Has Earthquake Engineering Broken the Power Law?

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Magnitude Paradox … Seismologist

- Radiated energy increases by 32 times for each unit of magnitude.
- The number of earthquakes decreases by 10 times for each unit of magnitude.
- There is as much energy between M_{max} to M_{max}-0.4 as in all other events combined.
- Large earthquakes do most of the work of plate tectonics. Although they are infrequent, they are inevitable.
- After the 1994 Northridge earthquake seismologists said, “this was only a moderate earthquake … wait till you see a great one.”

Magnitude Paradox … Engineer

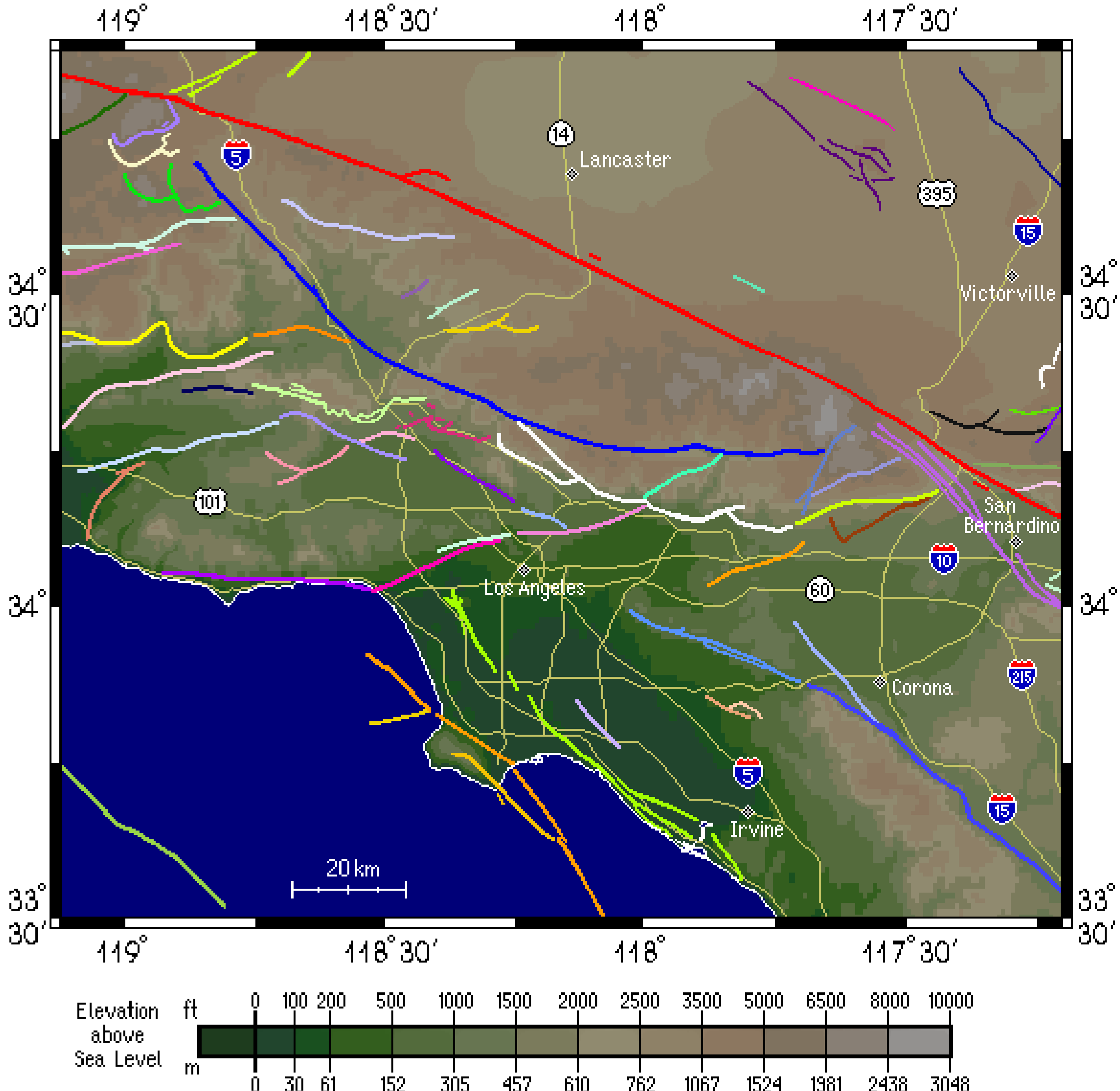
- Perhaps there can be larger motions, but these are extreme examples of extraordinary events that shouldn't be used for building design.
- Eyewitness reports of the 1906 earthquake indicate that the shaking was comparable to that in 1994, but it lasted longer and occurred over a larger area.
- Ground shaking in the Northridge earthquake was severe, economic loss was immense, but there was relatively low loss of life and the building code accomplished its objectives.
- Computer models shows that most of the risk comes from more frequent moderate size events.

Overview

- Earthquake frequency vs. size statistics are power law … the largest events dominate the action
- Global earthquake frequency vs. death statistics are also power law … the rare events (also large) dominate the action
- Current state of the art in assessing earthquake risk suggests that most of the risk is from frequent moderate-sized events (M ~ 7), but this is still an open question
- Where do these power laws come from, and has modern engineering “broken” the power law?
- If the power law still applies for damage and deaths, what is the best approach to minimize our losses?

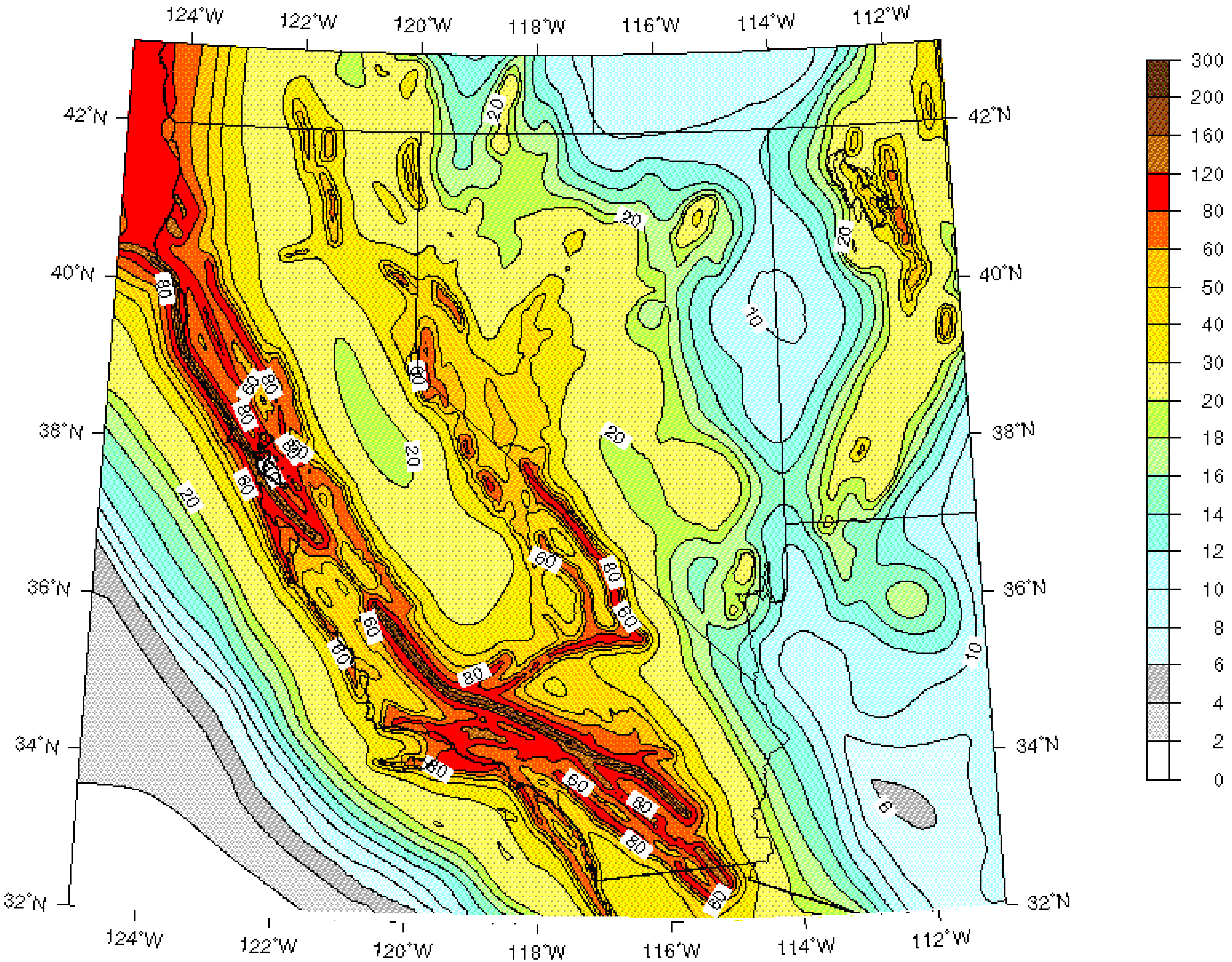
Power Laws in Earthquake Engineering

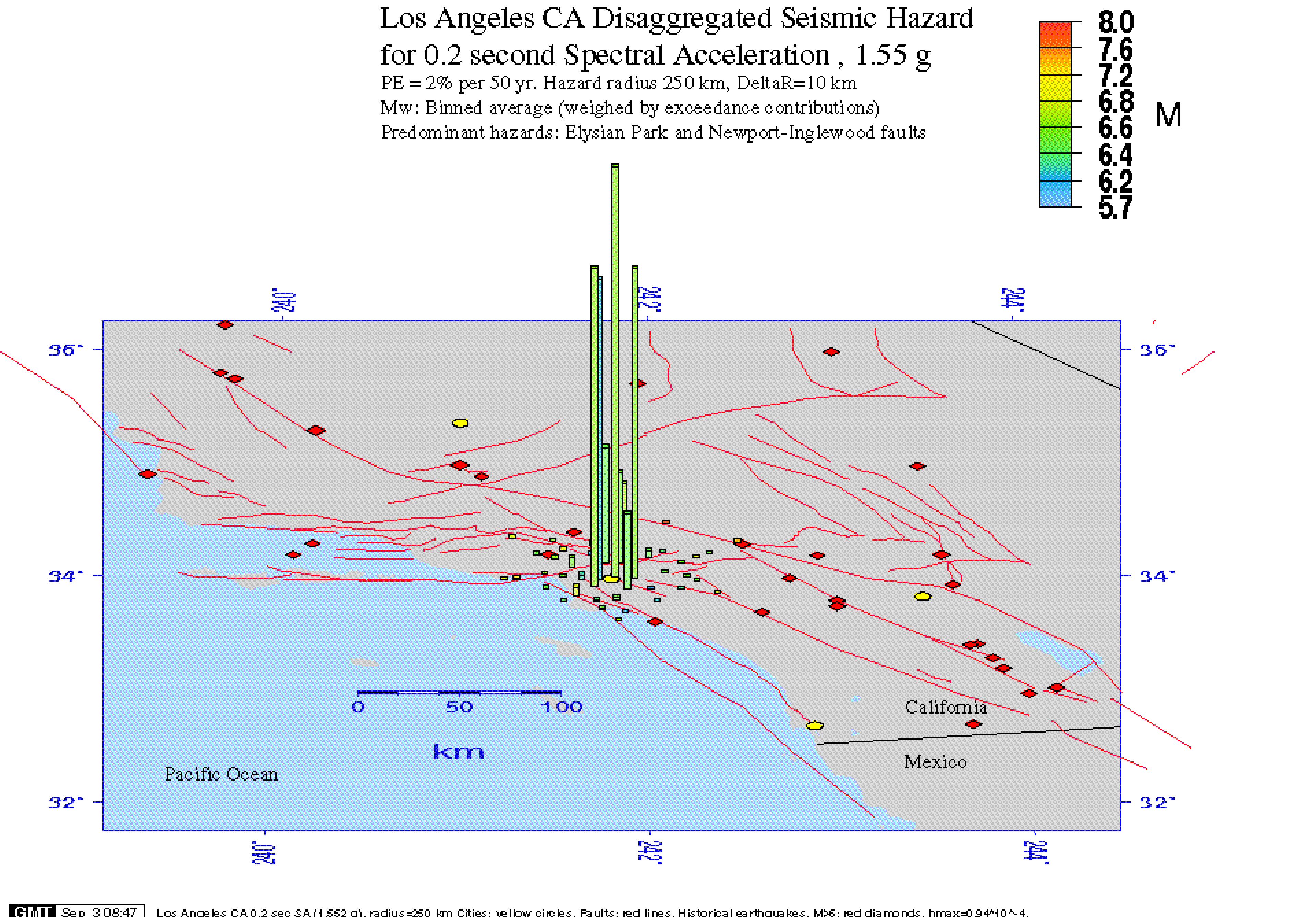
- Except for the frequency vs. size power law of seismology, there are no power laws in earthquake engineering
- Very large earthquakes are “rare events,” which is good since they have little impact on overall hazard (at least according to current state of the art)



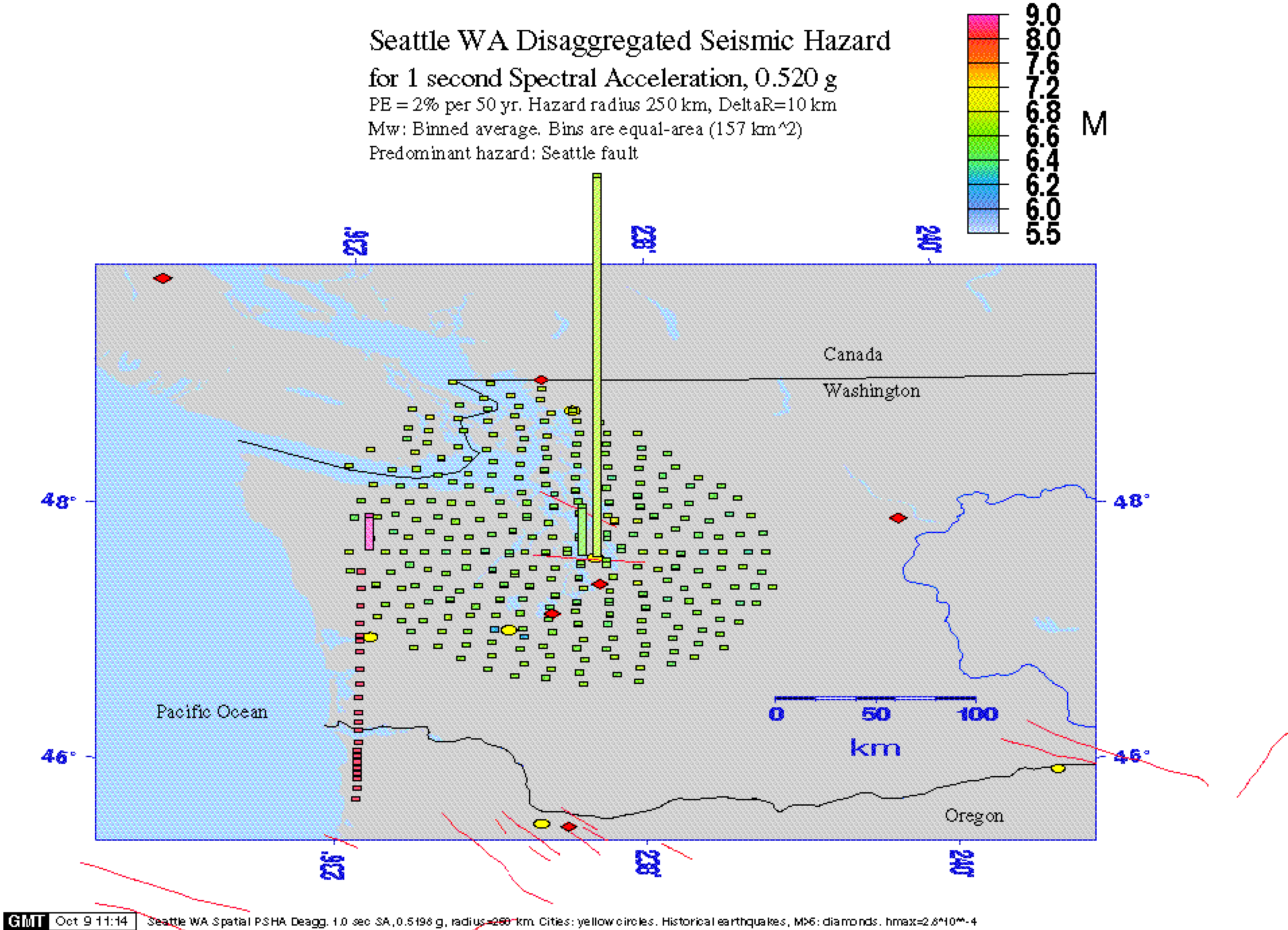
119°
118° 30′
118°
117° 30′
34° 30′
34°
33° 30′
Lancaster
Victorville
San Bernardino
Los Angeles
Corona
Irvine
5
14
395
15
101
10
60
215
20 km
Elevation above Sea Level
ft
0 100 200 500 1000 1500 2000 2500 3500 5000 6500 8000 10000
m
0 30 61 152 305 457 610 762 1067 1524 1981 2438 3048

1.0 sec SA (%g) with 2% Probability of Exceedance in 50 Years
USGS Map, Oct. 2002rev

