PEER Annual Meeting

Oakland, January 25-26, 2001

SEISMIC HAZARD SMULATION AND PREDICTION

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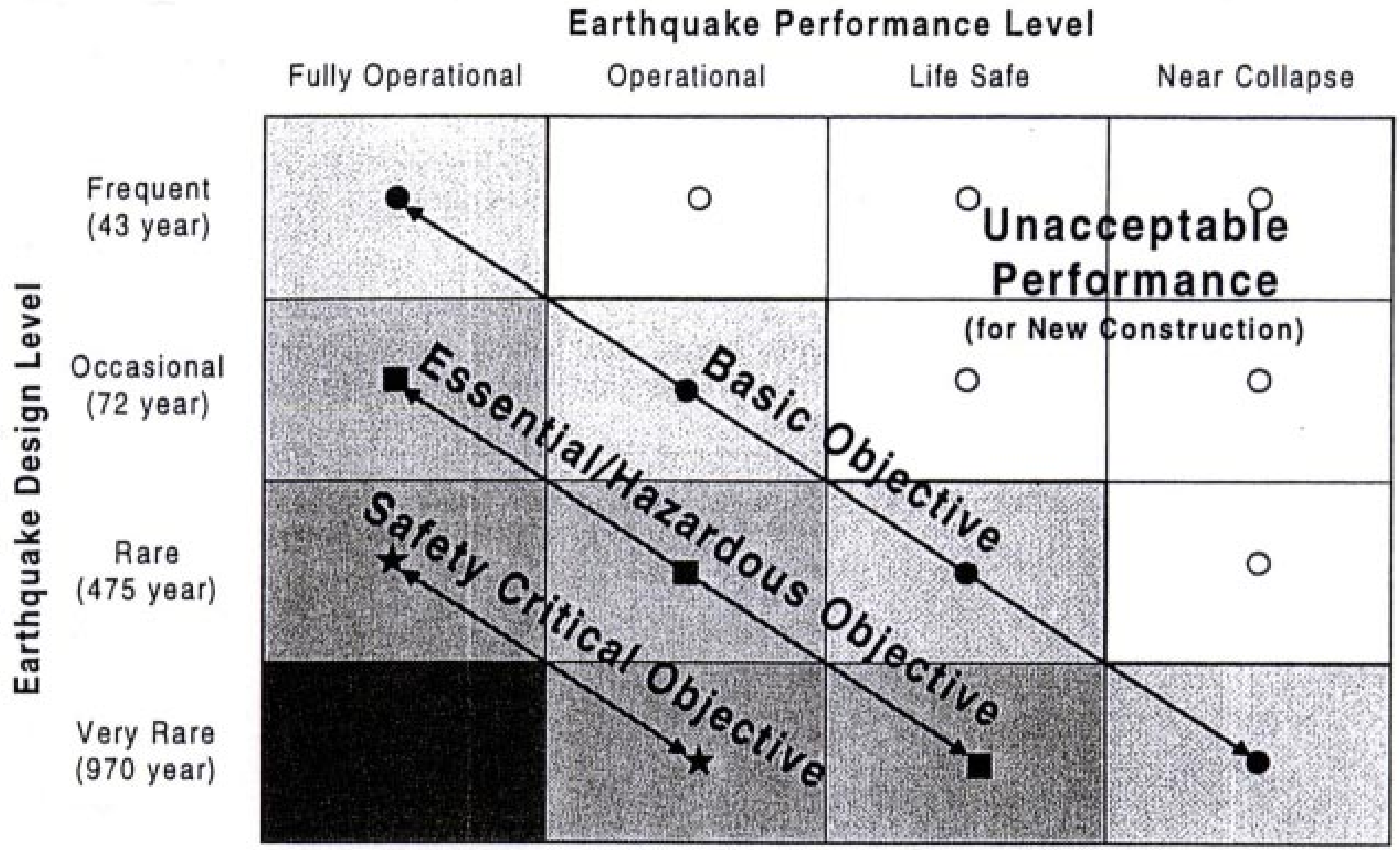
OUTLINE

Ground Motion Needs for Performance Based Engineering

Seismic Hazard Analysis Procedure

Ground Motion Simulation and Prediction

- Source - near-fault rupture directivity pulse
- Site - basin waves and basin edge waves



Earthquake Performance Level
Fully Operational
Operational
Life Safe
Near Collapse
Earthquake Design Level
Frequent
(43 year)
Occasional
(72 year)
Rare
(475 year)
Very Rare
(970 year)
Unacceptable
Performance
(for New Construction)
Basic Objective
Essential/Hazardous Objective
Safety Critical Objective

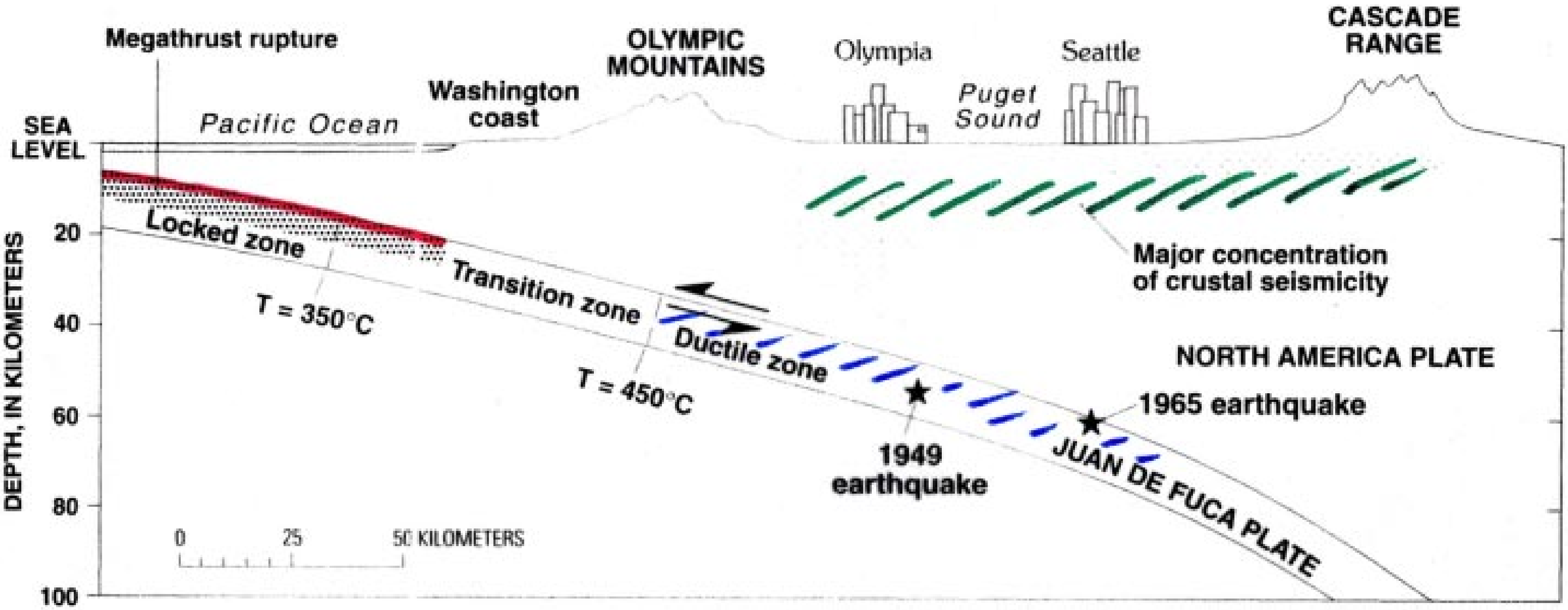
A Framing Equation

$$\lambda(\underline{DV}) = \int\int G(\underline{DV} \mid \underline{DM})\, dG(\underline{DM} \mid \underline{IM})\, d\lambda(\underline{IM})$$

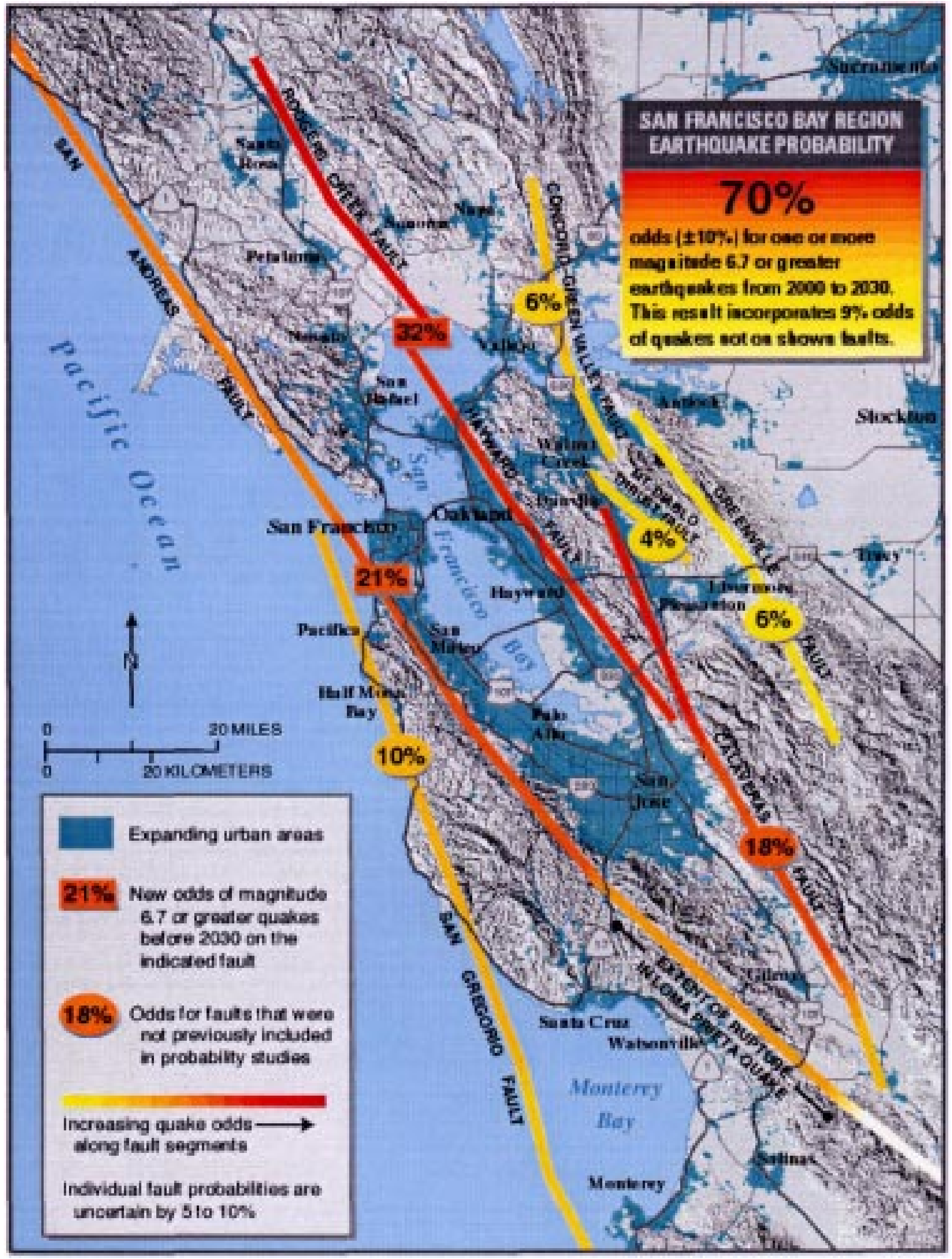
DV Decision Variable(s) *(costs, lives lost, collapse limit states, …)*

DM Damage Measure(s) *(displacements, fractures, …)*

IM Ground Motion Intensity Measure(s) *(PGA, S_a, …)*

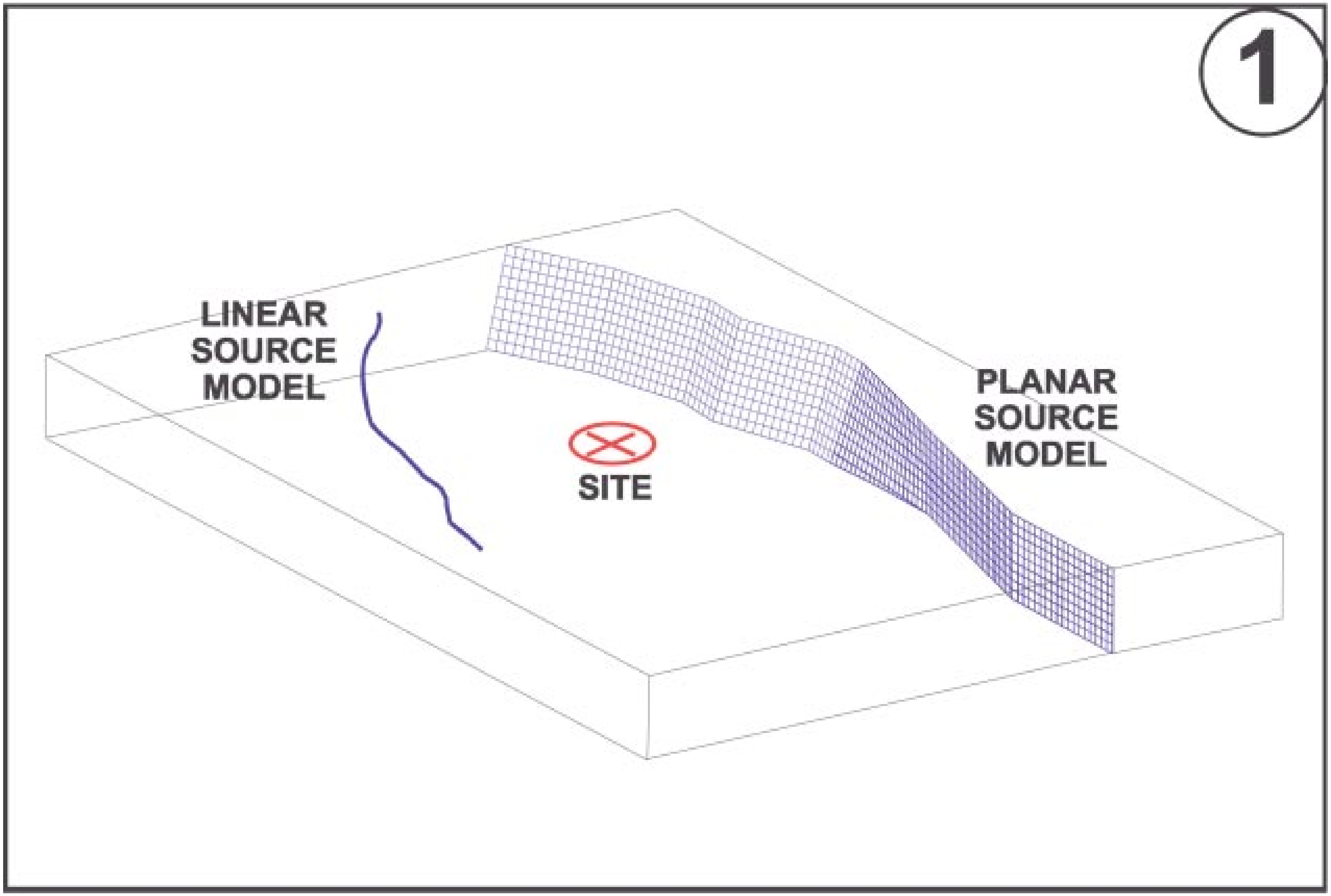


Megathrust rupture
OLYMPIC MOUNTAINS
Olympia
Seattle
CASCADE RANGE
Washington coast
Puget Sound
SEA LEVEL
Pacific Ocean
Locked zone
Transition zone
T = 350°C
Ductile zone
T = 450°C
Major concentration of crustal seismicity
NORTH AMERICA PLATE
1965 earthquake
1949 earthquake
JUAN DE FUCA PLATE
DEPTH, IN KILOMETERS
20
40
60
80
100
0
25
50 KILOMETERS

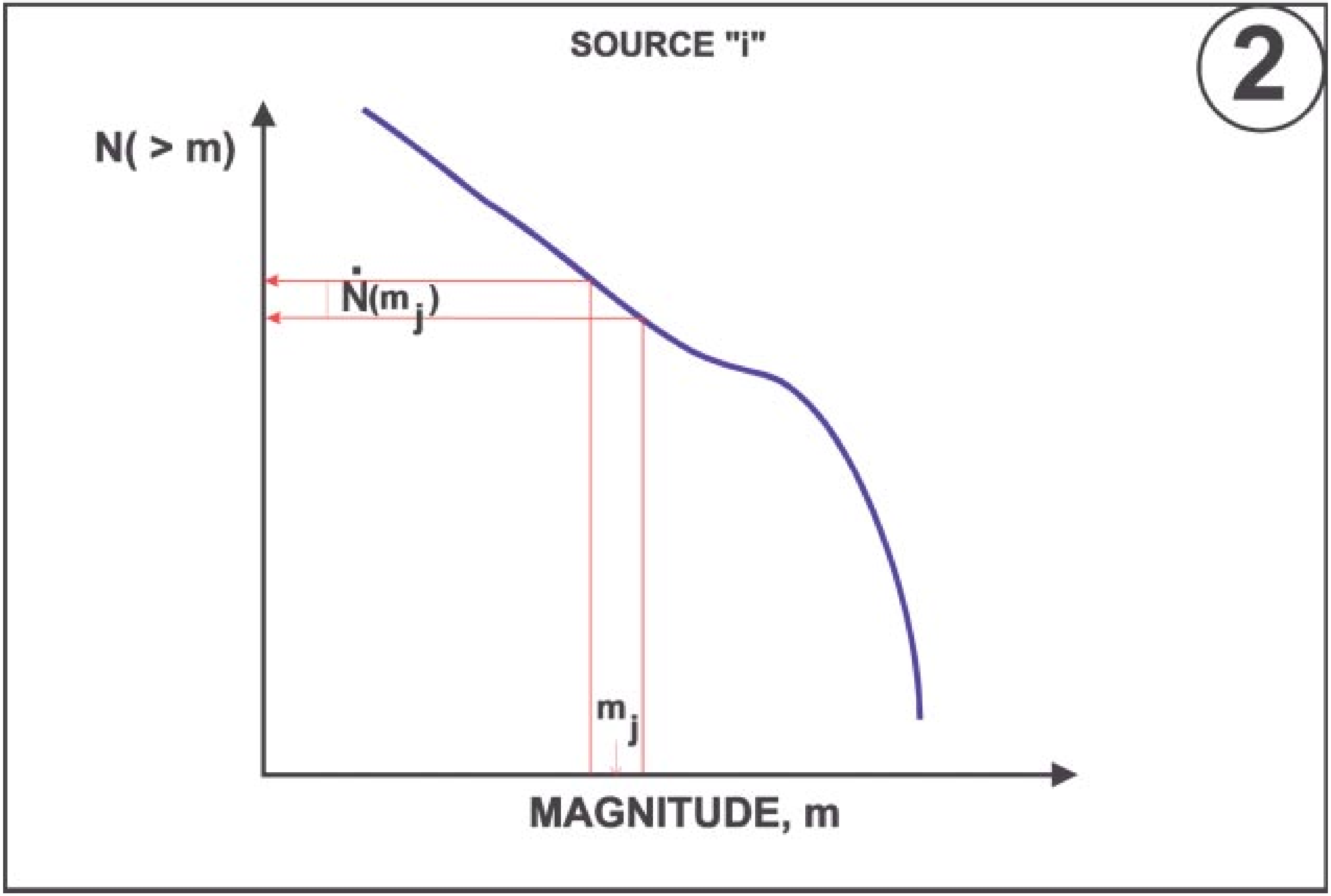


SAN FRANCISCO BAY REGION
EARTHQUAKE PROBABILITY
70%
odds (±10%) for one or more magnitude 6.7 or greater earthquakes from 2000 to 2030. This result incorporates 9% odds of quakes not on shown faults.
SAN ANDREAS FAULT
RODGERS CREEK FAULT
CONCORD-GREEN VALLEY FAULT
HAYWARD FAULT
MT. DIABLO THRUST FAULT
GREENVILLE FAULT
CALAVERAS FAULT
SAN GREGORIO FAULT
EXTENT OF RUPTURE IN LOMA PRIETA QUAKE
32%
6%
4%
6%
21%
10%
18%
Pacific Ocean
San Francisco Bay
Monterey Bay
Sacramento
Santa Rosa
Sonoma
Napa
Petaluma
Novato
Vallejo
San Rafael
Antioch
Stockton
Walnut Creek
Danville
San Francisco
Oakland
Tracy
Livermore
Pleasanton
Hayward
Pacifica
San Mateo
Half Moon Bay
Palo Alto
San Jose
Gilroy
Santa Cruz
Watsonville
Salinas
Monterey
N
0 20 MILES
0 20 KILOMETERS
Expanding urban areas
21% New odds of magnitude 6.7 or greater quakes before 2030 on the indicated fault
18% Odds for faults that were not previously included in probability studies
Increasing quake odds along fault segments
Individual fault probabilities are uncertain by 5 to 10%

