CENA GMPEs from Stochastic Method Simulations: Review, Issues, Recent Work

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Senior Seismic Hazard
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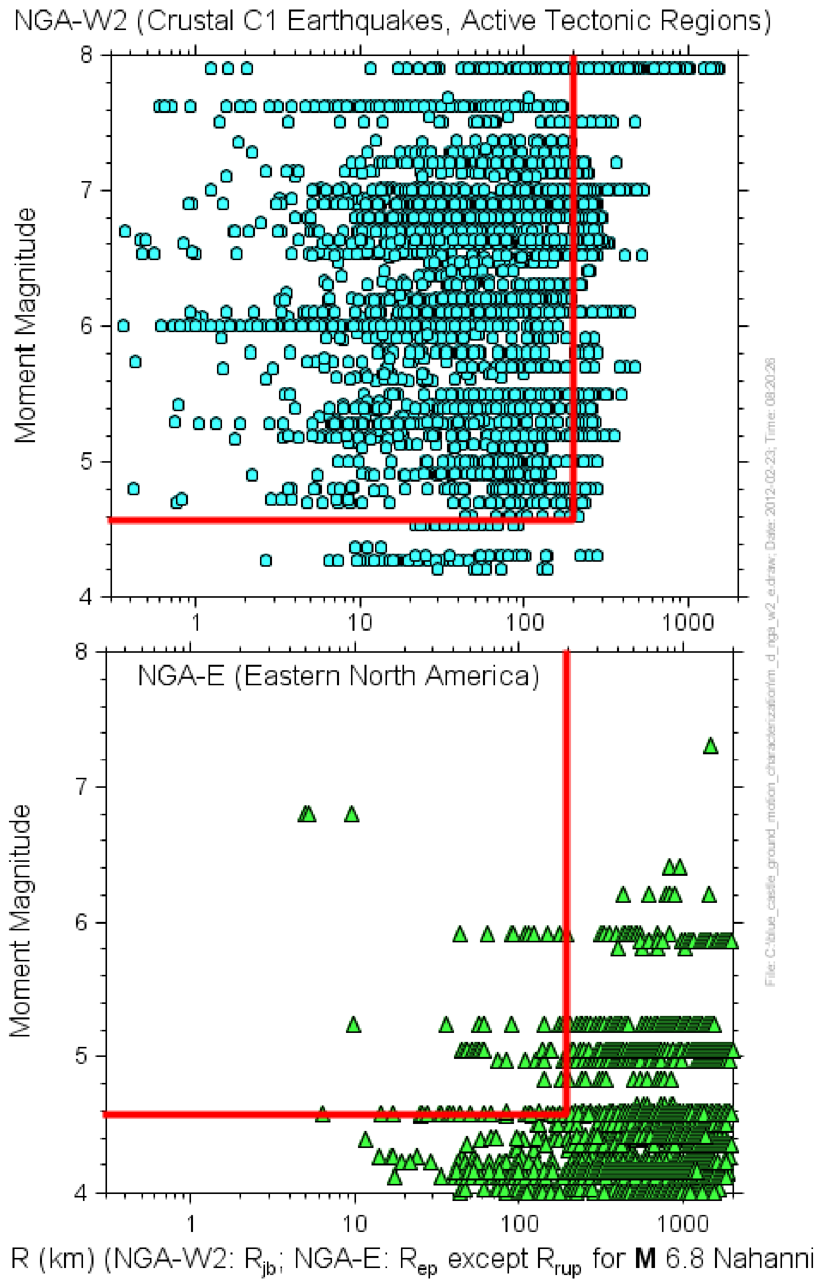


Observed data adequate for regression except
close to large 'quakes

Observed data not adequate for regression, **use simulated data**

Stochastic simulations

- Point source
  - With appropriate choice of source scaling, duration, geometrical spreading, and distance can capture some effects of finite source
- Finite source
  - Many models (deterministic and/or stochastic, and can also use empirical Green's functions), no consensus on the best (blind prediction experiments show large variability)
  - Usually use point-source stochastic model
  - Possible to capture extended rupture effects for high-frequency motions with the point-source model by adjusting the distance measure

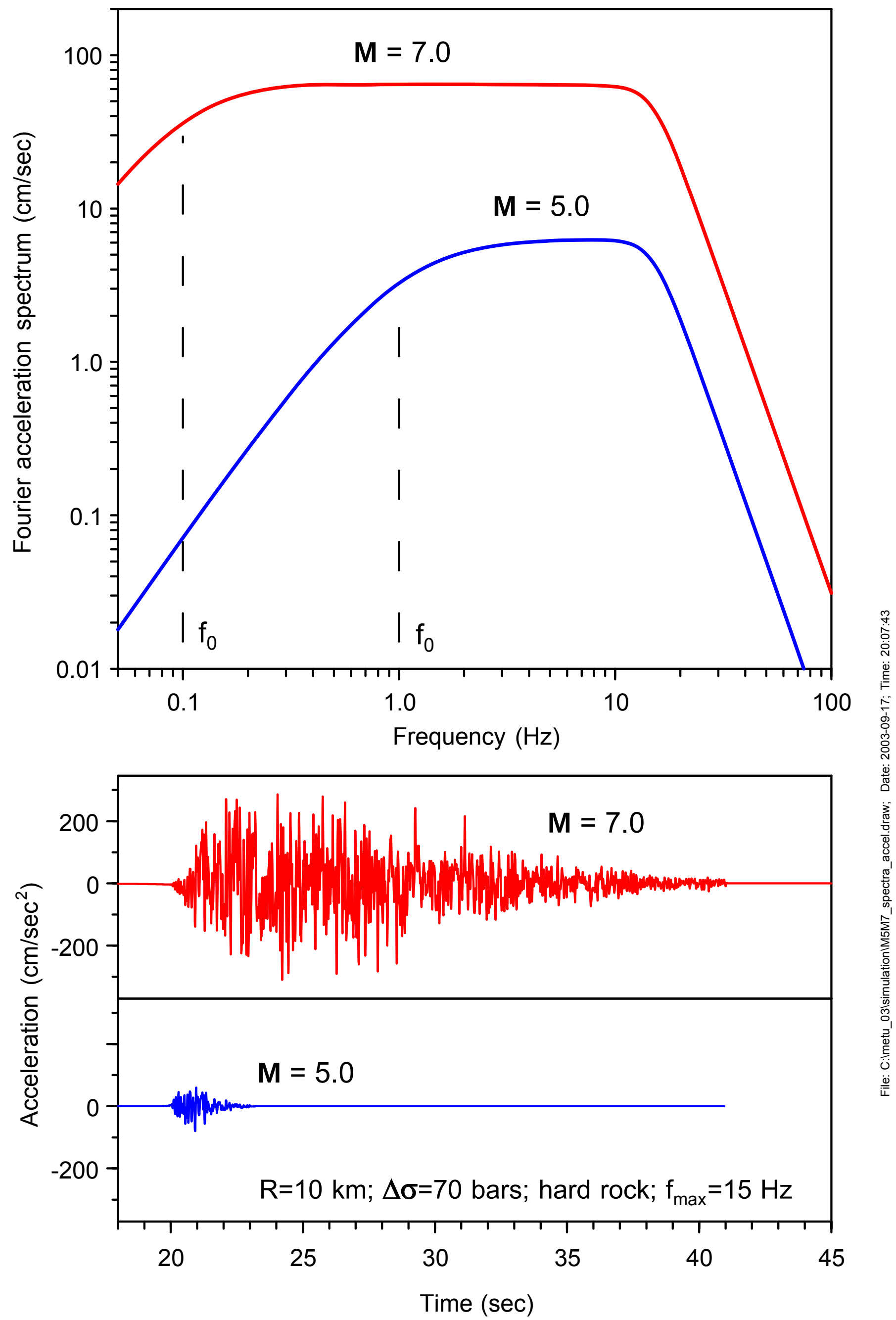
Stochastic modelling of ground-motion: Point Source

- Deterministic modelling of high-frequency waves not possible (lack of Earth detail and computational limitations)
- Treat high-frequency motions as filtered white noise (Hanks & McGuire , 1981).
- combine deterministic target amplitude obtained from simple seismological model and quasi-random phase to obtain high-frequency motion. Try to capture the essence of the physics using simple functional forms for the seismological model. **Use empirical data when possible to determine the parameters**.

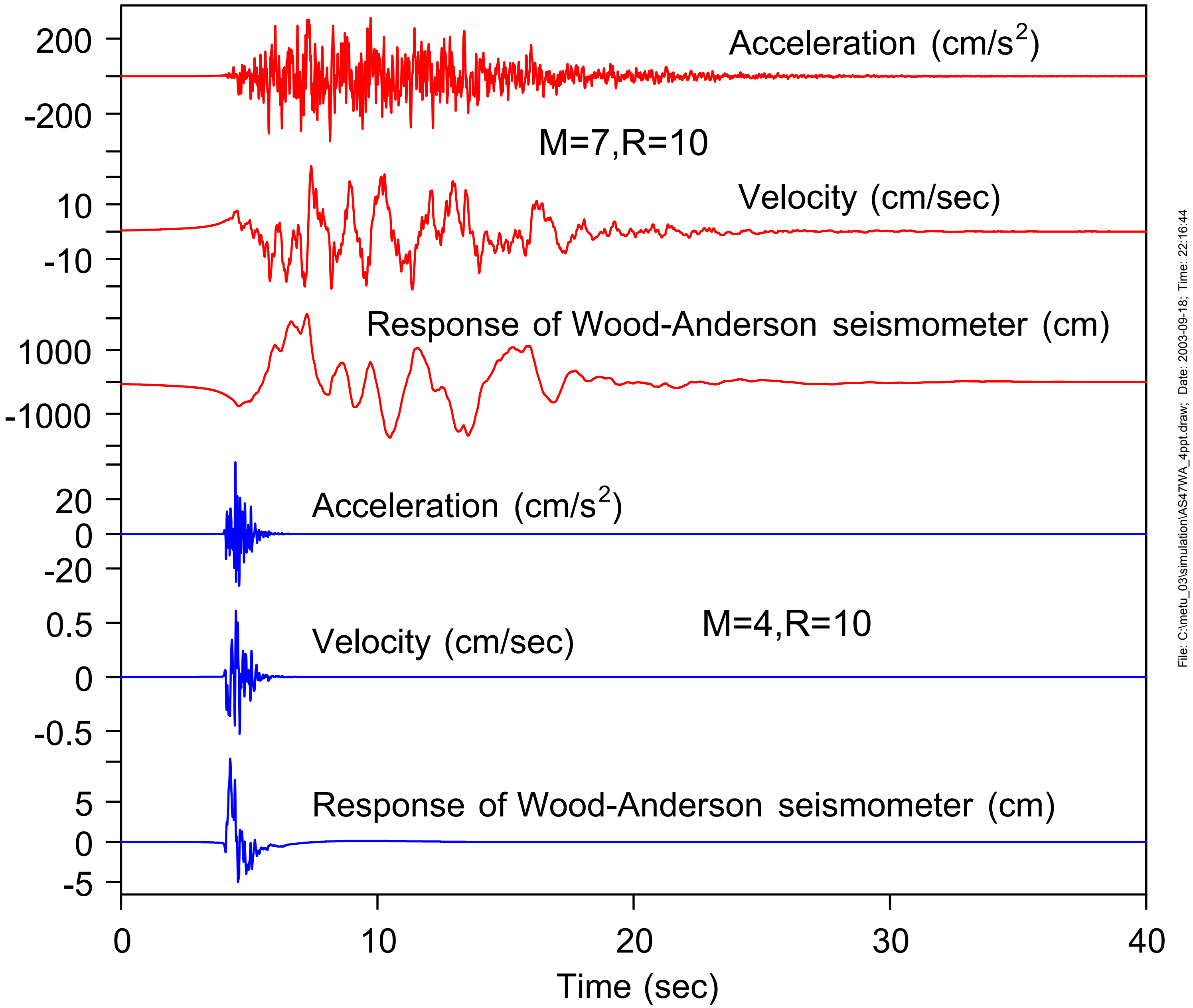
Basis of stochastic method

Radiated energy described by the spectra in the top graph is assumed to be distributed randomly over a duration given by the addition of the source duration and a distant-dependent duration that captures the effect of wave propagation and scattering of energy

These are the results of actual simulations; the only thing that changed in the input to the computer program was the moment magnitude (5 and 7)



Acceleration, velocity, oscillator response for two very different magnitudes, changing only the magnitude in the input file



- Ground motion and response parameters can be obtained via two separate approaches:
  - Time-series simulation:
    - Superimpose a quasi-random phase spectrum on a deterministic amplitude spectrum and compute synthetic record
    - All measures of ground motion can be obtained
  - Random vibration simulation:
    - Probability distribution of peaks is used to obtain peak parameters directly from the target spectrum
    - Very fast
    - Can be used in cases when very long time series, requiring very large Fourier transforms, are expected (large distances, large magnitudes)
    - Elastic response spectra, PGA, PGV, PGD, equivalent linear (SHAKE-like) soil response can be obtained

