Deterministic Seismic Ground Motions and the PEER NGA Ground Motion Prediction Equations (GMPEs)

David M. Boore

EERI Utah Chapter Short Course on Seismic Ground Motions
West Jordan, Utah
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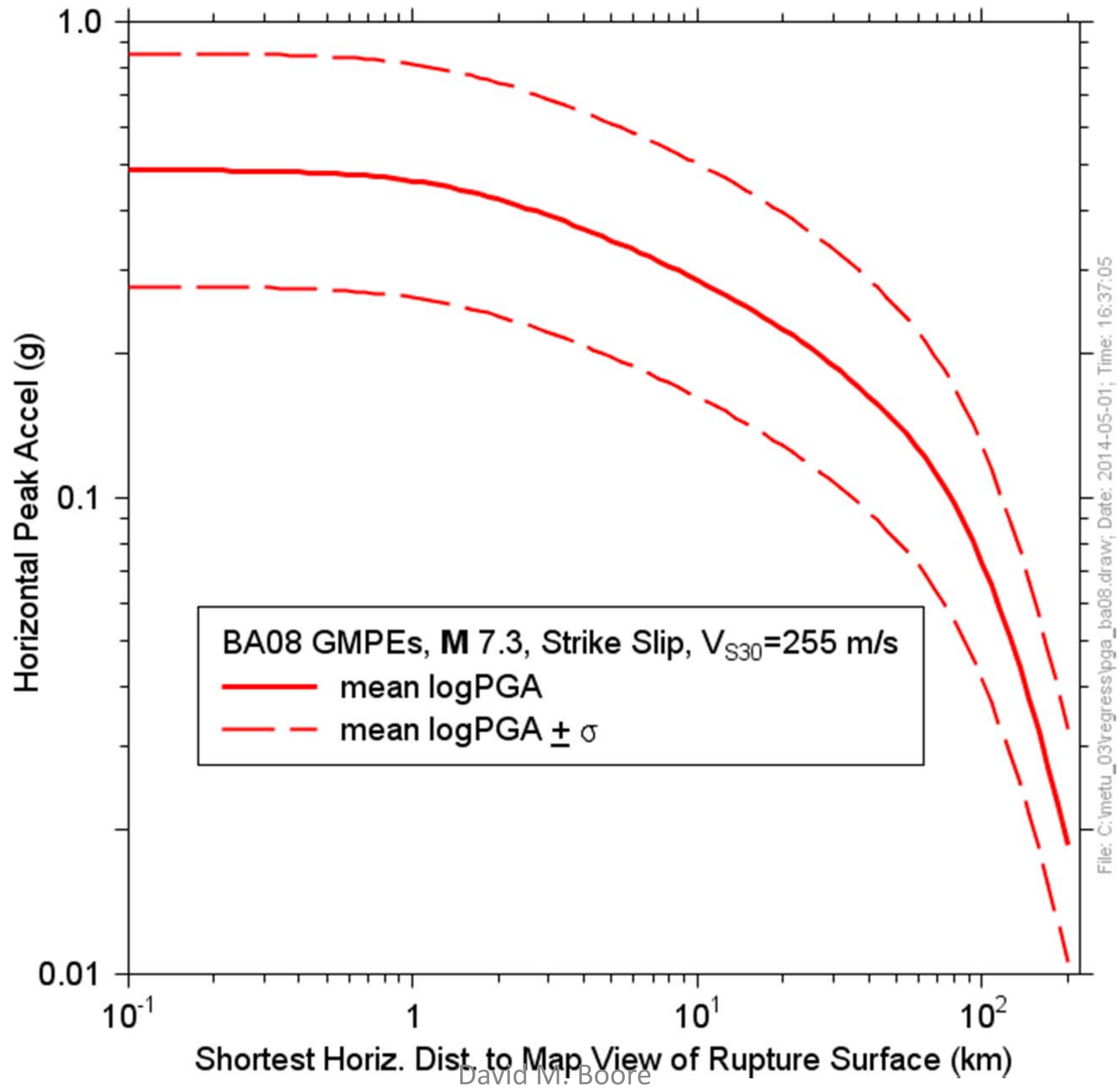
http://www.daveboore.com/presentations.html

Contents of the Lecture

- Overview of Ground-Motion Prediction Equations (GMPEs)
- Predicted and Predictor Variables
- The PEER NGA-West2 GMPEs
  - Data
  - Functions
  - Comparisons of median predictions
  - Aleatory and Epistemic Uncertainties
- Comparing Greek Data to NGA-West2 Predictions
- Present and Future Work
- Resources

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 (e.g., close to **M**≈8 earthquakes)
- 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.

Input Parameters in PEER Spreadsheet: Source

- Moment magnitude
- Fault Width
- Fault Dip
- Fault Type
  - Unspecified
  - Strikeslip
  - Normal
  - Reverse
- Depth to Top of Rupture
- Hypocentral Depth
- Aftershock or Mainshock?

Input Parameters in PEER Spreadsheet: Site

- V_{S30}
- Was V_{S30} measured or inferred? (Needed for uncertainty calculation)
- Depth to 1.0 km/s shear-wave velocity
- Depth to 2.5 km/s shear-wave velocity

Input Parameters in PEER Spreadsheet: Path

- Region
- R_{JB}
- R_{RUP}
- R_X
- R_{Y0}

Wave Type and Frequencies of Most Interest

Horizontal S waves are most important for engineering seismology:

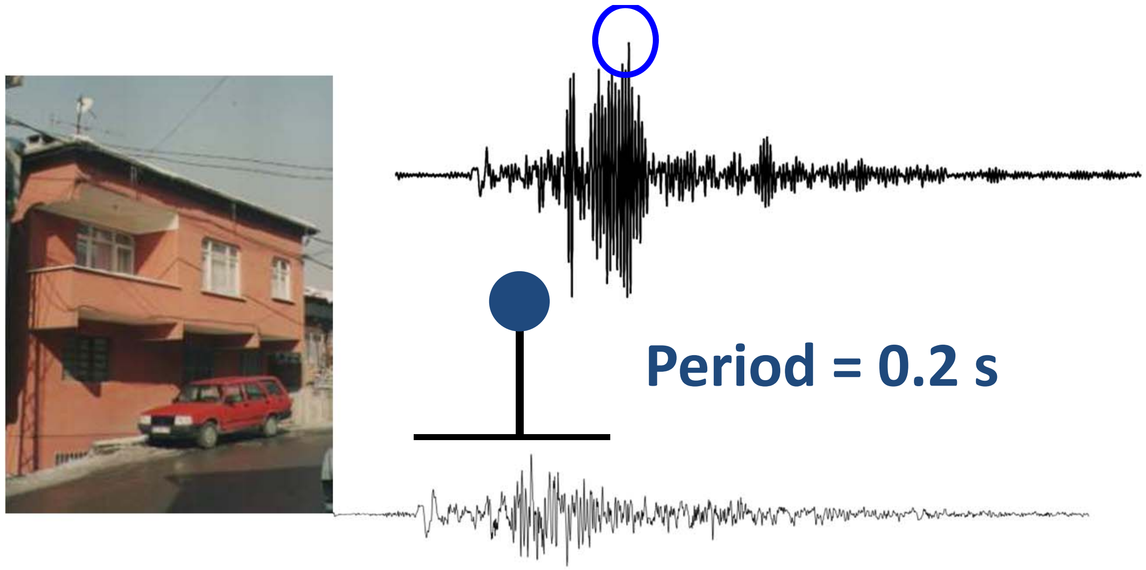
- Seismic shaking in range of resonant frequencies of structures
- Shaking often strongest on horizontal component:
  - Earthquakes radiate larger S waves than P waves
  - Refraction of incoming waves toward the vertical $\Rightarrow$ S waves primarily horizontal motion
- Buildings generally are weakest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

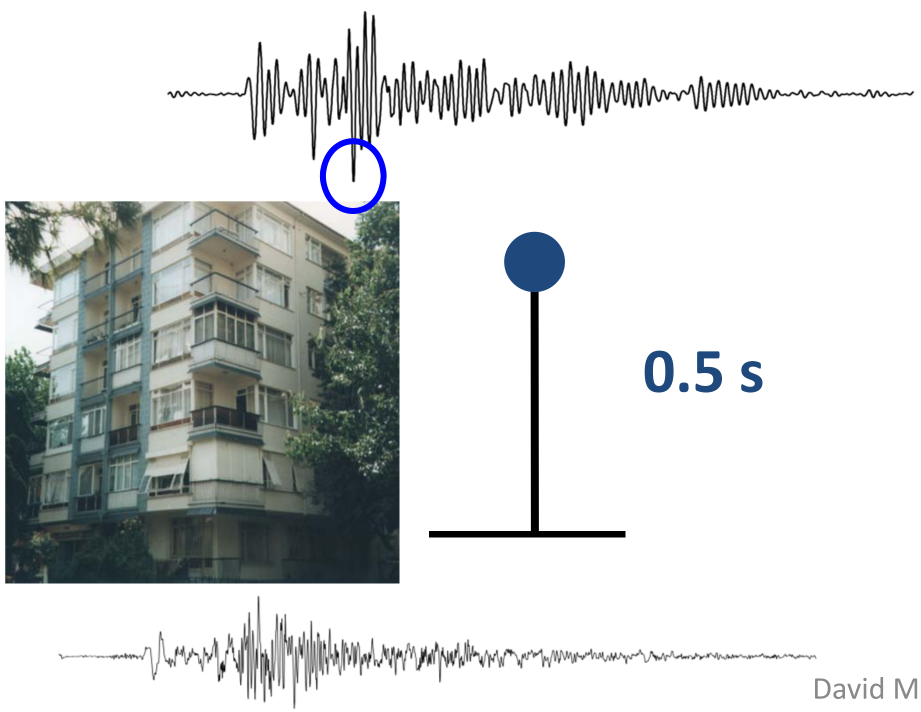
Frequencies of ground-motion for engineering purposes

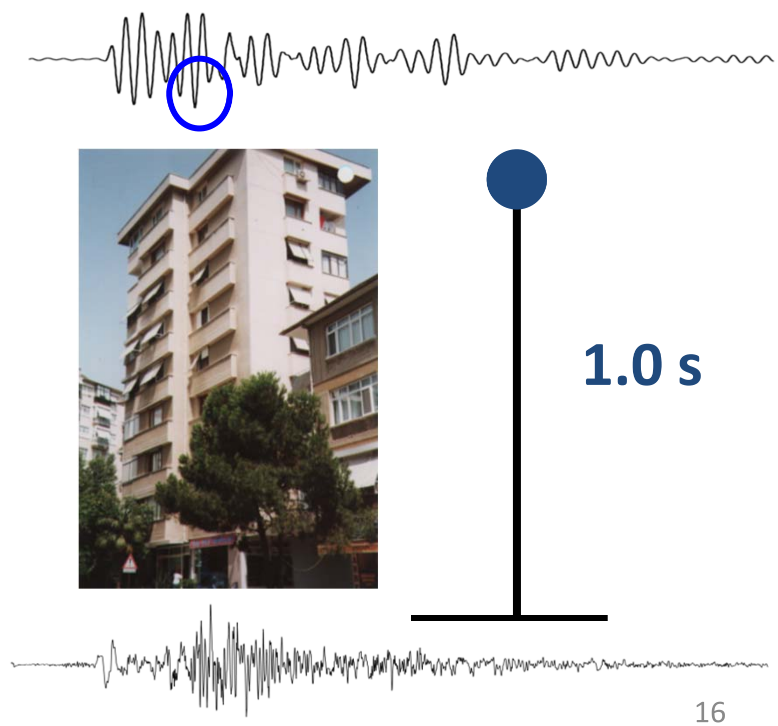
- 20 Hz --- 10 sec (usually less than about 3 sec)
- Resonant period of typical N story structure ≈ N/10 sec
  - – What is the resonant period of the building in which we are located?

What are response spectra?

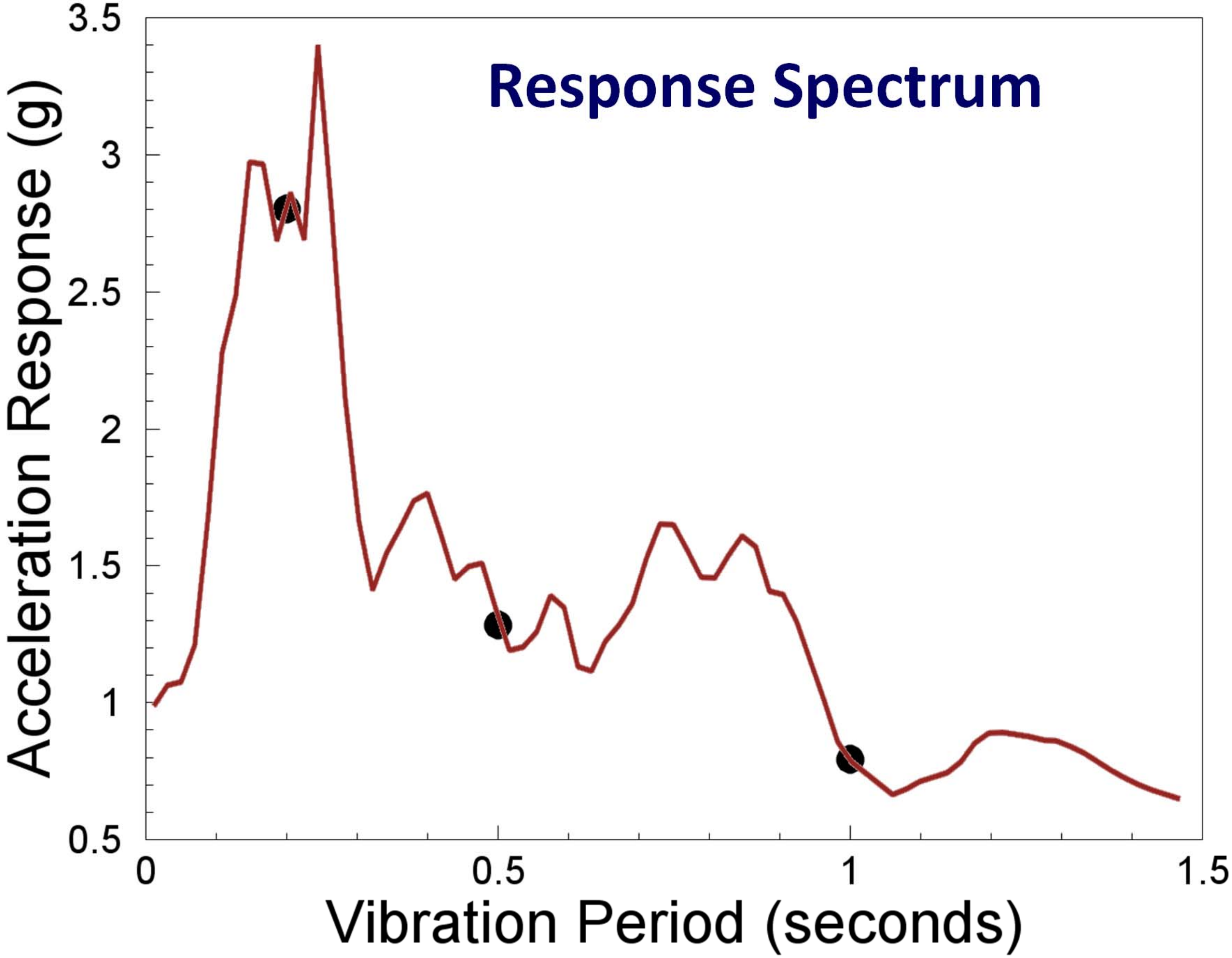
- The maximum response of a suite of single degree of freedom (SDOF) damped oscillators with a range of resonant periods for a given input motion
- Why useful? Buildings can often be represented as SDOF oscillators, so a response spectrum provides the motion of an arbitrary structure to a given input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



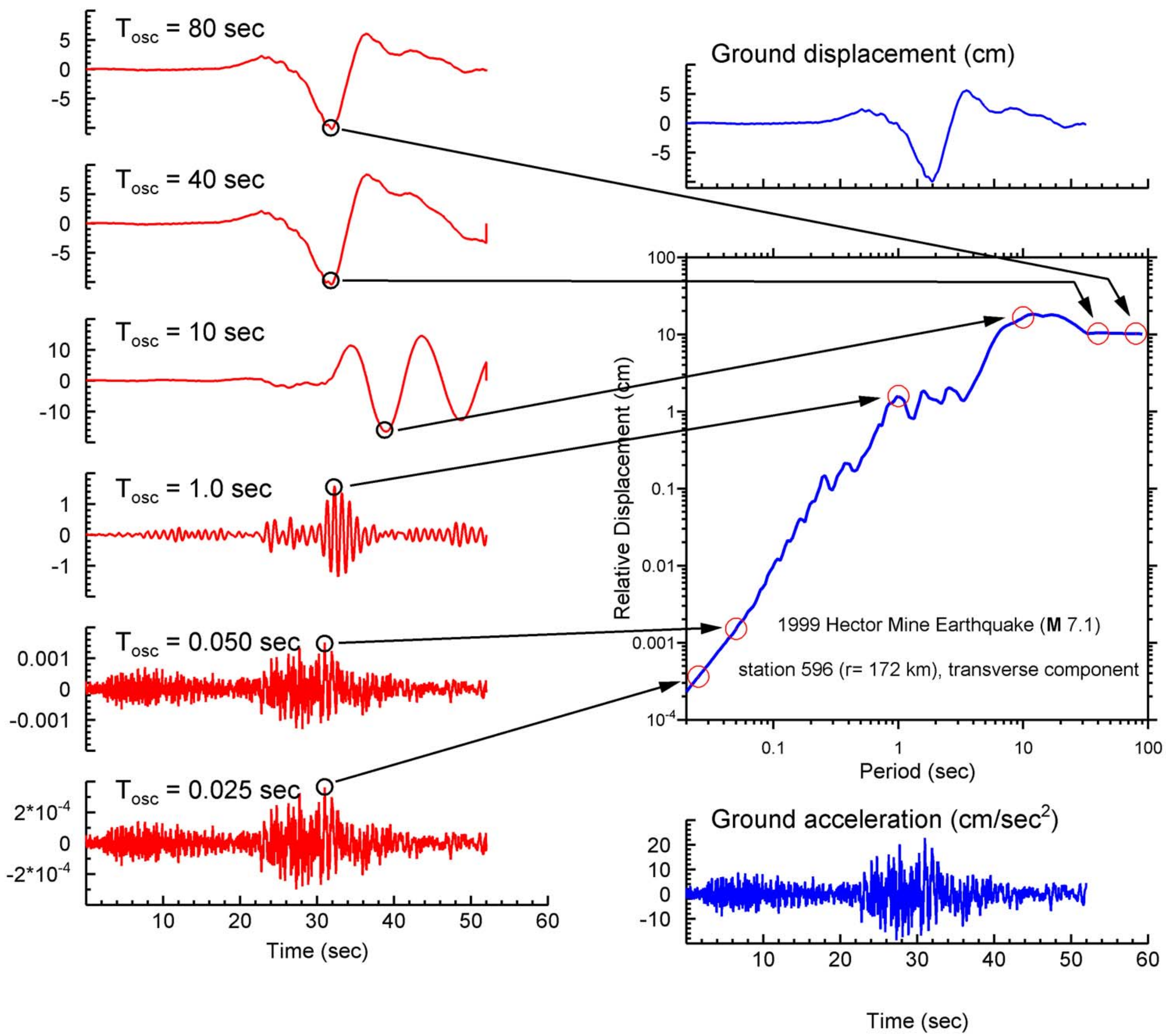




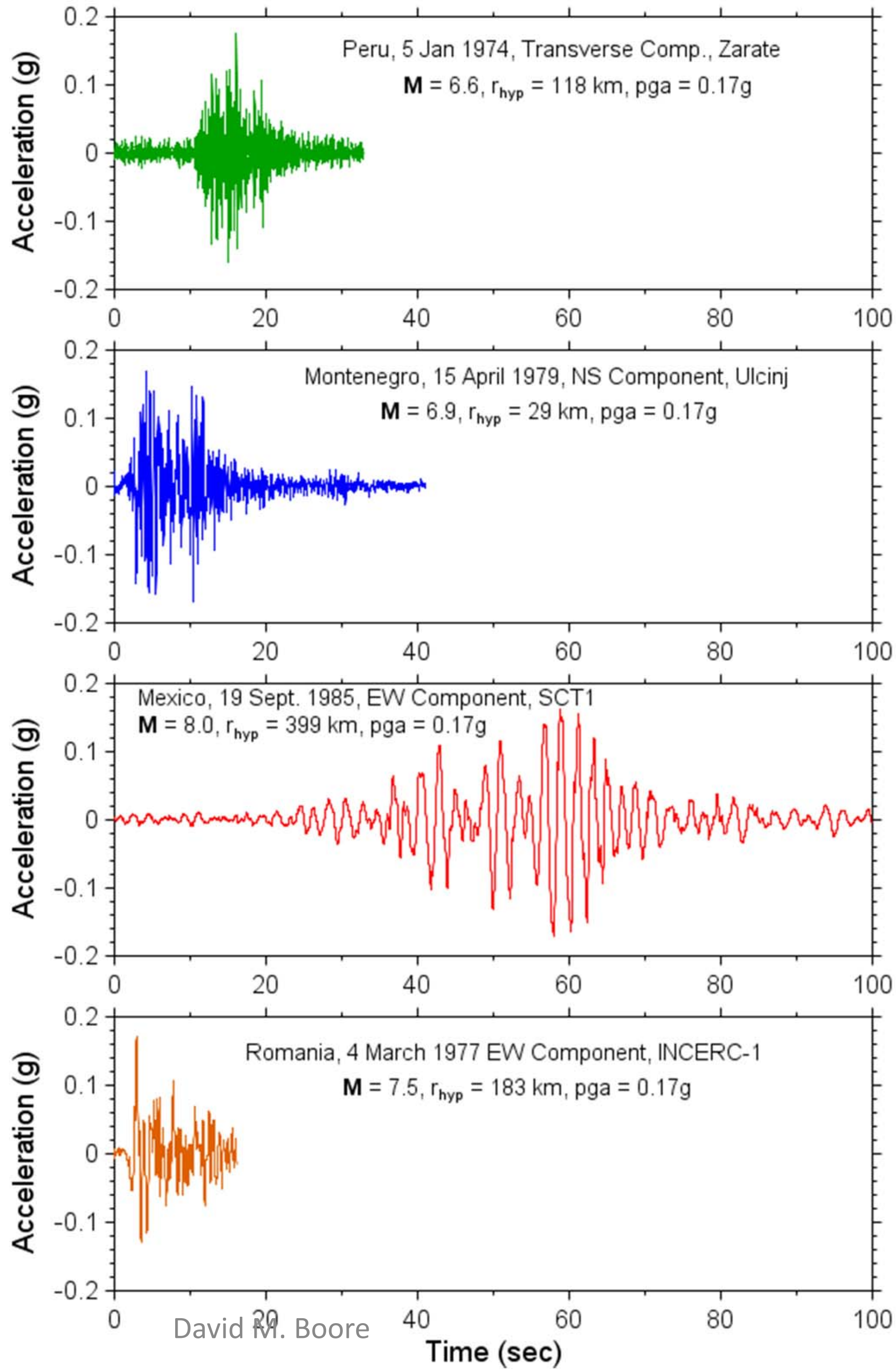
Courtesy of J. Bommer



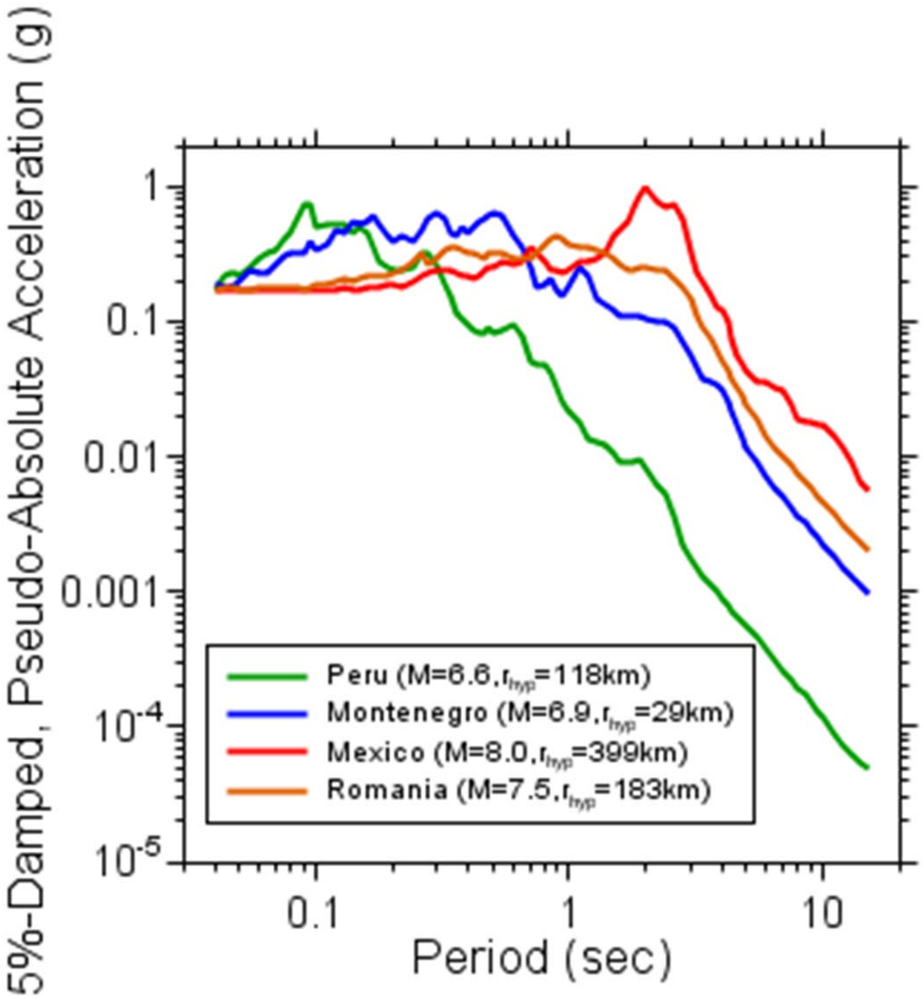
Courtesy of J. Bommer


T_osc = 80 sec
T_osc = 40 sec
T_osc = 10 sec
T_osc = 1.0 sec
T_osc = 0.050 sec
T_osc = 0.025 sec
Time (sec)
Ground displacement (cm)
Relative Displacement (cm)
Period (sec)
1999 Hector Mine Earthquake (M 7.1)
station 596 (r= 172 km), transverse component
Ground acceleration (cm/sec²)
Time (sec)

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



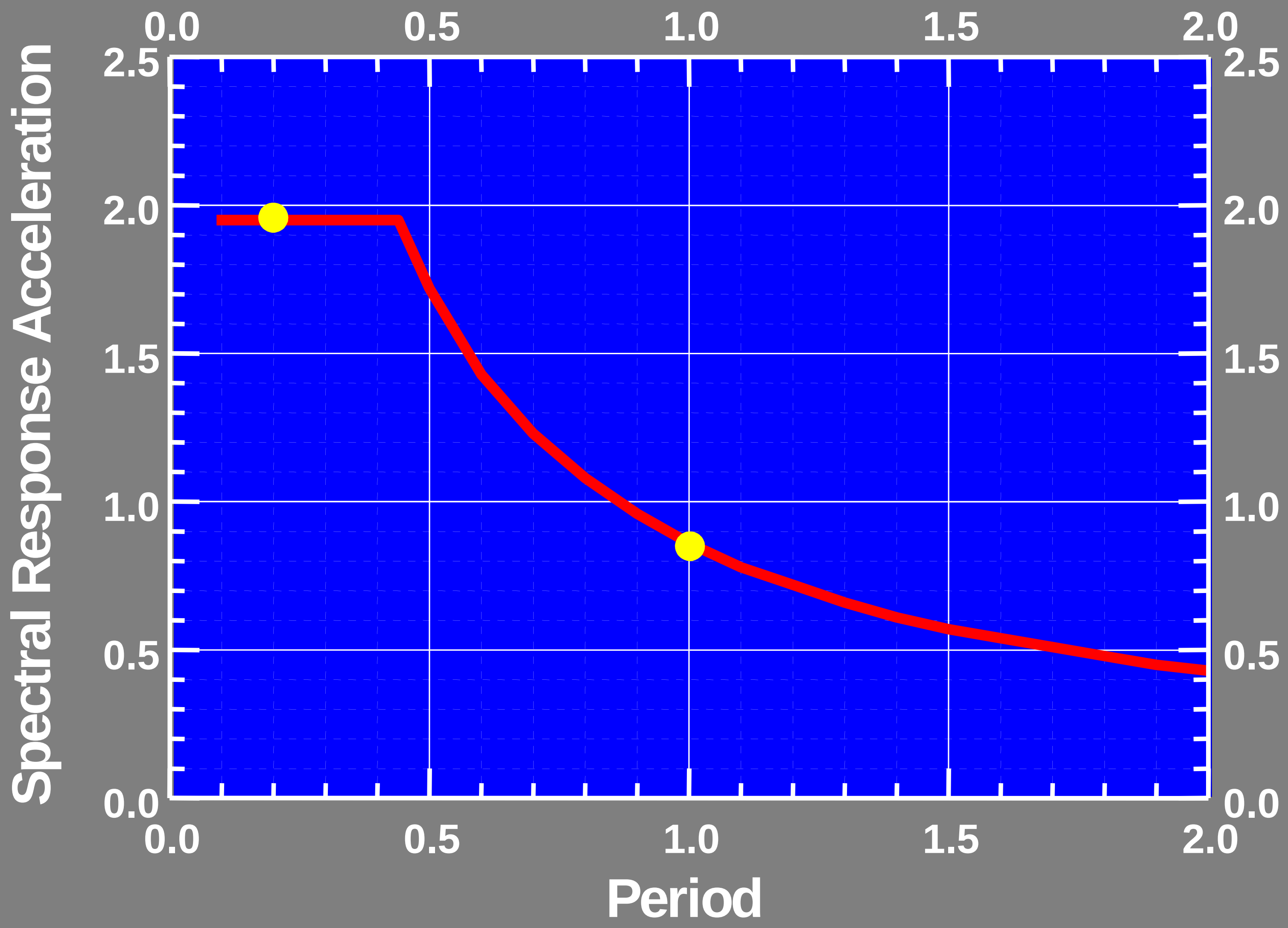
But the response spectra (and consequences for structures) are quite different:



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

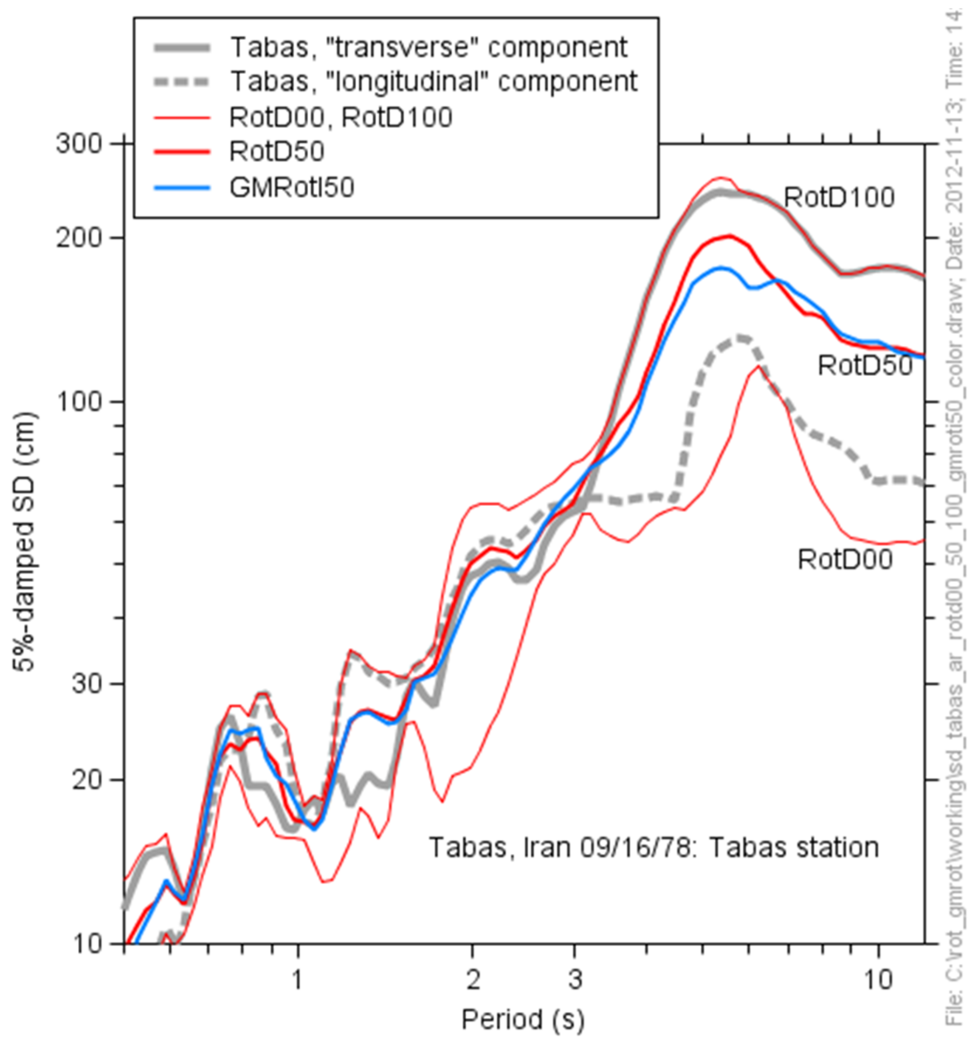
- Design values at other periods are obtained by anchoring curves to the T=0.2 and T=1.0 s values, as shown in the next slide
- But PGA useful in liquefaction analysis (along with duration)

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



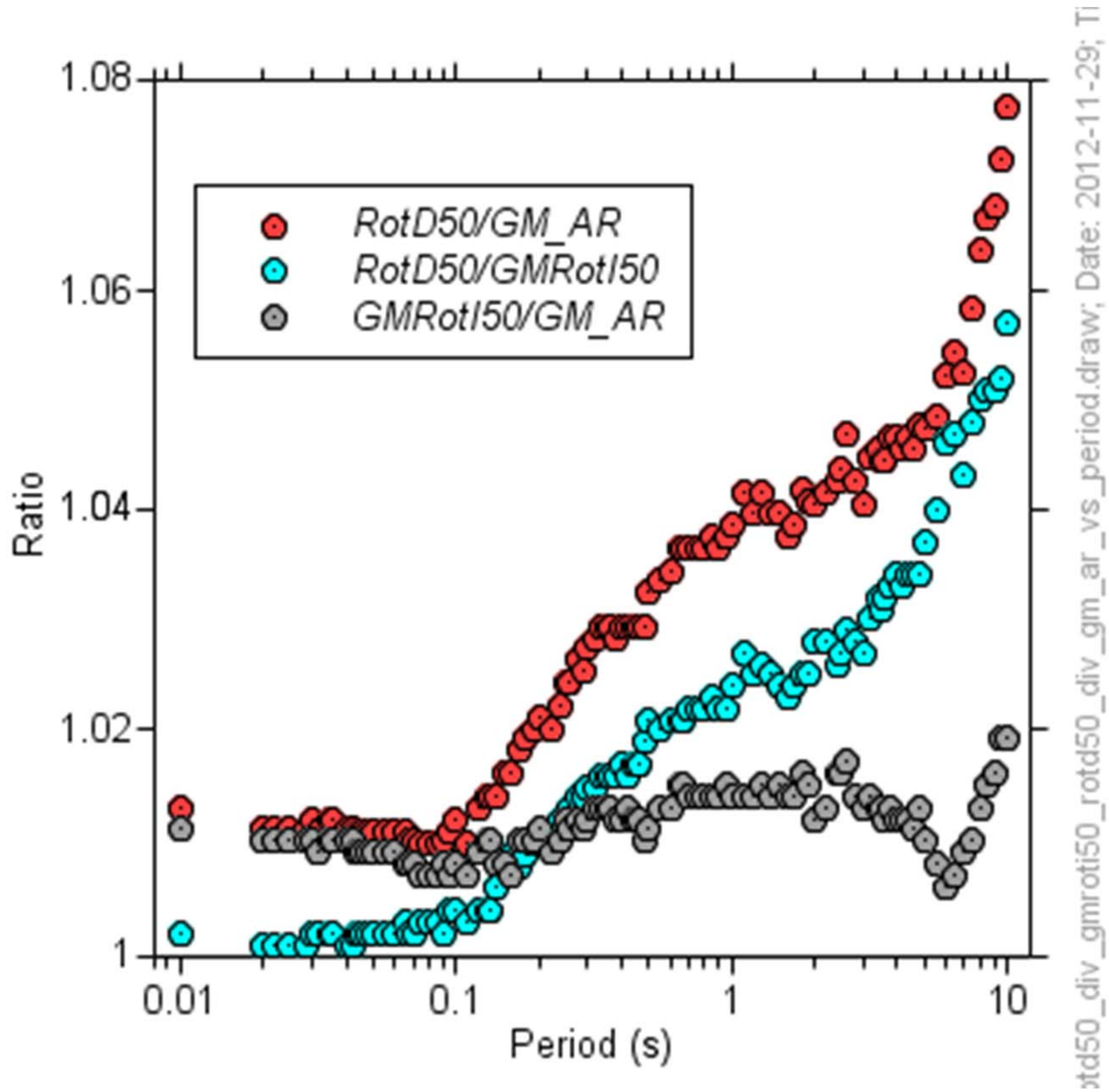
Computing RotD50

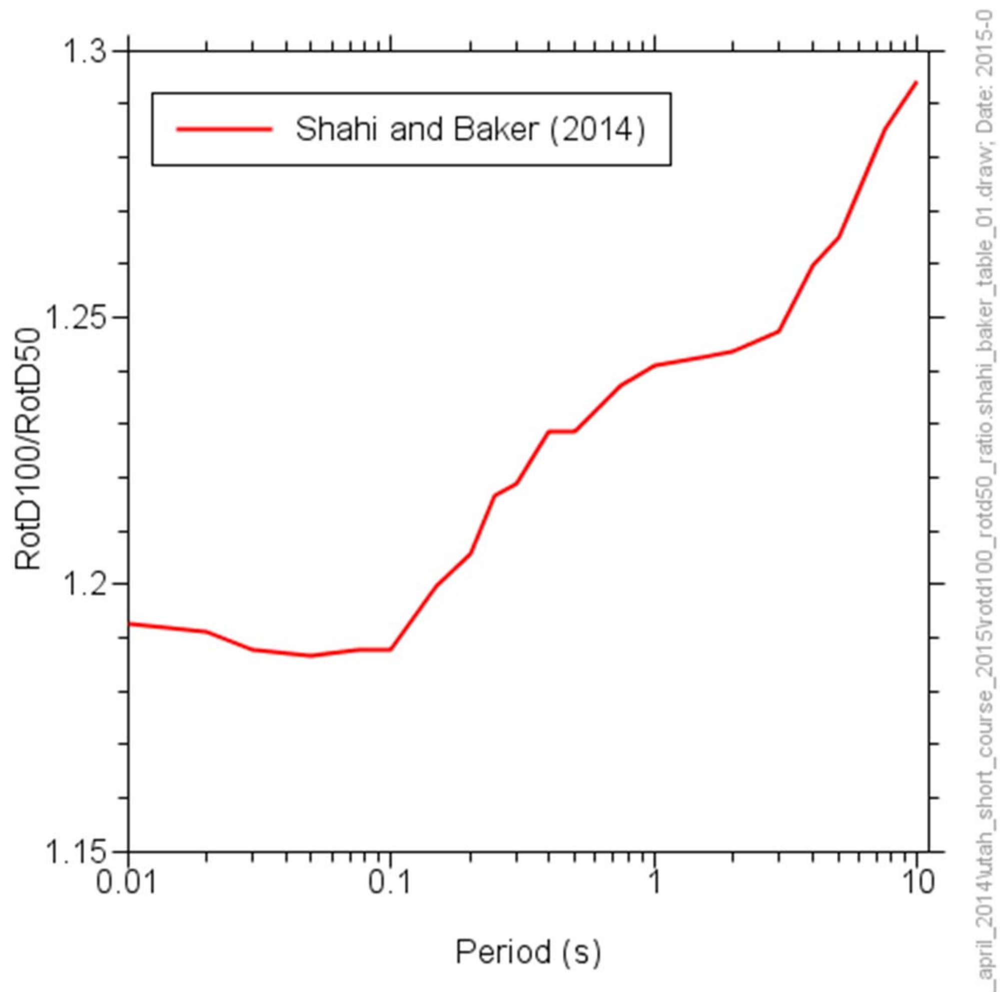
- Project the two as-recorded horizontal time series into azimuth Az
- For each period, compute PSA, store Az, PSA pairs in an array
- Increment Az by $\delta\alpha$ and repeat first two steps until Az=180
- Sort array over PSA values
- RotD50 is the median value
- RotD00, RotD100 are the minimum and maximum values
- **NO geometric means are used**


Tabas, "transverse" component
Tabas, "longitudinal" component
RotD00, RotD100
RotD50
GMRotI50
RotD100
RotD50
RotD00
Tabas, Iran 09/16/78: Tabas station
5%-damped SD (cm)
Period (s)
300
200
100
30
20
10
1
2
3
10
File: C:\rot_gmrot\working\sd_tabas_ar_rotd00_50_100_gmroti50_color.draw; Date: 2012-11-13; Time: 14:

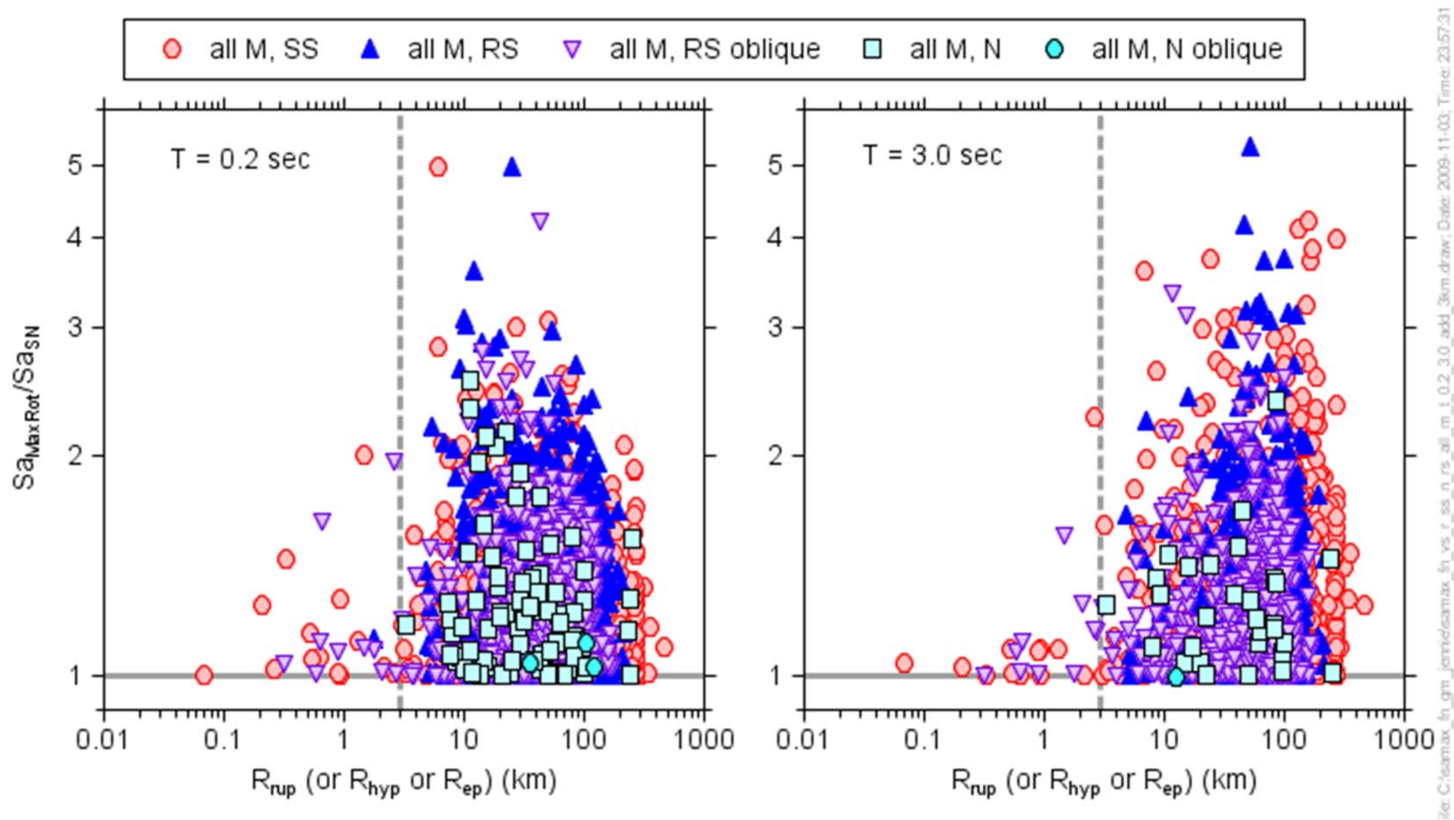
To convert GMPEs using random component as the IM (essentially, the as-recorded geometric mean), multiply by RotD50/GM_AR

To convert GMPEs using GMRotI50 as the IM (e.g., 2008 NGA GMPEs), multiply by RotD50/GMRotI50




1.3
1.25
1.2
1.15
RotD100/RotD50
Shahi and Baker (2014)
0.01
0.1
1
10
Period (s)
_april_2014\utah_short_course_2015\rotd100_rotd50_ratio.shahi_baker_table_01.draw; Date: 2015-0

Strike-normal (also known as “fault-normal”) motion only close to maximum motion within about 3 km of the fault

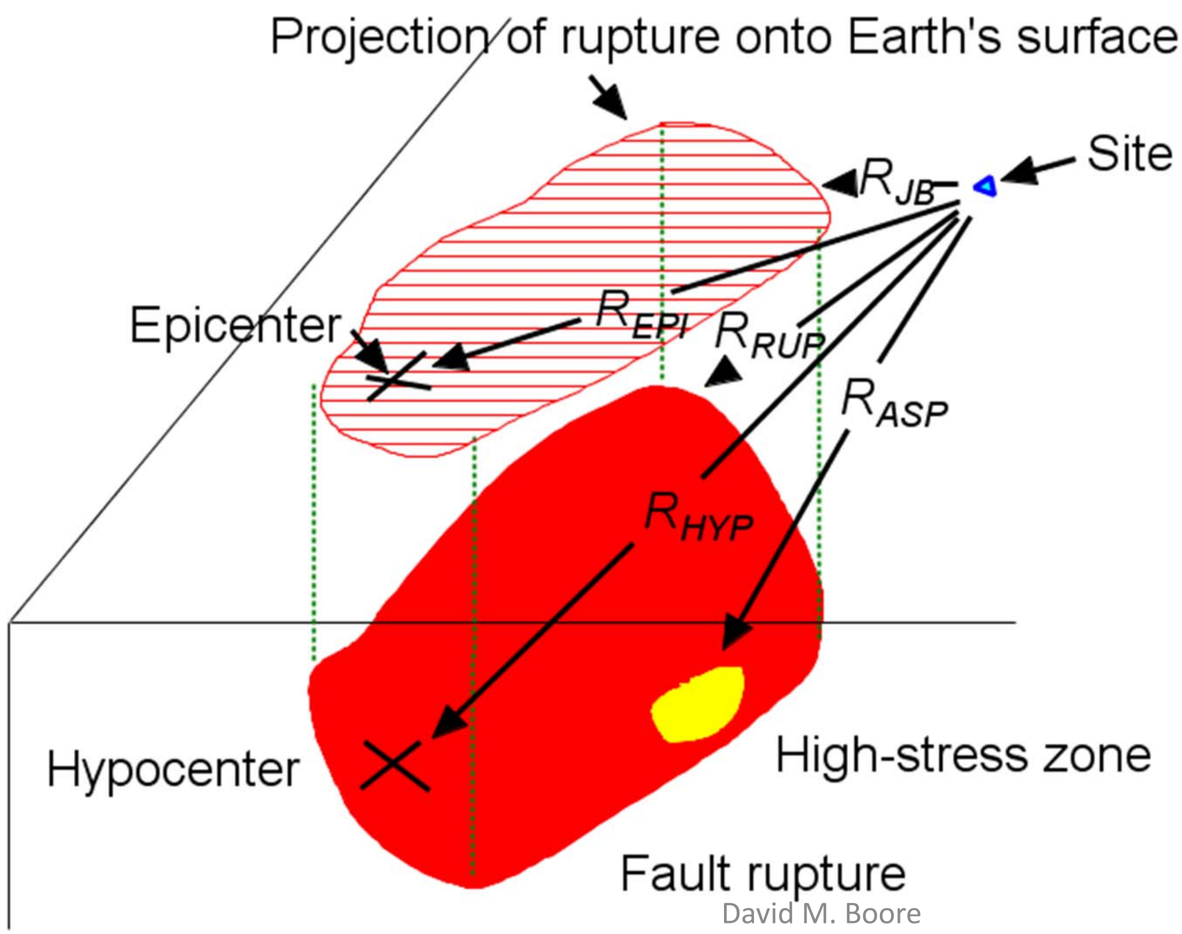


What to use for the basic predictor variables?

- 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

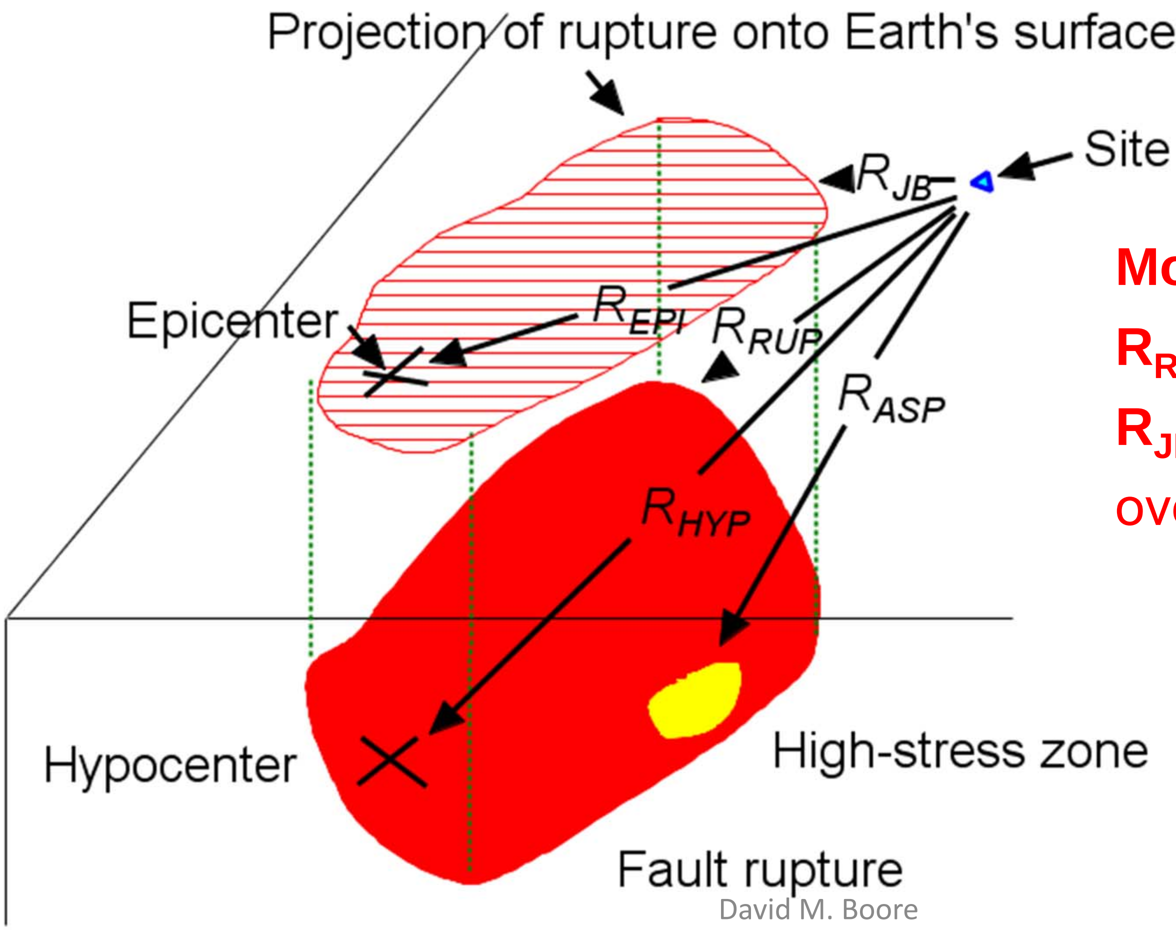


What to use for the basic predictor variables?

- 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?

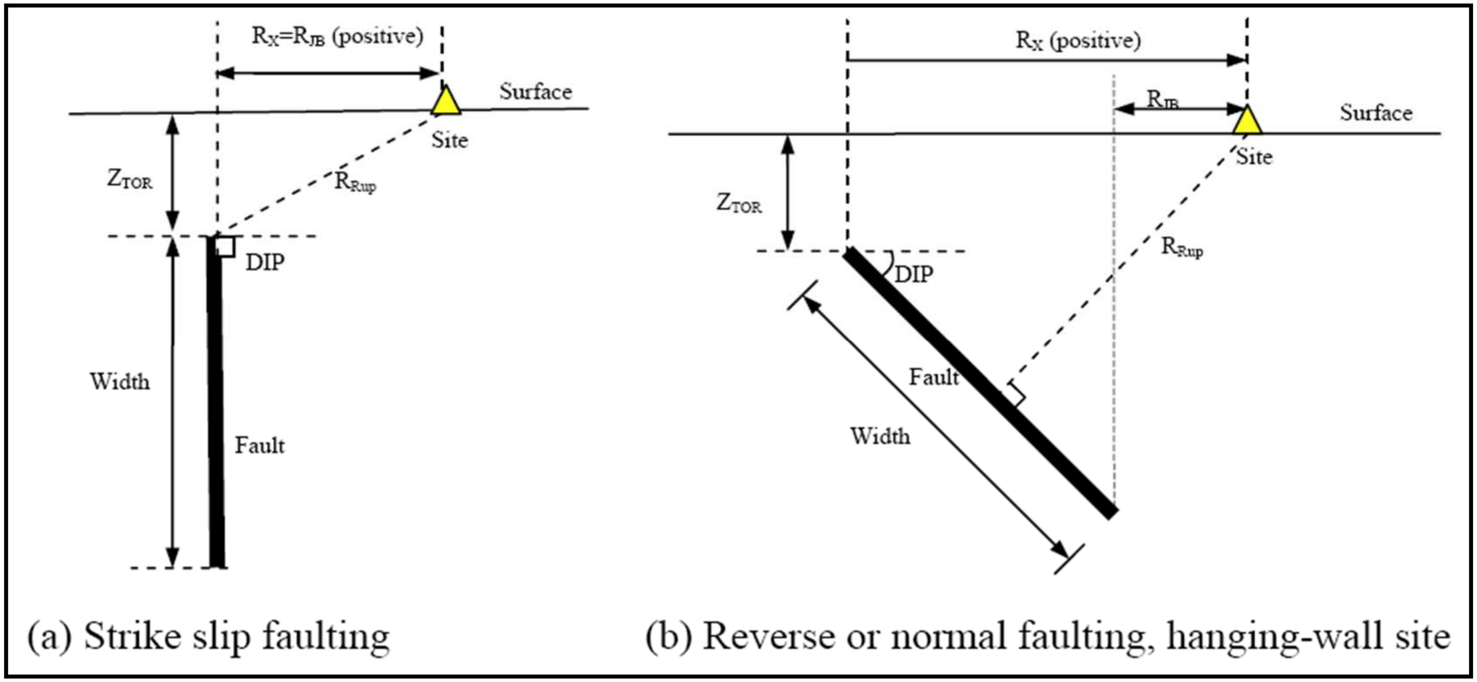
- Distance – not all measures useful for future events



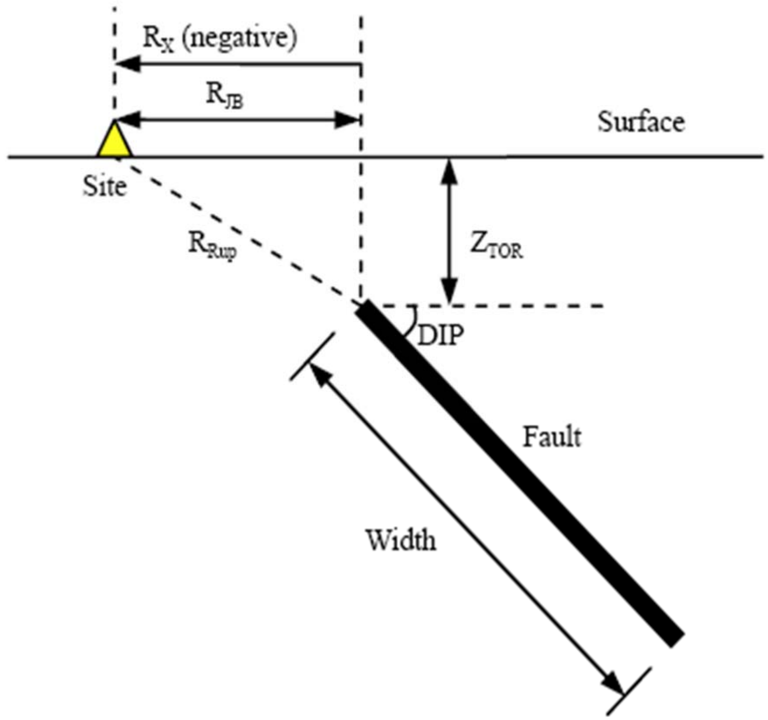
Most Commonly Used:

R_{RUP}

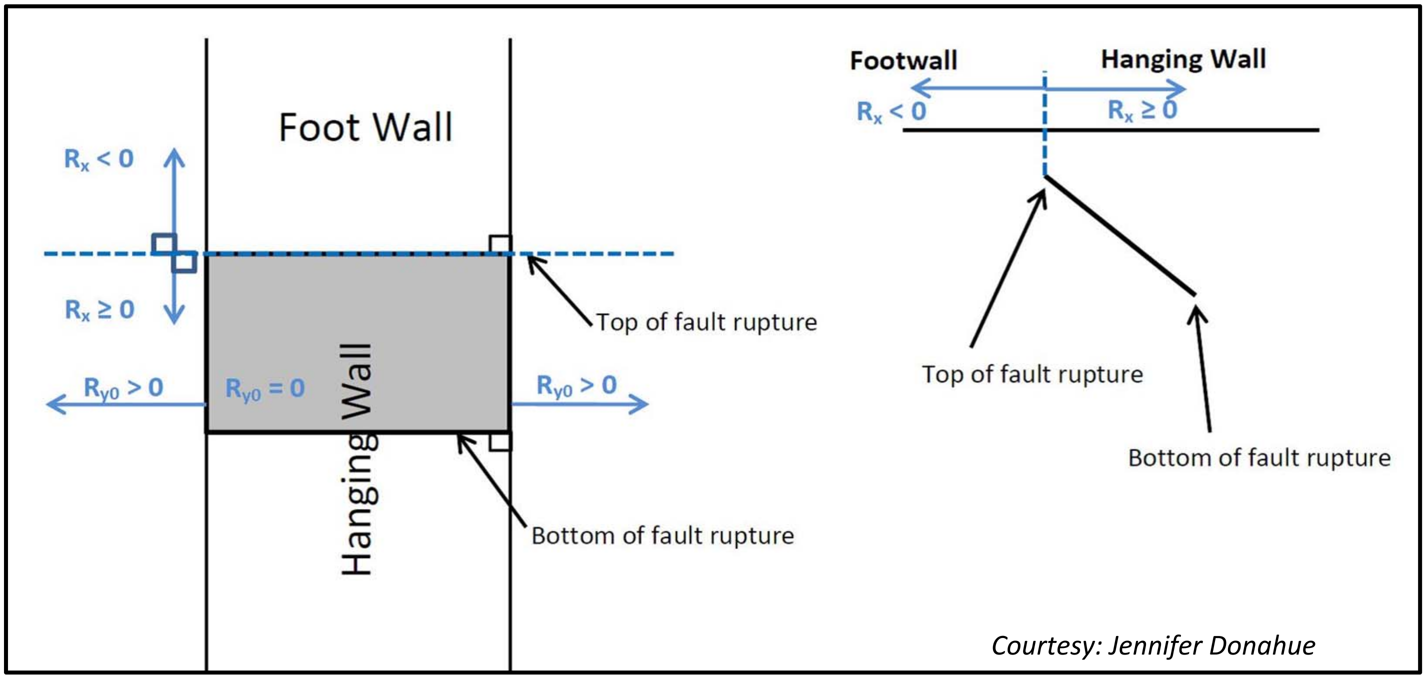
R_{JB} (0.0 for station over the fault)



R_X=R_{JB} (positive)
Surface
Site
Z_{TOR}
R_{Rup}
DIP
Width
Fault
(a) Strike slip faulting
R_X (positive)
R_{JB}
Surface
Site
Z_{TOR}
R_{Rup}
DIP
Fault
Width
(b) Reverse or normal faulting, hanging-wall site



(c) Reverse or normal faulting, foot-wall site


Foot Wall
Rx < 0
Rx ≥ 0
Top of fault rupture
Ry0 > 0
Ry0 = 0
Ry0 > 0
Hanging Wall
Bottom of fault rupture
Footwall
Hanging Wall
Rx < 0
Rx ≥ 0
Top of fault rupture
Bottom of fault rupture
Courtesy: Jennifer Donahue

What to use for the basic predictor variables?

- A measure of local site geology

Site Classifications for Use With Ground-Motion Prediction Equations

1. Rock/Soil

- Rock = less than 5m soil over "granite", "limestone", etc.
- Soil= everything else

2. NEHRP Site Classes (based on V_{S30})

TABLE 4.
Definition of NEHRP site classes (BSSC, 1994)

Site Class	Range of Shear Velocities*
A	greater than 1500 m/sec
B	760 m/sec to 1500 m/sec
C	360 m/sec to 760 m/sec
D	180 m/sec to 360 m/sec
E	less than 180 m/sec

* Shear velocity is averaged over the upper 30 m.

620 m/s = typical rock

310 m/s = typical soil

3. Continuous Variable (V_{S30})

Time-averaged shear-wave velocity to depth z:

$$V_{SZ} = \frac{z}{\int_0^z \frac{d\xi}{V_S(\xi)}}$$

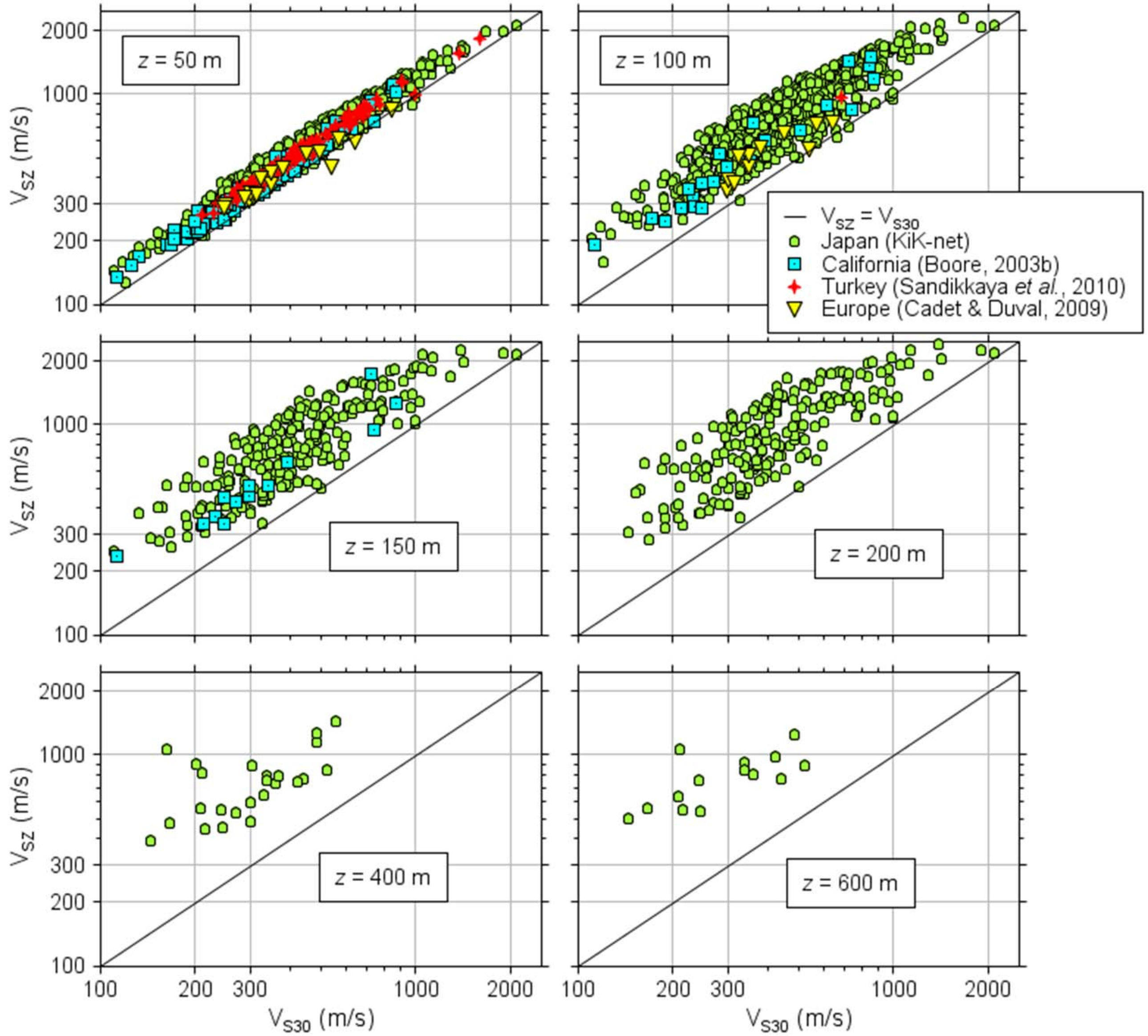
Average shear-wave slowness to depth z:

$$S_{SZ} = \frac{1}{V_{SZ}} = \frac{1}{z}\int_0^z S_S(\xi)\,d\xi$$

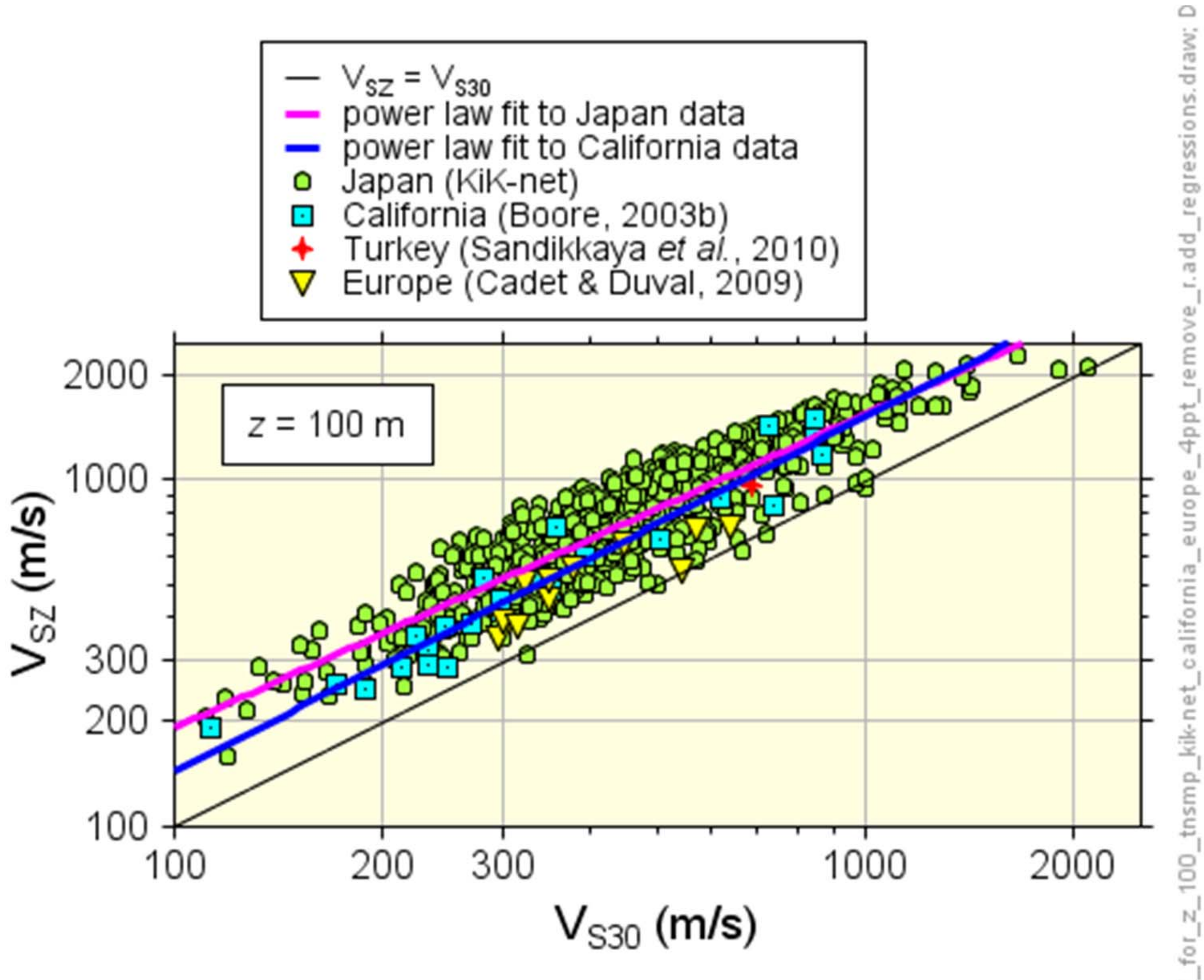
Why V_{S30}?

- Most data available when the idea of using average Vs was developed were from 30 m holes, the average depth that could be drilled in one day
- Better would be V_{sz}, where z corresponds to a quarter-wavelength for the period of interest, but
- Few observations of V_s are available for greater depths
- V_{sz} correlates quite well with V_{s30} for a wide range of z greater than 30 m (see next slide, from Boore et al., BSSA, 2011, pp. 3046—3059)

V_{sz} correlates quite well with V_{s30} for a wide range of z greater than 30 m

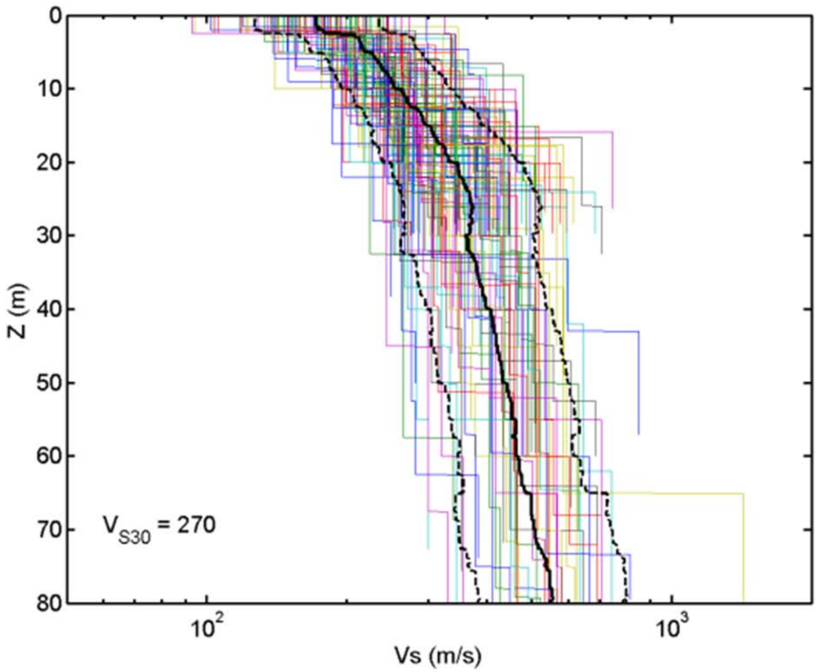


But regional differences exist

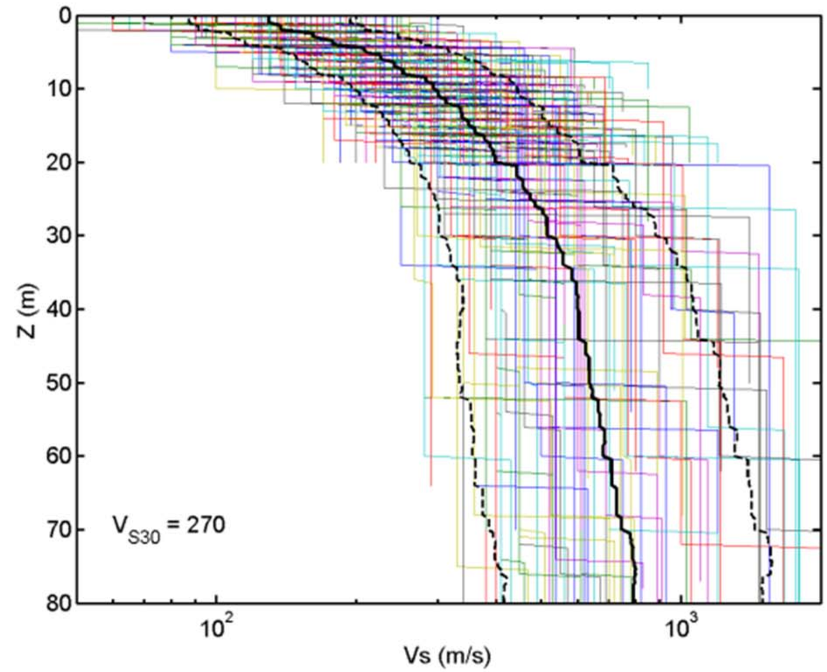


V_S Profiles for V_{S30}=270 (± 5%)

CALIFORNIA



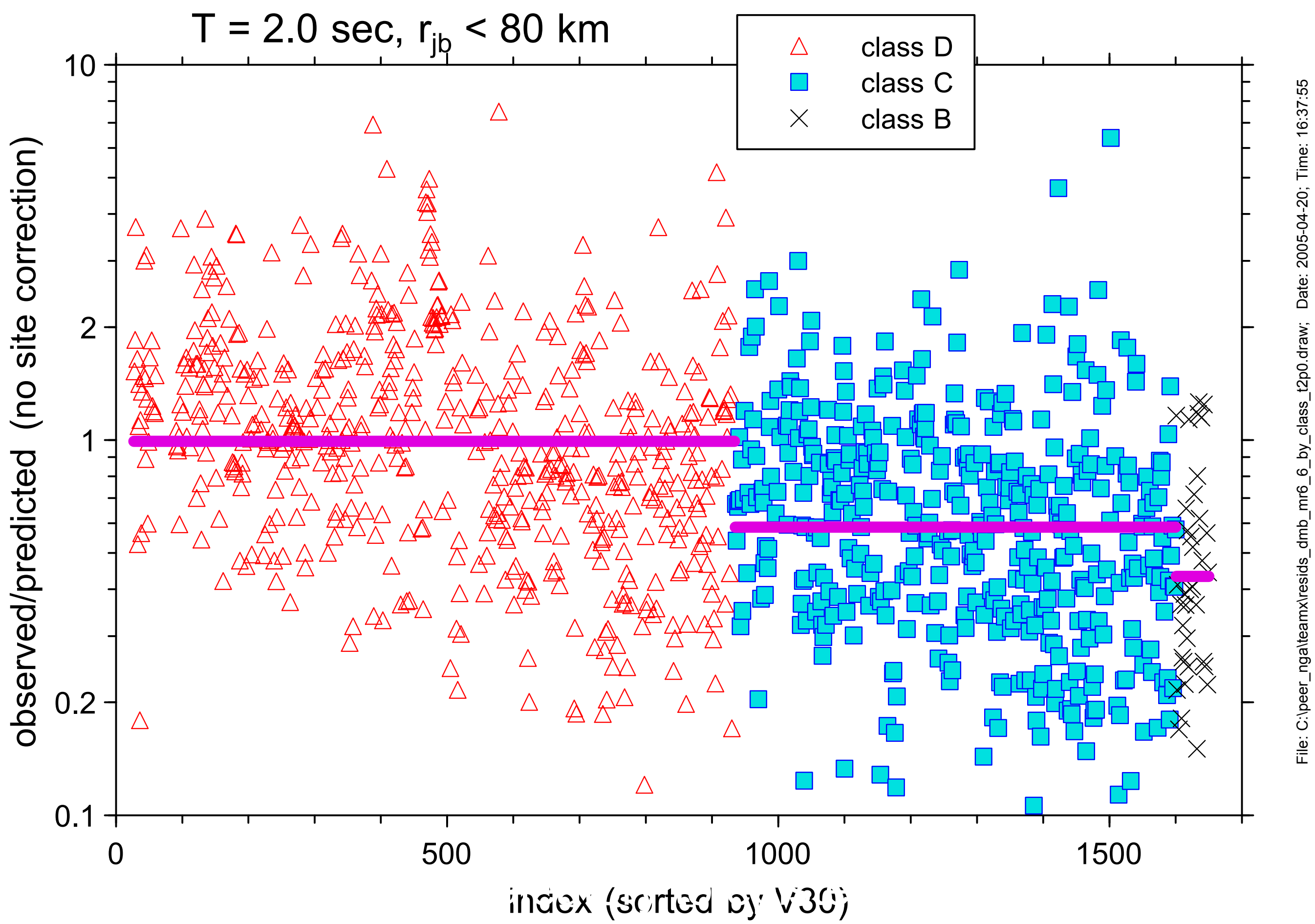
JAPAN



From Kamai et al (2015)

Abrahamson (2015)

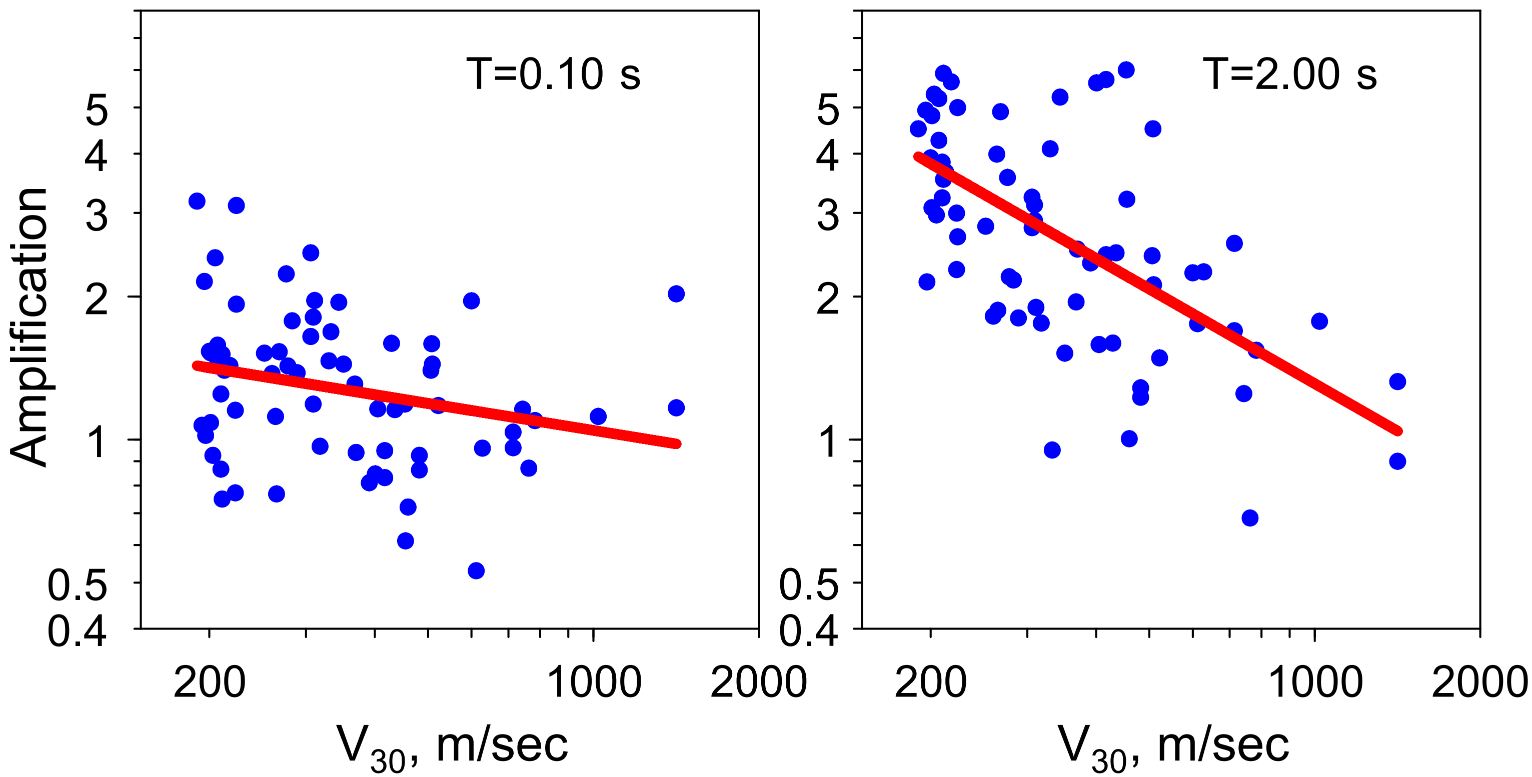
Large scatter would remain after removing site effect based on site class



This figure is also a good representation of the data availability for various site classes: most data are from class D, very few from class B (rock)

V_{S30} as continuous variable

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

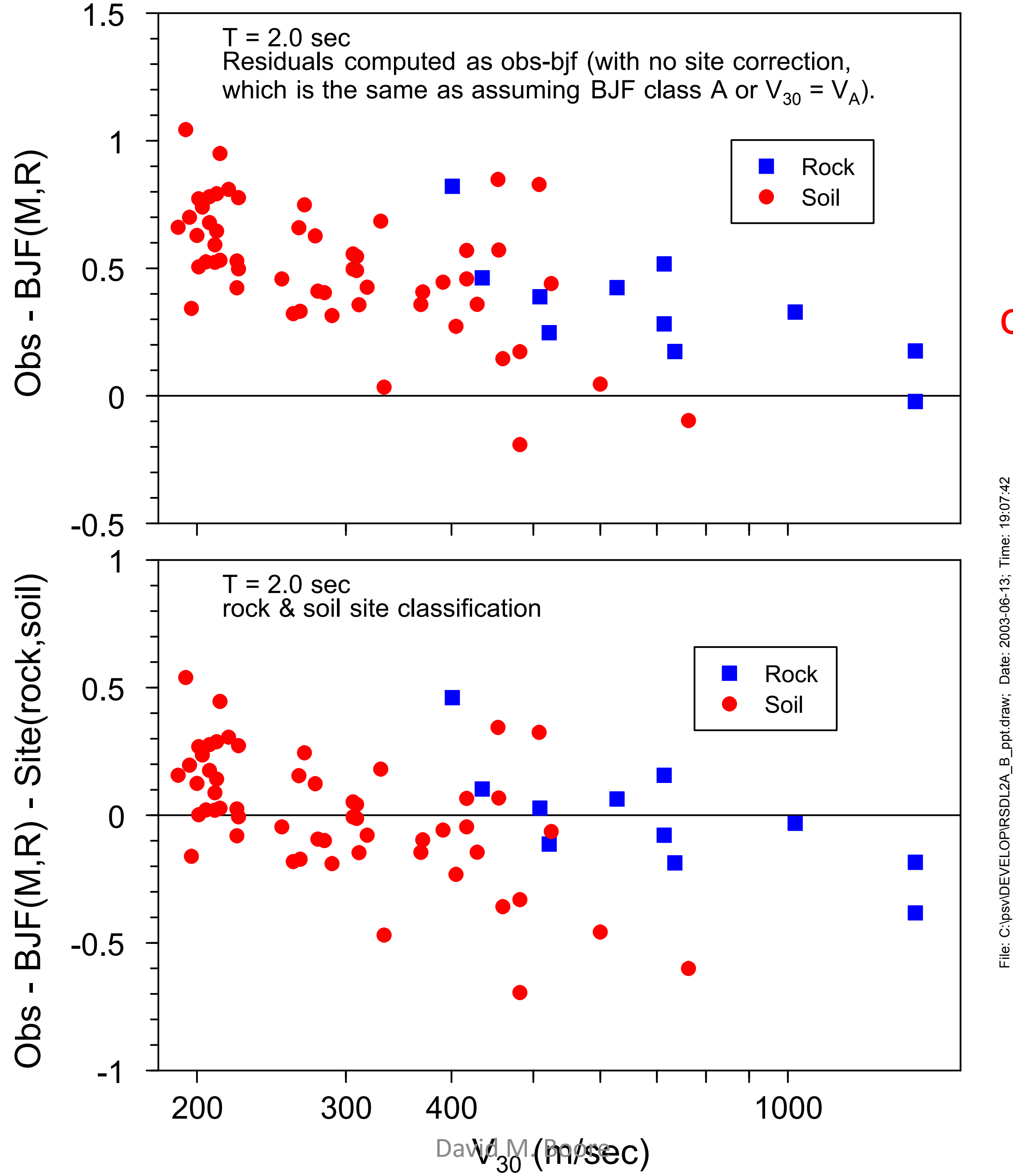


Note period dependence of site response

David M. Boore

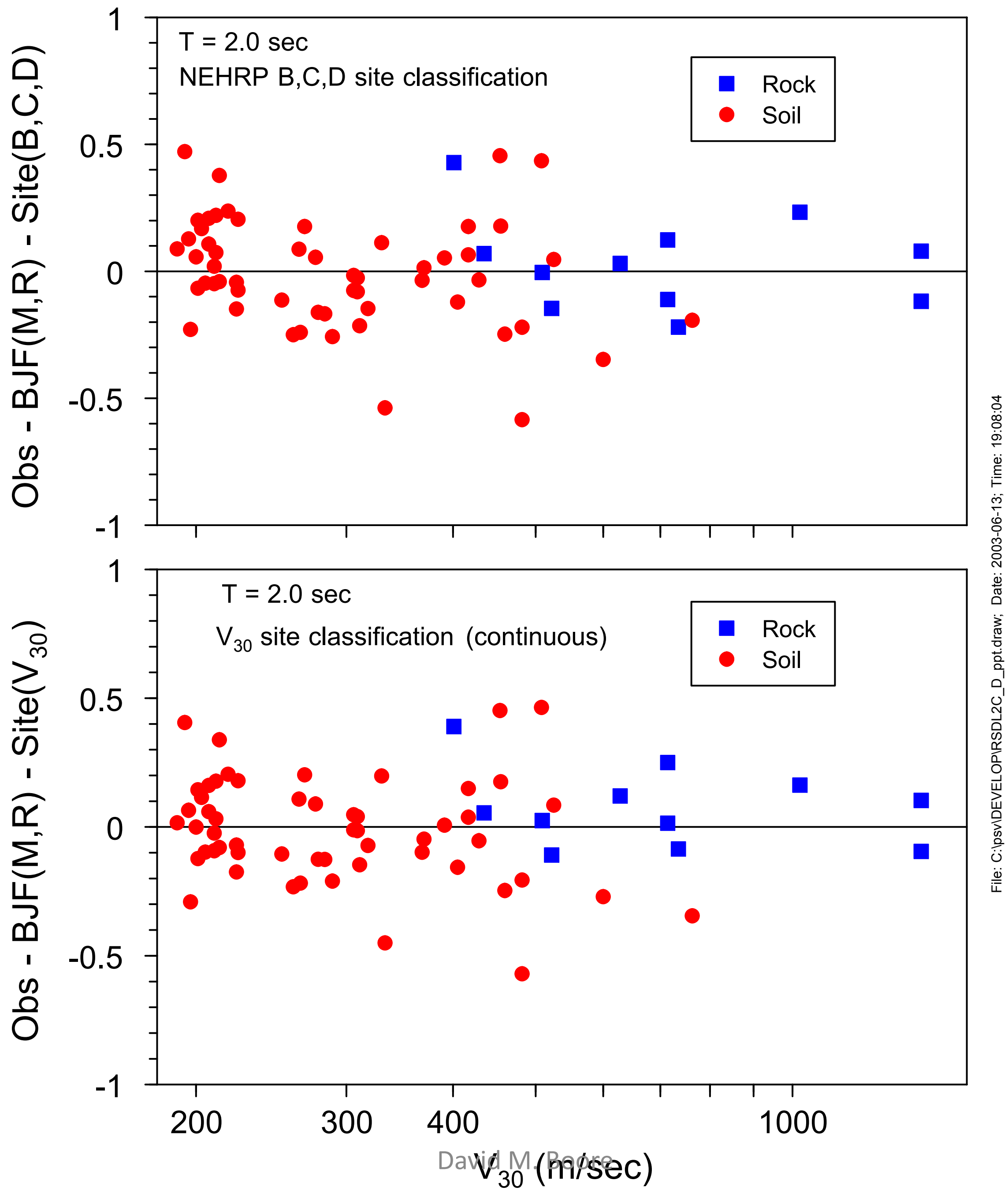
Effect of different site characterizations for a small subset of data for which V30 values are available

- No site characterization
- Rock/soil
- NEHRP class
- V30 (continuous variable)


T = 2.0 sec
Residuals computed as obs-bjf (with no site correction, which is the same as assuming BJF class A or $V_{30} = V_A$).
Rock
Soil
Obs - BJF(M,R)
T = 2.0 sec
rock & soil site classification
Rock
Soil
Obs - BJF(M,R) - Site(rock,soil)
200
300
400
1000
V_{30} (m/sec)
File: C:\psv\DEVELOP\RSDL2A_B_ppt.draw; Date: 2003-06-13; Time: 19:07:42

σ=0.25

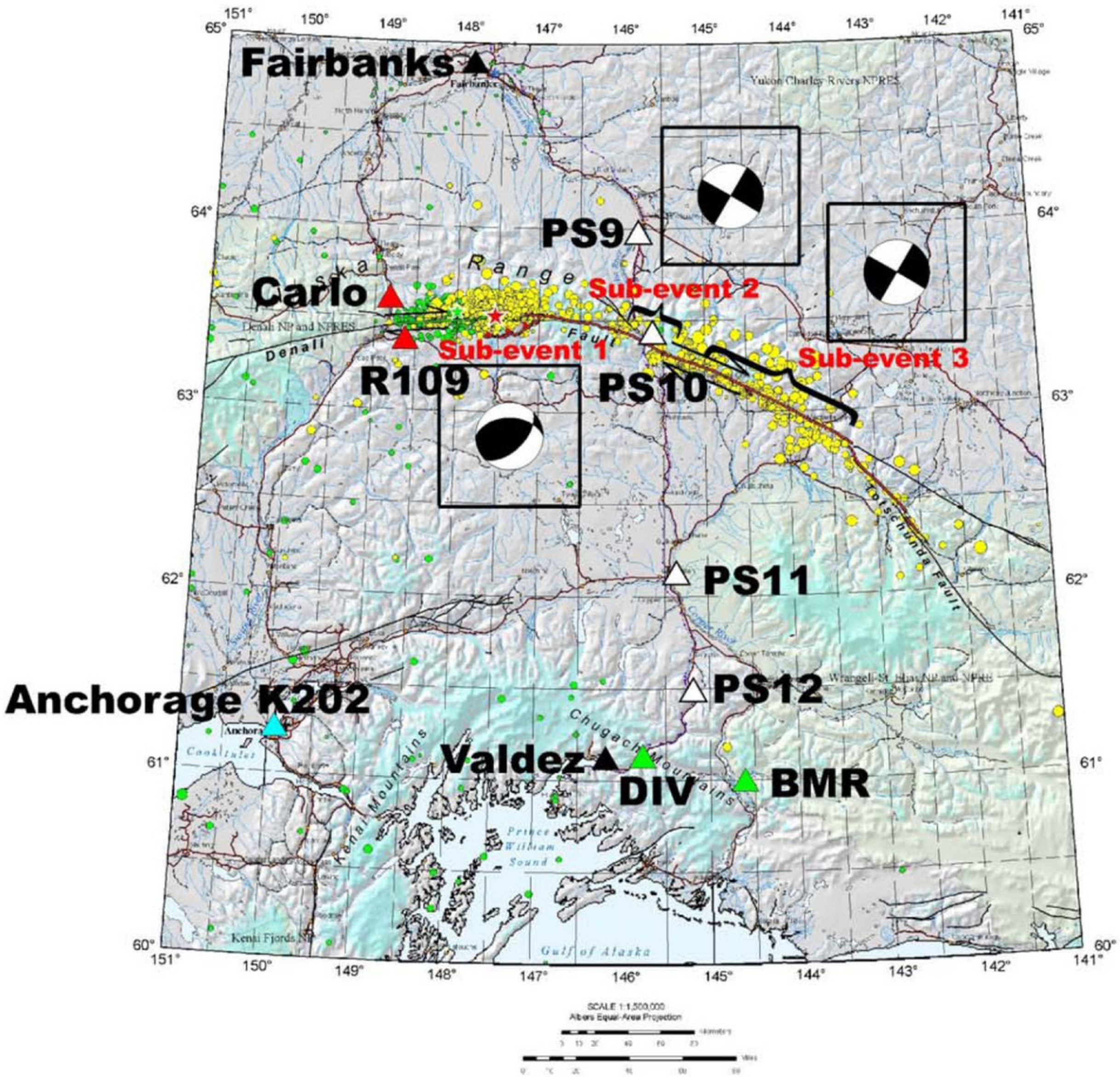
σ=0.25


T = 2.0 sec
NEHRP B,C,D site classification
Rock
Soil
Obs - BJF(M,R) - Site(B,C,D)
1
0.5
0
-0.5
-1
T = 2.0 sec
V30 site classification (continuous)
Rock
Soil
Obs - BJF(M,R) - Site(V30)
200
300
400
1000
V30 (m/sec)
File: C:\psv\DEVELOP\RSDL2C_D_ppt.draw; Date: 2003-06-13; Time: 19:08:04

σ=0.21

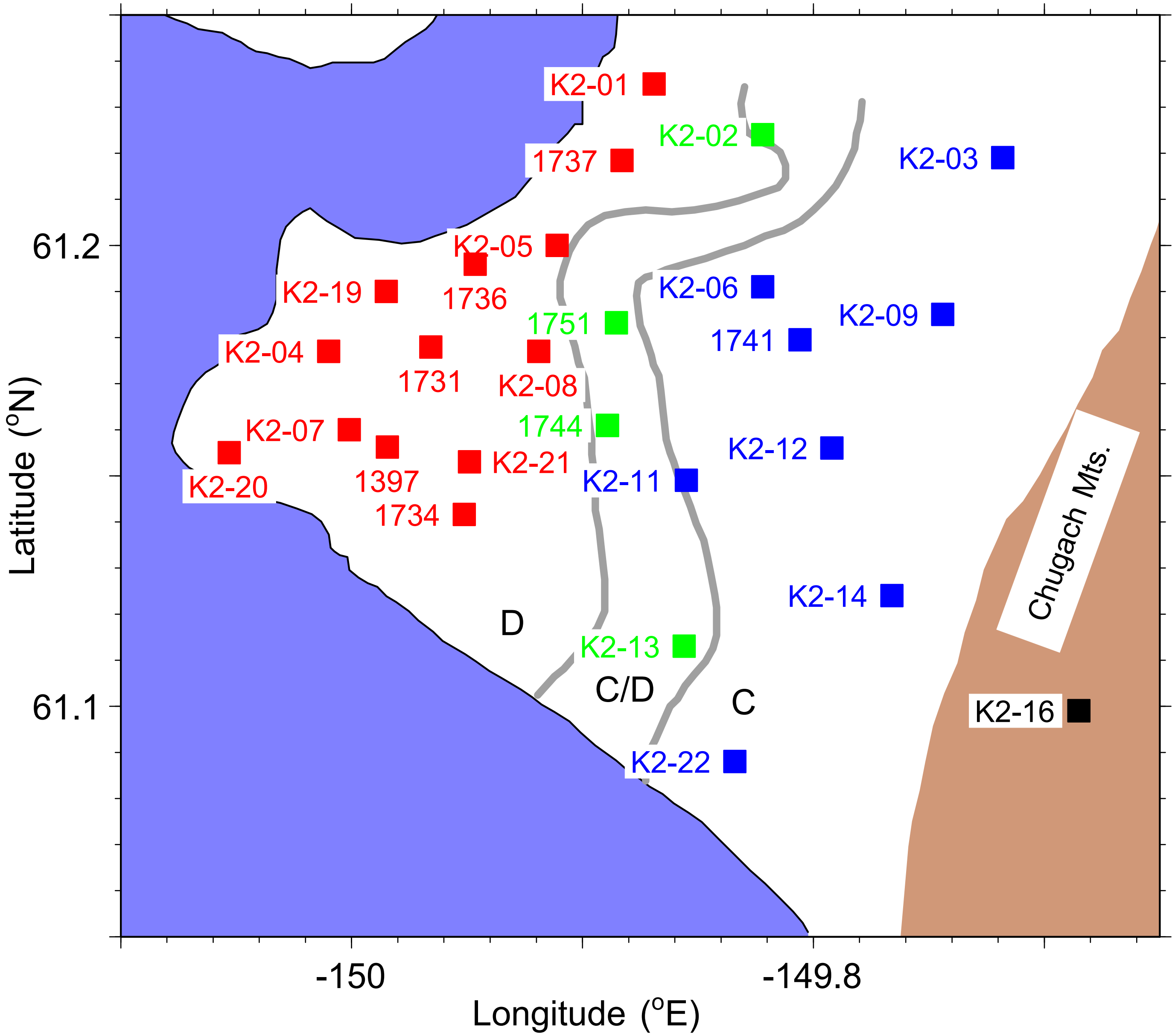
σ=0.20

2002 M 7.9 Denali Fault

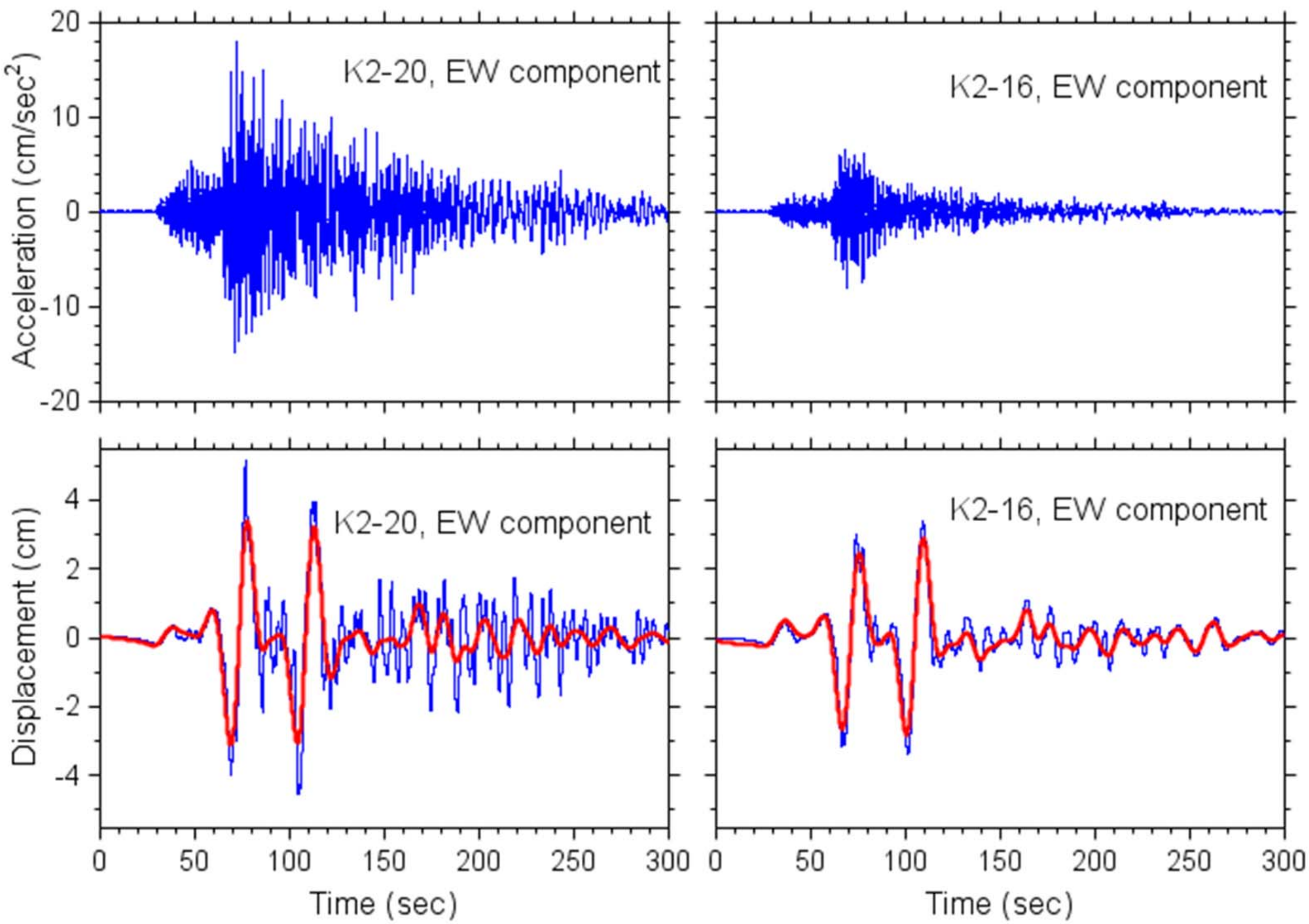


- Geophysical Inst., Univ. Of Alaska, portable
- Geophysical Inst., Univ. Of Alaska, permanent
- USGS National Strong Motion Network
- CREST
- Alyeska station

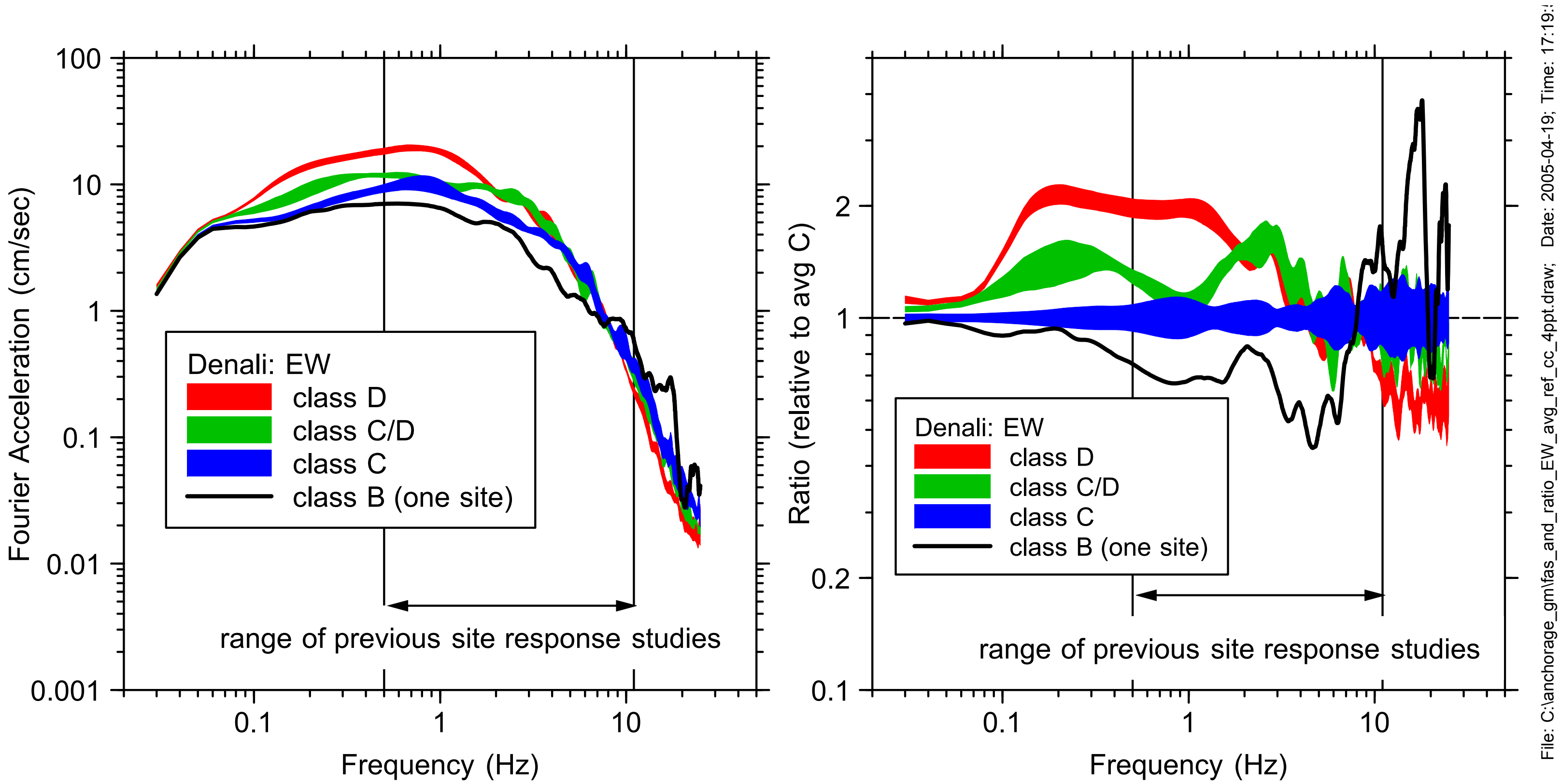
From Frankel, 2003



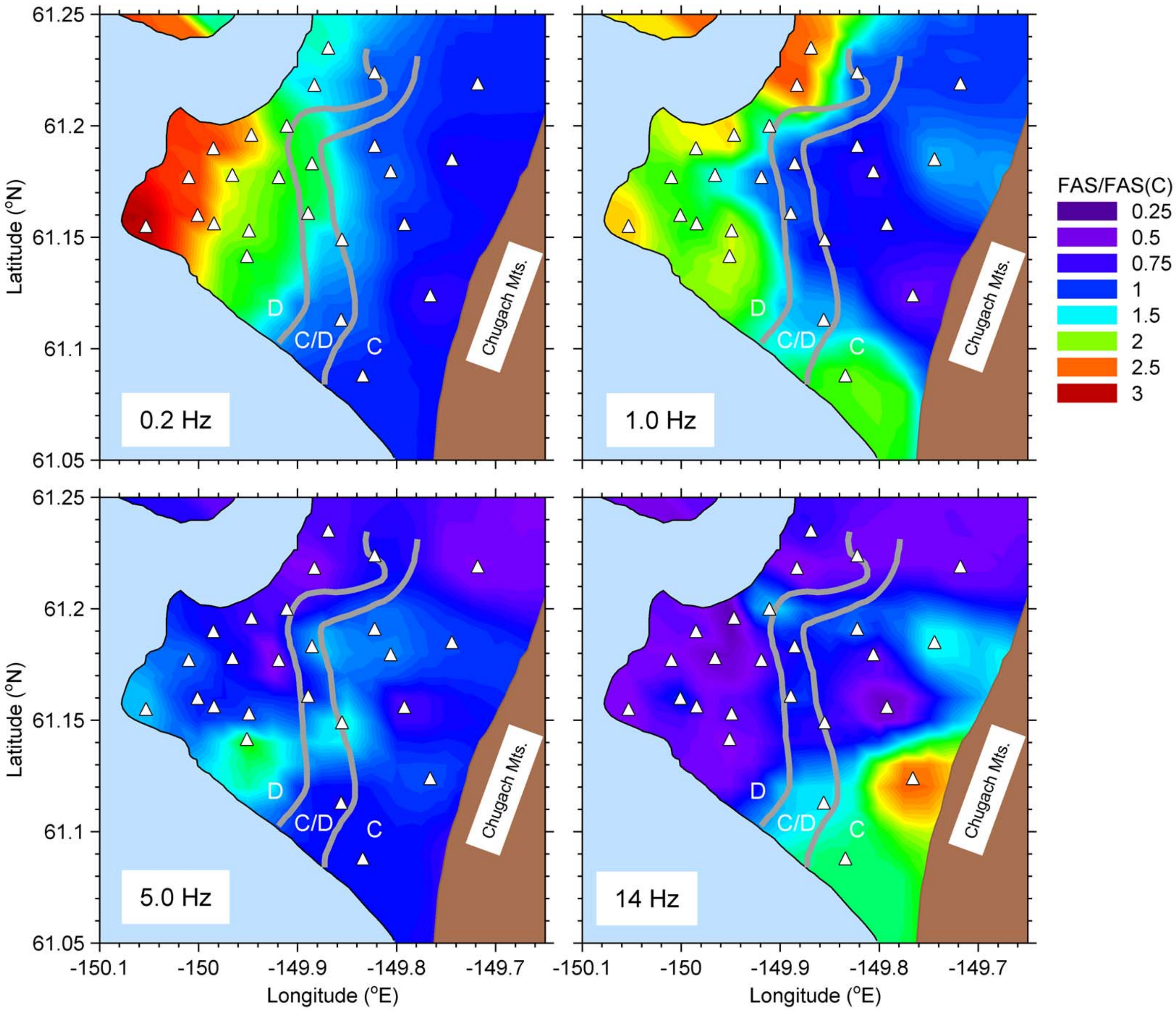
Site Classes are based on the average shear-wave velocity in the upper 30 m



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



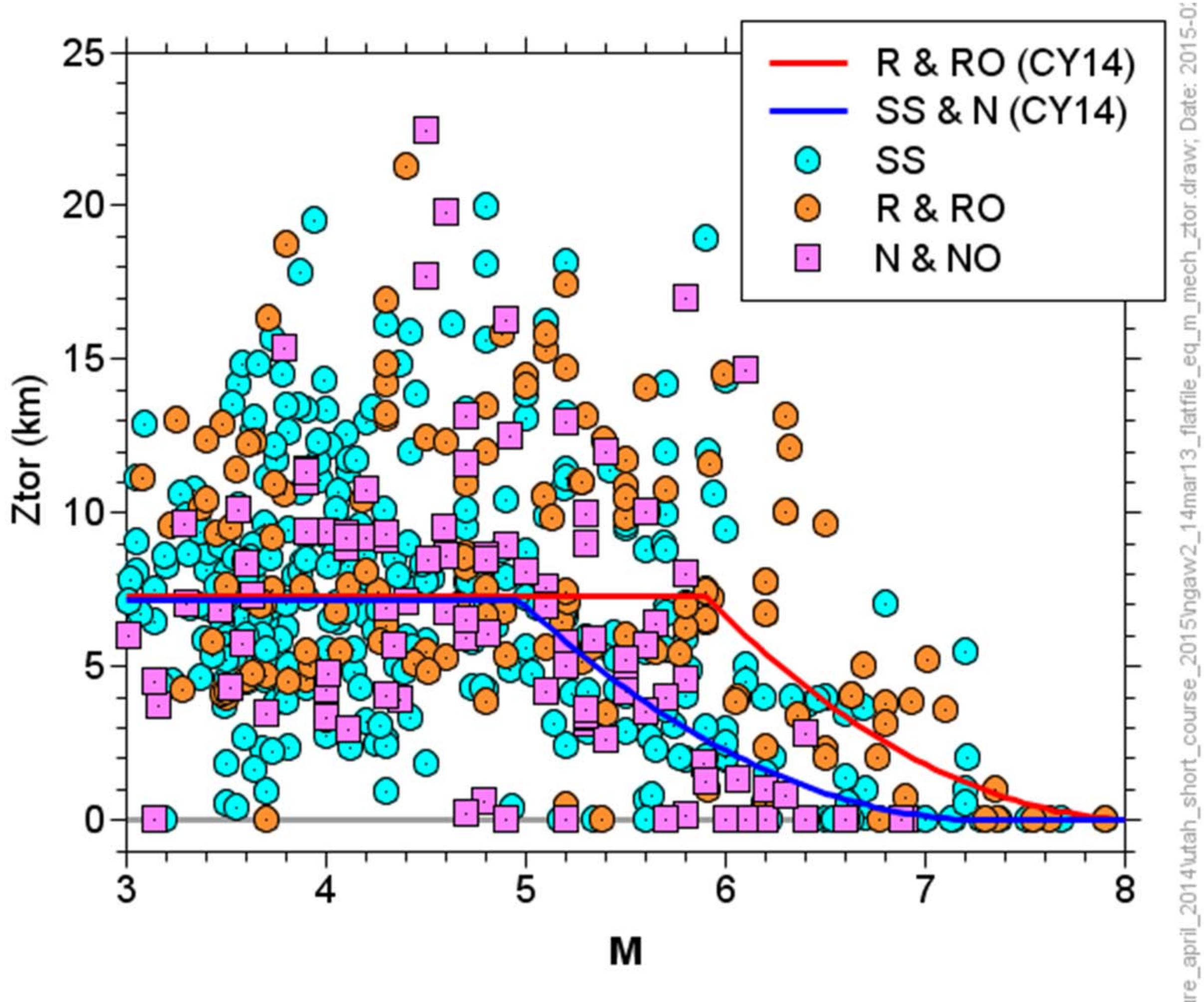
Fourier Acceleration (cm/sec)
100
10
1
0.1
0.01
0.001
Denali: EW
class D
class C/D
class C
class B (one site)
range of previous site response studies
0.1
1
10
Frequency (Hz)
Ratio (relative to avg C)
2
1
0.2
0.1
Denali: EW
class D
class C/D
class C
class B (one site)
range of previous site response studies
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:

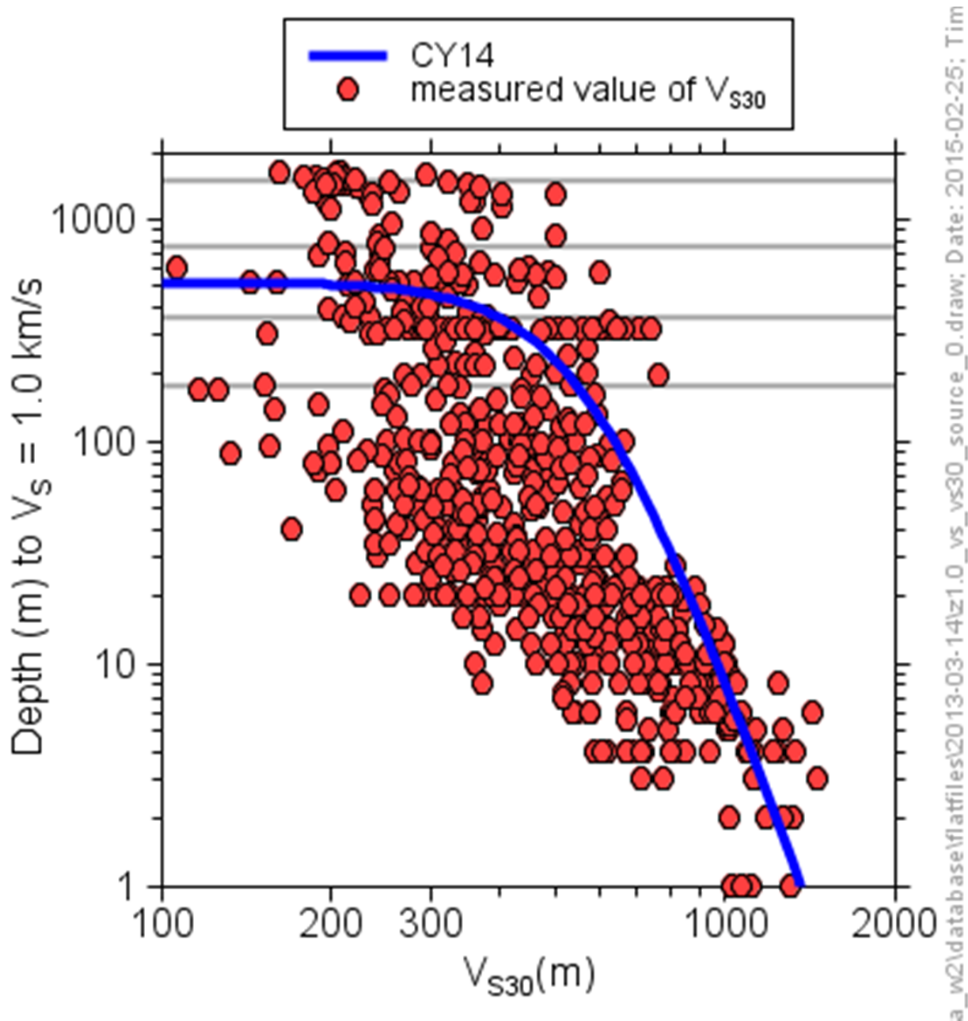


61.25
61.2
61.15
61.1
61.05
Latitude (°N)
D
C/D
C
Chugach Mts.
0.2 Hz
1.0 Hz
5.0 Hz
14 Hz
FAS/FAS(C)
0.25
0.5
0.75
1
1.5
2
2.5
3
-150.1
-150
-149.9
-149.8
-149.7
Longitude (°E)

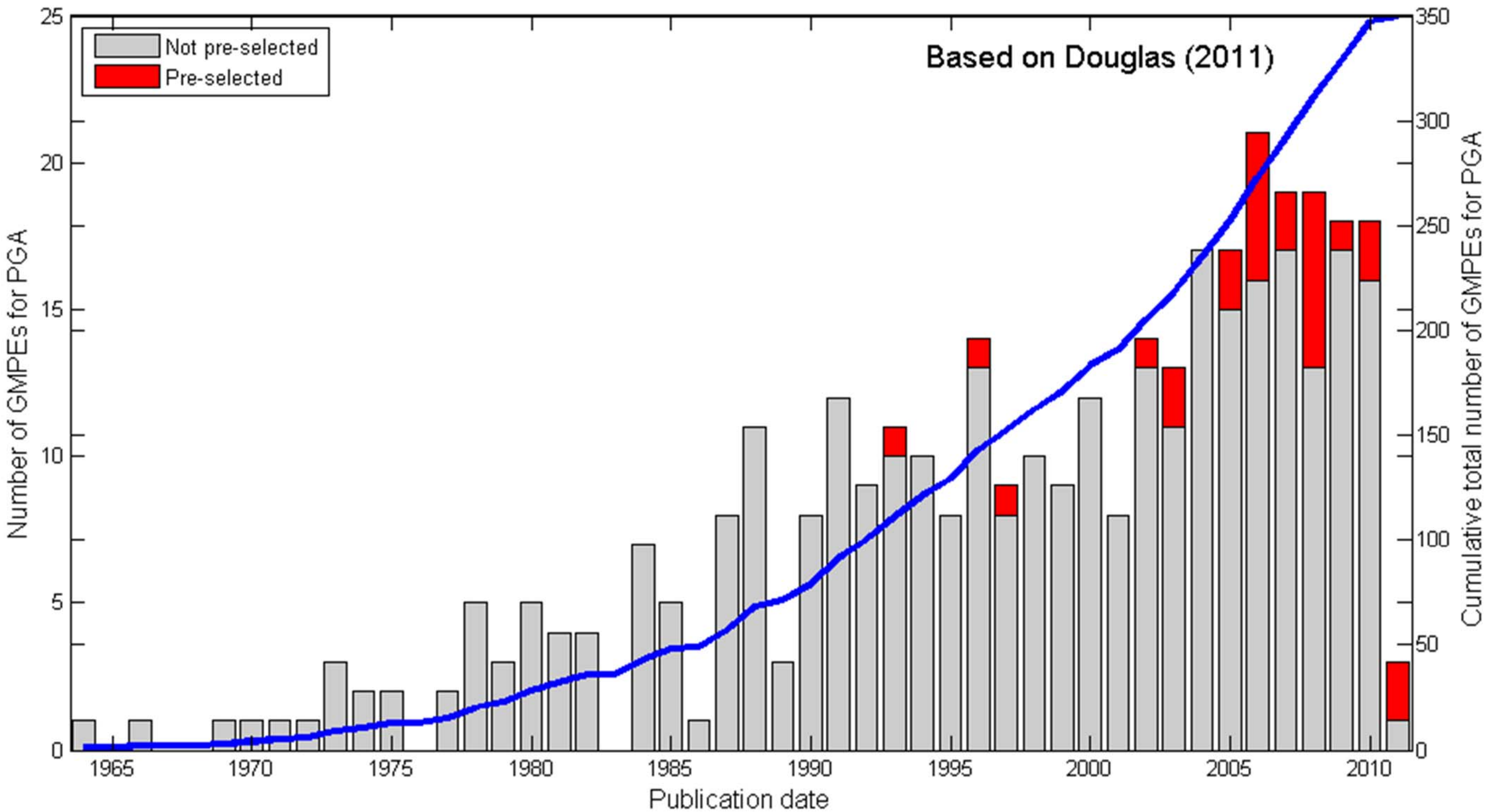
Correlation between Ztor, mechanism, and **M**

- Strong correlation between Ztor and **M**
- Most **M**>7 earthquakes reach the surface (but no data for normal-fault earthquakes with **M**>7)



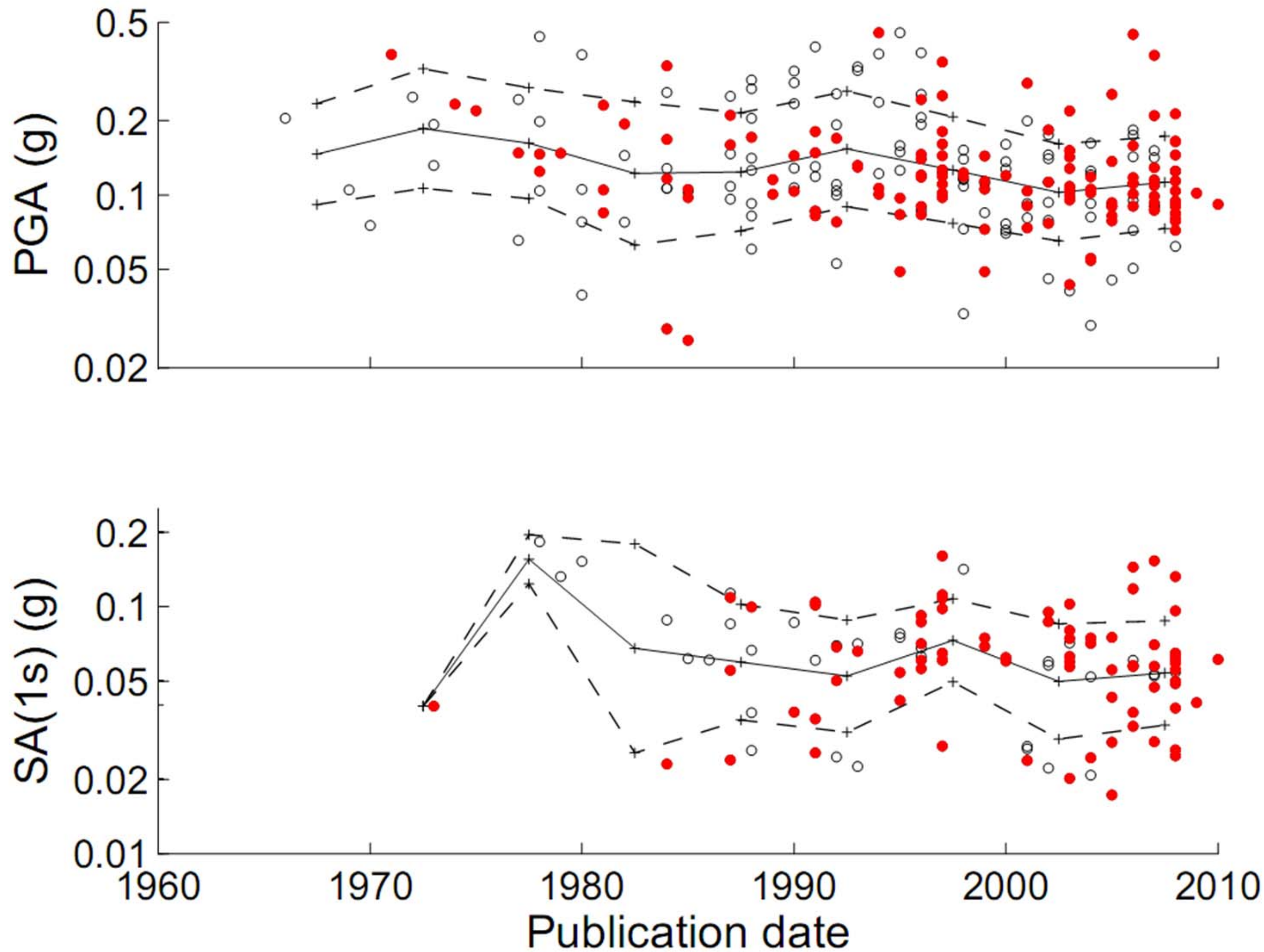

CY14
measured value of V_{S30}
Depth (m) to V_S = 1.0 km/s
1000
100
10
1
100
200
300
1000
2000
V_{S30}(m)

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)

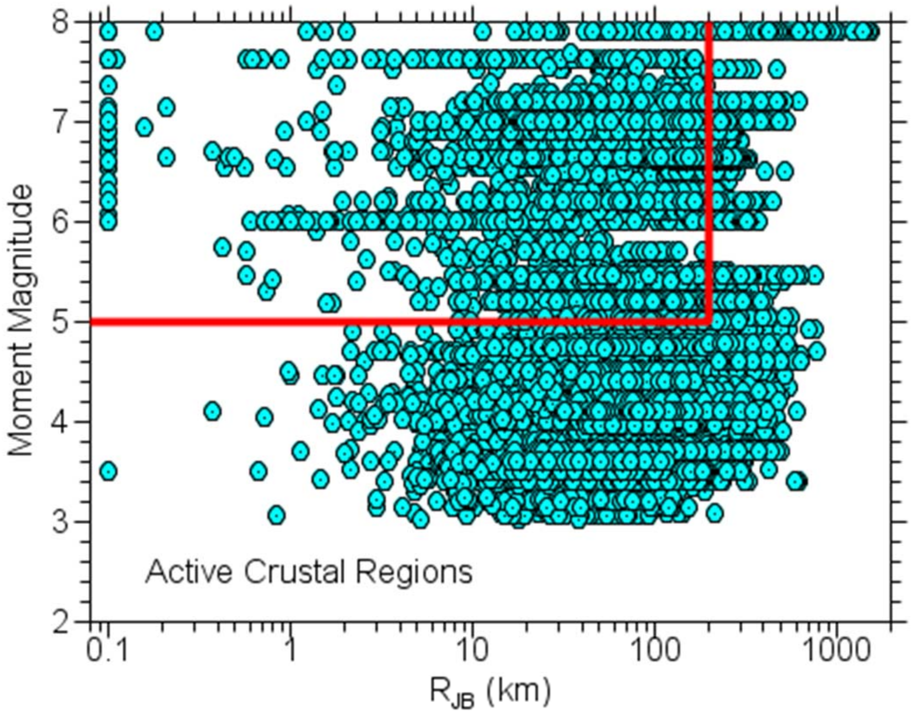
- Supporting Working Groups
  - Directivity
  - Site Response
  - Database
  - Directionality
  - Uncertainty
  - Vertical Component
  - Adjustment for Damping

NGA-West2 Developer Teams:

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

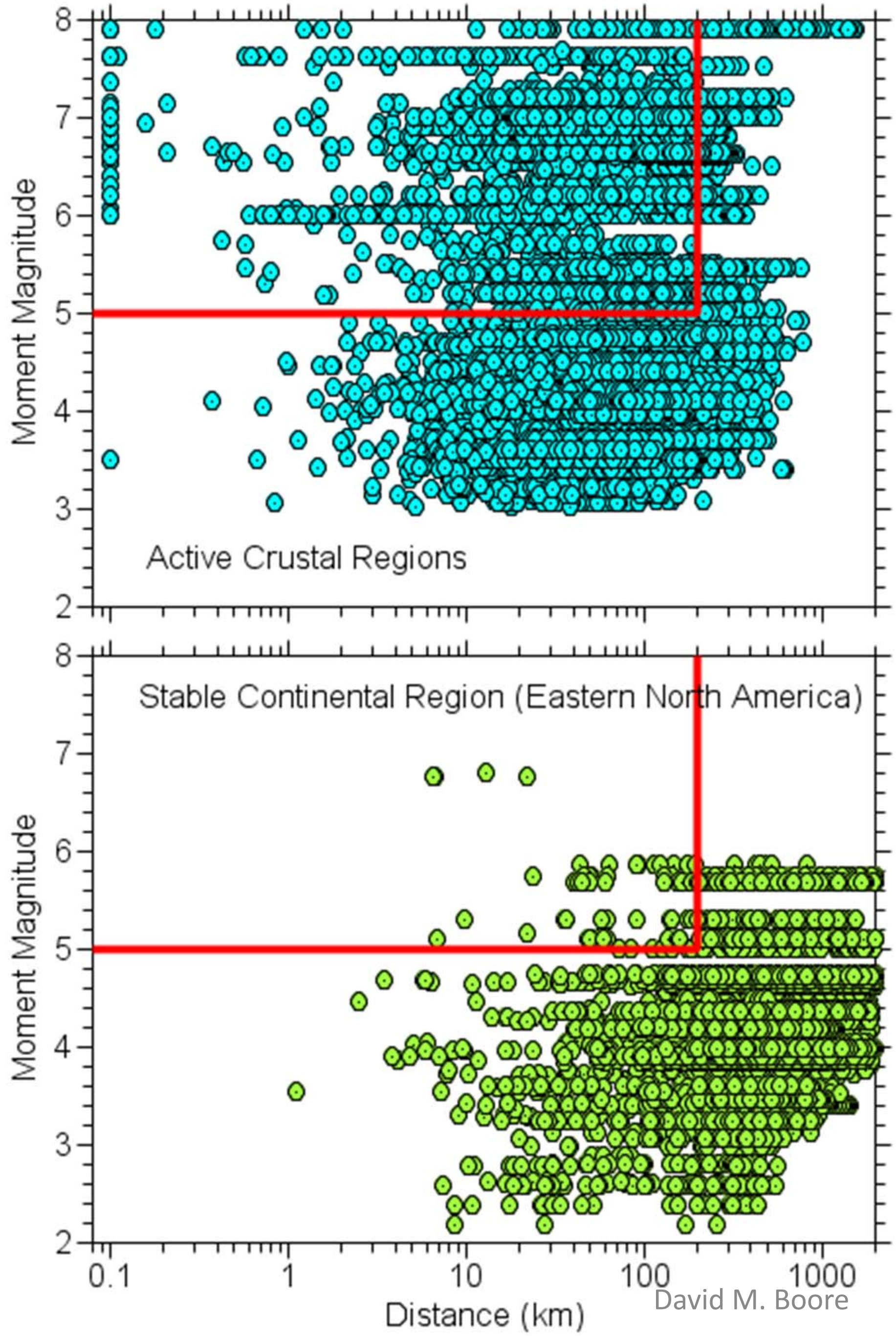
PEER NGA-West 2 Project Overview

- 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**



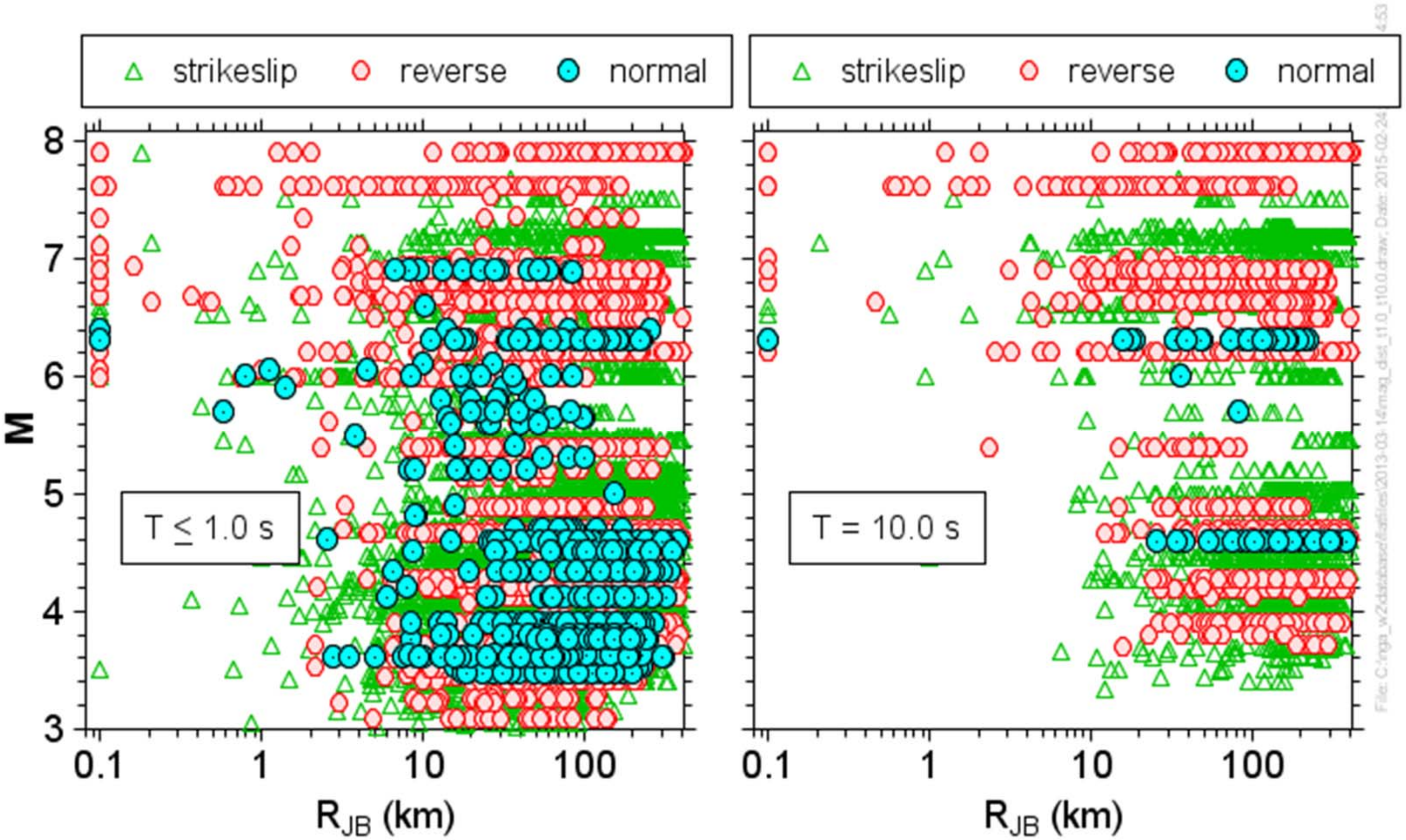
Observed data generally adequate for regression, but note relative lack of data for distances less than 10 km. Data are available for few large magnitude events.

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

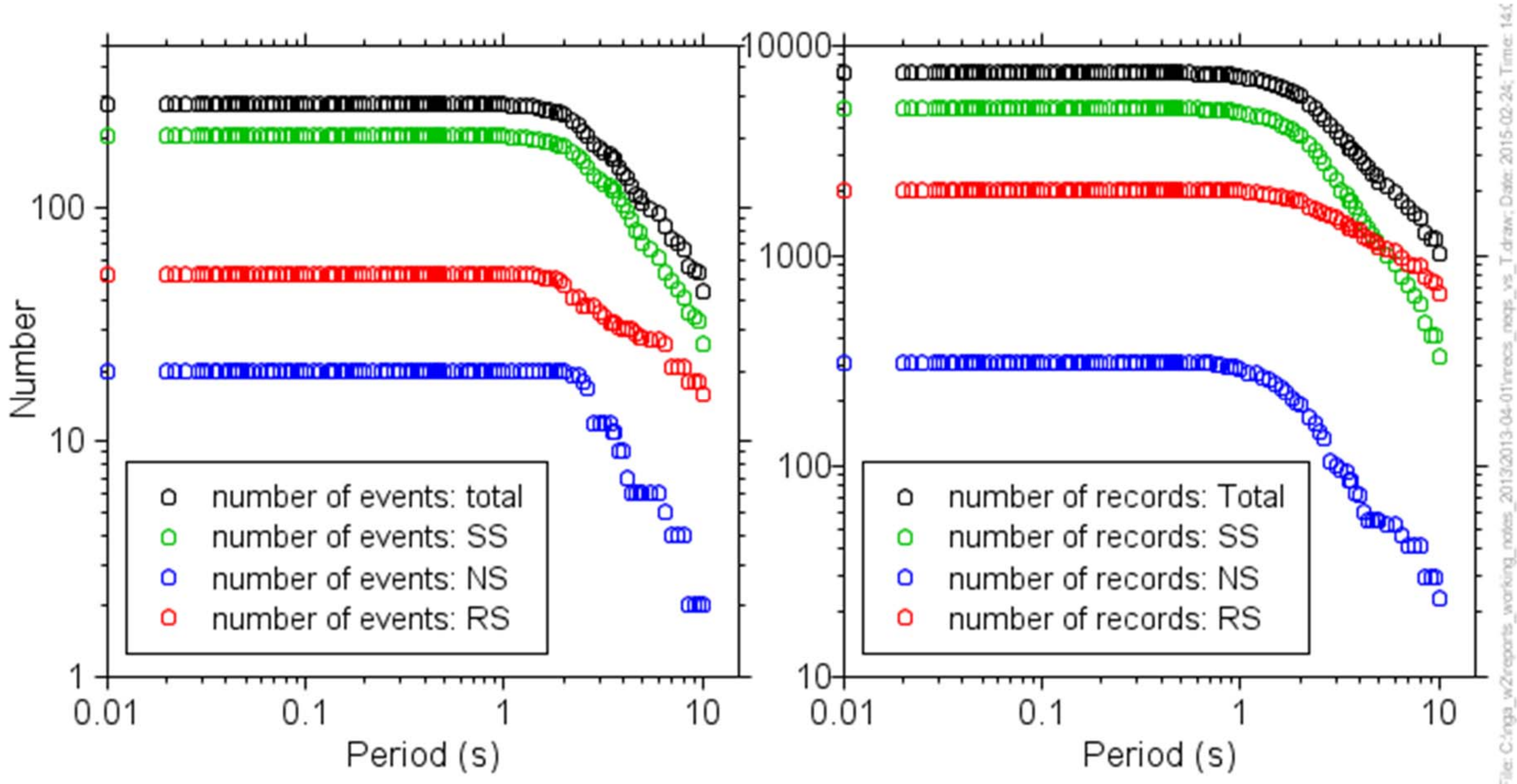


Observed data adequate for regression except close to large 'quakes

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

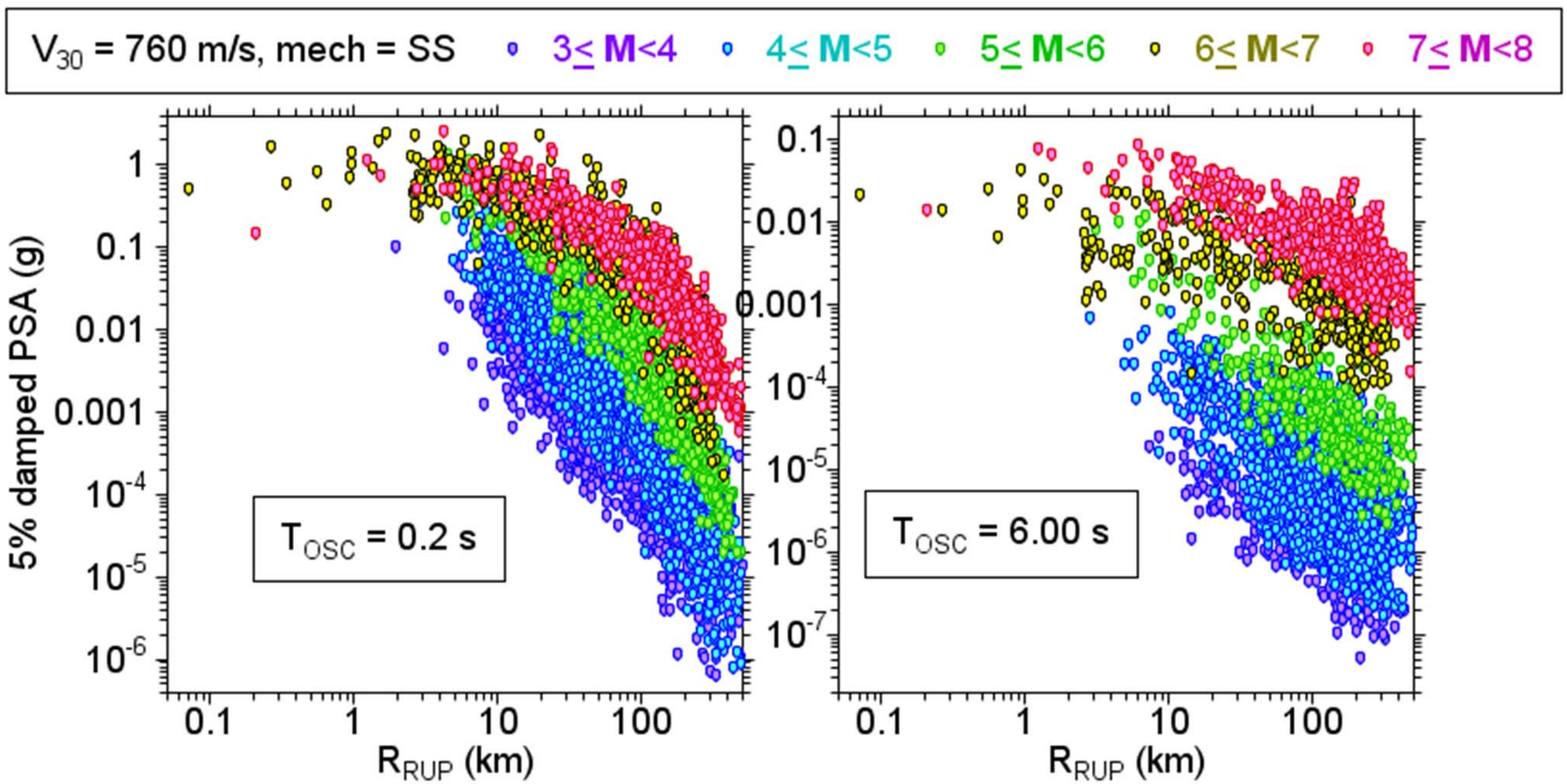


strikeslip
reverse
normal
M
T ≤ 1.0 s
T = 10.0 s
R_JB (km)



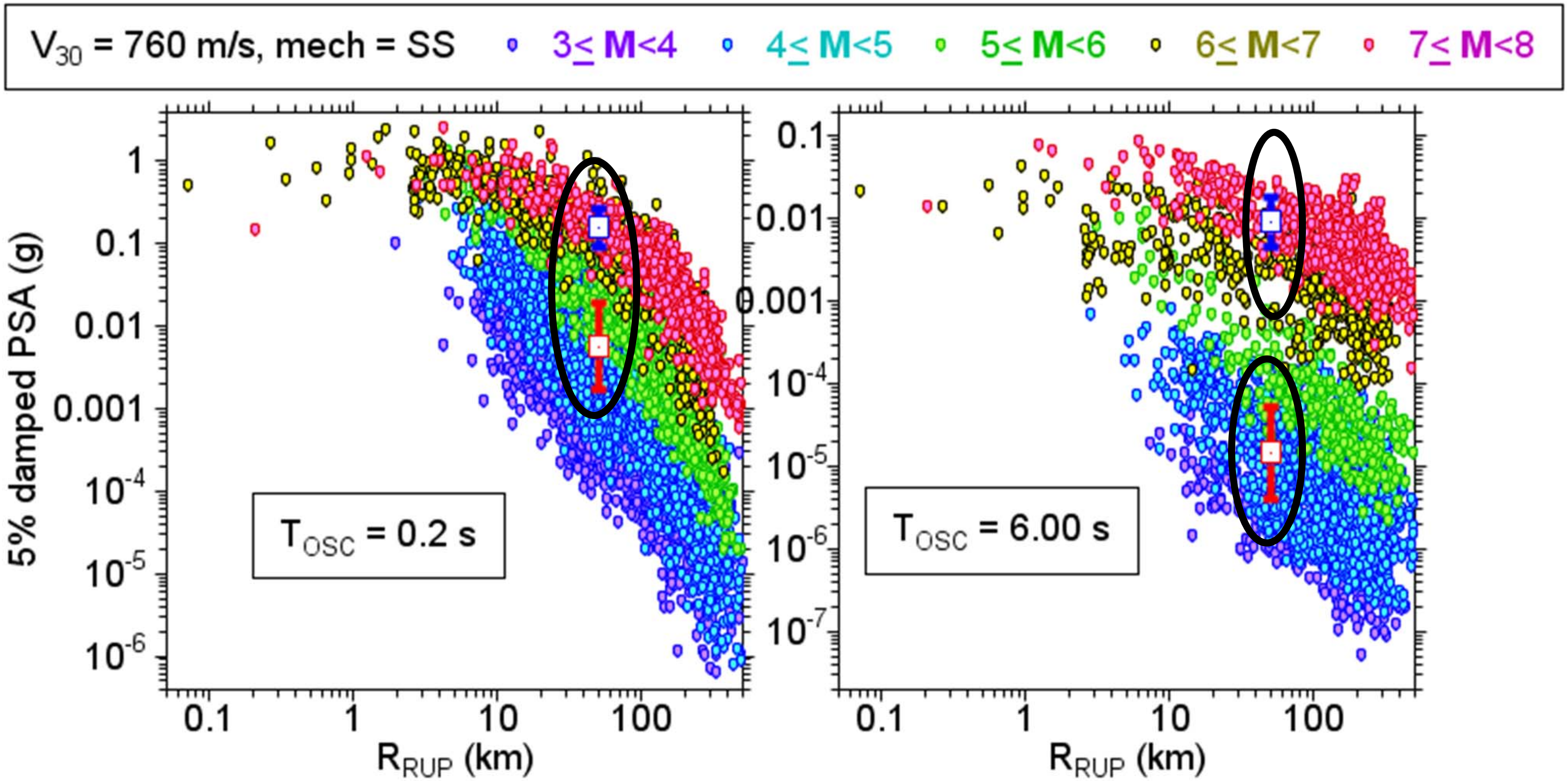
Restricted to data within 80 km with at least 4 recordings per event

NGA-West2 PSAs for ss events (adjusted to Vs30=760 m/s) vs. R_{RUP}



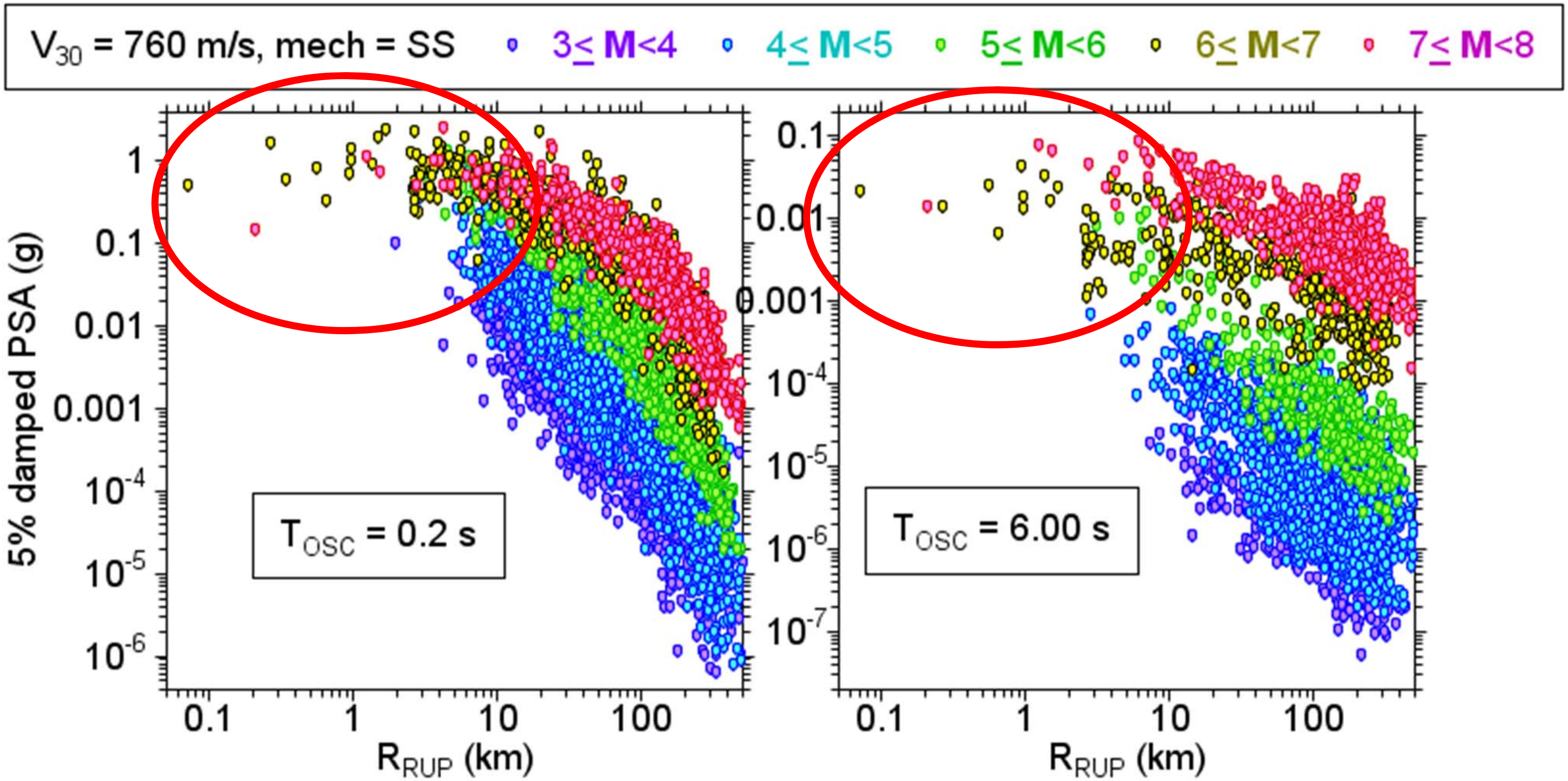
nrecs = 11,318 for T_{OSC}=0.2 s; nrecs = 3,359 for T_{OSC}=6.0 s

NGA-West2 PSAs for ss events (adjusted to Vs30=760 m/s) vs. R_{RUP}



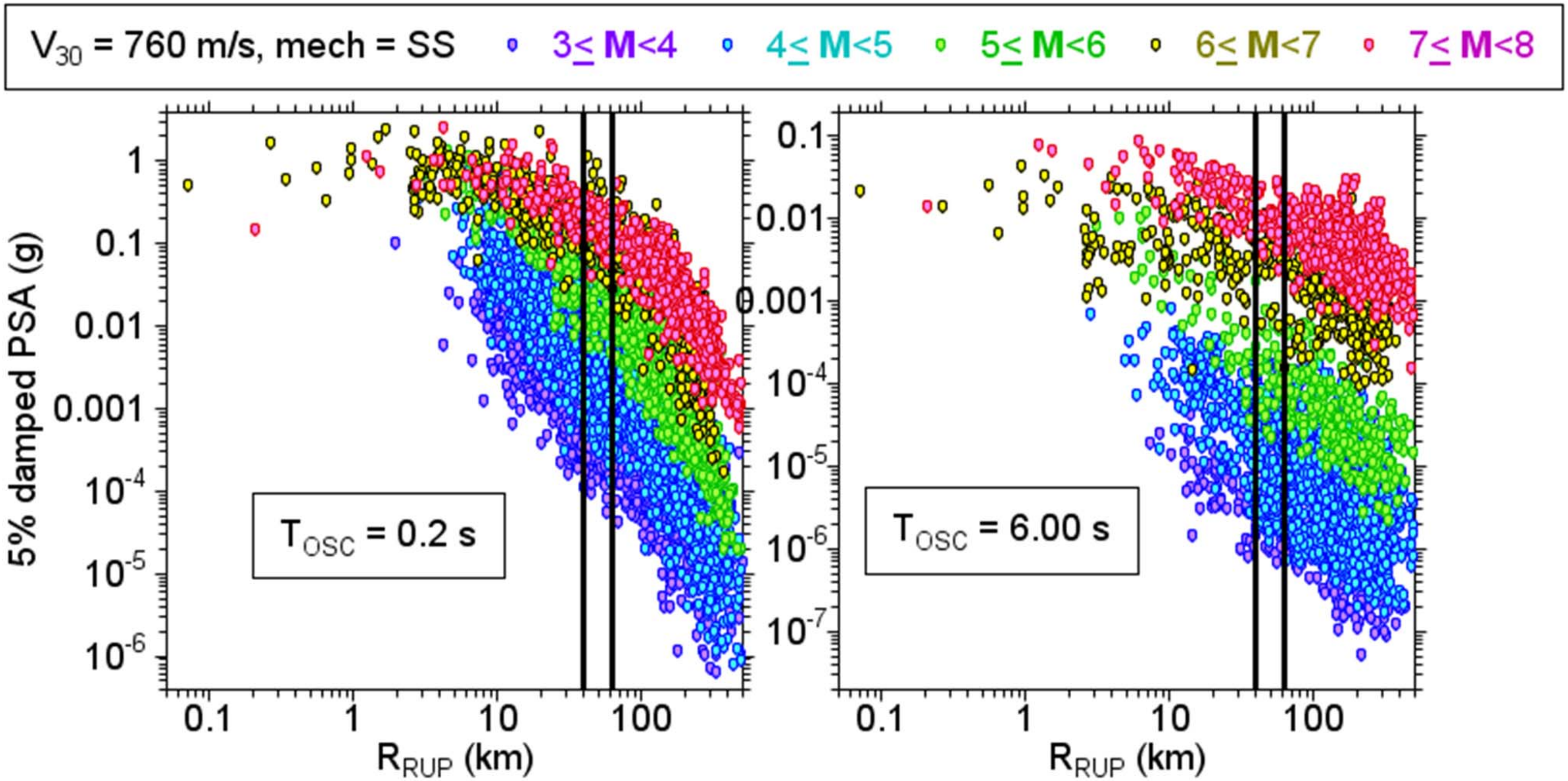
There is significant scatter in the data, with scatter being larger for small earthquakes.

NGA-West2 PSAs for ss events (adjusted to Vs30=760 m/s) vs. R_{RUP}



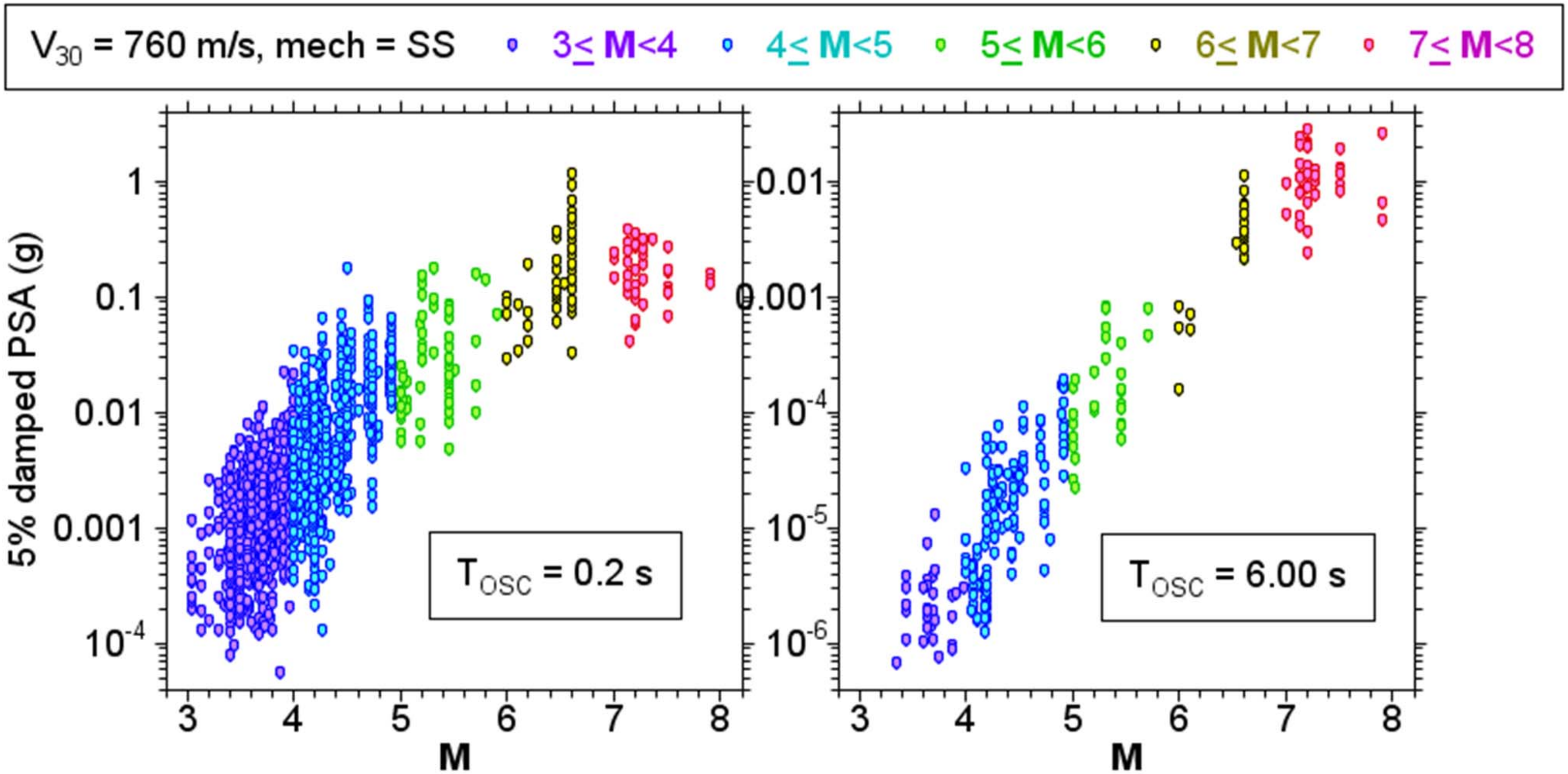
For a single magnitude and for all periods the motions tend to saturate for large earthquakes as the distance from the fault rupture to the observation point decreases.

NGA-West2 PSAs for ss events (adjusted to Vs30=760 m/s) vs. R_{RUP}

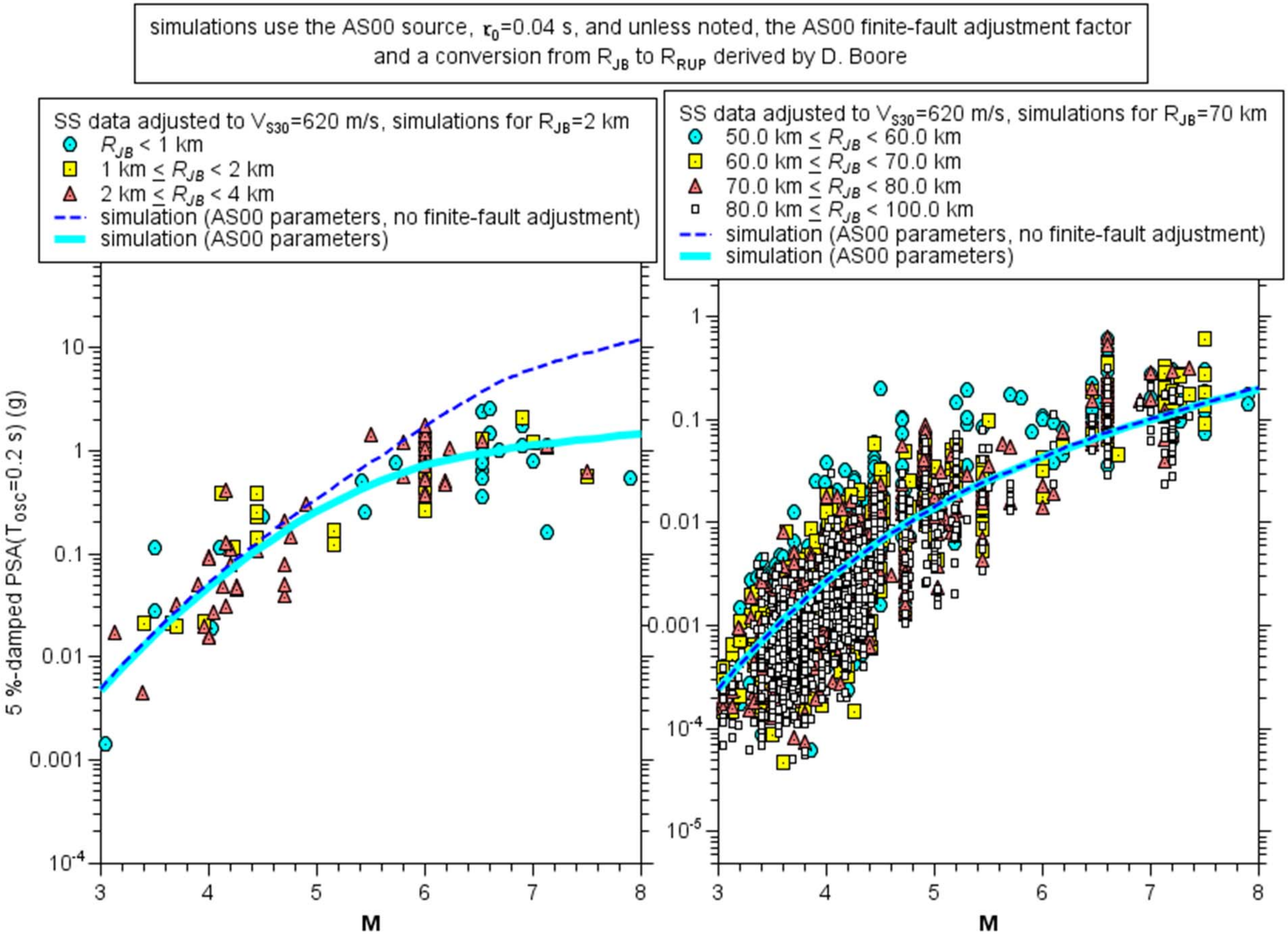


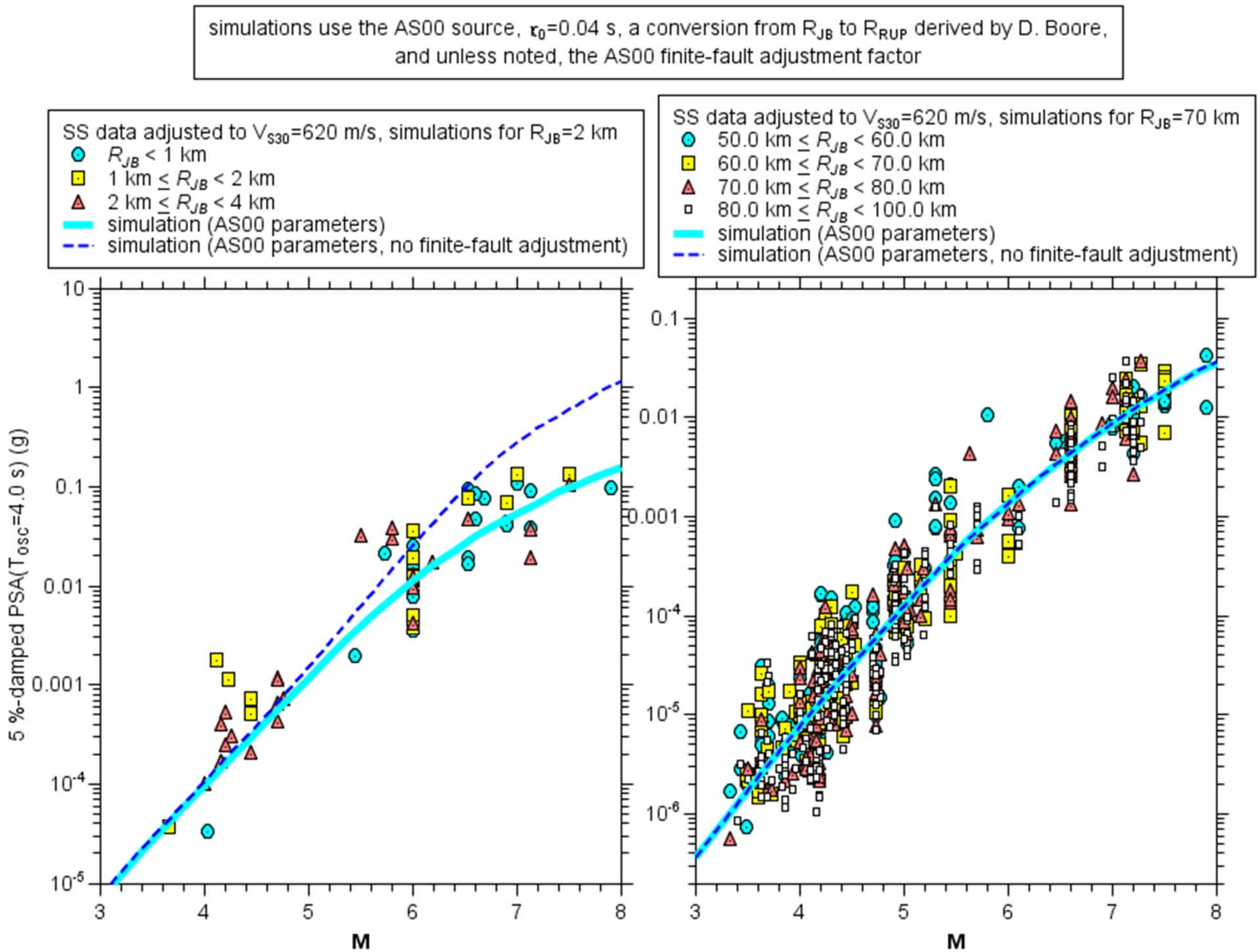
At any fixed distance the ground motion increases with magnitude in a nonlinear fashion, with a tendency to saturate for large magnitudes, particularly for shorter period motions. To show this, plot PSA within the bands vs. M.

NGA-West2 PSAs for ss events (adjusted to Vs30=760 m/s) vs. R_{RUP}

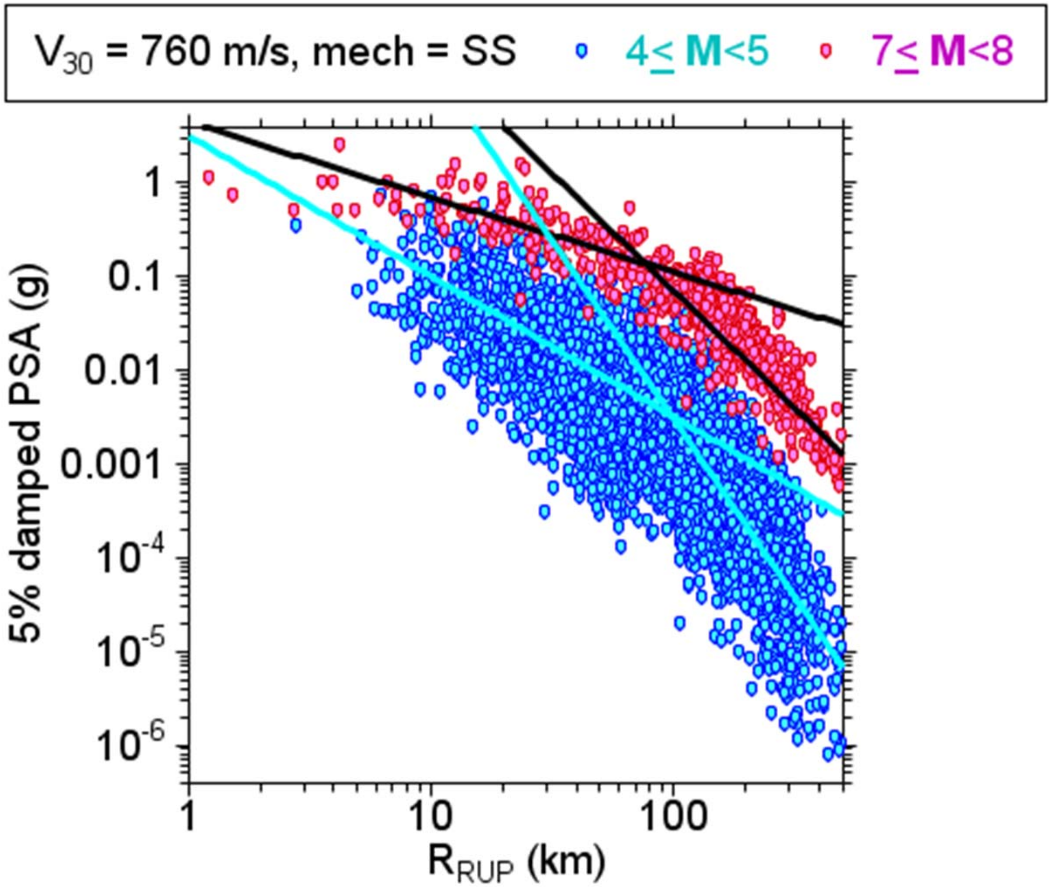


At any fixed distance (centered on 50 km here, including PSA in the 40 km to 62.5 km range) the ground motion increases with magnitude in a nonlinear fashion, with a tendency to saturate for large magnitudes, particularly for shorter period motions. PSA for larger magnitudes is more sensitive to M for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


simulations use the AS00 source, κ_0=0.04 s, and unless noted, the AS00 finite-fault adjustment factor and a conversion from R_{JB} to R_{RUP} derived by D. Boore
SS data adjusted to V_{S30}=620 m/s, simulations for R_{JB}=2 km
R_{JB} < 1 km
1 km ≤ R_{JB} < 2 km
2 km ≤ R_{JB} < 4 km
simulation (AS00 parameters, no finite-fault adjustment)
simulation (AS00 parameters)
SS data adjusted to V_{S30}=620 m/s, simulations for R_{JB}=70 km
50.0 km ≤ R_{JB} < 60.0 km
60.0 km ≤ R_{JB} < 70.0 km
70.0 km ≤ R_{JB} < 80.0 km
80.0 km ≤ R_{JB} < 100.0 km
simulation (AS00 parameters, no finite-fault adjustment)
simulation (AS00 parameters)
5 %-damped PSA(T_{osc}=0.2 s) (g)
10
1
0.1
0.01
0.001
10^{-4}
0.1
0.01
0.001
10^{-5}
3
4
5
6
7
8
M
M


simulations use the AS00 source, τ0=0.04 s, a conversion from RJB to RRUP derived by D. Boore, and unless noted, the AS00 finite-fault adjustment factor
SS data adjusted to VS30=620 m/s, simulations for RJB=2 km
RJB < 1 km
1 km ≤ RJB < 2 km
2 km ≤ RJB < 4 km
simulation (AS00 parameters)
simulation (AS00 parameters, no finite-fault adjustment)
SS data adjusted to VS30=620 m/s, simulations for RJB=70 km
50.0 km ≤ RJB < 60.0 km
60.0 km ≤ RJB < 70.0 km
70.0 km ≤ RJB < 80.0 km
80.0 km ≤ RJB < 100.0 km
simulation (AS00 parameters)
simulation (AS00 parameters, no finite-fault adjustment)
5 %-damped PSA(Tosc=4.0 s) (g)
M
M

NGA-West2 PSAs for ss events (adjusted to Vs30=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

- Magnitude-distance distribution depends on region
- Change of amplitude with distance for fixed magnitude
- 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)

In 2014

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$f_{site,J} = \begin{cases} (c_{12} + k_2 n)\left[\ln\left(\frac{V_{S30}}{k_1}\right) - \ln\left(\frac{200}{k_1}\right)\right]; & V_{S30} \le 2(\\ (c_{13} + k_2 n)\ln\left(\frac{V_{S30}}{k_1}\right); & \text{All } V_{S30} \end{cases}$$

(Courtesy of Yousef Bozorgnia)

Boore, Stewart, Seyhan, and Atkinson (BSSA14) GMPEs

- ***General form:***

$$\ln Y = F_E(\mathbf{M}, mech) + F_P(R_{JB}, \mathbf{M}, region) + F_S(V_{S30}, R_{JB}, \mathbf{M}, region, z_1) + \varepsilon_n \sigma(\mathbf{M}, R_{JB}, V_{S30})$$

- ***M scaling***

M ≤ M$_h$: $F_E(\mathbf{M}, mech) = e_0 U + e_1 SS + e_2 NS + e_3 RS + e_4(\mathbf{M} - \mathbf{M}_h) + e_5(\mathbf{M} - \mathbf{M}_h)^2$

M >M$_h$: $F_E(\mathbf{M}, mech) = e_0 U + e_1 SS + e_2 NS + e_3 RS + e_6(\mathbf{M} - \mathbf{M}_h)$

- ***Distance scaling:***

$$F_P(R_{JB}, \mathbf{M}, region) = \left[c_1 + c_2(\mathbf{M} - \mathbf{M}_{ref})\right]\ln(R / R_{ref}) + (c_3 + \Delta c_3)(R - R_{ref})$$

$$R = \sqrt{R_{JB}^2 + h^2}$$

Modified from a slide by E. Seyhan

Boore, Stewart, Seyhan, and Atkinson (BSSA14) GMPEs

- ***General form:***

$$\ln Y = F_E(\mathbf{M}, mech) + F_P(R_{JB}, \mathbf{M}, region) + F_S(V_{S30}, R_{JB}, \mathbf{M}, region, z_1) + \varepsilon_n \sigma(\mathbf{M}, R_{JB}, V_{S30})$$

- ***M scaling***

focal mechanism — quadratic M-scaling

M ≤ M$_h$: $$F_E(\mathbf{M}, mech) = e_0 U + e_1 SS + e_2 NS + e_3 RS + e_4(\mathbf{M} - \mathbf{M}_h) + e_5(\mathbf{M} - \mathbf{M}_h)^2$$

M >M$_h$: $$F_E(\mathbf{M}, mech) = e_0 U + e_1 SS + e_2 NS + e_3 RS + e_6(\mathbf{M} - \mathbf{M}_h)$$

linear M-scaling

- ***Distance scaling:***

$$F_P(R_{JB}, \mathbf{M}, region) = \left[c_1 + c_2(\mathbf{M} - \mathbf{M}_{ref})\right]\ln(R / R_{ref}) + (c_3 + \Delta c_3)(R - R_{ref})$$

$$R = \sqrt{R_{JB}^2 + h^2}$$

Modified from a slide by E. Seyhan

BSSA14 GMPEs

- ***General form:***

$$\ln Y = F_E(\mathbf{M}, mech) + F_P(R_{JB}, \mathbf{M}, region) + F_S(V_{S30}, R_{JB}, \mathbf{M}, region, z_1) + \varepsilon_n \sigma(\mathbf{M}, R_{JB}, V_{S30})$$

- ***M scaling***

M ≤ M$_h$: $$F_E(\mathbf{M}, mech) = e_0 U + e_1 SS + e_2 NS + e_3 RS + e_4(\mathbf{M} - \mathbf{M}_h) + e_5(\mathbf{M} - \mathbf{M}_h)^2$$

M >M$_h$: $$F_E(\mathbf{M}, mech) = e_0 U + e_1 SS + e_2 NS + e_3 RS + e_6(\mathbf{M} - \mathbf{M}_h)$$

- ***Distance scaling:*** M-indep.

$$F_P(R_{JB}, \mathbf{M}, region) = \left[c_1 + c_2(\mathbf{M} - \mathbf{M}_{ref})\right]\ln(R / R_{ref}) + (c_3 + \Delta c_3)(R - R_{ref})$$

M-dependent distance decay

$$R = \sqrt{R_{JB}^2 + h^2}$$

pseudo depth

Modified from a slide by E. Seyhan

BSSA14 GMPEs

- ***General form:***

$$\ln Y = F_E(\mathbf{M}, mech) + F_P(R_{JB}, \mathbf{M}, region) + F_S(V_{S30}, R_{JB}, \mathbf{M}, region, z_1) + \varepsilon_n \sigma(\mathbf{M}, R_{JB}, V_{S30})$$

- ***M scaling***

M ≤ M$_h$: $$F_E(\mathbf{M}, mech) = e_0 U + e_1 SS + e_2 NS + e_3 RS + e_4(\mathbf{M} - \mathbf{M}_h) + e_5(\mathbf{M} - \mathbf{M}_h)^2$$

M >M$_h$: $$F_E(\mathbf{M}, mech) = e_0 U + e_1 SS + e_2 NS + e_3 RS + e_6(\mathbf{M} - \mathbf{M}_h)$$

- ***Distance scaling:***

regional corrections

$$F_P(R_{JB}, \mathbf{M}, region) = \left[c_1 + c_2(\mathbf{M} - \mathbf{M}_{ref})\right]\ln(R/R_{ref}) + (c_3 + \Delta c_3)(R - R_{ref})$$

$$R = \sqrt{R_{JB}^{\ 2} + h^2}$$

anelastic attenuation

Modified from a slide by E. Seyhan

BSSA14 GMPEs

- ***Site term***

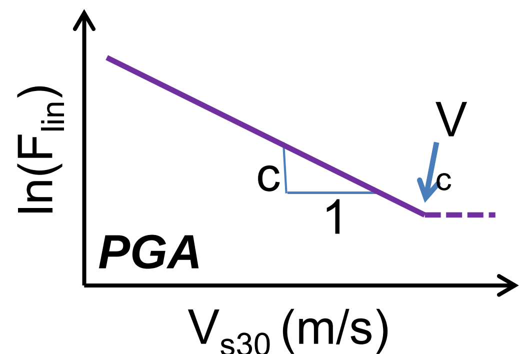
$$F_S\left(V_{S30},\mathbf{M},R_{JB},z_1,region\right)=\ln\left(F_{lin}\right)+\ln\left(F_{nl}\right)+F_{\delta z_1}(\delta z_1,region)$$

Linear site term

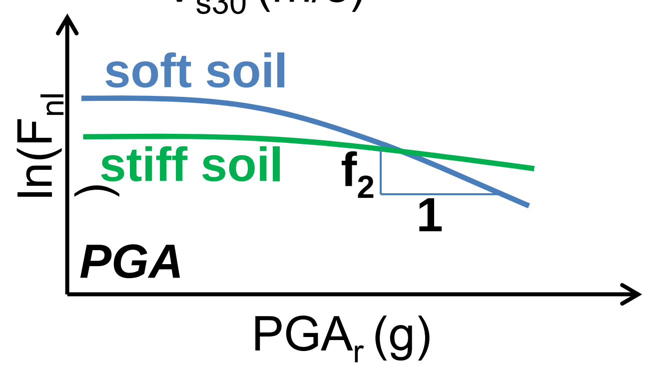
V_{S30}-scaling

$$\ln\left(F_{lin}\right)=\begin{cases} c\ln\left(\dfrac{V_{S30}}{V_{ref}}\right) & V_{S30}\le V_c \\ c\ln\left(\dfrac{V_c}{V_{ref}}\right) & V_{S30}> V_c \end{cases}$$

Break velocity



Nonlinear site term



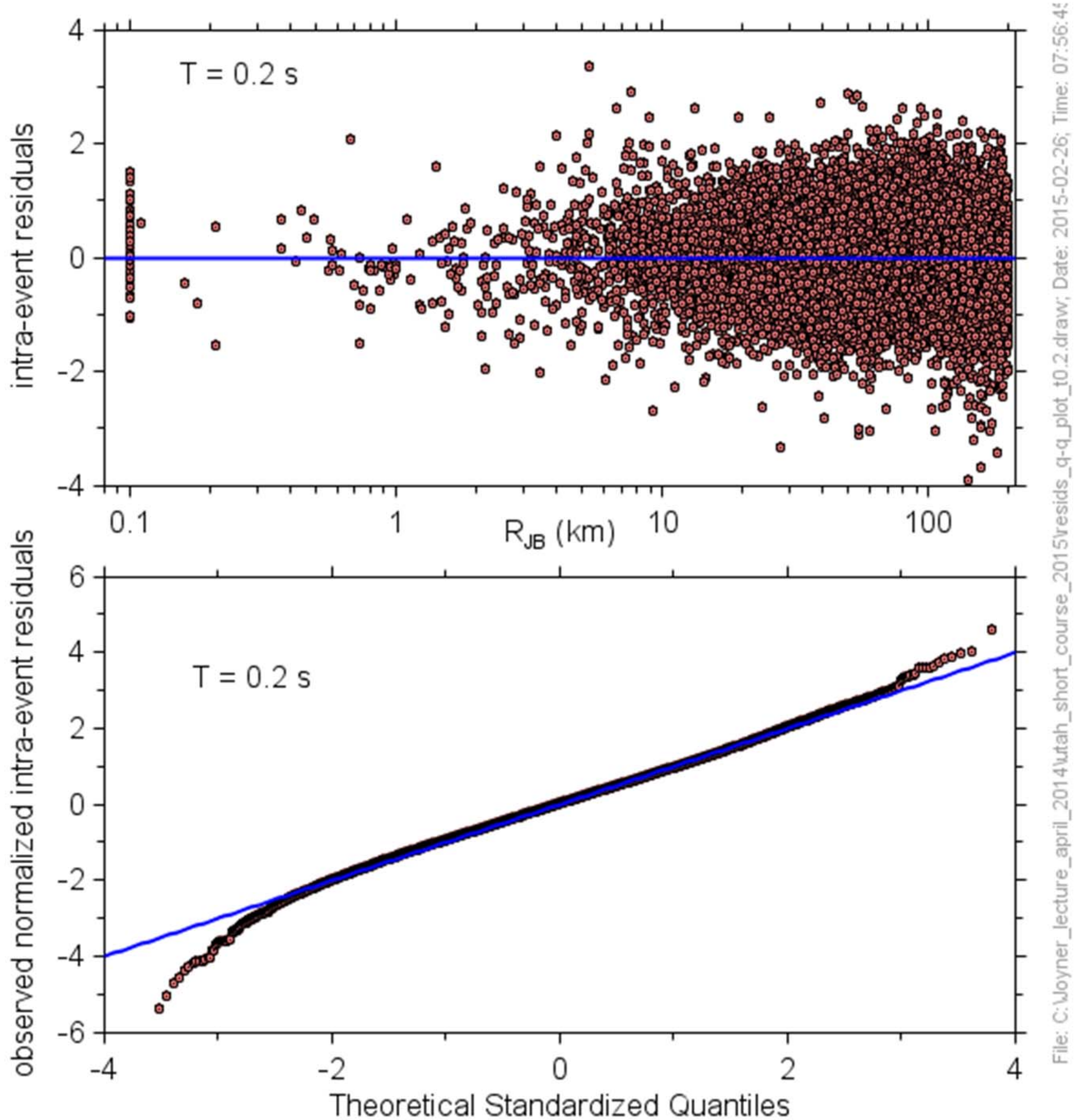
Slope of nonlinearity

$$\ln(F_{nl})=f_1+f_2*\ln\left(\frac{PGAr+f_3}{f_3}\right)$$

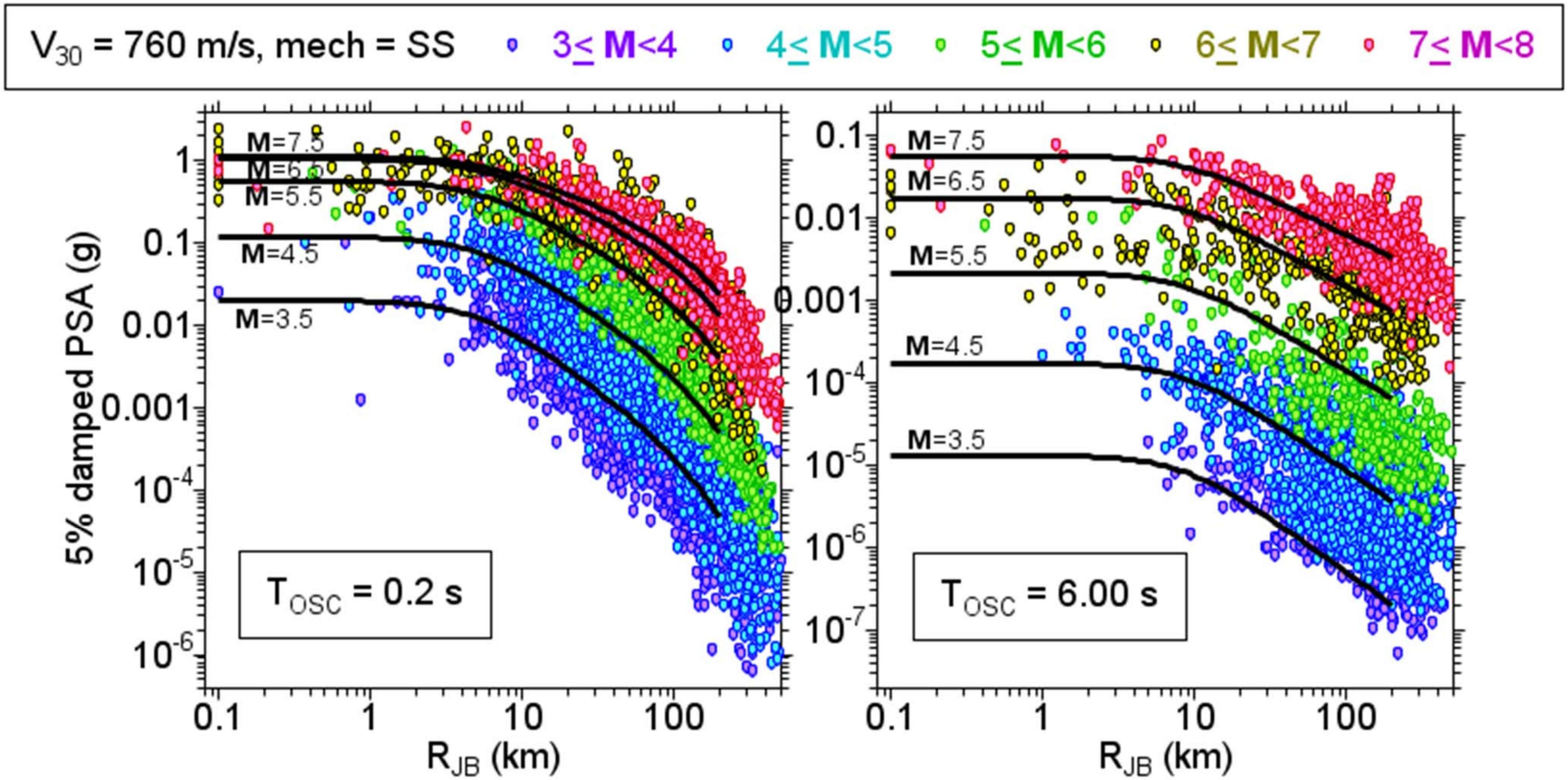
$$f_2\left(V_{s30},T\right)=f_4(T)\left[\exp\left\{f_5(T)*\left(\min\left(V_{s30},760\right)-360\right)\right\}-\exp\left\{f_5(T)*\left(760-360\right)\right\}\right]$$

Modified from a slide by E. Seyhan

Why ln Y?
Residuals are log-normally distributed



Adding BSSA14 curves to data plots shown before



- 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.

Courtesy of Yousef Bozorgnia)

Table 2. Summary of model parameters used in the five GMPEs

Parameter	ASK	BSSA	CB	CY	IM
Moment magnitude	**M**	**M**	**M**	**M**	**M**
Depth to top of tupture (km)	Z_{TOR}, Z_{TOR}[b]	–	Z_{TOR}[b]	$Z_{TOR}Z_{TOR}$[b]	–
Hypocentral depth (km)	–	–	Z_{HYP}	–	–
Style of faulting[a]	SS, RV, NM	SS, RV, NM, U	SS, RV, NM	SS, RV, NM	SS, RV
Class 2 event flag	F_{AS}	–	–	–	–
Dip (degrees)	δ[b]	–	δ, δ[b]	δ, δ[b]	–
Down-dip rupture width (km)	W[b]	–	W[b]	–	–
Closest distance to rupture plane (km)	R_{RUP}	–	R_{RUP}	R_{RUP}	R_{RUP}
Horizontal distance to surface project of rupture plane (km)	R_{JB}[b]	R_{JB}	R_{JB}[b]	R_{JB}[b]	–
Horizontal distance to top edge of rupture plane measured perpendicular to strike (km)	R_X[b]	–	R_X[b]	R_X[b]	–
Horizontal distance off the end of rupture plane measured parallel to strike (km)	R_{Y0}[b]	–	–	–	–
Average shear-wave velocity in top 30 m (m/s)	V_{S30}	V_{S30}	V_{S30}	V_{S30}	V_{S30}
Depth to 1.0 km/s boundary (km)	$Z_{1.0}$	$\delta Z_{1.0}$	–	$Z_{1.0}$, $\Delta Z_{1.0}$	–
Depth to 2.5 km/s boundary (km)	–		$Z_{2.5}$	–	–
Rock motion PGA for nonlinear site response	–	PGA_r	A_{1100}	–	–
Rock motion PSA for nonlinear site response	PSA_{1100}	–	–	$Y_{ref}(T)$	–
V_{S30} of rock motion used for nonlinear site response (m/s)	1,100	760	1,100	1,130	–
Regional adjustments	Taiwan, China, Japan	China/ Turkey, Italy/ Japan	E. China, Italy/ Japan	Italy/ Japan, Wenchuan	–

[a]Style of faulting terms: SS = strike-slip, RV = reverse, NM = normal, U = unspecified.
[b]Used only in hanging-wall model.

Model Applicability

Developer	M	R	Vs30
ASK14	3.0-8.5	0-300	180-1000
BSSA14	3.0-8.5	0-400	150-1500
	3.0-7.0 (NS)	0-400	150-1500
CB14	3.3-8.5 (SS)	0-300	150-1500
	3.3-8.0 (RS)	0-300	150-1500
	3.3-7.5 (NS)	0-300	150-1500
CY14	3.5-8.5 (SS)	0-300	180-1500
	3.5-8.0 (RS, NS)	0-300	180-1500
I14	>=5.0	0-150	>=450

Comparisons of NGA-West1 and NGA-West2 results for each developer

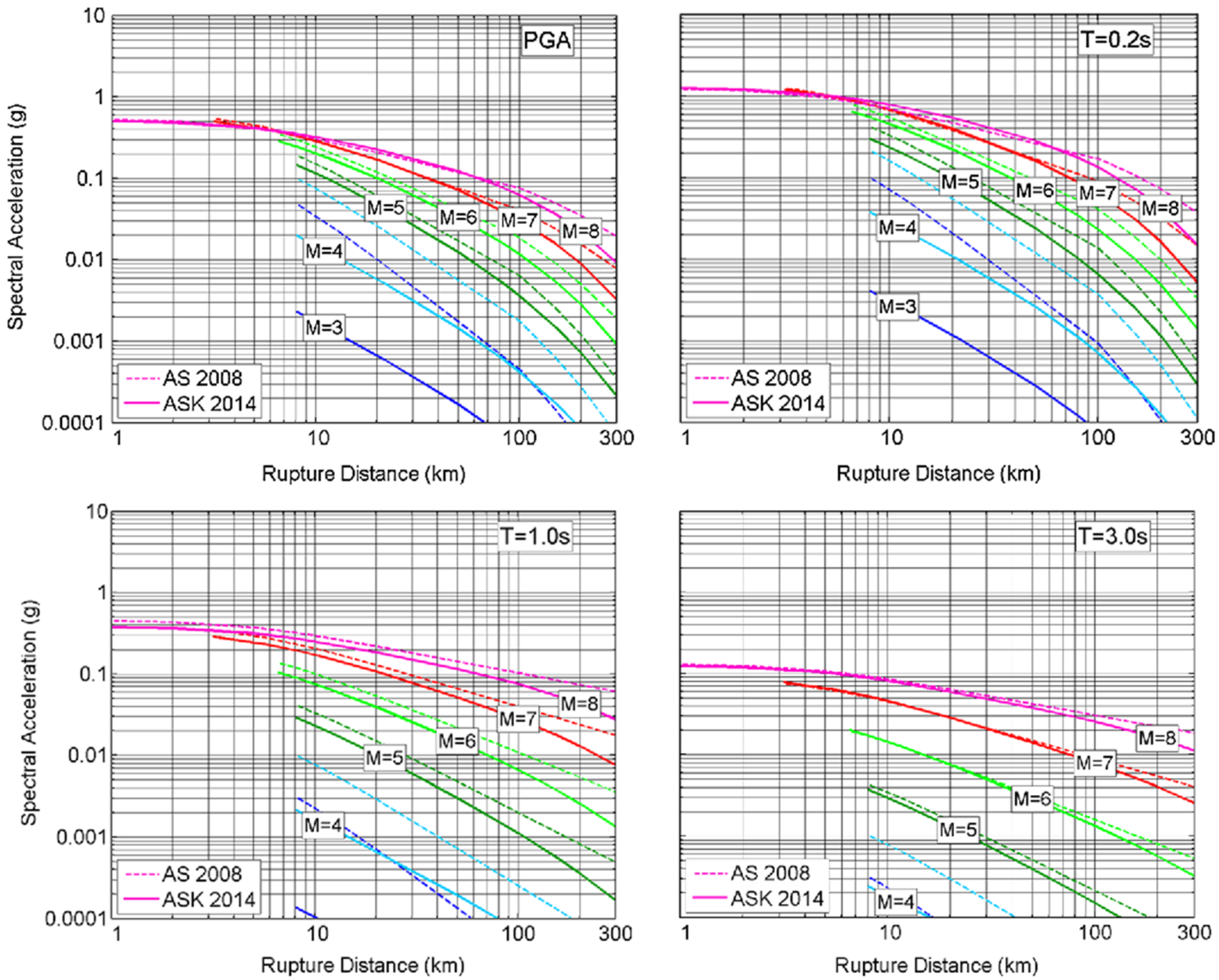
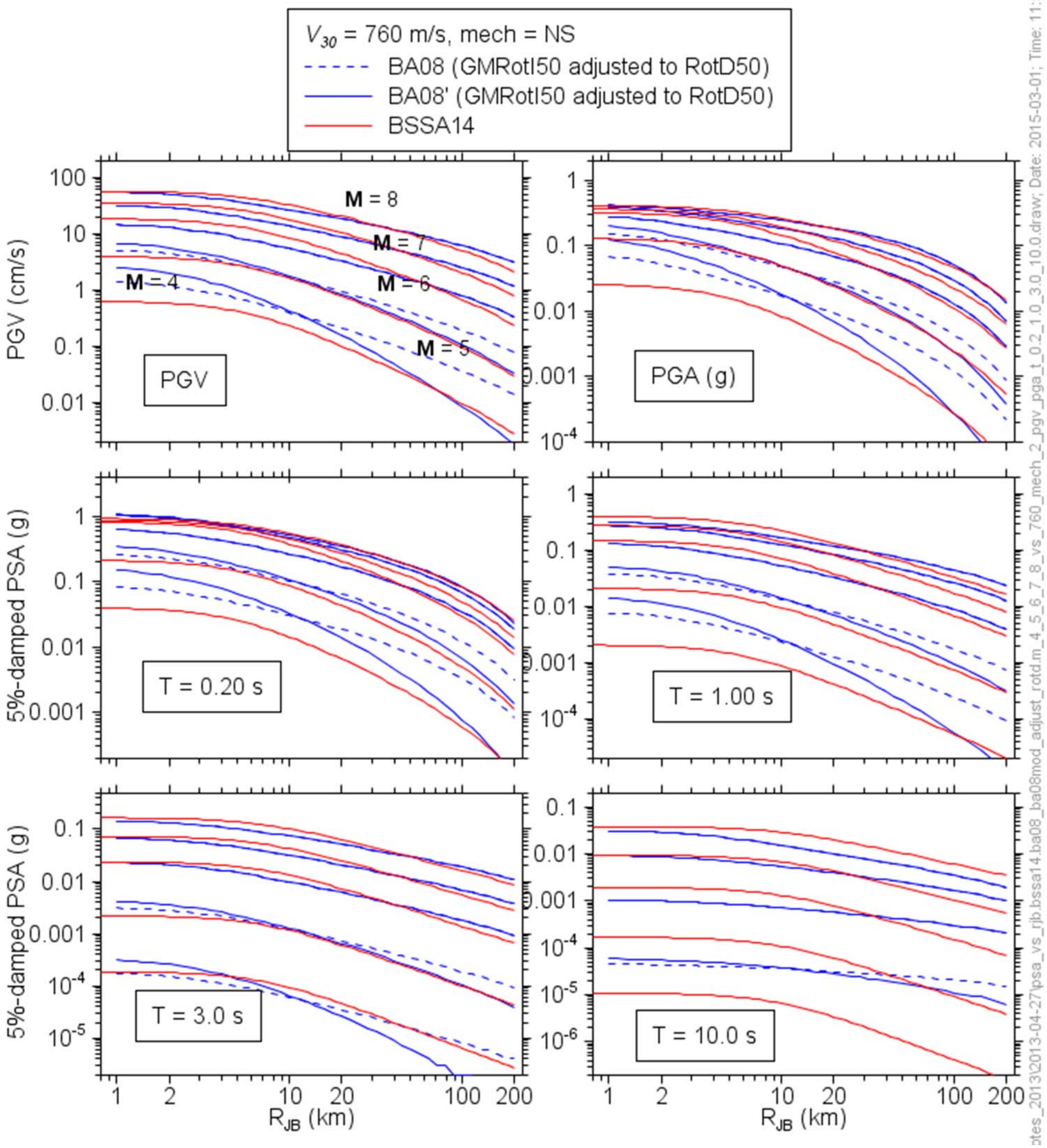


Figure 8. Comparison of the scaling with distance for the current model with the AS08 model for strike-slip earthquakes and rock site conditions ($V_{S30} = 760$ m/s).



V_{30} = 760 m/s, mech = NS
BA08 (GMRotI50 adjusted to RotD50)
BA08' (GMRotI50 adjusted to RotD50)
BSSA14
PGV (cm/s)
M = 8
M = 7
M = 6
M = 5
M = 4
PGV
PGA (g)
5%-damped PSA (g)
T = 0.20 s
T = 1.00 s
T = 3.0 s
T = 10.0 s
R_{JB} (km)
otes_2013\2013-04-27\psa_vs_rjb.bssa14.ba08_ba08mod_adjust_rotd.m_4_5_6_7_8_vs_760_mech_2_pgv_pga_t_0.2_1.0_3.0_10.0.draw; Date: 2015-03-01; Time: 11:5

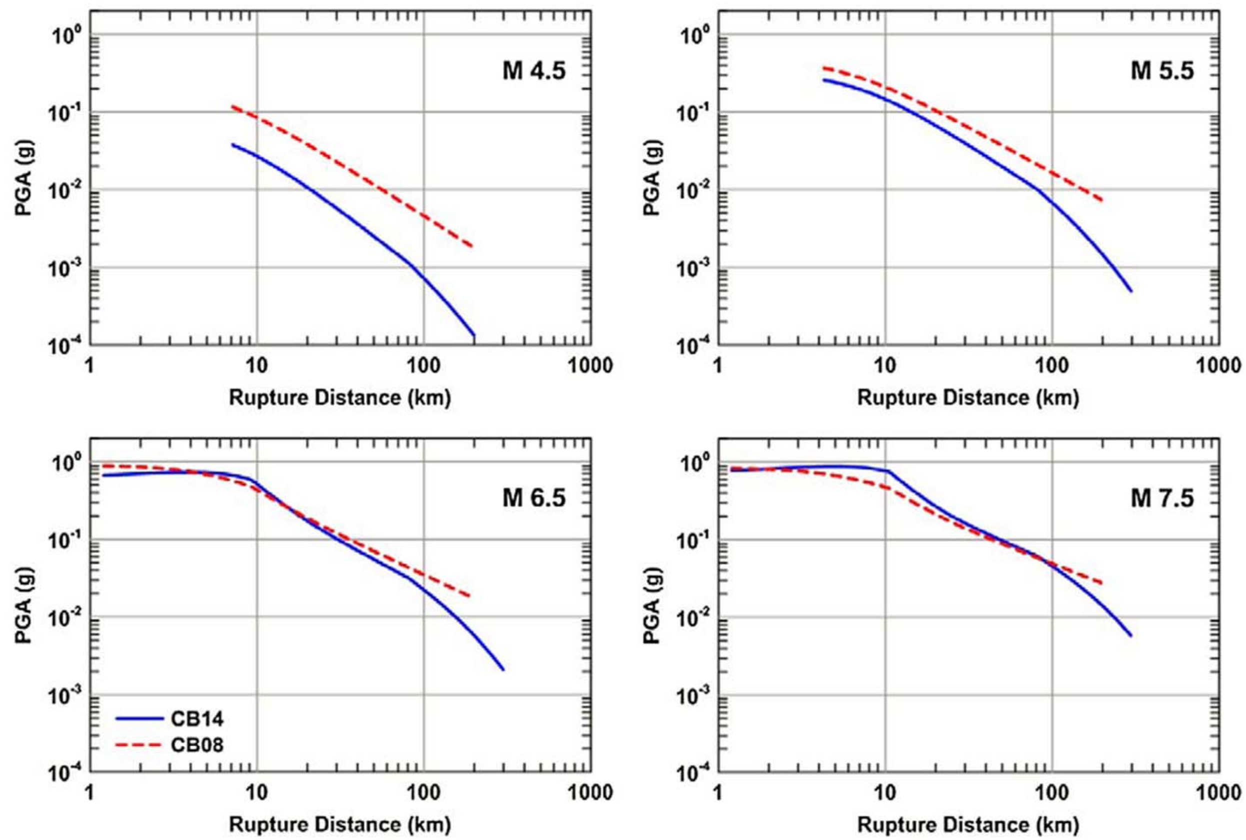


Figure 7. Comparison of median CB14 and CB08 estimates for $\mathbf{M} = 4.5$ to 7.5 showing how PGA attenuates with distance for a site located on the hanging wall (positive R_X) side of a 45°-dipping reverse fault. All other predictor variables are evaluated as indicated in the caption to Figure 6, except for default values of Z_{TOR}, Z_{HYP}, and W, which are given in Table C2 of Appendix C in the Electronic Supplement to this manuscript.

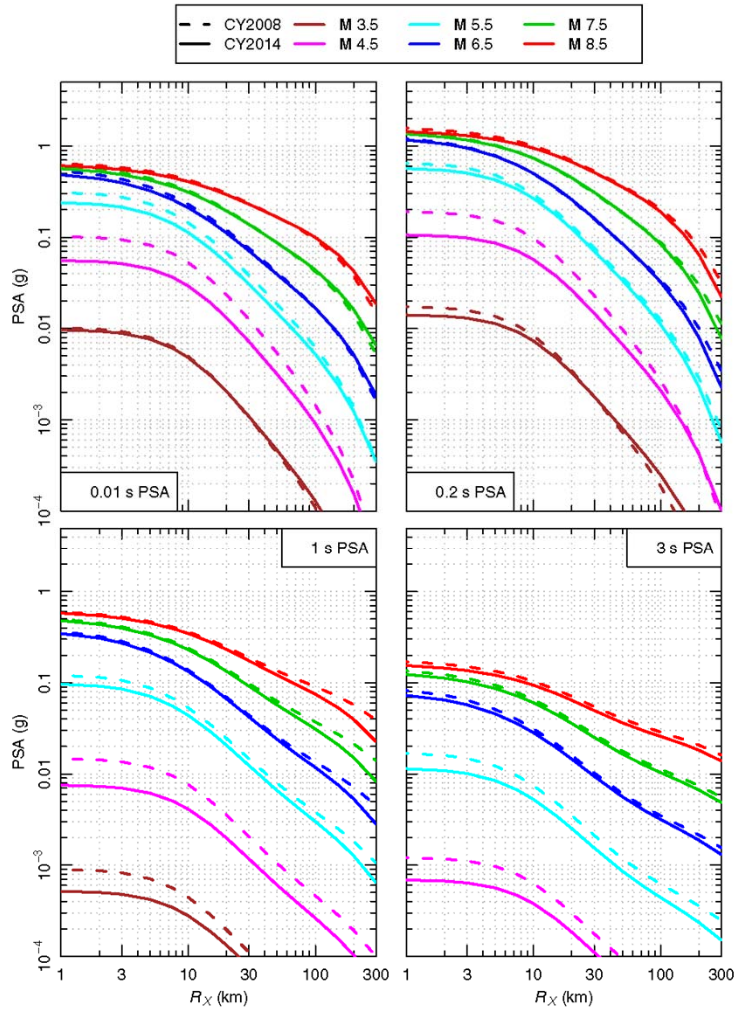


Figure 14. Median amplitude versus R_X predicted by the 2008 Chiou and Youngs NGA model (CY2008) and the updated model (CY2014) for vertical strike slip earthquake, $V_{S30} = 760$ m/s average Z_{TOR} ($\Delta Z_{TOR} = 0$), and ΔDPP = 0.

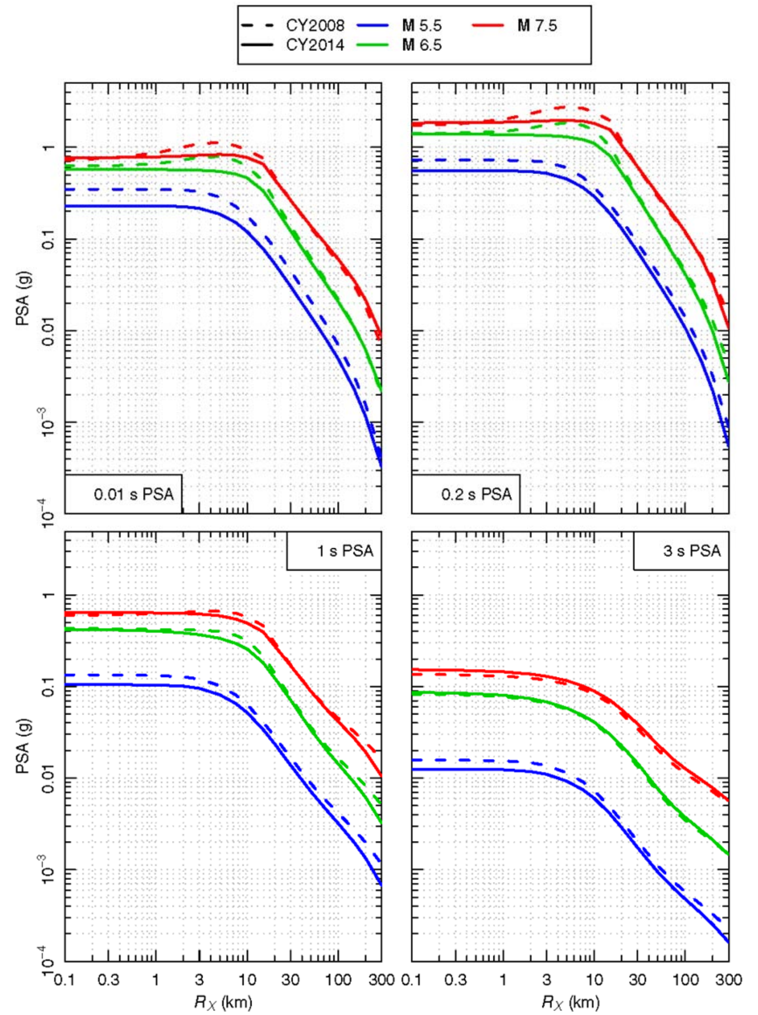


Figure 15. Median amplitude versus R_X predicted by the 2008 Chiou and Youngs NGA model (CY2008) and the updated model (CY2014) for reverse earthquake of 45° dip. Predictions are for average Z_{TOR} ($\Delta Z_{TOR} = 0$), $V_{S30} = 760$ m/s, $\Delta DPP = 0$, and for sites on the hanging wall ($R_{JB} = 0$).

Comparisons of NGA-West2 results for the five developer teams

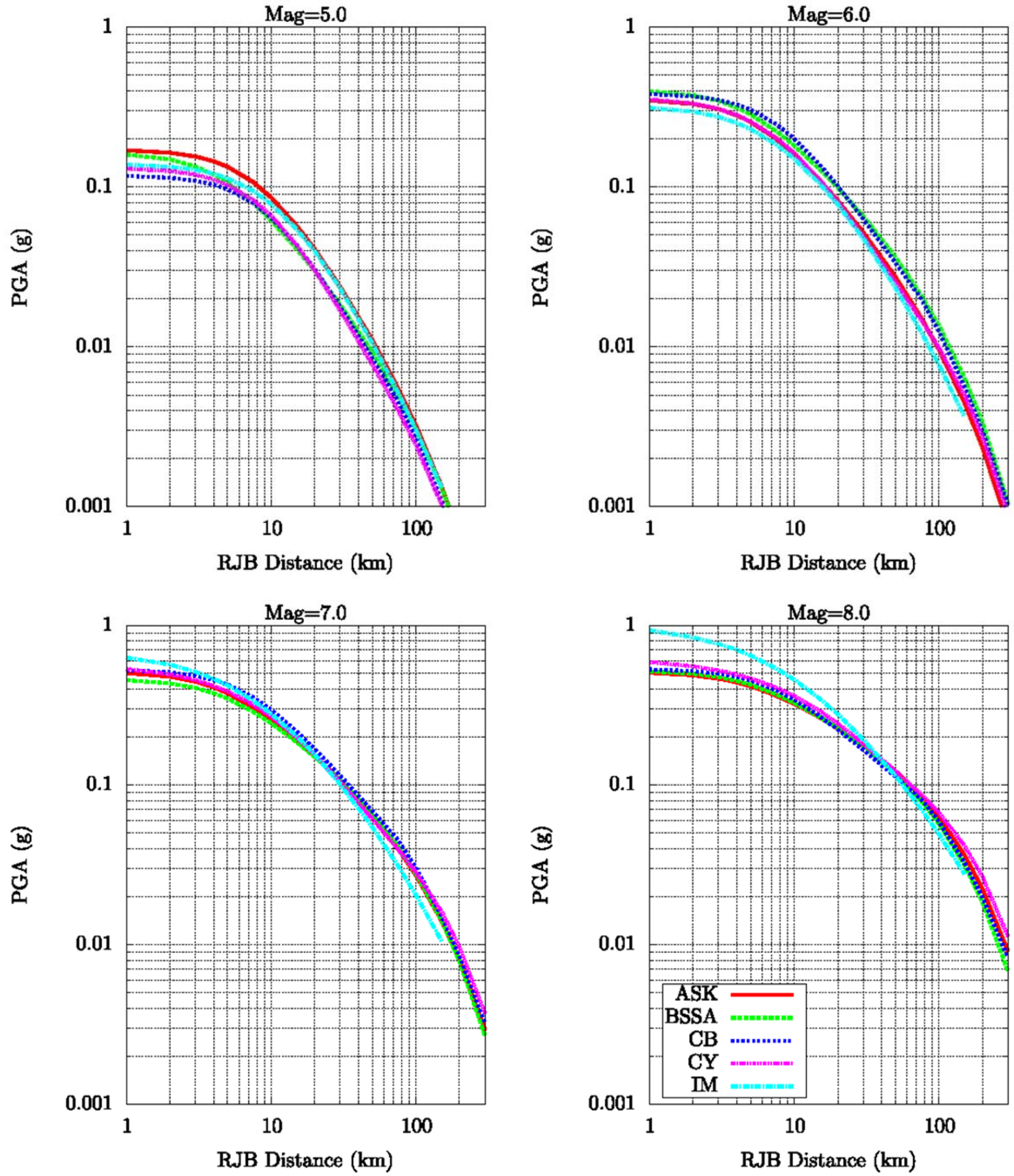


Figure 1. Comparison of distance scaling of PGA for strike-slip earthquakes for $V_{S30} = 760$ m/s.

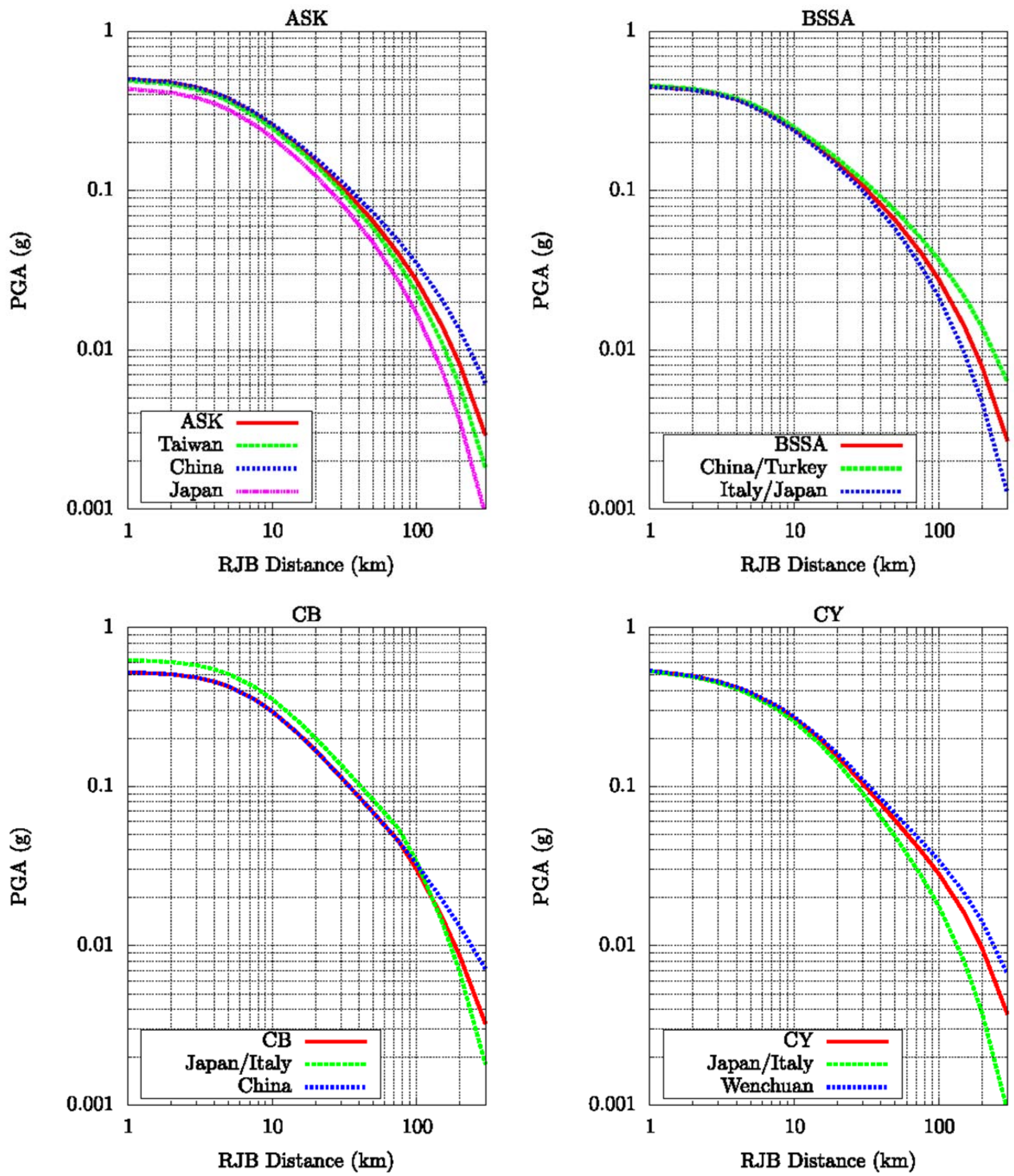


Figure 7. Comparison of regional attenuation adjustments for a **M** 7 strike-slip earthquake for PGA.