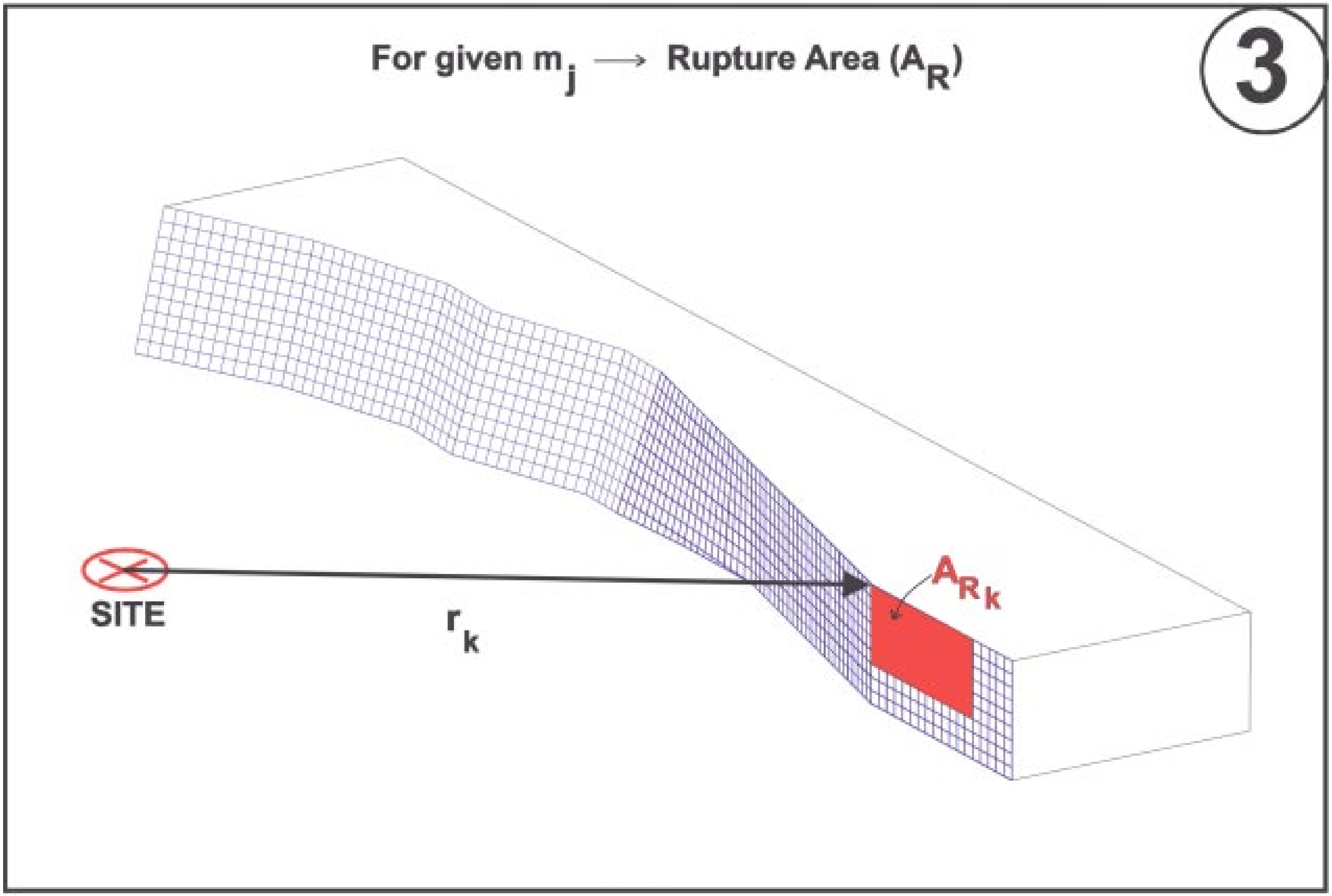
CHARACTERIZATION OF SEISMOGENIC SOURCES



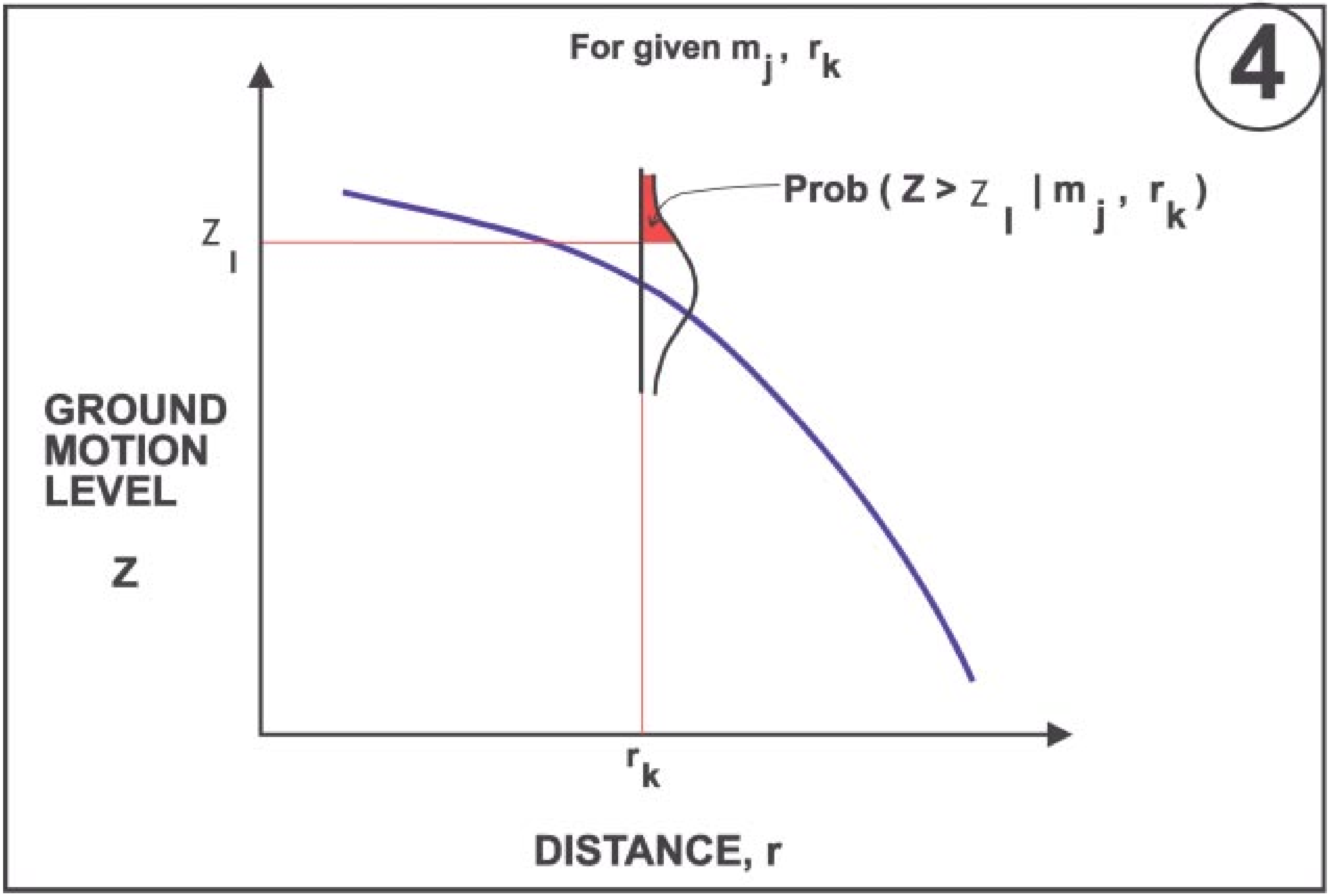
SPECIFICATION OF RECURRENCE RELATIONSHIP



