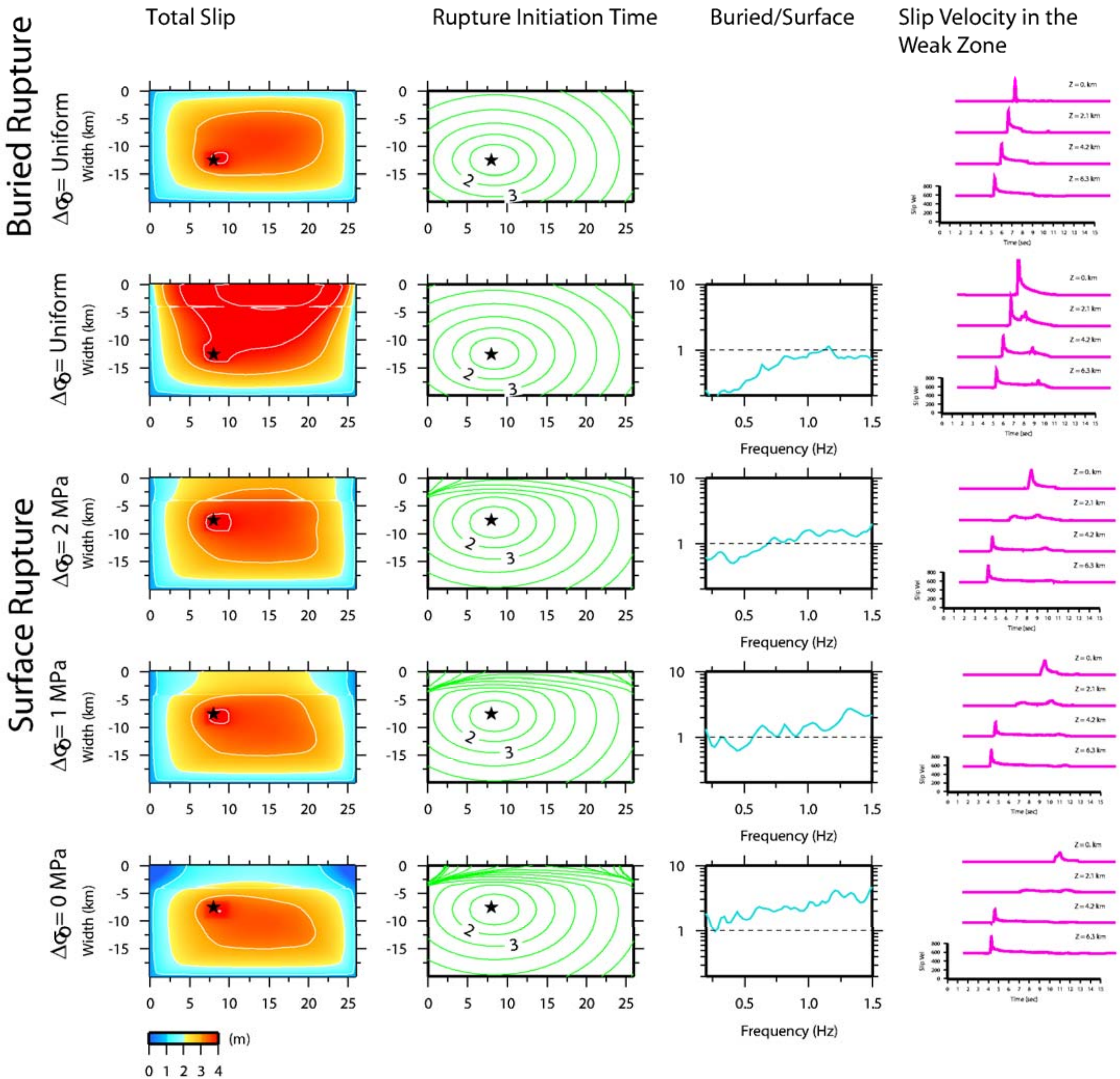
- Large for surface faulting events
- Small for subsurface events

- Large fracture energy events may produce mainly long period seismic radiation
- This is consistent with surface faulting events producing weak high frequency ground motions

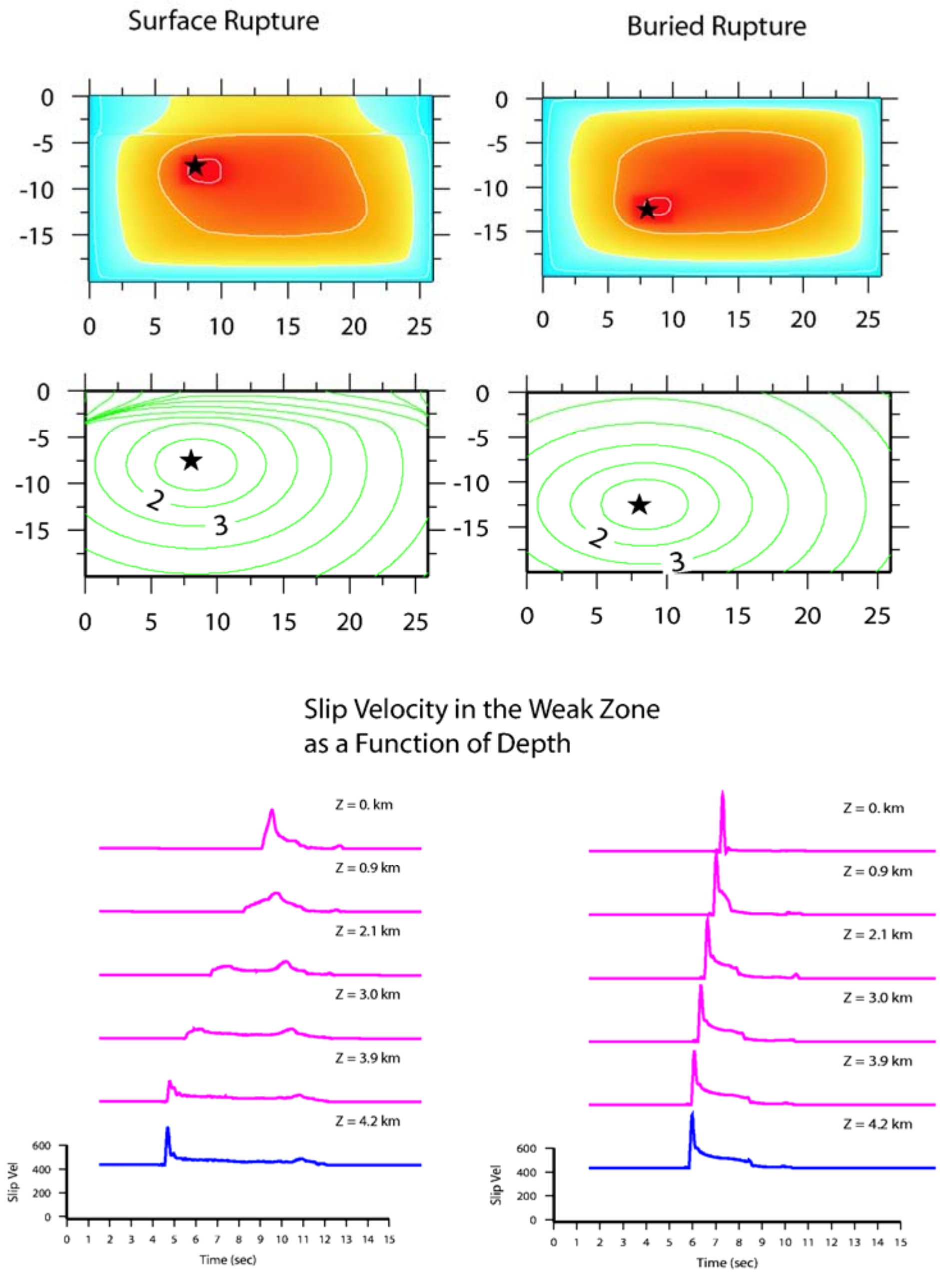
Dynamic Rupture Modeling of Shallow Faulting

