Chiou and Youngs (2006) - The Next Generation of Sadigh et al. (1997)

An Empirical Ground Motion Model for Horizontal Spectral Accelerations for Earthquakes in Active Tectonic Regions

Part of the PEER-NGA Project

Brian Chiou and Robert Youngs

Philosophy

- To update and extend the Sadigh et al. (1997) ground motion model
  - Use expanded and vetted strong motion data base
  - Incorporate concepts/trends from ground motion modeling and seismological observation
  - Incorporate additional effects (e.g. hanging wall)
  - Define smooth functional forms for effects of magnitude, distance, hanging wall location, site conditions, etc.
  - Prevent model parameters from being controlled by a single earthquake

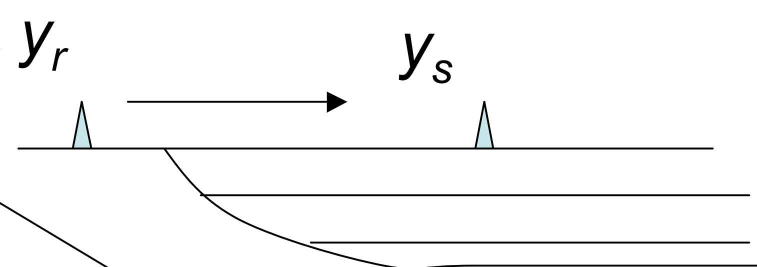
Data Selection

- Excluded earthquakes
  - Gorda plate earthquakes – oceanic crust
  - Subduction zone earthquakes
  - Poorly known overseas earthquakes
    - Northwest China earthquakes
    - Earthquakes recorded by SMART1 array, offshore Taiwan
- Excluded records
  - In basements
  - In large structures
  - No site data
  - One horizontal component

Model Form

- Reference site motion (Vs=1130m/sec)

$$\ln(y_{\text{ref}}) = C_1 + f_{\text{source}}(M, F_{\text{type}}, Z_{TOR}) + f_{\text{path}}(M, R, HW/FW, Q)$$
$$+ \tau \cdot z_i$$



- Site effects

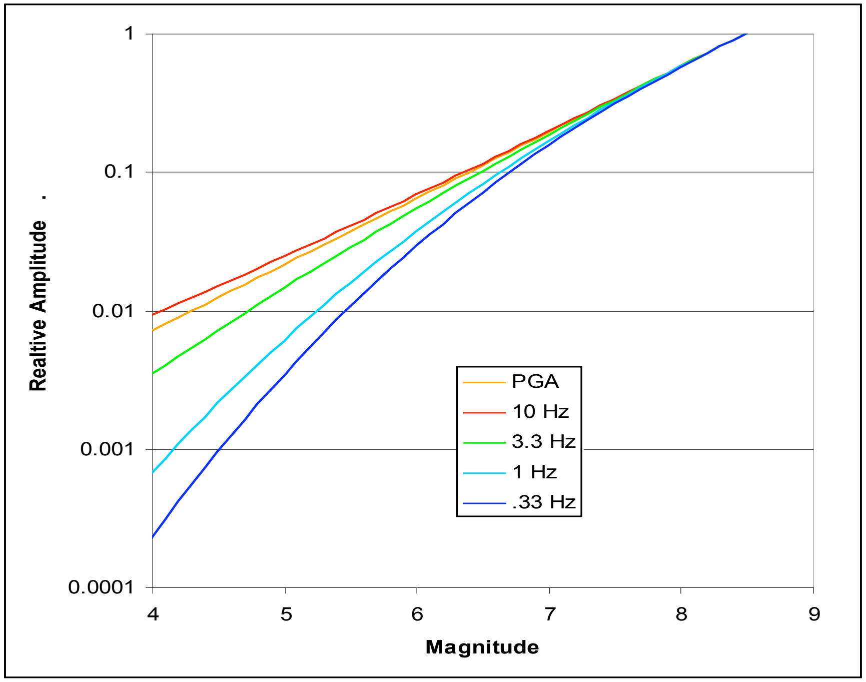
$$\ln(y_s) = \ln(y_{\text{ref}}) + f_{\text{site}}(V_{S30}, Z_1, y_{\text{ref}}) + \sigma\varepsilon_j$$

Magnitude Scaling

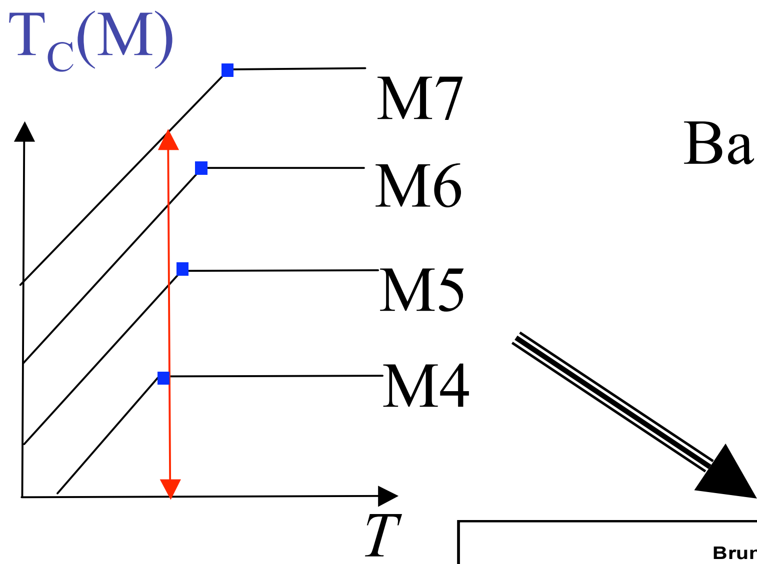
- Sadigh et al. (1997) form

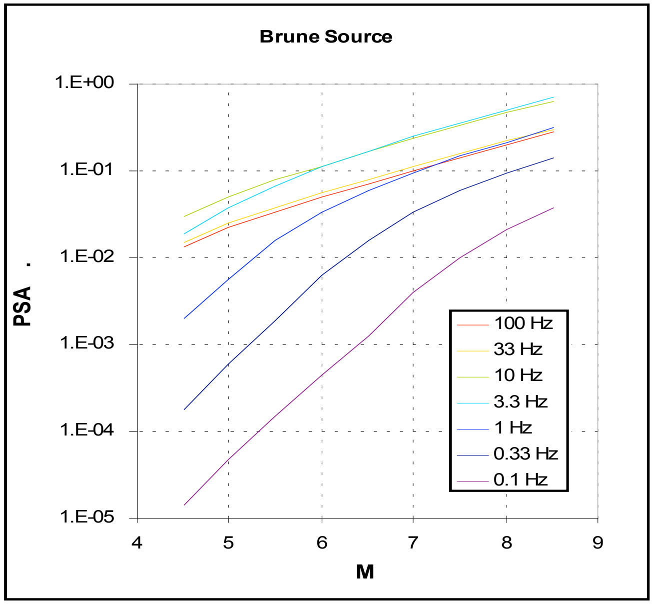
$$\ln(y) \propto c_2 M + c_3(T) \times (8.5 - M)^{2.5}$$

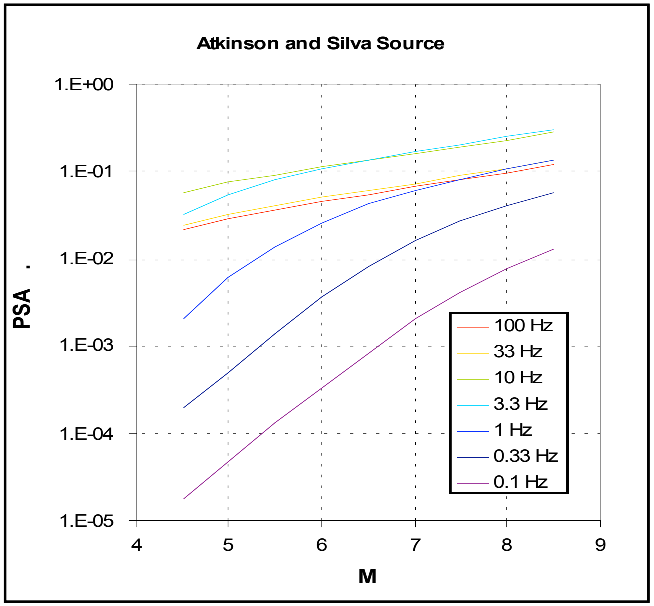
  - Linear scaling for PGA (c_3=0)
  - Curvature at a given magnitude is the same for all spectral frequencies



Form of Magnitude Scaling
Based on Earthquake Source Models







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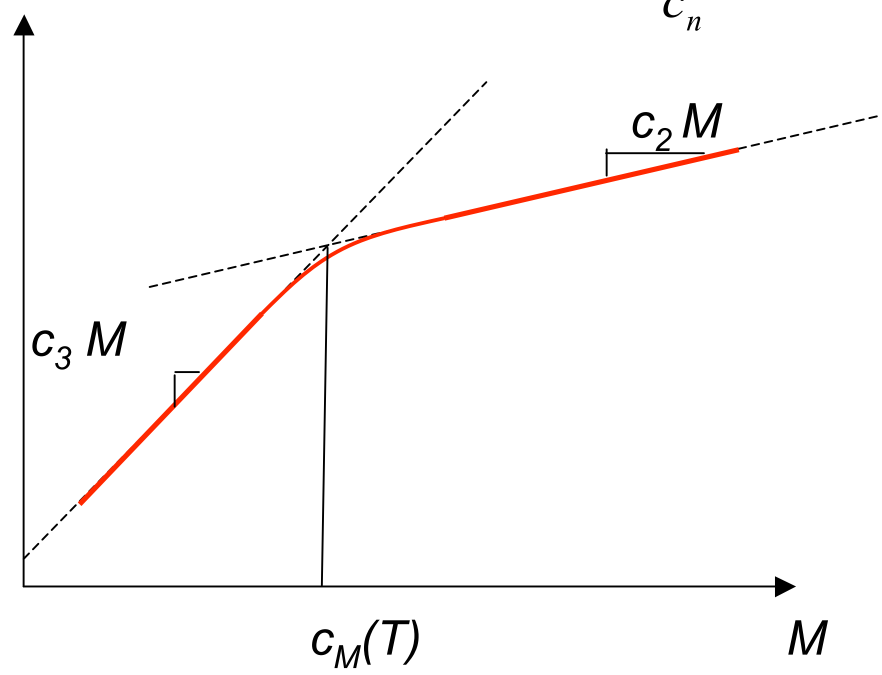
Magnitude Scaling

