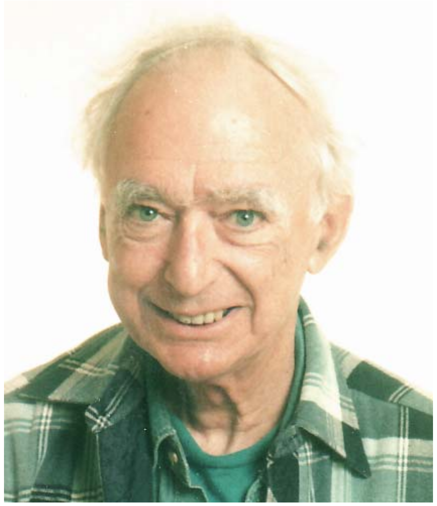
Ground-Motion Prediction Equations: Past, Present, and Future

The 2014 William B. Joyner Lecture

David M. Boore

As presented at the SMIP15 meeting, Davis, California, 22 October 2015



The William B. Joyner Memorial Lectures were established by the Seismological Society of America (SSA) in cooperation with the Earthquake Engineering Research Institute (EERI) to honor Bill Joyner's distinguished career at the U.S. Geological Survey and his abiding commitment to the exchange of information at the interface of earthquake science and earthquake engineering, so as to keep society safer from earthquakes.

Road Map

- Giving proper credit
- Ground-Motion Prediction Equations (GMPEs)
    - Basics
    - Past
    - Present (illustrated by PEER NGA-West 2 project)
    - Future
- Use of GMPEs in building codes

Giving proper credit

Boore, Joyner, and Fumal (1993, 1994, 1997)

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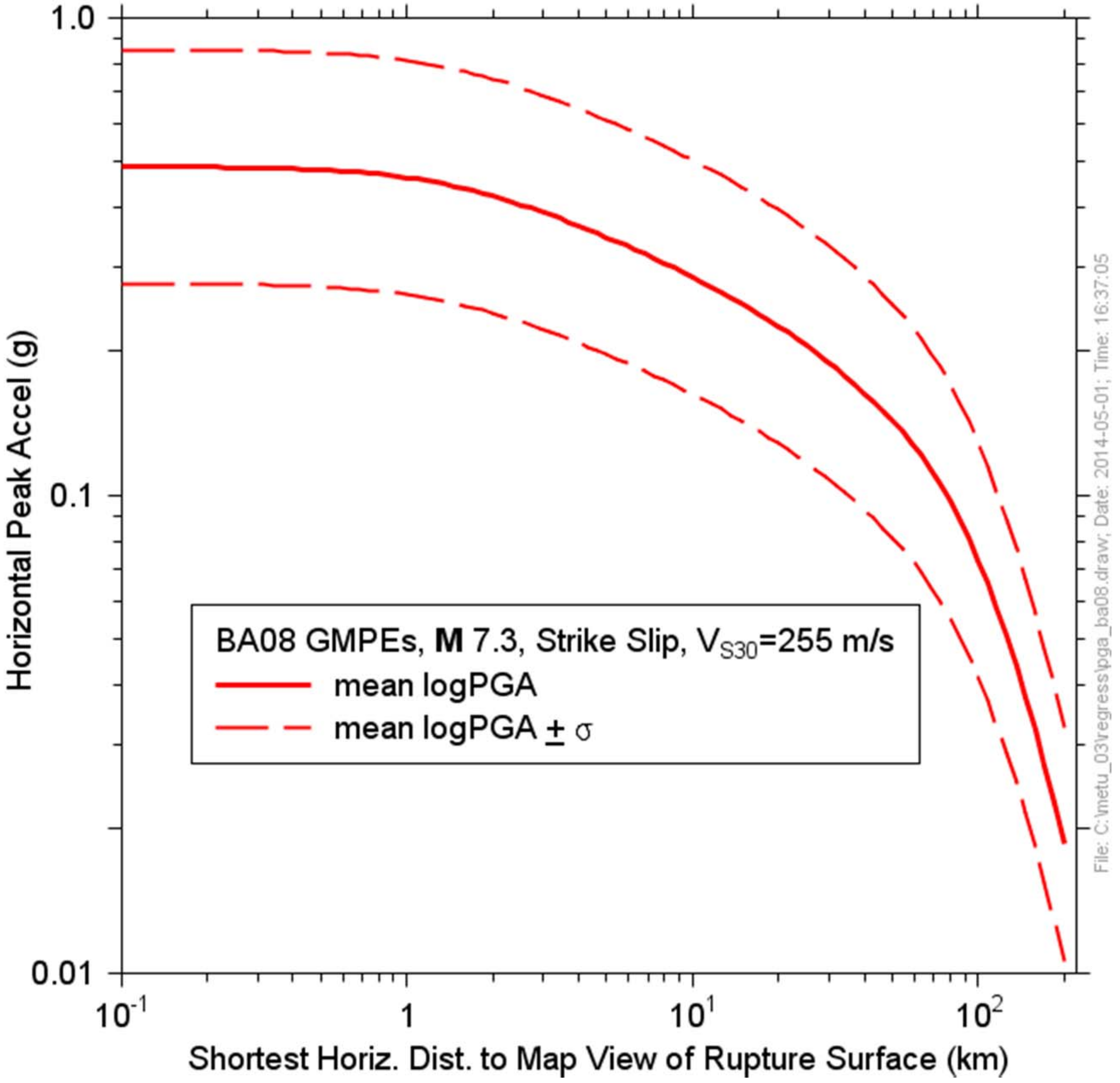
Why Bill wanted me as the first author is a mystery, but at least the work is known as BJF rather than Boore et al.

Ground-Motion Prediction Equations (GMPEs): What are they?



Ground-Motion Prediction Equations (GMPEs): How are they used?

- Engineering: Specify motions for seismic design (critical individual structures as well as building codes)
- Seismology: Convenient summary of average M and R variation of motion from many recordings
    - Source scaling
    - Path effects
    - Site effects

Developing GMPEs requires knowledge of:

- Data acquisition and processing
- Source physics
- Velocity determination
- Linear and nonlinear wave propagation
- Simulations of ground motion
- Model building and regression analysis

How are GMPEs derived?

- Collect data
- Choose functions (**keeping in mind the application of predicting motions in future earthquakes**).
- Do regression fit
- Study residuals
- Revise functions if necessary
- Model building, not just curve fitting

Considerations for the functions

- "…as simple as possible, but not simpler.." (A. Einstein)
- Give reasonable predictions in data-poor but engineering-important situations
- Use simulations to guide some functions and set some coefficients (an example of model building, not just curve fitting)

Predicted and Predictor Variables

- Ground-motion intensity measures
  - Peak acceleration
  - Peak velocity
  - Response spectra
- Basic predictor variables
  - Magnitude
  - Distance
  - Site characterization
- Additional predictor variables
  - Basin depth
  - Hanging wall/foot wall
  - Depth to top of rupture
  - etc.

Wave Type and Frequencies of Most Interest

Horizontal S waves are most important for engineering seismology:

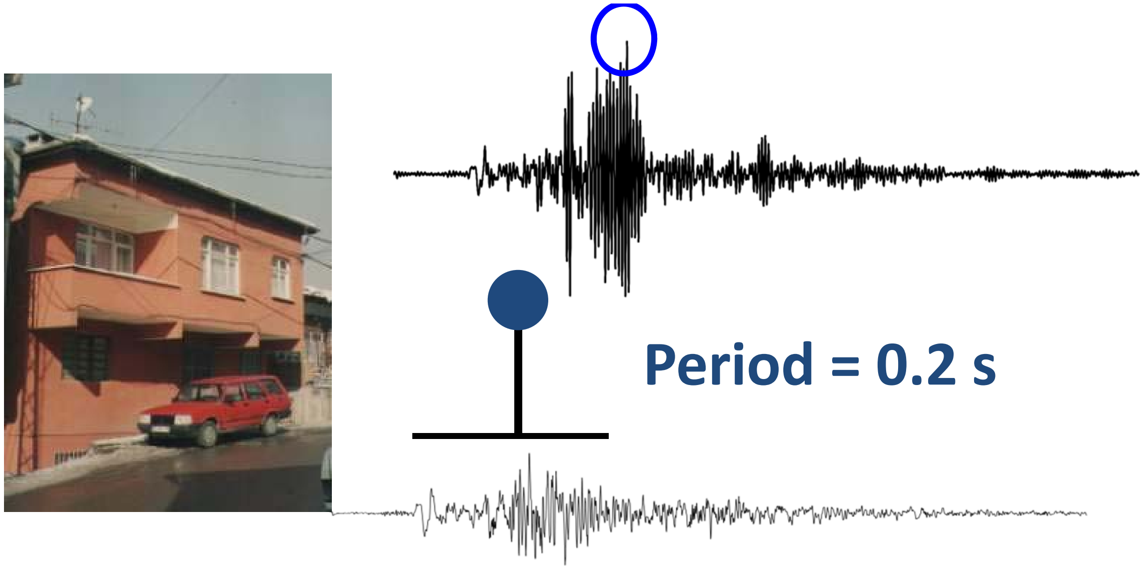
- Seismic shaking in range of resonant frequencies of structures
- Shaking often strongest on horizontal component:
  - Earthquakes radiate larger S waves than P waves
  - Refraction of incoming waves toward the vertical ⇒ S waves primarily horizontal motion
- Buildings generally are weakest for horizontal shaking
- **GMPEs for horizontal components have received the most attention**

Frequencies of ground-motion for engineering purposes

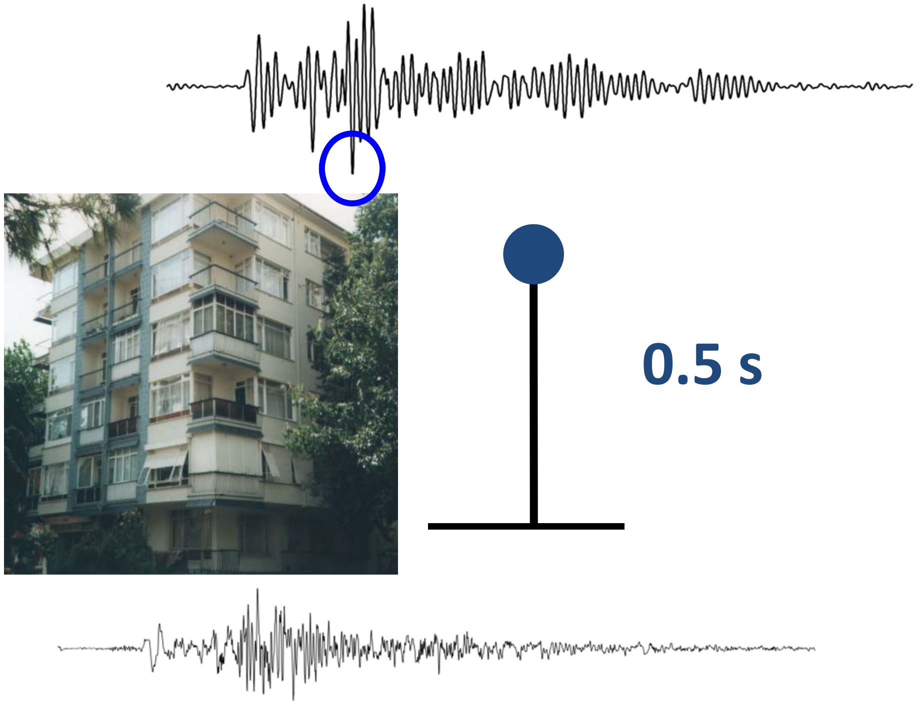
- 20 Hz --- 10 sec (usually less than about 3 sec)
- Resonant period of typical N story structure ≈ N/10 sec
  - What is the resonant period of the building in which we are located?

What are response spectra?

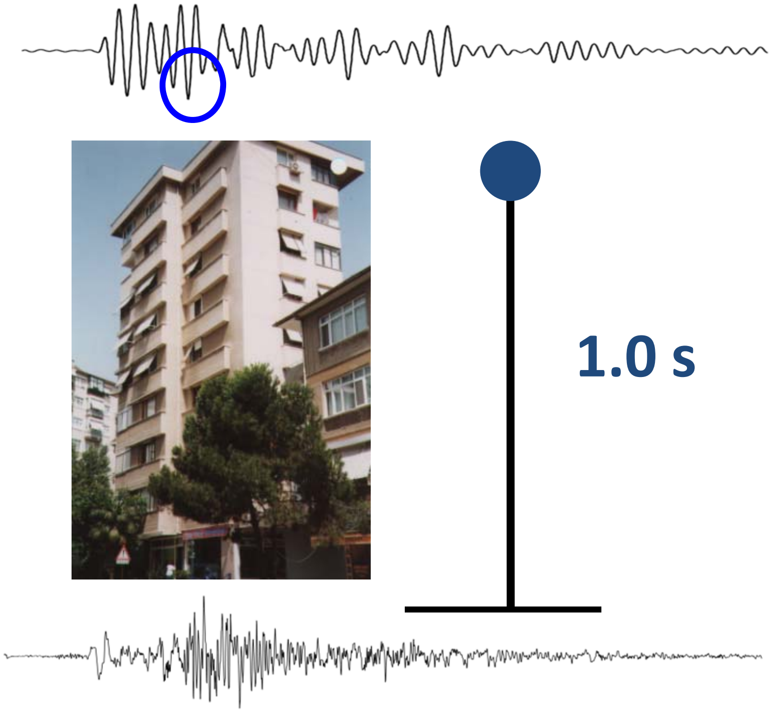
- The maximum response of a suite of single degree of freedom (SDOF) damped oscillators with a range of resonant periods for a given input motion
- Why useful? Buildings can often be represented as SDOF oscillators, so a response spectrum provides the motion of an arbitrary structure to a given input motion



Period = 0.2 s



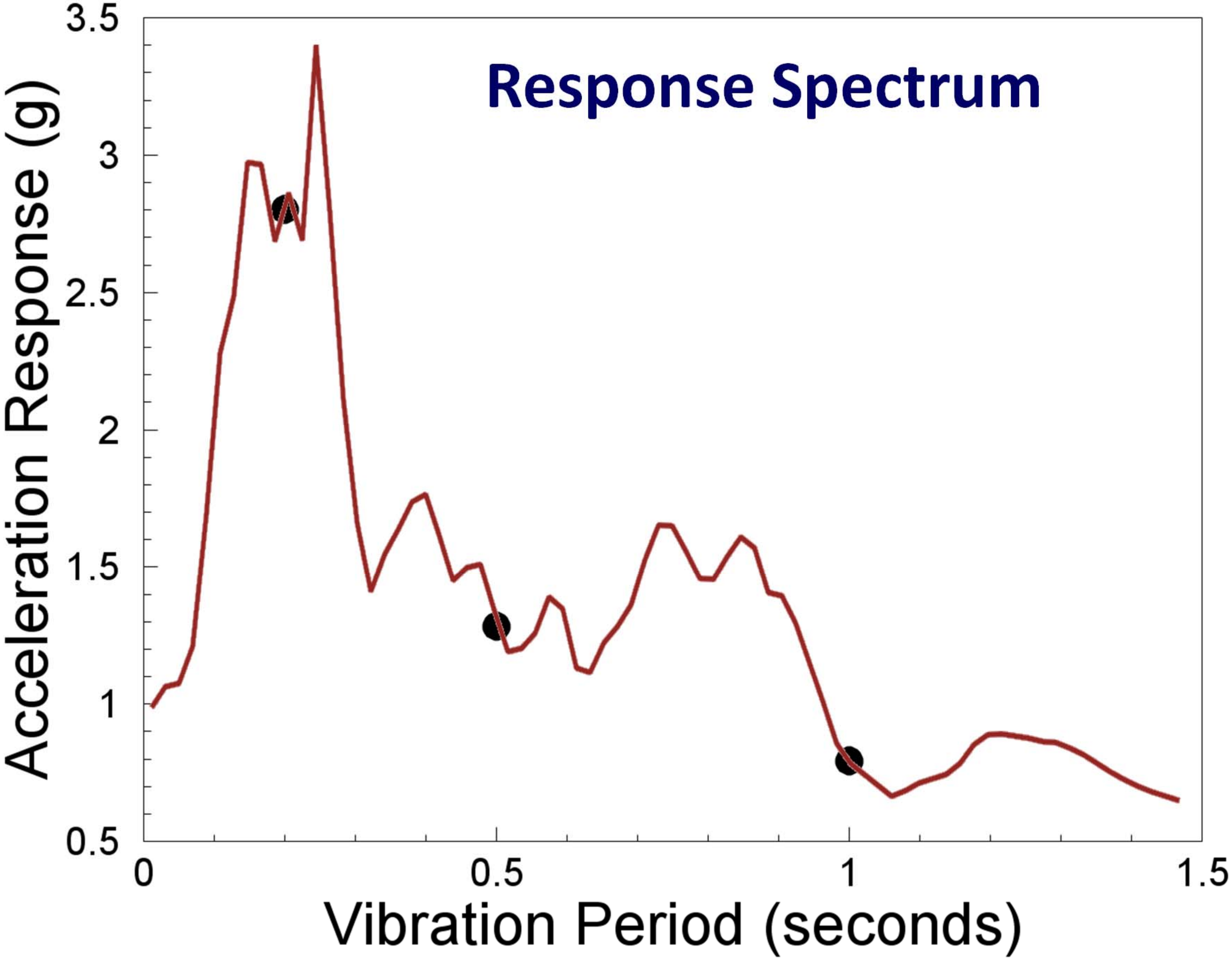
0.5 s



1.0 s

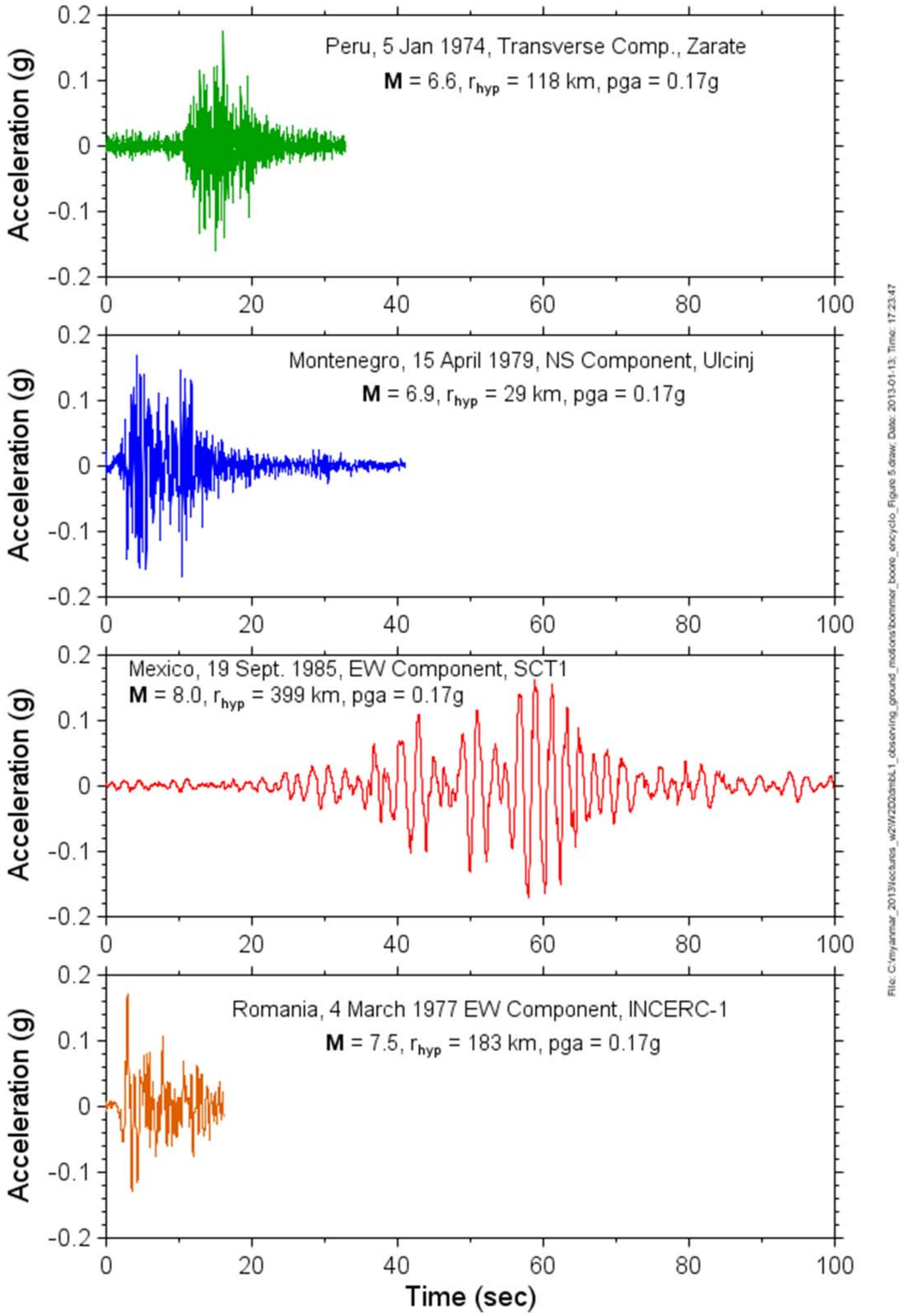
Courtesy of J. Bommer

Response Spectrum

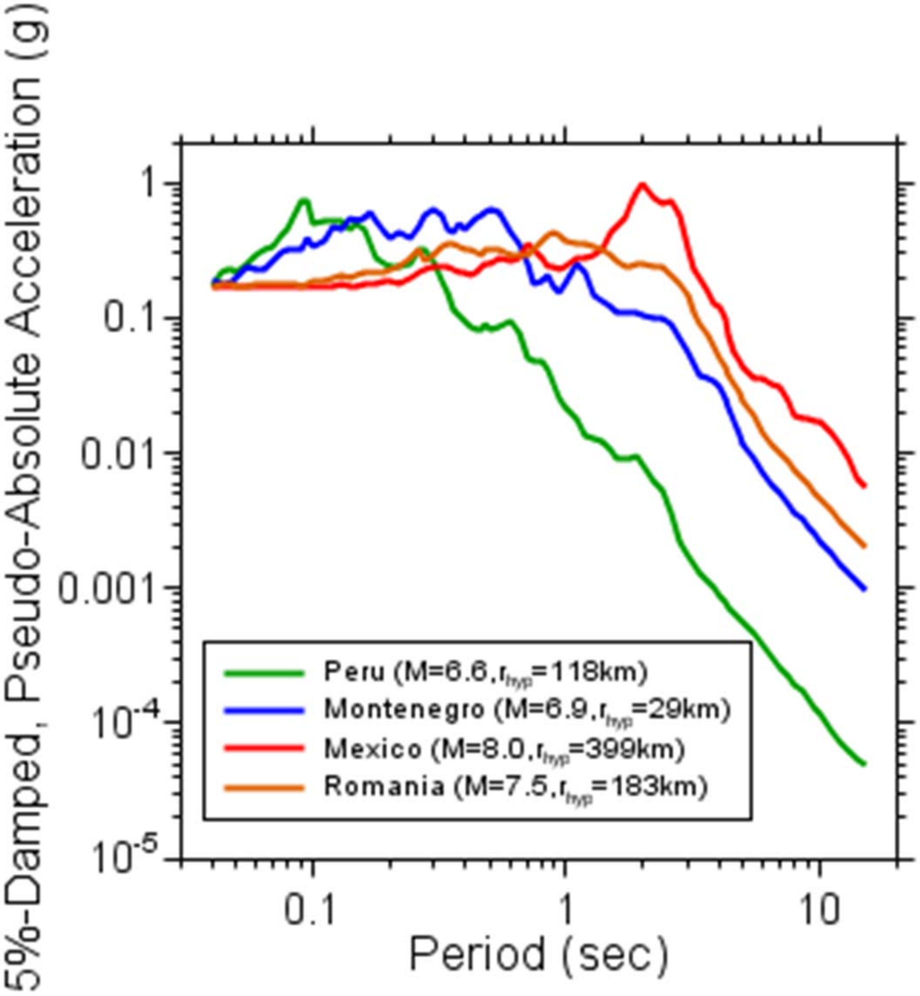


Courtesy of J. Bommer

PGA generally a poor measure of ground-motion intensity. All of these time series have the same PGA:



But the response spectra (and consequences for structures) are quite different:

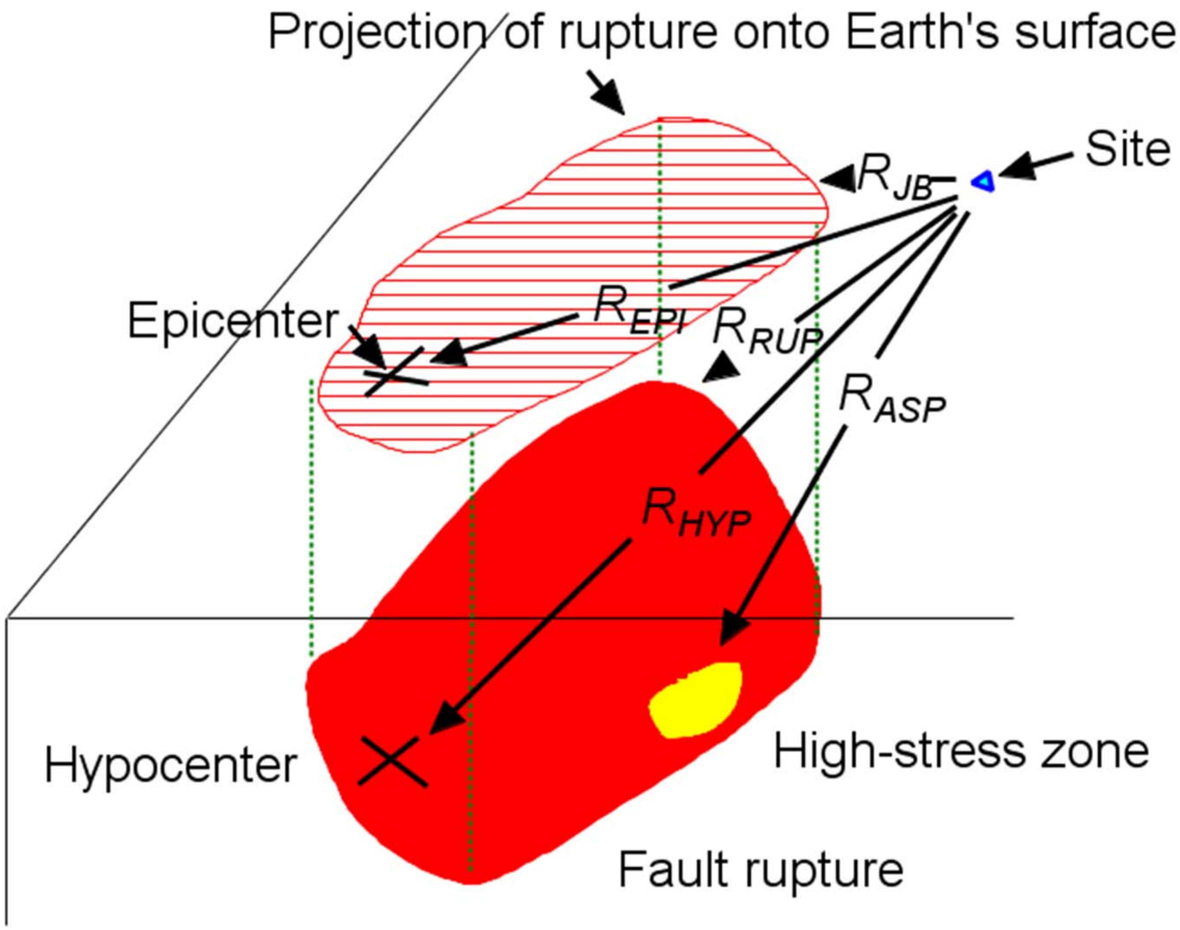


What to use for the basic predictor variables?