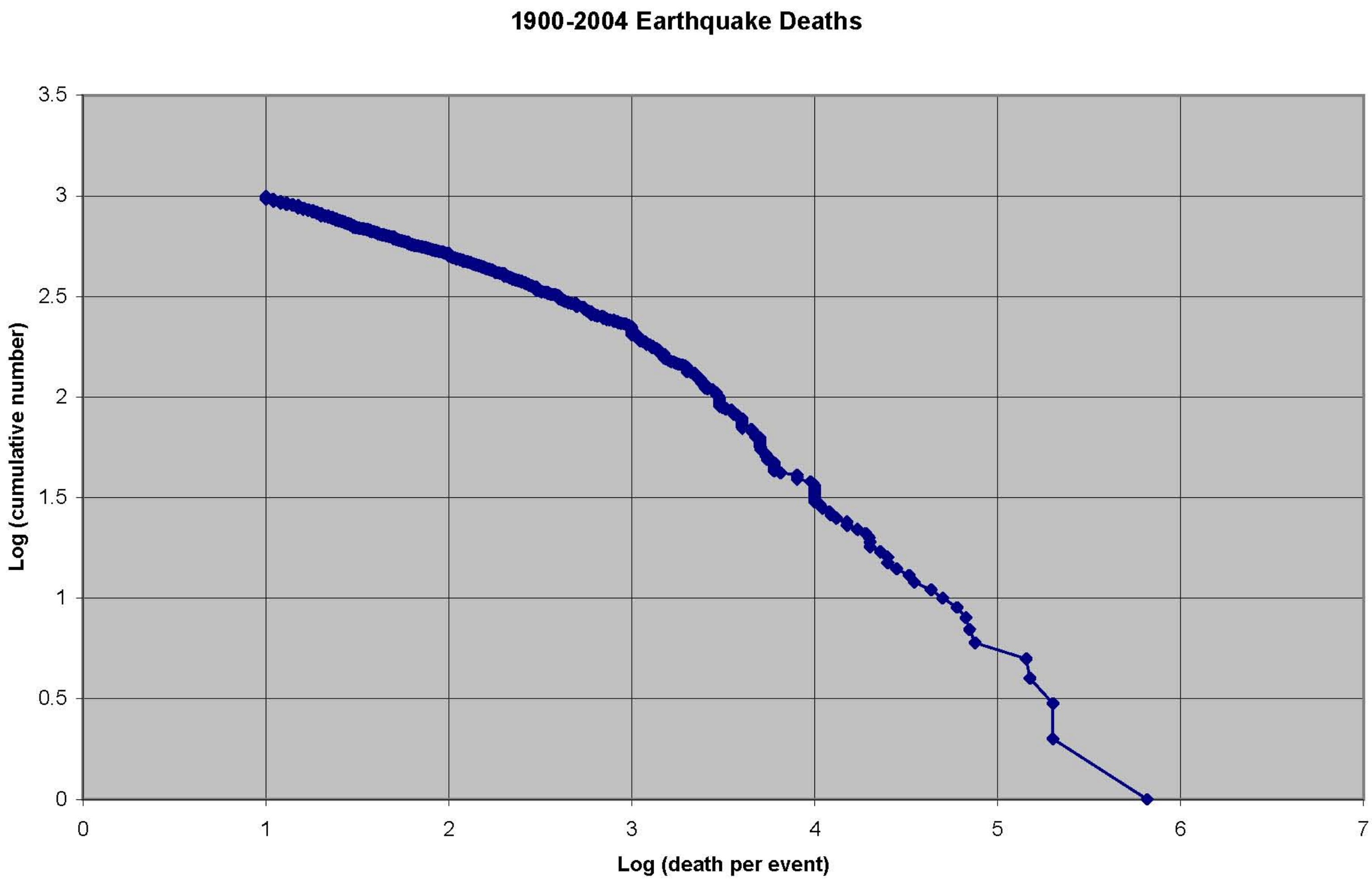




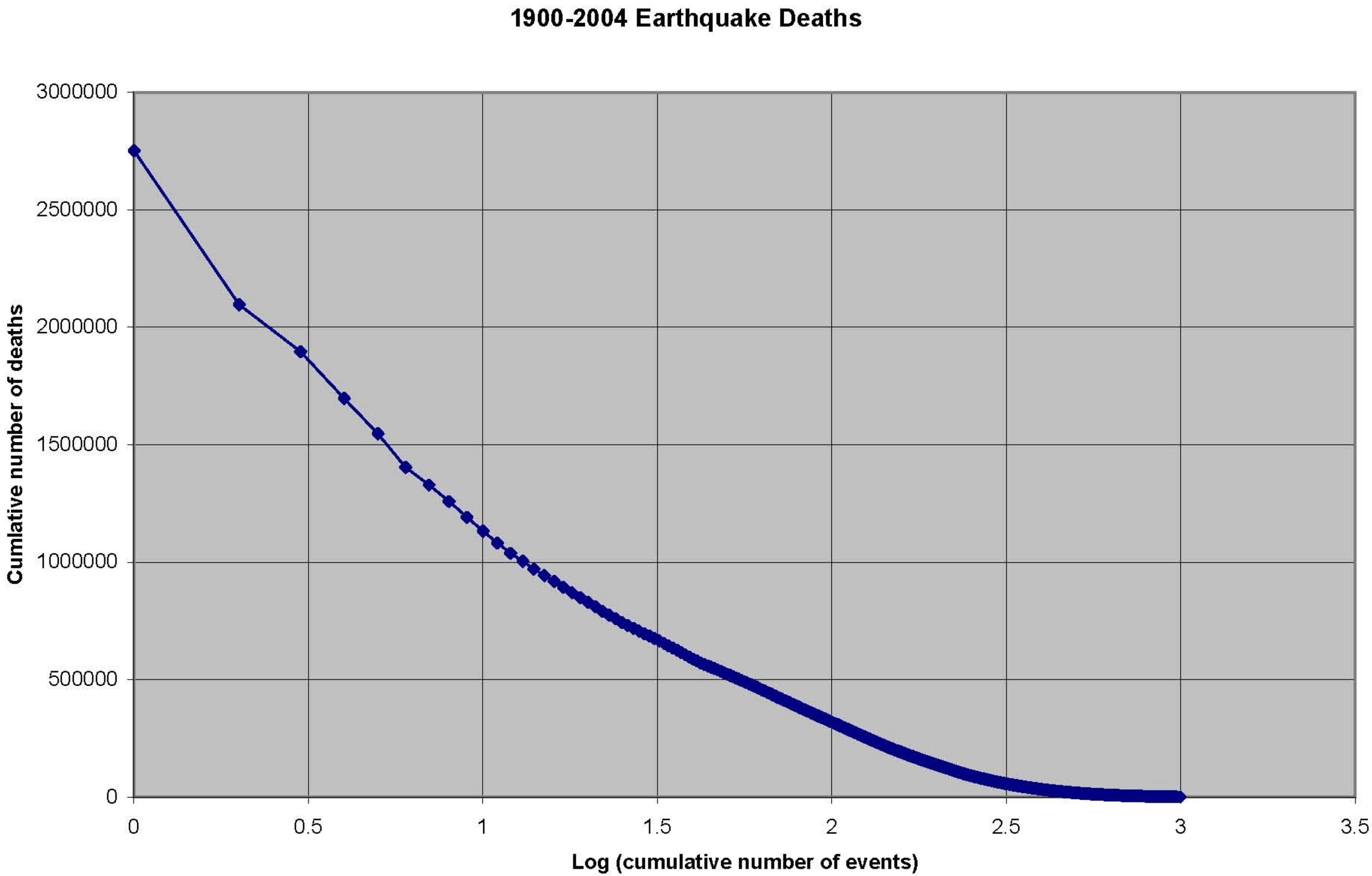
Los Angeles CA Disaggregated Seismic Hazard
for 0.2 second Spectral Acceleration , 1.55 g
PE = 2% per 50 yr. Hazard radius 250 km, DeltaR=10 km
Mw: Binned average (weighed by exceedance contributions)
Predominant hazards: Elysian Park and Newport-Inglewood faults
8.0
7.6
7.2
6.8
6.6
6.4
6.2
5.7
M
36°
34°
32°
0
50
100
km
California
Mexico
Pacific Ocean
GMT Sep 3 08:47
Los Angeles CA 0.2 sec SA (1.552 g), radius=250 km Cities: yellow circles. Faults: red lines. Historical earthquakes, M>6: red diamonds. hmax=0.94*10^-4.



Seattle WA Disaggregated Seismic Hazard
for 1 second Spectral Acceleration, 0.520 g
PE = 2% per 50 yr. Hazard radius 250 km, DeltaR=10 km
Mw: Binned average. Bins are equal-area (157 km^2)
Predominant hazard: Seattle fault
9.0
8.0
7.6
7.2
6.8
6.6
6.4
6.2
6.0
5.5
M
Canada
Washington
Pacific Ocean
Oregon
48°
46°
0
50
100
km
GMT Oct 9 11:14
Seattle WA Spatial PSHA Deagg. 1.0 sec SA, 0.5196 g, radius=250 km. Cities: yellow circles. Historical earthquakes, M>6: diamonds. hmax=2.6*10**-4



$$(\text{frequency of occurrences}) \quad (\text{number of deaths in an event})^{-0.86}$$



½ of the deaths occurred in the 7 deadliest earthquakes

Basic Engineering Issue

- Most of these deaths occurred in poorly designed or constructed buildings (with notable exceptions).
- Can modern building codes change the conclusion that most of the hazard comes from rare events?
- If the loss probability is really a power law, what is the best strategy to deal with this?

Why were these disasters power law?

- The prevailing practice was inappropriate for the coming earthquake
- If people had known the consequences of their misjudgment, they would have done things differently
- Because of the tremendous loss, they fixed the problem with building codes

Current Building Code

- Current building codes are mostly prescriptive rules based on the building type and seismic zone.
- Codes have been developed by fixing deficiencies from past earthquakes.
- If you've got a good building code, who needs a seismologist?

Have building codes broken the power law?

- Are there new systematic lessons that will be learned in future earthquakes?
- Lessons from large (M>7) earthquakes beneath a major city have yet to be learned.
- The largest events, 1906 San Francisco (M7.8), 1923 Tokyo (M8.0), and 1976 Tangshan (M7.5) had severe consequences.
- Large magnitude earthquakes produce larger ground velocities and displacements than are considered for the design of most modern high-rise buildings.
- Have we really solved the fire problem?

How do buildings resist earthquake forces?

Front View

Top View

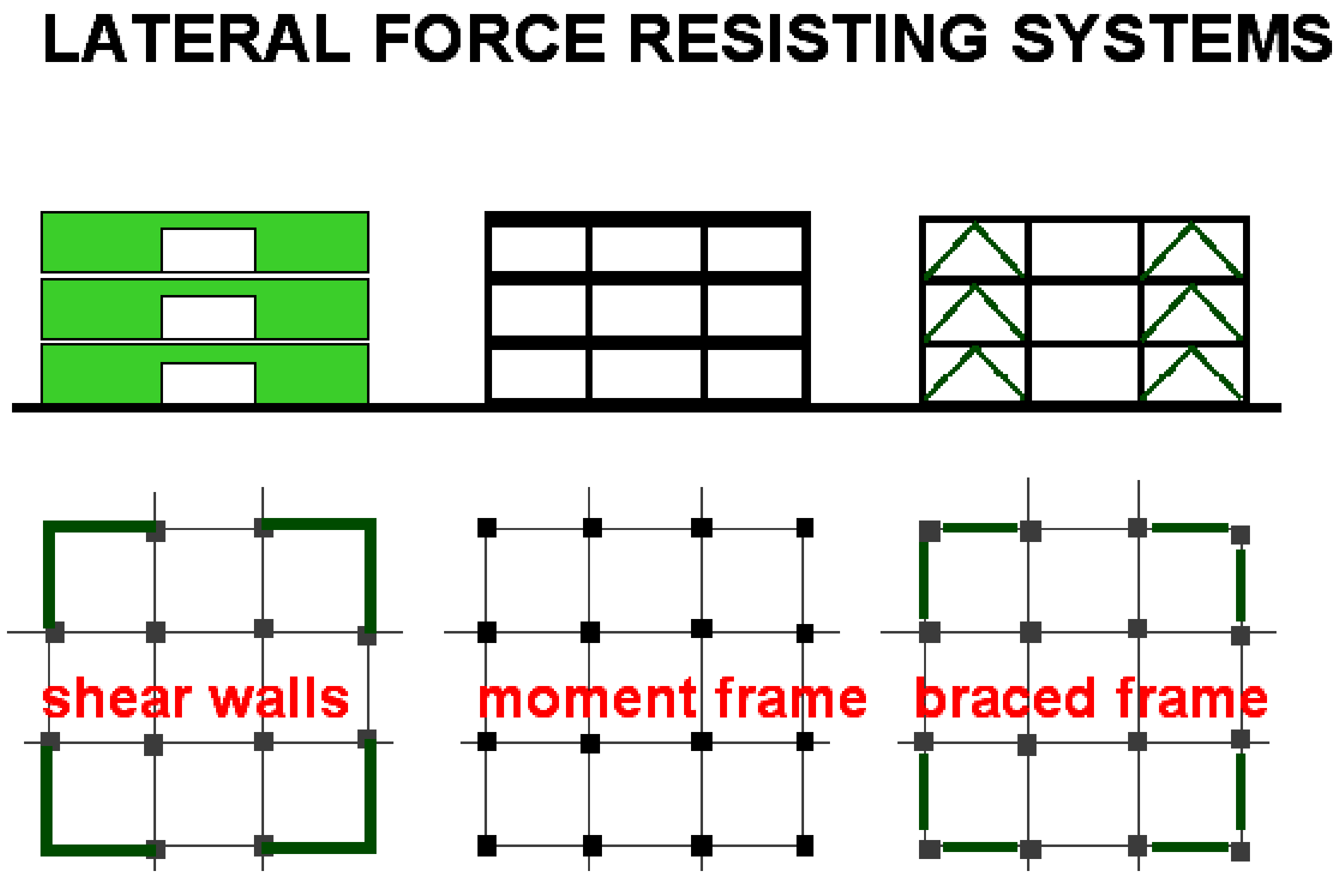


Image: Courtesy EERI

Flexible or Strong?

- Stress ~ (density)x(particle velocity)x(wave speed)
- Therefore stiff buildings tend to have high stresses.
- Making a building strong increases the stiffness, which increases the stresses, which increases the required strength of the building (a vicious circle).
- Making a building flexible tends to decrease the stress, but it also decreases the strength of a building (another vicious circle).

Tall buildings cannot withstand large drifts

- Integrity of the columns is critical.
- Gravity loads are normally axial compressional loads on the columns.
- Tilted columns result in bending moments on the columns caused by the weight of the building.
- (moment) ~ cos(tilt)x(weight)x(story height).
- Drift (e.g. column tilt) should not exceed 0.03 for tall MRF buildings.

Failure of Welded MRF Connections

- Steel beams are intended to plastically yield
- Integrity of welded MRF connections is key to applying moments such that the beam yields.
- Northridge and Kobe showed that the welded connections fractured before any plastic yielding occurred. That is, the buildings were brittle.

John Hall's design of a 20-story steel MRF building

Designed to 1994 UBC zone 4, stiff soil

3.5 second natural period

Includes weld fracture

top flange $\frac{\varepsilon_F}{\varepsilon_y} = 1$ for 40%

=10 for 30%

=100 for 30%

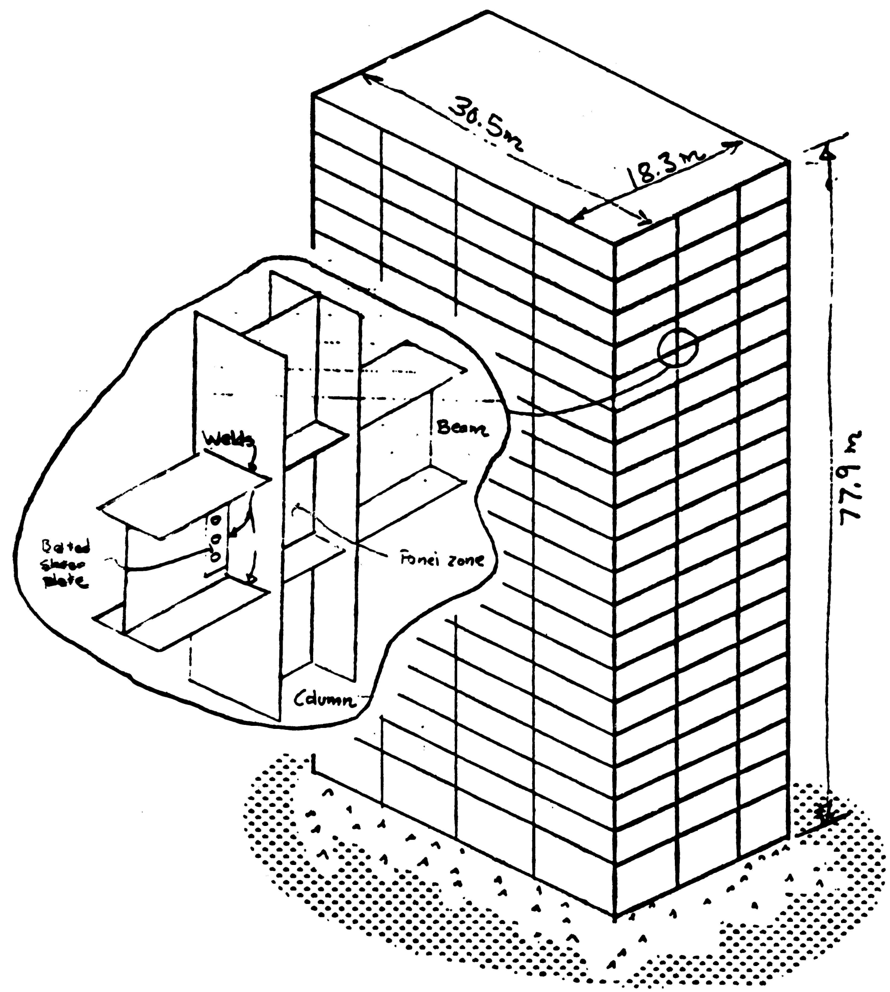
bottom flange $\frac{\varepsilon_F}{\varepsilon_y} = 0.7$ for 20%

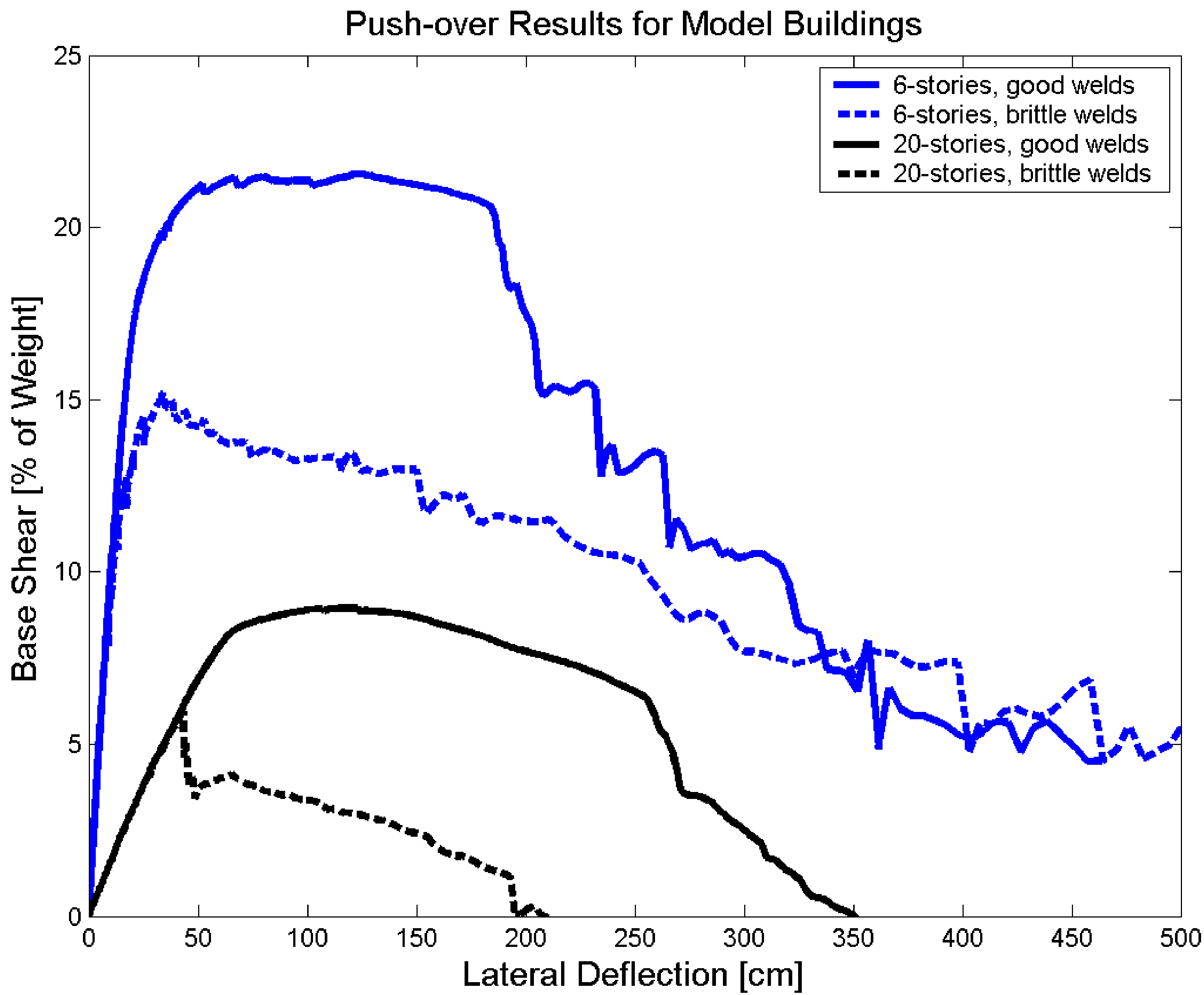
=1 for 40%

=10 for 20%

=50 for 10%

=100 for 10%





Push-over Results for Model Buildings
6-stories, good welds
6-stories, brittle welds
20-stories, good welds
20-stories, brittle welds
Base Shear [% of Weight]
Lateral Deflection [cm]
0
5
10
15
20
25
0
50
100
150
200
250
300
350
400
450
500

20-story steel-frame building subjected to a 2-meter near-source displacement pulse (from Hall)

- triangles on the frame indicate the failures of welded column-beam connections (loss of stiffness).

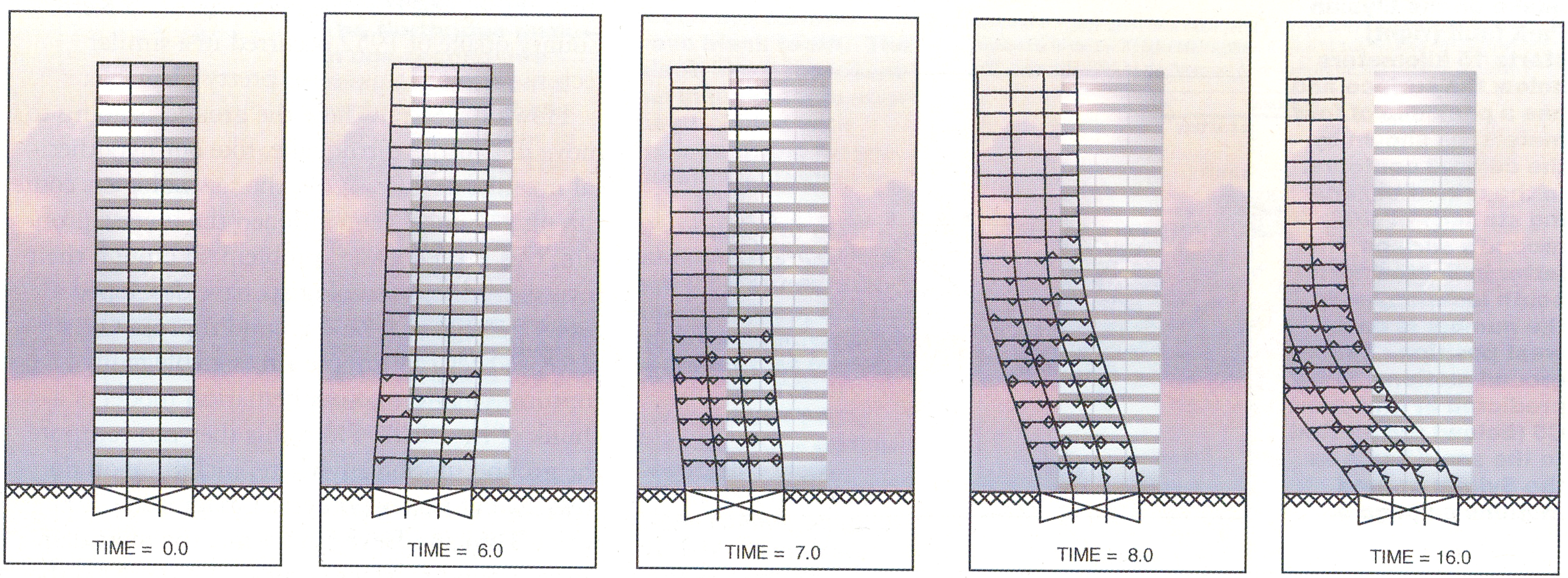
The 20-story building before the C5 ground motion hits. The displacement pulse will be toward the left.