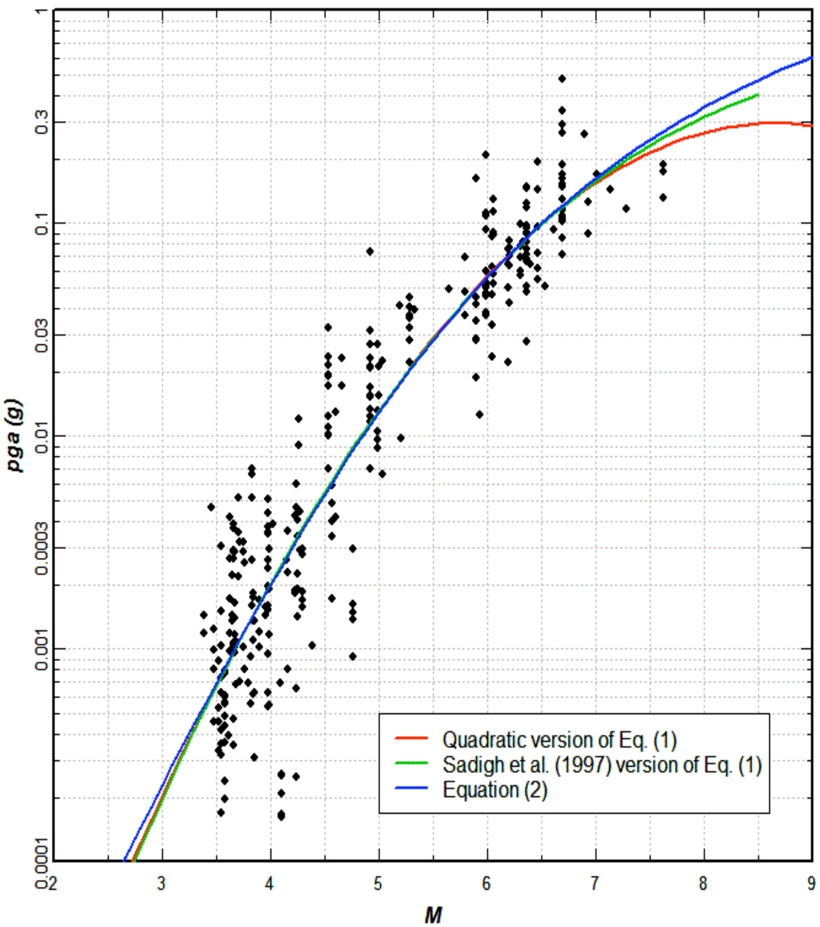
Sadigh et al. (1997) form: $\ln(y) \propto c_2 M + c_3(T) \times (8.5 - M)^{2.5}$

Updated form: $\ln(y) \propto c_2 M + \frac{c_2 - c_3}{c_n} \ln\left[1 + e^{-c_n(M - c_M(T))}\right]$



c_M is a function of response spectra period, T

Comparison of Magnitude Scaling Forms



- PGA data from the PEER-NGA database and from TriNet
  - $30 \leq R_{RUP} \leq 50$
  - $300 \leq V_{S30} \leq 400$
- Alternative forms of magnitude scaling provide comparable fits to data
- Updated form selected because it is more consistent with source models (e.g. Brune, 1970; Atkinson and Silva 1997, 2000)

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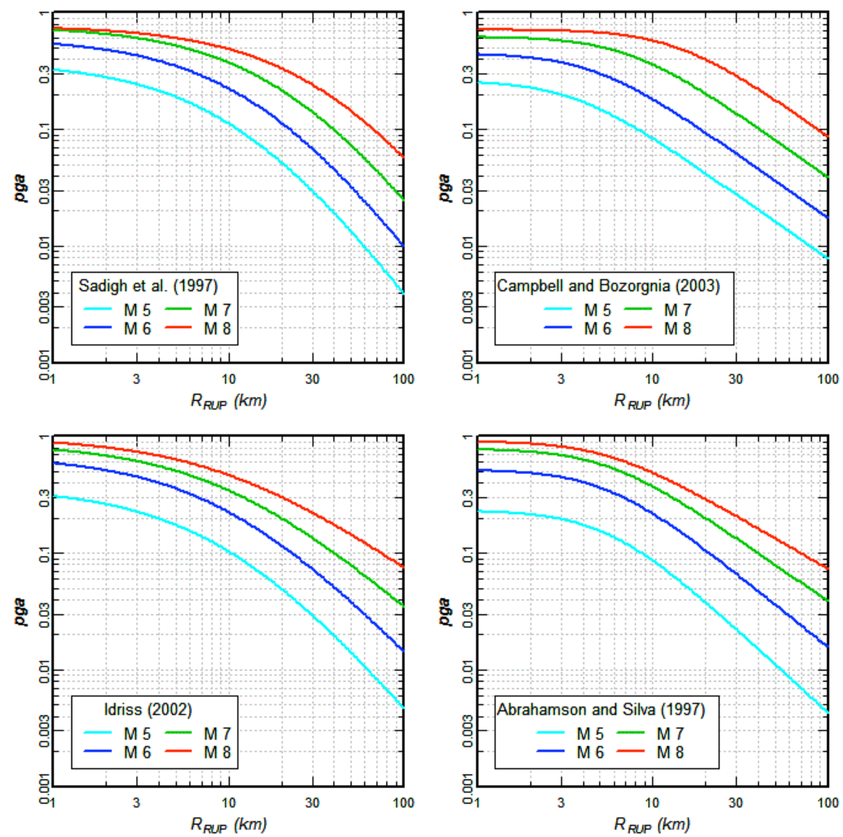
Distance Scaling

- Variety of forms can be used to model effect of extended ruptures at small R_{RUP}
- Form used by Sadigh et al. (1997) leads to ~distance-independent magnitude scaling at large distances – selected for use

$$\ln(y) \propto \ln\left[R_{RUP} + C(m)\right]$$



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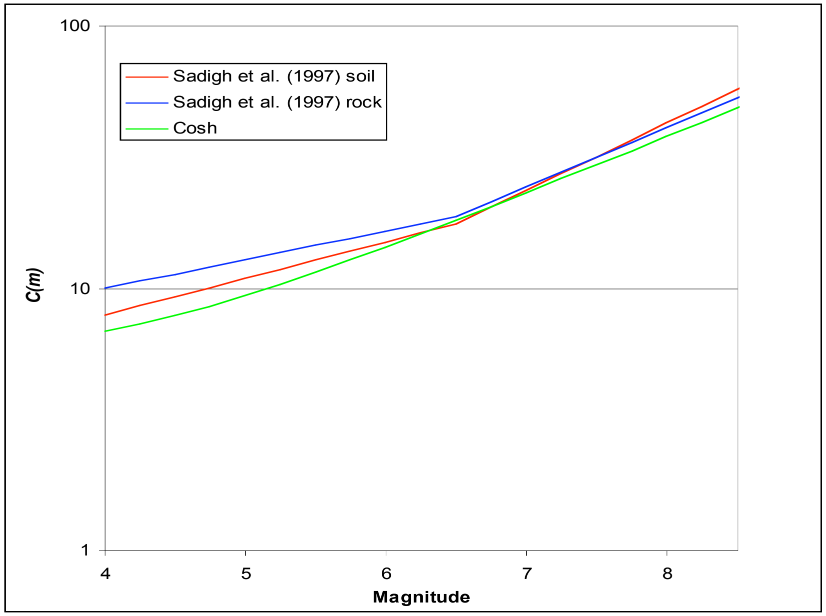
Modification of "extended rupture term" $C(m)$

- Sadigh et al. (1997) uses bilinear form $C(m)=\exp(c_5+c_6\mathbf{M})$ with change in c_5 and c_6 at **M** 6.5
- Updated form $C(m)=c_5\cosh[c_6(\mathbf{M}-3)]$ results in smooth variation over full magnitude range with $C(m) \propto \exp(c_6\mathbf{M})$ at large magnitudes



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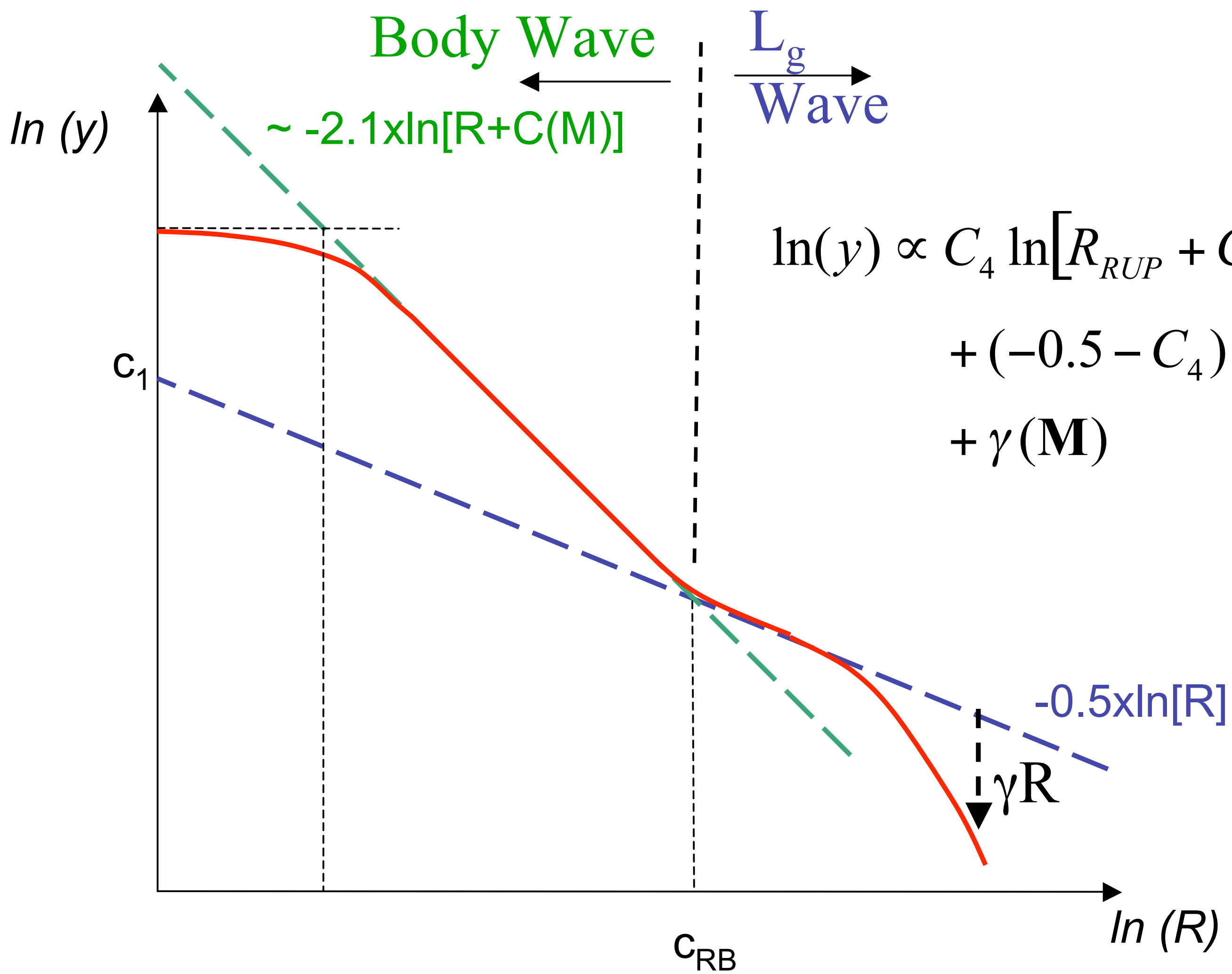
Extension to Model Distance Scaling at Large Distances



$$\ln(y) \propto C_4 \ln\left[R_{RUP} + C(m)\right] + (-0.5 - C_4)\ln\sqrt{R_{RUP}^2 + C_{RB}^2} + \gamma(\mathbf{M})$$