Time-domain simulation

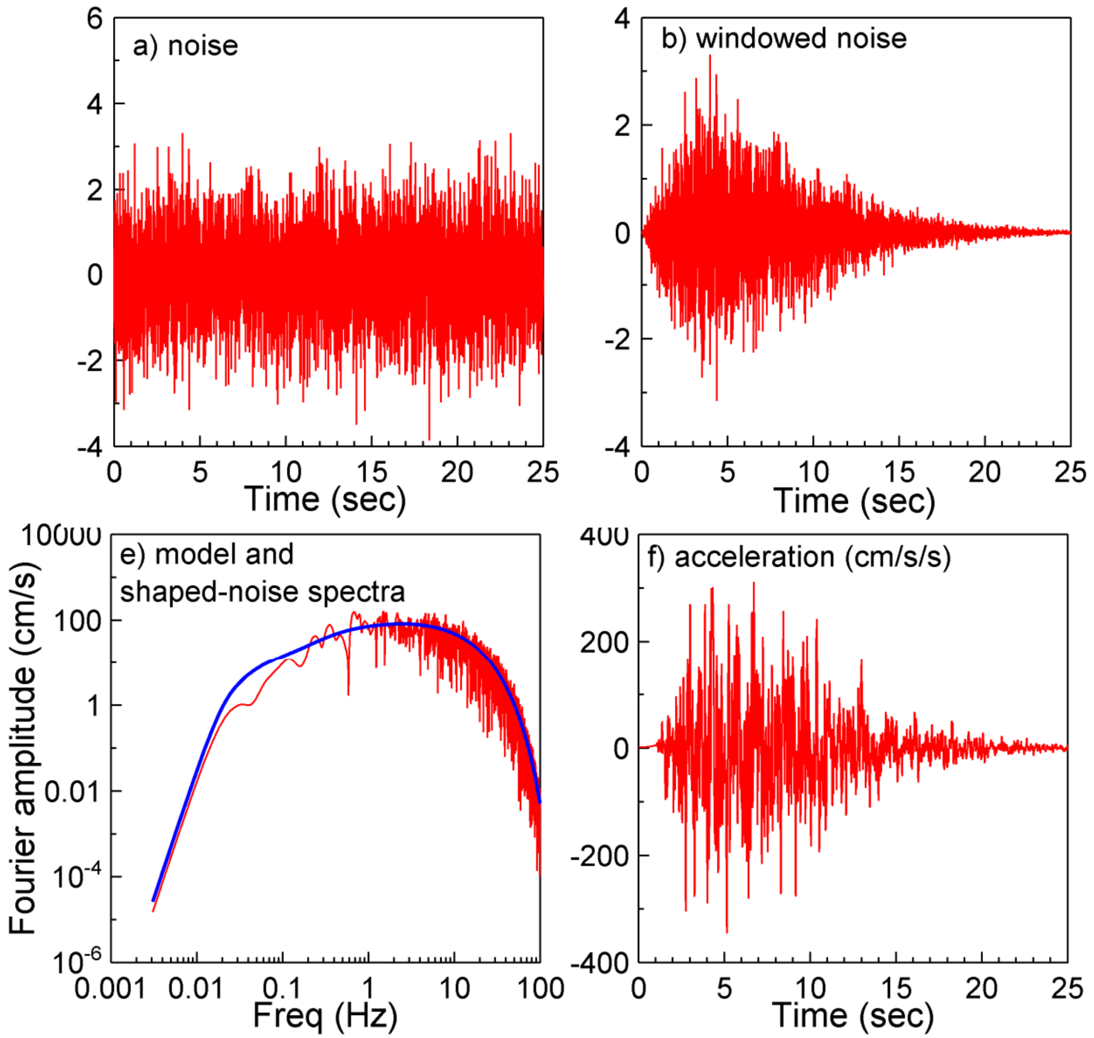
Steps in simulating time series

- Generate Gaussian or uniformly distributed random white noise

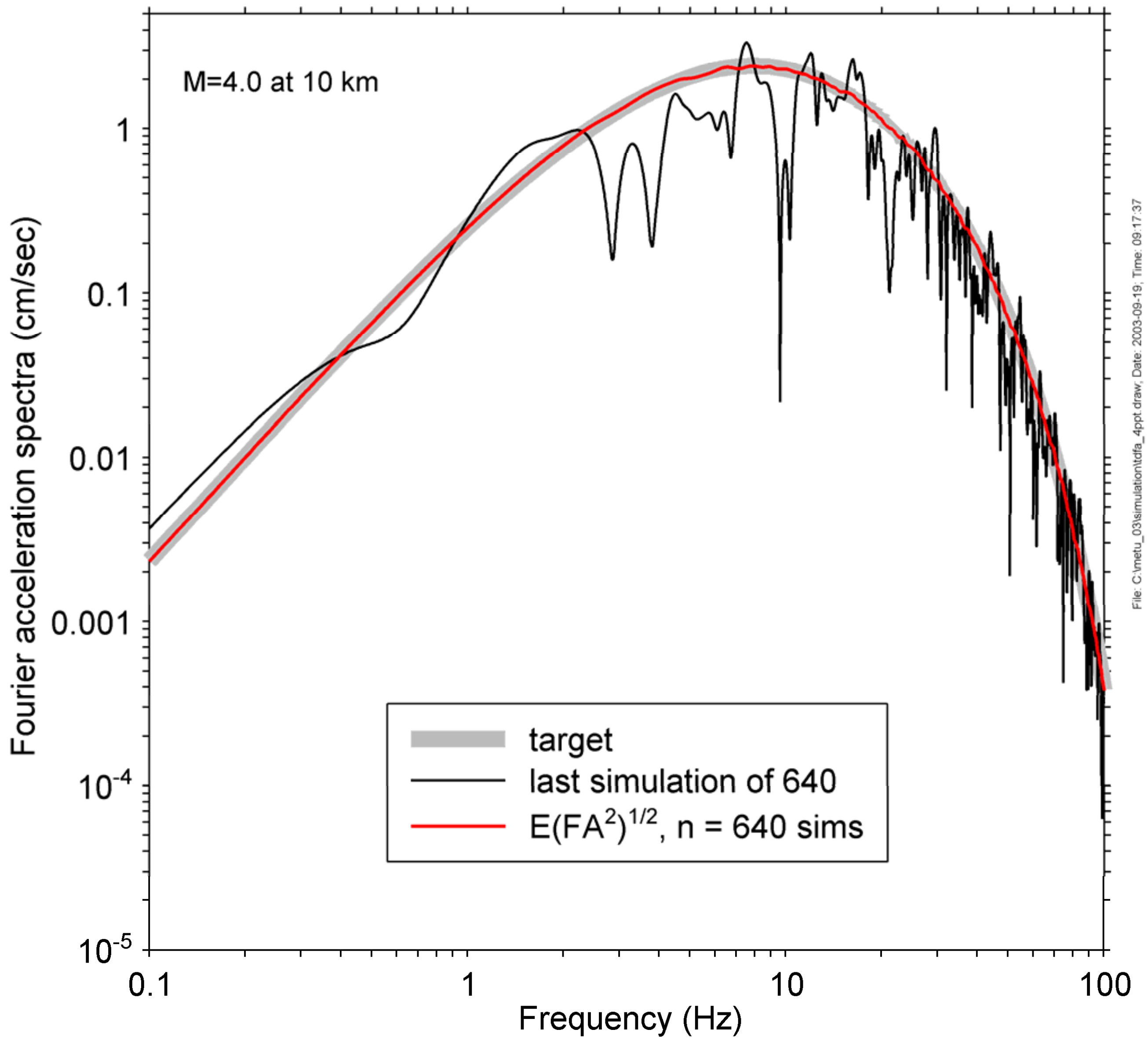
- Apply a shaping window in the time domain

- Multiply by the spectral amplitude and shape of the ground motion

- Transform back to the time domain



Warning: the spectrum of any one simulation may not closely match the specified spectrum. Only the average of many simulations is guaranteed to match the specified spectrum



Random Vibration Simulation

- y_{rms} is easy to obtain from amplitude spectrum:

$$\left(y_{rms}\right)^2 = \frac{1}{D_{rms}} \int_0^{T_d} \left[u(t)\right]^2 dt = \frac{2}{D_{rms}} \int_0^{\infty} \left|U(f)\right|^2 df$$

y_{rms} is root-mean-square motion

$\ddot{u}(t)$ Is ground-motion time series (e.g., accel. or osc. response)

D_{rms} is a duration measure

$\left|U(f)\right|^2$ is Fourier amplitude spectrum of ground motion

- But need extreme value statistics to relate rms acceleration to peak time-domain ground-motion intensity measure (y_{max})

Peak parameters from random vibration theory:

For long duration (D) this equation gives the peak motion given the rms motion:

$$\frac{y_{\max}}{y_{rms}} = \left[2\ln N_Z\right]^{1/2}$$

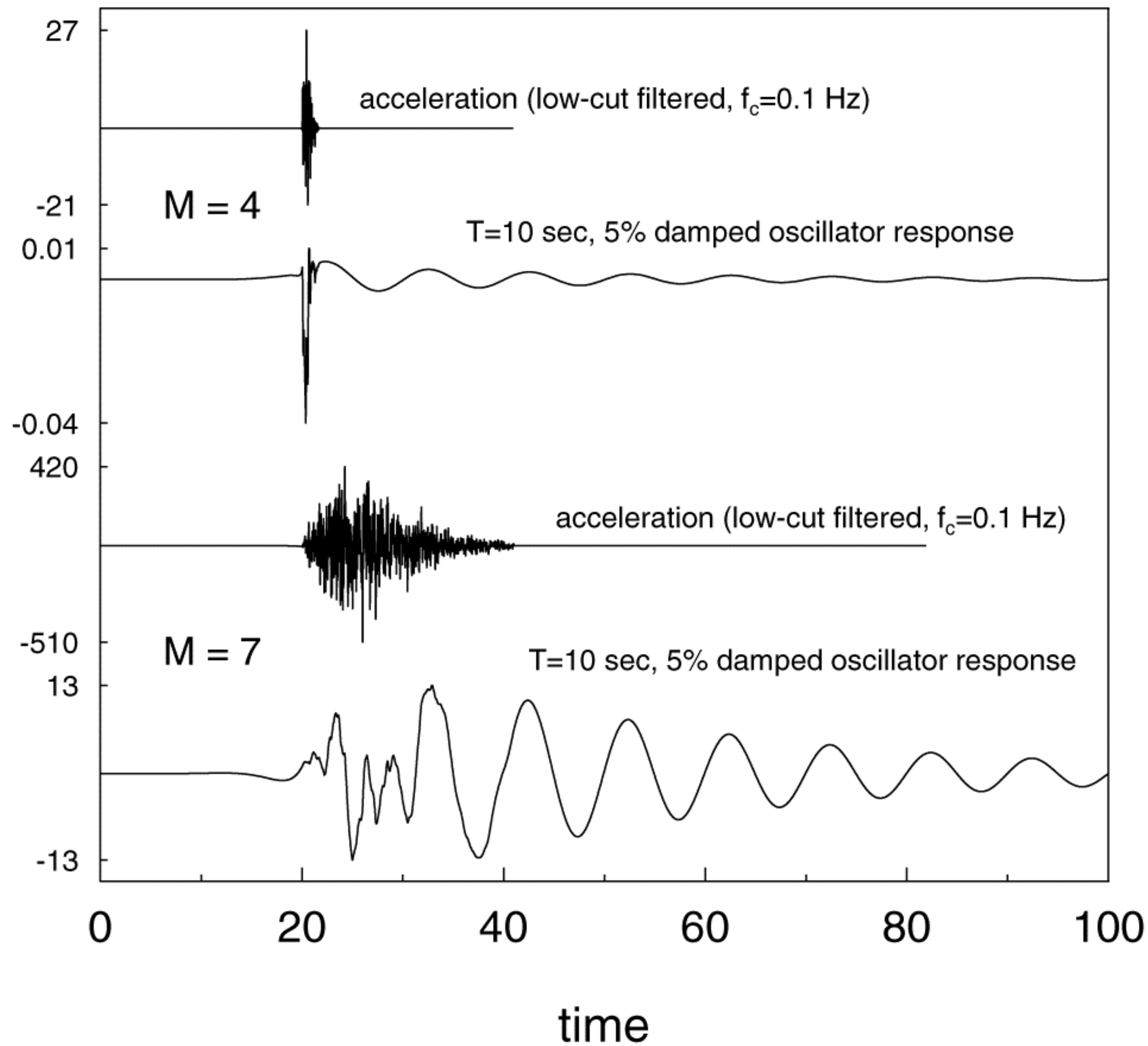
where

$$N_Z = 2 f_Z D$$

$$f_Z = \frac{1}{2\pi}\left(m_2/m_0\right)^{1/2}$$

m_0 and m_2 are spectral moments, given by integrals over the Fourier spectra of the ground motion

