# Overview of EPRI (2004, 2006) GMM Review Project


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**Nuclear Regulatory Commission**
**Public Meeting**

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# Topics

- Phase 1 Work
  - Information gathering (ground-motion data, new GMPEs, Vs)
  - Approaches for correcting ground-motion data to reference site conditions
  - Comparisons of adjusted data to EPRI (2004)
  - Conclusions

# Topics (2)

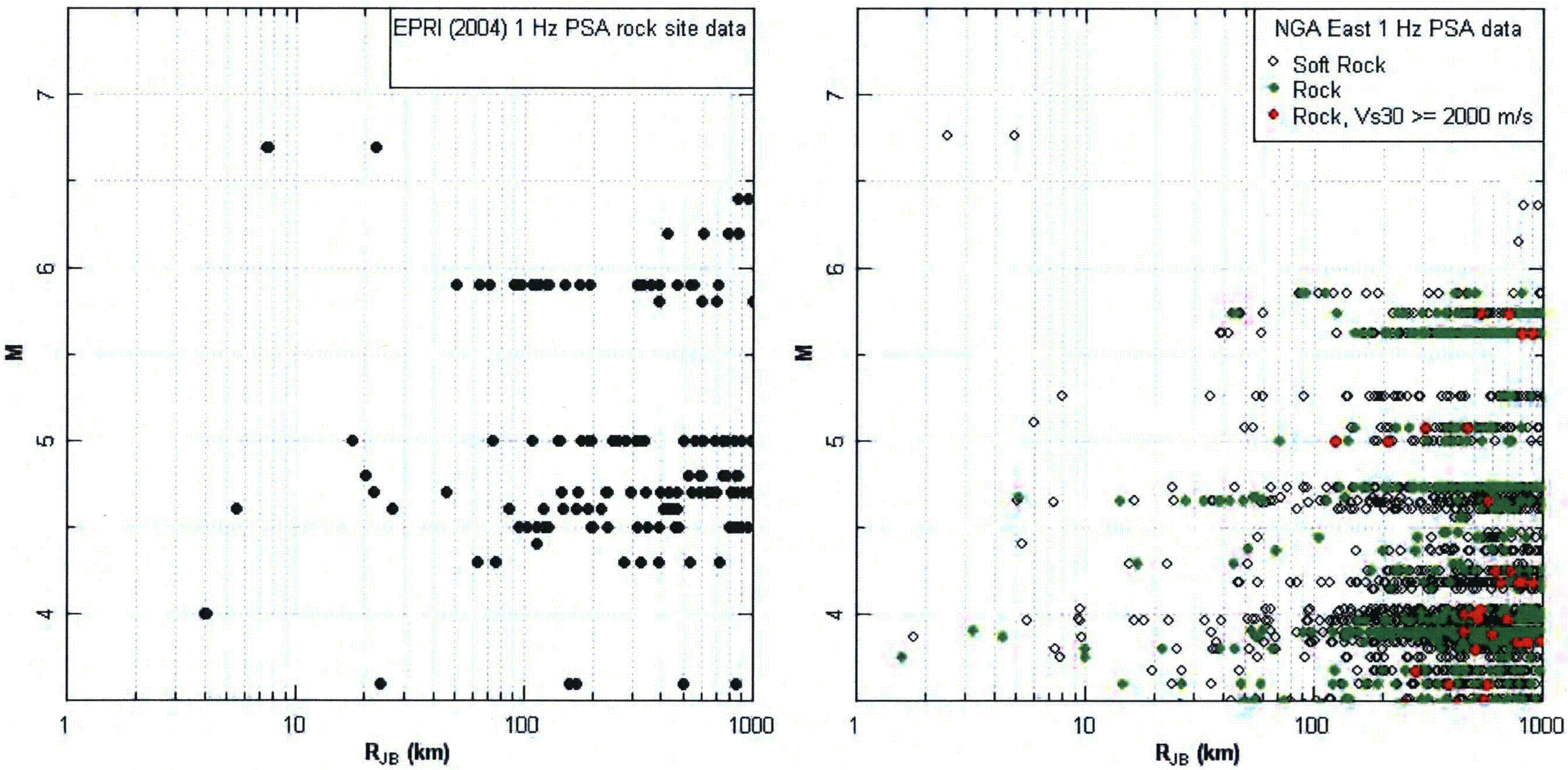
- Phase 2 Work
  - Update Process
  - New GMM Clusters
  - Cluster weights, cluster medians, within-cluster epistemic uncertainty
  - Cluster weights & final GMM
  - Aleatory Variability
  - Gulf region (data gathering, GMM modifications)

# Phase 1 – Review & Data Gathering

- Task 1: Develop Project Plan
- Task 2:
  - Review and process Ground-Motion Database
  - Review New CEUS GMPEs
  - Resource Expert and Proponent Interviews;
- Task 3: Obtain Shear Wave Velocity Measurements at Recording Stations;
- Task 4:
  - Adjust recordings to reference site conditions
  - Test the EPRI (2004, 2006) Ground Motion Model (GMM) against new data and models
  - Decide if an update is needed

# Ground-Motion Database
Bob Youngs

# Comparison of EPRI 2004 and NGA East 1 Hz PSA Datasets



# CENA Ground Motion Database

- Starting point PEER NGA-East ground motion database (April, 2012 version)
- Revisions to database
  - Compute geometric mean of horizontal components (used only these data
  - Review and refine **M** assignments (minor adjustments)
  - Estimate $R_{Rup}$ and $R_{JB}$ for all stations using simulation method from NGA West
  - Incorporate $V_S$ data (measured and inferred)
  - Classify sites base on $V_S$ data and geologic descriptions from PEER NGA-East database

# Site Categorization (1 of 4)

- Used geologic descriptions in PEER NGA-East site database to classify sites
  - Class A: Older (Mesozoic and older), harder rocks
  - Class B: Younger (Cenozoic), softer rocks
  - Class C: Soils
- Added $V_S$ values where available
  - PEER NGA-East site database
  - New $V_S$ measurements (USGS and Project)
  - Inferred values (Silva et al., 2011; Atkinson et al., 2012)

# Site Categorization (2 of 4)

- Initial Categories

| Rock Site Category | Criteria |
|---|---|
| Hard Rock | Class A or B $V_{S30} \geq 2{,}000$ m/s |
| Intermediate Rock | Class A or B with $1{,}000 \leq V_{S30} < 2{,}000$ m/s or Class A with unknown $V_{S30}$ |
| Soft Rock | Class A or B with $500 \leq V_{S30} < 1{,}000$ m/s or Class B with unknown $V_{S30}$ |

- Refined categories based on all available $V_S$ information and review of site classes

| Rock Site Category | Criteria |
|---|---|
| Hard Rock | Class A or B $V_{S30} \geq 1{,}890$ m/s |
| Intermediate Rock | Class A or B with $1{,}000 \leq V_{S30} < 1{,}890$ m/s or Class A with unknown $V_{S30}$ |
| Soft Rock | Class A or B with $500 \leq V_{S30} < 1{,}000$ m/s or Class B with unknown $V_{S30}$ |

# Size of Ground Motion Database

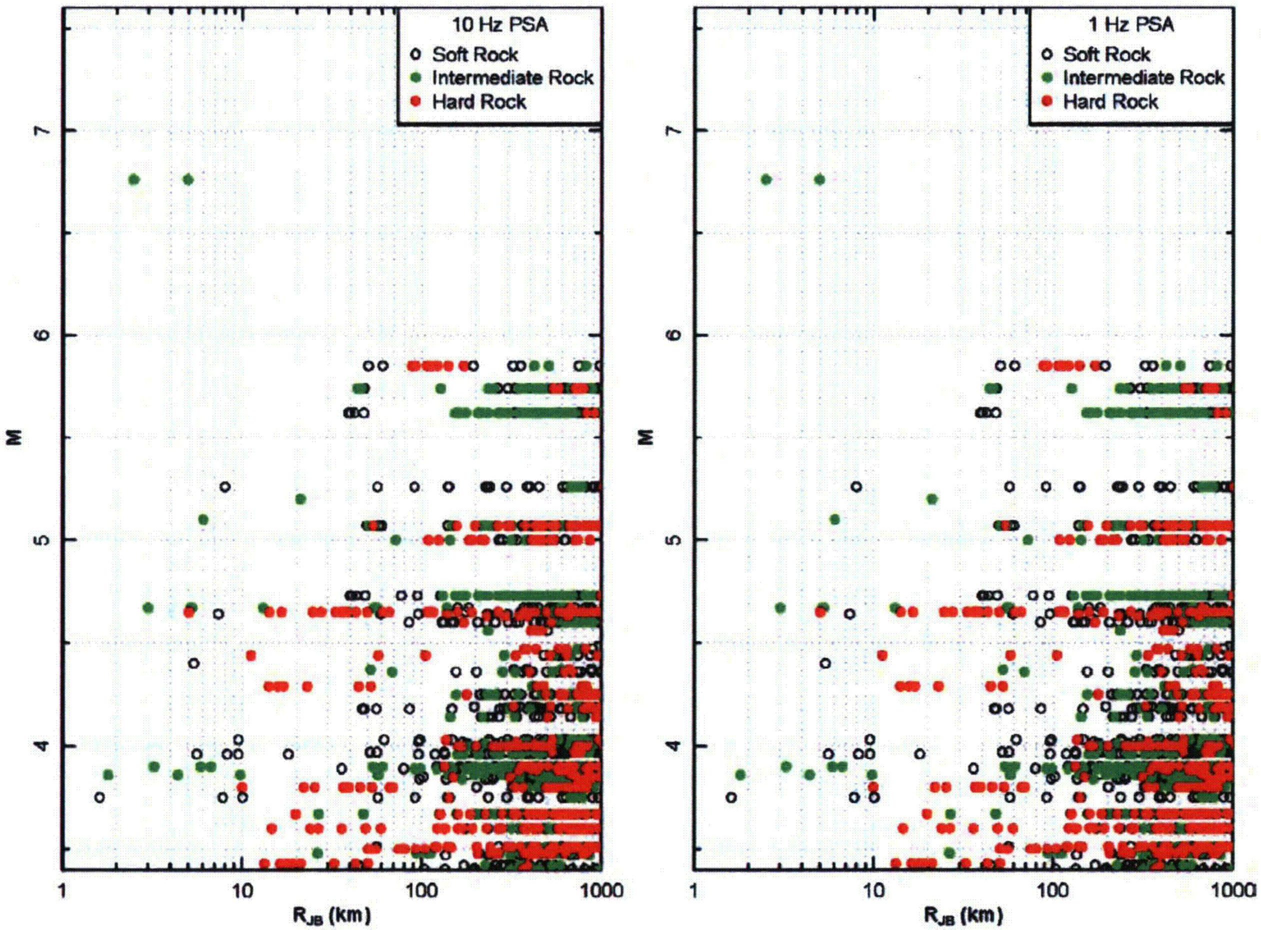
- Initial

| Magnitude Range | Distance Range | Rock Category | Number of Recordings for PSA at Frequency of: | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | **0.5 Hz** | **1 Hz** | **2.5 Hz** | **5 Hz** | **10 Hz** | **25 Hz** |
| 3.75 ≤ **M** < 4.75 | $R_{JB}$ ≤ 500 km | Soft | 1392 | 1685 | 1686 | 1524 | 835 | 143 |
| | | Intermediate | 416 | 505 | 504 | 466 | 277 | 58 |
| | | Hard | 13 | 22 | 22 | 22 | 14 | 2 |
| **M** ≥ 4.75 | $R_{JB}$ ≤ 500 km | Soft | 321 | 316 | 306 | 298 | 238 | 84 |
| | | Intermediate | 144 | 158 | 157 | 154 | 130 | 30 |
| | | Hard | 11 | 11 | 11 | 11 | 9 | 3 |

- Final

| **Magnitude Range** | **Distance Range** | **Rock Category** | **Number of Recordings for PSA at Frequency of:** | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | **0.5 Hz** | **1 Hz** | **2.5 Hz** | **5 Hz** | **10 Hz** | **25 Hz** |
| 3.75 ≤ **M** < 4.75 | $R_{JB}$ ≤ 500 km | Soft | 612 | 738 | 736 | 689 | 340 | 62 |
| | | Intermediate | 348 | 431 | 430 | 402 | 250 | 46 |
| | | Hard | 152 | 235 | 241 | 233 | 181 | 93 |
| **M** ≥ 4.75 | $R_{JB}$ ≤ 500 km | Soft | 174 | 182 | 183 | 180 | 140 | 51 |
| | | Intermediate | 120 | 134 | 135 | 132 | 116 | 33 |
| | | Hard | 67 | 68 | 68 | 68 | 65 | 37 |

# Magnitude-Distance Distribution for Final Ground Motion Database



# Review of EPRI (2004) GMPEs and Identification of New GMPE's

Gabriel Toro

# GMPEs Used in EPRI (2004) GMM

| Cluster | Model Type | Models |
|---|---|---|
| 1 | Single Corner Stochastic (0.275/0.351) | ~~Hwang and Huo (1997)~~<br>~~Silva et al (2002) - SC-CS~~<br>Silva et al (2002) - SC-CS-Sat<br>Silva et al (2002) - SC-VS<br>Toro et al (1997)<br>Frankel et al (1996) |
| 2 | Double Corner Stochastic (0.312/0.399) | ~~Atkinson and Boore (1995)~~<br>~~Silva et al (2002) DC~~<br>Silva et al (2002) DC - Sat |
| 3 | Hybrid (0.196/0.250) | ~~Abrahamon & Silva (2002)~~<br>~~Atkinson (2001) & Sadigh et al (1997)~~<br>~~Campbell (2003)~~ |
| 4 | Finite Source /Greens Function (0.217/0.000) | Somerville et al. (2001) |

# Identification of New Candidate GMPEs

- Process initiated during meetings and calls in late 2011
- Literature reviews (more than 20 relevant publications)
- Interactions with many Resource Experts in the area of CENA ground motions
- TI Team deliberations

# New Candidate Models

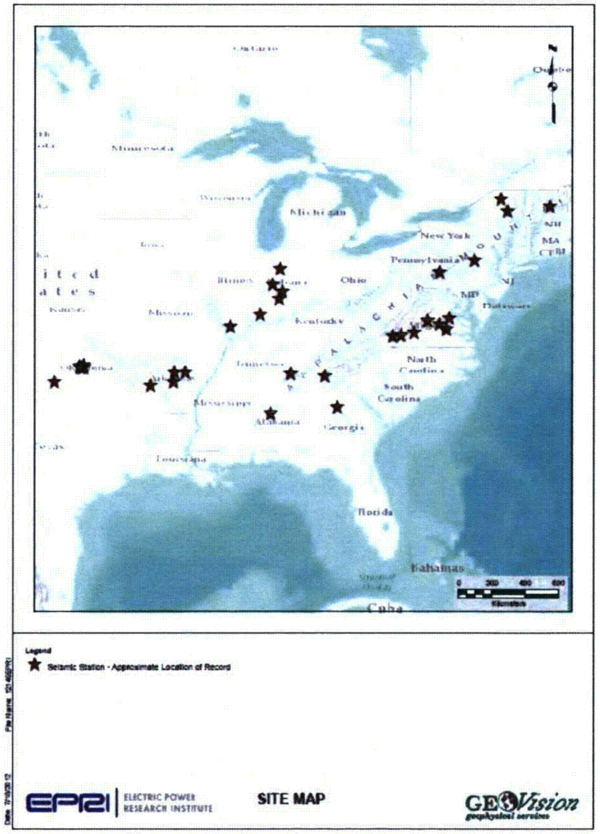
- Atkinson-Boore (2006 with 2011 revisions: AB06')
  - Recommended by Atkinson and Boore
- Atkinson (2008, with 2011 revisions; A08')
  - Recommended by Atkinson
- Pezeshk et al. (2011)
  - Recommended by Campbell and Pezeshk
- Silva et al. (2003):
  - nearly identical to Silva et al. (2002); treat as equivalent

Updated model will use these models plus the remaining EPRI (2004) models that are still considered relevant

# Shear-Wave Velocity Measurements

Gabriel Toro

# Task 3: Shear Wave Velocity Measurements




- Augment existing recording site data and ongoing USGS measurement program
- Measured shear wave velocities at 33 recording sites covering a range of locations in the CEUS. Criteria:
  - Proximity to interesting recordings
  - Biased towards form sites

# Other Profile Data

- USGS ongoing work (Rob Kayen, inter-project coordination by Rob Williams)
- NGA-East Geotechnical Working Group (from literature)

→54 sites with profile information were used

Note: profile data extend to 30-50 m depths

# Adjustment to Reference Site Conditions

Gabriel Toro

# Motivation

- Reference site conditions in EPRI (2004) are defined as hard rock
  - Vs 2,830 m/s at the surface
  - Kappa=0.006 s
  - Not practical to re-define site conditions, given the nature of this project
- Most data come from sites with lower Vs30
- Need to adjust data to reference site conditions (to the extent possible)
  - Analytical adjustment: applicable to sites for which profile information
  - Empirical adjustment: use Vs30 and examination of residuals by category

# Analytical Adjustment

- Approach: Quarter Wavelength (QWL) method of Boore and Joyner (1997)

$$A_{site/ref}(f) = \sqrt{\frac{\overline{\rho_{ref}}(f)\overline{\beta_{ref}}(f)}{\overline{\rho_{site}}(f)\overline{\beta_{site}}(f)}} \exp\left[-\pi(\kappa_{site} - \kappa_{ref})f\right]$$

β(z): is shear-wave velocity and

ρ(z): density

κ: kappa

f: frequency (Hz)

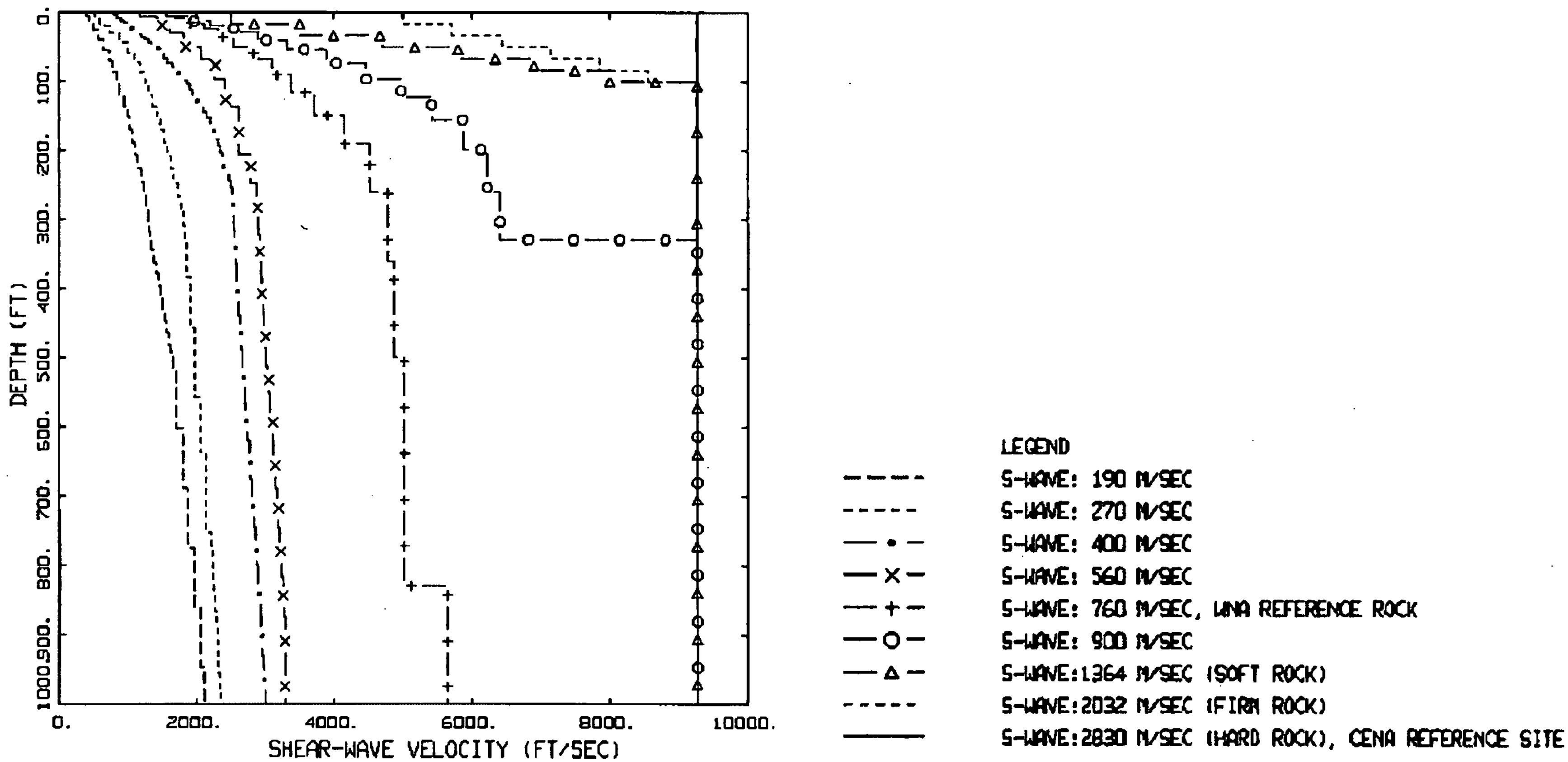
----: time-weighted average over a depth equal to 1/4 of the wavelength associated with frequency f

# Treatment of Profile for Calculation of Site Adjustments

Profile:

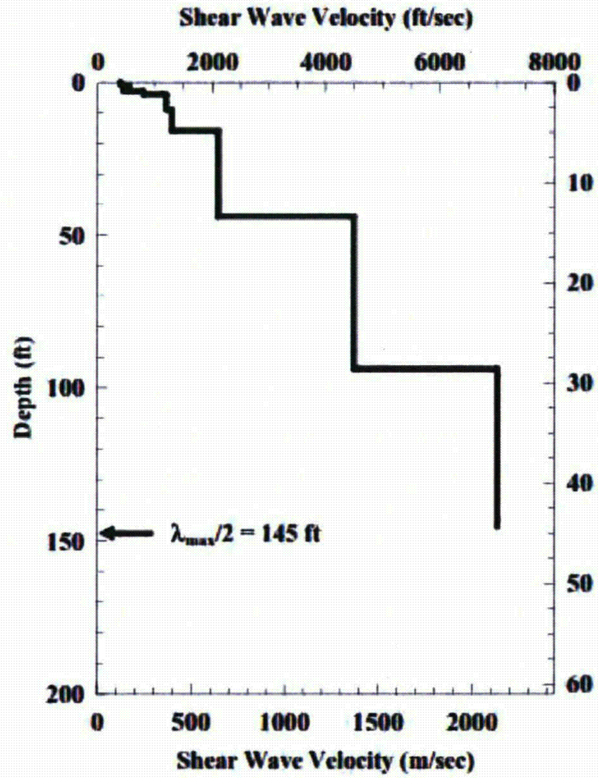
- Most profiles extend to 30-50 m depth (not enough to apply QWL for f as low as 0.1 Hz)
- Modified for instrument location
  - Material above instrument not included in calculations
  - Other modifications
- Extend to greater depths (interpolate between Silva's NEI template profiles, anchor at bottom of measured profile)

# Silva Template Profiles




TEMPLATE VELOCITY PROFILES

# Example: ET.SWET (Tennessee)




Shear Wave Velocity Profile Determined at Station ET.SWET by SASW Method

# Kappa at Recording Site: use Silva's NEI approach

- Rock with at least 1000m of firm sedimentary rock (>500 m/s): use Silva's k=f(Vs30) formula

$$\ln[\kappa(s)] = 3.9575 - 1.093\ln[V_{S30}(m/s)]$$

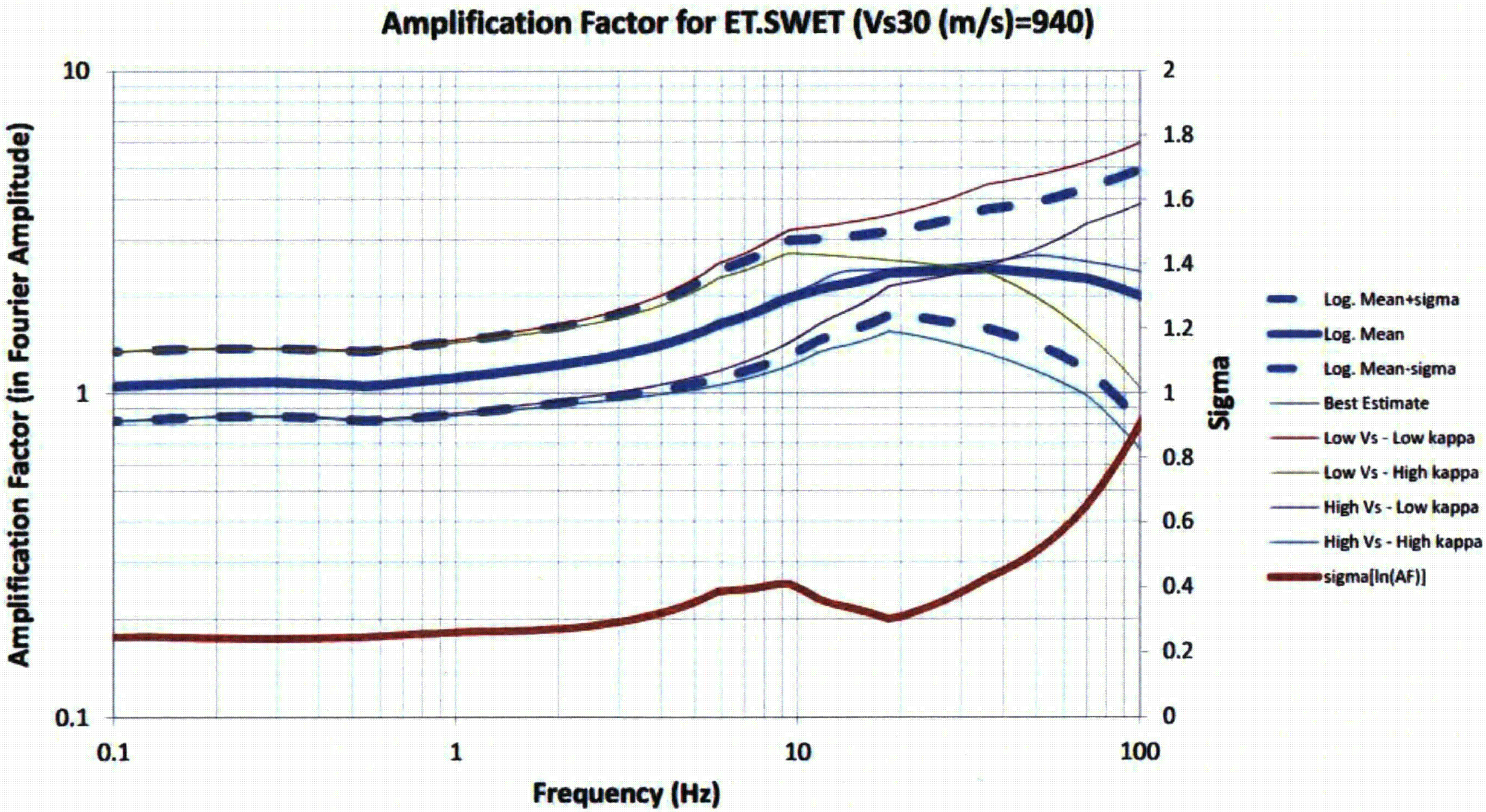
- Rock with thinner layers of sedimentary rocks, use the kappa associated with Q=40
- Soil: kappa(ms)=0.0605 H(m) + 6; max=0.04

# Uncertainty in Site Parameters Use Silva's NEI Values

- Vs profile ($\beta$): $\sigma_{ln}$=0.35 (use 2-pt randomization: $\pm\sigma_{ln}$)
- Density: $\sigma_{ln}$=0.35/4=0.0875 (fully correlated with Vs)
- Kappa: $\sigma_{ln}$=0.4 (use 2-pt randomization)

Randomization: 4 parameter combinations (also run median case)

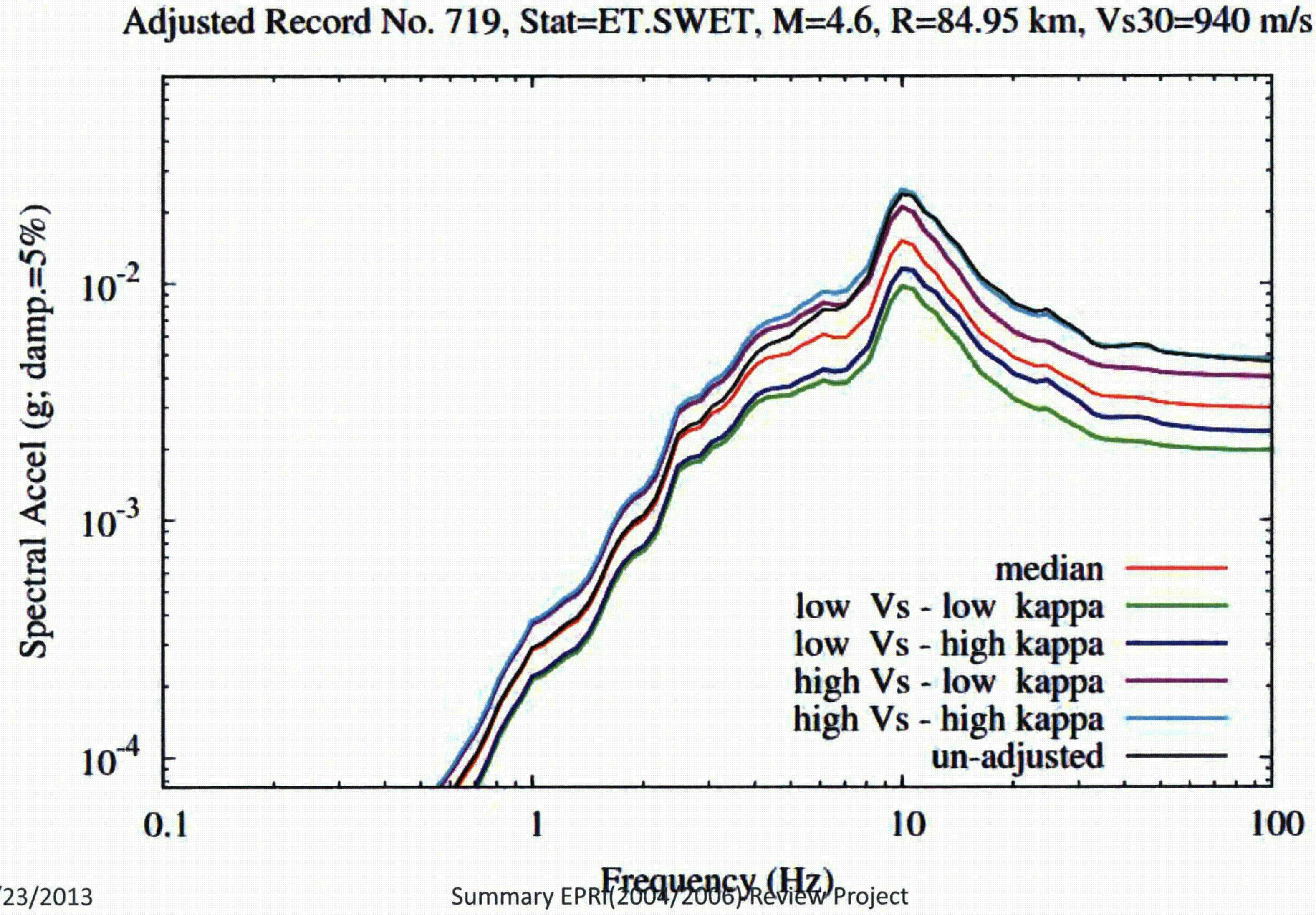
# Typical Result



# Calculations (for each recording)

- IRVT calculation to obtain station Fourier spectrum from observed response spectrum (HF portion based on FAS from time history)
- Divide Fourier spectrum by amplification factor $A_{site/reference}(f)$ → rock Fourier spectrum
- RVT calculation to obtain corrected response spectrum + uncertainty

# Example: calculated spectrum



# Empirical Adjustment for Site Conditions

Bob Youngs

# Empirical Scaling Factors

- Compute residuals = $PSA_{observed}/PSA_{predicted}$
- Fit residuals with linear mixed effects models
  - Model 1: No site category scaling

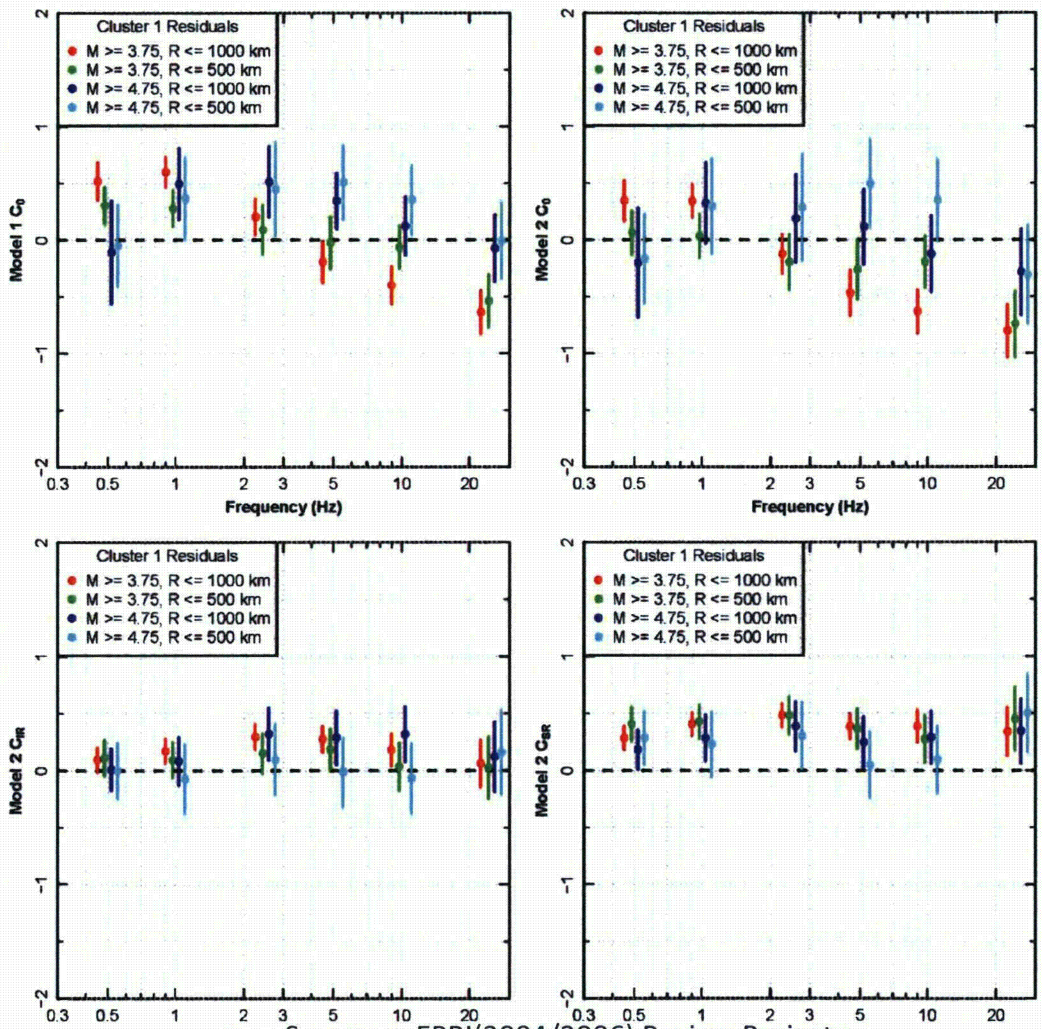
$$\ln(\text{Residual})_{\text{Model 1}} = C_0 + \varepsilon_{i,j}$$

  - Model 2: Site category scaling

$$\ln(\text{Residual})_{\text{Model 2}} = C_0 + C_{IR}F_{IR} + C_{SR}F_{SR} + \varepsilon_{i,j}$$

  - FIR and FSR are indicator (0,1) variables for station category

# Example Results for Models 1 and 2 Fit to Residuals Computed Using EPRI (2004) Cluster 1 Median GMPE



# Analysis of Models 1 and 2

- Using updated database, Model 2 (including site category factors) produces better fit to the residuals than Model 1 (no site category factors)
- Intermediate rock site coefficient $C_{IR}$, often not statistically significant
- Model with only scaling for soft rock found to be better at fitting residuals

# Model 3 Used to Fit Residuals

- Model 3

$$\ln(\text{Residual})_{\text{Model 3}} = C_0 + C_{SR}F_{SR} + \varepsilon_{i,j}$$

- Empirically scaled residuals used for GMPE weighting

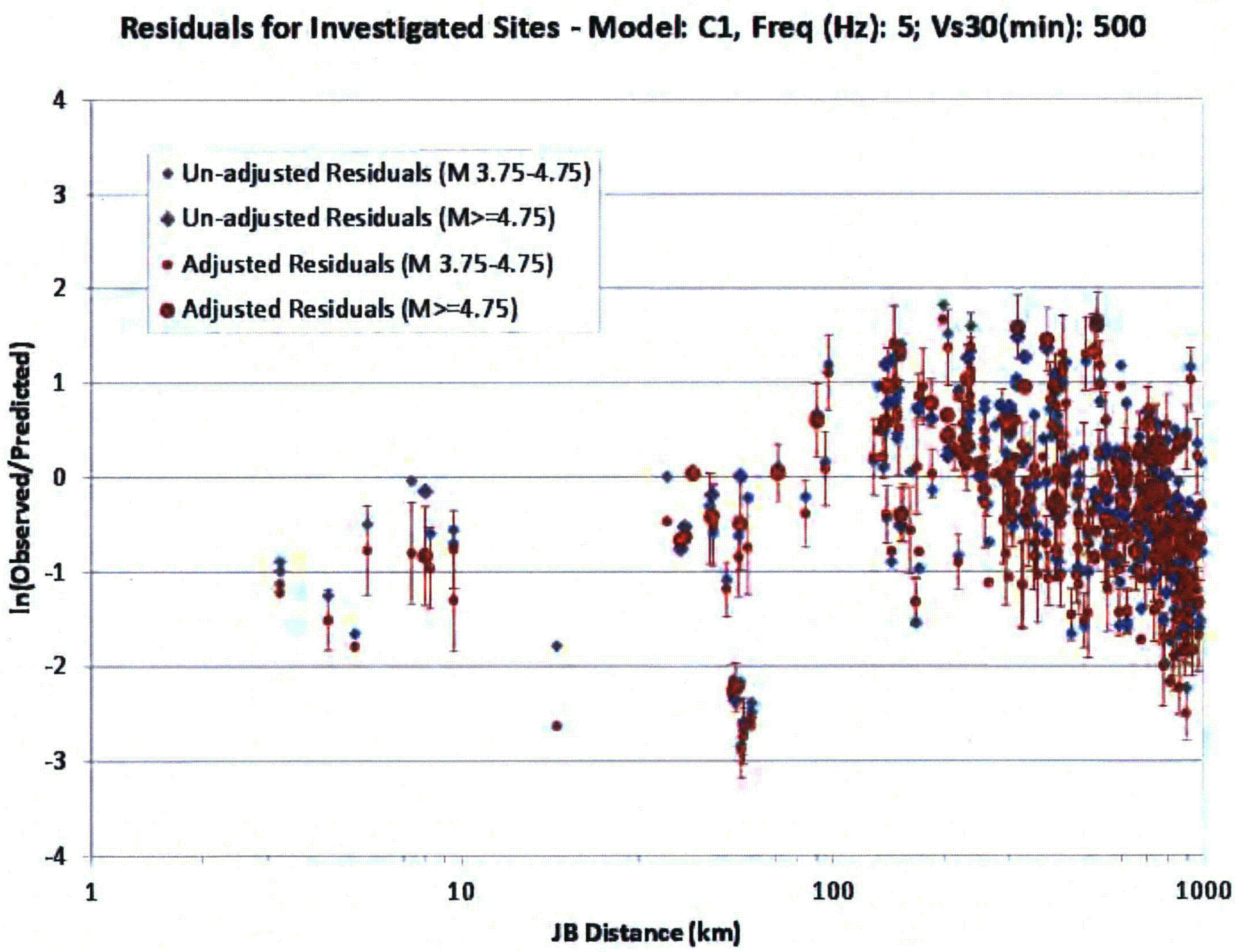
$$\varepsilon_{ij}^{\text{empirically adjusted}} = \varepsilon_{ij} - C_{SR}F_{jk}^{SR}$$

  - $F_{jk}^{SR}$ is the soft rock indicator variable (0,1) for the $k^{th}$ site that represents the $j^{th}$ recording of the $i^{th}$ earthquake in the database

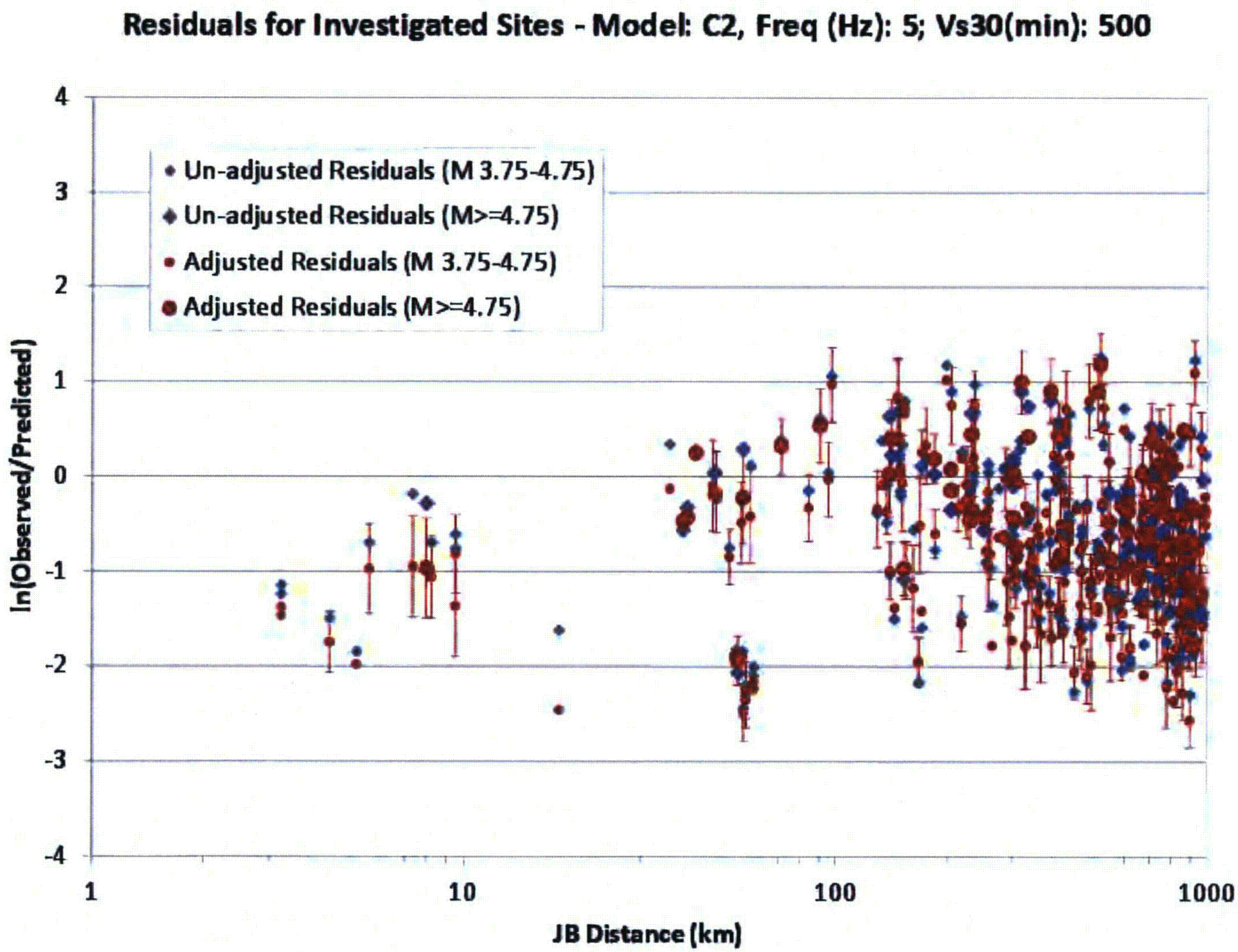
# Task 4: Review of 2004 Model Versus Data: G. Toro

- Compute residuals of NGA East database relative to EPRI (2004) cluster medians (clusters 1, 2, and 3)
  - Use analytically adjusted data
  - Use empirically adjusted data

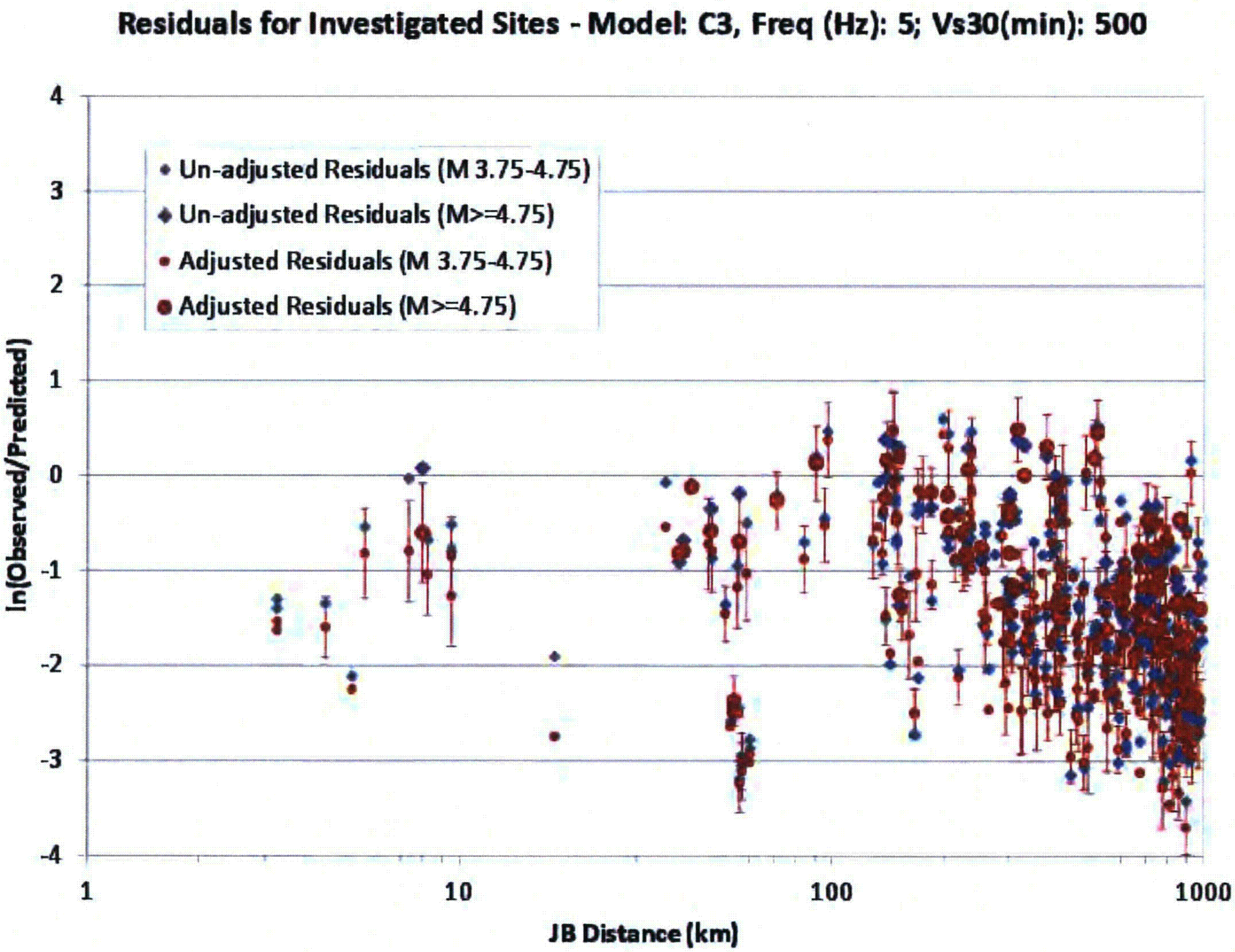
- Results indicated over prediction of ground motions in some magnitude-distance-frequency ranges



Residuals for Investigated Sites - Model: C1, Freq (Hz): 5; Vs30(min): 500
Un-adjusted Residuals (M 3.75-4.75)
Un-adjusted Residuals (M>=4.75)
Adjusted Residuals (M 3.75-4.75)
Adjusted Residuals (M>=4.75)
ln(Observed/Predicted)
4
3
2
1
0
-1
-2
-3
-4
1
10
100
1000
JB Distance (km)



Residuals for Investigated Sites - Model: C2, Freq (Hz): 5; Vs30(min): 500
Un-adjusted Residuals (M 3.75-4.75)
Un-adjusted Residuals (M>=4.75)
Adjusted Residuals (M 3.75-4.75)
Adjusted Residuals (M>=4.75)
ln(Observed/Predicted)
JB Distance (km)
4
3
2
1
0
-1
-2
-3
-4
1
10
100
1000



Residuals for Investigated Sites - Model: C3, Freq (Hz): 5; Vs30(min): 500
Un-adjusted Residuals (M 3.75-4.75)
Un-adjusted Residuals (M>=4.75)
Adjusted Residuals (M 3.75-4.75)
Adjusted Residuals (M>=4.75)
ln(Observed/Predicted)
4
3
2
1
0
-1
-2
-3
-4
1
10
100
1000
JB Distance (km)

# EPRI (2004) Residuals Using Empirically Adjusted Data

Bob Youngs

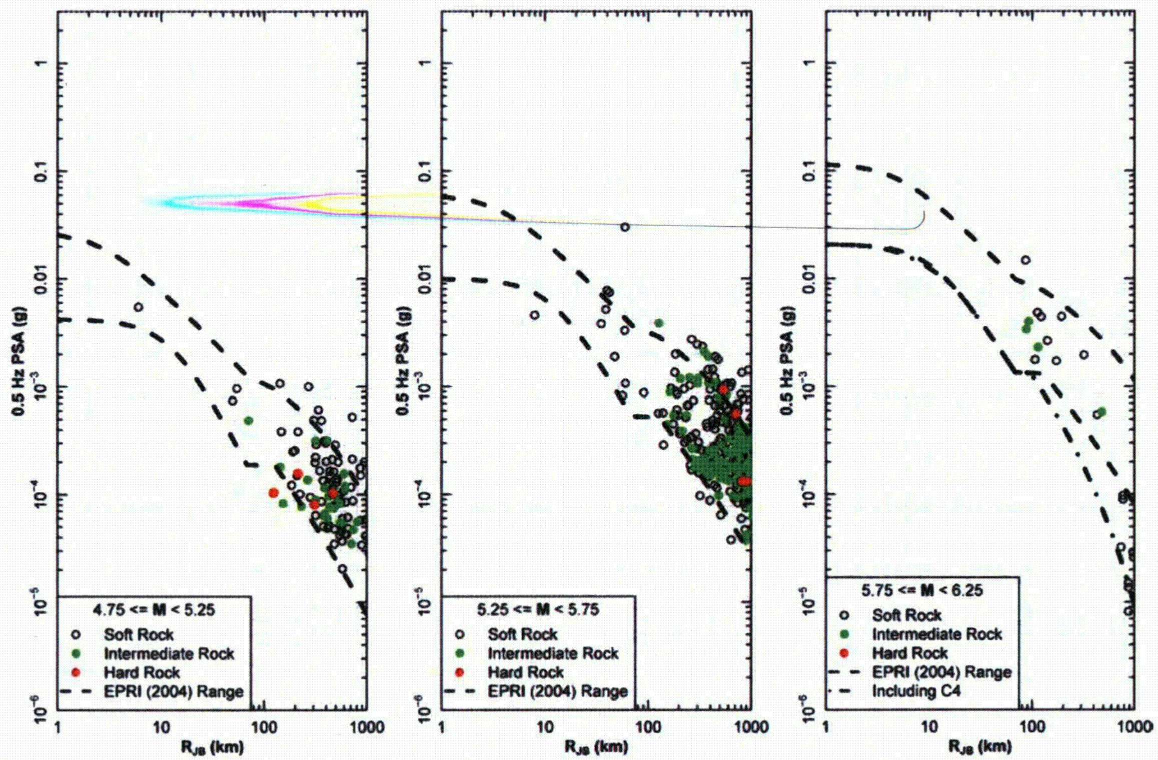
# Comparisons with EPRI (2004) GMPEs

- Comparison of unscaled ground motion data with range of predictions for EPRI (2004) GMPEs
- Calculate scaling factors using Model 2
- Scale ground motion data using the average of the scaling factors for EPRI  Revisions to database

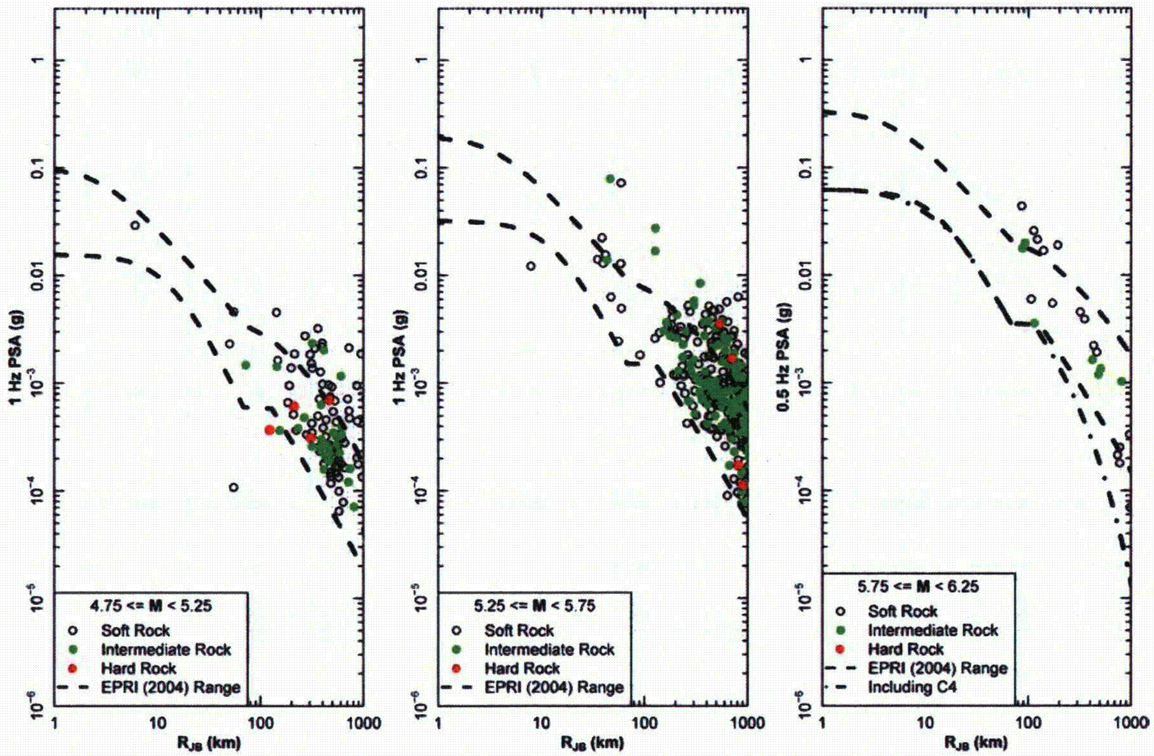
$$PSA_{ij}^{scaled} = PSA_{ij} \times \exp\left\{-\overline{C}_{IR} F_{jk}^{IR} - \overline{C}_{SR} F_{jk}^{SR}\right\}$$

- Comparison of scaled ground motion data with range of predictions for EPRI (2004) GMPEs

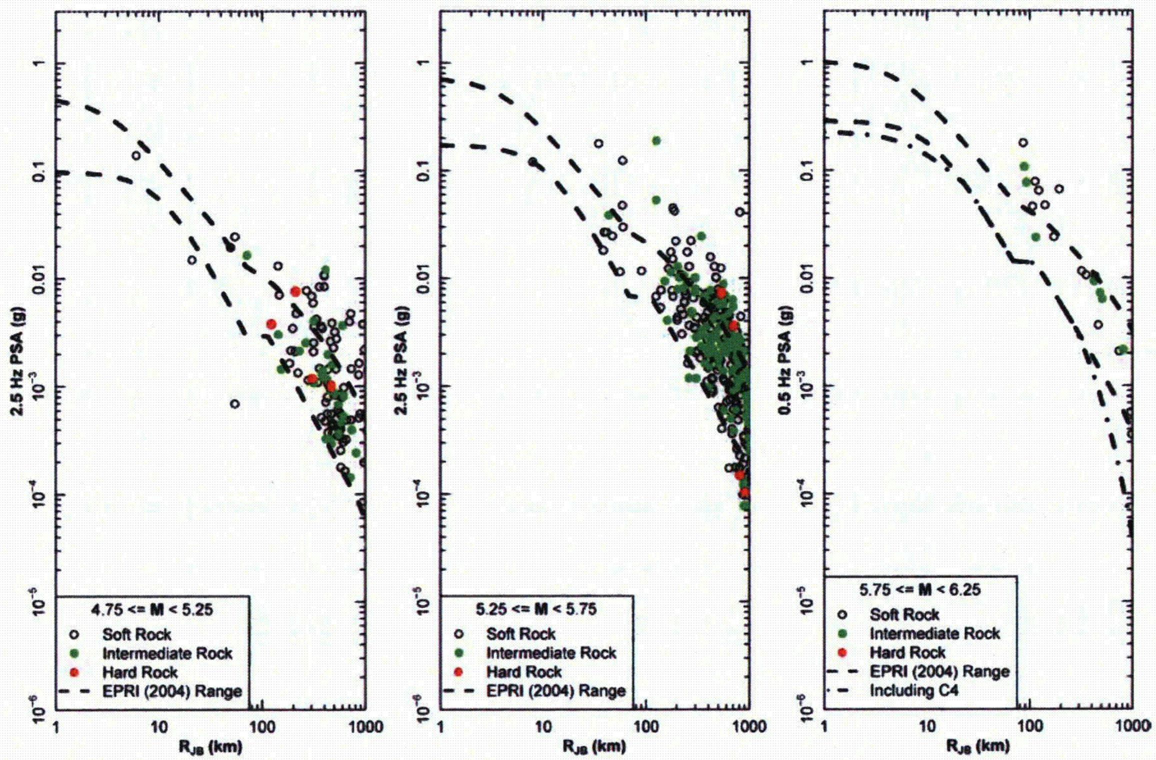
# Unscaled 0.5 Hz Data



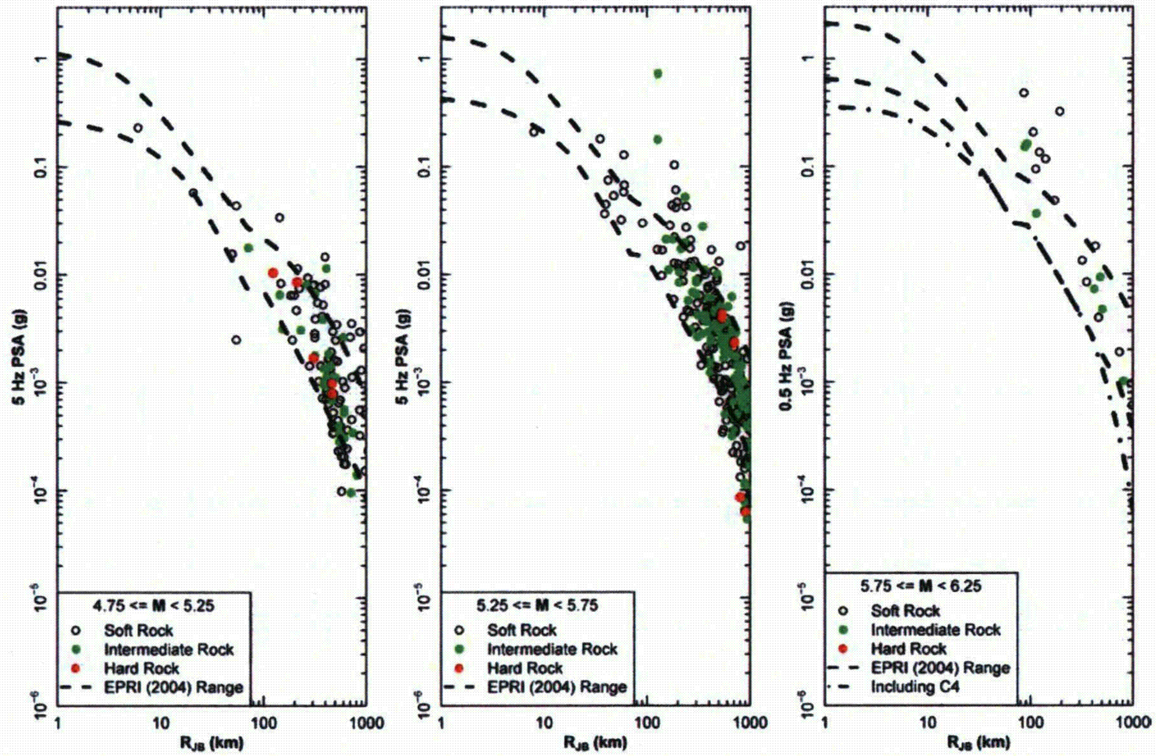
# Unscaled 1 Hz Data



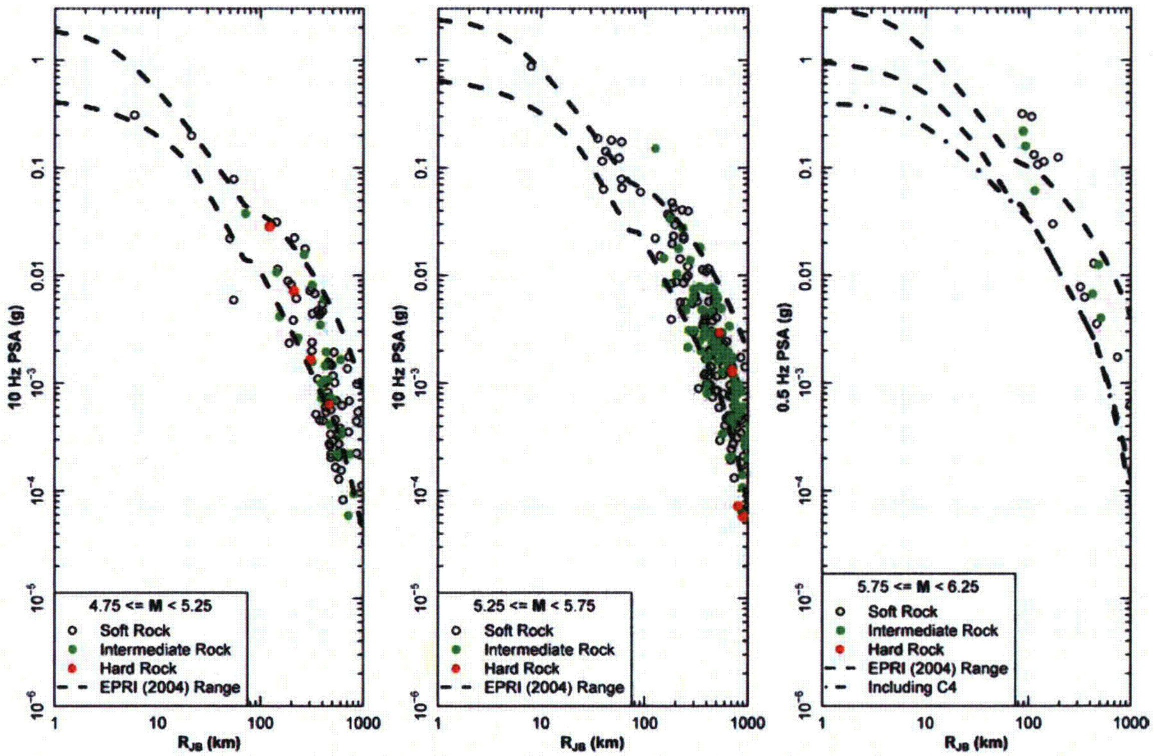
# Unscaled 2.5 Hz Data



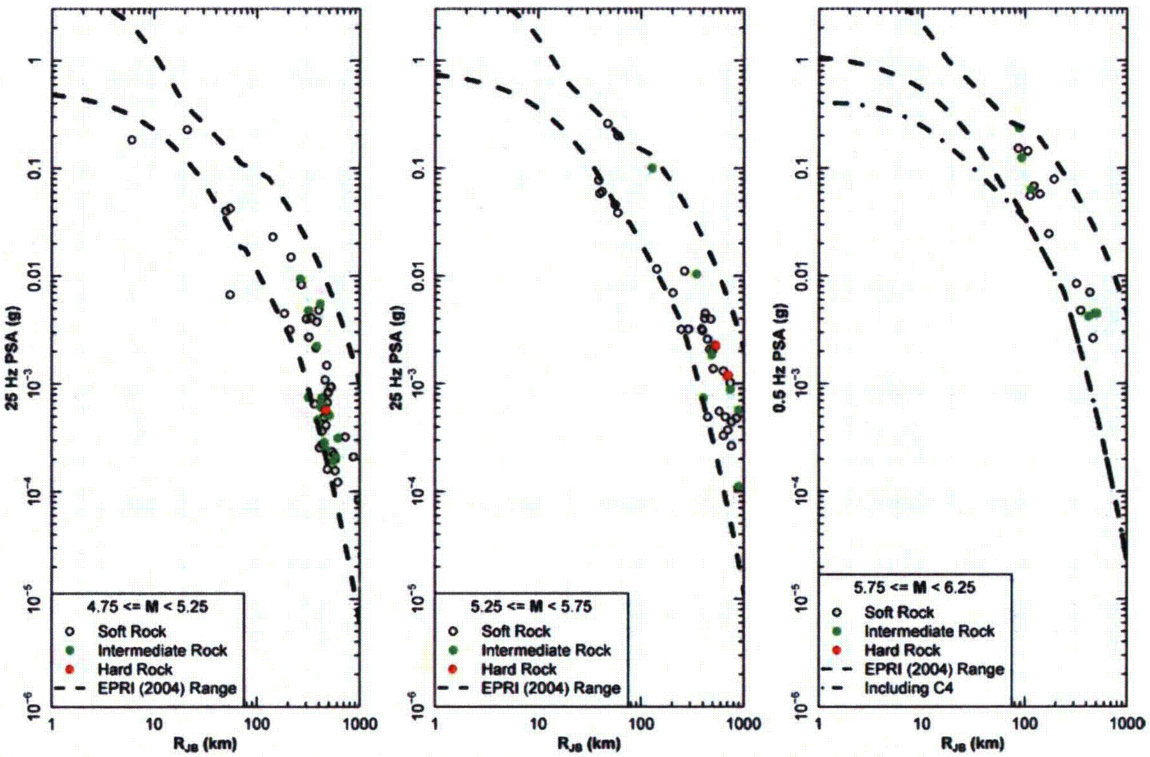
# Unscaled 5 Hz Data



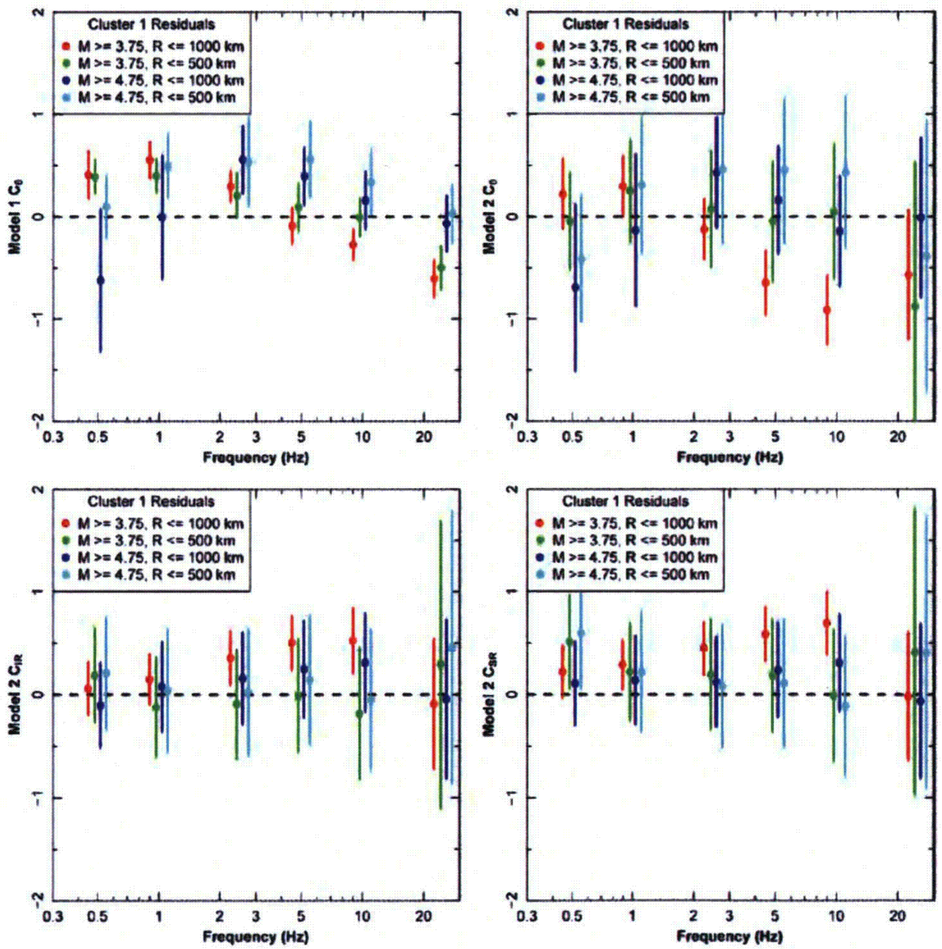
# Unscaled 10 Hz Data



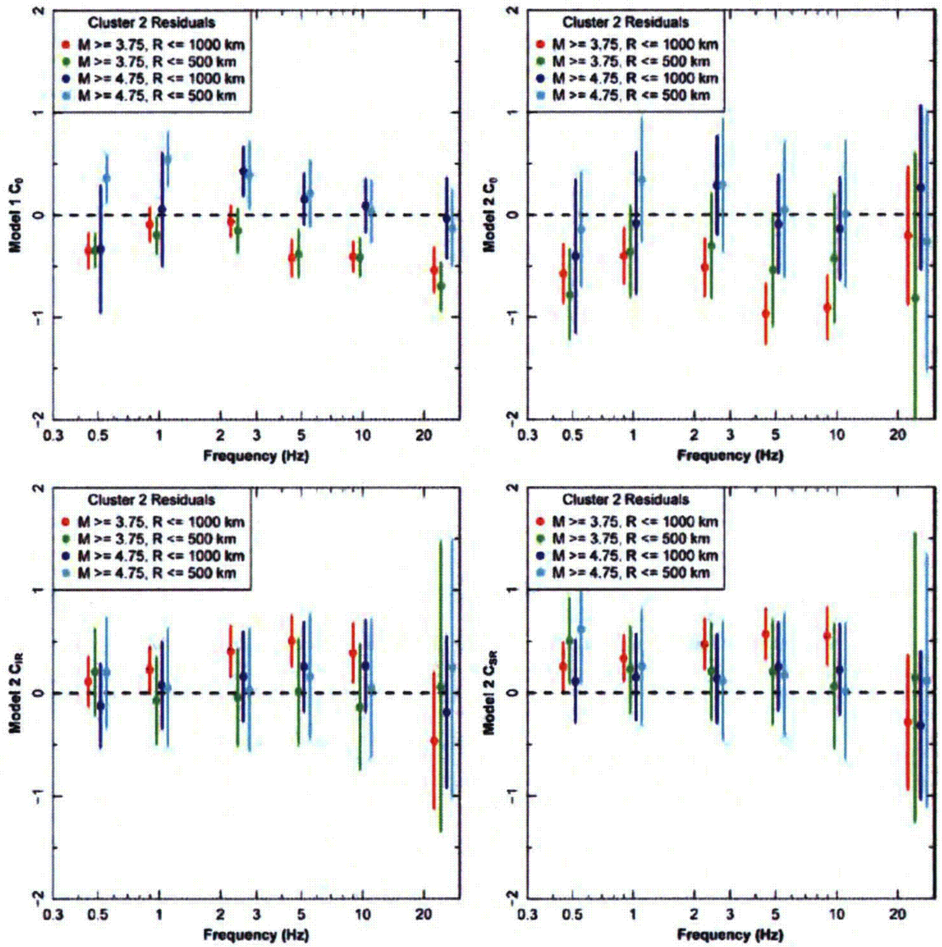
# Unscaled 25 Hz Data



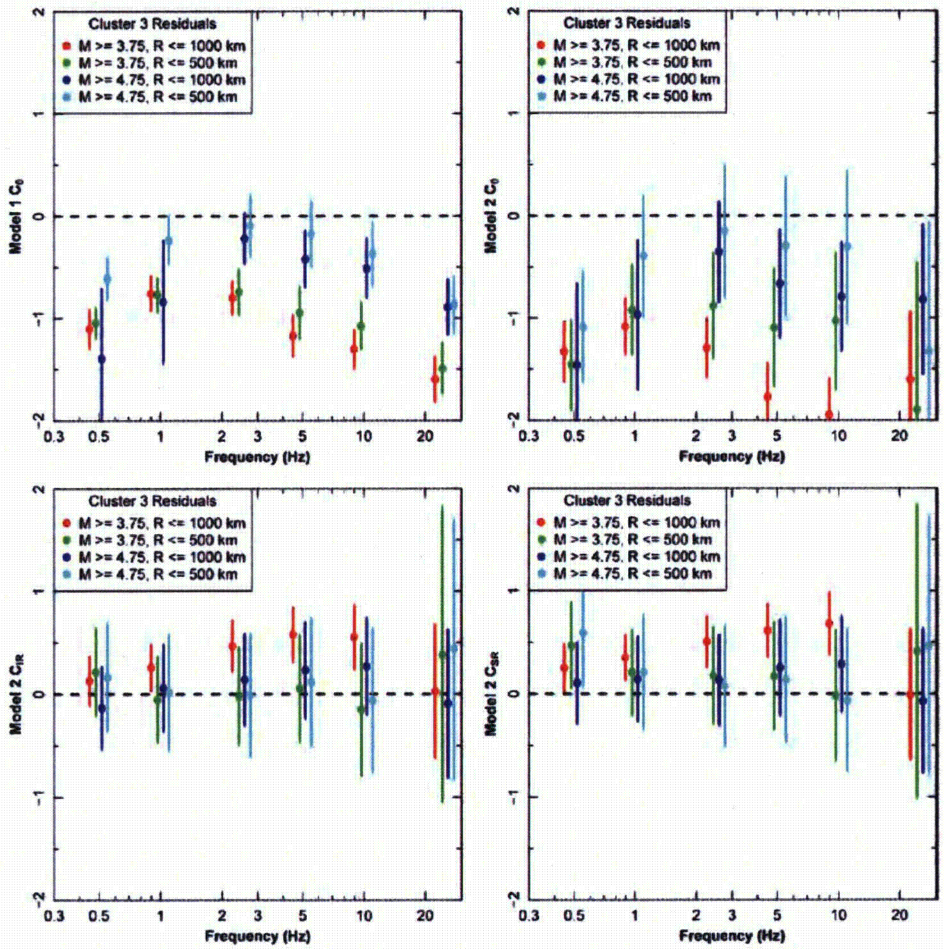
# Site Category Coefficients for EPRI (2004) Cluster 1 GMPE Using Initial Database



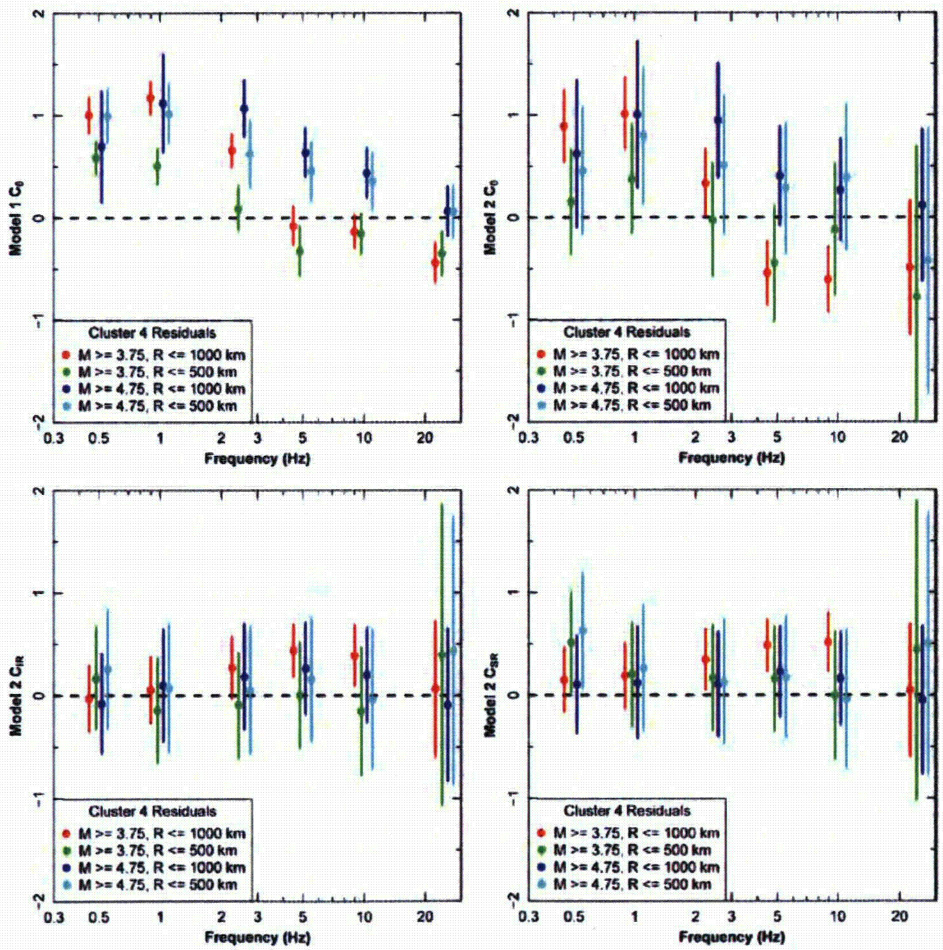
# Site Category Coefficients for EPRI (2004) Cluster 2 GMPE Using Initial Database