- Shallow zone modeled using low stress drop and large slip weakening distance Dc
- Velocity hardening in the weak shallow zone (upper 5 km) reduces the ground motion level of surface faulting earthquakes

Dynamic Modeling of Buried and Surface Faulting



Larger Slip Velocity for Buried than for Surface Faulting



Features of Rupture in the Shallow Part of Fault (0 – 5 km depth)

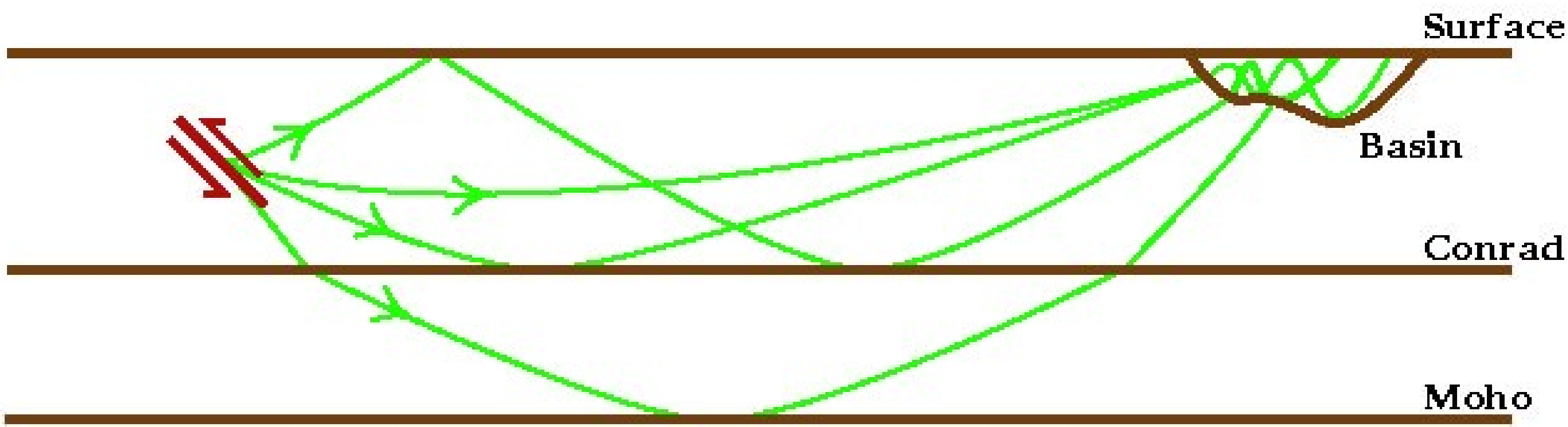
- Controlled by velocity strengthening
- Larger slip weakening distance Dc
- Larger fracture energy i.e.much energy absorbed from the crack tip
- Lower rupture velocity
- Lower slip velocity
- Causes lower ground motions for surface faulting than for buried faulting events

Ground Motion Time Histories from Simulation

- Ground motions are conventionally represented by a probabilistic response spectrum
- Nonlinear time domain response analysis requires time histories
- Simulation procedures can be used to generate source and site specific time histories for scenario earthquakes that dominate the probabilistic response spectrum
- Large scale simulations can be used to provide a probabilistic description of the ground motions in the form of large suites of time histories

Ground Motion Prediction Models

	Earthquake Source	Path	Site
Empirical:	*Magnitude*	*Distance*	*Soil Category*
Seismological:	*Shear Dislocation*	*Crustal Waveguide*	*Complex 3D Structure*



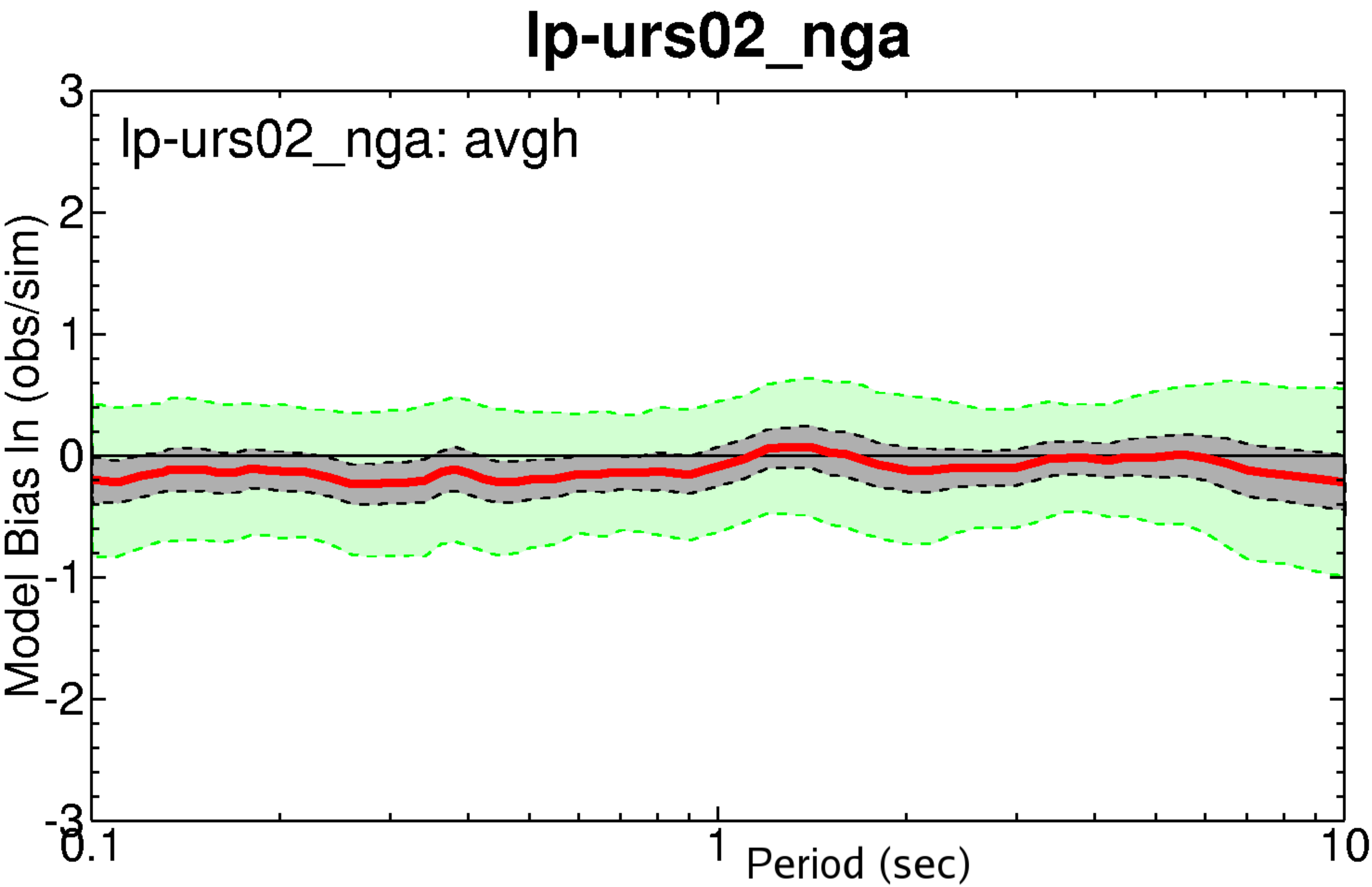
Ground Motion Effects Represented by Simulations

Related to fault and station geometry:

- Rupture directivity effects
- Hanging wall effects

Related also to underground structure:

- Basin effects and basin edge effects

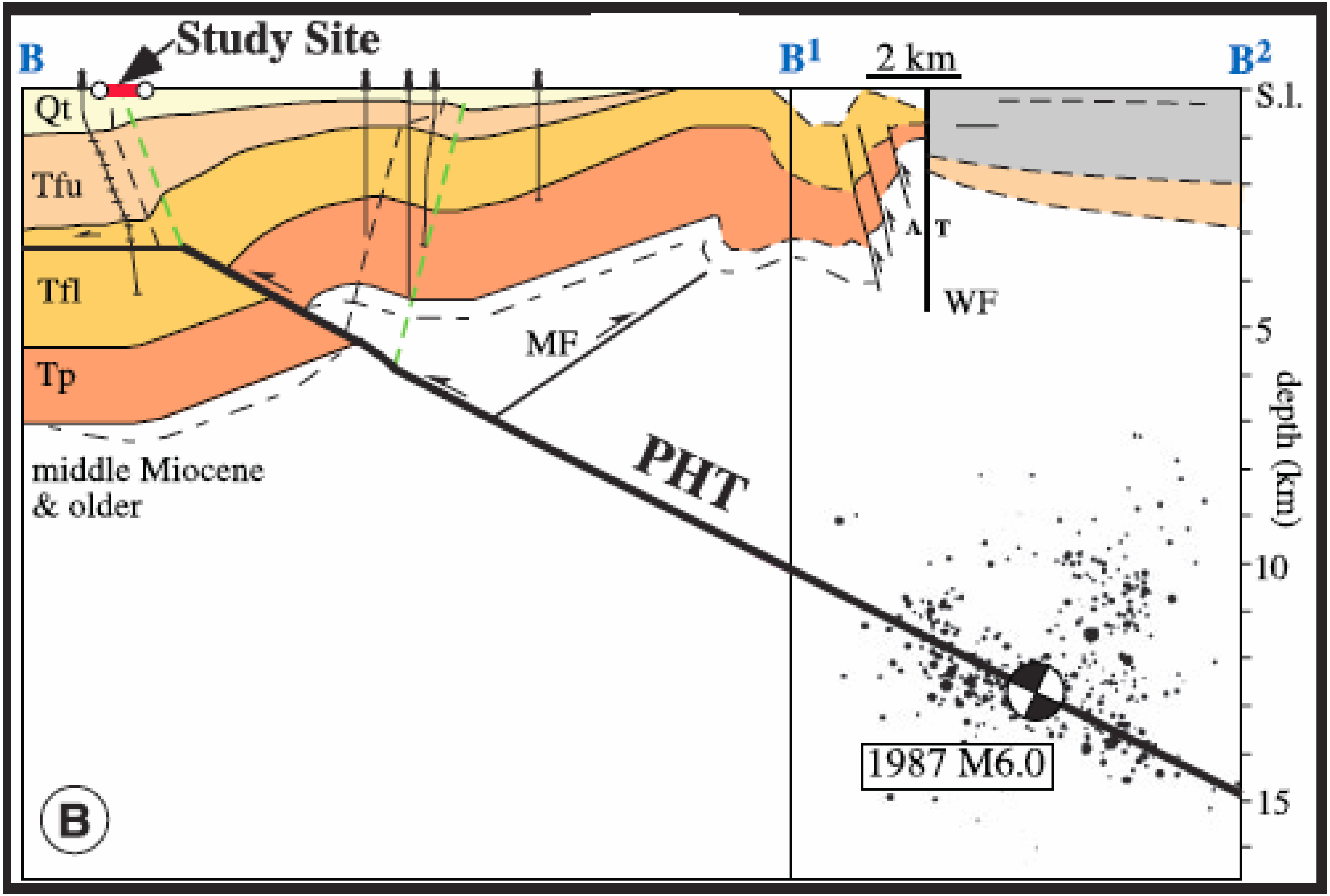

lp-urs02_nga
lp-urs02_nga: avgh
Model Bias ln (obs/sim)
3
2
1
0
-1
-2
-3
0.1
1
10
Period (sec)

Simulation Approach to Ground Motion Prediction

- Go beyond “empirical” ground motion attenuation equations (NGA)
- Use physics-based strong motion simulation procedures
- Large scale simulations

    Scenario - Terashake

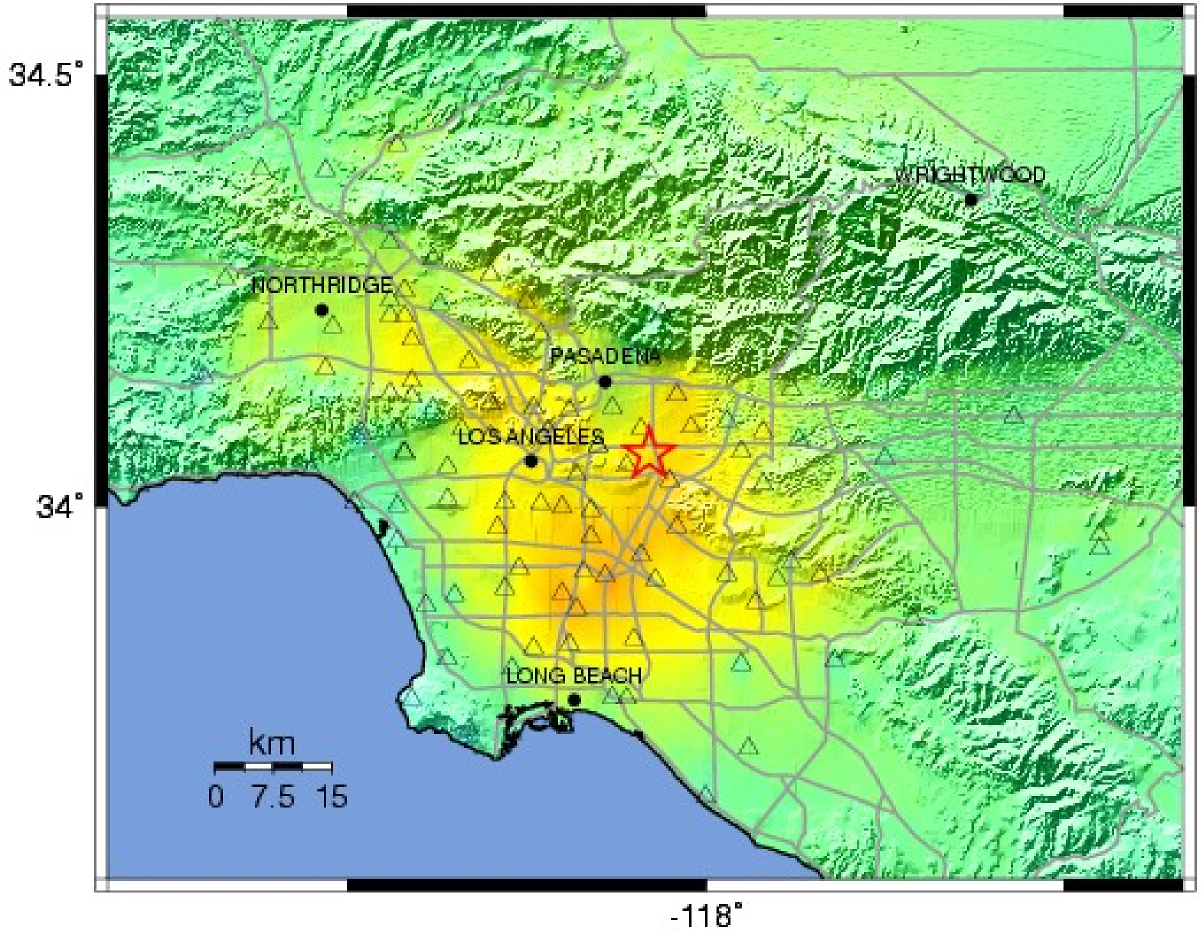
    Probabilistic - Cybershake



Study Site
B
B1
2 km
B2
S.l.
Qt
Tfu
Tfl
Tp
A
T
WF
MF
PHT
middle Miocene
& older
5
10
15
depth (km)
1987 M6.0
B

TriNet Rapid Instrumental Intensity Map for Whittier Narrows Earthquake

Thu Oct 1, 1987 07:42:20 AM PDT M 5.9 N34.06 W118.08 Depth: 9.5km ID:Whittier_Narrows



PROCESSED: Wed Sep 25, 2002 05:09:06 PM PDT,

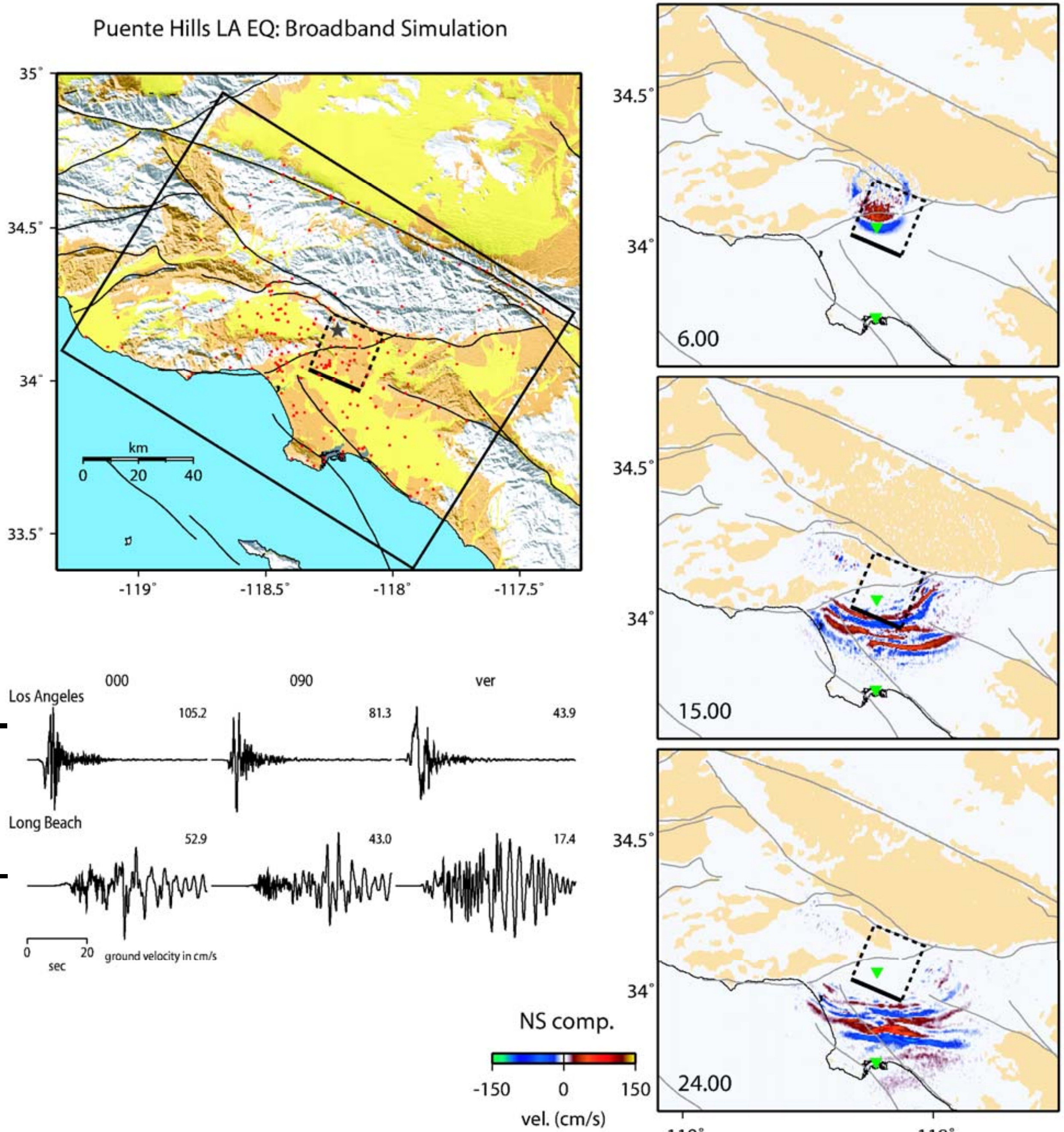
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Focusing of Energy by Rupture Directivity and Basin Effects

Puente Hills Blind Thrust

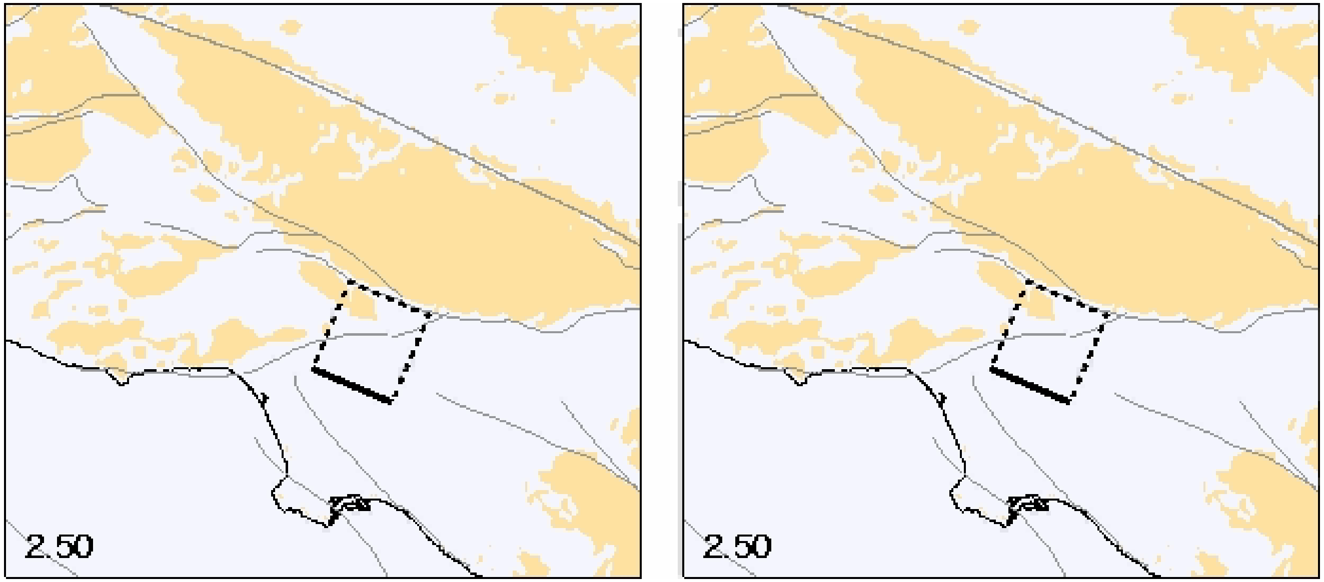
Los Angeles - Directivity

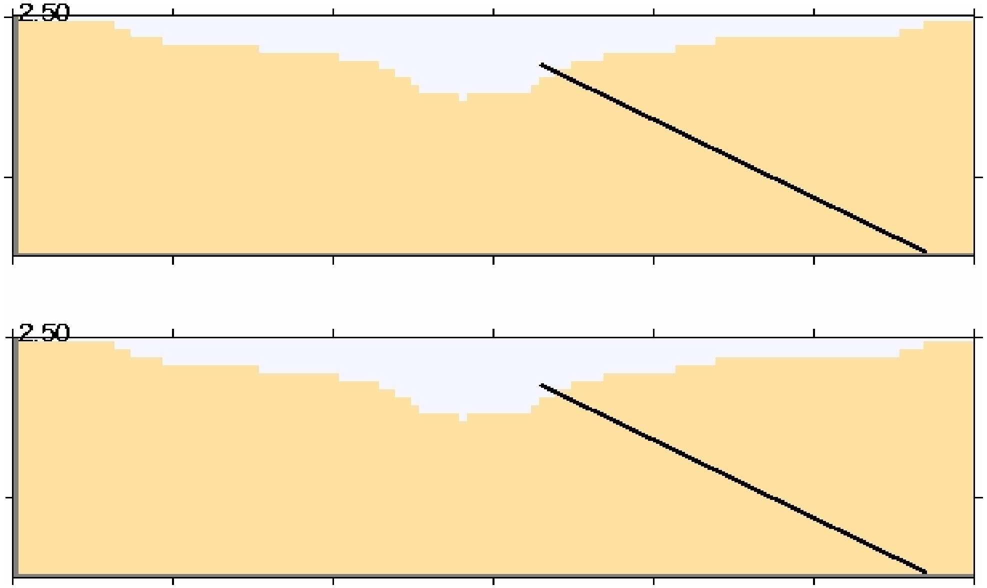
Long Beach – Basin Effect

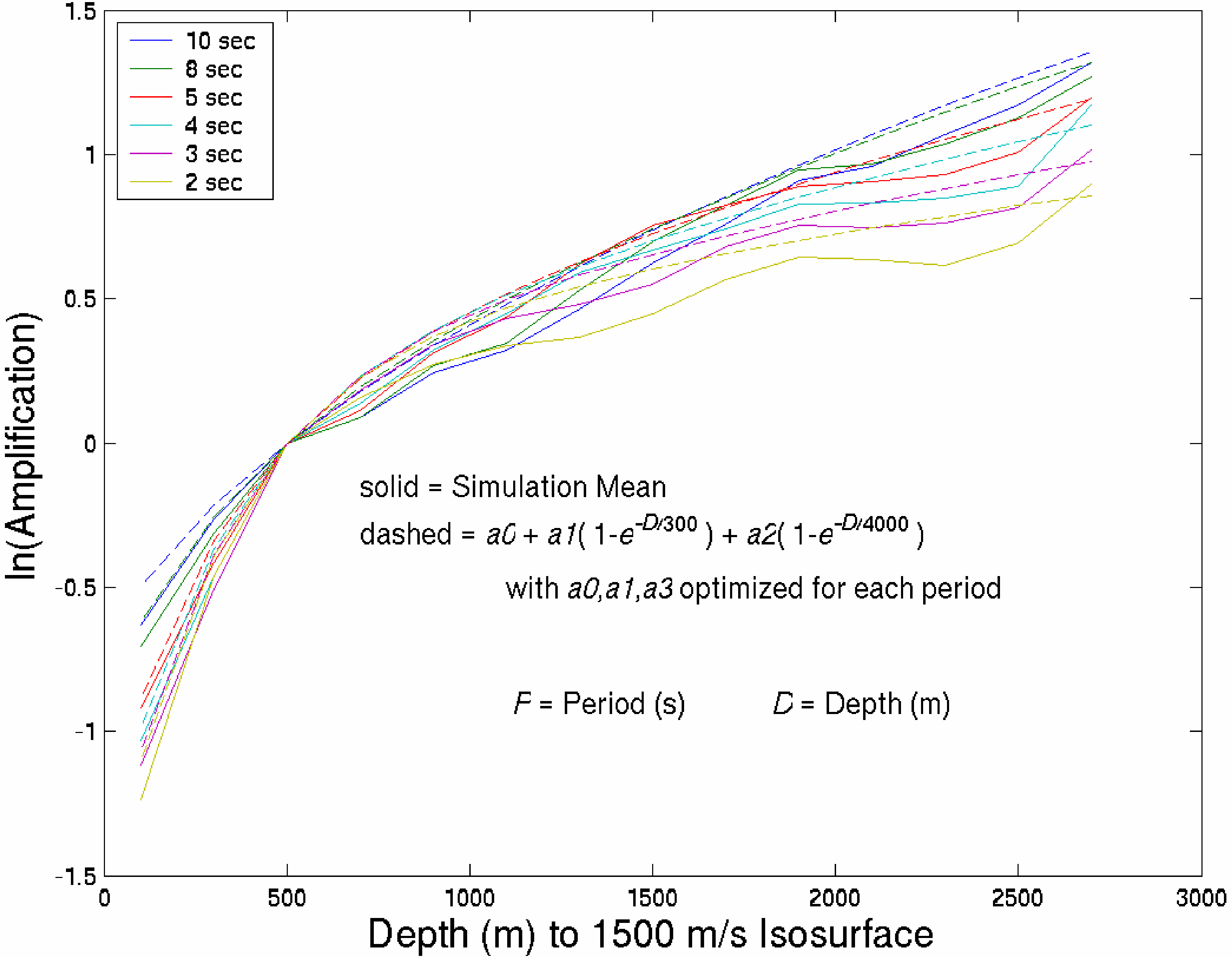


No Picture

Kobe-EQ.mov

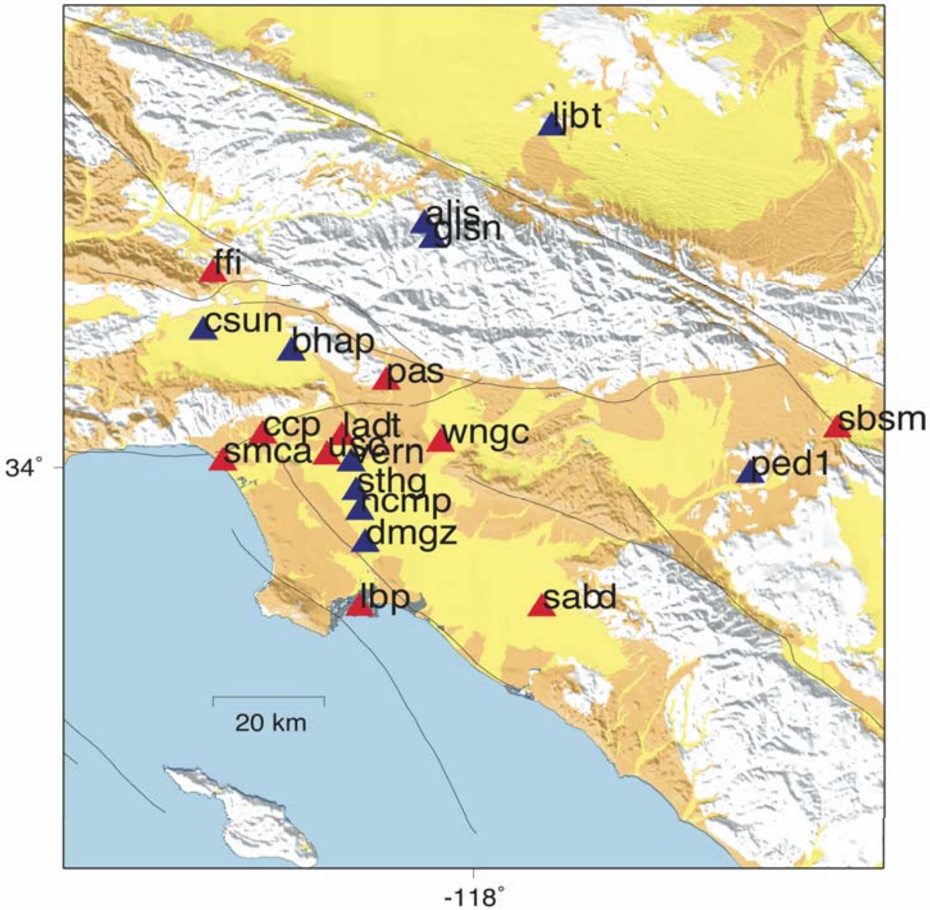

2.50
2.50


2.50
2.50



10 sec
8 sec
5 sec
4 sec
3 sec
2 sec
solid = Simulation Mean
dashed = a0 + a1(1-e^-D/300) + a2(1-e^-D/4000)
with a0,a1,a3 optimized for each period
F = Period (s)
D = Depth (m)
ln(Amplification)
Depth (m) to 1500 m/s Isosurface
1.5
1
0.5
0
-0.5
-1
-1.5
0
500
1000
1500
2000
2500
3000

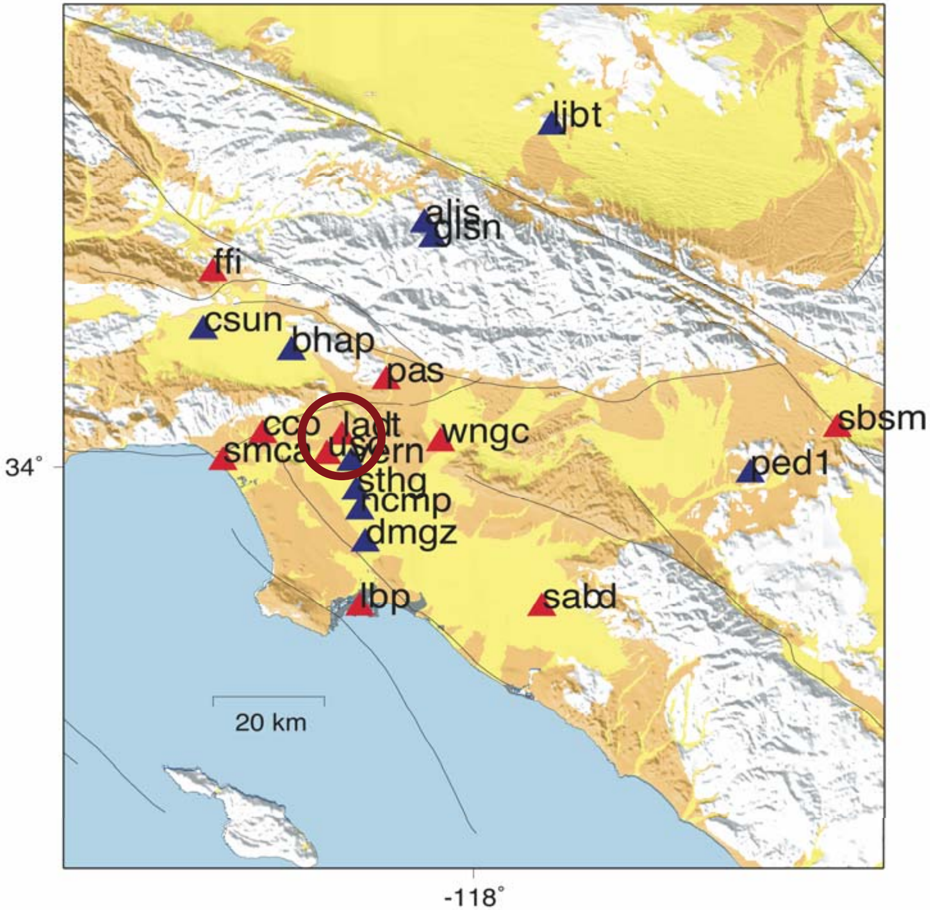
CyberShake Platform

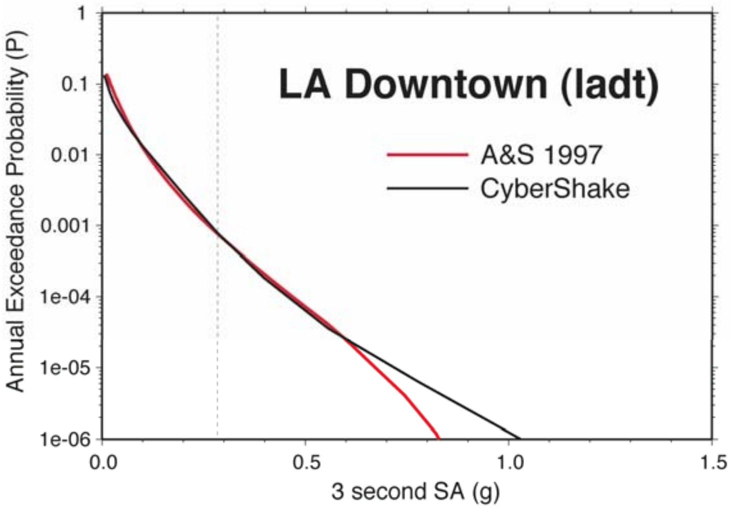


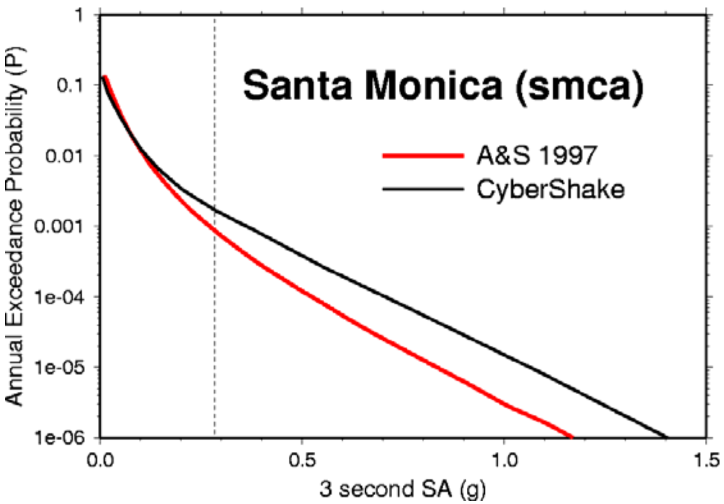
- Simulates ground motions for potential fault ruptures within 200 km of each site
  - ~ 12,700 sources in Southern California from USGS 2002 earthquake source model
- Extends USGS 2002 to multiple hypocenters and slip models for each source
  - ~ 100,000 ground motion simulations for each site

Robert Graves et al., SCEC

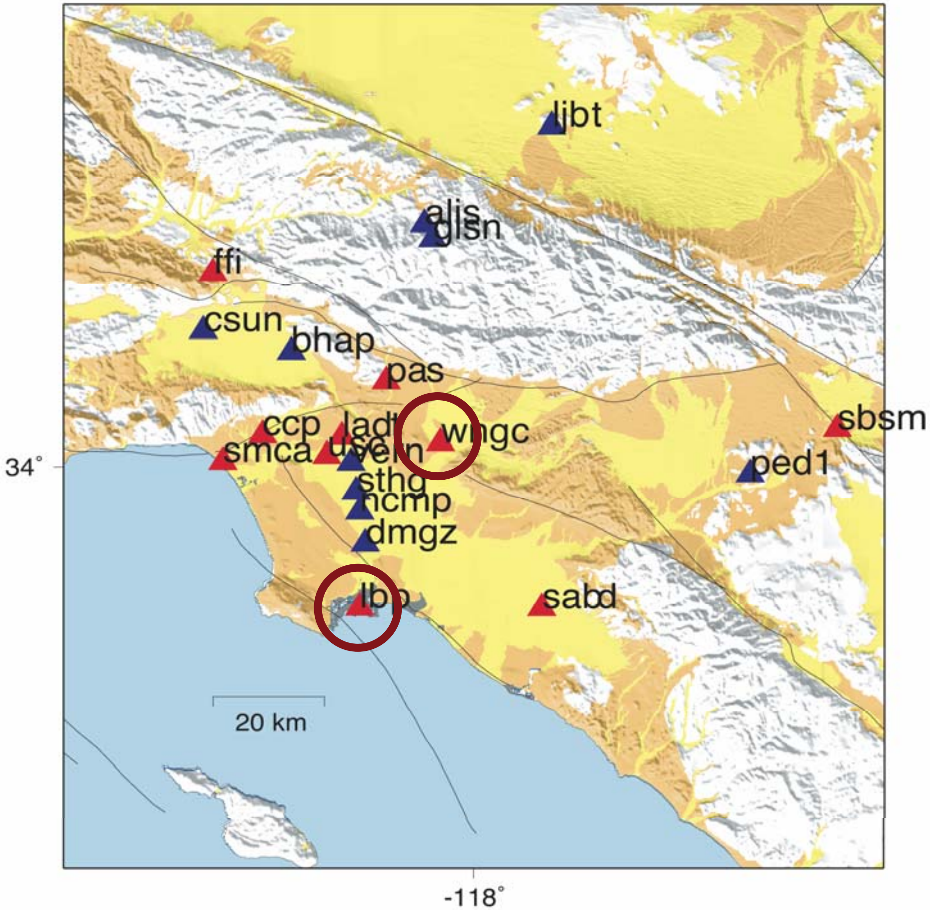
CyberShake Platform

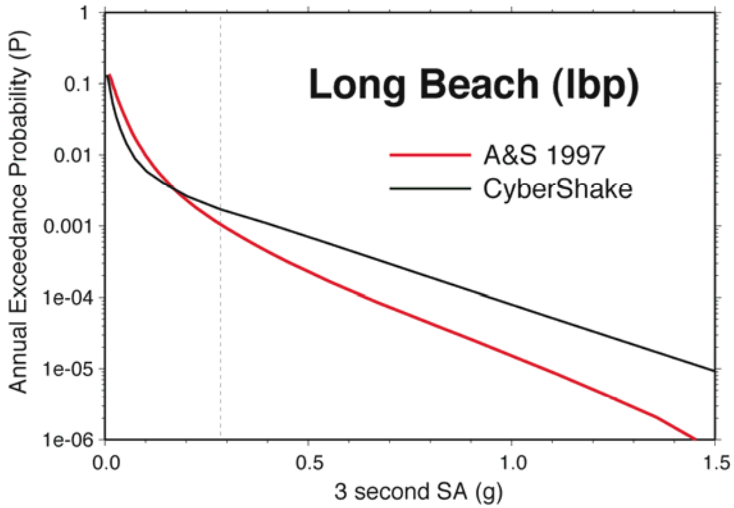


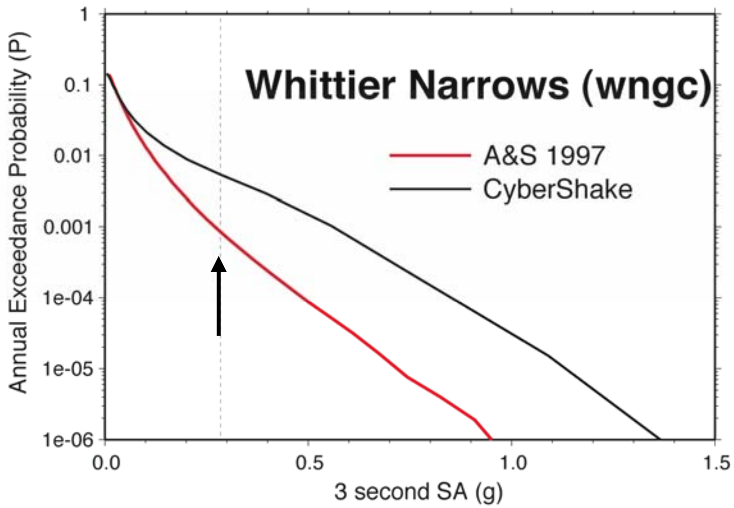




CyberShake Platform

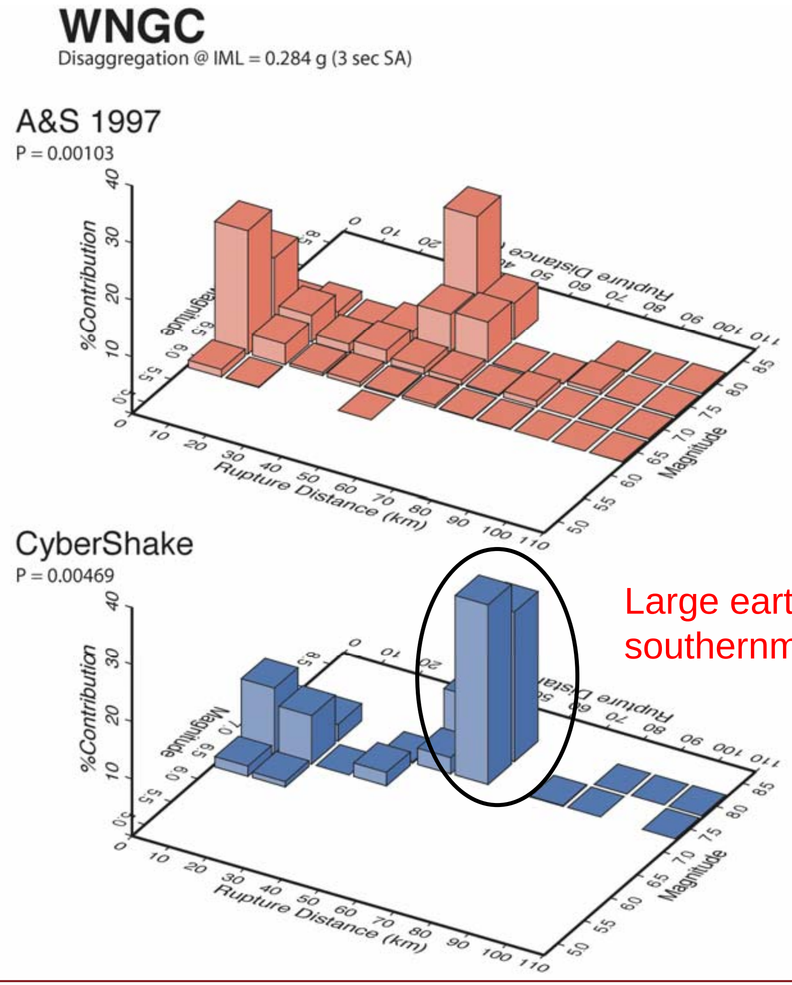






CyberShake Platform

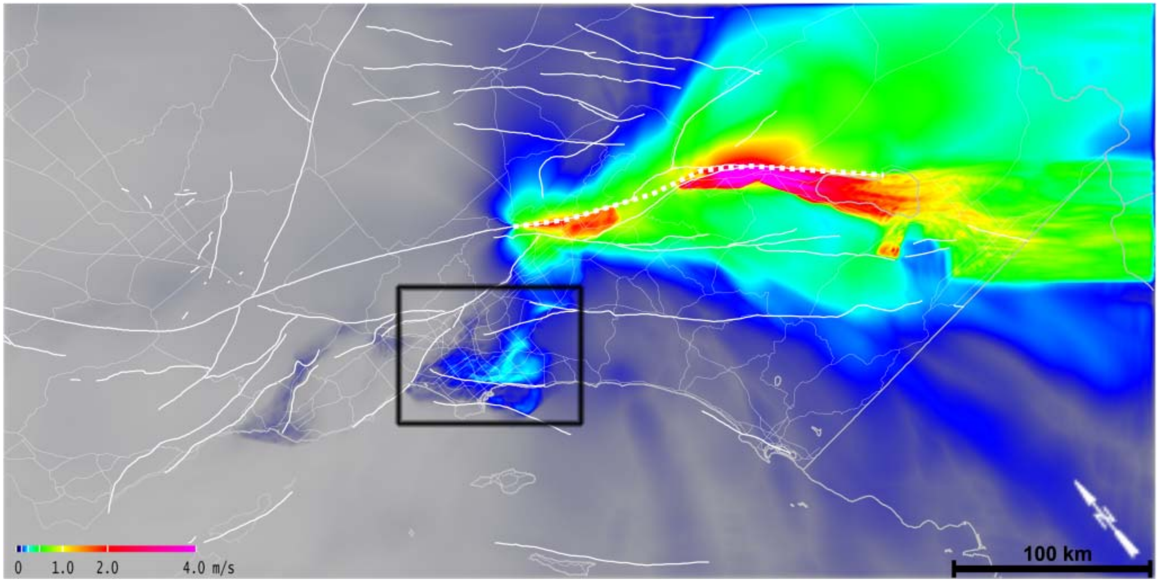
Disaggregation for Whittier at 0.28 g

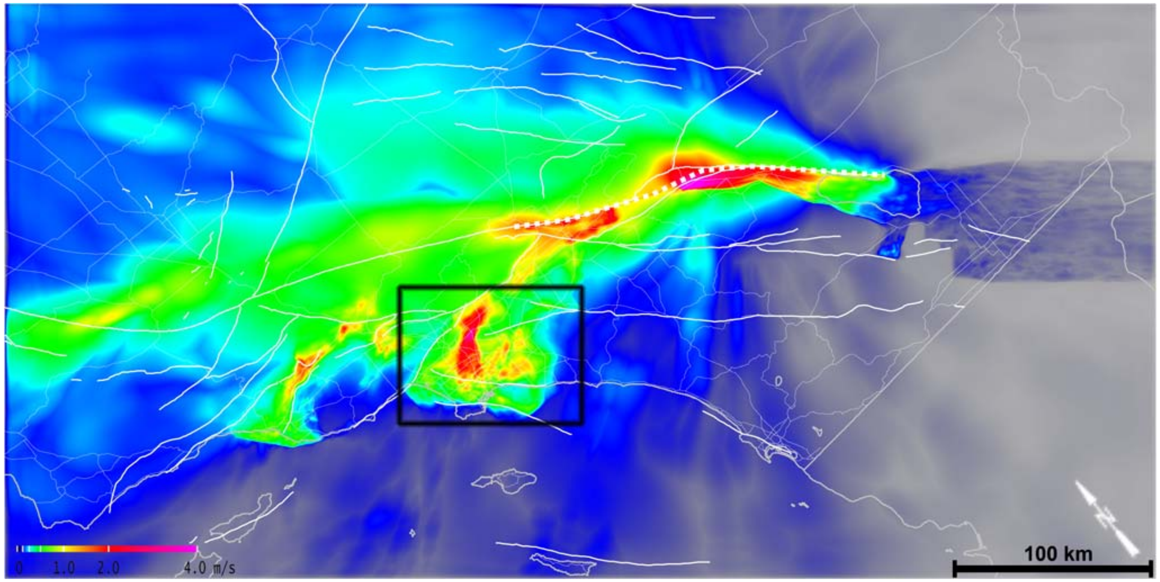


Large earthquakes on southernmost SAF

Robert Graves et al., SCEC

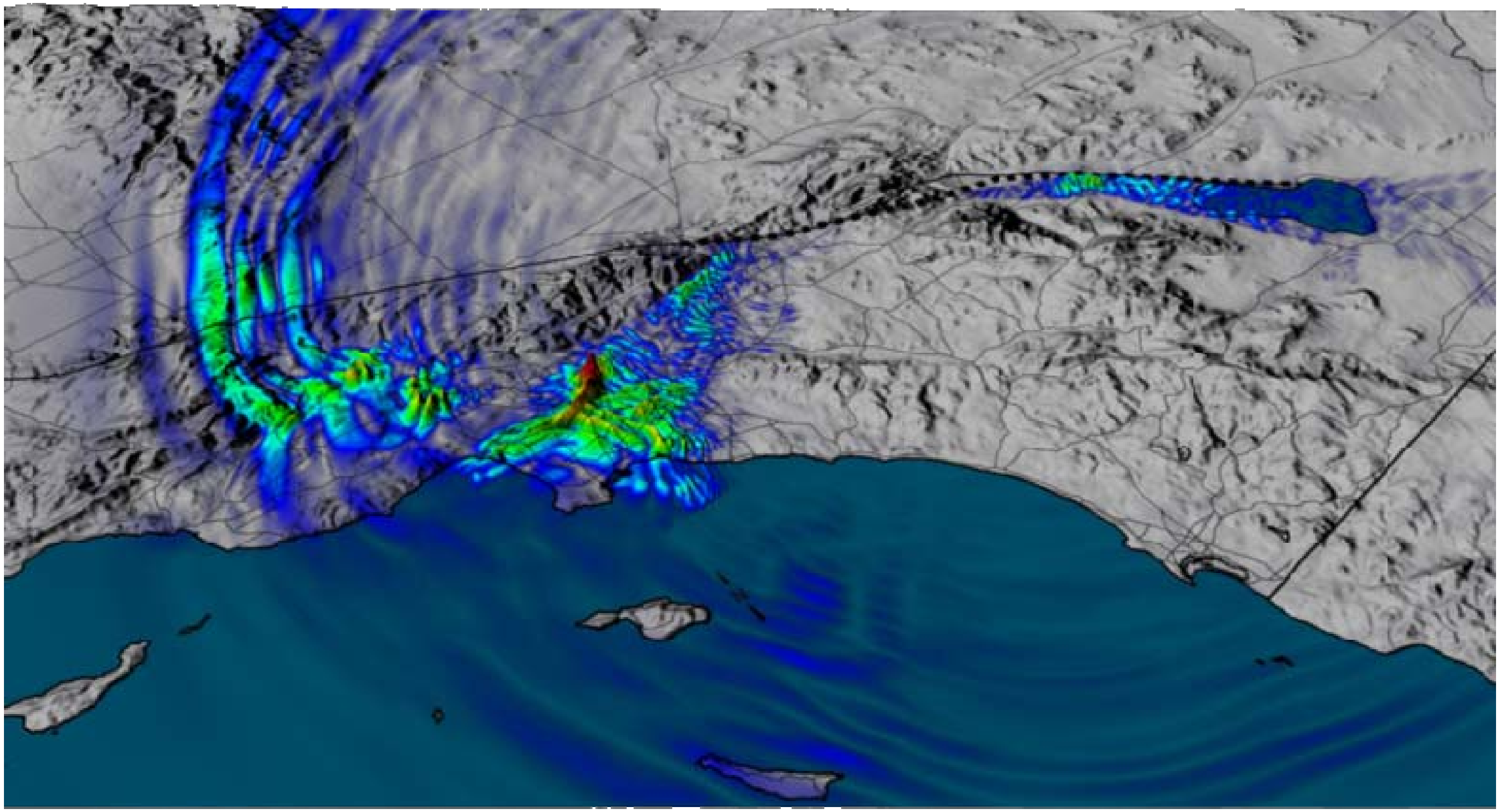
TeraShake:
Southern San Andreas Fault Earthquake





TeraShake Platform

M7.7 Earthquake on Southernmost San Andreas Fault



Summary – Part 1

- New ground motion models predict weaker ground motions for large earthquakes
- Weak ground motions from large surface faulting earthquakes can be explained physically as resulting from ductile behaviour in the shallow crust
- Ground motion prediction using empirical models is subject to large random variability
- Simulations may be able to reduce that variability at long periods e.g. in directivity and basin effects

Summary – Part 2

- Ground motions are conventionally represented by a probabilistic response spectrum
- Nonlinear time domain response analysis requires time histories
- Simulation procedures can be used to generate source and site specific time histories for scenario earthquakes that dominate the probabilistic response spectrum
- Large scale simulations can be used to provide a probabilistic description of the ground motions in the form of large suites of time histories