Has Earthquake Engineering Broken the Power Law?

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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?

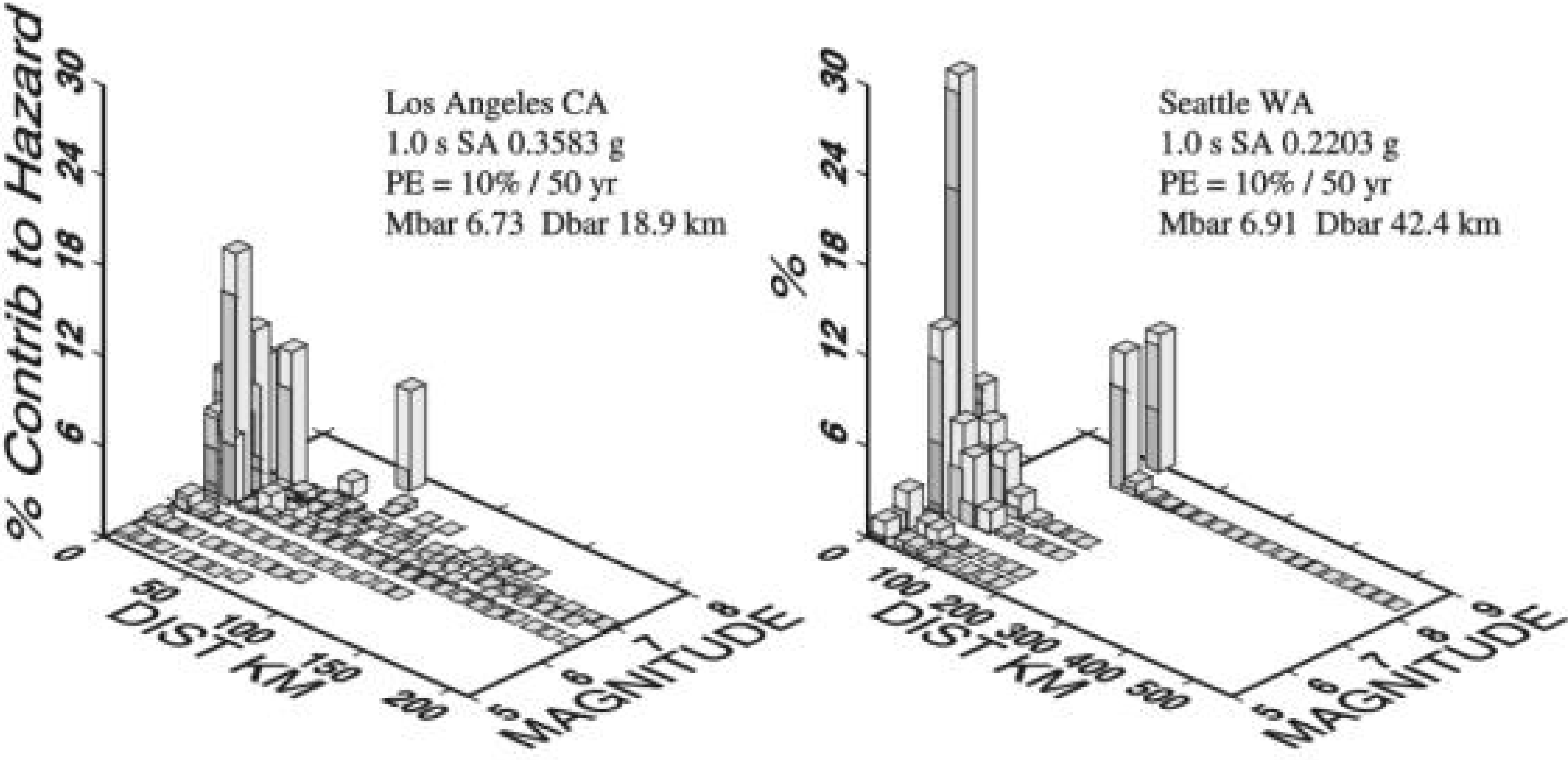
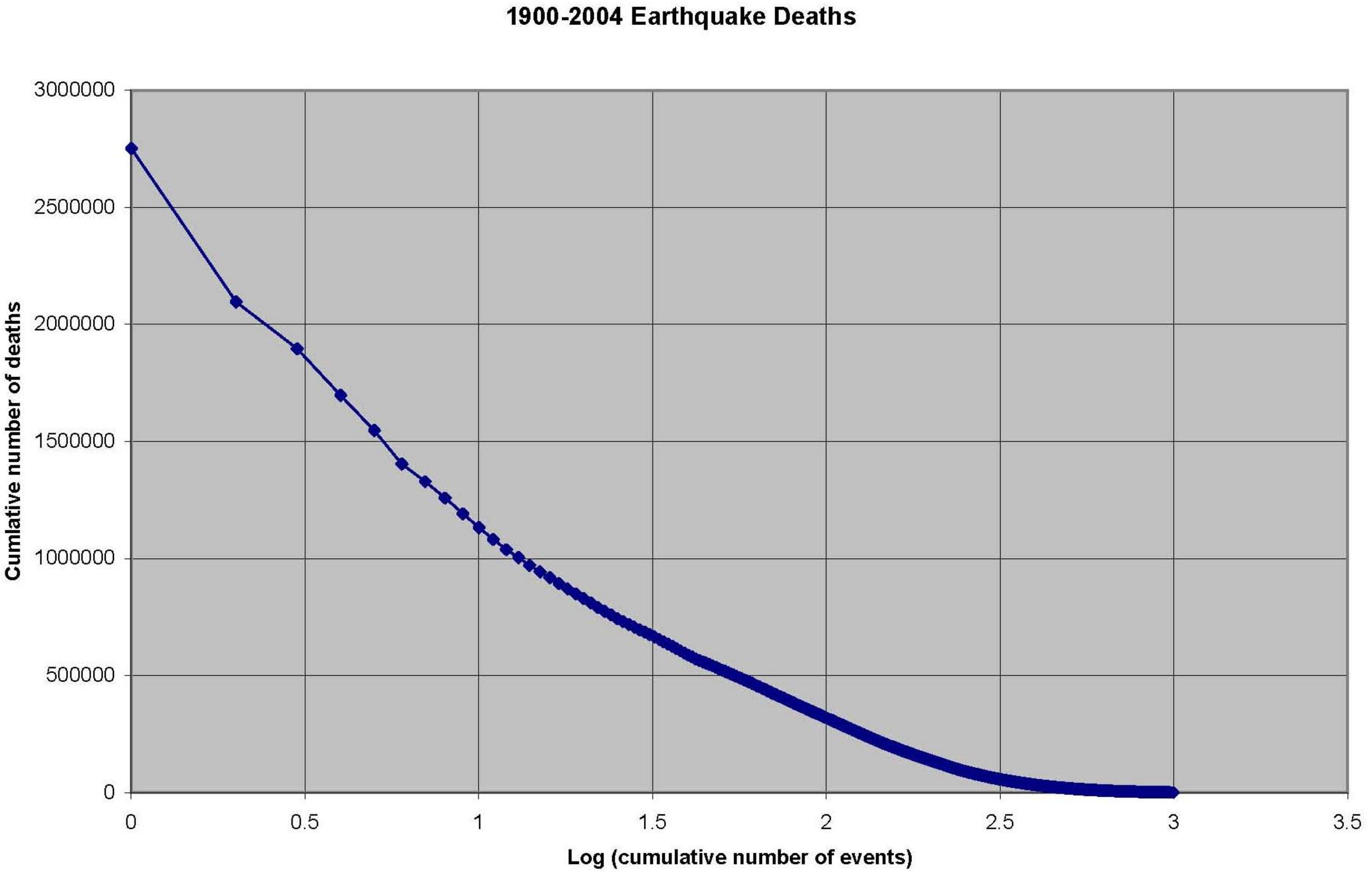
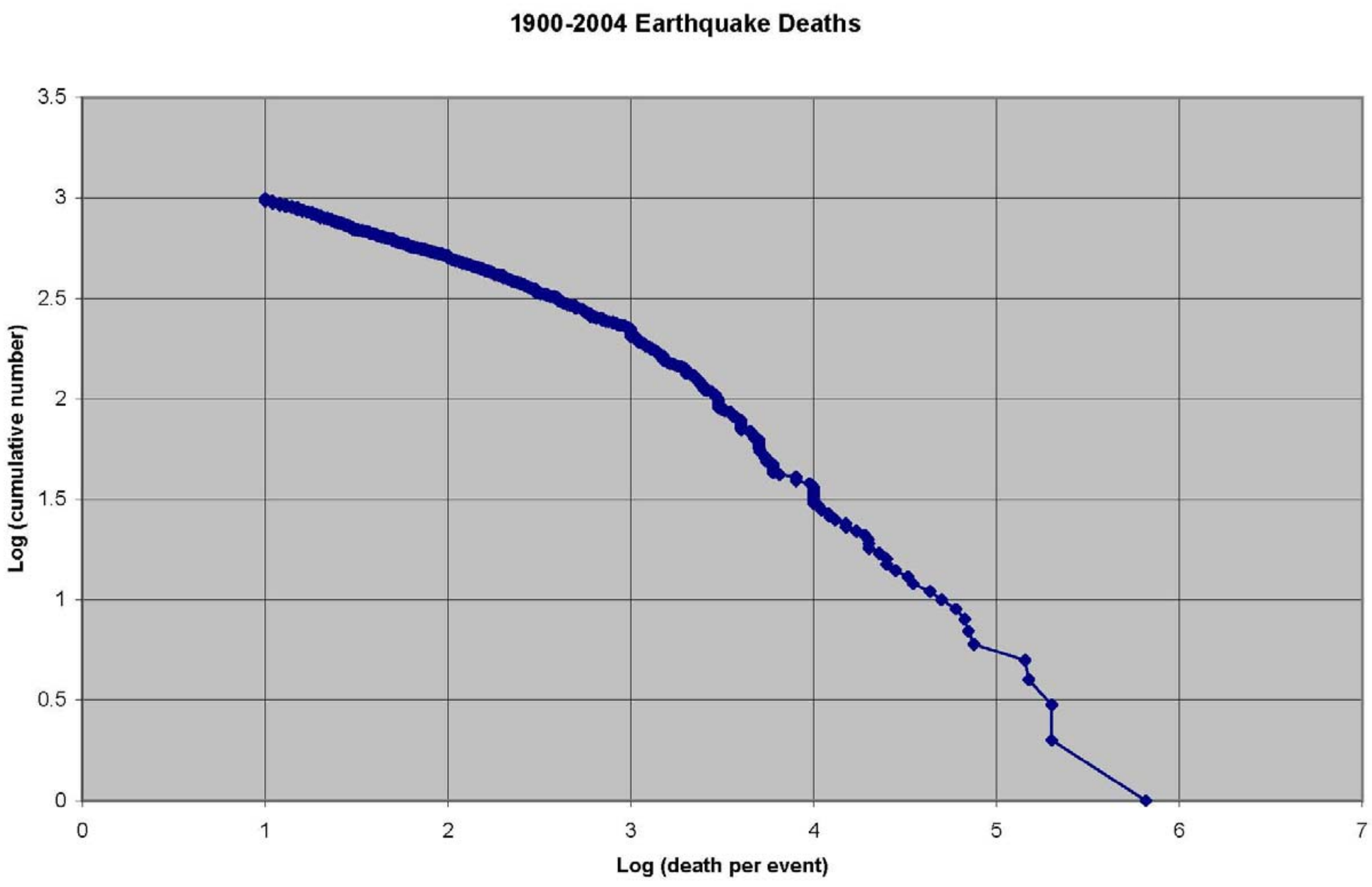