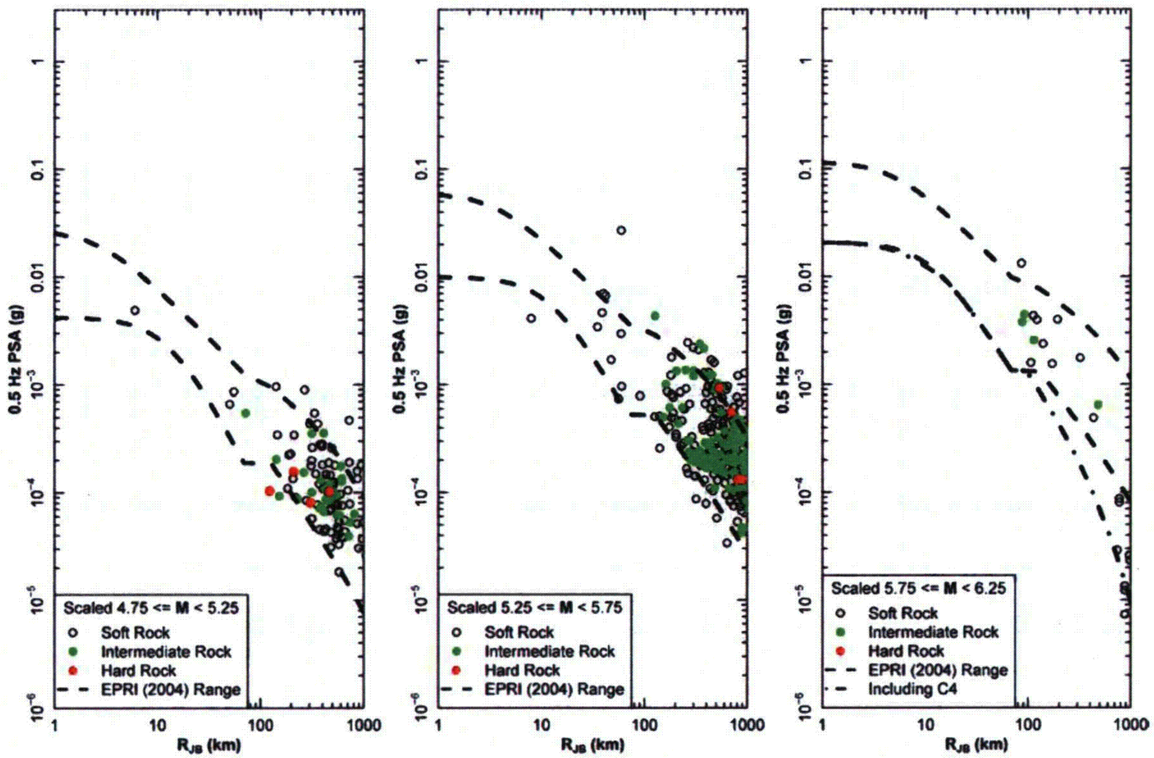
# Site Category Coefficients for EPRI (2004) Cluster 3 GMPE Using Initial Database



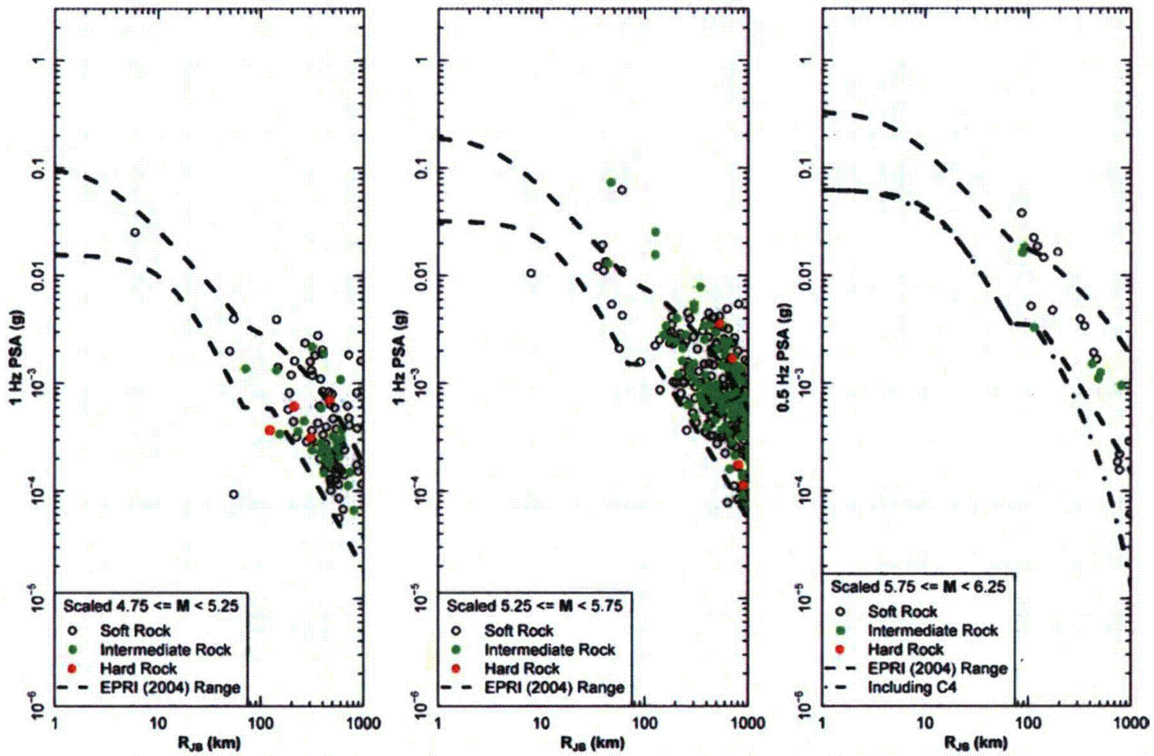
# Site Category Coefficients for EPRI (2004) Cluster 4 GMPE Using Initial Database



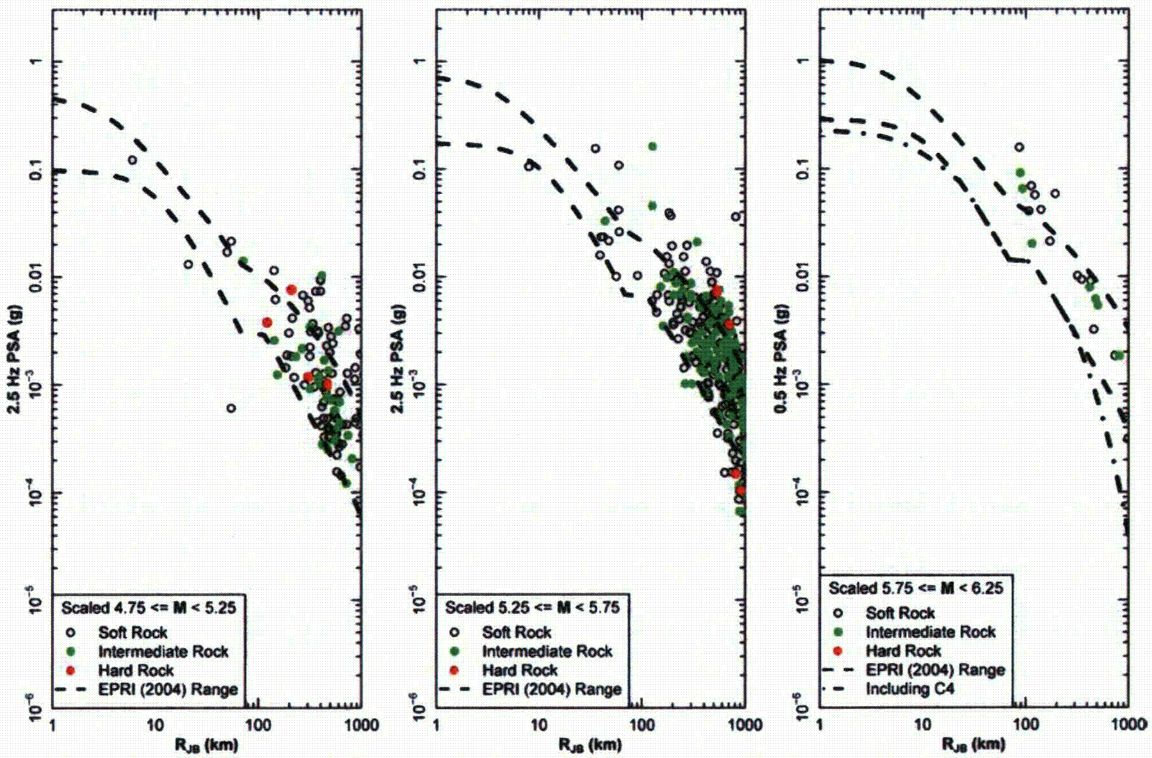
# Scaled 0.5 Hz Data



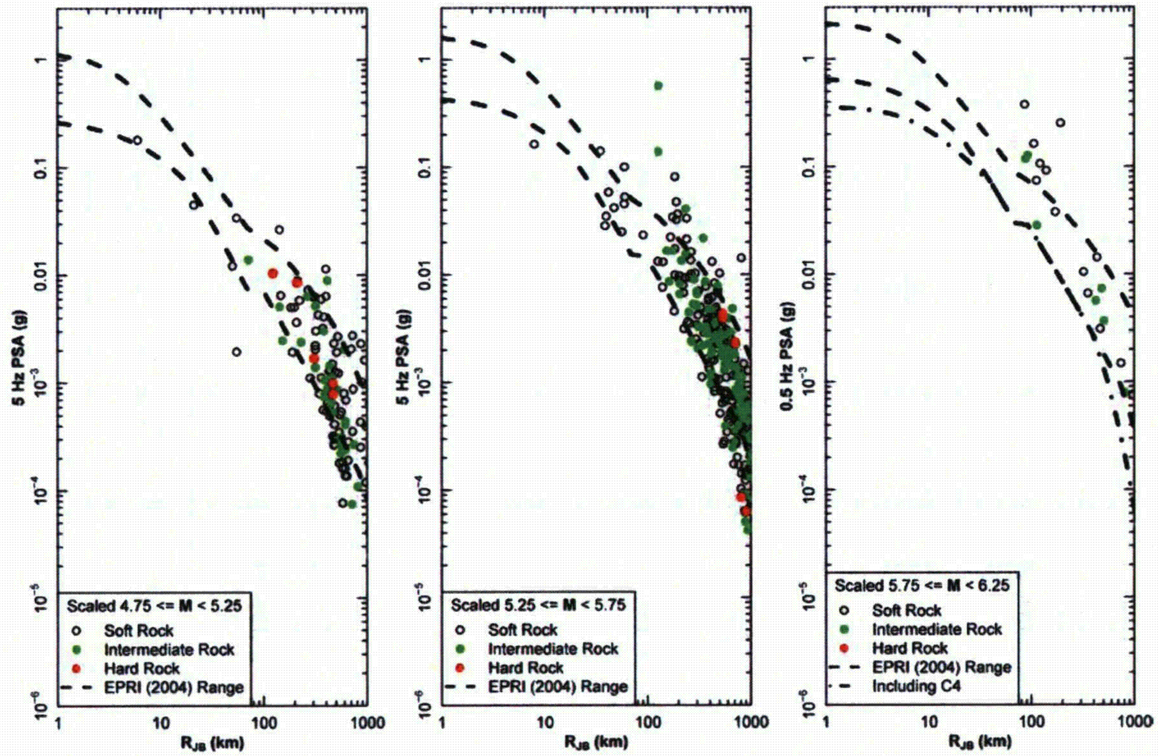
# Scaled 1 Hz Data



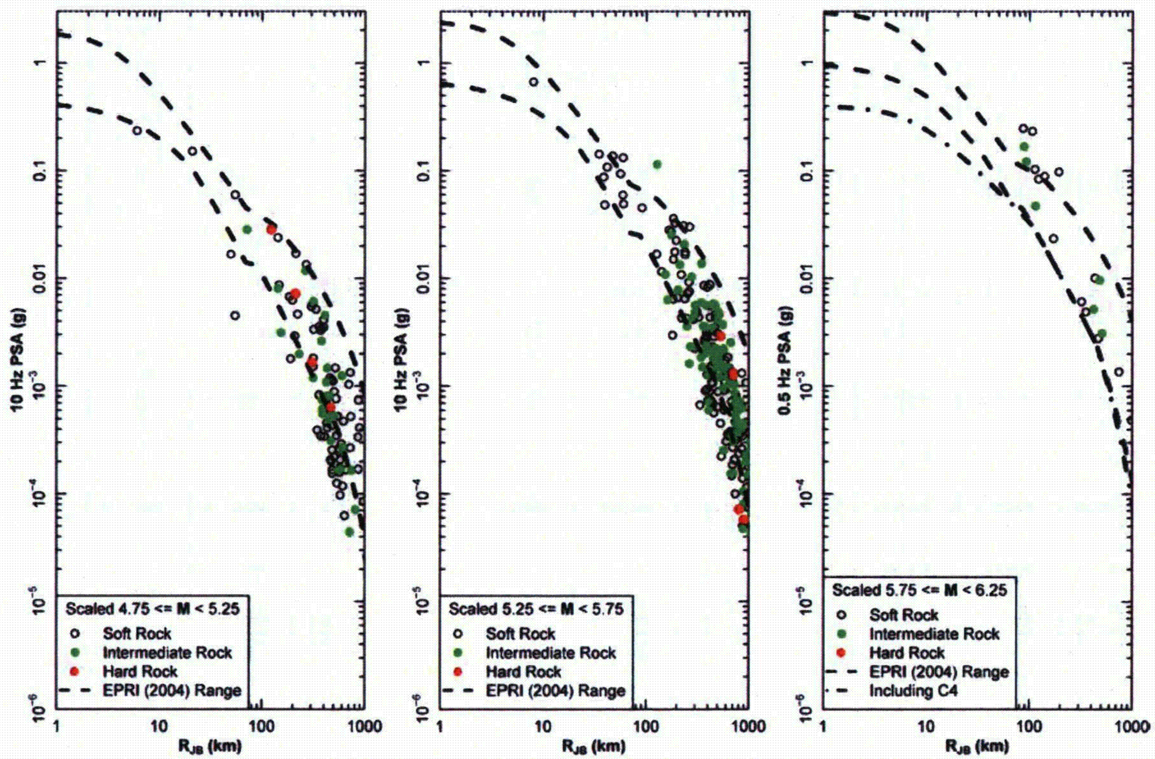
# Scaled 2.5 Hz Data



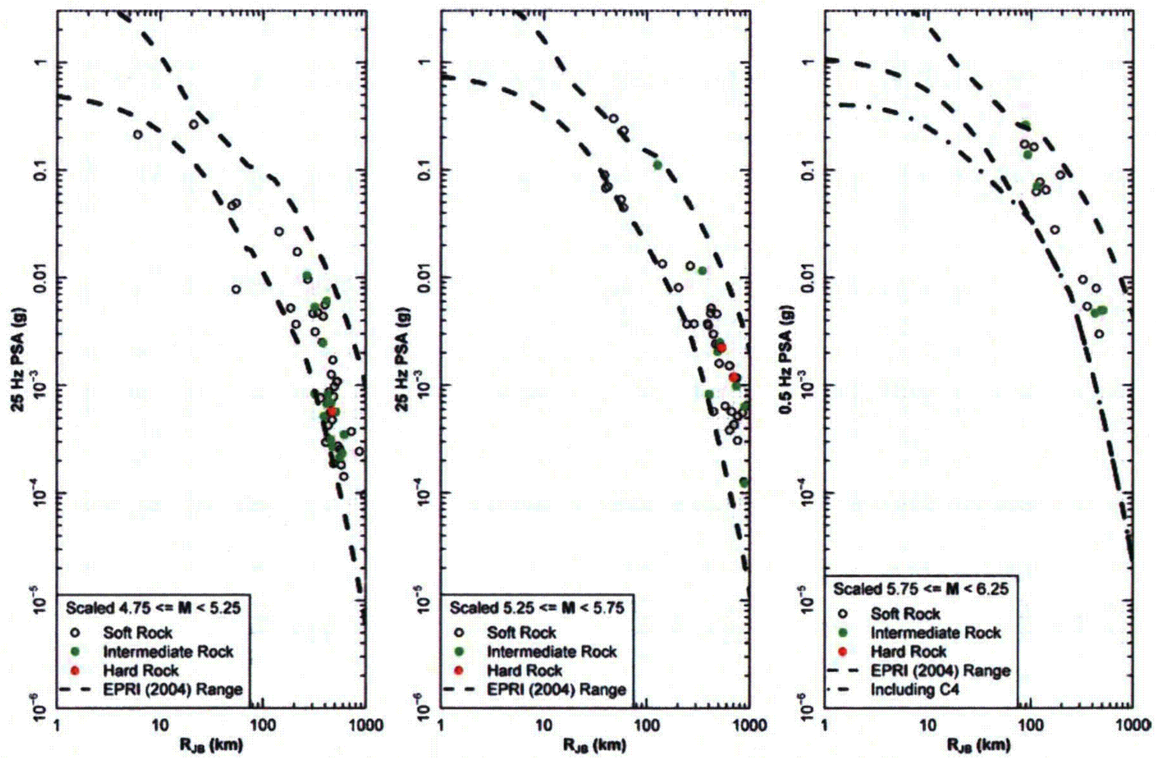
# Scaled 5 Hz Data



# Scaled 10 Hz Data



# Scaled 25 Hz Data



# Summary

- Ground motion data generally fall within range predicted by EPRI (2004) GMPEs
- EPRI (2004) GMPEs capture most of data
  - Range for 2004 GMPEs developed to capture range in ***median*** motions
  - Range for 2004 GMPEs also capturing large portion of aleatory variability, thus perhaps too large

# Phase 1 Conclusions & Phase 2 Update Process

Gabriel Toro

# Rationale for Recommendation to Update

- Seven (7) of the thirteen (13) developers of the ground motion prediction equations (GMPEs) used in the EPRI (2004, 2006) GMM recommended that their GMPEs be replaced.
- There are three new GMPEs developed by ground motion experts during the past ten (10) years.
- Eighty percent (80%) of the earthquake records in a new ground motion database are from earthquakes that occurred after the development of the EPRI (2004) GMM.
- The EPRI (2004, 2006) GMM over-predicts ground motions at some magnitude-distance-frequency ranges important to nuclear power plant (NPP) probabilistic seismic hazard assessments (PSHAs).

# Phase 2 – Approach for Update

a. Use EPRI (2004) approach of grouping candidate models into clusters
b. Assess residuals of candidate models using NGA-East database
   – Use analytical adjustment
   – Use empirical adjustment
c. Develop within-cluster weights using computed residuals
d. Generate 3 GMPEs per cluster to represent within-cluster epistemic uncertainty
e. Develop cluster weights using fit to data and other considerations
f. Modify for Gulf Coast conditions using new zone and and Q model
g. Update EPRI (2006) aleatory variability model using final version of NGA (2008) and preliminary results from NGA-West2

# Updating of EPRI (2004) Clusters

| Cluster | Model Type | Models | |
|---|---|---|---|
| 1 | Single Corner Stochastic (0.275/0.351) | ~~Hwang and Huo (1997)~~<br>~~Silva et al (2002) - SC-CS~~<br>Silva et al (2002) - SC-CS-Sat<br>Silva et al (2002) - SC-VS<br>Toro et al (1997)<br>Frankel et al (1996) | |
| 2 | Double Corner Stochastic (0.312/0.399) | ~~Atkinson and Boore (1995)~~<br>~~Silva et al (2002) DC~~<br>Silva et al (2002) DC - Sat | ←AB06' ? |
| 3 | Hybrid (0.196/0.250) | ~~Abrahamon & Silva (2002)~~<br>~~Atkinson (2001) & Sadigh et al (1997)~~<br>~~Campbell (2003)~~ | ←PZT11 ?<br>←A08' ? |
| 4 | Finite Source /Greens Function (0.217/0.000) | Somerville et al. (2001) | |

# Re-Definition of Clusters 2 and 3

**Background**: EPRI-04 clusters 2 and 3 were based on approach (2-corner stochastic vs. hybrid), but some new models did not fit very well (i.e., AB06' spectrum does not have 2 corners; A08' is not a hybrid model in the traditional sense)

**Practical Motivation**: very large within-cluster differences at ~50-100 km

→difficult in in generating high and low GMPEs ($\pm$1.64 $\sigma_{epistemic}$) for clusters

# New GMPE Clusters

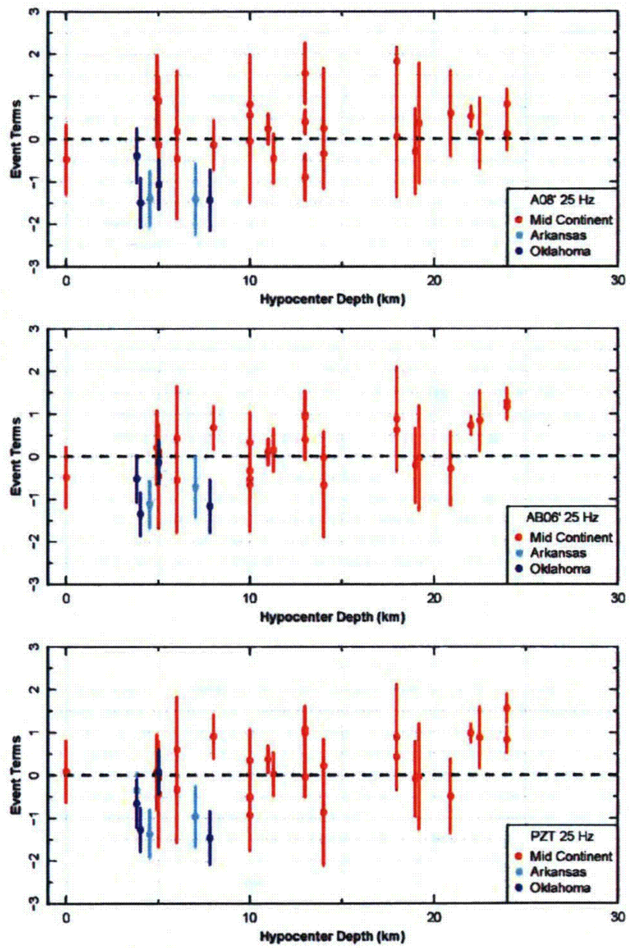
| Cluster | Model Type | Models |
|---|---|---|
| 1 | Single Corner Brune Source | Silva et al (2002) - SC-CS-Sat*<br>Silva et al (2002) - SC-VS*<br>Toro et al (1997)<br>Frankel et al (1996)<br>* Treated as one model for calculation of weights |
| 2 | Complex/Empirical Source<br>~$R^{-1}$ Geometrical spreading < 70 km | Silva et al (2002) DC – Sat<br>A08' |
| 3 | Complex/Empirical Source<br>~$R^{-1.3}$ Geometrical spreading < 70 km | AB06'<br>PZT11 |
| 4 | Finite Source /Green's Function | Somerville et al. (2001); slightly different models for rifted and non-rifted |

# Treatment of Earthquakes in Oklahoma and Arkansas

Bob Youngs

# Results of Arkansas-Oklahoma Tests

- Event terms for AR/OK earthquakes consistently lower at 25 Hz and 10 Hz, but not at lower frequencies
- Difference statistically significant at 25 Hz, marginally significant at 10 Hz
- Modeling a linear trend with depth has mixed results across GMPEs



# Conclusion from AR/OK Tests

- Lower motions observed primarily for 25 Hz and possibly for 10 Hz
- Factors that may cause observations
  - Lower stress drops than average for CENA
  - Higher site kappa than average for CENA rock sites
  - Lower motions because of shallower than average depth
- Definitive choice of reason not possible with existing data. Therefore, compute GMPE weights for two cases, with and without AR/OK earthquake data

# Approach for Calculation of Within-Cluster Weights

Gabriel Toro

# Requirements

Weights must account for:

- Inter-event correlation
- Uncertainty in the soil correction (correlated)
- Weights that depend on magnitude and distance, to account for the engineering importance and diagnostic power of data in the various M-R ranges.
- Sensitivity to sample size

# Approach for Within-Cluster Weights

- Based on approach developed by Scherbaum and co-workers, but includes correlations and weights
- Use covariance matrix takes into account correlation (similar to random-effects formulation)

$$w_i = \frac{L(\boldsymbol{\varepsilon}_i)}{\sum_i L(\boldsymbol{\varepsilon}_i)} \qquad L(\boldsymbol{\varepsilon}_i) = \exp\left(-\frac{1}{2}\boldsymbol{\varepsilon}_i^{\,T}\boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}^{-1}\boldsymbol{\varepsilon}_i\right)$$

- More flexible and less ad-hoc than EPRI (2004) approach, but similar in spirit

# Building the Covariance Matrix

$$Cov\left[\varepsilon_{ijk}, \varepsilon_{ij'k'}\right] = \tau^2 \delta_{jj'} + \phi^2 \delta_{jj'} \delta_{kk'} + \sigma_{C,jk} \sigma_{C,j'k'} \delta_{kk'}$$

- First term: $\tau^2$ if both residuals are associated with the same earthquake and zero otherwise
- Second term: $\varphi^2$ between a residual and itself (same earthquake, same station)
- Third term: $\sigma_{C,jk}\sigma_{C,j'k'}$ if both residuals are associated with recordings at the same station and zero otherwise.

Note: tau and phi taken from aleatory variability model described later

# Calculation of Within-Cluster weights: Implementation

4 levels of aggregation to obtain weights:

- M-R ranges (according to importance)*
- Frequencies (25 Hz to 0.5 Hz, PGA not used)*
  - High frequency (25, 10, and 5 Hz)
  - Low frequency (2.5, 1, and 0.5 Hz)
- Approaches for site adjustment (analytical vs. empirical)+
- With and without records from OK-AR earthquakes+

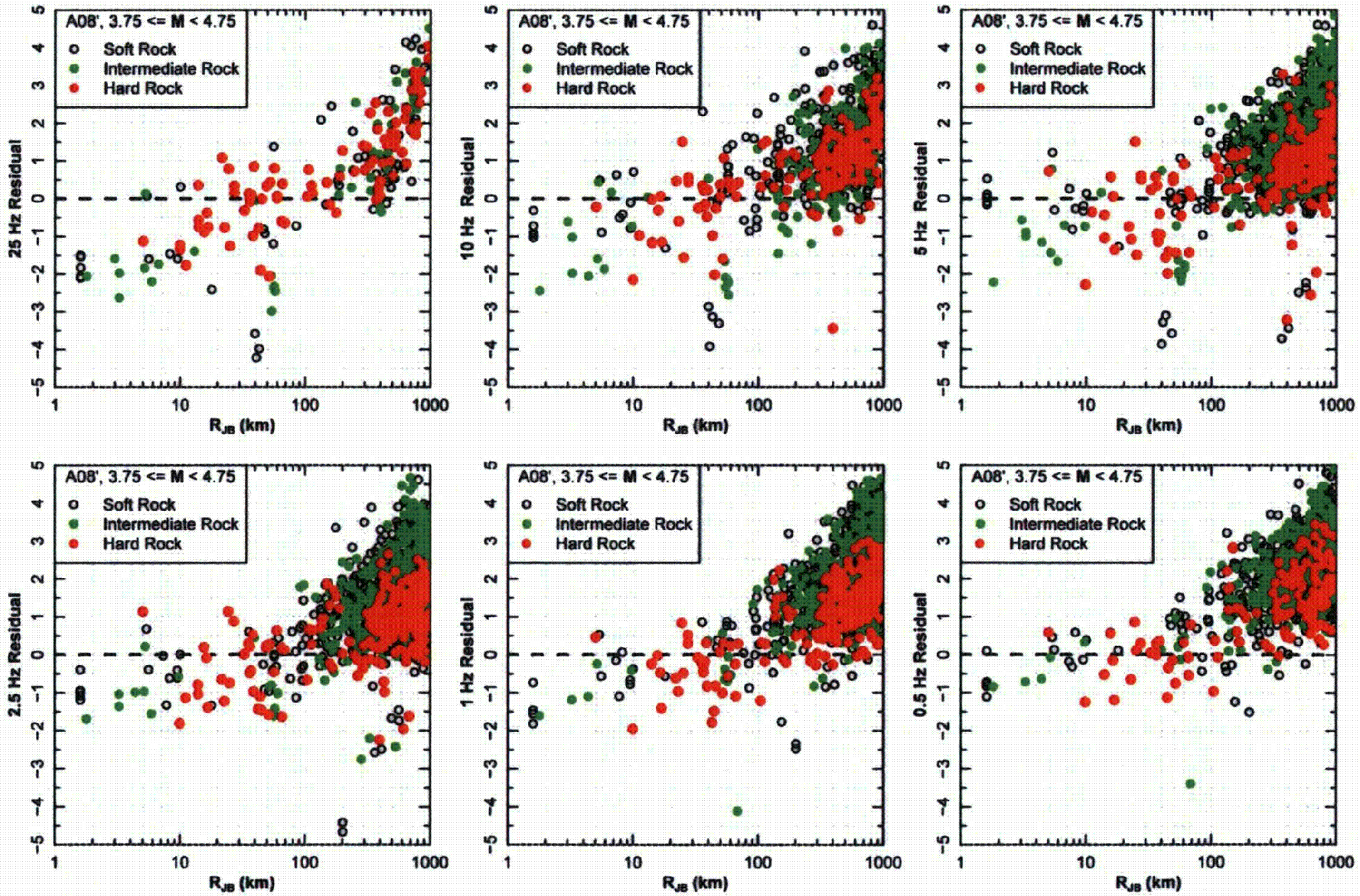
# Empirically Derived Within-Cluster Residuals

## Bob Youngs

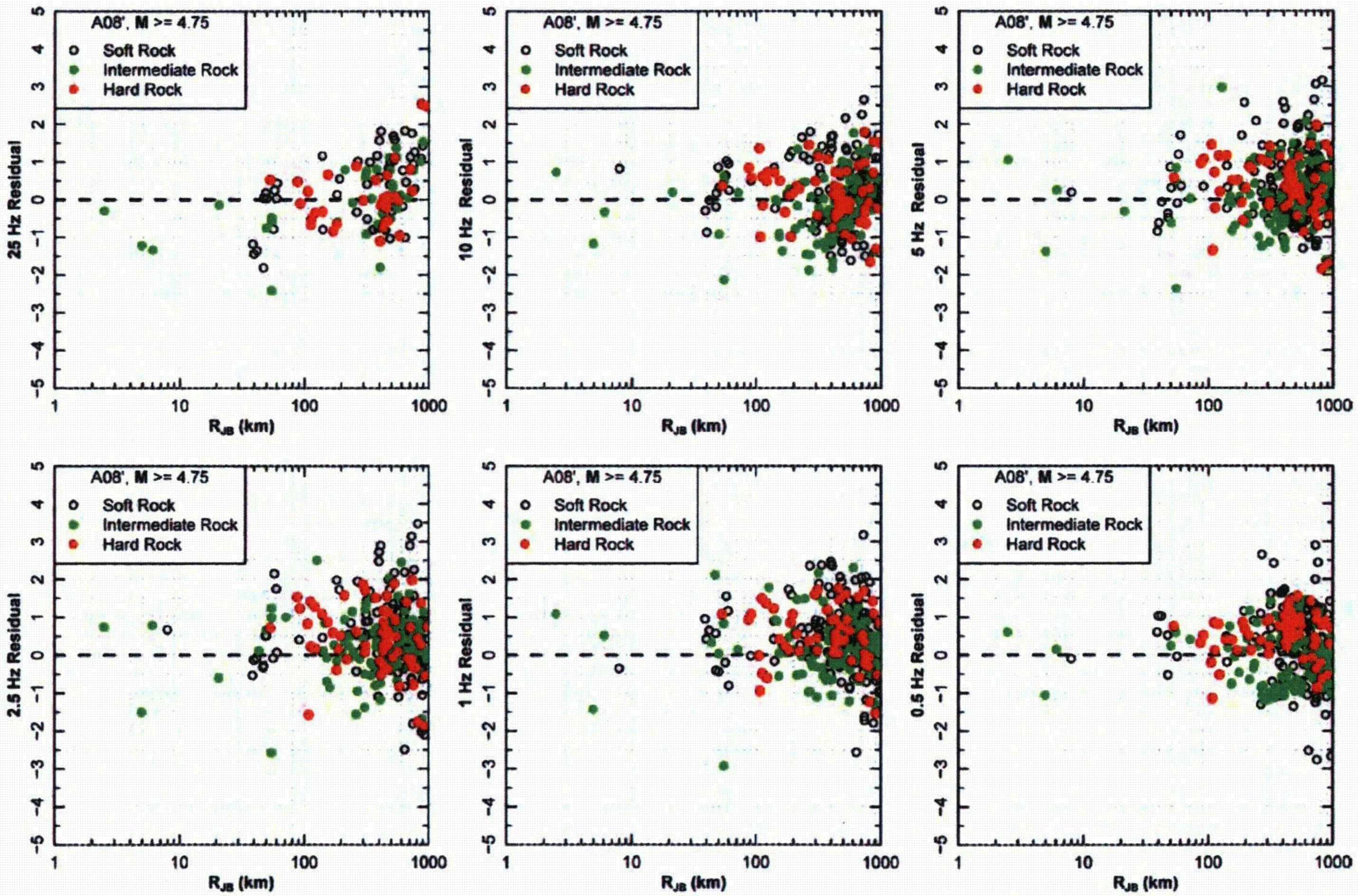
# Computation of Model Weights Based on Empirical Site Corrections

- Compute residuals from strong motion database using candidate GMPEs
- Fit residuals using Model 3, scaling for only soft rock sites, $C_{SR}$
- Compute likelihood function using scaled residuals
  - Use standard error in estimating $C_{SR}$ for site correction standard deviation in variance matrix

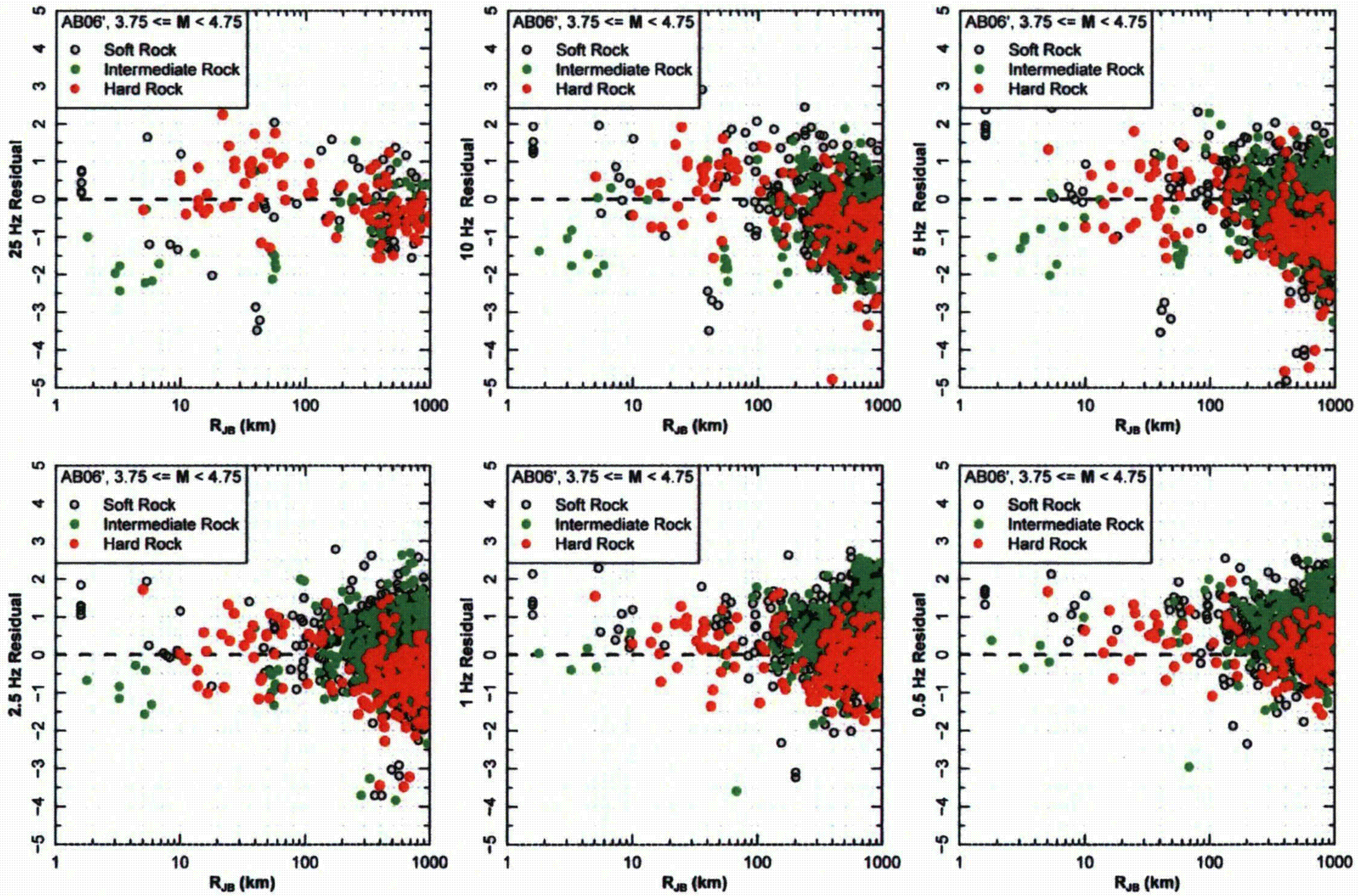
# A08’ Residuals for $3.75 \leq \mathbf{M} < 4.75$



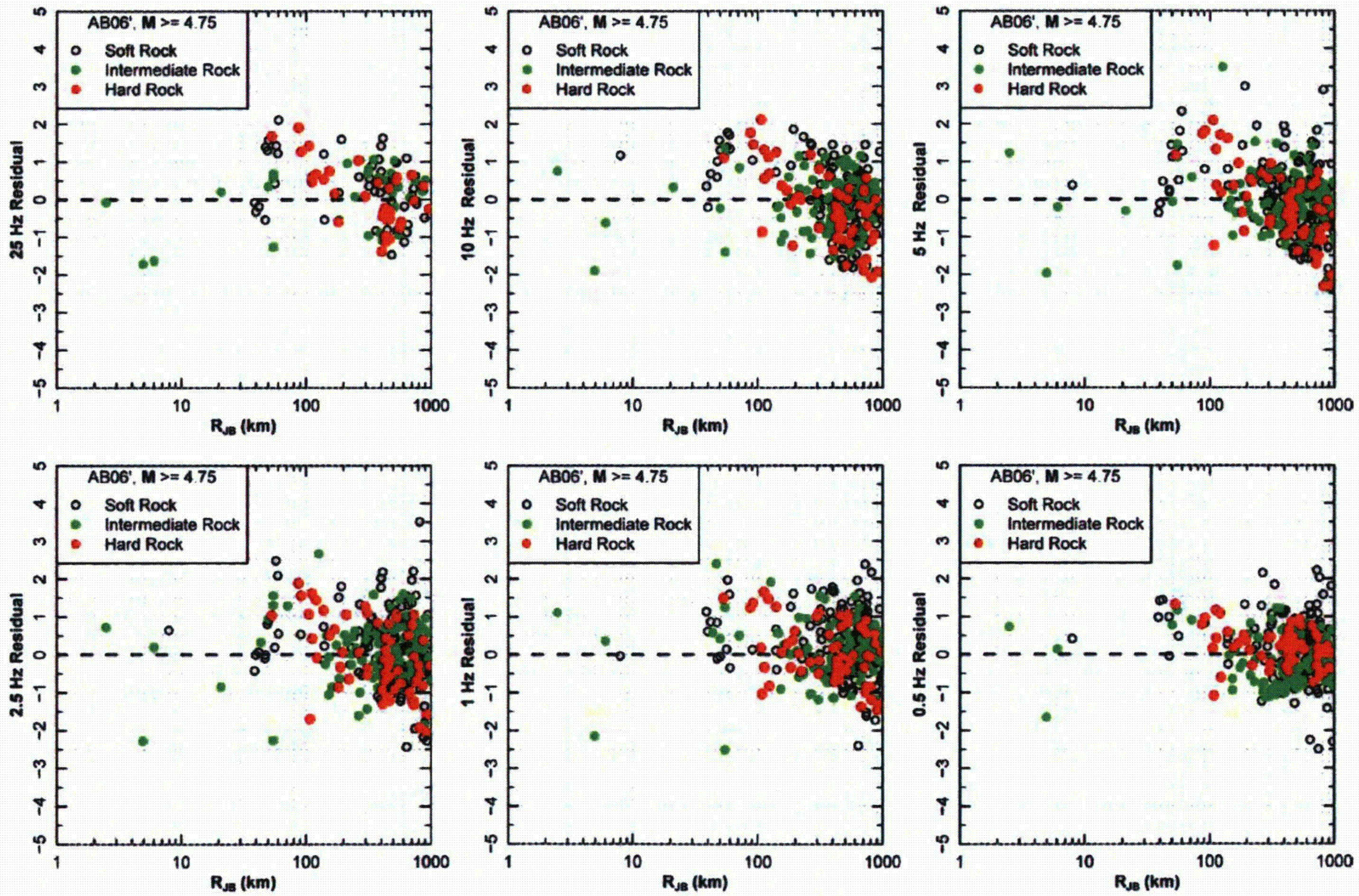
# A08’ Residuals for **M** ≥ 4.75



# AB06’ Residuals for 3.75 ≤ **M** < 4.75

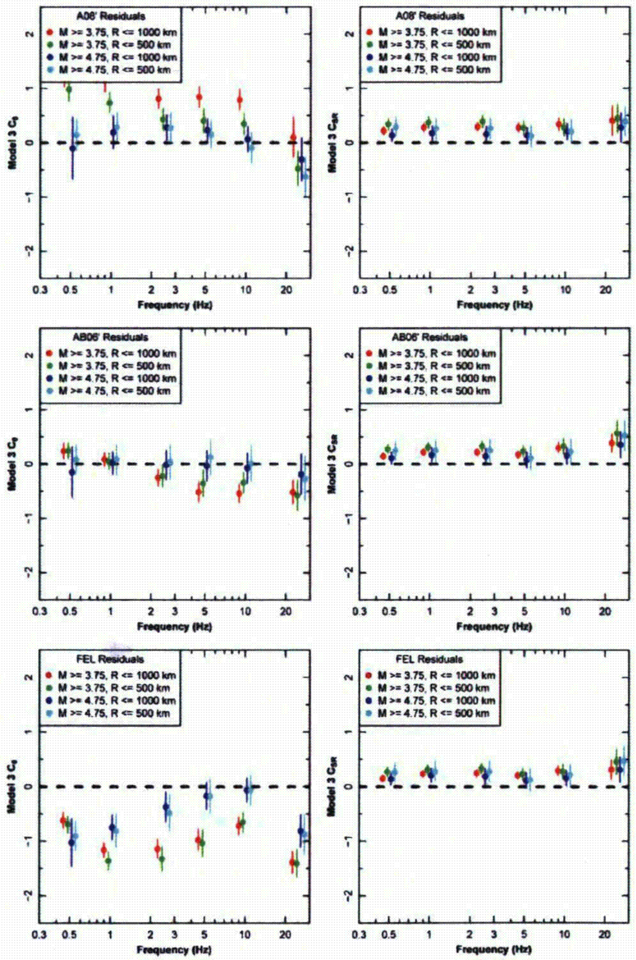


# AB06’ Residuals for **M** ≥ 4.75

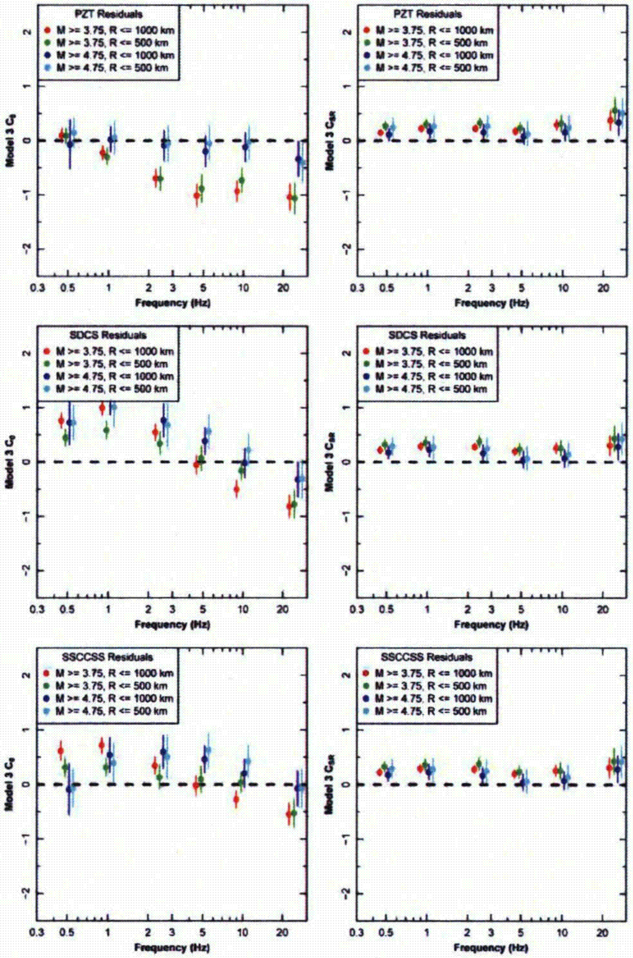


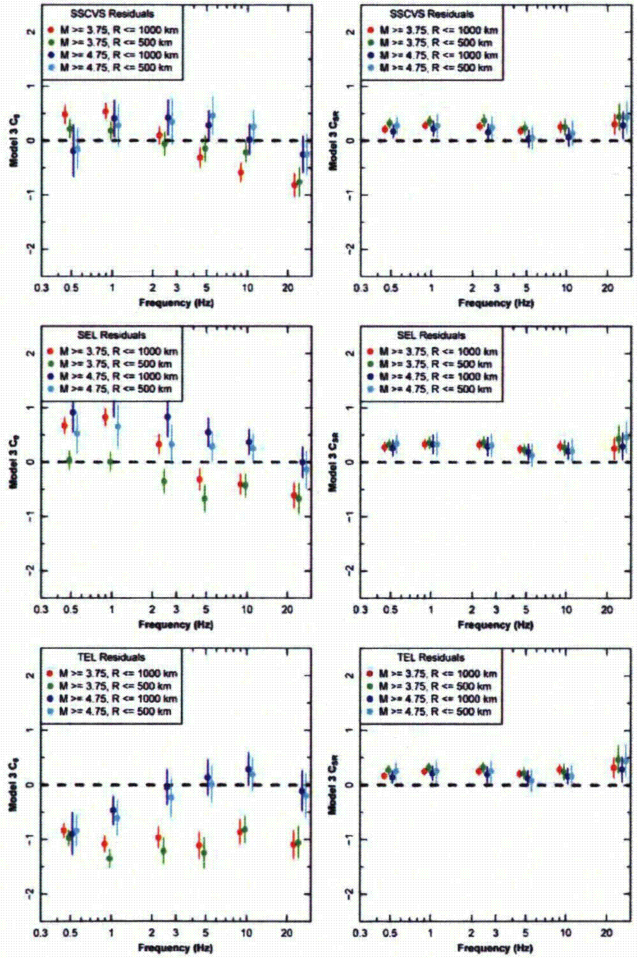
# Fit Residuals with Model 3

- Fit residuals for each candidate GMPE separately using Model 3
- Use $C_{SR}$ from fit for **M** ≥ 4.75, R ≤ 500 km data for computing scaled residuals



# Fit Residuals with Model 3 (cont'd)



# Calculation of Within-Cluster Weights

## Gabriel Toro

# Importance Factors (Weights) for Magnitude-Distance Bins

| | **M** 3.75 to 4.75* | **M** 4.75 and greater |
|---|---|---|
| Rjb 0 to 70 km | 1/ 4 (1/4) | **1 (1)** |
| Rjb 70 to 150 km | 1/12 (1/4) | 1/3 (1) |
| Rjb 150 to 500 km | 1/24 (1/4 ) | 1/6 (1) |

Importance Factor for High Frequencies

Importance Factor for Low Frequencies

* Using 0 weight for M 3.75 to 4.75 causes small changes in results

# Weights for Cluster 1: 10 Hz (analytical, incl. OK-AR)

| Mmin | Mmax | Rmin | Rmax | Equiv. Sample Size | Importance Factor | Exponent | SSCCSS | SSCVS | TEL | FEL |
|---|---|---|---|---|---|---|---|---|---|---|
| 3.75 | 4.75 | 0.1 | 70 | 11.92 | 0.2500 | 0.1010 | 0.9936 | 0.7549 | 0.2663 | 0.4091 |
| 3.75 | 4.75 | 70 | 150 | 7.437 | 0.0833 | 0.0540 | 0.8672 | 0.9450 | 0.9218 | 0.9460 |
| 3.75 | 4.75 | 150 | 500 | 31.04 | 0.0417 | 0.0065 | 1.0000 | 0.9611 | 0.7296 | 0.8919 |
| 4.75 | - | 0.1 | 70 | 4.815 | 1.0000 | 1.0000 | 0.3332 | 0.2945 | 0.1665 | 0.2058 |
| 4.75 | - | 70 | 150 | 3.554 | 0.3333 | 0.3333 | 0.3957 | 0.4910 | 0.6802 | 0.7963 |
| 4.75 | - | 150 | 500 | 8.936 | 0.1667 | 0.0898 | 0.7466 | 0.8430 | 0.9516 | 0.8785 |
| | | | | | | Raw | 0.0424 | 0.0418 | 0.0193 | 0.0497 |
| | | | | | | **Normalized** | **0.2769** | **0.2727** | **0.1260** | **0.3244** |

# Combination of Weights for Cluster 1 (with OK-AR)

| | Analytical Site Adjustments | | | | Empirical Site Adjustments | | | |
|---|---|---|---|---|---|---|---|---|
| | SSCCSS | SSCVS | TEL | FEL | SSCCSS | SSCVS | TEL | FEL |
| **25 Hz** | 0.60 | 0.27 | 0.11 | 0.02 | 0.89 | 0.10 | 0.01 | 0.00 |
| **10 Hz** | 0.28 | 0.27 | 0.13 | 0.32 | 0.05 | 0.08 | 0.05 | 0.81 |
| **5 Hz** | 0.61 | 0.34 | 0.00 | 0.04 | 0.38 | 0.41 | 0.00 | 0.21 |
| **Combined HF** | **0.61** | **0.33** | **0.02** | **0.04** | **0.66** | **0.32** | **0.00** | **0.01** |
| **Comb. HF Analytical + Empirical** | **0.64** | **0.32** | **0.01** | **0.03** | | | | |
| | | | | | | | | |
| **2.5 Hz** | 0.30 | 0.68 | 0.01 | 0.00 | 0.04 | 0.96 | 0.00 | 0.00 |
| **1 Hz** | 0.43 | 0.57 | 0.00 | 0.00 | 0.09 | 0.91 | 0.00 | 0.00 |
| **0.5 Hz** | 0.43 | 0.51 | 0.01 | 0.05 | 0.41 | 0.59 | 0.00 | 0.00 |
| **Combined LF** | **0.36** | **0.64** | **0.00** | **0.00** | **0.07** | **0.93** | **0.00** | **0.00** |
| **Comb. LF Analytical + Empirical** | **0.22** | **0.78** | **0.00** | **0.00** | | | | |

# Combination of Weights for Cluster 1 (with and without OK-AR)

| | SSCCSS | SSCVS | TEL | FEL |
|---|---|---|---|---|
| **HF with** | 0.64 | 0.32 | 0.01 | 0.03 |
| **HF without** | 0.26 | 0.24 | 0.20 | 0.31 |
| **HF Combined** | 0.45 | 0.28 | 0.11 | 0.17 |
| | | | | |
| **LF with** | 0.22 | 0.78 | 0.00 | 0.00 |
| **LF without** | 0.27 | 0.73 | 0.00 | 0.00 |
| **LF Combined** | 0.24 | 0.76 | 0.00 | 0.00 |

# Weights for Cluster 3: 10 Hz (analytical, incl. OK-AR)

| Mmin | Mmax | Rmin | Rmax | Equiv. Sample Size | Importance Factor | exponent | AB06’ | PZT |
|---|---|---|---|---|---|---|---|---|
| 3.75 | 4.75 | 0 | 70 | 11.92 | 0.25 | 0.1010 | 0.9998 | 0.5246 |
| 3.75 | 4.75 | 70 | 150 | 7.44 | 0.08 | 0.0540 | 0.9768 | 0.9454 |
| 3.75 | 4.75 | 150 | 500 | 31.04 | 0.04 | 0.0065 | 1.0000 | 0.8375 |
| 4.75 | - | 0 | 70 | 4.81 | 1.00 | 1.0000 | 0.5071 | 0.4929 |
| 4.75 | - | 70 | 150 | 3.55 | 0.33 | 0.3333 | 0.7870 | 0.8003 |
| 4.75 | - | 150 | 500 | 8.94 | 0.17 | 0.0898 | 0.9494 | 0.9288 |
| | | | | | | Raw | 0.1850 | 0.0761 |
| | | | | | | **Normalized** | **0.7086** | **0.2914** |

# Combination of Weights for Cluster 3 (with OK-AR)

| | Analytical Site Adjustments | | Empirical Site Adjustments | |
|---|---|---|---|---|
| | AB06p | PZT | AB06p | PZT |
| **25 Hz** | 0.91 | 0.09 | 0.91 | 0.09 |
| **10 Hz** | 0.71 | 0.29 | 0.76 | 0.24 |
| **5 Hz** | 0.83 | 0.17 | 0.85 | 0.15 |
| **Combined HF** | **0.89** | **0.11** | **0.91** | **0.09** |
| **Comb. HF Analytical + Empirical** | **0.90** | **0.10** | | |
| | | | | |
| **2.5 Hz** | 0.79 | 0.21 | 1.00 | 0.00 |
| **1 Hz** | 0.49 | 0.51 | 0.38 | 0.62 |
| **0.5 Hz** | 0.60 | 0.40 | 0.53 | 0.47 |
| **Combined LF** | **0.68** | **0.32** | **0.90** | **0.10** |
| **Comb. LF Analytical + Empirical** | **0.79** | **0.21** | | |

# Combination of Weights for Cluster 1 (with and without OK-AR)

| | AB06p | PZT |
|---|---|---|
| **HF with** | 0.90 | 0.10 |
| **HF without** | 0.37 | 0.63 |
| **HF Combined** | 0.63 | 0.37 |
| | | |
| **LF with** | 0.79 | 0.21 |
| **LF without** | 0.70 | 0.30 |
| **LF Combined** | 0.75 | 0.25 |

# Combined Within-Cluster Weight

| Cluster | 1 | | | | 2 | | 3 | |
|---|---|---|---|---|---|---|---|---|
| GMPE | SSCCSS | SSCVS | TEL | FEL | A08' | SDCS | AB06p | PZT |
| HF Weight | 0.45 | 0.28 | 0.11 | 0.17 | 0.59 | 0.41 | 0.63 | 0.37 |
| LF Weight | 0.24 | 0.76 | 0.00 | 0.00 | 0.99 | 0.01 | 0.75 | 0.25 |

# Development of Cluster Median GMPEs

Bob Youngs

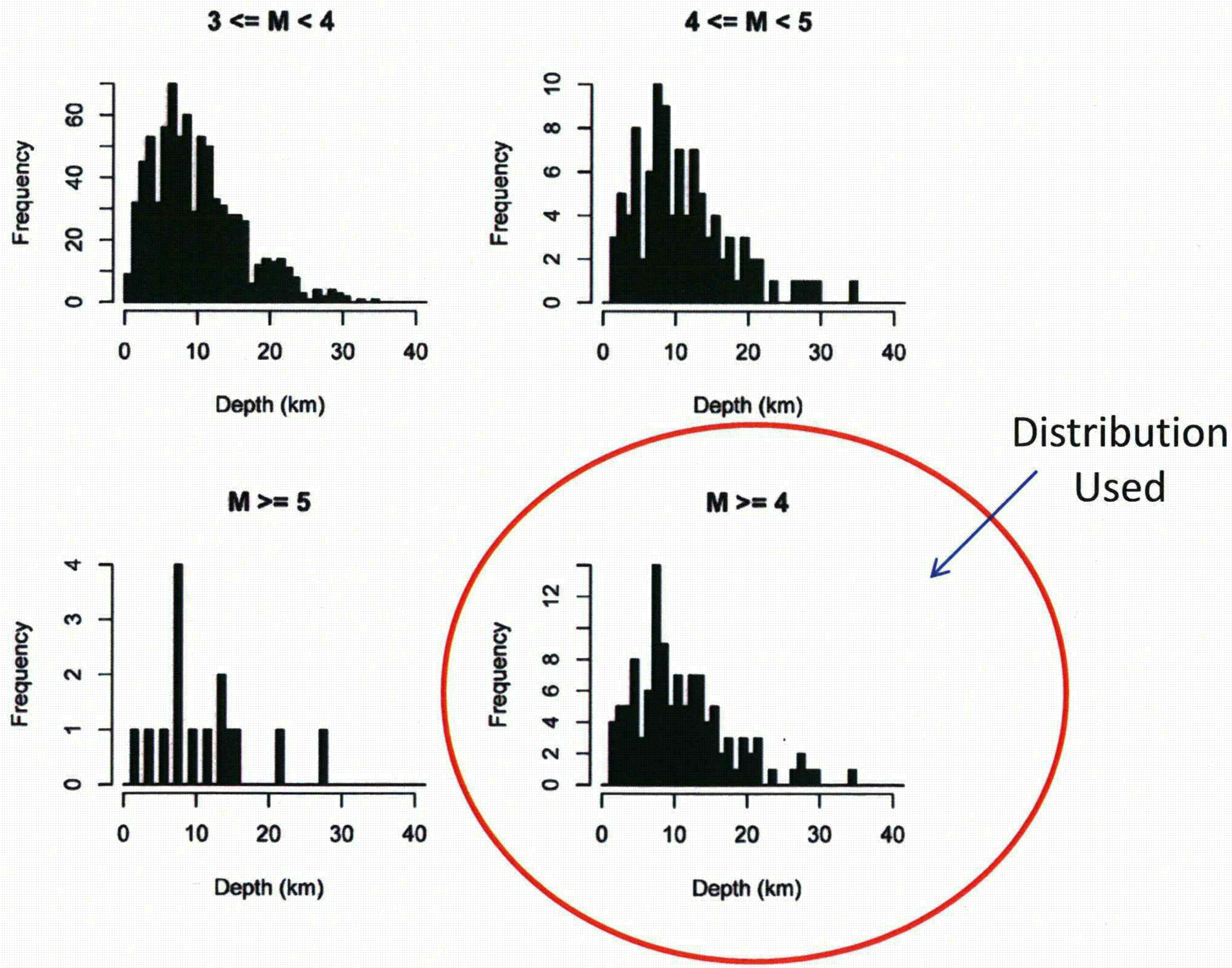
# Development of Cluster Median GMPEs for Mid-Continent

- Develop $R_{JB}$ versions of AB06' and PZT
- Use intra-cluster weights to develop median (mean ln) PSA values for a range of magnitudes and distances
  - **M** 5 to 8 in 0.5 unit spacing
  - $\ln(R_{JB})$ from 0 to ln(1000) in 0.02 units
- Fit median PSA with flexible algebraic forms for use in PSHA

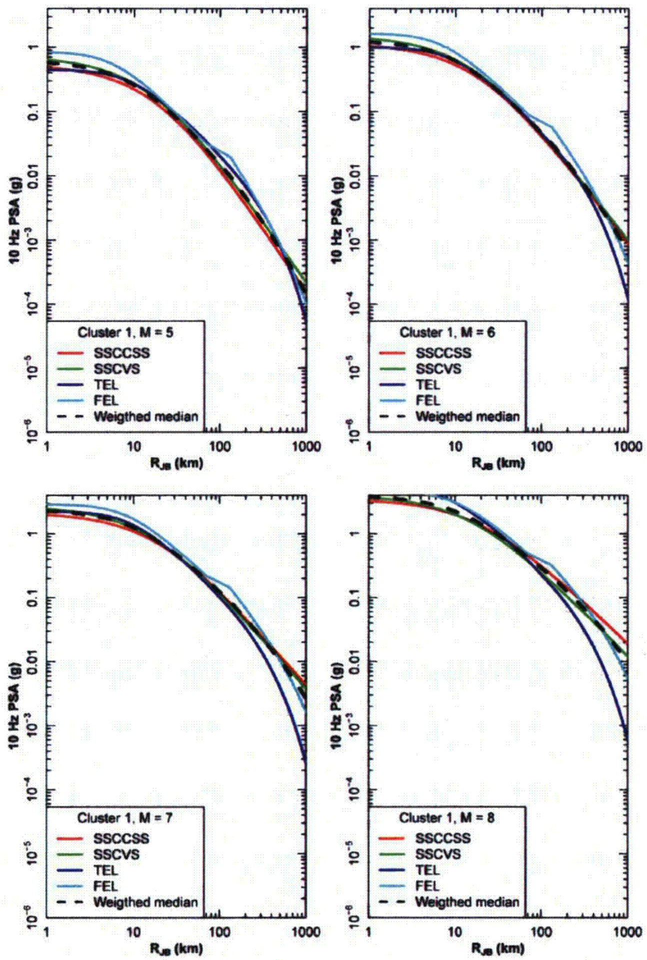
# Developing RJB Model

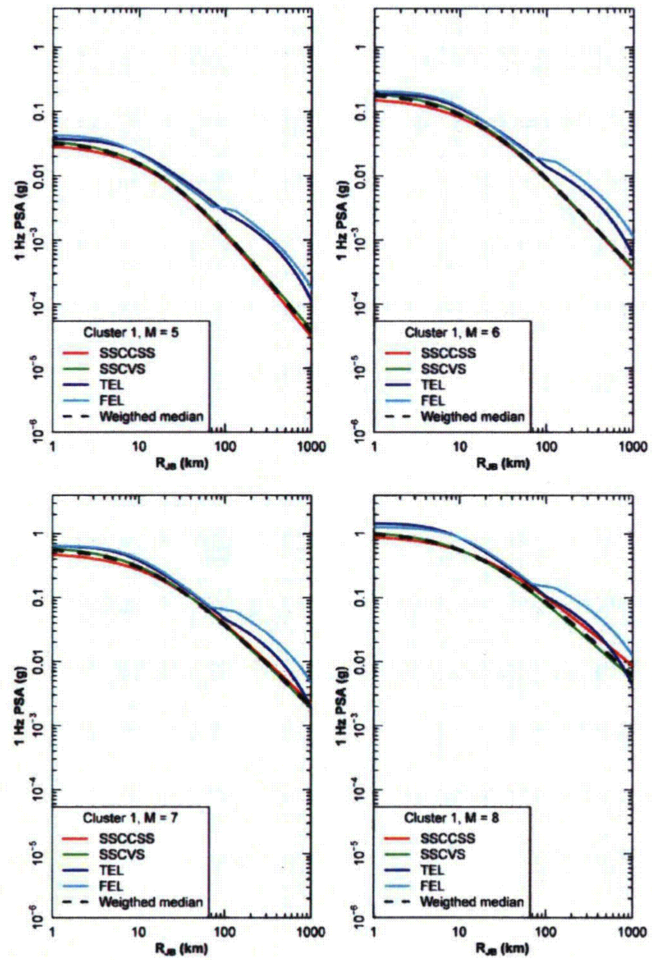
- For a given value of $R_{JB}$, simulate magnitude dependent rupture areas
  - Distribution of focal depths from well located earthquakes in NUREG-2115 catalog
  - log(RA) = **M** – 4.35 (Somerville et al., 2001 + Hanks and Kanamori, 1970)
  - Equal mixture of 90° and 45° rupture dip
  - Hypocenter depth distribution
  - Hypocenter placed at 2/3 rupture width
  - Trim resulting distributions of rupture locations to remove ruptures extending outside of range 0 to 30 km
- Compute mean ln(PSA) for resulting $R_{Rup}$ distances and assign to $R_{JB}$ distance

# Focal Depth Distributions from NUREG-2115 Catalog

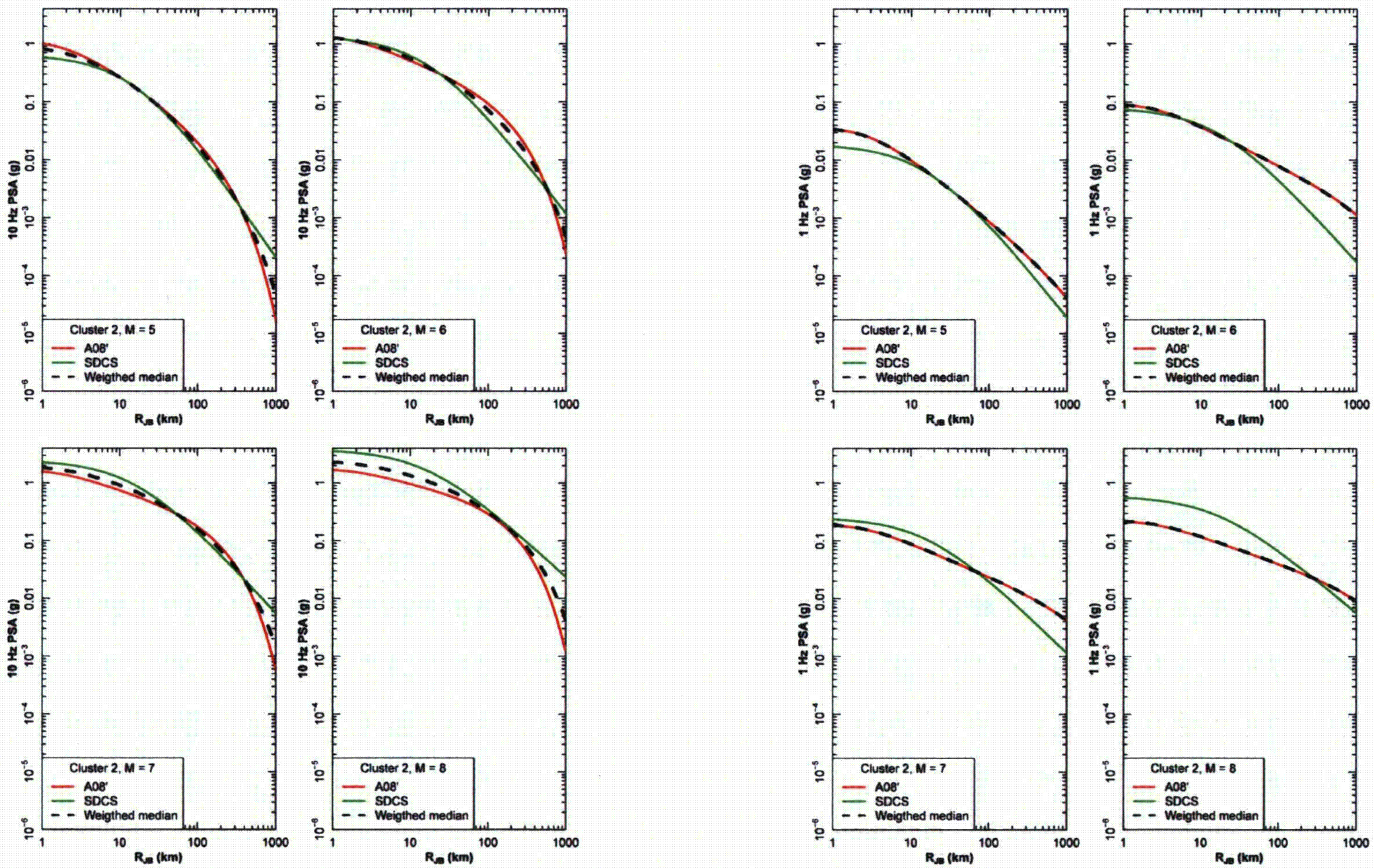


# Median PSA for New Cluster 1

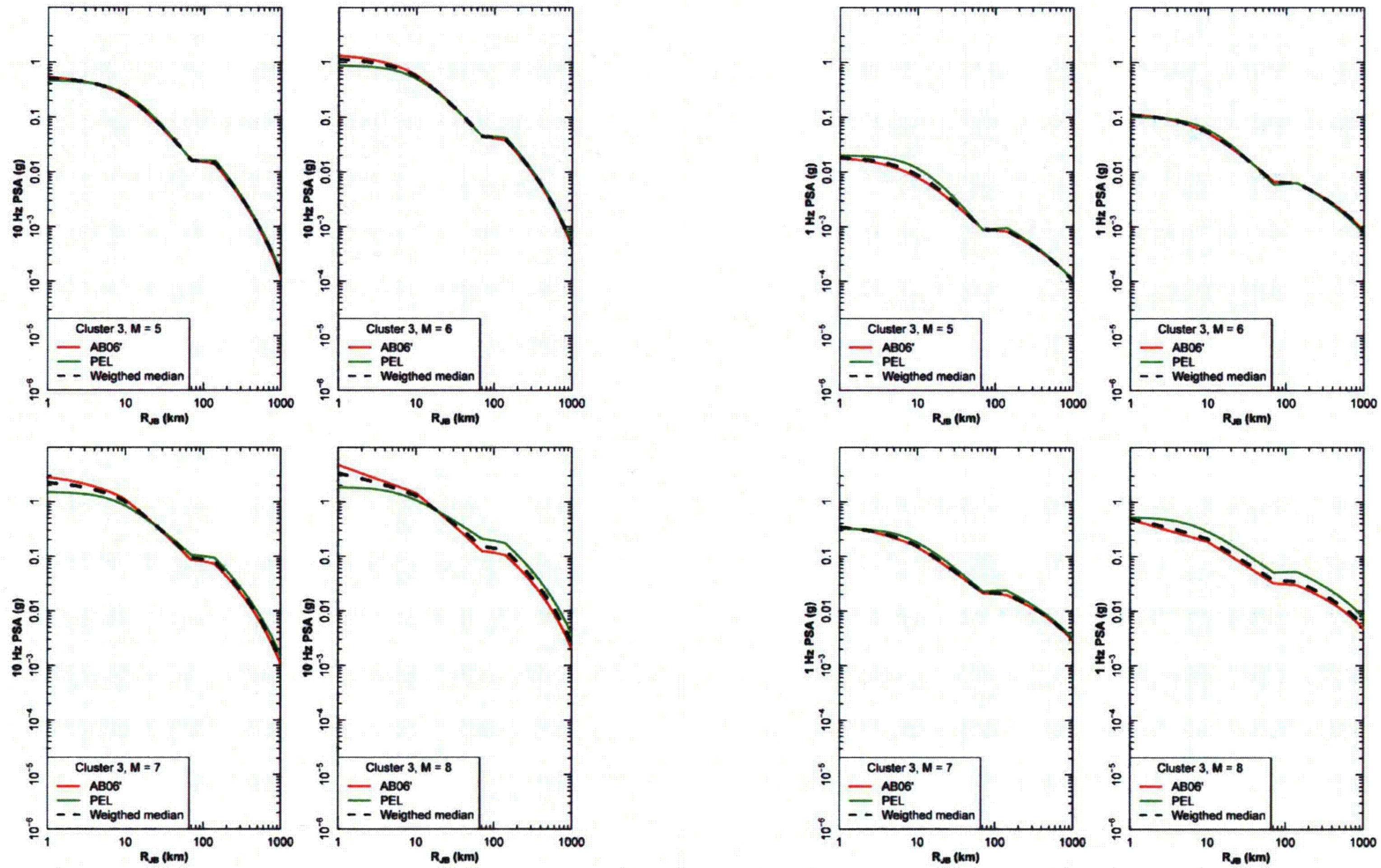


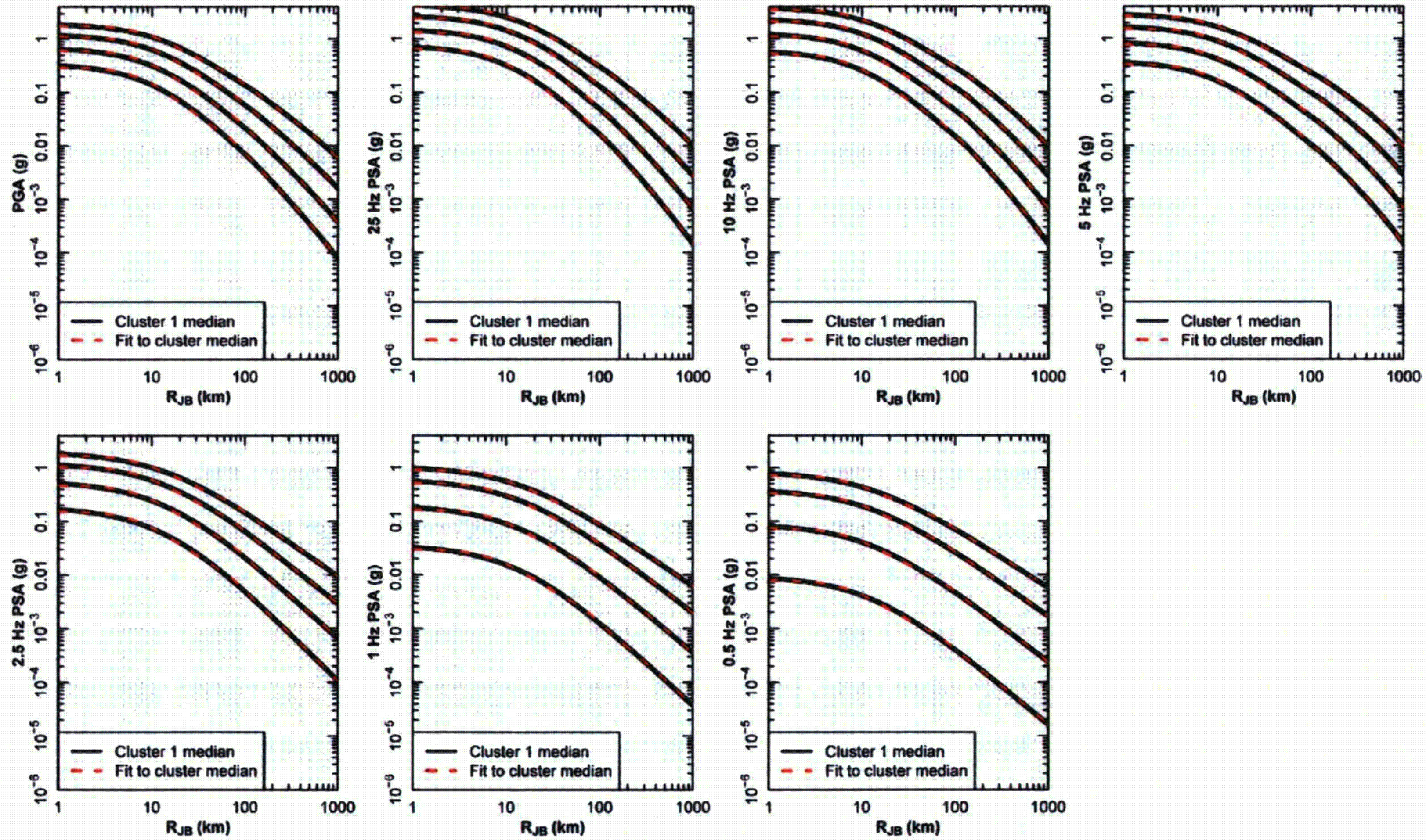
# Median PSA for New Cluster 2



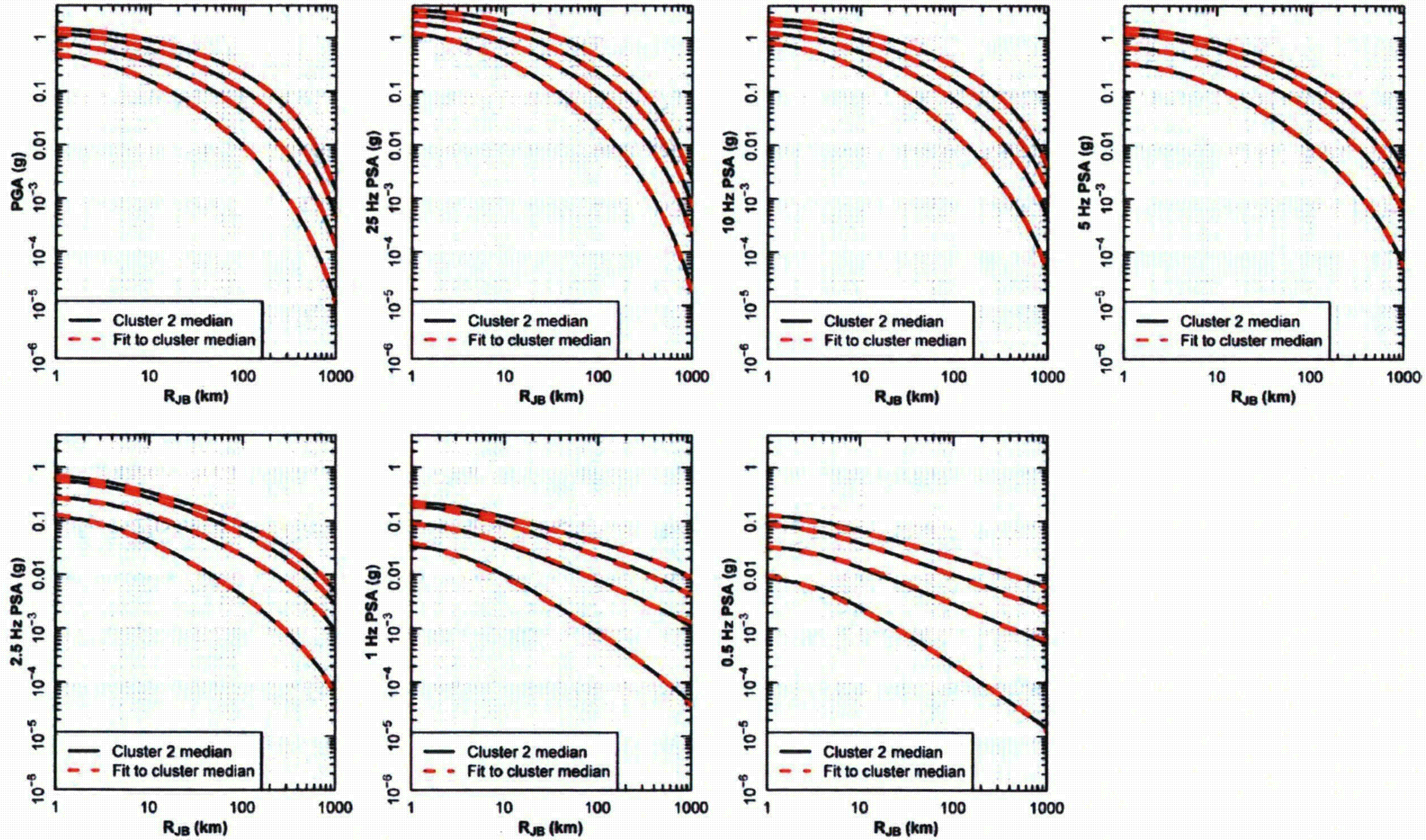
# Median PSA for New Cluster 3



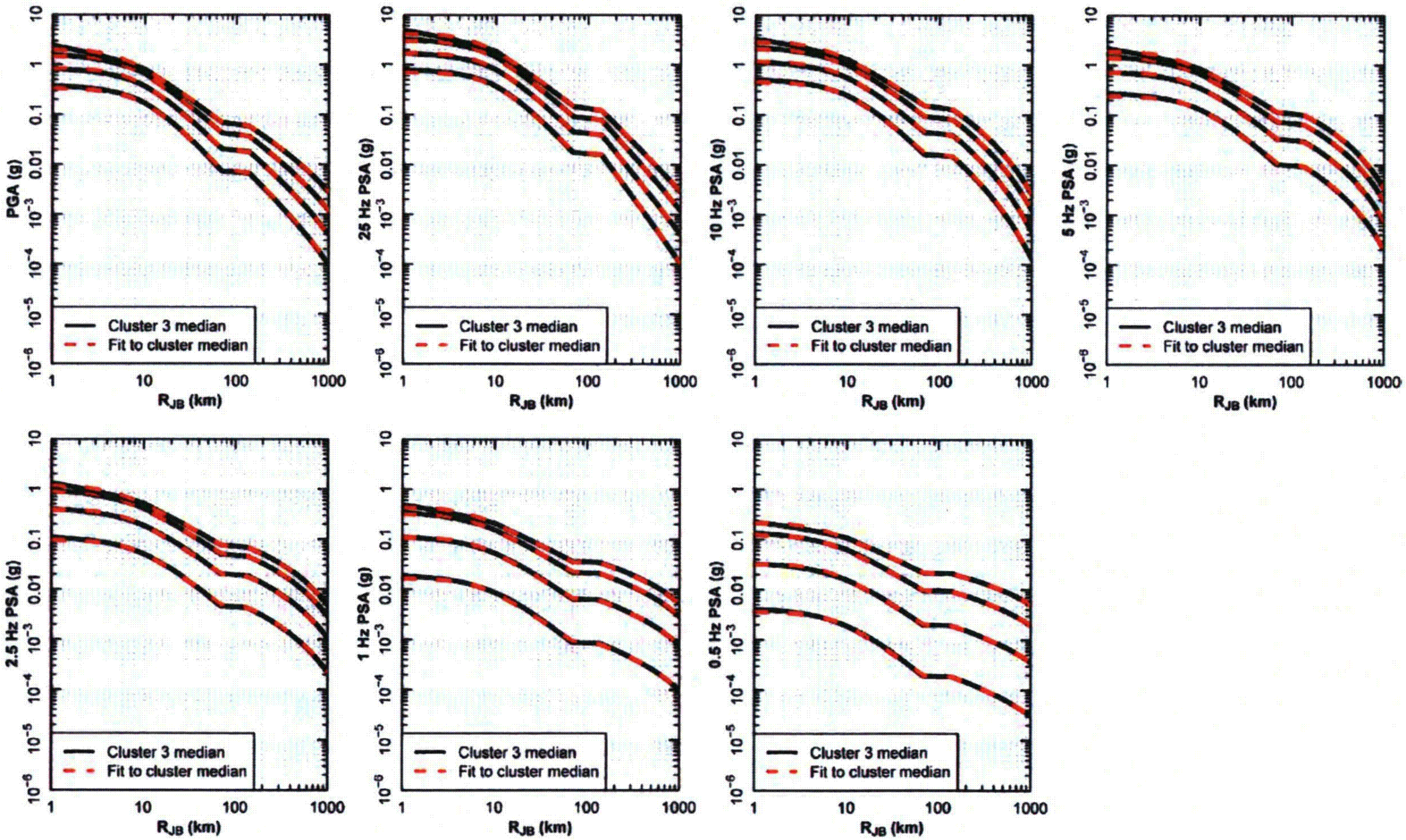
# Fitted Median GMPE for New Cluster 1



# Fitted Median GMPE for New  Cluster 2



# Fitted Median GMPE for New Cluster 3



# Epistemic Uncertainty in Cluster Median Models

Bob Youngs

# Representation of Epistemic Uncertainty in Cluster Median Models

- EPRI (2004) – sum of variances for model to model variation, parametric source and parametric path uncertainty, and fit of cluster median

$$\sigma(m,r,f)_{\text{cluster median-2004}} = \left\{ \begin{matrix} \sigma^2(m,r,f)_{\text{model-to-model}} + \sigma^2(m,r,f)_{\text{source}} + \\ \sigma^2(m,r,f)_{\text{path}} + \sigma^2(m,r,f)_{\text{median fit}} \end{matrix} \right\}^{1/2}$$

# Updated Model (1 of 4)

- Parametric uncertainty not used
  - Source and path cannot be treated as independent as in 2004 because estimates of parameters are correlated
  - Question of applicability of simple source uncertainty used in 2004 (1-C stochastic) to complex source models underlying some of the GMPEs

# Updated Model (2 of 4)

- Model fitting standard error not used as it is very small (as evidences by fits to cluster medians) and would have negligible contribution

# Updated Model (3 of 4)

- Greatly expanded database provides for use of data-constrained estimate of median uncertainty
  - Standard error of mean of analytical adjusted residuals accounting for correlation matrix
  - Represent by piece-wise linear function of $\ln(R_{JB})$

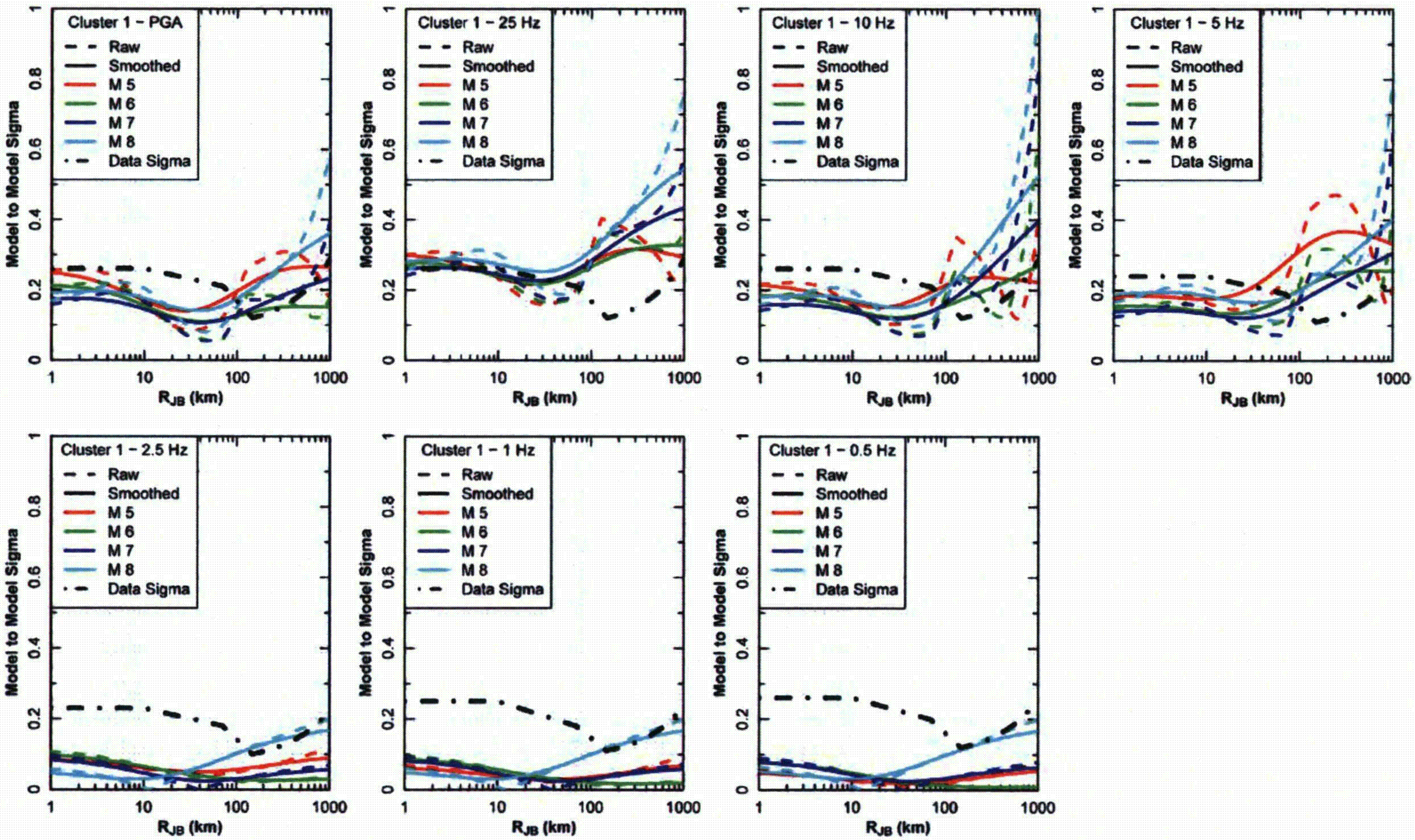
# Updated Model (4 of 4)

- Use envelope of model-to-model and data constraint uncertainty rather than sum of variances

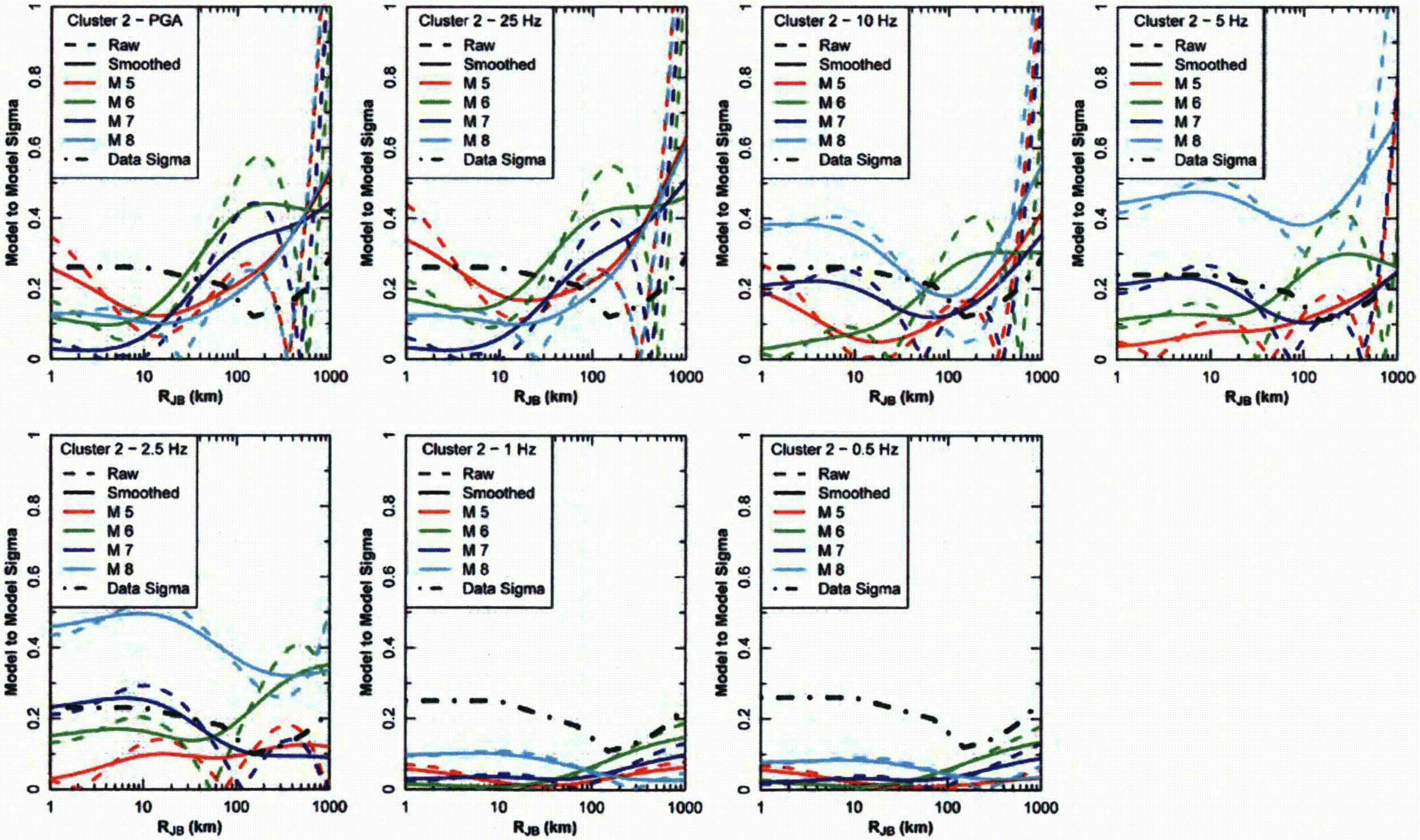
$$\sigma(m,r,f)_{\text{clustermedian-2013}} = \max\left\{\sigma^2(m,r,f)_{\text{model-to-model}}, \sigma^2(m,r,f)_{\text{data constraint}}\right\}$$

- These are considered to be different manifestations of the same underlying uncertainty

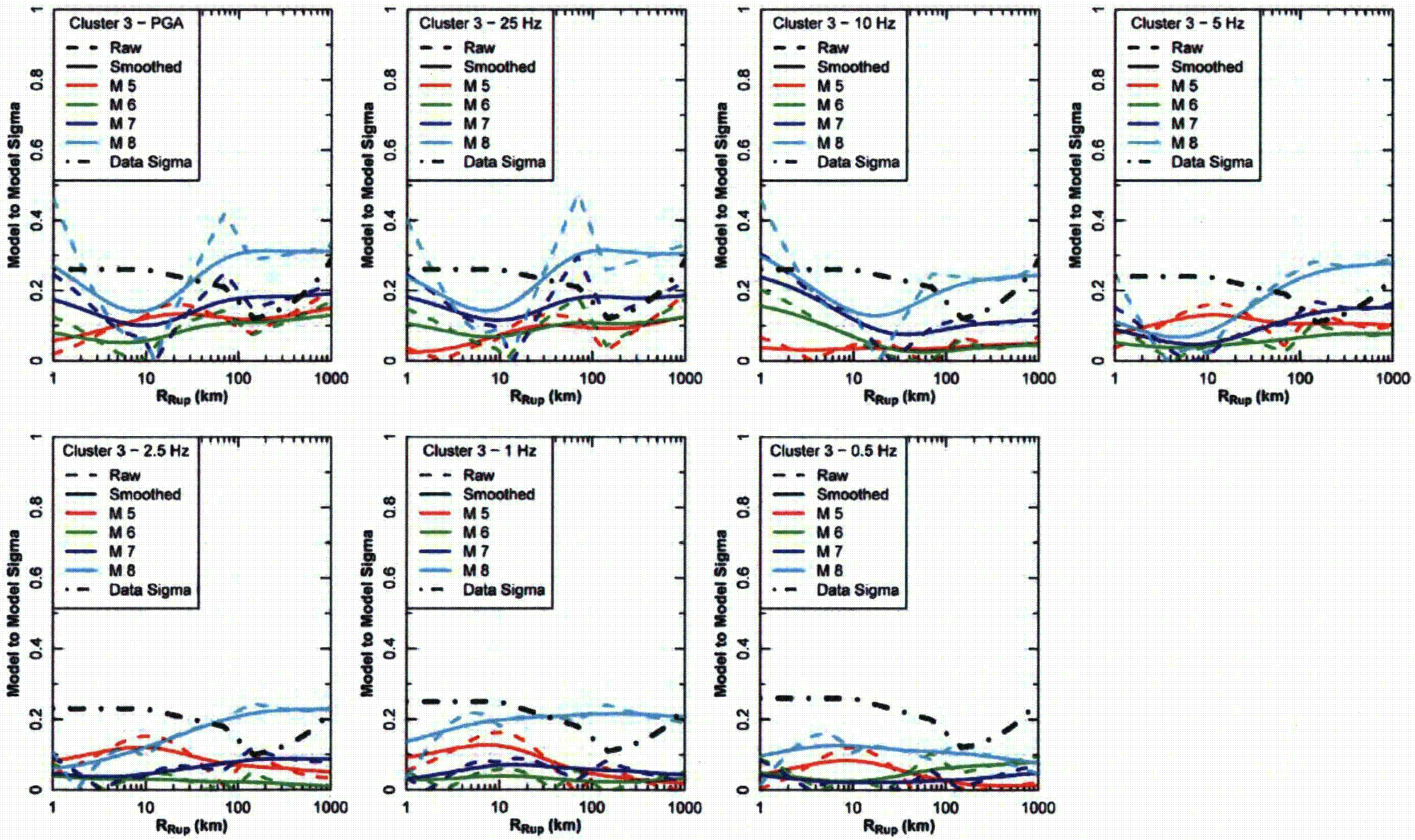
# Components of Epistemic Uncertainty for New Cluster 1



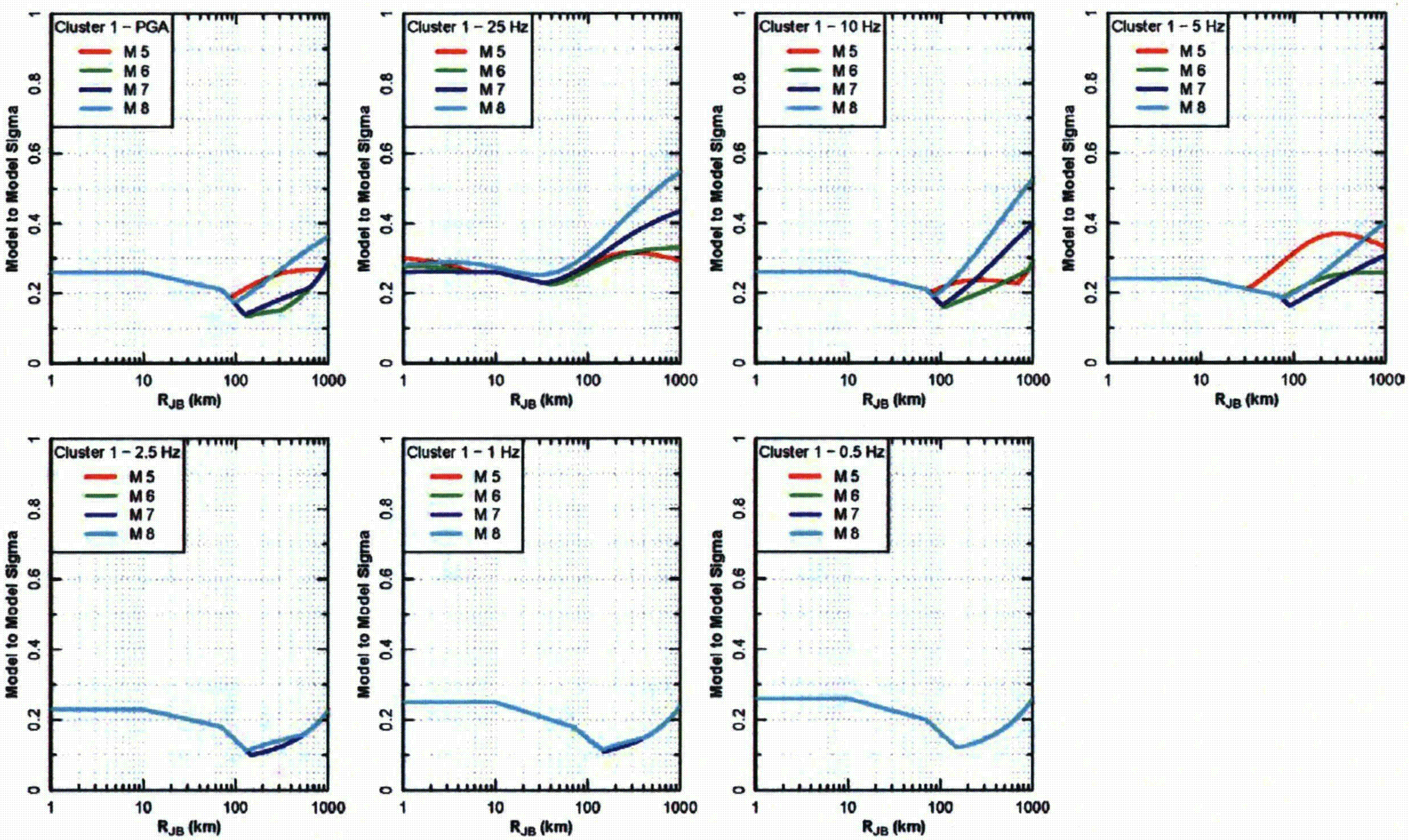
# Components of Epistemic Uncertainty for New Cluster 2



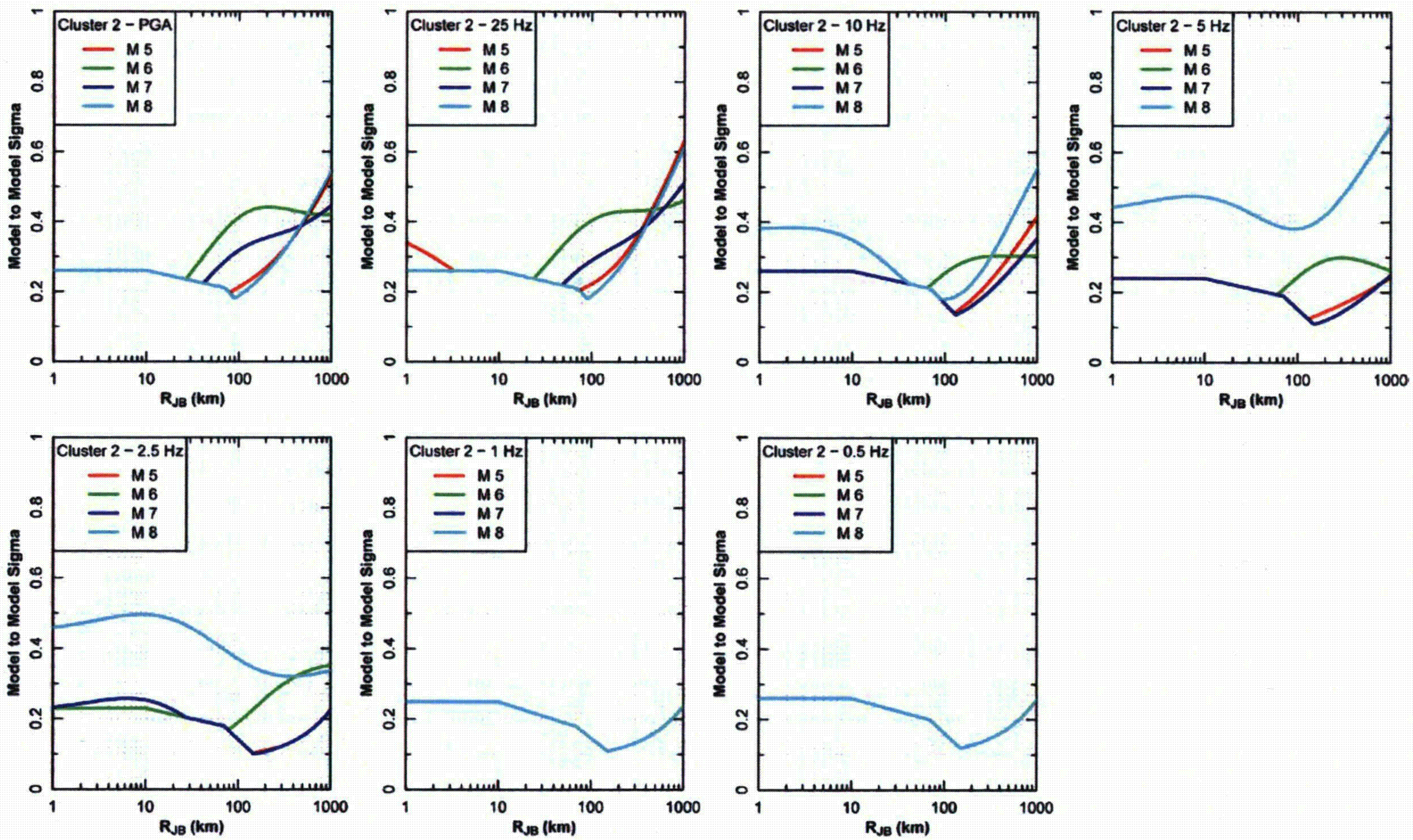
# Components of Epistemic Uncertainty for New Cluster 3



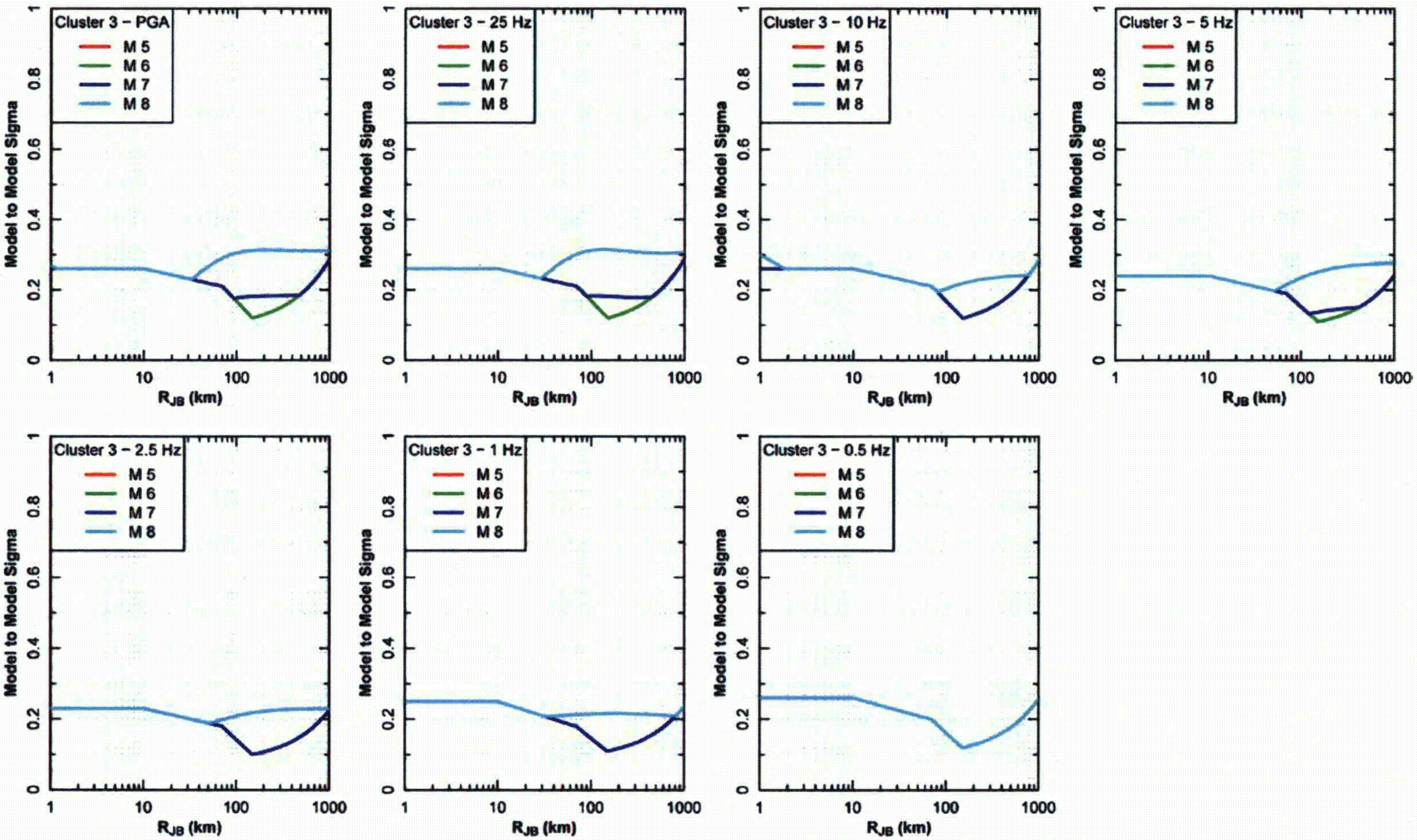
# Envelope of Smoothed Epistemic Uncertainty for New Cluster 1



# Envelope of Smoothed Epistemic Uncertainty for New Cluster 2



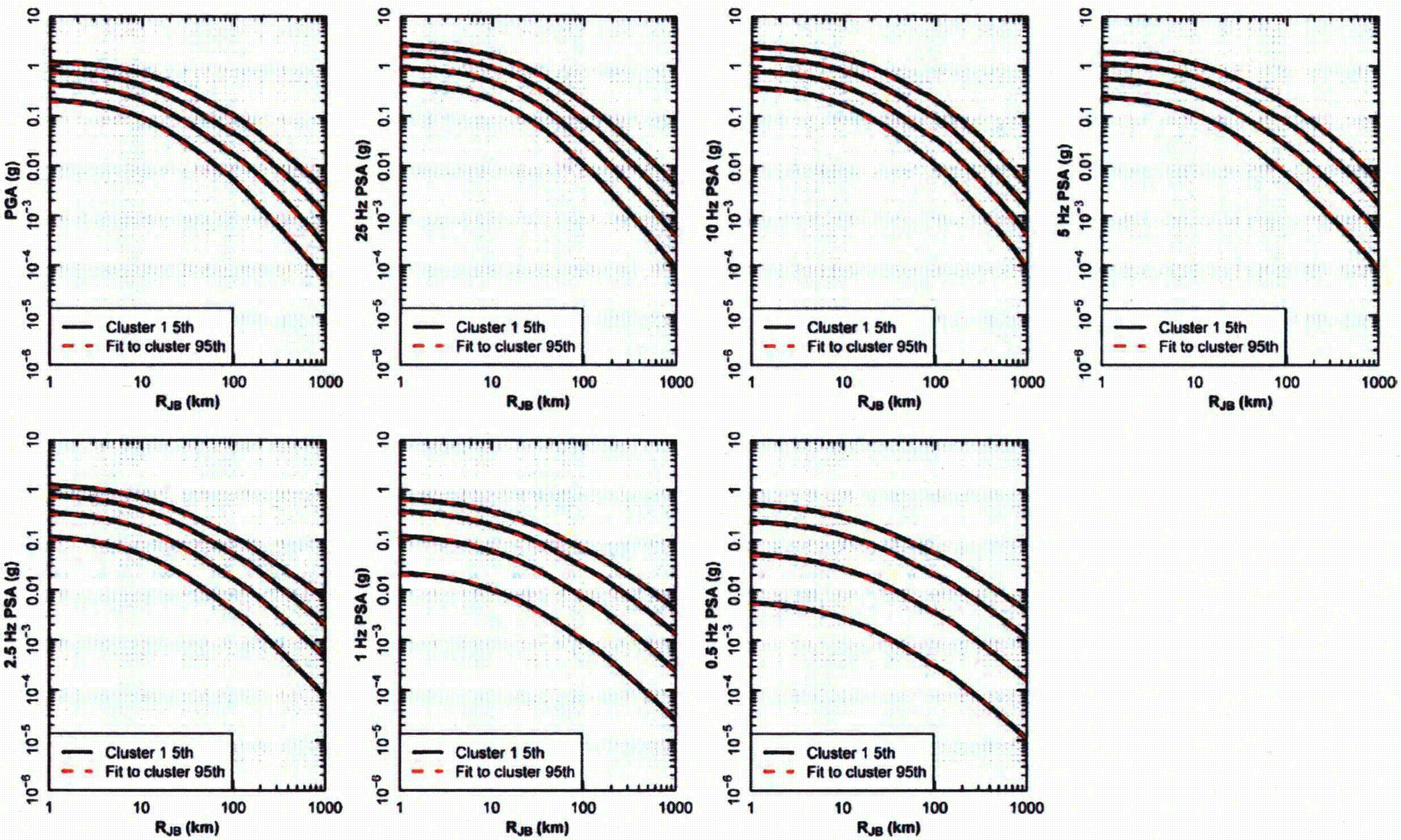
# Envelope of Smoothed Epistemic Uncertainty for New Cluster 3



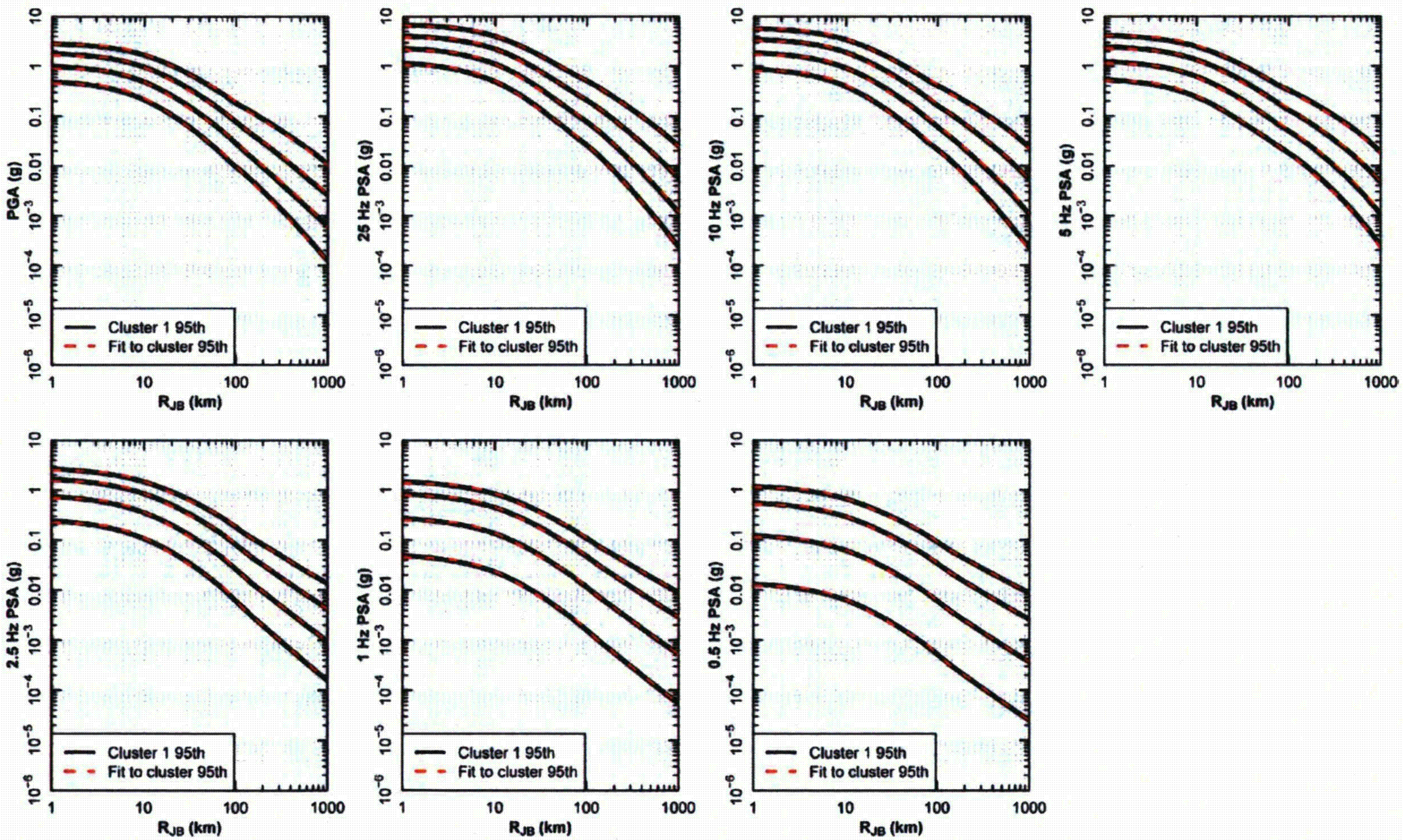
# Representing Within-Cluster Epistemic Uncertainty

- Following EPRI (2004) use three-point discrete distribution to represent uncertainty
  - Median model with weight 0.63
  - 5th and 95th percentile models with weight 0.185
  - 5th and 95th percentile models computed as $\ln(PSA_{\text{cluster median}}) \pm 1.645\ \sigma(m,r,f)_{\text{clustermedian-2013}}$
  - Fit resulting values with same algebraic forms used to fit median models

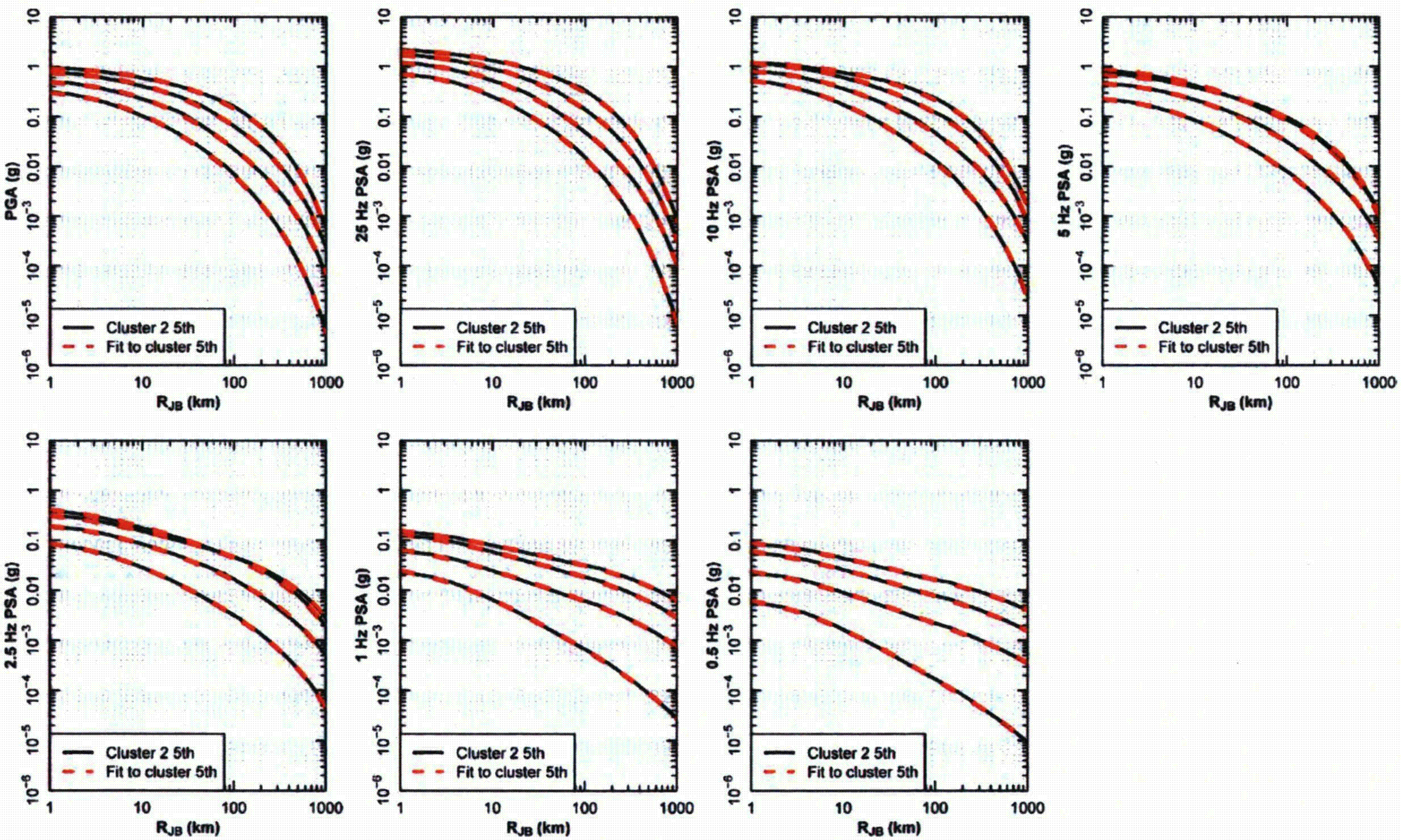
# Fitted 5th Percentile GMPE for New Cluster 1



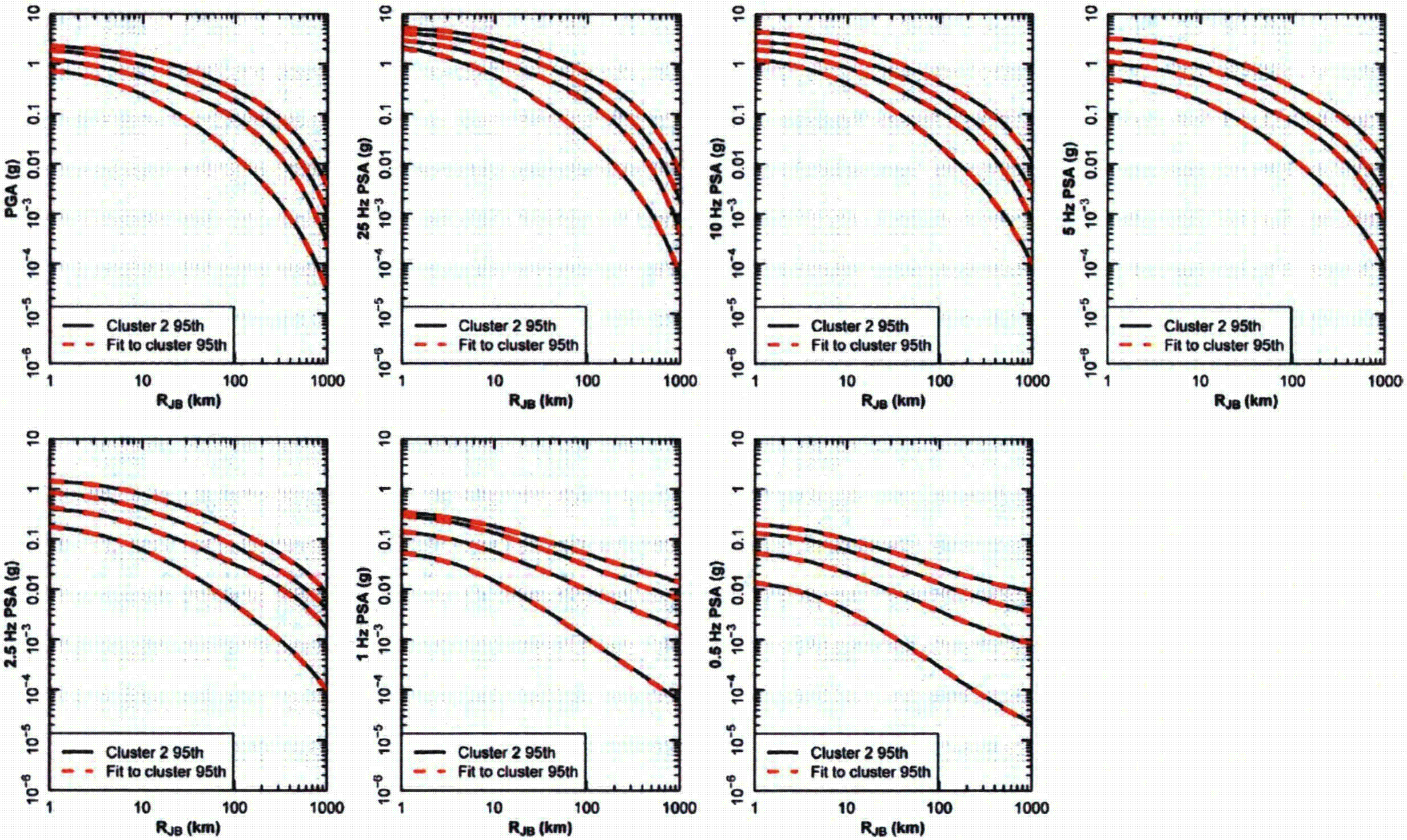
# Fitted 95$^{th}$ Percentile GMPE for New Cluster 1



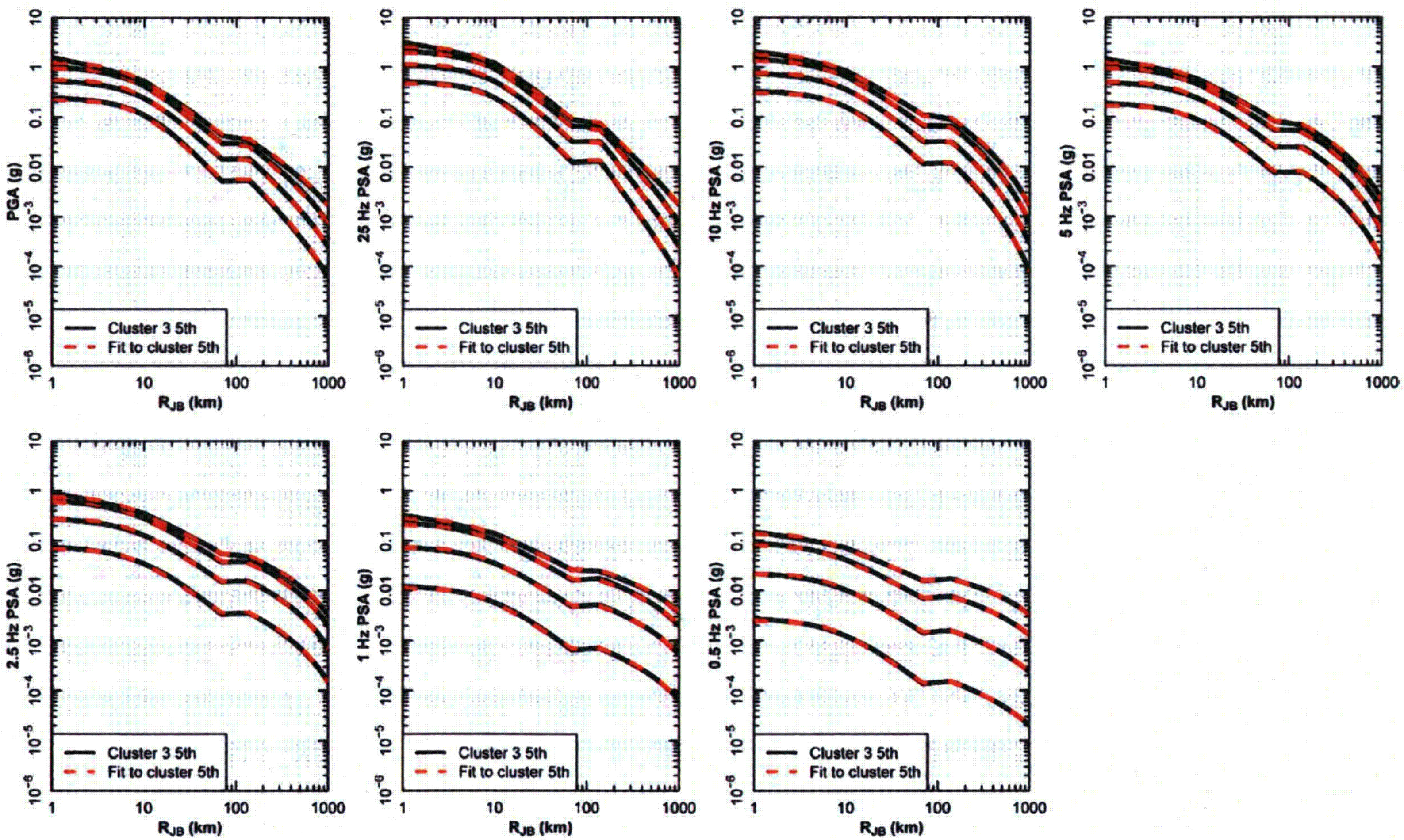
# Fitted 5$^{th}$ Percentile GMPE for New Cluster 2



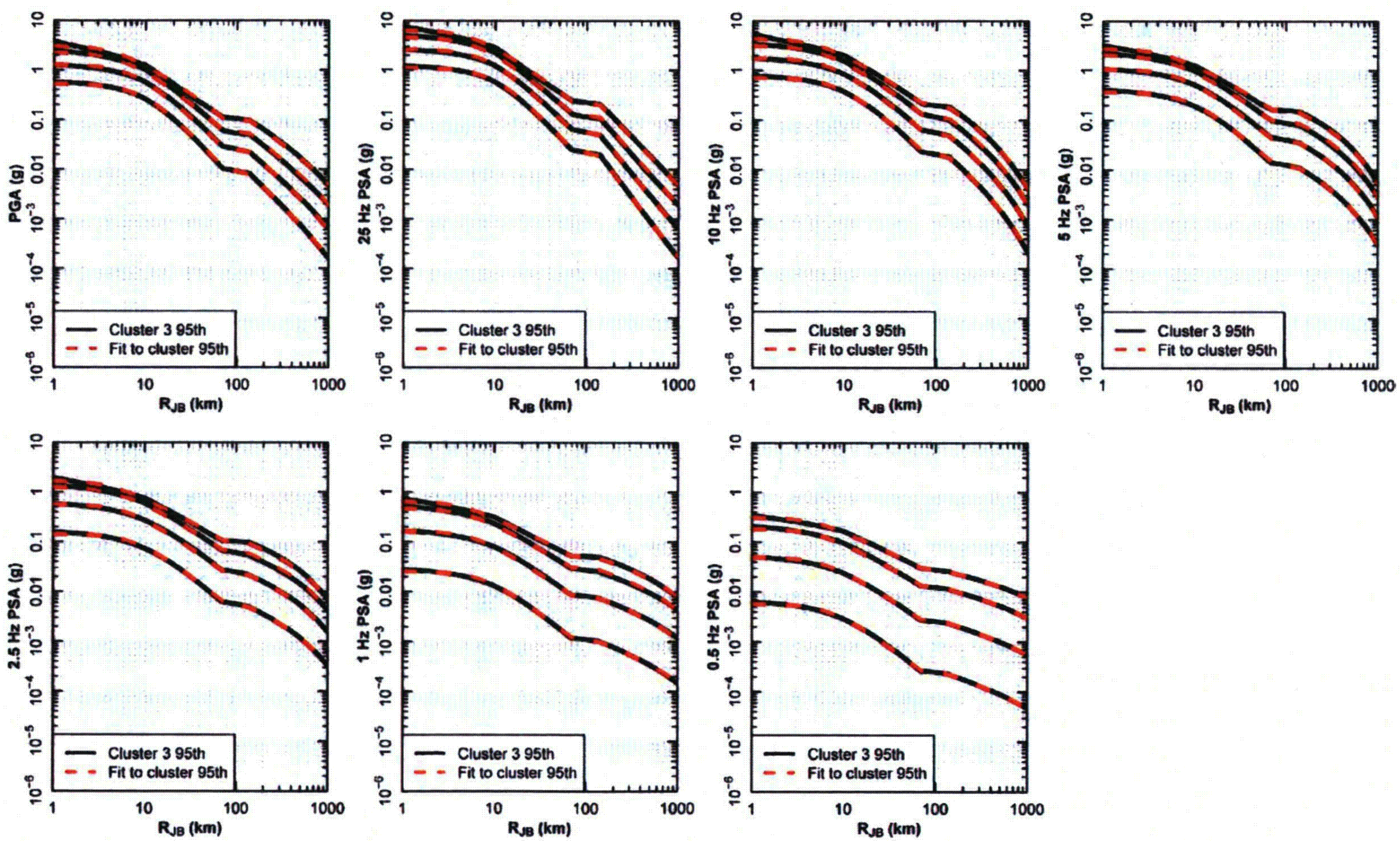
# Fitted 95$^{th}$ Percentile GMPE for New Cluster 2



# Fitted 5$^{th}$ Percentile GMPE for New Cluster 3



# Fitted 95th Percentile GMPE for New Cluster 3



# Development of Cluster Weights

Gabriel Toro

# Approach (similar to EPRI, 2004)

Two contributors to cluster weight:

- Agreement of cluster medians (clusters 1-4) with data
  - Use same approach used for the calculation of within-cluster weights
  - Average high-frequency and low-frequency weights
- TI Team's confidence in the ability of GMPEs represented in cluster to serve as robust interpolators to predict motions at MR ranges for which we have little or no data

# Cluster Weights using OK-AR

| | Analytical Site Adjustments | | | | Empirical Site Adjustments | | | |
|---|---|---|---|---|---|---|---|---|
| | **Cluster 1** | **Cluster 2** | **Cluster 3** | **Cluster 4** | **Cluster 1** | **Cluster 2** | **Cluster 3** | **Cluster 4** |
| **25 Hz** | 0.04 | 0.01 | 0.60 | 0.35 | 0.03 | 0.03 | 0.24 | 0.69 |
| **10 Hz** | 0.20 | 0.29 | 0.34 | 0.17 | 0.02 | 0.97 | 0.01 | 0.00 |
| **5 Hz** | 0.03 | 0.16 | 0.75 | 0.06 | 0.00 | 0.91 | 0.06 | 0.03 |
| **Combined HF** | **0.04** | **0.07** | **0.75** | **0.14** | **0.01** | **0.85** | **0.08** | **0.06** |
| **Comb. HF Analytical + Empirical** | **0.03** | **0.46** | **0.42** | **0.10** | | | | |
| | | | | | | | | |
| **2.5 Hz** | 0.00 | 0.00 | 0.99 | 0.01 | 0.00 | 0.01 | 0.99 | 0.00 |
| **1 Hz** | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 |
| **0.5 Hz** | 0.56 | 0.01 | 0.08 | 0.34 | 0.03 | 0.00 | 0.97 | 0.00 |
| **Combined LF** | **0.00** | **0.00** | **0.99** | **0.01** | **0.00** | **0.00** | **1.00** | **0.00** |
| **Comb. LF Analytical + Empirical** | **0.00** | **0.00** | **0.99** | **0.01** | | | | |

# Cluster Weights not using OK-AR

| | Analytical Site Adjustments | | | | Empirical Site Adjustments | | | |
|---|---|---|---|---|---|---|---|---|
| | Cluste r 1 | Cluster 2 | Cluster 3 | Cluster 4 | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 |
| 25 Hz | 0.05 | 0.01 | 0.49 | 0.45 | 0.13 | 0.78 | 0.03 | 0.06 |
| 10 Hz | 0.17 | 0.13 | 0.42 | 0.28 | 0.03 | 0.96 | 0.00 | 0.01 |
| 5 Hz | 0.06 | 0.10 | 0.65 | 0.19 | 0.01 | 0.46 | 0.02 | 0.51 |
| **Combined HF** | **0.05** | **0.03** | **0.63** | **0.29** | **0.02** | **0.94** | **0.00** | **0.04** |
| **Comb. HF Analytical + Empirical** | **0.03** | **0.49** | **0.32** | **0.16** | | | | |
| | | | | | | | | |
| 2.5 Hz | 0.00 | 0.01 | 0.98 | 0.01 | 0.00 | 0.02 | 0.98 | 0.00 |
| 1 Hz | 0.00 | 0.01 | 0.99 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 |
| 0.5 Hz | 0.18 | 0.13 | 0.51 | 0.18 | 0.00 | 0.00 | 1.00 | 0.00 |
| **Combined LF** | **0.00** | **0.01** | **0.99** | **0.00** | **0.00** | **0.00** | **1.00** | **0.00** |
| **Comb. LF Analytical + Empirical** | **0.00** | **0.00** | **0.99** | **0.00** | | | | |

# Cluster Weights: Final Steps

| | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 |
|---|---|---|---|---|
| **HF with** | 0.03 | 0.46 | 0.42 | 0.10 |
| **HF without** | 0.03 | 0.49 | 0.32 | 0.16 |
| **HF Combined** | 0.03 | 0.47 | 0.37 | 0.13 |
| | | | | |
| **LF with** | 0.00 | 0.00 | 0.99 | 0.01 |
| **LF without** | 0.00 | 0.00 | 0.99 | 0.00 |
| **LF Combined** | 0.00 | 0.00 | 0.99 | 0.00 |

| | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 |
|---|---|---|---|---|
| **Weight Based on Consistency with Data (avg. HF and LF) 50%** | 0.02 | 0.24 | 0.68 | 0.07 |
| **Weight Based on Confidence in GMPEs 50%** | 0.20 | 0.30 | 0.30 | 0.20 |
| **Combined Weight** | 0.11 | 0.27 | 0.49 | 0.13 |

# Rationale for Confidence Weights

- Data are more abundant than in 2004 (thus, data weight was raised from 25% to 50%
- Data are still limited, especially in the magnitude-distance range of interest
- Clusters 2 and 3 (30% each) include recent GMPEs, which have had the benefit of more CEUS data and more technical insights work in other regions
- Clusters 1 and 4 (20% each) approaches still carry weight within the technical community
- Overall effect: combined data & confidence weights generate a more robust GMM

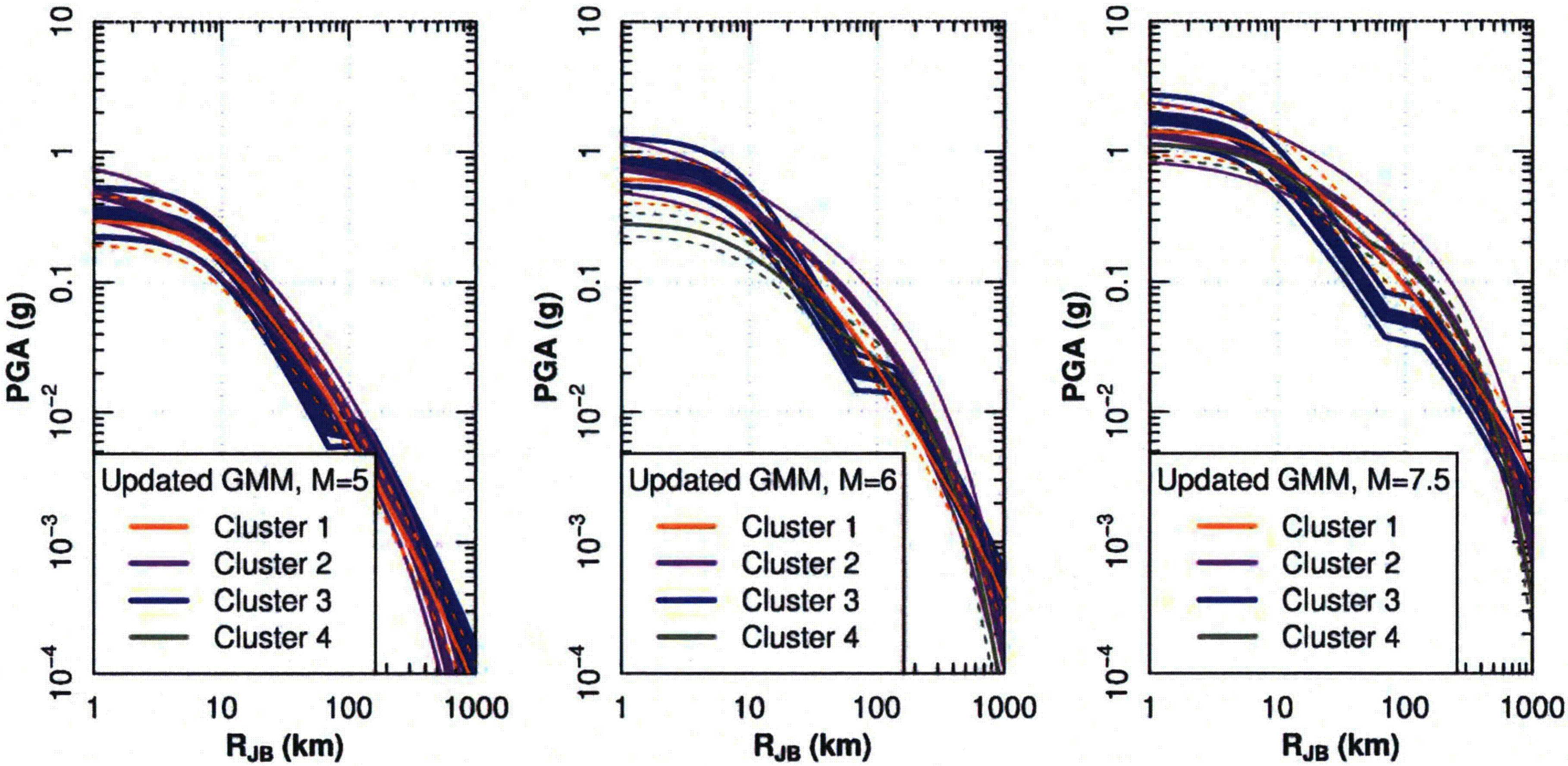
# GMM Summary

Gabriel Toro

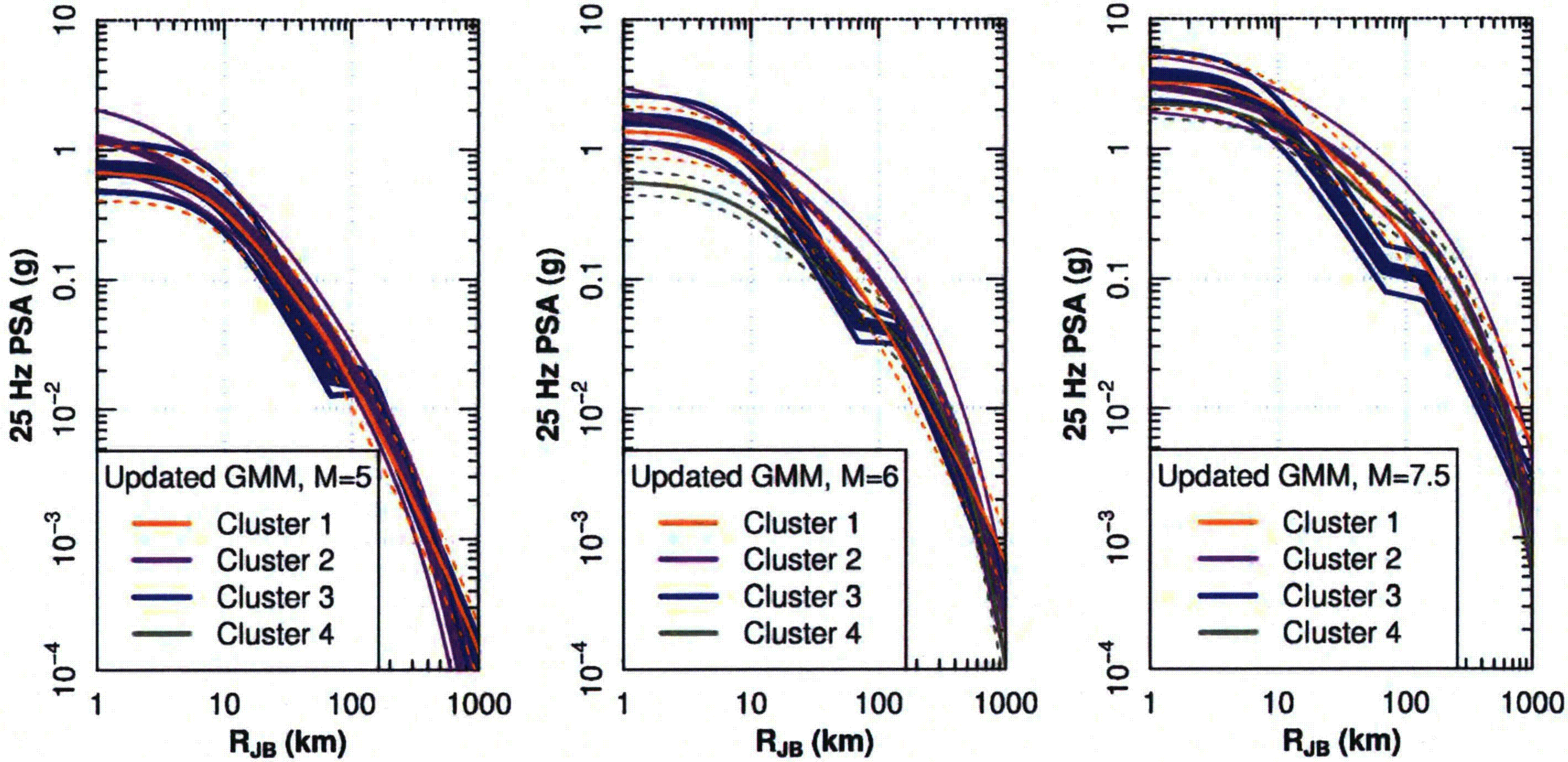
# New Clusters (Mid-Continent) & Weights

| Cluster | Model Type | Models |
|---|---|---|
| 1 | Single Corner Brune Source (0.11/0.127) | Silva et al (2002) - SC-CS-Sat*<br>Silva et al (2002) - SC-VS*<br>Toro et al (1997)<br>Frankel et al (1996)<br>* Treated as one model for calculation of weights |
| 2 | Complex/Empirical $\sim R^{-1}$ Geometrical spreading for R<100 km (0.27/0.310) | Silva et al (2002) DC – Sat<br>A08' |
| 3 | Complex/Empirical $\sim R^{-1.3}$ Geometrical spreading for R<70 km (0.49/0.563) | AB06'<br>PZT11 |
| 4 | Finite Source /Green's Function (0.13/0) | Somerville et al. (2001); slightly different models for rifted and non-rifted<br>(not used for distributed seismicity sources with large contribution from **M** < 6) |

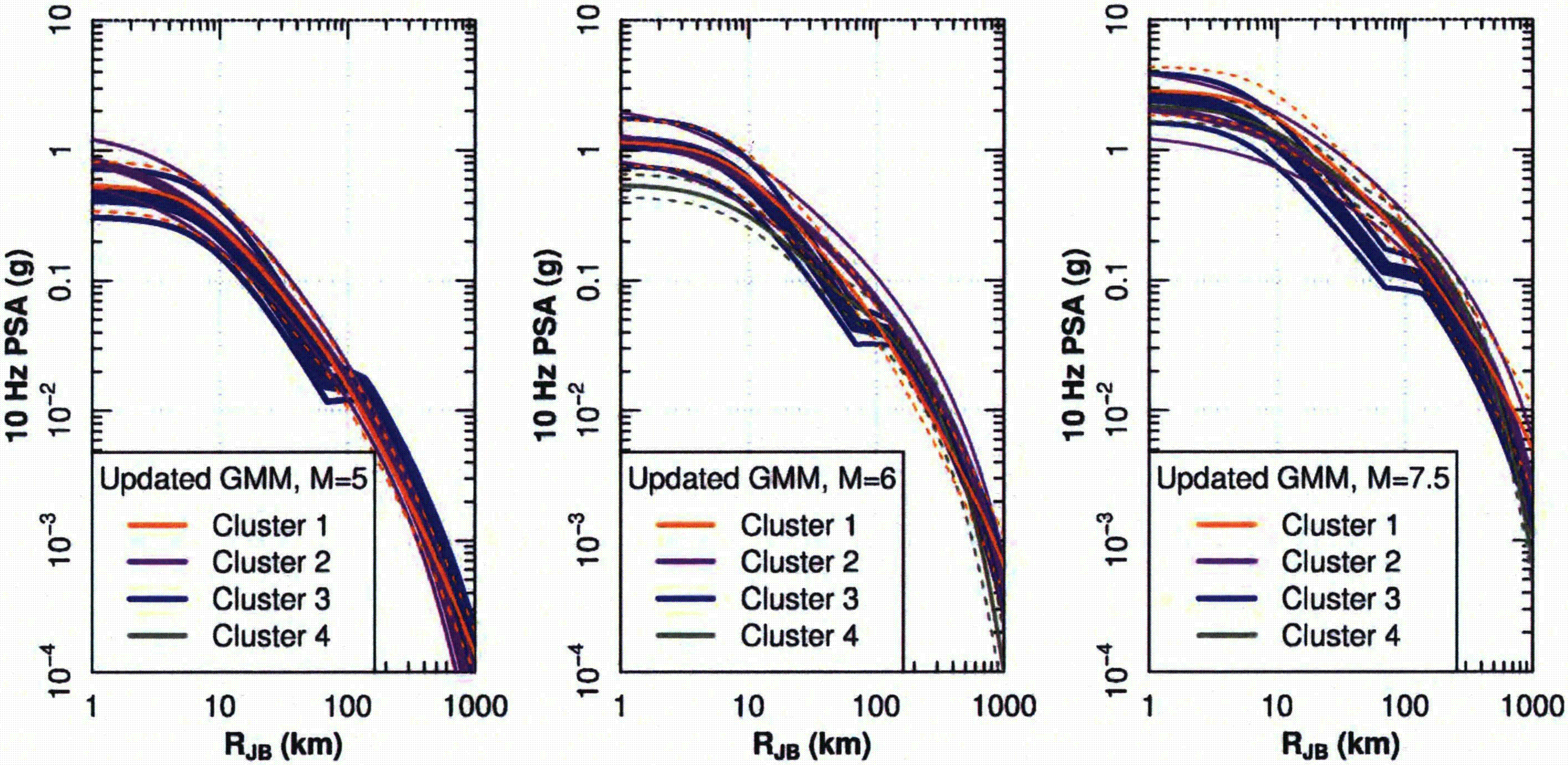
# New Clusters (Mid-Continent): PGA



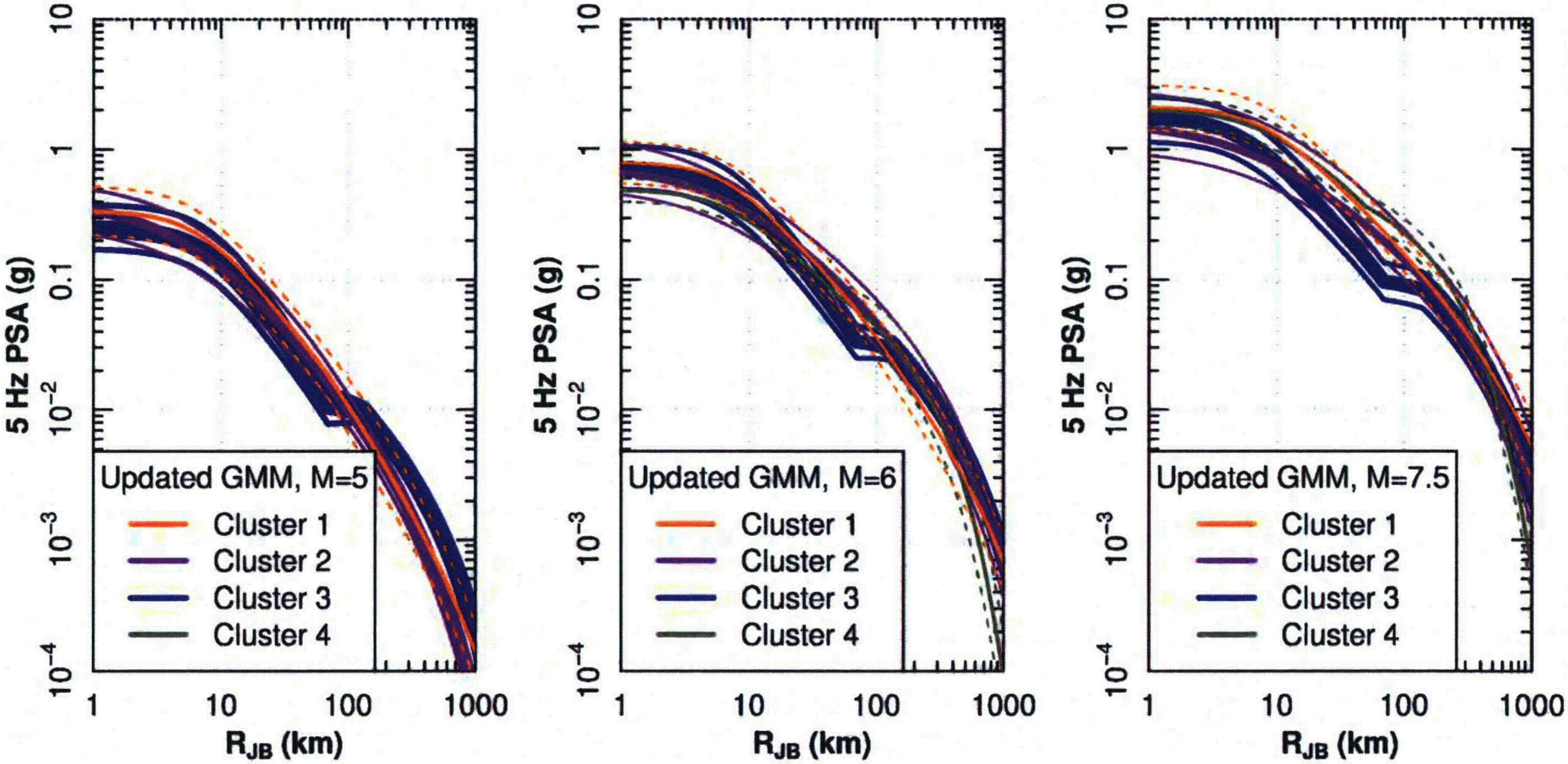
# New Clusters (Mid-Continent): 25 Hz



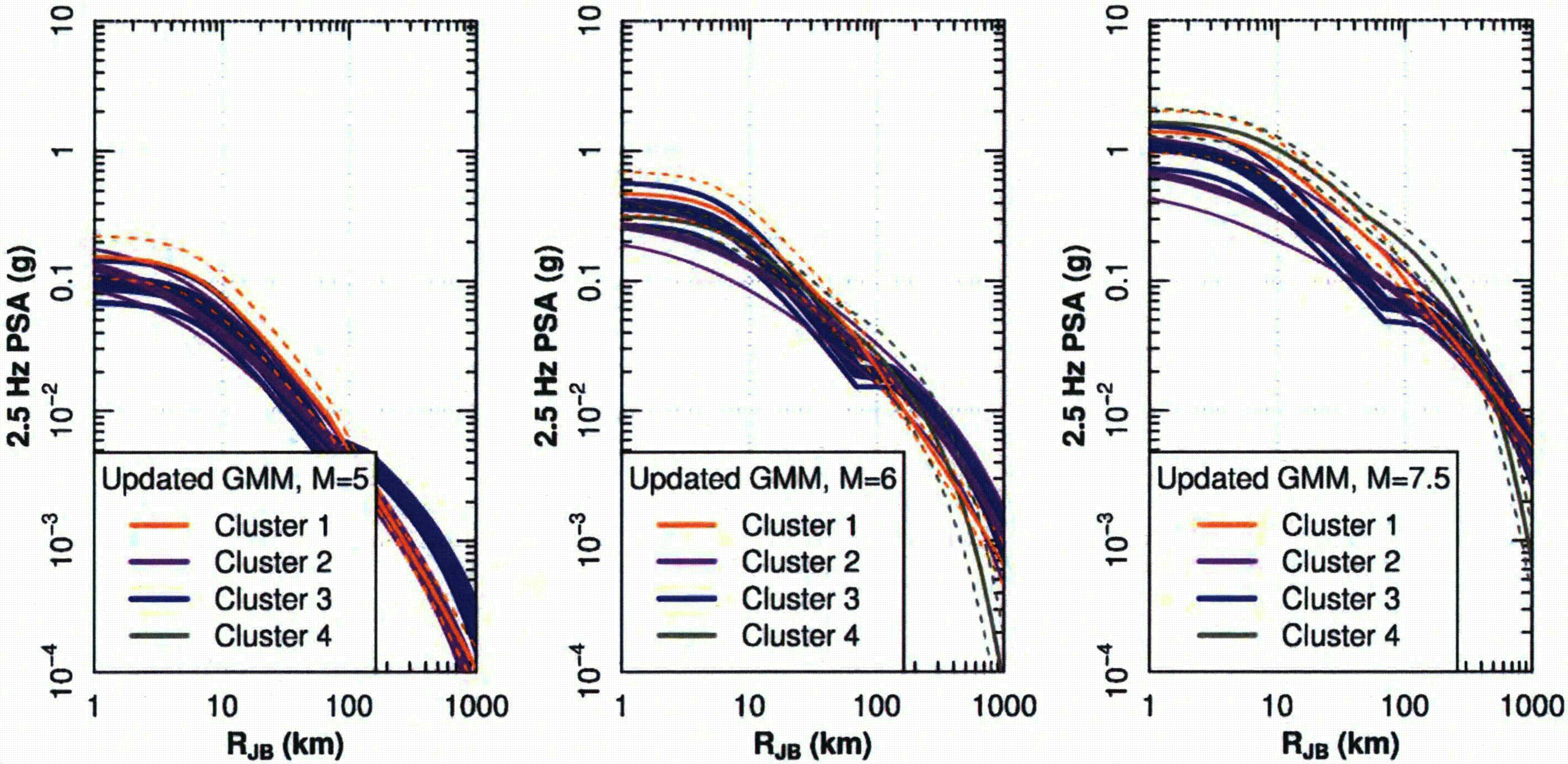
# New Clusters (Mid-Continent): 10 Hz



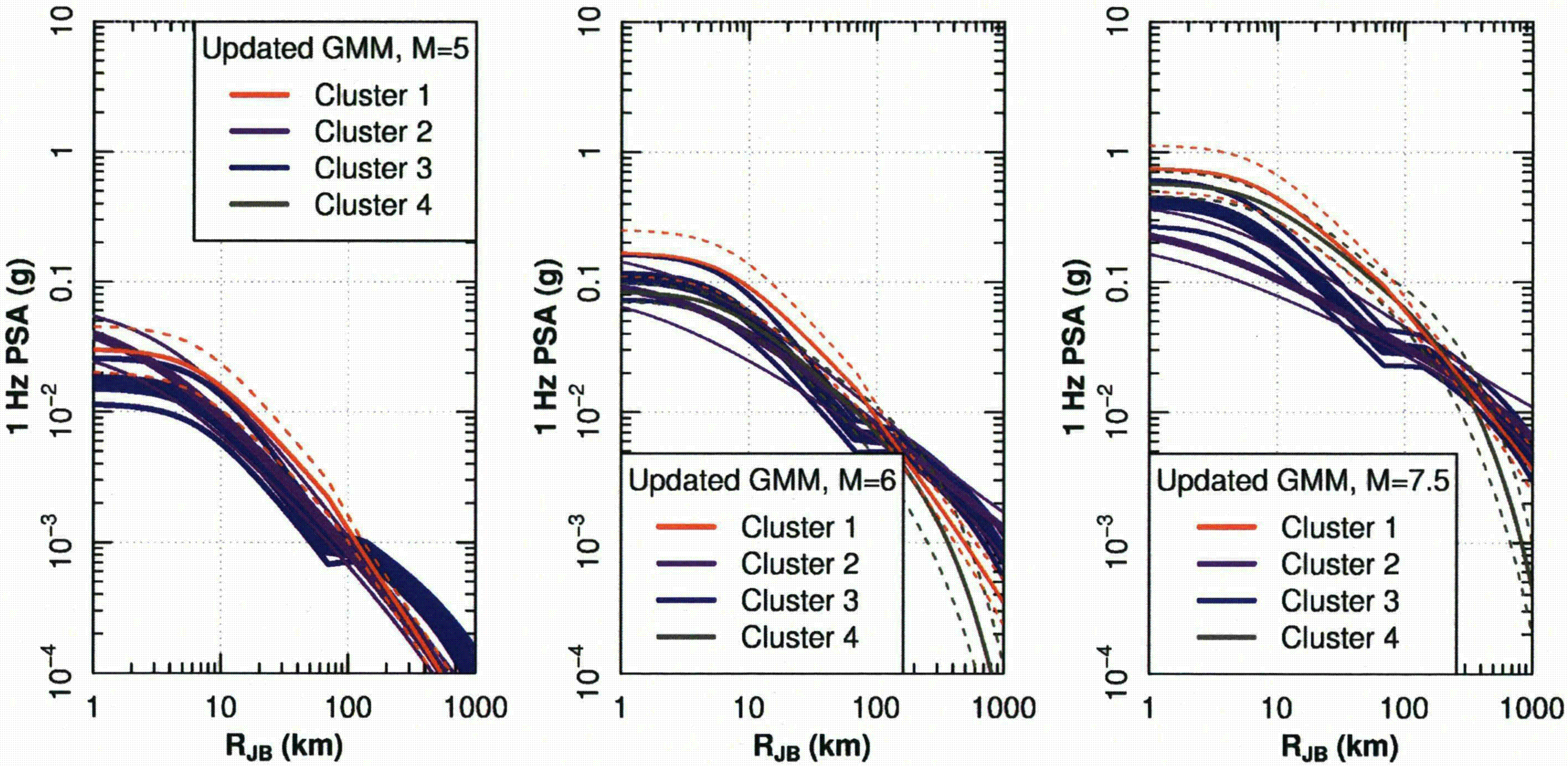
# New Clusters (Mid-Continent): 5 Hz



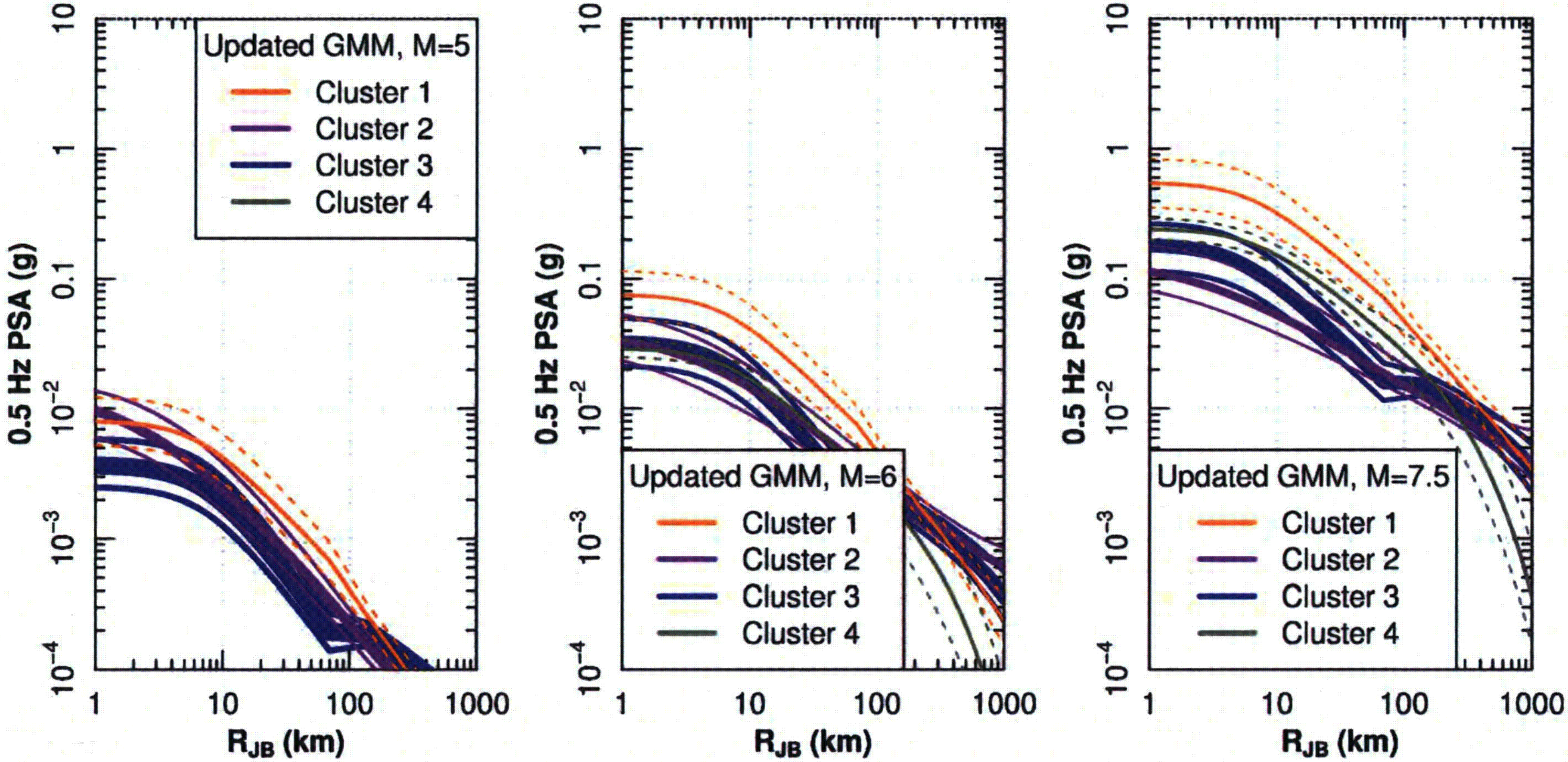
# New Clusters (Mid-Continent): 2.5 Hz



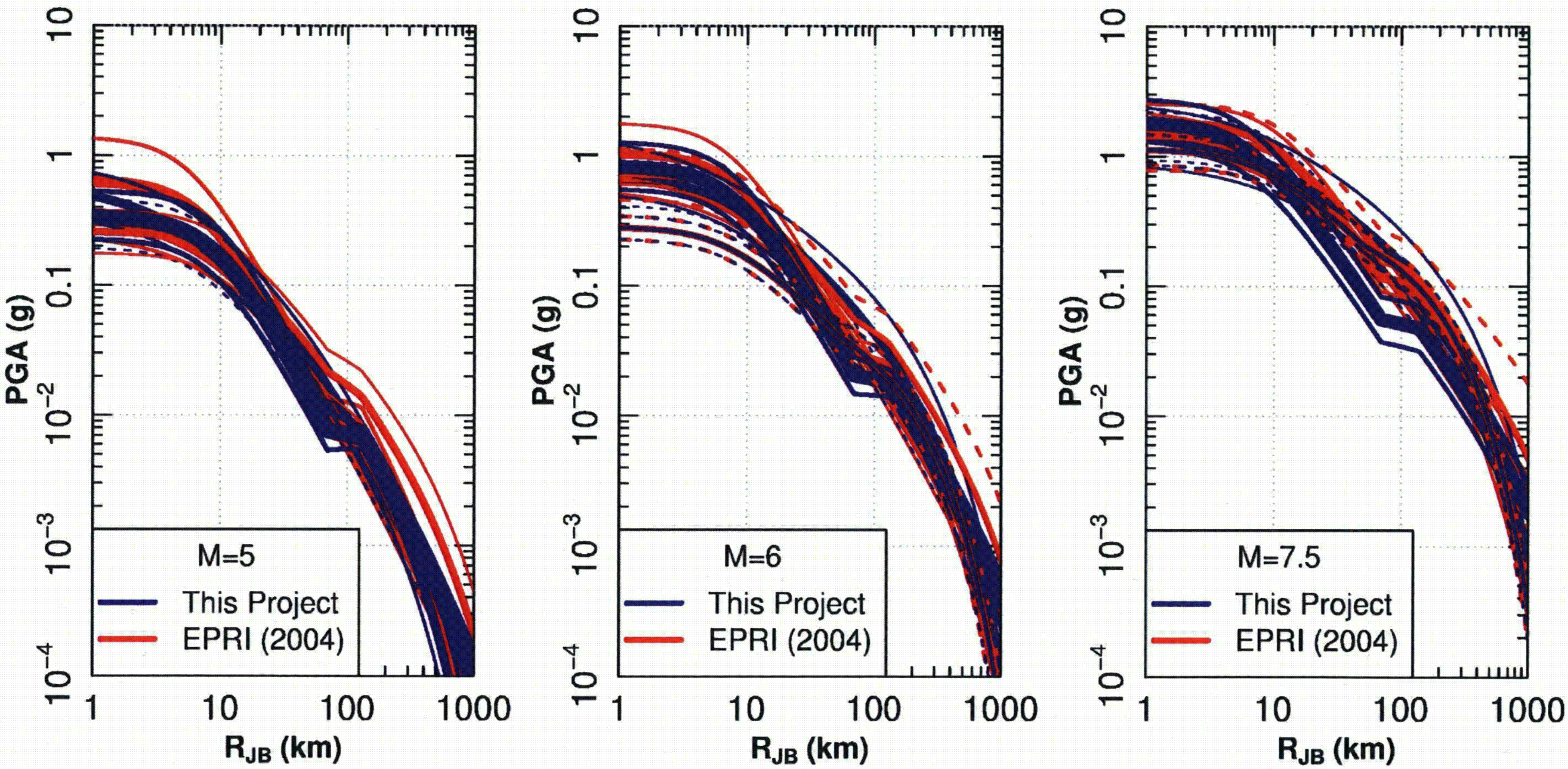
# New Clusters (Mid-Continent): 1 Hz



# New Clusters (Mid-Continent): 0.5 Hz

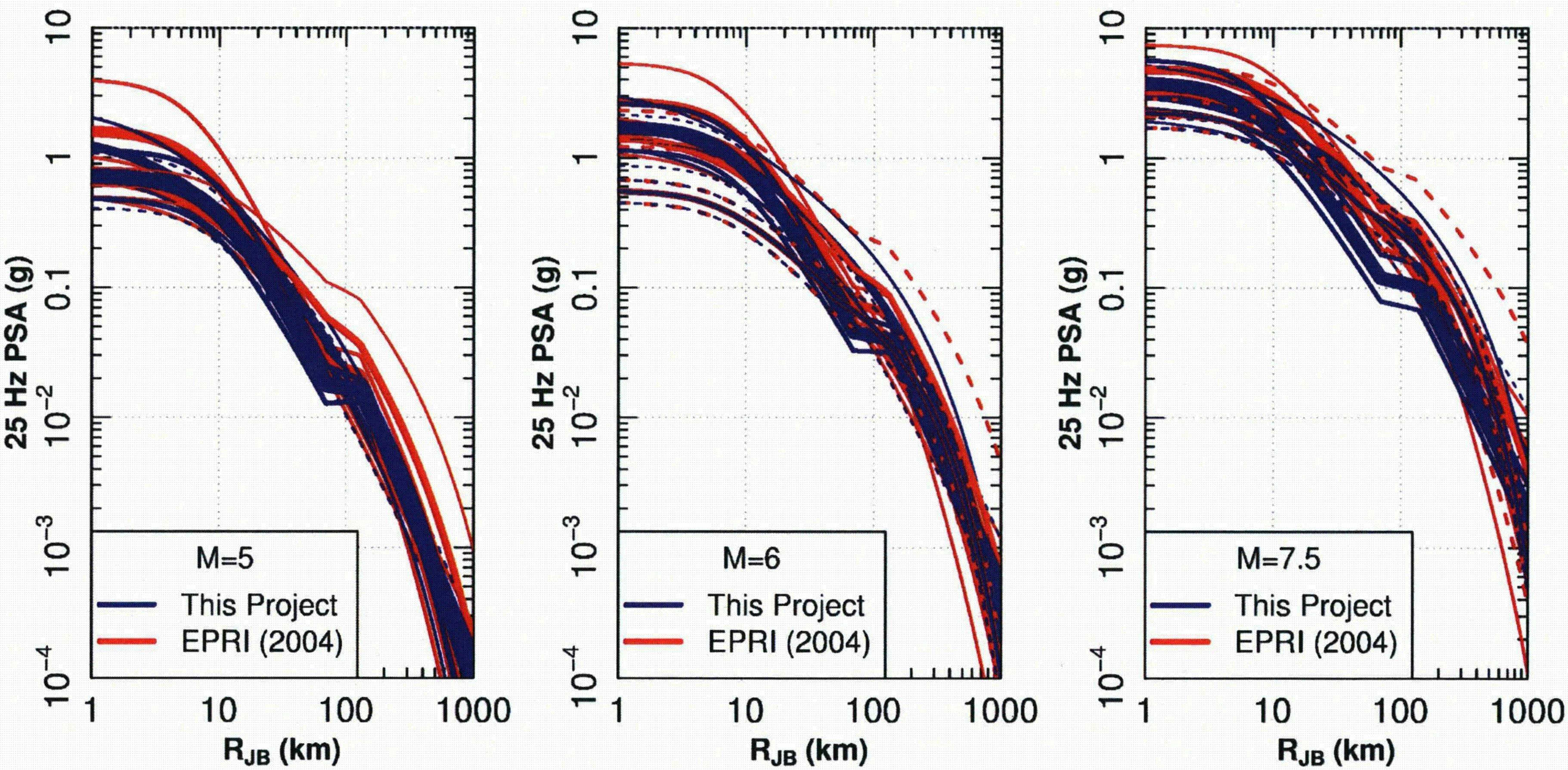


# Comparison to EPRI (2004)*: PGA

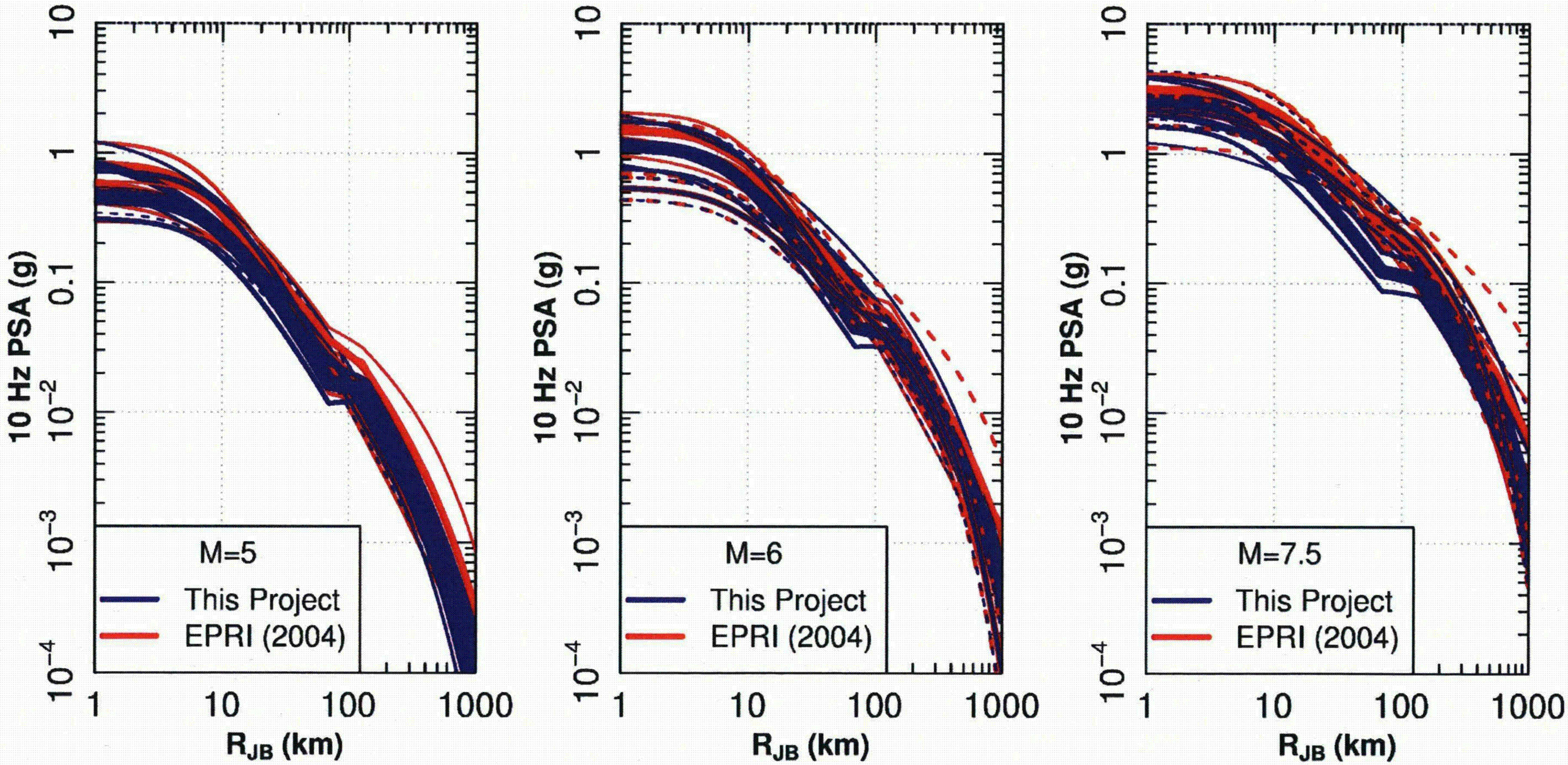



* This figure and the 6 figures that follow apply to the Mid-Continent

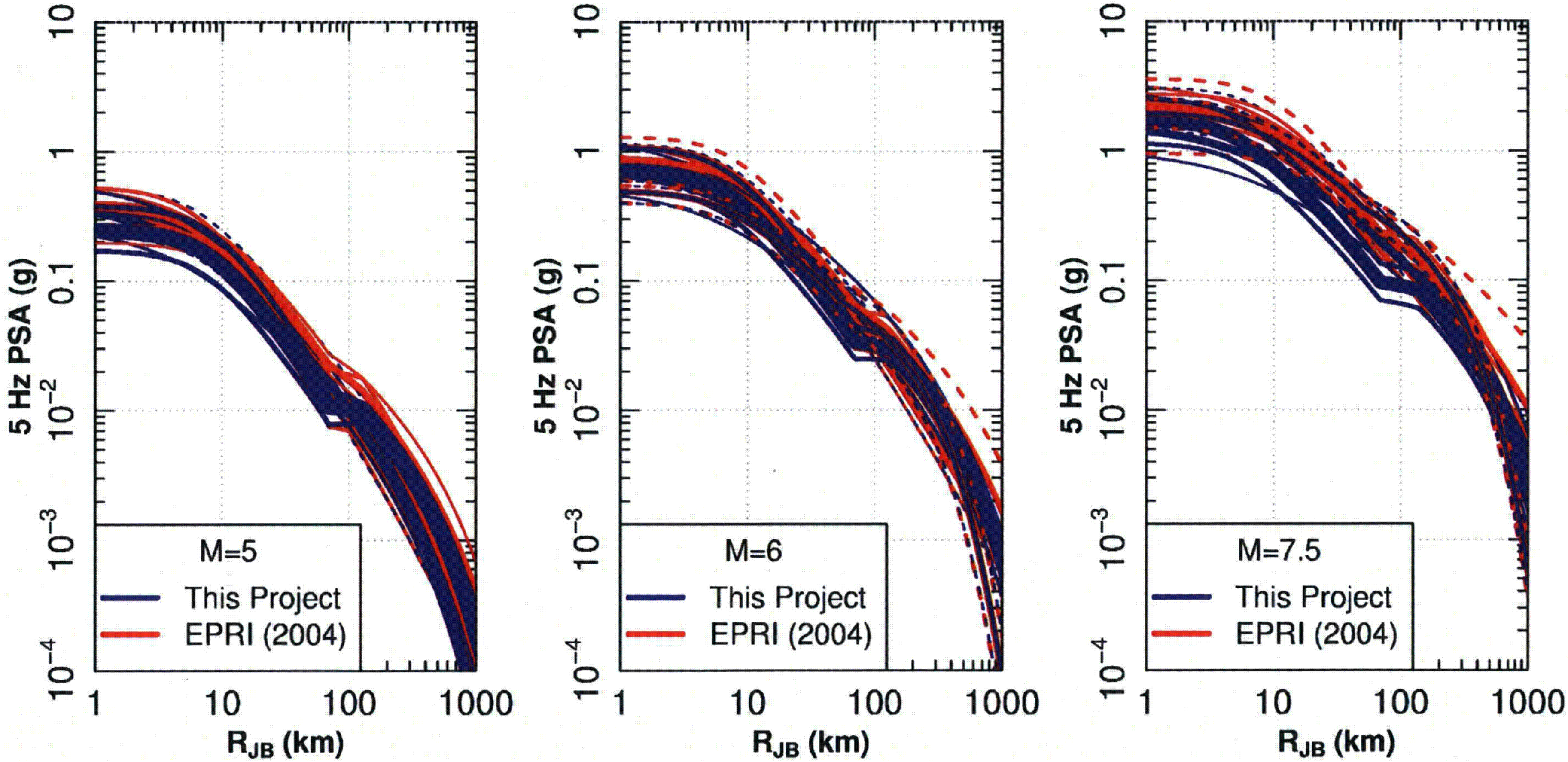
# Comparison to EPRI (2004): 25 Hz



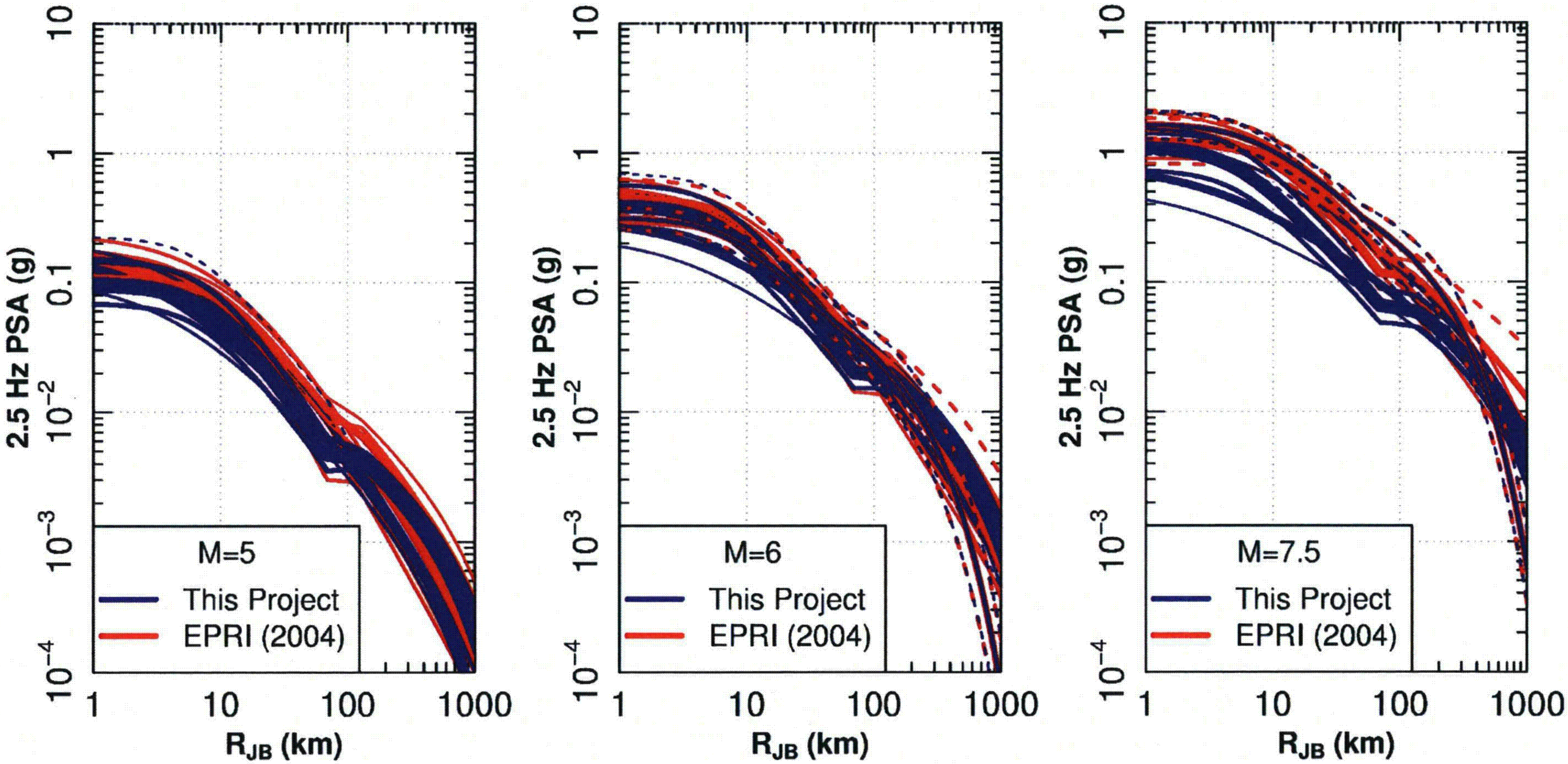
# Comparison to EPRI (2004): 10 Hz



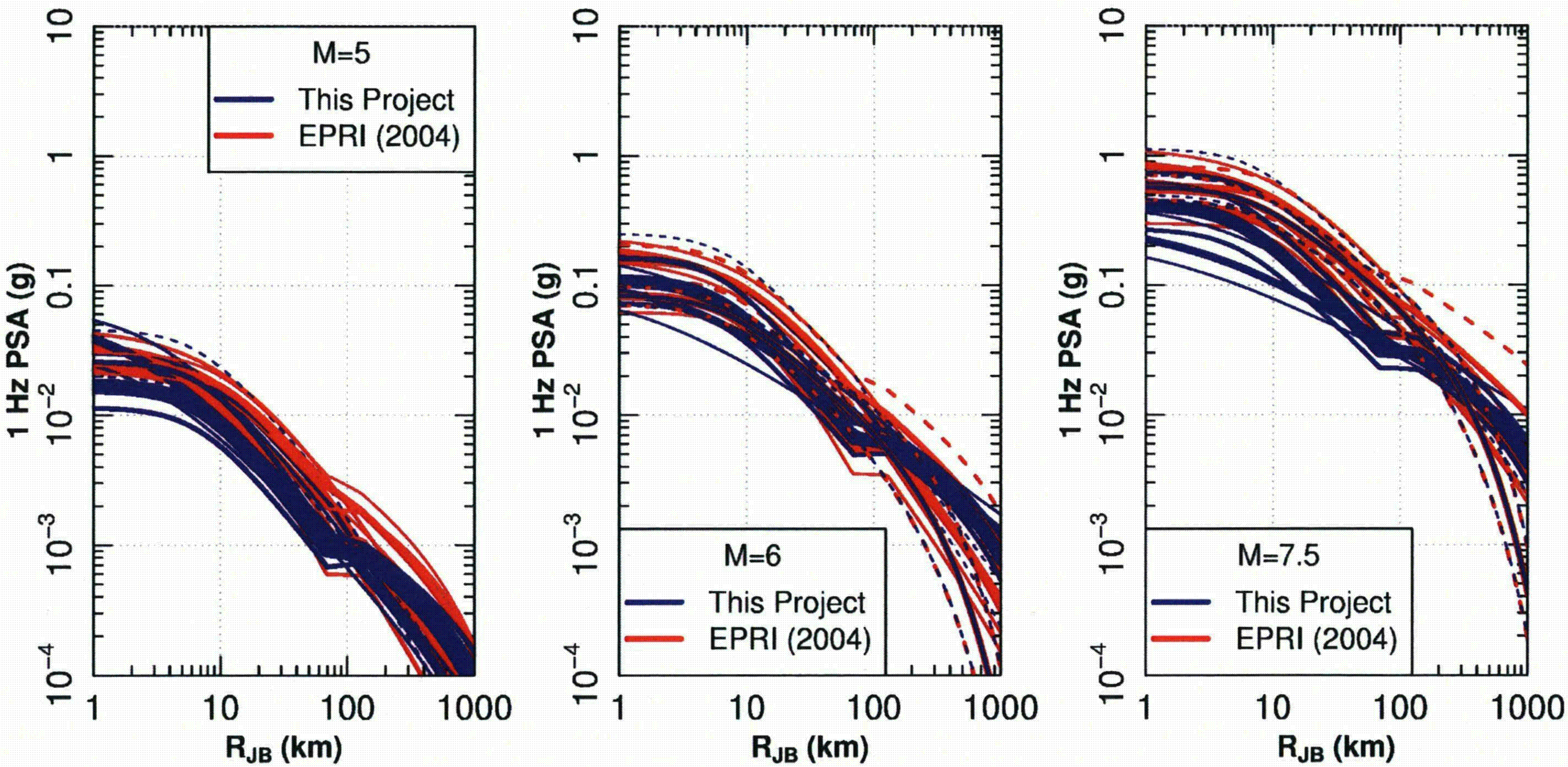
# Comparison to EPRI (2004): 5 Hz



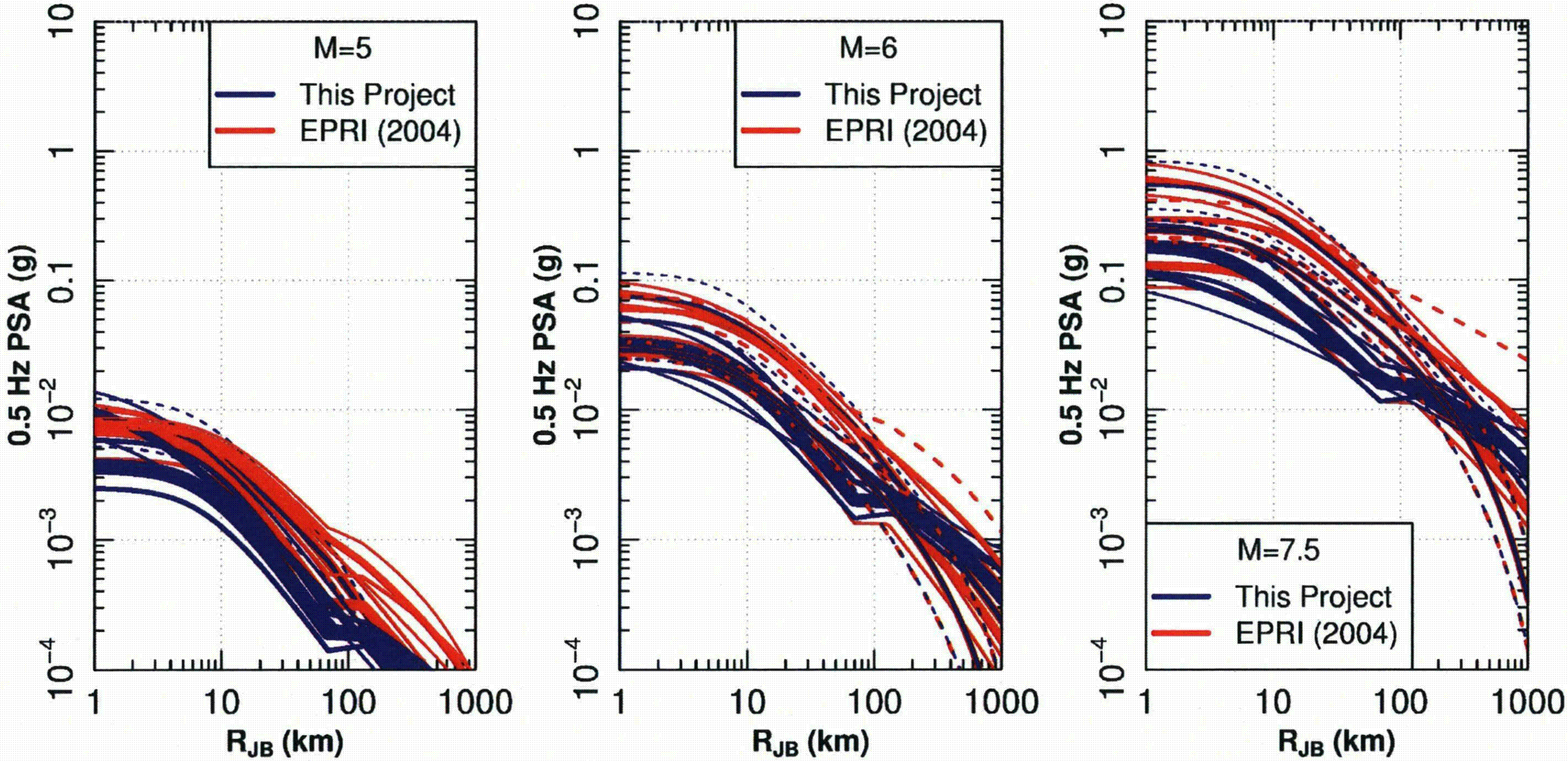
# Comparison to EPRI (2004): 2.5 Hz



# Comparison to EPRI (2004): 1 Hz



# Comparison to EPRI (2004): 0.5 Hz



# Range of Applicability of GMM

- GMM was developed for **M** 5 to 8.5 and distances (Rjb) 0 to 500 km (same as EPRI, 2004)
- Also applicable to distances 500 to 1,000 km, although the uncertainty is greater
- Not applicable to distances > 1,000 km (GMMs not checked or compared to data, data likely affected by selection bias)

# Updated Aleatory Variability Model

# EPRI (2006) Approach

- Concluded that CENA and active tectonic region (e.g. WNA) aleatory variability should be similar
- Used average of preliminary NGA West results to develop aleatory model for active tectonic regions
- Included small increase in event-to-event variability, $\tau$, to account for slightly larger variability noted in data
- Included a lower weighted (0.3) option for lower within-earthquake variability, $\phi$, to represent more uniformity in CENA hard rock sites
- Increase values for frequencies above 10 Hz (excluding PGA) to equal 10 Hz values to account for greater high frequency content in CENA ground motions

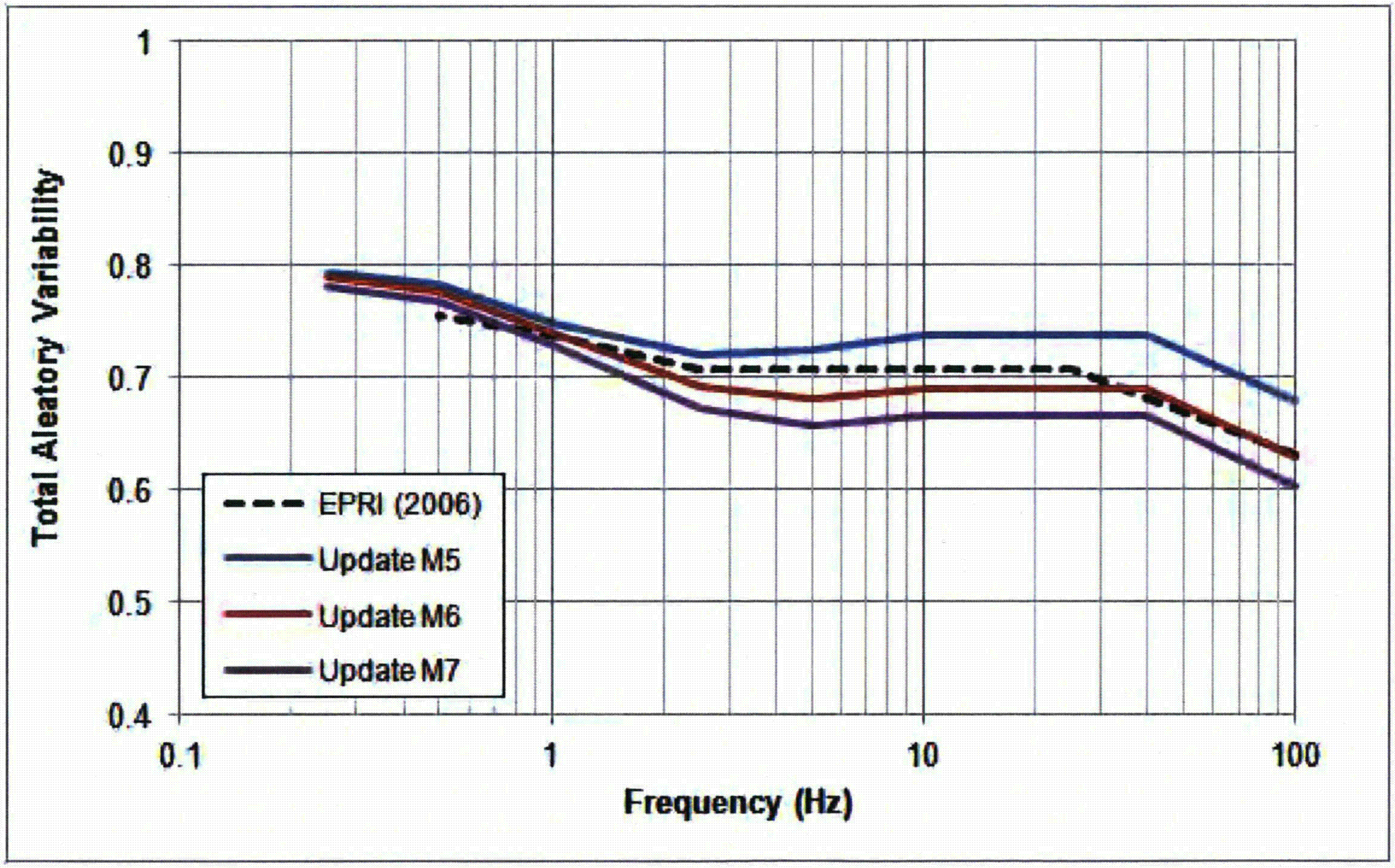
# Update Approach

- Follow EPRI (2006) concept - CENA and active tectonic region (e.g. WNA) aleatory variability should be similar
- Used average of preliminary NGA West2 results augmented by published NGA 2008 models to develop aleatory model for active tectonic regions
- Included small increase in event-to-event variability, $\tau$, to account for slightly larger variability noted in data
- For simplicity, drop alternative option for lower within-earthquake variability, $\phi$, to represent more uniformity in CENA hard rock sites as impact on mean hazard is small

# Updated Aleatory Uncertainties

| Spectral Period (sec) | Average of NGA West 2 | | | | | | Adjusted for CENA | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | M 5 | | M 6 | | M ≥ 7 | | M 5 | | M 6 | | M ≥ 7 | |
| | $\tau$ | $\phi$ | $\tau$ | $\phi$ | $\tau$ | $\phi$ | $\tau$ | $\phi$ | $\tau$ | $\phi$ | $\tau$ | $\phi$ |
| 0.01 (PGA) | 0.35 | 0.55 | 0.33 | 0.51 | 0.31 | 0.50 | 0.38 | 0.55 | 0.36 | 0.51 | 0.34 | 0.50 |
| 0.025 | 0.35 | 0.56 | 0.33 | 0.52 | 0.31 | 0.50 | 0.42 | 0.60 | 0.40 | 0.56 | 0.38 | 0.54 |
| 0.04 | 0.37 | 0.58 | 0.34 | 0.53 | 0.32 | 0.52 | 0.42 | 0.60 | 0.40 | 0.56 | 0.38 | 0.54 |
| 0.1 | 0.39 | 0.60 | 0.37 | 0.56 | 0.35 | 0.54 | 0.42 | 0.60 | 0.40 | 0.56 | 0.38 | 0.54 |
| 0.2 | 0.36 | 0.60 | 0.34 | 0.57 | 0.32 | 0.55 | 0.39 | 0.60 | 0.37 | 0.57 | 0.35 | 0.55 |
| 0.4 | 0.35 | 0.61 | 0.33 | 0.59 | 0.31 | 0.57 | 0.38 | 0.61 | 0.36 | 0.59 | 0.34 | 0.57 |
| 1.0 | 0.39 | 0.62 | 0.38 | 0.62 | 0.36 | 0.61 | 0.42 | 0.62 | 0.41 | 0.62 | 0.39 | 0.61 |
| 2.0 | 0.45 | 0.61 | 0.44 | 0.61 | 0.42 | 0.61 | 0.48 | 0.61 | 0.47 | 0.61 | 0.45 | 0.61 |
| 4.0 | 0.47 | 0.61 | 0.45 | 0.62 | 0.44 | 0.61 | 0.50 | 0.61 | 0.48 | 0.62 | 0.47 | 0.61 |

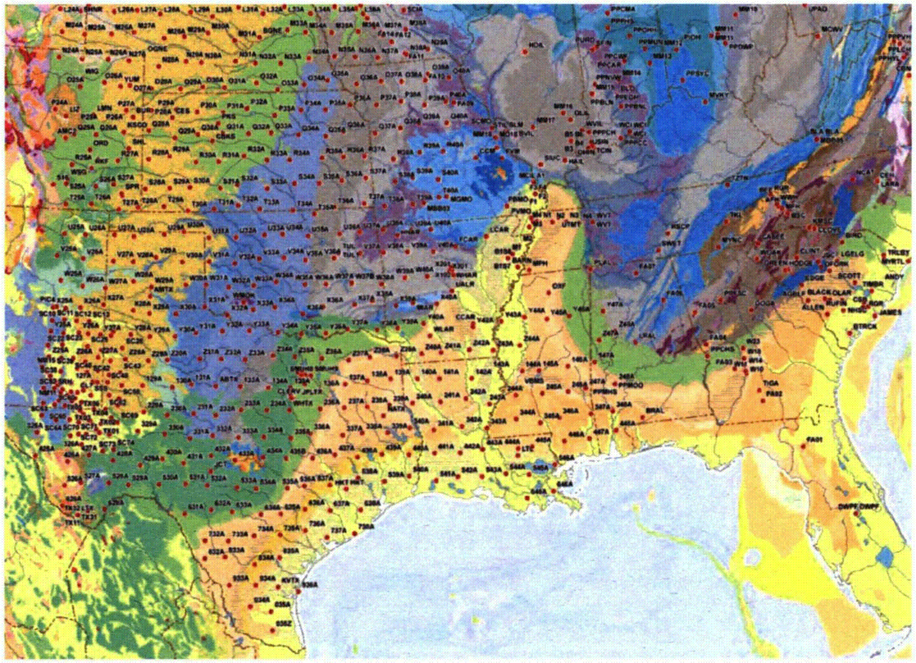
# Comparison of EPRI (2006) and Updated Models



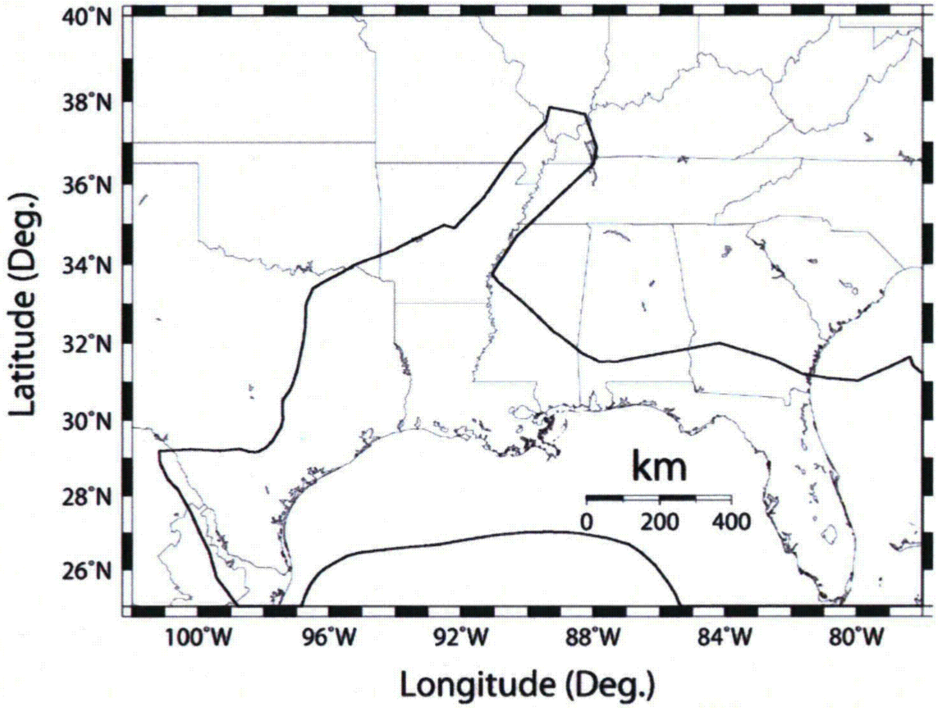
# Estimation of Q in the Basement of the Gulf Coast Region

Martin Chapman
Dept. Geosciences, Virginia Tech

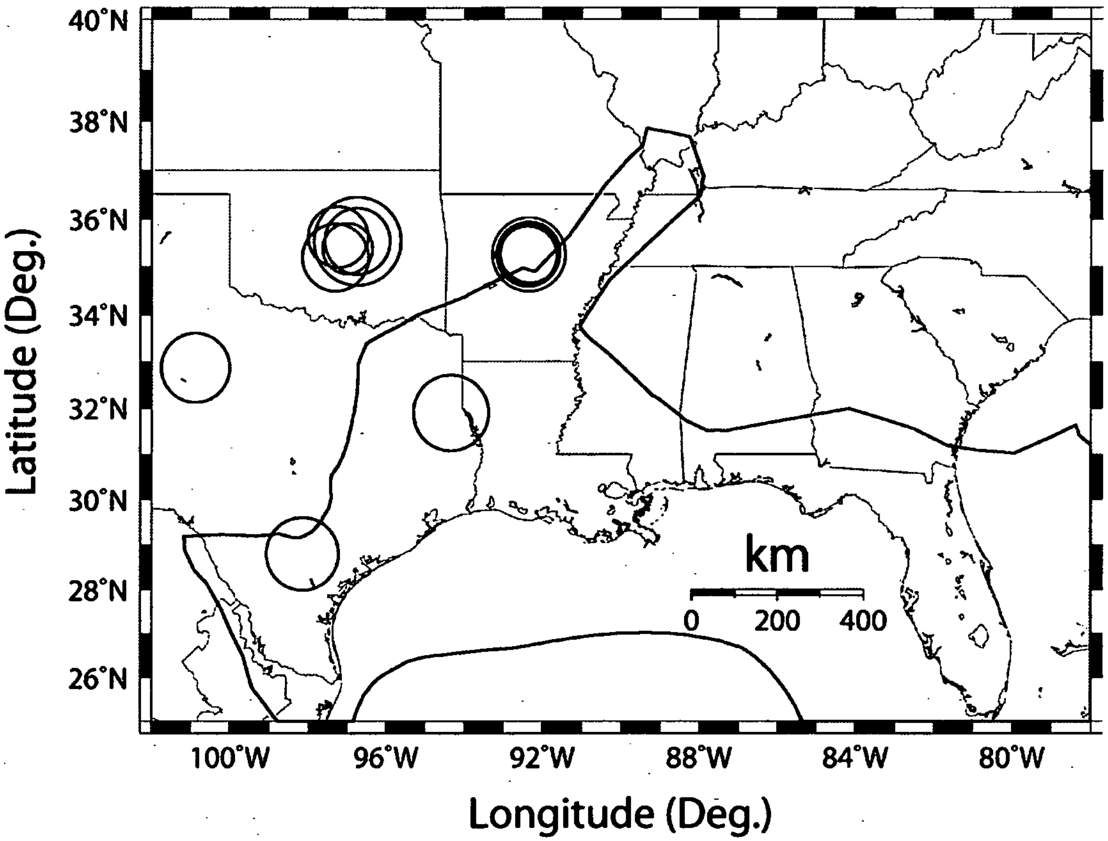
January, 2013



*Geologic map showing the locations of EARTHSCOPE Transportable Array stations installed as of April, 2011, as well as other regional broadband stations.*




Gulf Coast region used for attenuation study.




*Circles show epicenters of 16 earthquakes listed in Table 1.*

Table 1

| Date | Lat. | Long. | Moment Magnitude |
|---|---|---|---|
| 10-13-2010 | 35.202 | -97.309 | 4.33 |
| 10-15-2010 | 35.276 | -92.322 | 3.80 |
| 11-20-2010 | 35.316 | -92.317 | 3.90 |
| 11-24-2010 | 35.627 | -97.246 | 3.90 |
| 12-27-2010 | 35.540 | -96.750 | 4.15 |
| 12-12-2010 | 35.392 | -96.995 | 3.20 |
| 02-17-2011 | 35.276 | -92.361 | 3.80 |
| 02-18-2011 | 35.257 | -92.370 | 3.90 |
| 02-18-2011 | 35.271 | -92.377 | 4.10 |
| 02-28-2011 | 35.265 | -93.340 | 4.65 |
| 04-07-2011 | 35.350 | -92.373 | 3.73 |
| 04-08-2011 | 35.261 | -92.362 | 3.90 |
| 11-06-2011 | 35.537 | -96.747 | 5.60 |
| 09-11-2011 | 32.874 | -100.876 | 4.40 |
| 10-20-2011 | 28.806 | -98.147 | 4.60 |
| 05-17-2012 | 31.902 | -94.332 | 4.83 |

## Regression Model

$$Ln\left[\frac{A_{ij}(f)}{S_i(f)G(r_{ij})}\right] = R_j(f) - \frac{\pi r_{ij} f}{QV}$$

$A_{ij}(f)$ = Fourier acceleration amplitude (geometric mean of the two horizontal components),
$S_i(f)$ = Earthquake source amplitude spectrum,
$G(r_{ij})$= Geometrical spreading (independent of frequency f),
$R_j(f)$ = Receiver (Site) amplitude term,
$r_{ij}$ = epicentral distance, from ith earthquake to the jth receiver station.
V = Lg velocity (3.53 km/s).

Geometrical Spreading Model 1

$$G(r) = r^{-1.3},\ r \le 60\ km$$

$$G(r) = 60^{-1.3}, 60 \le r \le 120\ km$$

$$G(r) = 60^{-1.3}\left(\frac{r}{120}\right)^{-0.5}, r > 120\ km$$

Geometrical Spreading Model 2

$$G(r) = r^{-1.0}, \qquad r \le 60\ km$$

$$G(r) = 60^{-1.0}, \qquad 60 \le r \le 120\ km$$

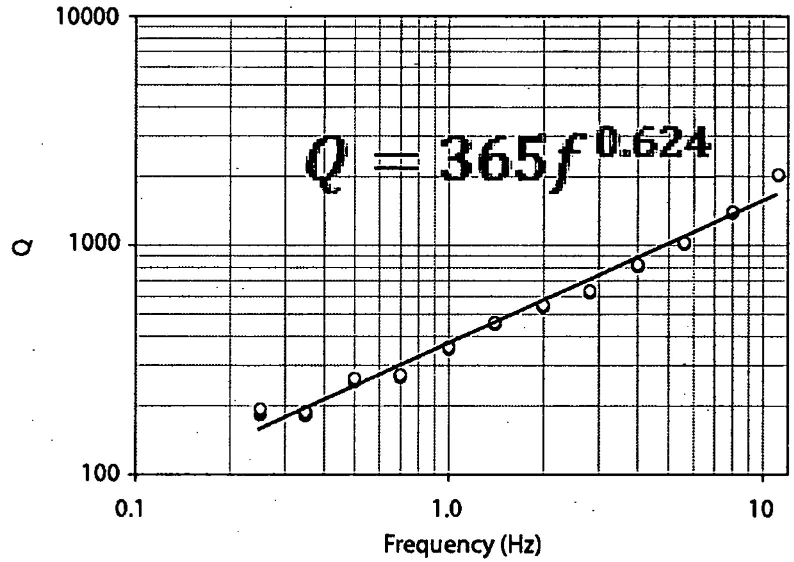
$$G(r) = 60^{-1.0}\left(\frac{r}{120}\right)^{-0.5}, r > 120\ km$$

Estimates of Q: 10 MPa stress drop

| | Geo. spreading model 1 | | Geo. spreading model 2 | |
|---|---|---|---|---|
| Frequency (Hz) | Q | σ | Q | σ |
| 0.25 | 182 | 37 | 179 | 37 |
| 0.35 | 180 | 17 | 179 | 16 |
| 0.50 | 254 | 22 | 252 | 23 |
| 0.70 | 265 | 17 | 265 | 16 |
| 1.00 | 352 | 21 | 350 | 22 |
| 1.40 | 451 | 25 | 449 | 25 |
| 2.00 | 537 | 25 | 535 | 25 |
| 2.80 | 620 | 25 | 617 | 25 |
| 4.00 | 806 | 32 | 805 | 32 |
| 5.60 | 1013 | 40 | 1013 | 40 |
| 8.00 | 1377 | 62 | 1374 | 61 |
| 11.2 | 2009 | 141 | 2012 | 142 |

The estimates of Q are not sensitive to the choice of geometrical spreading

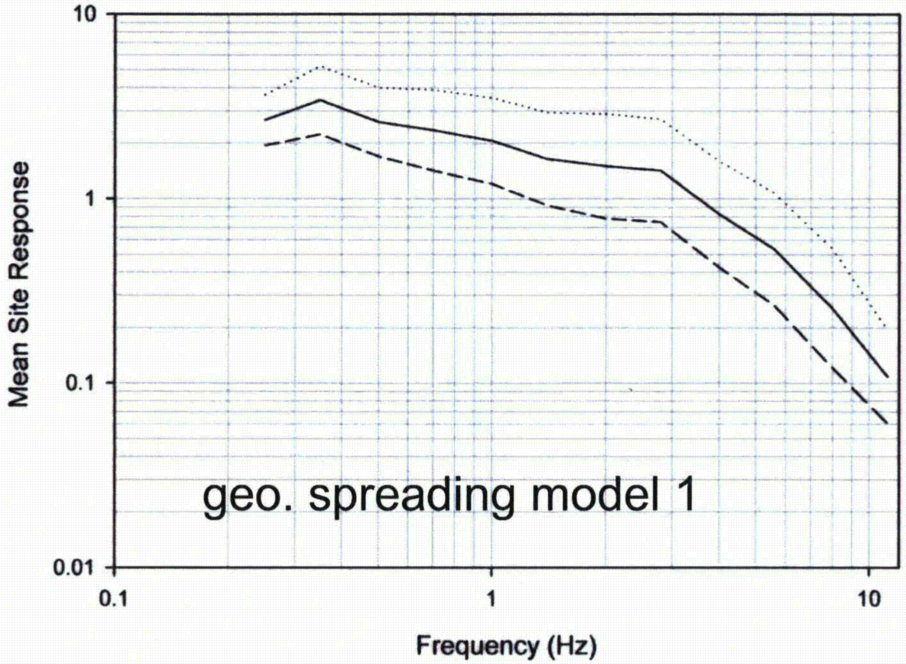
# Q for the Basement in the Gulf Coast Region

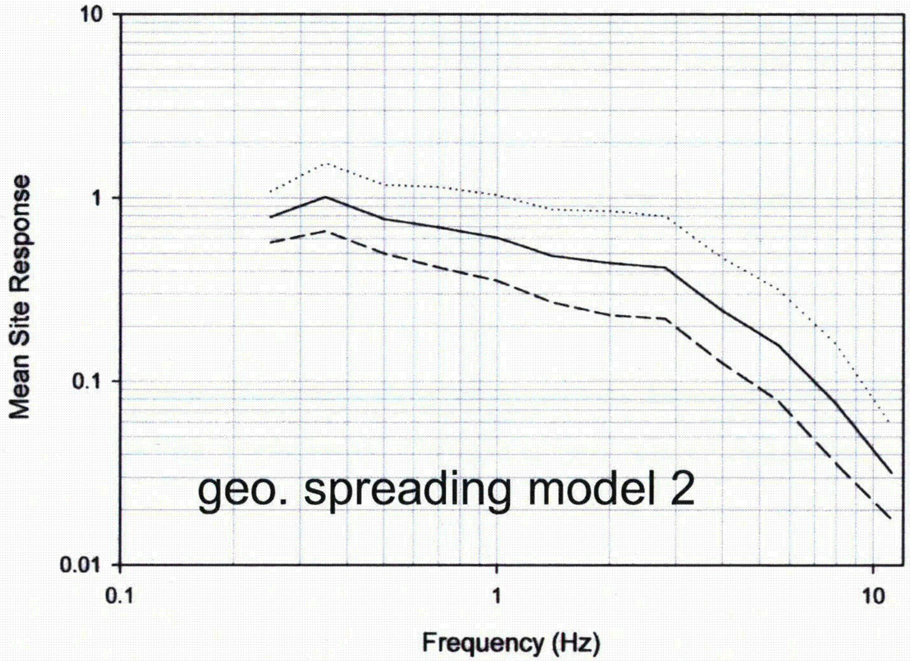



Open Circles: 10 MPa stress drop
Filled Circles: 5 MPa stress drop

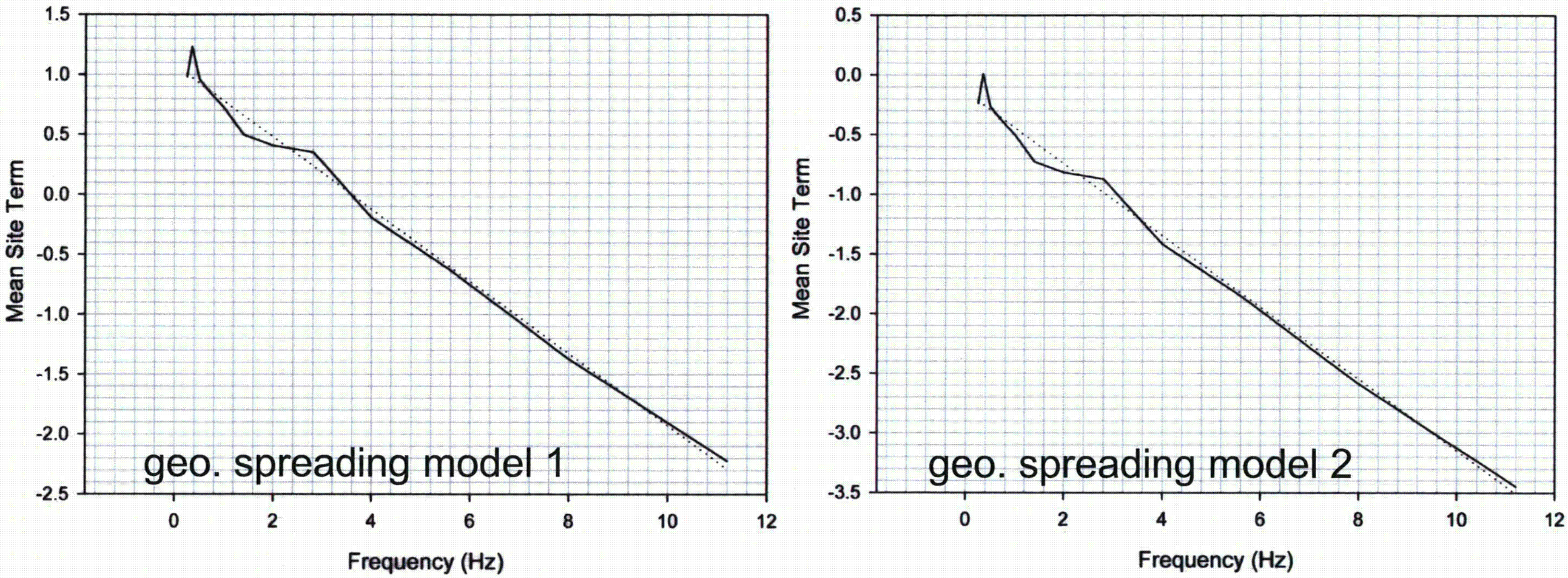
The estimates of Q are not sensitive to the assumed stress drop

Mean +/- 1 Standard Deviation Site Response For Stations South of 33N Lat.




The amplitudes of the site response terms are sensitive to the assumed model for geometrical spreading. But the shape of the average site response spectrum not. This means that average Kappa for sites in the Gulf Region can be reliably estimated from the Earthscope TA data.




The slope of the Site Term versus frequency function gives an estimate of Kappa. For the average site condition in the Gulf Region south of Latitude 33N, $K_o$ = 0.096 seconds.

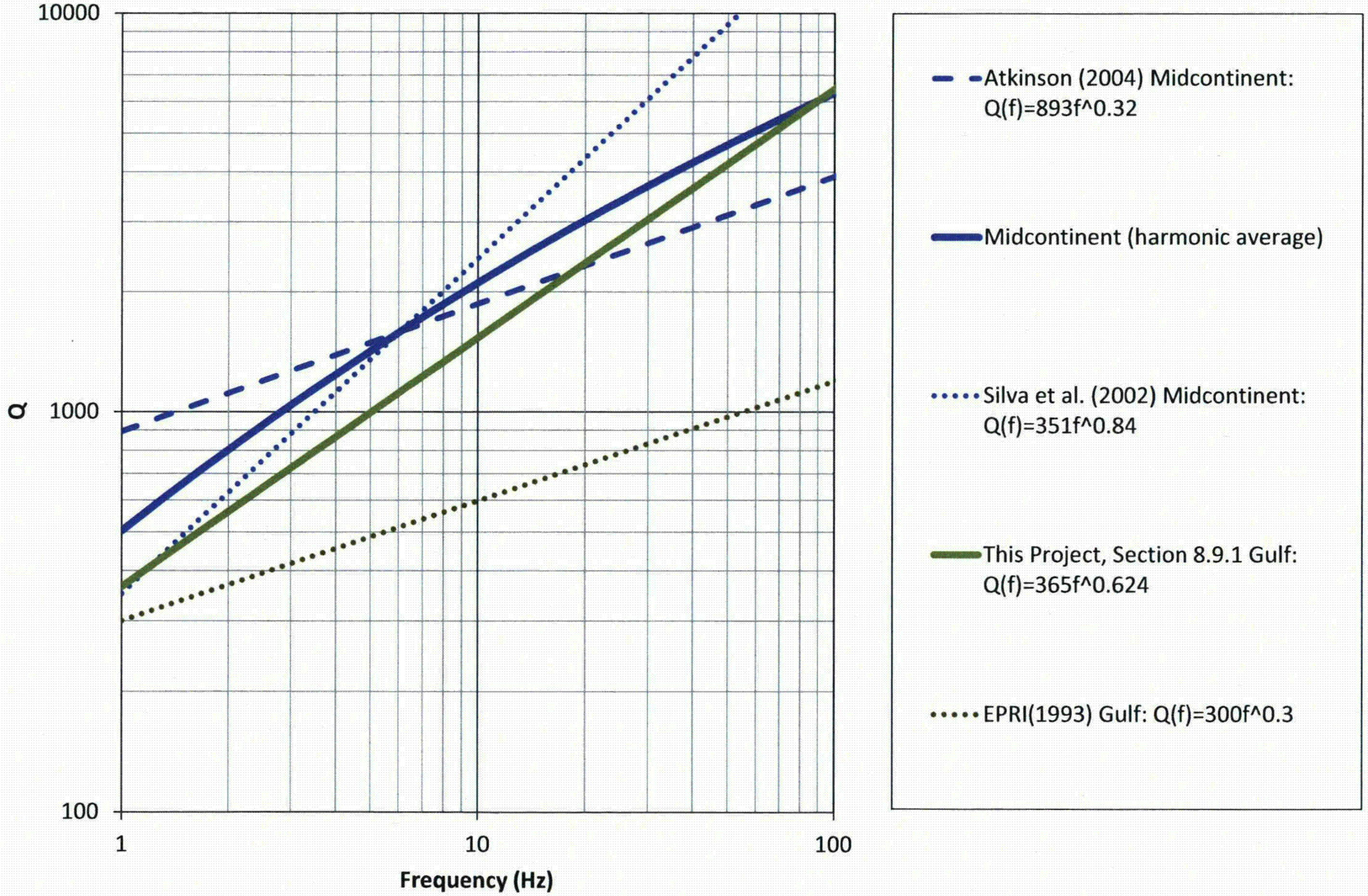
# Modification of Midcontinent GMM for Application to the Gulf of Mexico Crustal Region

Gabriel Toro

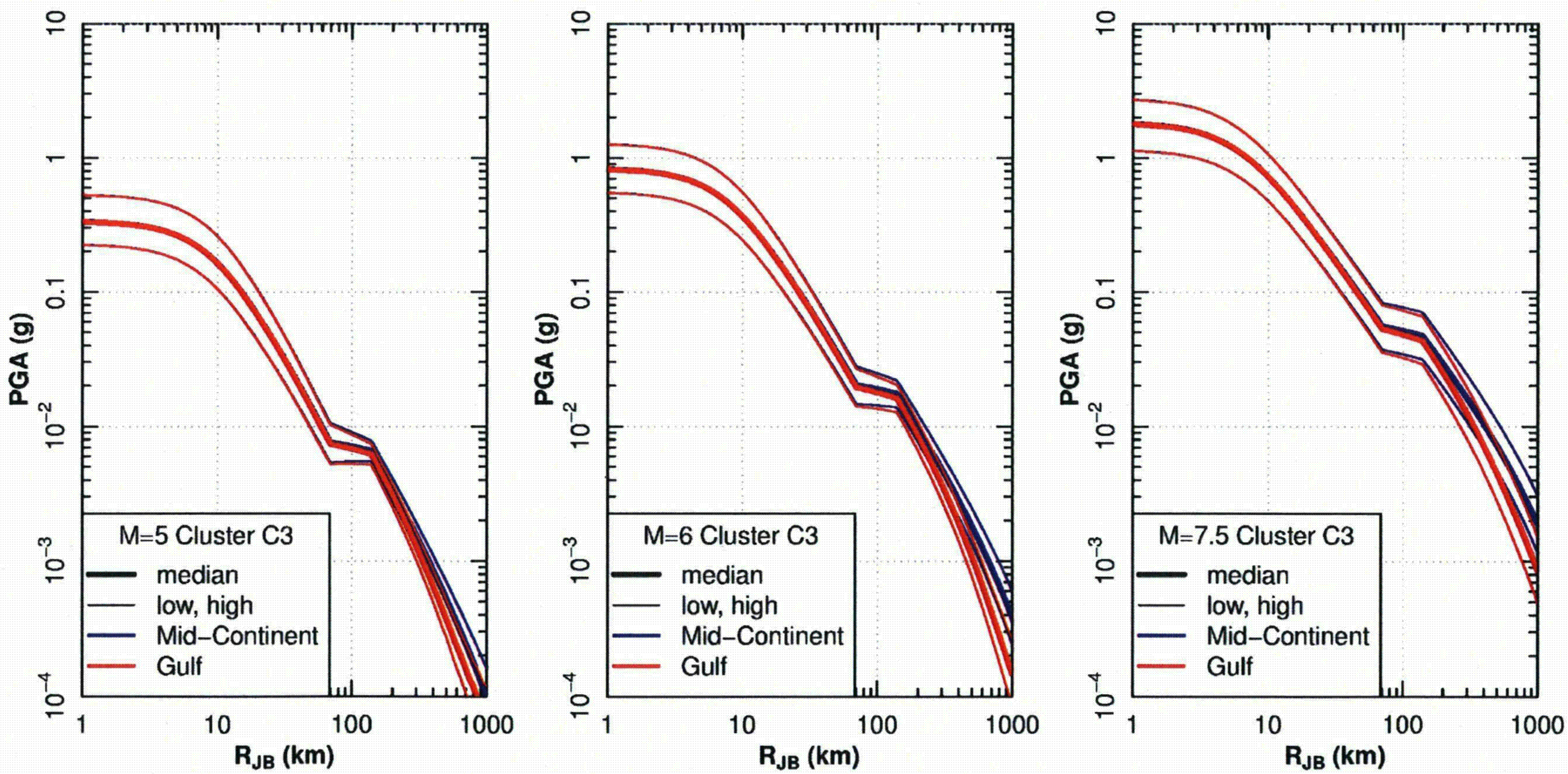
# Approach (similar to EPRI, 2004)

1. Adjust for differences in Q
   a. Calculate Mid-Continent Response Spectrum
   b. Use IRVT to calculate corresponding Fourier Spectrum
   c. Correct for effect of differences in Q
   d. Convert back to response spectrum using RVT
   e. Correct HF shape (mostly at long distances)
      - e.g Sa(25)/PGA should not be lower for Gulf than for Mid-Contient
2. Repeat steps a-e for all curves, many magnitudes & distances
3. Fit new GMPEs using same functional forms

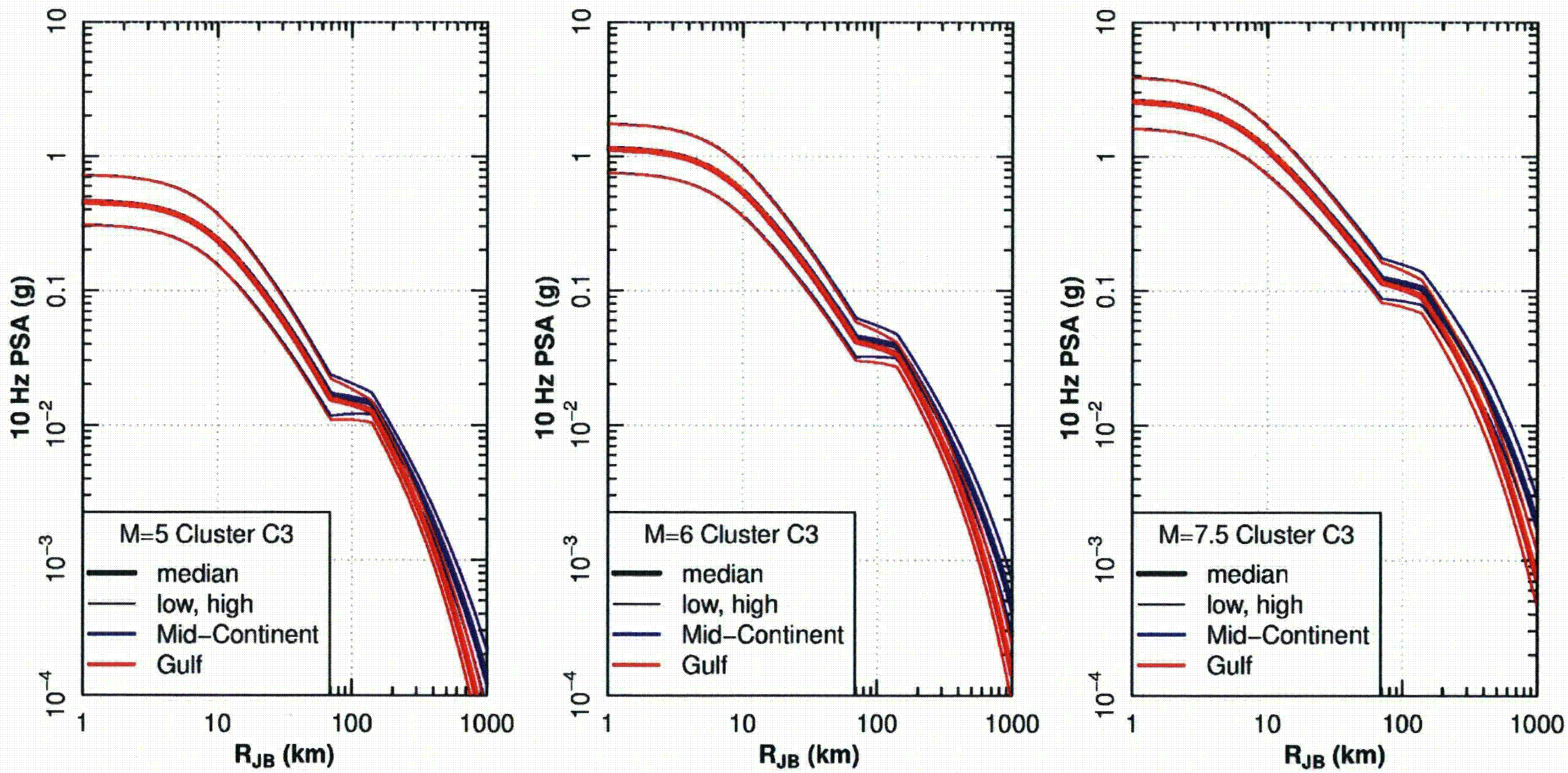
# Q(f) Models for Mid-Continent and Gulf



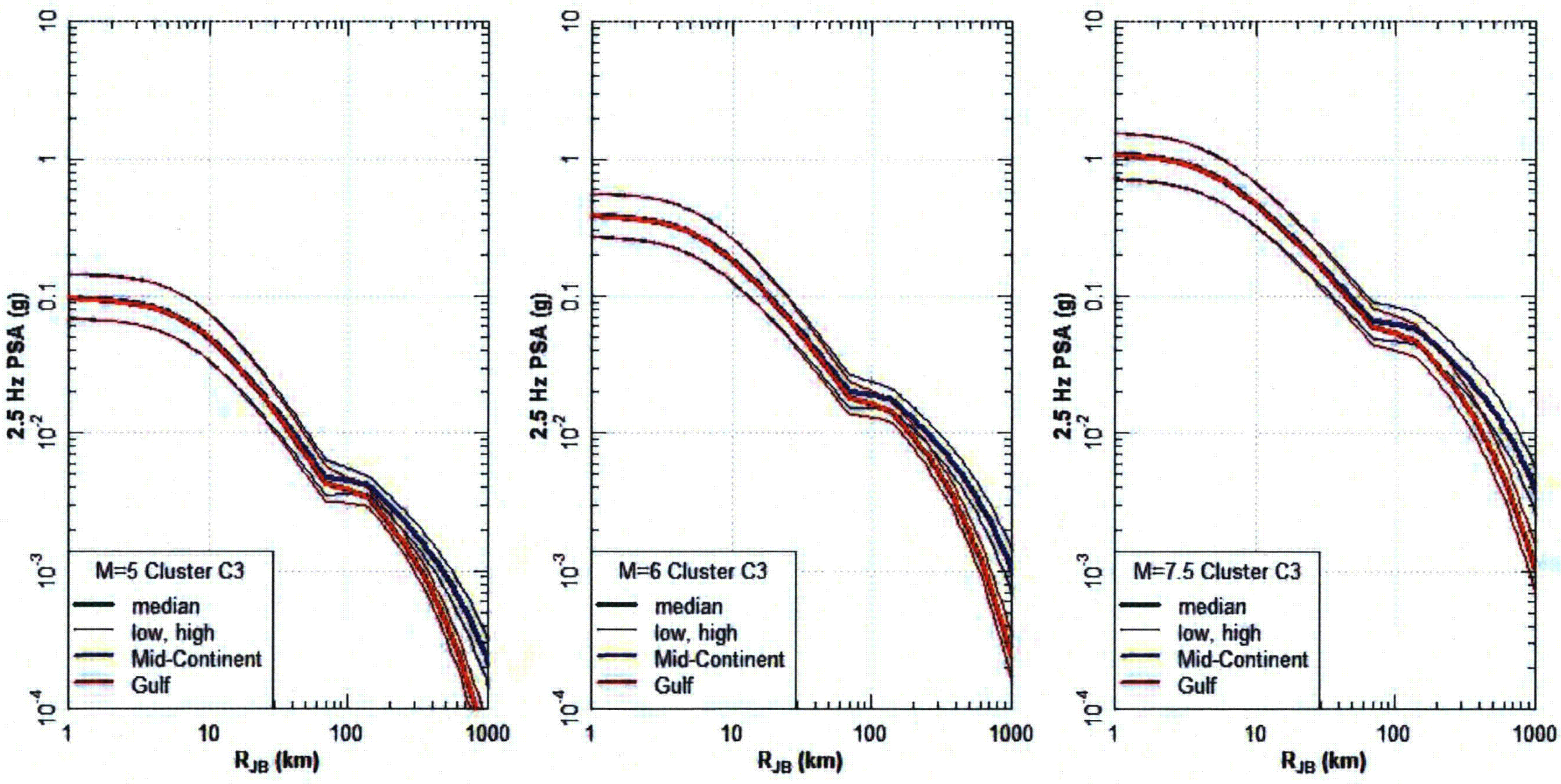
# Gulf vs. Mid-Continent: Cluster 3 PGA



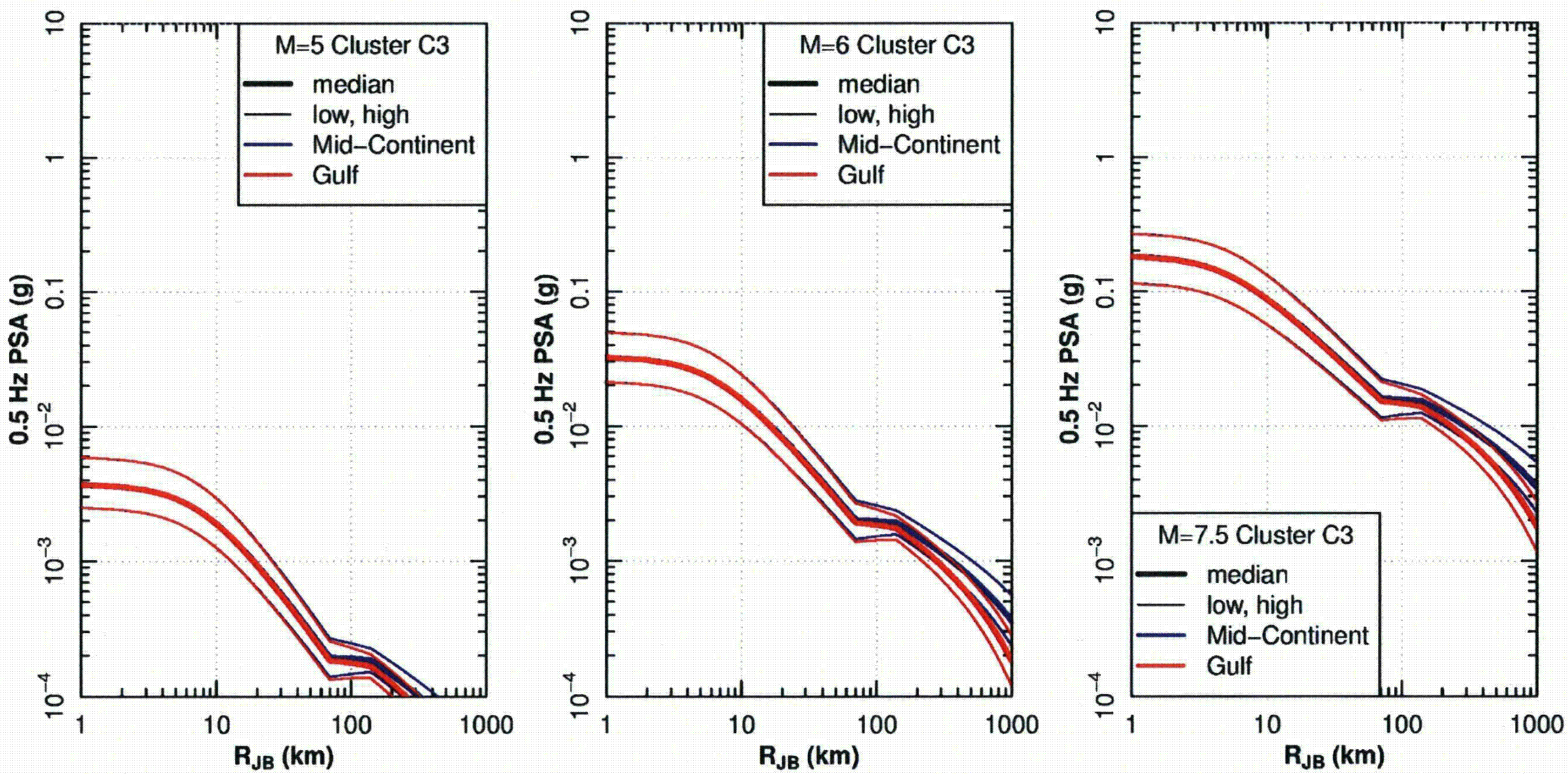
# Gulf vs. Mid-Continent: Cluster 3 10 Hz



# Gulf vs. Mid-Continent: Cluster 3 2.5 Hz



# Gulf vs. Mid-Continent: Cluster 3 0.5 Hz



# Thank you