At t=6 seconds, the ground is approaching its maximum horizontal displacement of 182 centimeters.

At t=7 seconds, the ground is returning to its original position, causing the building to "crack the whip."

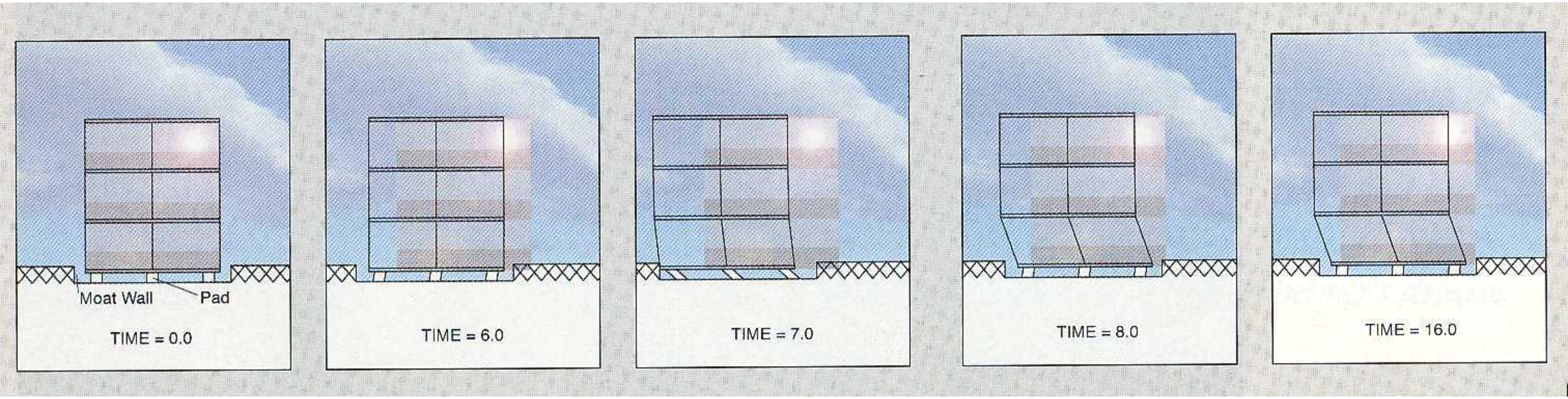
This flexure creates a ripple of breaking welds that travels up the building.

By t=16 seconds, the building is hopelessly overbalanced and on its way to oblivion.



Large displacements can overwhelm base isolation systems

- 2-meter displacement pulse as input for a simulation of the deformation of a 3-story base-isolated building (Hall, Heaton, Wald, and Halling
- The Sylmar record from the 1994 Northridge earthquake also causes the building to collide with the stops



CUREe

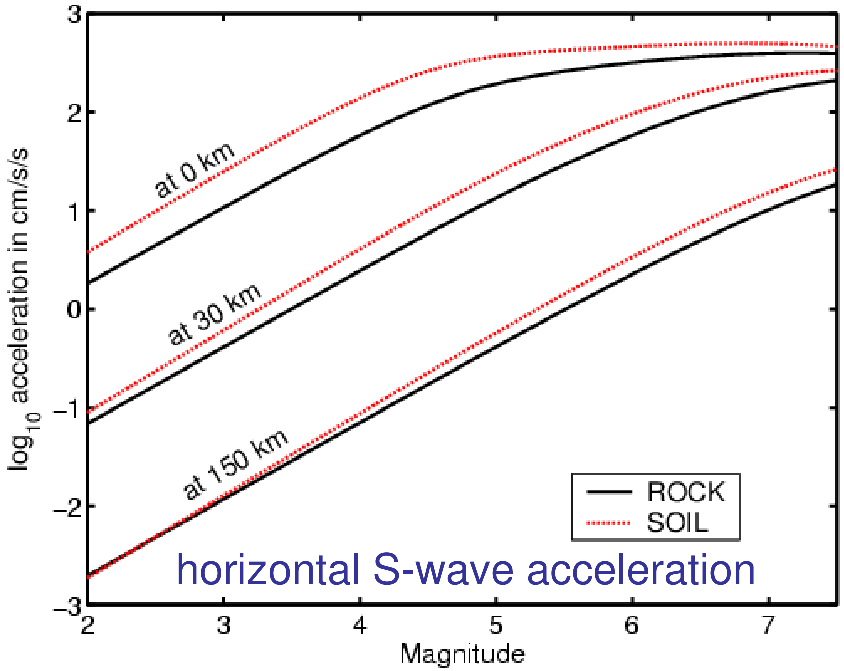
11 years ago... Mexico Earthquake, September 19, 21-story building collapsed onto 14-story neighbor, Pino Suarez complex

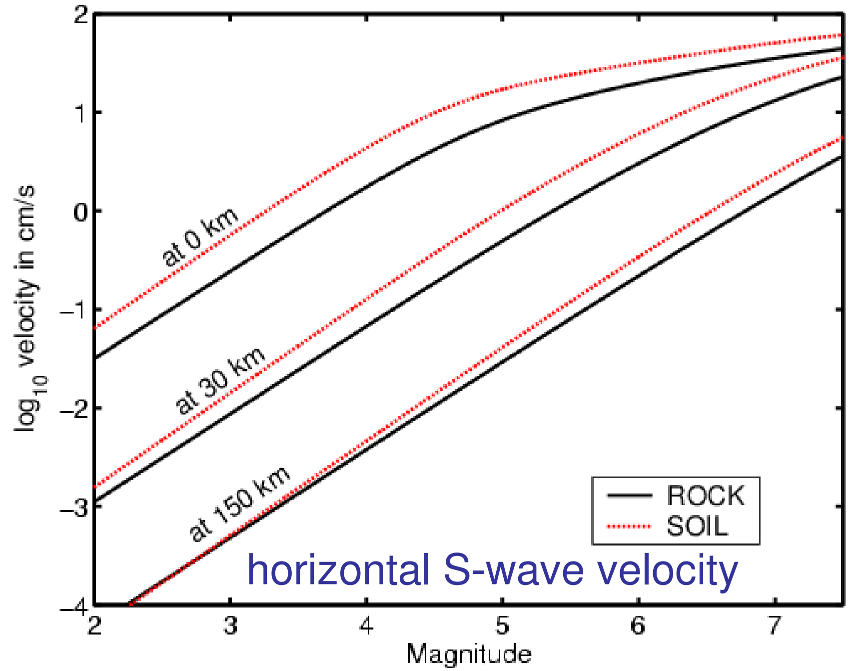
1996

1906 earthquake rupture with large ground displacement.
Notice that the farm buildings were largely intact.

Pt Reyes Station 1906

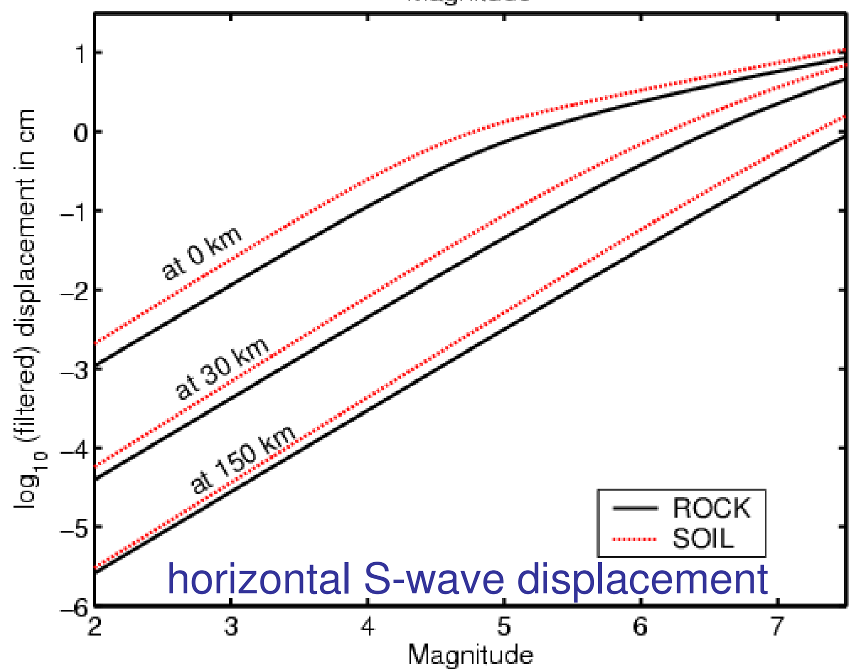
Magnitude-dependent saturation of rock and soil sites (S-waves)

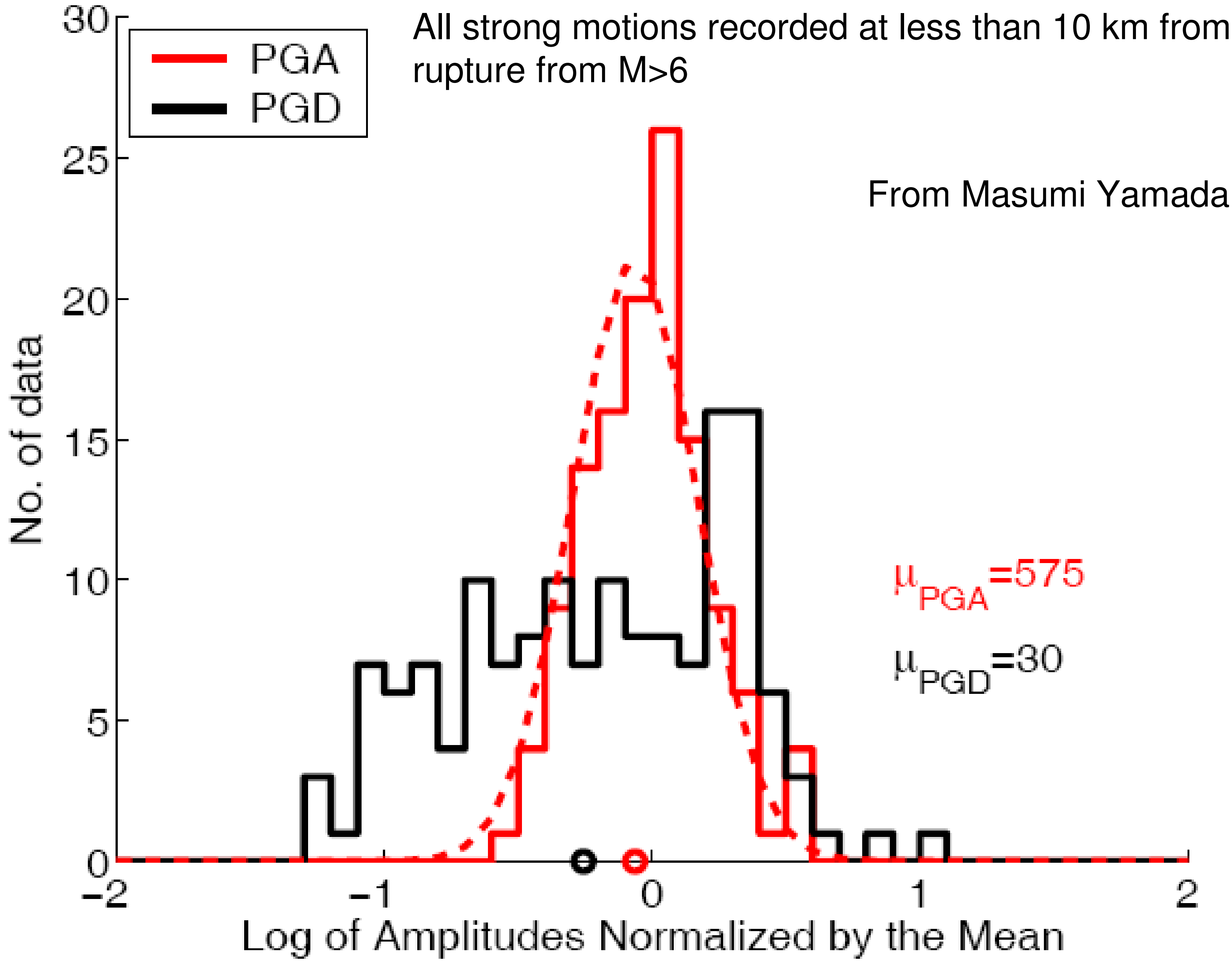




- Saturation important for M>5, when source dimensions become comparable to station distance, large amplitudes may induce yielding in soils
- Magnitude-dependent saturation appears to be primarily a source effect, since rock and soil are equally affected
- The exception is horizontal acceleration at close distances to large events. Slight over-saturation of soil ground motions, possibly due to non-linear site effects.

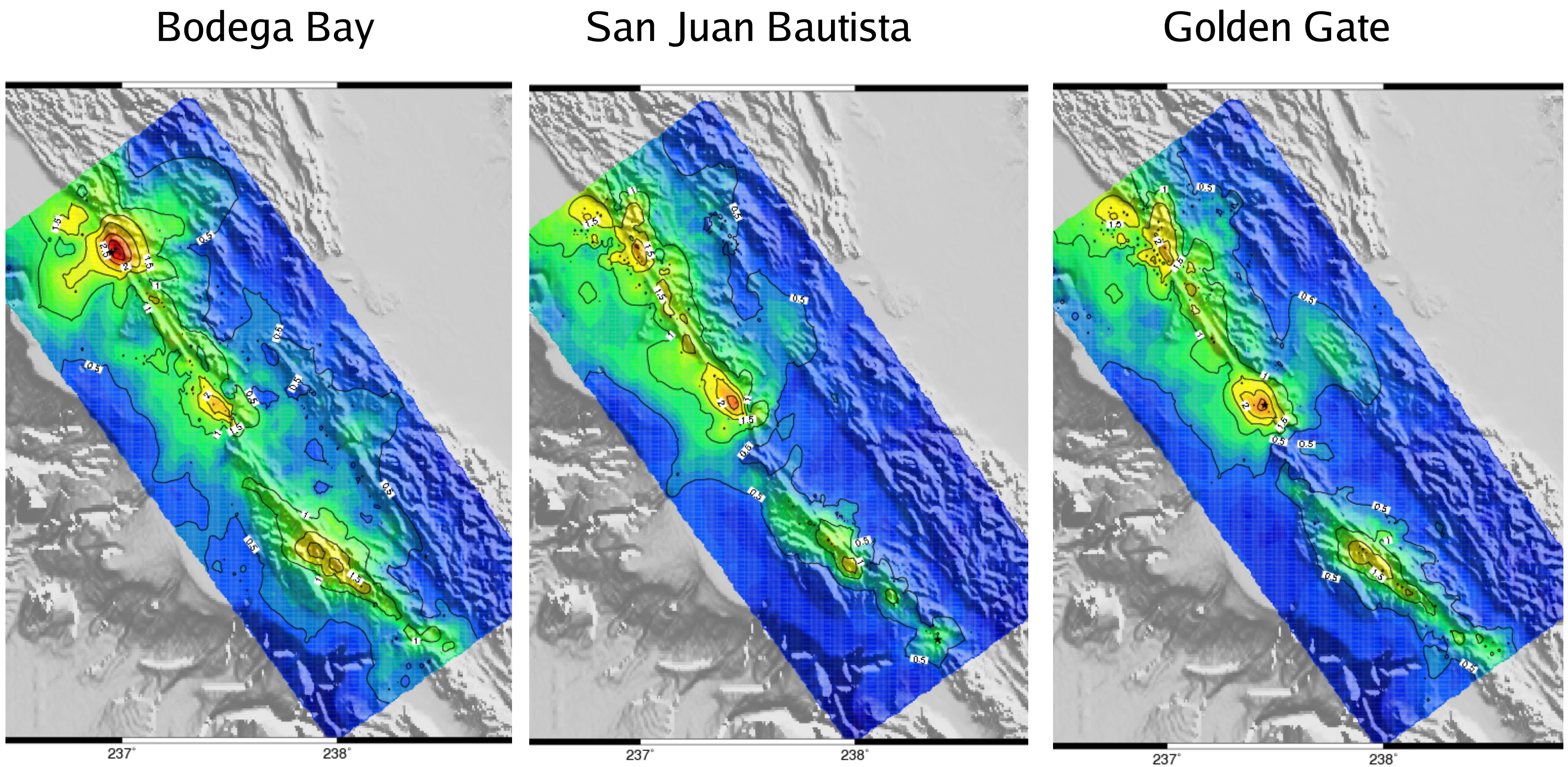
From Georgia Cua

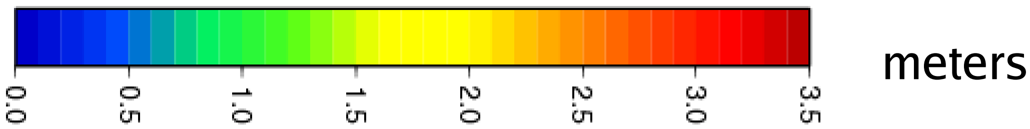




All strong motions recorded at less than 10 km from rupture from M>6
From Masumi Yamada
PGA
PGD
μ_{PGA}=575
μ_{PGD}=30
No. of data
Log of Amplitudes Normalized by the Mean
30
25
20
15
10
5
0
-2
-1
0
1
2