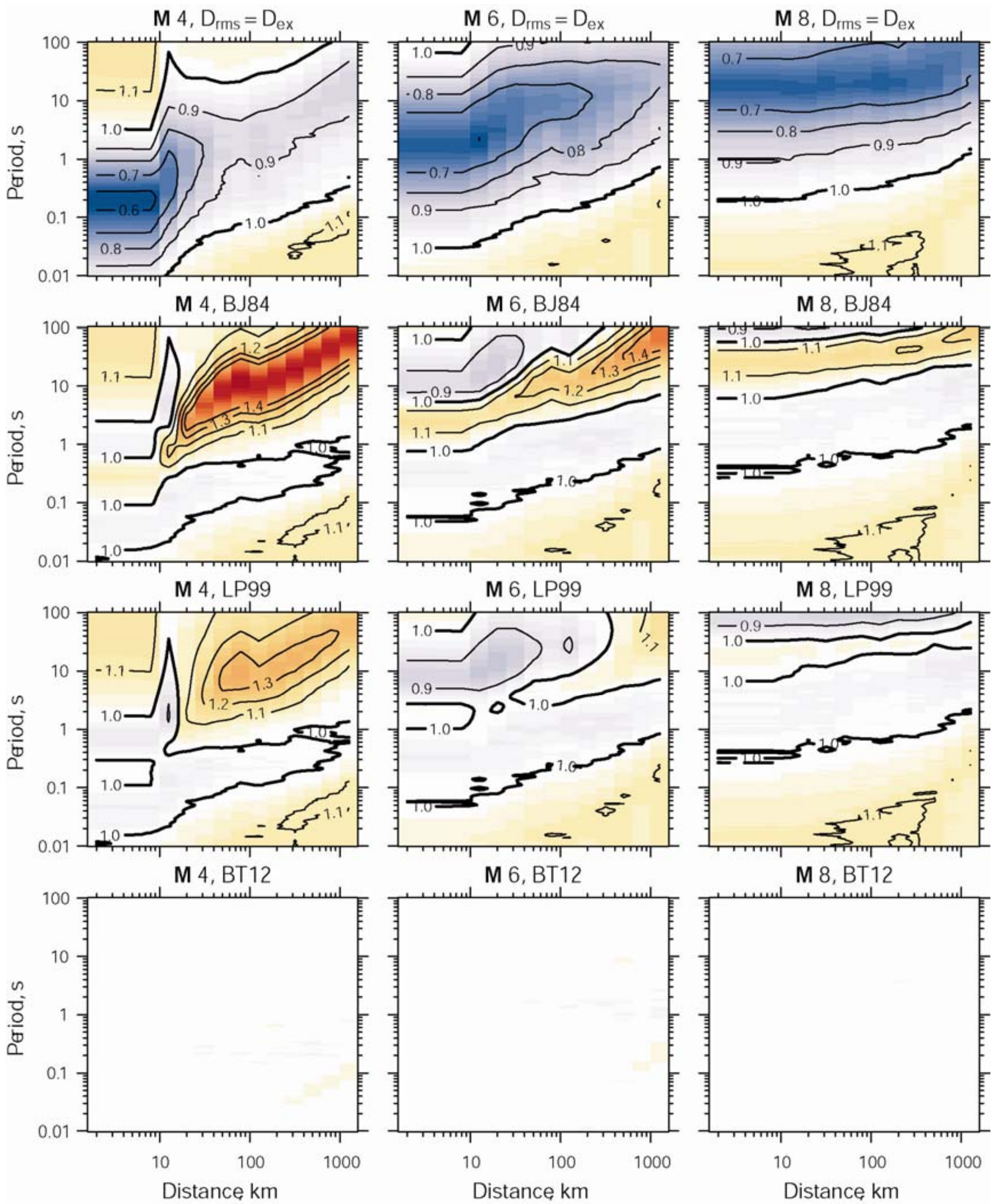
Special consideration needs to be given to choosing the proper duration D_{rms} to be used in random vibration theory for computing the response spectra for small magnitudes and long oscillator periods. In this case the oscillator response is short duration, with little ringing as in the response for a larger earthquake. Several modifications to rvt have been published to deal with this.



Recent improvements on determining D_{rms} (Boore and Thompson, 2012):

Contour plots of TD/RV ratios for an ENA SCF 250 bar model for 4 ways of determining D_{rms}:

1. $D_{rms} = D_{ex}$
2. BJ84
3. LP99
4. BT12



Parameters needed for Stochastic Simulations

- *Frequency-independent parameters*
  - Density near the source
  - Shear-wave velocity near the source
  - Average radiation pattern
  - Partition factor of motion into two components (usually $1/\sqrt{2}$)
  - Free surface factor (usually 2)

Parameters needed for Stochastic Simulations

- *Frequency-dependent parameters*
  - Source:
    - Spectral shape (e.g., single corner frequency; two corner frequency)
    - Scaling of shape with magnitude (controlled by the stress parameter $\Delta\sigma$ for single-corner-frequency models)

Parameters needed for Stochastic Simulations

Frequency-dependent parameters

- Path (and site):
  - Geometrical spreading (multi-segments?)
  - Q (frequency-dependent? What shear-wave and geometrical spreading model used in Q determination?)
  - Duration
  - Crustal amplification (can include local site amplification)
  - Site diminution (fmax? κ_0?)

correlated

Parameters needed for Stochastic Simulations

- *RV or TD parameters*
  - Low-cut filter
  - RV
    - Integration parameters
    - Method for computing D_{rms}
    - Equation for y_{max}/y_{rms}
  - TD
    - Type of window (e.g., box, shaped?)
    - dt, npts, nsims, etc.

Parameters that might be obtained from empirical analysis of small earthquake data

- Focal depth distribution
- Crustal structure
  - S-wave velocity profile
  - Density profile
- Path Effects
  - Geometrical spreading
  - Q(f)
  - Duration
  - κ_0
  - Site characteristics

Parameters difficult to obtain from small earthquake data

- Source Spectral Shape
- Scaling of Source Spectra (including determination of $\Delta\sigma$)

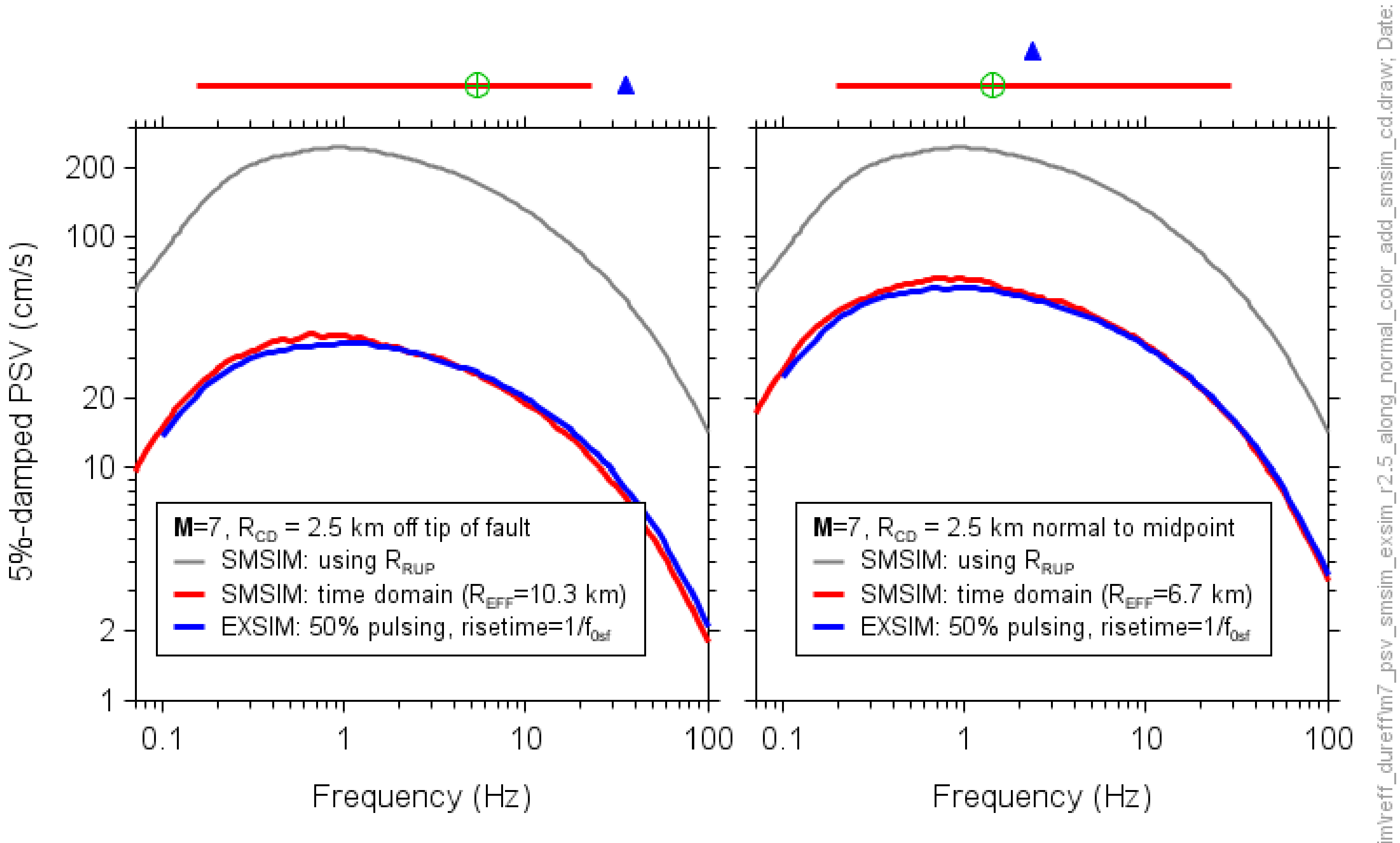
Some Issues in Using the Stochastic Method

- Using point-source model near extended rupture
- Consistency in model parameters
- Obtaining parameters for a specific application
- Dealing with the attenuation—$\Delta\sigma$ correlation
- Adjusting ENA GMPEs from very hard rock to softer sites (importance of κ_0)
- Using square-root-impedance calculations for site amplification

Applicability of Point Source Simulations near Extended Ruptures

- Modify the value of R_{rup} used in point source, to account for finite fault effects
  - Use R_{eff} (similar to R_{rms}) for a particular source-station geometry)
  - Use a more generic modification, based on finite-fault modeling (e.g., Atkinson and Silva, 2000; Toro, 2002)

Use a scenario-specific modification to R_{rup}



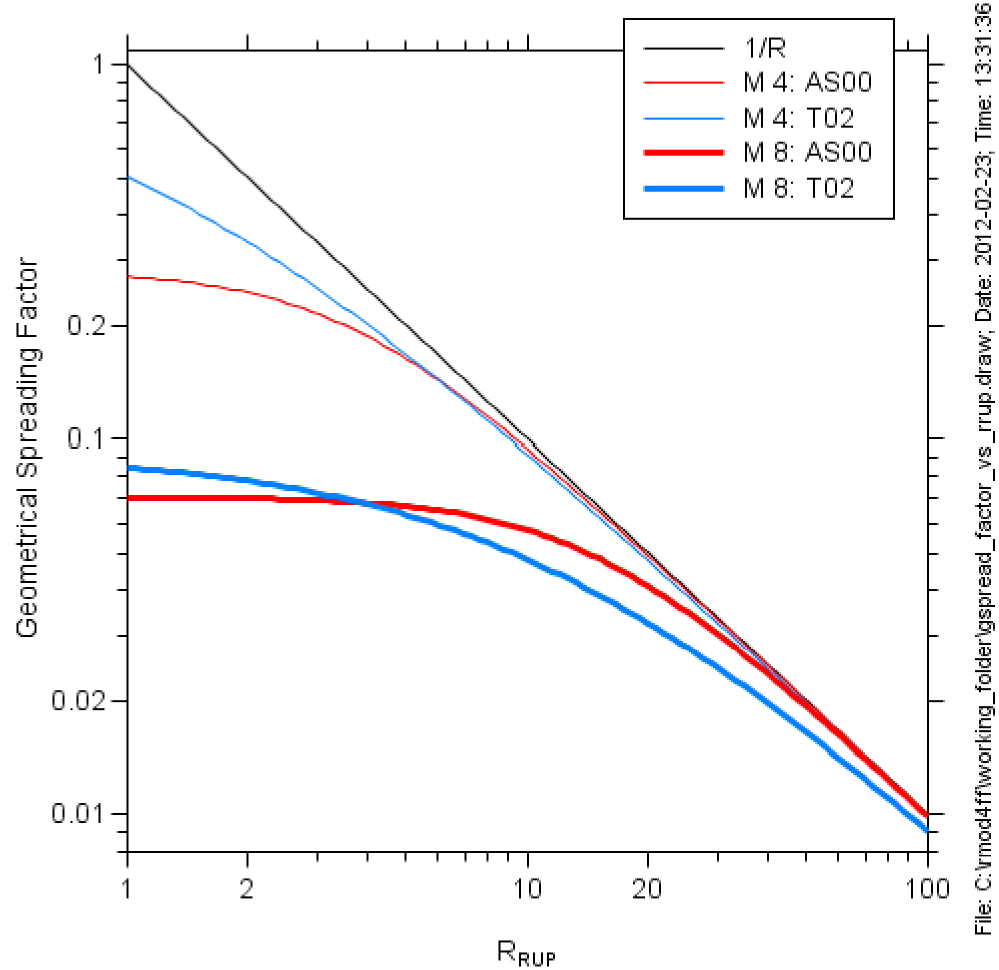
(note: No directivity---EXSIM results are an average of motions from 100 random hypocenters)

Modified from Boore (2010)