Figure 4.4: Deaggregation plots for Los Angeles and Seattle

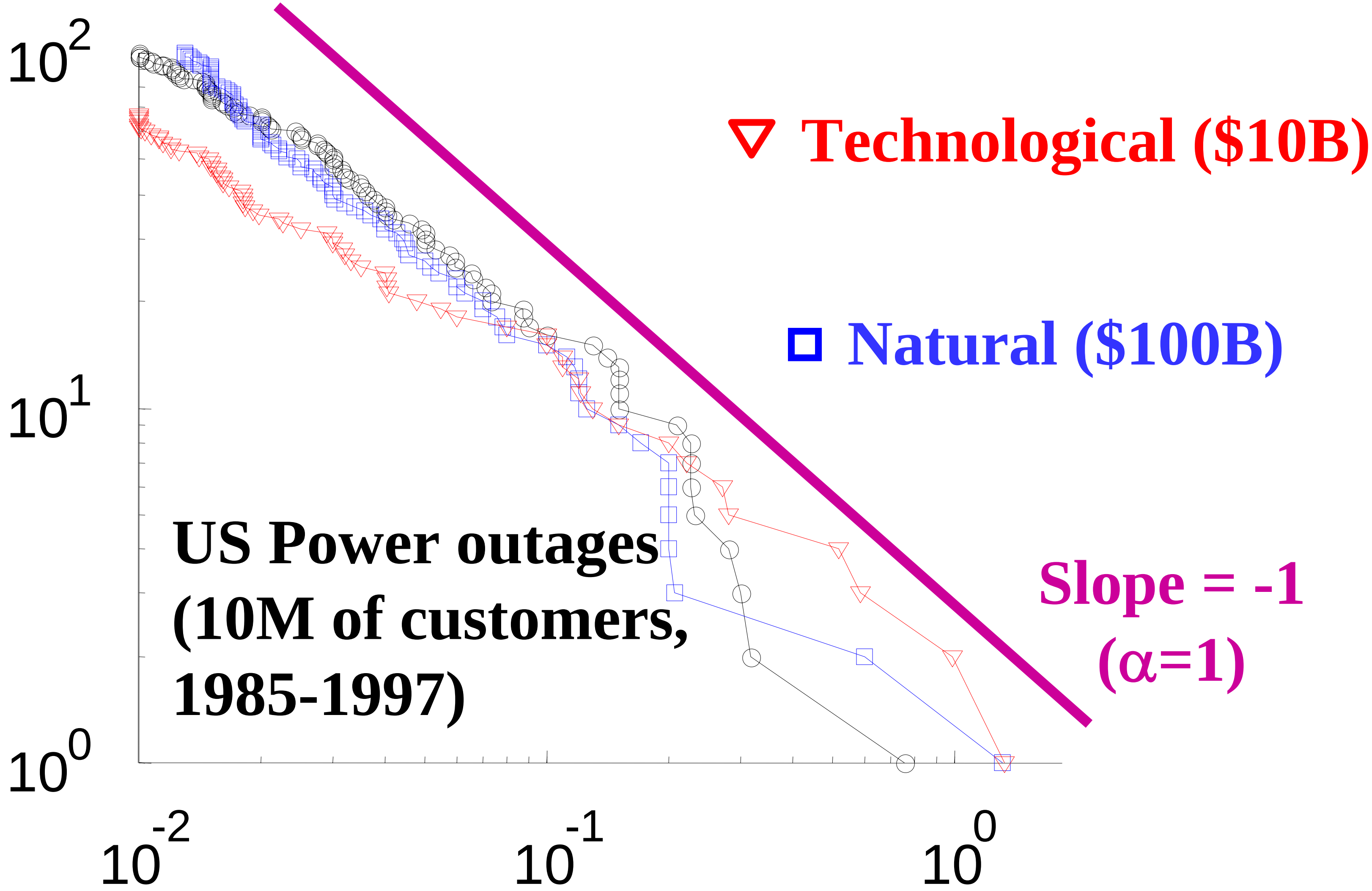


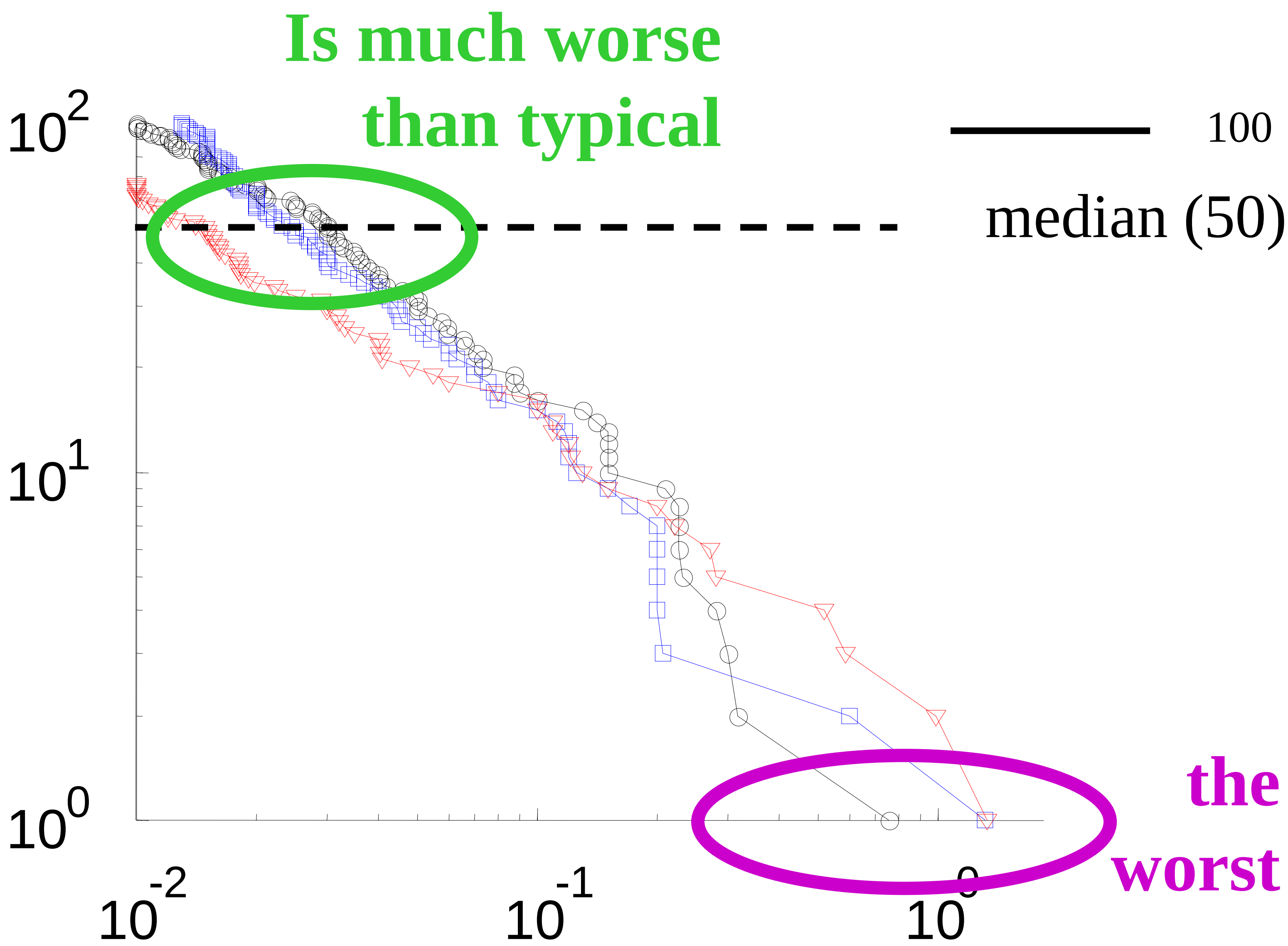
½ of the deaths occurred in the 7 deadliest earthquakes



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

20th Century's 100 largest disasters worldwide





Is much worse
than typical
100
median (50)
the
worst
10^2
10^1
10^0
10^{-2}
10^{-1}
10^0

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?

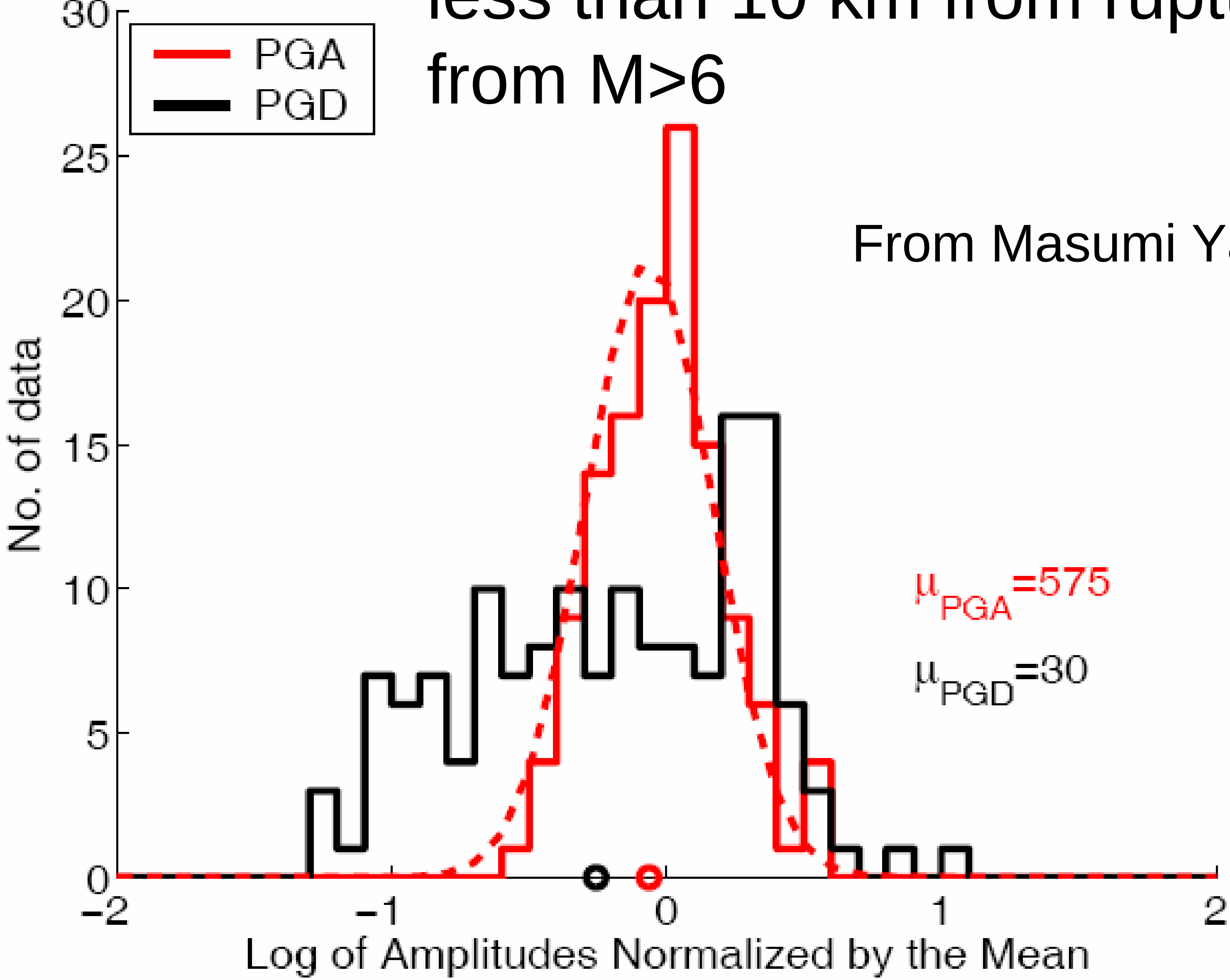
- People live in spatial clusters (cities)
- The prevailing practice was inappropriate for the coming earthquake
- If people had known the consequences of their misjudgment, they would have done things differently
- Because of the tremendous loss, they "fixed" the problem with building codes

Current Building Code

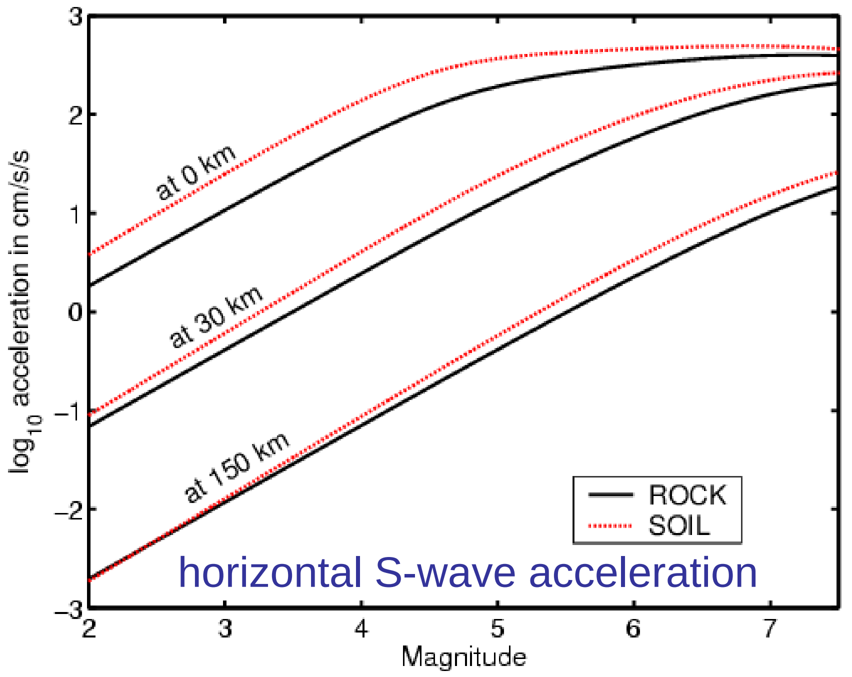
- Current building codes are mostly prescriptive rules based on the building type and seismic zone.
- Codes have been developed by fixing deficiencies from past earthquakes.
- If you’ve got a good building code, who needs a seismologist?
- If the least frequent events pose the greatest risk, we may not have “learned the lessons yet.

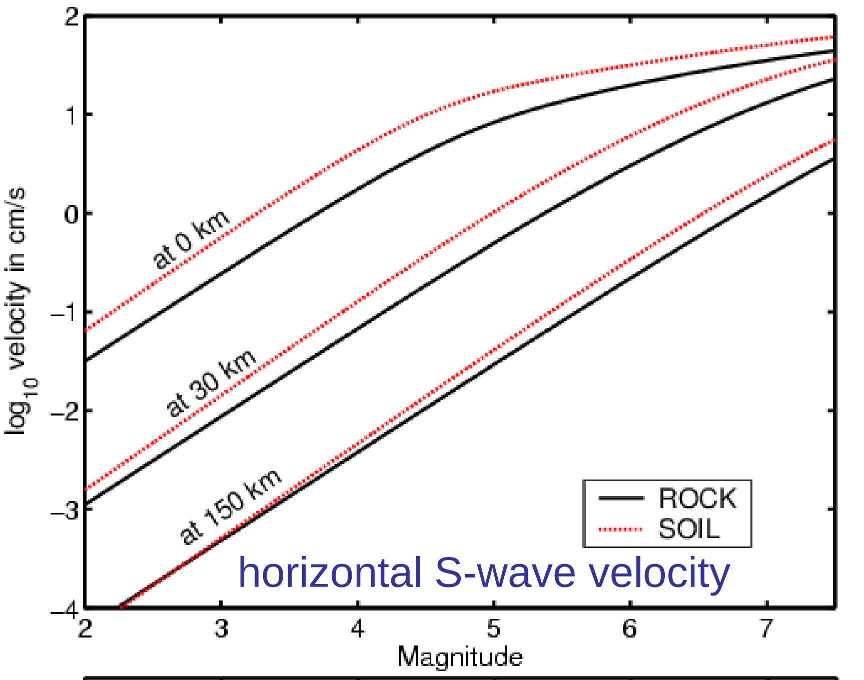
All strong motions recorded at less than 10 km from rupture from M>6

From Masumi Yamada

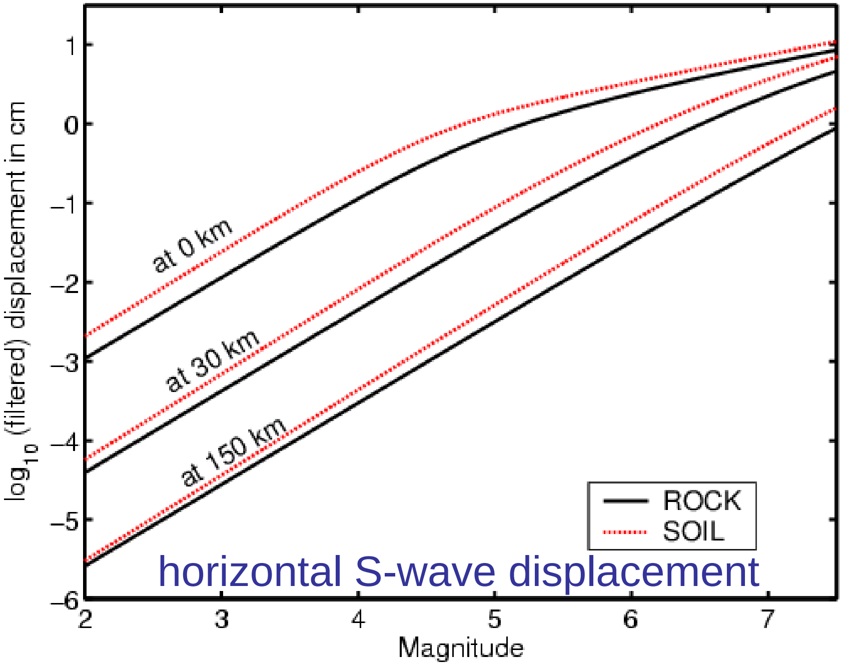


Magnitude-dependent saturation of rock and soil sites (S-waves)