- Moment magnitude
  - Best single measure of overall size of an earthquake (it does not saturate)
  - It can be estimated from geological observations
  - Can be estimated from paleoseismological studies
  - Can be related to slip rates on faults

What to use for the basic predictor variables?

- Distance – many measures can be defined

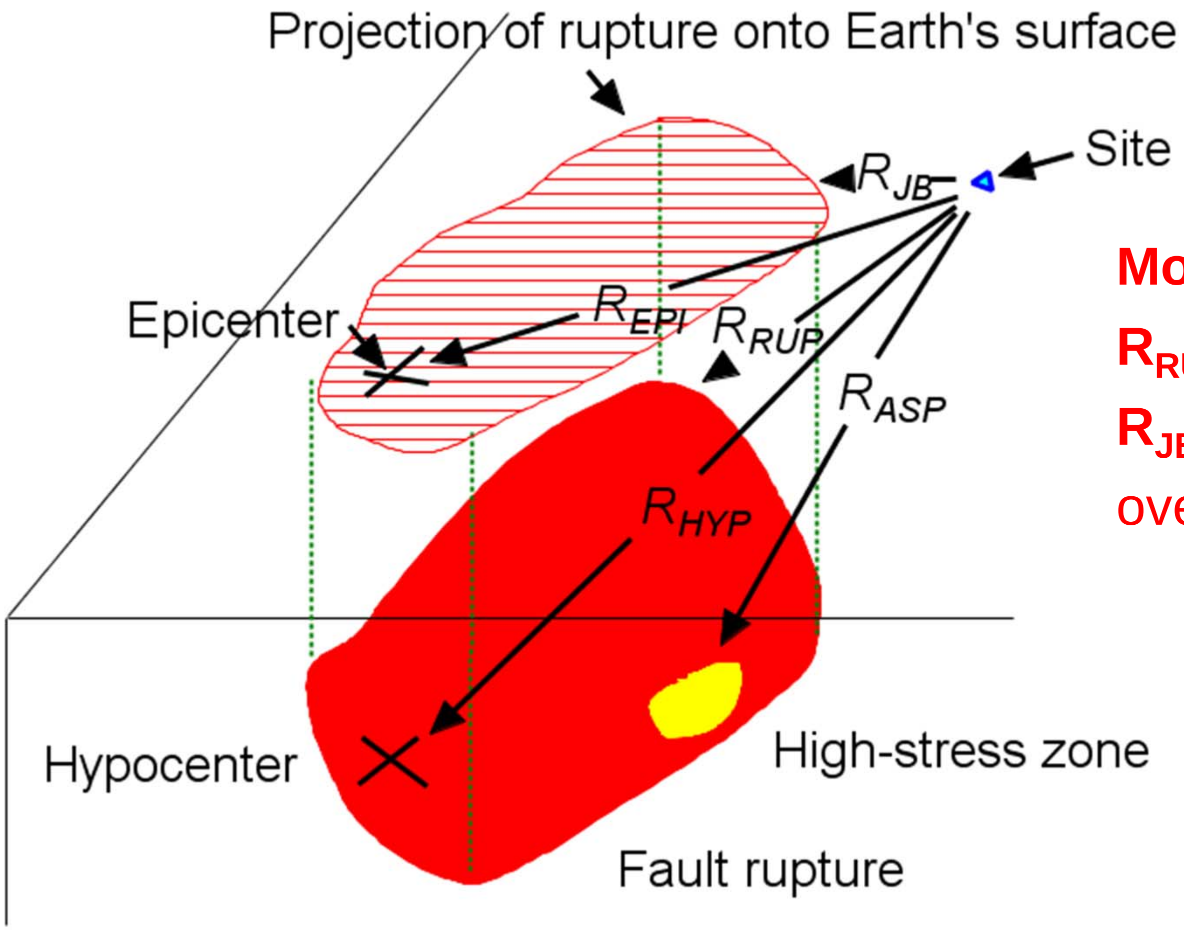


What to use for the basic predictor variables?

- Distance
  - The distance measure should help account for the extended fault rupture surface
  - The distance measure must be something that can be estimated for a future earthquake

What to use for the basic predictor variables?

- Distance – not all measures useful for future events



Most Commonly Used:

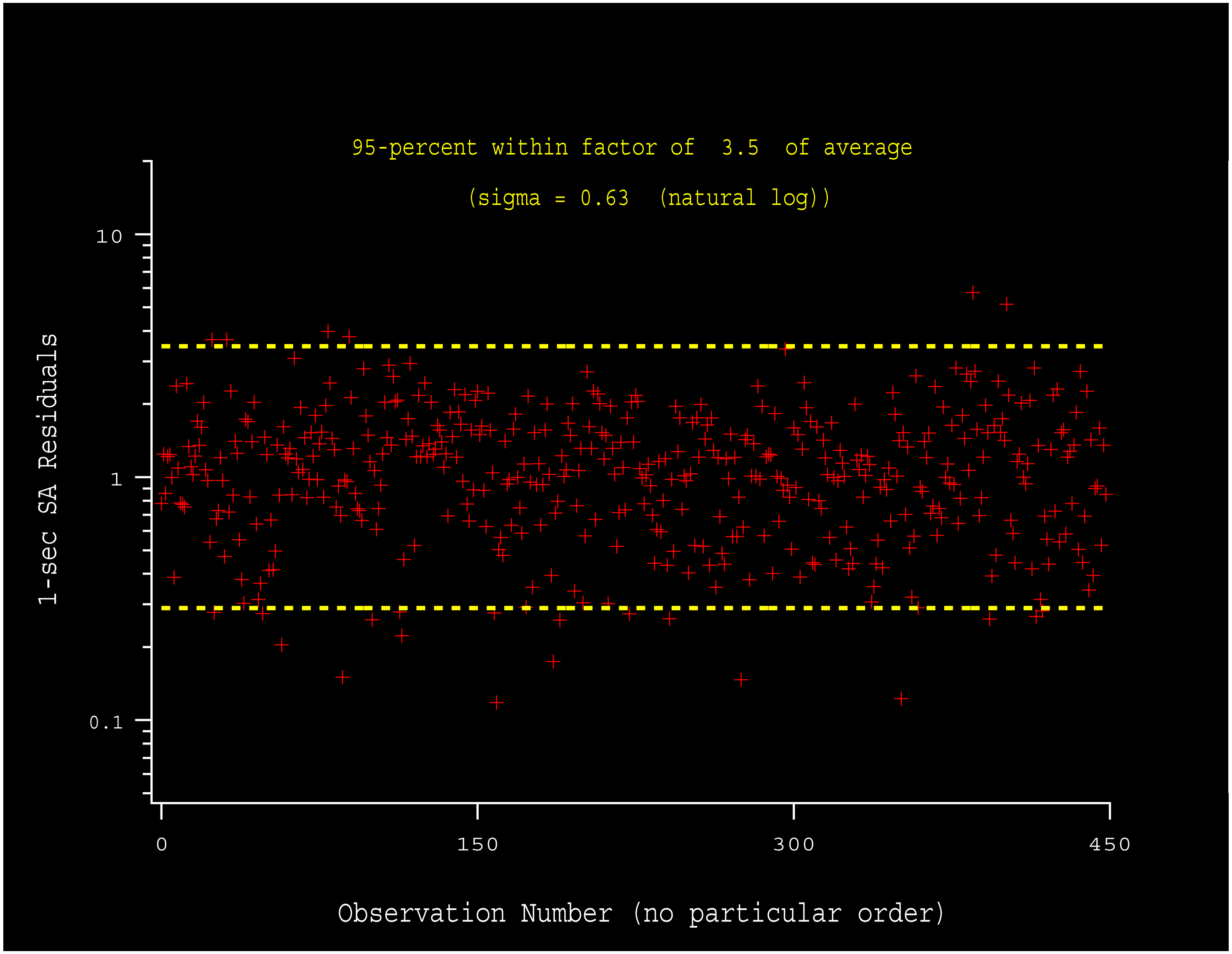
R_{RUP}

R_{JB} (0.0 for station over the fault)

What to use for the basic predictor variables?

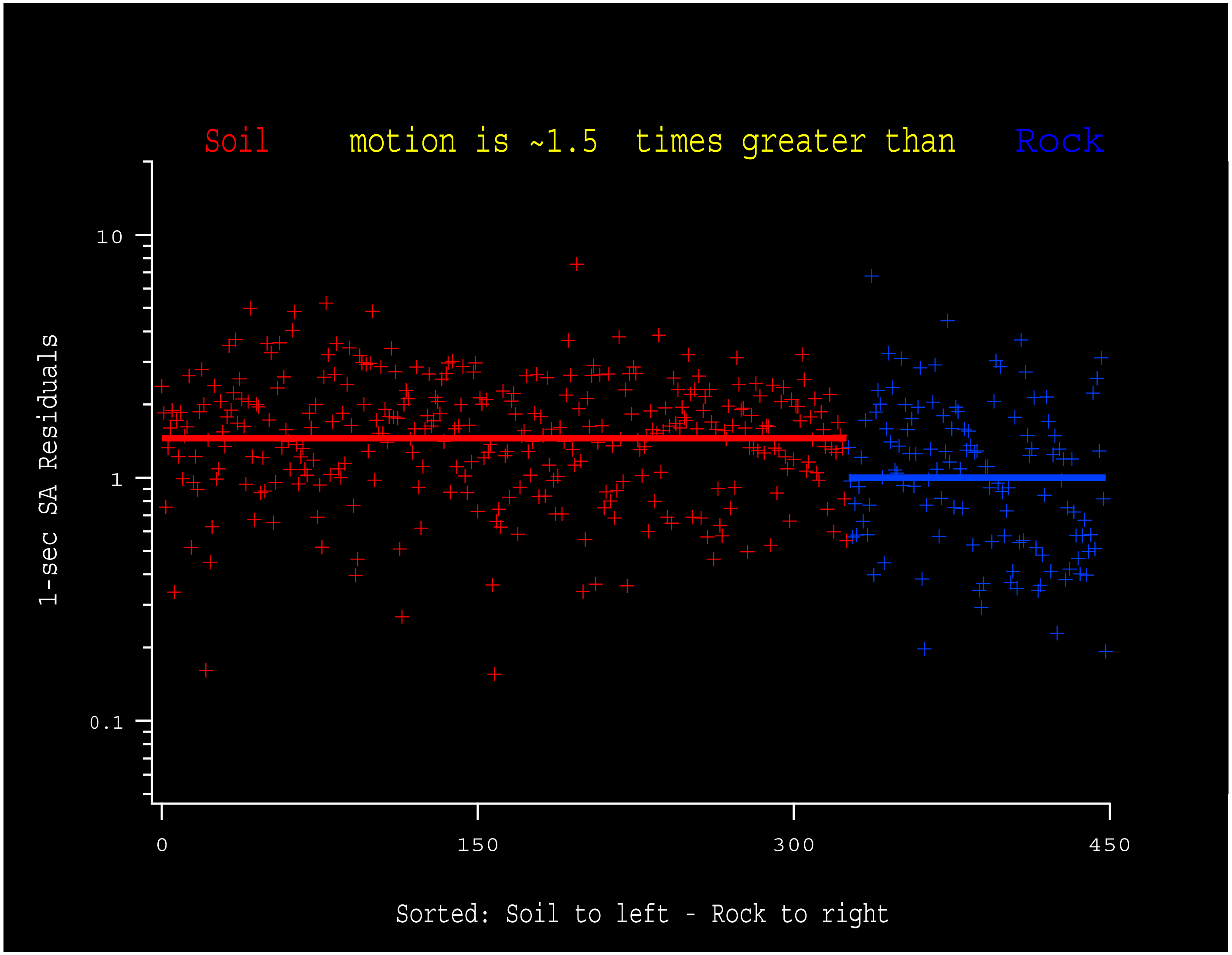
- A measure of local site geology

Uncertainty after Mag & Dist Correction



(E. Field)

Simplest: Rock vs Soil



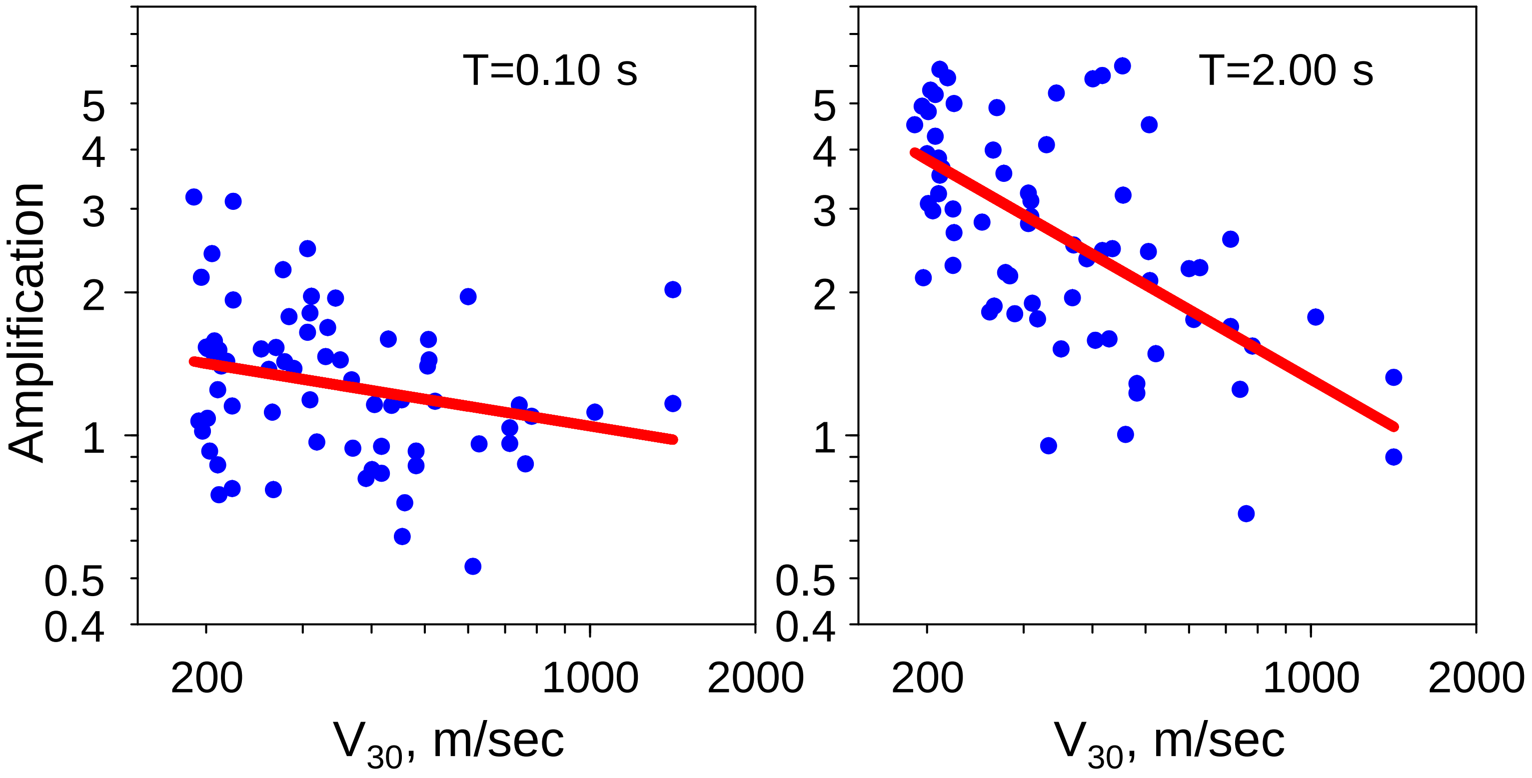
(E. Field)

Site Classifications for Use With Ground-Motion Prediction Equations

- Rock/soil
- NEHRP site classes (based on $V_{S30,}$ the time-weighted average shear-wave velocity from the surface to 30 m)
- Continuous variable (V_{S30})
- Some measure of resonant period (e.g., H/V)

V_{S30} as continuous variable

slope = b_v, where $Y \propto (V_{30})^{b_V}$

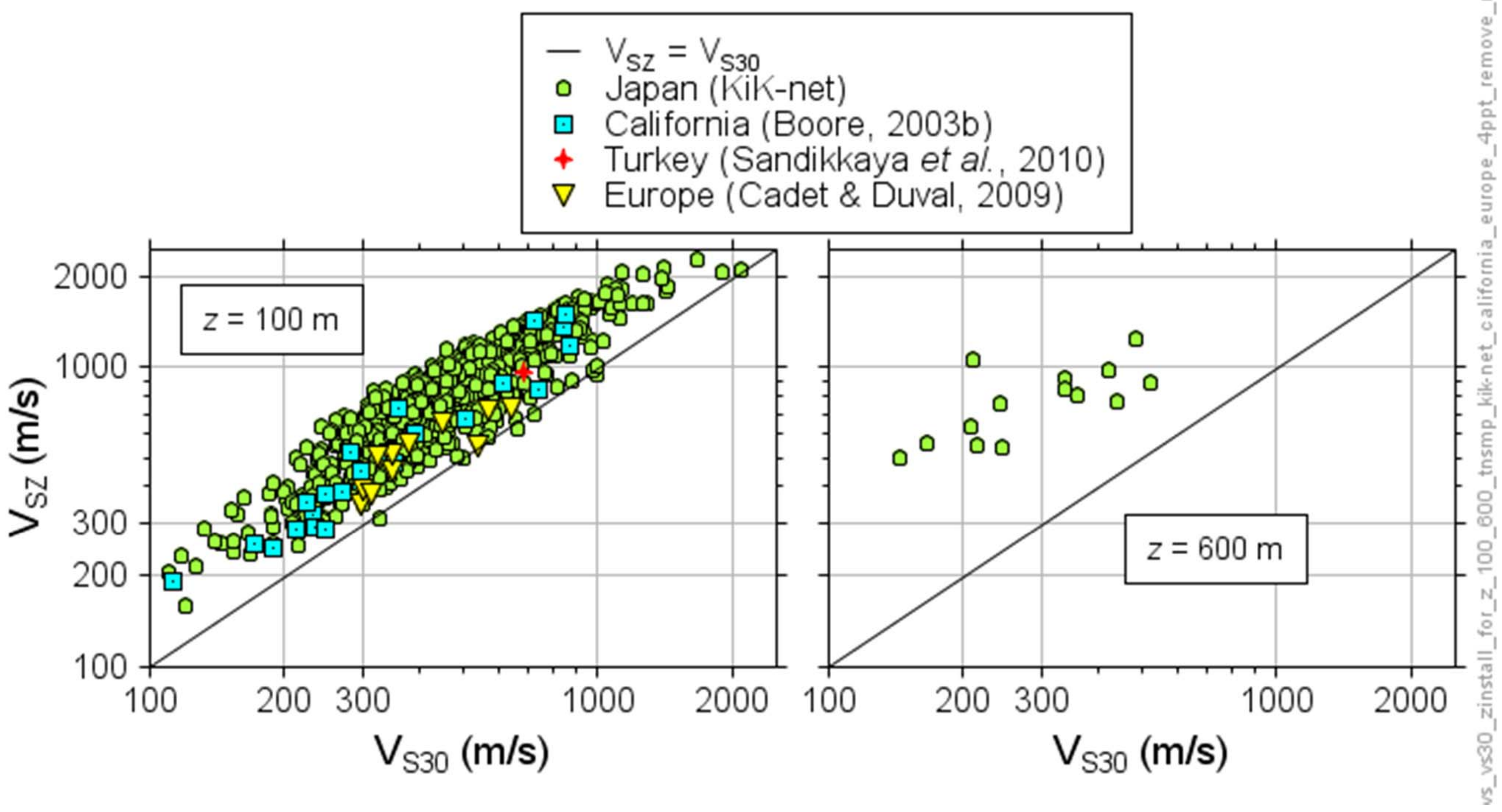


Note period dependence of site response

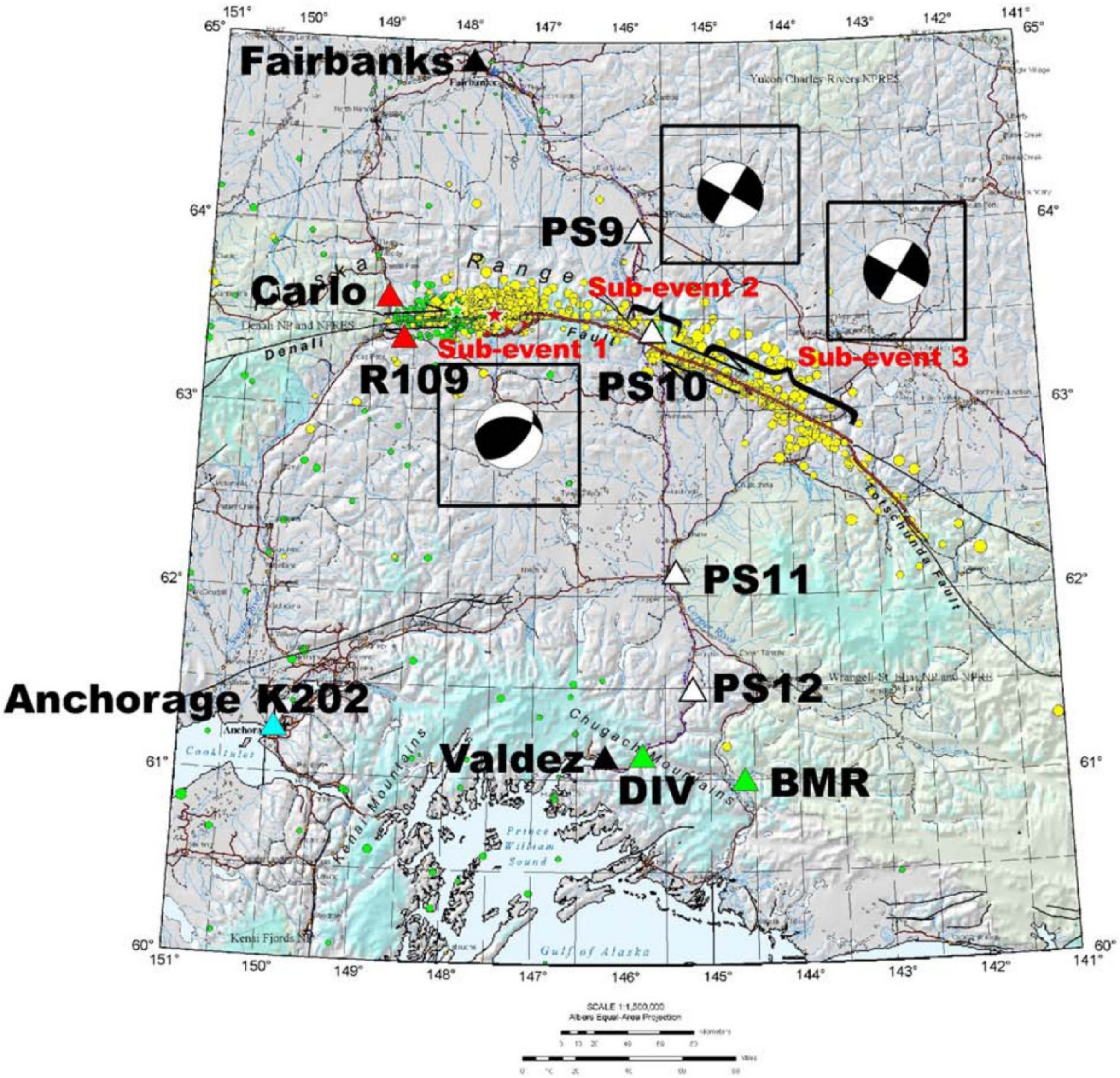
Why V_{S30}?

- Most data from 30 m holes, the average depth that could be drilled in one day
- Better: V_{Sz}, where z is determined by the wavelength for the period of interest
- Few observations of V_S are available for greater depths
- But V_{sz} correlates quite well with V_{S30} for a wide range of z greater than 30 m

V_{Sz} correlates quite well with V_{S30} for a wide range of z greater than 30 m



2002 M 7.9 Denali Fault



▲ Geophysical Inst., Univ. Of Alaska, portable

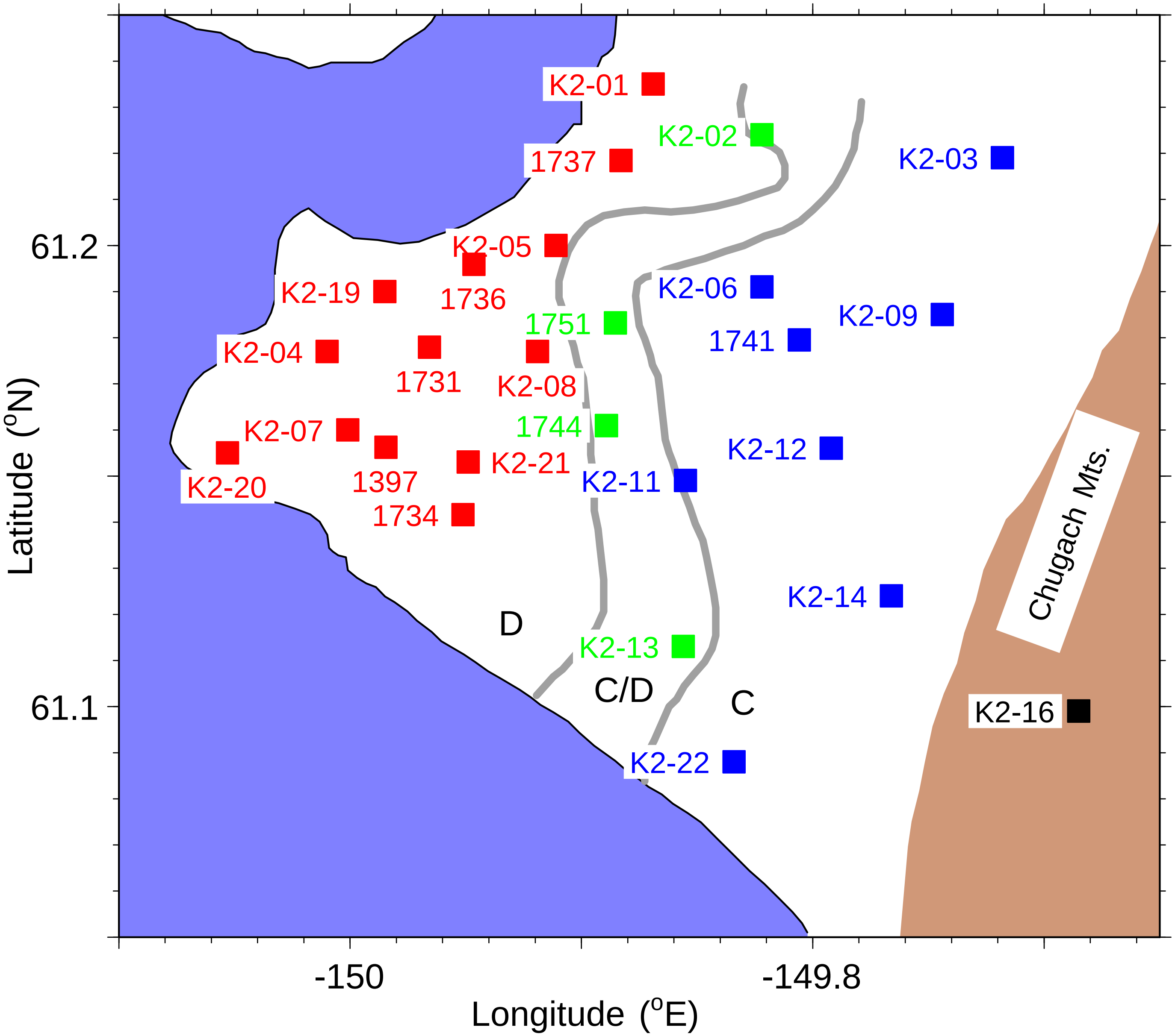
▲ Geophysical Inst., Univ. Of Alaska, permanent

▲ USGS National Strong Motion Network

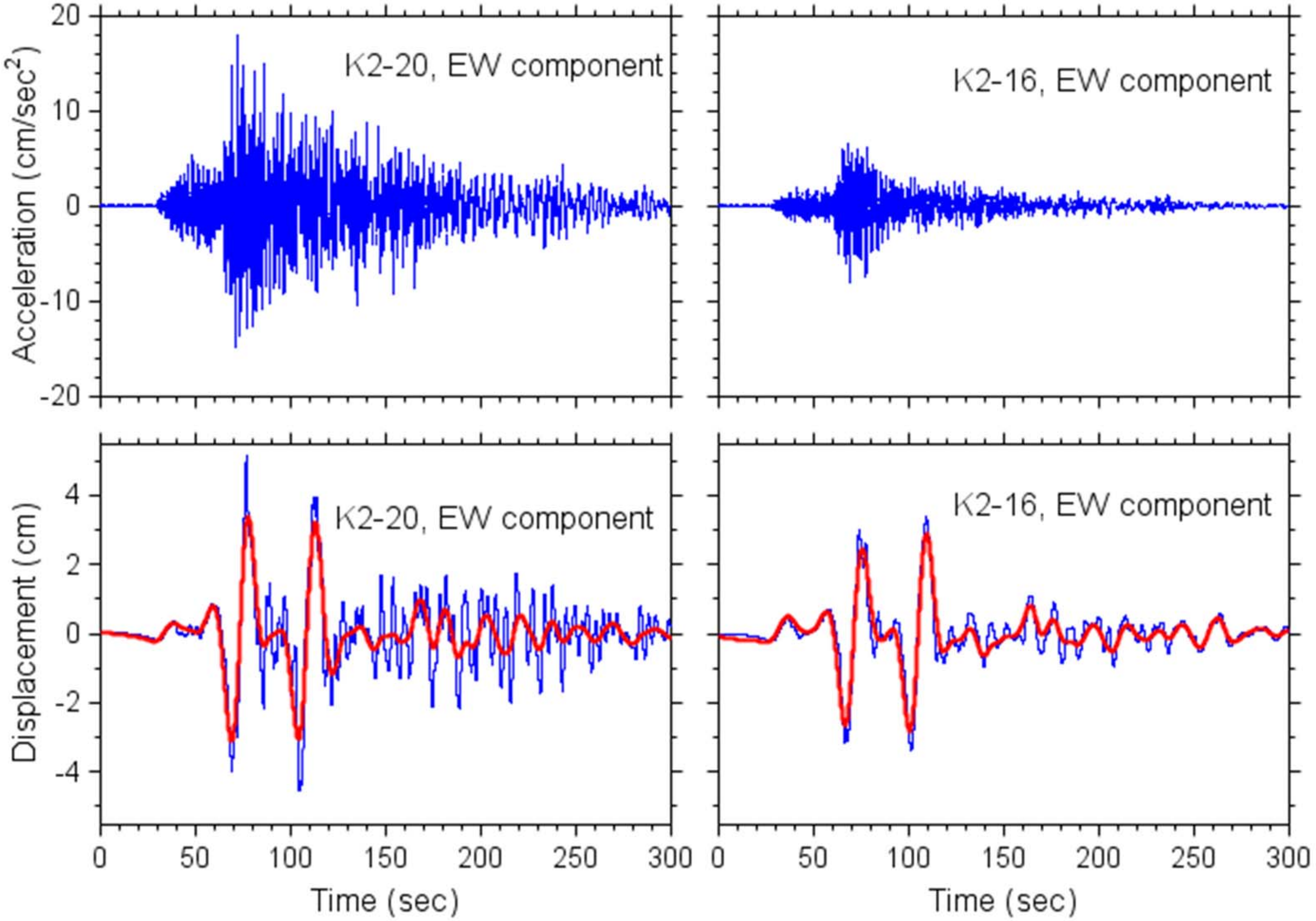
▲ CREST

△ Alyeska station

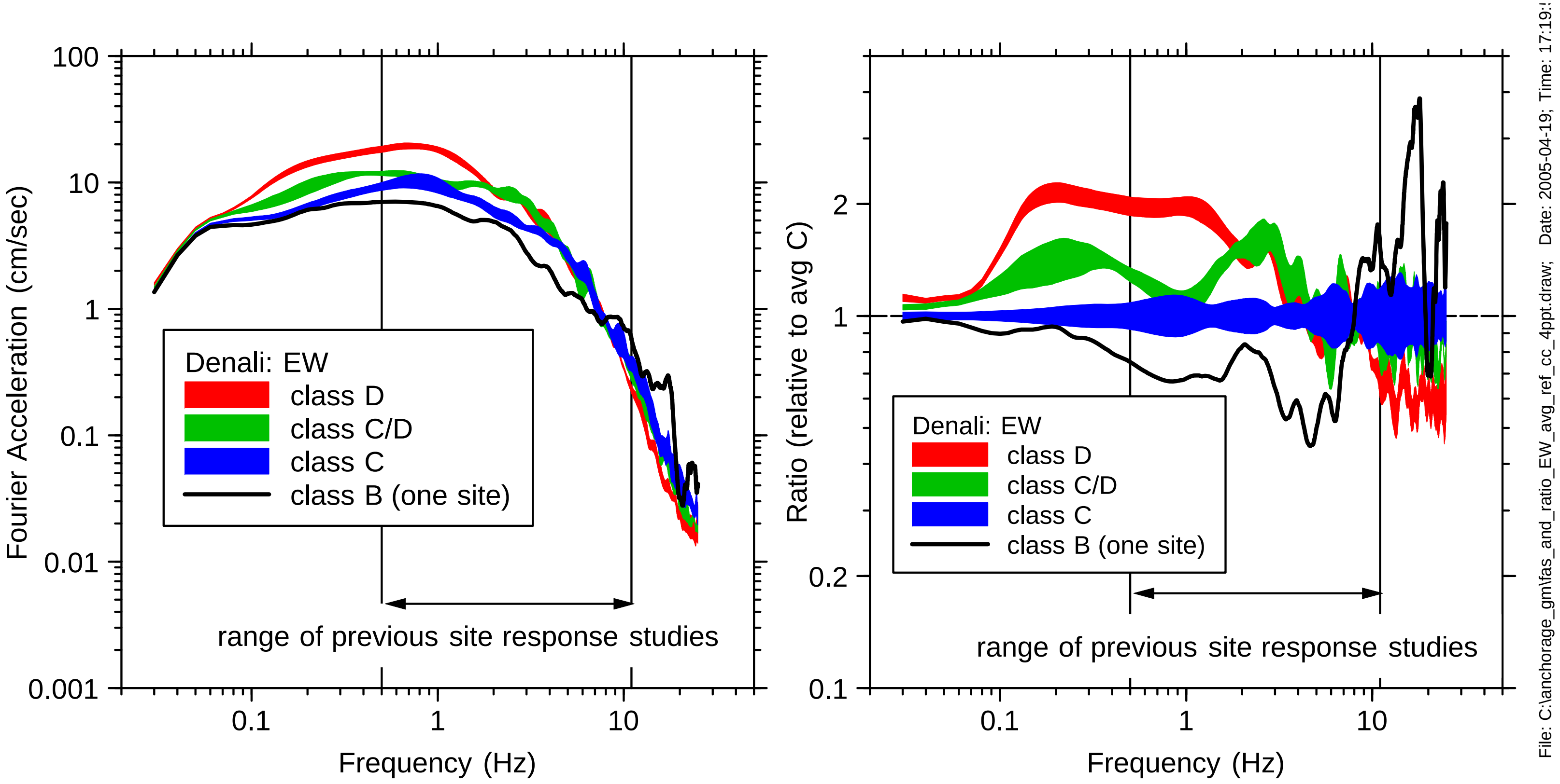
From Frankel, 2003

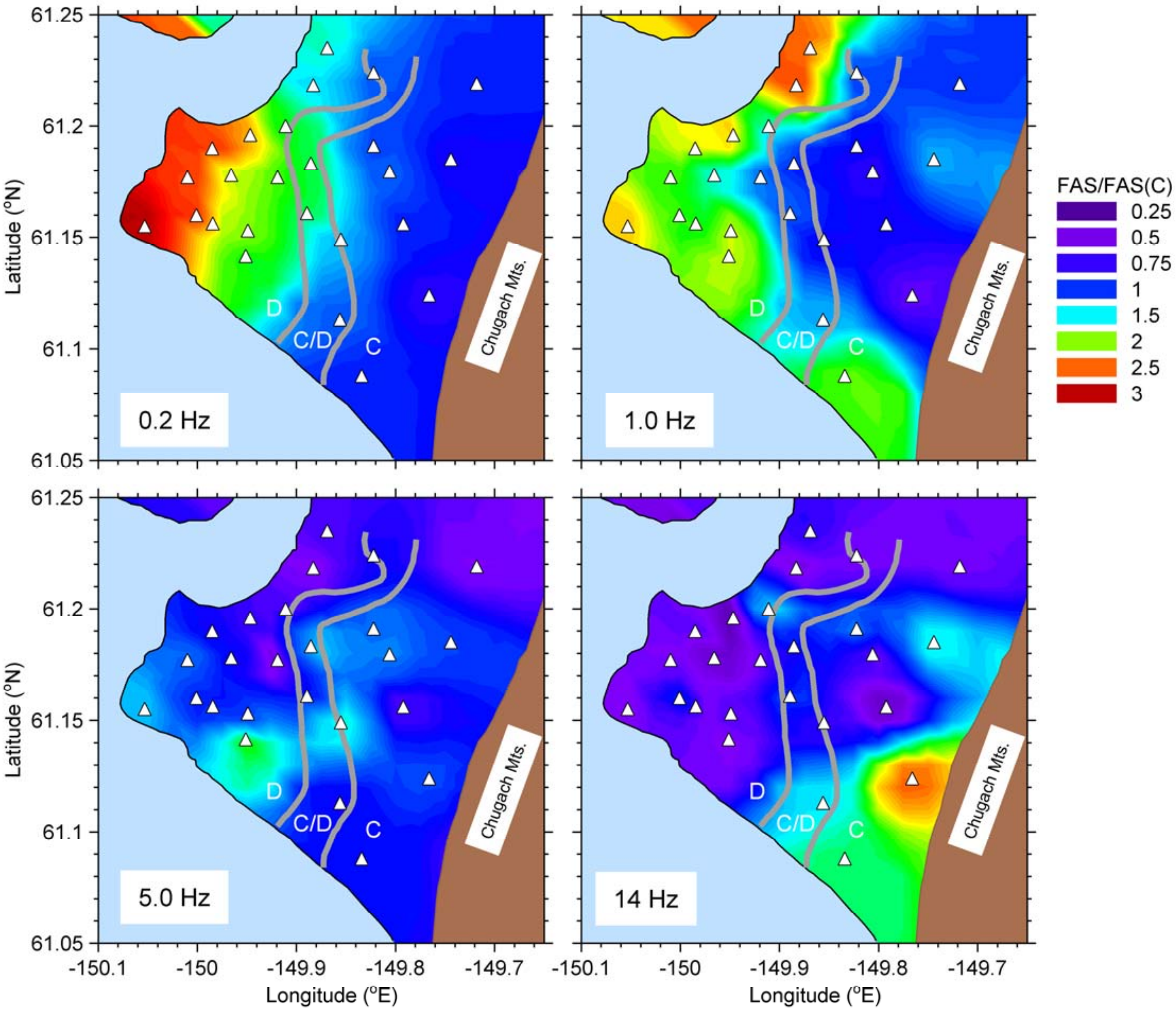


Site Classes are based on the average shear-wave velocity in the upper 30 m



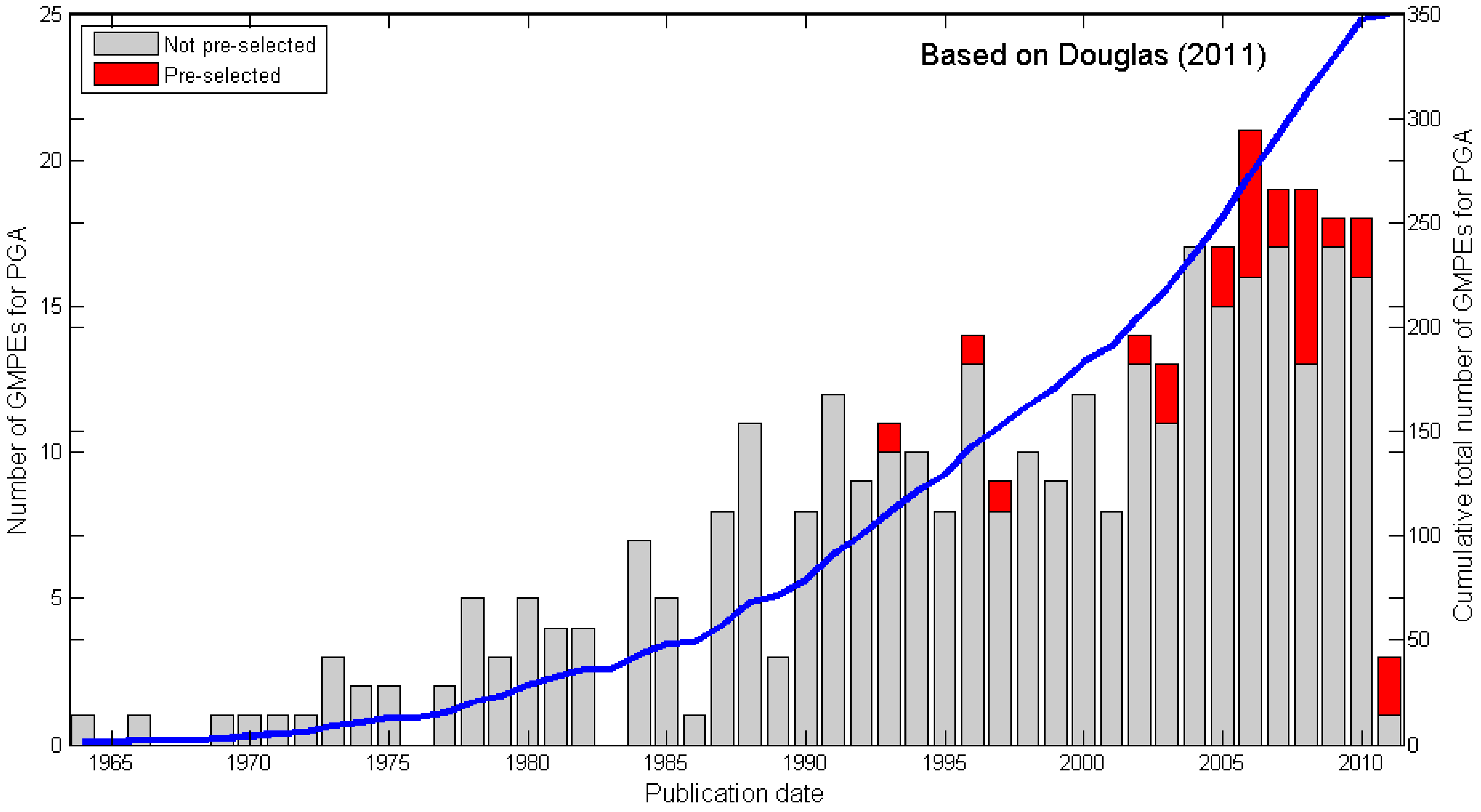
Remove high frequencies by filtering to emphasize similarity of longer-period waveforms


100
10
1
0.1
0.01
0.001
Fourier Acceleration (cm/sec)
Denali: EW
class D
class C/D
class C
class B (one site)
range of previous site response studies
0.1
1
10
Frequency (Hz)
2
1
0.2
0.1
Ratio (relative to avg C)
Denali: EW
class D
class C/D
class C
class B (one site)
range of previous site response studies
0.1
1
10
Frequency (Hz)
File: C:\anchorage_gm\fas_and_ratio_EW_avg_ref_cc_4ppt.draw; Date: 2005-04-19; Time: 17:19:!



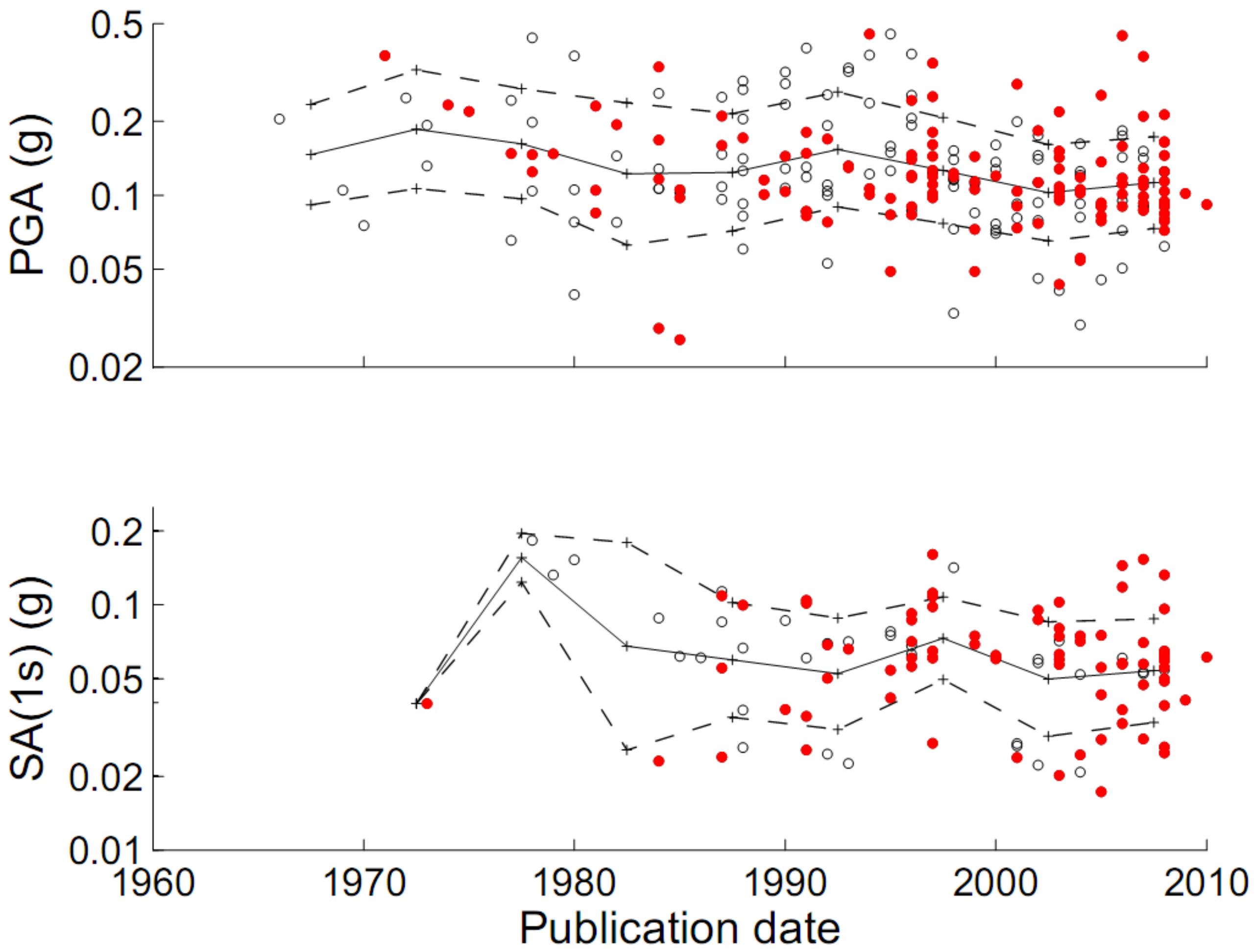
61.25
61.2
61.15
61.1
61.05
Latitude (°N)
D
C/D
C
Chugach Mts.
0.2 Hz
1.0 Hz
5.0 Hz
14 Hz
FAS/FAS(C)
0.25
0.5
0.75
1
1.5
2
2.5
3
-150.1
-150
-149.9
-149.8
-149.7
Longitude (°E)

GMPEs: The Past



Stewart et al., PEER 2013/22; Courtesy of Y. Bozorgnia

The large epistemic variations in predicted motions are not decreasing with time **(M**=6, R=20 km)



GMPEs: The Present

- Illustrate Empirical GMPEs with PEER NGA-West 2
- (**NGA** = **N**ext **G**eneration **A**ttenuation relations, although the older term "attenuation relations" has been replaced by "ground-motion prediction equations")

PEER NGA-West 2 Project Overview

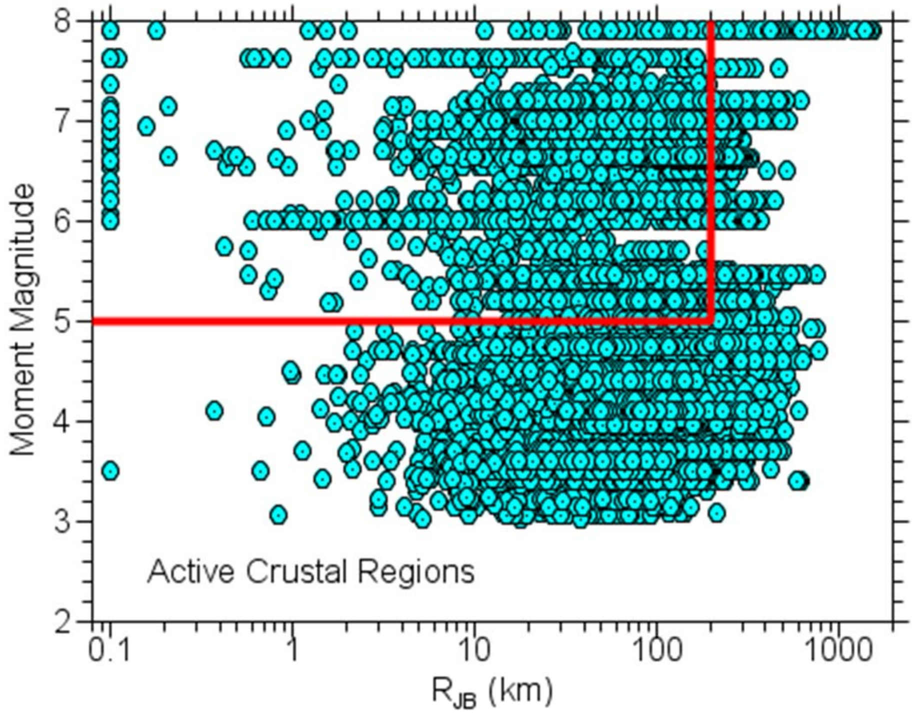
- Developer Teams (each developed their own GMPEs)
- Supporting Working Groups
  - Directivity
  - Site Response
  - Database
  - Directionality
  - Uncertainty
  - Vertical Component
  - Adjustment for Damping

NGA-West2 Developer Teams:

- Abrahamson, Silva, & Kamai (ASK14)
- Boore, Stewart, Seyhan, & Atkinson (BSSA14)
- Campbell & Bozorgnia (CB14)
- Chiou & Youngs (CY14)
- Idriss (I14)

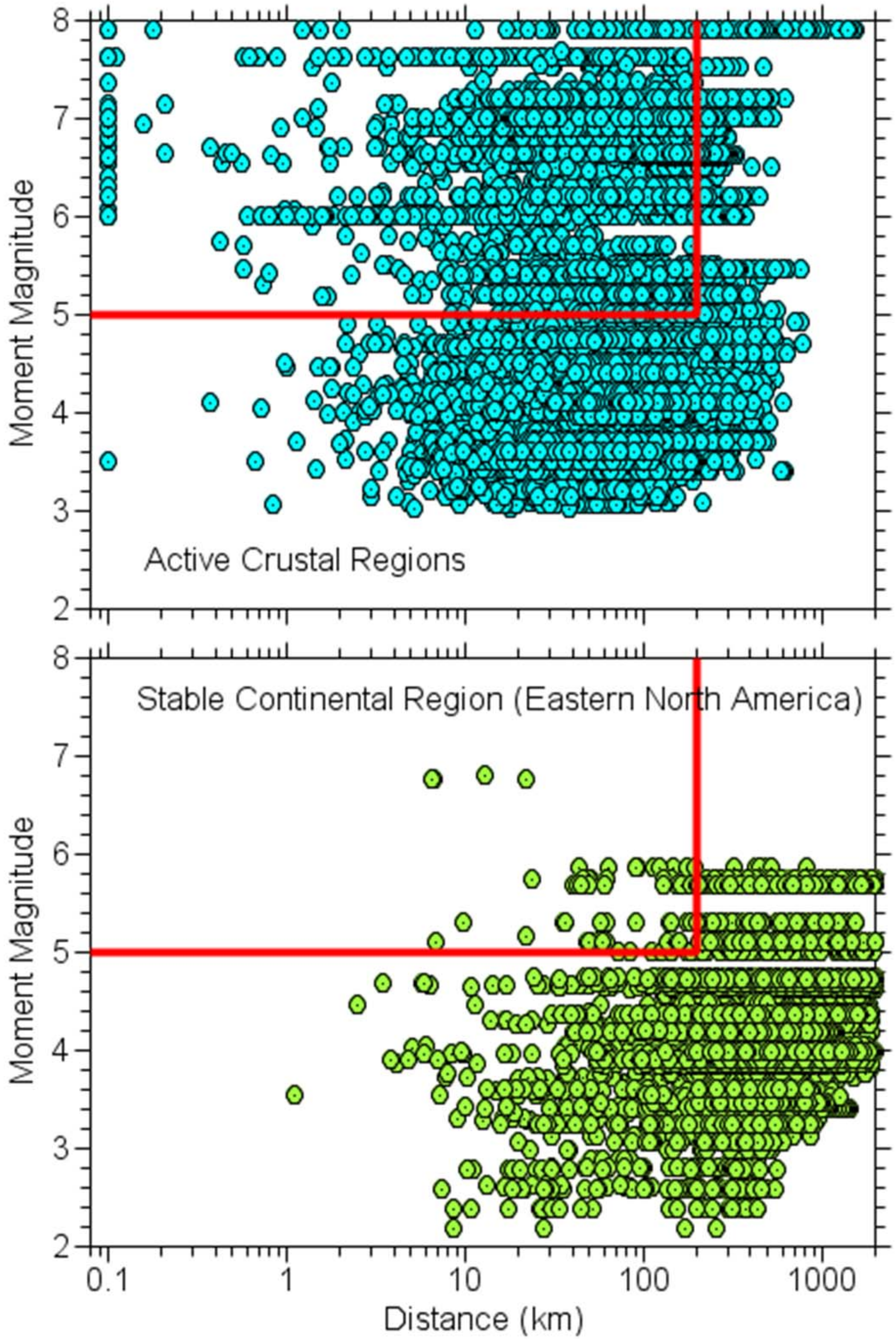
PEER NGA-West 2 Project Overview

- All developers used subsets of data chosen from a common database
  - Metadata
  - Uniformly processed strong-motion recordings
  - U.S. and foreign earthquakes
  - Active tectonic regions (**subduction, stable continental regions are separate projects**)
- **The database development was a major time-consuming effort**



Observed data generally adequate for regression, but note relative lack of data for distances less than 10 km. Data are available for few large magnitude events.

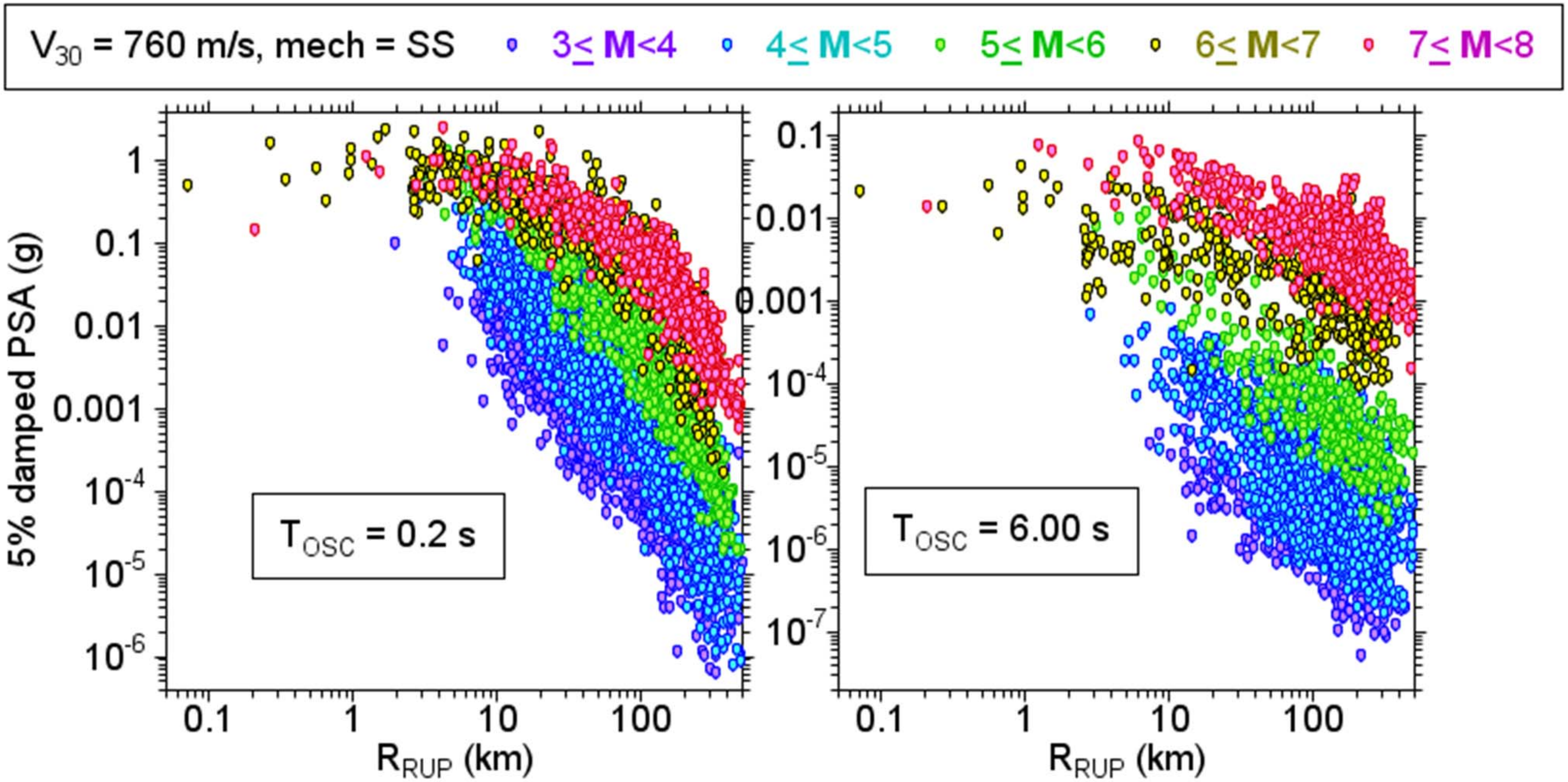
NGA-West2 database includes over 21,000 three-component recordings from more than 600 earthquakes



Observed data adequate for regression except close to large 'quakes

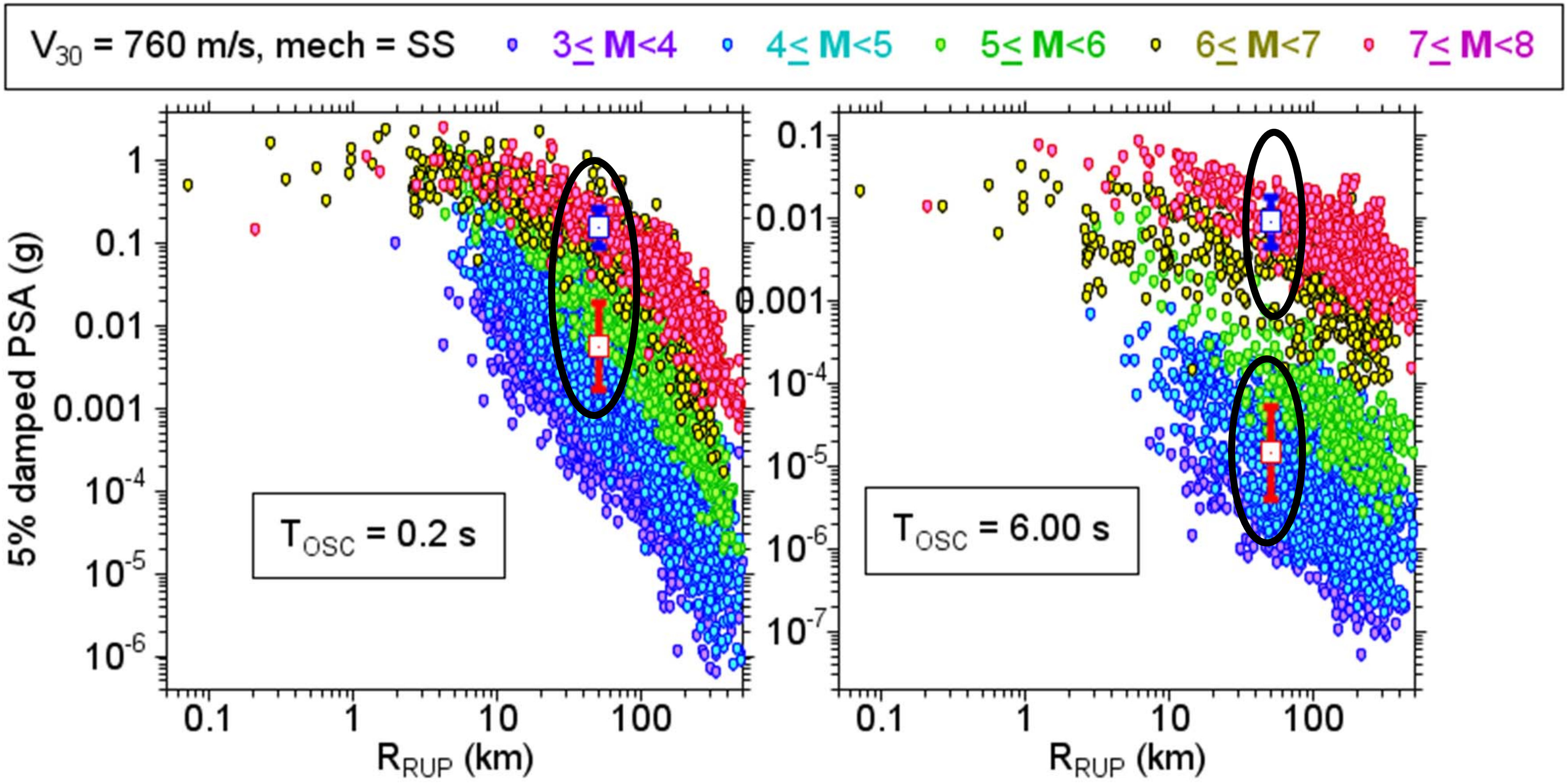
Observed data not adequate for regression, use simulated data (the subject of a different lecture)

NGA-West2 PSAs for SS events (adjusted to V_{S30}=760 m/s) vs. R_{RUP}



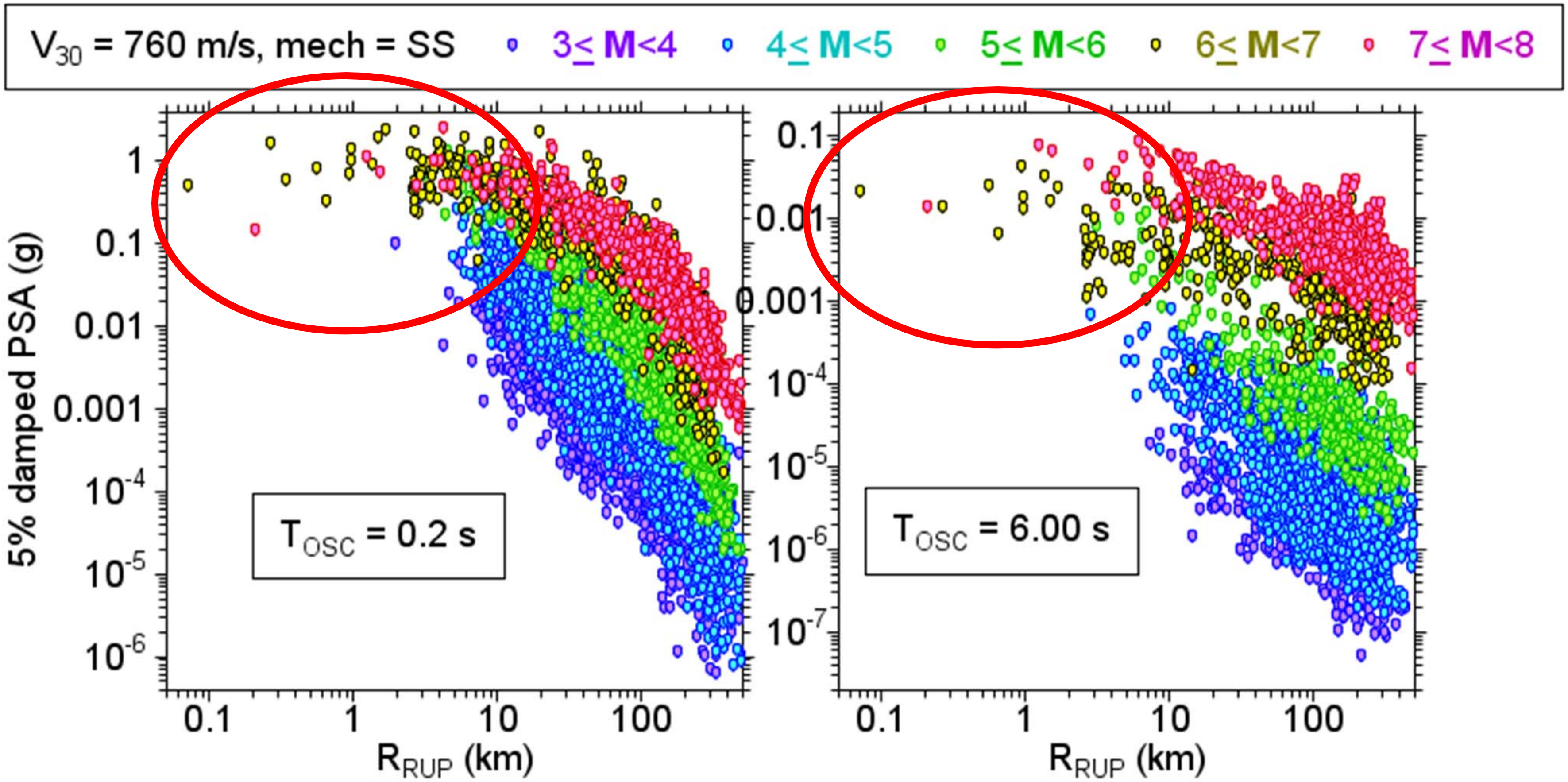
nrecs = 11,318 for T_{OSC}=0.2 s; nrecs = 3,359 for T_{OSC}=6.0 s

NGA-West2 PSAs for SS events (adjusted to V_{S30}=760 m/s) vs. R_{RUP}



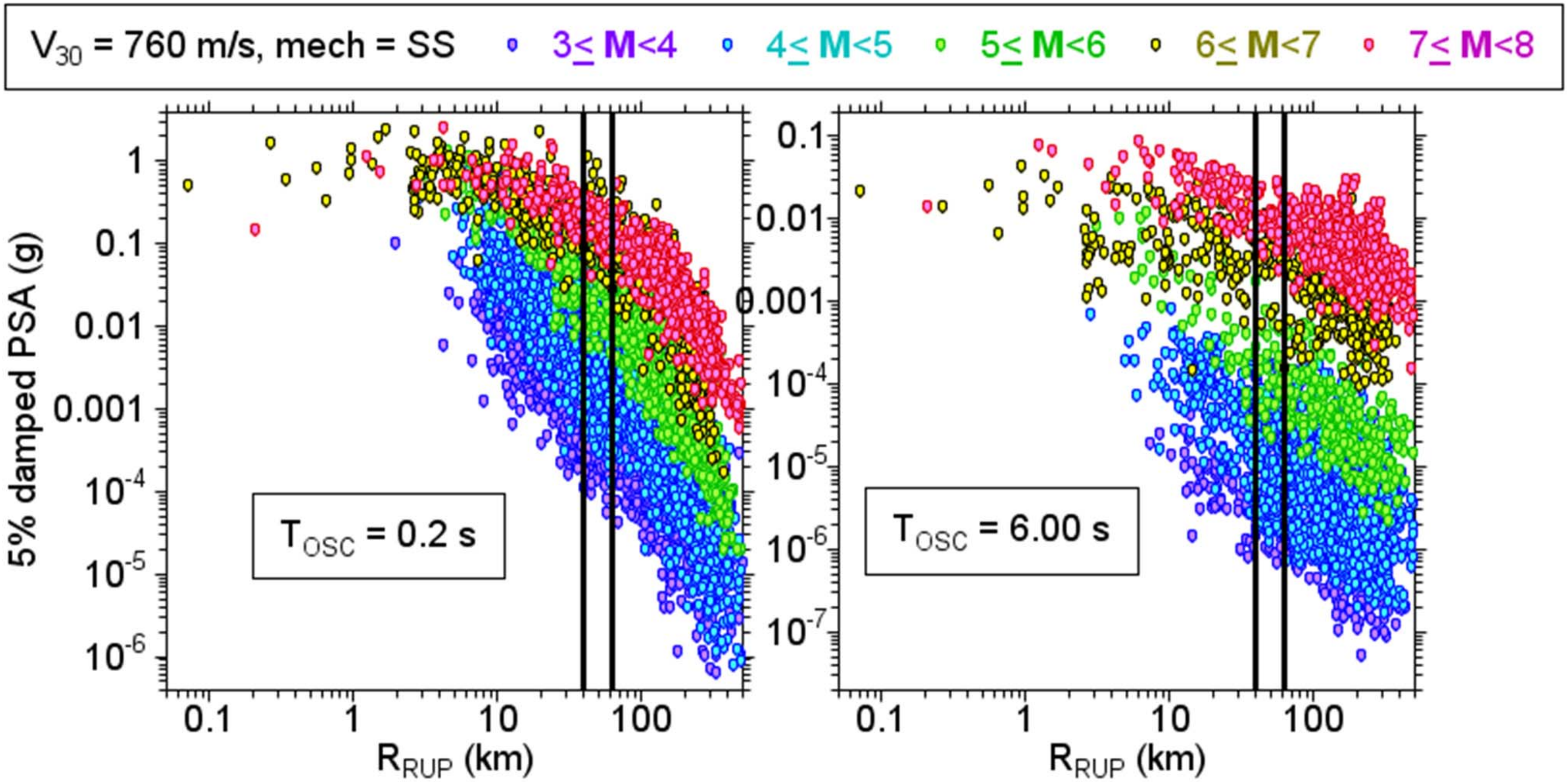
There is significant scatter in the data, with scatter being larger for small earthquakes.

NGA-West2 PSAs for SS events (adjusted to V_{S30}=760 m/s) vs. R_{RUP}



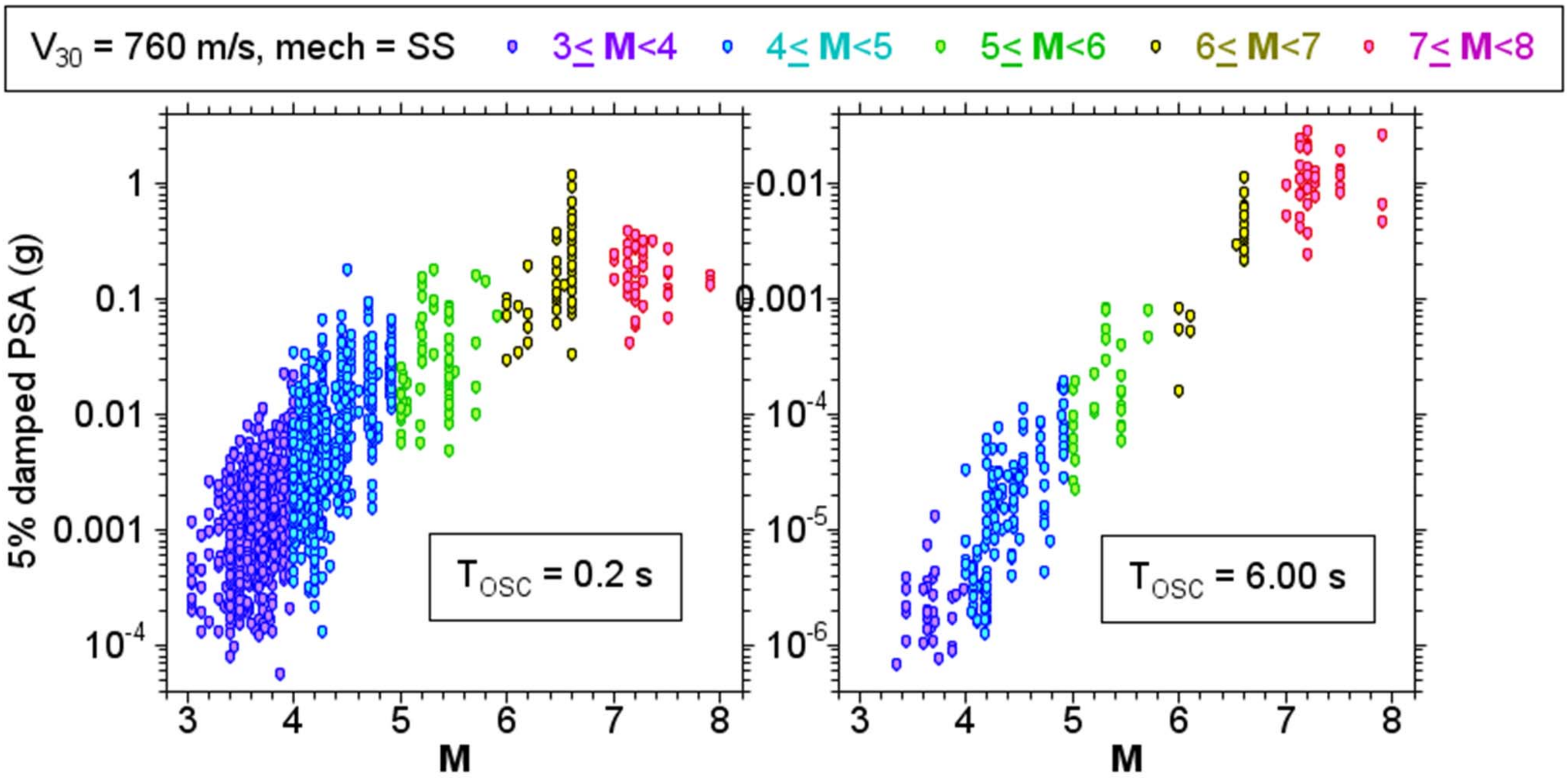
For a single magnitude and for all periods the motions tend to saturate for large earthquakes as the distance from the fault rupture to the observation point decreases.

NGA-West2 PSAs for SS events (adjusted to V_{S30}=760 m/s) vs. R_{RUP}



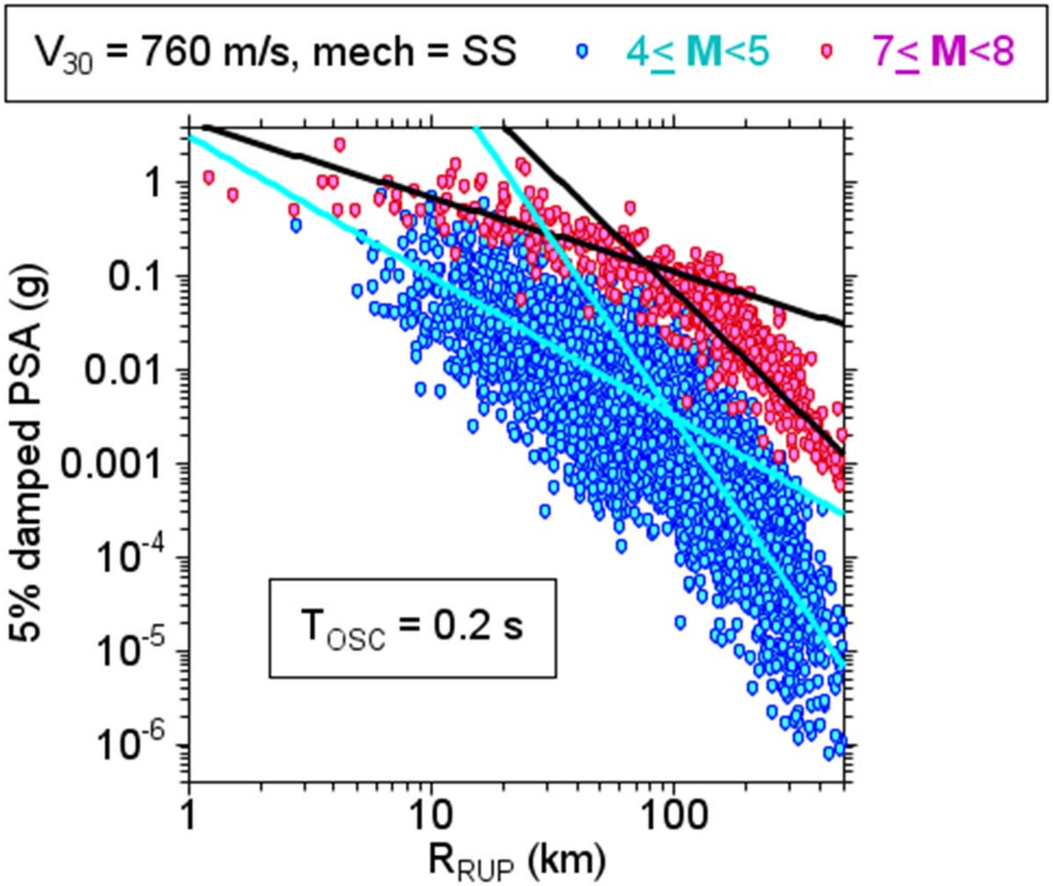
At any fixed distance the ground motion increases with magnitude in a nonlinear fashion, with a tendency to saturate for large magnitudes, particularly for shorter period motions. To show this, the next slide is a plot of PSA within the R_{RUP} bands vs. M.

NGA-West2 PSAs for SS events (adjusted to V_{S30}=760 m/s) vs. R_{RUP}



At any fixed distance (centered on 50 km here, including PSA in the 40 km to 62.5 km range) the ground motion increases with magnitude in a nonlinear fashion, with a tendency to saturate for large magnitudes, particularly for shorter period motions. PSA for larger magnitudes is more sensitive to M for long-period motions than for short-period motions

NGA-West2 PSAs for SS events (adjusted to V_{S30}=760 m/s) vs. R_{RUP}



For a given period and magnitude the median ground motions decay with distance; this decay shows curvature at greater distances, more pronounced for short than long periods.

(lines are drawn by eye and are intended to give a qualitative indication of the trends)

Characteristics of Data that GMPEs need to capture

- Change of amplitude with distance for fixed magnitude
- Possible regional variations in the distance dependence
- Change of amplitude with magnitude after removing distance dependence
- Site dependence (including basin depth dependence and nonlinear response)
- Earthquake type, hanging wall, depth to top of rupture, etc.
- Scatter

In 1994

- Typical functional form of GMPEs

$$\ln Y = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_V \ln \frac{V_S}{V_A}$$

$$b_1 = \begin{cases} b_{1SS} & \text{for strike-slip earthquakes;} \\ b_{1RS} & \text{for reverse-slip earthquakes;} \\ b_{1ALL} & \text{if mechanism is not specified.} \end{cases}$$

$$r = \sqrt{r_{jb}^{\;2} + h^2}$$

(Boore, Joyner, and Fumal, 1994)

(Courtesy of Yousef Bozorgnia)

Twenty years later…

$$\ln Y = \begin{cases} \ln PGA; & PSA < PGA \text{ and } T < 0.25 \text{ s} \\ f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed} + f_{hyp} + f_{dip} + f_{atn}; & \text{otherwise} \end{cases}$$

$$f_{mag} = \begin{cases} c_0 + c_1\mathbf{M}; & \mathbf{M} \le 4.5 \\ c_0 + c_1\mathbf{M} + c_2(\mathbf{M} - 4.5); & 4.5 < \mathbf{M} \le 5.5 \\ c_0 + c_1\mathbf{M} + c_2(\mathbf{M} - 4.5) + c_3(\mathbf{M} - 5.5); & 5.5 < \mathbf{M} \le 6.5 \\ c_0 + c_1\mathbf{M} + c_2(\mathbf{M} - 4.5) + c_3(\mathbf{M} - 5.5) + c_4(\mathbf{M} - 6.5); & \mathbf{M} > 6.5 \end{cases}$$

$$f_{dis} = (c_5 + c_6\mathbf{M})\ln\left(\sqrt{R_{RUP}^2 + c_7^2}\right)$$

$$f_{flt} = f_{flt,F} f_{flt,M}$$

$$f_{flt,F} = c_8 F_{RV} + c_9 F_{NM}$$

$$f_{flt,M} = \begin{cases} 0; & \mathbf{M} \le 4.5 \\ \mathbf{M} - 4.5; & 4.5 < \mathbf{M} \le \\ 1; & \mathbf{M} > 5.5 \end{cases}$$

$$f_{hng} = c_{10} f_{hng,R_X} f_{hng,R_{RUP}} f_{hng,M} f_{hng,Z} f_{hng,\delta}$$

$$f_{hng,R_X} = \begin{cases} 0; & R_X < 0 \\ f_1(R_X); & 0 \le R_X < R_1 \\ \max[f_2(R_X), 0]; & R_X \ge R_1 \end{cases}$$

$$f_1(R_X) = h_1 + h_2(R_X/R_1) + h_3(R_X/R_1)^2$$

$$f_2(R_X) = h_4 + h_5\left(\frac{R_X - R_1}{R_2 - R_1}\right) + h_6\left(\frac{R_X - R_1}{R_2 - R_1}\right)^2$$

$$R_1 = W\cos(\delta)$$

$$R_2 = 62\mathbf{M} - 350$$

$$f_{hng,R_{RUP}} = \begin{cases} 1; & R_{RUP} = 0 \\ (R_{RUP} - R_{JB}) / R_{RUP}; & R_{RUP} > 0 \end{cases}$$

$$f_{hng,M} = \begin{cases} 0; & \mathbf{M} \le 5.5 \\ (\mathbf{M} - 5.5)[1 + a_2(\mathbf{M} - 6.5)]; & 5.5 < \mathbf{M} \le 6.5 \\ 1 + a_2(\mathbf{M} - 6.5); & \mathbf{M} > 6.5 \end{cases}$$

$$f_{hng,Z} = \begin{cases} 1 - 0.06\,Z_{TOR}; & Z_{TOR} \le 16.66 \\ 0; & Z_{TOR} > 16.66 \end{cases}$$

$$f_{hng,\delta} = (90 - \delta)/45$$

$$f_{site} = f_{site,G} + S_J f_{site,J}$$

$$f_{site,G} = \begin{cases} c_{11}\ln\left(\frac{V_{S30}}{k_1}\right) + k_2\left\{\ln\left[A_{1100} + c\left(\frac{V_{S30}}{k_1}\right)^n\right] - \ln\left[A_{1100} + c\right]\right\}; & V_{S30} \le k_1 \\ (c_{11} + k_2 n)\ln\left(\frac{V_{S30}}{k_1}\right); & V_{S30} > k_1 \end{cases}$$

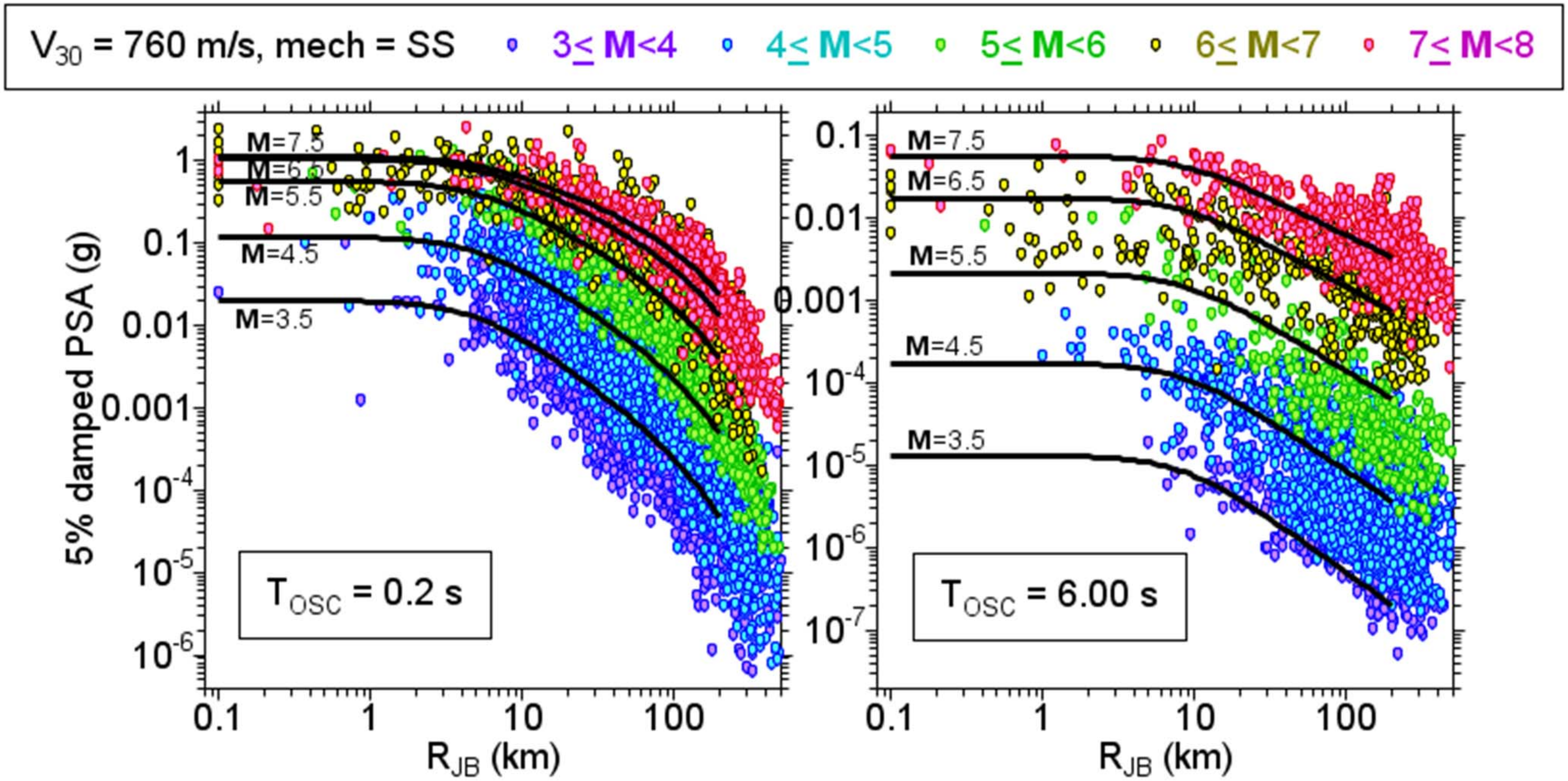
$$f_{site,J} = \begin{cases} (c_{12} + k_2 n)\left[\ln\left(\frac{V_{S30}}{k_1}\right) - \ln\left(\frac{200}{k_1}\right)\right]; & V_{S30} \le 200 \\ (c_{13} + k_2 n)\ln\left(\frac{V_{S30}}{k_1}\right); & \text{All } V_{S30} \end{cases}$$

(Courtesy of Yousef Bozorgnia)

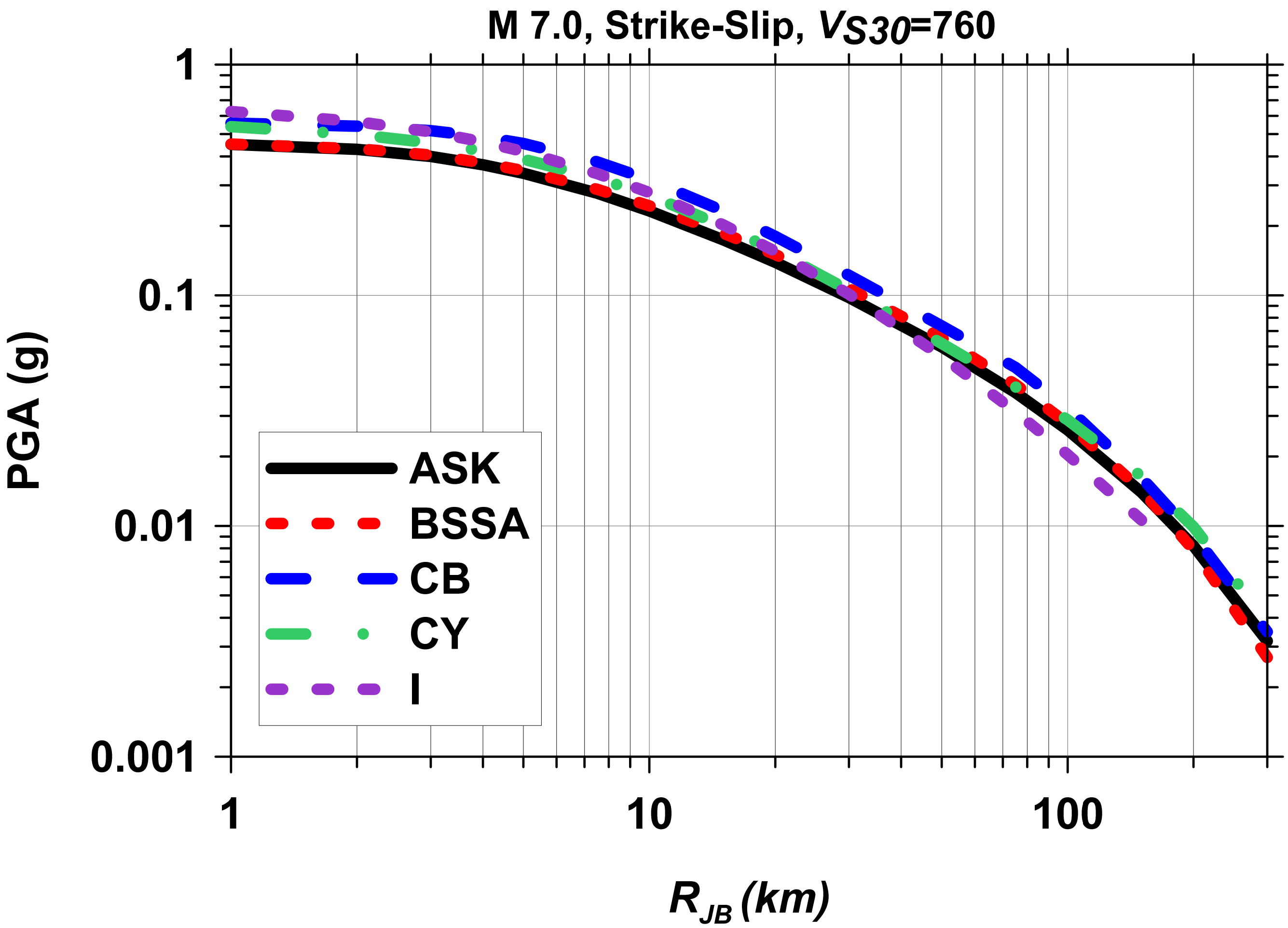
- Need complicated equations to capture effects of:
  - **M**: 3 to 8.5 (strike-slip)
  - Distance: 0 to 300km
  - Hanging wall and footwall sites
  - Soil V_{S30}: 150-1500 m/sec
  - Soil nonlinearity
  - Deep basins
  - Strike-slip, Reverse, Normal faulting mechanisms
  - Period: 0-10 seconds
- The BSSA14 GMPEs are probably the simplest, but there may be situations where they should be used with caution (e.g., over a dipping fault).

Courtesy of Yousef Bozorgnia)

Adding BSSA14 curves to data plots shown before

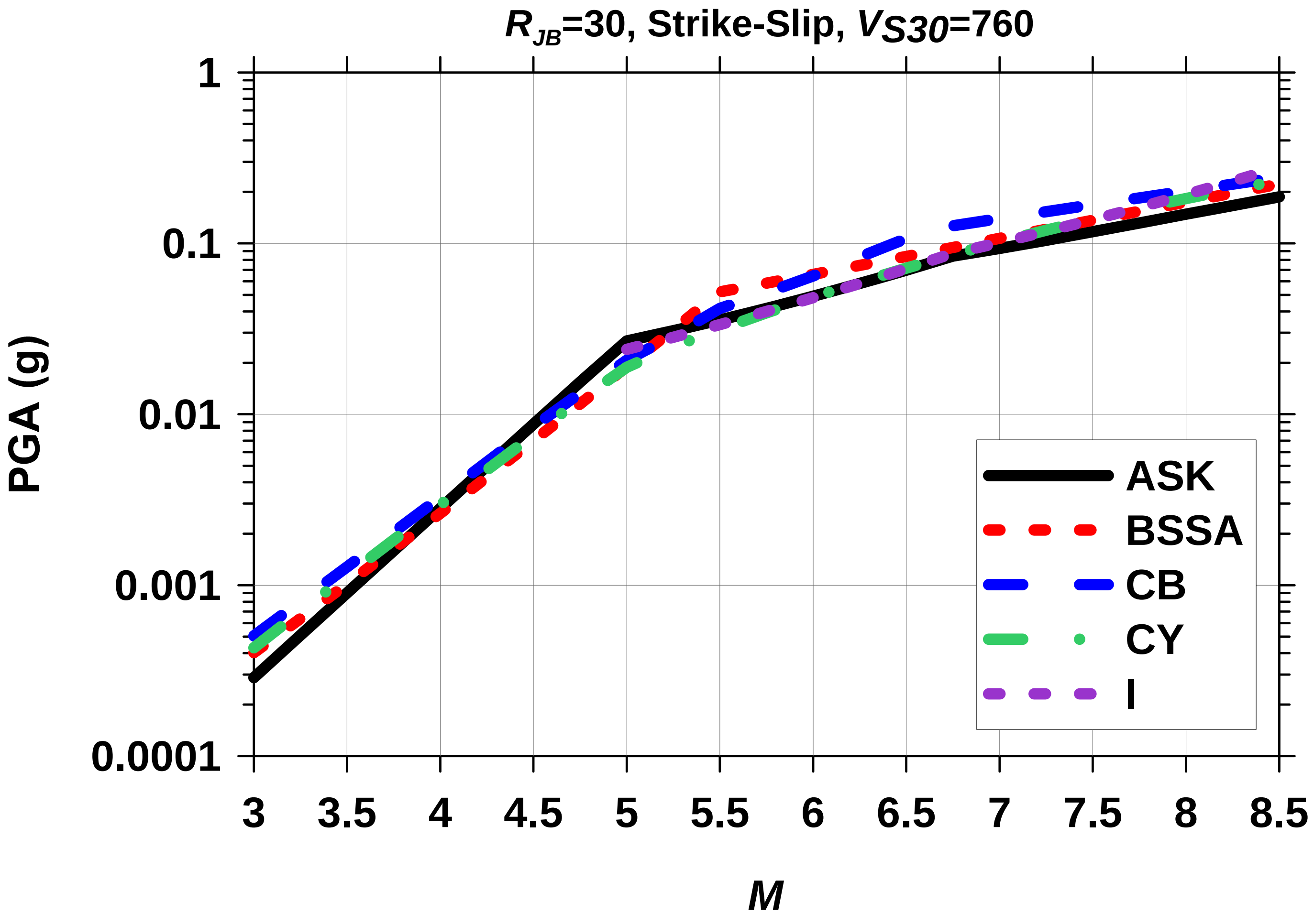


Example of comparison of horizontal GMPEs



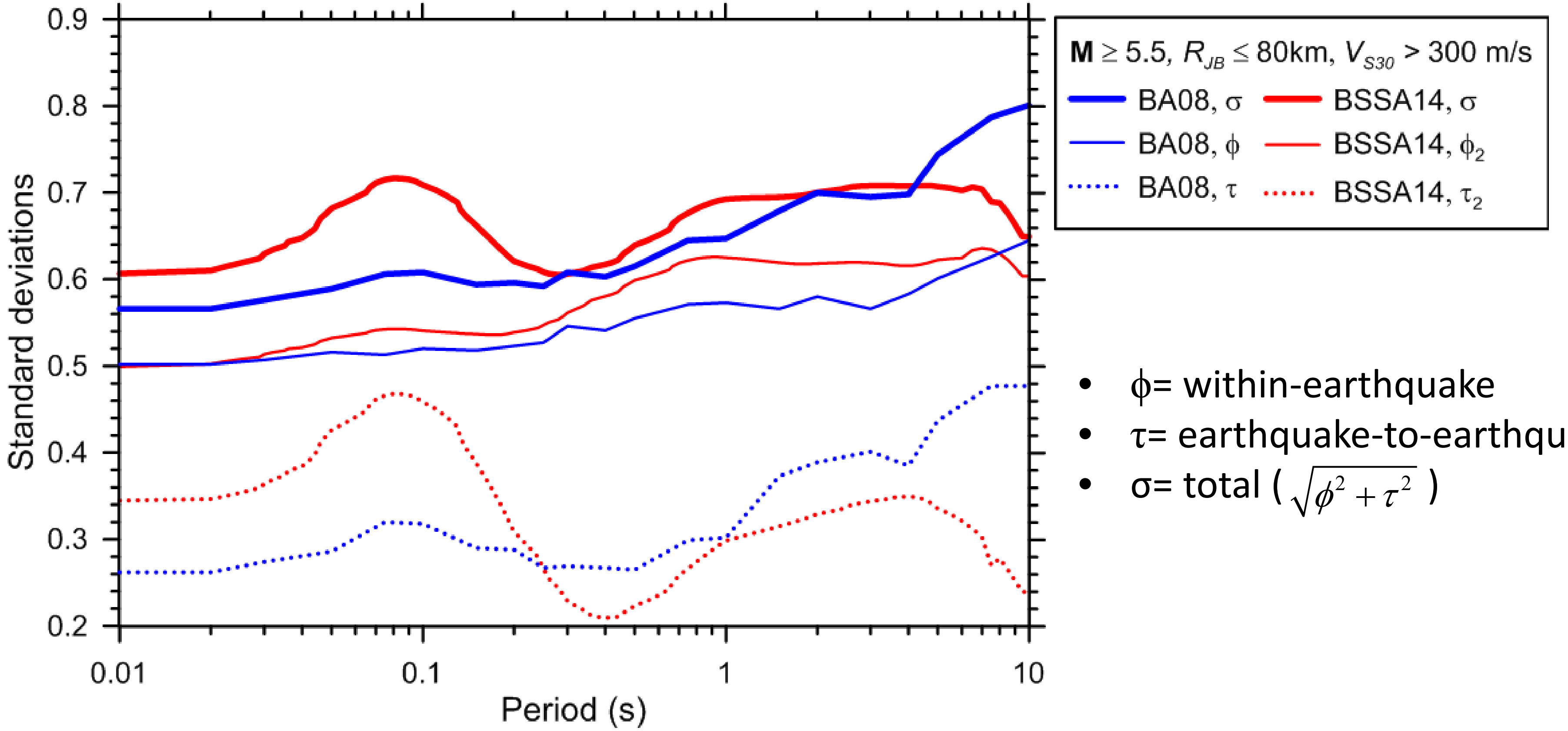
Courtesy of Y. Bozorgnia

Example of comparison of horizontal GMPEs



Courtesy of Y. Bozorgnia

Comparison of BSSA14 and BA08 Aleatory Uncertainties



- ϕ= within-earthquake
- τ= earthquake-to-earthquake
- σ= total ($\sqrt{\phi^2 + \tau^2}$)

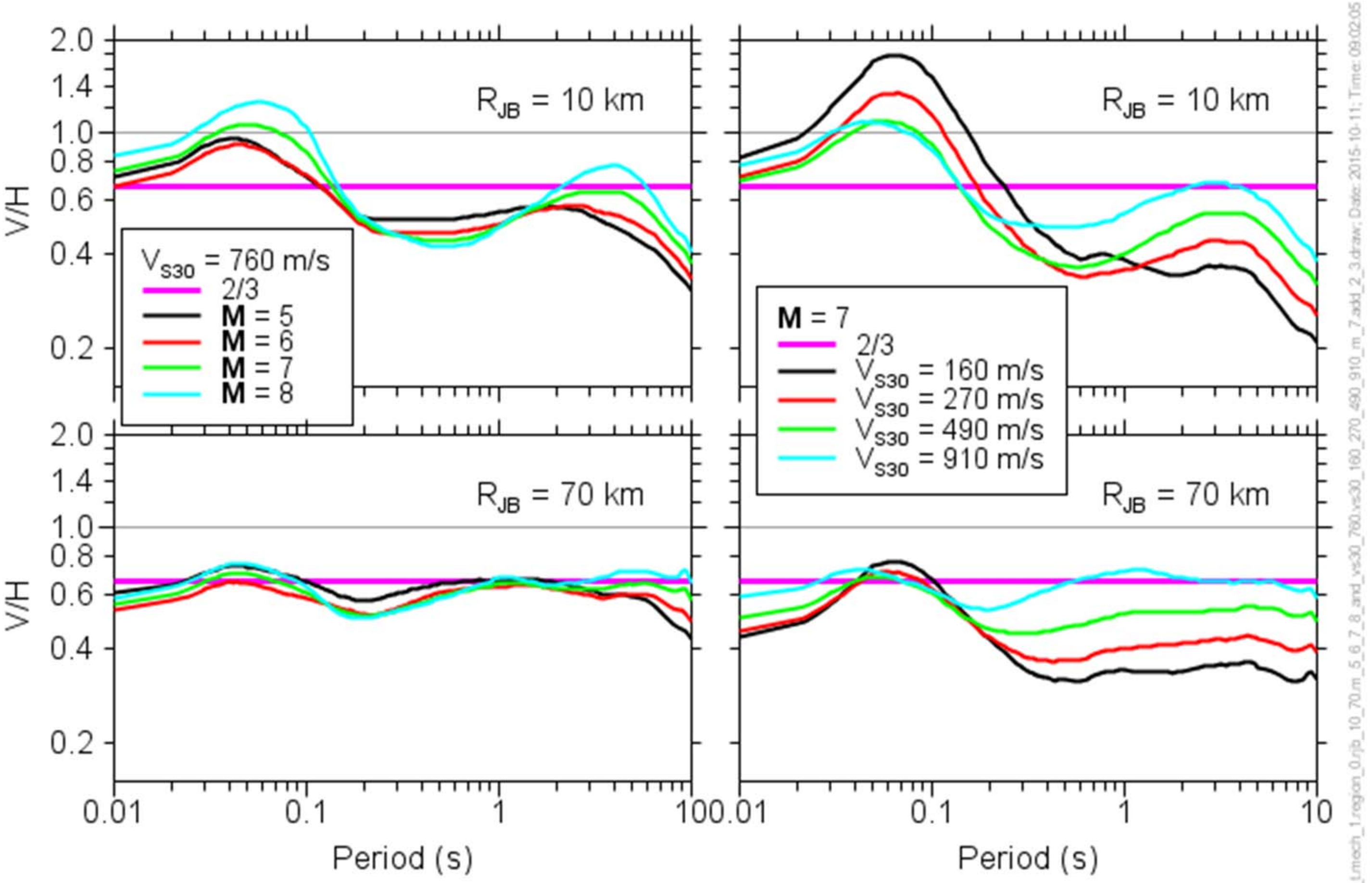
Vertical Component Results (Stewart et al., 2015) (SBSA15):

Compared to our horizontal-component GMPEs

- attenuation rates are broadly comparable (somewhat slower geometric spreading, faster apparent
- anelastic attenuation)
- V_{S30}-scaling is reduced
- nonlinear site response is much weaker
- within-earthquake variability is comparable
- earthquake-to-earthquake variability is greater

V/H (SBSA15/BSSA14)

- V>H for short periods, close distances
- V/H generally less than 2/3 (“rule-of-thumb” value)
- V/H strongly dependent on Vs30 for longer periods (because of greater Vs30 scaling of H component)
- V/H not strongly dependent on **M**, in general



GMPEs: The Future

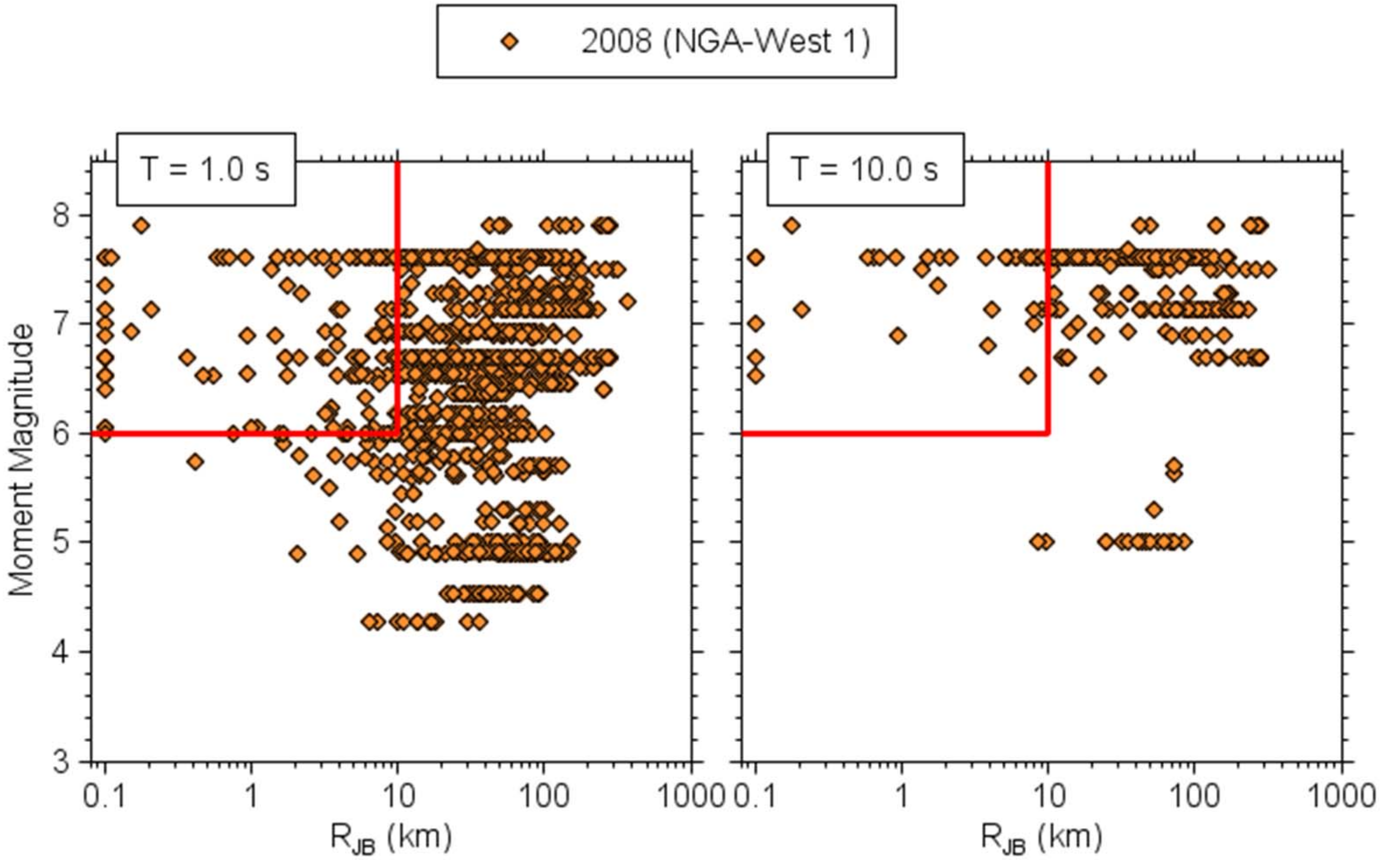
- Future PEER NGA Work
- Using simulations to fill in gaps in existing recorded motions

NGA: 2014 and beyond

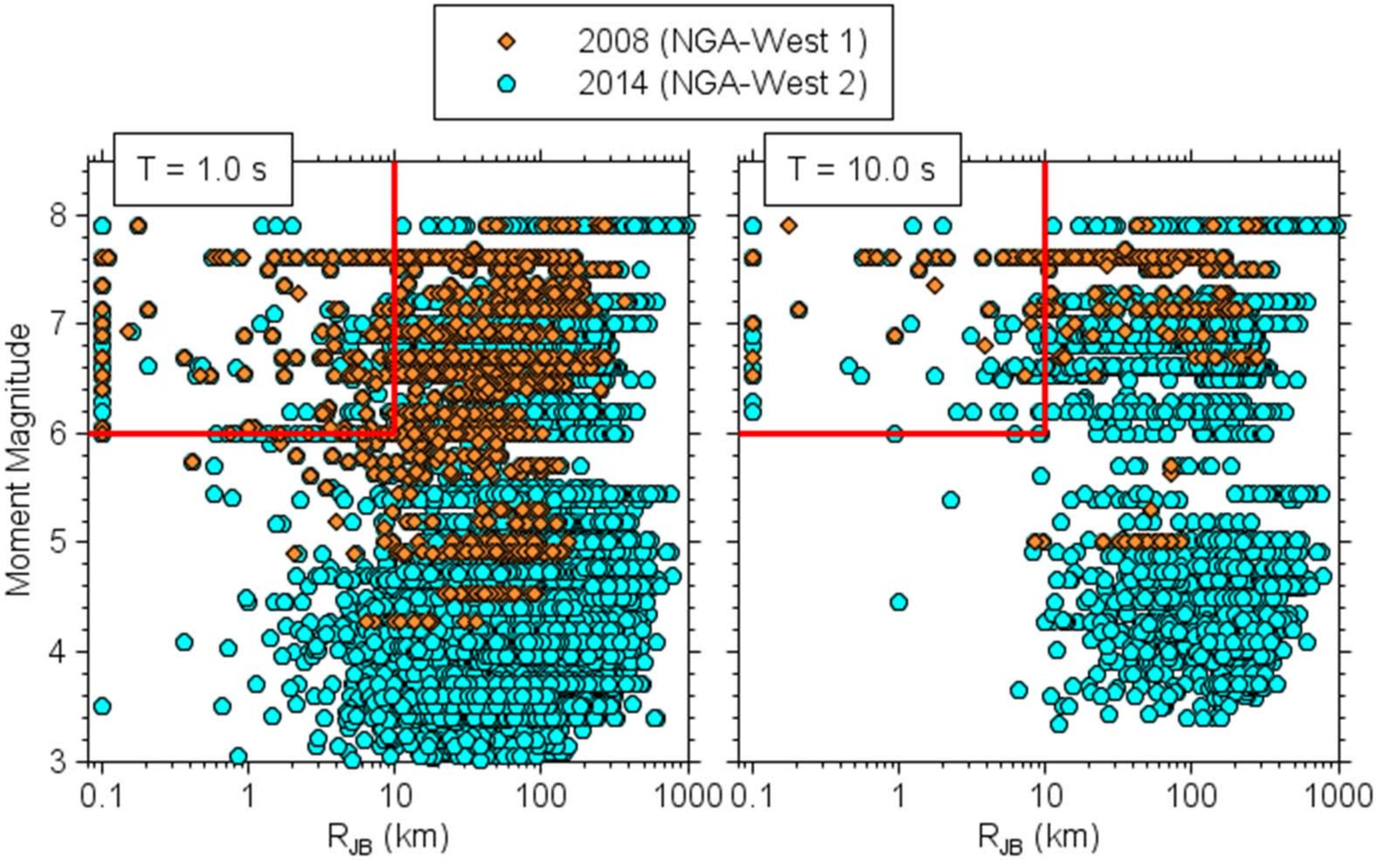
- **NGA-West**
  - Vertical-component GMPEs
  - Add directivity
- **NGA-East**
  - GMMs for stable continental regions
  - 2015
- **NGA-Sub**
  - GMMs for subduction regions
  - 2016

Adapted from a slide from Y. Bozorgnia

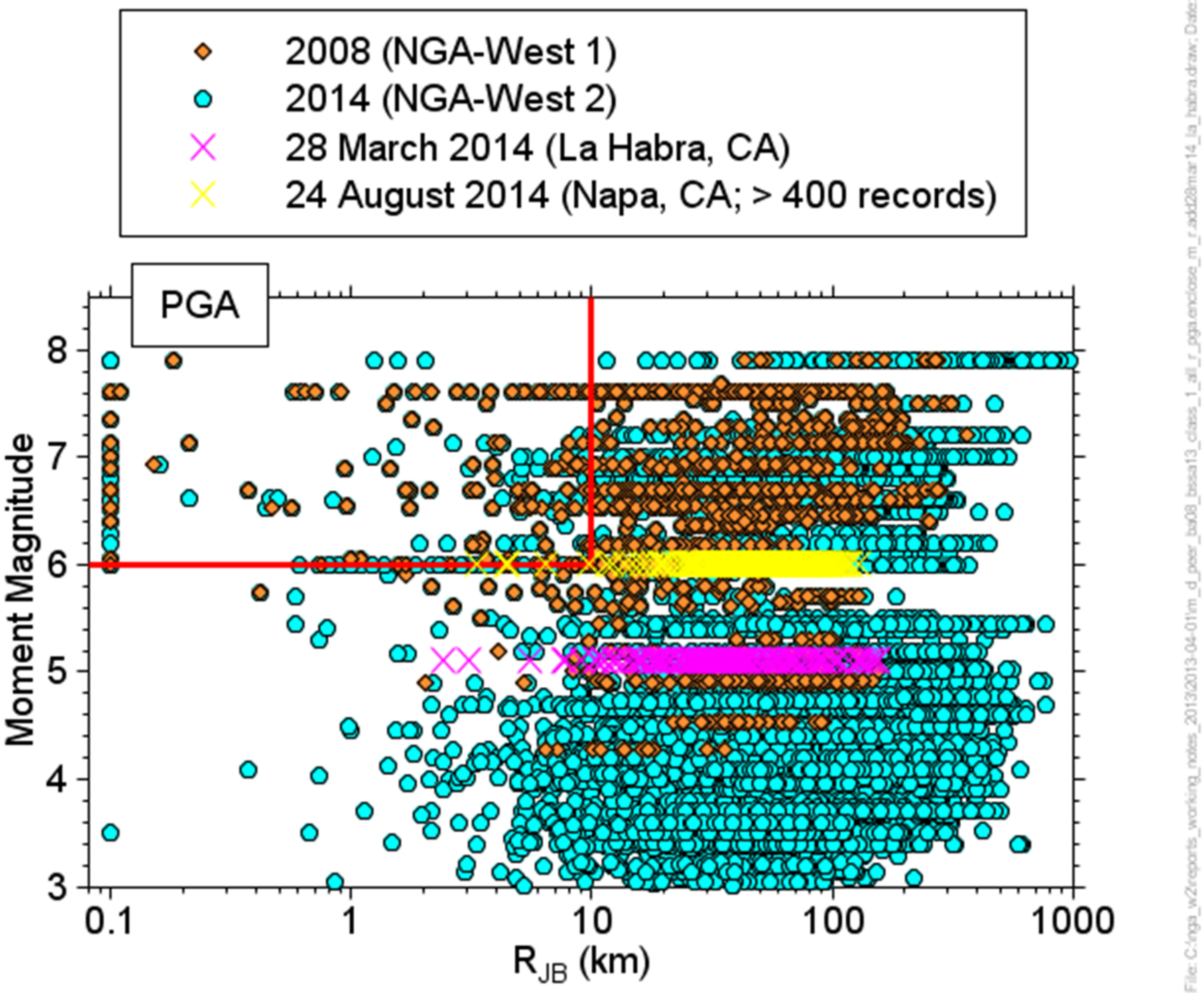
New recordings may not fill data-gaps in the near term, particularly close to large earthquakes and for important fault-site geometries, such as over the hanging wall of a reverse-slip fault.



New recordings may not fill data-gaps in the near term, particularly close to large earthquakes and for important fault-site geometries, such as over the hanging wall of a reverse-slip fault.



New recordings may not fill data-gaps in the near term, particularly close to large earthquakes and for important fault-site geometries, such as over the hanging wall of a reverse-slip fault.



Use of Simulated Motions

- Supplement observed data and derive GMPEs from the combined observed and simulated motions
- Constrain/adjust GMPEs for things such as:
  - Hanging wall
  - Saturation
  - Directivity
  - Splay faults and complex fault geometry
  - Nonlinear soil response

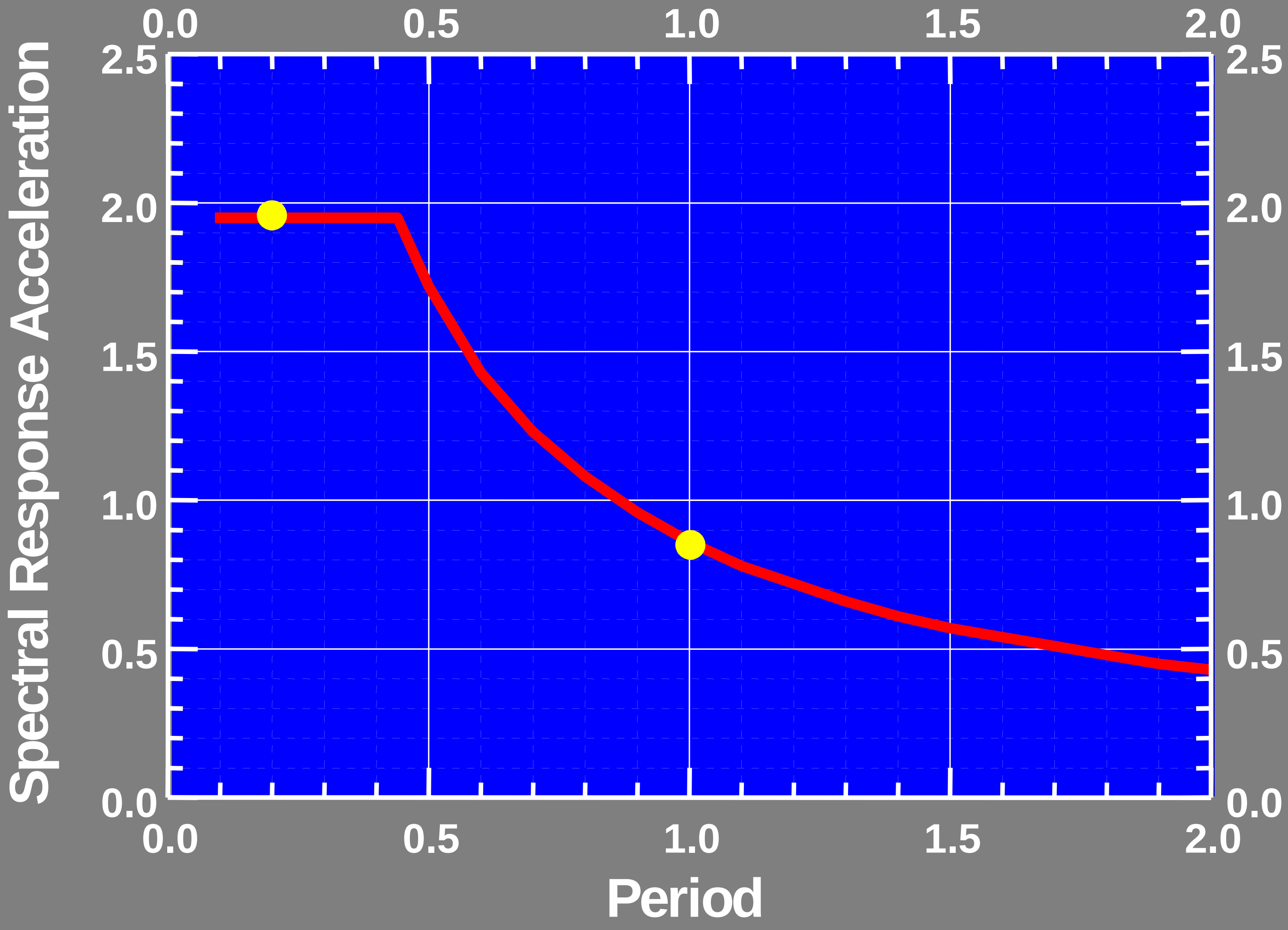
Using GMPEs in Building Codes

- For any site, find PSA at 0.2 s and 1 s that have a 2% in 50 year frequency of exceedance (this uses GMPEs)
- Map the resulting values (hazard maps)
- Transform the hazard maps to design maps included in building codes

Design maps in building codes are for T=0.2 and T=1.0 s

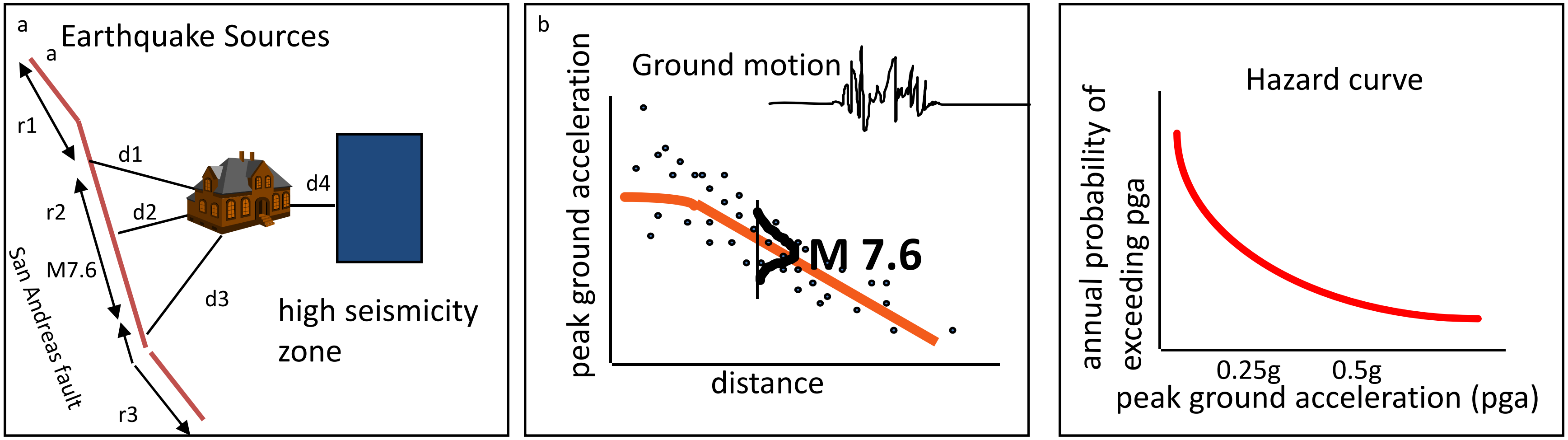
- Design values at other periods are obtained by anchoring curves to the T=0.2 and T=1.0 s values, as shown in the next slide

Construct response spectrum at all periods using T = 0.2 and 1.0 sec values

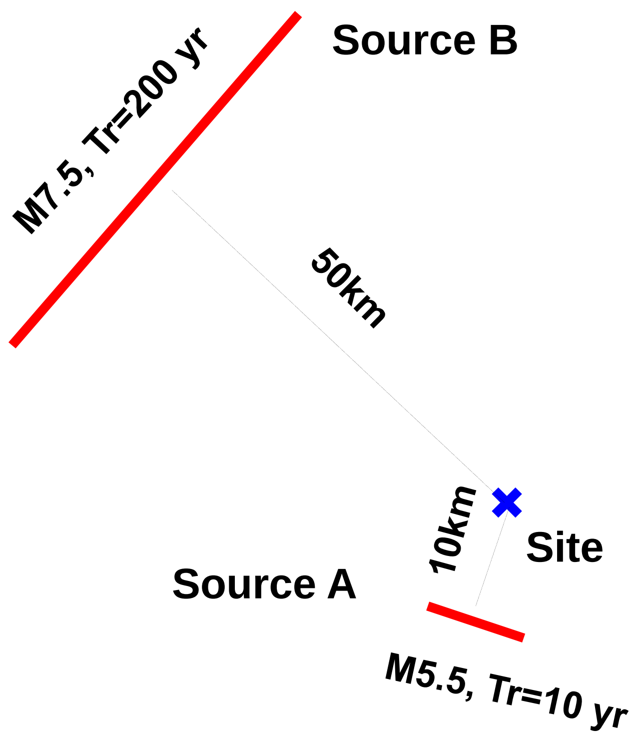


The first step in making hazard maps: construct a hazard curve at each site

Hazard Methodology Procedure Cartoon



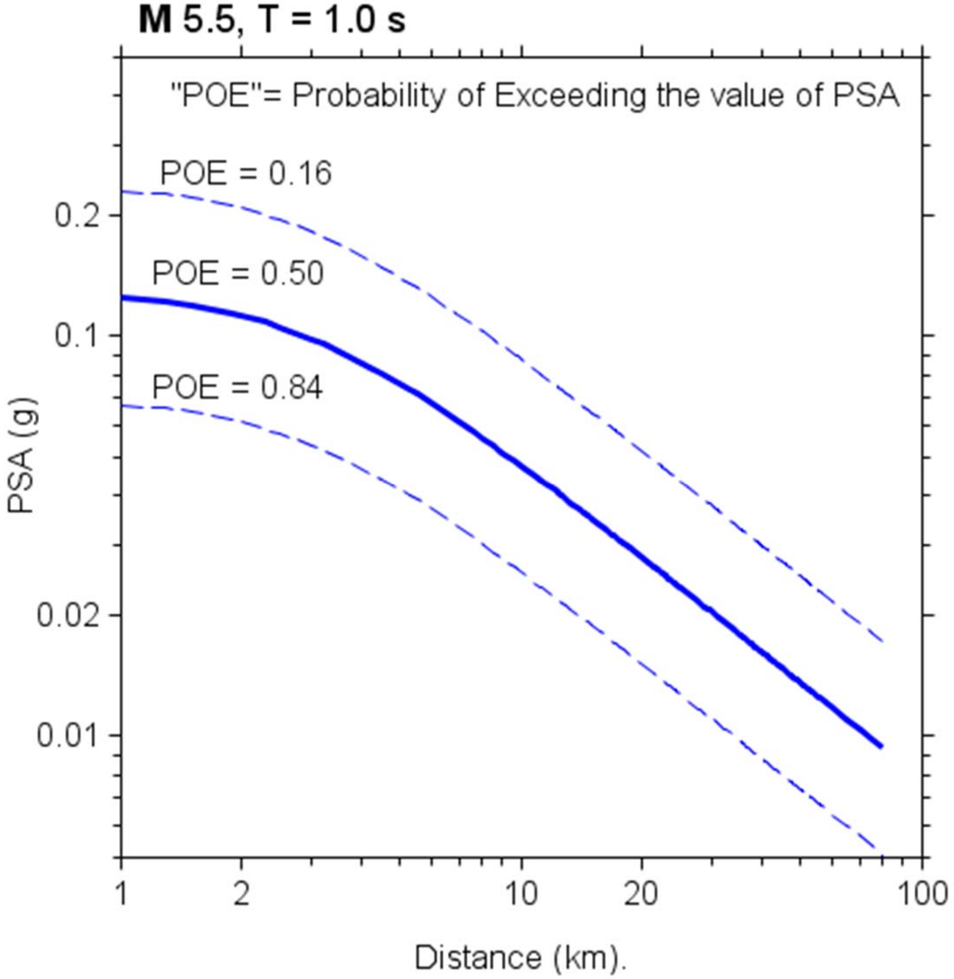
Constructing a hazard curve: a real example



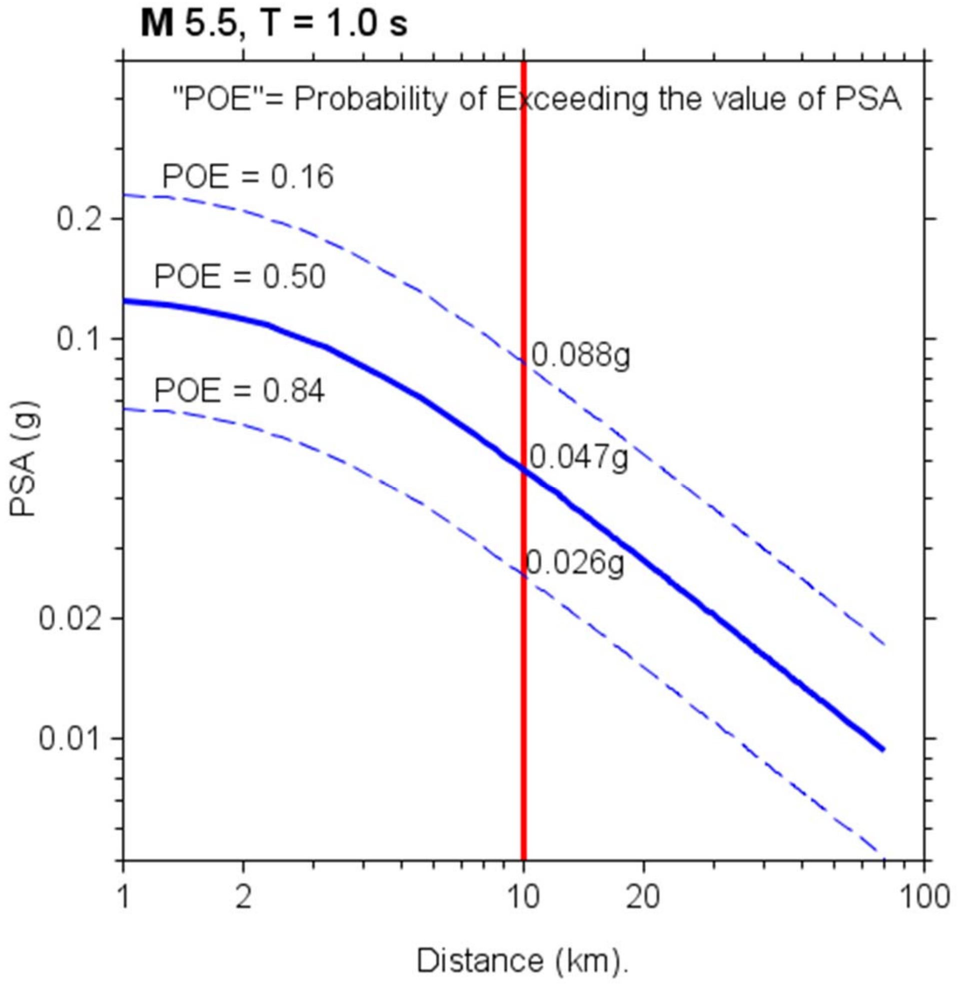
Annual probability that earthquake occurs:

Source A: 1/10 = 0.10
Source B: 1/200 = 0.005

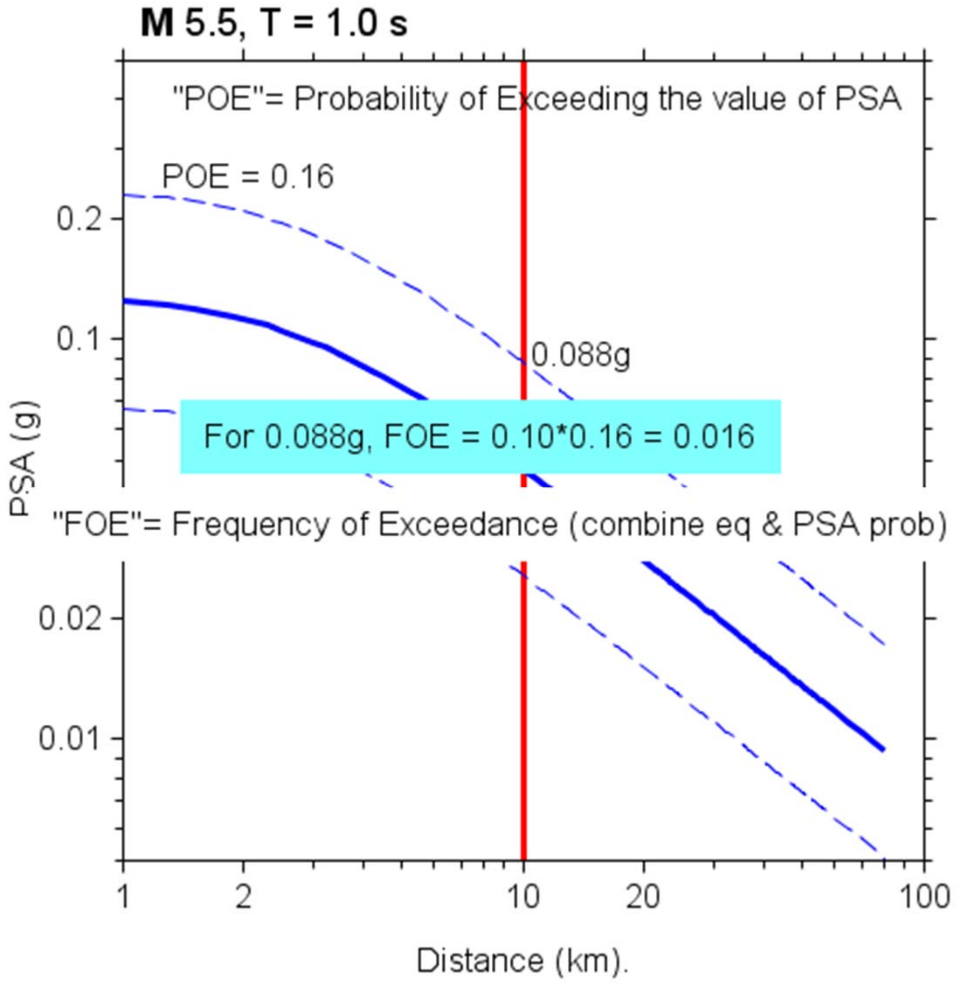
Consider the uncertainty in motions from GMPEs



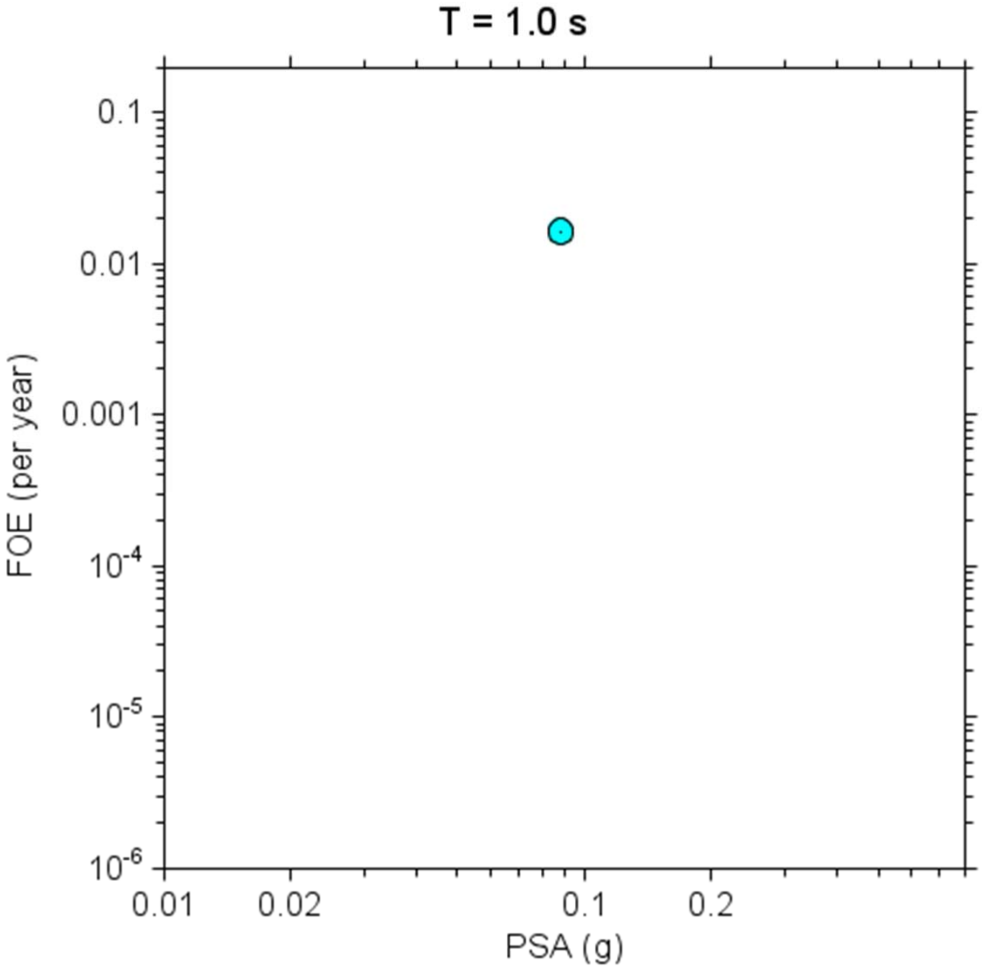
Consider the uncertainty in motions from GMPEs



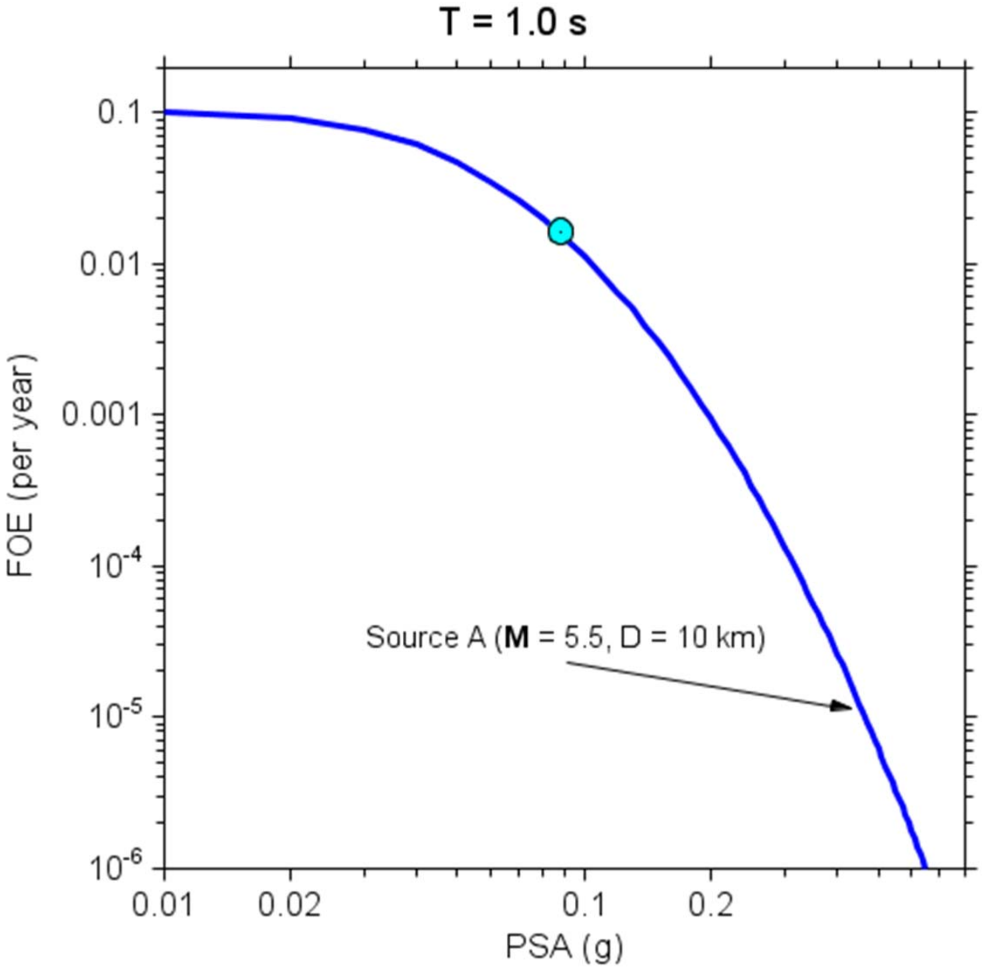
Combine the source and ground-motion uncertainties



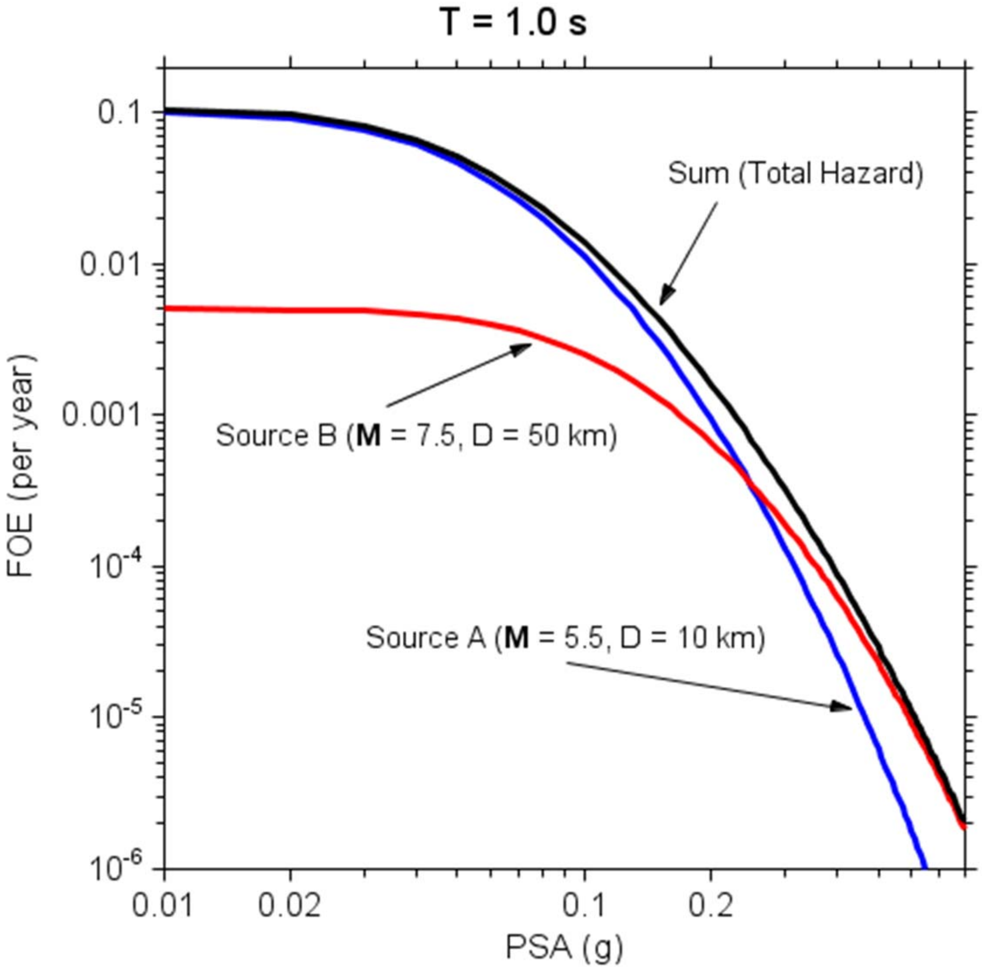
Plot the resulting FOE for the PSA value



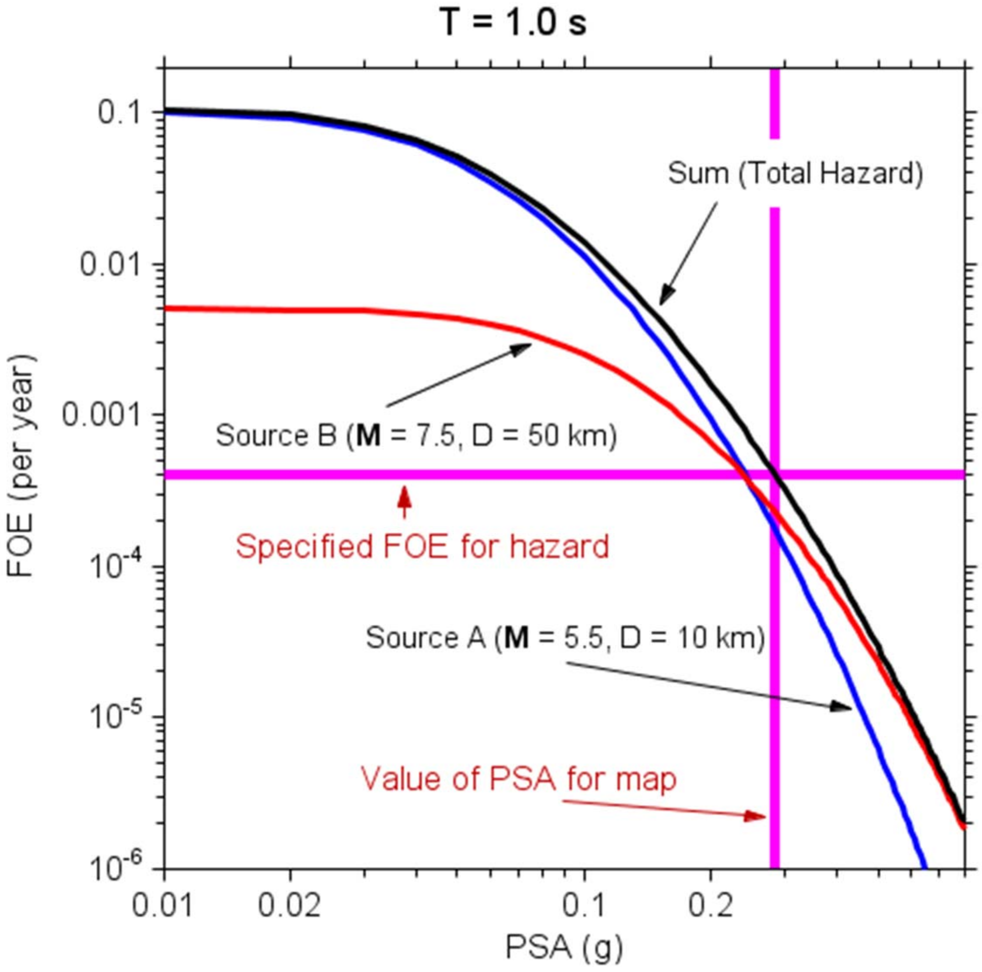
Do this for all possible ground motions from Source A to make a hazard curve for Source A



Combine hazard curves for all sources to make the final hazard curve

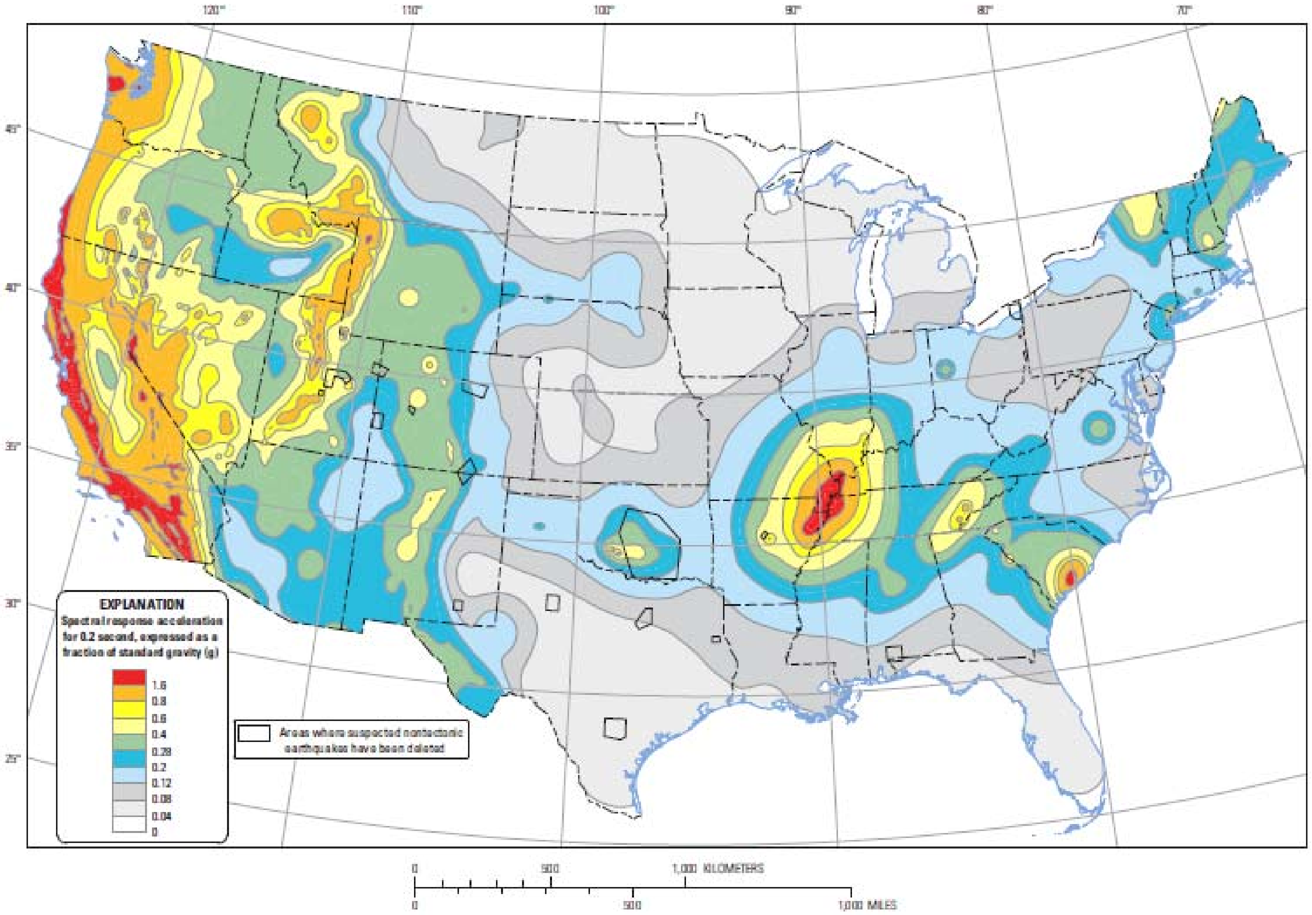


Pick off value for hazard map



2% probability of exceedance in 50 years

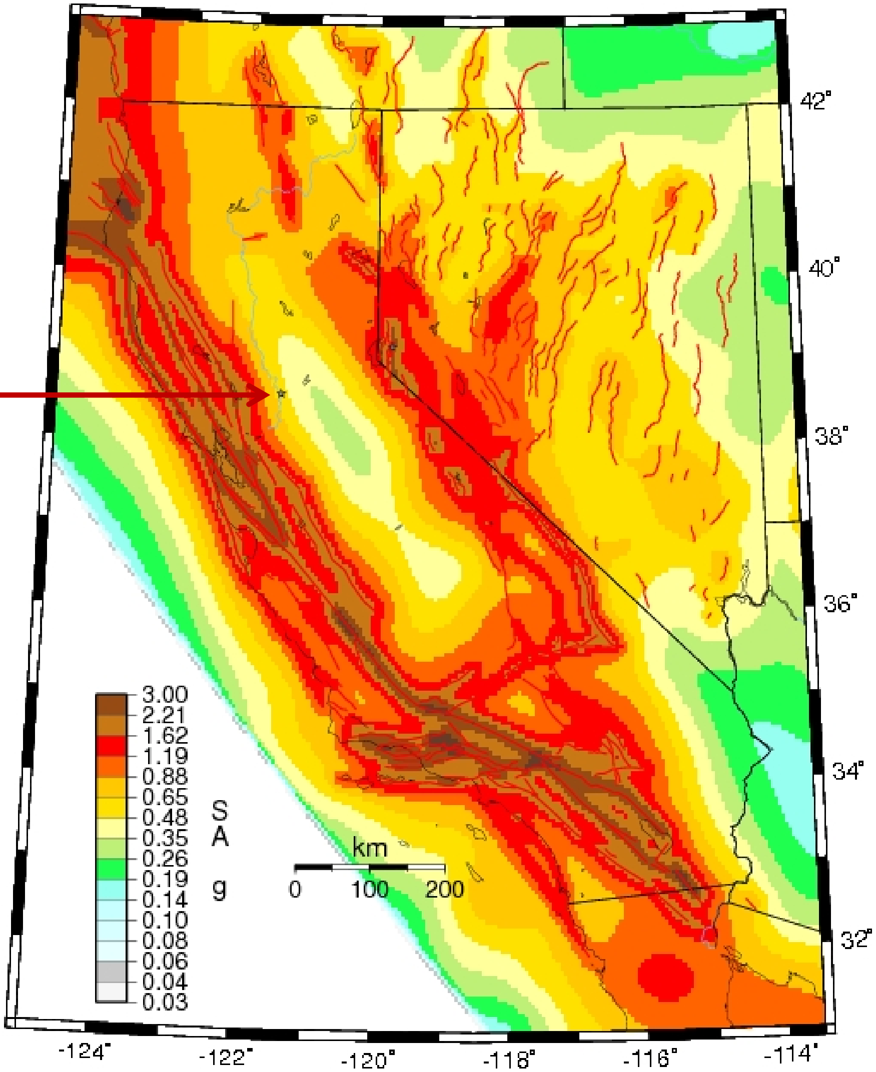
Make a map of the ground-motion values for a given FOE; this is the hazard map that is the basis for the design maps included in building codes



Two-percent probability of exceedance in 50 years map of 0.2 second spectral response acceleration

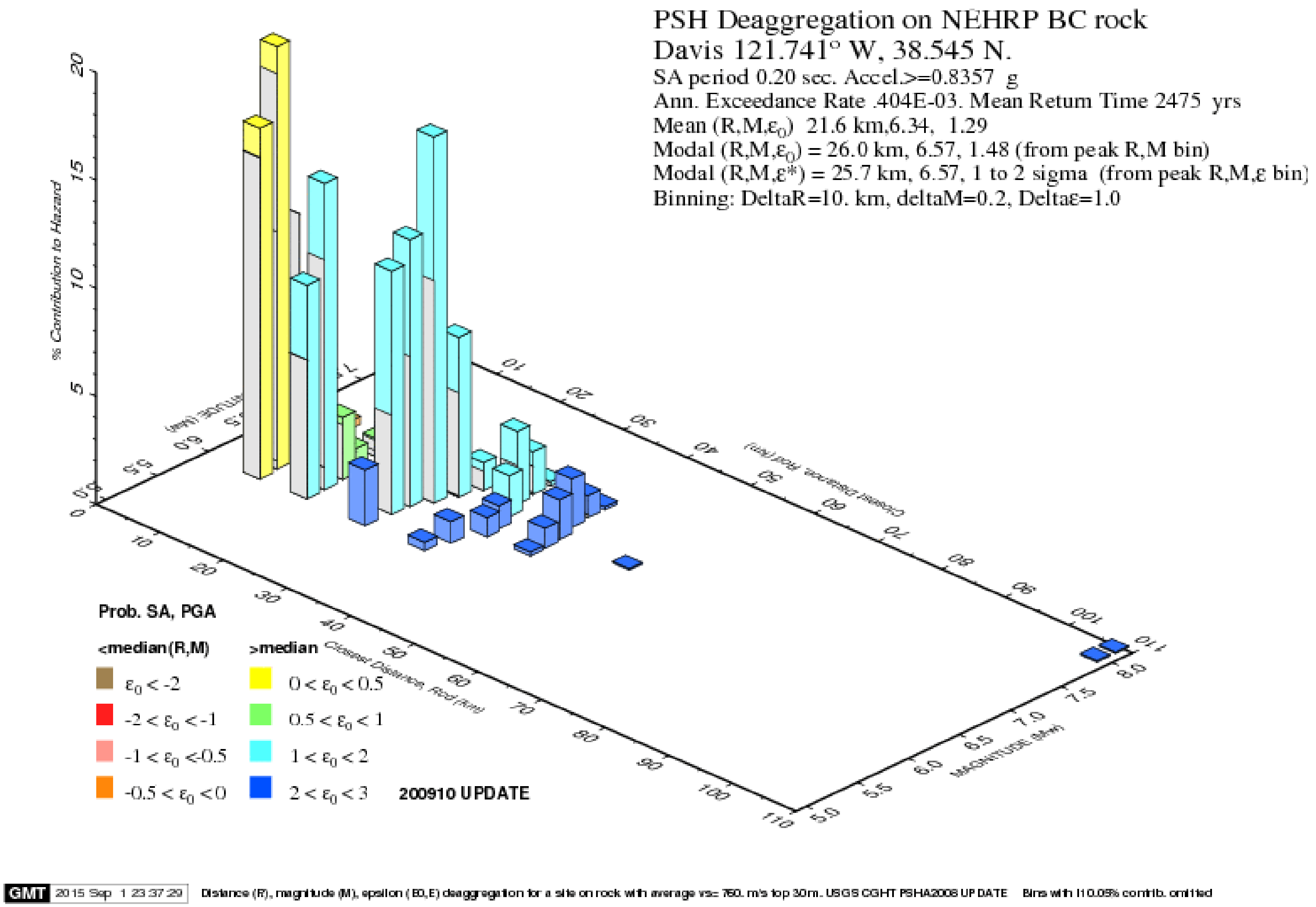
Calif NV, 5-Hz SA w/2%PE50yr. 760 m/s Rock

Davis



GMT 2009 Apr 7 09:22:24 SA for 2008. Red lines are Qfaults. Site 760 m/s. 5 Hz 2%50 yr PE.

FOE=0.0004 (~2500 year return period); T=0.2 s



PSH Deaggregation on NEHRP BC rock
Davis 121.741° W, 38.545 N.
SA period 0.20 sec. Accel.>=0.8357 g
Ann. Exceedance Rate .404E-03. Mean Return Time 2475 yrs
Mean (R,M,ε_0) 21.6 km,6.34, 1.29
Modal (R,M,ε_0) = 26.0 km, 6.57, 1.48 (from peak R,M bin)
Modal (R,M,ε*) = 25.7 km, 6.57, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR=10. km, deltaM=0.2, Deltaε=1.0

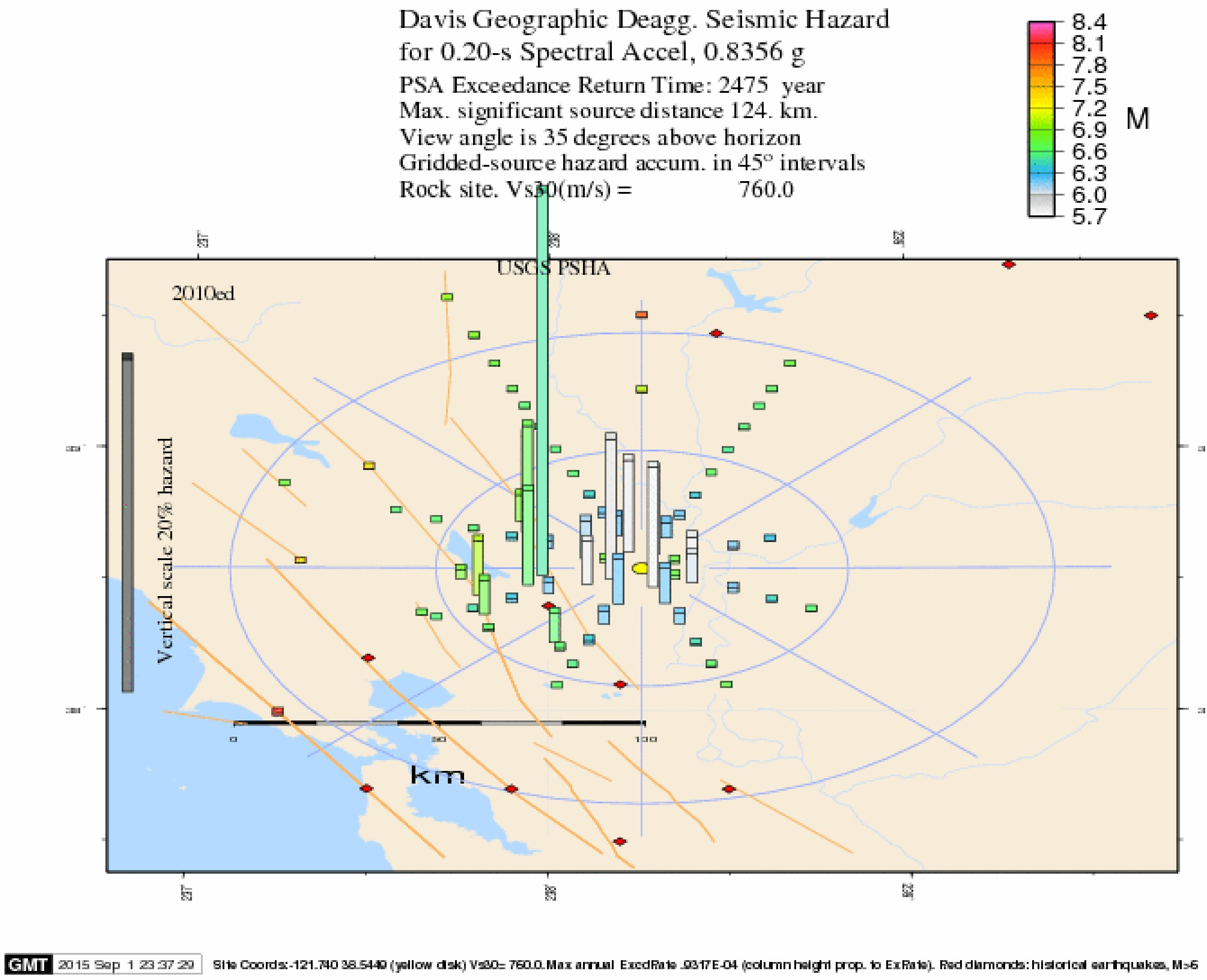
Prob. SA, PGA

<median(R,M)	>median
$\varepsilon_0 < -2$	$0 < \varepsilon_0 < 0.5$
$-2 < \varepsilon_0 < -1$	$0.5 < \varepsilon_0 < 1$
$-1 < \varepsilon_0 < -0.5$	$1 < \varepsilon_0 < 2$
$-0.5 < \varepsilon_0 < 0$	$2 < \varepsilon_0 < 3$

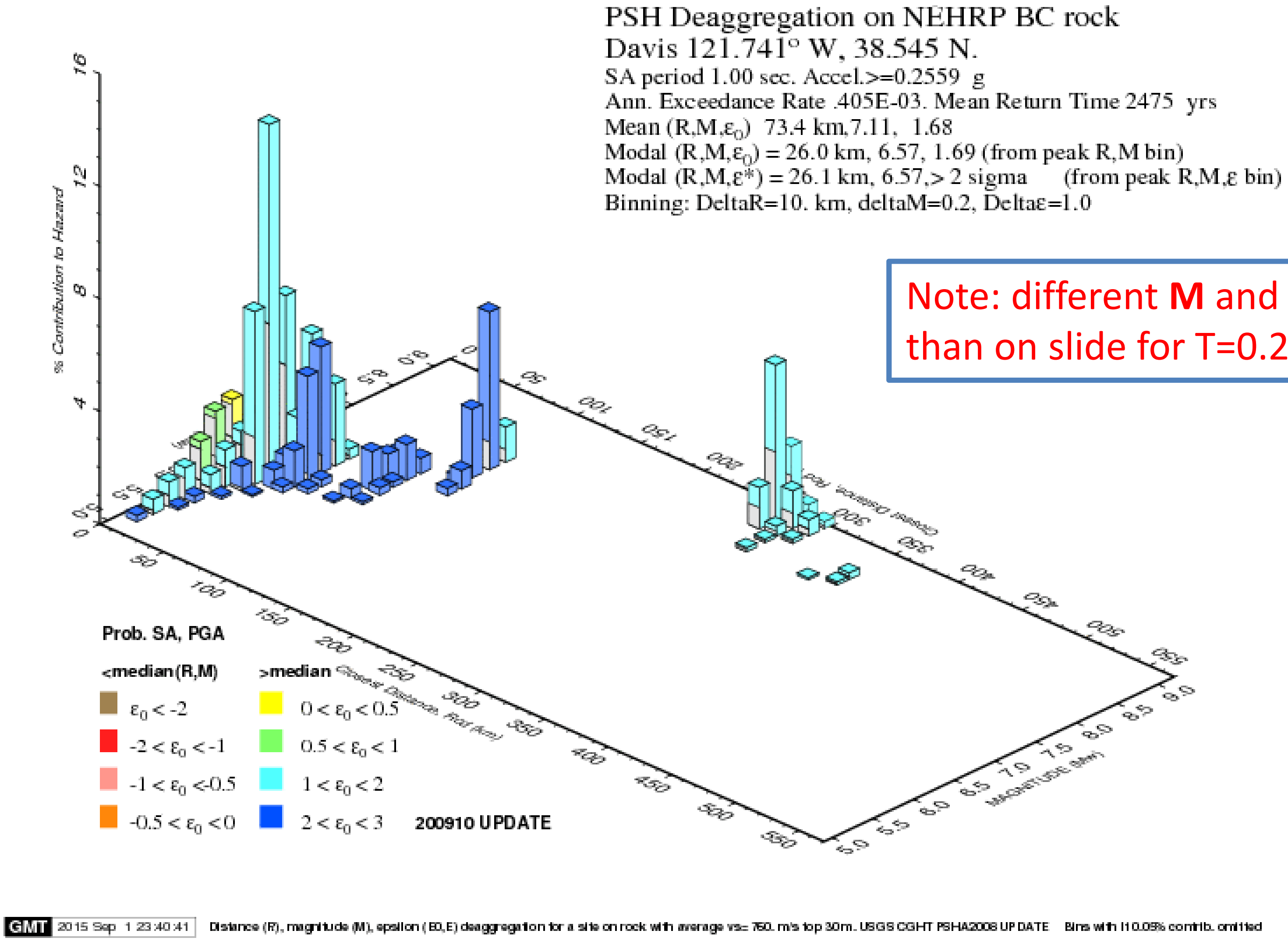
200910 UPDATE

GMT 2015 Sep 1 23:37:29 Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted

FOE=0.0004 (~2500 year return period); T=0.2 s



FOE=0.0004 (~2500 year return period); T=1.0 s

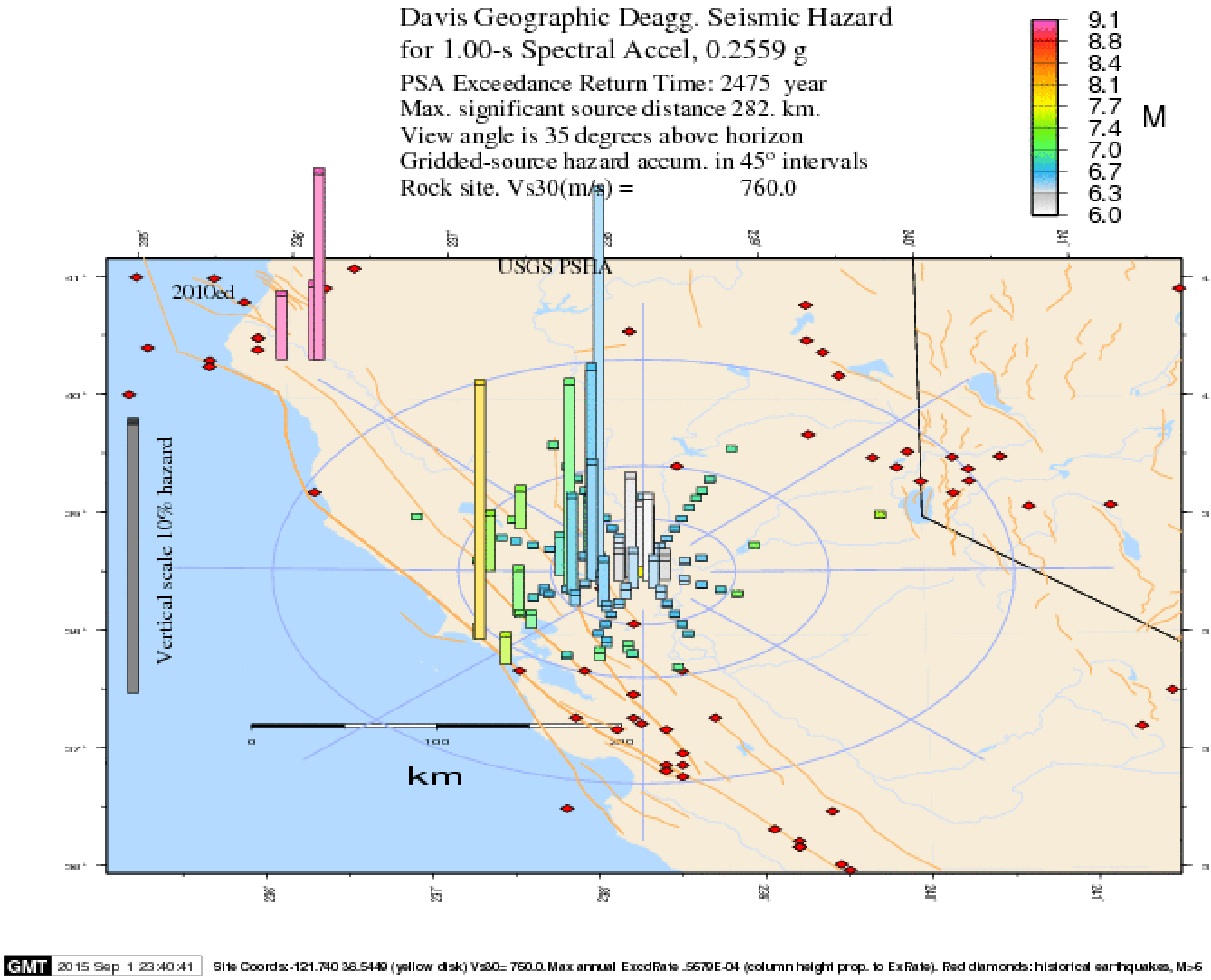


PSH Deaggregation on NEHRP BC rock
Davis 121.741° W, 38.545 N.
SA period 1.00 sec. Accel.>=0.2559 g
Ann. Exceedance Rate .405E-03. Mean Return Time 2475 yrs
Mean (R,M,ε_0) 73.4 km,7.11, 1.68
Modal (R,M,ε_0) = 26.0 km, 6.57, 1.69 (from peak R,M bin)
Modal (R,M,ε*) = 26.1 km, 6.57,> 2 sigma (from peak R,M,ε bin)
Binning: DeltaR=10. km, deltaM=0.2, Deltaε=1.0

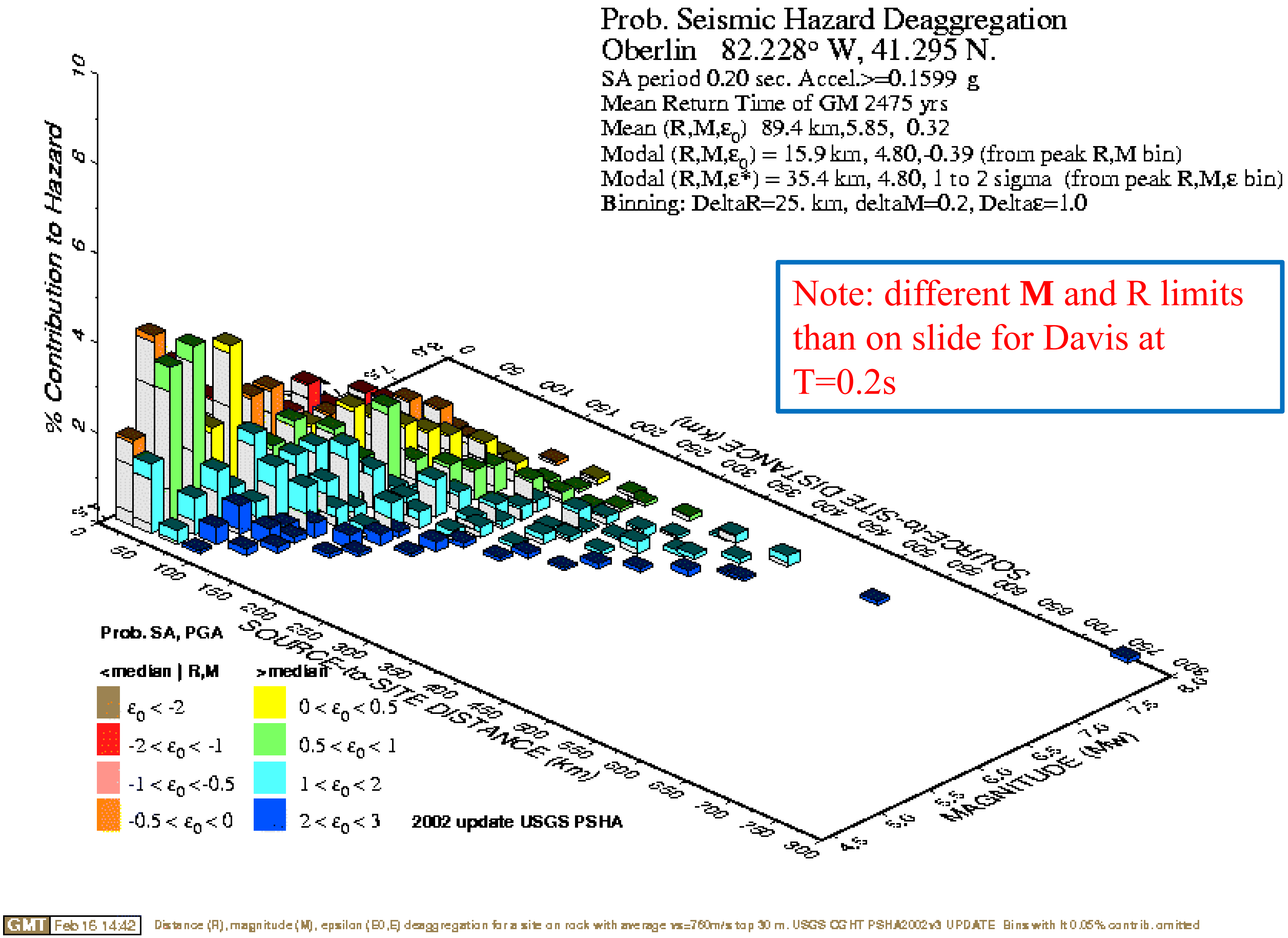
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted

Note: different **M** and R limits than on slide for T=0.2s

FOE=0.0004 (~2500 year return period); T=0.2 s



FOE=0.0004 (~2500 year return period); T=0.2 s



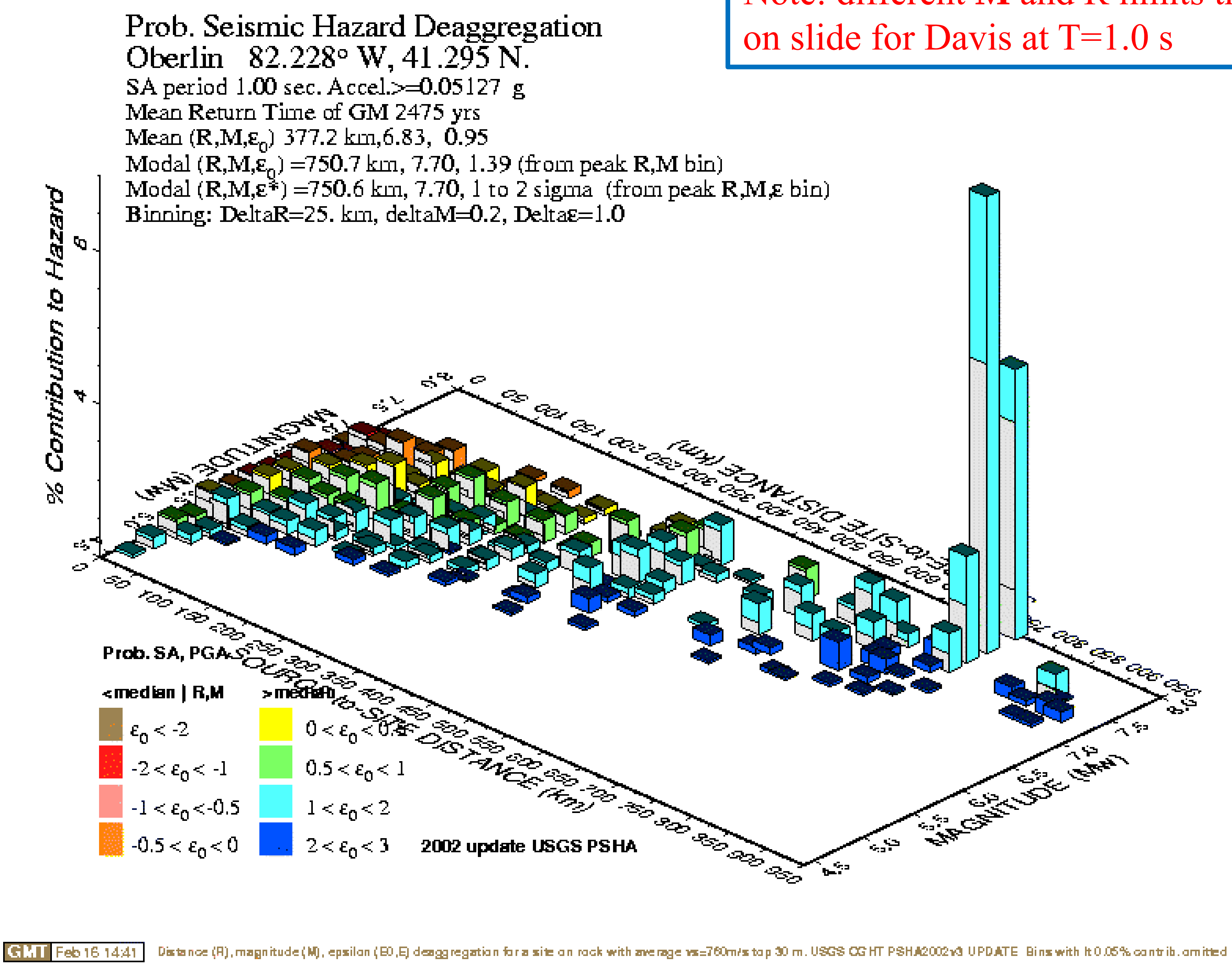
Prob. Seismic Hazard Deaggregation
Oberlin 82.228° W, 41.295 N.
SA period 0.20 sec. Accel.>=0.1599 g
Mean Return Time of GM 2475 yrs
Mean (R, M, ε_0) 89.4 km, 5.85, 0.32
Modal (R, M, ε_0) = 15.9 km, 4.80, -0.39 (from peak R,M bin)
Modal (R, M, ε^*) = 35.4 km, 4.80, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR=25. km, deltaM=0.2, Deltaε=1.0

Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs=760m/s top 30 m. USGS CGHT PSHA2002v3 UPDATE Bins with lt 0.05% contrib. omitted

Note: different **M** and R limits than on slide for Davis at T=0.2s

FOE=0.0004 (~2500 year return period); T=1.0 s

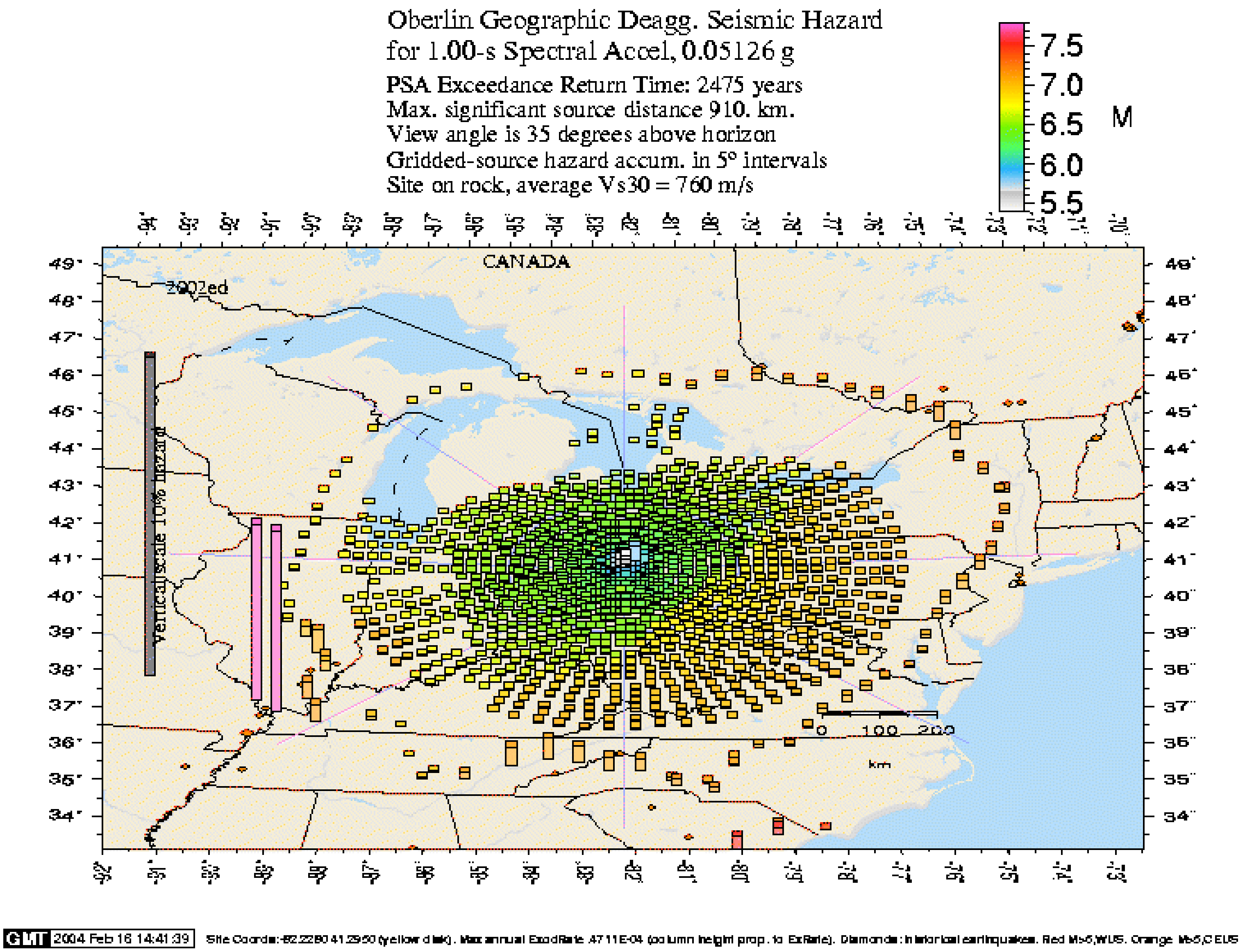
Note: different **M** and R limits than on slide for Davis at T=1.0 s



Prob. Seismic Hazard Deaggregation
Oberlin 82.228° W, 41.295 N.
SA period 1.00 sec. Accel.>=0.05127 g
Mean Return Time of GM 2475 yrs
Mean (R,M,ε_0) 377.2 km,6.83, 0.95
Modal (R,M,ε_0) =750.7 km, 7.70, 1.39 (from peak R,M bin)
Modal (R,M,ε^*) =750.6 km, 7.70, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR=25. km, deltaM=0.2, Deltaε=1.0

GMT Feb 15 14:41 Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs=760m/s top 30 m. USGS CGHT PSHA2002v3 UPDATE Bins with lt 0.05% contrib. omitted

FOE=0.0004 (~2500 year return period); T=1.0 s



Oberlin Geographic Deagg. Seismic Hazard
for 1.00-s Spectral Accel, 0.05126 g
PSA Exceedance Return Time: 2475 years
Max. significant source distance 910. km.
View angle is 35 degrees above horizon
Gridded-source hazard accum. in 5° intervals
Site on rock, average Vs30 = 760 m/s

GMT 2004 Feb 16 14:41:39 Site Coords: -82.2280 41.2950 (yellow disk). Max annual ExcdRate .4711E-04 (column height prop. to ExRate). Diamonds: historical earthquakes. Red M>6,WUS. Orange M>5,CEUS

Some final remarks…

Thank You