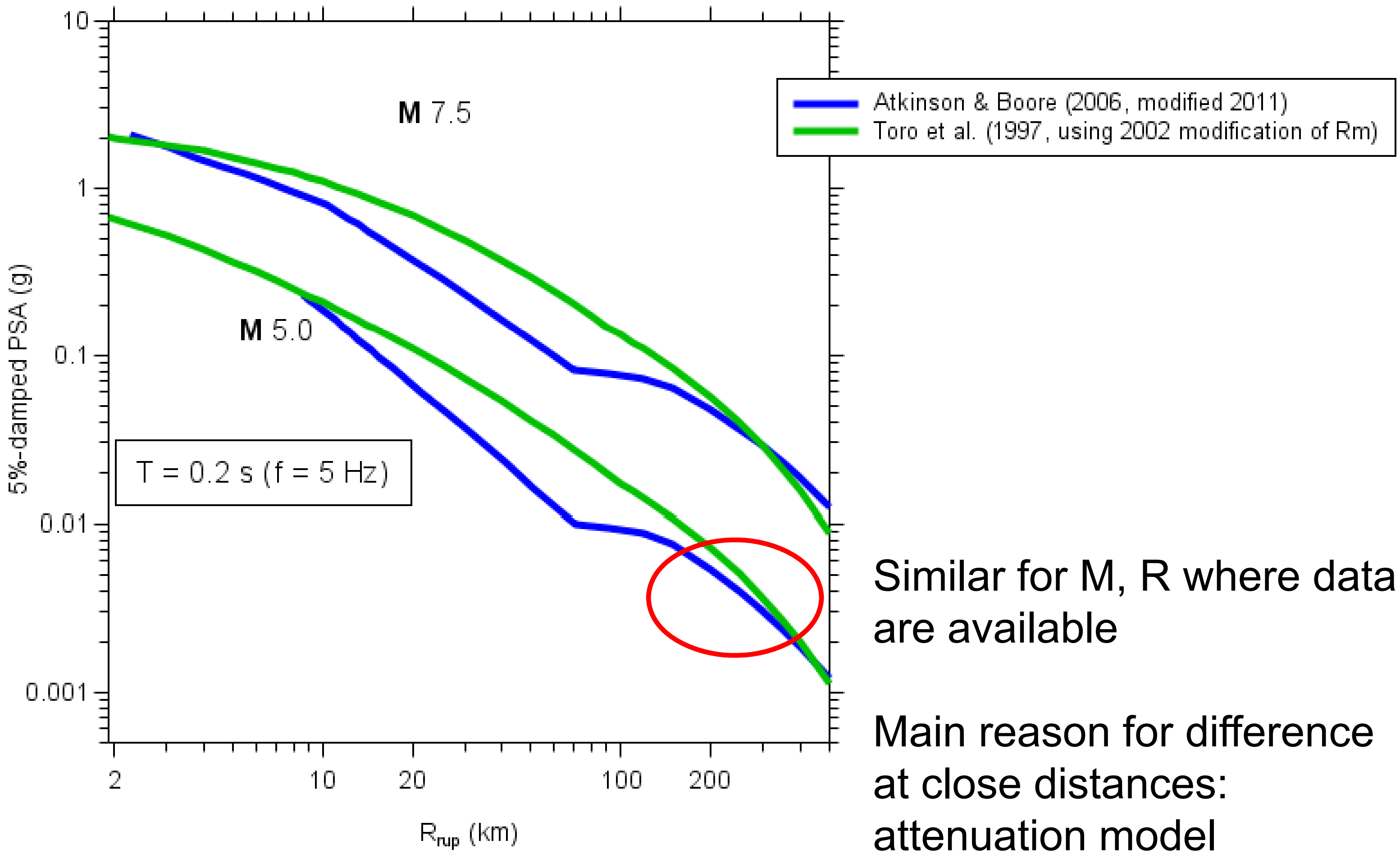
Using generic modifications to R_{rup}. For the situation in the previous slide (**M** 7, R_{rup} = 2.5):

R_{eff} = 10.3 km for AS00
R_{eff} = 8.4 km for T02

Compared to R_{eff} = 10.3 (off tip) and 6.7 (normal) in the previous slide



Comparison of two GMPEs used in 2008 USGS NSHMs



Similar for M, R where data are available

Main reason for difference at close distances: attenuation model

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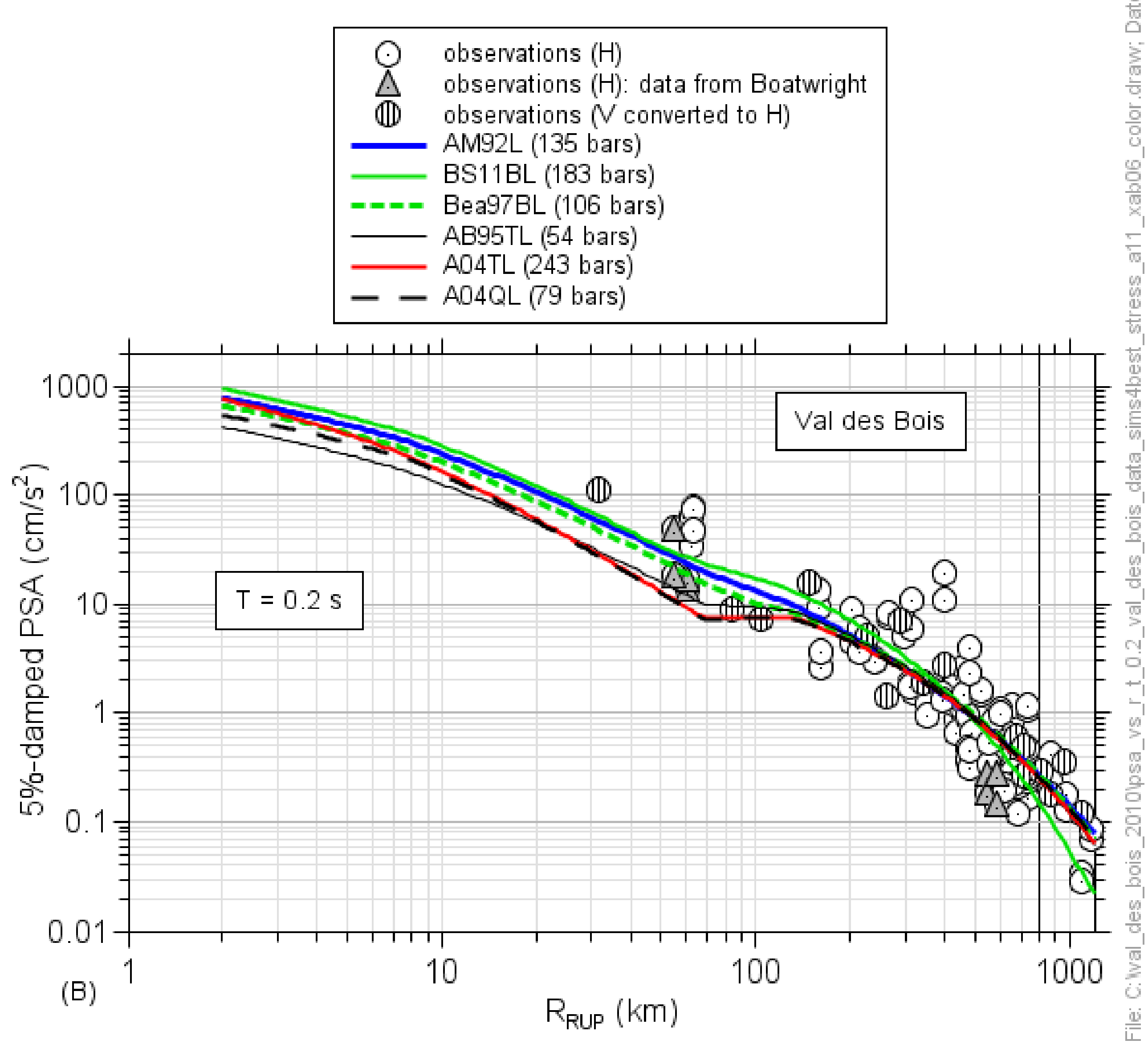
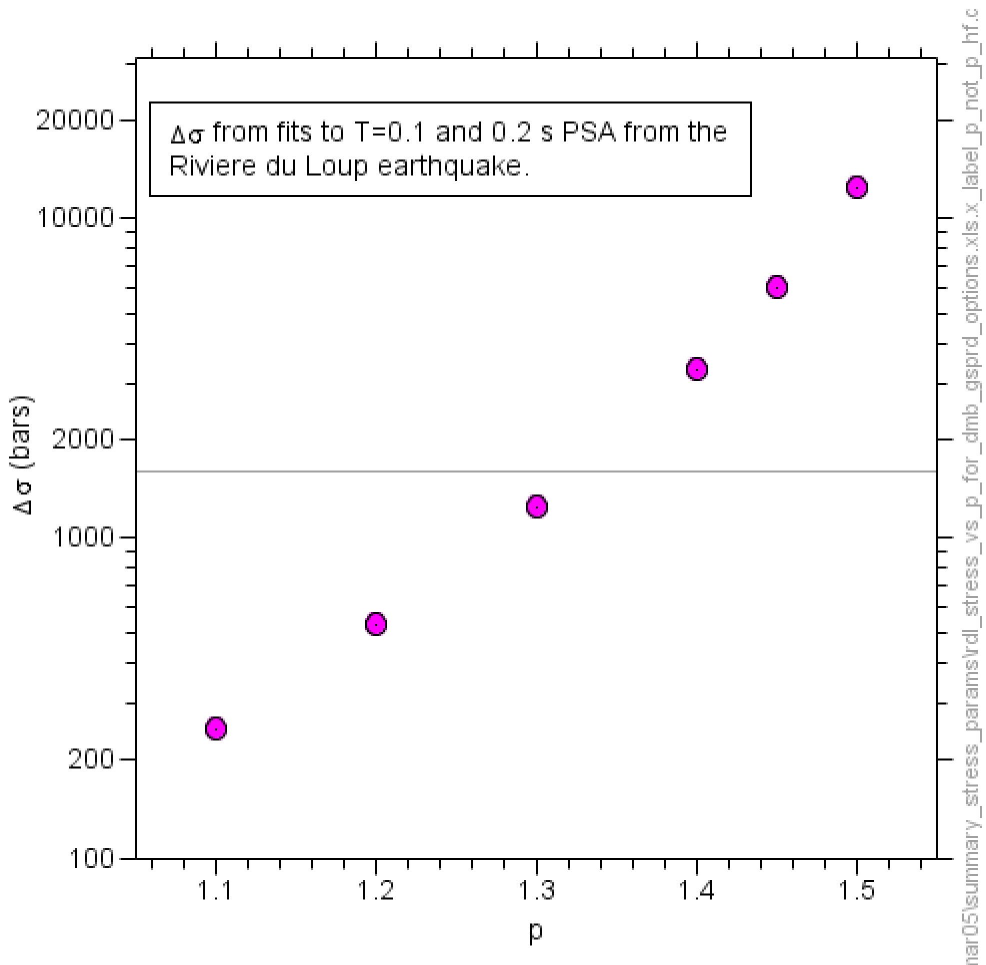
Δσ-attenuation model correlation