Peak Ground Displacement

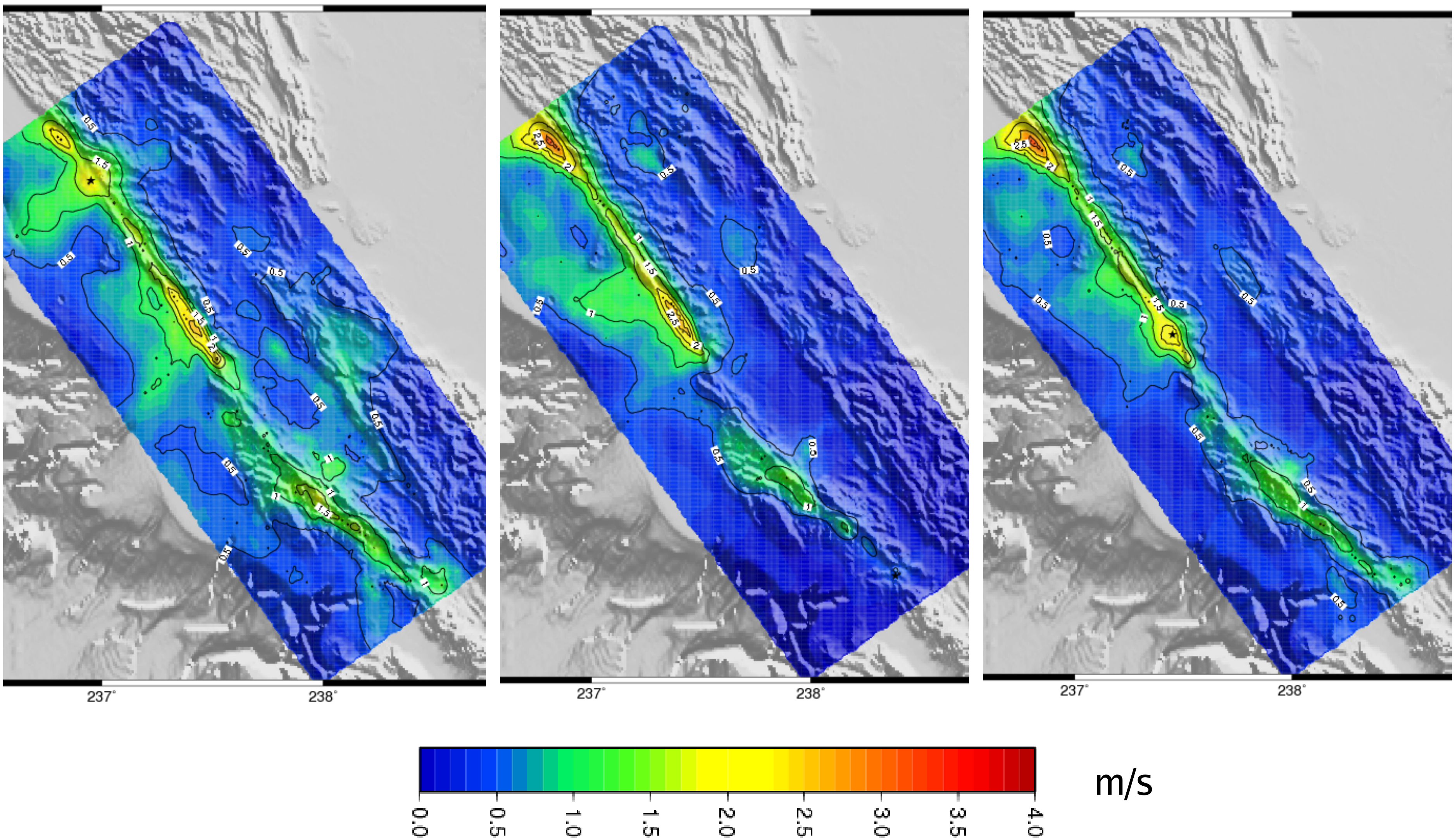




Ground motions
From Brad Aagaard

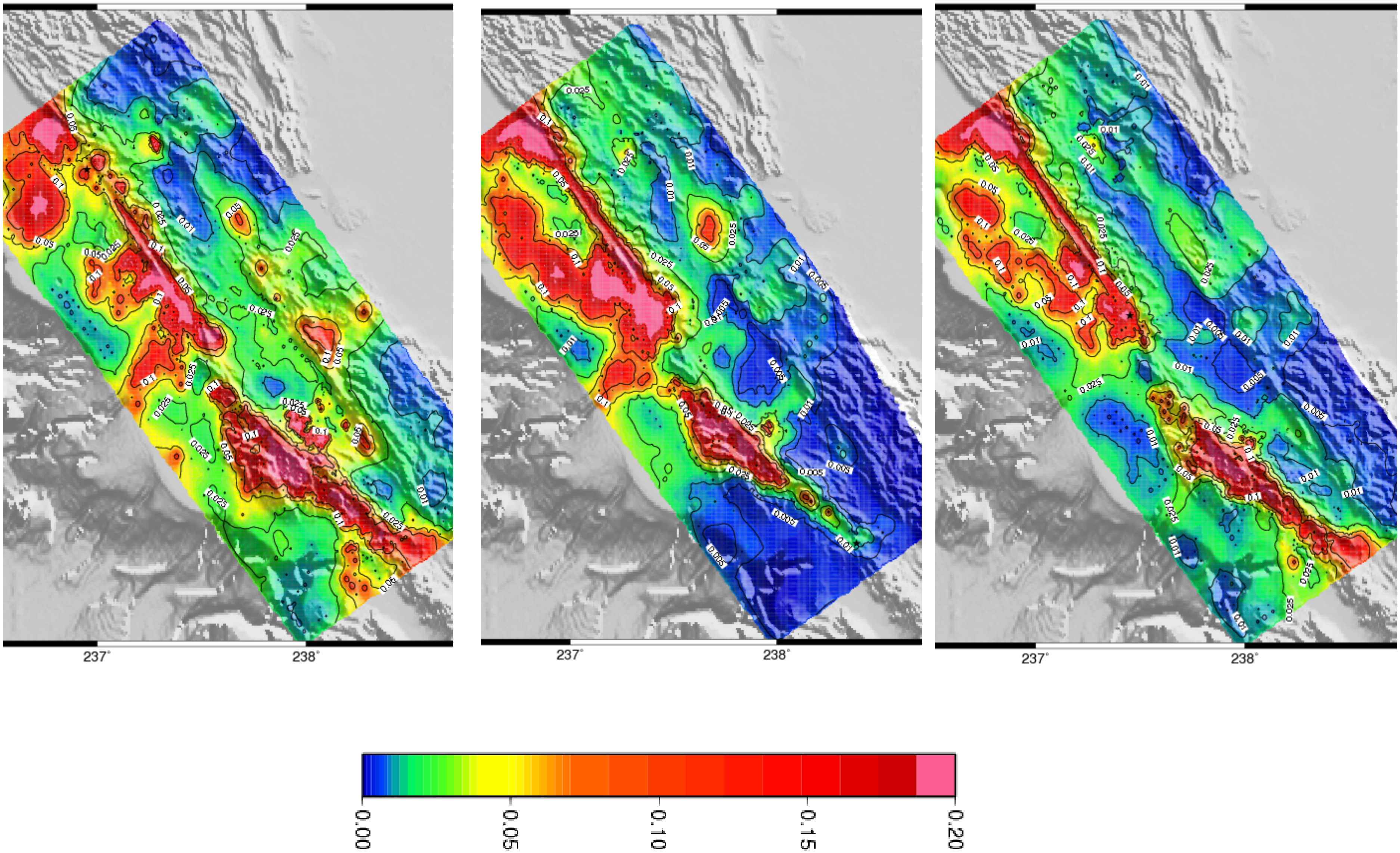
Peak Ground Velocities

Bodega Bay San Juan Bautista Golden Gate



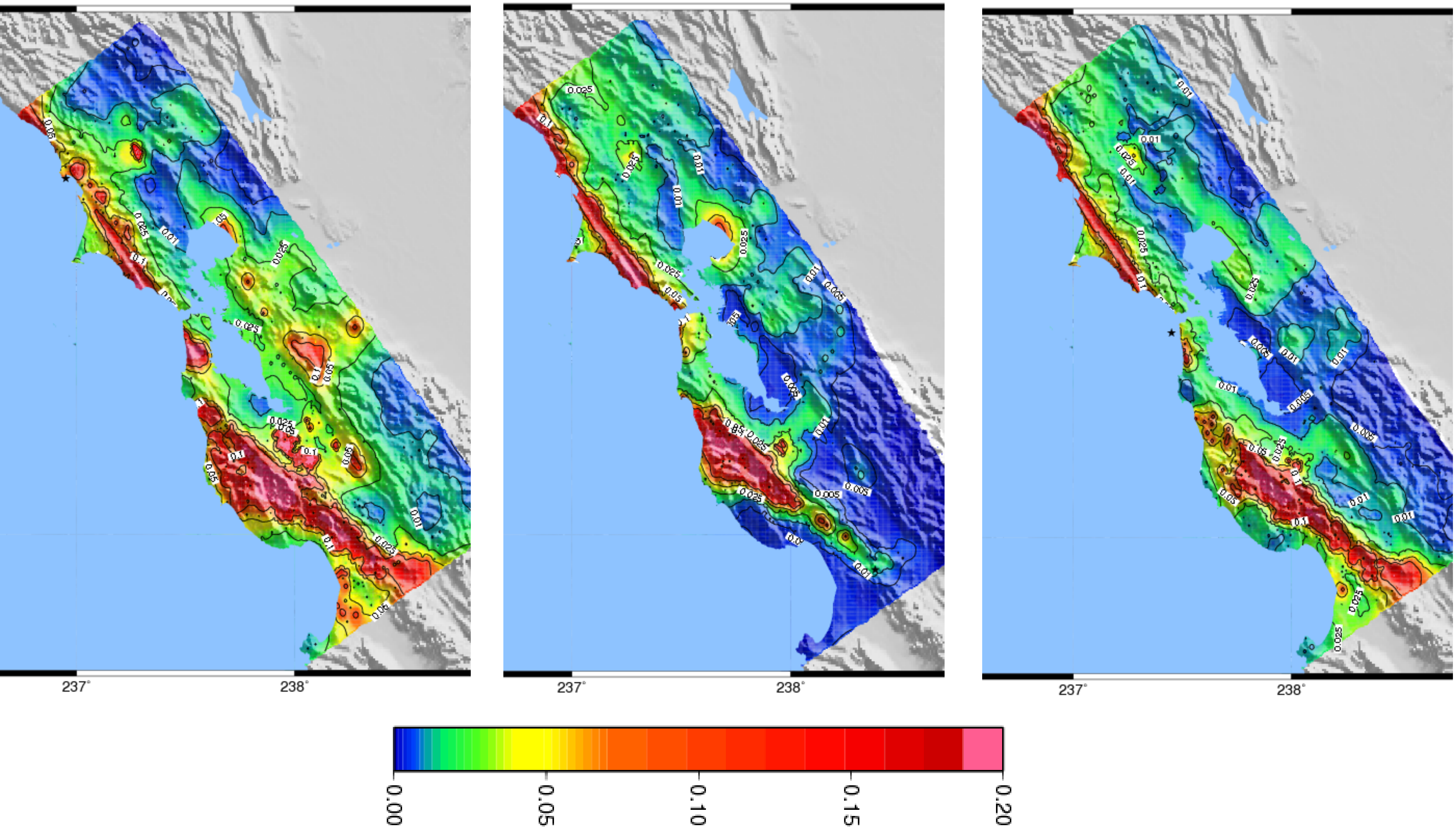
20-story brittle welds peak drift

Bodega Bay | San Juan Bautista | Golden Gate



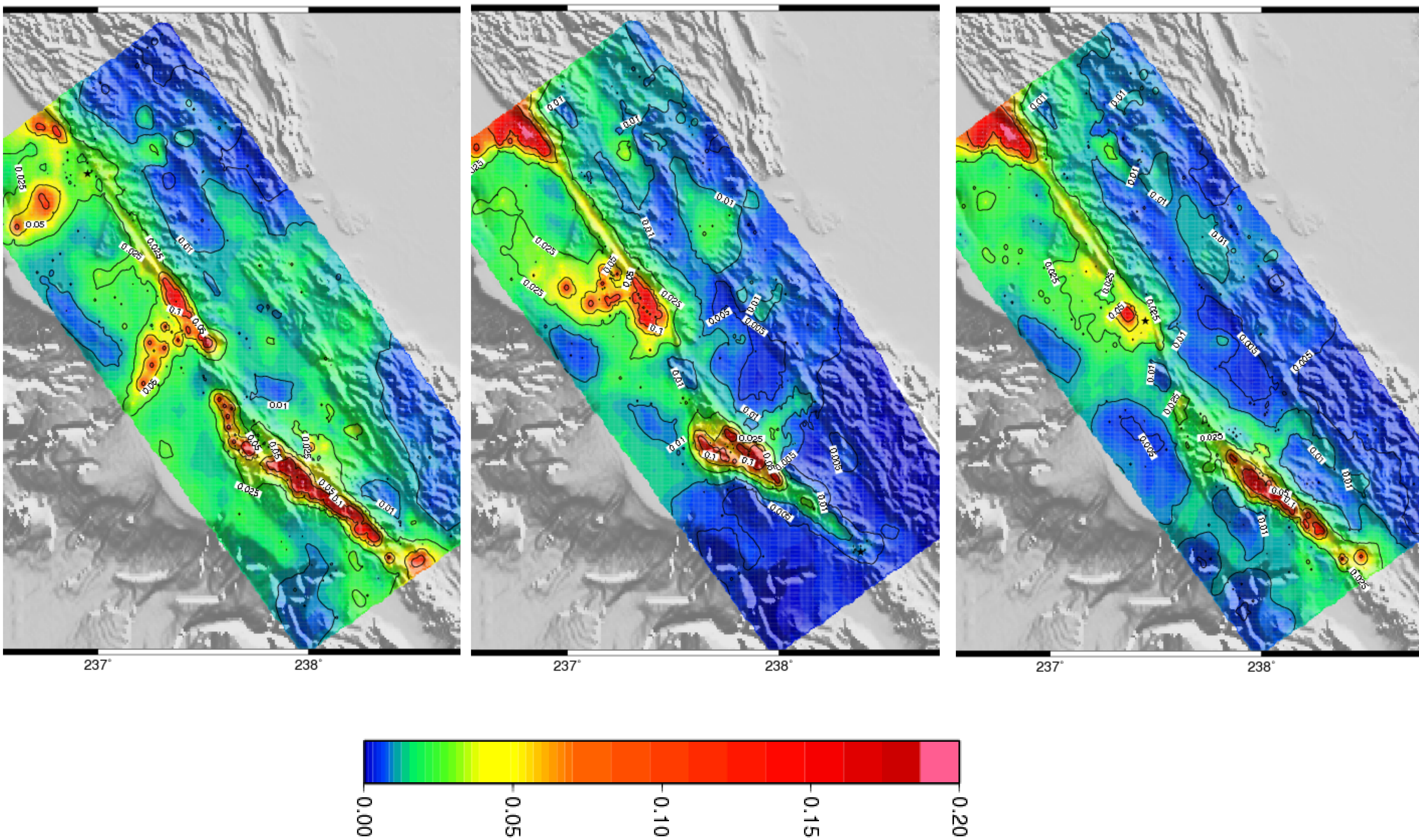
20-story brittle welds peak drift

Bodega Bay | San Juan Bautista | Golden Gate

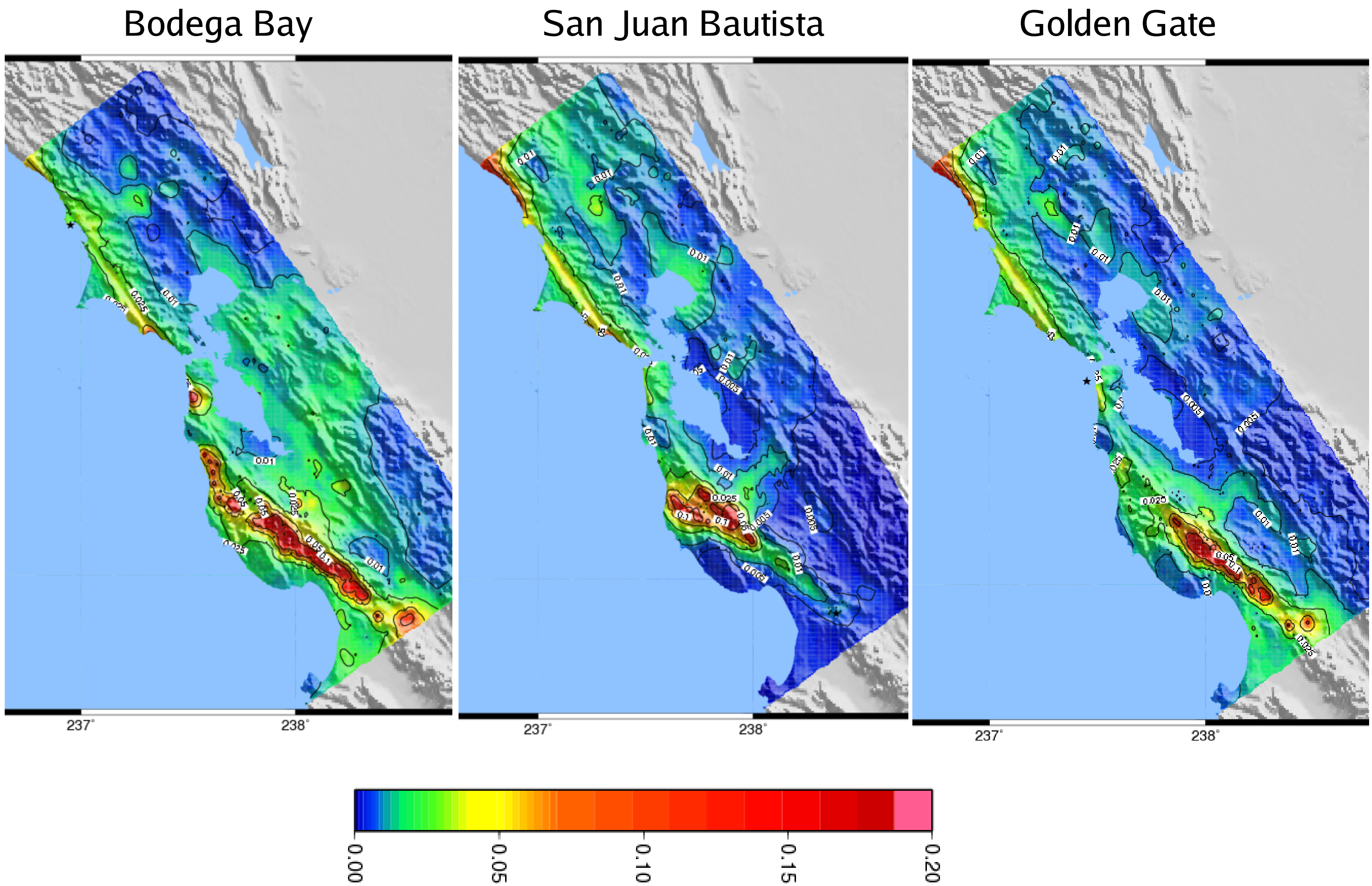


20-story perfect welds peak drift

Bodega Bay San Juan Bautista Golden Gate

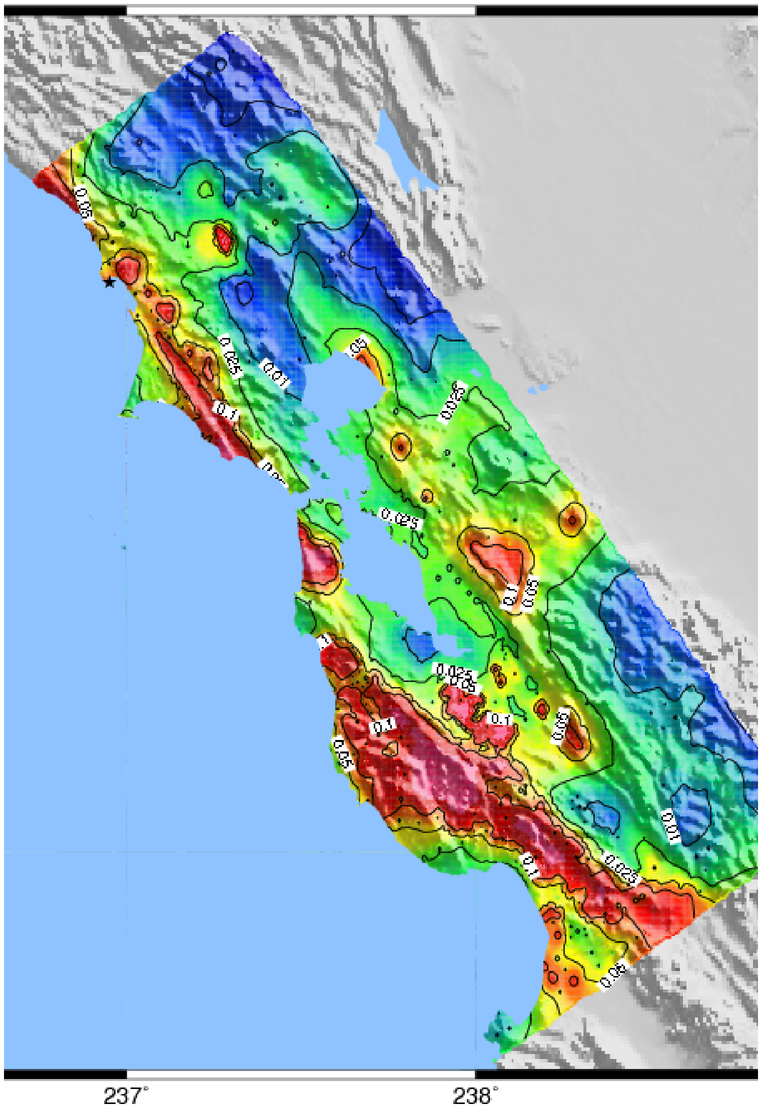


20-story perfect welds peak drift

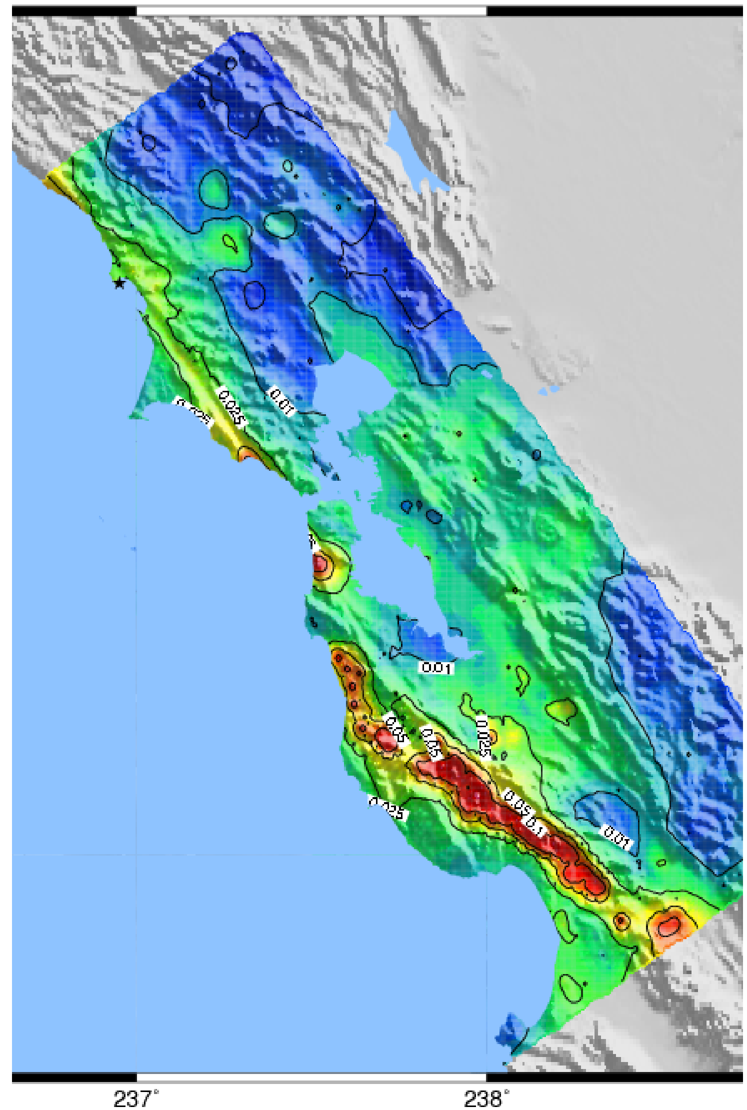


Fix the Brittle Welds

Ft Ross with brittle welds



Ft Ross with perfect welds



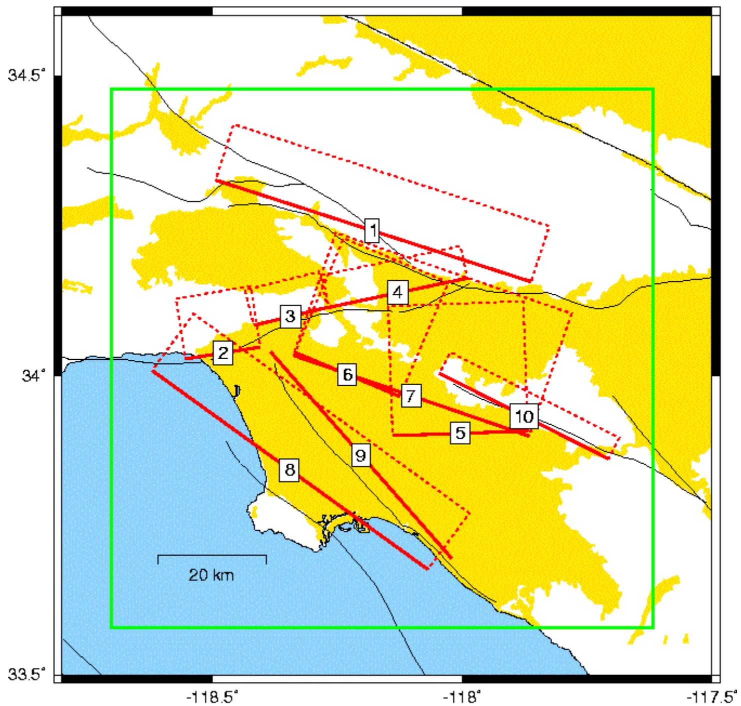
Other factors that may increase the building deformation

- There is no soil layer … no bay mud
- The ground motions are heavily filtered at frequencies higher than ½ Hz
- Sub-shear rupture velocities may increase the strength of directivity pulses

Faults Modeled

Day and others, 2005

Scenario Faults



1) smad: Mw 7.0 Sierra_Madre
2) smon1: Mw 6.3 Santa_Monica_south_west
3) hwood: Mw 6.4 Hollywood
4) raym2: Mw 6.6 Raymond_connectors
5) ph2e: Mw 6.8 Puente_Hills_Santa_Fe_Coyote_Hills
6) phla: Mw 6.7 Puente_Hills_Los_Angeles
7) phall: Mw 7.1 Puente_Hills_all
8) comp: Mw 6.9 Compton
9) nin: Mw 6.9 Newport_Inglewood_north
10) whitn: Mw 6.7 Whittier_north

- 1. Sierra Madre (7.0)
- 2. Santa Monica SW (6.3)
- 3. Hollywood (6.4)
- 4. Raymond (6.6)
- 5. Puente Hills I (6.8)
- 6. Puente Hills II (6.7)
- 7. Puente Hills (all) (7.1)
- 8. Compton (6.9)
- 9. Newport-Inglewood (6.9)
- 10. Whittier (6.7)

Coordination Scheme

	UCB LLNL	UCSB	CMU	URS (RG)	URS (AP)
S. Madre	F,R,S		C		
S. Mon.	F,R		C		
HollyW	F,R			C	
Raym	F,R			C	
P.Hills6.8		F,R		C	
P.Hills6.7		F,R		C	
P.Hills7.1		F,R,R,S			C
Comp		F,R,S			C
N-I N.	R,S		F		C
Whit N.	R		F		C

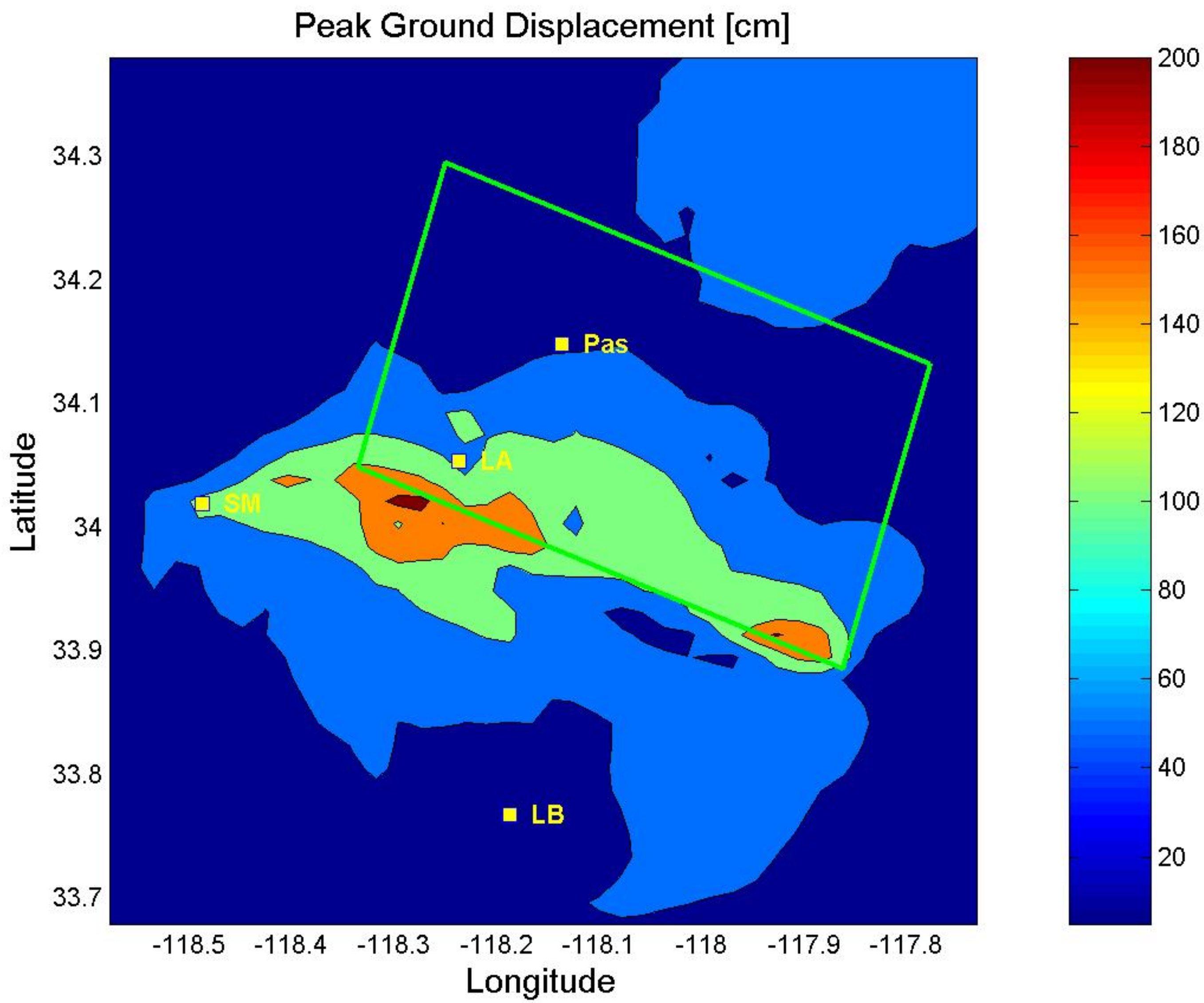
F = 6 3D scenarios

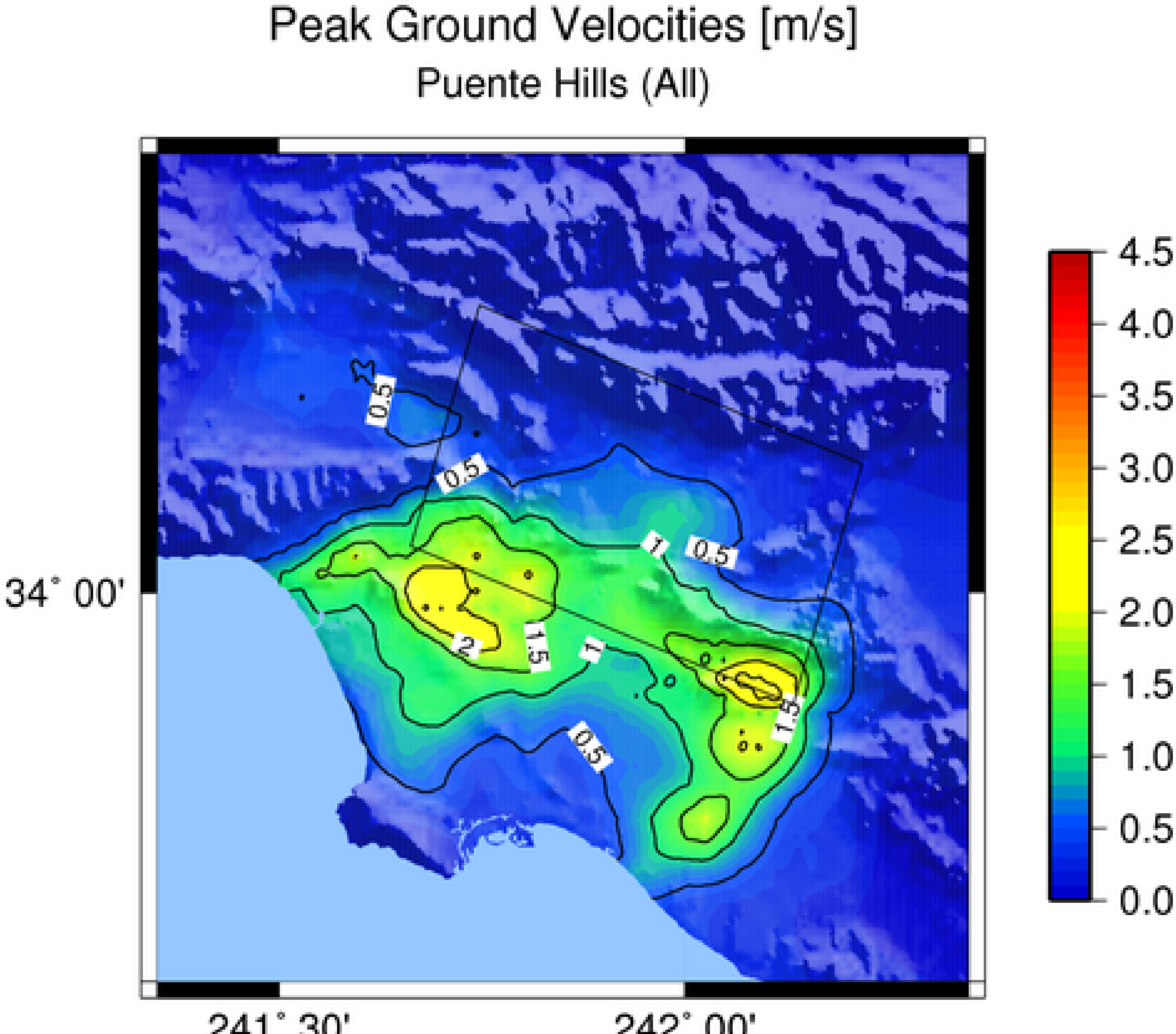
C = single cross-check

R = 1D rock reference simulation

S = 1D basin-profile simulation

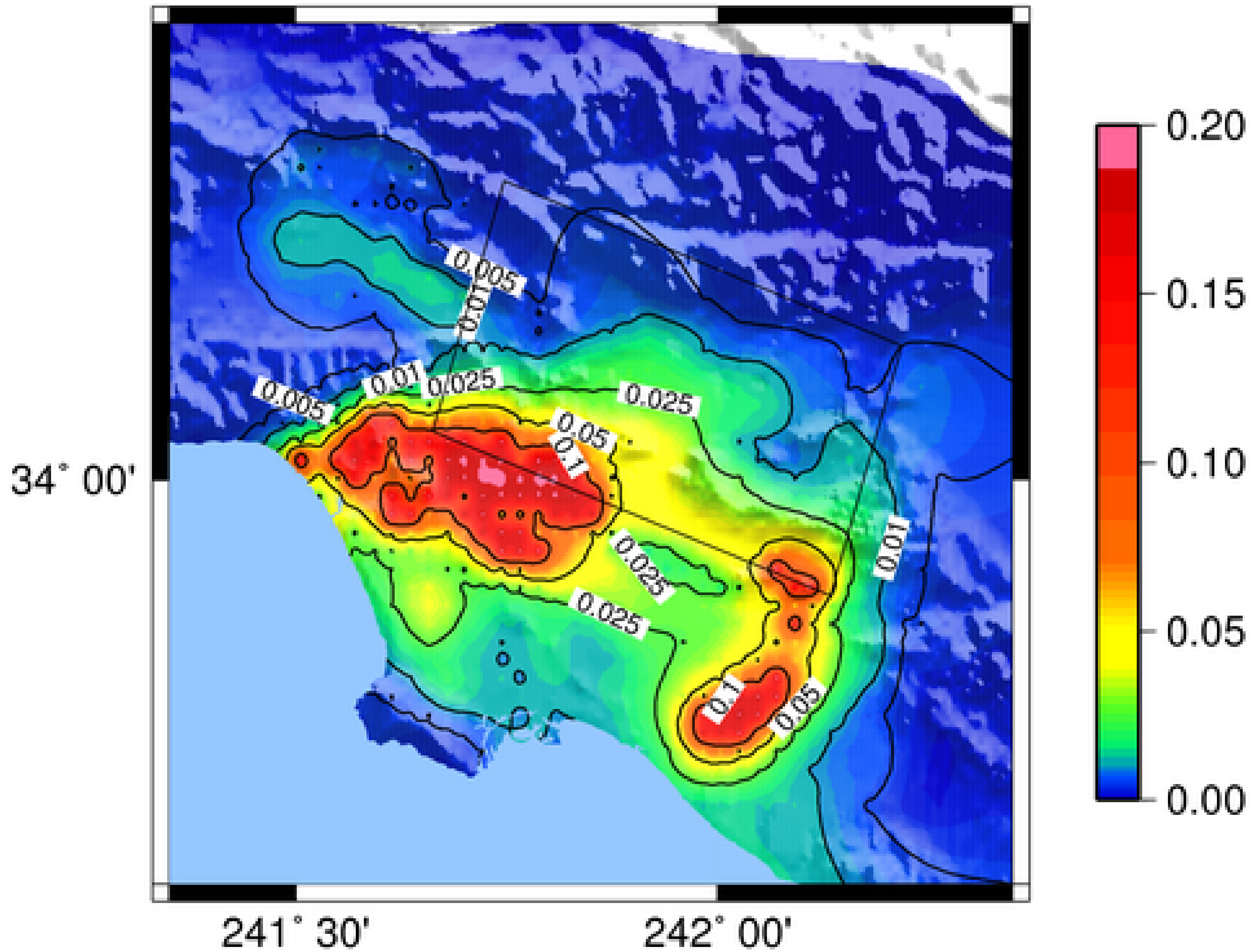
Puente Hills M 7.1

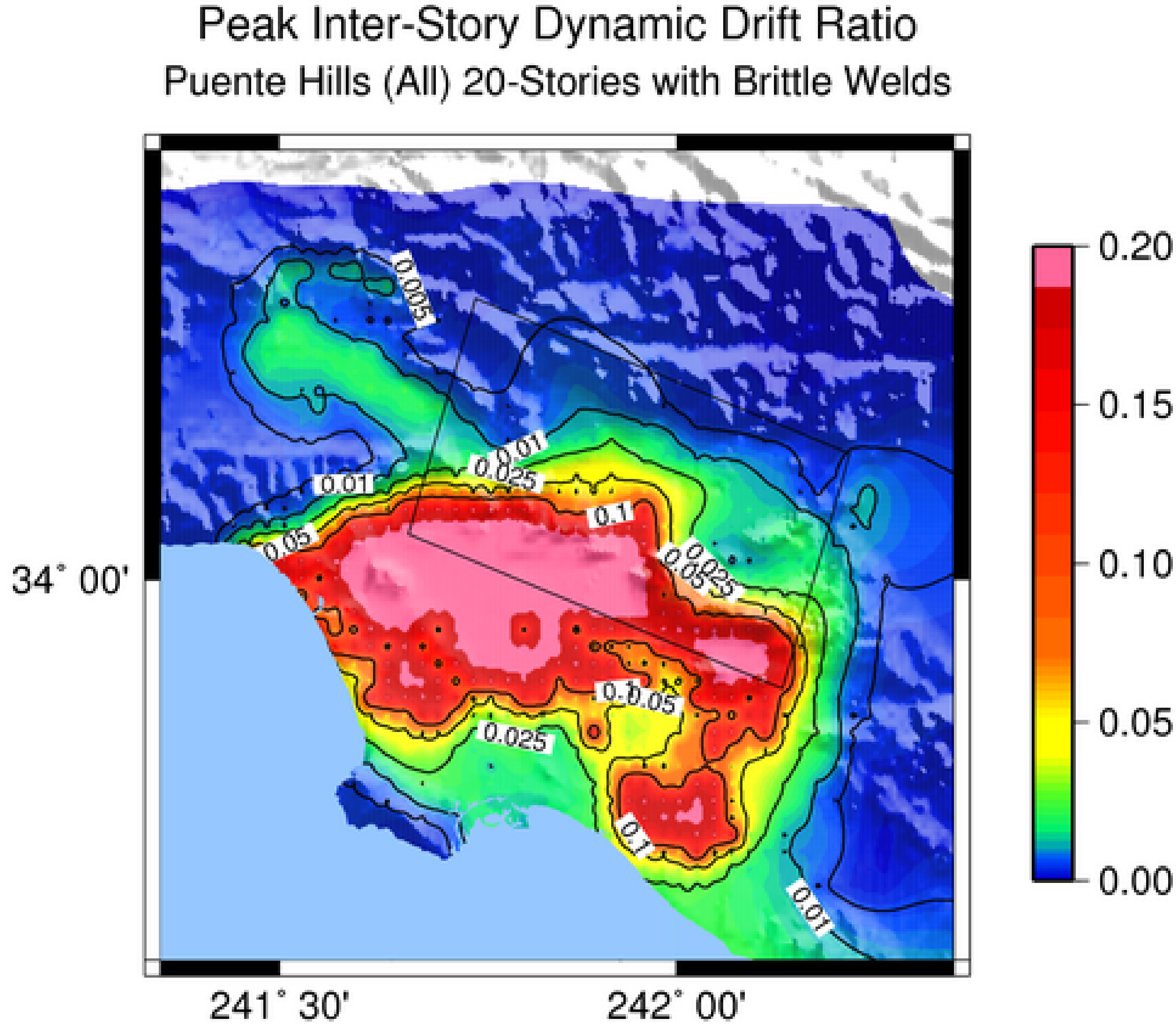




Peak Ground Velocities [m/s]
Puente Hills (All)
34° 00'
241° 30'
242° 00'
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.5
0.5
0.5
1
0.5
2
1.5
1
1.5
0.5

Peak Inter-Story Dynamic Drift Ratio
Puente Hills (All) 20-Stories with Good Welds

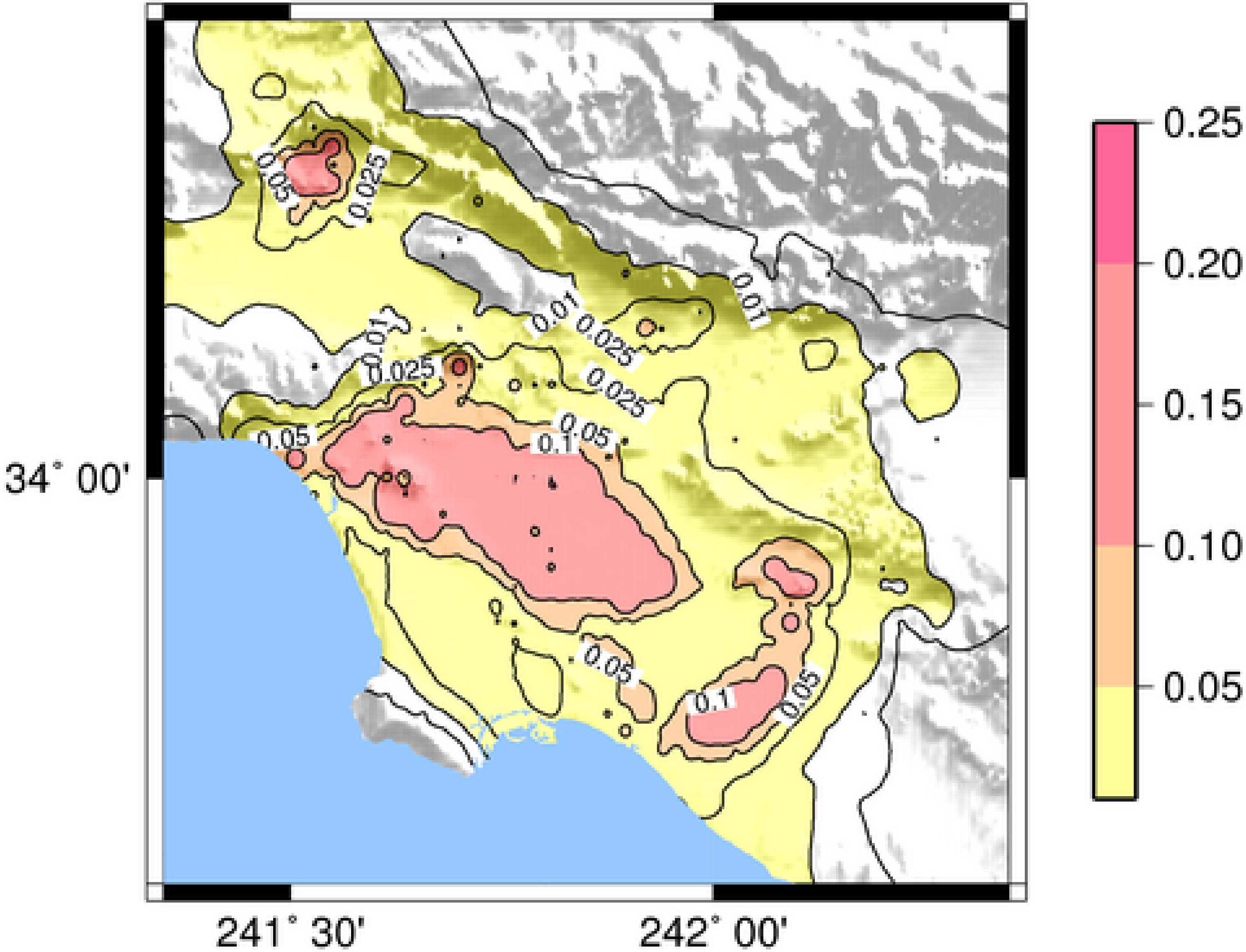




Peak Inter-Story Dynamic Drift Ratio
Puente Hills (All) 20-Stories with Brittle Welds
0.005
0.01
0.01
0.025
0.05
0.1
0.025
0.05
0.1
0.05
0.025
0.1
0.01
34˚ 00'
241˚ 30'
242˚ 00'
0.20
0.15
0.10
0.05
0.00

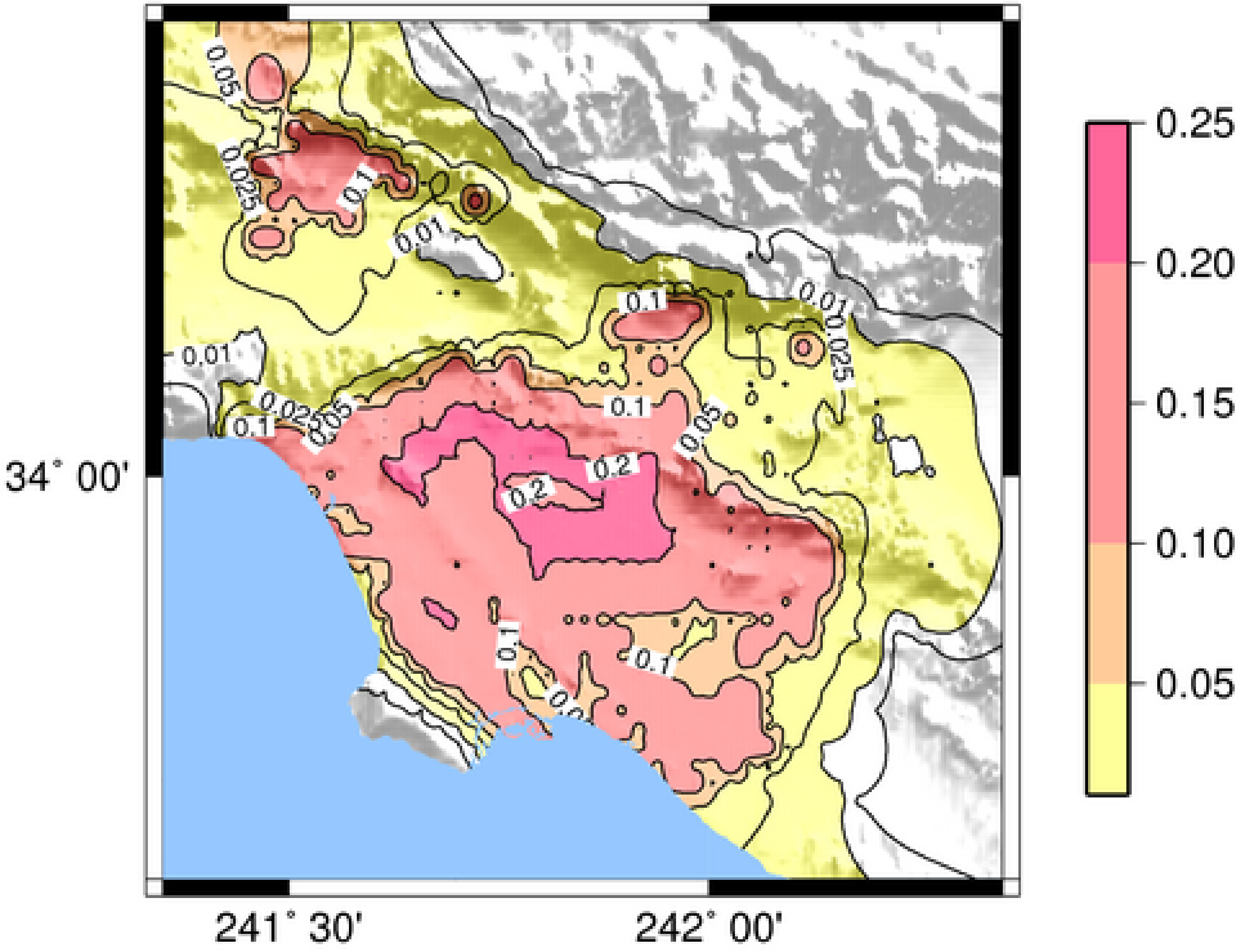
Maximum Inter-Story Dynamic Drift Ratio

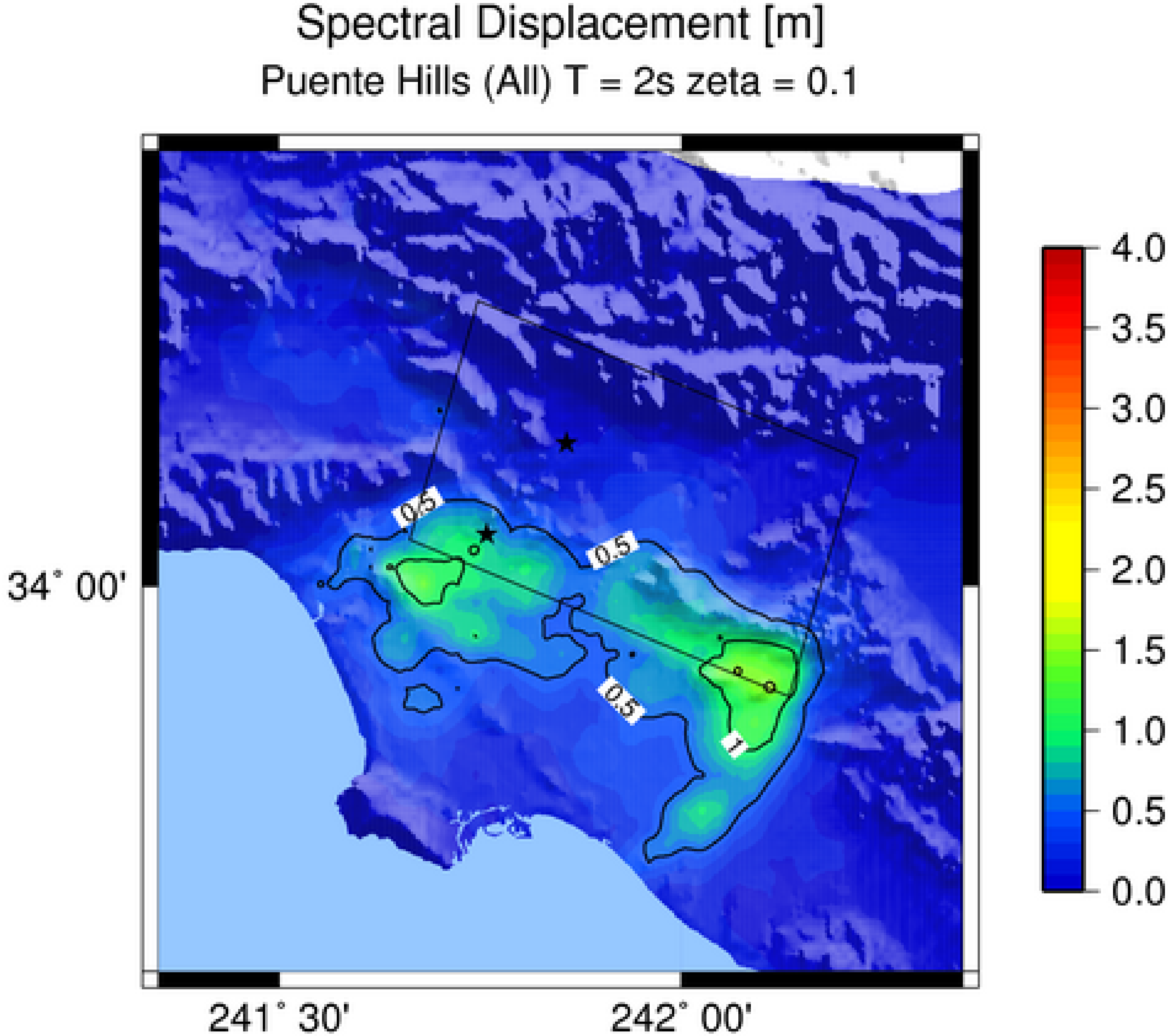
Composite 20-Stories with Good Welds



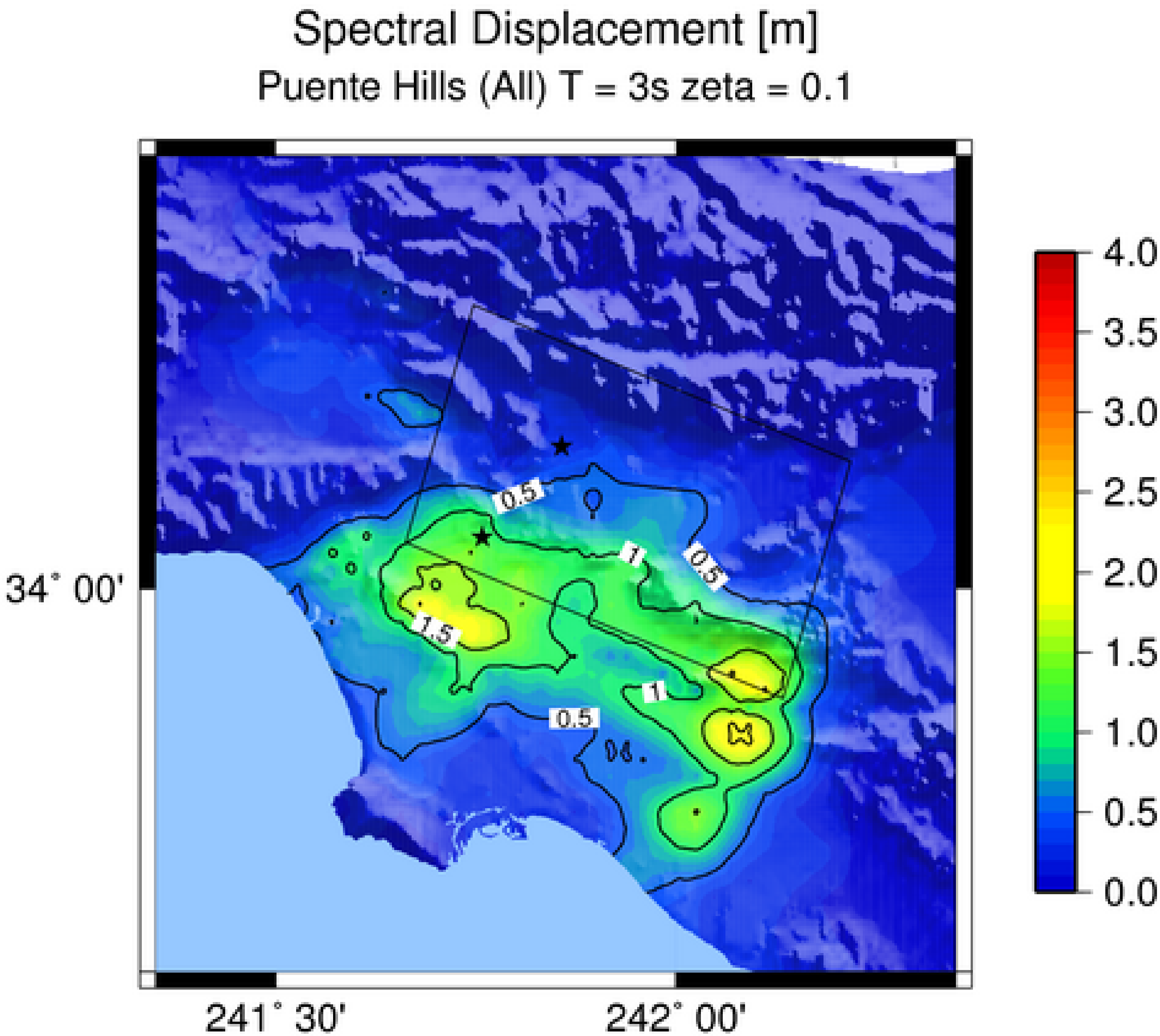
Maximum Inter-Story Dynamic Drift Ratio

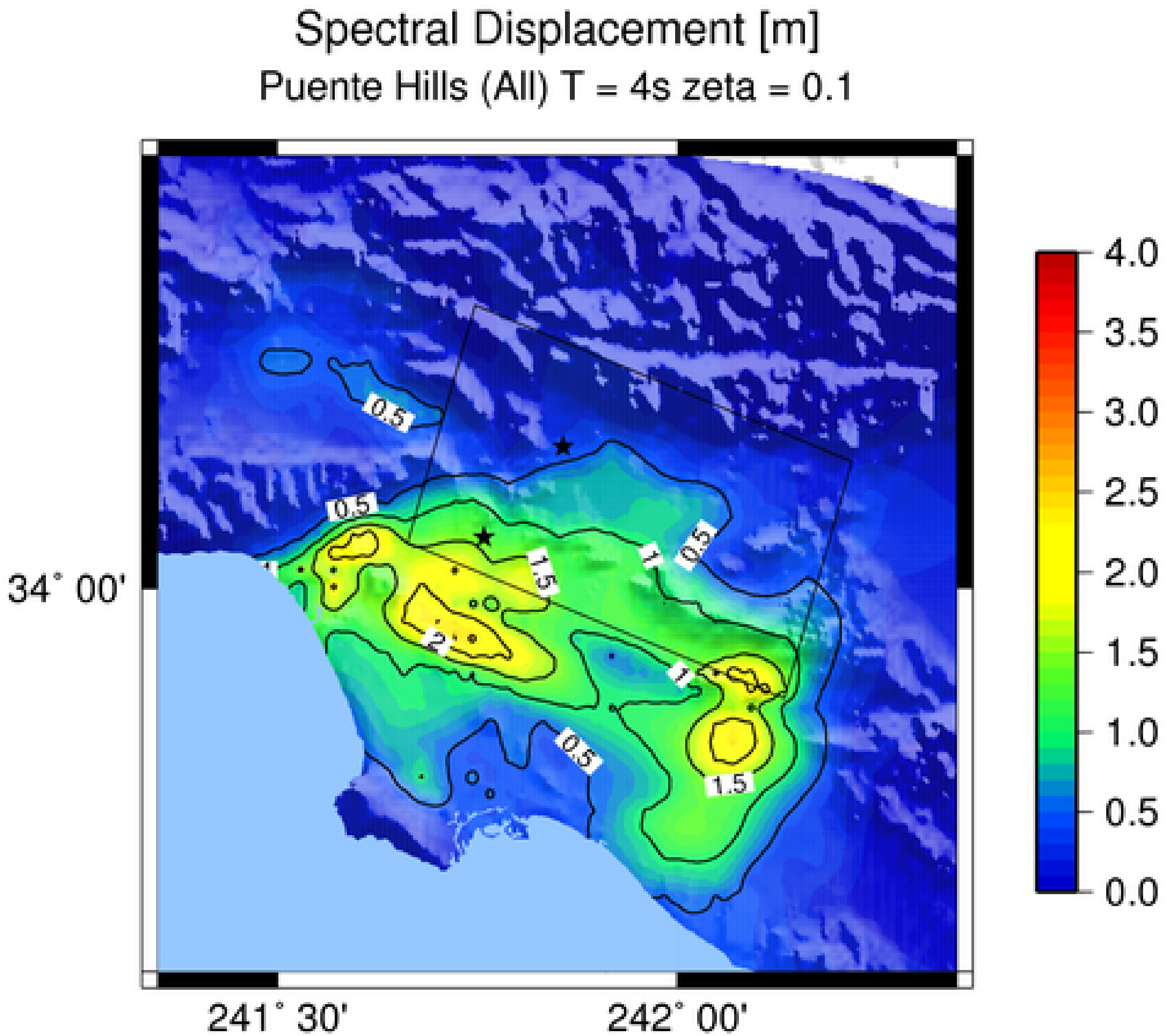
Composite 20-Stories with Brittle Welds



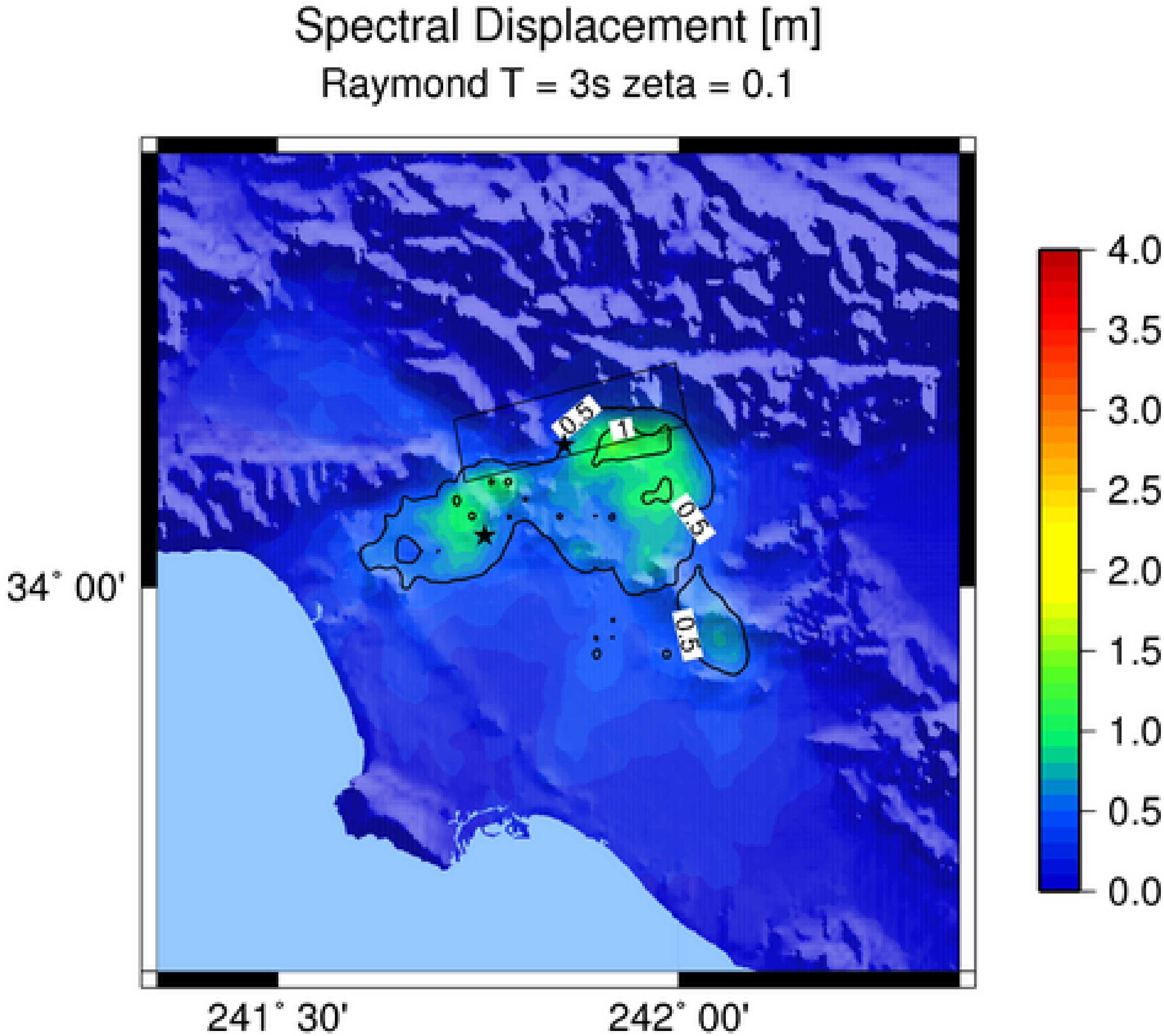


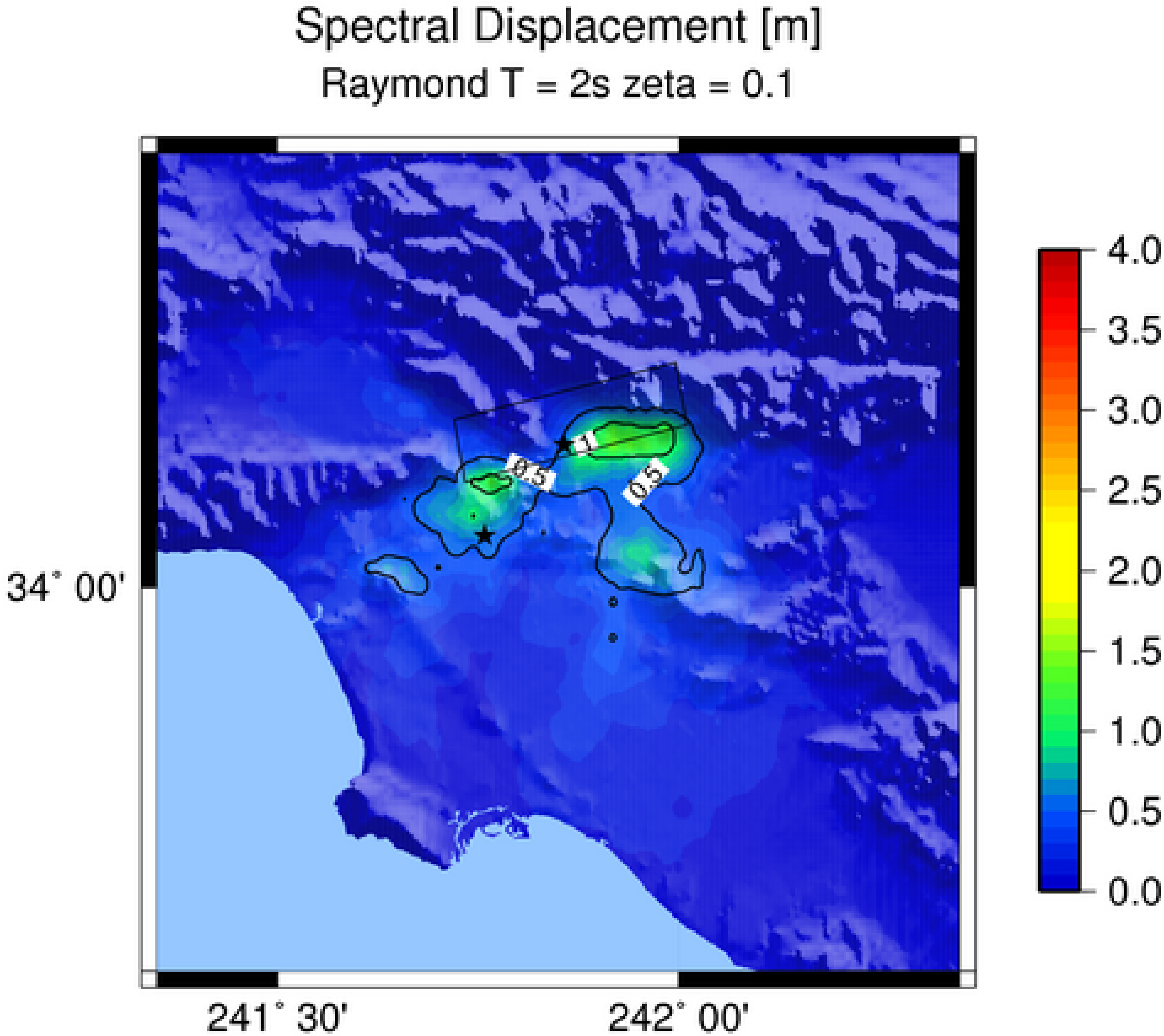
Spectral Displacement [m]
Puente Hills (All) T = 2s zeta = 0.1
34˚ 00'
241˚ 30'
242˚ 00'
0.5
0.5
0.5
1
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0


Spectral Displacement [m]
Puente Hills (All) T = 3s zeta = 0.1
0.5
0.5
1
1.5
1
0.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
34˚ 00'
241˚ 30'
242˚ 00'

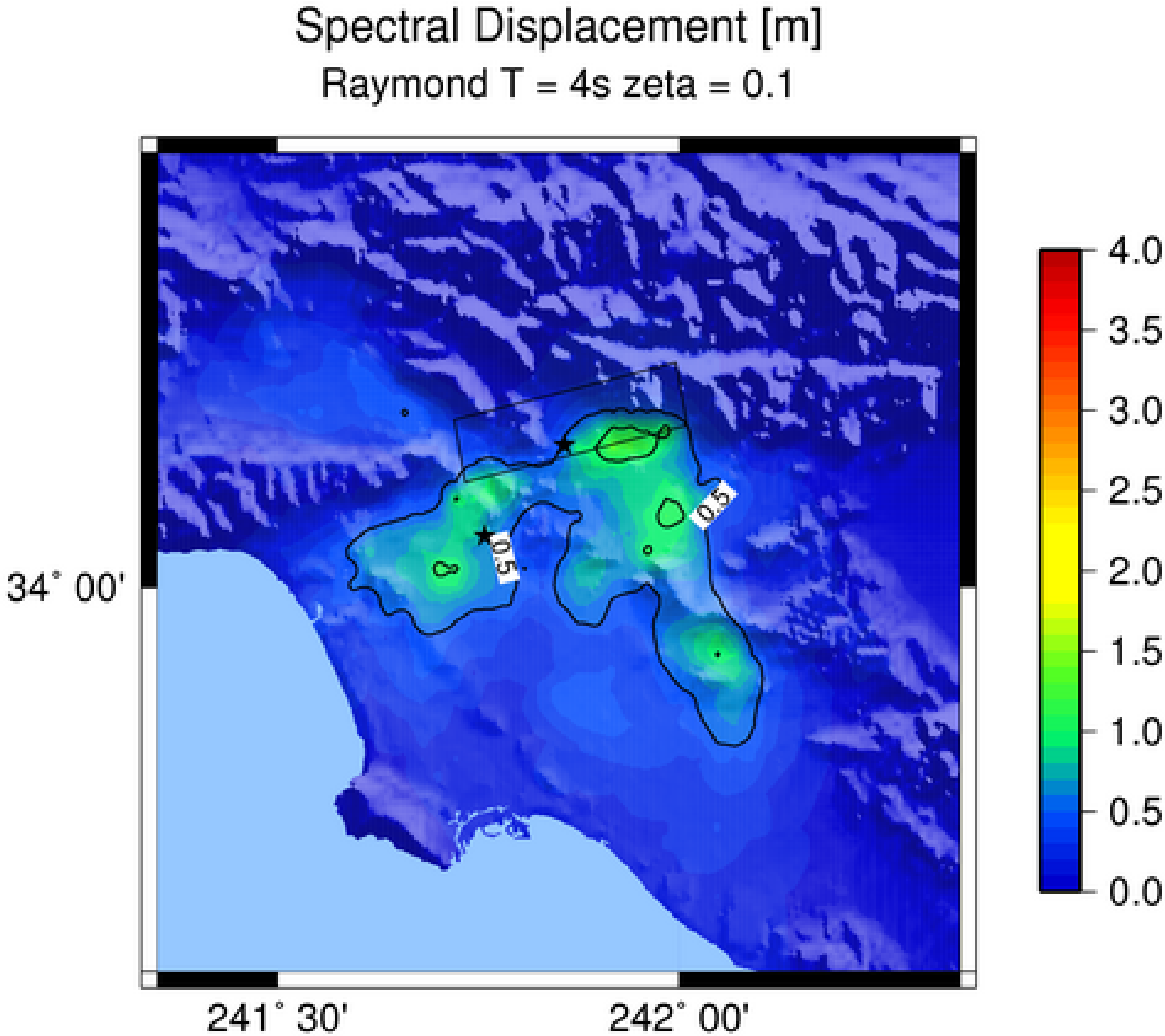


Spectral Displacement [m]
Puente Hills (All) T = 4s zeta = 0.1
0.5
0.5
0.5
0.5
1
1
1.5
1.5
2
34˚ 00'
241˚ 30'
242˚ 00'
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0


Spectral Displacement [m]
Raymond T = 3s zeta = 0.1
0.5
1
0.5
0.5
34˚ 00'
241˚ 30'
242˚ 00'
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0



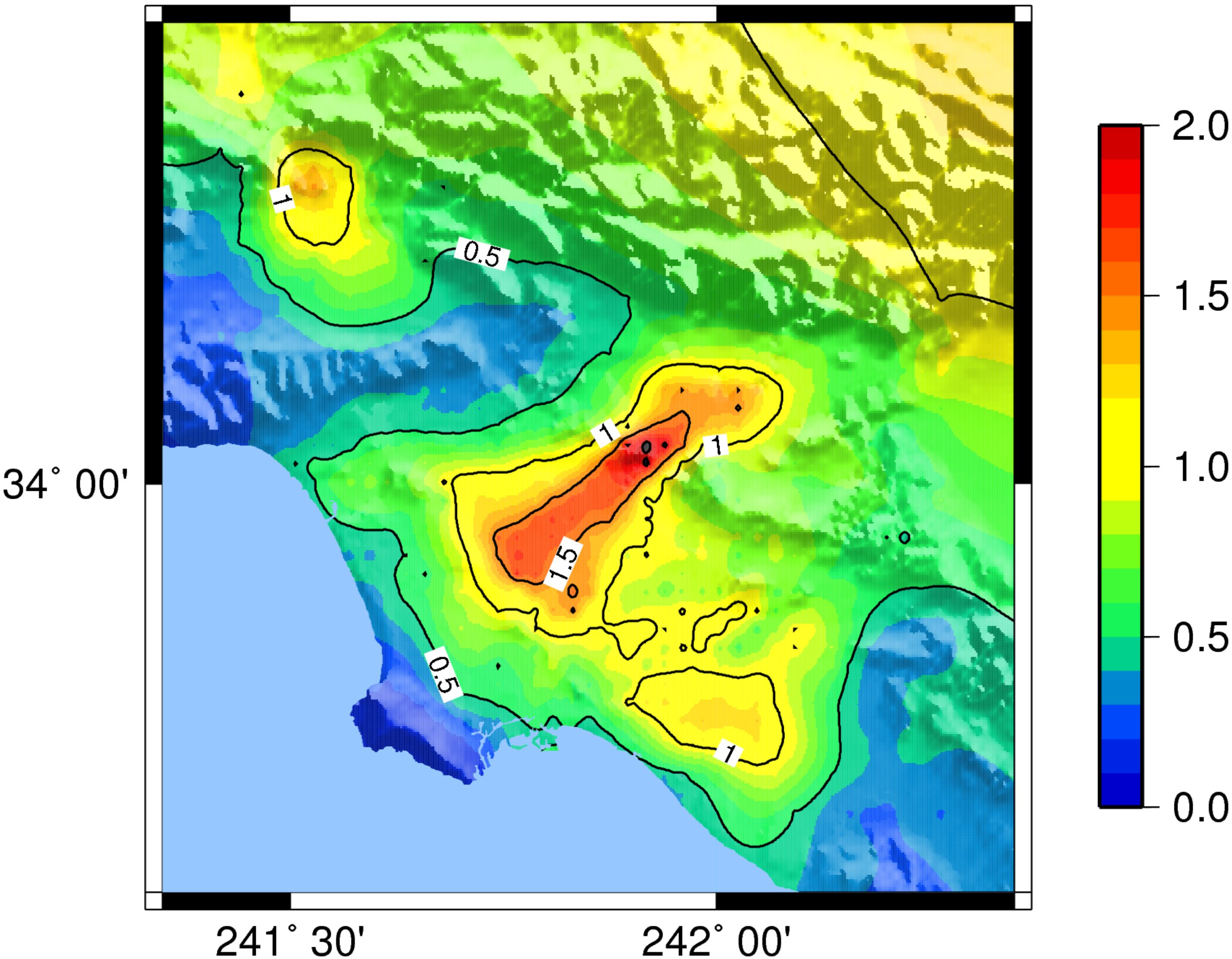
Spectral Displacement [m]
Raymond T = 2s zeta = 0.1
0.5
0.5
1
34° 00'
241° 30'
242° 00'
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0



Spectral Displacement [m]
Raymond T = 4s zeta = 0.1
34˚ 00'
241˚ 30'
242˚ 00'
0.5
0.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0

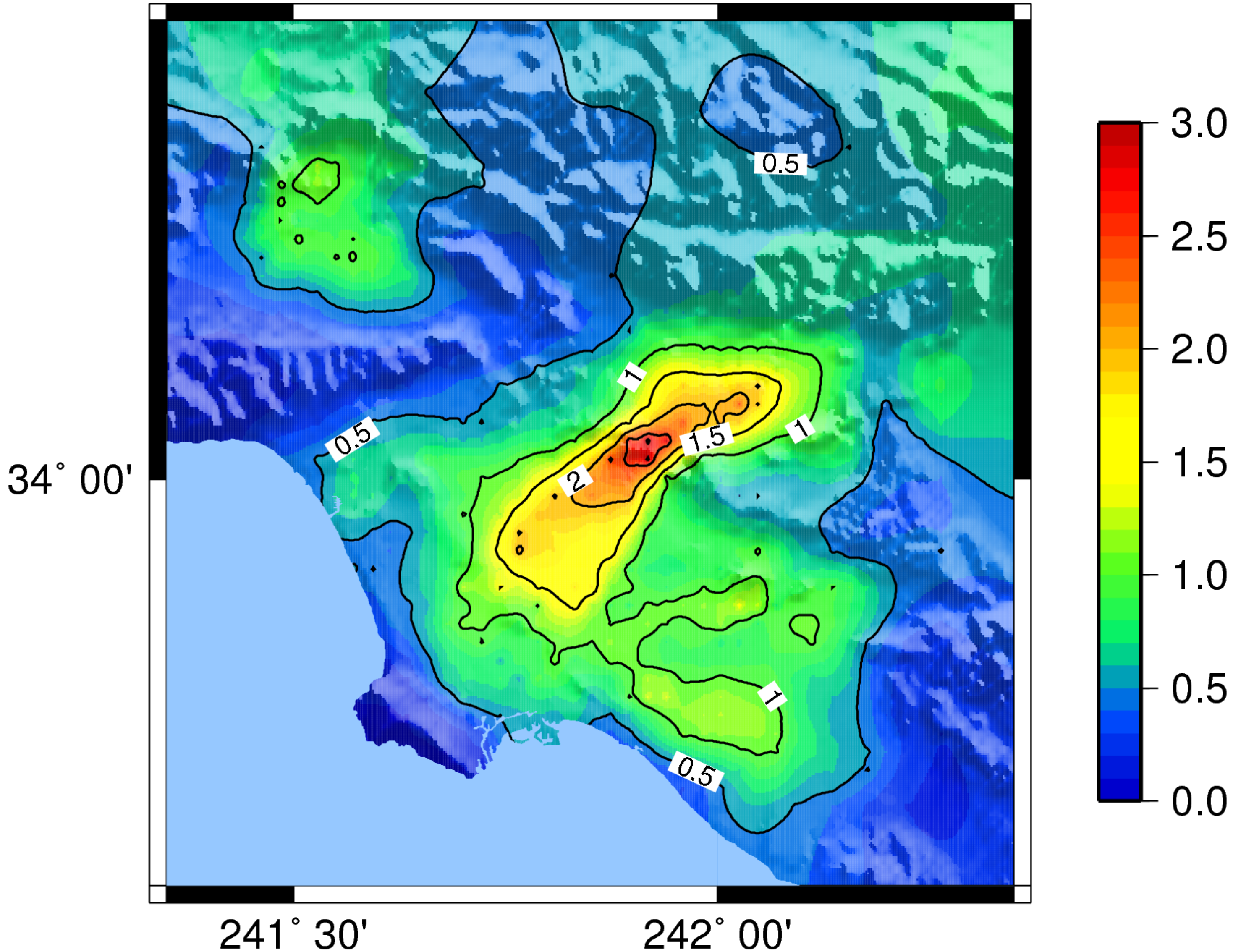
Peak Ground Displacements [m]

TeraShake 1.2



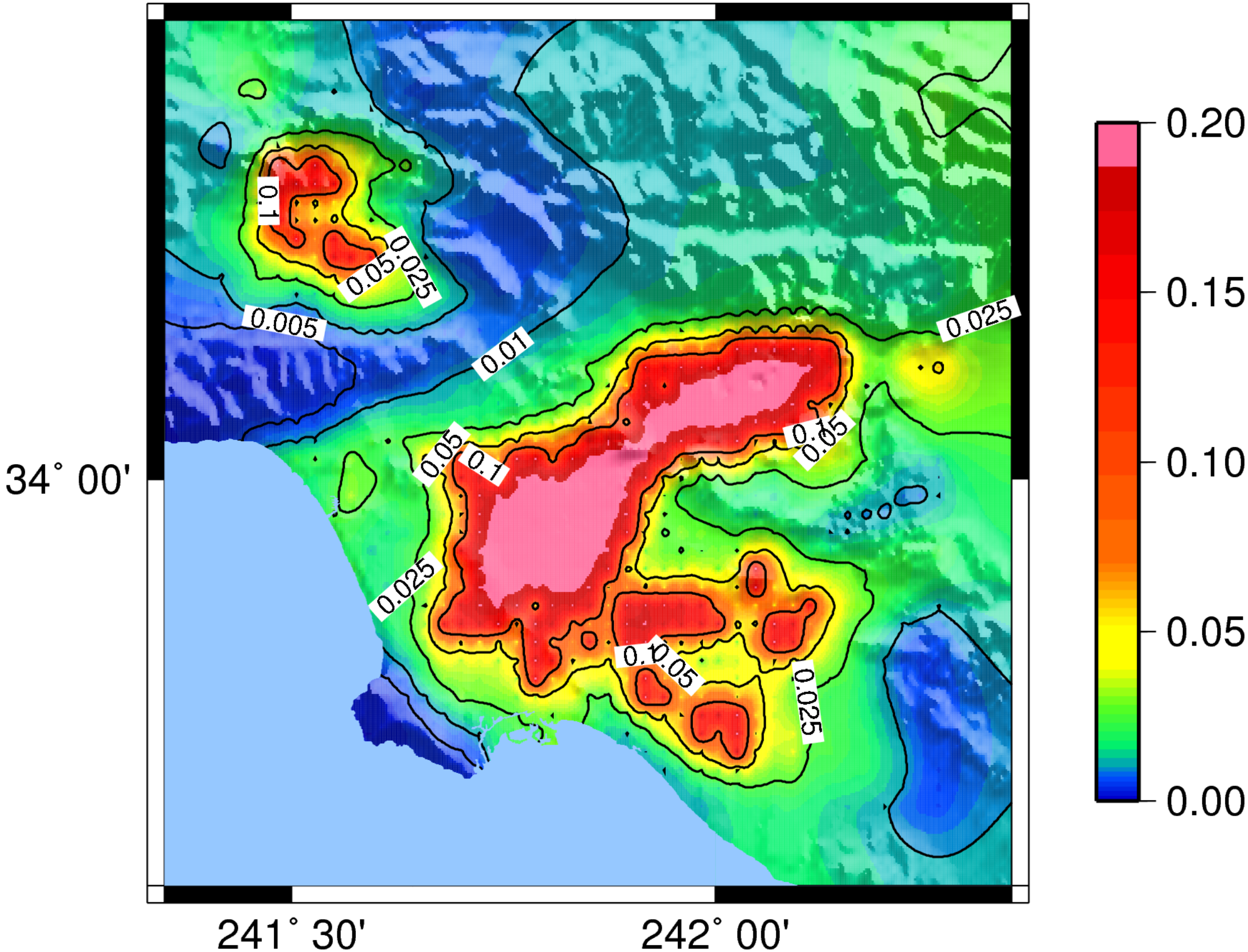
Peak Ground Velocities [m/s]

