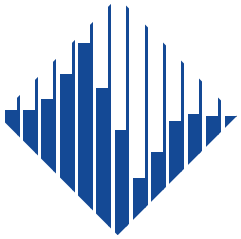

PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

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PEER Report No. 2018/02
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ABSTRACT

An update to the BCHydro ground-motion model for subduction earthquakes has been developed using the 2018 PEER NGA-SUB dataset. The full NGA-SUB database includes over 70,000 recordings from 1880 earthquakes. A subset of 8144 recordings from 181 earthquake is used in this study. The update modifies the BCHydro model to include regional terms for the V_{S30} scaling, large distance (linear R) scaling, and constant terms, which is consistent with the regionalization approach used in the NGA-West2 ground-motion models. A total of six regions were considered: Cascadia, Central America, Japan, New Zealand, South America, and Taiwan. Region-independent terms are used for the small-magnitude scaling, geometrical spreading, depth to top of rupture (Z_{TOR}) scaling, and intraslab/interface scaling. The break in the magnitude scaling at large magnitudes for intraslab earthquakes is based on thickness of the intraslab and is subduction-zone dependent. The magnitude scaling for large magnitudes is constrained based on finite-fault simulations as given in the 2016 BCHydro model. Nonlinear site response is also constrained to be the same as the 2016 BCHydro model. The sparse ground-motion data from Cascadia show a factor of 2–3 lower ground motions than for other regions. Without a sound physical basis for this large reduction, the Cascadia model is adjusted to be consistent with the average from all regions for the center range of the data: $\mathbf{M}$ = 6.5, R = 100 km, V_{S30} = 400 m/sec. Epistemic uncertainty is included using the scaled backbone approach, with high and low models based on the differences in the average ground motions for the different regions. The lwer range of the epistemic uncertainty does not encompass the the full range of the very low short-period ground motions in Cascadia. For the Cascadia region, the ground-motion model is considered applicable to distance up to 800 km, magnitudes of 5.0 to 9.5, and periods from 0 to 10 sec. The intended use of this update is to provide an improved ground-motion model for consideration for use in the development of 2020 U.S. national uniform-hazard maps. It is not intended to be used for other regions around the world. This updated ground-motion model will be superseded by the suite of NGA-SUB ground-motion models when they are completed.

ACKNOWLEDGMENTS

This updated ground-motion model is the result of collaboration by the NGA-SUB developer group. The work was partially supported by both funding and in-kind support from FM Global, Pacific Gas & Electric Company, and Caltrans. The U.S. Geological Survey partially supported Stewart and Bozorgnia for the NGA-SUB database development and the ground-motion model development. Many other members of the NGA-SUB developer group have participated without financial support from PEER, providing in-kind contributions of their expertise. Silvia M, …

A key input to this study is the NGA-SUB ground-motion data base which is a result of several years effort by the database team. In particular, we want to acknowledge the efforts of Tadahiro Kishida, Silvia Mazzoni, Victor Contreras, Sean Ahdi and Robert Darragh to develop the NGA-SUB flat file that was used in this study.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the sponsoring agencies or the Pacific Earthquake Engineering Research Center and the Regents of the University of California.

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1 Introduction

The U.S. Geological Survey (USGS) is in the process of reviewing and updating the seismic source characterization and ground-motion characterization models used in the national seismic hazard mapping project for the 2020 update of the national uniform-hazard maps. To give the USGS adequate time to review the new models, any new models for consideration need to be provided to the USGS in the June 2018 time frame. Currently, the NGA-SUB project is developing a suite of alternative ground-motion models (GMMs) for subduction zones based on a greatly expanded dataset and additional finite-fault numerical simulations. The full set of NGA-SUB GMMs with improved model parametrization will not be completed in time for consideration by the USGS in the 2020 update. To meet the USGS review time requirements, the NGA-SUB developers developed a single GMM that is an update of the 2016 BCHydro GMM [Abrahamson et al. 2016]. This updated BCHydro GMM uses the expanded dataset to regionalize V_{S30}, linear R, and constant terms in the GMM, similar to the approach to regionalization used by the NGA-West2 GMMs (Gregor et al, [2014]). This approach provides an improved subduction ground-motion model that includes region-specific terms for Cascadia and meets the schedule for consideration by the USGS as part of the 2020 update of the national uniform-hazard maps.

In this report, the updated GMM is called the updated BCHydro model to reflect the original model used as the starting point, but it does not imply that BCHydro reviewed or approved this update.

2 Dataset Selection

The NGA subduction (NGA-SUB) database includes recordings from seven different regions: Alaska, Cascadia, Central America, Japan, New Zealand, South America, and Taiwan as described by Kishida et al. [2018]. The full dataset includes over 70,000 3-component recordings. The June 12, 2018, version of the NGA-SUB dataset was used for this study. Given the large size of the NGA-SUB dataset, QA checks of the meta data and response spectral values are still ongoing at the time of this study. Therefore, for the current study, the parts of the dataset that show questionable scaling and which are still under review are excluded. The main criteria used for selecting the subset of data for use in this study can be grouped into three main headings: selection criteria for regions, selection criteria for earthquakes, and selection criteria for recordings.

Data selection is an interative process. After the initial selection is made, preliminary regression analyses are performed and, using residuals, outlier data are identified and evaluated. Based on the evaluation of the outlier data, the data selection is modified and the process repeated. The selection criteria listed below the is final result of this interactive process. As examples of the process, some residual plots from the preliminary regression analyses are shown before the model is discussed.

2.1 SELECTION CRITERIA FOR REGIONS

A preliminary analysis of the June 12, 2018, version of the dataset showed that the distance scaling of the recordings from earthquakes in the Alaska region are unusual. For example, the distance scaling of PGA for $\mathbf{M} > 6$ earthquakes in Alaska is shown in Figure 2.1. The large scatter (factor of 100) and lack of attenuation with distance indicate that this version of the dataset may include some errors in the distances or response spectral values from the Alaska region. Therefore, all of the recordings in the Alaska dataset are excluded from this analysis.

An analysis of distance scaling from Taiwan earthquakes also showed unusually large scatter for the smaller magnitude earthquakes. The metadata for some of the smaller magnitude Taiwanese events in the June 12, 2018, version of the dataset contain some errors that are currently being corrected. For this study, rather than determine which of the earthquakes have meta data errors, all of the Taiwanese earthquakes with $\mathbf{M} < 5.5$ have excluded. A second issue for the Taiwan data is the data from the "TW" network. The ground motions from the TW network appear to be biased to much lower values than the other networks. As an example, Figure 2.2 compares the residuals for the CWB and TW networks from a preliminary regression analysis. Given the

apparent bias from the TW network, all of the recordings from this network are excluded. The TW network represents about 10% of the recordings in Taiwan dataset.

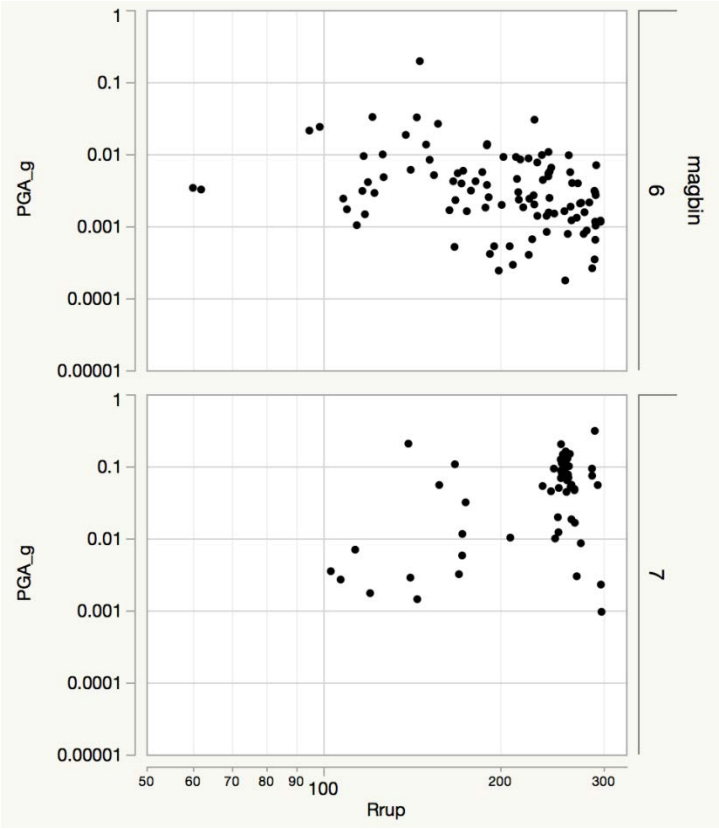

Figure 2.1 Scaling of PGA with rupture distance for the Mw > 6 events in the Alaska database.

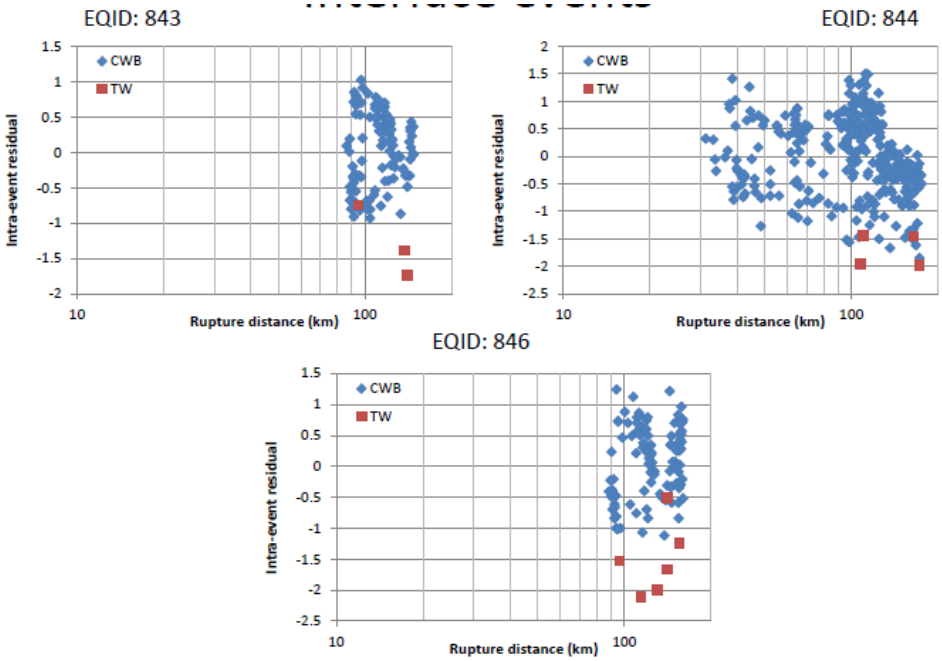

Figure 2.2 **Distribution of the residuals from preliminary analysis for events in the Taiwan dataset that includes data from the TW and CWB seismic networks.**

2.2 SELECTION CRITERIA FOR EARTHQUAKES

The ground-motion model is developed for two event types: interface and intraslab earthquakes. The NGA-SUB dataset includes six event classifications shown in Table 2.1. For interface events, only class 0 events were used. For intraslab events, both class 1 and class 5 (event from lower part of a double seismic zone) are used. To avoid potential event classification issues, the unusually shallow intra-slab events (Z_{TOR} < 20 km) and unusually deep interface events (Z_{TOR} > 50 km) are excluded.

For all earthquakes, the minimum magnitude of 5 was used, which is consistent with the 2016 BCHydro model. The minimum of 3 recordings per event (after all of the selection criteria have been met) is applied.

Table 2.1 Event classes.

Event class index	Event class description
0	Subduction interface event
1	Subduction intraslab event
2	Shallow crustal/overriding plate event
3	Mantle event
4	Outer rise event
5	Intraslab, lower double seismc zone event
-999	Unknown
-888	Interface event with small confidence
-777	Intraslab event with small confidence
-666	Shallow crustal/overriding plte events with small confidence
-444	Outer rise event with small confidence

2.3 SELECTION CRITERIA FOR RECORDINGS

To avoid potential bias in the ground motions, the following selection criteria are applied:

- Remove recordings with multiple event flag equal to 1 (time history that includes more than one earthquake)
- Remove recordings with late *P*-trigger
- Remove recordings that have missing data in magnitude, distance and V_{S30} fields
- Remove stations with GMX first letter N, Z, and F (non-free-field stations)
- Remove downhole recordings with instrument depth >2 m

The distance scaling can be strongly influenced by wave propagation from earthquakes in the forearc to stations in the backarc. Ground-motion data from the Japan region show much faster attenuation for backarc stations; however, a preliminary analysis of the data in the Cascadia region showed no difference between the attenuation for stations located in the forearc from those located in the backarc. To avoid the lower ground motions from the backarc stations in other regions affecting the Cascadia ground-motion model, recordings in the backarc for regions other than Cascadia are removed. For the Cascadia region, stations location in both forearc and backarc regions are included.

For regions other than Cascadia, the distance is limited to 300 km as the main use of the global data is to constrain the magnitude scaling, short-distance scaling, and depth scaling. To capture the large-distance scaling in Cascadia, data out to a distance of 800 km from the Cascadia region are included. Two of the four earthquakes in the Cascadia region are from Washington and two are from northern California. The attenuation beyond 300 km is different for the Washington

and Northern California recordings. To capture the large distance scaling in Washington, the two northern California earthquakes are also limited to 300 km. Data out to 800 km is only included for the two Washington earthquakes.

The large-distance slope of the recordings from the Tohoku earthquake is quite different than the others; see Figure 2.3. This difference can affect the event terms estimated in the regression analysis. In this case, including the Tohoku data beyond 300 km would lead to smaller (more negative) event terms. To have the event terms representative of the Tohoku ground motions in the 100-km range, the recordings from the Tohoku earthquake with $R_{rup} > 200$ km are removed.

The data includes an estimate of the maximum distance, R_{max}, for which the dataset is not affected by censoring of the ground motions. Censoring can occur when there are missing recordings (not triggered or no stations installed) that would have shown lower ground motions than the recorded ground motions. The procedure for estimating R_{max} will be described in the NGA-SUB database report which is under preparation. The recordings with $R_{rup} > R_{max}$ are removed to avoid a bias to larger ground motions at large distances. This criterion has the largest effects on the Taiwan dataset. Finally, a small number of outlier recordings and events, identified by visual inspection, are removed.