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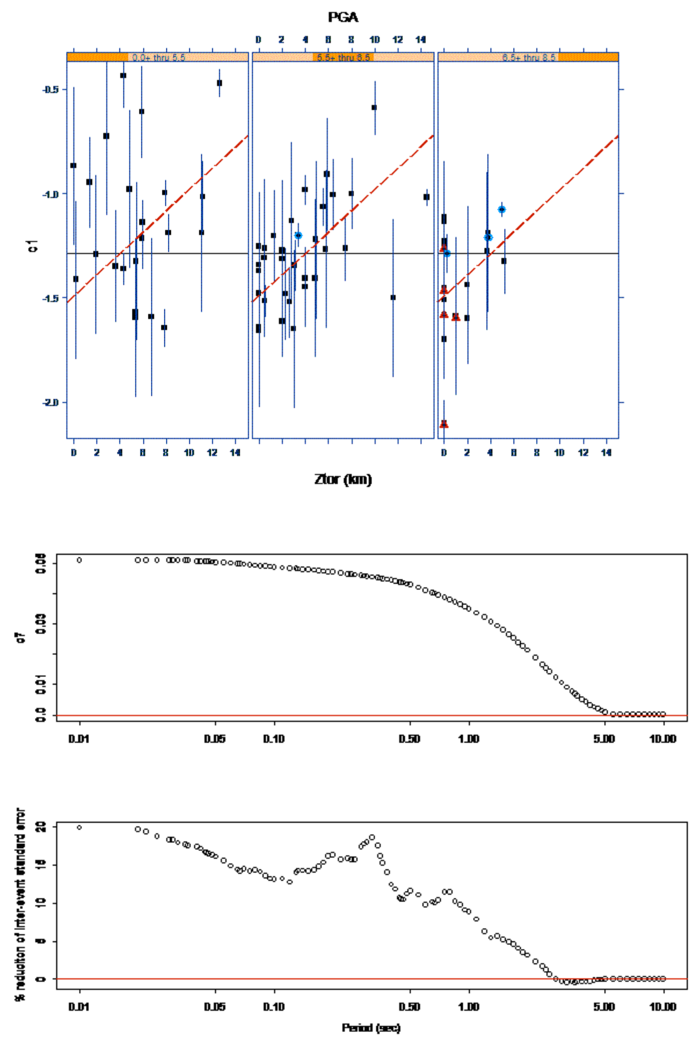
Style of Faulting

- Reverse and Reverse-oblique
  (rake 30 to 150)
  - Marginally significant (5 to 10% increase)
- Normal (rake -120 to -60)
  - Significantly lower than SS (20 to 30%) when normal-oblique is included in SS group
- Strike slip and Normal-oblique

Depth to Top of Rupture

- Significant effect for higher frequenies
- Magnitude dependence not significant
- Aftershocks have stronger trend than main shocks



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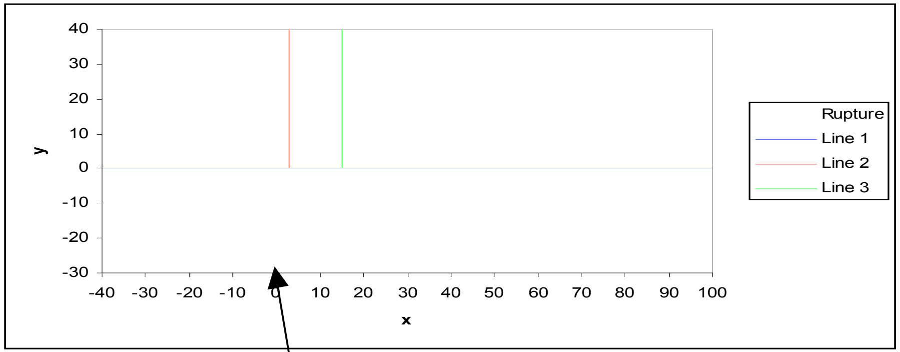
Aftershock Recordings

- Included to help define soil model parameters
- Aftershocks have lower motion on average than main shocks
- Stronger dependence on depth
- Weaker dependence on style of faulting

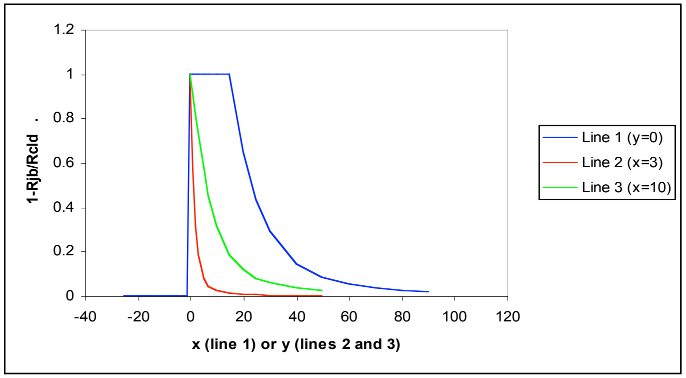
Hanging Wall Effect

$$f_{HW} \propto [1 - R_{JB} / (R_{Cld} + 0.0001)]$$

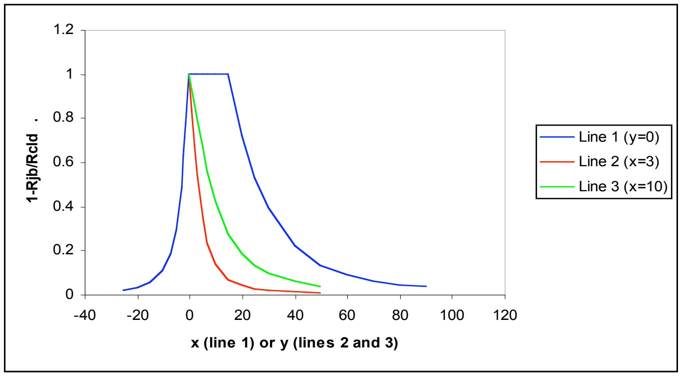


Top of Rupture

Surface Rupture



Buried Rupture (5 km)



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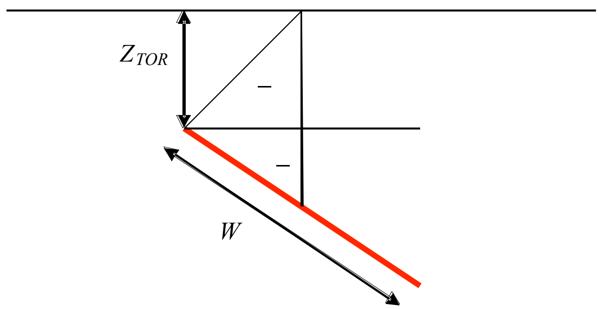
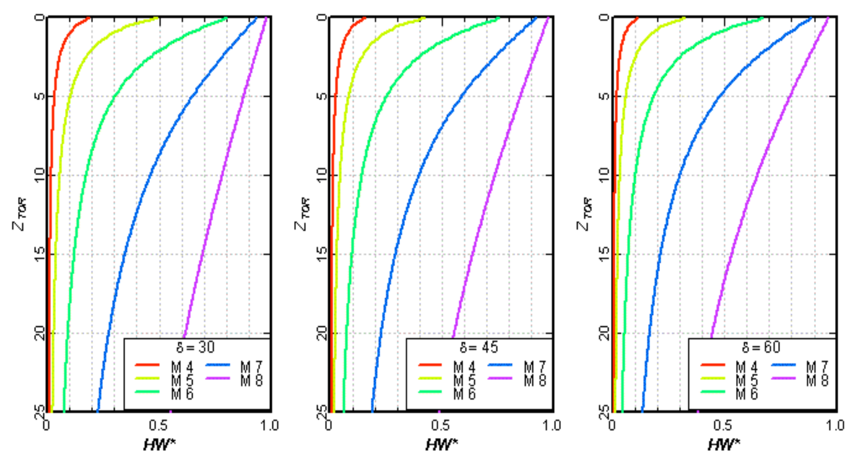
Hanging Wall a Geometric Effect

$$f_{HW} = \tanh(0.5R_{RUP}) \times \cos^2(\delta) \times \frac{2}{\pi}\tan^{-1}\left(\frac{W\cos(\delta)}{2(Z_{TOR}+1)}\right) \times \left[1 - \frac{R_{JB}}{R_{RUP}+0.001}\right]$$

- RMS distance works well, but computationally expensive
- Decreasing effect with increasing dip
- Effect expected to decrease with decreasing magnitude (smaller extent of rupture)
- Effect expected to decrease with increasing depth of source
- Smooth variation instead of magnitude and depth "ramps"





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Site Response Model

- At low amplitudes a linear function of $\ln(V_{S30})$ based on empirical data
- Nonlinear effects based on empirical data guided by modeling results
- Depth to V_S ~ 1 km/s included after model development as a fit to residuals for sites with estimated depths
  - Strong trade off between V_{S30} and $Z_{1.0}$ scaling for periods > 1 second.

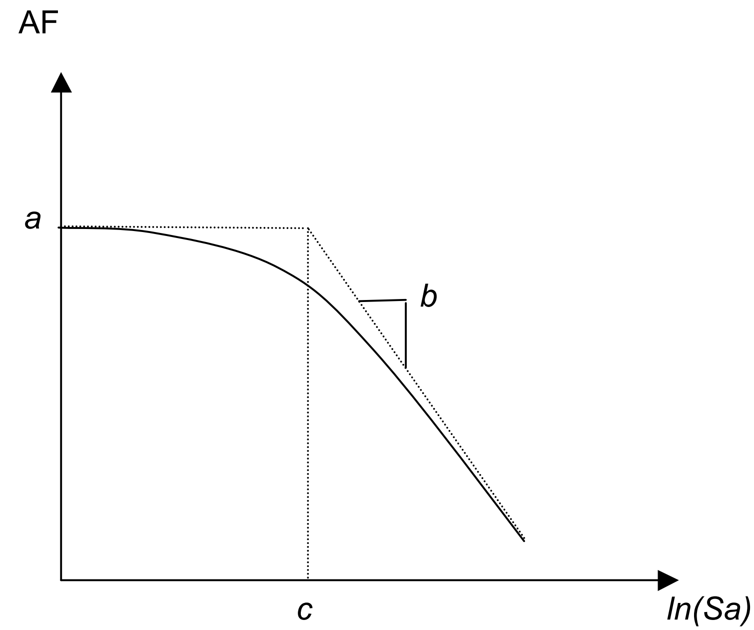
Site Response Model (cont'd)

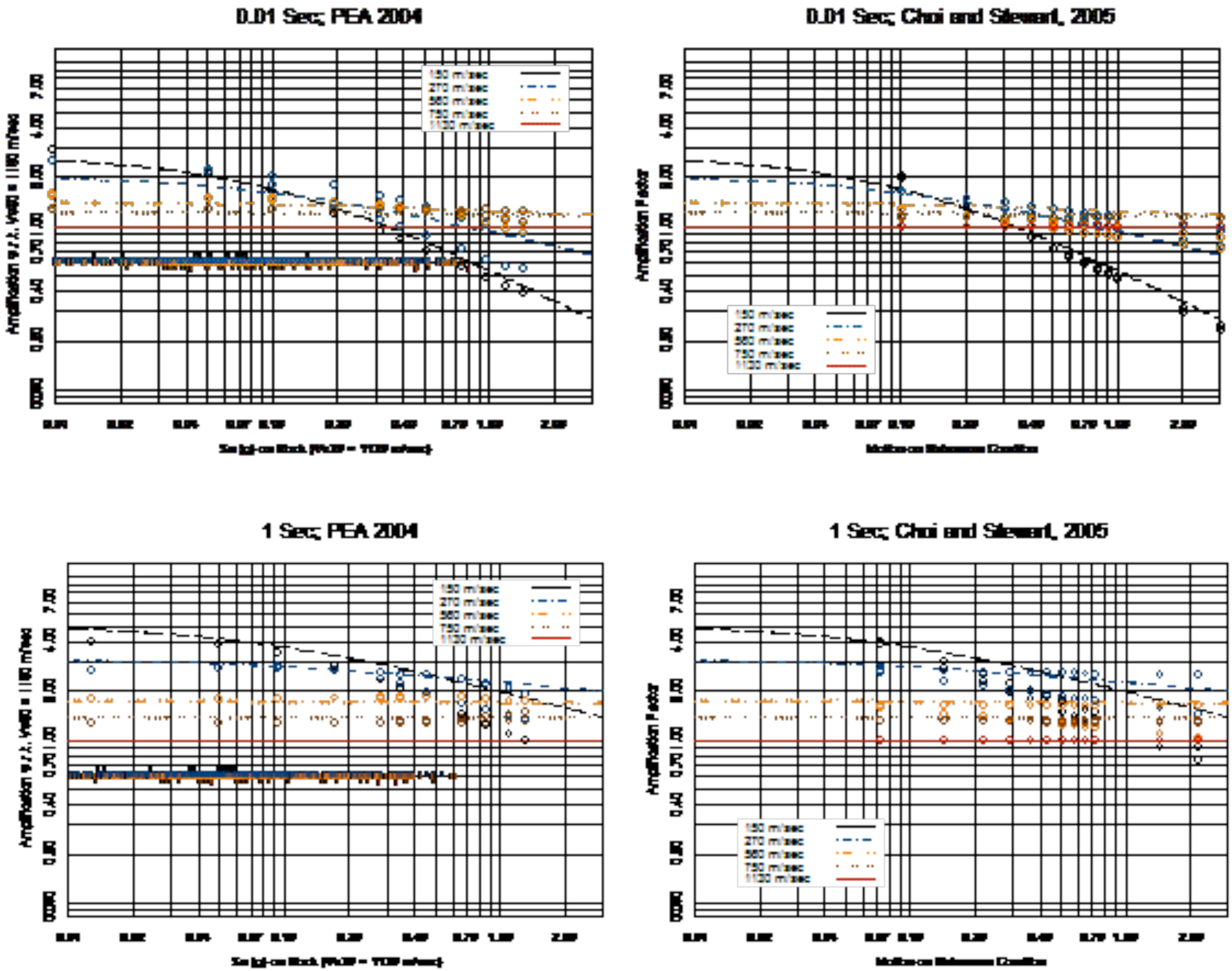
$$\ln(AmpFactor) = a + b\ln(\frac{y_r + c}{c})$$

$$a = \phi_1 \ln(V_{S30}/1130)$$

$$b = \phi_2 e^{\phi_3 V_{S30}}$$

$$\phi_1, \phi_2, \phi_3, c = f(T)$$





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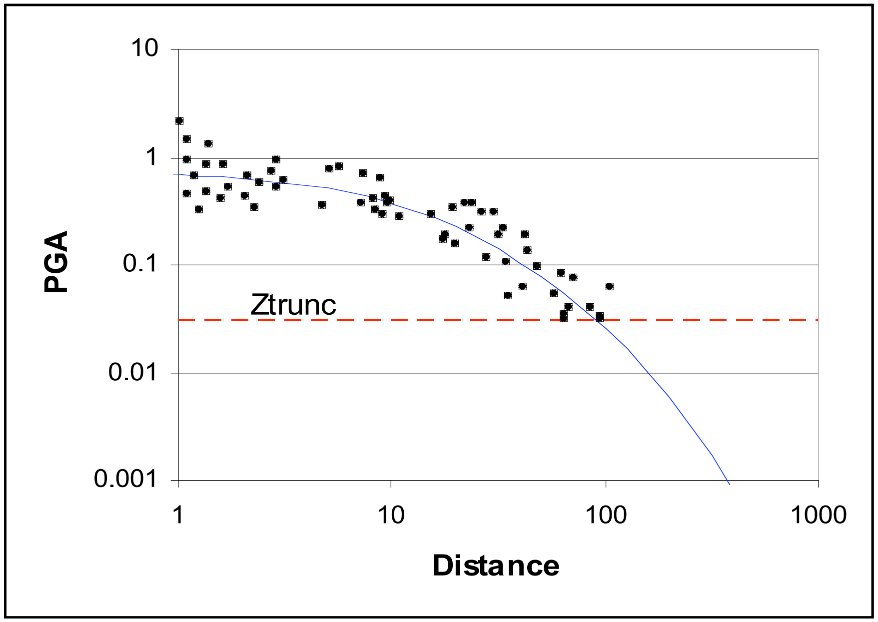
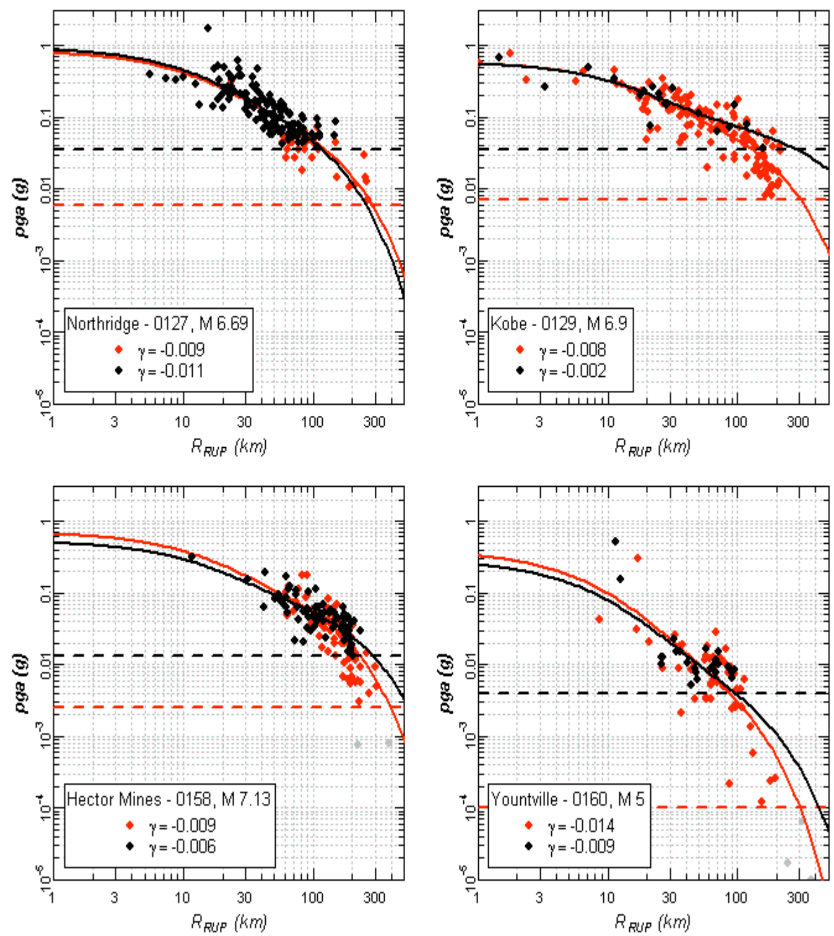
Potential Bias at Large Distances



- Data truncated horizontally at a level Z_{trunc}
- Unknown number of recordings where value of $pga < Z_{trunc}$
- Published methods for ordinary regression (e.g. Toro, 1981)
- Extended method to random (mixed) effects regression

Truncated Regression for Selected Earthquakes with Extensive Data Sets

- Extended PEER-NGA *pga* data sets with TriNet data and other published *pga* values
- Unable to obtain extended data set value of γ from PEER-NGA data alone
- Therefore, limited data to ≤ 70 km and used 13 California earthquakes to define $\gamma(m)$



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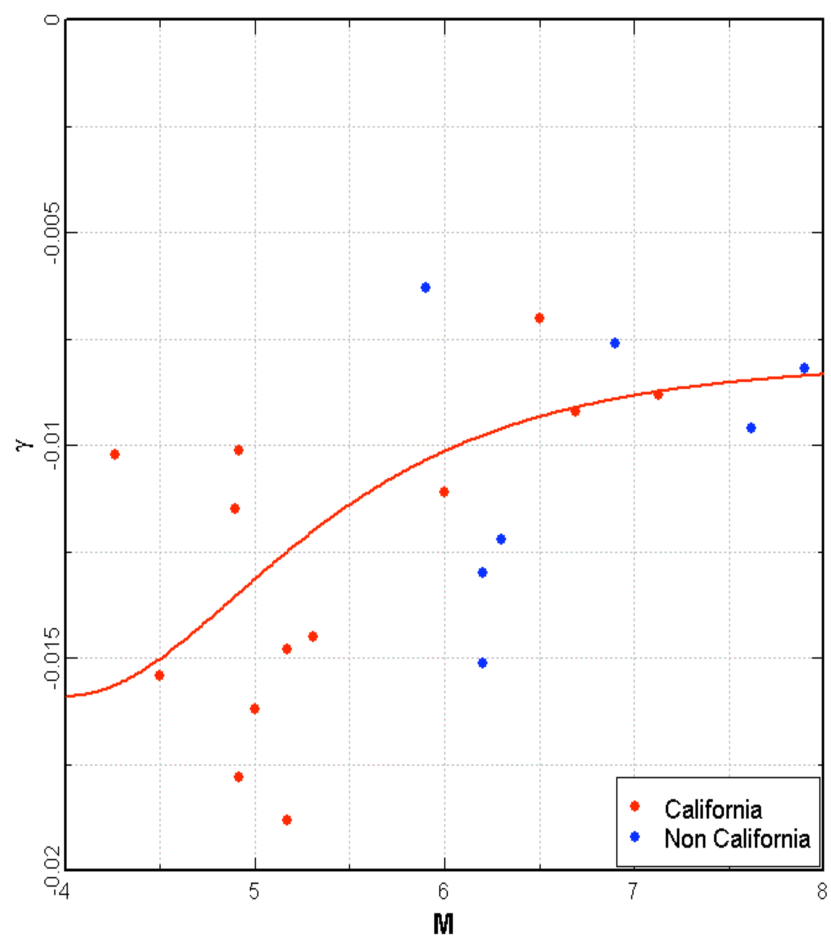
Model for γ

EQID	Earthquake	M	PEER-NGA Data Set		Expanded Data Set		Region
			–	Number of Recordings	–	Number of Recordings	
0127	Northridge	6.69	-0.0108	122	-0.0092	154	California
0129	Kobe	6.9	-0.0020	22	-0.0076	157	Japan
0137	Chi-Chi	7.62	-0.0096	305			Taiwan
0157	San Juan Bautis ta	5.17	-0.0392	2	-0.0188	23	California
0158	Hector Mines	7.13	-0.0056	82	-0.0088	163	California
0160	Yountville	5	-0.0088	24	-0.0162	76	California
0162	Mohawk Val, Portola	5.17	-0.0191	6	-0.0148	36	California
0163	Anza-02	4.92	-0.0164	72	-0.0178	193	California
0165	CA/Baja Border Area	5.31	-0.0433	9	-0.0145	142	California
0166	Gilroy	4.9	-0.0054	34	-0.0115	136	California
0167	Yorba Linda	4.265	-0.0851	12	-0.0102	207	California
0169	Denali	7.9	-0.0082	23			Alaska
0170	Big Bear City	4.92	-0.0004	35	-0.0101	262	California
0171	Chi-Chi, Taiwan -02	5.9	-0.0063	277			Taiwan
0172	Chi-Chi, Taiwan -03	6.2	-0.0151	225			Taiwan
0173	Chi-Chi, Taiwan -04	6.2	-0.0130	241			Taiwan
0174	Chi-Chi, Taiwan -05	6.2	-0.0130	310			Taiwan
0175	Chi-Chi, Taiwan -06	6.3	-0.0122	260			Taiwan
	Loma Linda	4.5			-0.0154	93	California
	Parkfield	6			-0.0111	308	California
	San Simeon	6.5			-0.0070	225	California



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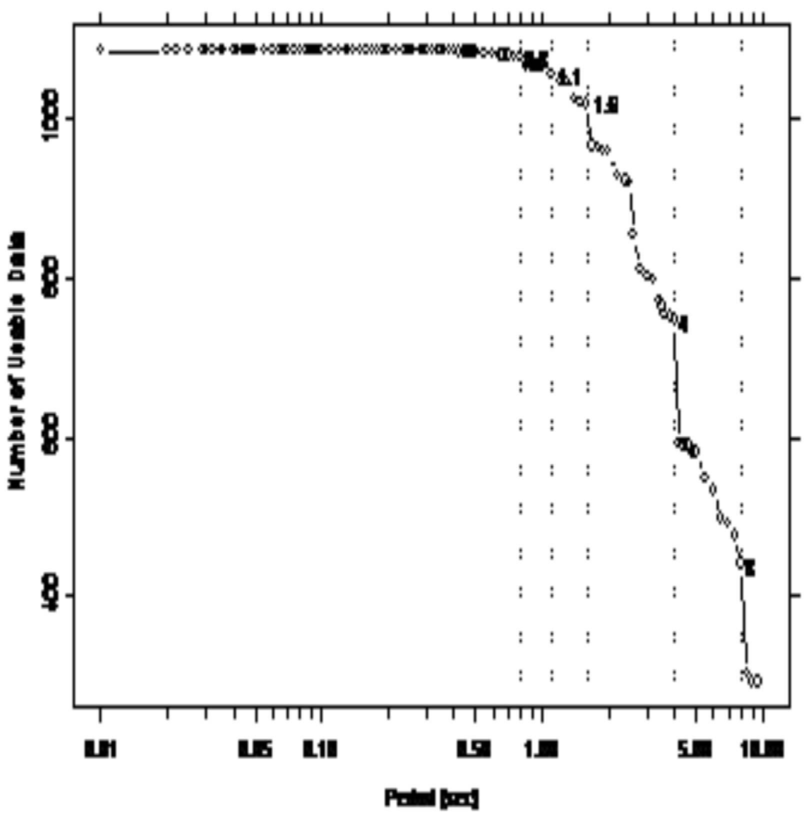
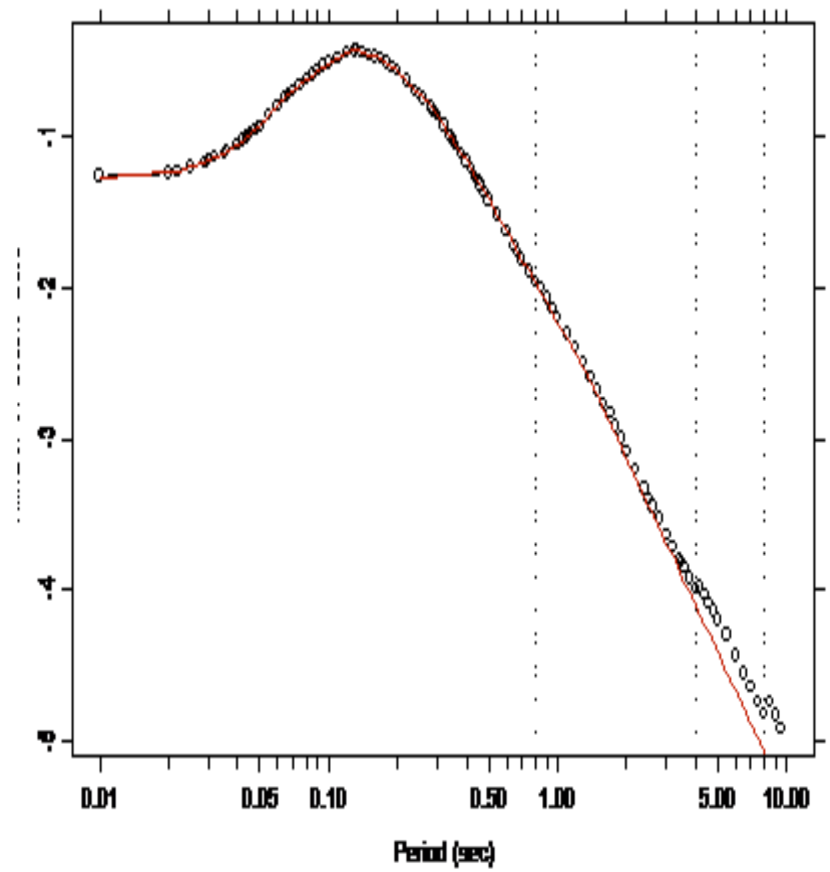
Extension to Long Periods





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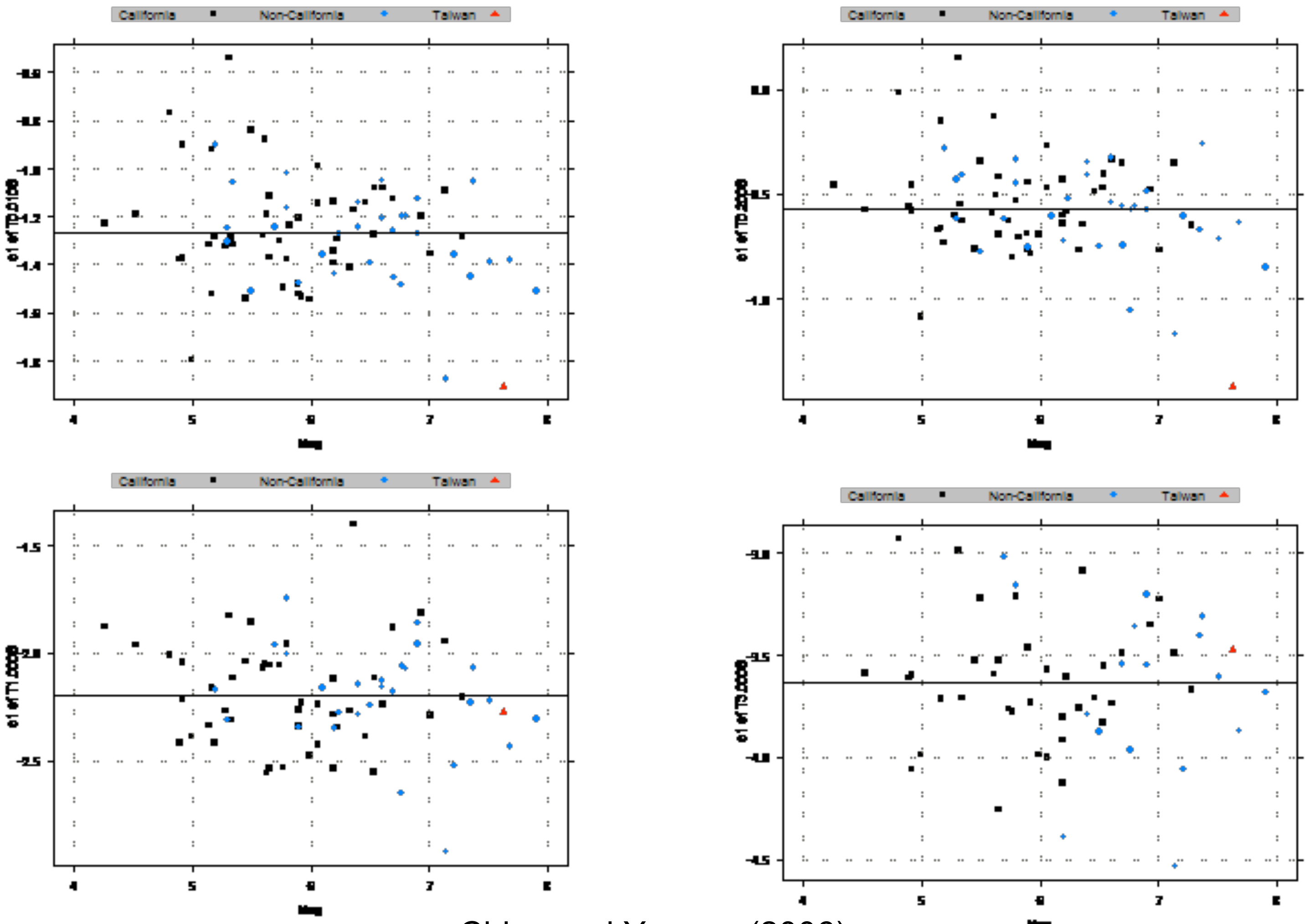
Inter-Event Residuals



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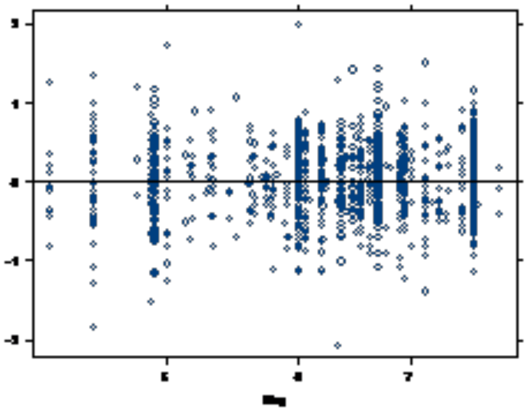
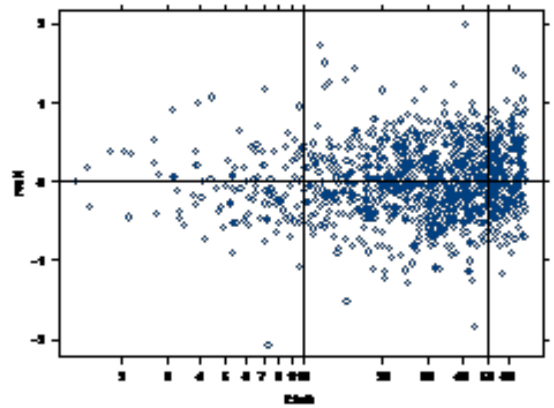
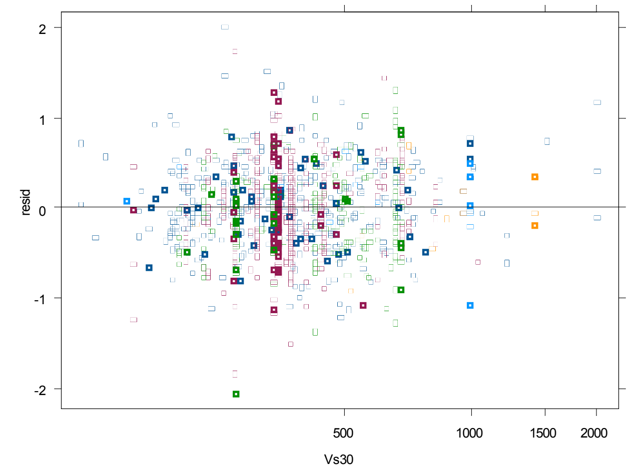
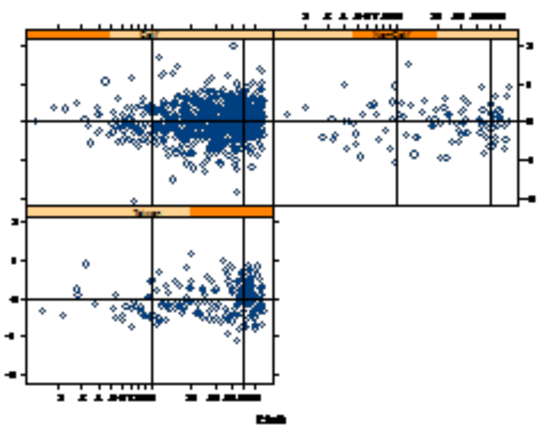
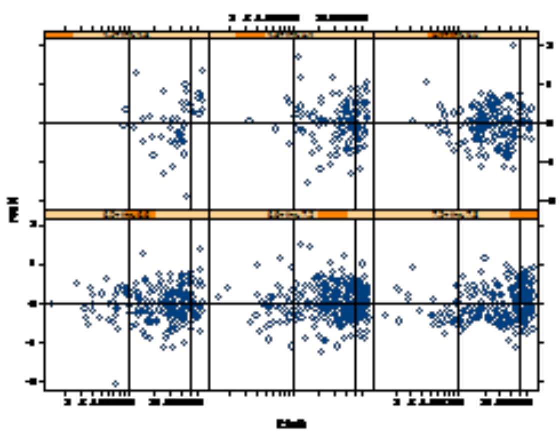
PGA Intra-Event Residuals