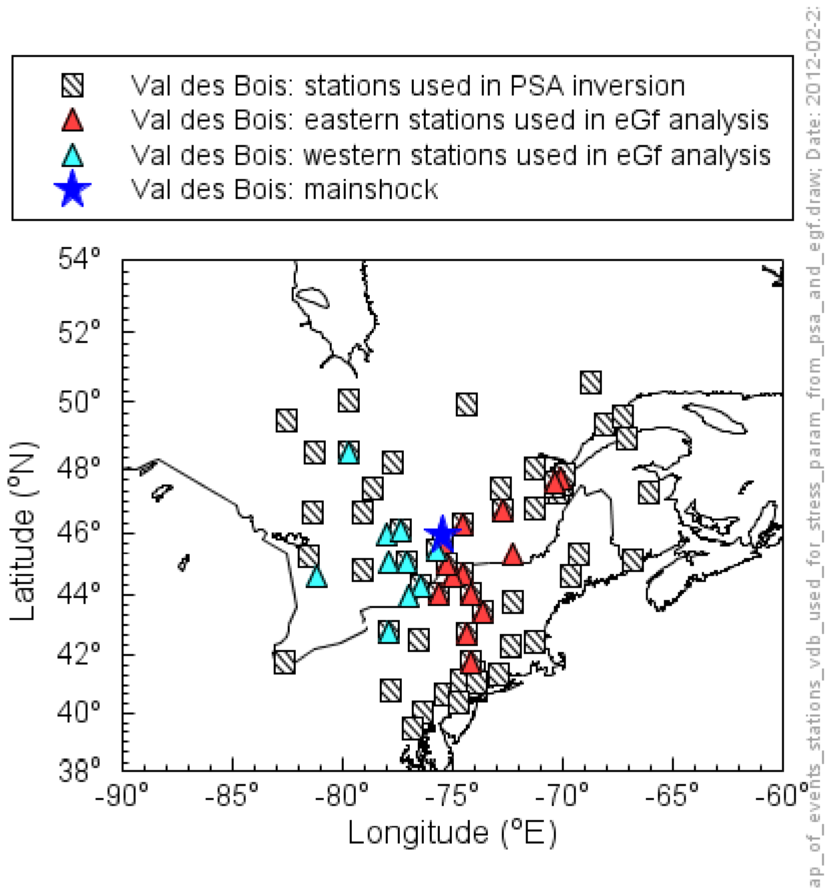


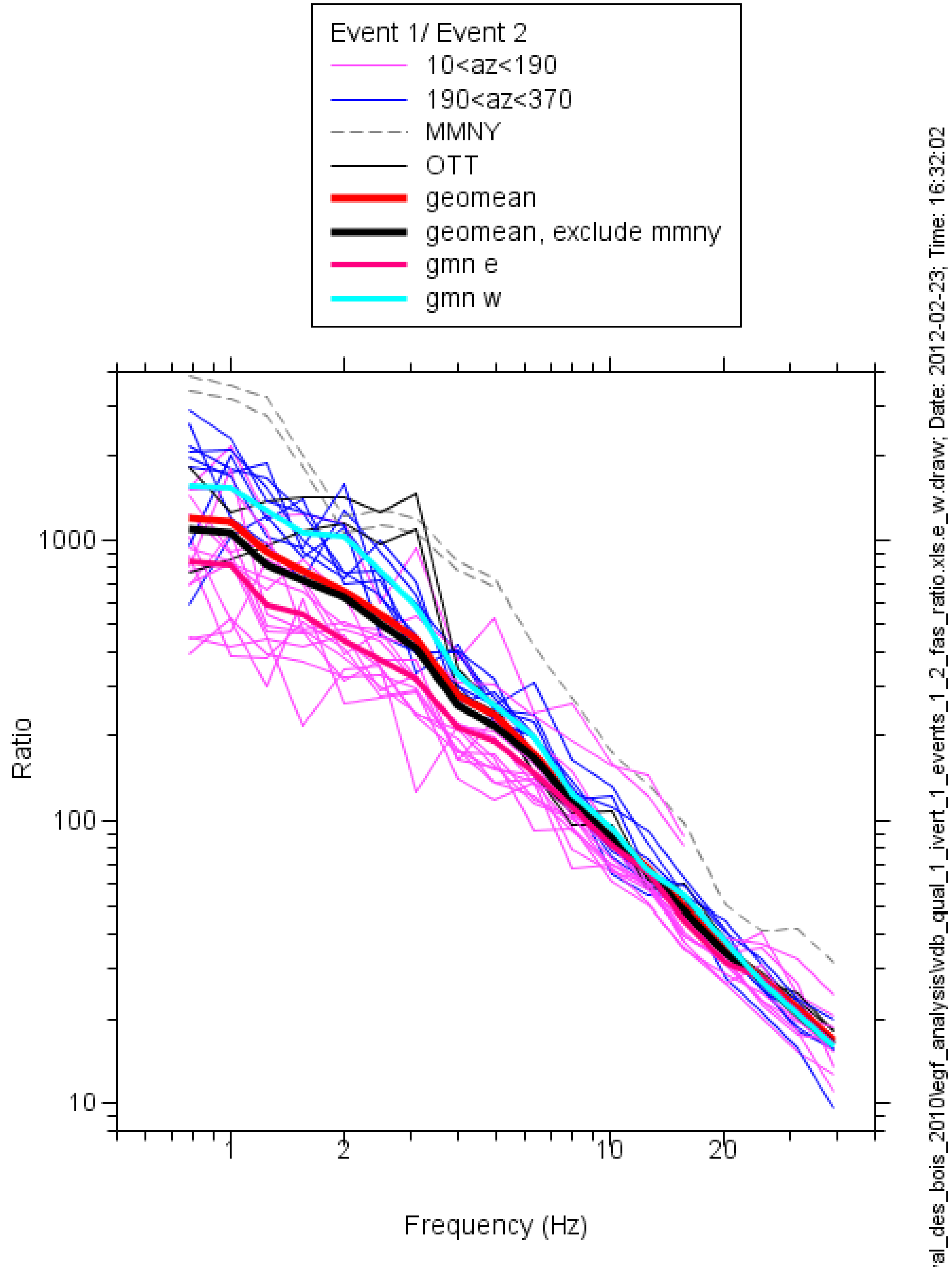
observations (H)
observations (H): data from Boatwright
observations (V converted to H)
AM92L (135 bars)
BS11BL (183 bars)
Bea97BL (106 bars)
AB95TL (54 bars)
A04TL (243 bars)
A04QL (79 bars)
Val des Bois
T = 0.2 s
5%-damped PSA (cm/s²)
1000
100
10
1
0.1
0.01
1
10
100
1000
(B)
R_RUP (km)
File: C:\wal_des_bois_2010\psa_vs_r_t_0.2_val_des_bois_data_sims4best_stress_a11_xab06_color.draw; Date: :

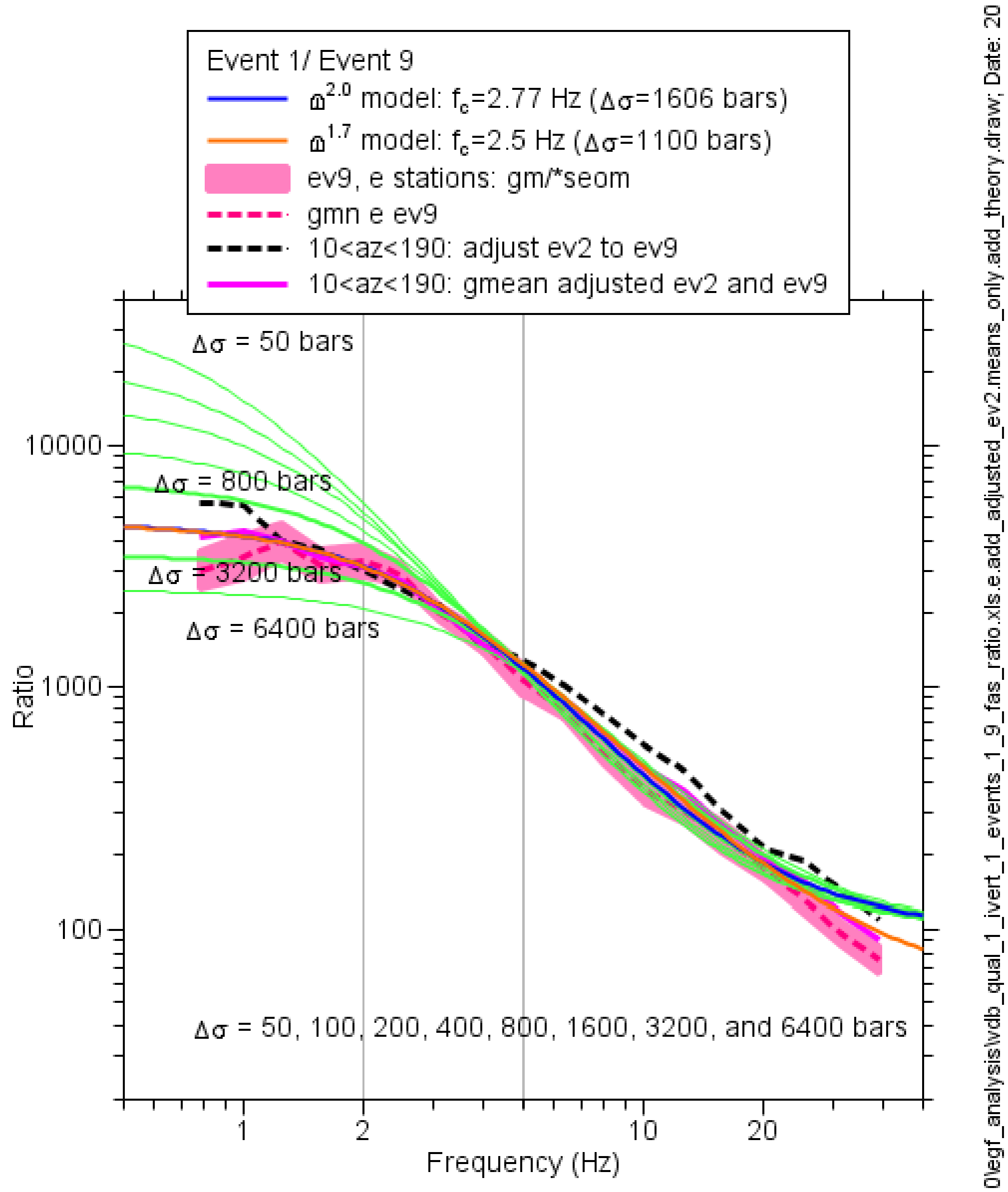


geometrical spreading ($1/R^p$)

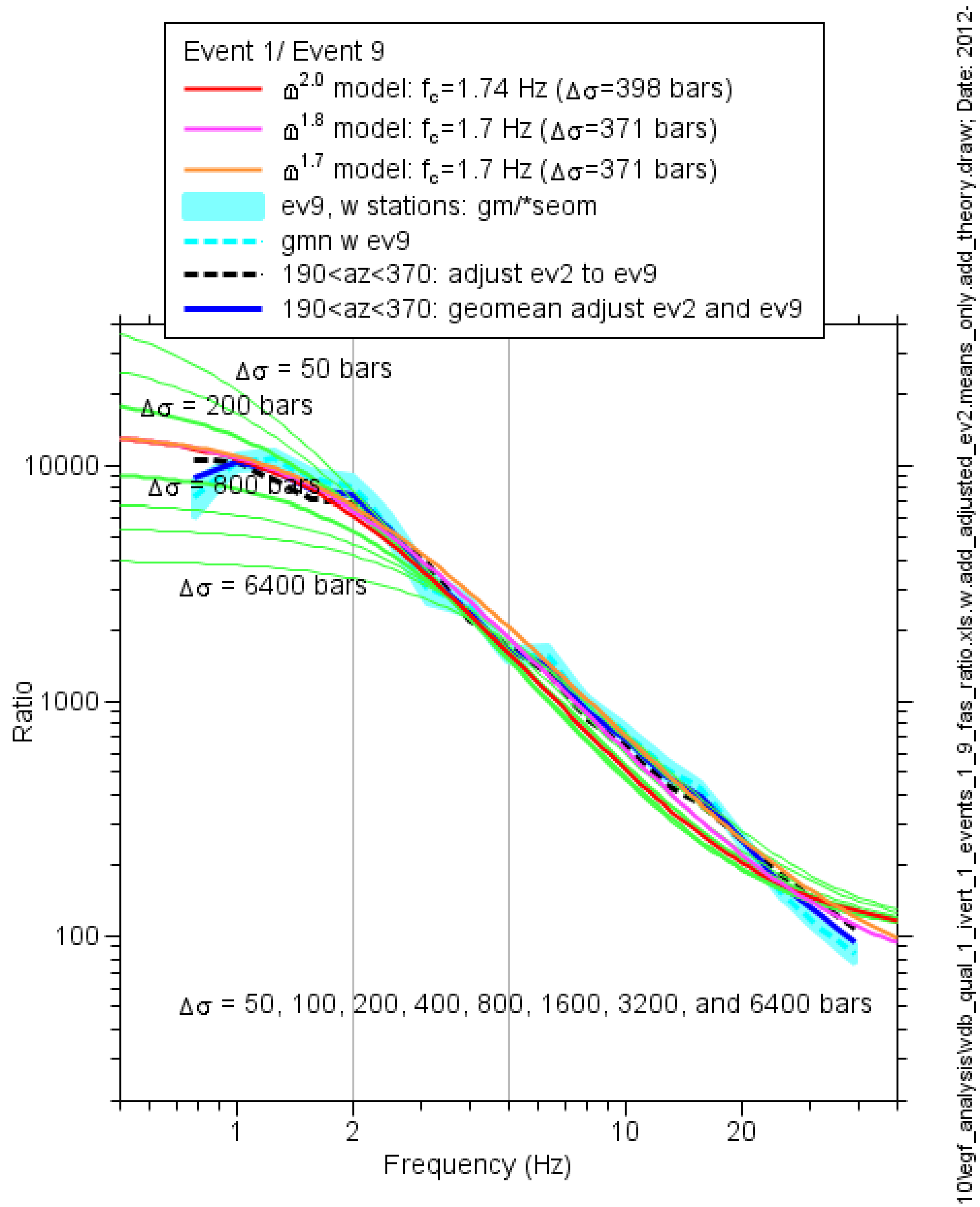
Using empirical Green's functions (eGf) to constrain Δσ (and thus discriminate between various attenuation models)


Val des Bois: stations used in PSA inversion
Val des Bois: eastern stations used in eGf analysis
Val des Bois: western stations used in eGf analysis
Val des Bois: mainshock
54°
52°
50°
48°
46°
44°
42°
40°
38°
Latitude (°N)
-90°
-85°
-80°
-75°
-70°
-65°
-60°
Longitude (°E)

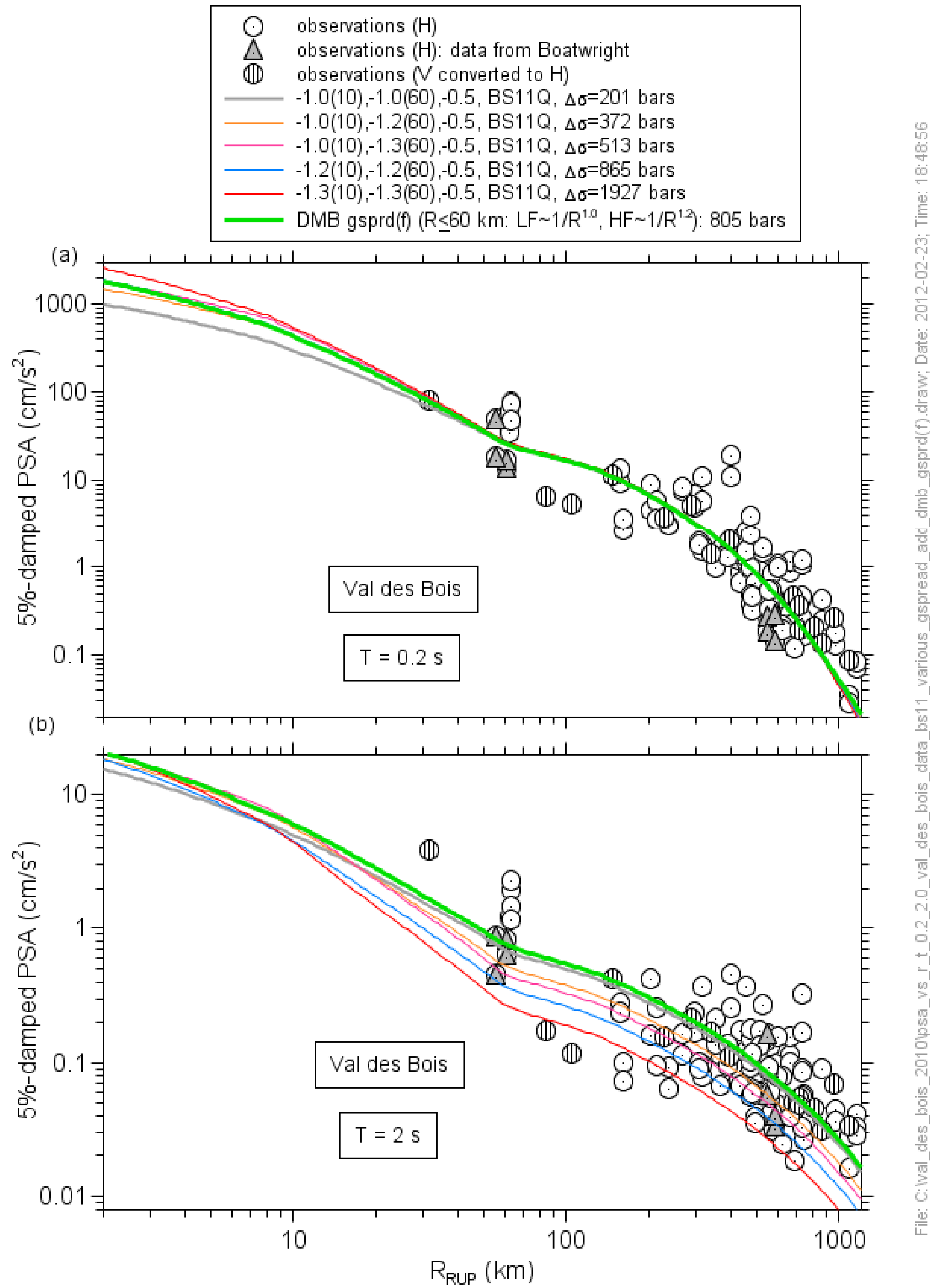

Event 1/ Event 2
10<az<190
190<az<370
MMNY
OTT
geomean
geomean, exclude mmny
gmn e
gmn w
1000
100
10
Ratio
1
2
10
20
Frequency (Hz)
al_des_bois_2010\egf_analysis\wdb_qual_1_jvert_1_events_1_2_fas_ratio.xls.e_w.draw; Date: 2012-02-23; Time: 16:32:02