TeraShake 1.2



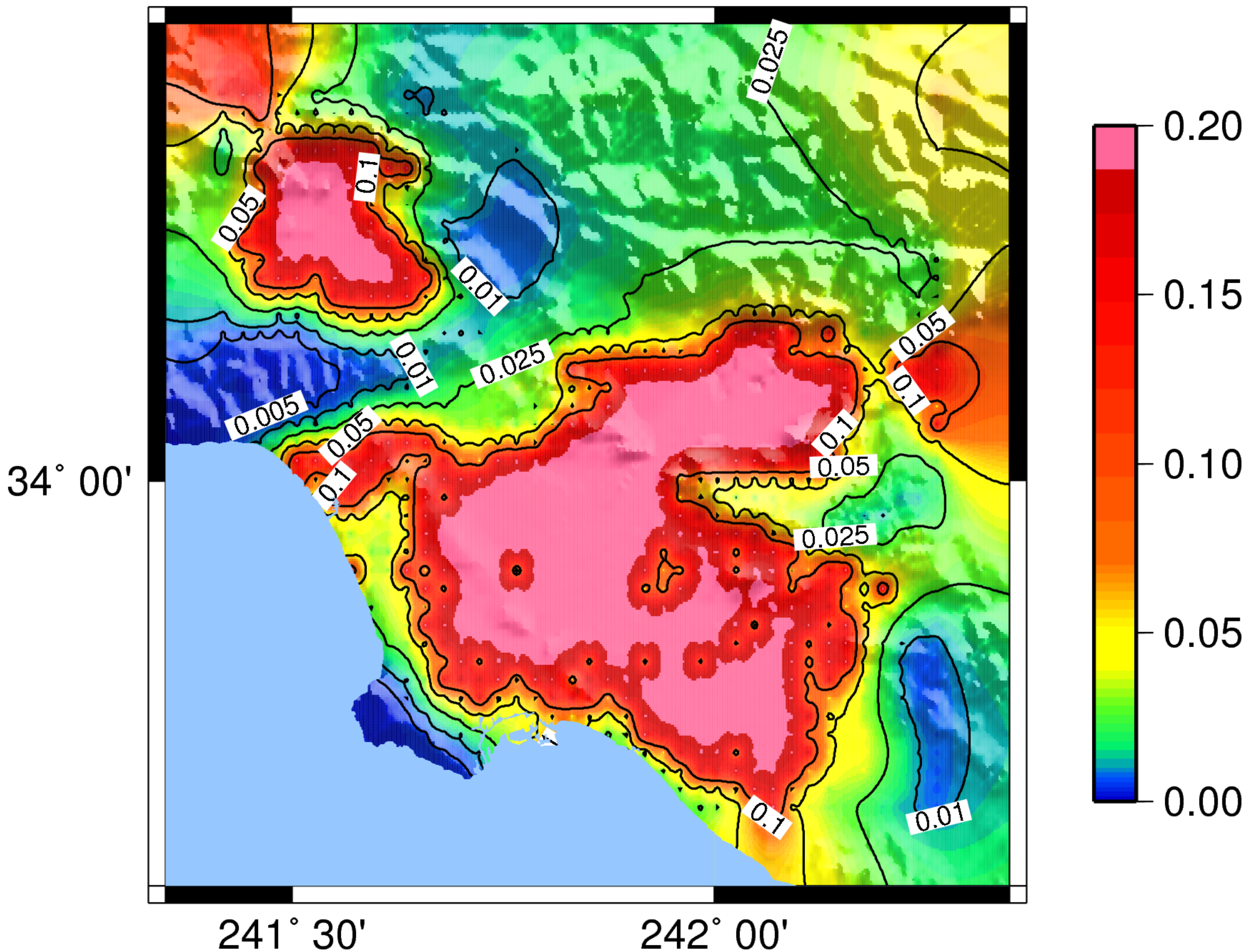
Peak Inter-Story Dynamic Drift Ratio

TeraShake 1.2 20-Stories with Good Welds



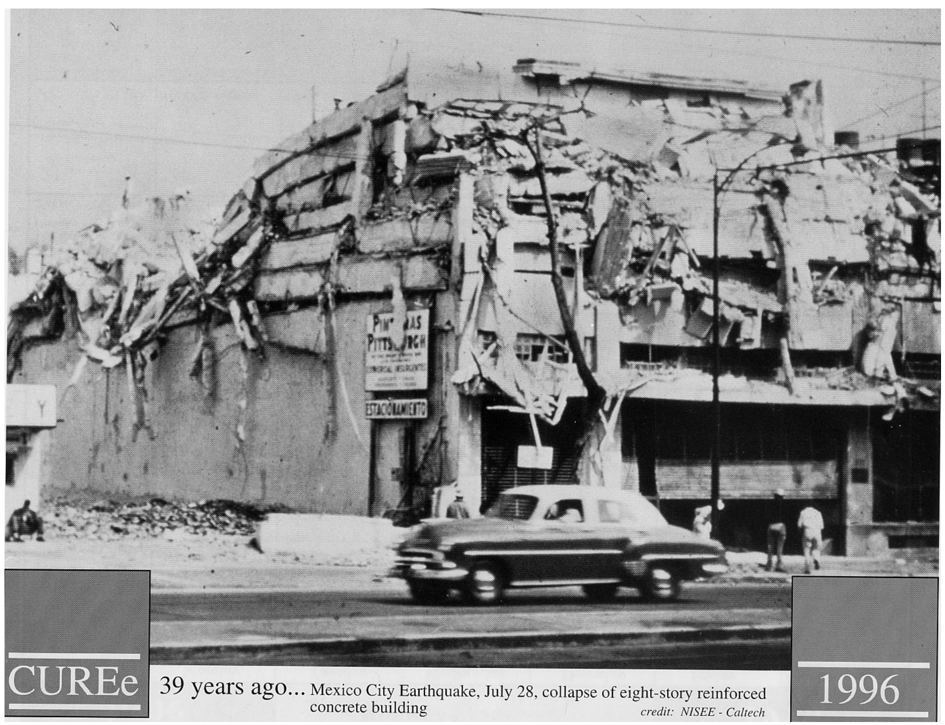
Peak Inter-Story Dynamic Drift Ratio

TeraShake 1.2 20-Stories with Brittle Welds

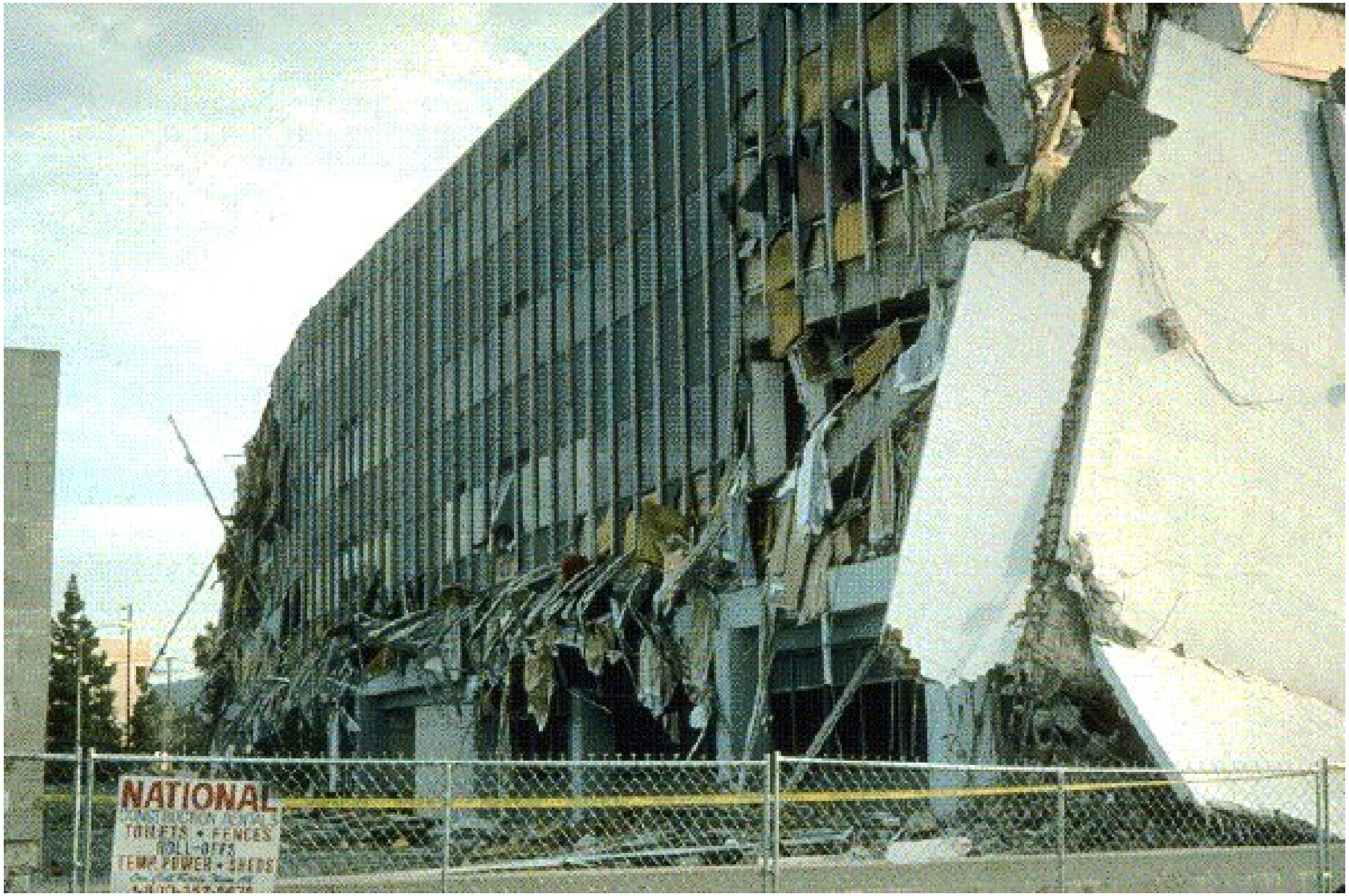


A special problem with non-ductile concrete frame buildings

- These are generally flexible buildings that have low yield strength and low ductility.
- Drifts of only 0.5% can result in collapse.
- In the U.S. most are pre 1975, but Turkey has many of these buildings.

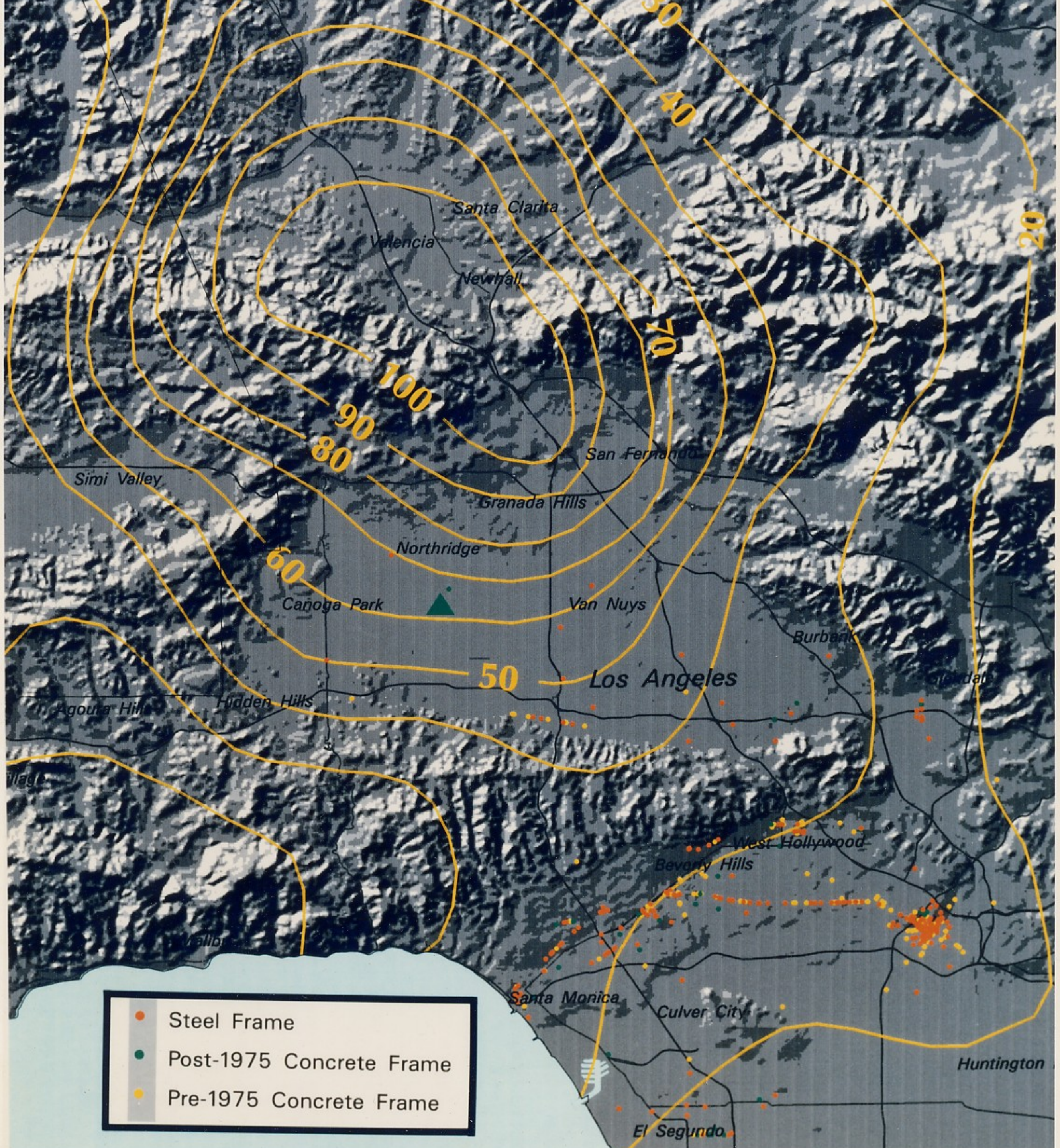


39 years ago... Mexico City Earthquake, July 28, collapse of eight-story reinforced concrete building



One of the great disappointments is that there has been little progress in the retrofitting of "nonductile" concrete frame buildings. Most people who live or work in them are not aware of the serious risk involved.

Example of “ductile” behavior of concrete columns. Although the parking structure performed poorly, the exterior columns did not fail.


30
40
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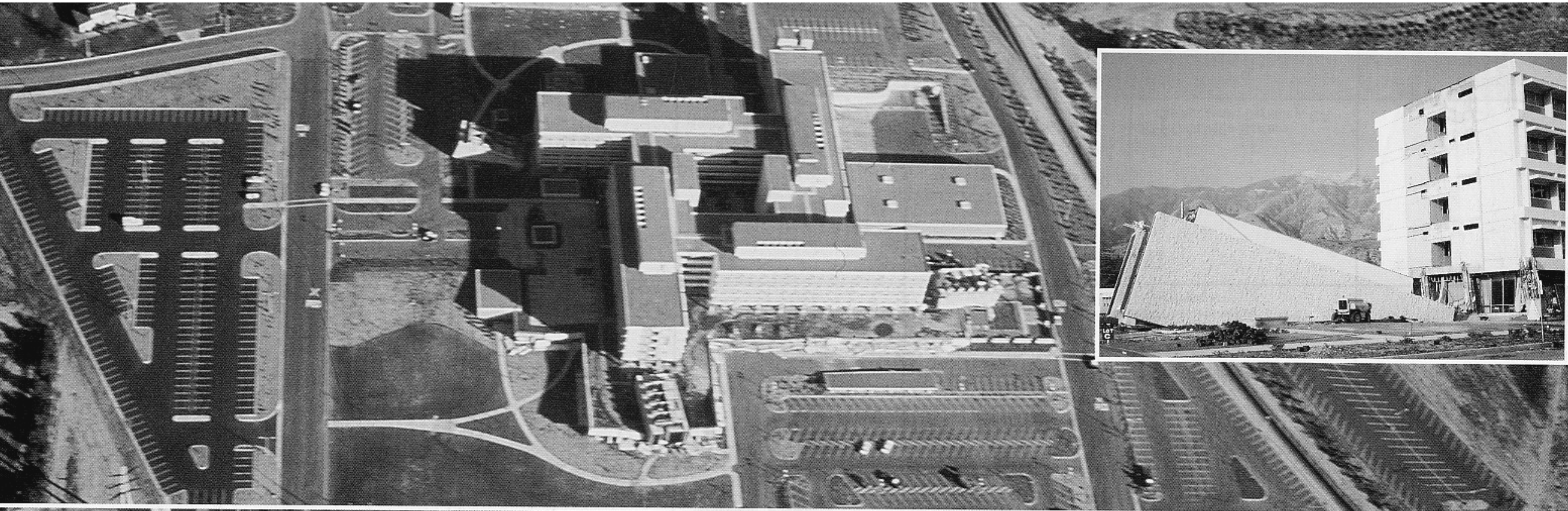
Santa Clarita
Valencia
Newhall
San Fernando
Simi Valley
Granada Hills
Northridge
Canoga Park
Van Nuys
Burbank
Los Angeles
Hidden Hills
West Hollywood
Beverly Hills
Santa Monica
Culver City
Huntington
El Segundo
Steel Frame
Post-1975 Concrete Frame
Pre-1975 Concrete Frame



CUREe

26 years ago...(Top) San Fernando Earthquake, February 9, severely damaged and later demolished Olive View Hospital, *photo credit Lloyd Cluff*. (Top inset) collapsed stair tower, *photo credit George Housner, NISEE-Caltech*. (Bottom) excellent structural performance of replacement Olive View Hospital after 1994 Northridge Earthquake, *photo credit Lloyd Cluff.*

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Have we broken the Power Law?

- If power law catastrophes occur because we make systematic errors in our designs ("we were surprised," "just how many unknown faults are there in LA?"), then I suspect that we have **not** broken the power law.
- Should we be doing something different?

Are We Addressing the Right Questions in Earthquake Engineering?

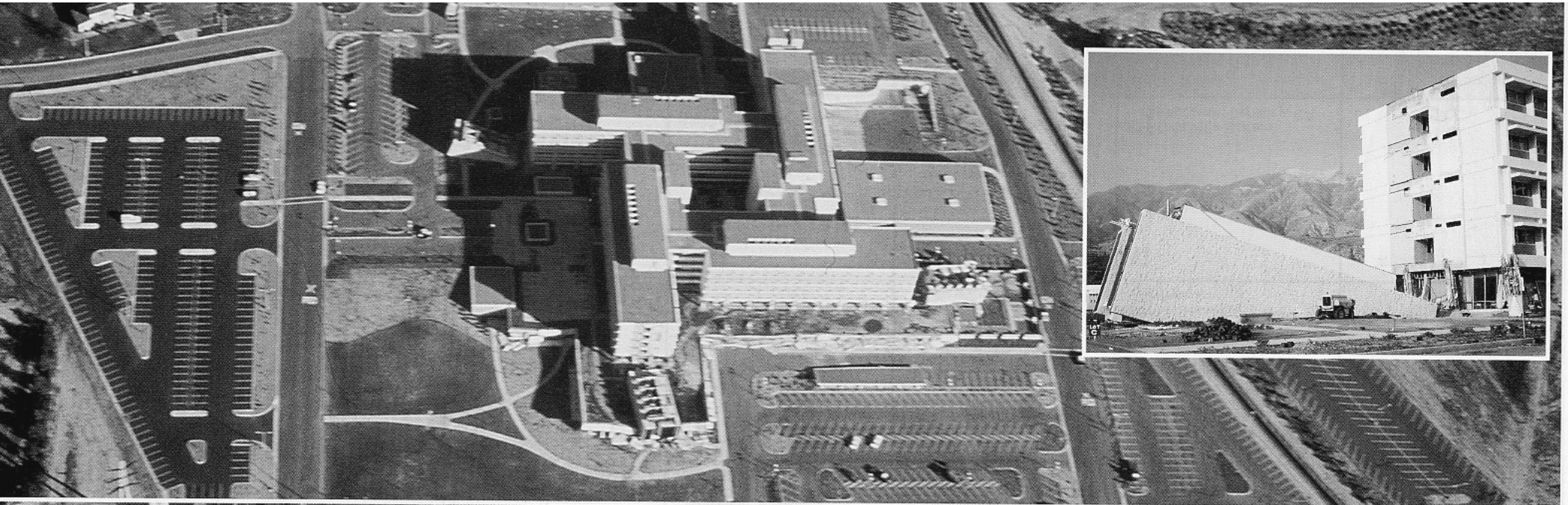
- Current methodology assumes 1) architecture and 2)seismic hazard.
- Very simplified assumptions about nonlinear building response (ductility factors) are used to produce a design.
- “collapse mechanisms” are rarely defined.
- Earth scientists are almost never asked if it is possible that the site will experience motions that can trigger the collapse mechanisms.

Designing for the Known

- Architect chooses the geometry of a design
- Define probability of forces that design will be subjected to
- Determine the size of elements that will satisfy statistical limits

Designing for the Unknown

- Determine the functional requirements of a structure
- Consider several geometries of the structure (different architectures)
- Determine the cost of different designs
- Assess the strengths and weaknesses of different designs
- Choose the design that is most robust



CUREe

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Conclusions

- Current probabilistic hazard analysis may seriously underestimate the importance of large earthquakes.
- Flexible buildings that rely on high ductility will be damaged beyond repair in large earthquakes and many may collapse.
- Base isolation systems may be overdriven by large near-source ground motions.
- High-rise buildings in Seattle, Vancouver, and Portland have been designed without any understanding of the shaking in giant Cascadia earthquakes.
- Strong shear-wall construction is best suited to resist large-magnitude earthquakes.
- Earth scientists should ask earthquake engineers to provide examples of ground motions that will cause collapse of a particular design.
- **Choose a design that is least vulnerable to our uncertainties!**