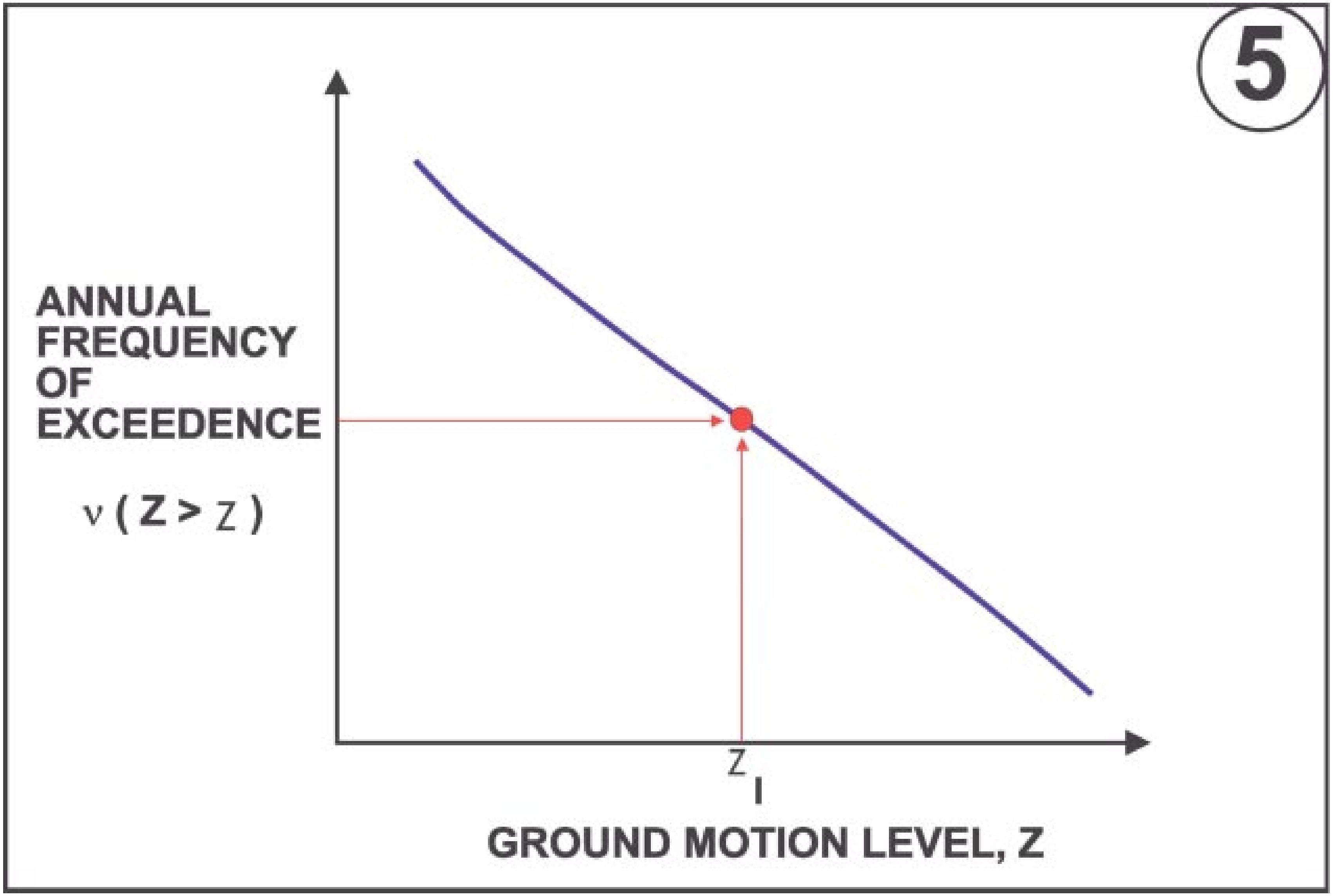
EVALUATION OF PROBABILITY OF DISTANCE TO RUPTURE

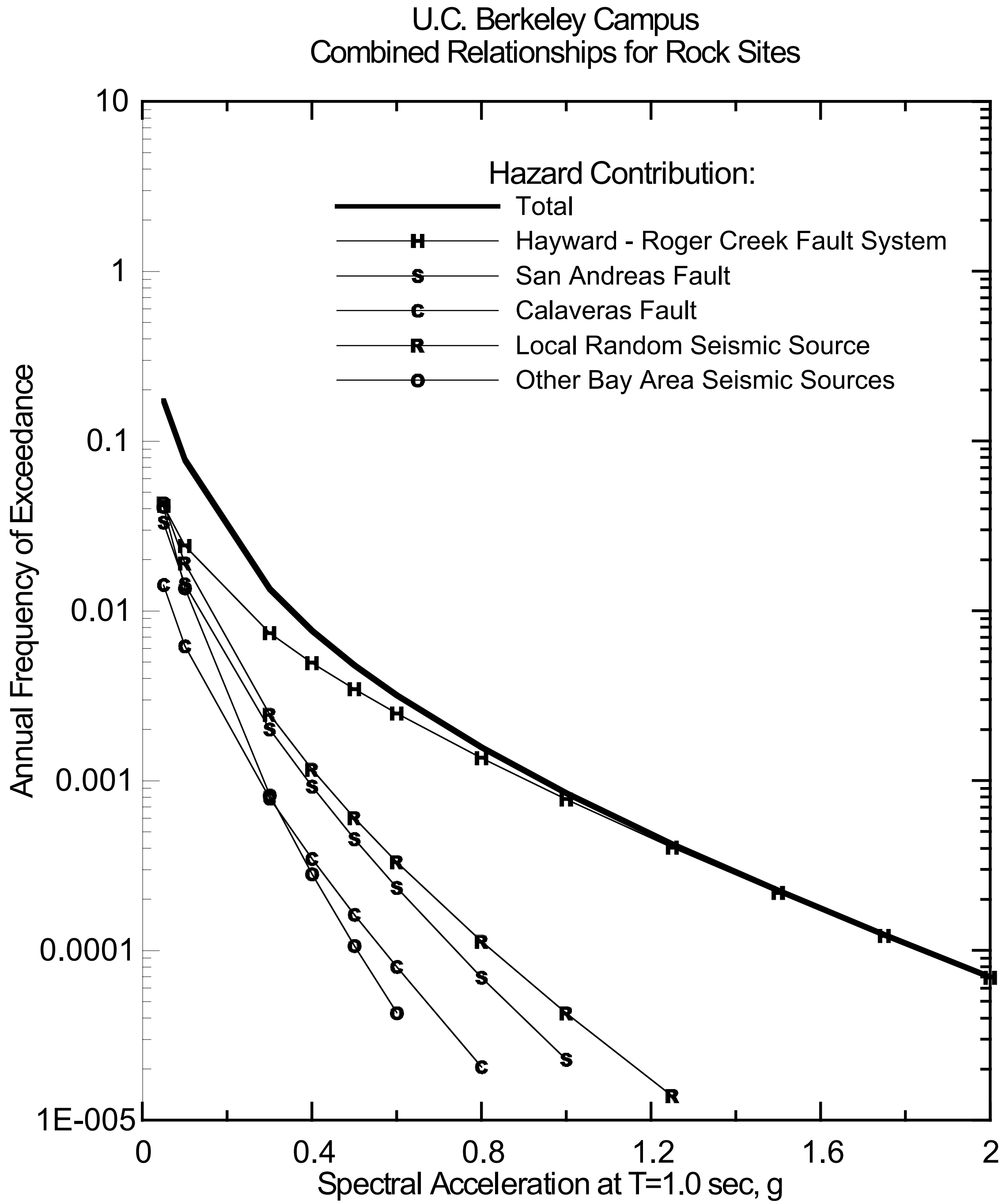


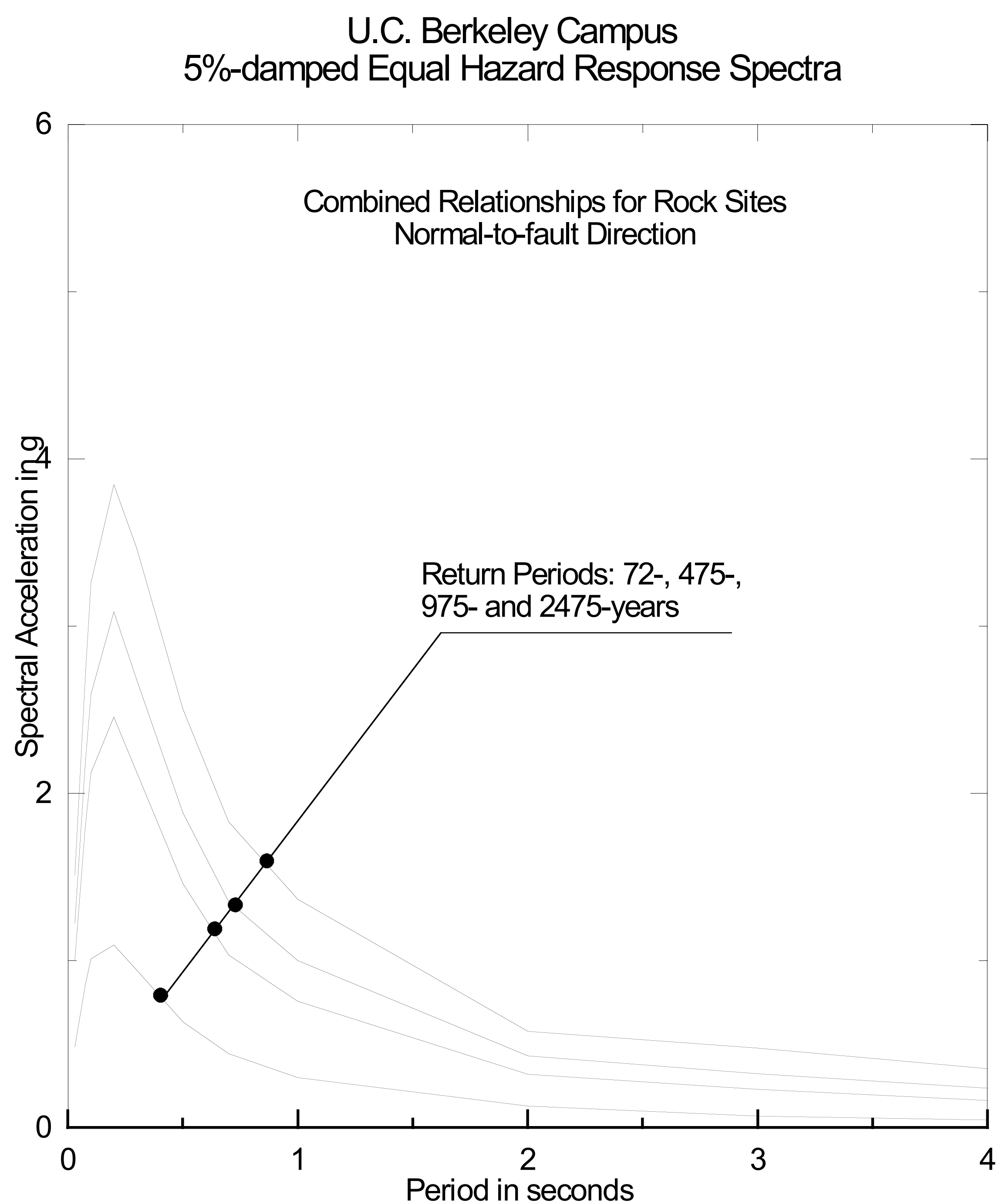
CALCULATION OF EXCEEDANCE USING ATTENUATION EQUATION

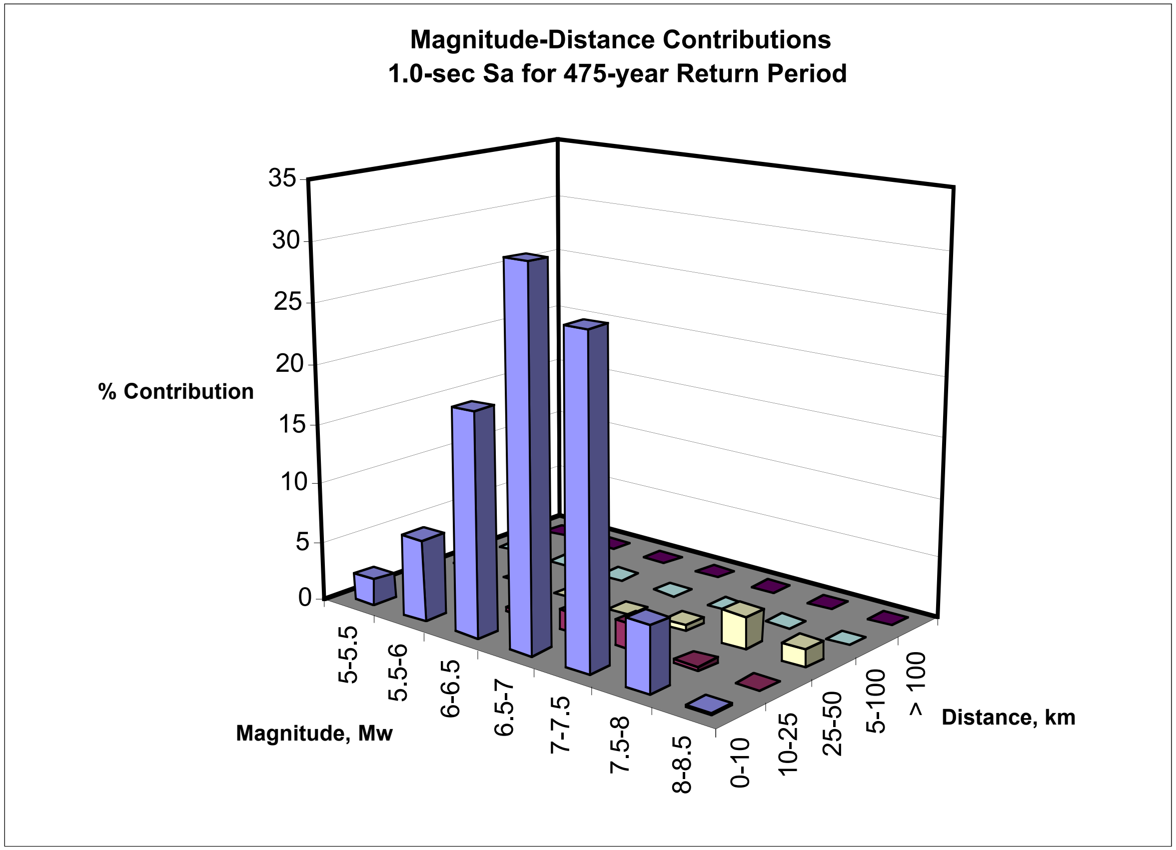


CALCULATION OF PROBABILISTIC SEISMIC HAZARD (HAZARD CURVE)

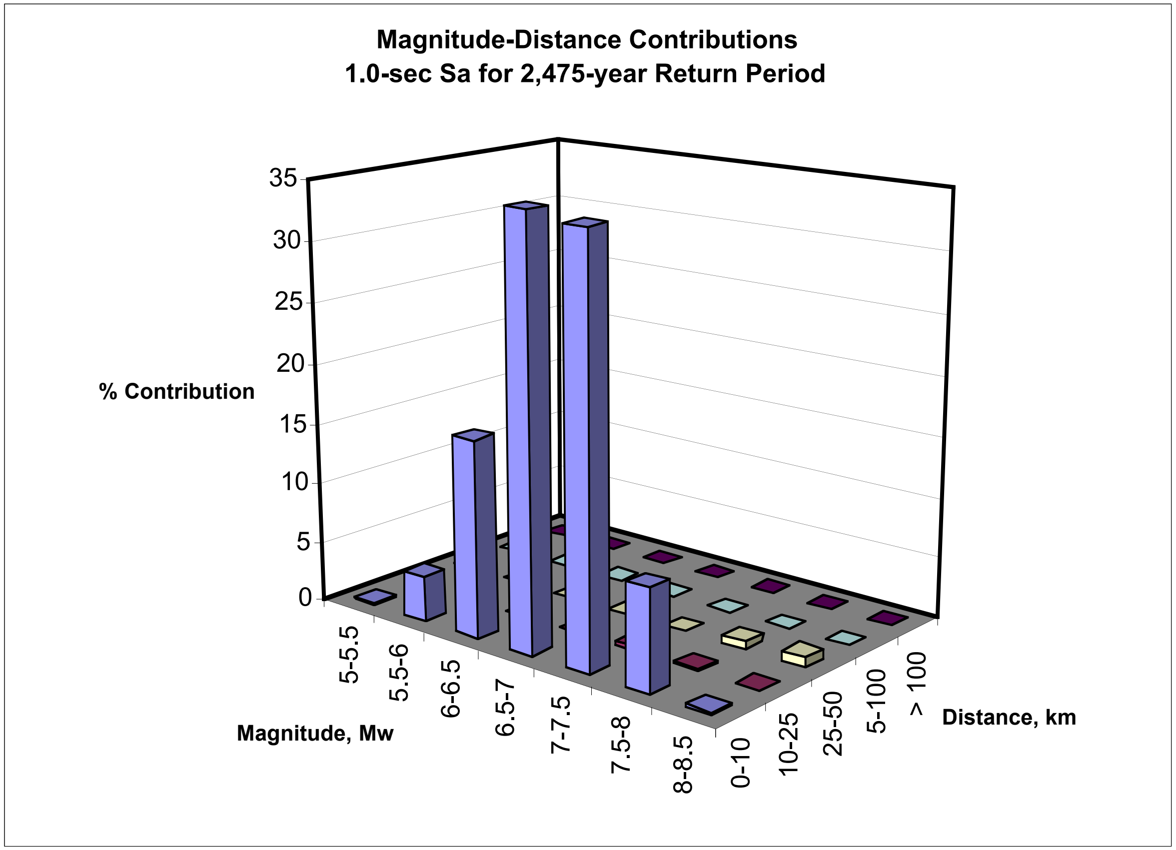



U.C. Berkeley Campus
Combined Relationships for Rock Sites
Hazard Contribution:
Total
Hayward - Roger Creek Fault System
San Andreas Fault
Calaveras Fault
Local Random Seismic Source
Other Bay Area Seismic Sources
Annual Frequency of Exceedance
Spectral Acceleration at T=1.0 sec, g
10
1
0.1
0.01
0.001
0.0001
1E-005
0
0.4
0.8
1.2
1.6
2

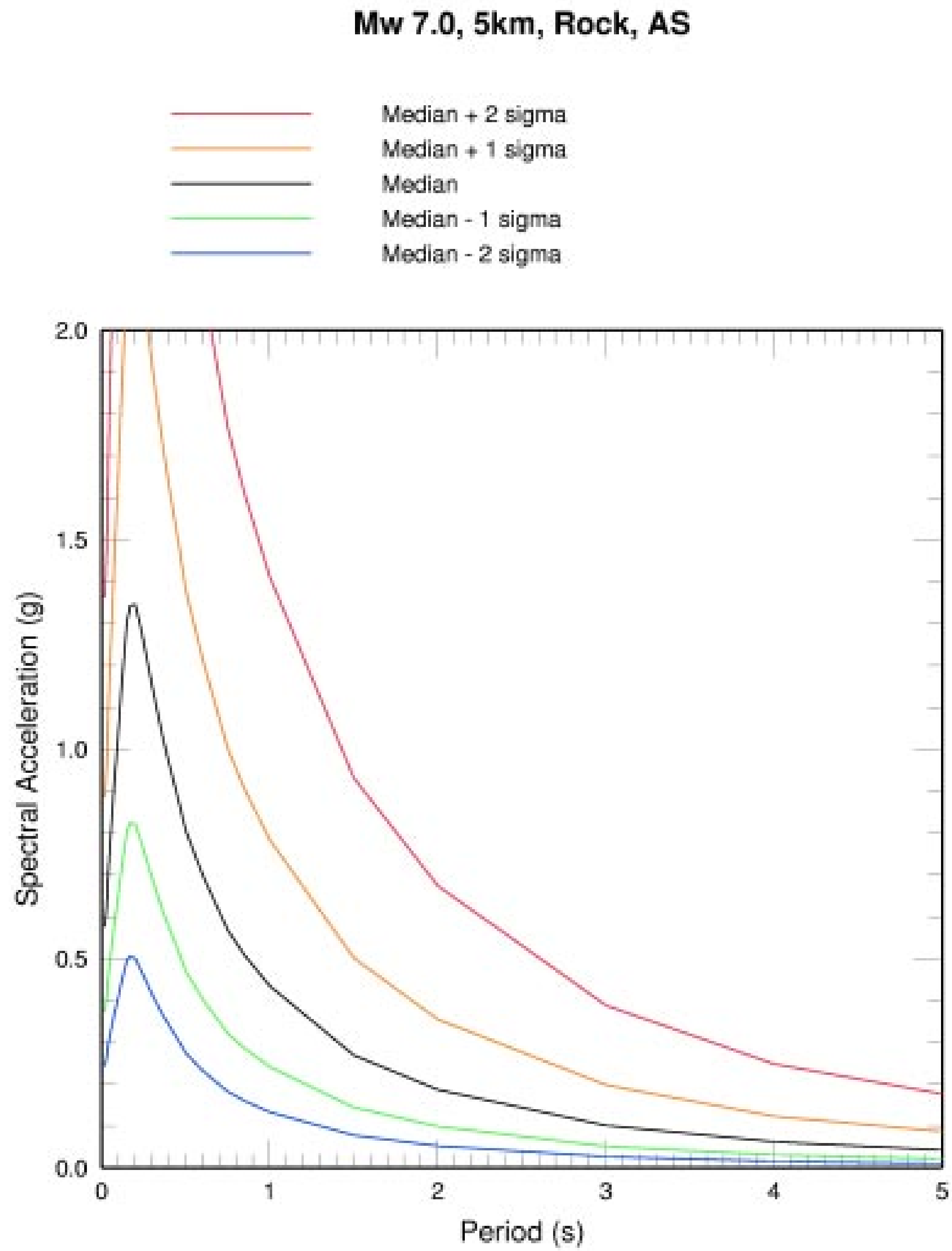

U.C. Berkeley Campus
5%-damped Equal Hazard Response Spectra
Combined Relationships for Rock Sites
Normal-to-fault Direction
Return Periods: 72-, 475-,
975- and 2475-years
Spectral Acceleration in g
Period in seconds
0
2
4
6
0
1
2
3
4



Magnitude-Distance Contributions
1.0-sec Sa for 475-year Return Period
% Contribution
35
30
25
20
15
10
5
0
5-5.5
5.5-6
6-6.5
6.5-7
7-7.5
7.5-8
8-8.5
Magnitude, Mw
0-10
10-25
25-50
5-100
> 100
Distance, km

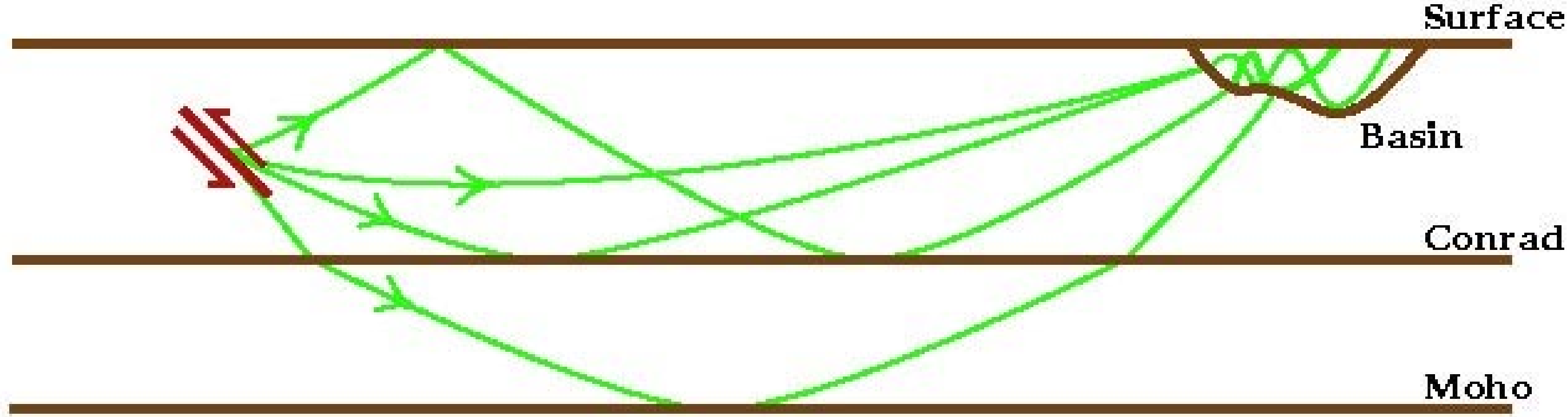


Magnitude-Distance Contributions
1.0-sec Sa for 2,475-year Return Period
% Contribution
35
30
25
20
15
10
5
0
5-5.5
5.5-6
6-6.5
6.5-7
7-7.5
7.5-8
8-8.5
Magnitude, Mw
0-10
10-25
25-50
5-100
> 100
Distance, km

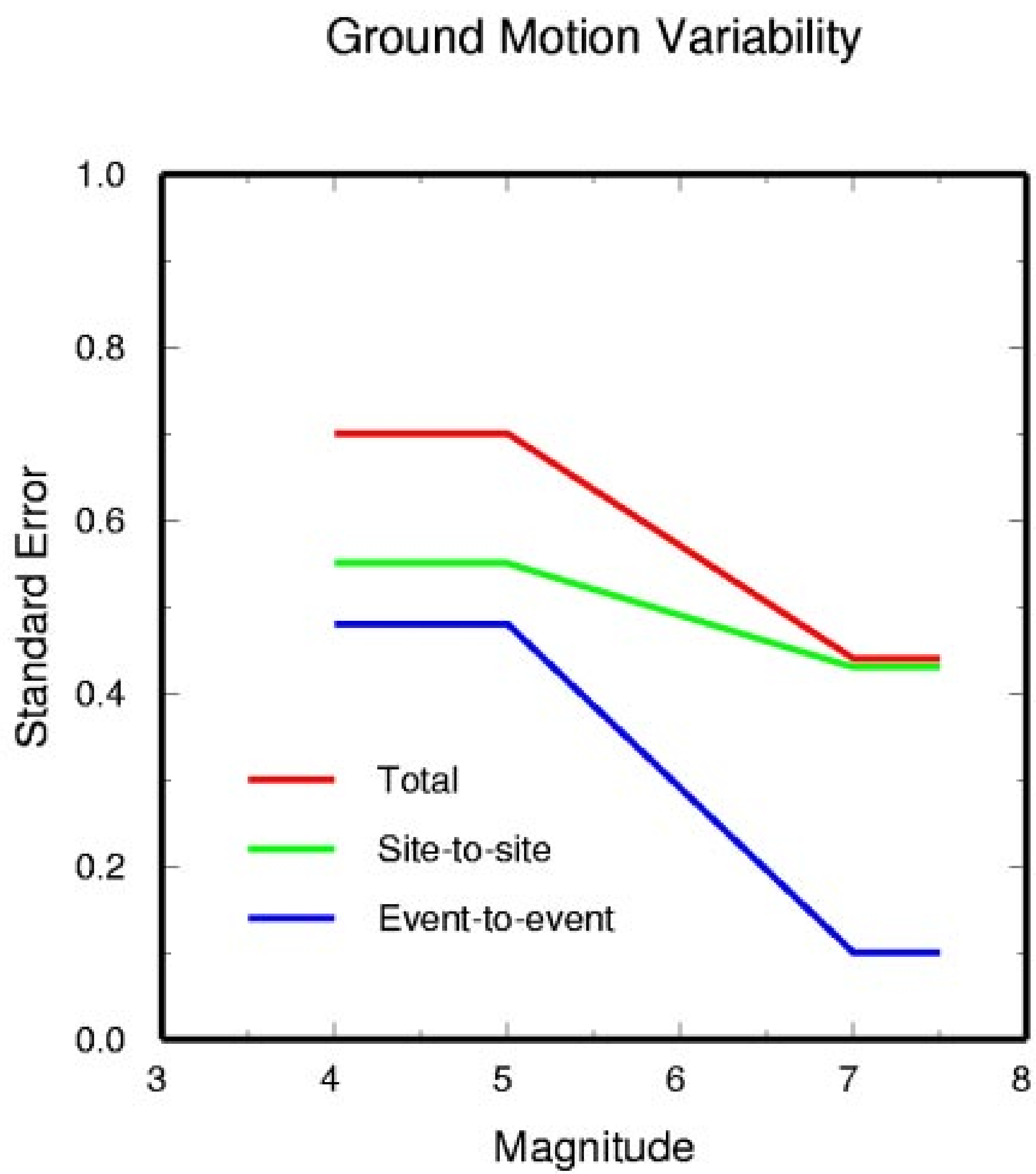


Mw 7.0, 5km, Rock, AS
Median + 2 sigma
Median + 1 sigma
Median
Median - 1 sigma
Median - 2 sigma
Spectral Acceleration (g)
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
Period (s)

Ground Motion Prediction Models



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


Ground Motion Variability
Standard Error
Magnitude
0.0
0.2
0.4
0.6
0.8
1.0
3
4
5
6
7
8
Total
Site-to-site
Event-to-event

GROUND MOTION VARIABILITY

For large earthquakes, site-to-site variability is much larger than event-to-event variability

So large earthquakes are basically similar, but a given earthquake looks different at different sites due to source, path and site effects that may in part be predictable

BROADBAND TIME HISTORY SIMULATION PROCEDURE

Elastodynamic Representation Theorem:

Ground motion U(t) can be calculated from the convolution of the slip time function D(t) on the fault with the Green's function G(t) for the appropriate distance and depth, integrated over the fault rupture surface

$$U(t) = \sum D(t) * G(t)$$

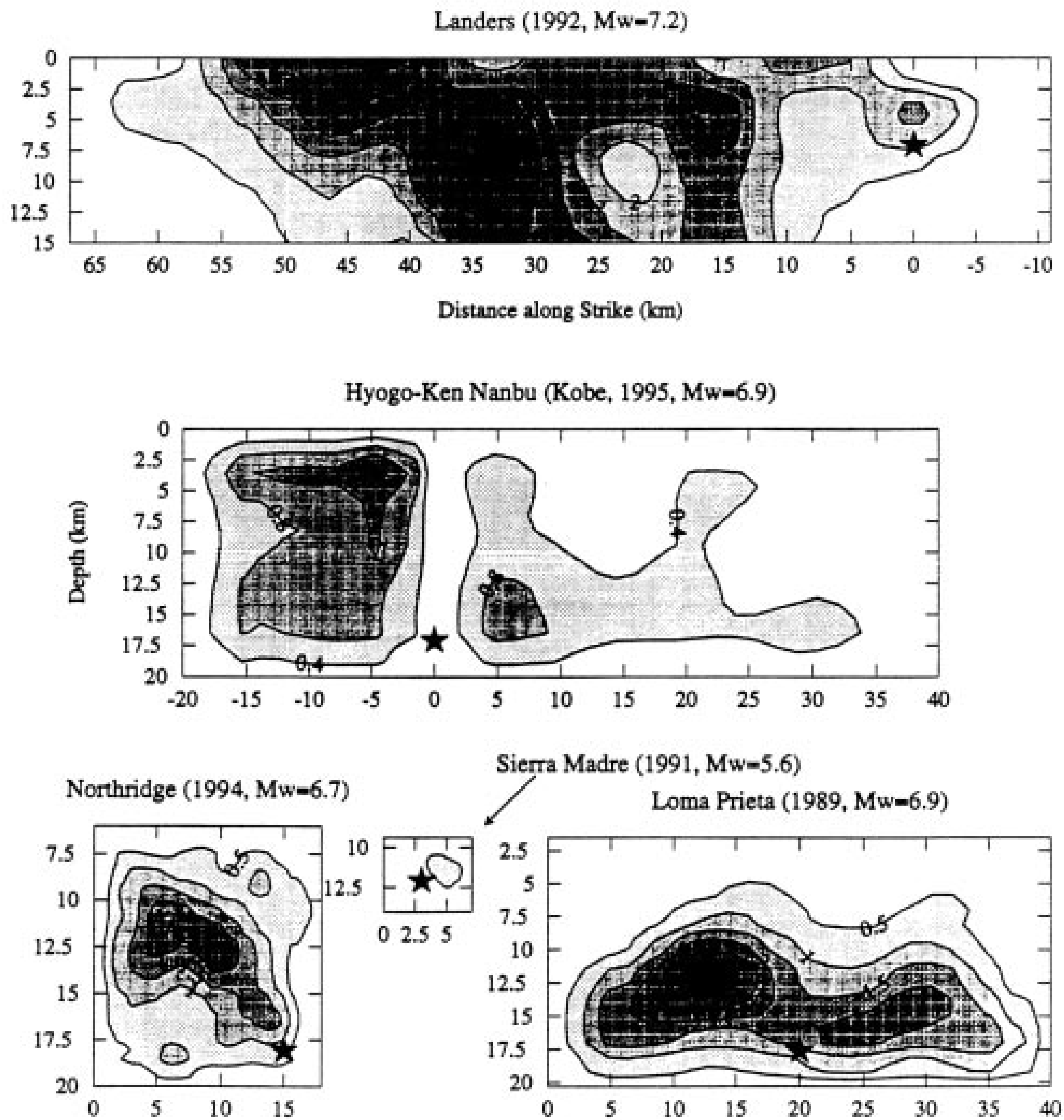
Combine long period and short period simulations to generate broadband time history

EARTHQUAKE SOURCE REPRESENTATION

Kinematic model of shear dislocation spreading over the fault rupture surface, in which several processes are coherent at long periods (>~ 1 second) and less coherent at short periods:

- Radiation Pattern
- Rupture Velocity
- Slip Velocity

Near fault pulse caused by rupture directivity and radiation pattern



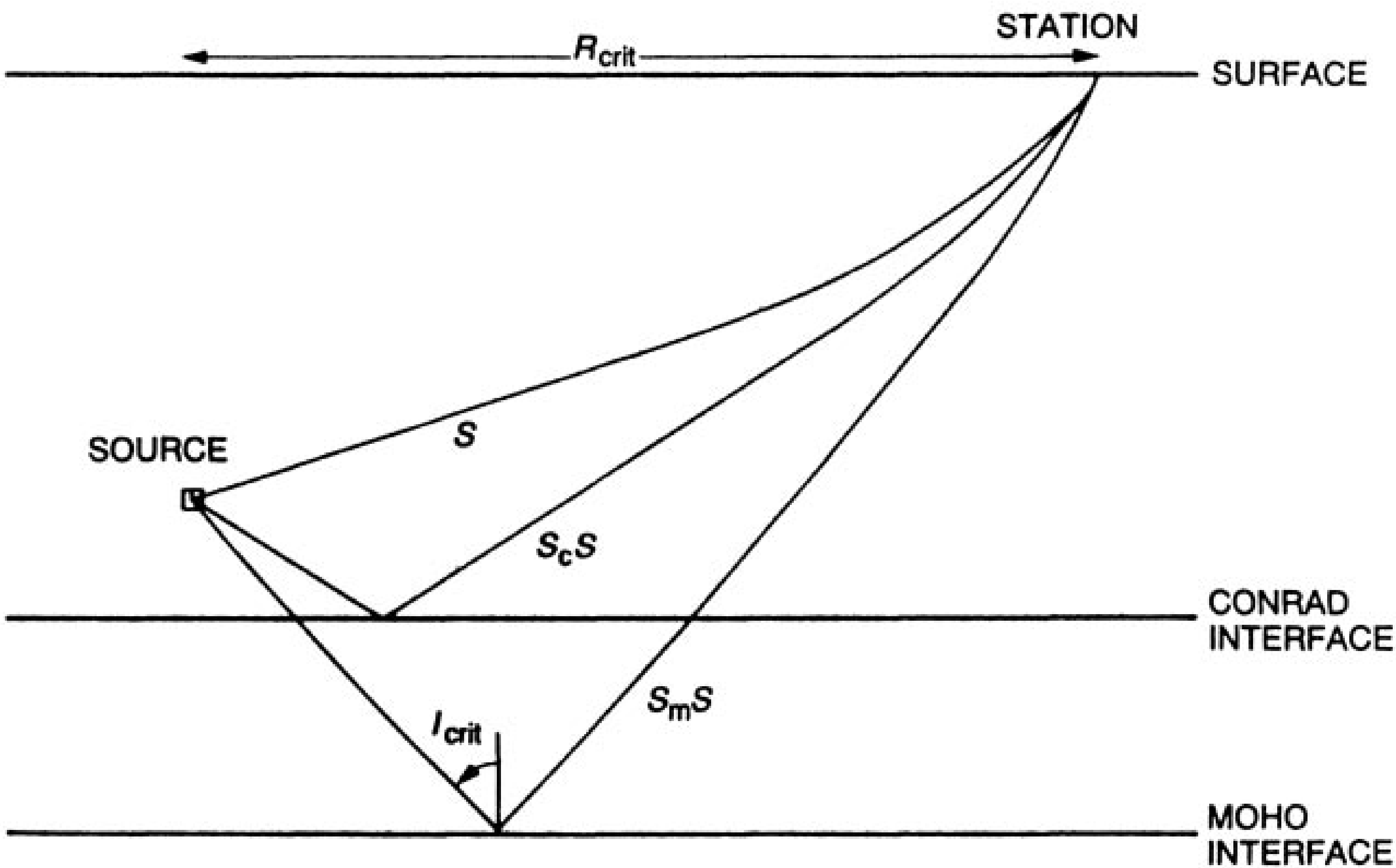
Landers (1992, Mw=7.2)
Distance along Strike (km)
Hyogo-Ken Nanbu (Kobe, 1995, Mw=6.9)
Depth (km)
Sierra Madre (1991, Mw=5.6)
Northridge (1994, Mw=6.7)
Loma Prieta (1989, Mw=6.9)

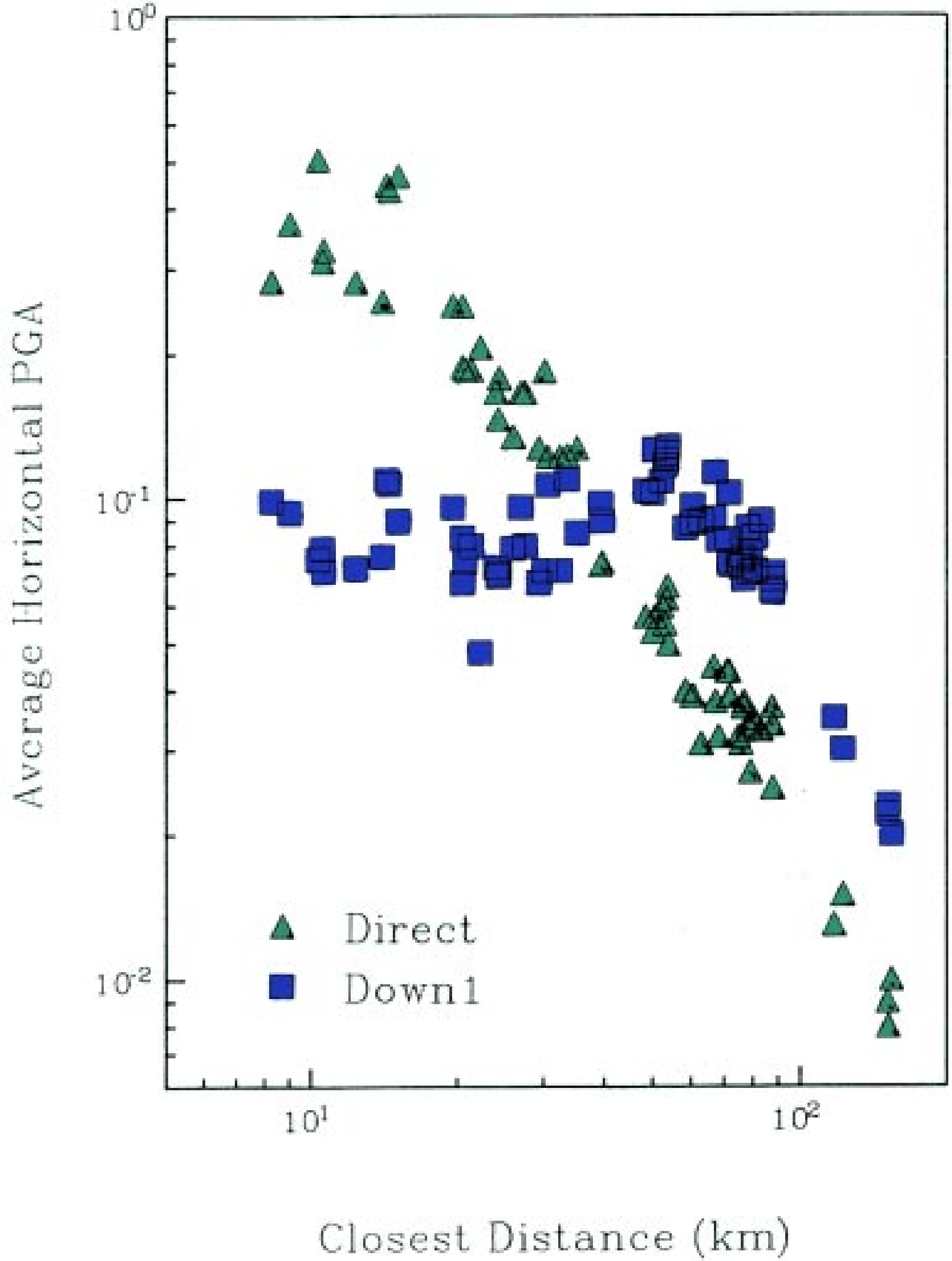
SEISMIC WAVE PROPAGATION

Green's functions calculated for the required distance and depth ranges in a crustal structure model

Long periods - 1D: frequency wavenumber integration
- 3D: finite difference
- these methods are deterministic

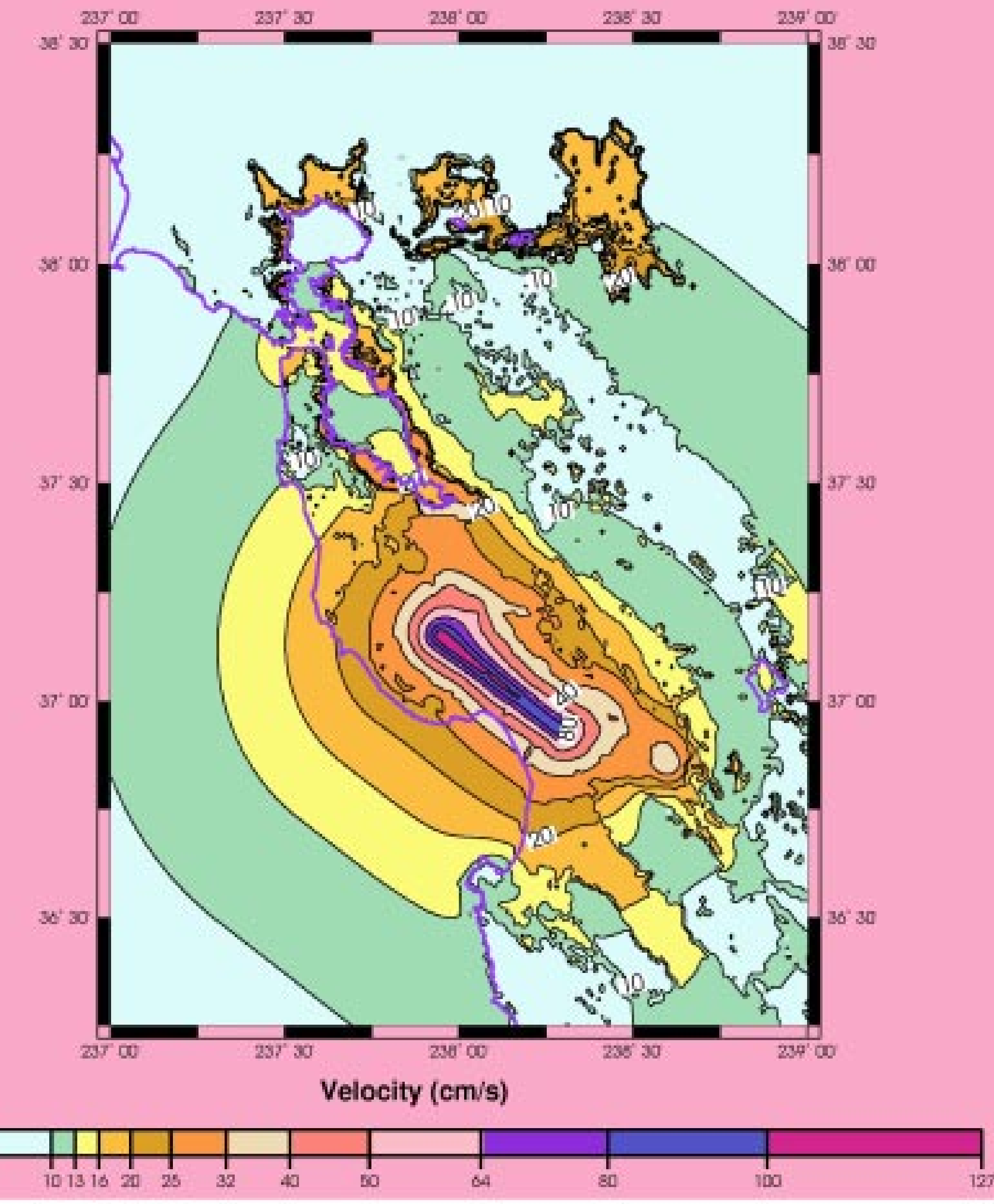
Short periods - generalized rays
- empirically incorporate stochastic effects


STATION
R_{crit}
SURFACE
SOURCE
S
S_cS
CONRAD
INTERFACE
S_mS
I_{crit}
MOHO
INTERFACE



Average Horizontal PGA
10^0
10^{-1}
10^{-2}
10^1
10^2
Direct
Down1
Closest Distance (km)

Horizontal Peak Velocity



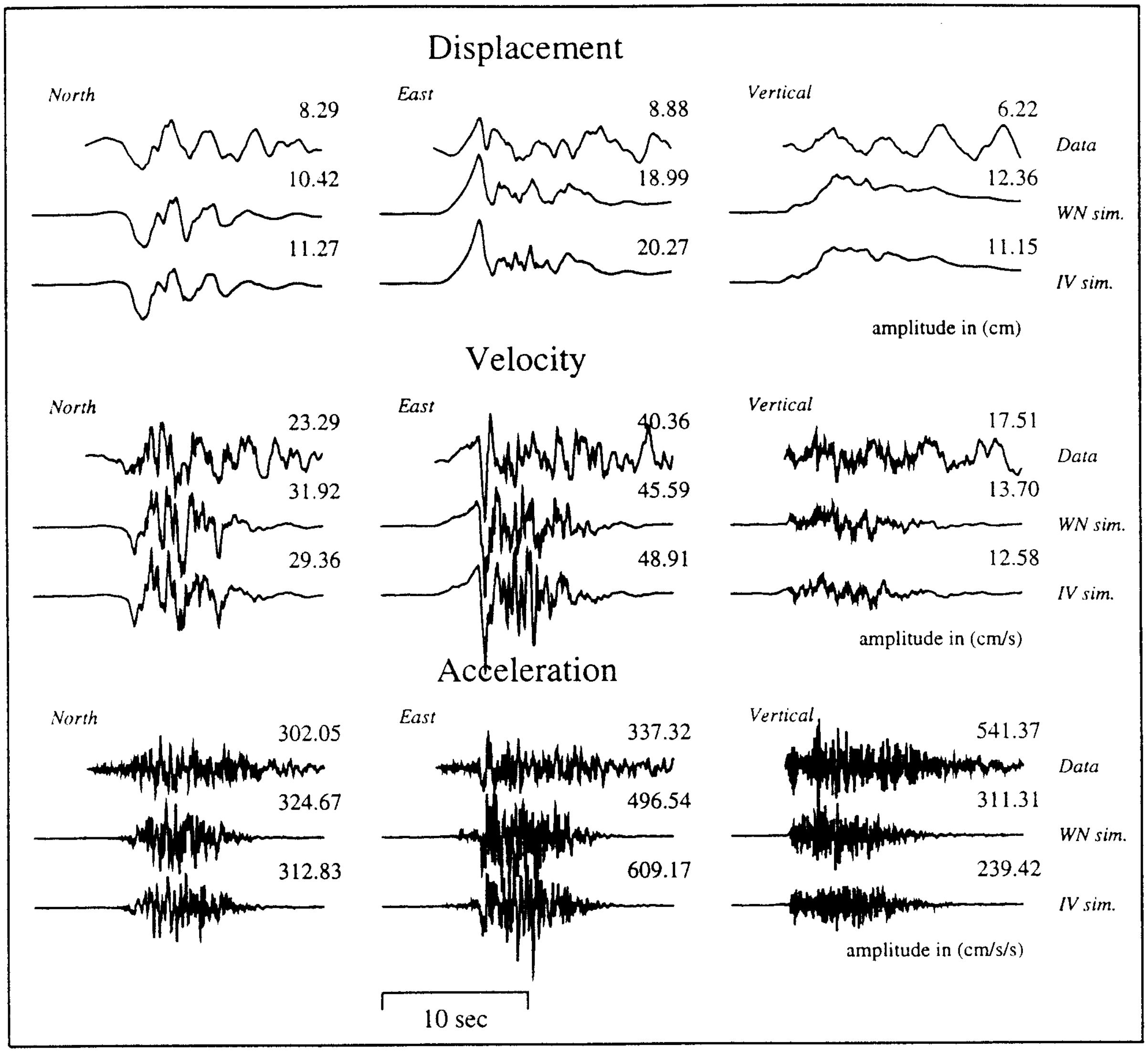
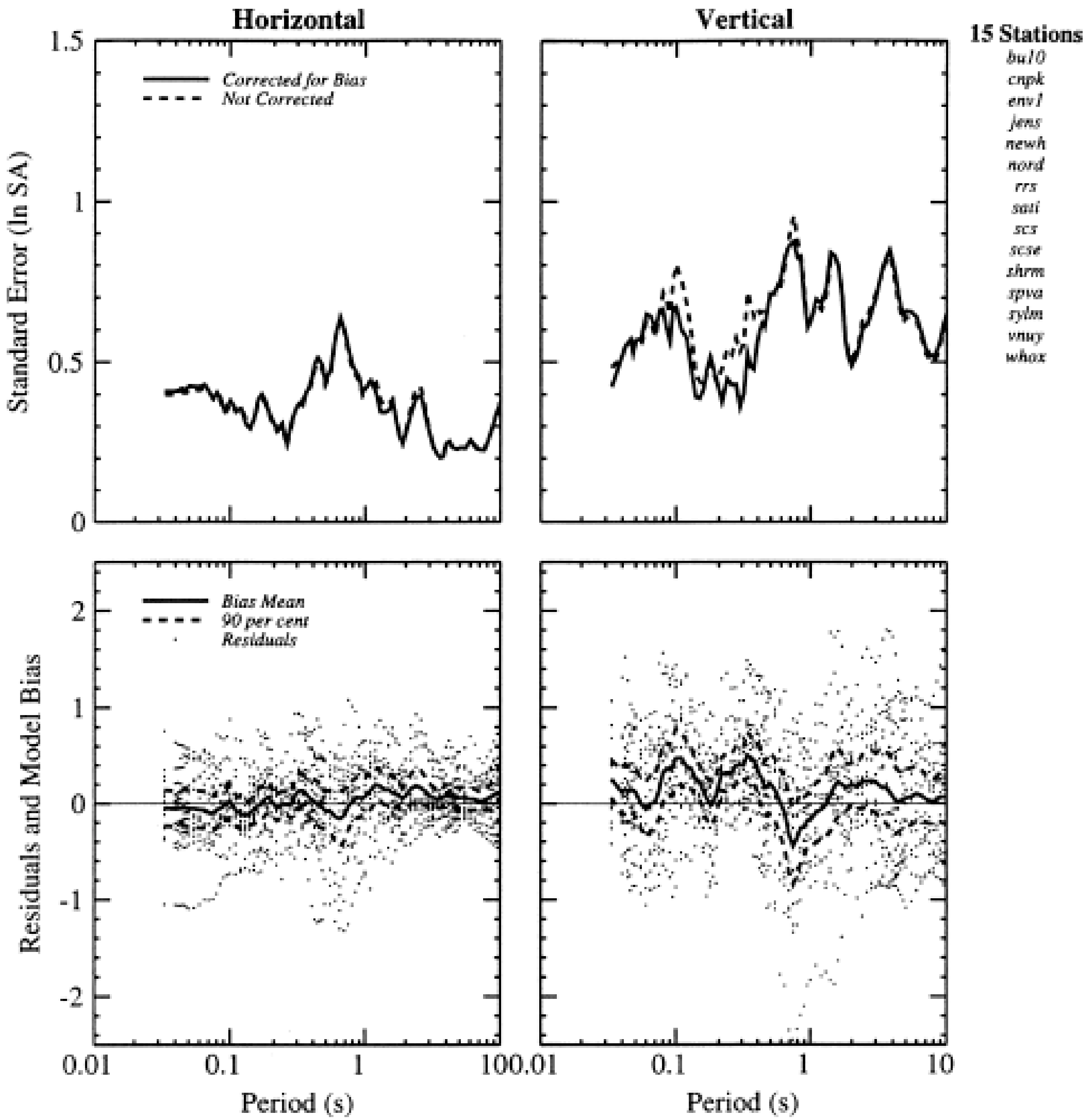


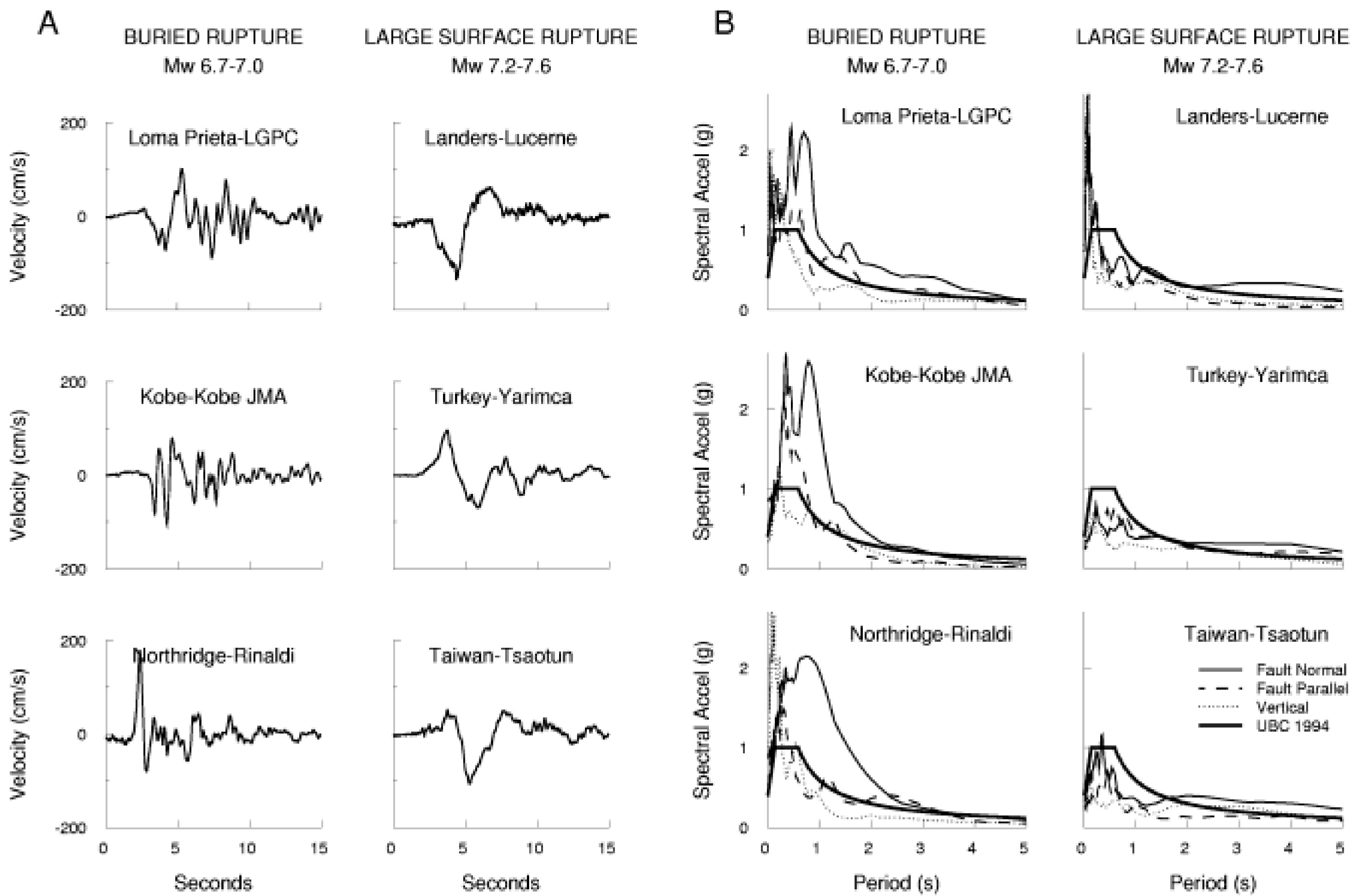
Figure 1. Comparison of recorded (top row) and simulated (middle and bottom rows) displacement, velocity and acceleration time histories at Arleta from the 1994 Northridge earthquake, plotted on a common scale, with peak value given in the top left corner. Source: Somerville et al. (1995).


Horizontal
Vertical
15 Stations
bu10
cnpk
env1
jens
newh
nord
rrs
sasi
scs
scse
shrm
spva
sylm
vnuy
whox
Corrected for Bias
Not Corrected
Standard Error (ln SA)
1.5
1
0.5
0
Bias Mean
90 per cent
Residuals
Residuals and Model Bias
2
1
0
-1
-2
0.01
0.1
1
10
Period (s)

RUPTURE DIRECTIVITY EFFECT

- Due to propagation of rupture toward a site
- Large pulse of horizontal motion in the direction normal to fault strike
- Large response spectral acceleration at periods longer than 0.5 second on fault normal cmpt.

1995 Kobe; 1994 Northridge


A
BURIED RUPTURE
Mw 6.7-7.0
LARGE SURFACE RUPTURE
Mw 7.2-7.6
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
Velocity (cm/s)
Spectral Accel (g)
Seconds
Period (s)
Fault Normal
Fault Parallel
Vertical
UBC 1994

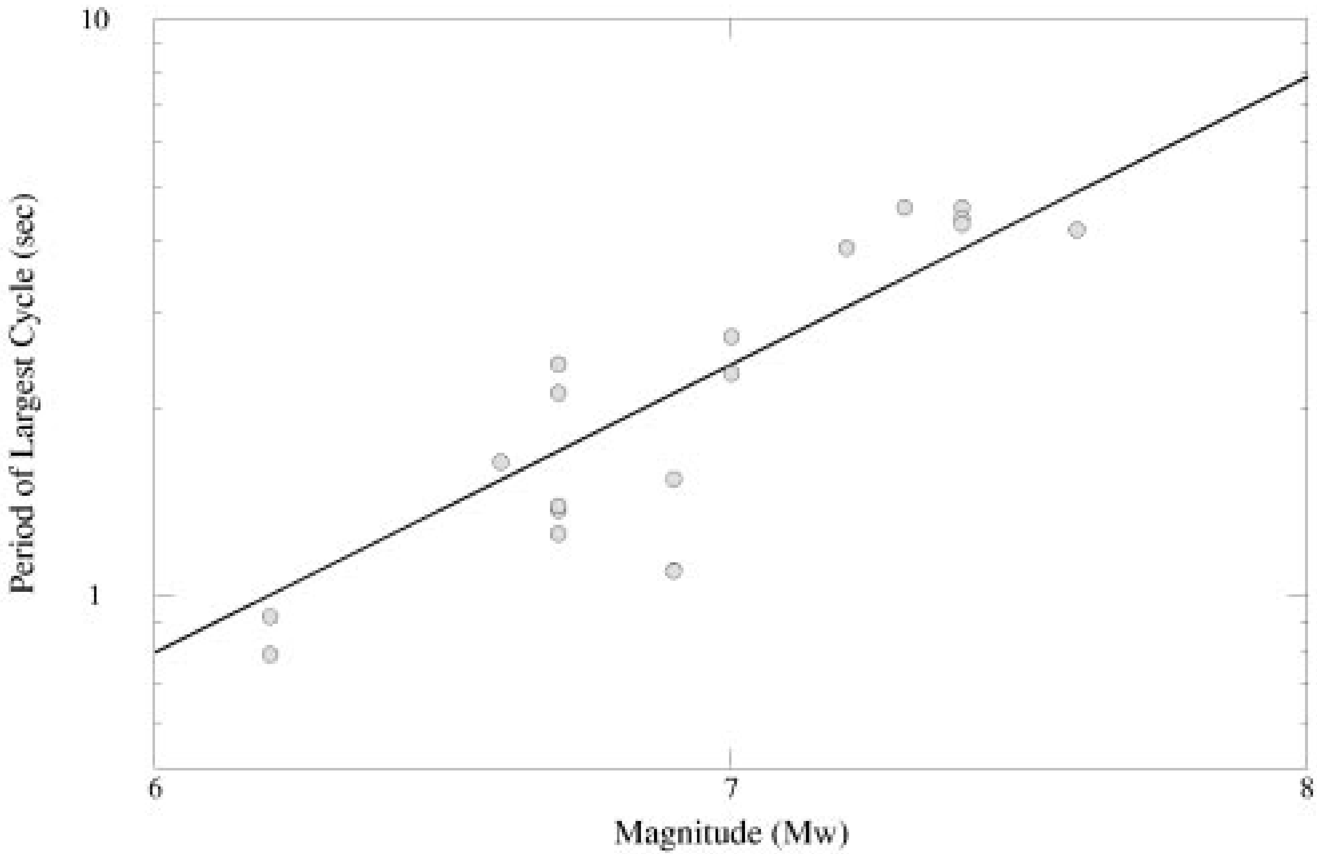
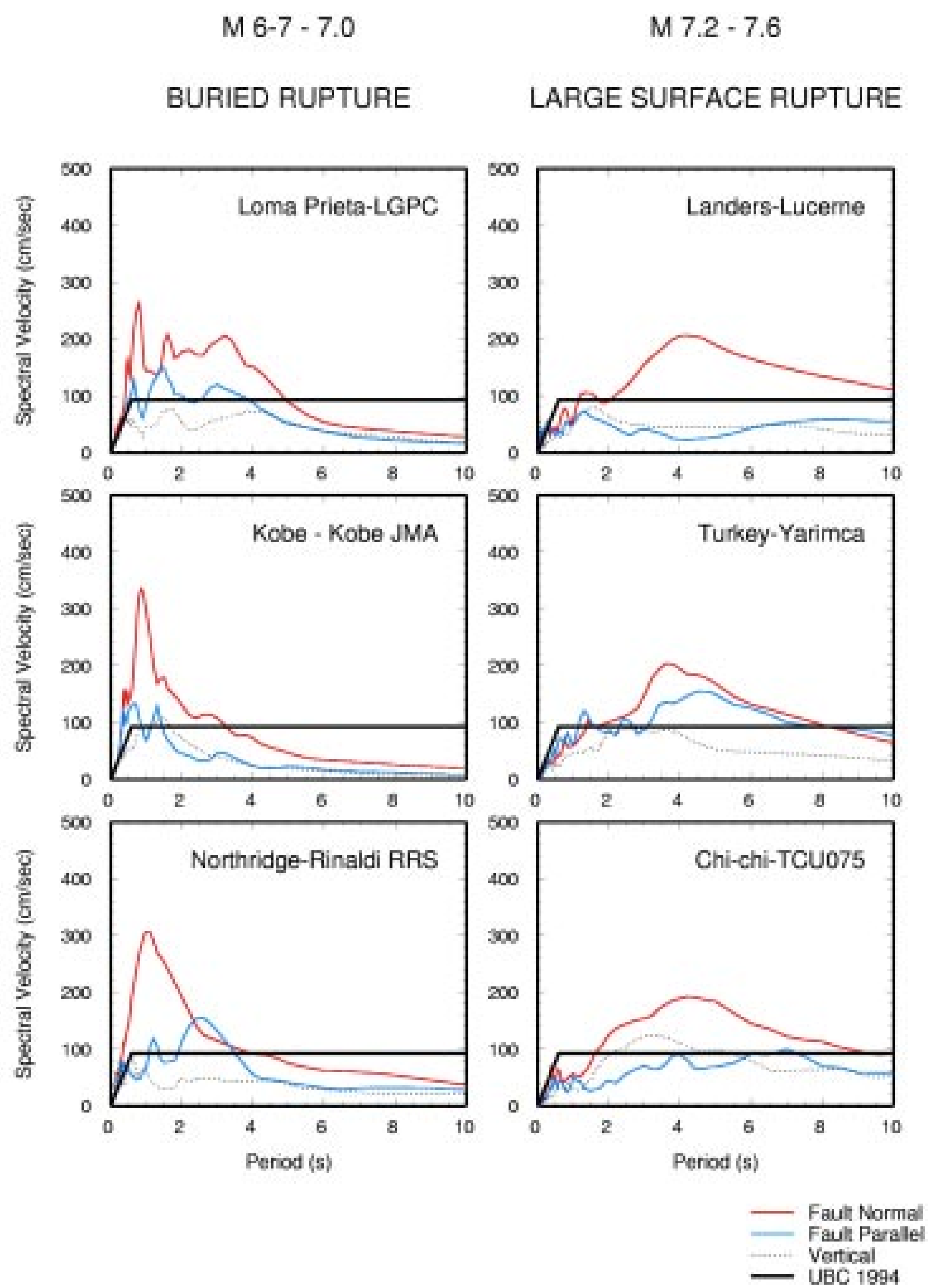


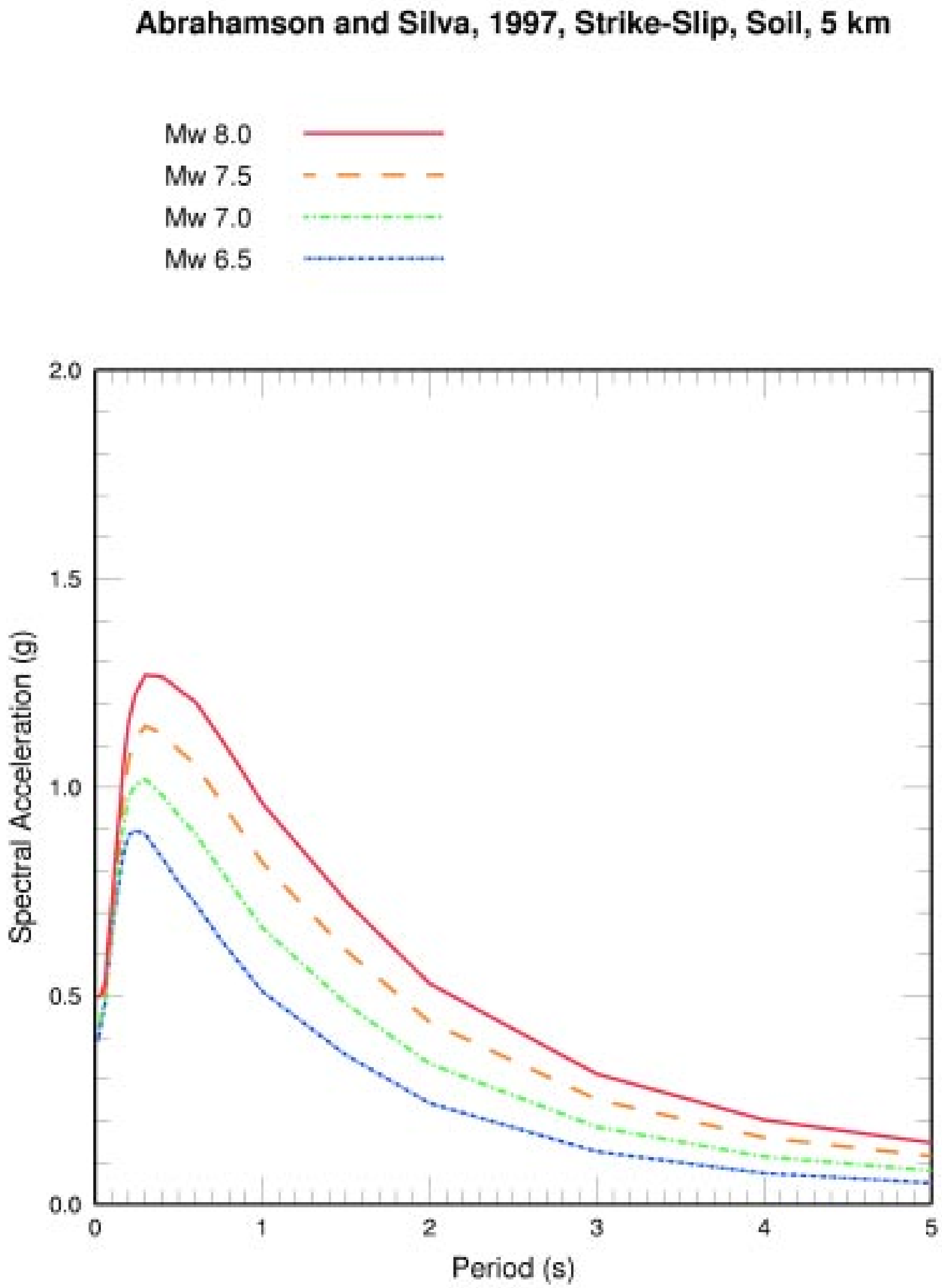
Figure 2. Relation between period of fault normal pulse and Mw for forward directivity



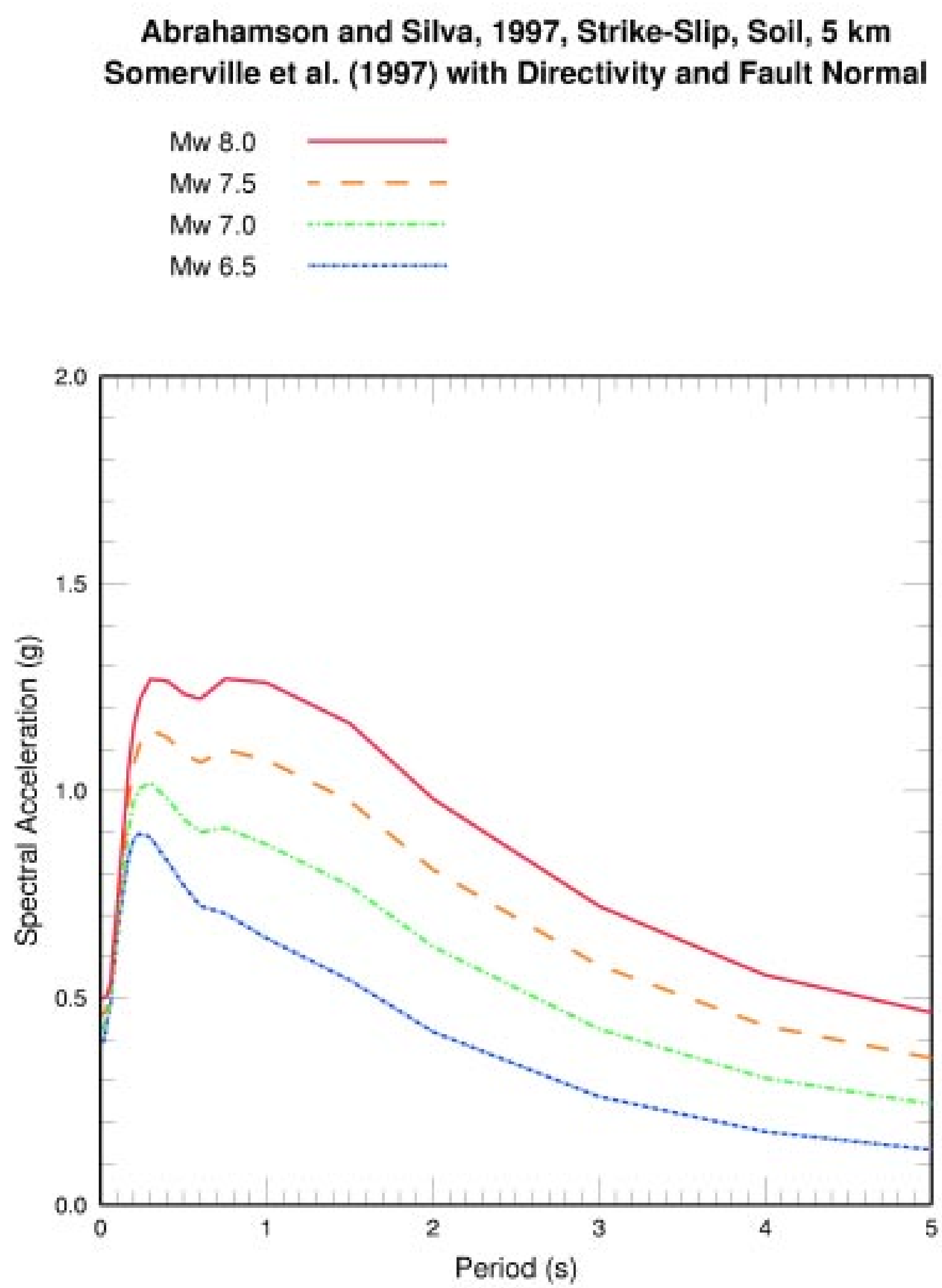
M 6-7 - 7.0
M 7.2 - 7.6
BURIED RUPTURE
LARGE SURFACE RUPTURE
Loma Prieta-LGPC
Landers-Lucerne
Kobe - Kobe JMA
Turkey-Yarimca
Northridge-Rinaldi RRS
Chi-chi-TCU075
Spectral Velocity (cm/sec)
Period (s)
Fault Normal
Fault Parallel
Vertical
UBC 1994

Magnitude Scaling Of Near Fault Ground Motions

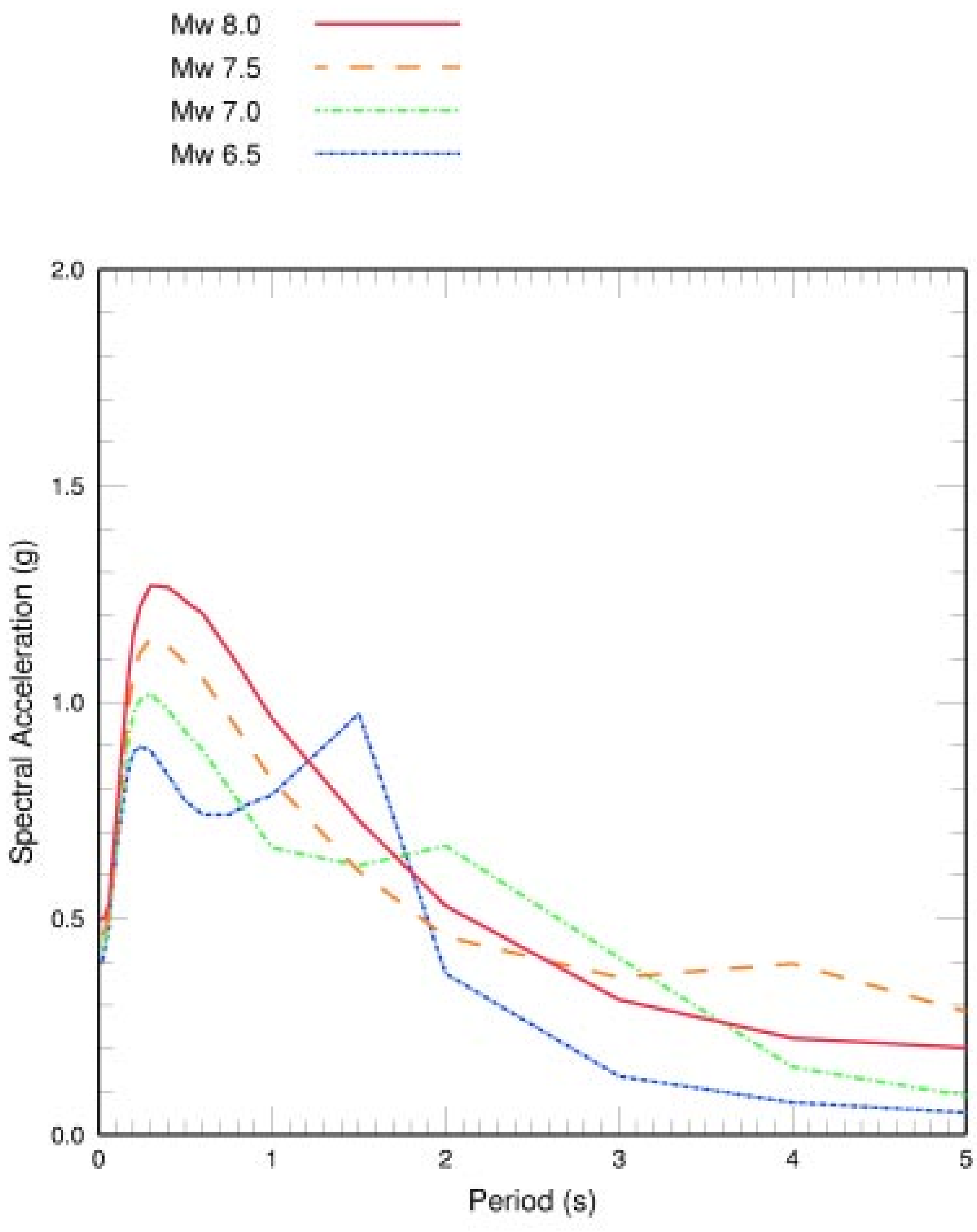
- The forward directivity pulse is narrow band
- The period of the pulse increases with magnitude
- The pulse causes a peak in the acceleration response spectrum whose period increases with magnitude

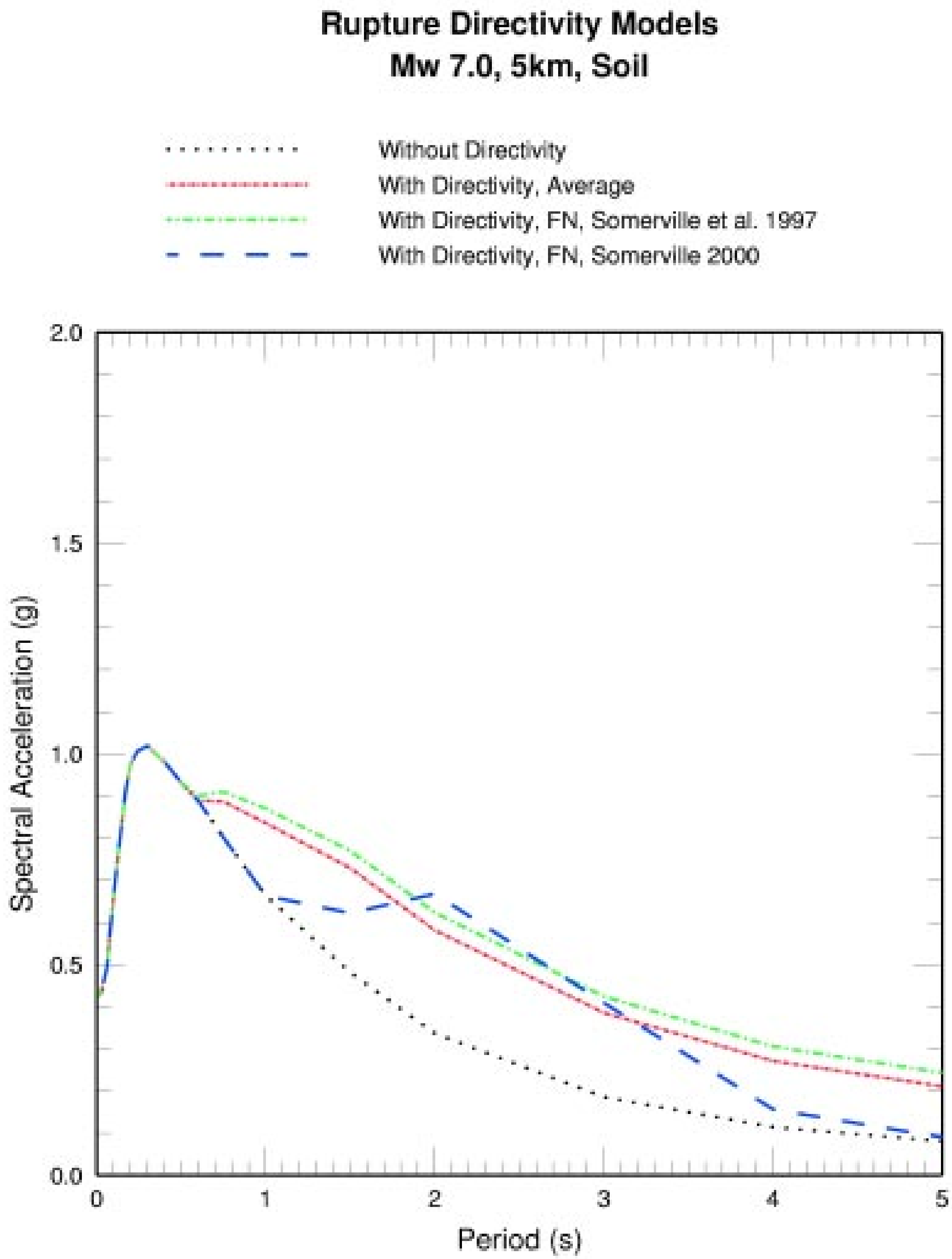


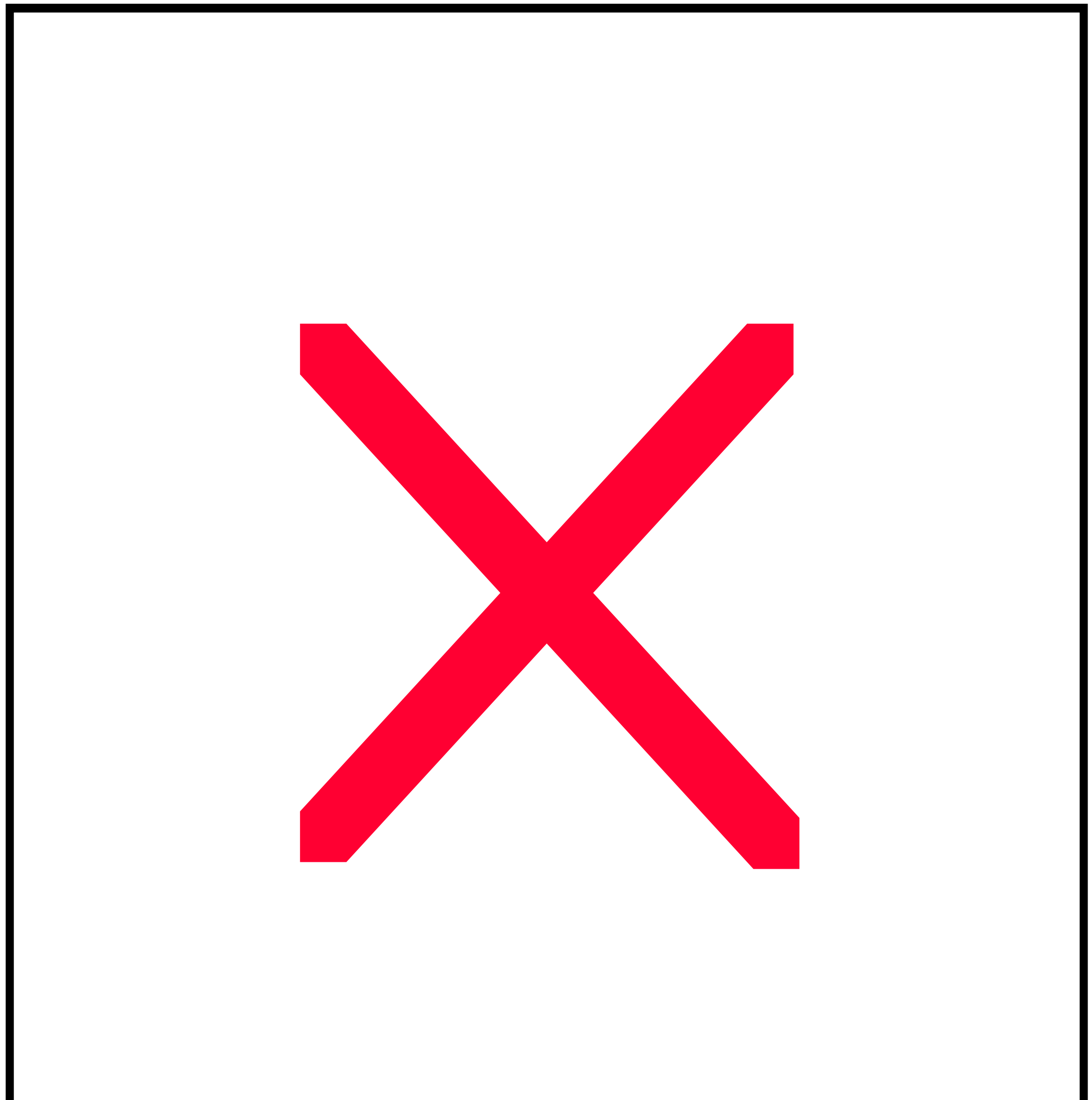
Abrahamson and Silva, 1997, Strike-Slip, Soil, 5 km
Mw 8.0
Mw 7.5
Mw 7.0
Mw 6.5
2.0
1.5
1.0
0.5
0.0
Spectral Acceleration (g)
0
1
2
3
4
5
Period (s)

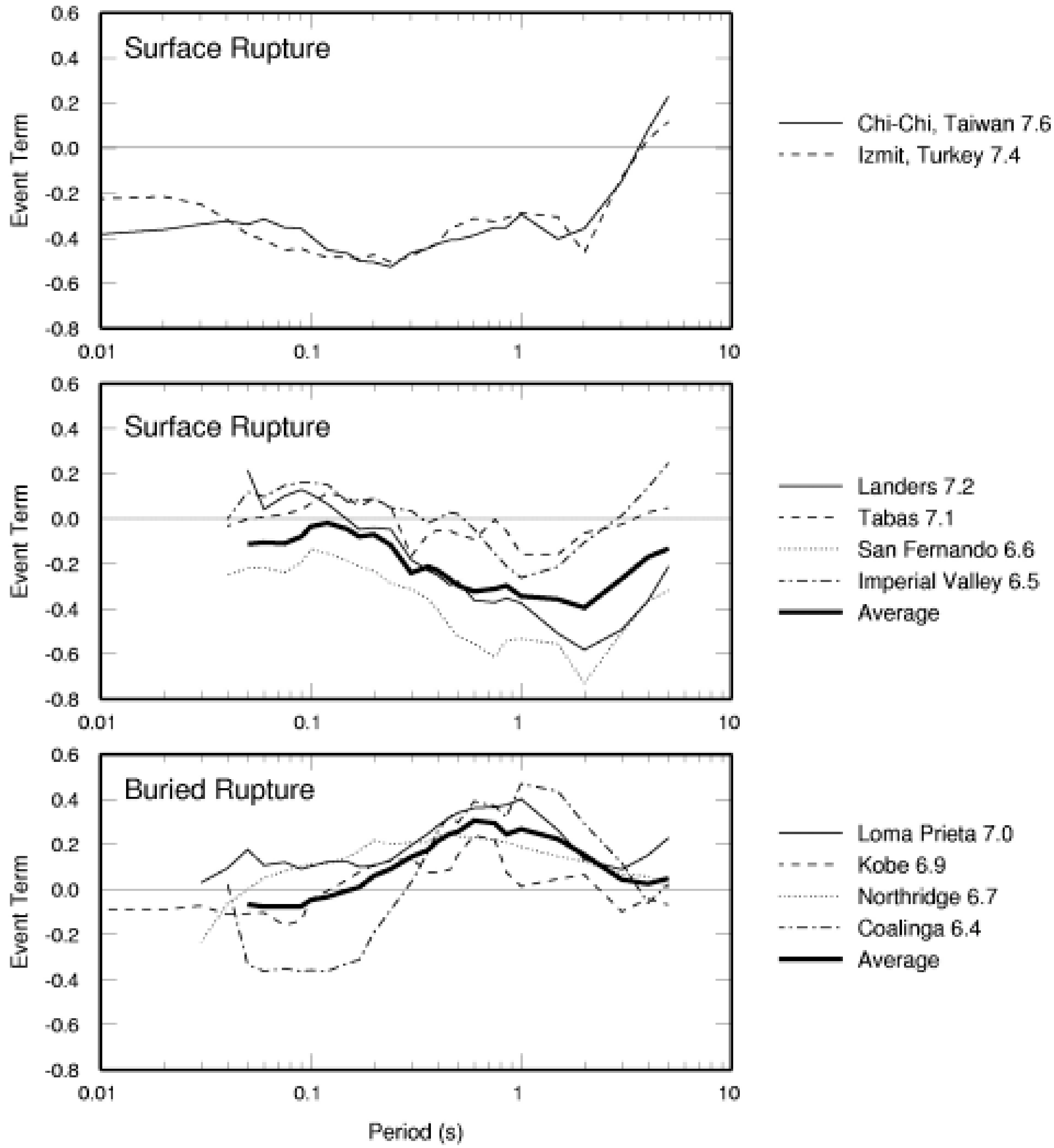

Abrahamson and Silva, 1997, Strike-Slip, Soil, 5 km
Somerville et al. (1997) with Directivity and Fault Normal
Mw 8.0
Mw 7.5
Mw 7.0
Mw 6.5
Spectral Acceleration (g)
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
Period (s)

Abrahamson and Silva, 1997, Strike-Slip, Soil, 5 km
Somerville (2001) with Directivity and Fault Normal



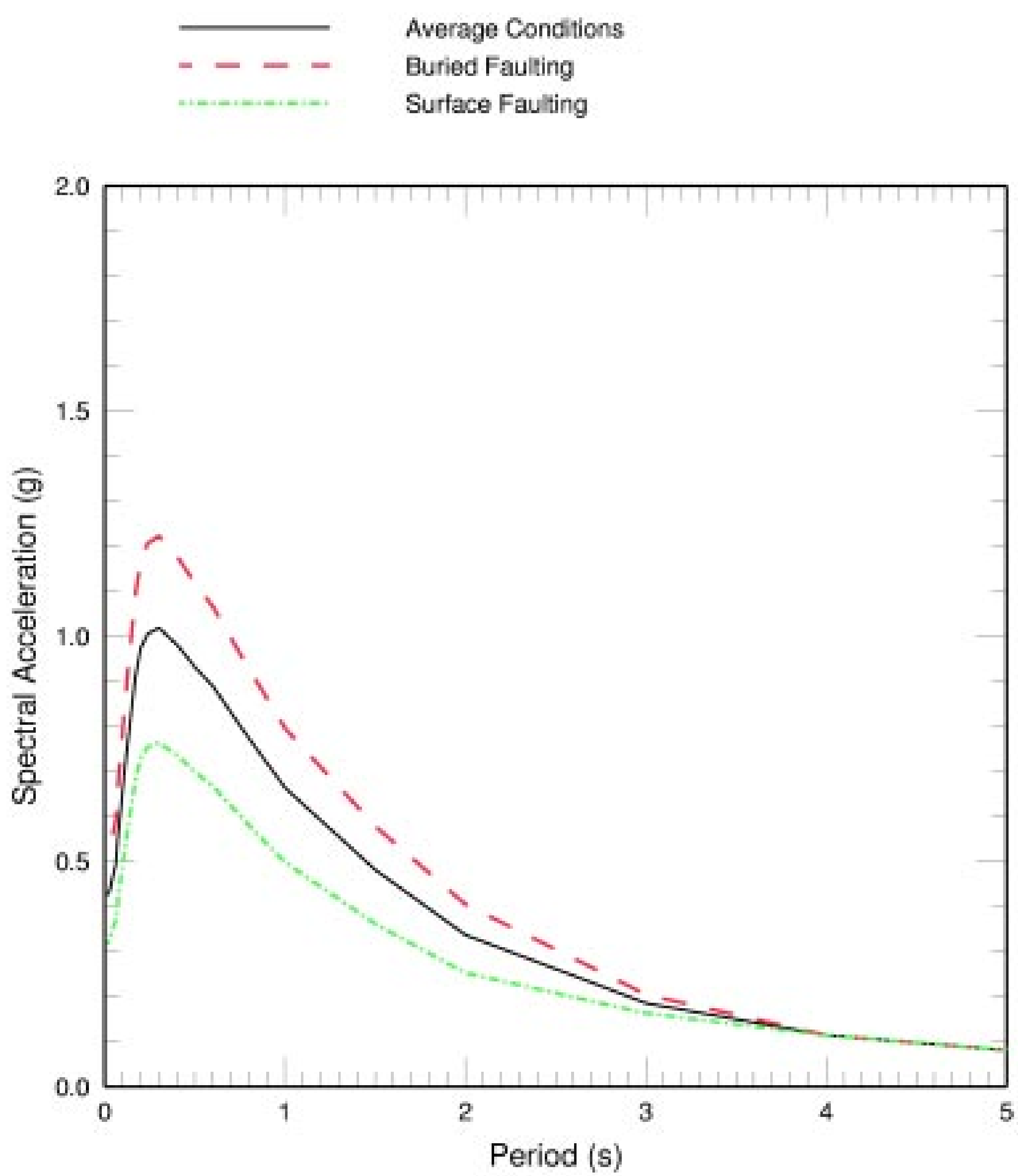

Rupture Directivity Models
Mw 7.0, 5km, Soil
Without Directivity
With Directivity, Average
With Directivity, FN, Somerville et al. 1997
With Directivity, FN, Somerville 2000
Spectral Acceleration (g)
Period (s)
0.0
0.5
1.0
1.5
2.0
0
1
2
3
4
5



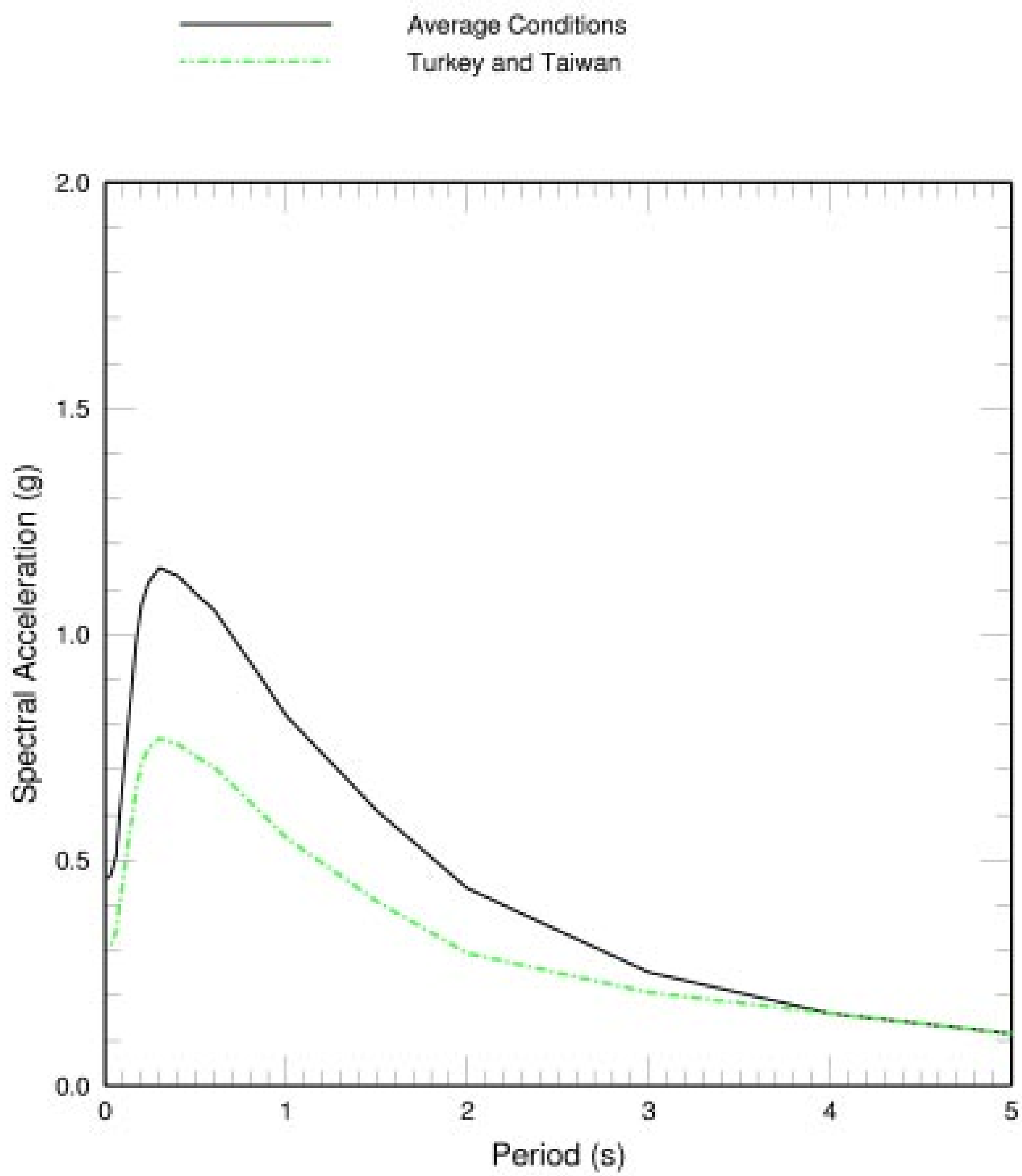


Surface Rupture
Chi-Chi, Taiwan 7.6
Izmit, Turkey 7.4
Surface Rupture
Landers 7.2
Tabas 7.1
San Fernando 6.6
Imperial Valley 6.5
Average
Buried Rupture
Loma Prieta 7.0
Kobe 6.9
Northridge 6.7
Coalinga 6.4
Average
Event Term
Period (s)
0.01
0.1
1
10
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8

Buried and Surface Faulting
Mw 7.0, 5km, Soil, AS



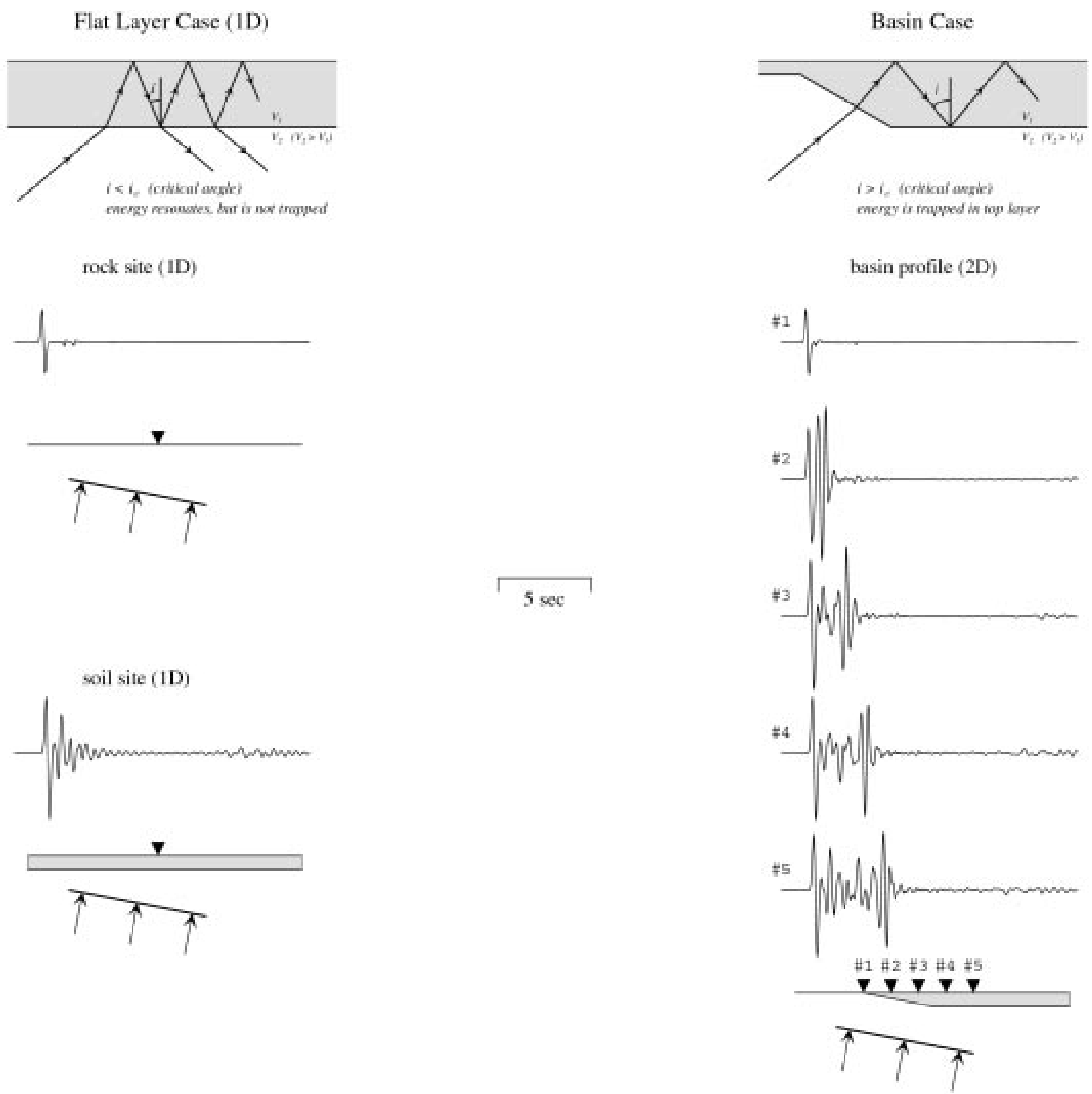
Turkey and Taiwan Spectra
Mw 7.5, 5km, Soil, AS

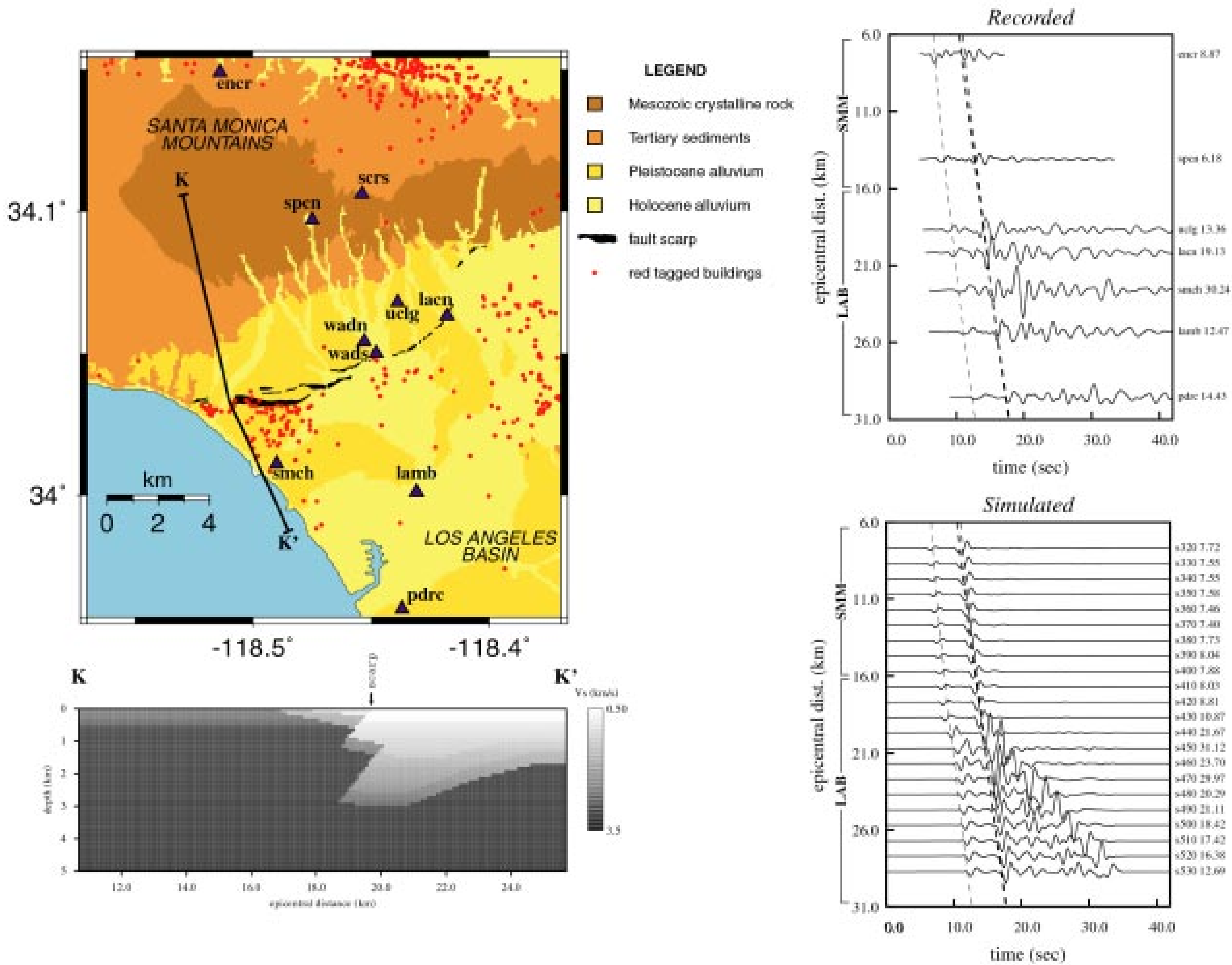


Difference in Ground Motions: Buried vs. Surface Faulting

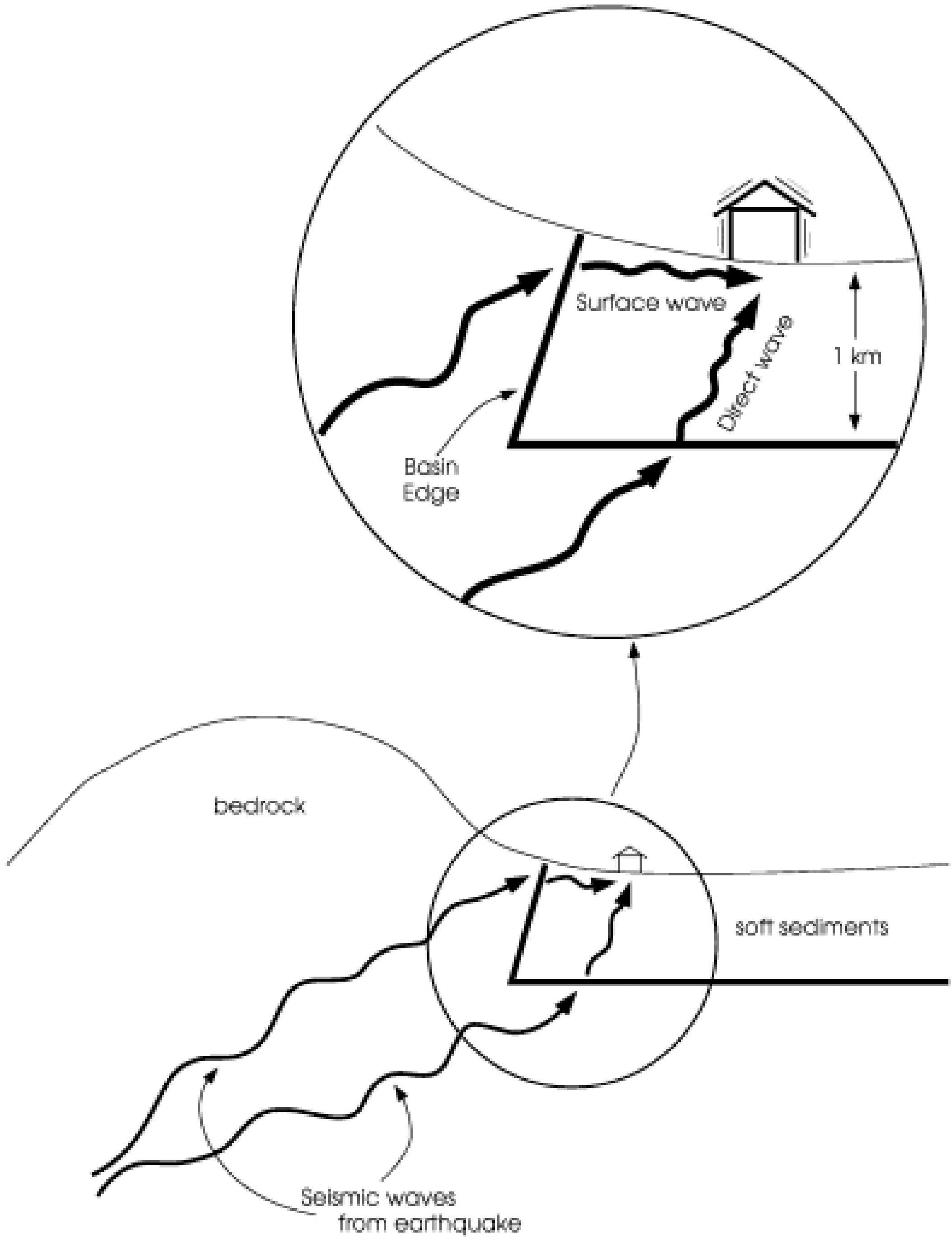
- Ground motions from buried faulting appear to be stronger than from surface faulting

- There may be differences in rupture dynamics between confined and runaway rupture

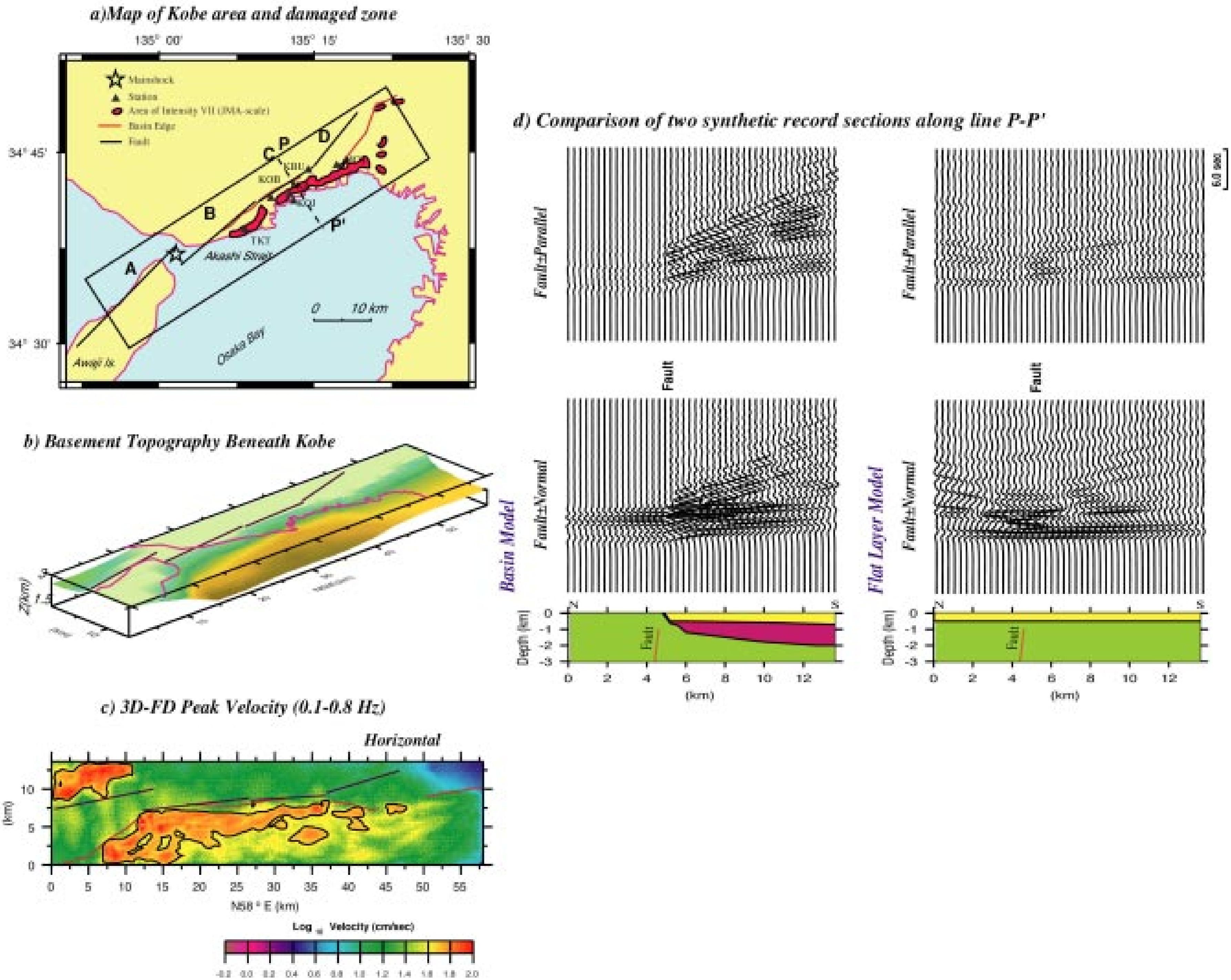

Flat Layer Case (1D)
Basin Case
V_1
V_2 ($V_2 > V_1$)
$i < i_c$ (critical angle)
energy resonates, but is not trapped
$i > i_c$ (critical angle)
energy is trapped in top layer
rock site (1D)
basin profile (2D)
#1
#2
#3
#4
#5
5 sec
soil site (1D)



LEGEND
Mesozoic crystalline rock
Tertiary sediments
Pleistocene alluvium
Holocene alluvium
fault scarp
red tagged buildings
SANTA MONICA MOUNTAINS
LOS ANGELES BASIN
encr
scrs
spcn
uclg
lacn
wadn
wads
smch
lamb
pdrc
K
K'
km
0
2
4
34.1°
34°
-118.5°
-118.4°
Recorded
Simulated
epicentral dist. (km)
time (sec)
SMM
LAB
depth (km)
epicentral distance (km)
Vs (km/s)



Surface wave
Direct wave
1 km
Basin
Edge
bedrock
soft sediments
Seismic waves
from earthquake



a)Map of Kobe area and damaged zone
135° 00'
135° 15'
135° 30
34° 45'
34° 30'
Mainshock
Station
Area of Intensity VII (JMA-scale)
Basin Edge
Fault
A
B
C
D
P
P'
KBU
KOB
TKT
Akashi Strait
0 10 km
Osaka Bay
Awaji Is.
b) Basement Topography Beneath Kobe
Z(km)
c) 3D-FD Peak Velocity (0.1-0.8 Hz)
Horizontal
(km)
N58 ° E (km)
Log 10 Velocity (cm/sec)
-0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
d) Comparison of two synthetic record sections along line P-P'
Fault±Parallel
Fault±Normal
Fault
Basin Model
Flat Layer Model
5.0 sec
N
S
Depth (km)
(km)

BASIN AND BASIN EDGE EFFECTS

- Due to trapping of body waves that enter a sedimentary basin through its thickening margins

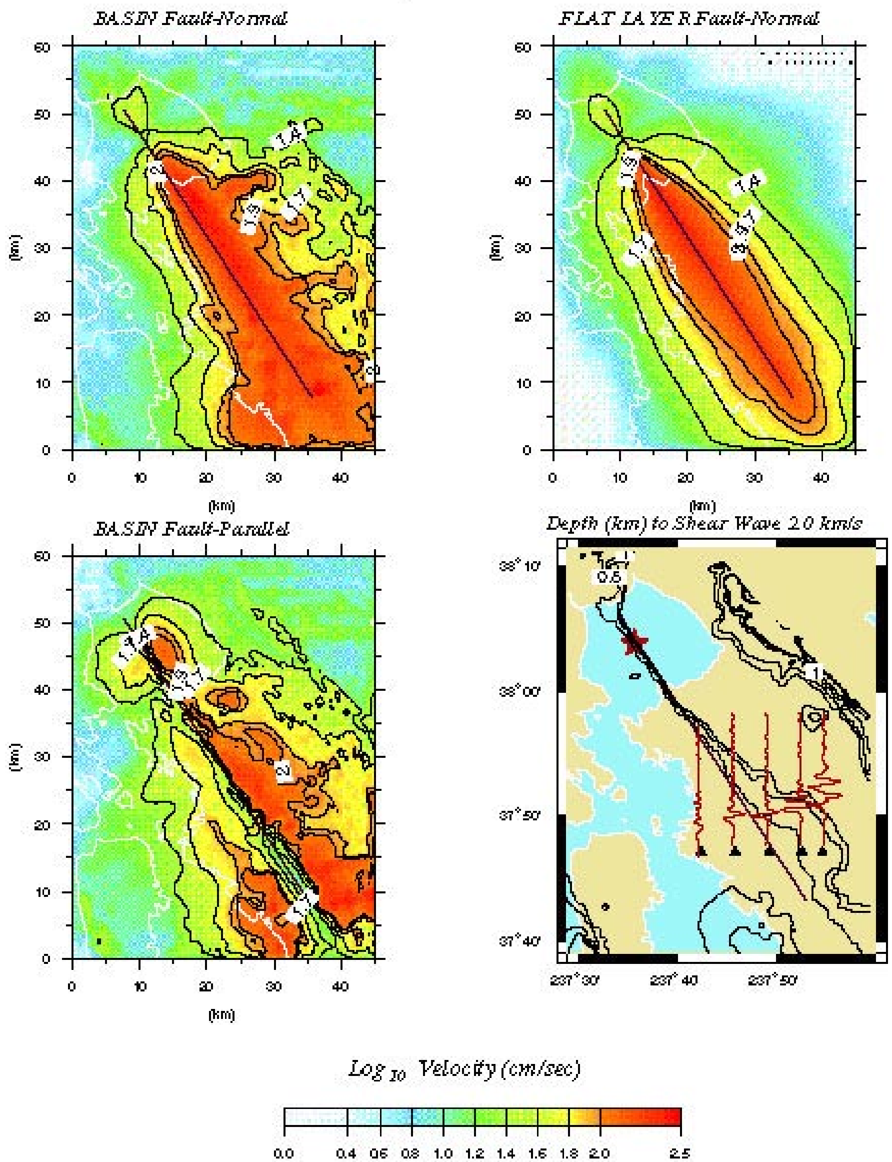
- Cause increased amplitude and duration of ground motions with periods longer than 1 second

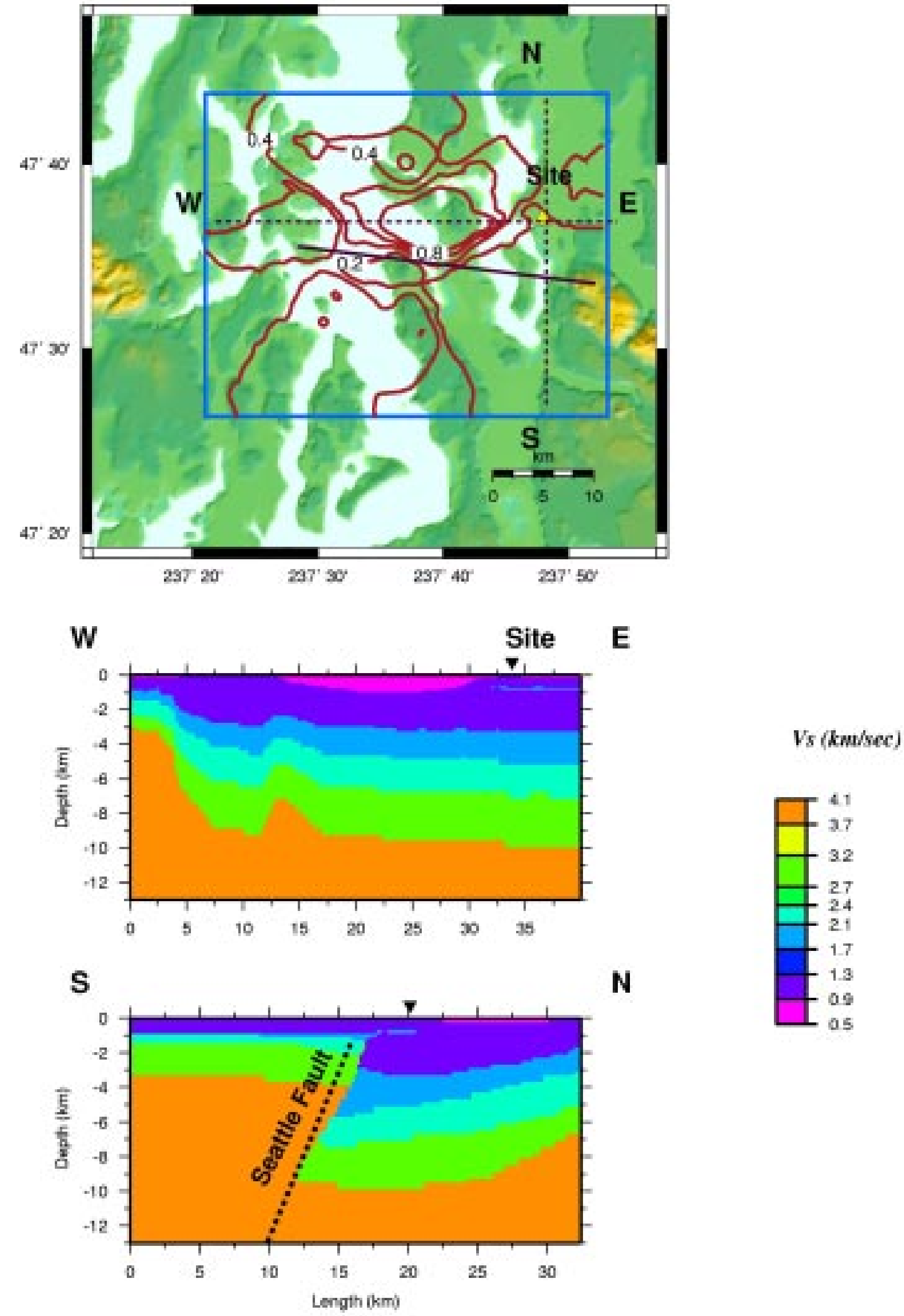
- Largest effects are located near the edges of basins due to the constructive interference of direct and diffracted arrivals

Kobe; Santa Monica (Northridge eq.)

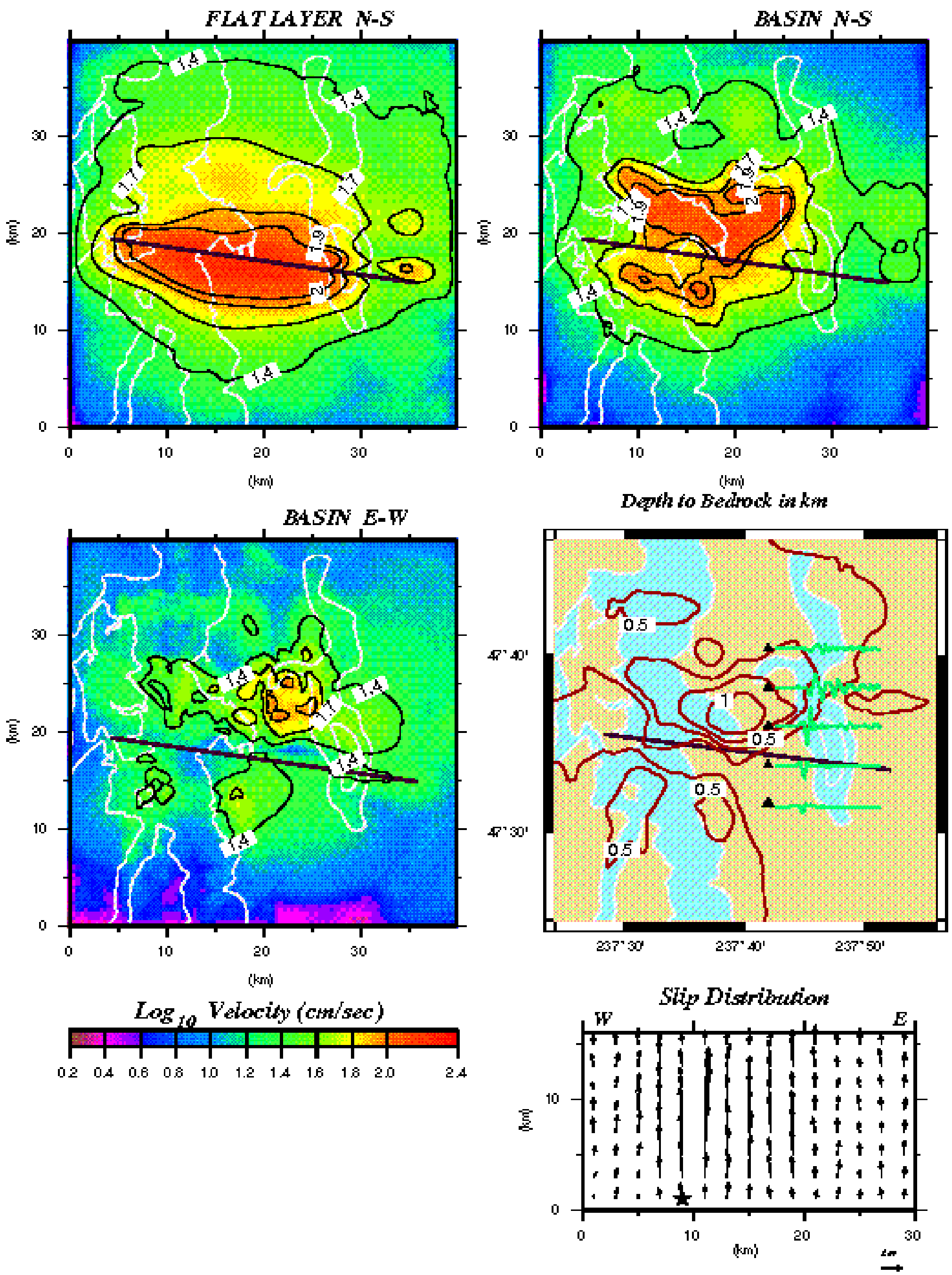
Simulated Peak Velocity (0.1-0.8 Hz)

M6.75 Hayward Fault Scenario




N
W
E
S
Site
0.4
0.4
0.8
0.2
km
0 5 10
47' 40'
47' 30'
47' 20'
237' 20'
237' 30'
237' 40'
237' 50'
W
Site
E
S
N
Depth (km)
Length (km)
Seattle Fault
Vs (km/sec)
4.1
3.7
3.2
2.7
2.4
2.1
1.7
1.3
0.9
0.5

Simulated Peak Velocity (0.1-1.0 Hz)



CONCLUSIONS

Variability in Ground Motions from Large Earthquakes:

•dominated by site-to-site variations that are partly predictable

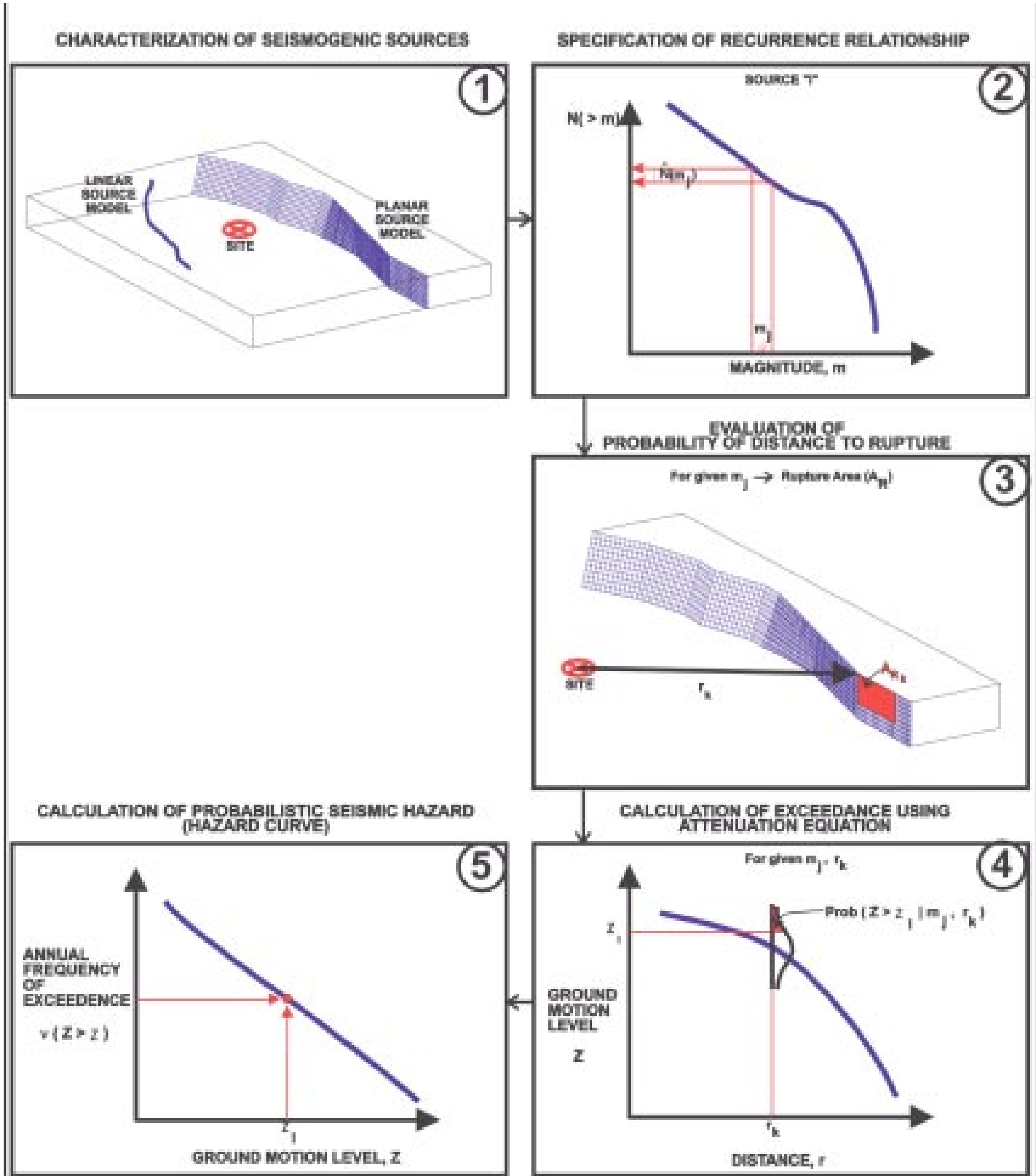
Applications of Seismological Ground Motion Models:

•provide more realistic representations of complex earthquake source, wave propagation, and site effects than simple empirical magnitude - distance - site category models

•explain unusually large ground motions

•reduce the uncertainty in ground motion prediction

•provide time histories for use in performance based design



PROBABILISTIC SEISMIC HAZARD ANALYSIS METHODOLOGY

Project No.	Date:	Project:	Fig.