Event 1/ Event 9
ω^2.0 model: fc=2.77 Hz (Δσ=1606 bars)
ω^1.7 model: fc=2.5 Hz (Δσ=1100 bars)
ev9, e stations: gm/*seom
gmn e ev9
10<az<190: adjust ev2 to ev9
10<az<190: gmean adjusted ev2 and ev9
Δσ = 50 bars
Δσ = 800 bars
Δσ = 3200 bars
Δσ = 6400 bars
Δσ = 50, 100, 200, 400, 800, 1600, 3200, and 6400 bars
10000
1000
100
Ratio
1
2
10
20
Frequency (Hz)
I0\egf_analysis\vdb_qual_1_ivert_1_events_1_9_fas_ratio.xls.e.add_adjusted_ev2.means_only.add_theory.draw; Date: 20



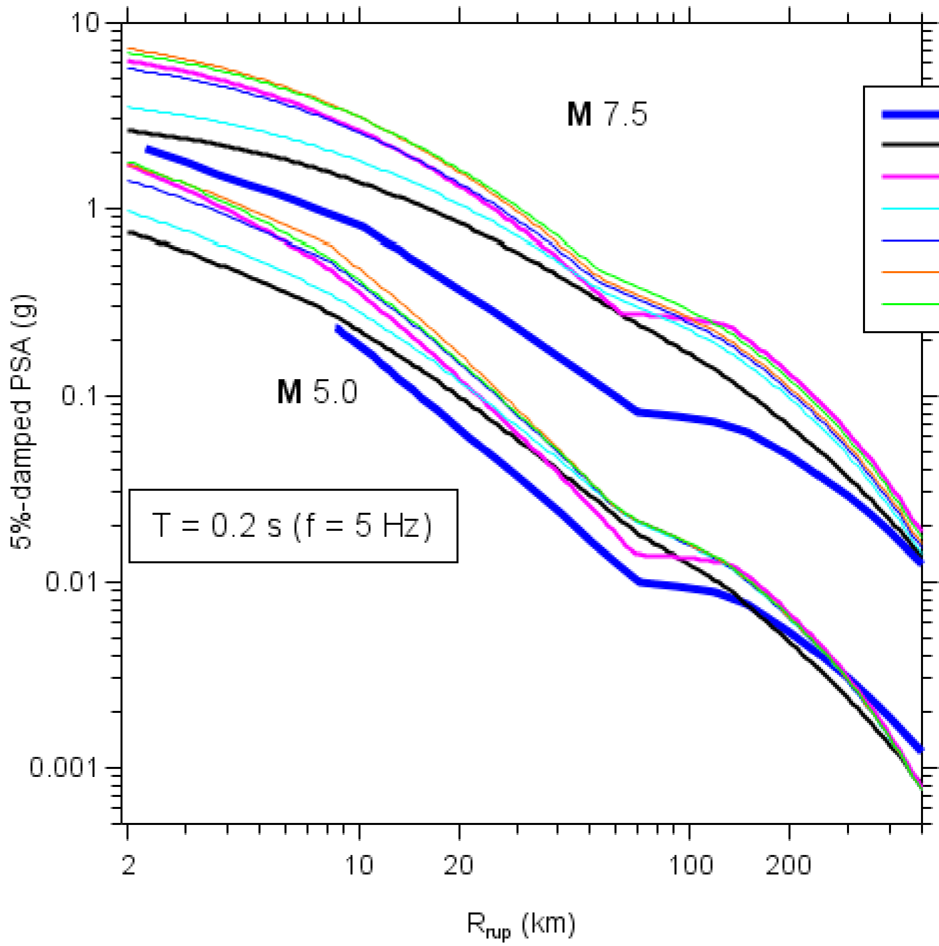
Event 1/ Event 9
ω^2.0 model: fc=1.74 Hz (Δσ=398 bars)
ω^1.8 model: fc=1.7 Hz (Δσ=371 bars)
ω^1.7 model: fc=1.7 Hz (Δσ=371 bars)
ev9, w stations: gm/*seom
gmn w ev9
190<az<370: adjust ev2 to ev9
190<az<370: geomean adjust ev2 and ev9
Δσ = 50 bars
Δσ = 200 bars
Δσ = 800 bars
Δσ = 6400 bars
Δσ = 50, 100, 200, 400, 800, 1600, 3200, and 6400 bars
Ratio
10000
1000
100
1
2
10
20
Frequency (Hz)
10\egf_analysis\wdb_qual_1_ivert_1_events_1_9_fas_ratio.xls.w.add_adjusted_ev2.means_only.add_theory.draw; Date: 2012-



Δσ from eGf suggests p>1.0

But underpredict longer period PSA. Implication: geometrical spreading may be frequency dependent.

Simulated PSA for various attenuation models, using Δσ from inverting T=0.1 and 0.2 s PSA data from Val des Bois (**M** 5.07)



eGf rules out *1/R*. models; Δσ for other models OK, depending on how combine eGf from the two regions. Conclusion: p>1.0, at least from 10 to 60 km.

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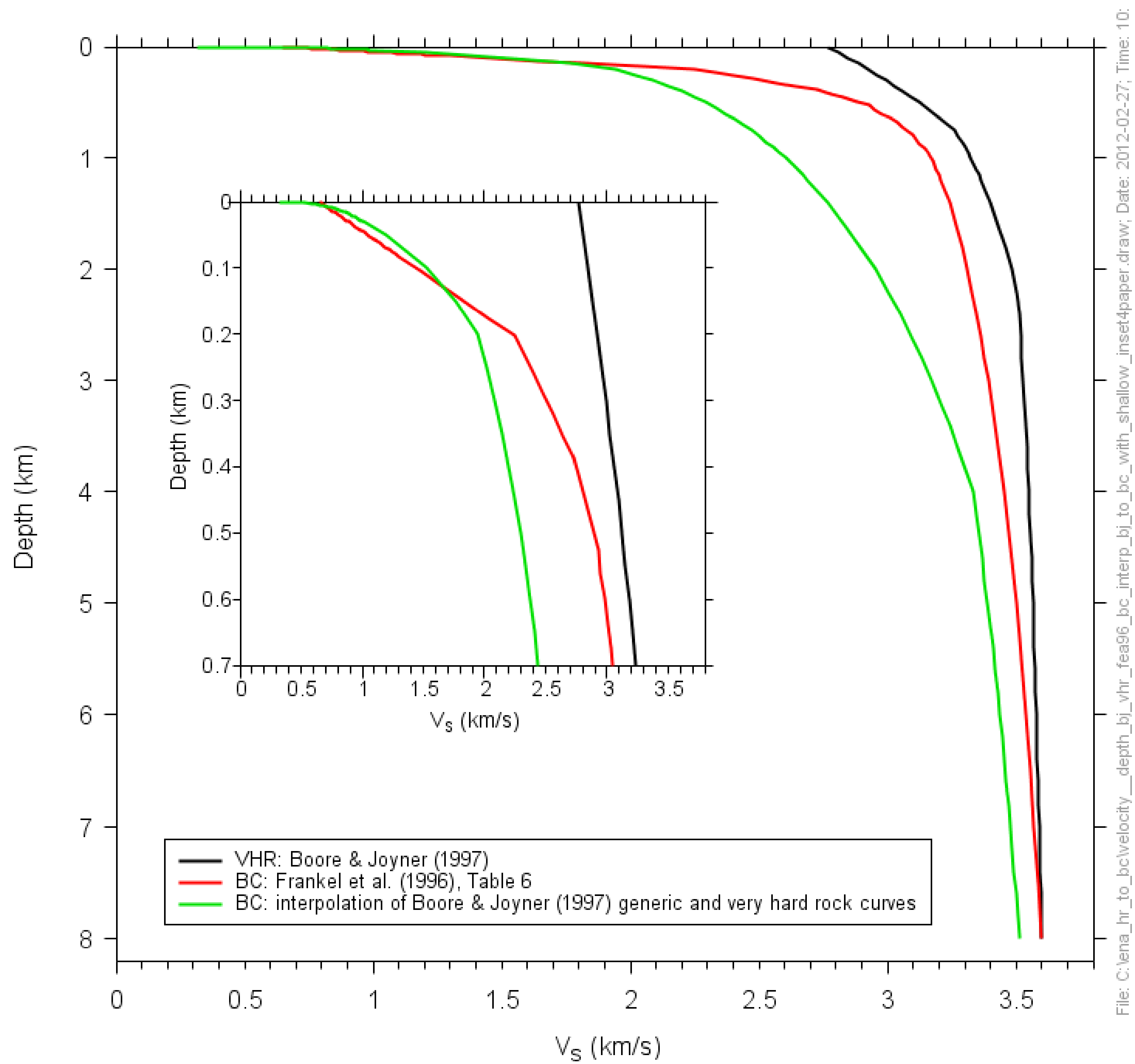
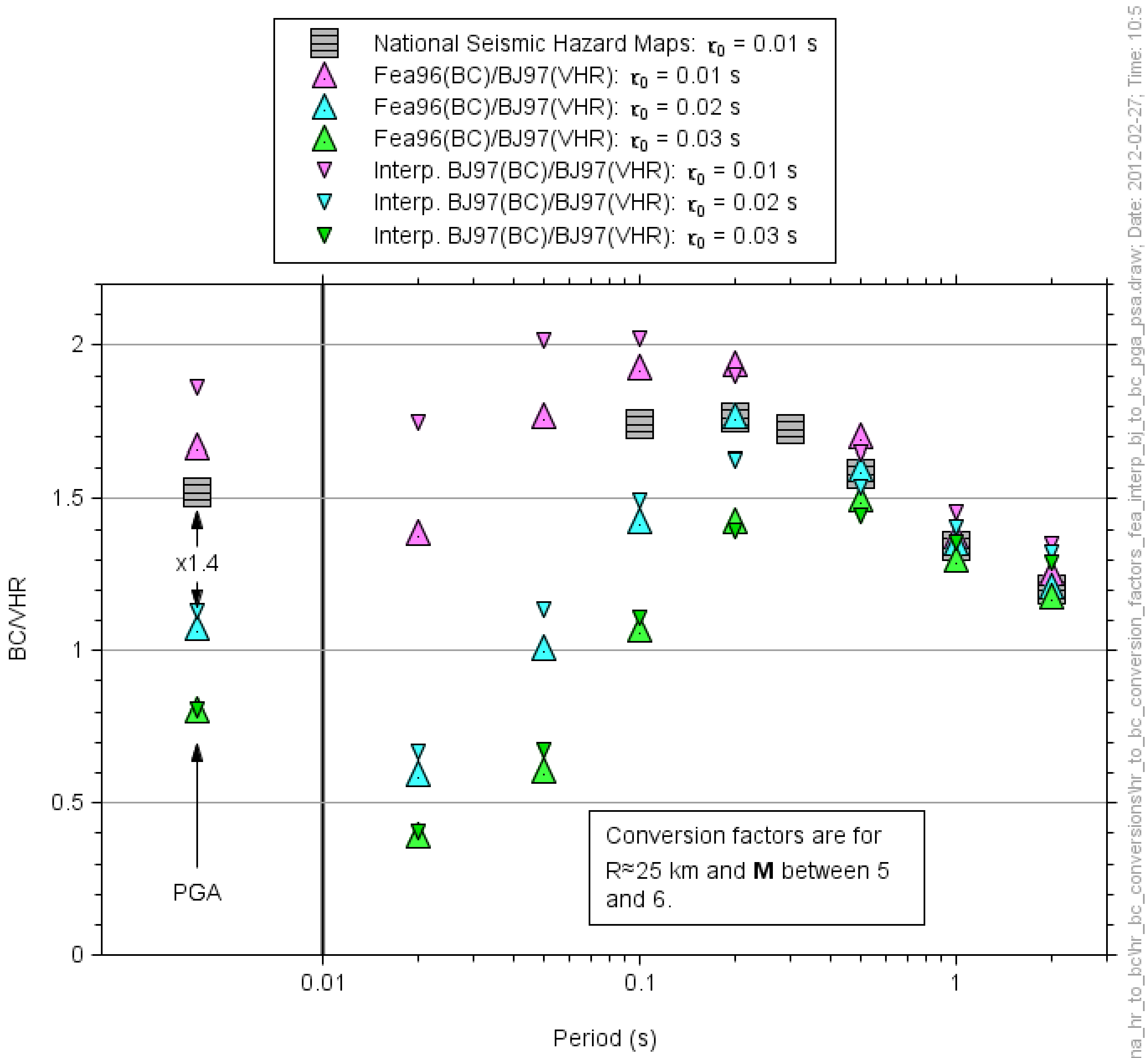
Adjusting VHR GMPEs to BC (importance of κ_0)

CENA Models used in 2008 USGS NSHMs (Petersen et al., 2008)