- 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



From Georgia Cua

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

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 $\dfrac{\varepsilon_F}{\varepsilon_y} = 1$ for 40%

=10 for 30%

=100 for 30%

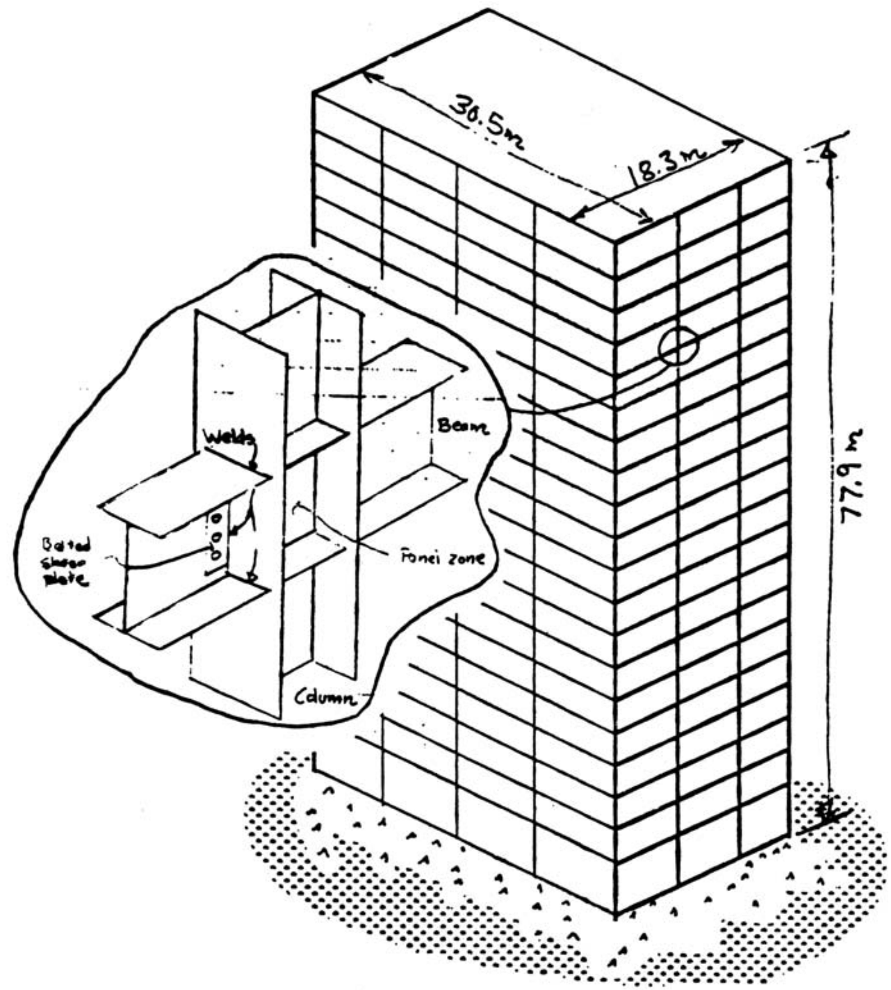
bottom flange $\dfrac{\varepsilon_F}{\varepsilon_y} = 0.7$ for 20%

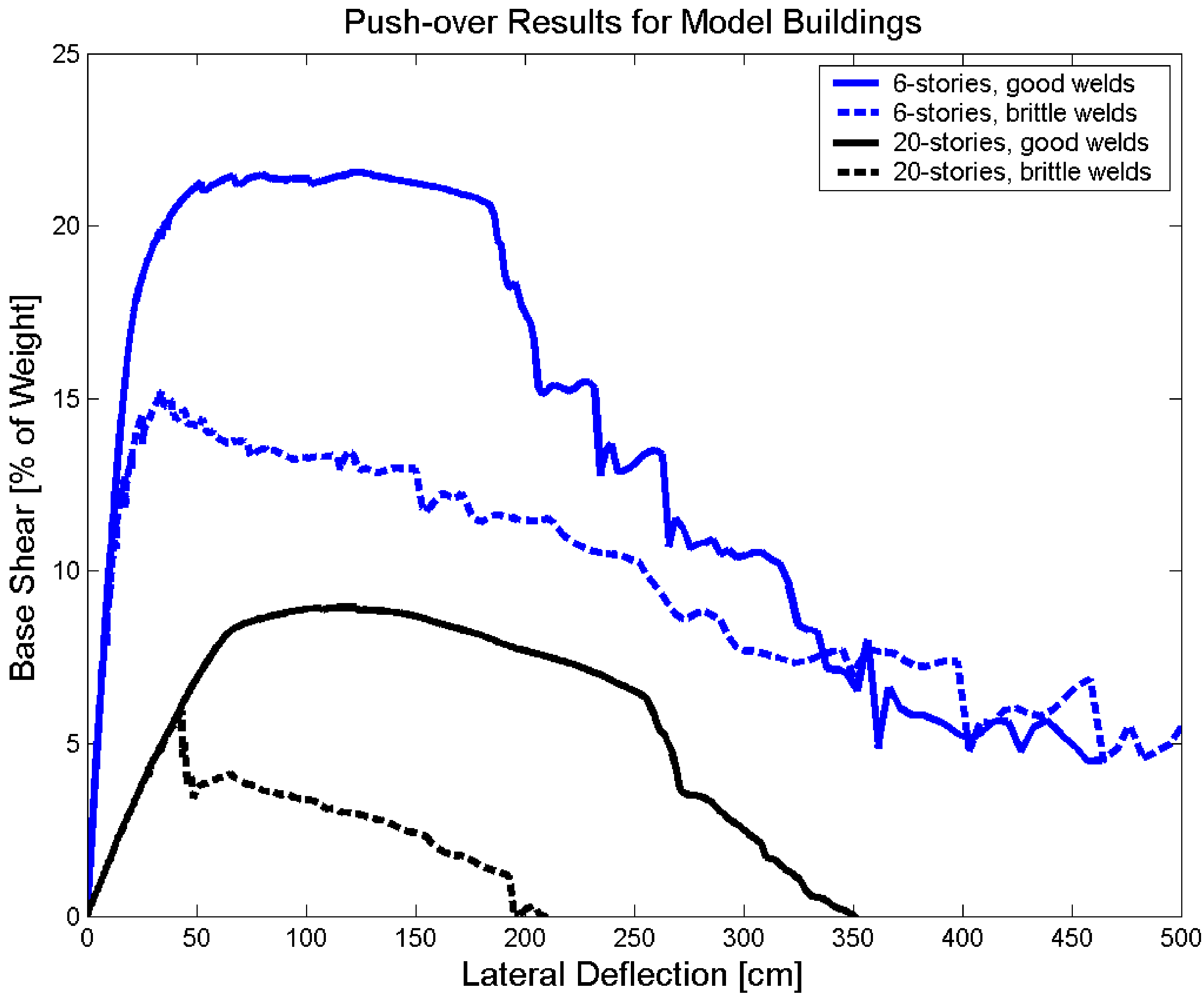
=1 for 40%

=10 for 20%

=50 for 10%

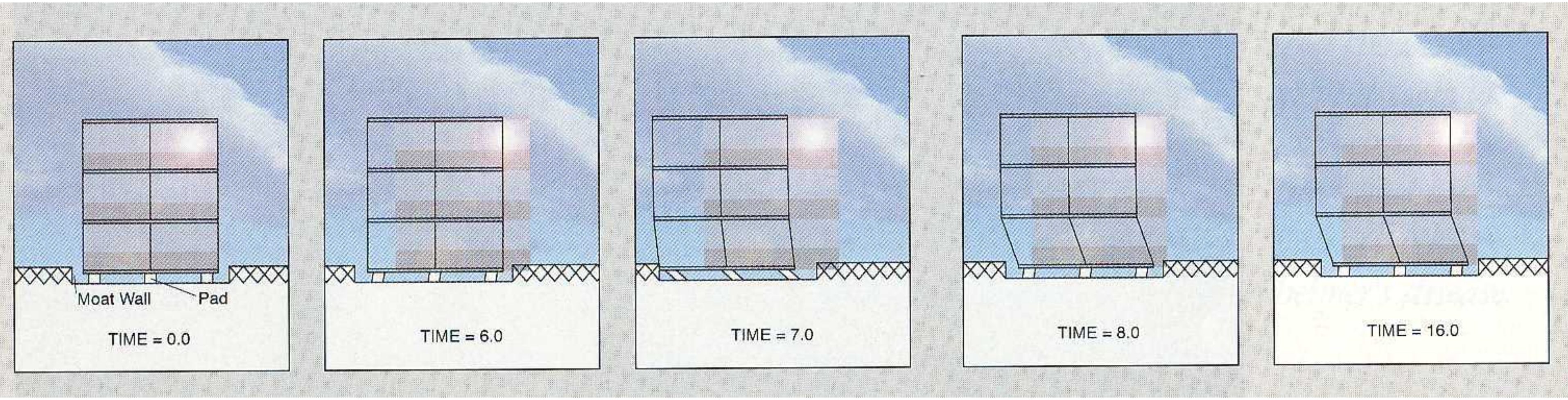
=100 for 10%



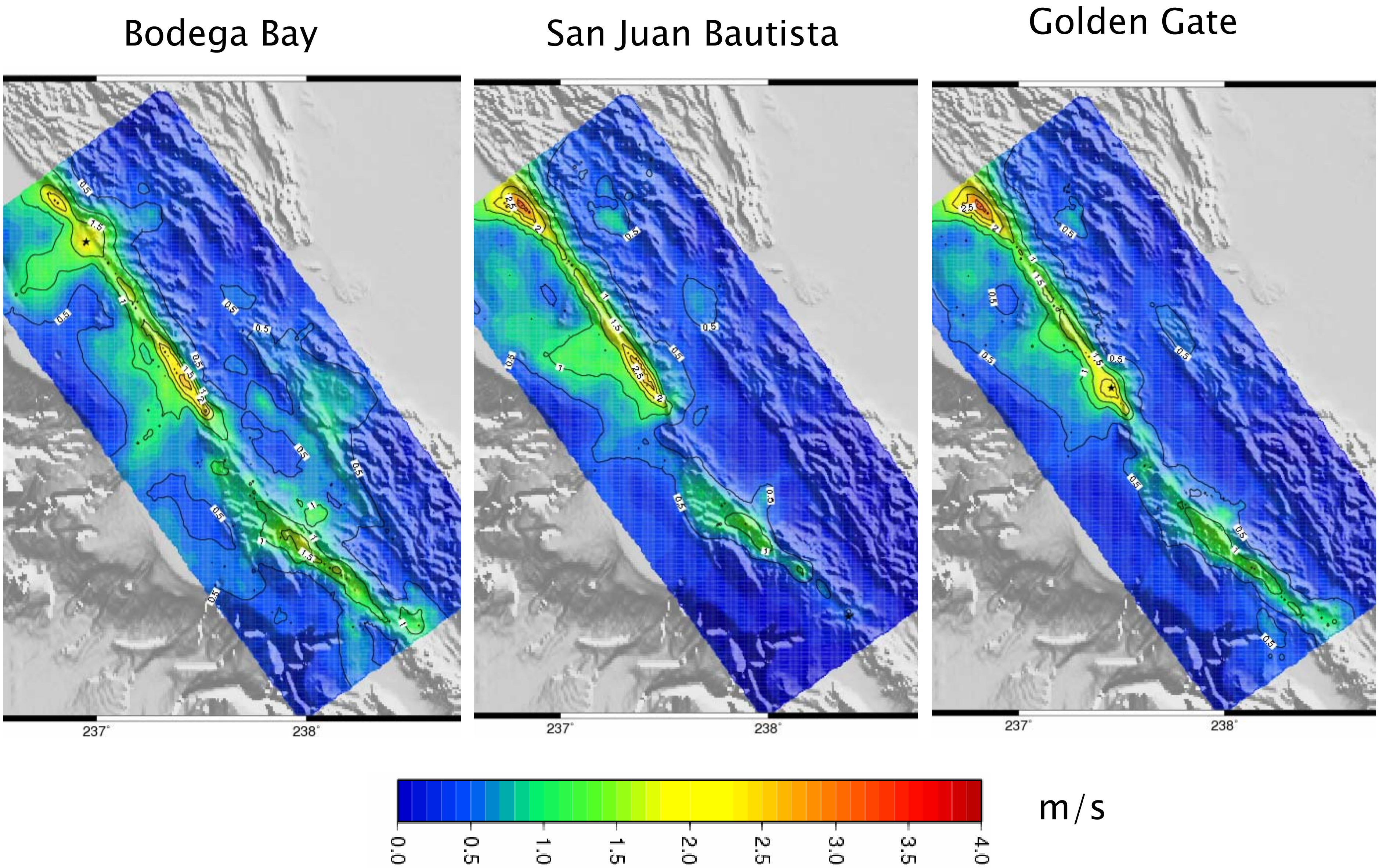

Push-over Results for Model Buildings
6-stories, good welds
6-stories, brittle welds
20-stories, good welds
20-stories, brittle welds
Base Shear [% of Weight]
Lateral Deflection [cm]
0
5
10
15
20
25
0
50
100
150
200
250
300
350
400
450
500