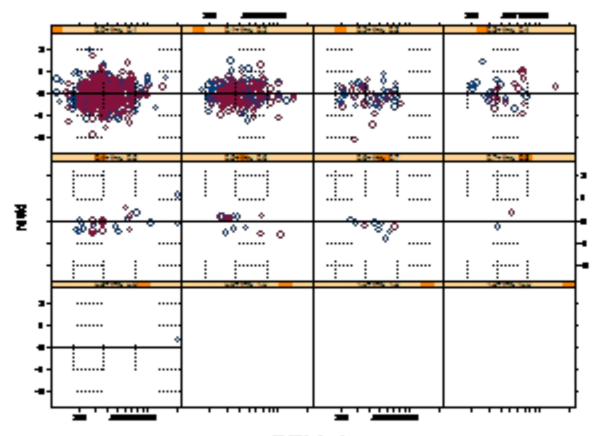












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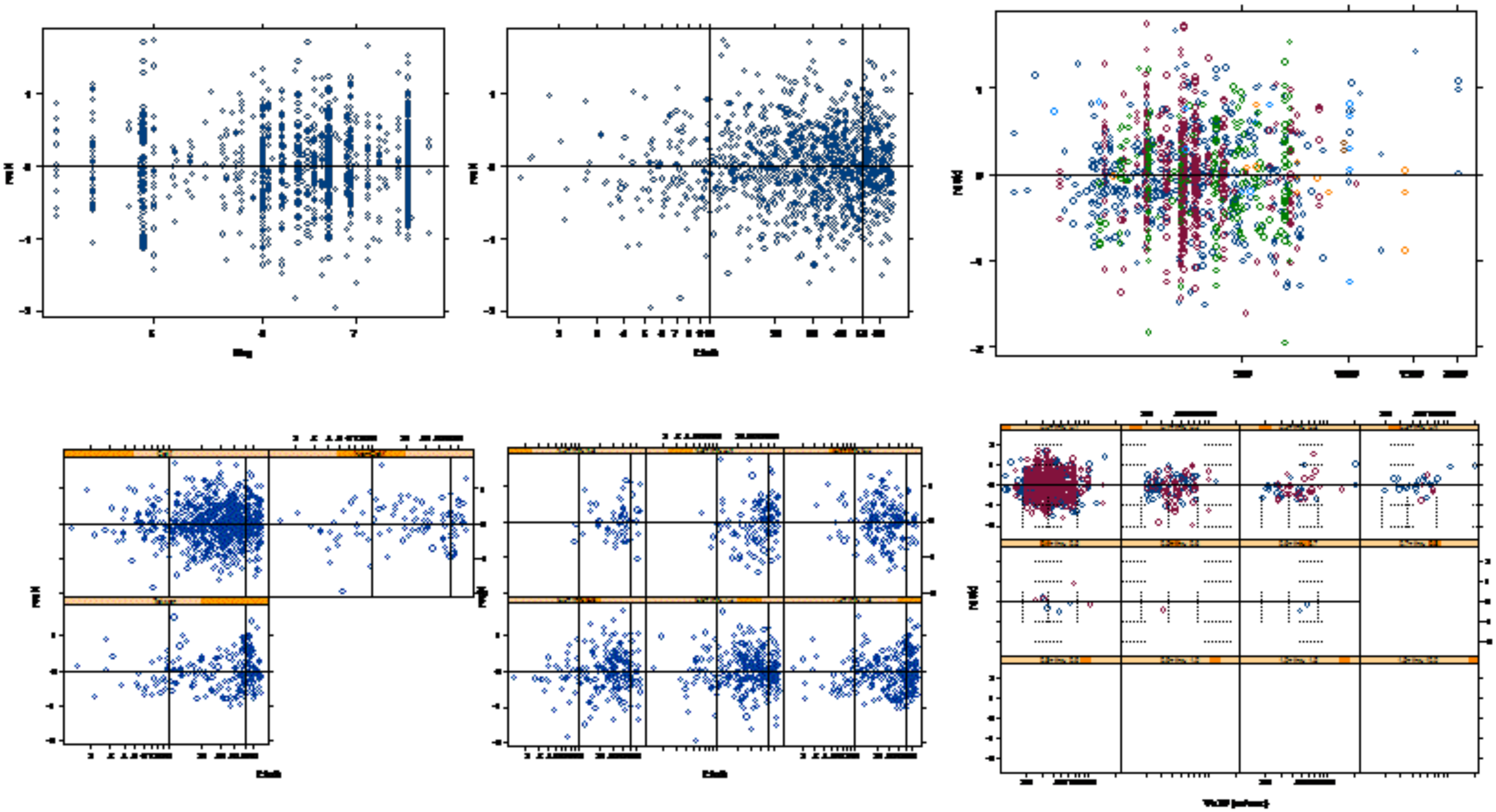
1 Hz PSA Intra-Event Residuals



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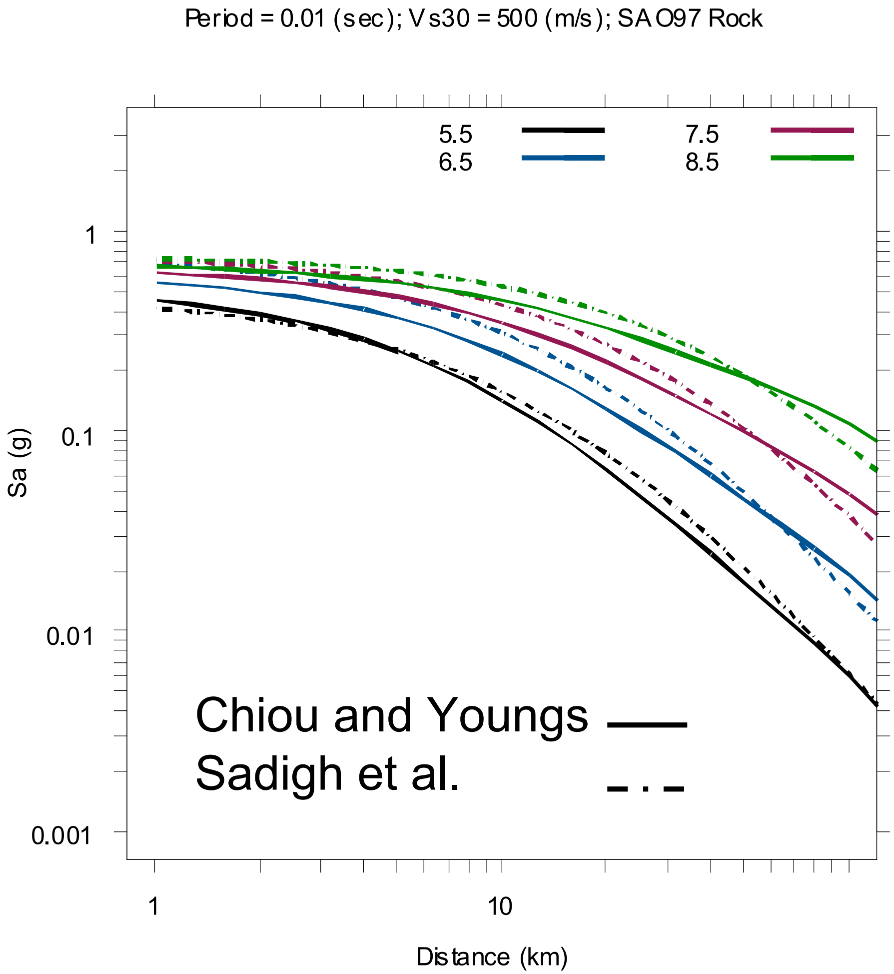
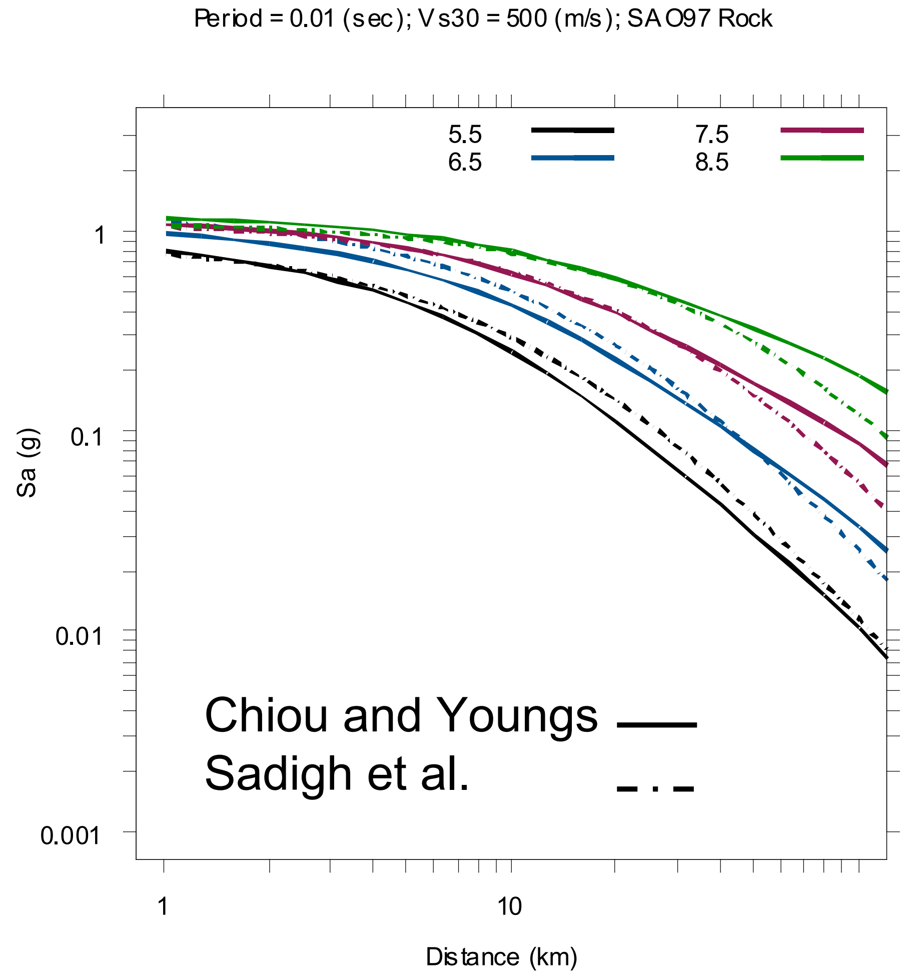
Comparison of Median and 84th% PGA





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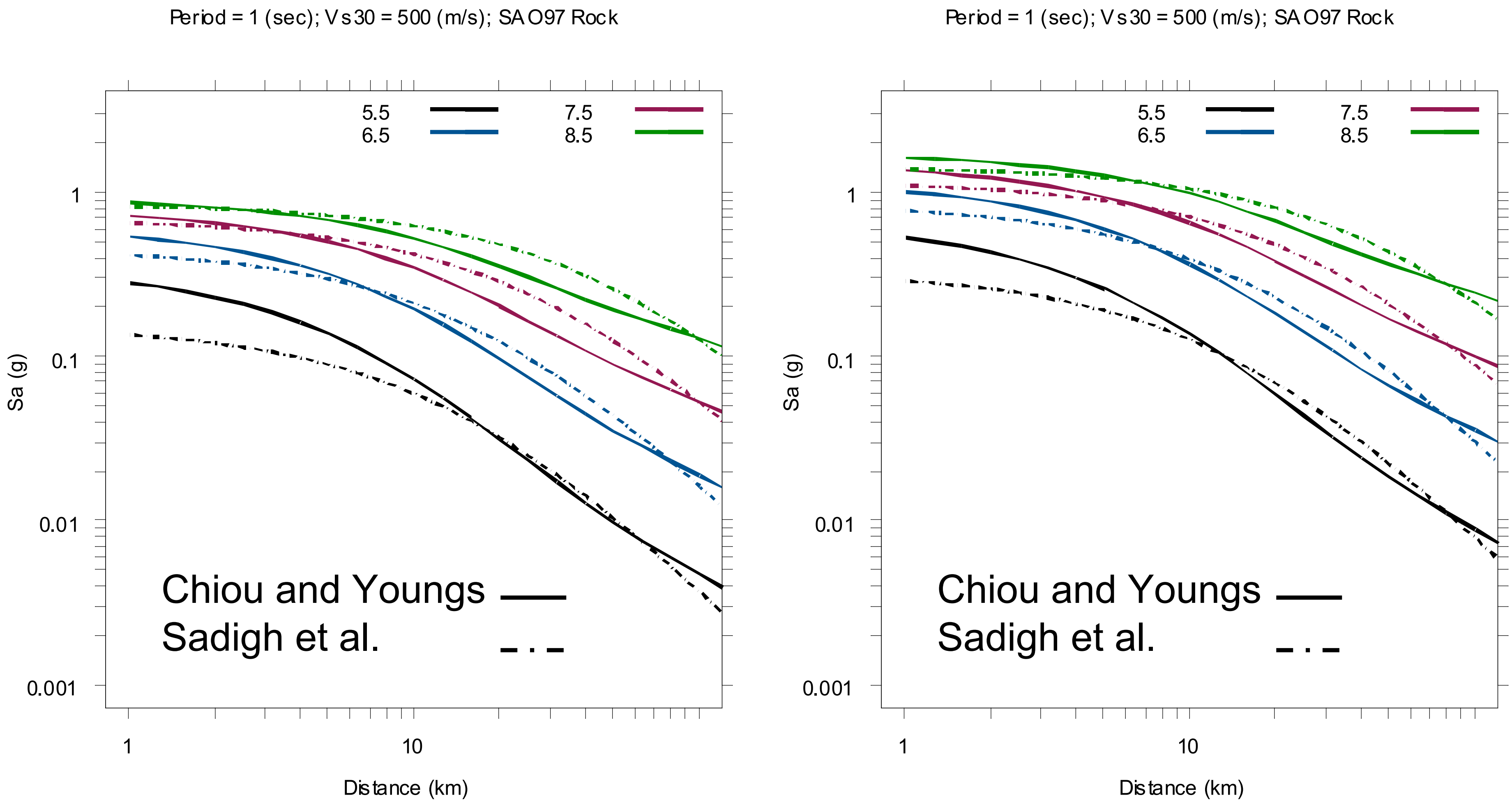
Comparison of Median and 84th% 1-Hz PSA



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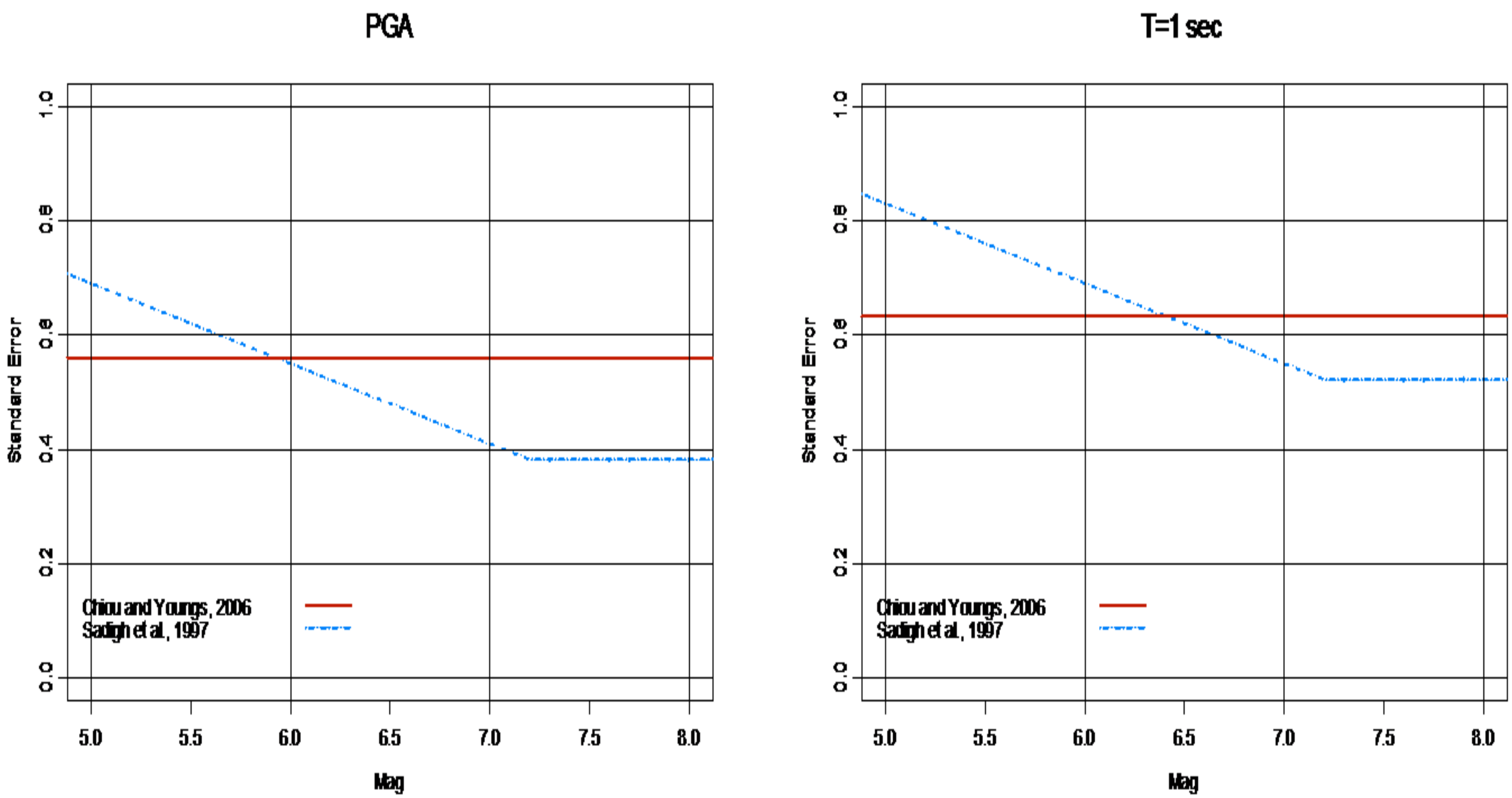
Aleatory Sigma



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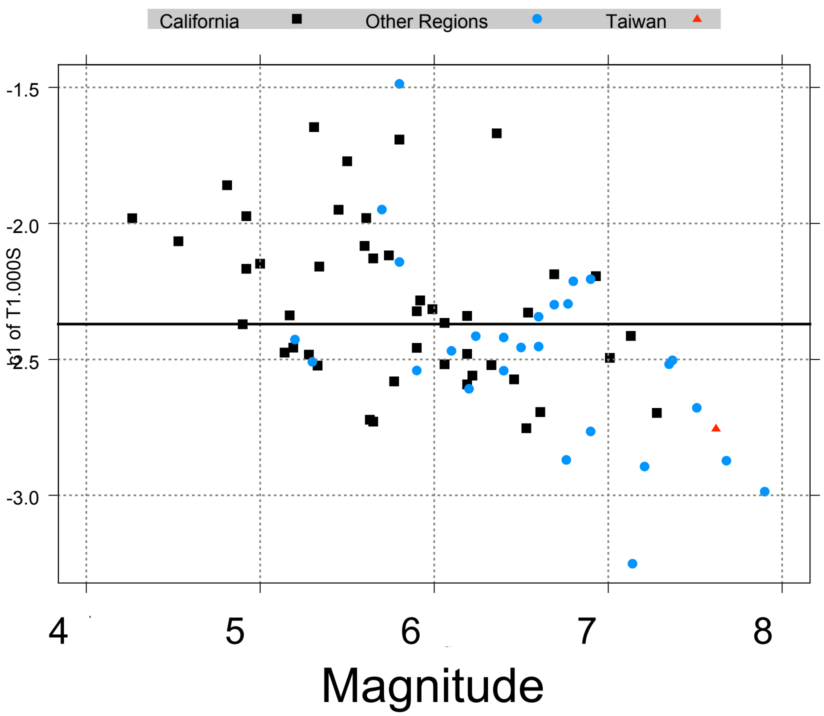
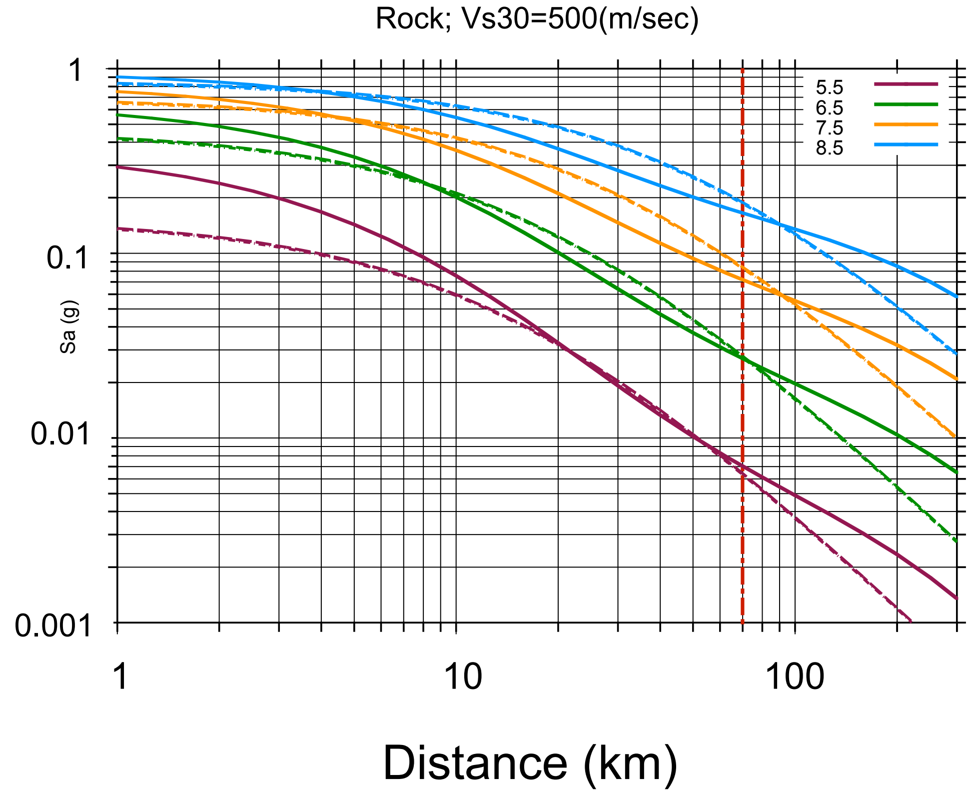
Sadigh et al. Needs to be Updated

1-Second Spectral Acceleration





California

Other Regions

Taiwan

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Updated Sadigh et al., Rock

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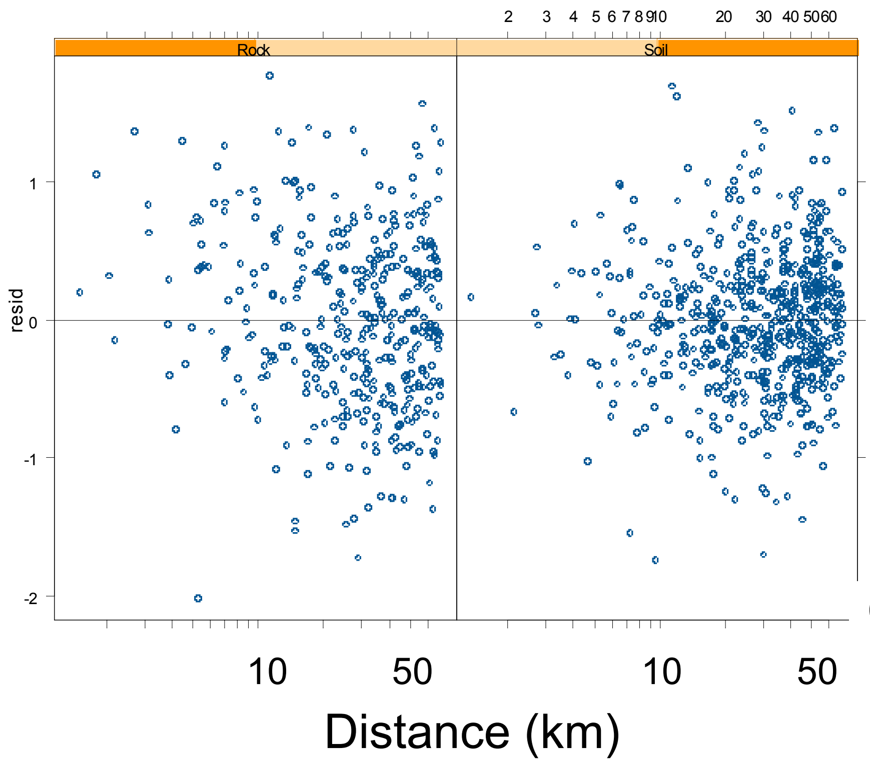
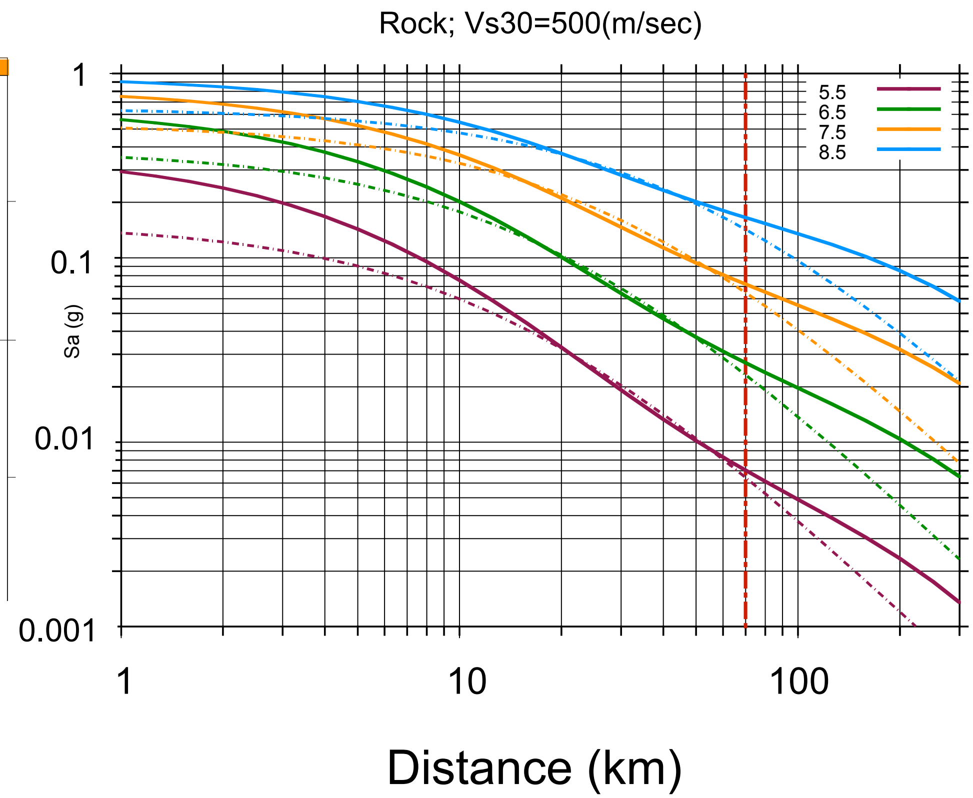
Update the Magnitude Scaling





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Updated Sadigh et al., Rock

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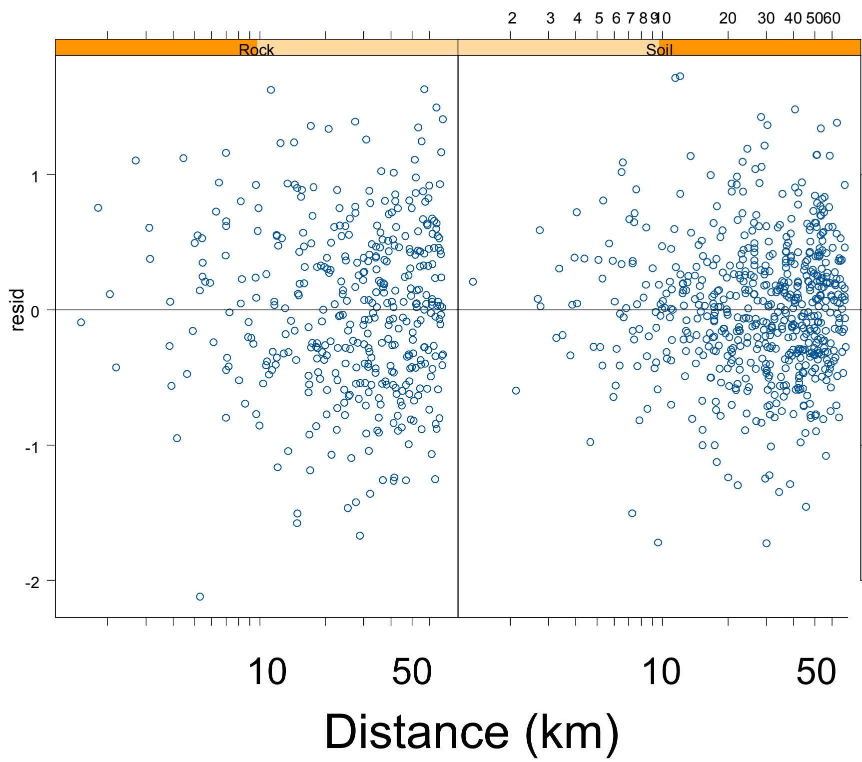
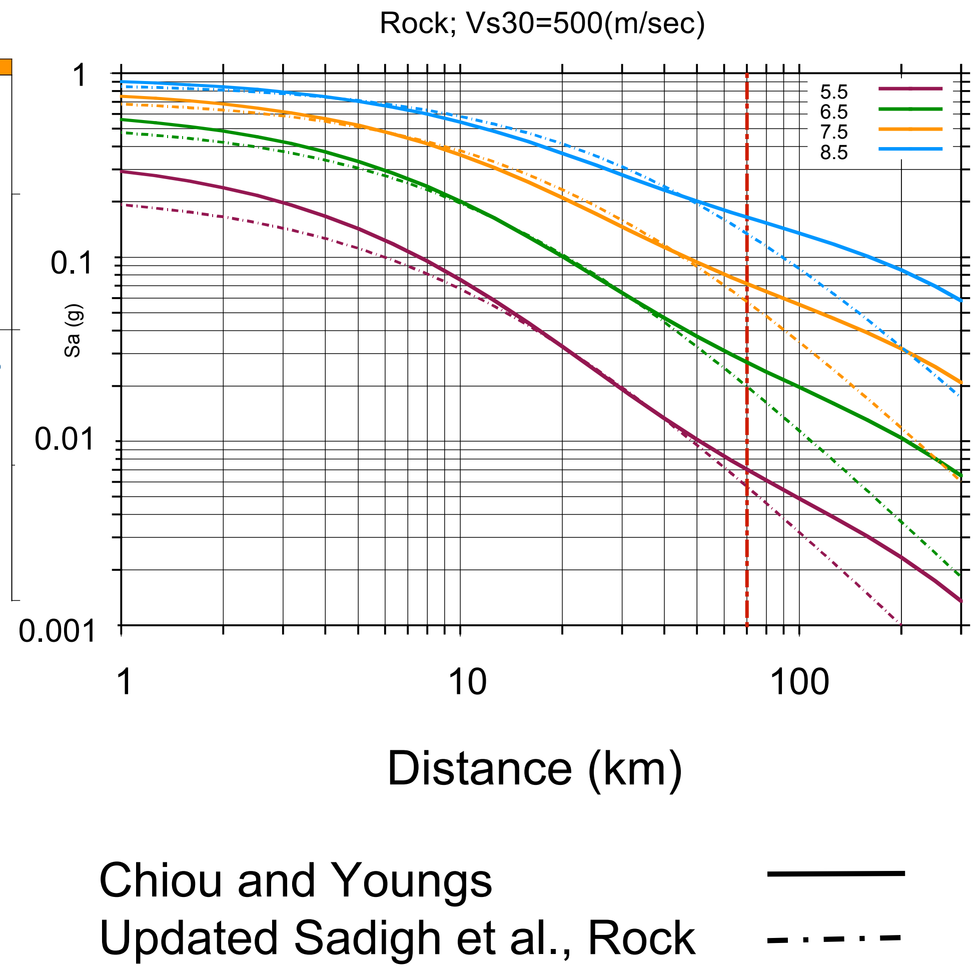
Update Ground Motions at Near-Source Distances





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