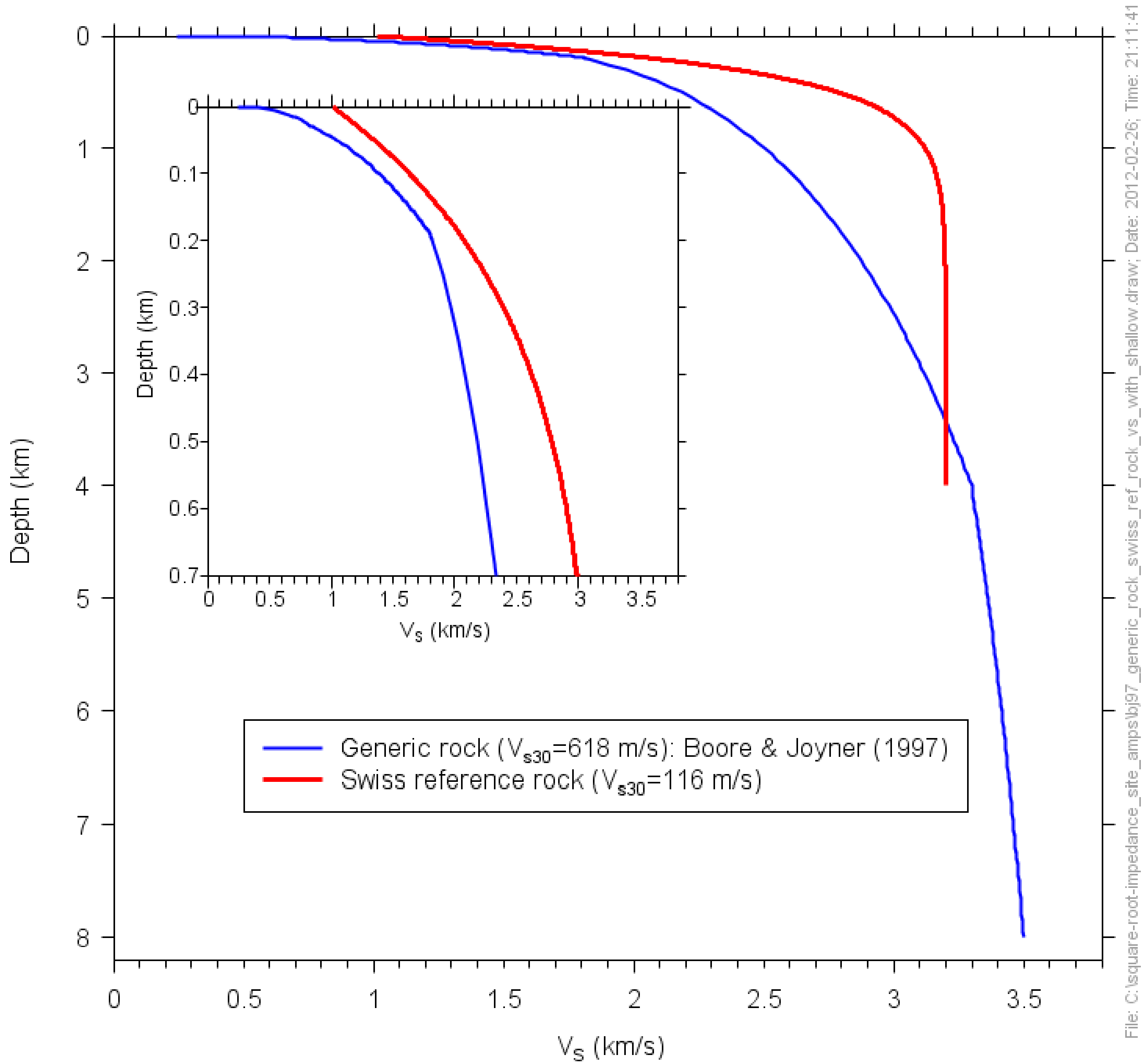
Model	Site	κ_0 for conversion
Frankel et al.	BC	0.01
Atkinson & Boore	BC	0.02
Toro et al.	VHR	0.01
Somerville et al.	VHR	0.01
Silva et al.	VHR	0.01
Campbell	VHR	0.01
Tavakoli & Pezeshk	VHR	0.01

Used same S-wave velocity model (Frankel et al. and Atkinson & Boore)

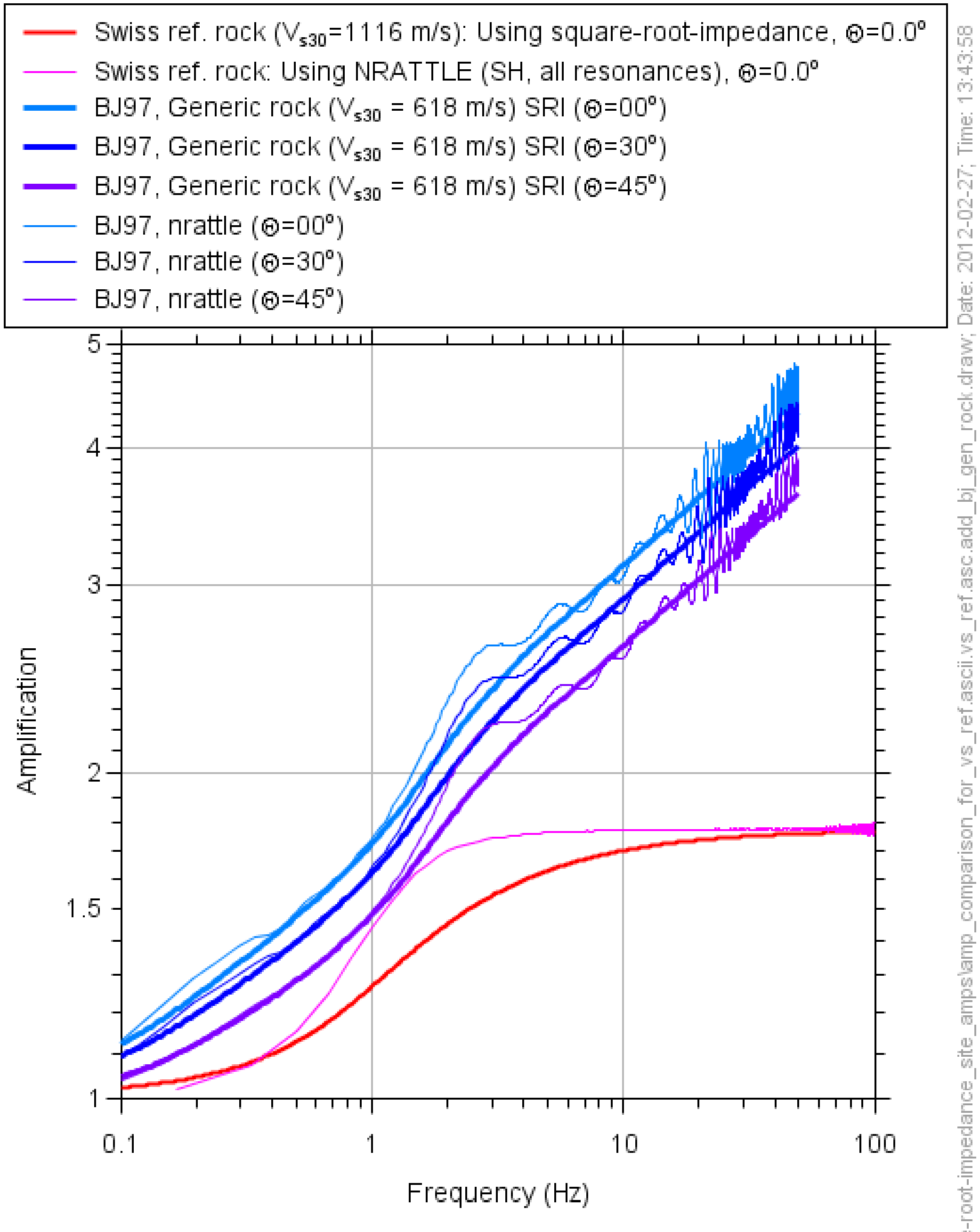

Depth (km)
V_S (km/s)
0
0.5
1
1.5
2
2.5
3
3.5
0
1
2
3
4
5
6
7
8
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
VHR: Boore & Joyner (1997)
BC: Frankel et al. (1996), Table 6
BC: interpolation of Boore & Joyner (1997) generic and very hard rock curves
File: C:\ena_hr_to_bc\velocity__depth_bj_vhr_fea96_bc_interp_bj_to_bc_with_shallow_inset4paper.draw; Date: 2012-02-27; Time: 10:


National Seismic Hazard Maps: τ_0 = 0.01 s
Fea96(BC)/BJ97(VHR): τ_0 = 0.01 s
Fea96(BC)/BJ97(VHR): τ_0 = 0.02 s
Fea96(BC)/BJ97(VHR): τ_0 = 0.03 s
Interp. BJ97(BC)/BJ97(VHR): τ_0 = 0.01 s
Interp. BJ97(BC)/BJ97(VHR): τ_0 = 0.02 s
Interp. BJ97(BC)/BJ97(VHR): τ_0 = 0.03 s
BC/VHR
2
1.5
1
0.5
0
x1.4
PGA
0.01
0.1
1
Period (s)
Conversion factors are for R≈25 km and **M** between 5 and 6.
\ena_hr_to_bc\hr_bc_conversions\hr_to_bc_conversion_factors_fea_interp_bj_to_bc_pga_psa.draw; Date: 2012-02-27; Time: 10:5

Comparison of square-root impedance and full resonance amplifications



Generic rock (Vs30=618 m/s): Boore & Joyner (1997)
Swiss reference rock (Vs30=116 m/s)
Depth (km)
Vs (km/s)
File: C:\square-root-impedance_site_amps\bj97_generic_rock_swiss_ref_rock_vs_with_shallow.draw; Date: 2012-02-26; Time: 21:11:41



Swiss ref. rock (V_{s30}=1116 m/s): Using square-root-impedance, Θ=0.0°
Swiss ref. rock: Using NRATTLE (SH, all resonances), Θ=0.0°
BJ97, Generic rock (V_{s30} = 618 m/s) SRI (Θ=00°)
BJ97, Generic rock (V_{s30} = 618 m/s) SRI (Θ=30°)
BJ97, Generic rock (V_{s30} = 618 m/s) SRI (Θ=45°)
BJ97, nrattle (Θ=00°)
BJ97, nrattle (Θ=30°)
BJ97, nrattle (Θ=45°)
Amplification
1
1.5
2
3
4
5
0.1
1
10
100
Frequency (Hz)

Questions for Dave Boore

Please summarize your recent work on the development of stochastic GMPE's, including geometrical spreading.

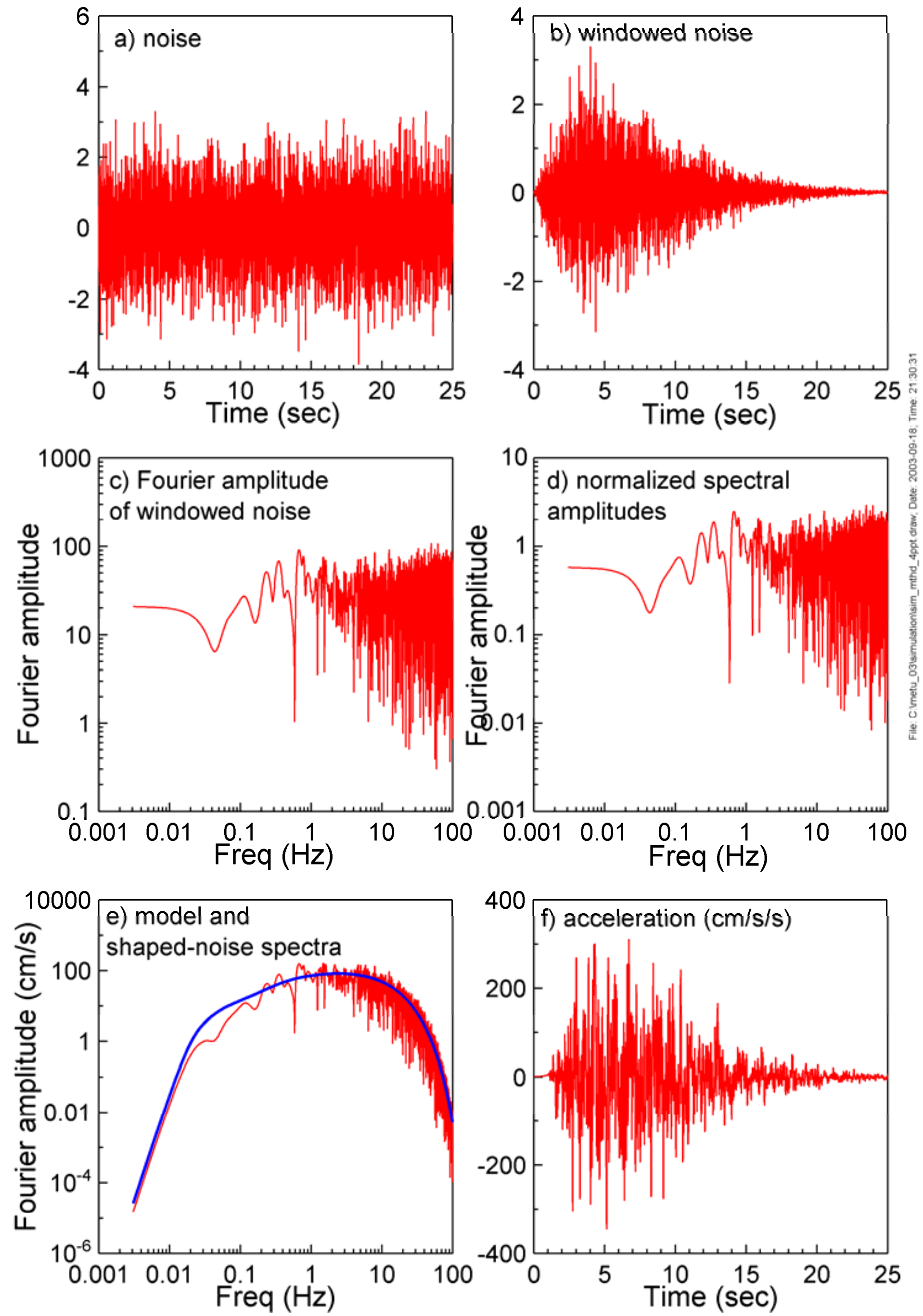
Please discuss which crustal factors may affect geometrical spreading and how one could take these factors into account when adjusting GMPE's from another region.