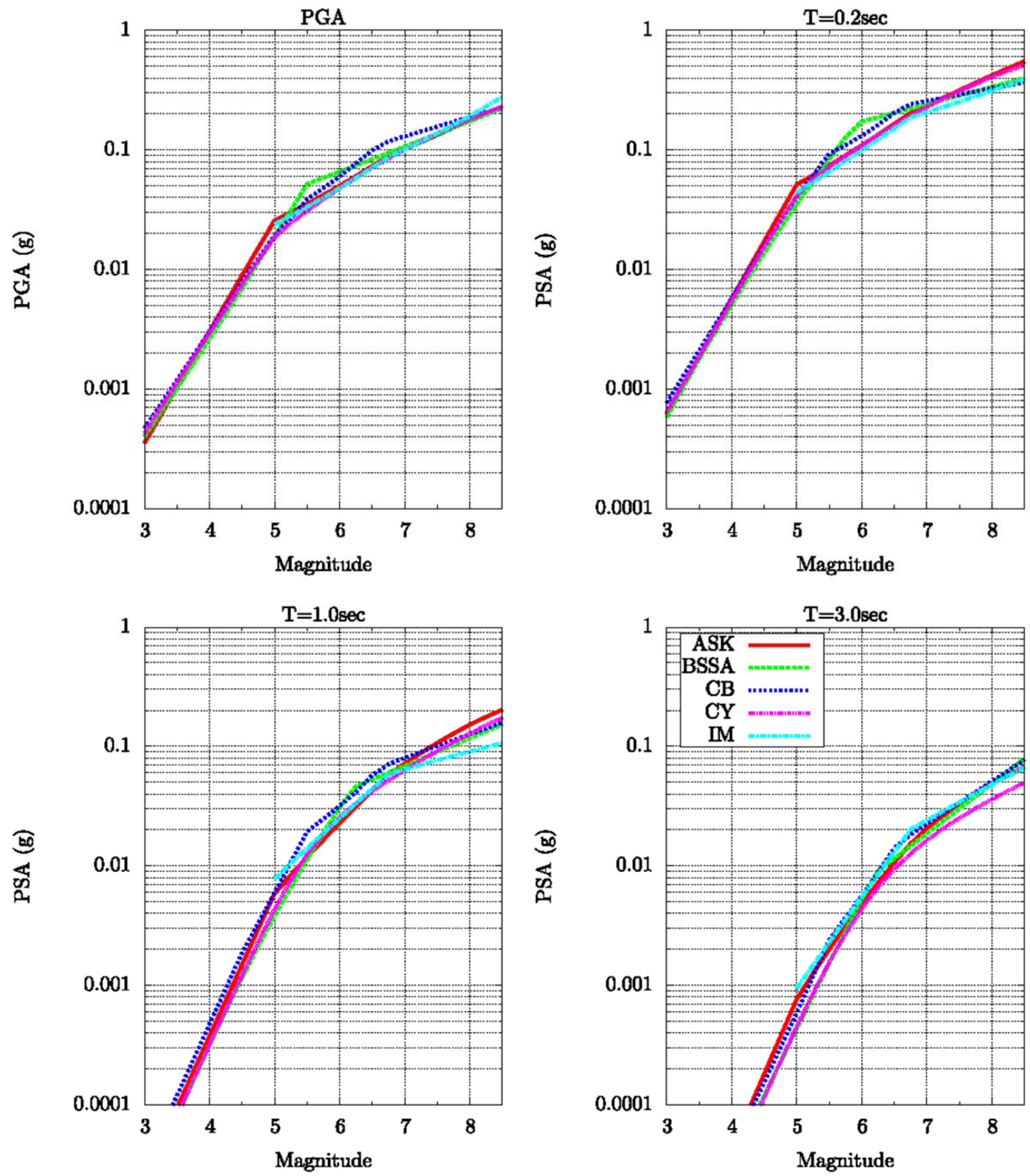


Figure 3. Comparison of magnitude scaling of the median ground motion for vertical strike-slip earthquakes at a distance of $R_{RUP} = 30$ km for $V_{S30} = 760$ m/s.

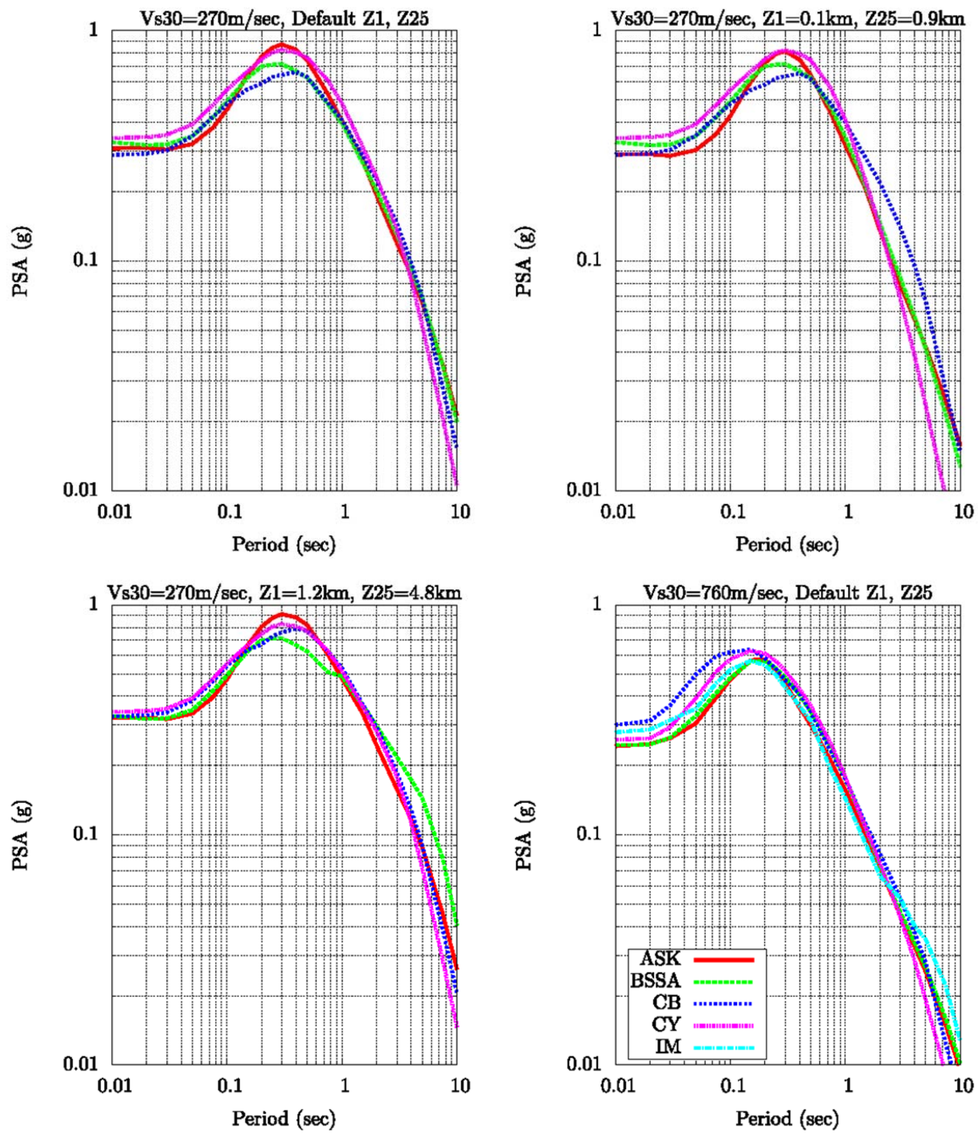


Figure 9. Comparison of median spectra for **M** 7 strike-slip earthquakes at an R_{JB} distance of 10 km with different soil depths for $V_{S30} = 270$ m/s default depth, shallow depth, deep depths, and $V_{S30} = 760$ m/s.

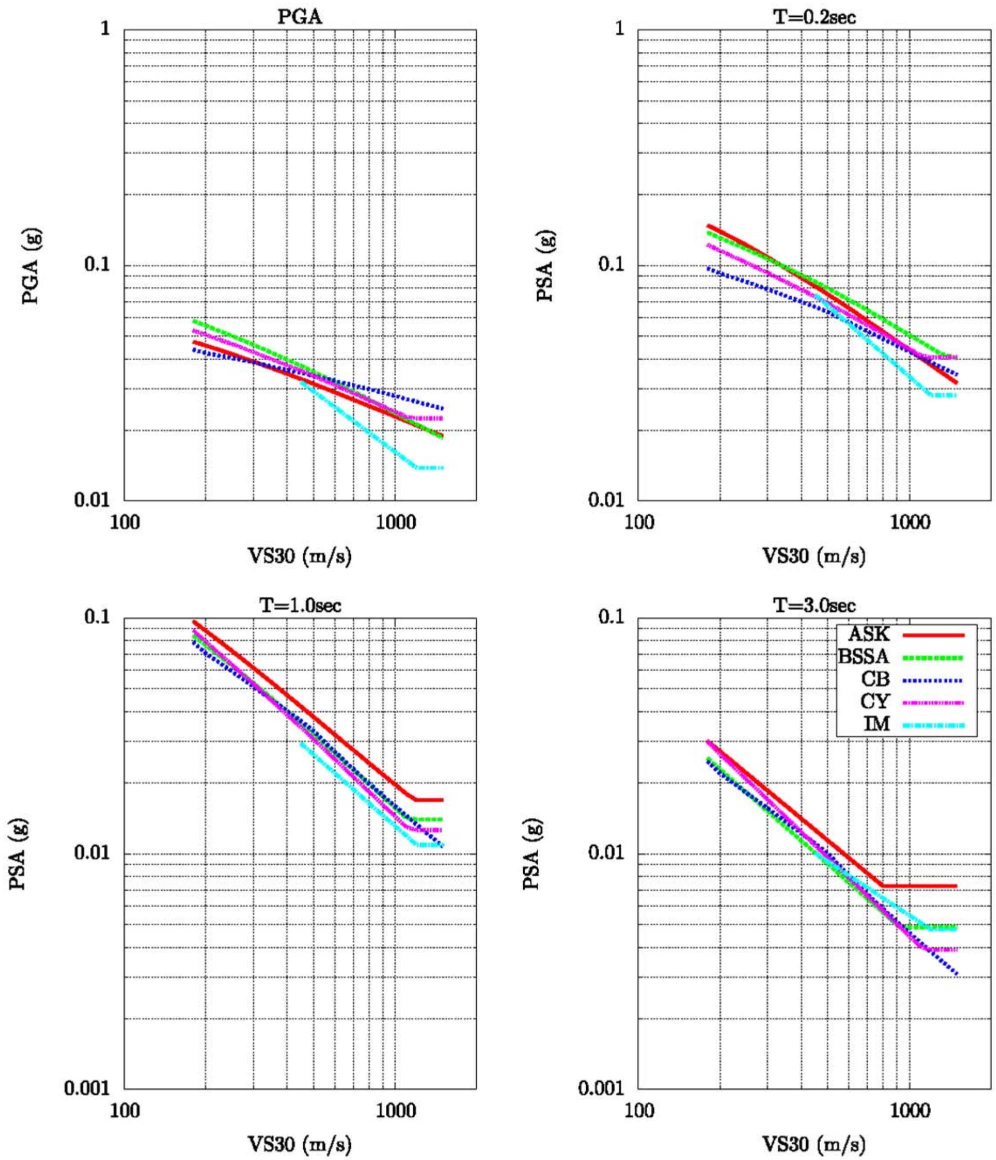


Figure 4. Comparison of V_{S30} scaling of the median ground motion for a **M** 7 strike-slip earthquake at a distance of $R_{JB} = 100$ km.

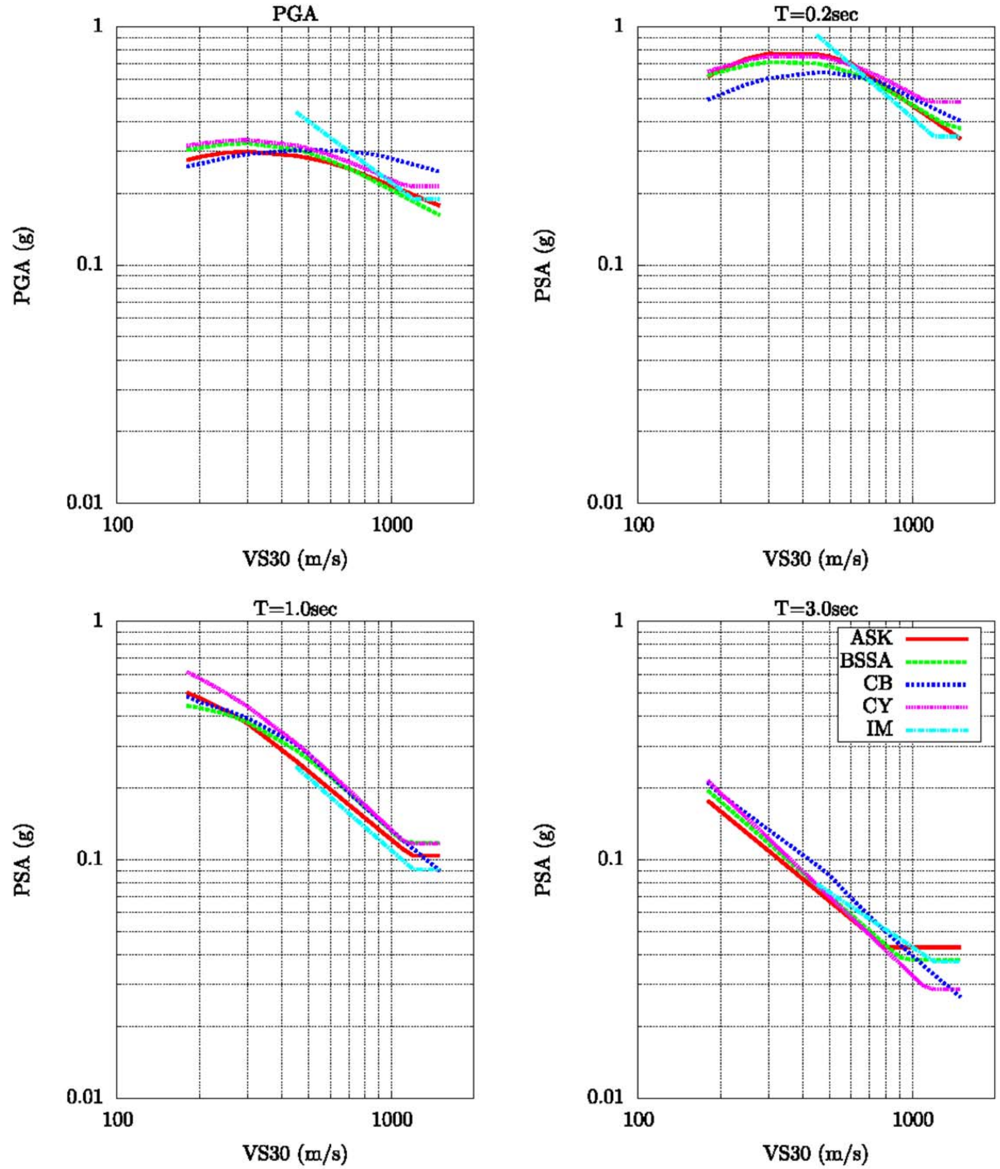


Figure 5. Comparison of V_{S30} scaling of the median ground motion for a **M** 7 strike-slip earthquake at a distance of $R_{JB} = 10$ km.

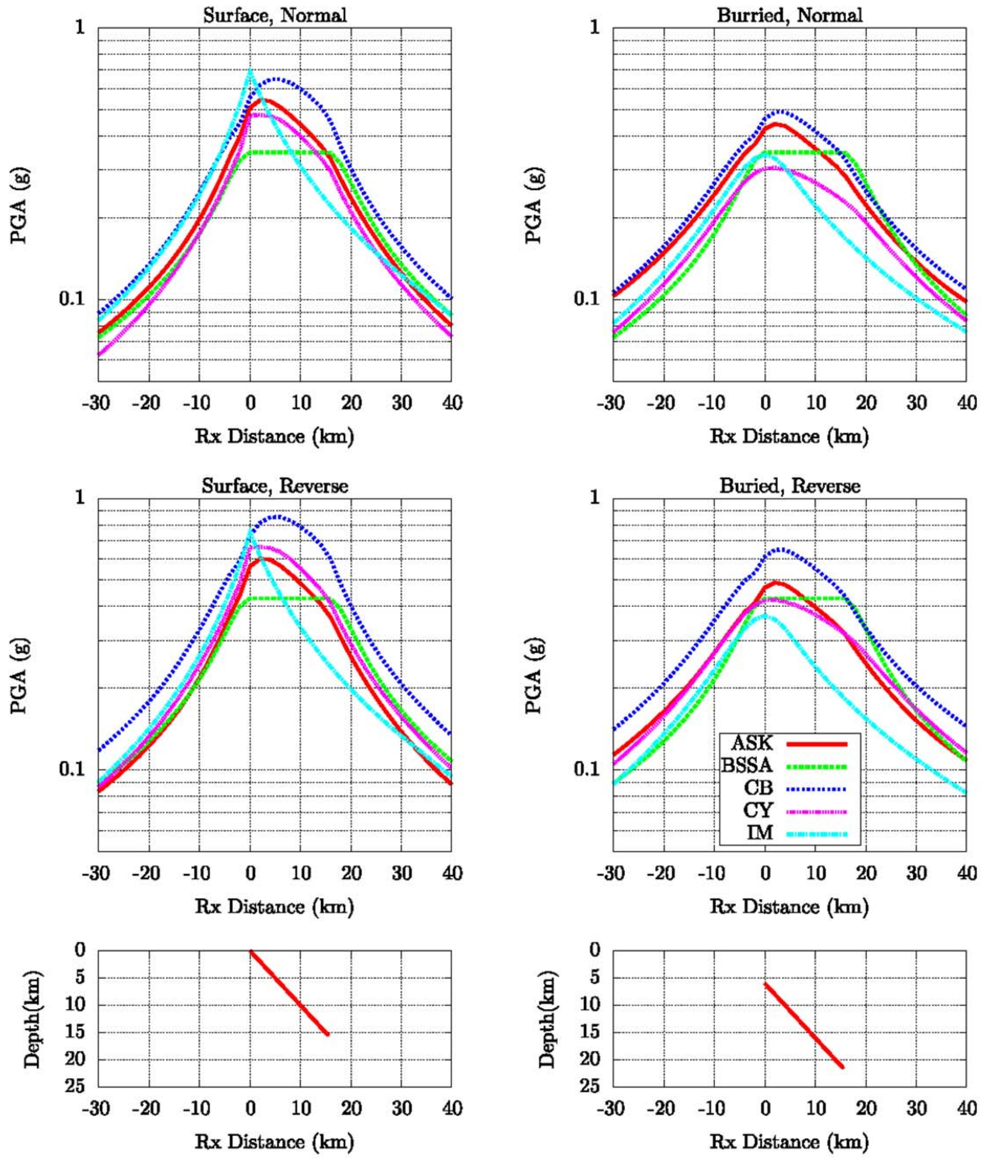
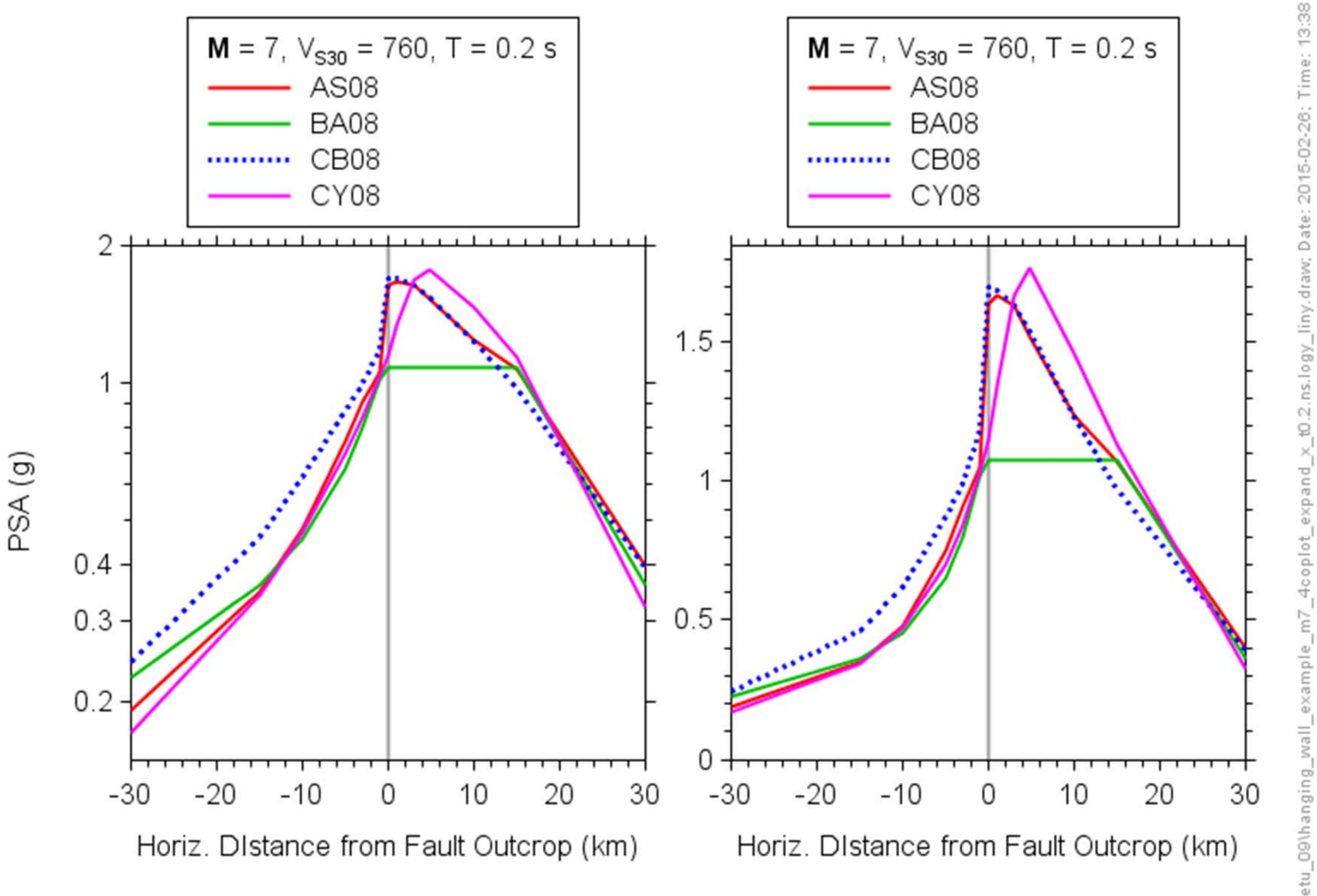


Figure 6. Comparison of FW and HW effects on PGA for a 45-degree, **M** 6.7 earthquake for $V_{S30} = 760$ m/s for both surface rupture (left side) and buried rupture (right side) with a top-of-rupture of 6 km.



Surface outcrop, 45 degree dip to right, to 15 km depth

Quantifying the Uncertainty

- The GMPEs predict the distribution of motions for a given set of predictor variables
- The dispersion about the median motions can be crucial for low annual-frequency-of-exceedance hazard estimates (rare occurrences for highly critical sites, such as nuclear power plants, nuclear waste repositories)
- Must be clear on type of uncertainty
- The scatter is very large; can it be reduced?

TYPES OF UNCERTAINTY:

Types of variability:

> **Epistemic Uncertainty**. Variability that is due to incomplete knowledge and data about the physics of the earthquake process. In principle, uncertainty can be reduced by the collection of additional information.
>
> **Aleatory Uncertainty**. Variability that is inherent to the unpredictable nature of future events. It represents unique details of source, path, and site response that cannot be quantified before the earthquake occurs. Given a model, one cannot reduce the aleatory uncertainty by the collection of additional information. One may be able, however, to better quantify the aleatory uncertainty using additional data (reduce the epistemic uncertainty in the aleatory uncertainty).

Total uncertainty = combination of epistemic and aleatory uncertainty

BSSA14 GMPEs

- ***Aleatory uncertainty***

$$\sigma\left(\mathbf{M}, R_{JB}, V_{S30}\right) = \sqrt{\phi^2\left(\mathbf{M}, R_{JB}, V_{S30}\right) + \tau^2\left(\mathbf{M}\right)}$$

Total aleatory uncertainty

$$\tau\left(\mathbf{M}\right) = \begin{array}{ll} \tau_1 & \mathbf{M} \le 4.5 \\ \tau_1 + \left(\tau_2 - \tau_1\right)\left(\mathbf{M} - 4.5\right) & 4.5 < \mathbf{M} < 5.5 \\ \tau_2 & \mathbf{M} \le 5.5 \end{array}$$

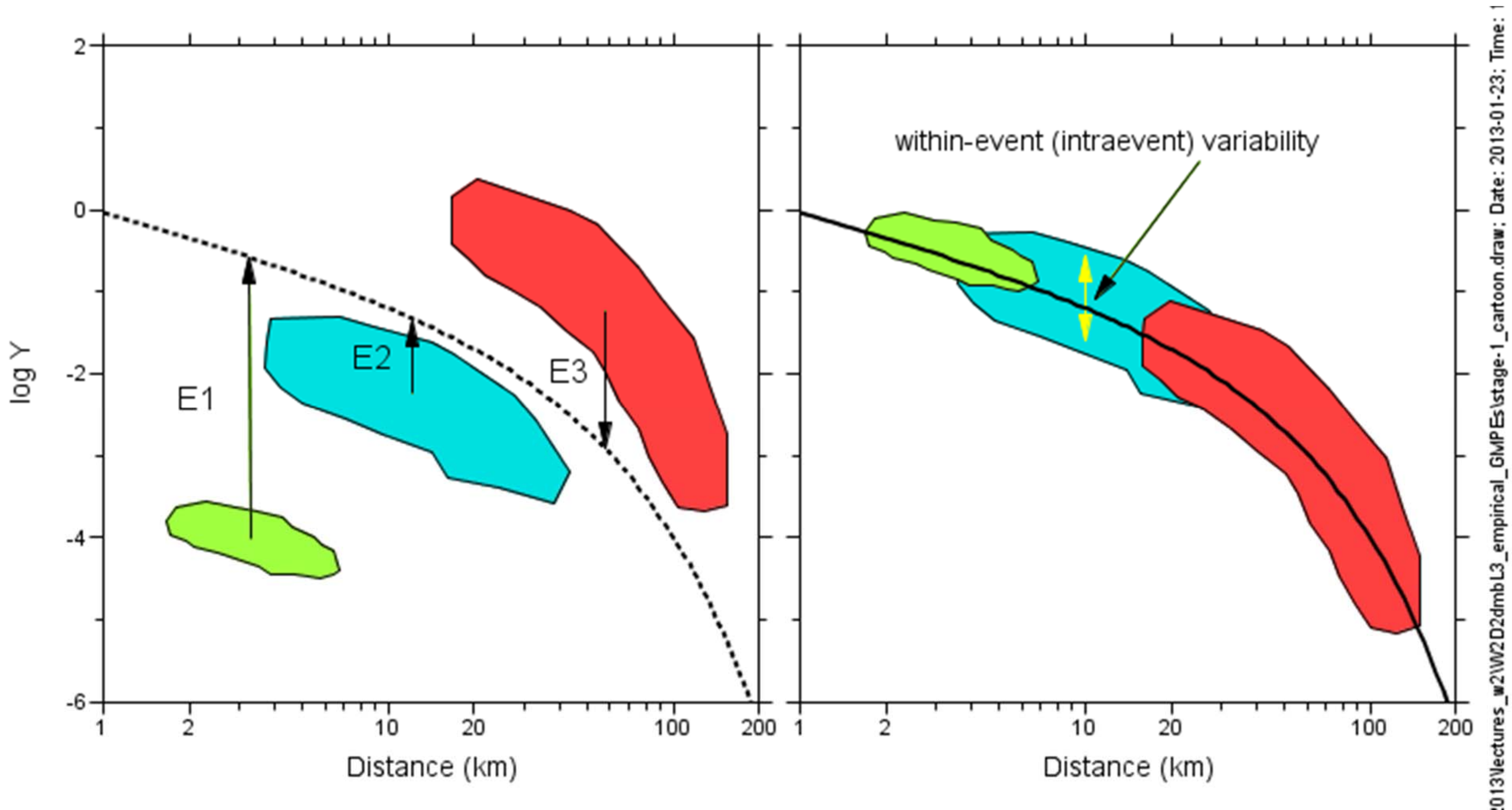
between-event aleatory uncertainty

$$\phi\left(\mathbf{M}, R_{JB}, V_{S30}\right)$$

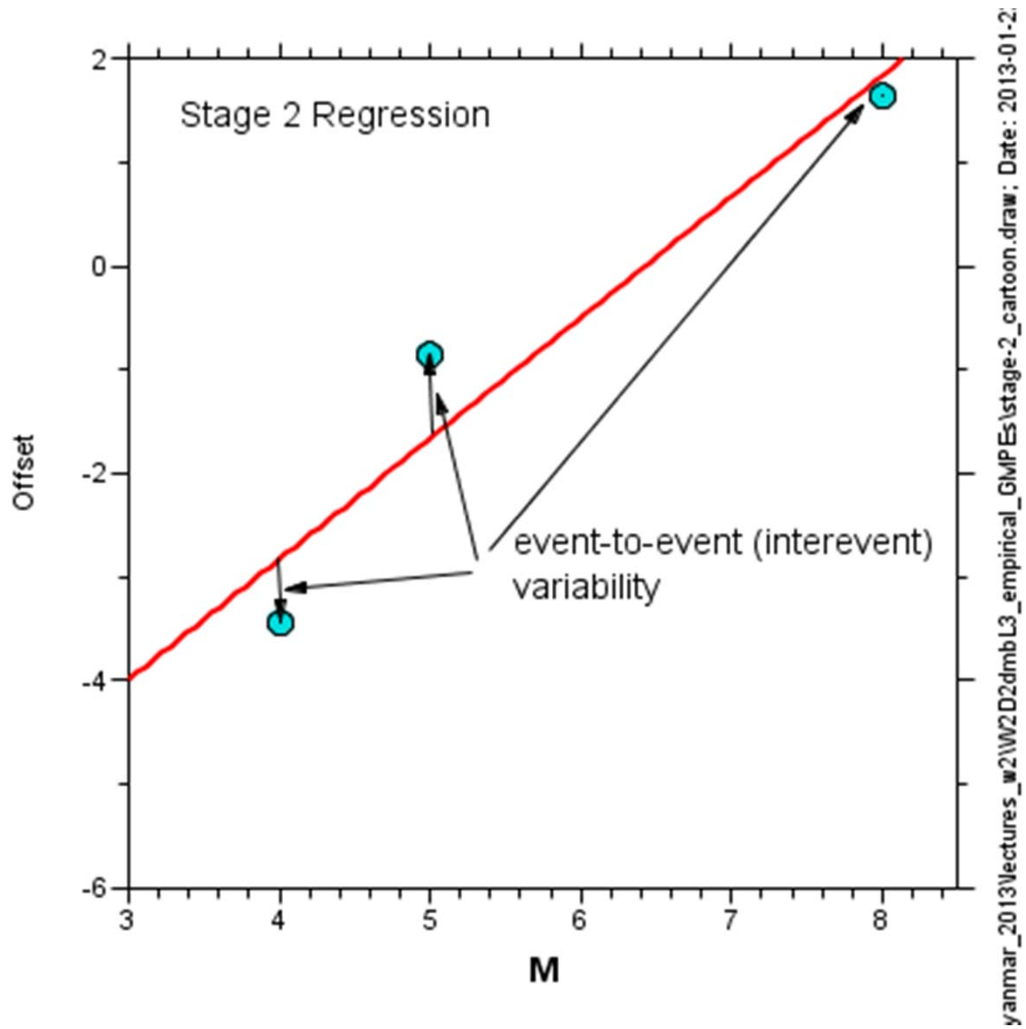
within-event aleatory uncertainty

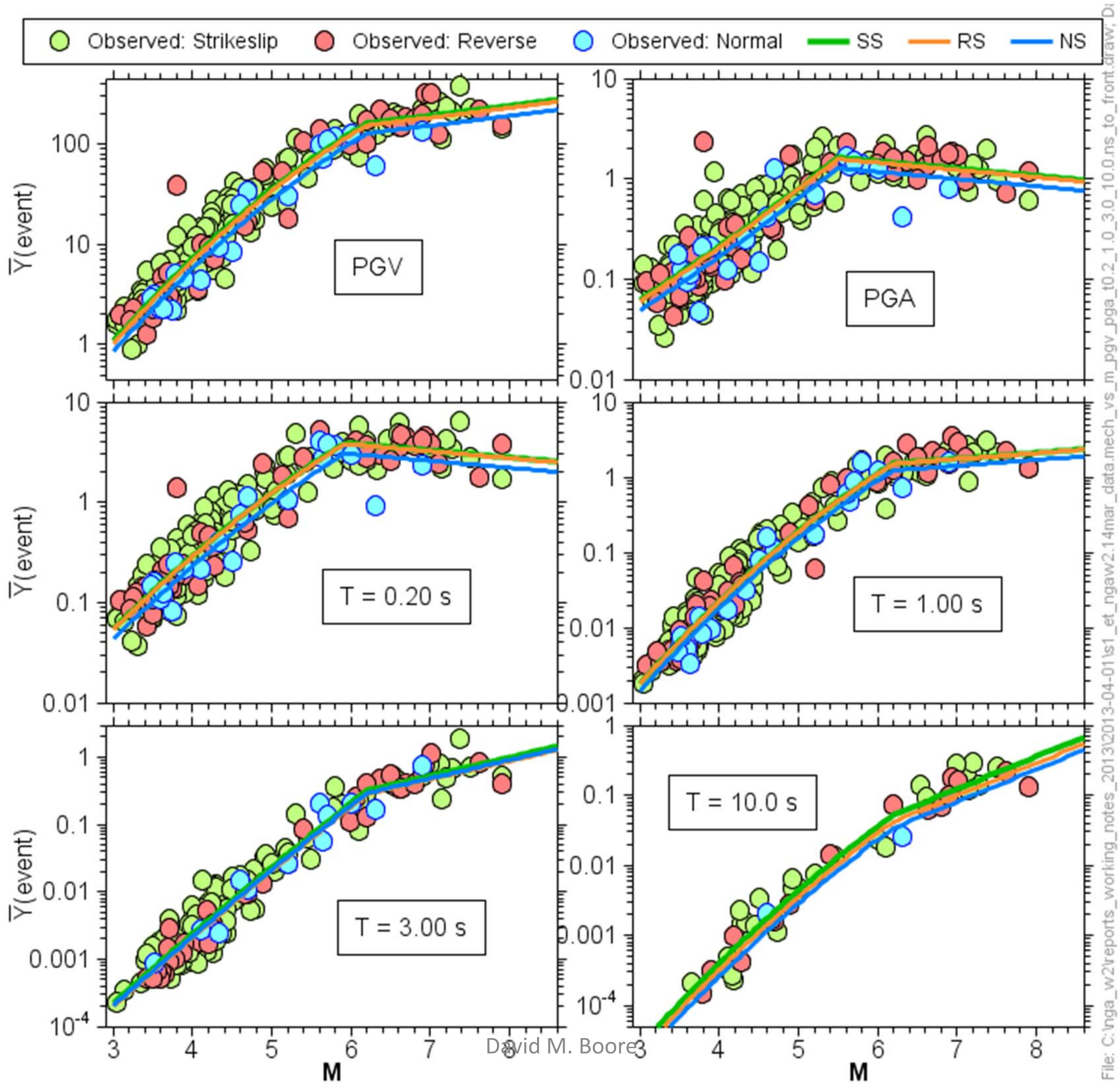
Modified from a slide by E. Seyhan

Stage 1 Regression: Determine the distance function and event offsets



Stage 2 Regression: Determine the magnitude scaling





Observed: Strikeslip
Observed: Reverse
Observed: Normal
SS
RS
NS
PGV
PGA
T = 0.20 s
T = 1.00 s
T = 3.00 s
T = 10.0 s
Y(event)
M
File: C:\nga_w2\reports_working_notes_2013\2013-04-01\s1_et_ngaw2.14mar_data.mech_vs_m_pgv_pga_t0.2_1.0_3.0_10.0.ns_to_front.draw; D

Example of comparison of total standard deviations

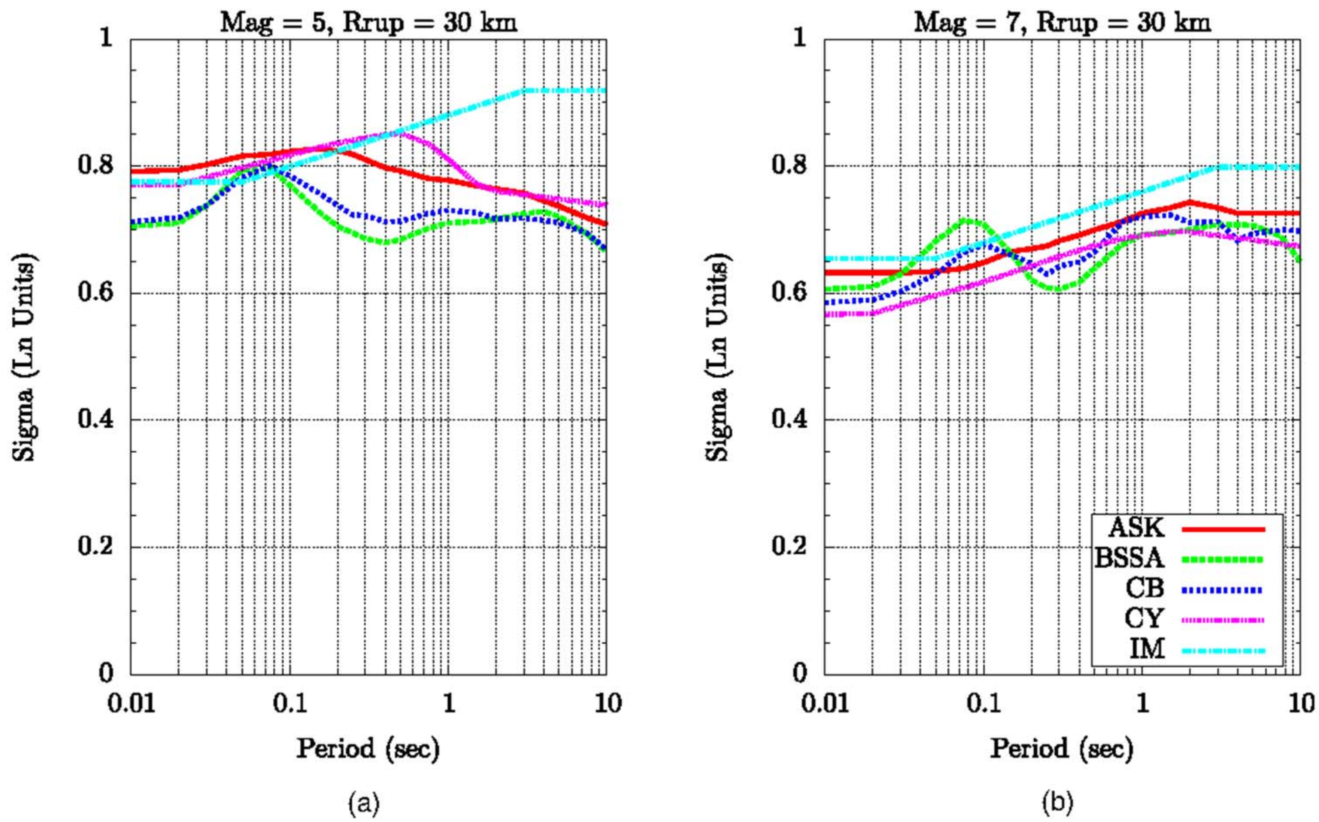


Figure 10. Comparison of the standard deviation for (a) **M** 5 and (b) **M** 7 strike-slip earthquakes at a distance of $R_{RUP} = 30$ km for $V_{S30} = 760$ m/s.

Gregor et al., 2014)

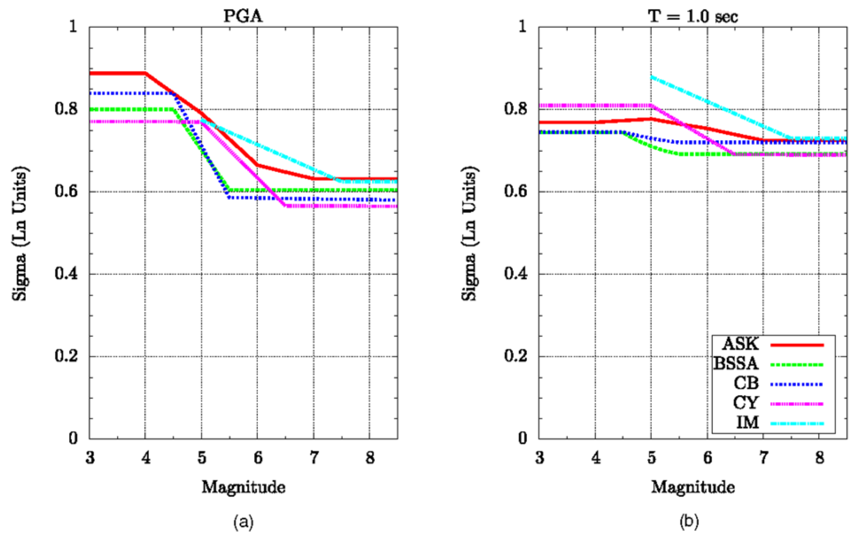


Figure 11. Comparison of magnitude dependence of the standard deviation for (a) PGA and (b) $T = 10$ s for strike-slip earthquakes at a distance of $R_{RUP} = 30$ km for $V_{S30} = 760$ m/s.

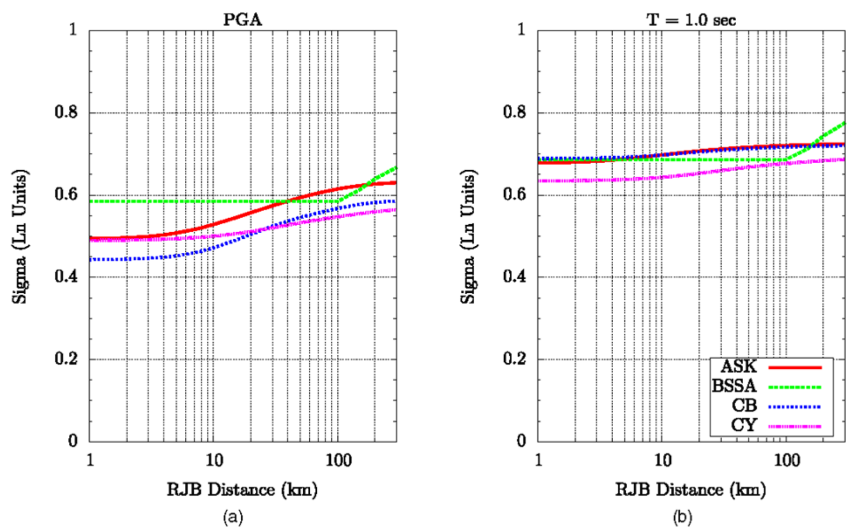


Figure 12. Comparison of the standard deviation for (a) PGA and (b) $T = 10$ s for a **M** 7 strike-slip earthquake and $V_{S30} = 270$ m/s.

Epistemic uncertainty for normal faults

Model-to-model variability is generally larger than the uncertainty in the medians of each model

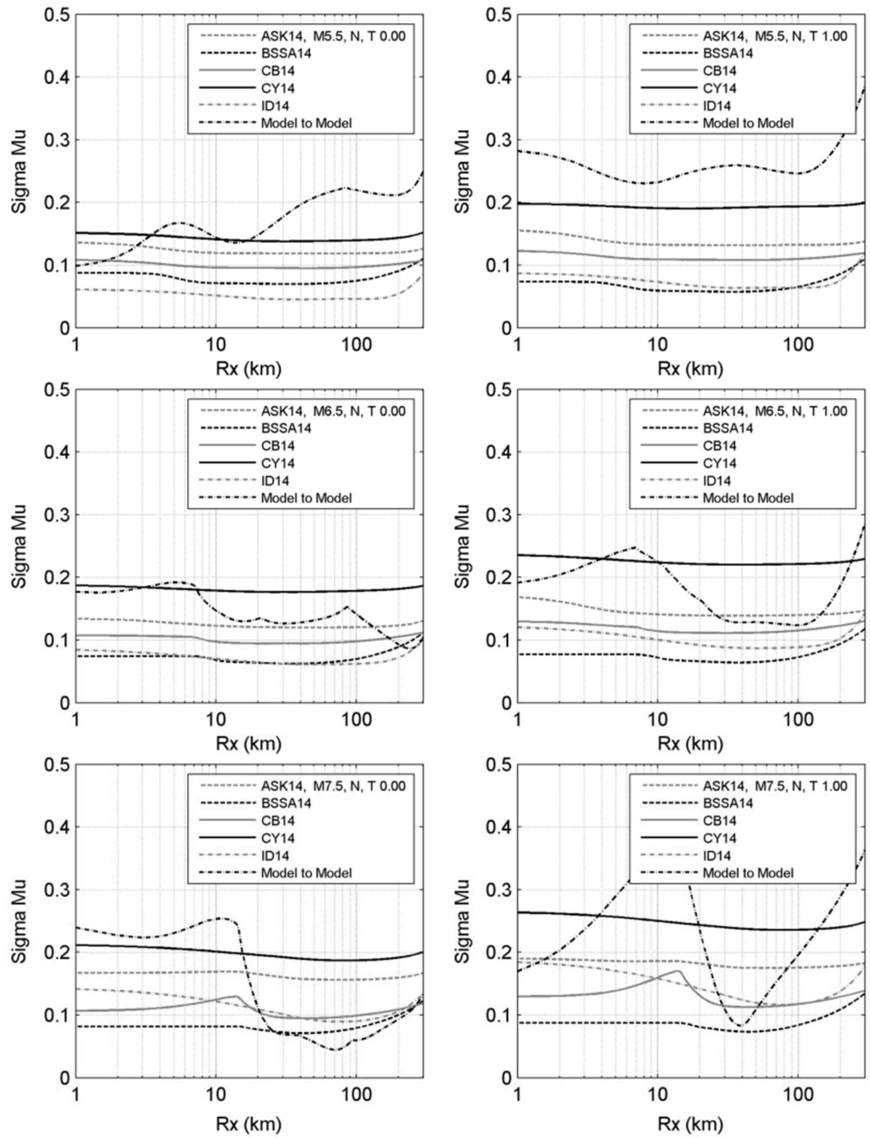


Figure 4. Asymptotic standard errors and model-to-model variability in median ln(PSA) for the five NGA-West2 models for the normal (N) rupture scenarios shown in Figure 1. Results are shown for PGA (left column) and 1.0 s PSA (right column) for **M** 5.5 (top row), **M** 6.5 (middle row), and **M** 7.5 (bottom row) earthquakes.

Al Atik and Youngs, 2014)

Comparisons of Greek Data and the NGA-W2 GMPEs

- Residual = ln Observed – ln Predicted from NGA-W2
- For each period, use mixed effects regression to separate residuals into
  - 1) overall bias
  - 2) earthquake-to-earthquake (inter-earthquake) variation
  - 3) within earthquake (intra-earthquake) variation

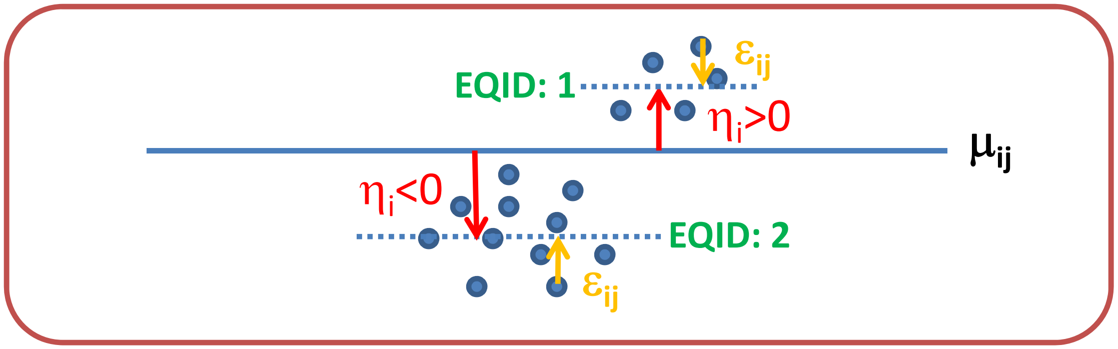
Mixed effects regressions

$$R_{ij} = \ln Y_{ij} - \mu_{ij}\left(M, mech, R_{JB}, V_{S30}\right)$$

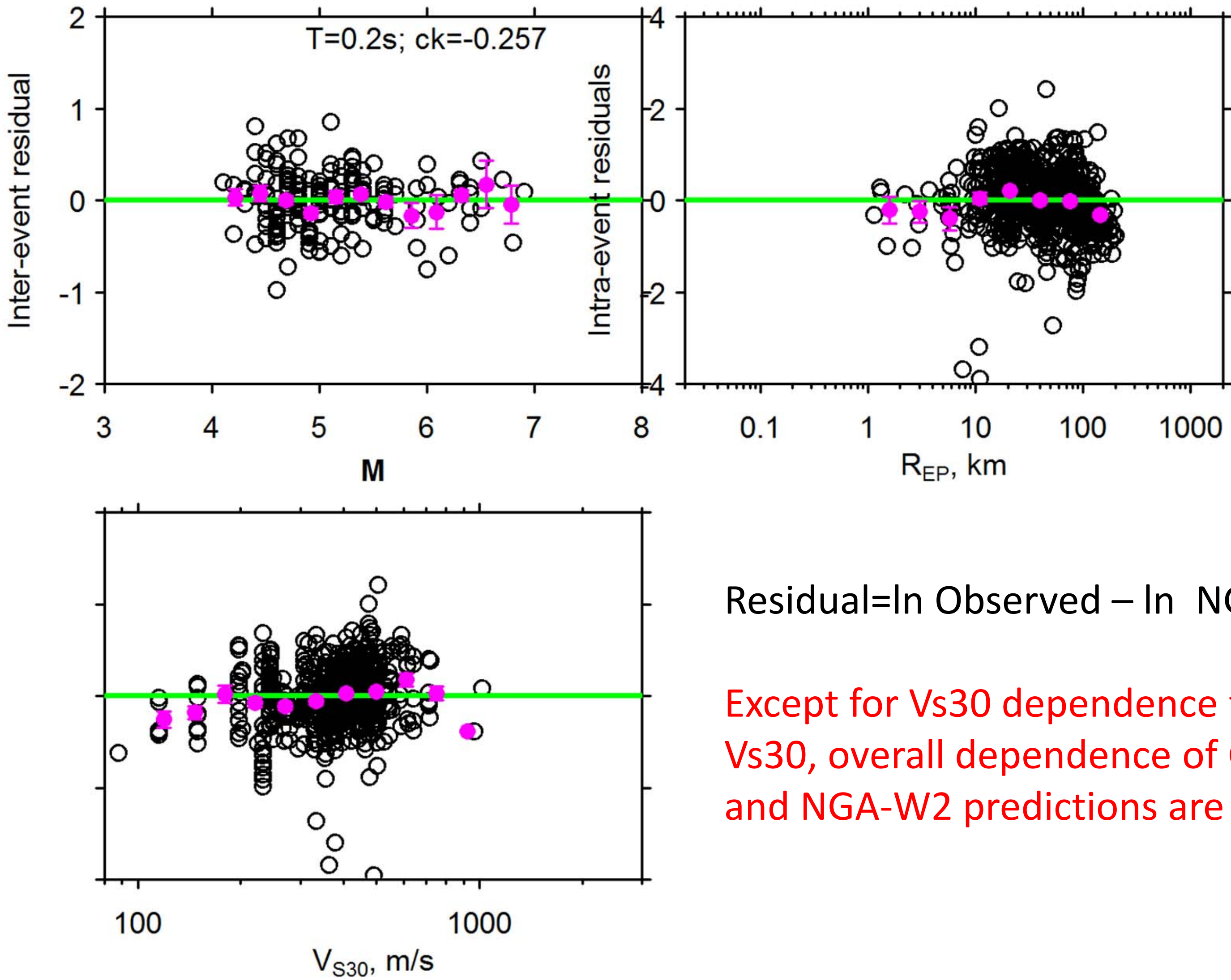
$$\boxed{R_{ij} = c_k + \eta_i \mid \mathrm{EQID} + \varepsilon_{ij}}$$

$\because$ The random part fits a mean to each of the random groups defined in EQID

ε_{ij} *vector IID random error terms with mean* $E(\varepsilon_{ij}) = 0$ *and* $\mathrm{var}(\varepsilon_{ij}) = Z$



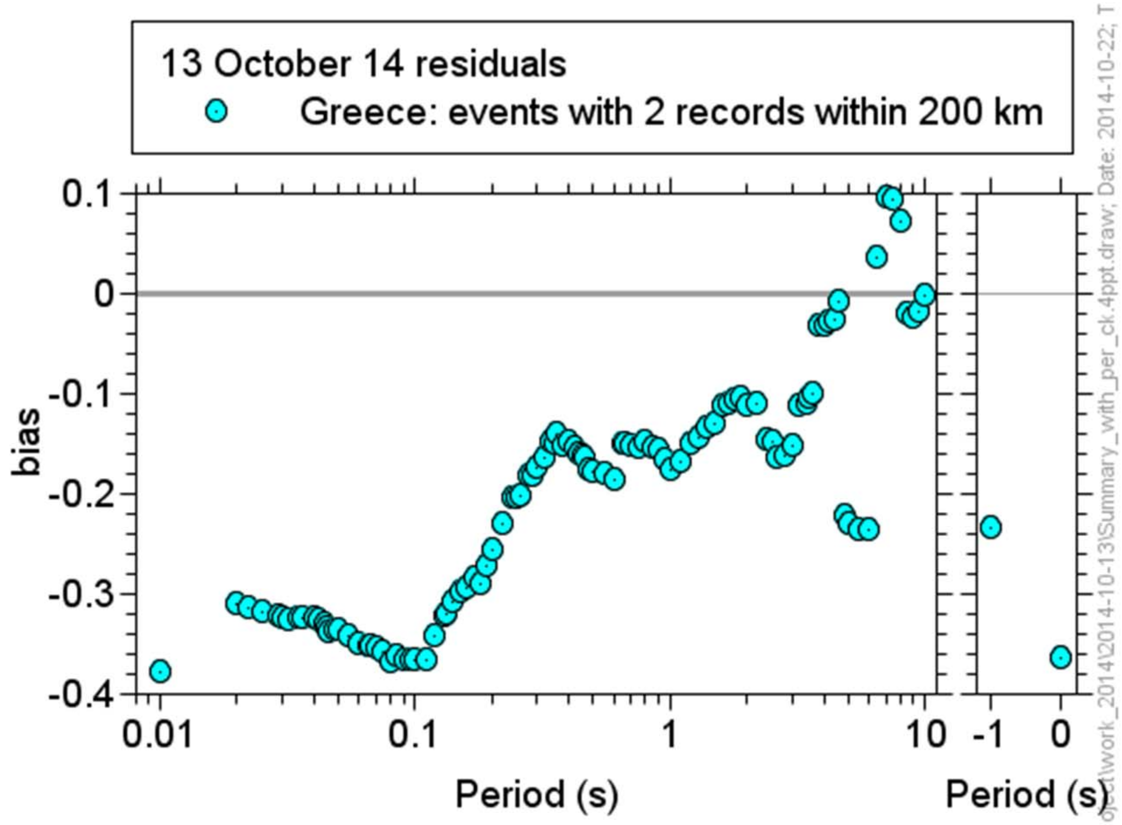
Greek Data compared with NGA-W2 GMPEs



Residual=ln Observed – ln NGA-W2

Except for Vs30 dependence for small Vs30, overall dependence of Greek and NGA-W2 predictions are similar

Significant overall bias for sort periods (max factor=0.68)—due to filtering effects of structures from which records were obtained?



GMPEs: The Future

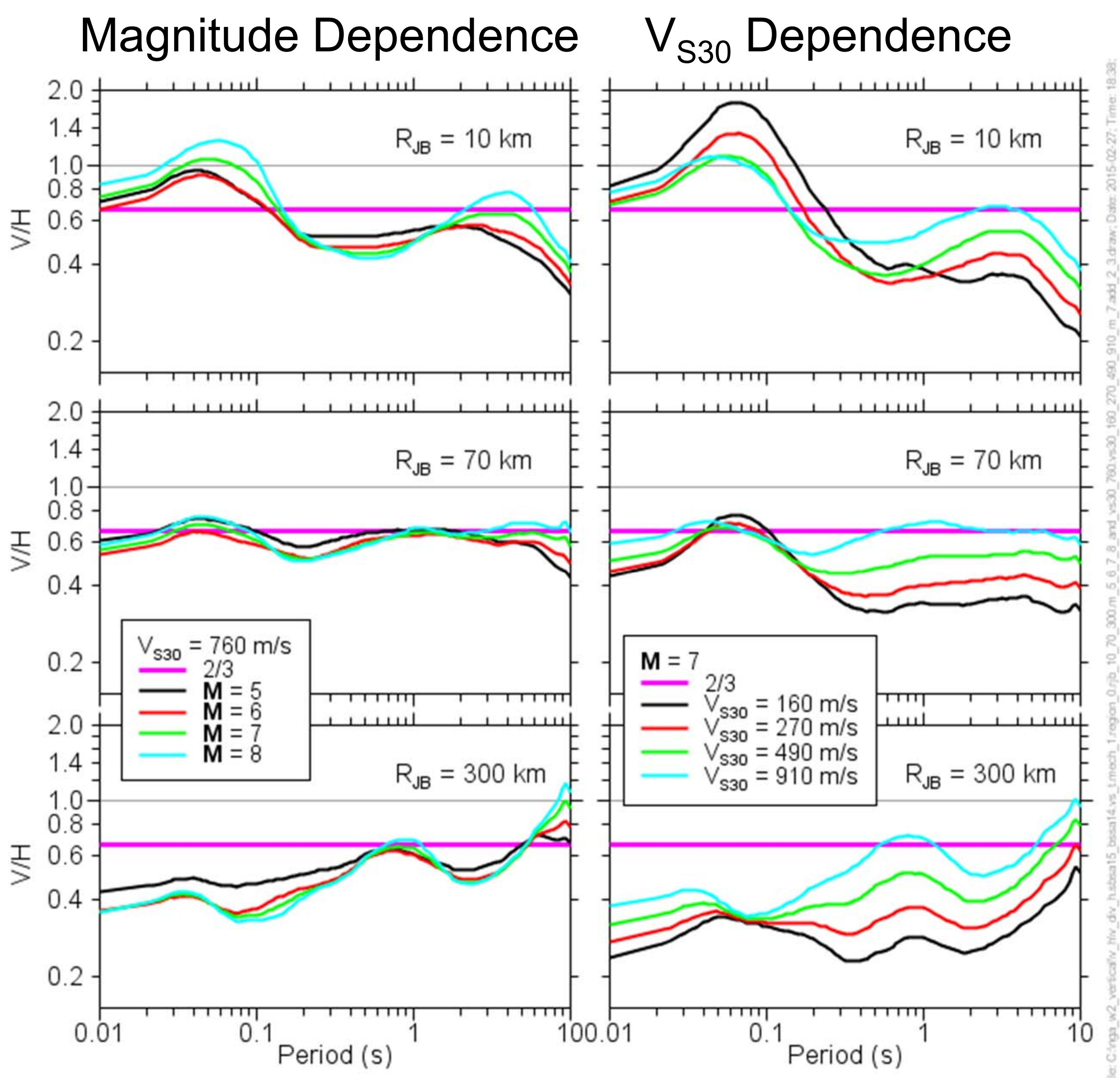
- Future PEER NGA Work
- Using simulations to fill in gaps in existing recorded motions

NGA: 2014 and beyond

- **NGA-West2 / 3**
  - Vertical component (finished)
  - Add directivity
- **NGA-East**
  - For stable continental regions
  - 2015
- **NGA-Sub**
  - For subduction regions
  - 2016

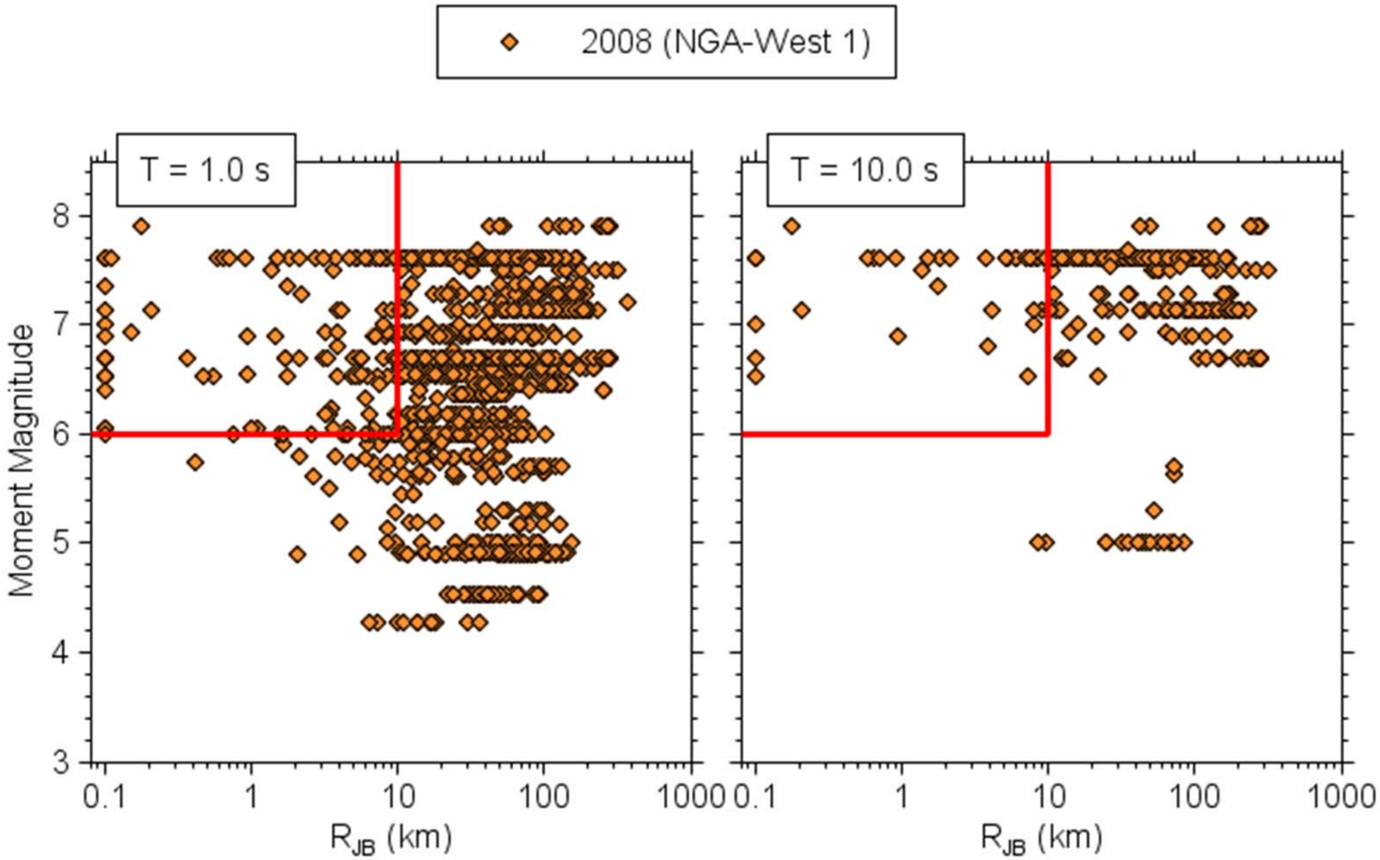
Slide from Y. Bozorgnia

Vertical/Horizontal (from SBSA14/BSSA14)



NOTE: Rule of thumb V/H=2/3 OK only for R_{JB}=70 km, V_{S30}= 760 m/s

New data may not fill in gaps in data 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.



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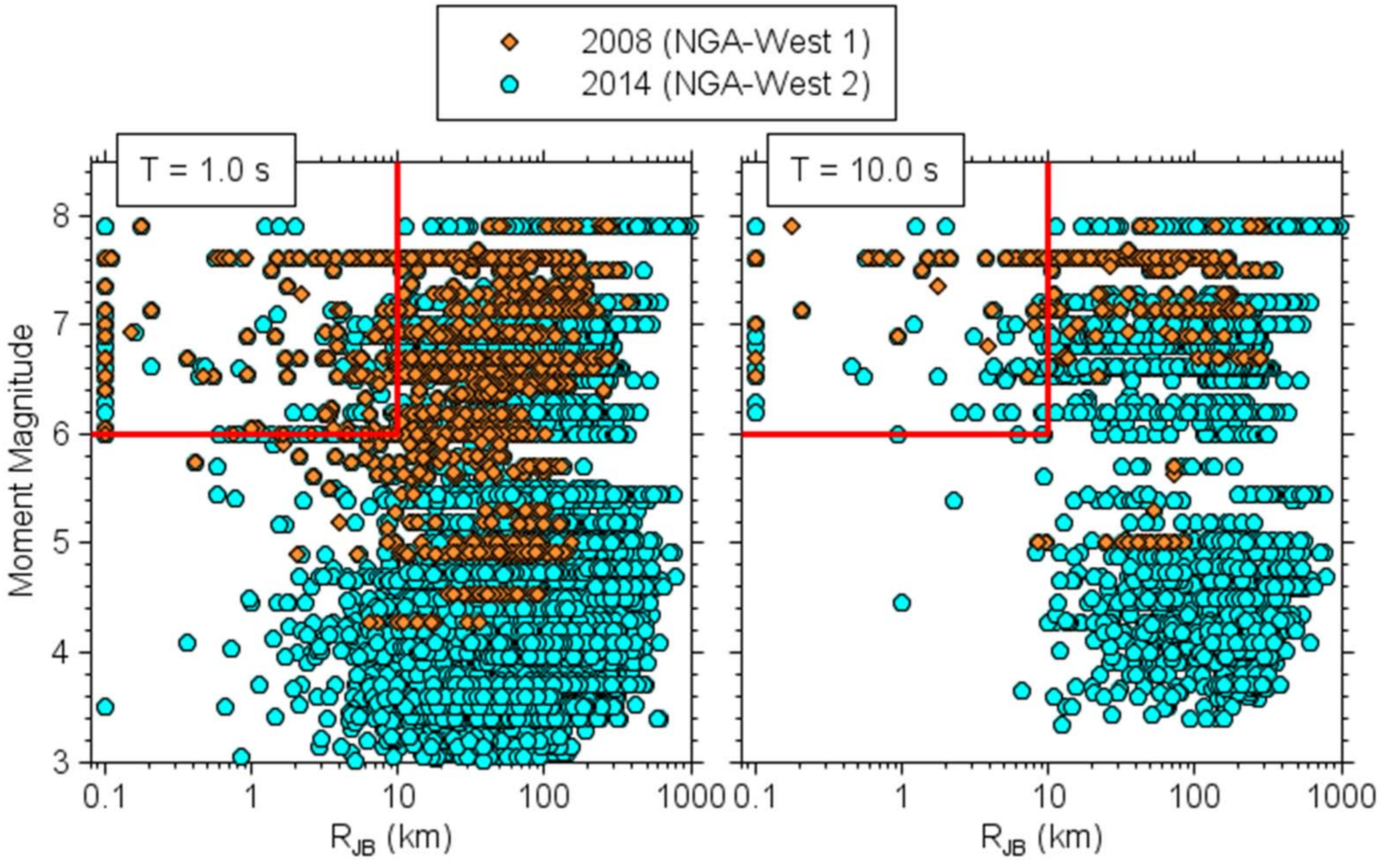

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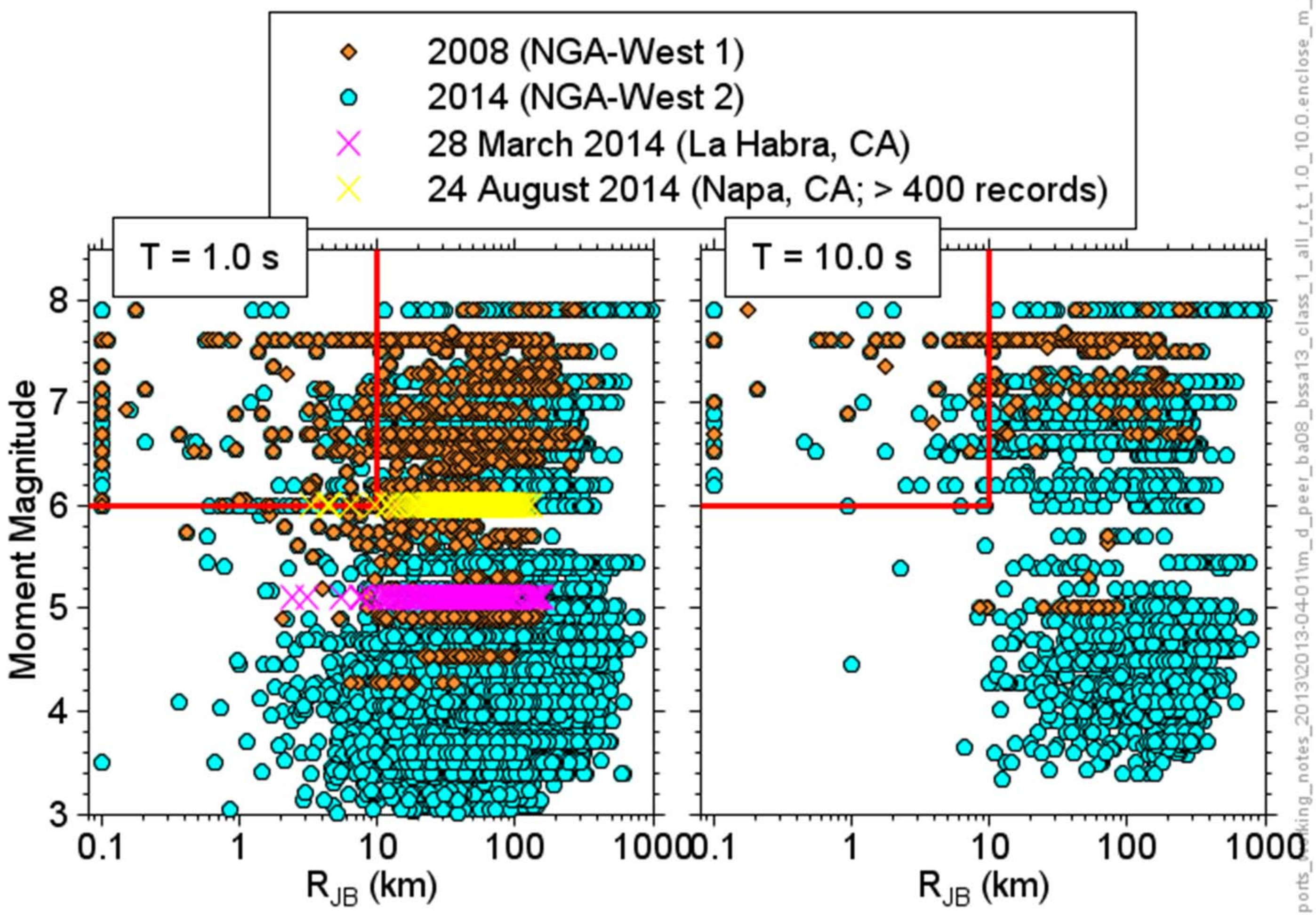

Use of Simulated Motions

- 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

Resources

- Web Sites
  - peer.berkeley.edu/ngawest2/
    - peer.berkeley.edu/ngawest2/final-products/
    - peer.berkeley.edu/ngawest2/databases/
  - www.daveboore.com
    - Papers
    - Software for evaluating GMPEs

Resources

- Paper and Reports
  - 2013 PEER Reports (from PEER web site)
  - 2014 Earthquake Spectra Papers (H component papers published in vol. 30(3), August, 2014)

Resources

- Programs to evaluate GMPEs
  - **NGA-West2 GMPEs Excel file (from databases page of NGA-West2 web site)**
  - **http://www.daveboore.com/pubs_online.html (Fortran programs available under the entry for BSSA14)**
  - **Matlab code for ASK14 from EqS supplement**

Thank You