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



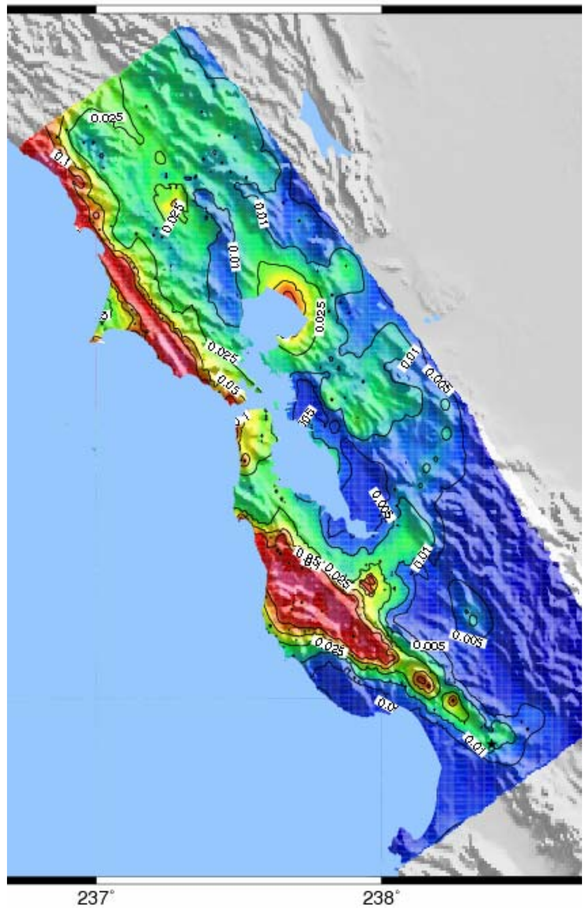
Peak Ground Velocities



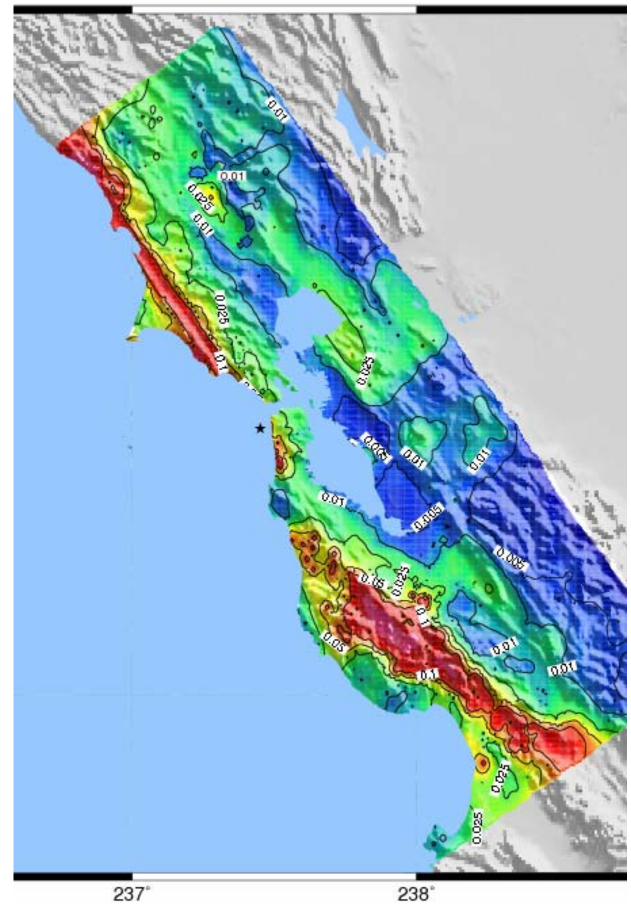
20-story brittle welds peak drift

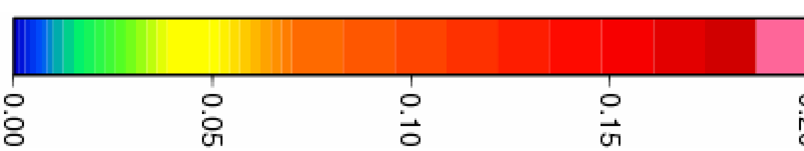
Bodega Bay

San Juan Bautista

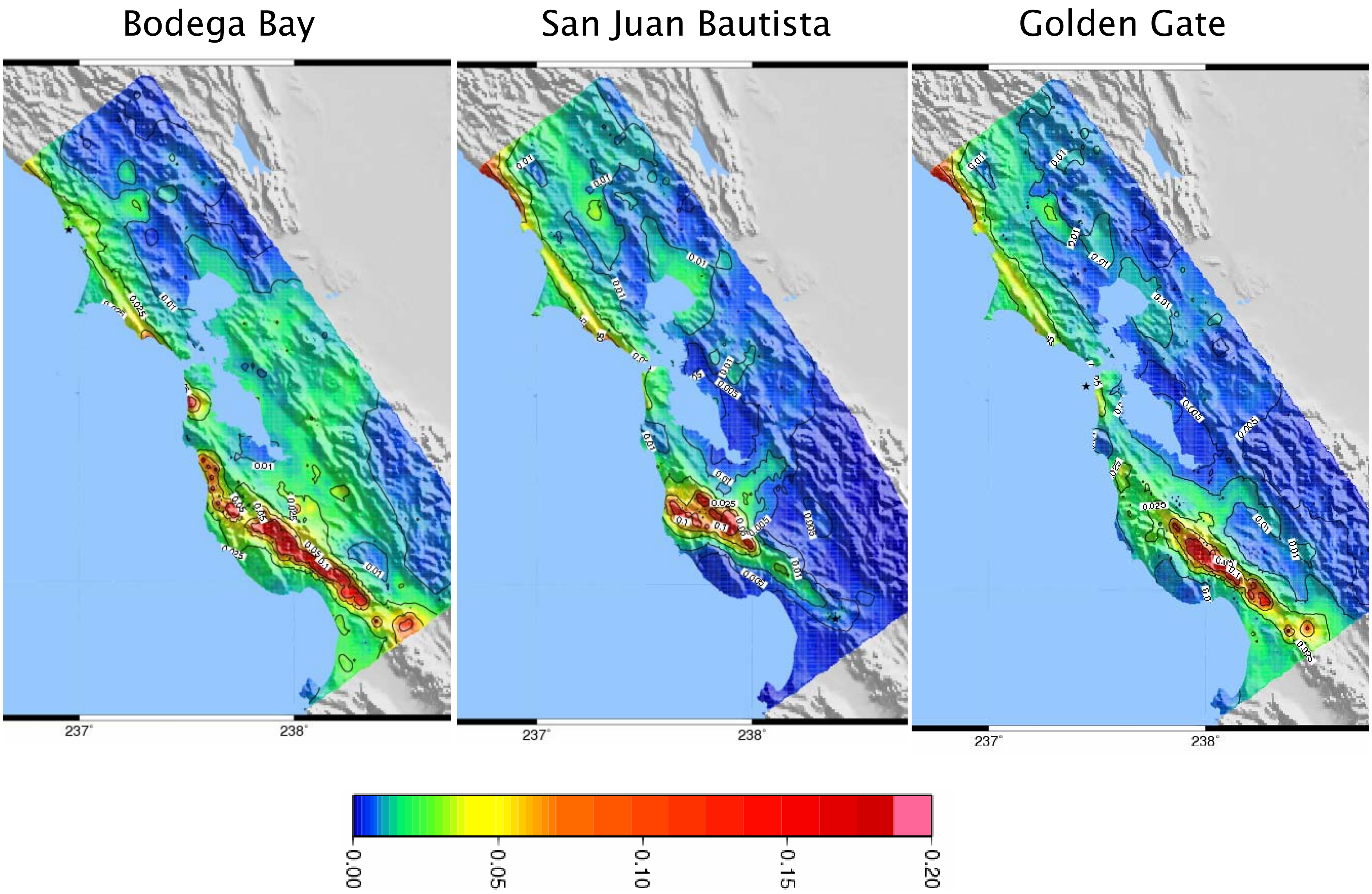


Golden Gate



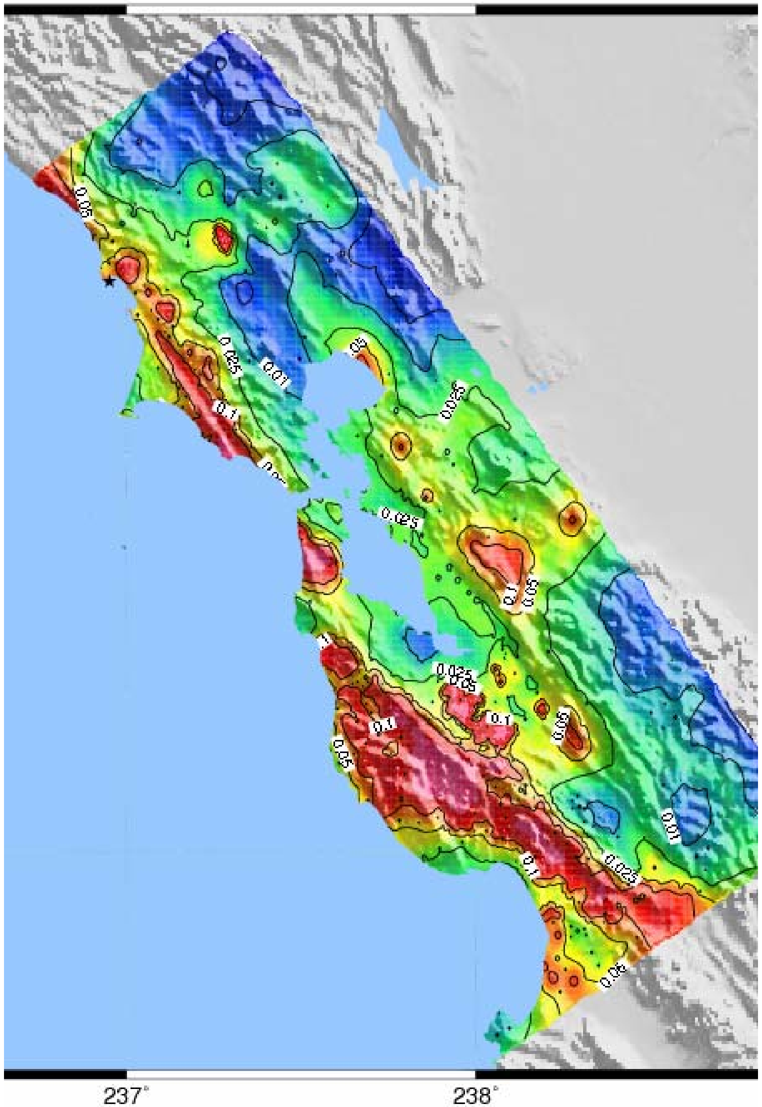


20-story perfect welds peak drift

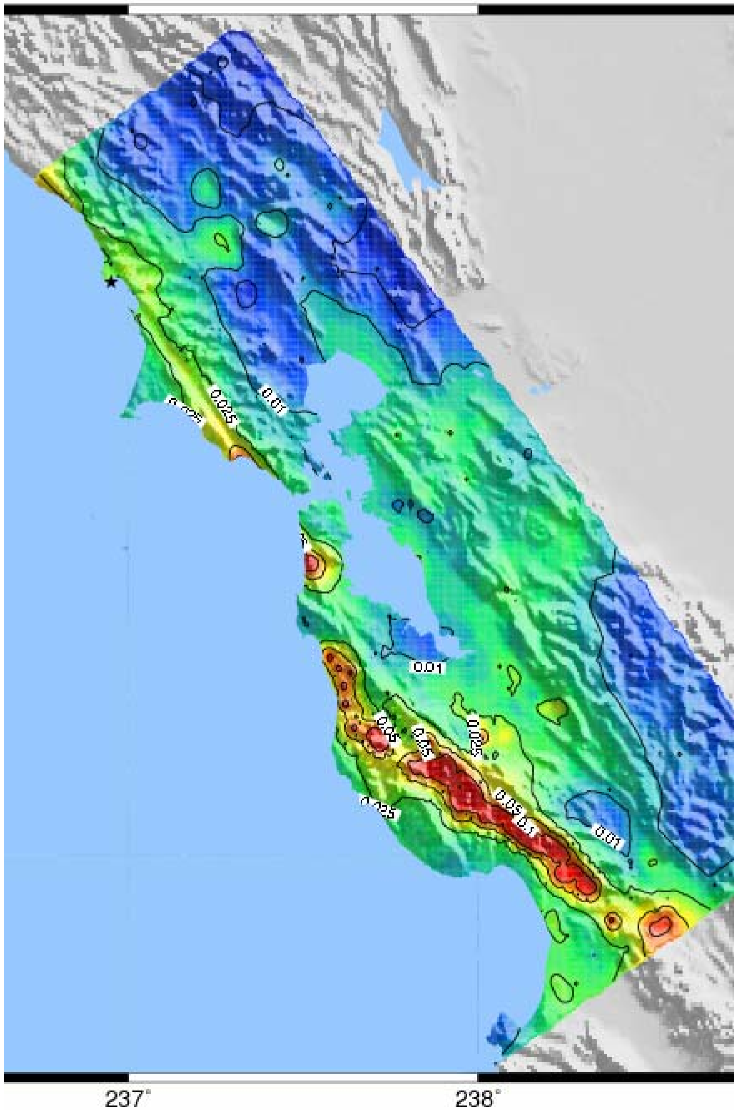


Fix the Brittle Welds

Ft Ross with brittle welds

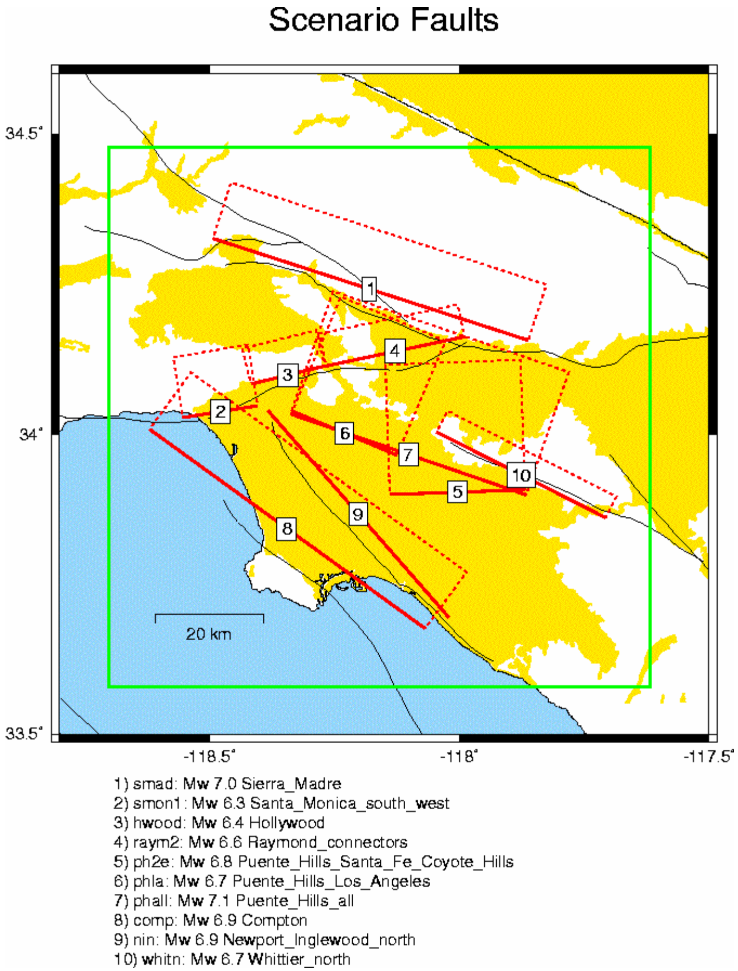


Ft Ross with perfect welds



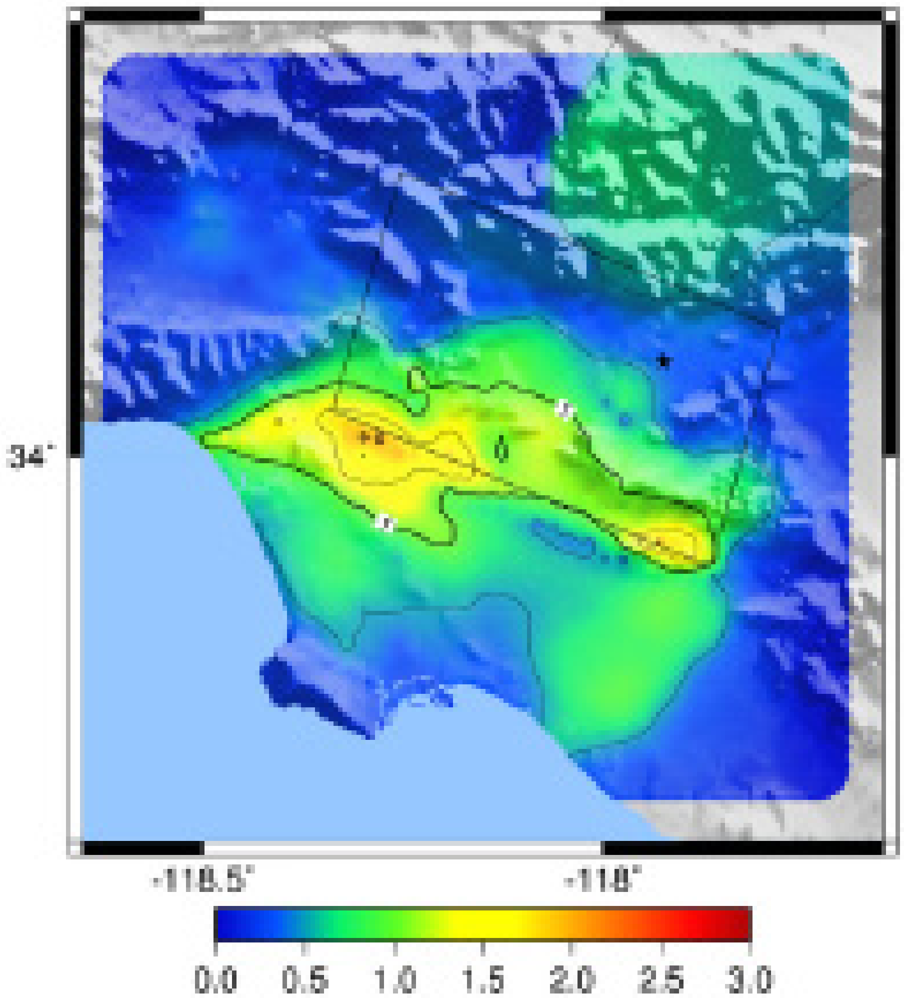
Faults Modeled

Day and others, 2005

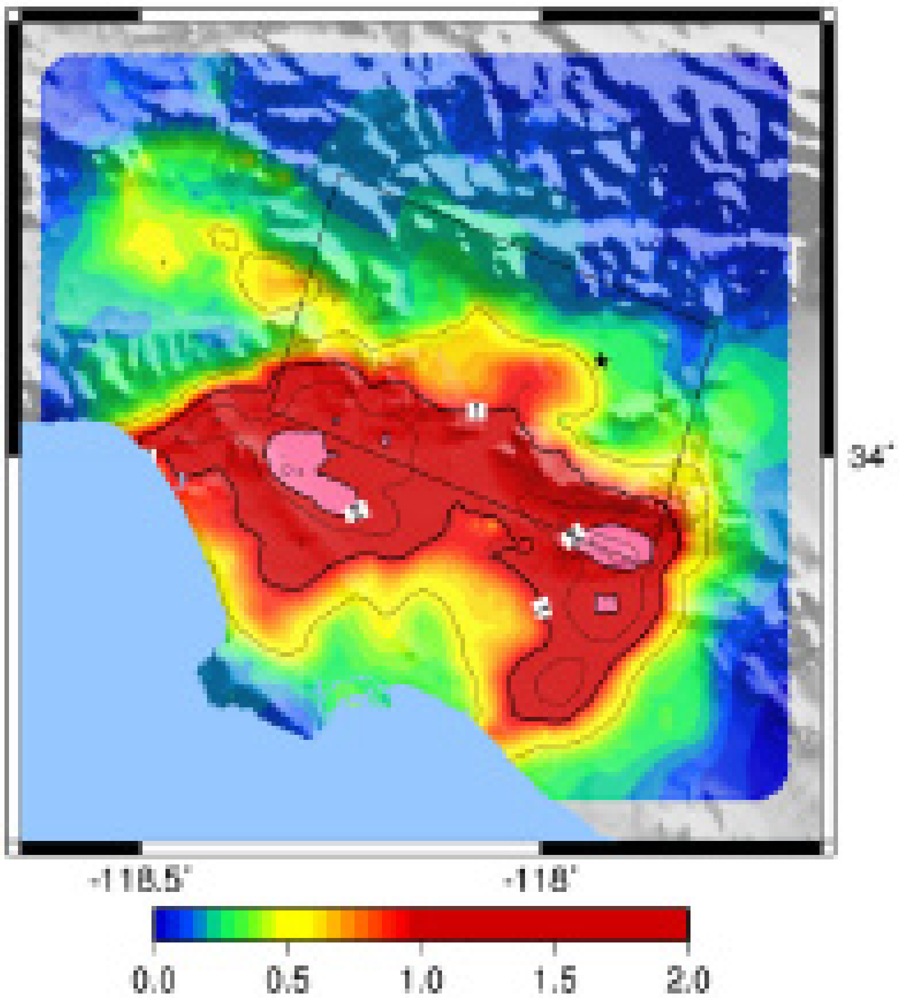


- 1. Sierra Madre (7.0)
- 2. Santa Monica SW (6.3)
- 3. Hollywood (6.4)
- 4. Raymond (6.6)
- 5. Puente Hills I (6.8)
- 6. Puente Hills II (6.7)
- 7. Puente Hills (all) (7.1)
- 8. Compton (6.9)
- 9. Newport-Inglewood (6.9)
- 10. Whittier (6.7)

Puente Hills M 7.1

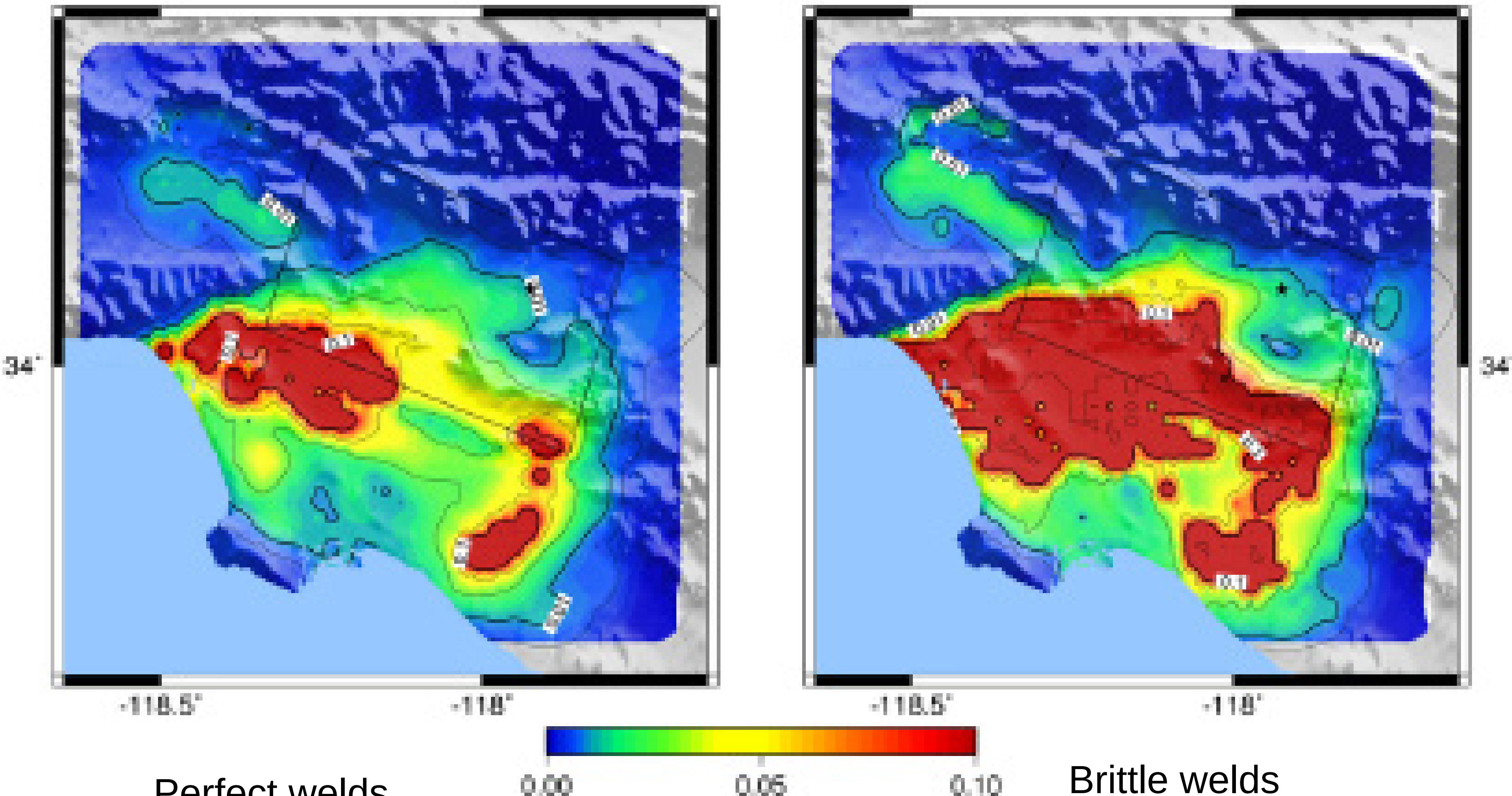


Ground displacement m



Ground velocity m/s

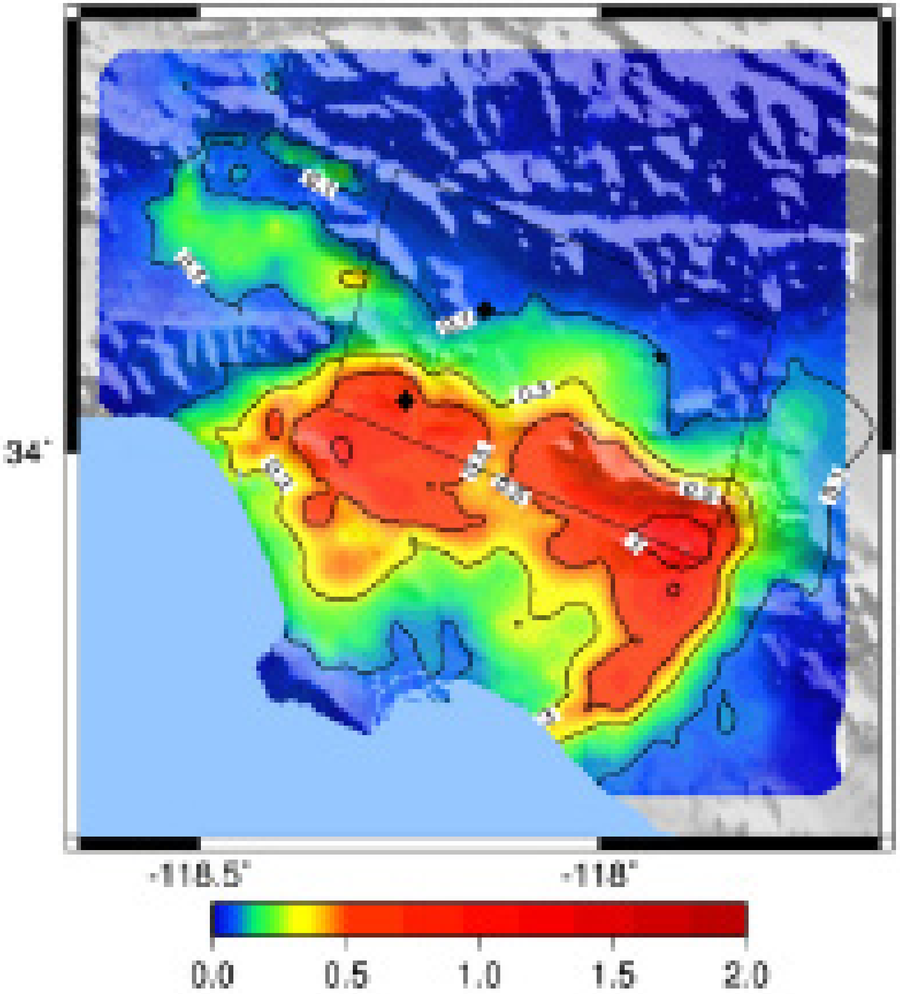
20-story peak drift in Puente Hills



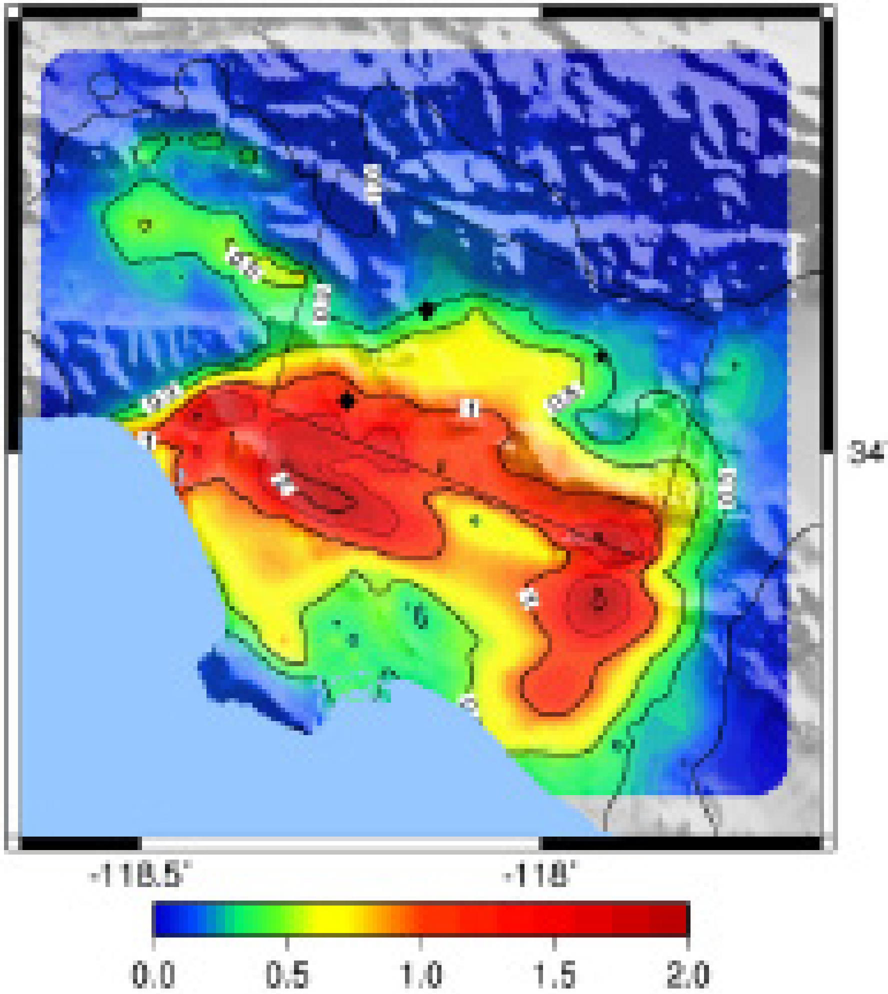
Perfect welds

Brittle welds

Base Isolator peak displacment



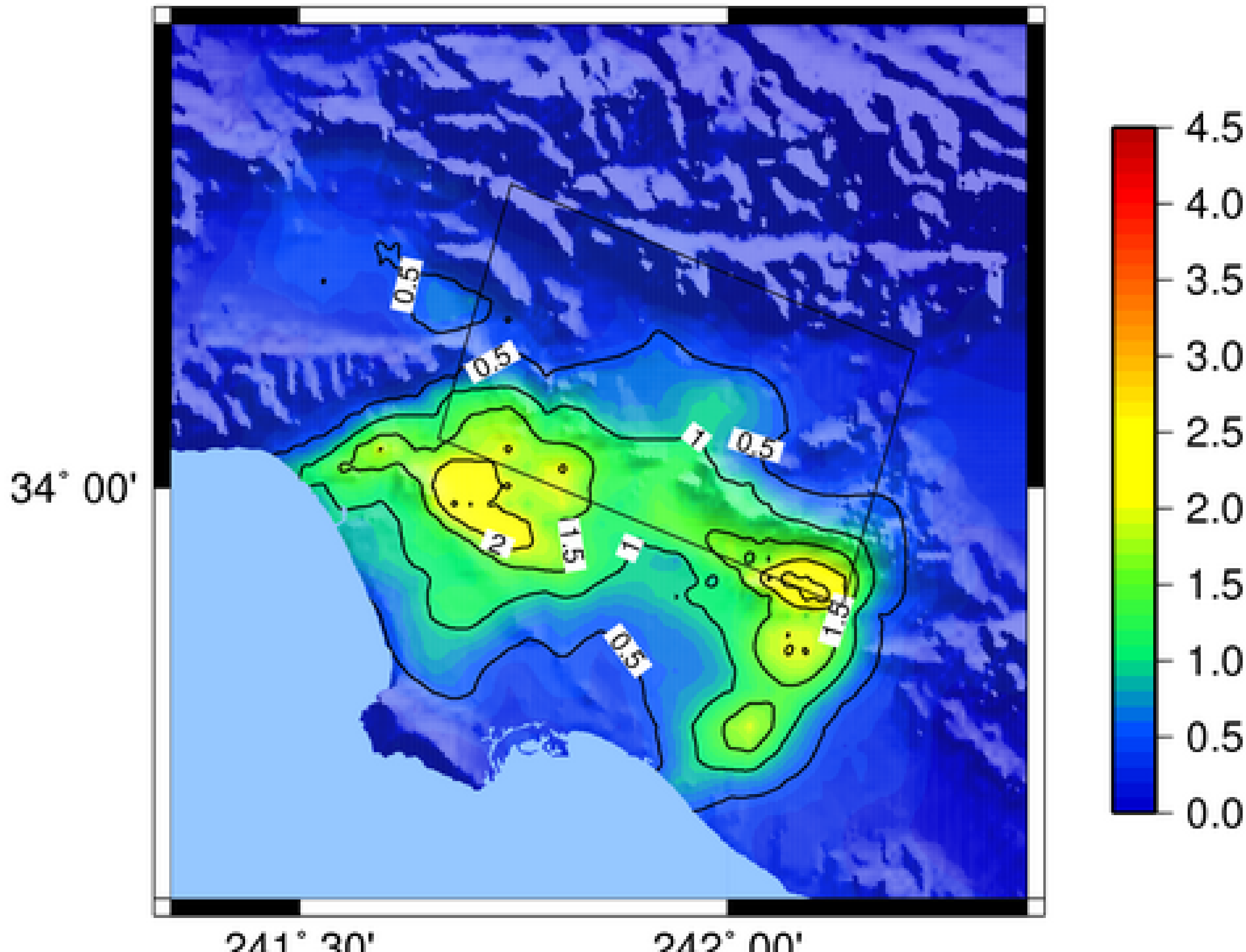
2-sec. period

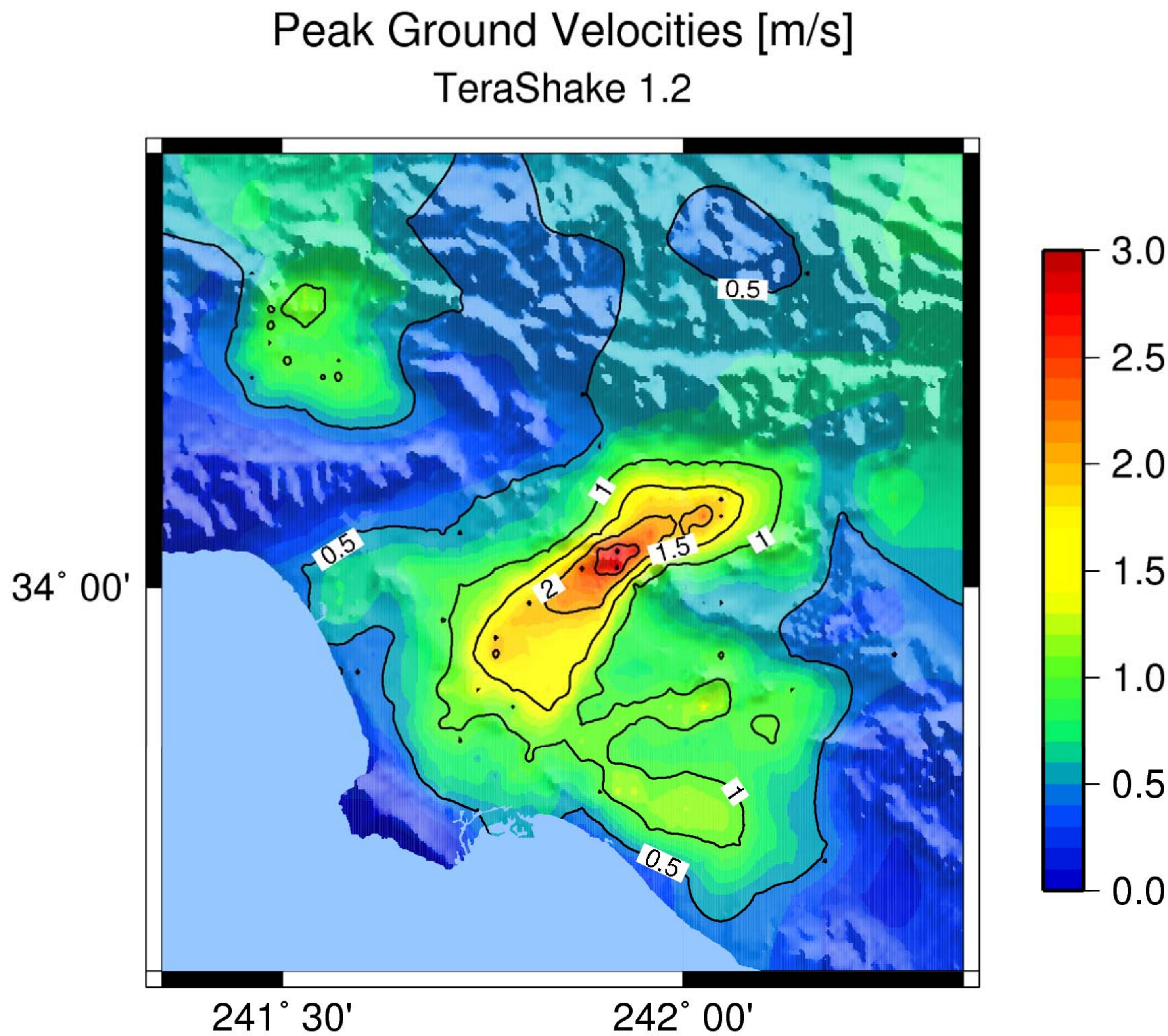


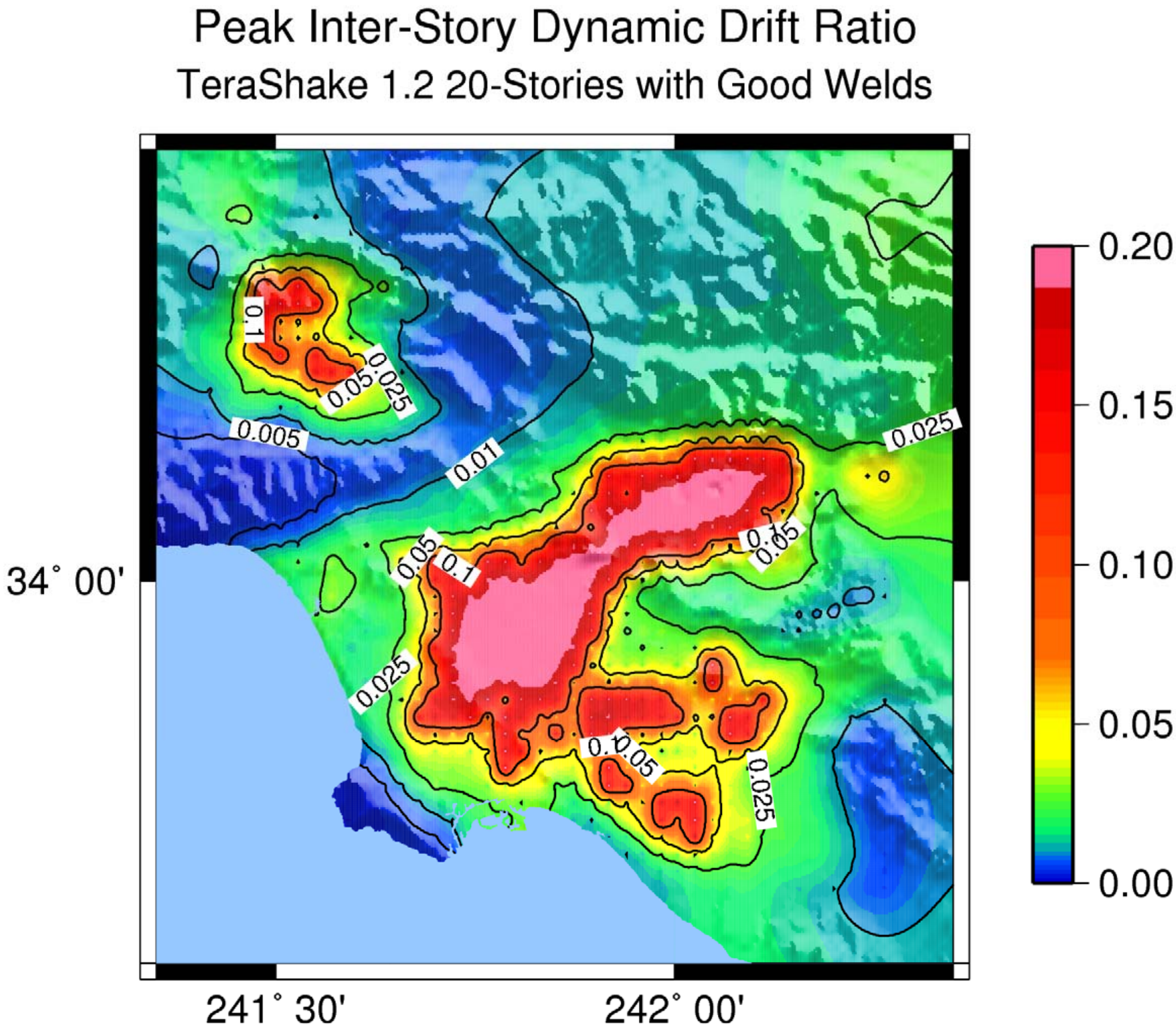
4-sec. period

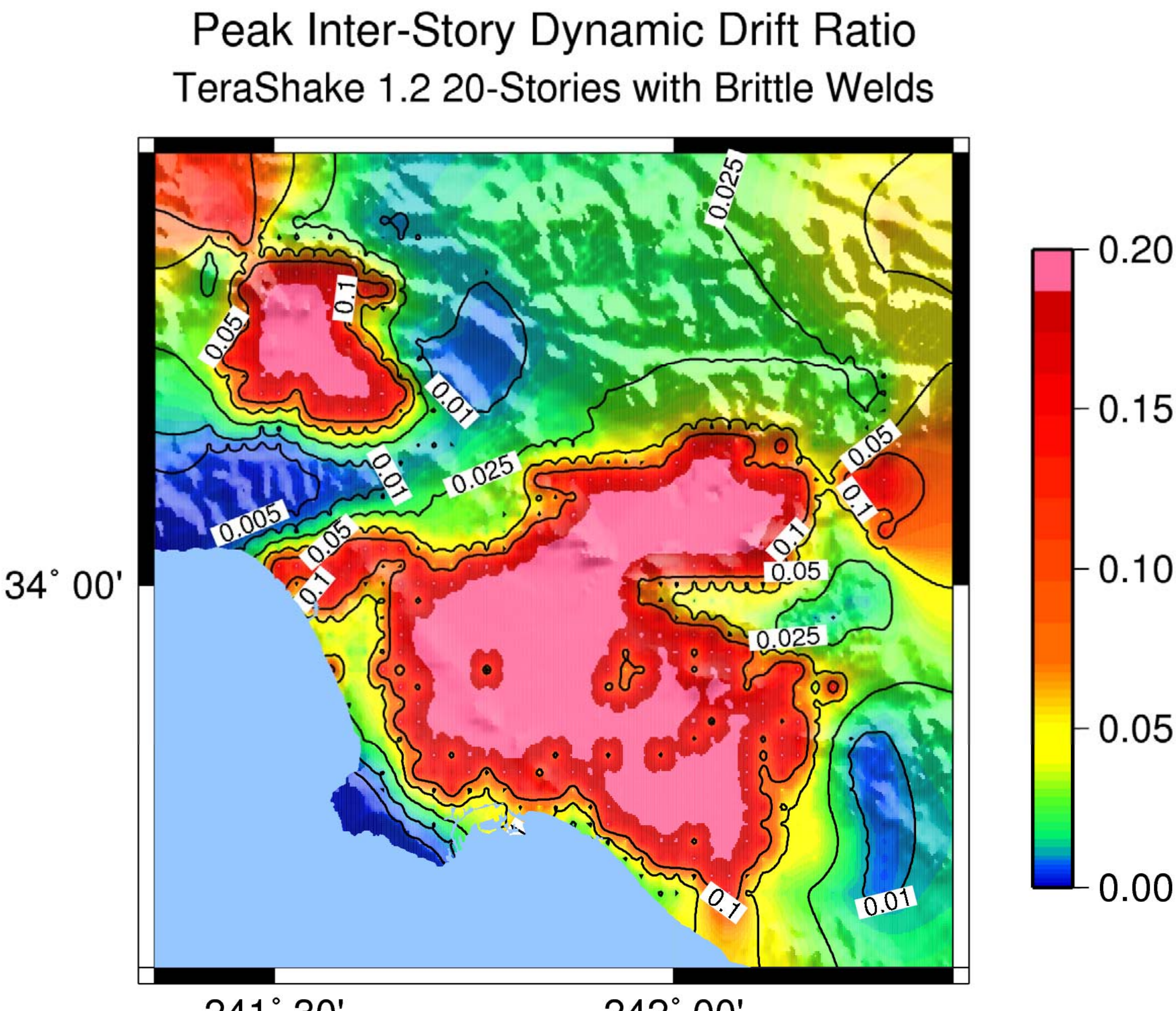
Peak Ground Velocities [m/s]

Puente Hills (All)




Peak Ground Velocities [m/s]
TeraShake 1.2
34˚ 00'
241˚ 30'
242˚ 00'
0.5
1
1.5
2
3.0
2.5
2.0
1.5
1.0
0.5
0.0


Peak Inter-Story Dynamic Drift Ratio
TeraShake 1.2 20-Stories with Good Welds
0.20
0.15
0.10
0.05
0.00
34˚ 00'
241˚ 30'
242˚ 00'
0.1
0.05
0.025
0.005
0.01
0.025
0.05
0.1
0.025
0.025



Peak Inter-Story Dynamic Drift Ratio
TeraShake 1.2 20-Stories with Brittle Welds
0.025
0.1
0.05
0.01
0.01
0.025
0.05
0.1
0.005
0.05
0.1
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

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
- Incomplete understanding leads to future systematic problems … nonductile concrete, brittle welds, …???
- Should we be doing something differently?

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
- This is “performance based design”

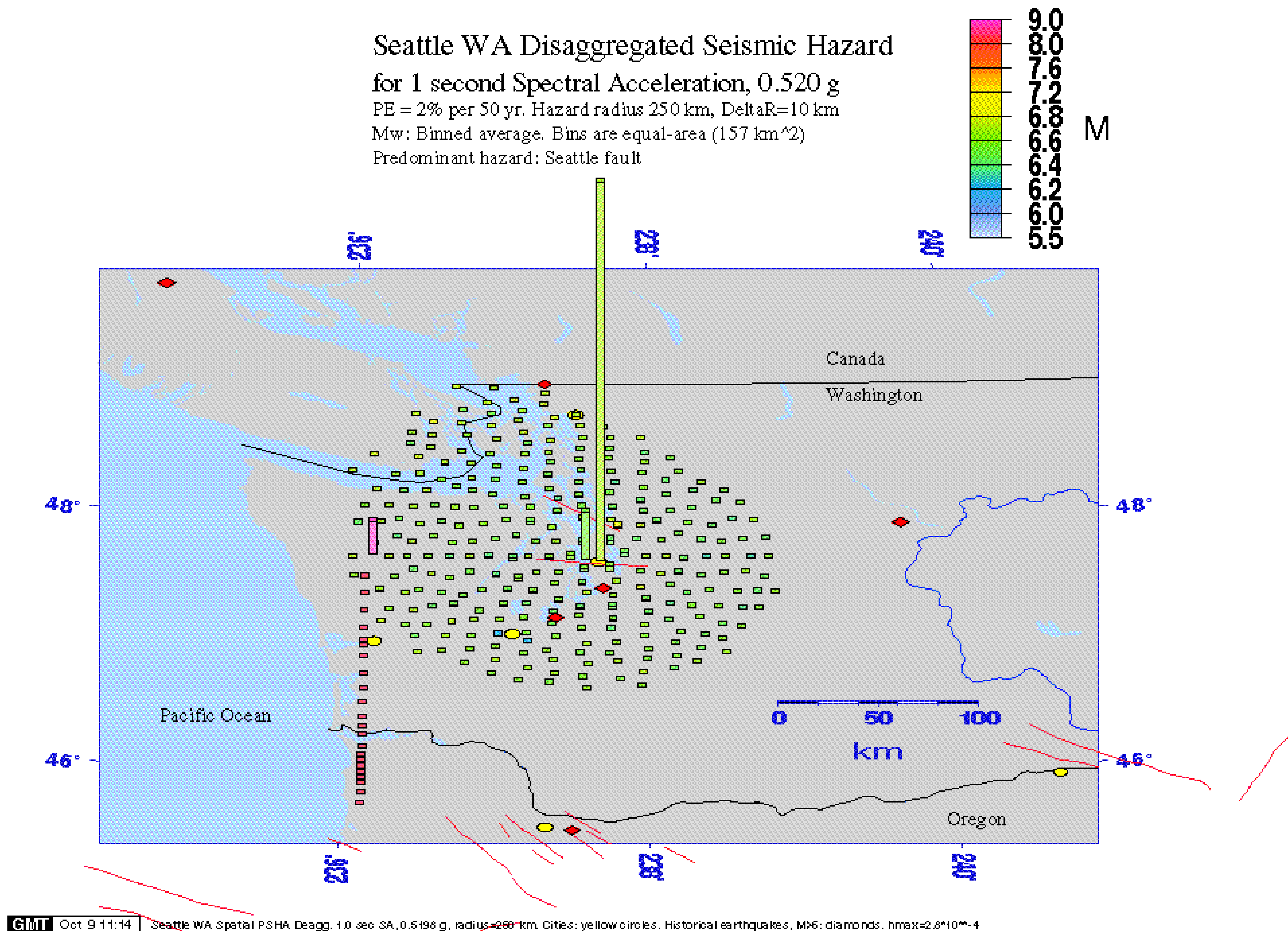
Designing for the Unknown

- 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

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.*

1997



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
236°
237°
238°
239°
240°
48°
46°
Canada
Washington
Pacific Ocean
Oregon
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

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).

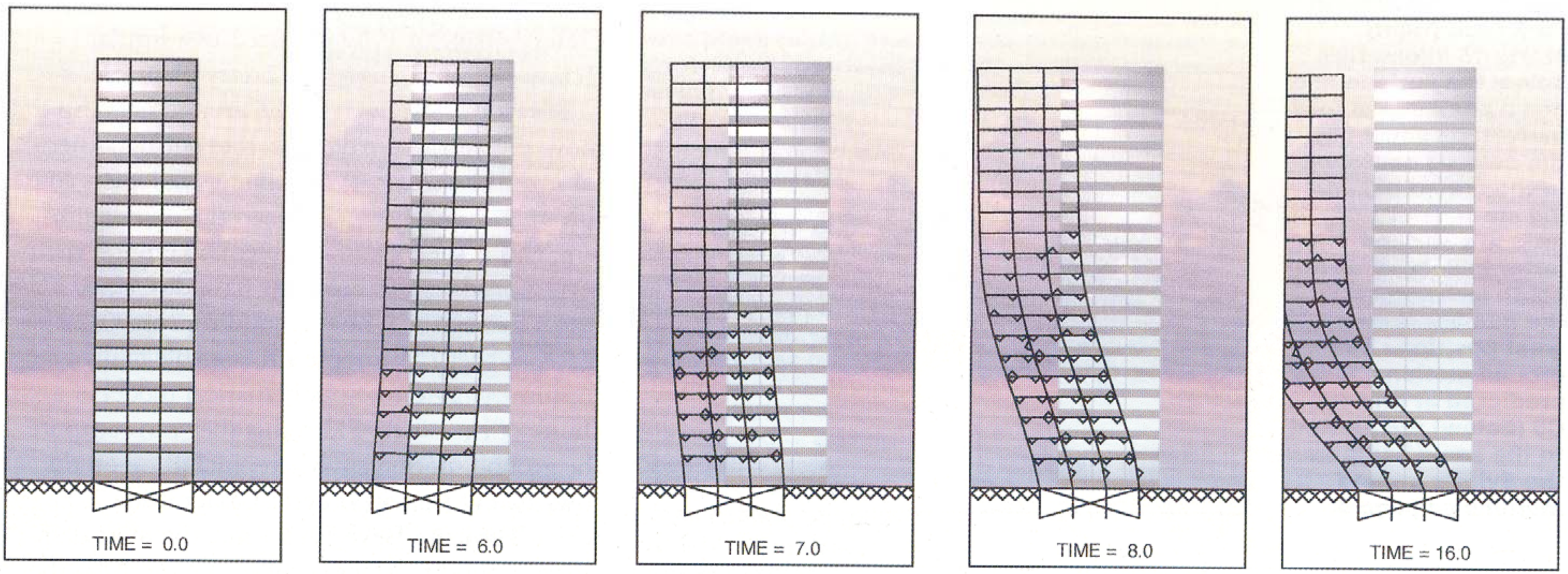
The 20-story building before the C5 ground motion hits. The displacement pulse will be toward the left.

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.



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

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

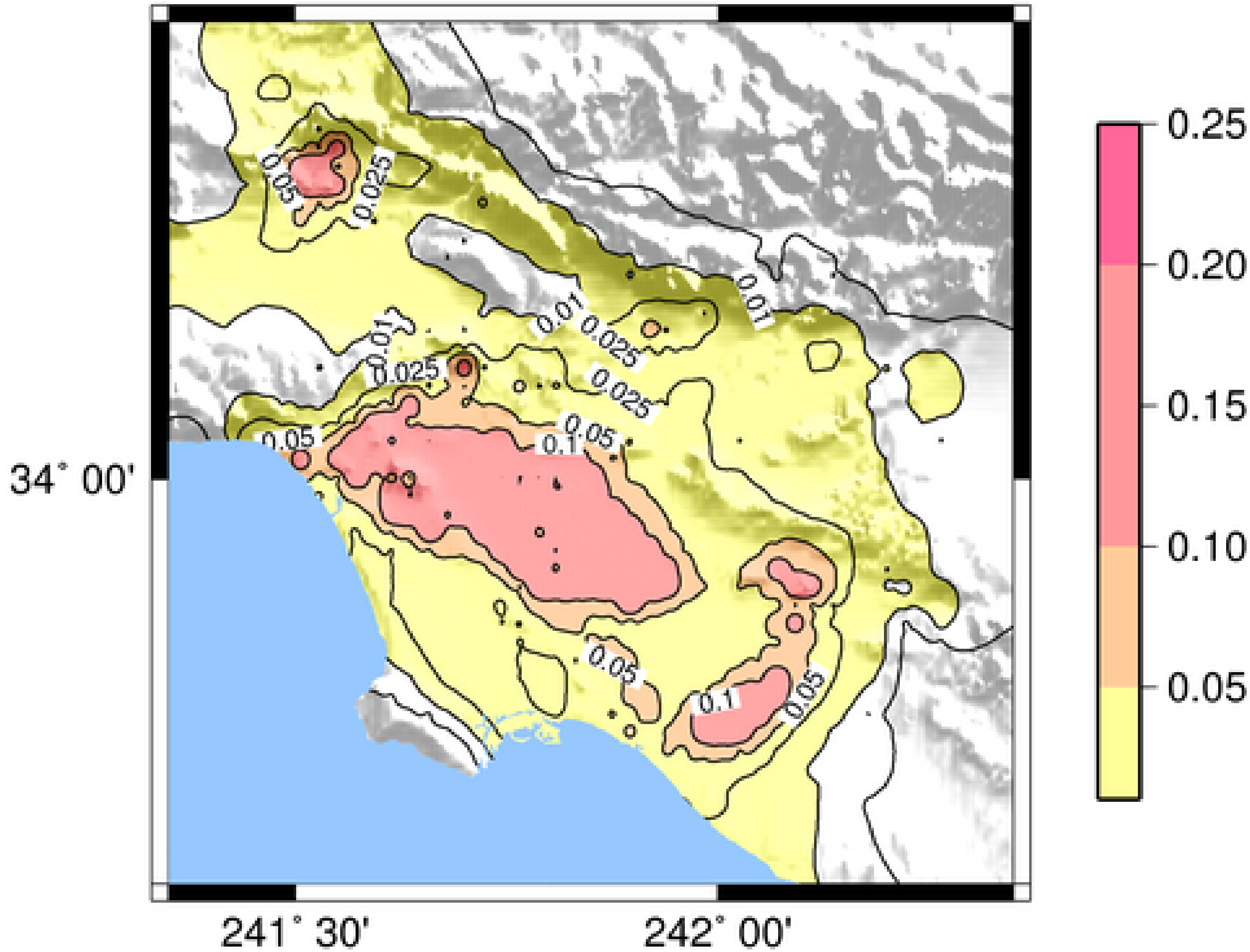
C = single cross-check

R = 1D rock reference simulation

S = 1D basin-profile simulation

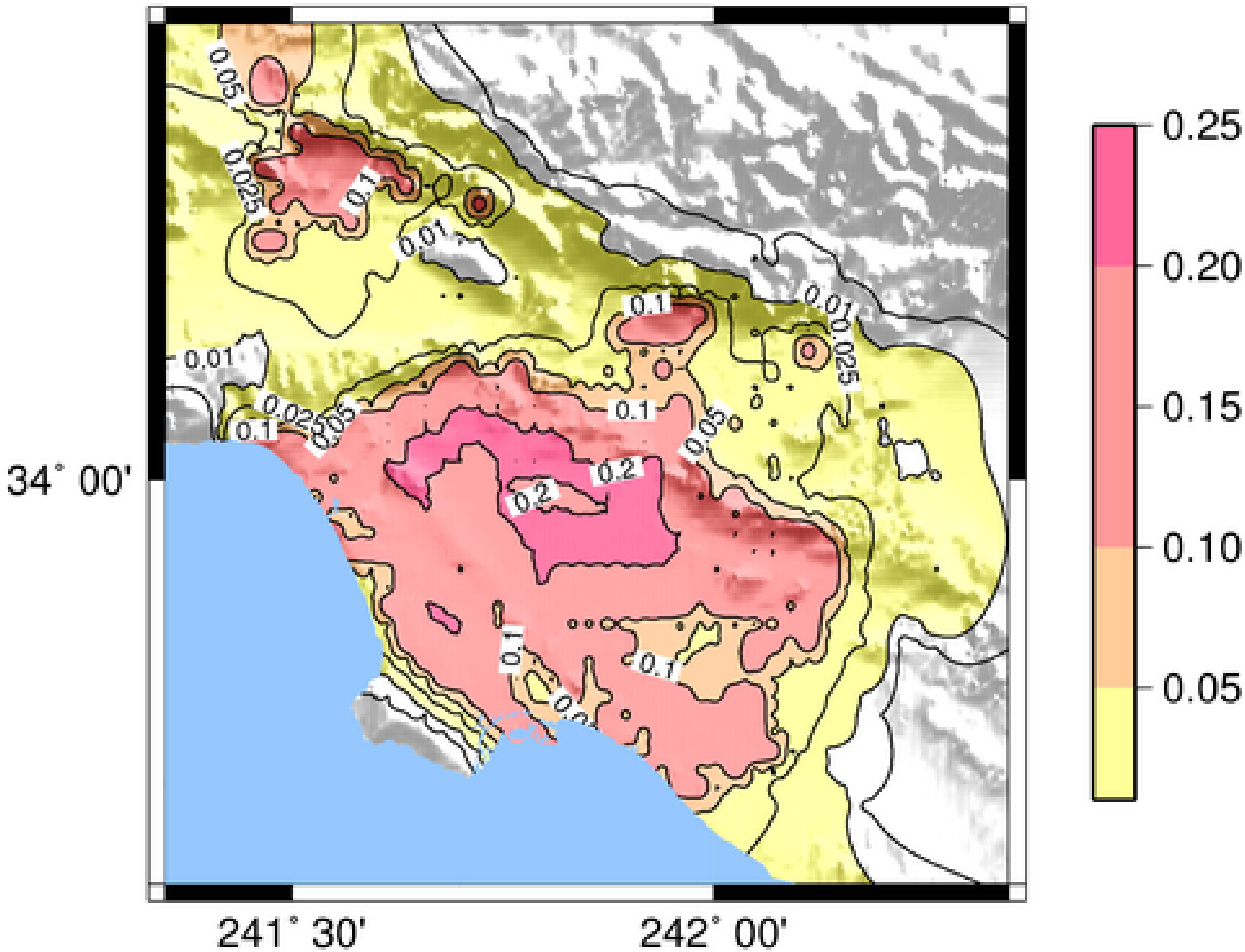
Maximum Inter-Story Dynamic Drift Ratio

Composite 20-Stories with Good Welds



Maximum Inter-Story Dynamic Drift Ratio

Composite 20-Stories with Brittle Welds



Normal Statistics (Gaussian)

- If events $A, B, C, \ldots$ are independent and if each event has probability distribution $P_A, P_B, P_C, \ldots$

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- Then joint probability of $A, B, C, \ldots$ is

$$P_A * P_B * P_C * \ldots \rightarrow \text{Gaussian}$$

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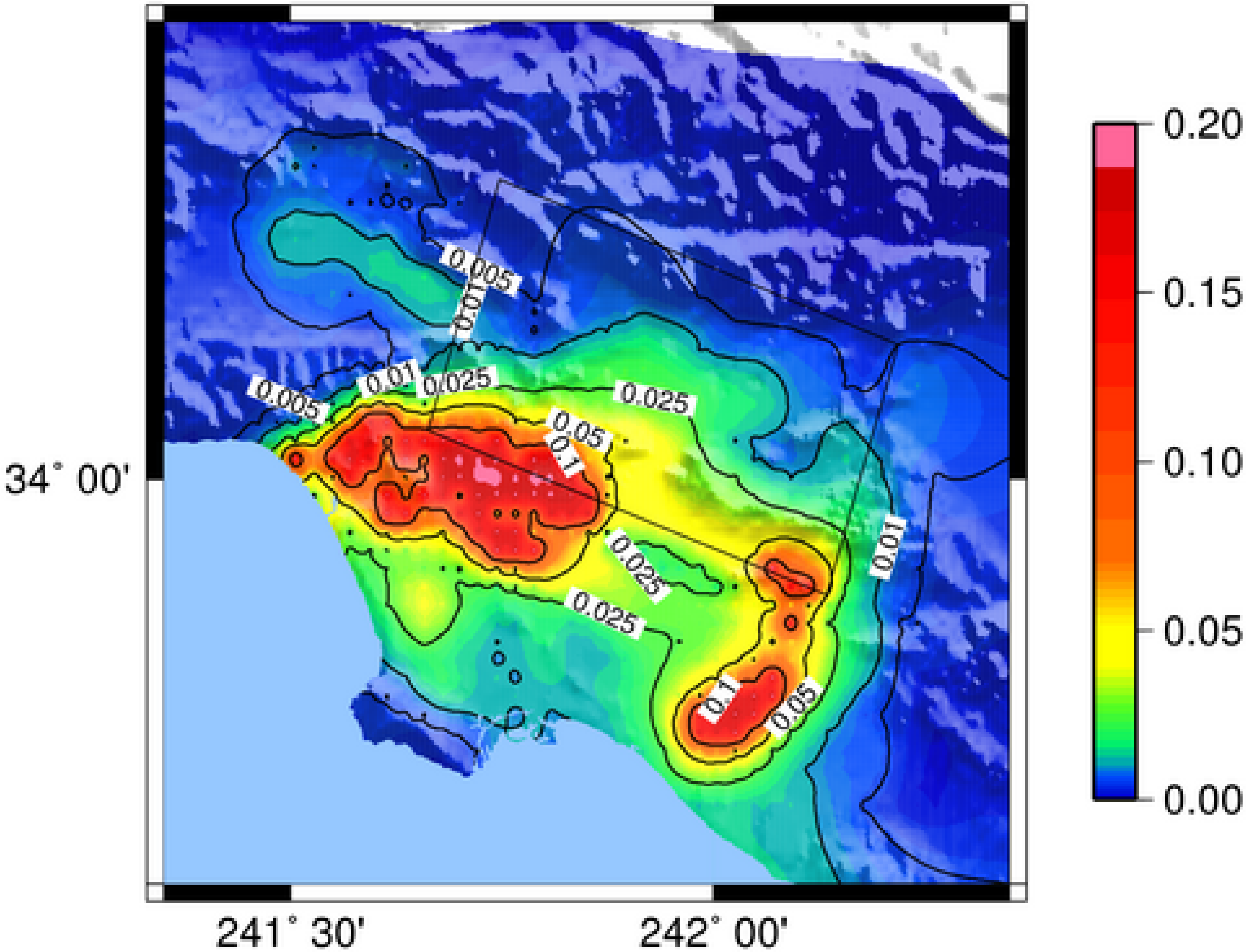
- Then joint probability of $A, B, C, \ldots$ is

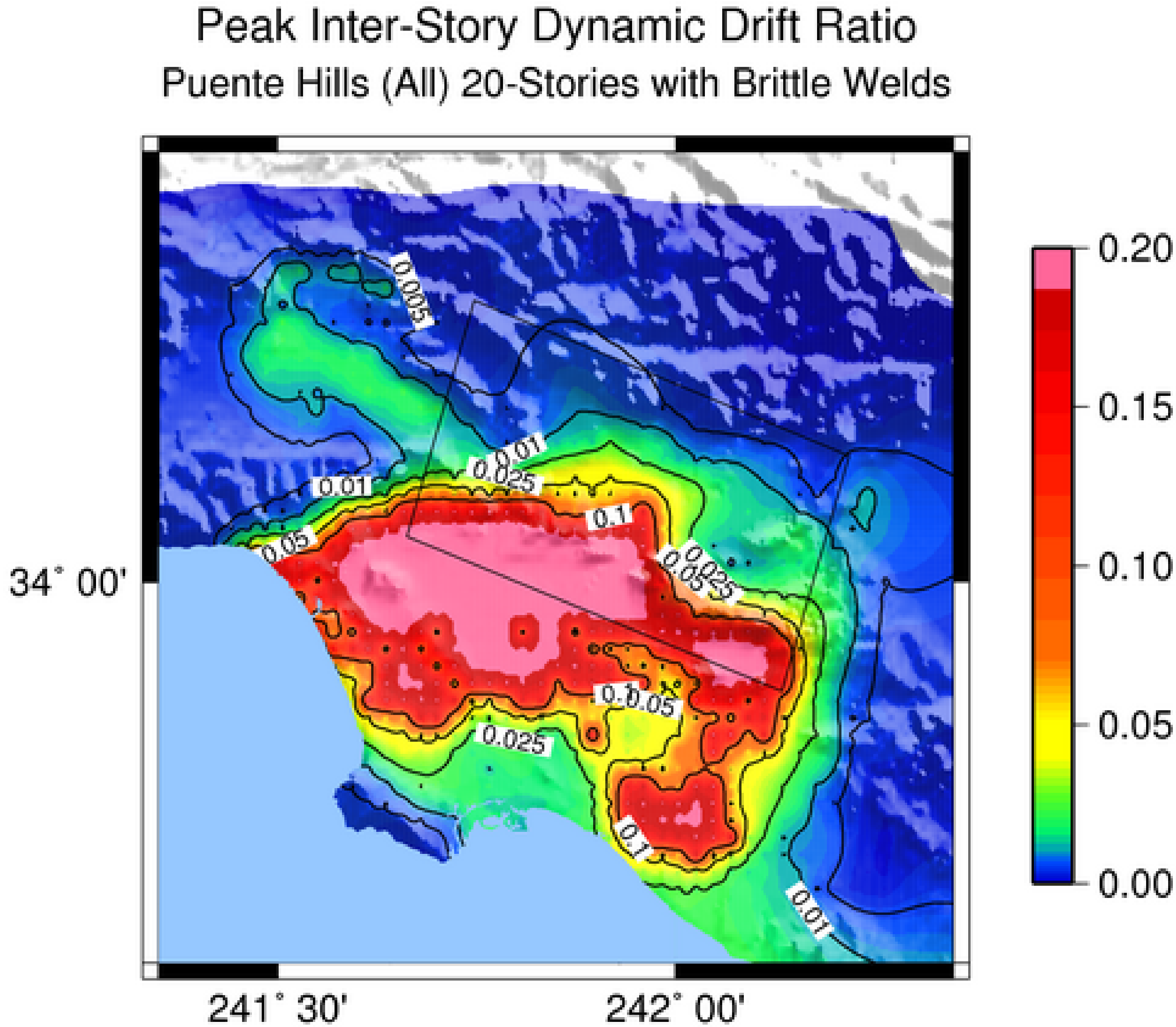
$$P_A * P_B * P_C * \ldots \rightarrow \text{ Gaussian}$$

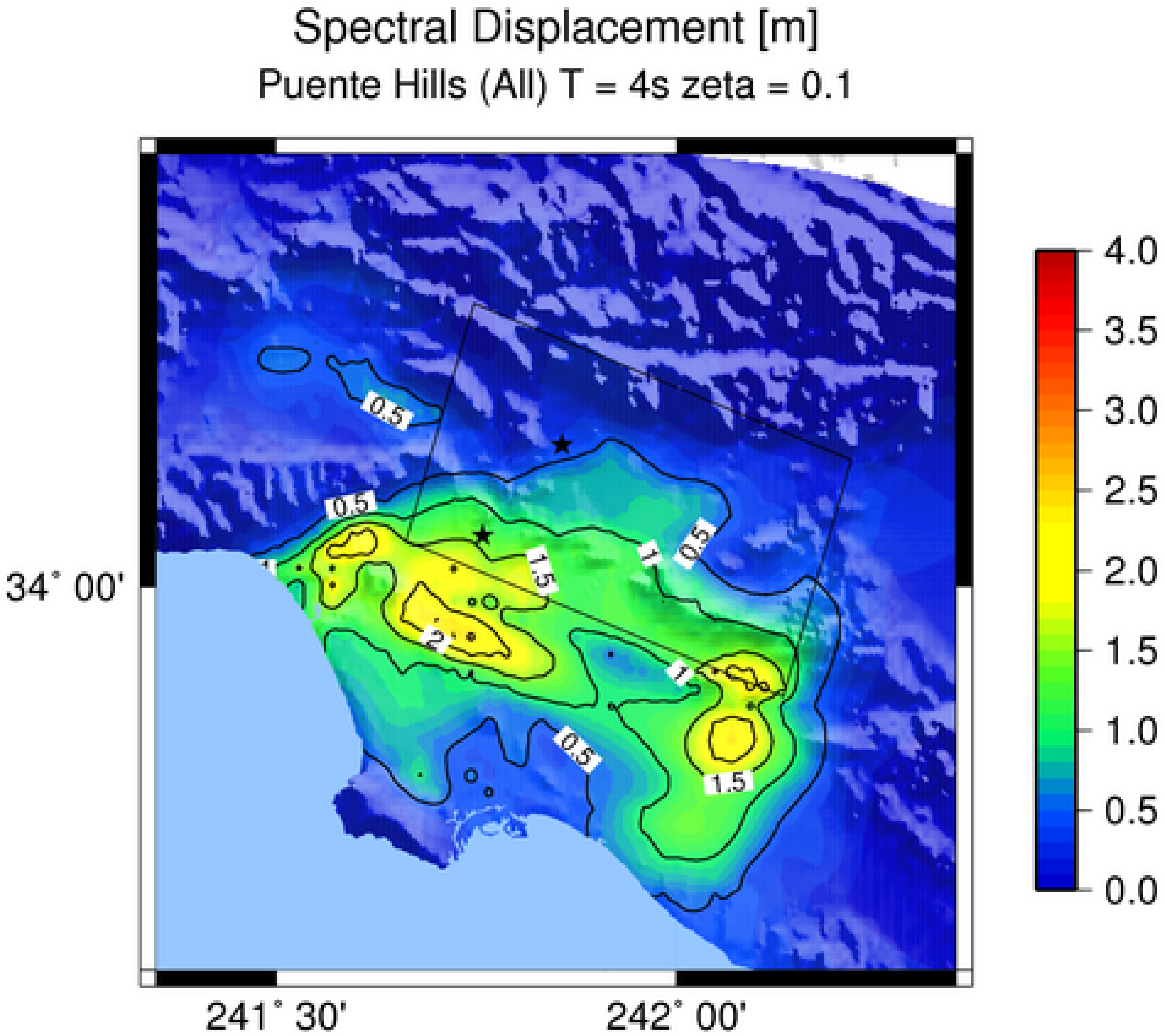
- Statistics of auto accidents, grades, heart attacks
- Loss statistics sensitive to median behavior

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
0.025
0.01
0.05
0.1
0.025
0.05
0.1
0.05
0.025
0.1
0.01
0.20
0.15
0.10
0.05
0.00
34° 00'
241° 30'
242° 00'


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