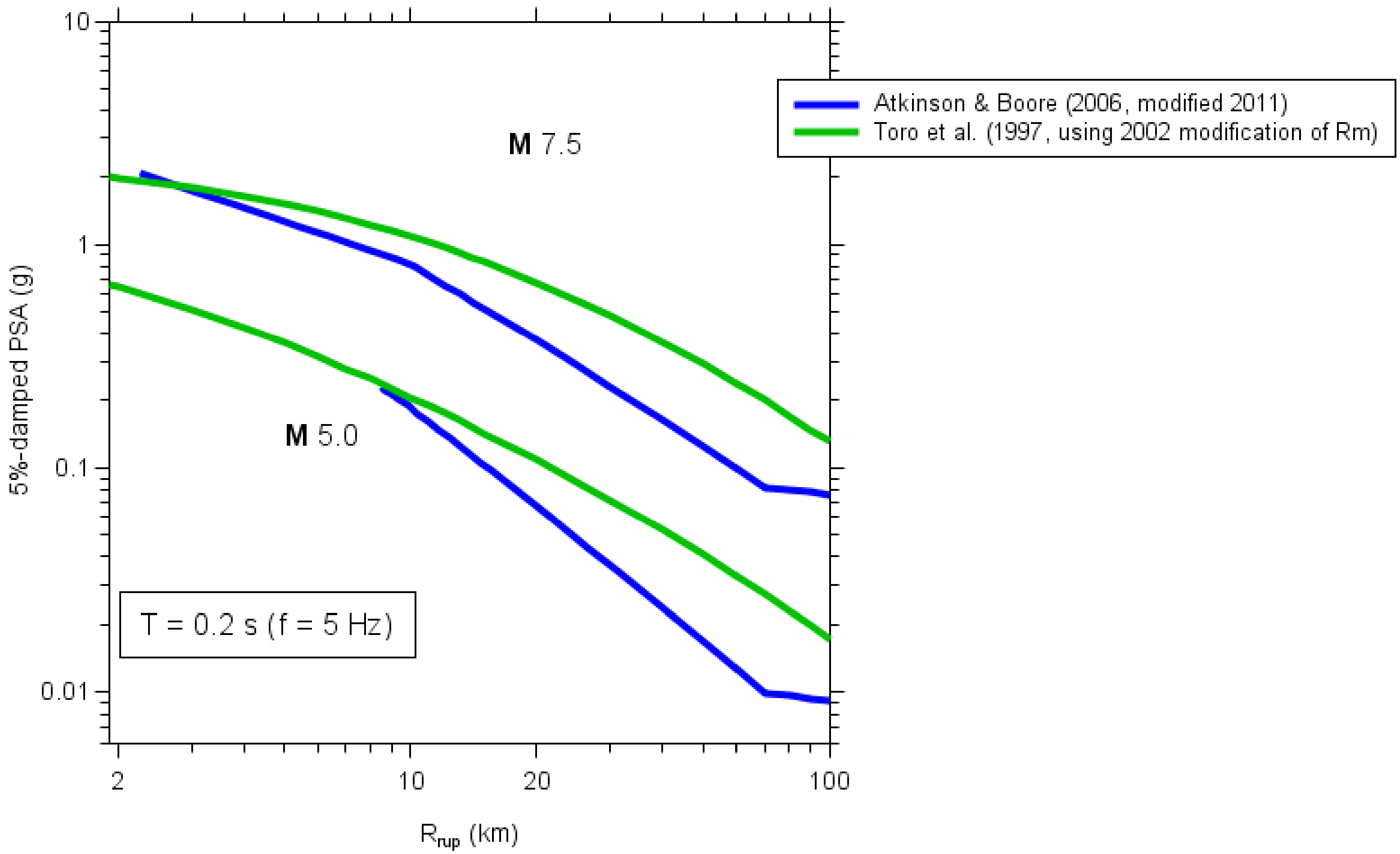
Please discuss how one should maintain consistency in parameters when adjusting GMPE's from another region

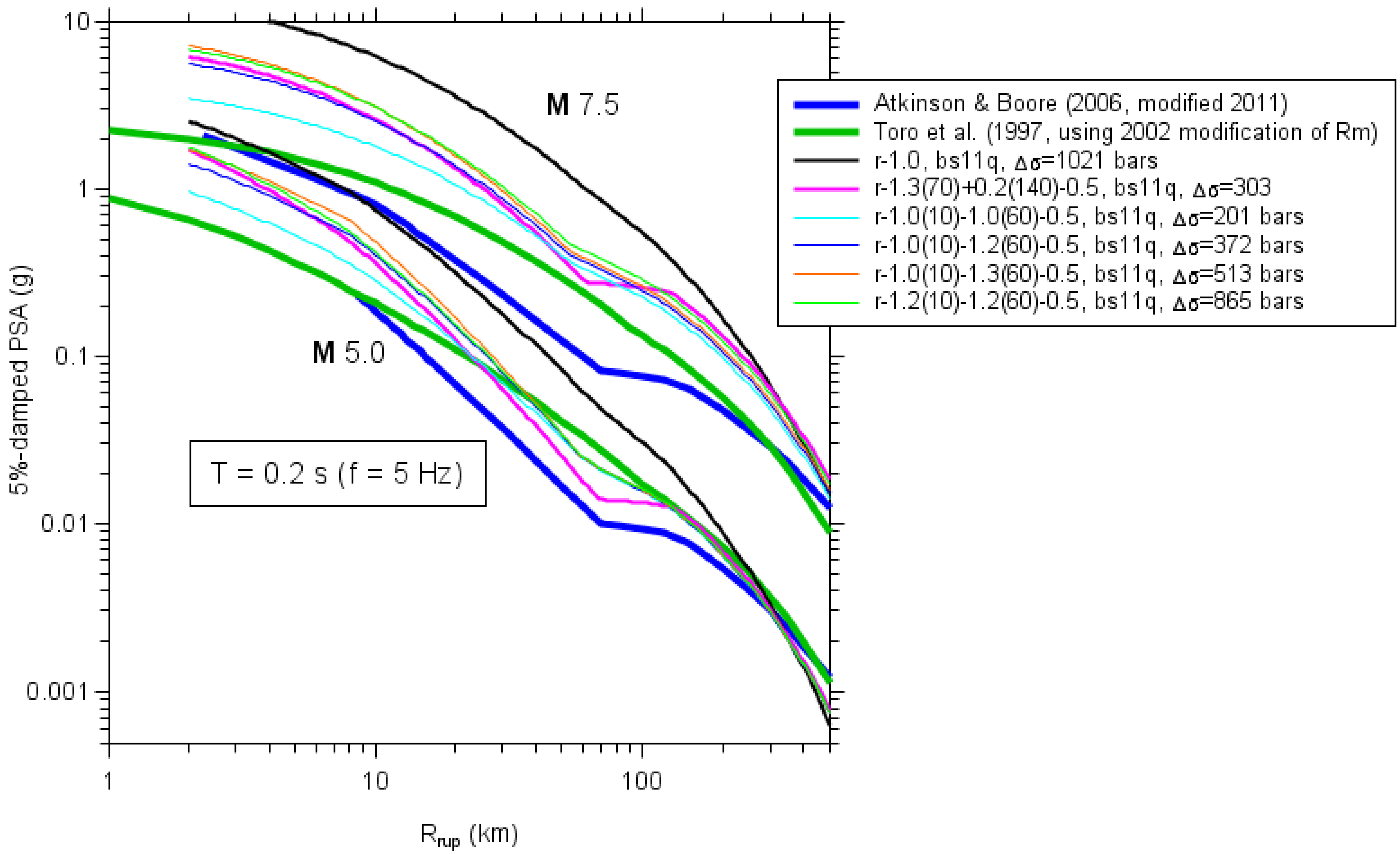
Fini

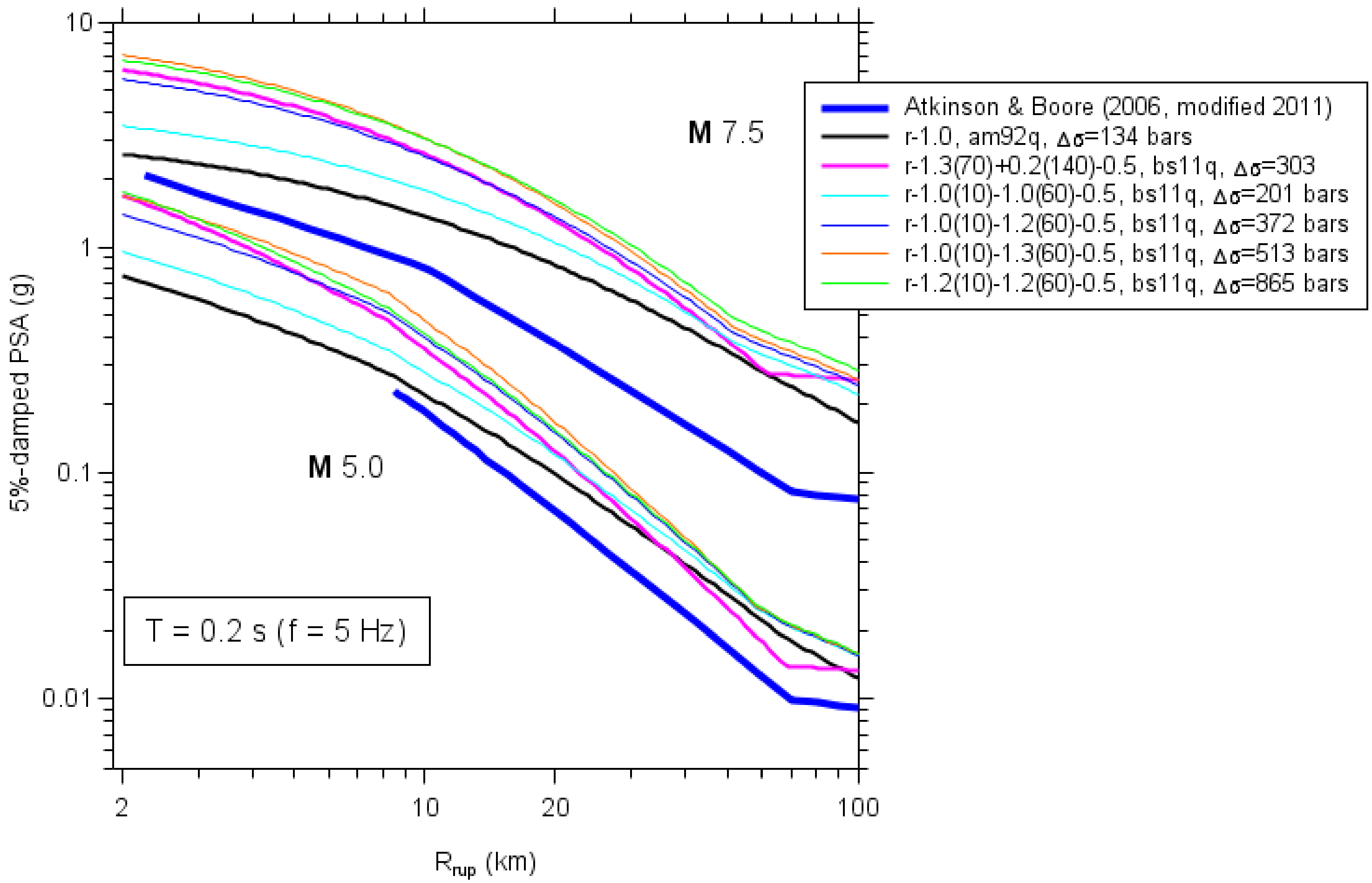
Steps in simulating time series

- Generate Gaussian or uniformly distributed random white noise
- Apply a shaping window in the time domain
- Compute Fourier transform of the windowed time series
- Normalize so that the average squared amplitude is unity
- Multiply by the spectral amplitude and shape of the ground motion
- Transform back to the time domain




Atkinson & Boore (2006, modified 2011)
Toro et al. (1997, using 2002 modification of Rm)
M 7.5
M 5.0
T = 0.2 s (f = 5 Hz)
5%-damped PSA (g)
10
1
0.1
0.01
2
10
20
100
Rrup (km)


M 7.5
M 5.0
T = 0.2 s (f = 5 Hz)
5%-damped PSA (g)
R_rup (km)
Atkinson & Boore (2006, modified 2011)
Toro et al. (1997, using 2002 modification of Rm)
r-1.0, bs11q, Δσ=1021 bars
r-1.3(70)+0.2(140)-0.5, bs11q, Δσ=303
r-1.0(10)-1.0(60)-0.5, bs11q, Δσ=201 bars
r-1.0(10)-1.2(60)-0.5, bs11q, Δσ=372 bars
r-1.0(10)-1.3(60)-0.5, bs11q, Δσ=513 bars
r-1.2(10)-1.2(60)-0.5, bs11q, Δσ=865 bars
10
1
0.1
0.01
0.001
1
10
100



File: C:\gm_predictions\working\ab06mod_vdb_fits_gm_m5.0_7.5_f5.0.expand_x_axis.draw; Date: 2012-02-27; Time: 1: