Differences in Source and Ground Motion Characteristics between Shallow and Buried Faulting

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Evidence for Differences in Source and Ground Motion Characteristics between Surface and Buried Earthquakes

- Asperity characteristics
- Recorded ground motions
- Presence of precariously balanced rocks near major surface faults
- Slip velocities from kinematic rupture models of past earthquakes
- Fracture energy from dynamic rupture models of past earthquakes
- Velocity hardening in dynamic rupture models

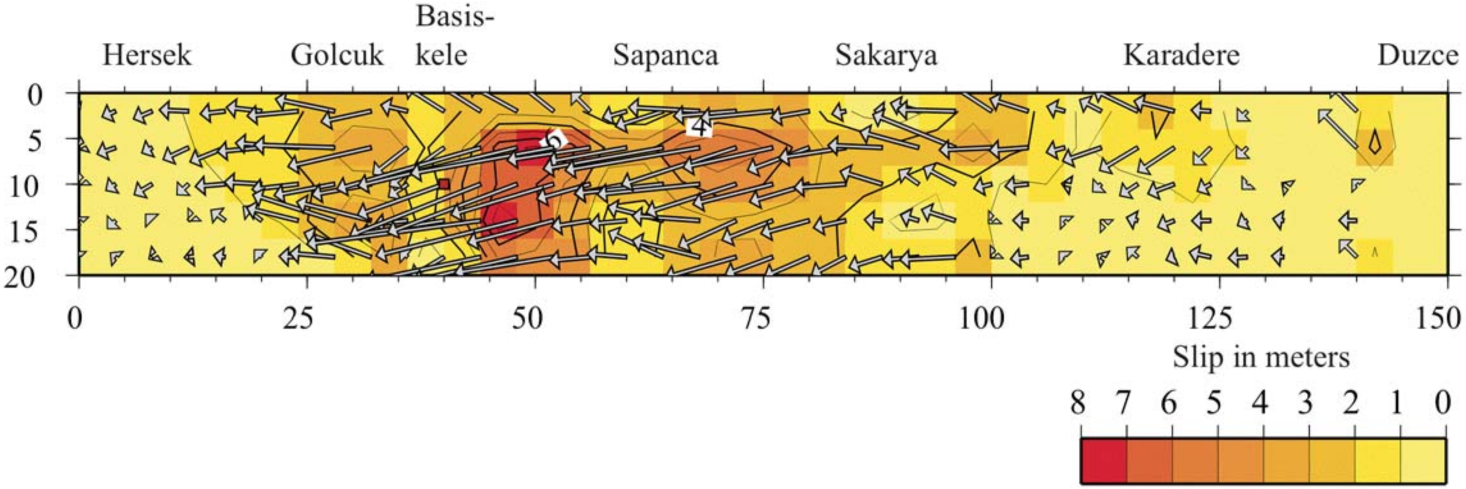


Figure 11. Our final slip map for the 1999 Kocaeli earthquake based on the inversion of teleseismic, surface wave, strong motion and geodetic data. The model was obtained for a maximum overall slip rupture velocity of 3.25 km/sec.

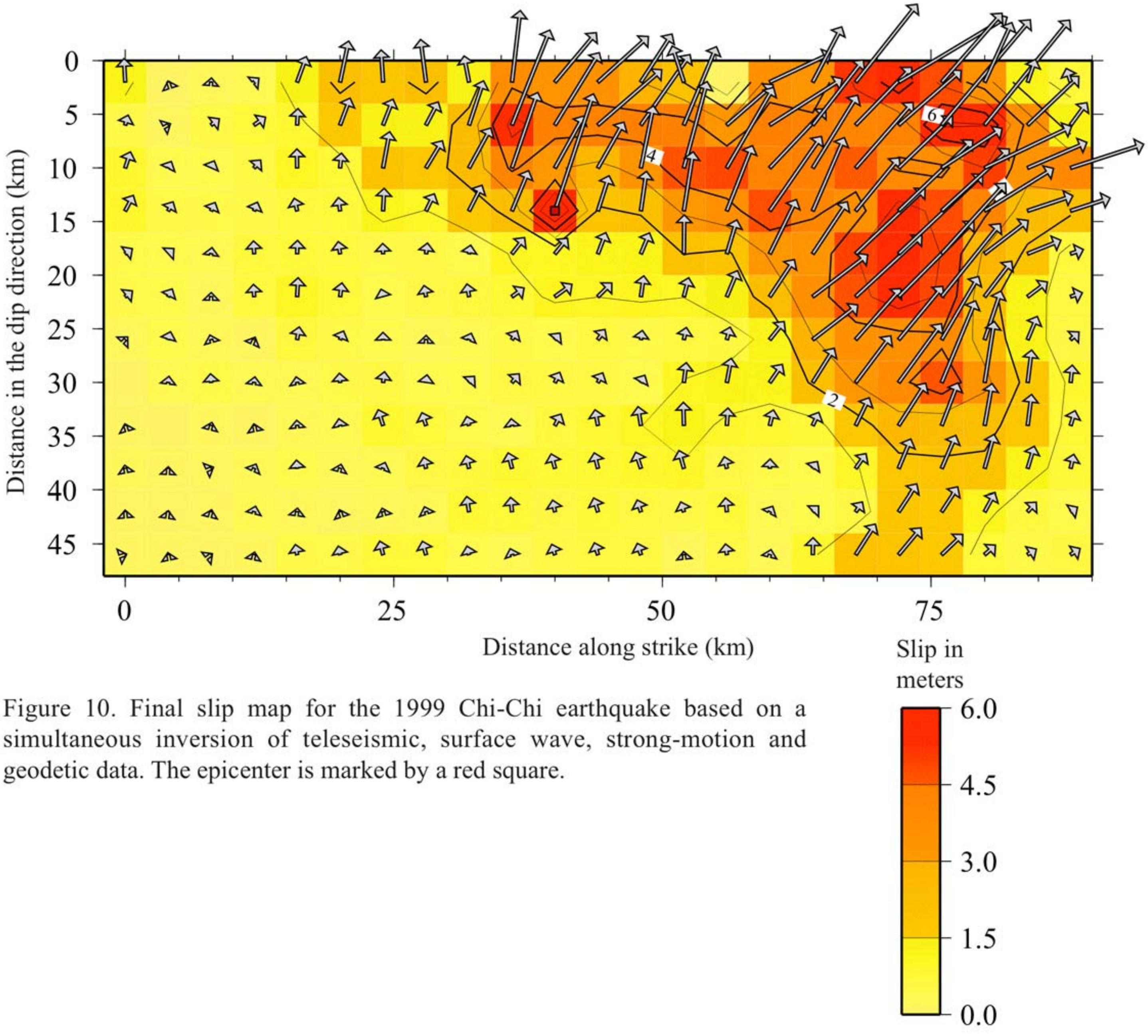


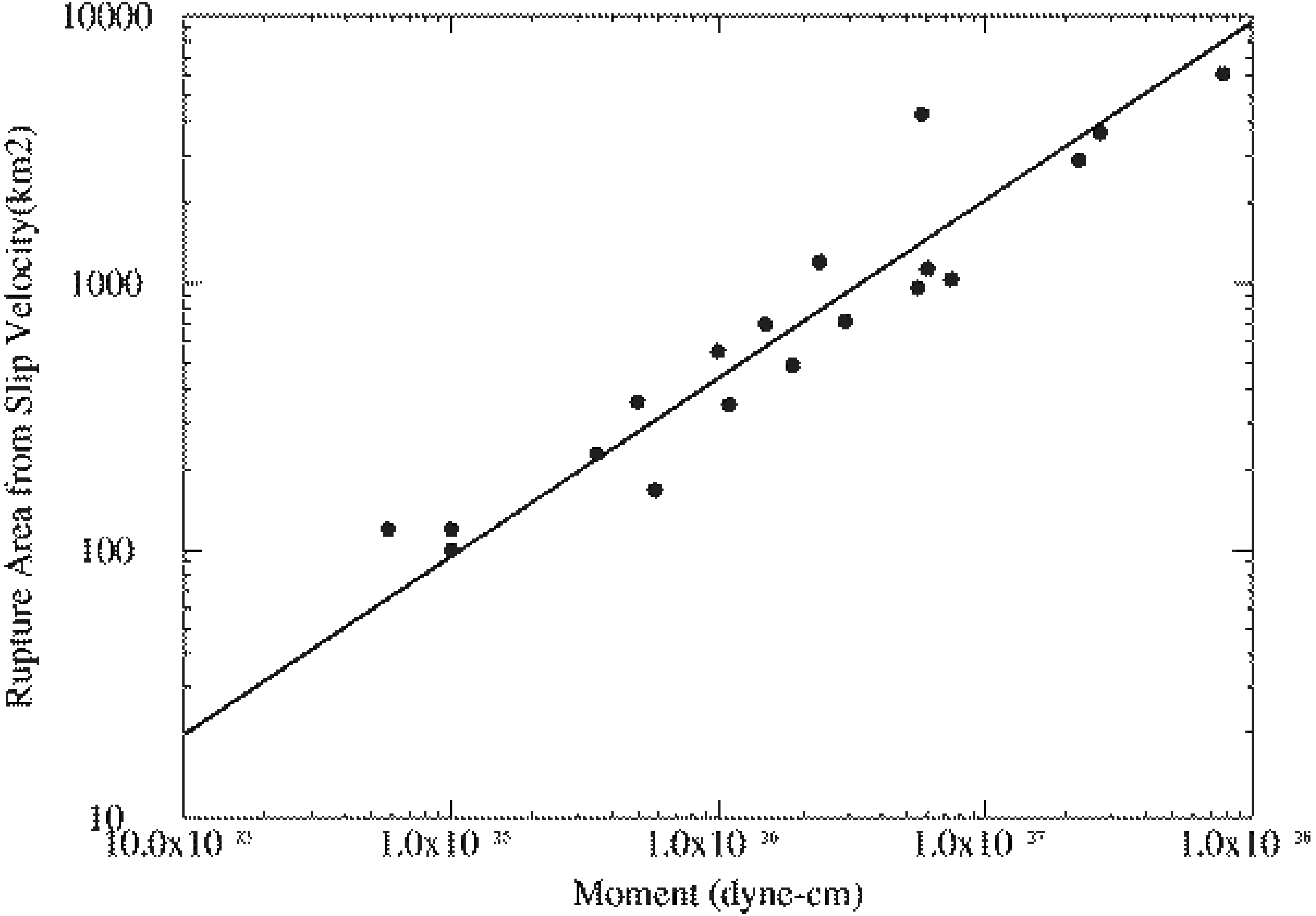
Figure 10. Final slip map for the 1999 Chi-Chi earthquake based on a simultaneous inversion of teleseismic, surface wave, strong-motion and geodetic data. The epicenter is marked by a red square.

Table 1. Source Parameters of Crustal Earthquakes

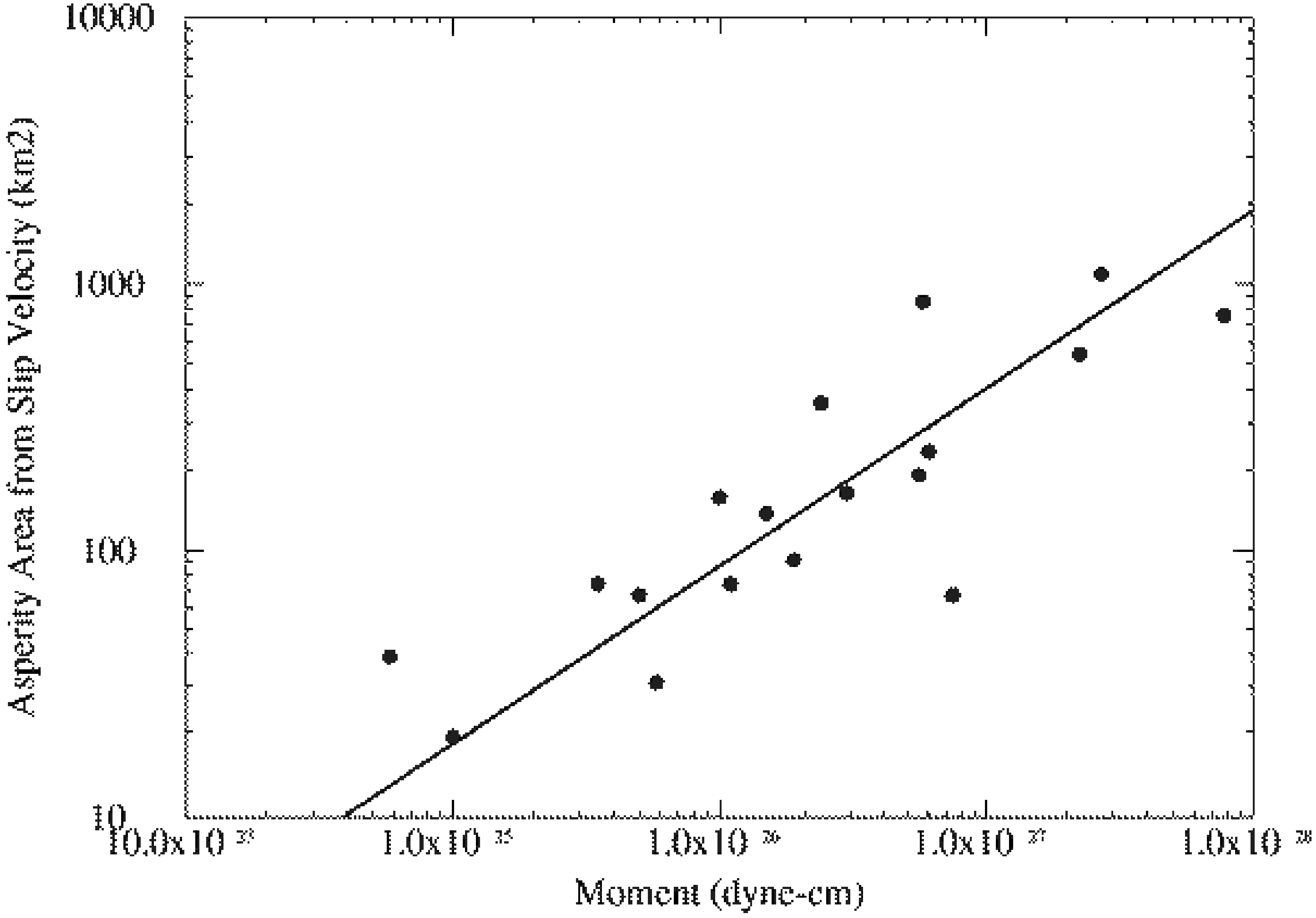
Location	Mech.	Mo x 10^{25} dyne-cm	Mw	Multiple Time Windows
Denali, Alaska	SS	800	7.9	Yes
San Francisco, California	SS	500	7.8	No
Chi-chi, Taiwan	RV	270	7.6	Yes
Kocaeli, Turkey	SS	225	7.5	Yes
Landers, Ca.	SS	75	7.22	Yes
Hector Mine	SS	62	7.16	Yes
Tabas, Iran	RV	58	7.14	Yes
Duzce, Turkey	SS	56	7.1	Yes
Loma Prieta, Ca.	OB	30	6.95	Yes
Kobe, Japan	SS	24	6.9	Yes
Borah Peak, Idaho	NM	23	6.87	No
Tottori, Japan	SS	19	6.8	Yes
Nahanni, N.W.T., Canada	RV	15	6.75	Yes
Northridge, Ca.	RV	11	6.66	Yes
Nahanni, N.W.T., Canada	RV	10	6.63	Yes
San Fernando, Ca. (S.M.)	RV	7	6.53	No
Imperial Valley, Ca.	SS	5	6.43	Yes
Superstition Hills, Ca. (#3)	SS	3.5	6.33	Yes
Morgan Hill, Ca.	SS	2.1	6.18	No
North Palm Springs, Ca.	OB	1.8	6.14	No
Kagoshima, Japan	SS	1.1	6.0	Yes
Whittier Narrows, Ca.	RV	1.0	5.97	Yes
Iwate, Japan	SS	0.58	5.8	Yes
Yamaguchi, Japan	SS	0.58	5.8	Yes
Coyote Lake, Ca.	SS	0.35	5.66	No

Scaling Relations of Fault Asperities from Kinematic Rupture Models

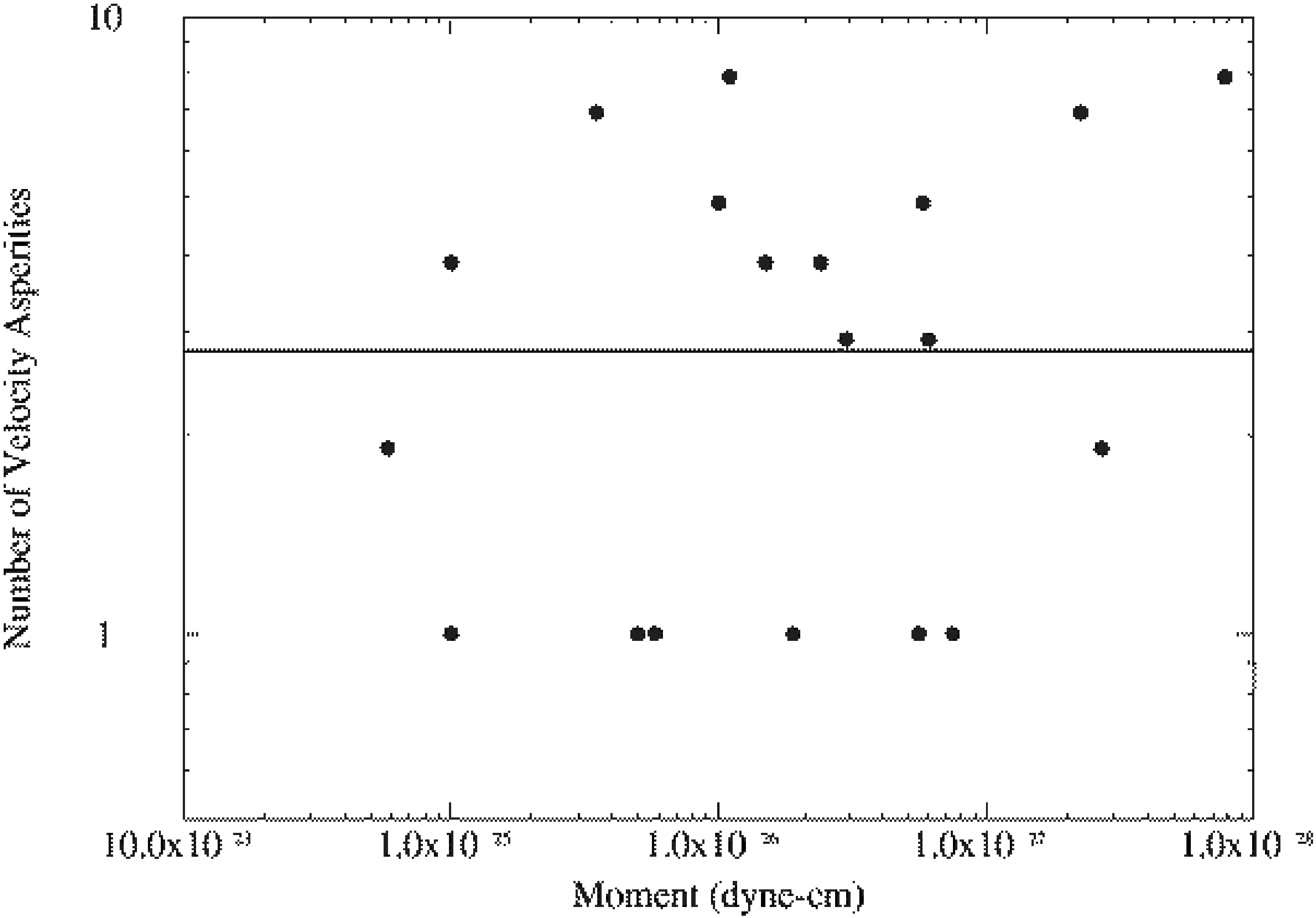
- Compile slip velocity models
- Run asperity picker algorithm for:
  - Slip on fault
  - Slip velocity on fault
- Measure asperity parameters:
  - Rupture area of asperity
  - Slip velocity of asperity
- Run regression for scaling relations



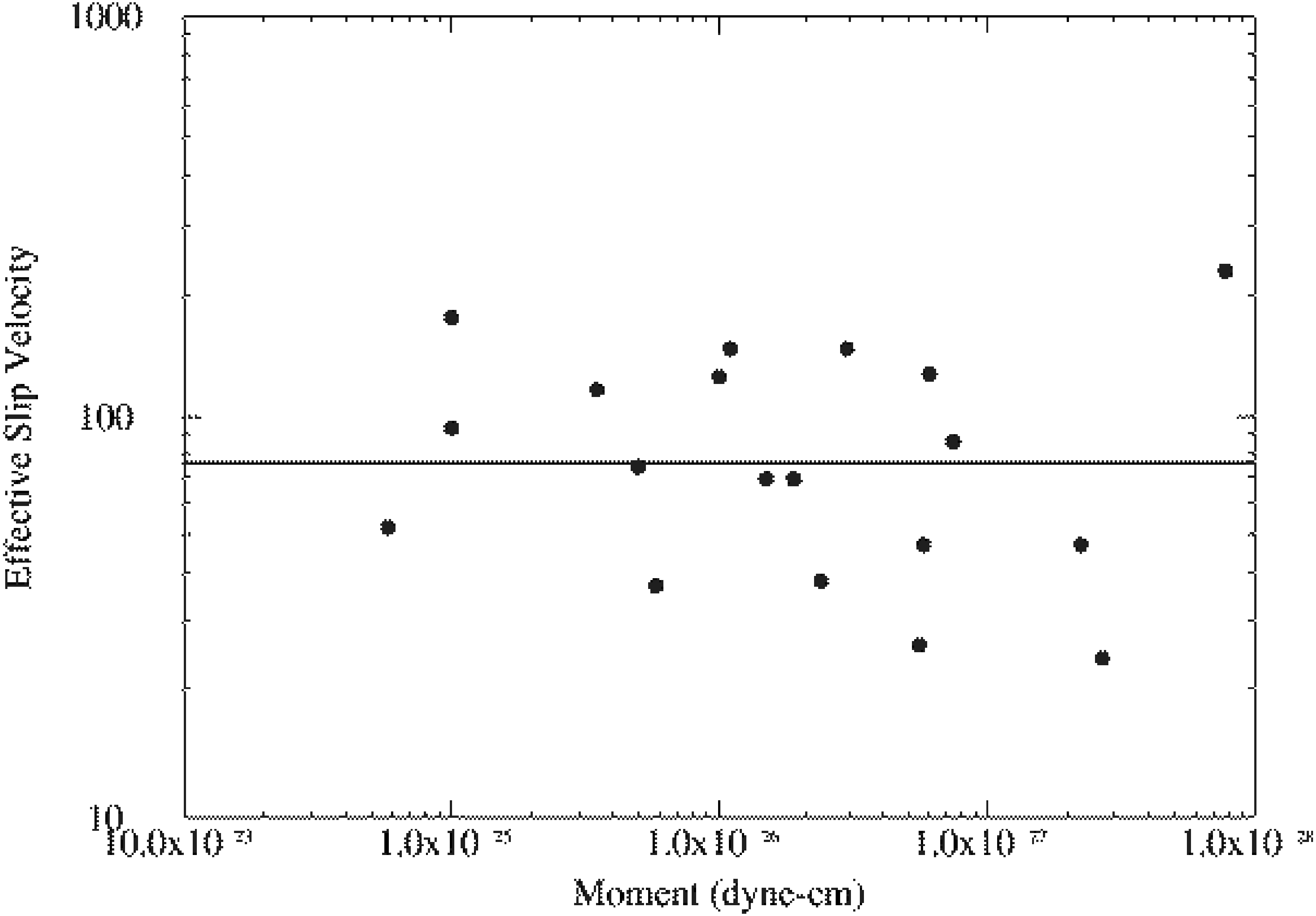
Crustal Earthquakes



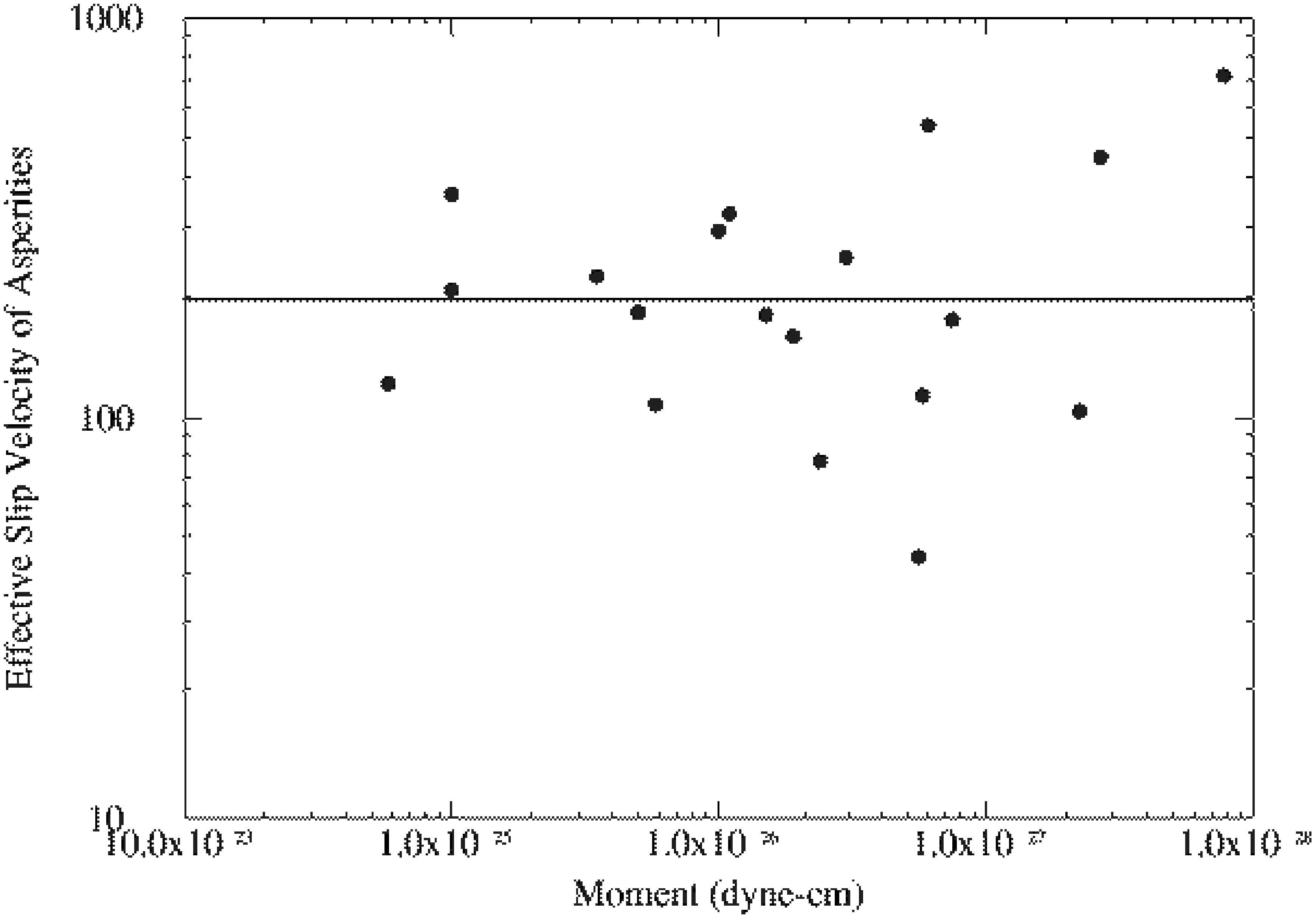
Crustal Earthquakes



Crustal Earthquakes



Crustal Earthquakes



Crustal Earthquakes

Scaling Properties of Asperities

- Scaling of slip velocity models of crustal earthquakes is self similar

- The number of asperities does not increase with magnitude

- The size of asperities increases with magnitude

Asperity Parameters

- The number of slip velocity asperities is 3
- The average slip velocity is 80 cm/sec
- The asperity slip velocity is 200 cm/sec

Differences in Source and Ground Motion Characteristics between Shallow and Buried Faulting

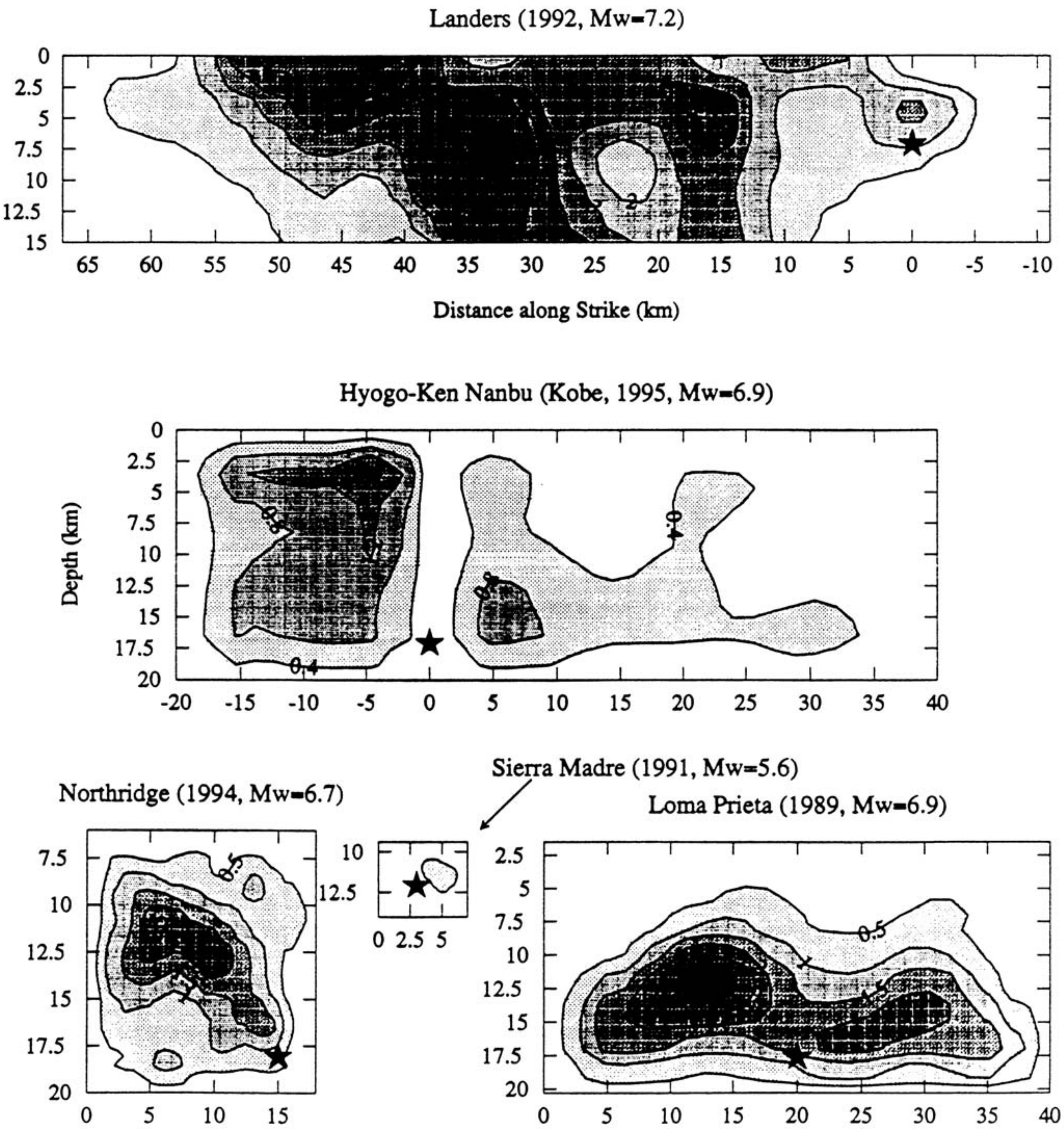
- Shallow faulting – top of shallowest asperity (defined by slip or slip velocity) is shallower than 5 km; there may also be asperities whose tops are deeper than 5 km

- Buried faulting – tops of all asperities are deeper than 5 km

Averaged Slip Velocities

Comparison of Shallow and Deep Asperity Events

	Average over fault	**Average over Asperities**
All events	77	198
Events with shallow asperities	65	144
Events with only deep aperities	124	228



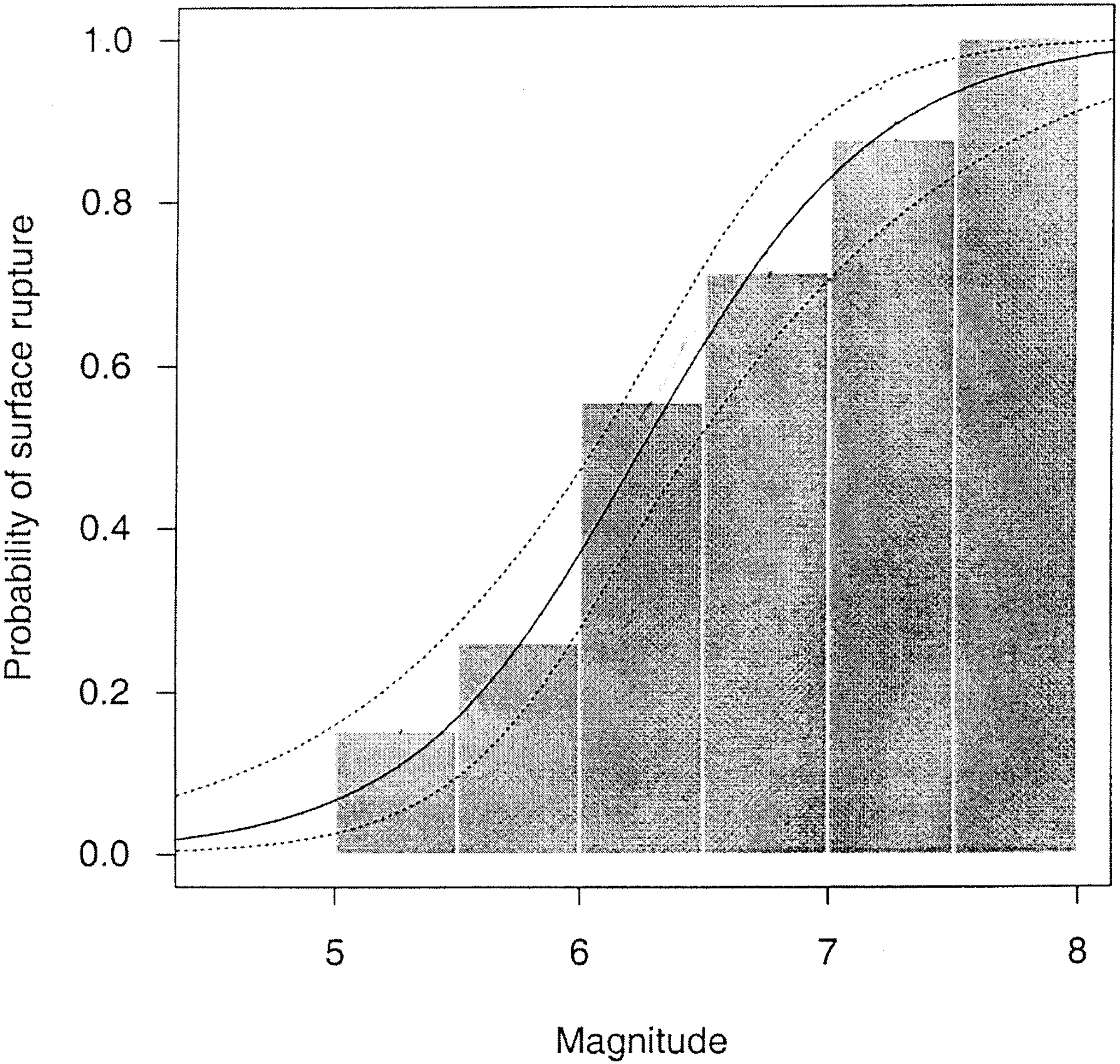
Landers (1992, Mw=7.2)

Hyogo-Ken Nanbu (Kobe, 1995, Mw=6.9)

Northridge (1994, Mw=6.7)

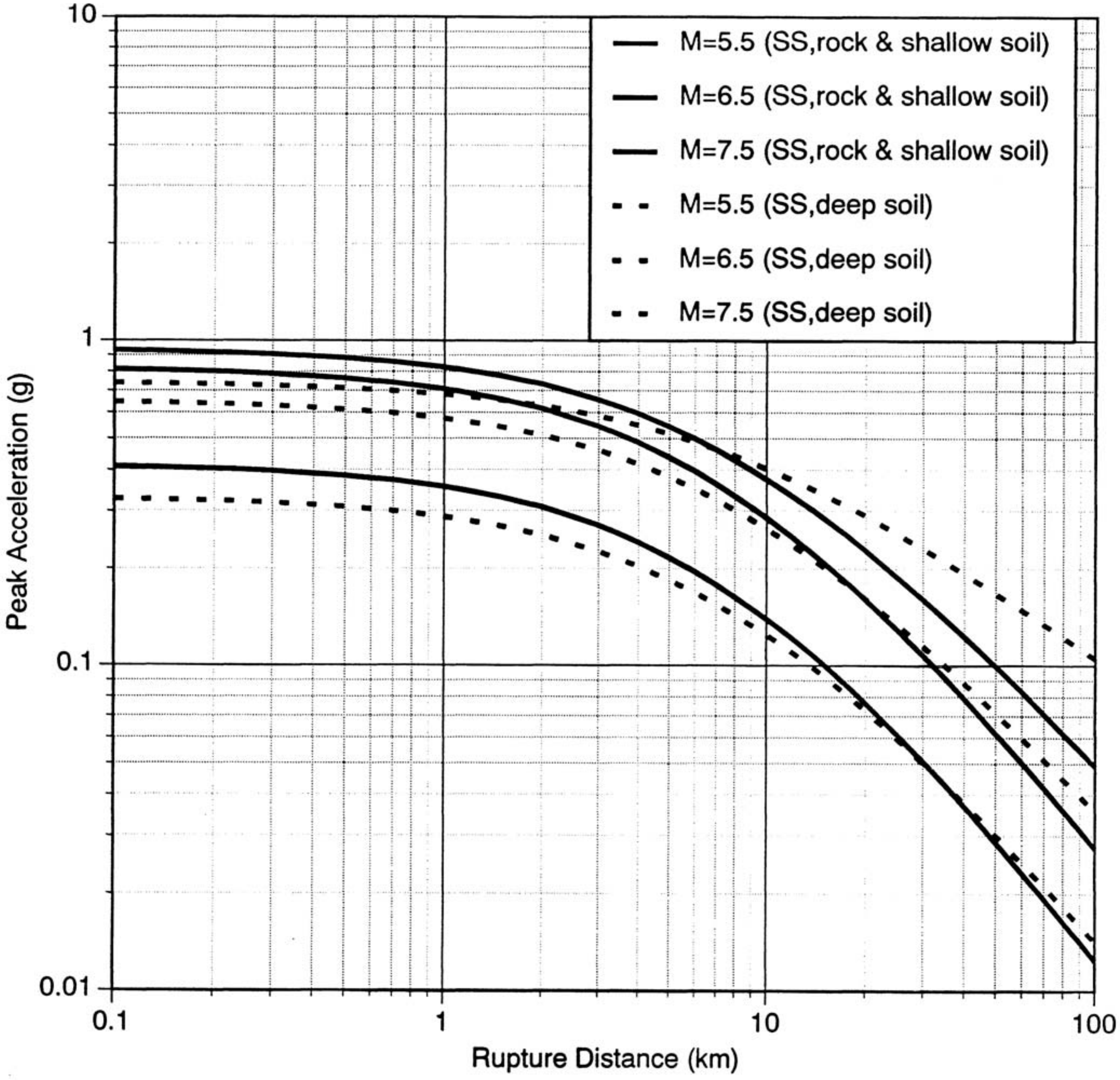
Sierra Madre (1991, Mw=5.6)

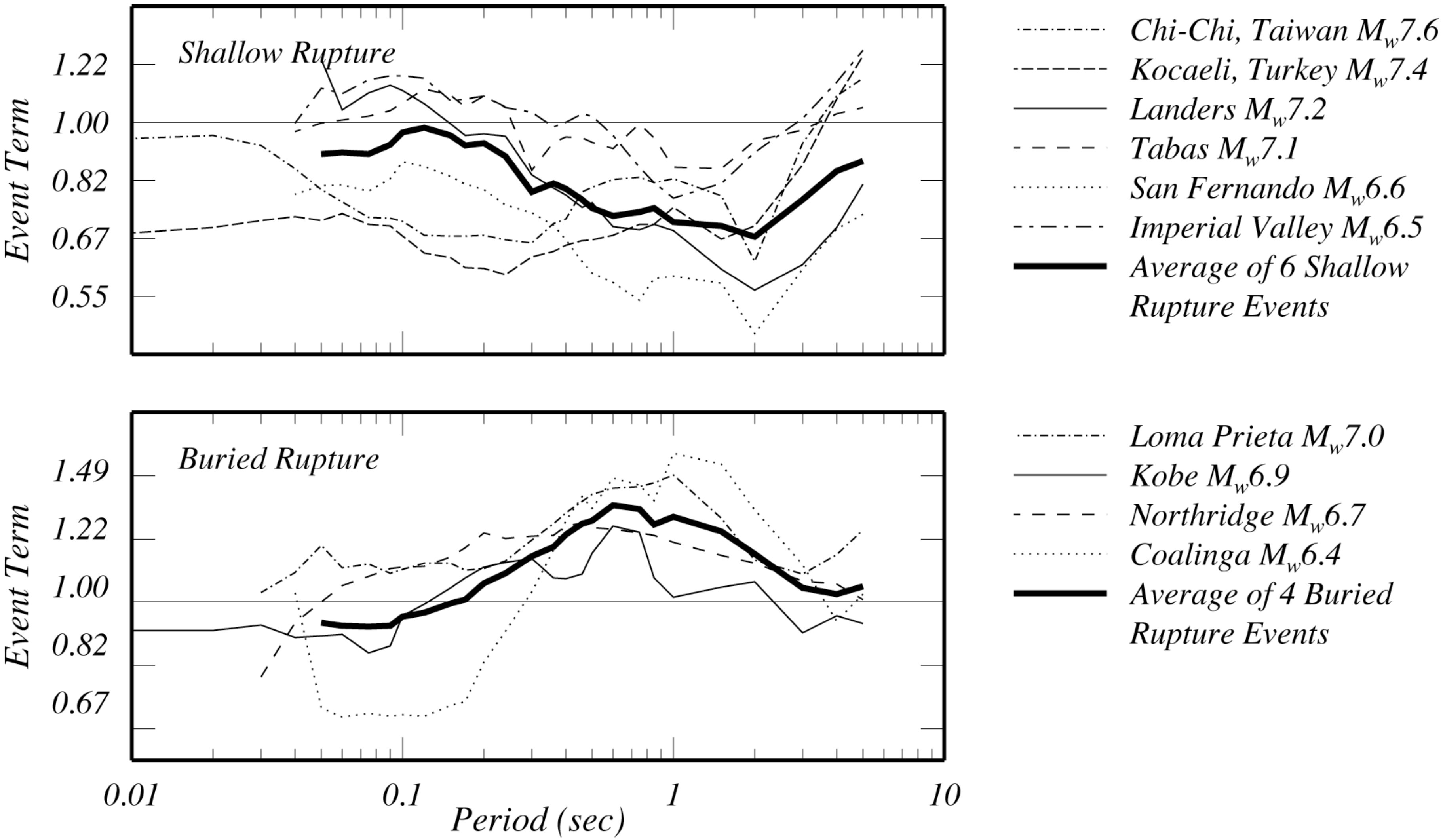
Loma Prieta (1989, Mw=6.9)

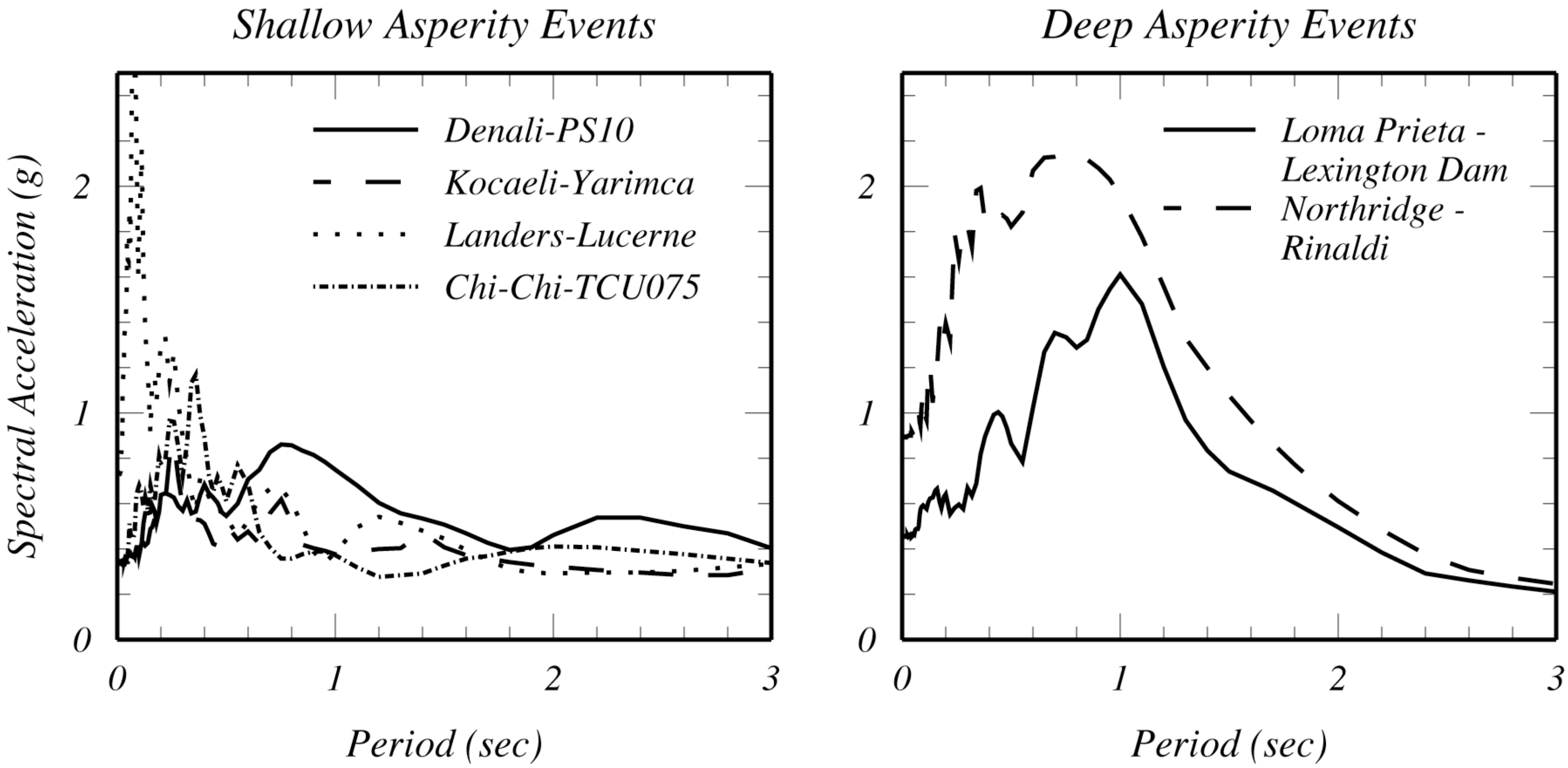


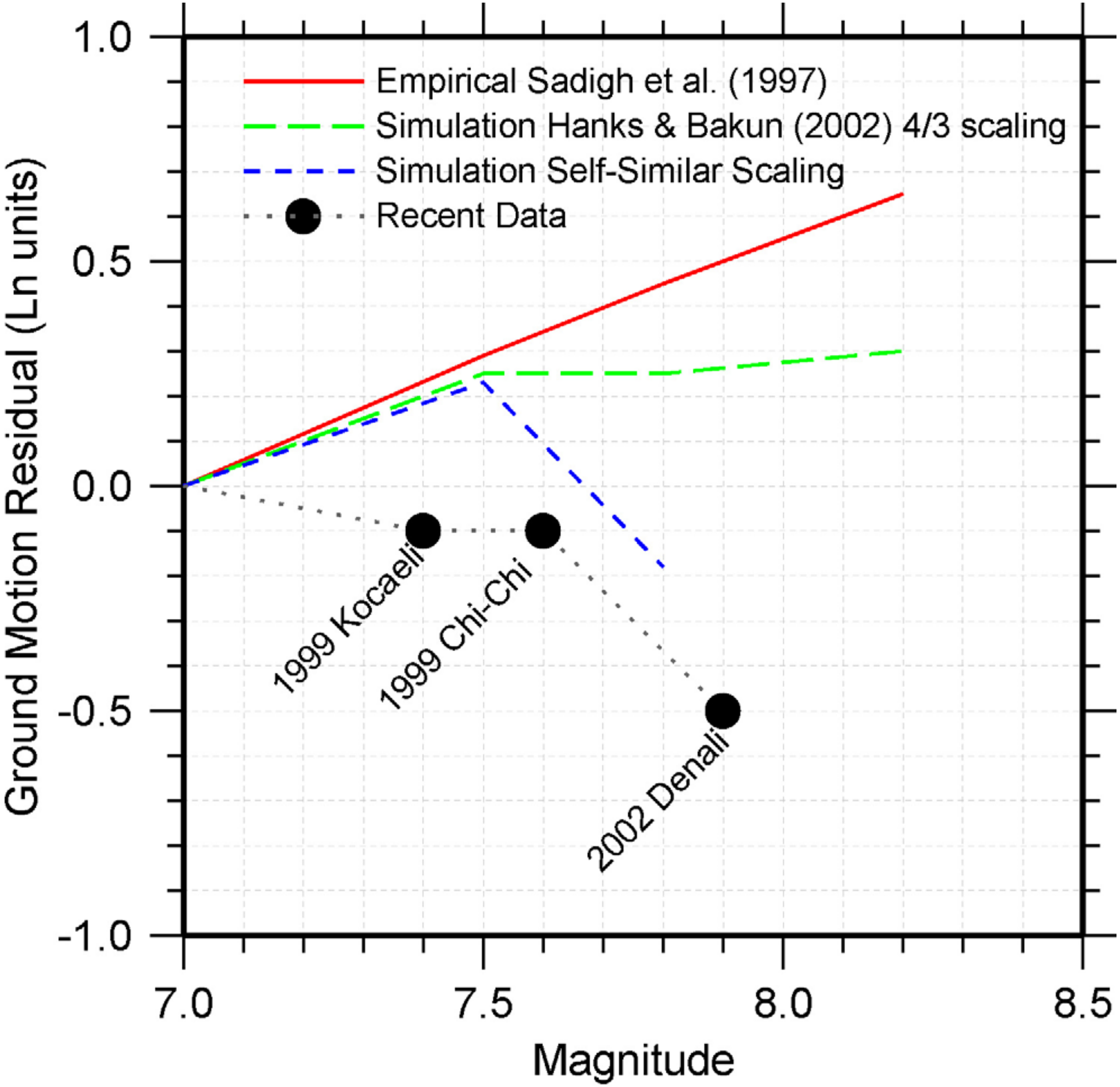
Probability of surface rupture
1.0
0.8
0.6
0.4
0.2
0.0
5
6
7
8
Magnitude

Abrahamson and Silva (1995)
Strike-Slip Events



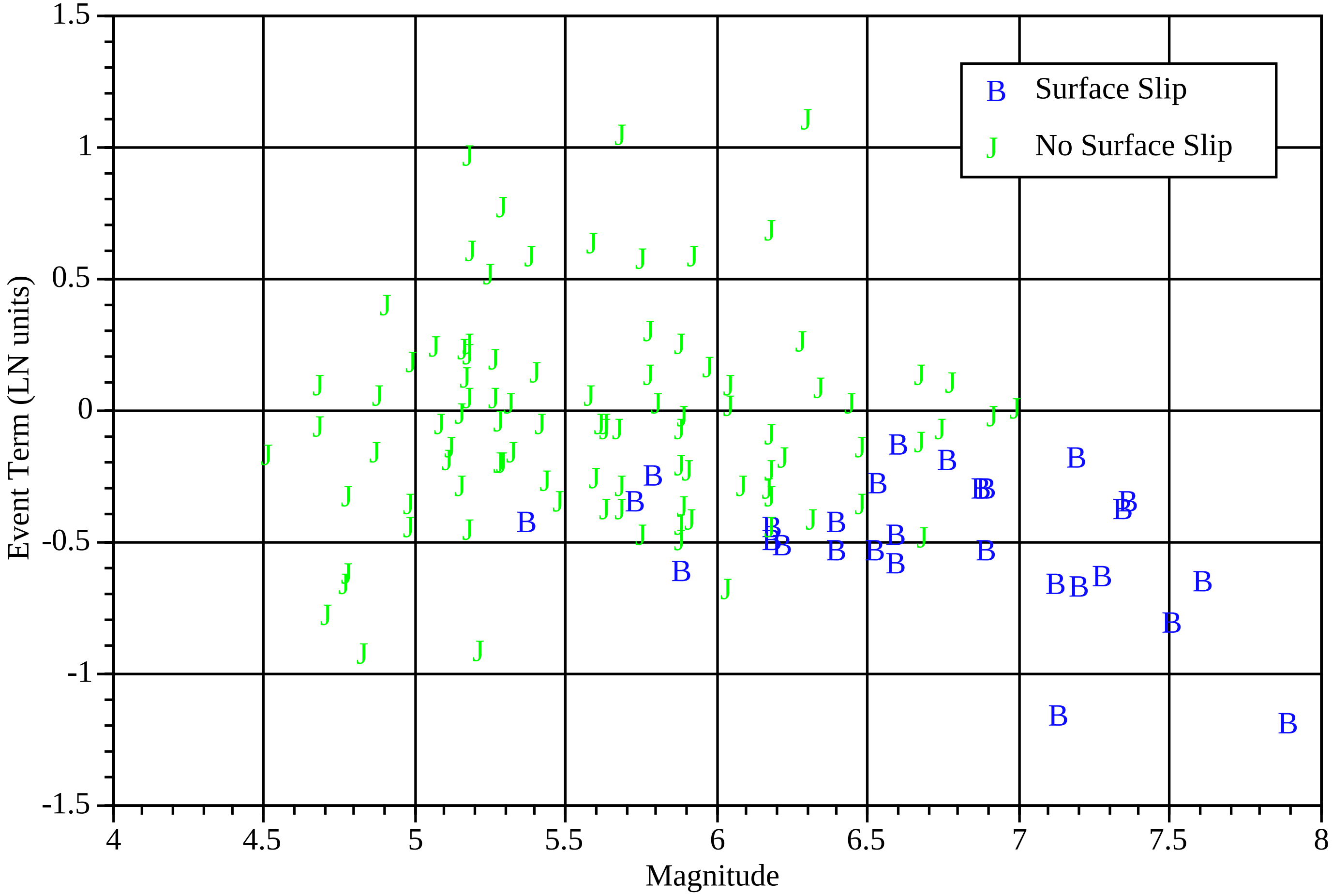

Shallow Rupture
Event Term
1.22
1.00
0.82
0.67
0.55
Chi-Chi, Taiwan M_w7.6
Kocaeli, Turkey M_w7.4
Landers M_w7.2
Tabas M_w7.1
San Fernando M_w6.6
Imperial Valley M_w6.5
Average of 6 Shallow Rupture Events
Buried Rupture
Event Term
1.49
1.22
1.00
0.82
0.67
Loma Prieta M_w7.0
Kobe M_w6.9
Northridge M_w6.7
Coalinga M_w6.4
Average of 4 Buried Rupture Events
0.01
0.1
1
10
Period (sec)


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


Empirical Sadigh et al. (1997)
Simulation Hanks & Bakun (2002) 4/3 scaling
Simulation Self-Similar Scaling
Recent Data
1999 Kocaeli
1999 Chi-Chi
2002 Denali
Ground Motion Residual (Ln units)
1.0
0.5
0.0
-0.5
-1.0
7.0
7.5
8.0
8.5
Magnitude

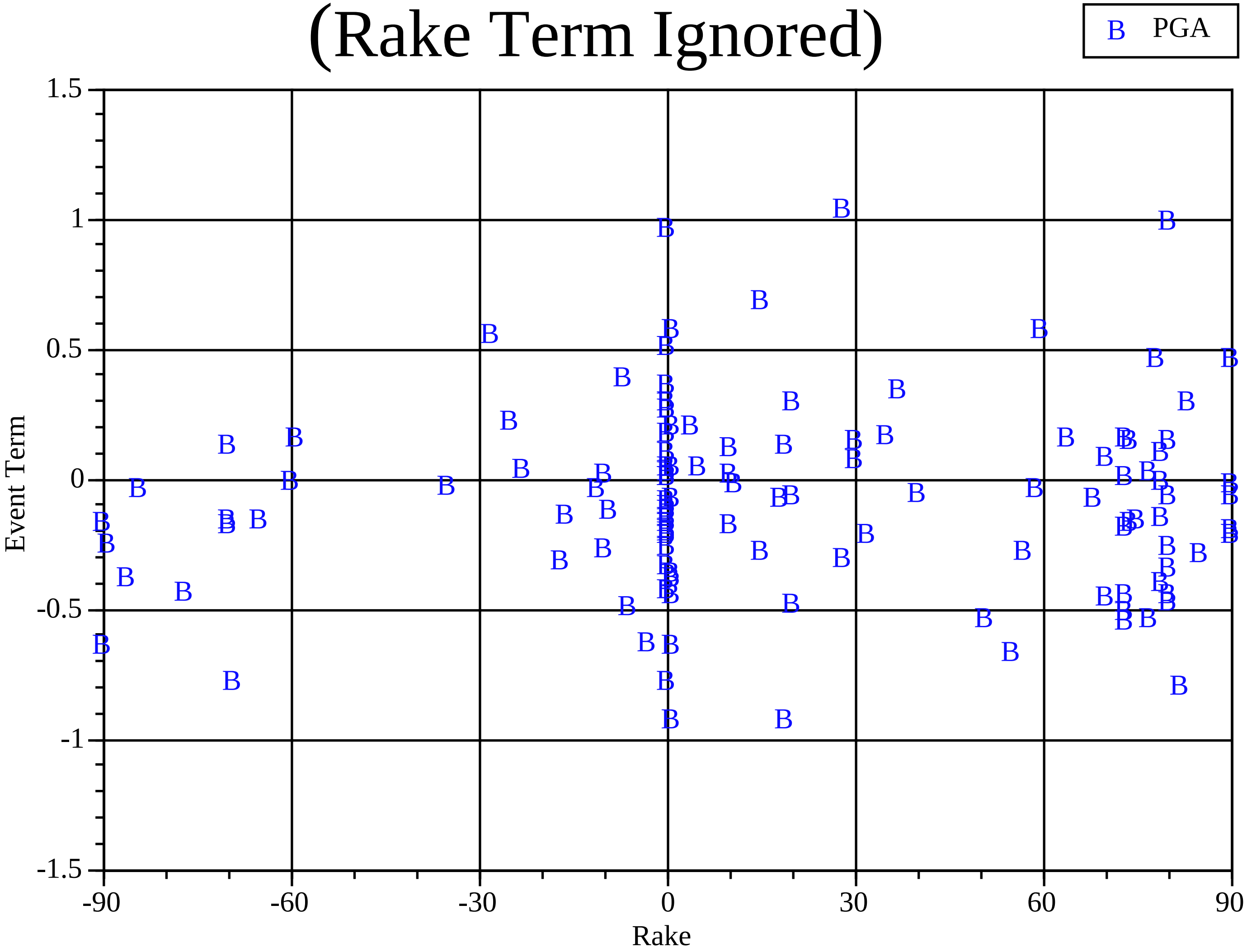
Event Terms- PGA

(Surface Slip Term Ignored)



Event Terms- PGA

(Rake Term Ignored)

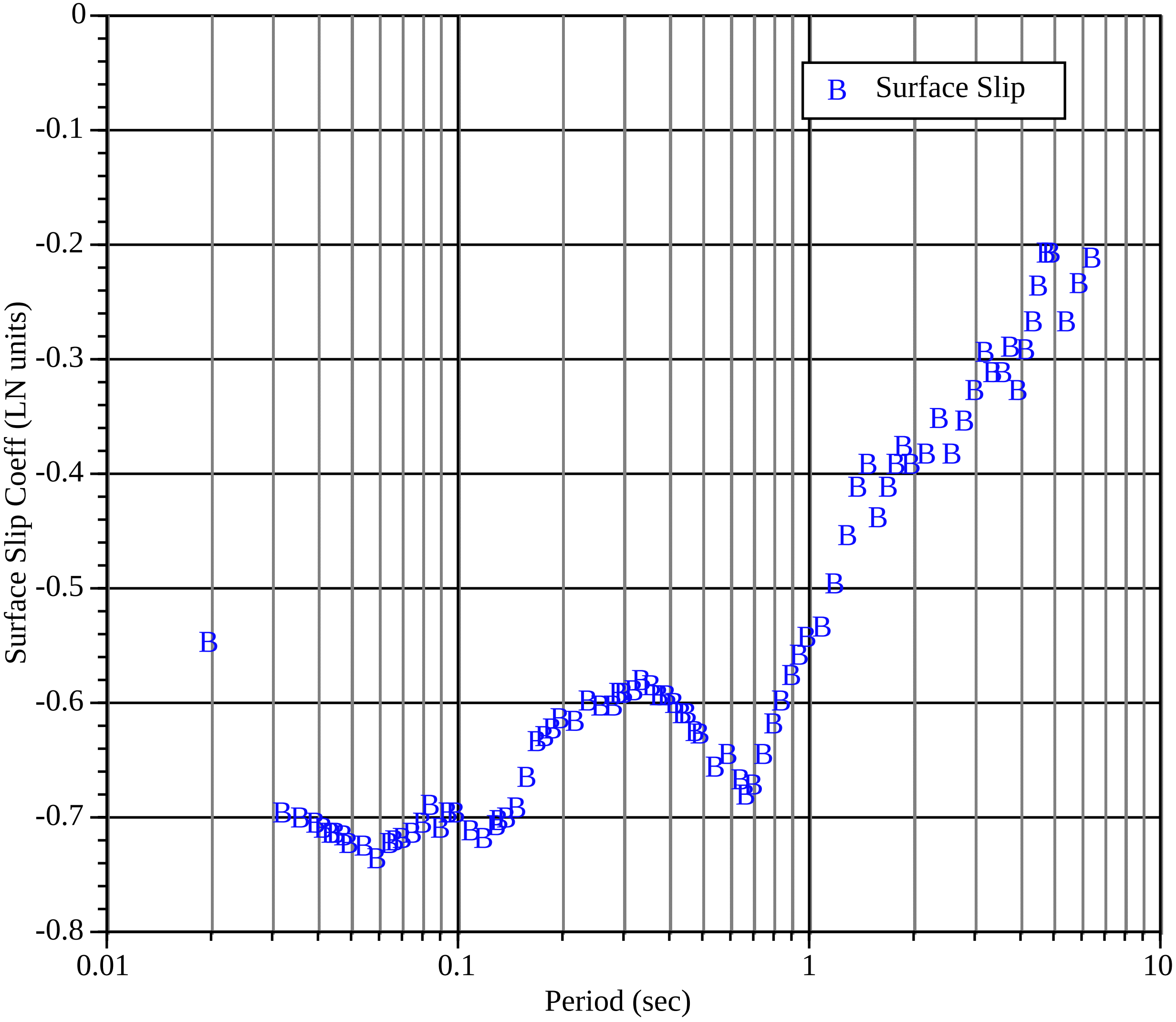


NML

SS

RV

Surface Slip Coeff



Evidence from Recorded Strong Ground Motions

- Ground motion is weaker for earthquakes that break the surface than for earthquakes that do not

- Ground motion is weaker for earthquakes having asperities within 5 km of the surface than for earthquakes that do not

Evidence from Precariously Balanced Rocks

The presence of precariously balanced rocks near major faults (e.g. the San Andreas fault) appears to be inconsistent with current ground motion models *(Brune, Anooshepoor, Purvance, Anderson, et al)*

Possible problems with existing ground motion models:

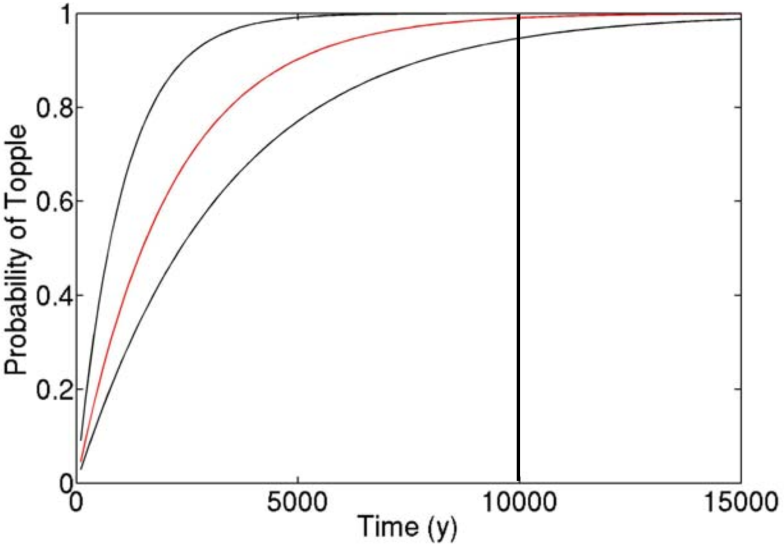
- Limitations of the ergodic assumption
- Variability in ground motion level too high
- Median ground motion level to high

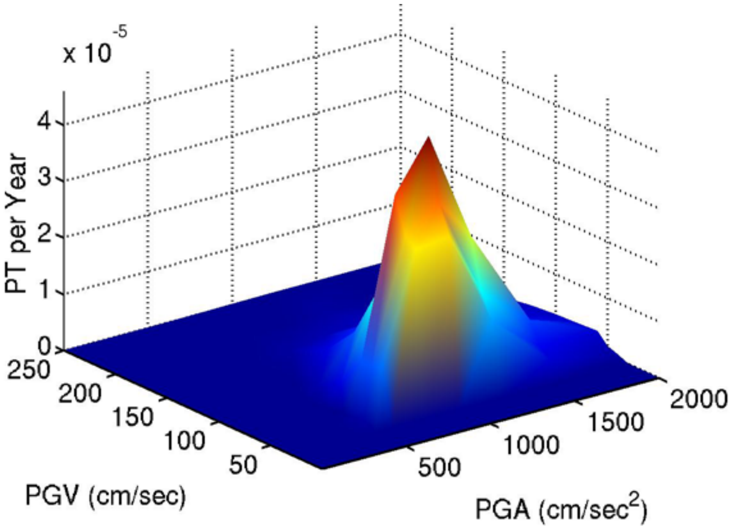
Analysis using Vector Valued Seismic Hazard

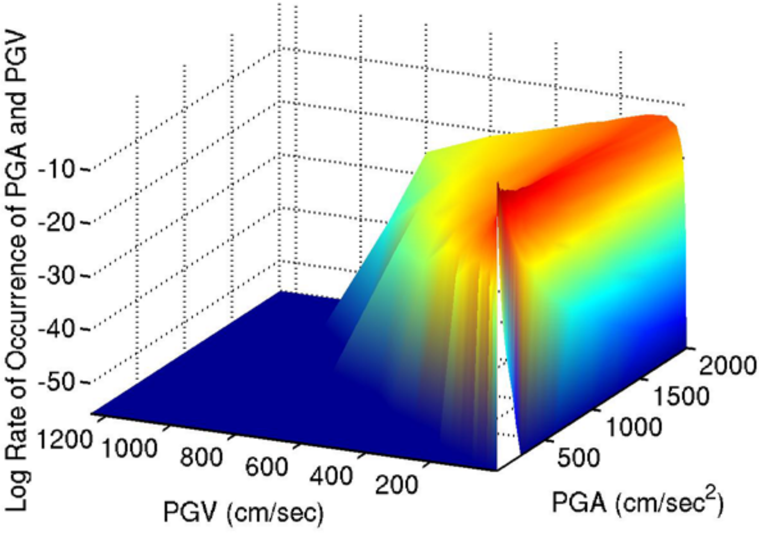
Toppling of rocks depends on both peak acceleration PGA and peak velocity PGV

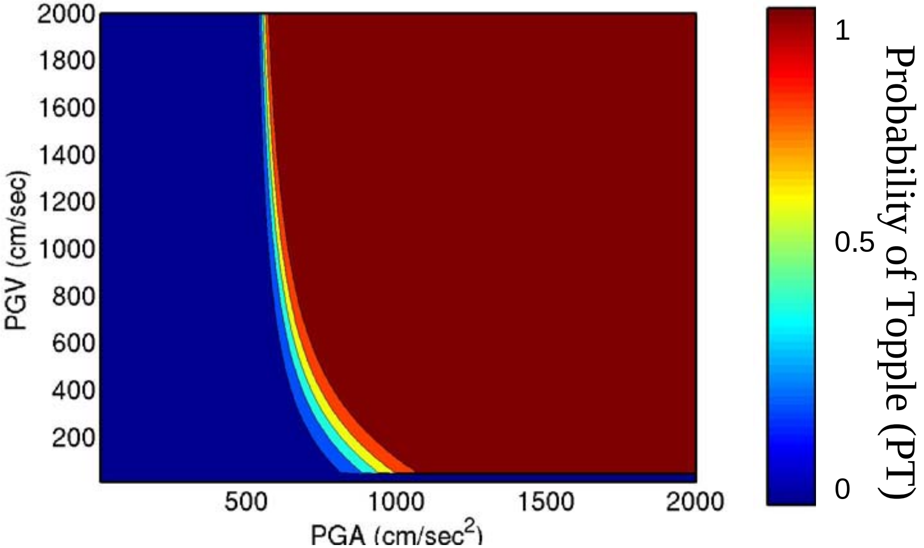
- Hazard surface for PGA and PGV
- Fragility surface for PGA and PGV
- Combine to give probability of toppling as a function of return period
- Results are incompatible with the presence of balanced rocks

Pedley- Alpha 0.4, R 51







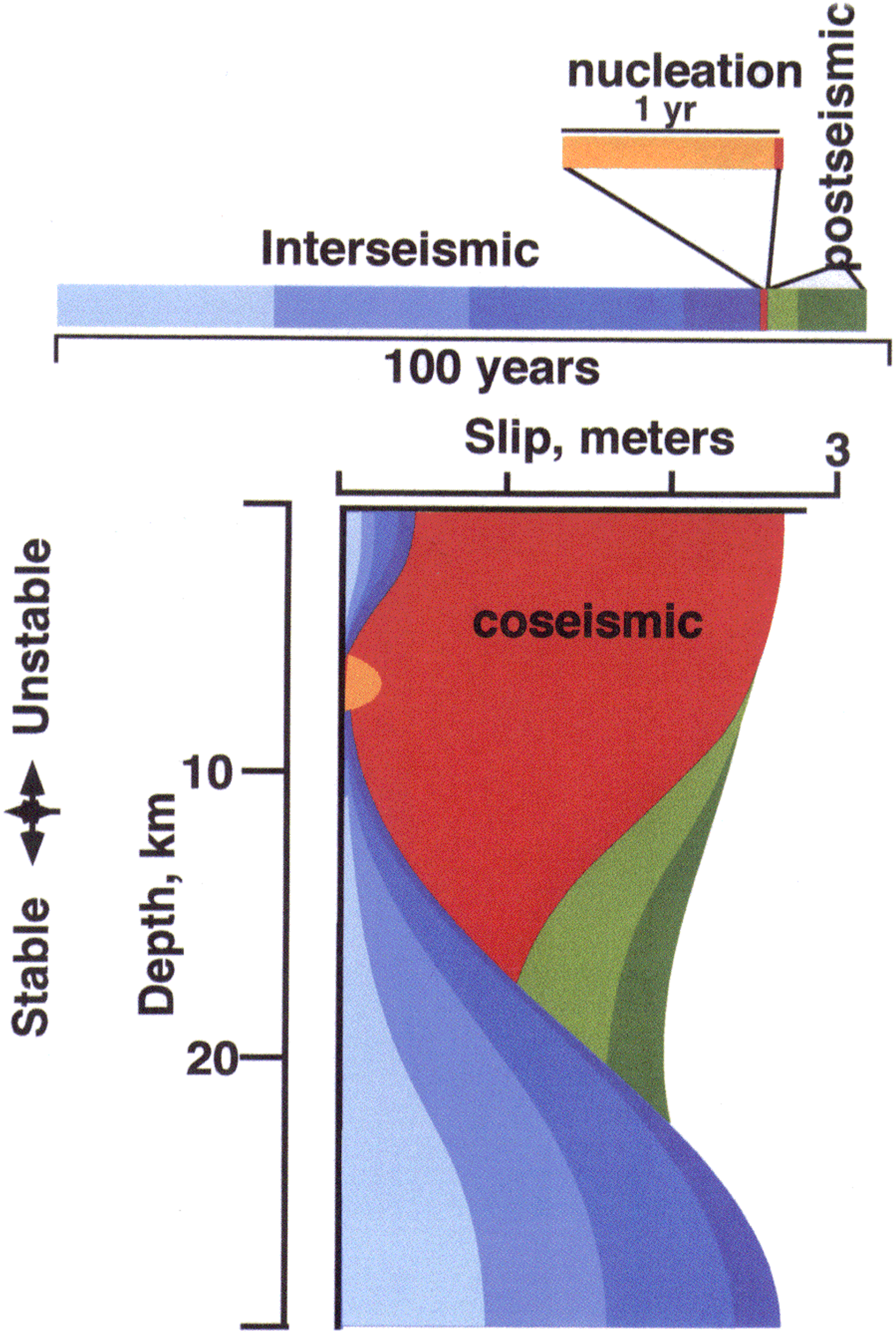


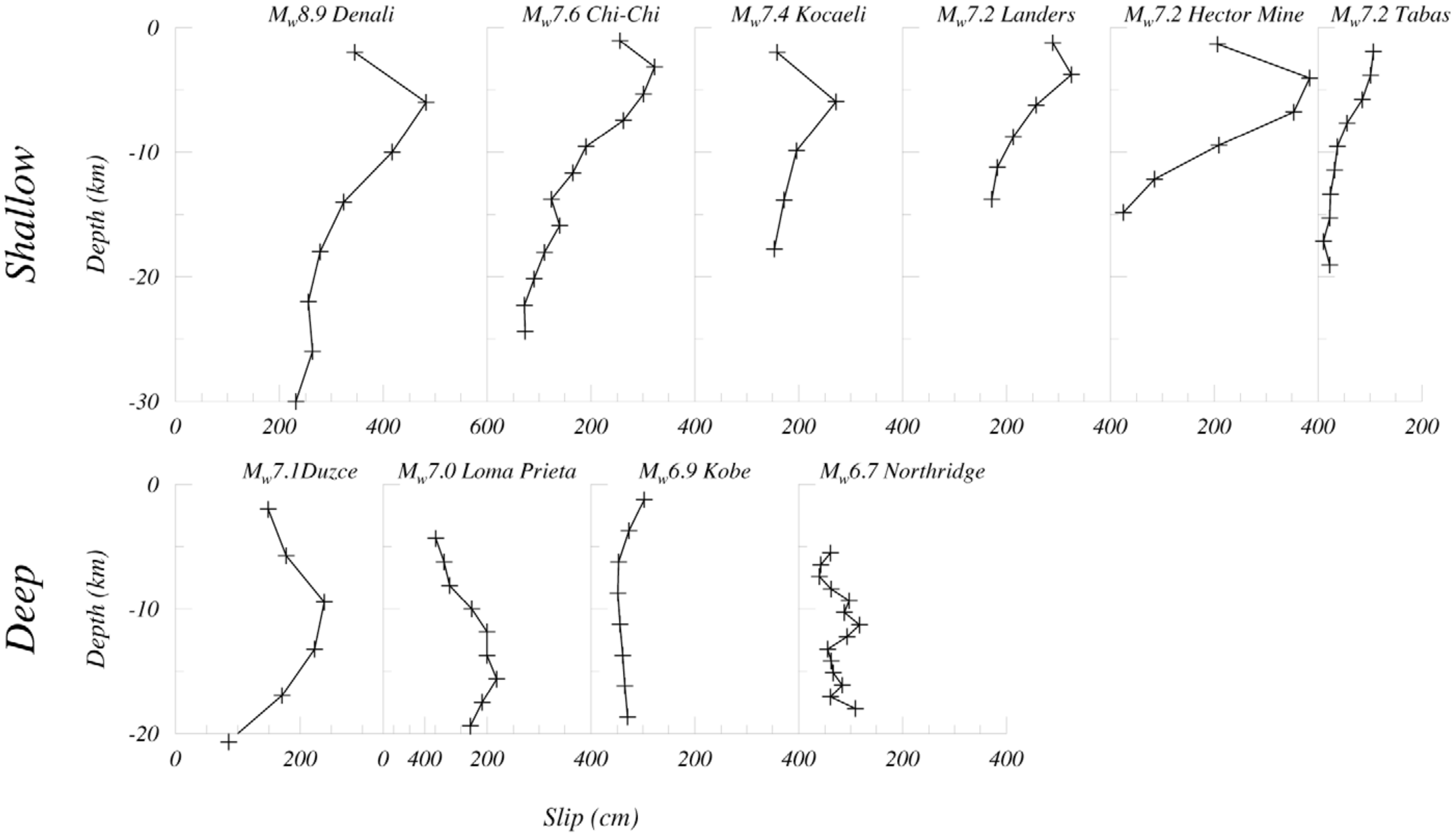
Evidence from Precarious Rocks

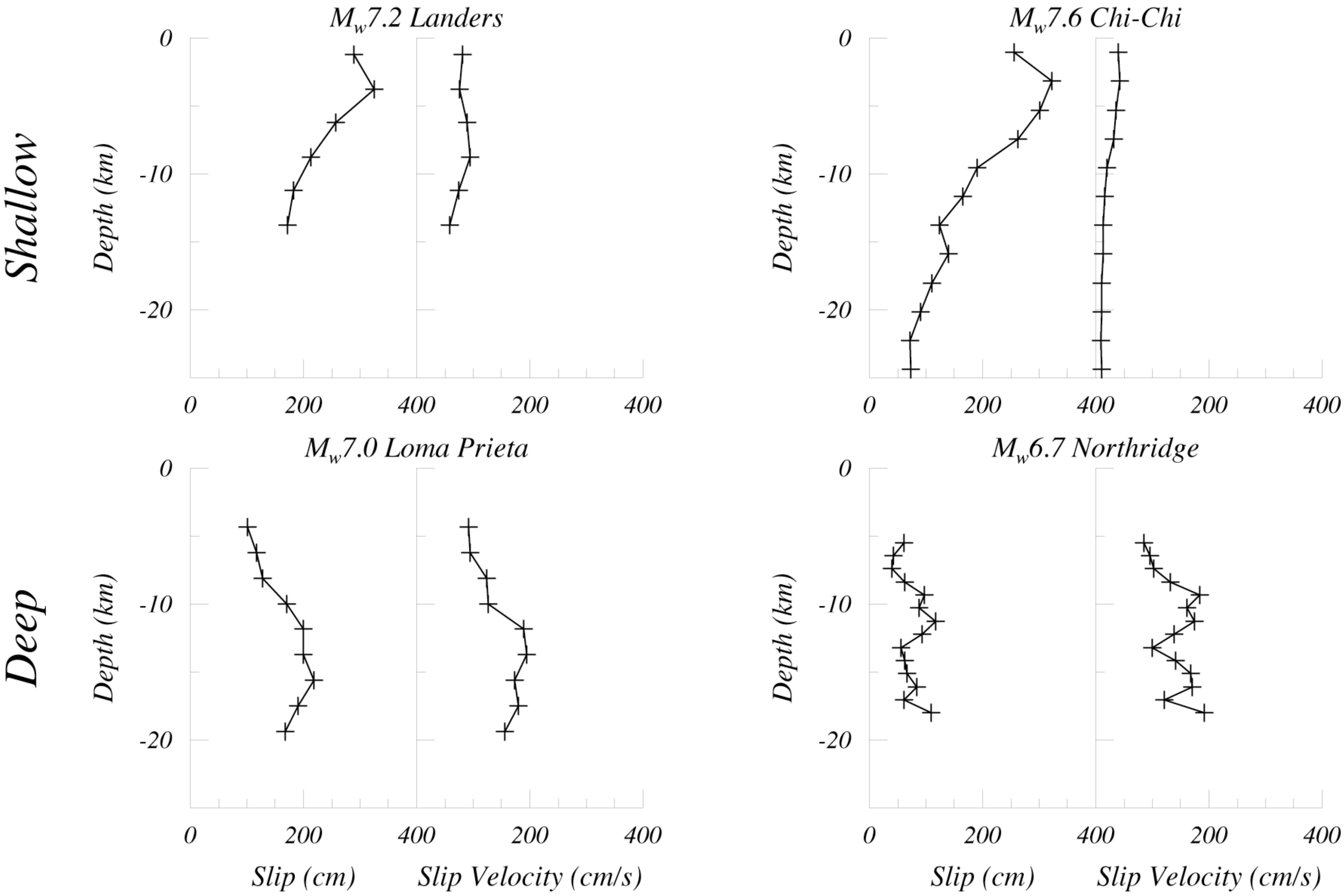
- Presence of precarious rocks is incompatible with current ground motion models

- Current ground motion models probably overpredict the median ground motion level of surface breaking earthquakes

Physical Insight into Differences in Source and Ground Motion Characteristics between Surface and Buried Faulting


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


Shallow
Deep
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
Depth (km)
0
-10
-20
-30
0
200
400
600
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)

Evidence from Kinematic Rupture Models of Crustal Earthquakes

- Shallow faulting – fault slip displacement may be large but slip velocity is low

- Buried faulting - fault slip displacement may be small but slip velocity may be large

Evidence from Dynamic Rupture Parameters of Shallow and Buried Faulting Earthquakes

Defined surface rupture

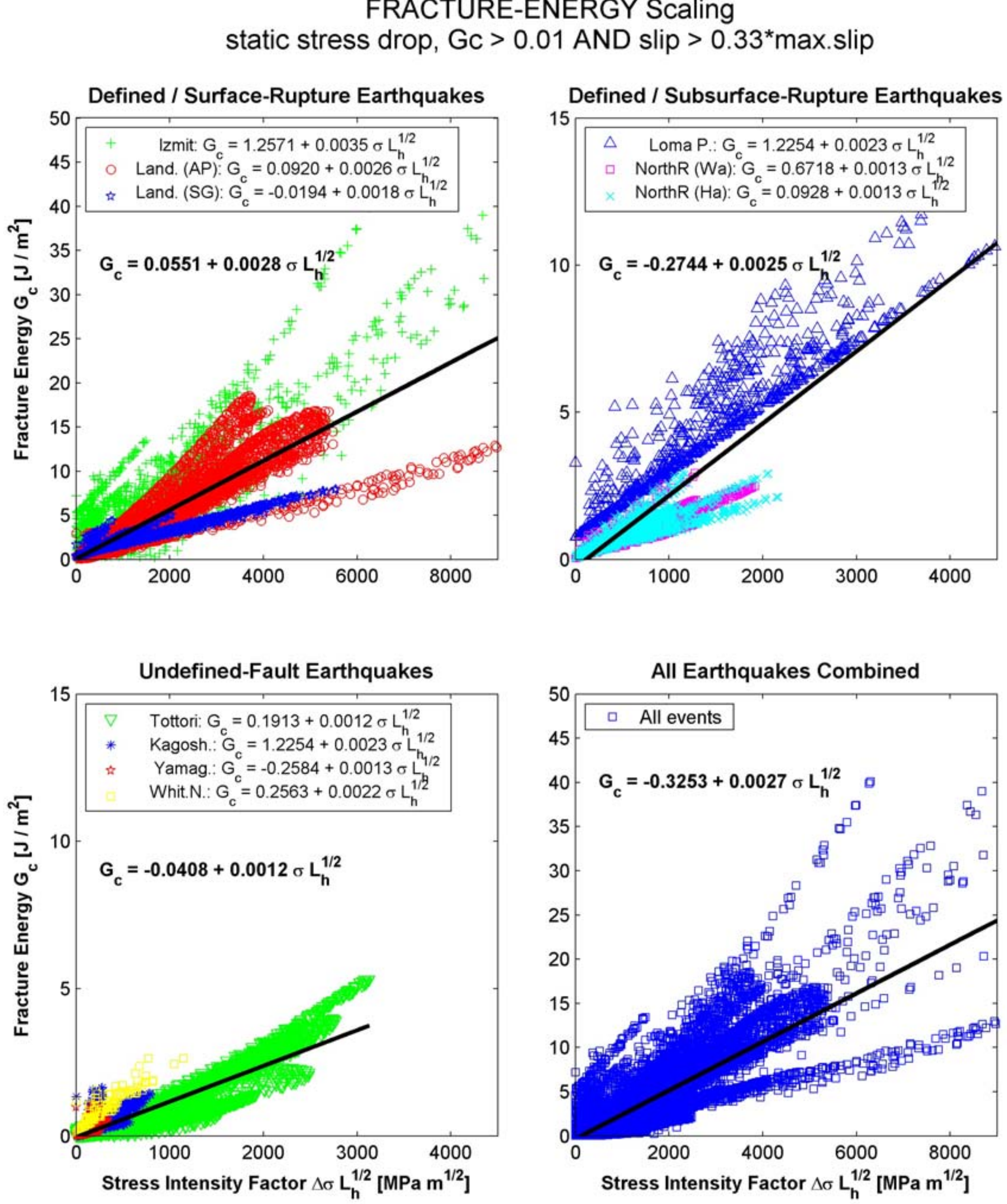
(1)	Izmit	Dalguer
(2)	Kobe	Song
(3)	Landers	Song
(4)	Landers	Pitarka

Defined subsurface rupture

(5)	Northridge	Guatteri
(6)	Northridge	Guatteri
(7)	Loma Prieta	Song

Undefined rupture

(8)	Tottori	Dalguer
(9)	Kagoshima	Dalguer
(10)	Yamaguchi	Dalguer
(11)	Whittier N.	Song



DYNAMIC SOURCE PARAMETERS

Fracture-Energy Scaling

Fracture Energy Scaling Based on STATIC STRESS DROP

Fracture Energy and Stress Intensity Factor

- Large for defined surface faulting events
- Small for defined subsurface and undefined faults

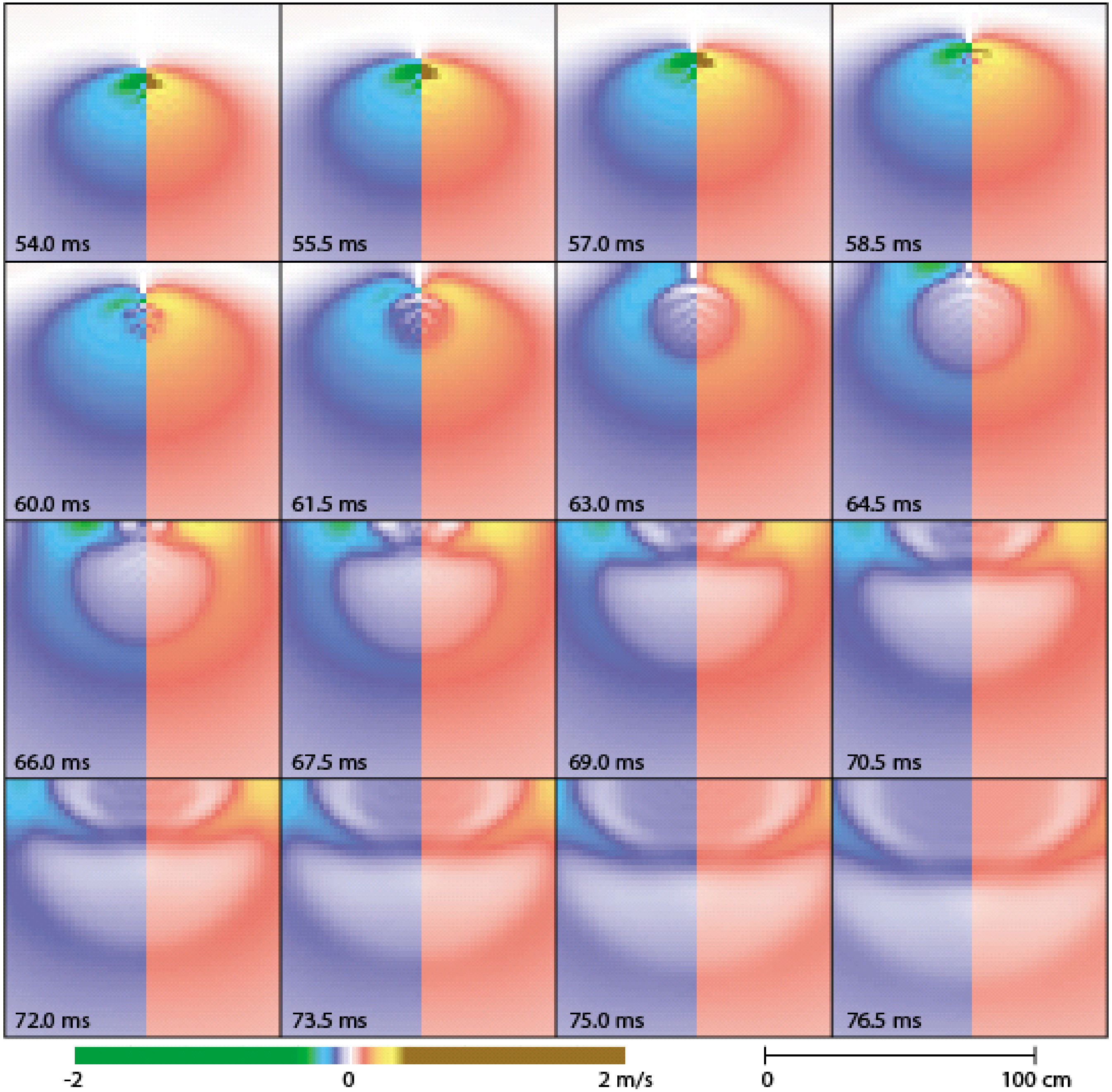
- Large fracture energy events may produce mainly long period seismic radiation
- This is consistent with surface faulting events producing weak high frequency ground motions

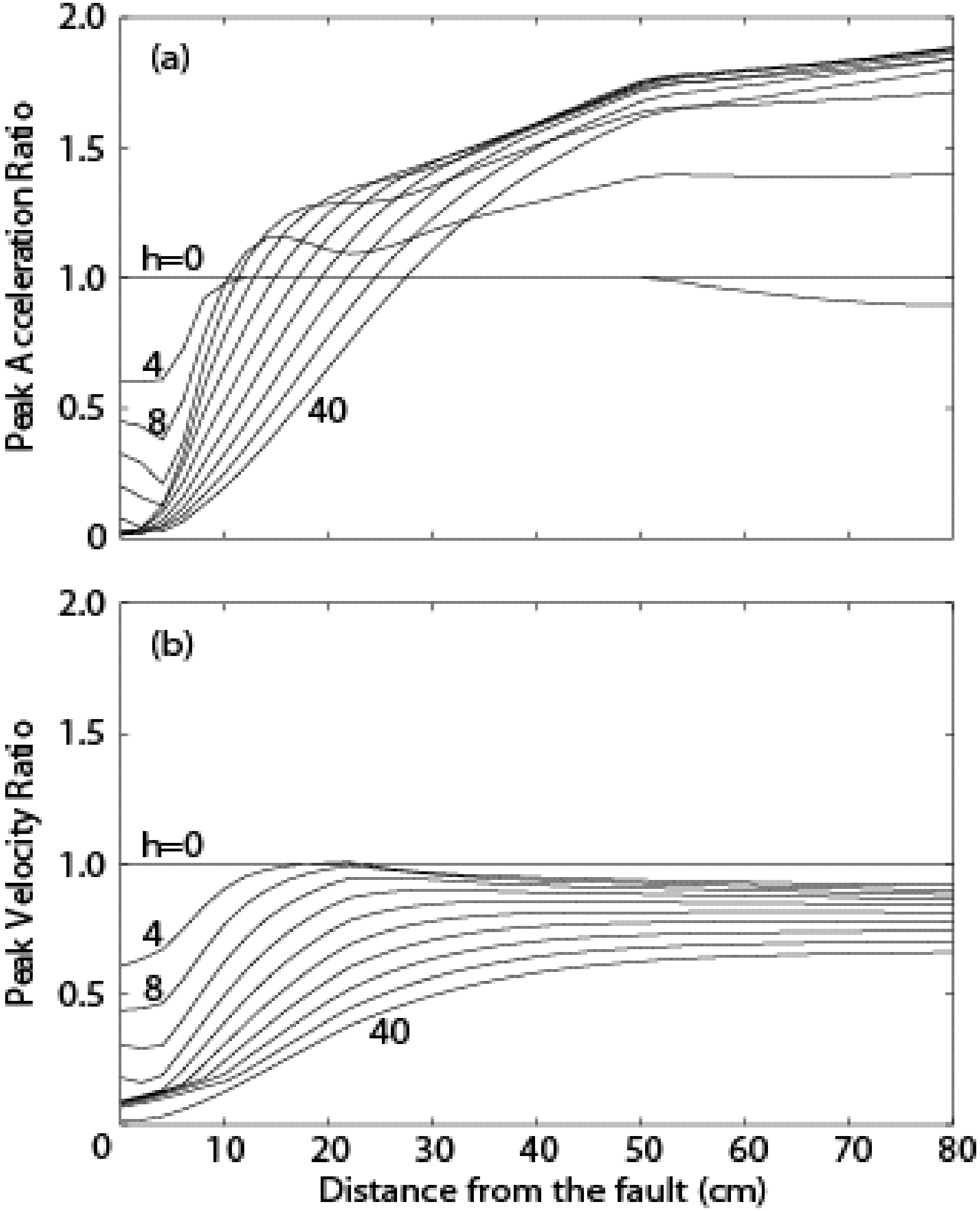
Evidence from Dynamic Rupture Modeling

Day and Ely, BSSA 2003

- Velocity hardening in the shallow part of the fault causes a stopping phase

- The stopping phase causes larger high frequency ground motions near a buried fault than near a surface breaking fault


54.0 ms
55.5 ms
57.0 ms
58.5 ms
60.0 ms
61.5 ms
63.0 ms
64.5 ms
66.0 ms
67.5 ms
69.0 ms
70.5 ms
72.0 ms
73.5 ms
75.0 ms
76.5 ms
-2
0
2 m/s
0
100 cm


(a)
Peak Acceleration Ratio
2.0
1.5
1.0
0.5
0
h=0
4
8
40
(b)
Peak Velocity Ratio
2.0
1.5
1.0
0.5
h=0
4
8
40
0
10
20
30
40
50
60
70
80
Distance from the fault (cm)

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
- Lower ground motions than buried faulting events

Evidence for Differences in Source and Ground Motion Characteristics between Surface and Buried Earthquakes

- Weak ground motions recorded near major surface faulting earthquakes
- Presence of precariously balanced rocks near major surface faults
- Low slip velocities at shallow depths from kinematic rupture models of past earthquakes
- Large fracture energy from dynamic rupture models of past earthquakes
- Stopping phases from velocity hardening in dynamic models of buried faulting

Implications for Characterizing Fault Asperities

- Properties of shallow and deep asperities may be different
- At a given site, the deterministic ground motions may be controlled by deep asperities, not shallow asperities
- This may not be true of probabilistic ground motions
  - Surface breaking fault may have high slip rate and short earthquake recurrence
  - Buried fault may have low slip rate and long earthquake recurrence

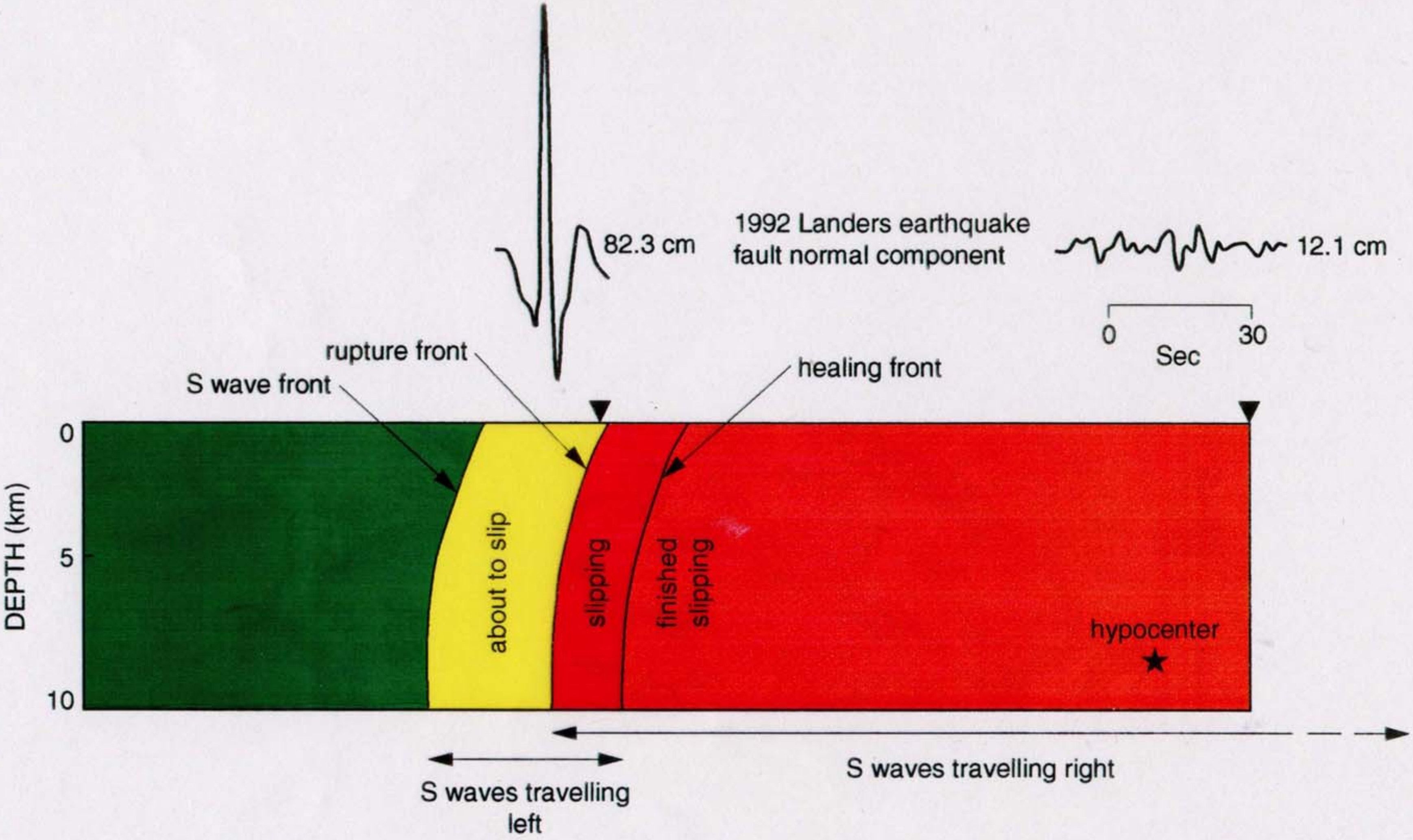
Implications for Seismic Hazards

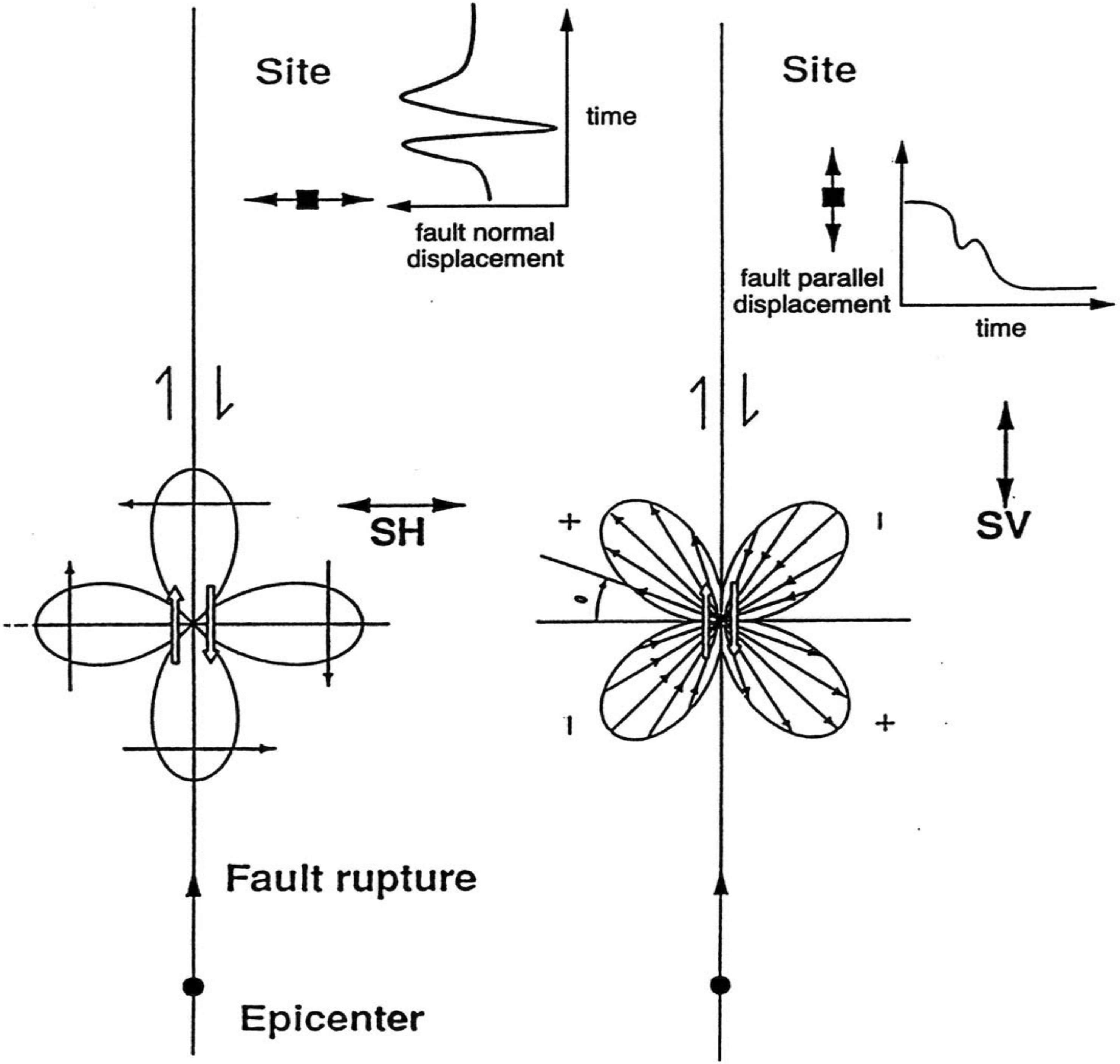
- Ground motion amplitudes from shallow faulting earthquakes may have been overestimated in current seismic hazard estimates
- Need separate ground motion models for shallow and buried faulting
- Need criteria for predicting surface and/or subsurface faulting on mapped surface faults

Near Fault Rupture Directivity Pulse

- Geometry and Orientation
- Magnitude Scaling of Period of Pulse

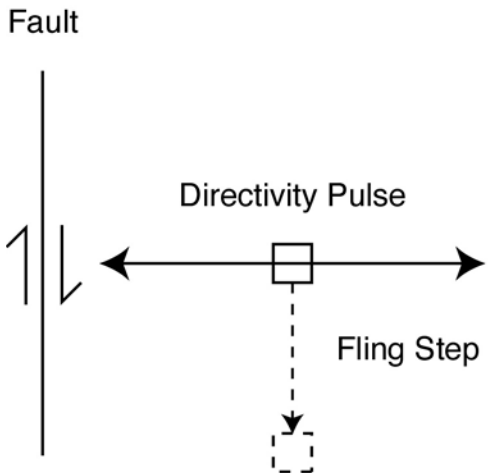
RUPTURE DIRECTIVITY




Site
time
fault normal displacement
SH
Fault rupture
Epicenter
Site
fault parallel displacement
time
SV
+
+
θ

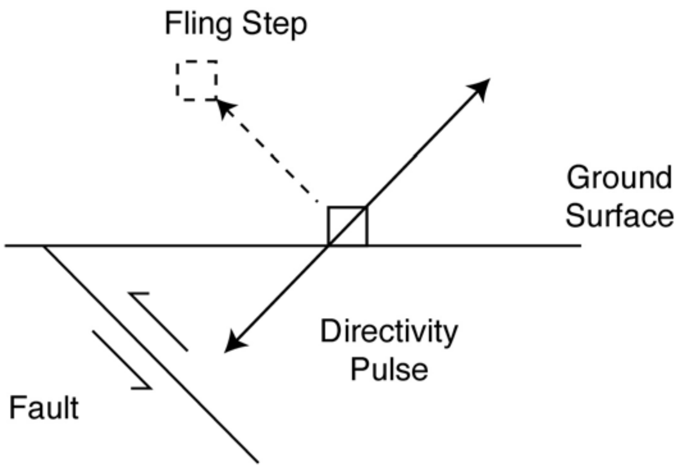
STRIKE SLIP

(Map View)



DIP SLIP

(Cross Section)



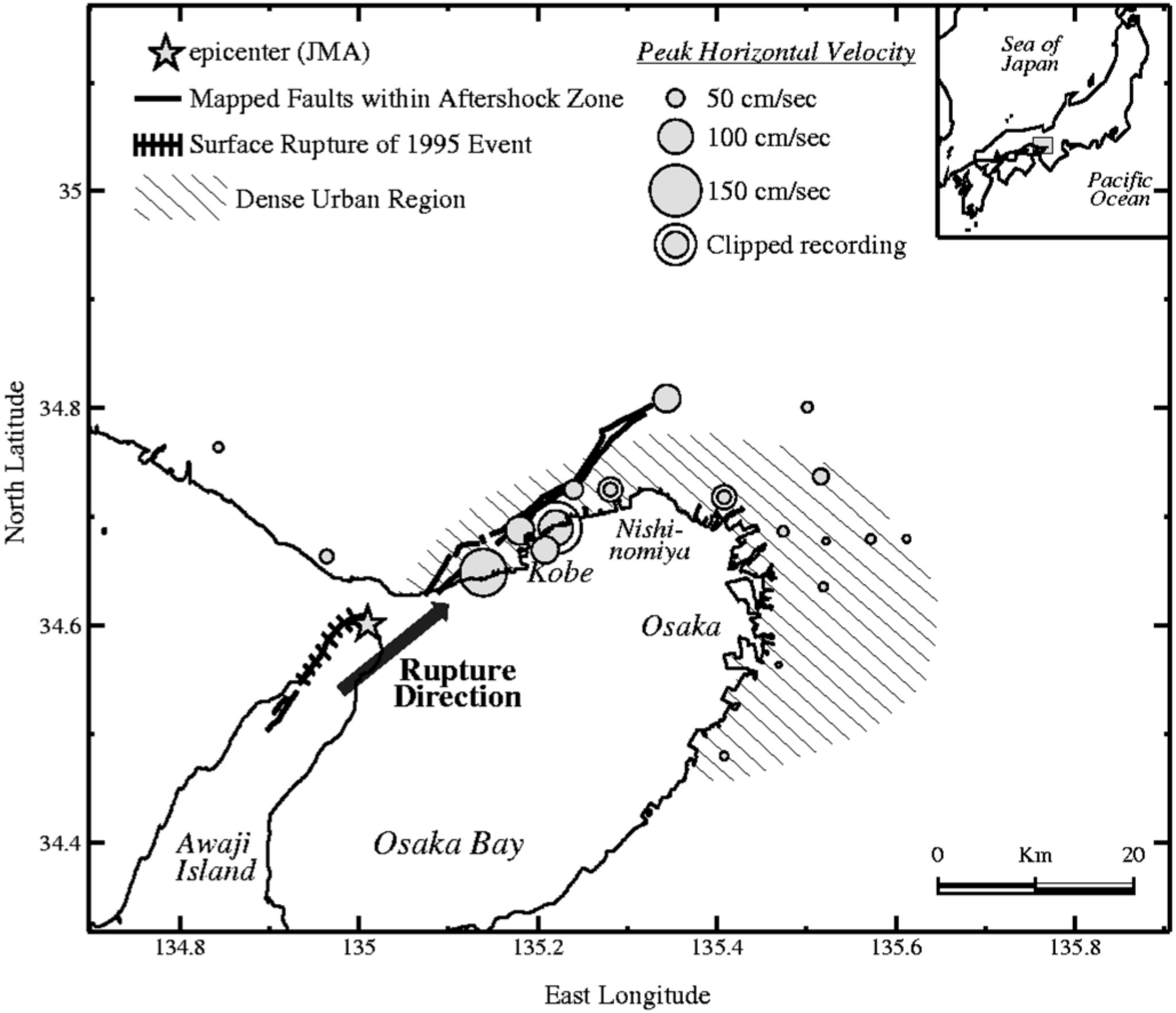
Rupture Directivity Pulse

- Large pulse of ground motion at near-fault sites
- Occurs on the fault normal component
- Causes large spectral acceleration at periods (longer than 0.5 sec) that depend on M_w

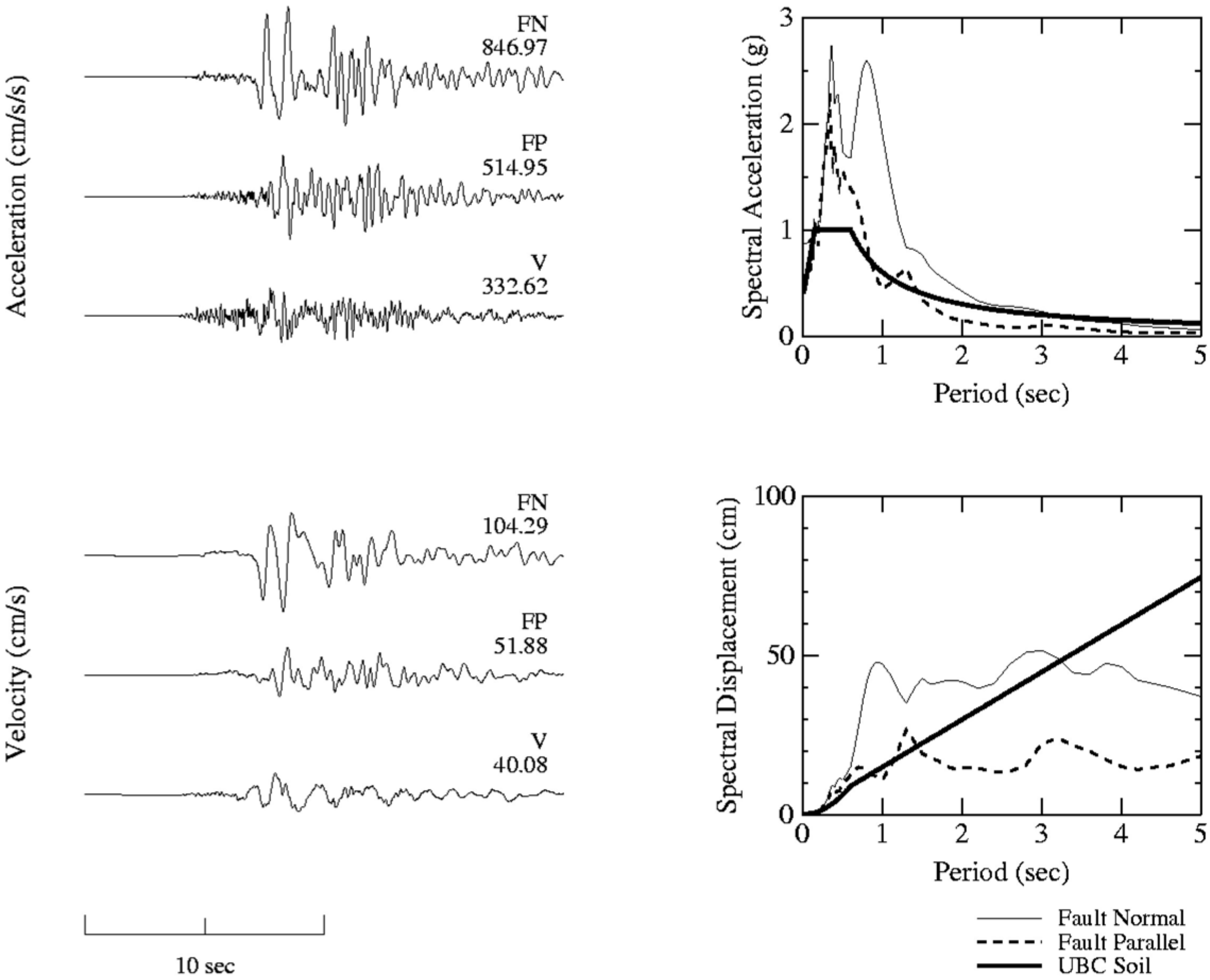
Fling Step

- Large permanent displacement of ground
- Occurs on the fault parallel component for strike-slip; fault normal for dip-slip
- May take several seconds to occur

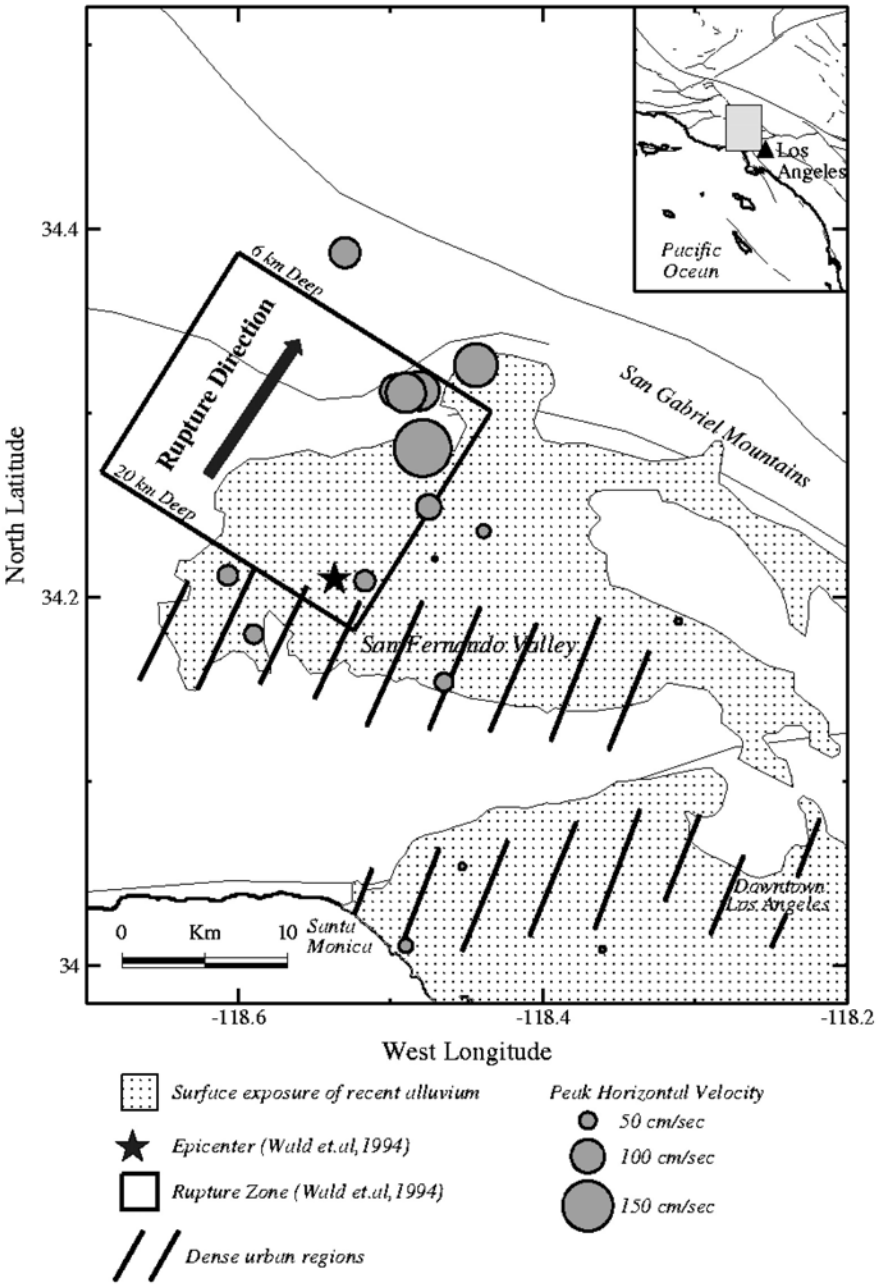
17 January 1995 Hyogoken Nanbu Earthquake, M = 6.9



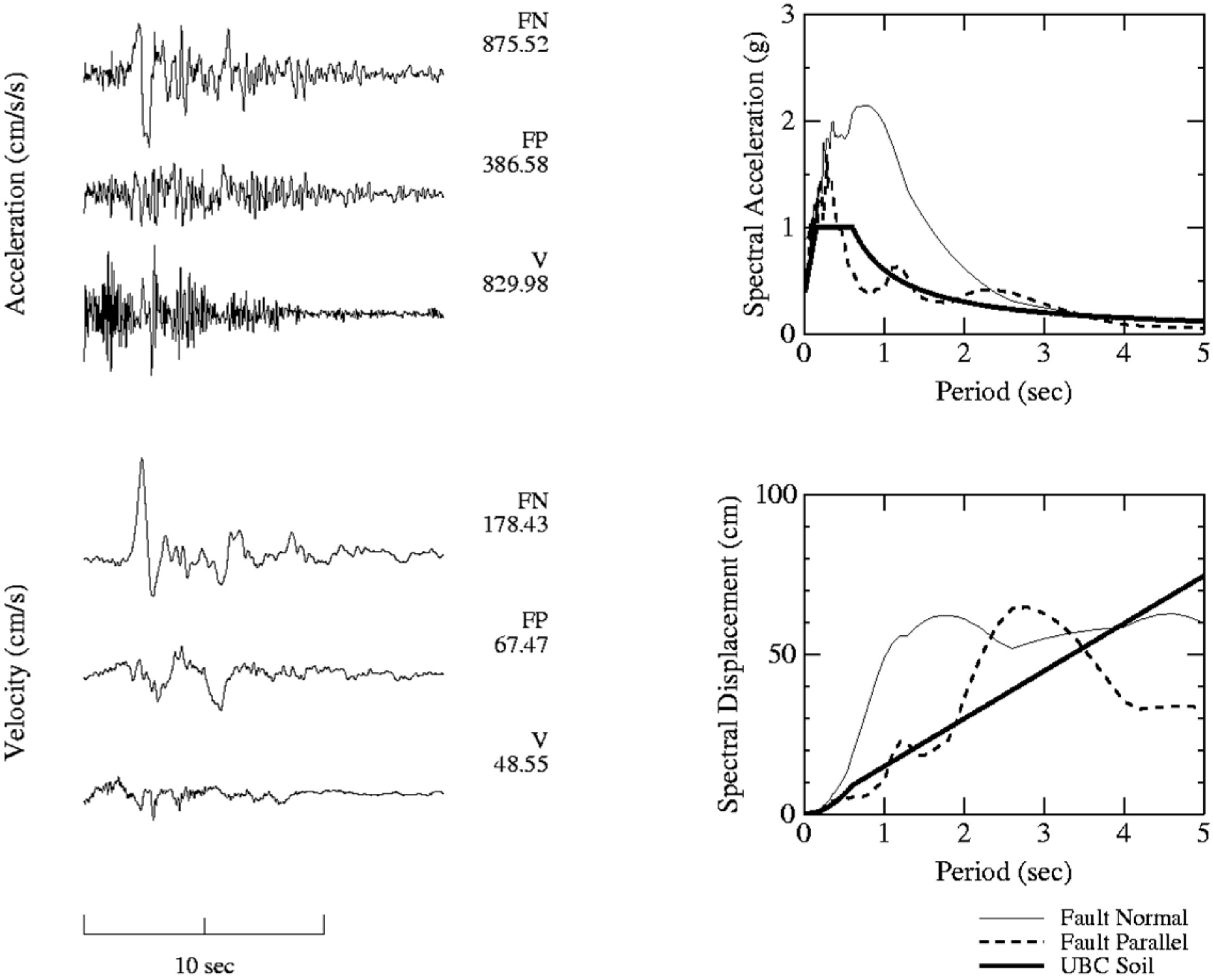
17 January 1995 Hyogoken Nanbu Earthquake, Mw 6.9, Kobe (JMA)



17 January 1994 Northridge Earthquake, M=6.7

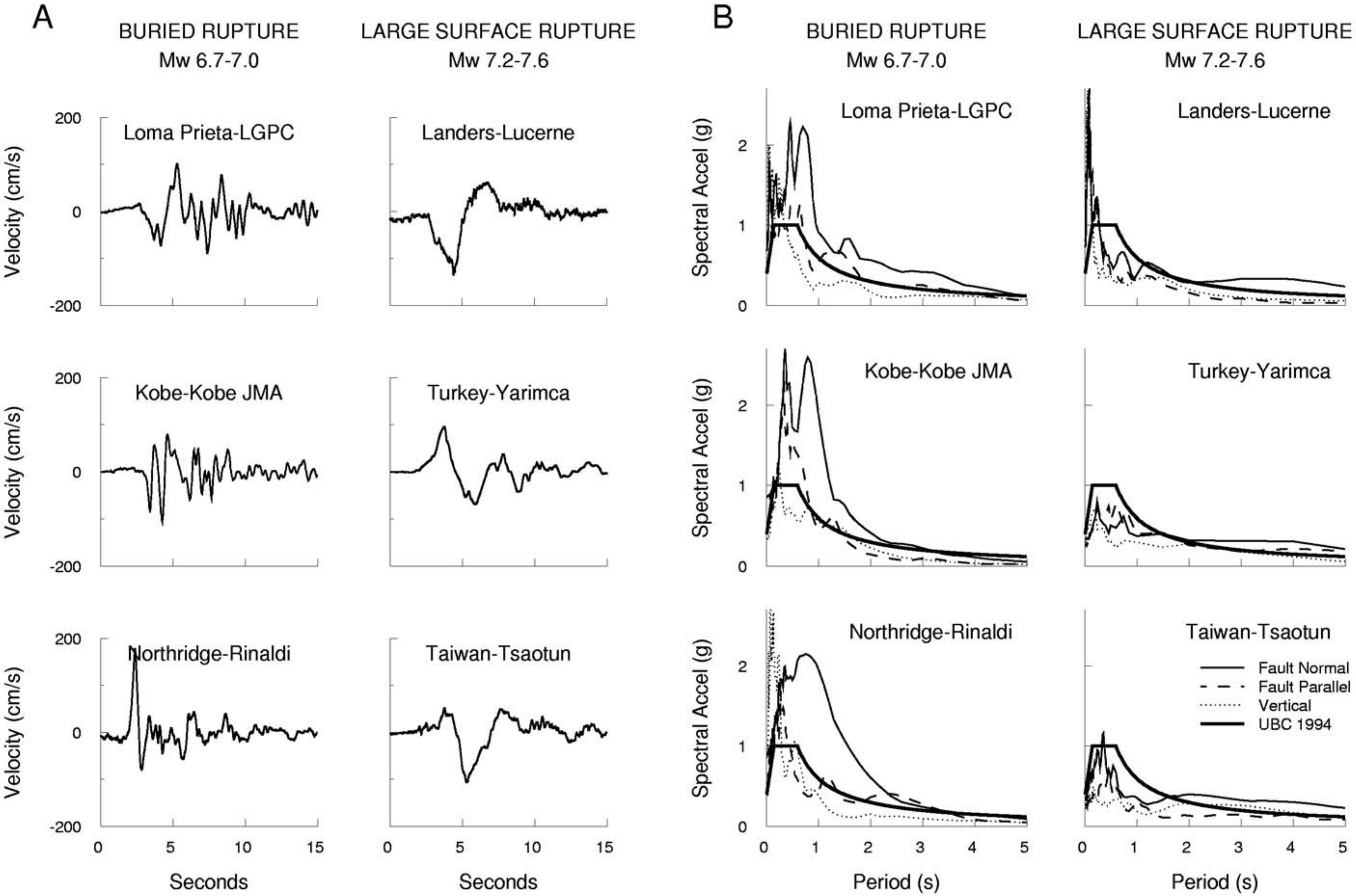


17 January 1994 Northridge Earthquake, Mw 6.7, Rinaldi



Conditions for Forward Directivity

- Rupture propagates toward the site
- The slip on the fault is aligned with the rupture propagation direction
    - Away from epicenter for strike-slip faulting
    - Updip from hypocenter for dip-slip faulting


A
BURIED RUPTURE
Mw 6.7-7.0
LARGE SURFACE RUPTURE
Mw 7.2-7.6
Loma Prieta-LGPC
Landers-Lucerne
Kobe-Kobe JMA
Turkey-Yarimca
Northridge-Rinaldi
Taiwan-Tsaotun
Velocity (cm/s)
200
0
-200
0
5
10
15
Seconds
B
BURIED RUPTURE
Mw 6.7-7.0
LARGE SURFACE RUPTURE
Mw 7.2-7.6
Loma Prieta-LGPC
Landers-Lucerne
Kobe-Kobe JMA
Turkey-Yarimca
Northridge-Rinaldi
Taiwan-Tsaotun
Spectral Accel (g)
0
1
2
0
1
2
3
4
5
Period (s)
Fault Normal
Fault Parallel
Vertical
UBC 1994

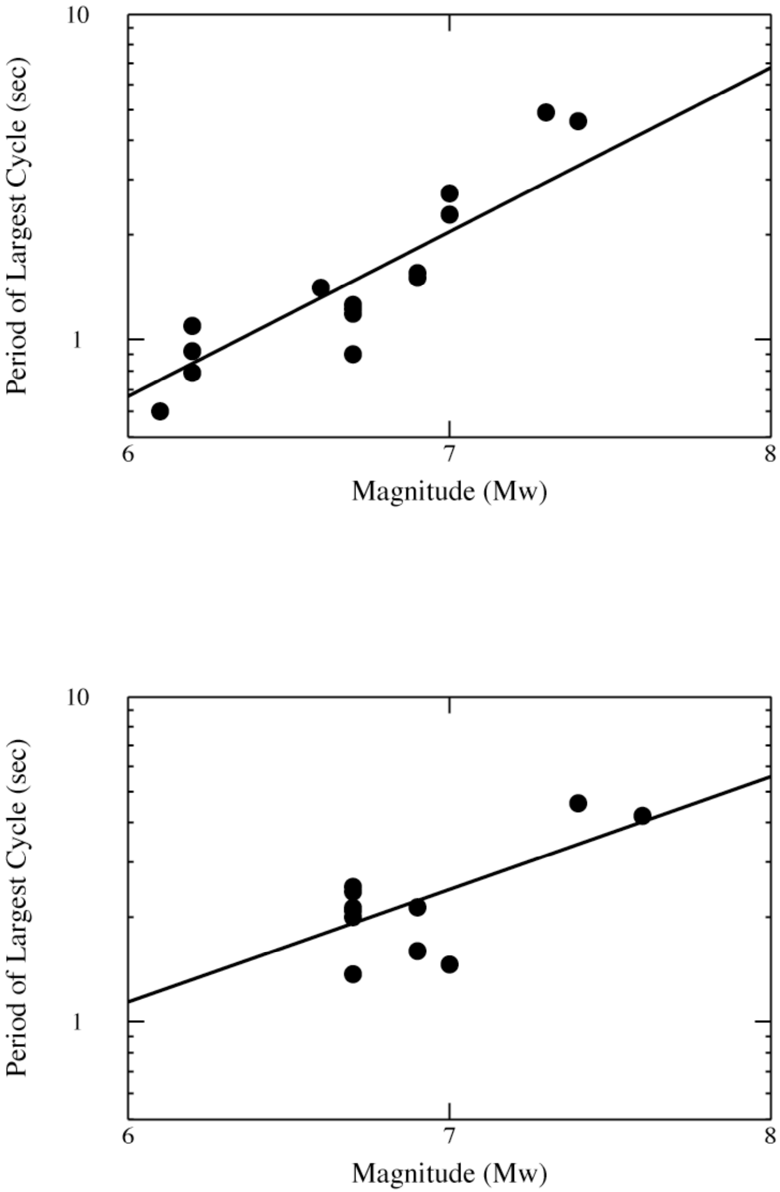
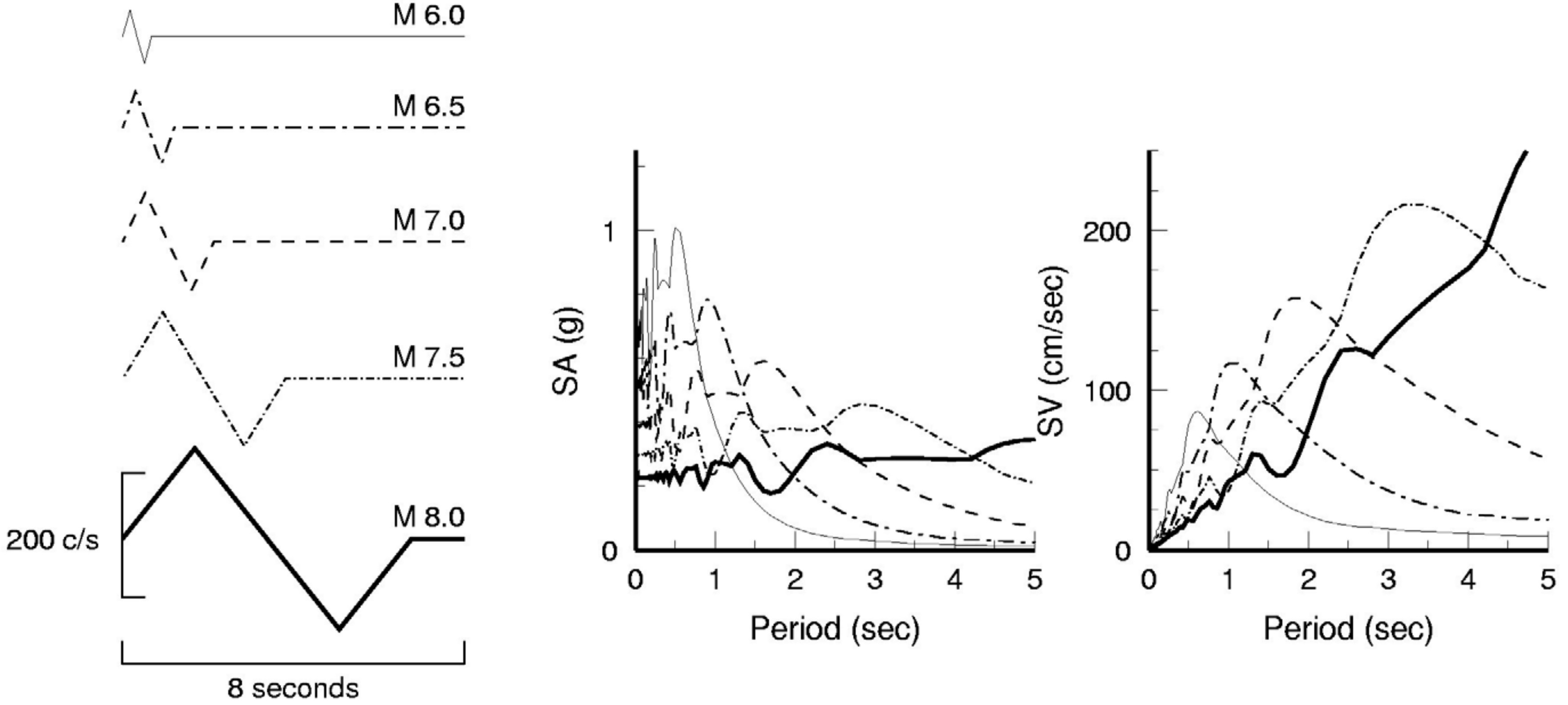
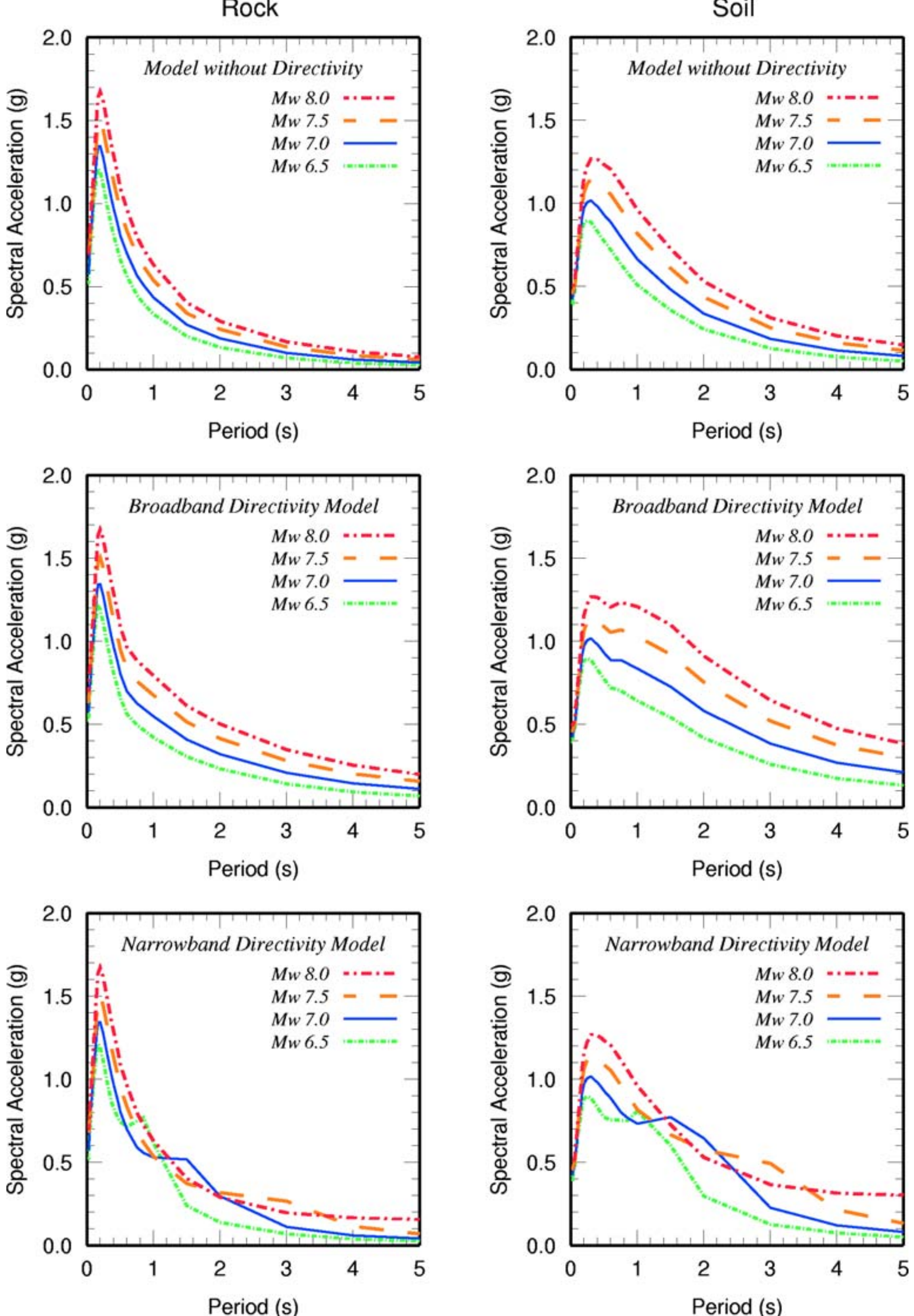


Figure 6. Mw scaling of the period of the forward rupture directivity velocity pulse on rock (top) and soil (bottom).


M 6.0
M 6.5
M 7.0
M 7.5
M 8.0
200 c/s
8 seconds
SA (g)
1
0
0
1
2
3
4
5
Period (sec)
SV (cm/sec)
200
100
0
0
1
2
3
4
5
Period (sec)


Rock
Soil
Model without Directivity
Broadband Directivity Model
Narrowband Directivity Model
Mw 8.0
Mw 7.5
Mw 7.0
Mw 6.5
Spectral Acceleration (g)
Period (s)
0.0
0.5
1.0
1.5
2.0
0
1
2
3
4
5

Magnitude Scaling Of Near Fault Ground Motions

- The forward directivity pulse is narrow band
- The period of the pulse increases with magnitude
- The pulse causes a peak in the acceleration response spectrum whose period increases with magnitude

Implications of Magnitude Scaling of Near Fault Directivity Pulse

- Ground motion amplitudes do not increase uniformly with magnitude at all response spectral periods
- At 1.5 seconds period, elastic response for M 7 is stronger than for M 7.5
- The difference between M 7 and M 7.5 may be less for inelastic response