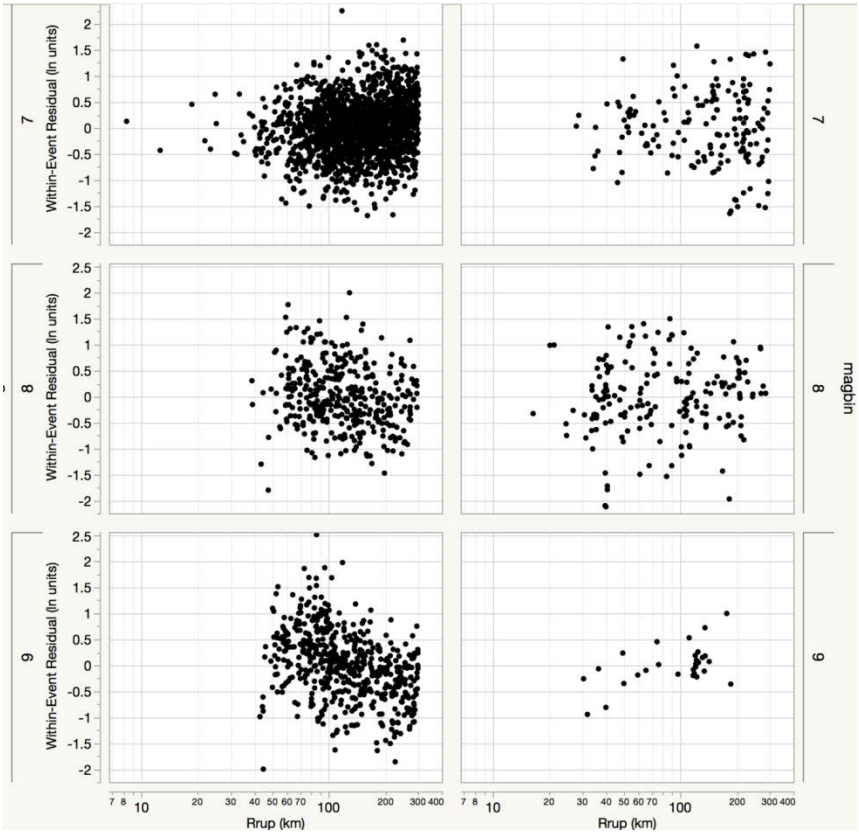

Figure 2.3 Distribution of the residuals from preliminary analysis with rupture distance (left: data from Japan, right: data from South America).

Regional distribution of the recordings used in the regression is given in Table 2.2. As defined in the NGA-West2 database (Ancheta, [2014]), the response spectral values for the selected recordings are only used in the regression analysis for spectral frequencies greater than 1.25 times the high-pass corner frequency used in the record processing. This requirement produces a dataset that varies as a function of period. The period dependence of the number of earthquakes and number of recordings used in the regression analysis is shown in Figure 2.4, which shows a slight drop in the number of recordings and earthquakes between 5–6 sec. The magnitude-distance distribution of the selected data set for short periods is shown in Figure 2.5.

Table 2.2 Distribution of the selected earthquakes and recordings.

Number	Region	Number of earthquakes	Number of recordings
1	Alaska	0	0
2	Cascadia	4	144
3	Central America	12	78
4	Japan	73	4953
5	New Zealand	34	541
6	South America	47	636
7	Taiwan	11	1792
	Total Used	181	8144
	Total in NGA-SUB	**1,880**	**71,343**

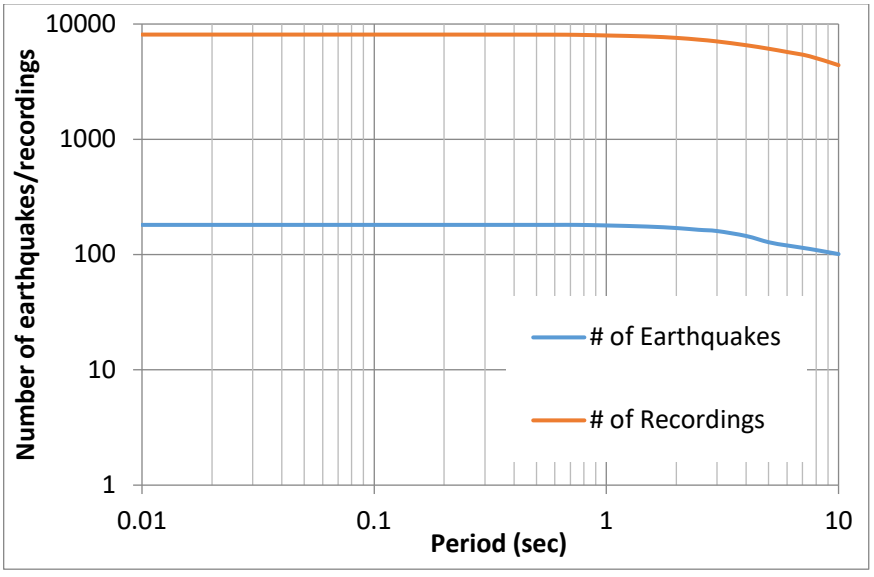

Figure 2.4 Number of earthquakes and number of recordings in the selected subset by period.

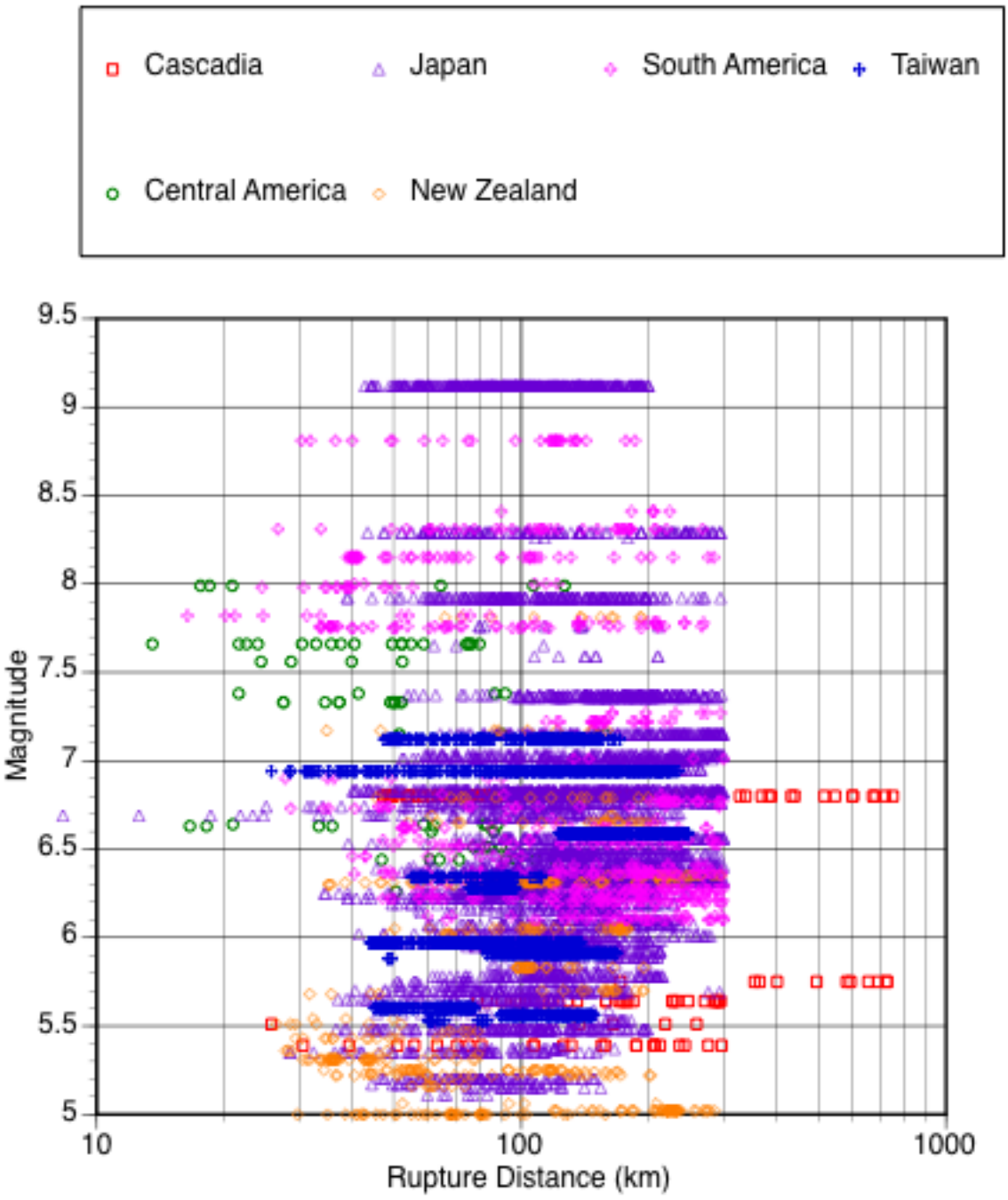

Figure 2.5 Magnitude-distance distributions for the final subset (for *PGA*).

3 Regression Analysis

3.1 FUNCTIONAL FORM

The functional form for the updated BCHydro ground-motion model is based on the functional form used in the 2016 BCHydro model with the backarc scaling removed. The base model is given by:

$$\ln\big(PSA(g)\big) = a_1 + a_4(C_{1\_slab} - C_{1\_inter})F + \big(a_2 + a_{14}F + a_3(M - 7.8)\big)\ln\Big(R_{rup} + C_4 exp\big((M-6)a_9\big)\Big) + a_6 R_{rup} + a_{10}F + f_{mag}(M) + f_{ZTOR}(Z_{TOR}, F) + f_{site}(PGA_{1000}, V_{S30})$$

where

M = moment magnitude

R_{rup} = rupture distance in km

F = event type (0 for interface and 1 for intraslab)

Z_{TOR} = depth of the top of rupture (km)

PGA_{1000} = median peak horizontal acceleration for V_{S30} = 1000 m/sec

The magnitude scaling is given by:

$$f_{mag}(M) = \begin{cases} a_4(M - C_1) + a_{13}(10 - M)^2 & for\ M \leq C_1 \\ a_5(M - C_1) + a_{13}(10 - M)^2 & for\ M > C_1 \end{cases}$$

where

$$C_1 = F\ C_{1\_slab} + (1 - F)\ C_{1\_inter}$$

The nonlinear site response scaling is given by:

$$f_{\text{site}}\left(\text{PGA}_{1000}, V_{S30}\right) = \begin{cases} a_{12}\ln\left(\dfrac{V_S^*}{V_{\text{lin}}}\right) - b\,\ln\left(\text{PGA}_{1000} + c\right) b\,\ln\left[\text{PGA}_{1000} + c\left(\dfrac{V_S^*}{V_{\text{lin}}}\right)^n\right] & \text{for } V_{S30} < V_{\text{lin}} \\ \left(a_{12} + b\,n\right)\ln\left(\dfrac{V_S^*}{V_{\text{lin}}}\right) & \text{for } V_{S30} \geq V_{\text{lin}} \end{cases}$$

where

$$V_S^* = \begin{cases} 1000 & \text{for } V_{S30} > 1000 \text{ m/sec} \\ V_{S30} & \text{for } V_{S30} \leq 1000 \text{ m/sec} \end{cases}$$

The BCHydro model used a quadratic magnitude scaling with a break in the scaling for large magnitudes (**M**7.6 to **M**8.0 for interface and **M** 7.5 for intraslab). The slope of the large-magnitude scaling was constrained based on finite-fault simulations by Gregor et al. [2006] and Atkinson and Macias [2008] for interface earthquakes. For the updated BCHydro model, this constraint on the large magnitude scaling is maintained, but the break points for the interface earthquakes are re-evaluated based on the event terms from the large magnitude earthquakes (M>8). The break in the magnitude scaling for intraslab events is based on the intraslab thickness as described by Archuleta and Ji [2018]: for Cascadia, $C_{1\_slab} = 7.2$.

For intraslab earthquakes, the 2016 BCHydro model used linear scaling with Z_{TOR} with a limit of 120 km on the depth range for the scaling. A preliminary analysis showed that the Z_{TOR} scaling does not apply for depth greater than about 100 km. Therefore, the limit on the Z_{TOR} scaling is modified to be 100 km rather than 120 km. The Z_{TOR} scaling is given by:

$$f_{Z_{\text{TOR}}}\left(Z_{\text{TOR}}, F\right) = \begin{cases} \theta_{11}\left(Z_{\text{TOR}} - 60\right) F & \text{for } Z_{\text{TOR}} \leq 100 \text{ km} \\ \theta_{11}\left(100 - 60\right) F & \text{for } Z_{\text{TOR}} > 100 \text{ km} \end{cases}$$

There are regional model coefficients for the three regional terms. The indexes for these coefficients are listed in Table 3.1.

Inclusion of basin effects is beyond the scope of this update. Basin effects will be addressed in the full NGA-SUB ground-motion models currently under development.

Table 3.1 Region-specific parameters.

Term	Region	Regression coefficient
Change in V_{S30} scaling	Cascadia	a_{18}
	Central America	$a_{19} = 0$ (fixed at global value)
	Japan	a_{20}
	New Zealand	a_{21}
	South America	a_{22}
	Taiwan	a_{23}
Change in Linear R term	Cascadia	a_{25}
	Central America	a_{26}
	Japan	a_{27}
	New Zealand	a_{28}
	South America	a_{29}
	Taiwan	a_{30}
Constant	Cascadia	a_{32}
	Central America	a_{33}
	Japan	a_{34}
	New Zealand	a_{35}
	South America	a_{36}
	Taiwan	a_{37}

3.2 REGRESSION ANALYSIS

The random-effects model was used for the regression analysis following the procedure described by Abrahamson and Youngs [1992]. The regression is performed in a number of steps to arrive at a smooth model. The coefficients are smoothed to either lead to smooth spectra or to constrain the model to be consistent with basic seismological constraints. Table 3.2 lists the parameters that were regressed in each step and those which were smoothed and fixed following each step.

The large-magnitude scaling was constrained to be equal to the BCHydro scaling. The large-magnitude scaling is controlled by four terms: the magnitude dependent geometrical spreading term (a_3), the linear magnitude scaling terms for large magnitude events (a_5), the magnitude-dependent finite-fault effect term (a_9), and the quadratic magnitude term (a_8). These four coefficients are set to the values given in 2016 BCHydro model. In the first run, the global geometrical spreading term (a_2) and the global linear V_{S30} scaling term (a_{12}) are smoothed; see Figures 3.1 and 3.2.

In the second run, the additional global geometrical spreading term for intraslab events (a_{14}) is smoothed based on the smoothed geometrical spreading term in the previous step. Similarly, the linear magnitude term for small-to-moderate magnitude events (a_4) is smoothed in Step 3; see Figure 3.3. In step 4, the global large distance scaling parameter (a_6) is smoothed; see Figure 3.4. In the same step, the Z_{TOR} scaling (a_{11}) is smoothed.

The next set of runs included estimation of the regional terms for the linear V_{S30} scaling for Cascadia (a_{18}) and other regions (a_{19}-a_{23}), large-distance scaling parameters for Cascadia (a_{25}) and other regions (a_{26}-a_{30}), and the constant terms for Cascadia (a_{31}) and other regions (a_{33}-a_{37}). The regional terms for Cascadia, a_{18} and a_{25}, are smoothed, but the other regional parameters are not smoothed because they are not intended to be used.

The values of the smoothed coefficients for the median ground motion are given in the following chapter; see Table 4.1.

3.3 RESIDUALS

The between-event residuals are shown as a function of magnitude in Figures 3.9 and 3.10 for six spectral periods: PGA, T = 0.1 sec, T = 0.2 sec, T = 0.5 sec, T = 1 sec, and T = 3 sec. Note that there is no clear trend in magnitude, indicating that the magnitude scaling is consistent with the available recorded data. A key issue is the extrapolation to the **M**9 range. The event terms for the two largest earthquakes (Maule and Tohoku) are shown in Figure 3.11. The event terms are balanced between these two events, indicating that the selected break points in the interface magnitude scaling are not unreasonable.

The within-event residuals for the same six spectral periods are shown by region in Figures 3.12, 3.13, and 3.14. In each case, the residuals are shown as functions of the magnitude, distance, V_{S30}, and PGA_{1000}. Figure 3.12 shows the residuals for the Cascadia region; Figure 3.13 shows the residuals for the Japan region; and Figure 3.14 shows the residuals for the other regions. Overall, there is not a strong trend in the residuals as functions of the four parameters.

Table 3.2 Estimated and constrained parameters at each step of regression

Step	Estimated parameters	Parameters held fixed	Parameters smoothed after run
1	a_1 (global constant), a_2 (geometrical spreading, GS), a_4 (linear magnitude for **M**<c_1), a_6 (global linear R), a_{10} (additional global constant for intraslab events), a_{11} (Z_{TOR}), a_{12} (global linear V_{S30}), a_{14} (additional global GS for intraslab events)	a_3 (mag dep GS), a_5 (linear magnitude for **M**>c_1), a_9 (finite-fault term), a_{13} (quadratic magnitude)	a_2, a_{12}
2	a_1, a_4, a_6, a_{10}, a_{11}, a_{14}	a_2, a_3, a_5, a_9, a_{12}	a_{14}
3	a_1, a_4, a_6, a_{10}, a_{11}	a_2, a_3, a_5, a_9, a_{12}, a_{14}	a_4
4	a_1, a_6, a_{10}, a_{11}	a_2, a_3, a_4, a_5, a_9, a_{12}, a_{14}	a_6
5	*global:* a_{10}, a_{11} regional V_{S30}: a_{18}, a_{20}, a_{21}, a_{22}, a_{23}, regional R: a_{25}, a_{26}, a_{27}, a_{28}, a_{29}, a_{30}, regional const: a_{32}, a_{33}, a_{34}, a_{35}, a_{36}, a_{37}	a_2, a_3, a_4, a_5, a_6, a_9, a_{12}, a_{14} $a_1 = 0$ $a_{19} = 0$ *(VS30 scaling for Central America fixed to the global value)*	a_{18}, a_{25}
7	*global:* a_{10}, a_{11} regional V_{S30}: a_{20}, a_{21}, a_{22}, a_{23}, regional R: a_{26}, a_{27}, a_{28}, a_{29}, a_{30}, regional const: a_{32}, a_{33}, a_{34}, a_{35}, a_{36}, a_{37}	a_2, a_3, a_4, a_5, a_6, a_9, a_{12}, a_{14}, a_{18}, a_{25}, $a_1 = 0$ $a_{19} = 0$	a_{11}
8	*global:* a_{10} regional V_{S30}: a_{20}, a_{21}, a_{22}, a_{23}, regional R: a_{26}, a_{27}, a_{28}, a_{29}, a_{30}, regional const: a_{32}, a_{33}, a_{34}, a_{35}, a_{36}, a_{37}	a_2, a_3, a_4, a_5, a_6, a_9, a_{10}, a_{12}, a_{14}, a_{18}, a_{25}, $a_1 = 0$ $a_{19} = 0$	a_{10}
9	regional V_{S30}: a_{20}, a_{21}, a_{22}, a_{23}, regional R: a_{26}, a_{27}, a_{28}, a_{29}, a_{30}, regional const: a_{32}, a_{33}, a_{34}, a_{35}, a_{36}, a_{37}	a_2, a_3, a_4, a_5, a_6, a_9, a_{10}, a_{11}, a_{12}, a_{14}, a_{18}, a_{25}, $a_1 = 0$ $a_{19} = 0$	a_{32}

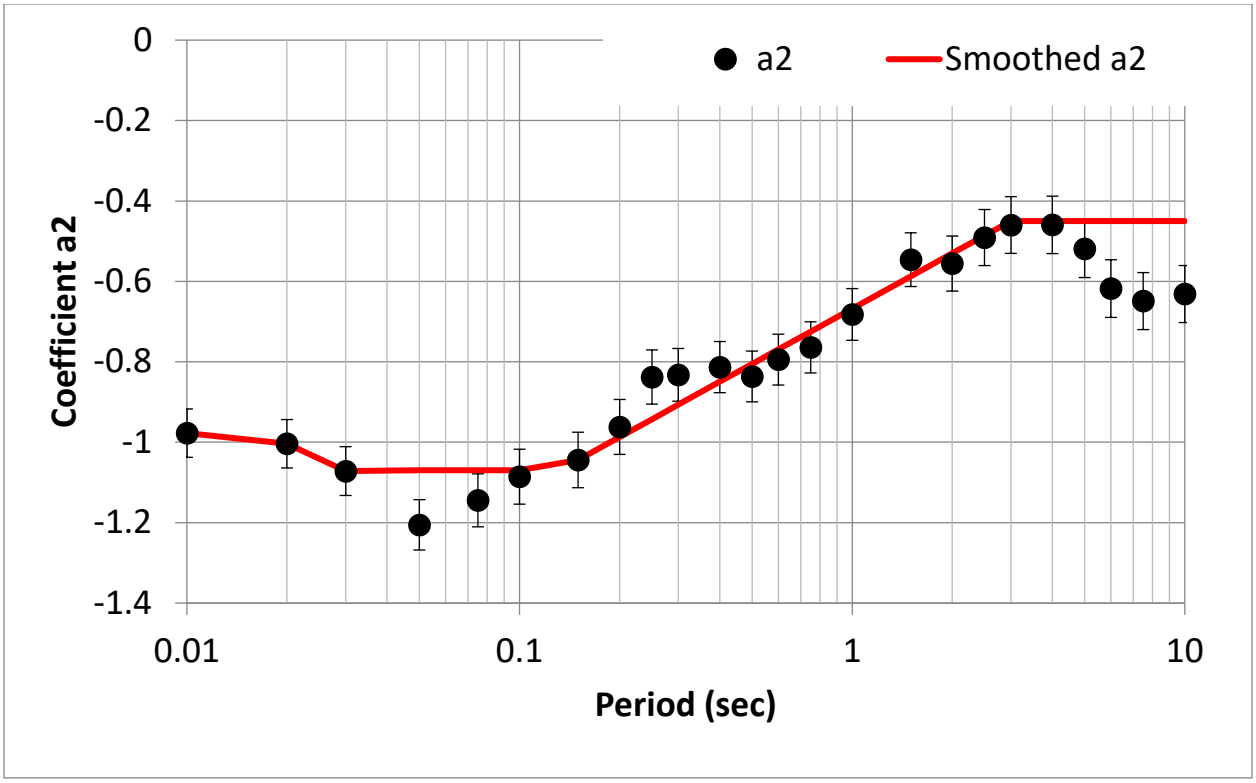

Figure 3.1 **Smoothing of coefficient a_2 (global geometrical spreading for interface).**

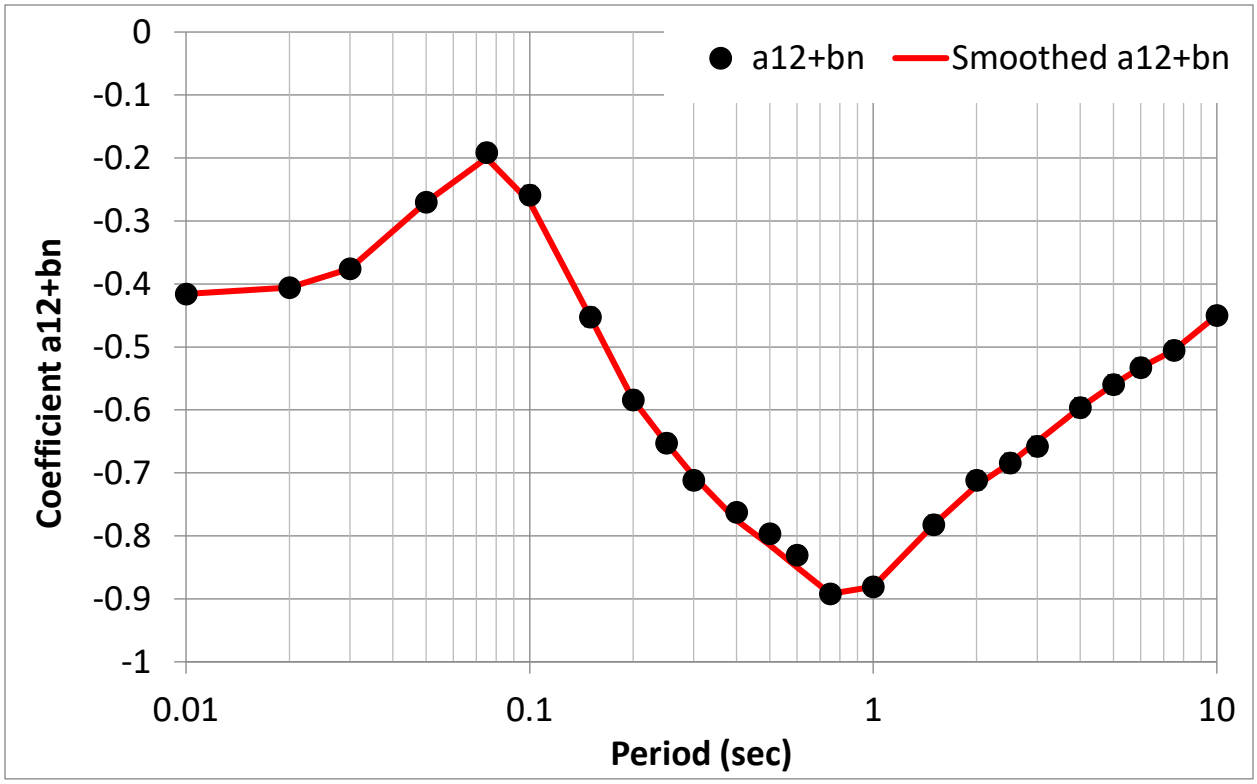

Figure 3.2 Smoothing of coefficient a_{12} (global V_{S30} scaling).

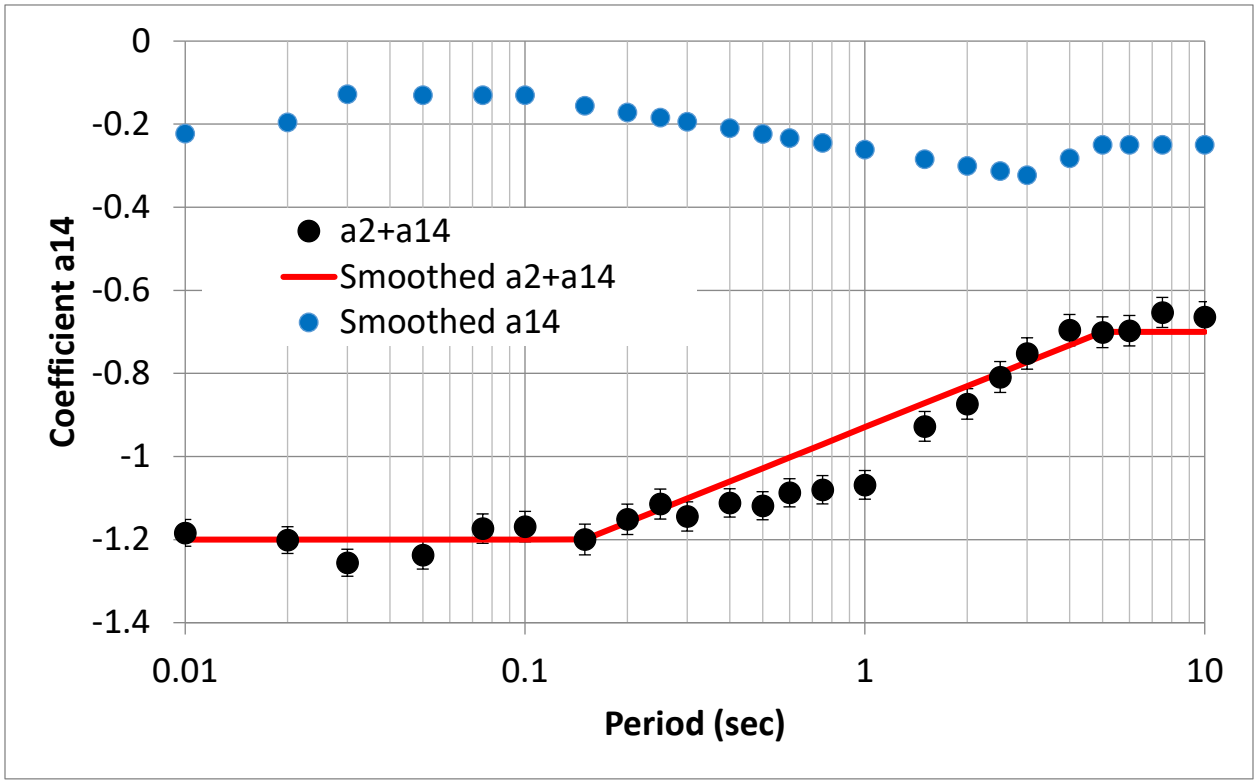

Figure 3.3 **Smoothing of coefficient a_{14} (global additional geometrical spreading for intraslab).**

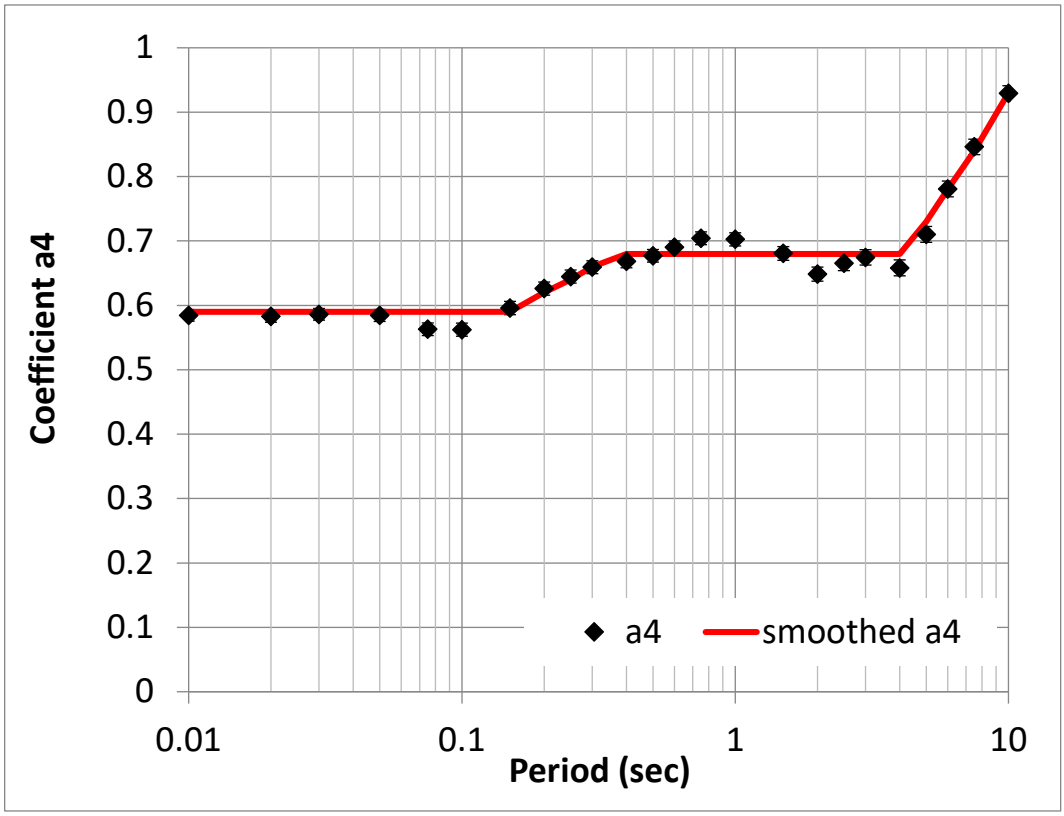

Figure 3.4 **Smoothing of coefficient a_4 (global small magnitude scaling).**

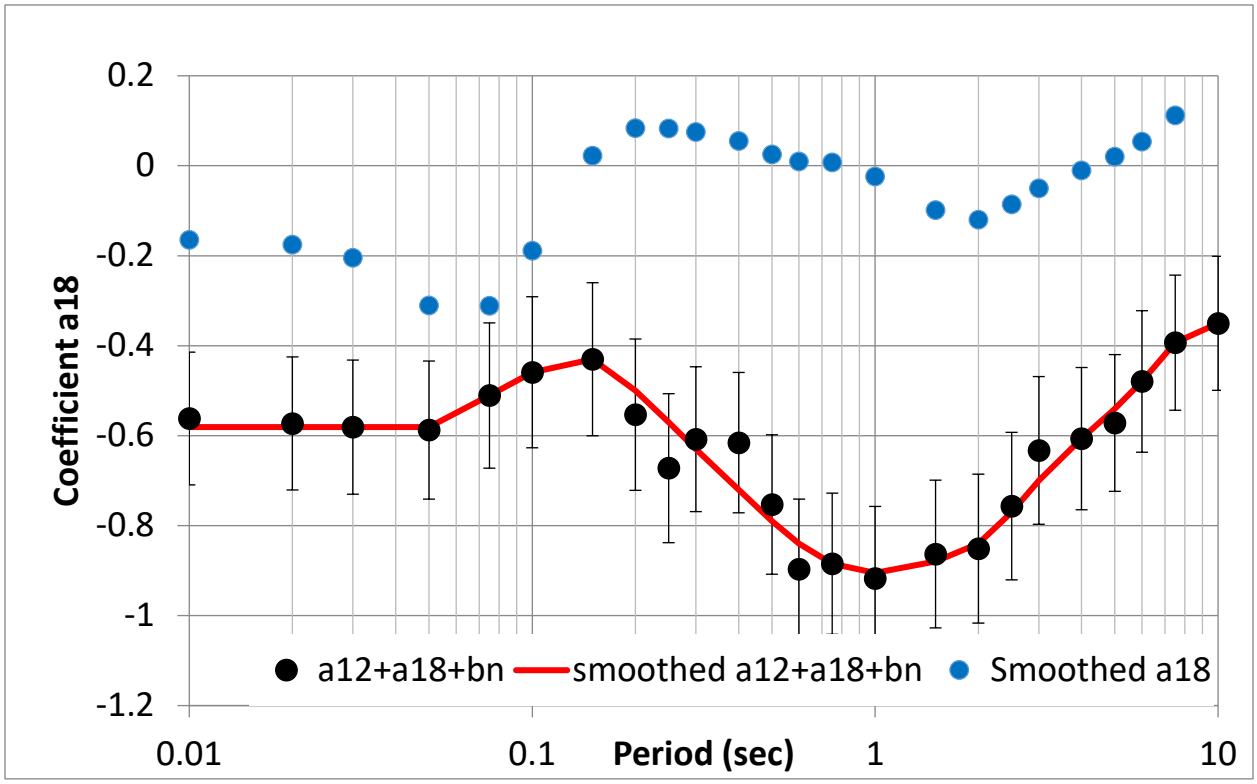

Figure 3.5 Smoothing of coefficient a_{18} (Cascadia VS30 scaling).

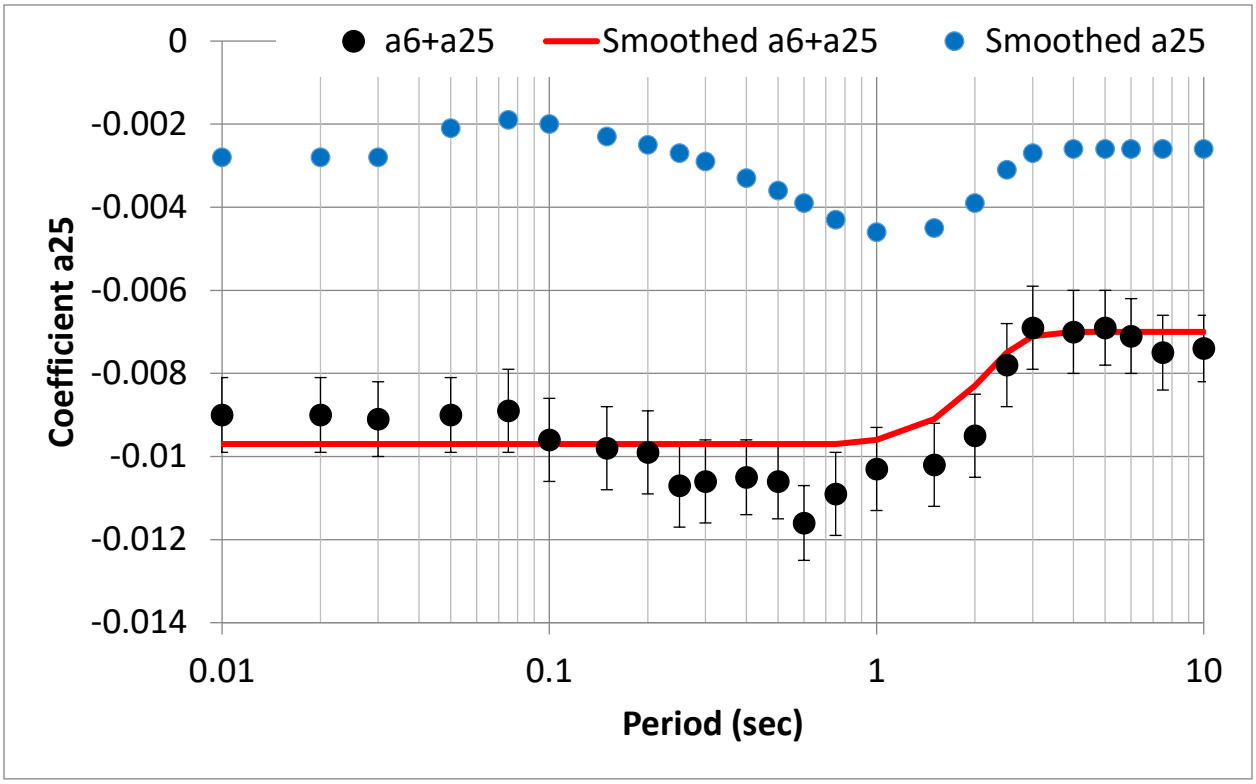

Figure 3.6 Smoothing of coefficient a_{25} (Cascadia linear *R* scaling).

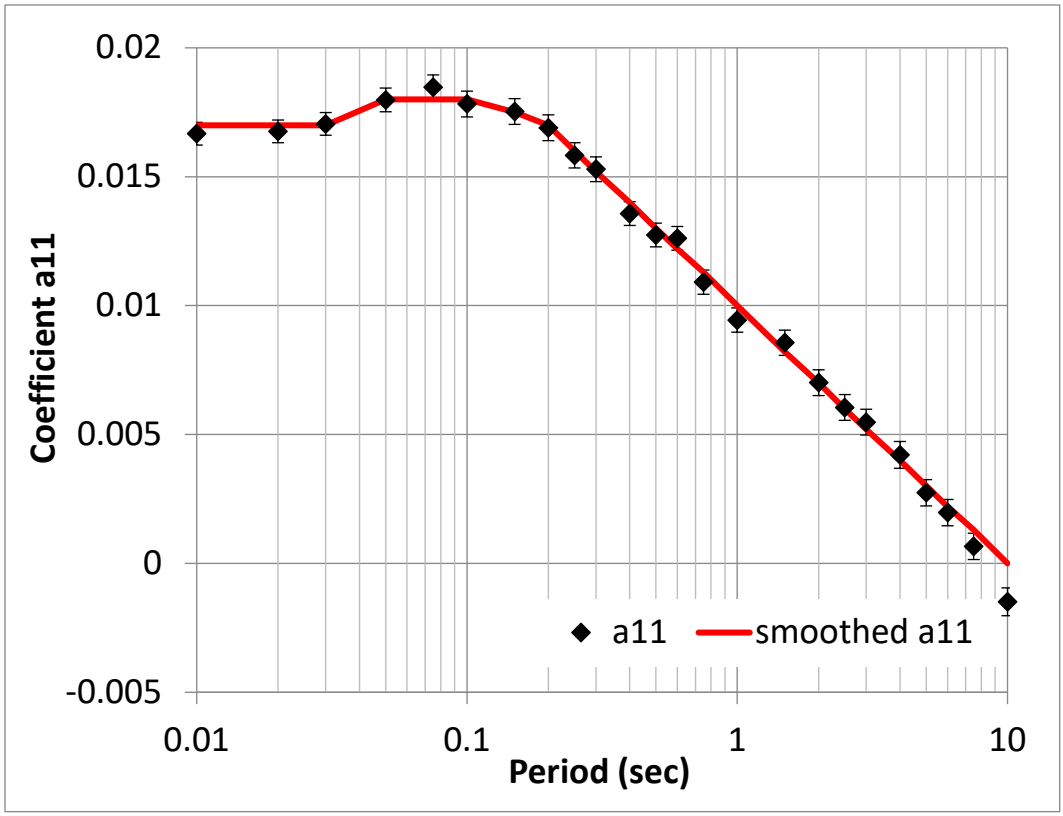

Figure 3.7 **Smoothing of coefficient a_{11} (global Z_{TOR} scaling for intraslab).**

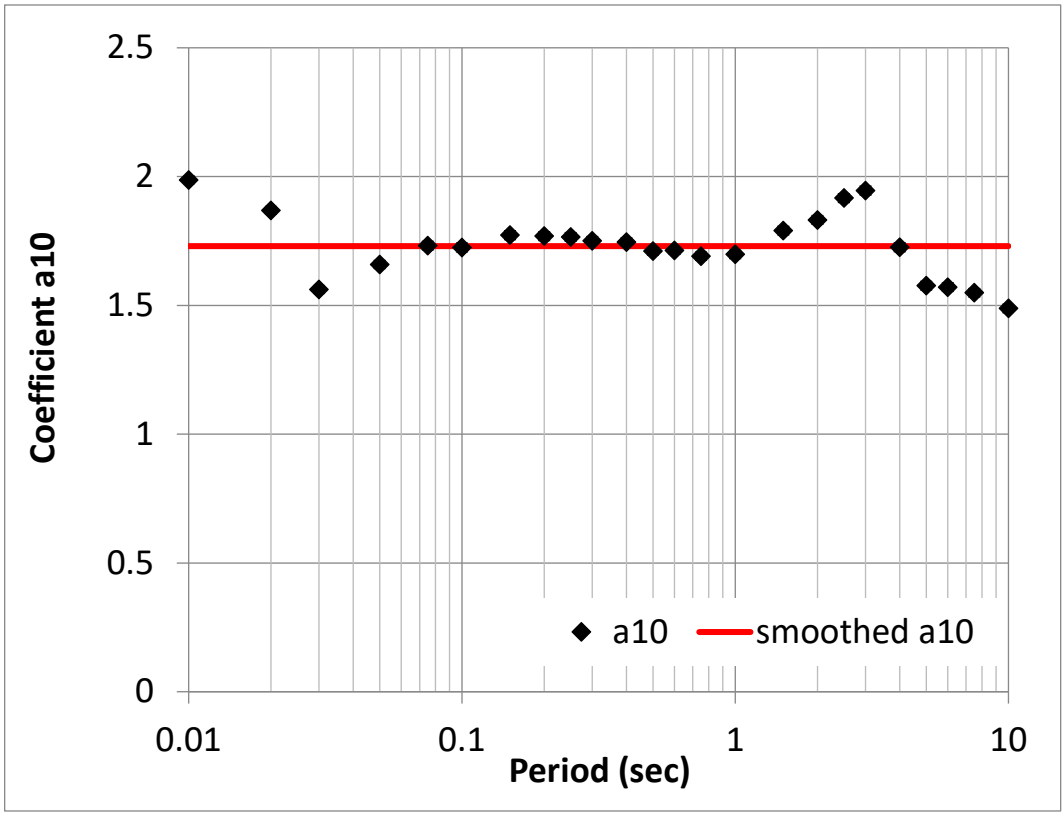

Figure 3.8 Smoothing of coefficient a_{10} (global intraslab constant term).

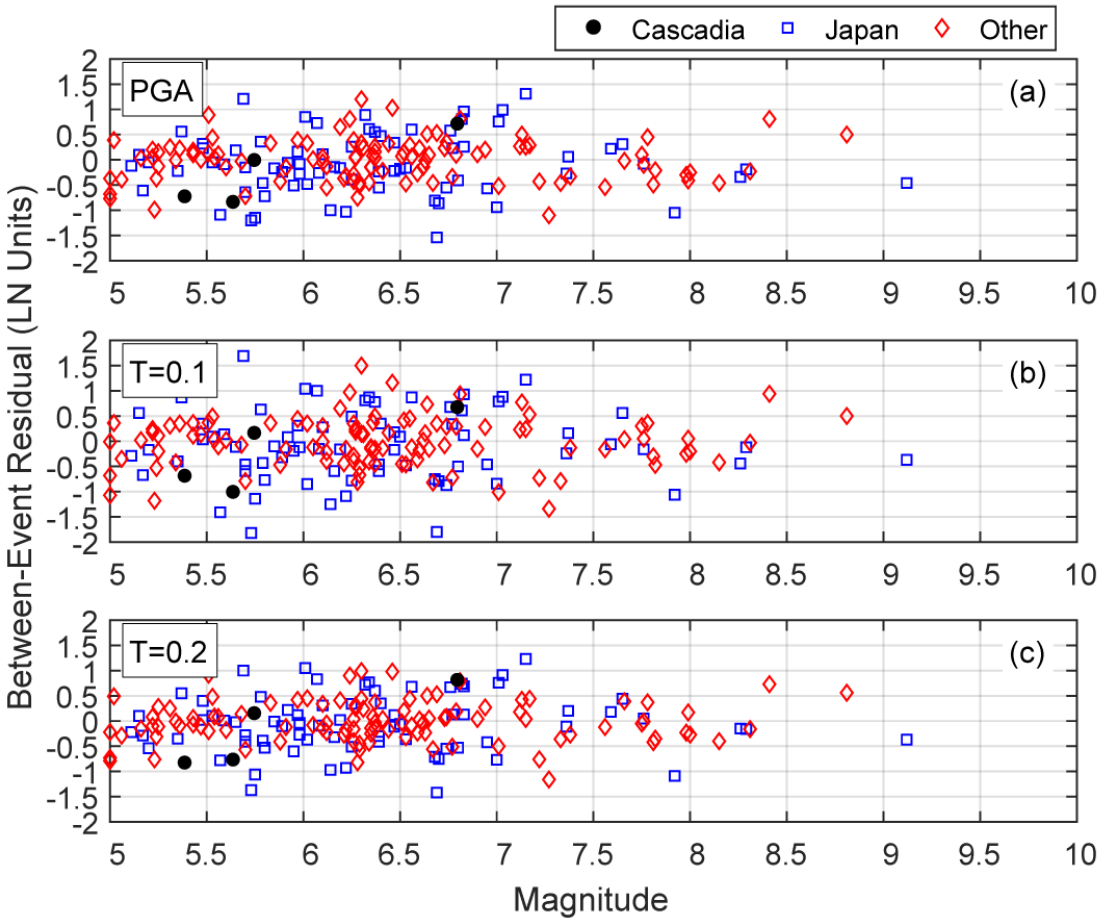

Figure 3.9 **Between-event residuals: (a) PGA, (b) *T* = 0.1 sec, and (c) *T* = 0.2 sec.**

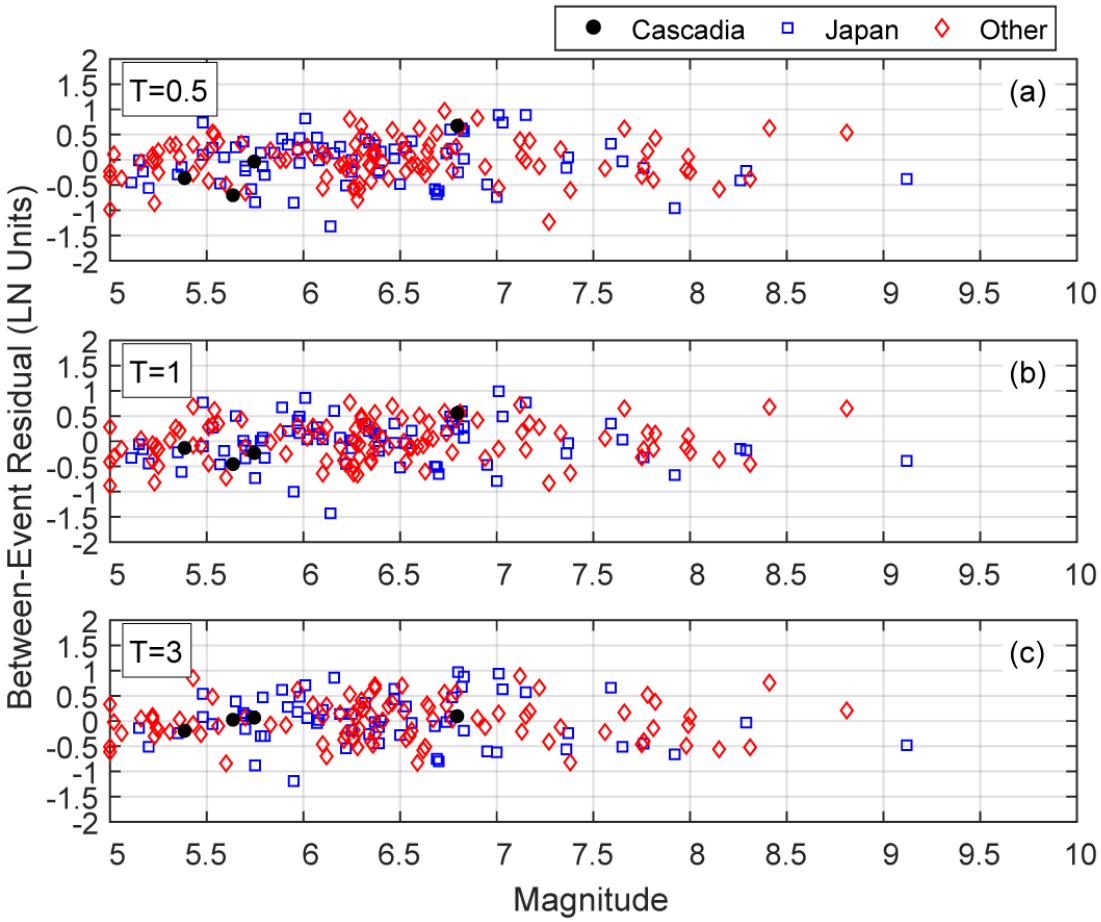

Figure 3.10 Between-event residuals: (a) *T* = 0.5 sec, (b) *T* = 1 sec, and (c) *T* = 3 sec.

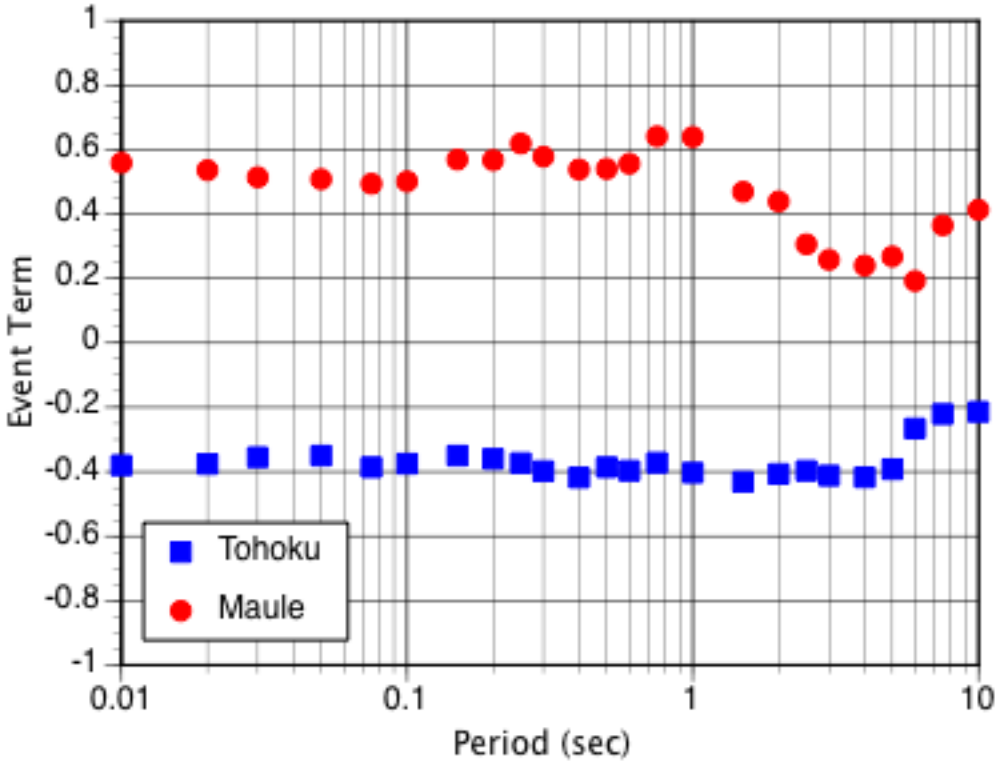

Figure 3.11 Between-event residuals for the largest events: Tohoku and Maule, Chile.

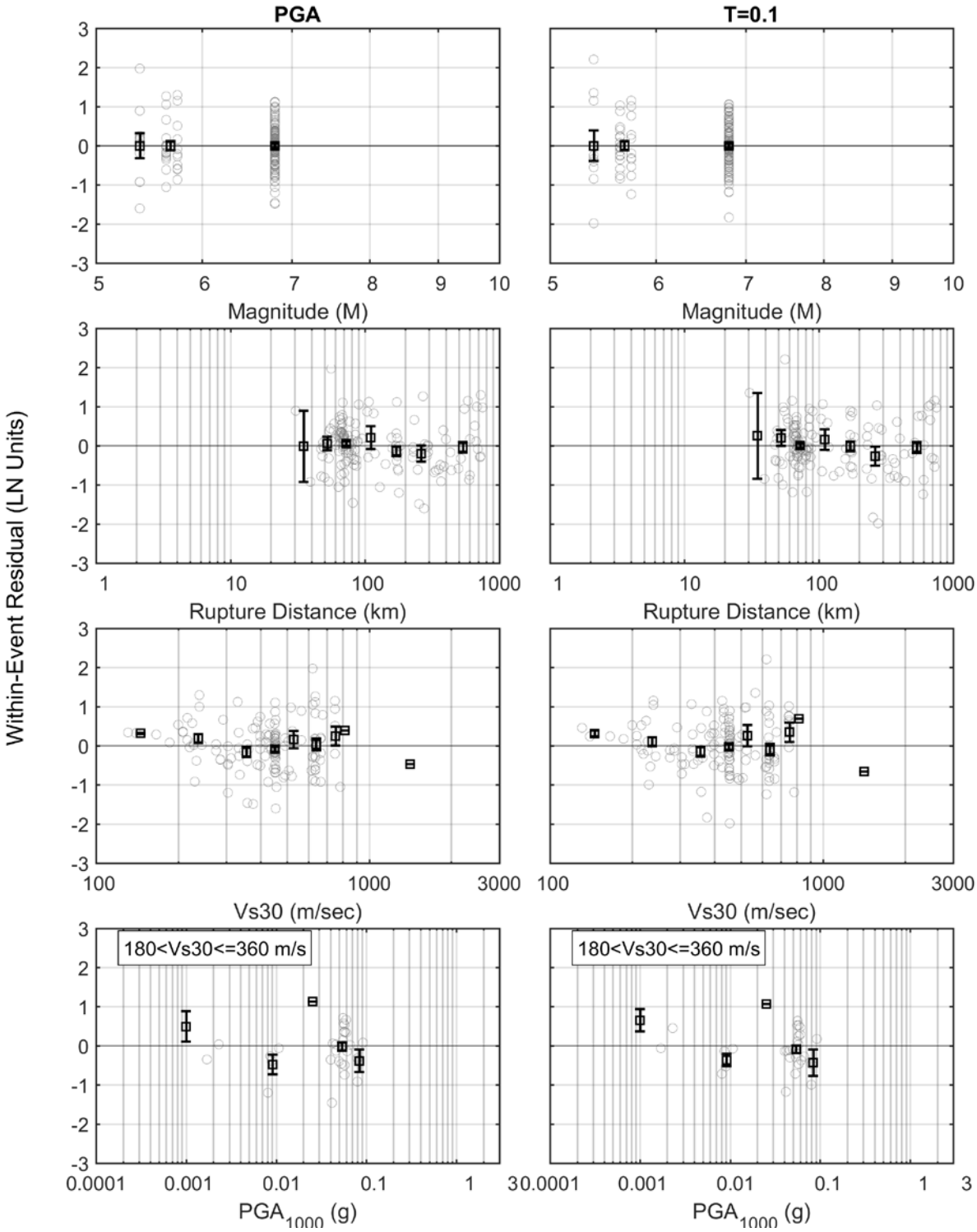

Figure 3.12(a) Within-event residuals for Cascadia: PGA and *T* = 0.1 sec.

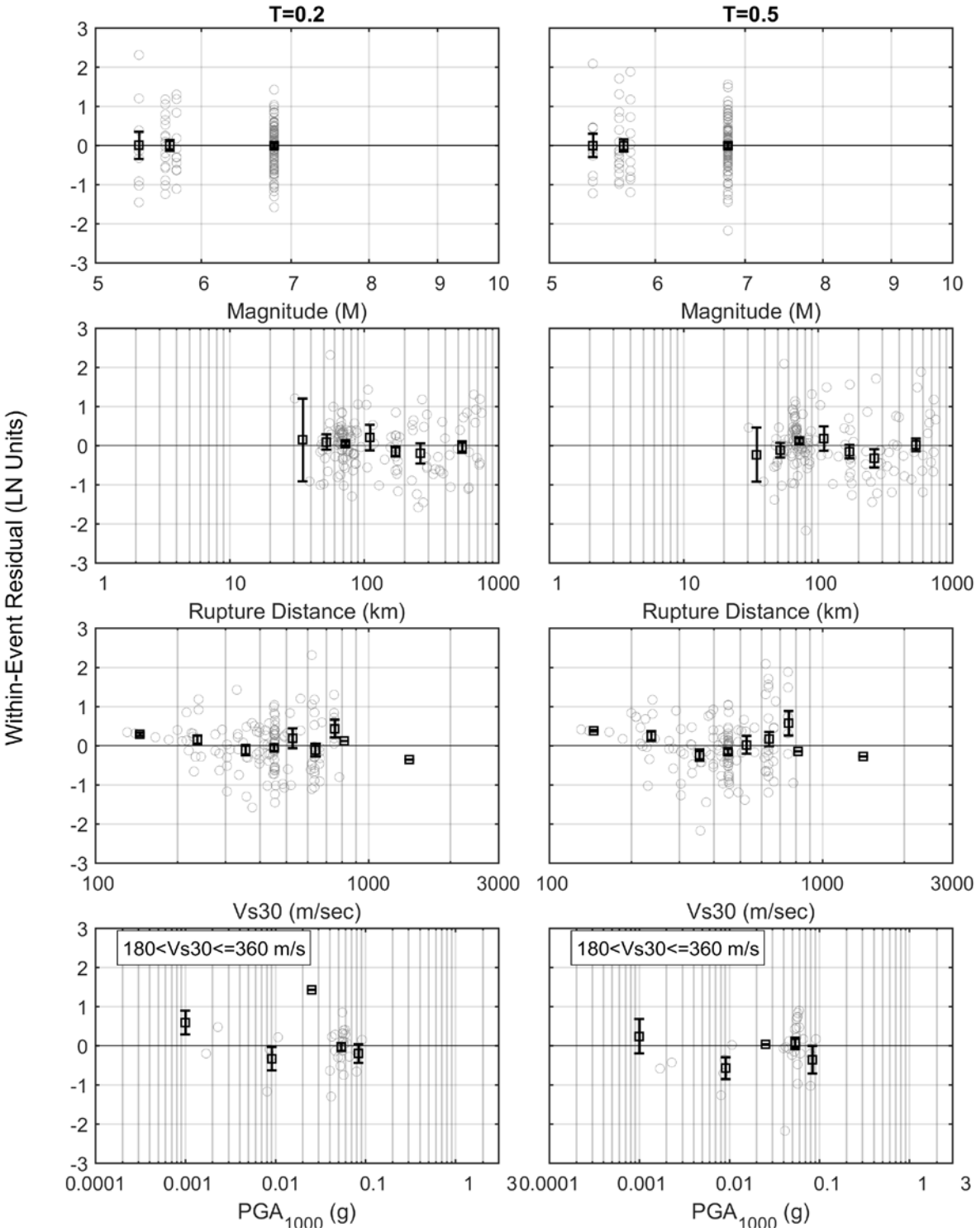

Figure 3.12(b) Within-event residuals for Cascadia: *T* = 0.2 sec and *T* = 0.5 sec.

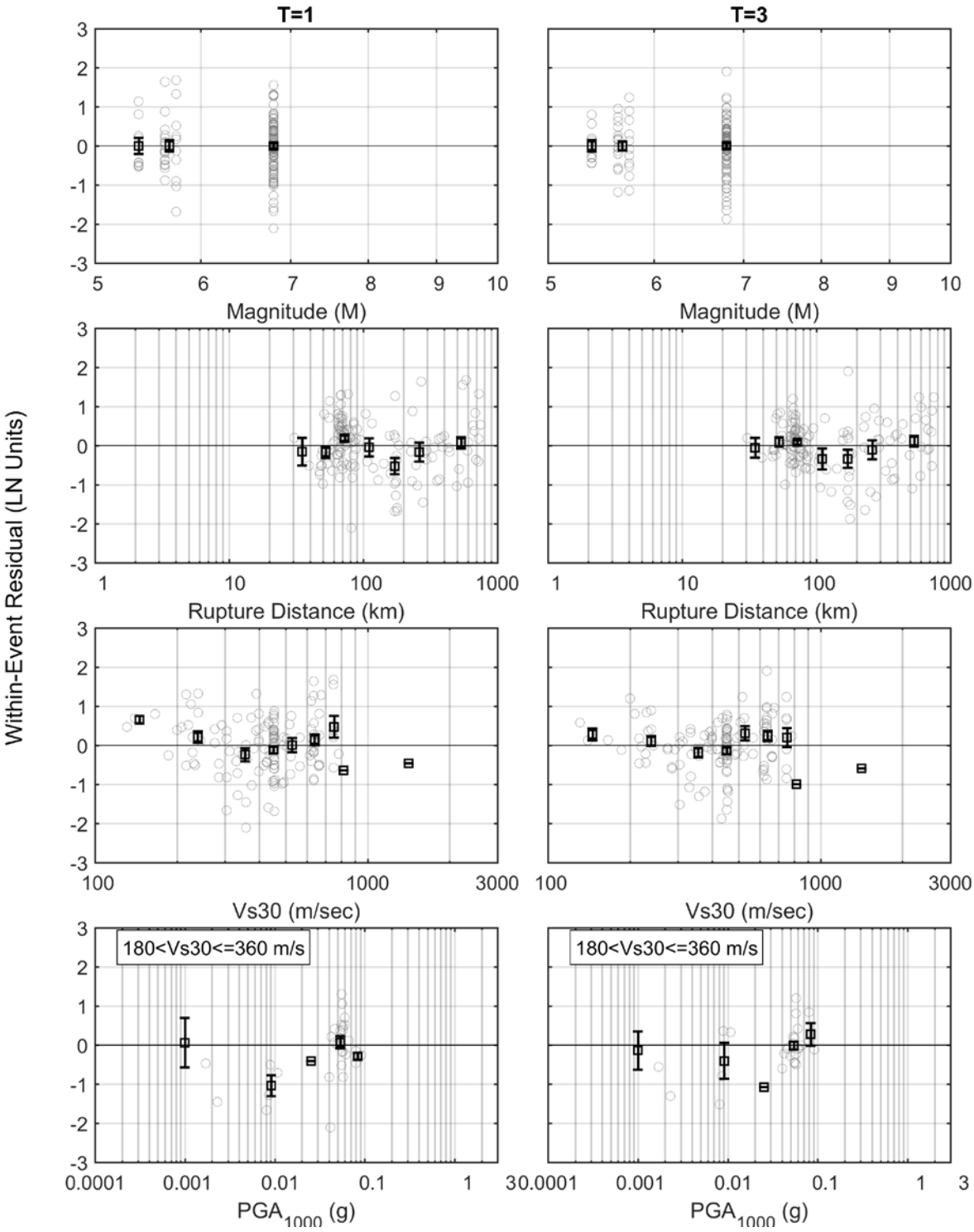

Figure 3.12(c) Within-event residuals for Cascadia: T = 1 sec and T = 3 sec.

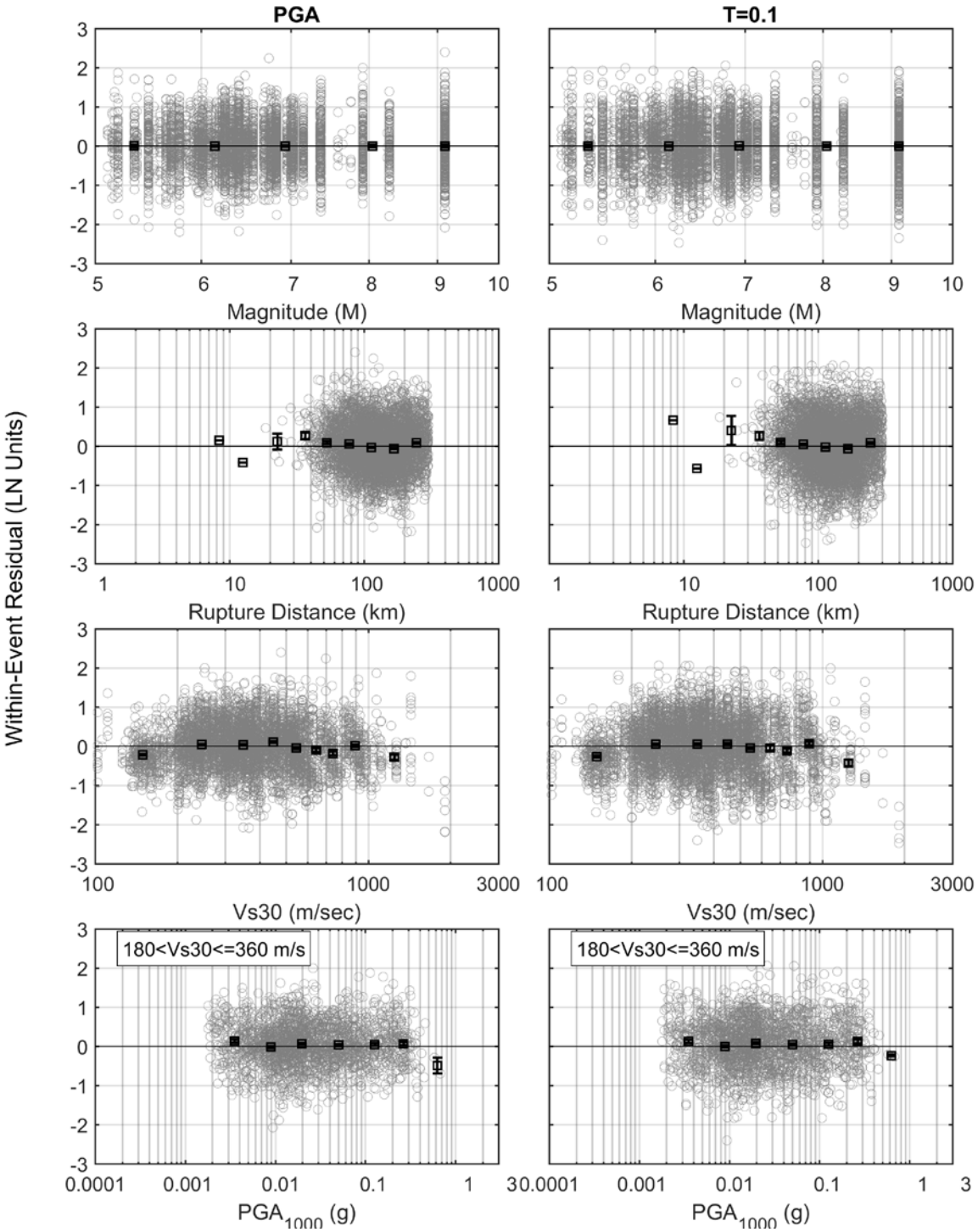

Figure 3.13(a) Within-event residuals for Japan: PGA and *T* = 0.1 sec.

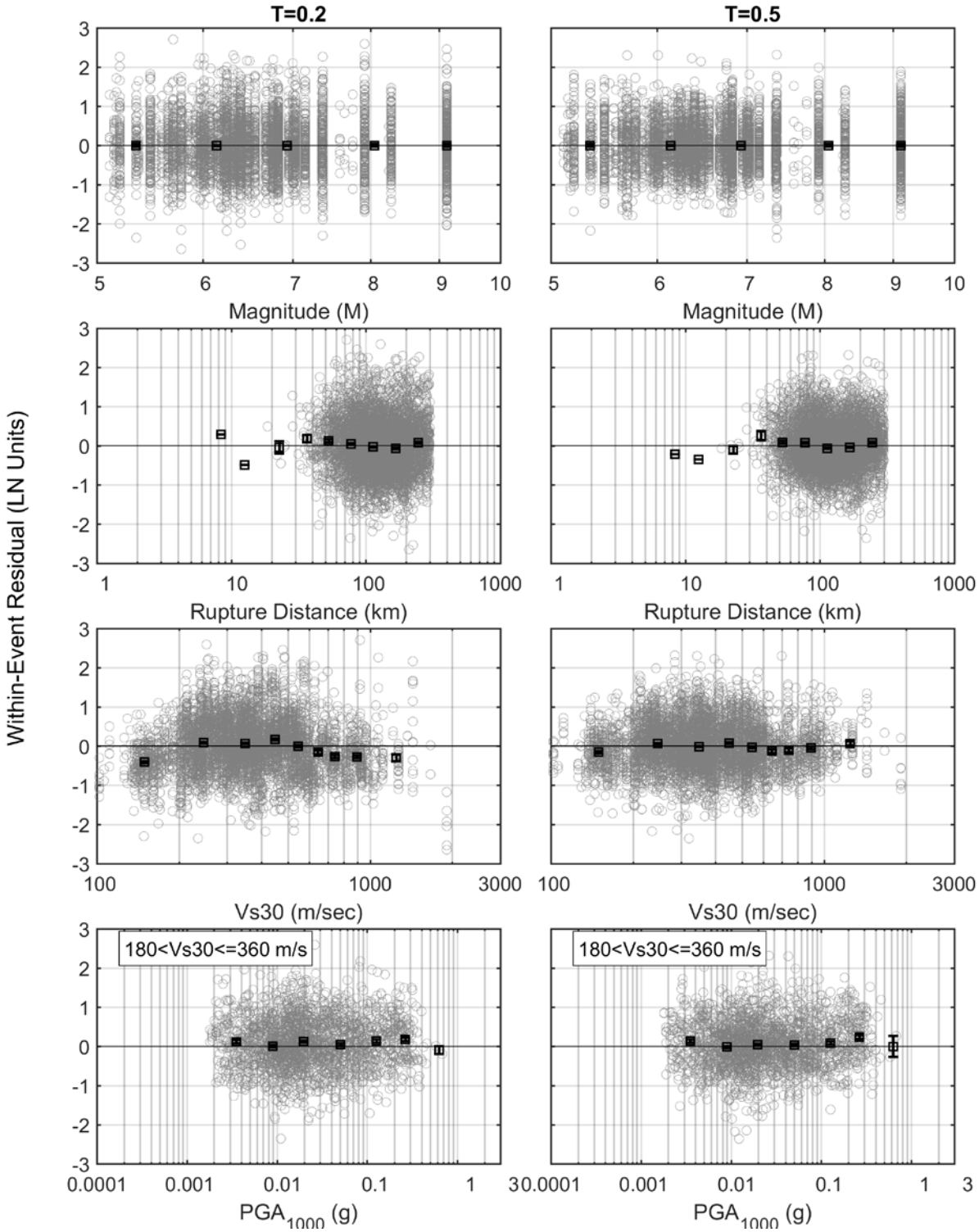

Figure 3.13(b) Within-event residuals for Japan: T = 0.2 sec and T = 0.5 sec.

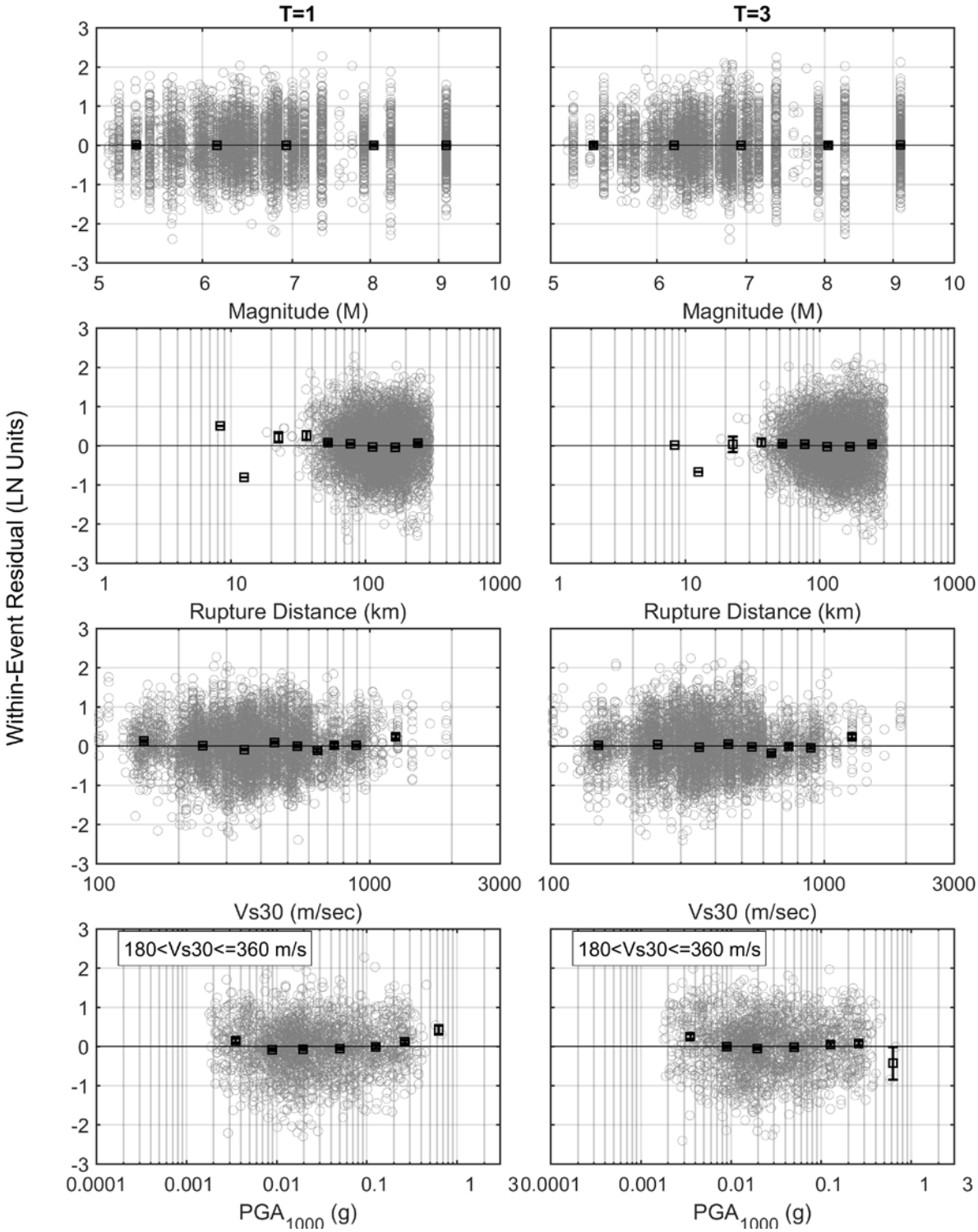

Figure 3.13(c) Within-event residuals for Japan: *T* = 1 sec and *T* = 3 sec.

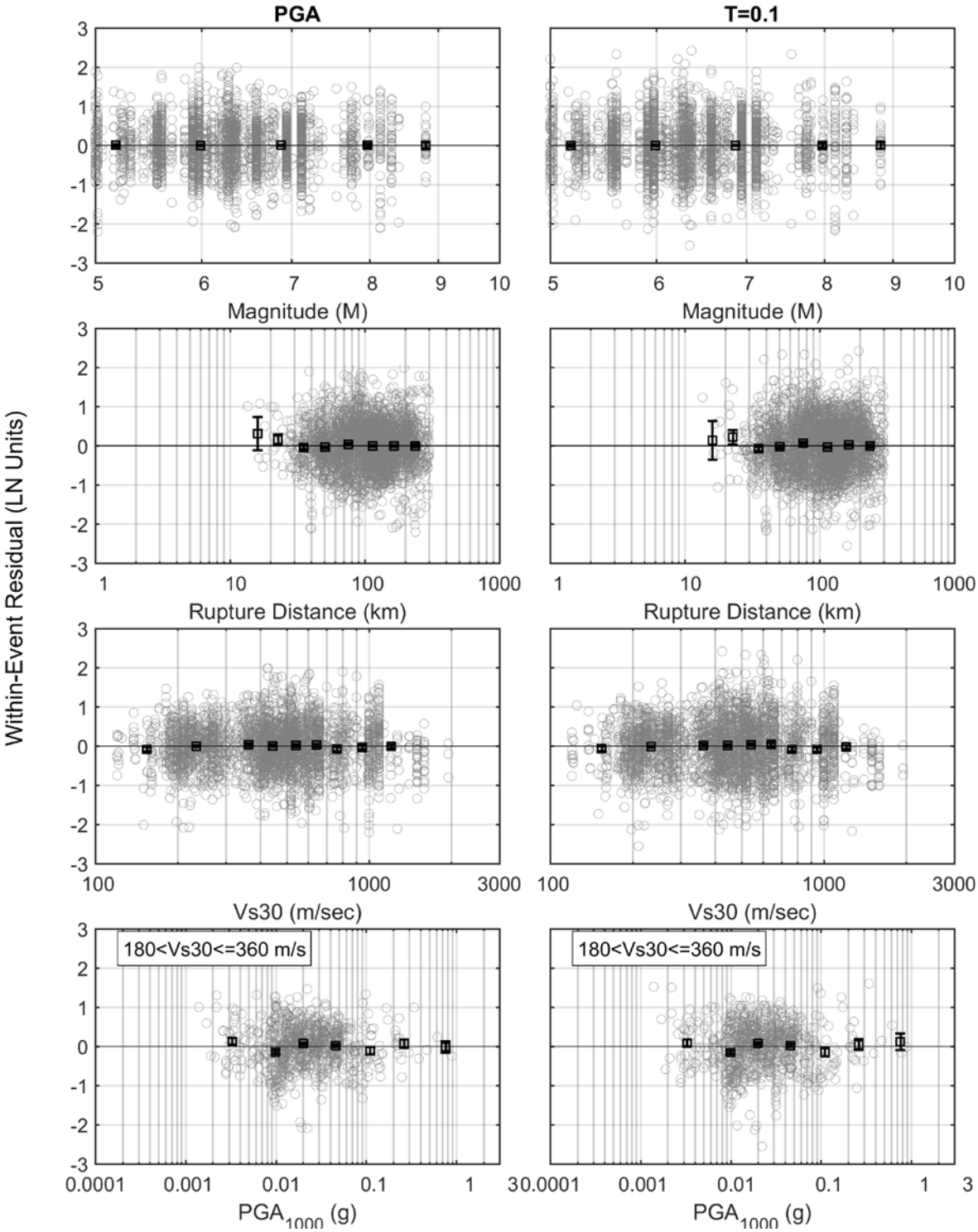

Figure 3.14(a) Within-event residuals for other regions: PGA and *T* = 0.1 sec.

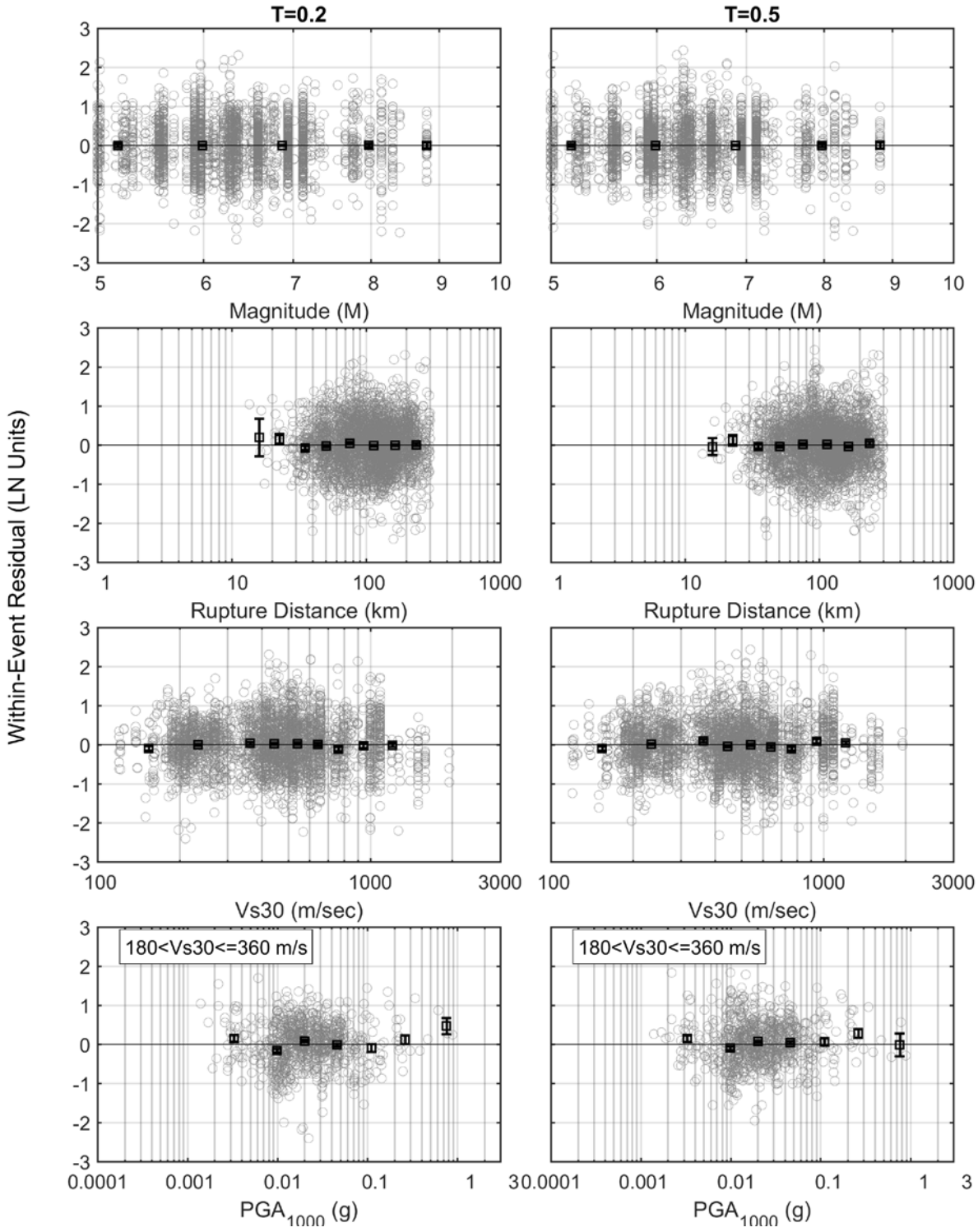

Figure 3.14(b) Within-event residuals for other regions: *T* = 0.2 sec and *T* = 0.5 sec.

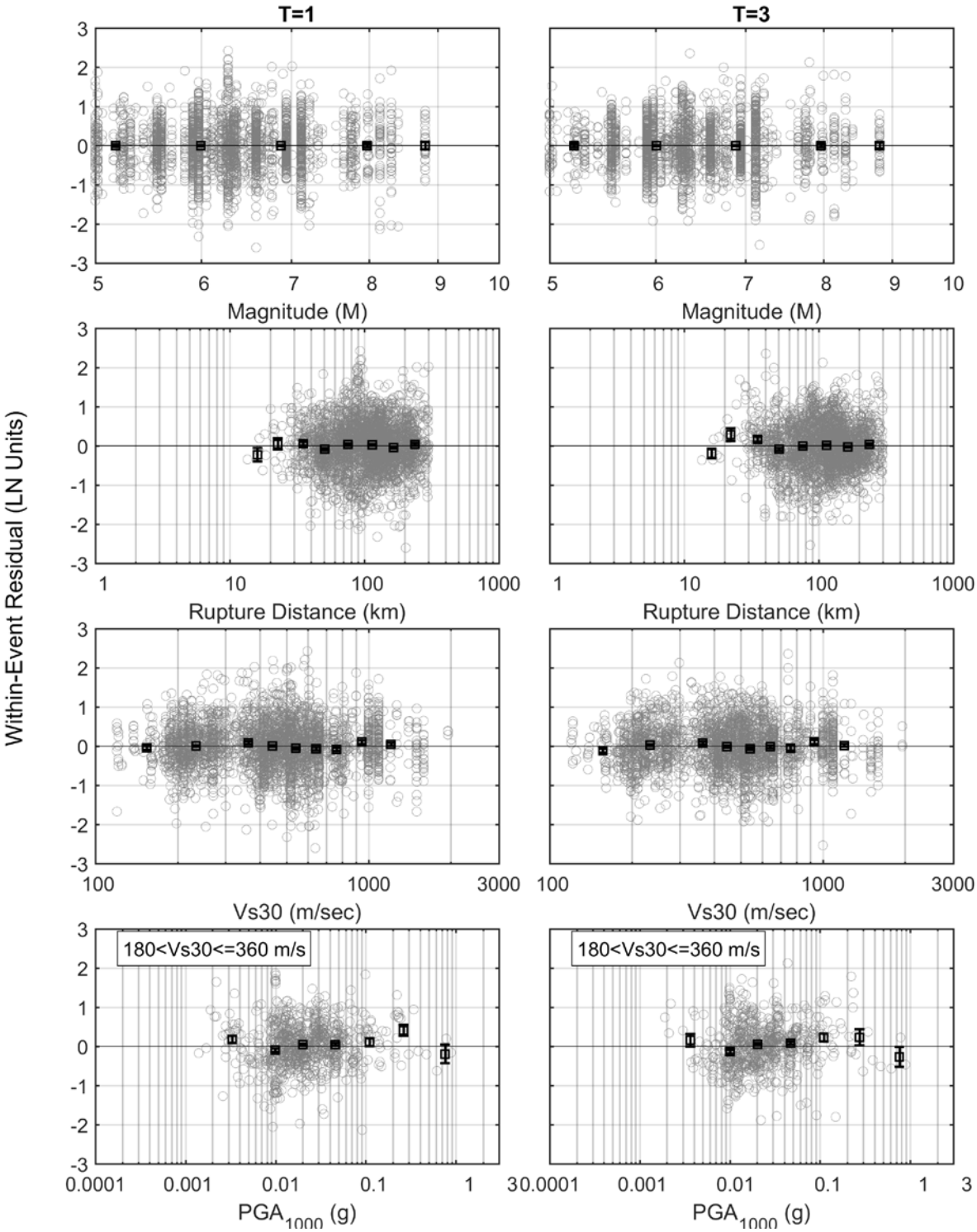

Figure 3.14(c) Within-event residuals for other regions: *T* = 1 sec and *T* = 3 sec.

3.4 REGIONAL DIFFERENCES

There are three terms that are allowed to vary regionally: the linear ln(V_{S30}) scaling (a_{12}+bn), the linear R term (a_6), and the constant term.

The regional V_{S30} scaling coefficients are compared in Figure 3.15. For the linear V_{S30} scaling, the Central America region does not have an adequate range of VS30 to constrain the linear V_{S30} scaling, so it is fixed at the global model value. Overall, four of the five regions have similar trends in the VS30 scaling. The exception is the South America region which shows much weaker scaling for the long spectral periods. The VS30 scaling for the Cascadia region is similar to the global model for periods greater than 0.1 sec and has stronger scaling for periods less than 0.1 sec.

The regional linear R scaling coefficients are compared in Figure 3.16. Four of the six regions have similar trends in the linear R scaling. The Taiwan region shows almost no need for a linear R term. This is related to the limited distance range in the Taiwan data, due in part to the dimension of the Taiwan. The Central America region shows highly variability in the linear R scaling, indicating that this term is not well constrained. The linear R scaling for Cascadia shows stronger attenuation than the global average at periods between 0.1 and 3 seconds. This results in a rapid decay in the Cascadia ground motions at large distances.

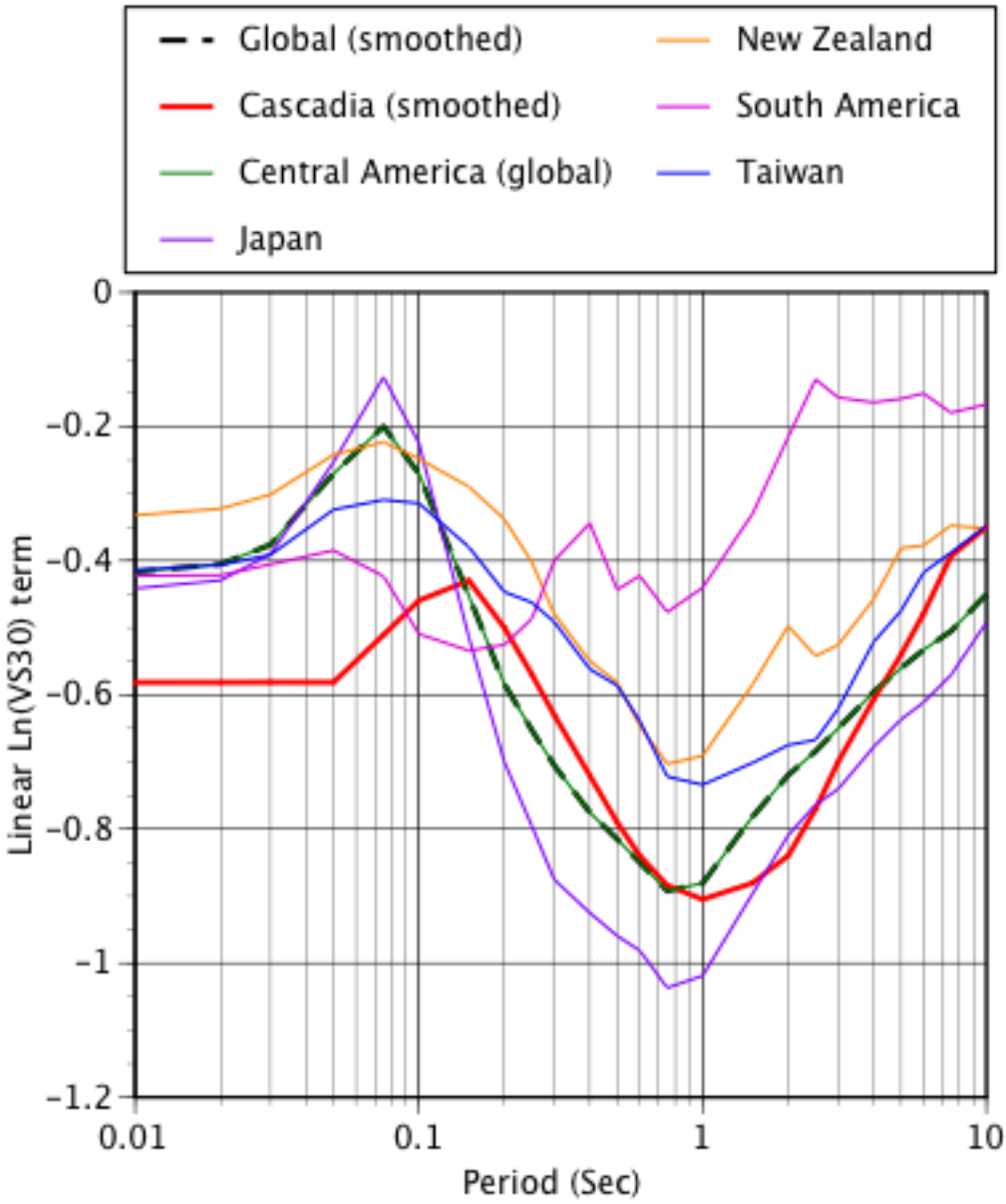

Figure 3.15 Regional differences in the linear VS30 term (a_{12}).

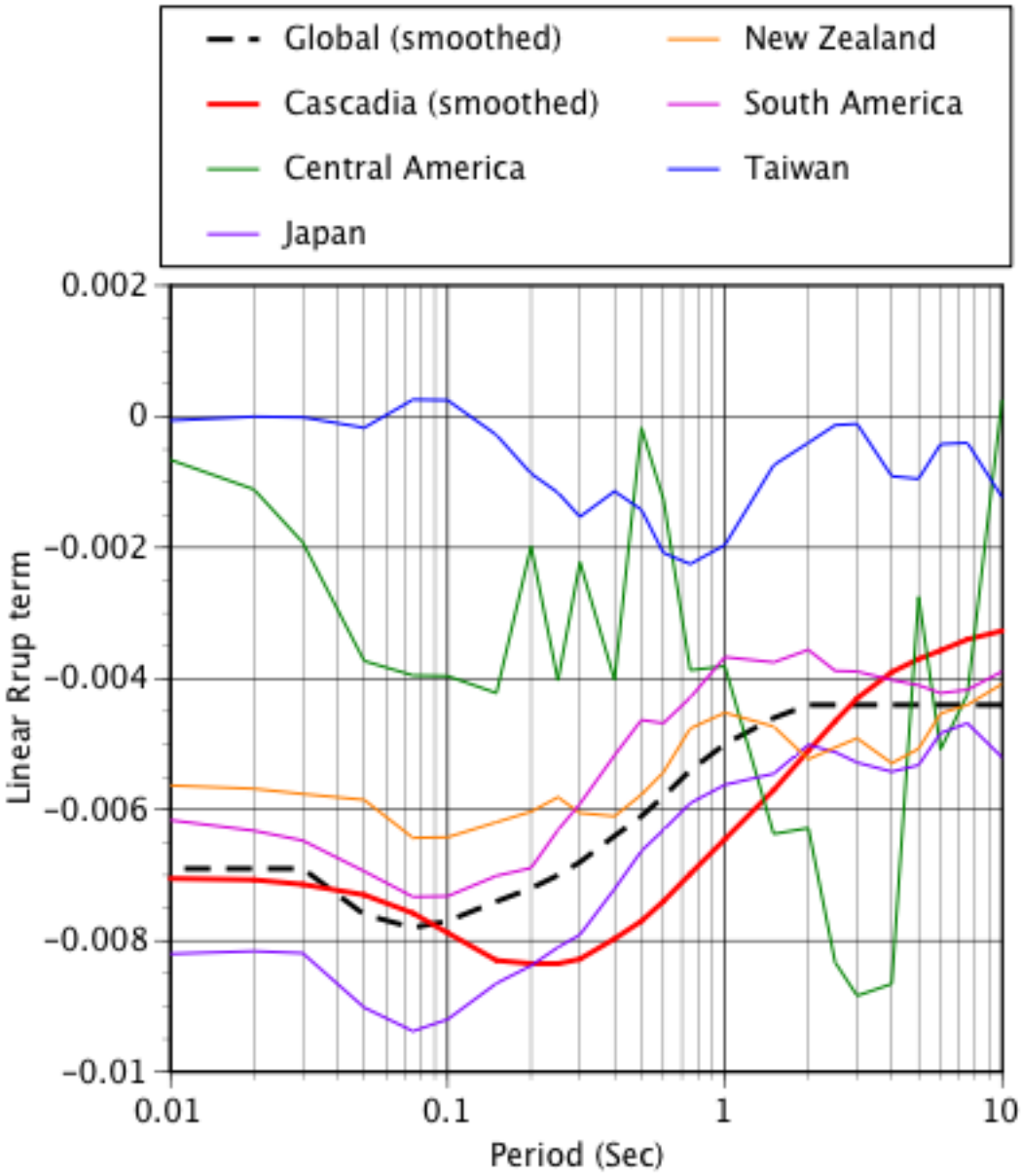

Figure 3.16 Regional differences in the linear R term (a_6).

4 Model Results

4.1 ADJUSTING THE CASCADIA MODEL

There are only four earthquakes in the Cascadia region in the selected subset. Of these four events, three have very low ground motions at short periods, leading to a median that is 2–3 times smaller than for other regions. The Cascadia median spectrum for a **M**6.5 intraslab and interface earthquakes at a distance of 100 km is compared to the median spectra for other regions in Figures 4.1 and 4.2, respectively. Other Cascadia earthquakes with **M** < 5, which are not in the selected subset, also show very low short-period ground motions. Of the four earthquakes classified as the Cascadia region, two are from Washington and two are from northern California. The largest earthquake of the four is the **M**6.8 Nisqually event. The event terms from this earthquake are much higher than the other three Cascadia events; see Figure 3.9 and 3.10.

Without a sound physical basis for the large reduction in the short-period ground motions in Cascadia as compared to other regions, and the observation that the short-period Nisqually ground-motion amplitudes are similar to other regions, the NGA-SUB developers judged that the reduction in the short-period ground motions for the small earthquakes in Cascadia should not be incorporated into the updated BCHydro ground-motion model. Therefore, the Cascadia model is adjusted so that the ground-motions for an earthquake scenario near the center of the data (**M**6.5, R = 100 km, V_{S30} = 400 m/sec) are consistent with the average over all regions.

The median ground motion for the average scenario is computed for each region using the region-specific terms. The log ratio of the median for each region to the median for Cascadia is shown in Figure 4.3 for intraslab events and in Figure 4.4 for interface events. For the intraslab events, the median is computed for all six regions, and the adjustment is based on the average term over the six regions. That is: the low Cascadia ground motions are included in the average region term for the intraslab. For the interface events, the adjustment is based on the average term over only four regions: Central America, Japan, New Zealand, and Japan. There is not enough data from Cascadia or Taiwan to constrain an interface model; therefore, they are not included in the regional average. The adjustments to the Cascadia constant term are shown in Figure 4.5. The adjustment terms are smoothed based spectral shape using all of the terms. In particular, the sum of the regional Cascadia constant term and the adjustment terms. The resulting smoothed adjustment term (keeping the Cascadia constant terms unsmoothed) are shown in Figure 4.5.

The adjusted Cascadia intraslab model is compared to the median from Nisqually data in Figure 4.6. The Nisqually data are adjusted to a V_{S30} of 400 m/sec using the V_{S30} scaling for Cascadia, and the median of the data in distance range of 70 to 120 km is shown. The adjusted Cascadia intraslab model is shown along with the 16th and 84th percentile range from the standard

deviation of the event terms. This figure shows that the average from the Nisqually data are not inconsistent with the adjusted Cascadia model. In addition, the final regression step was repeated including the data from the M6.7 1949 Olympia and M6.6 1965 Seattle earthquakes which had only two recordings for each event. Although the event terms are not well constrained, they are similar to the event terms for the Nisqually earthquake and do not show the very low short-period ground motions observed for other Cascadia earthquakes.

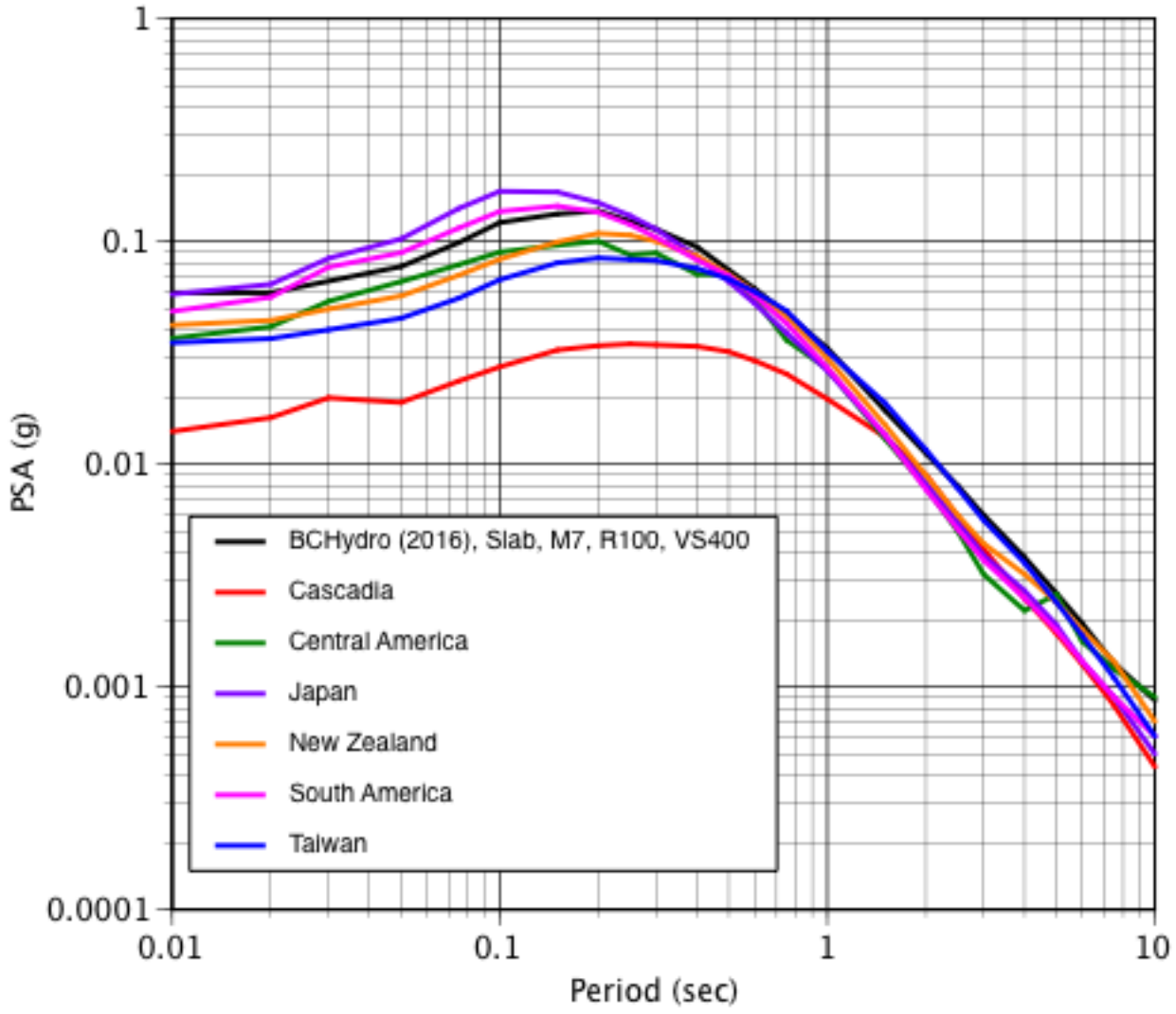

Figure 4.1 **Median spectra for different regions for intraslab, M7, Z_{TOR} = 50 km, R_{rup} = 100 km, and V_{S30}=400 m/sec.**

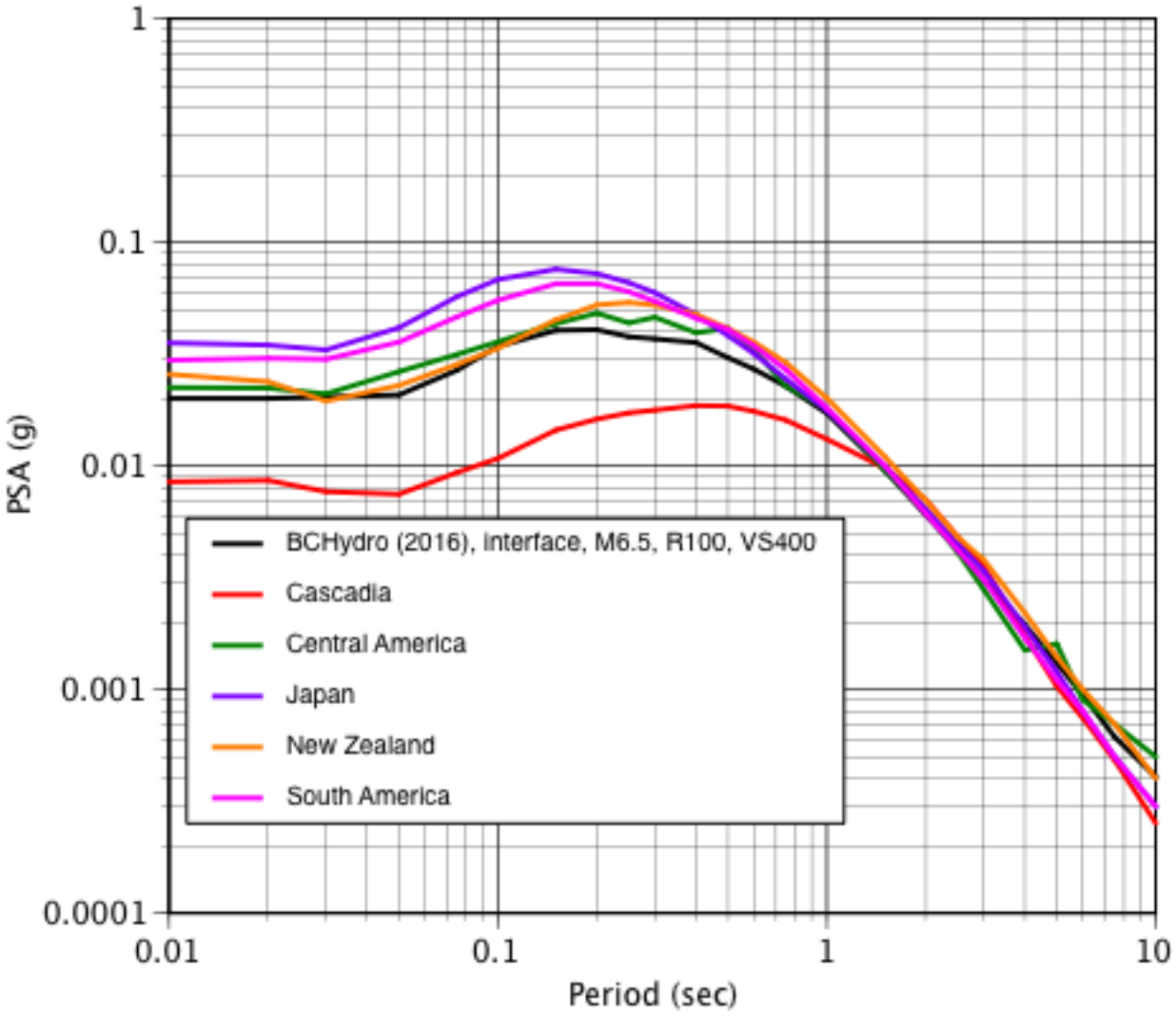

Figure 4.2 **Median spectra for different regions for interface, M7, Z_{TOR} = 20 km, R_{rup} = 100 km, and V_{S30}=400 m/sec.**

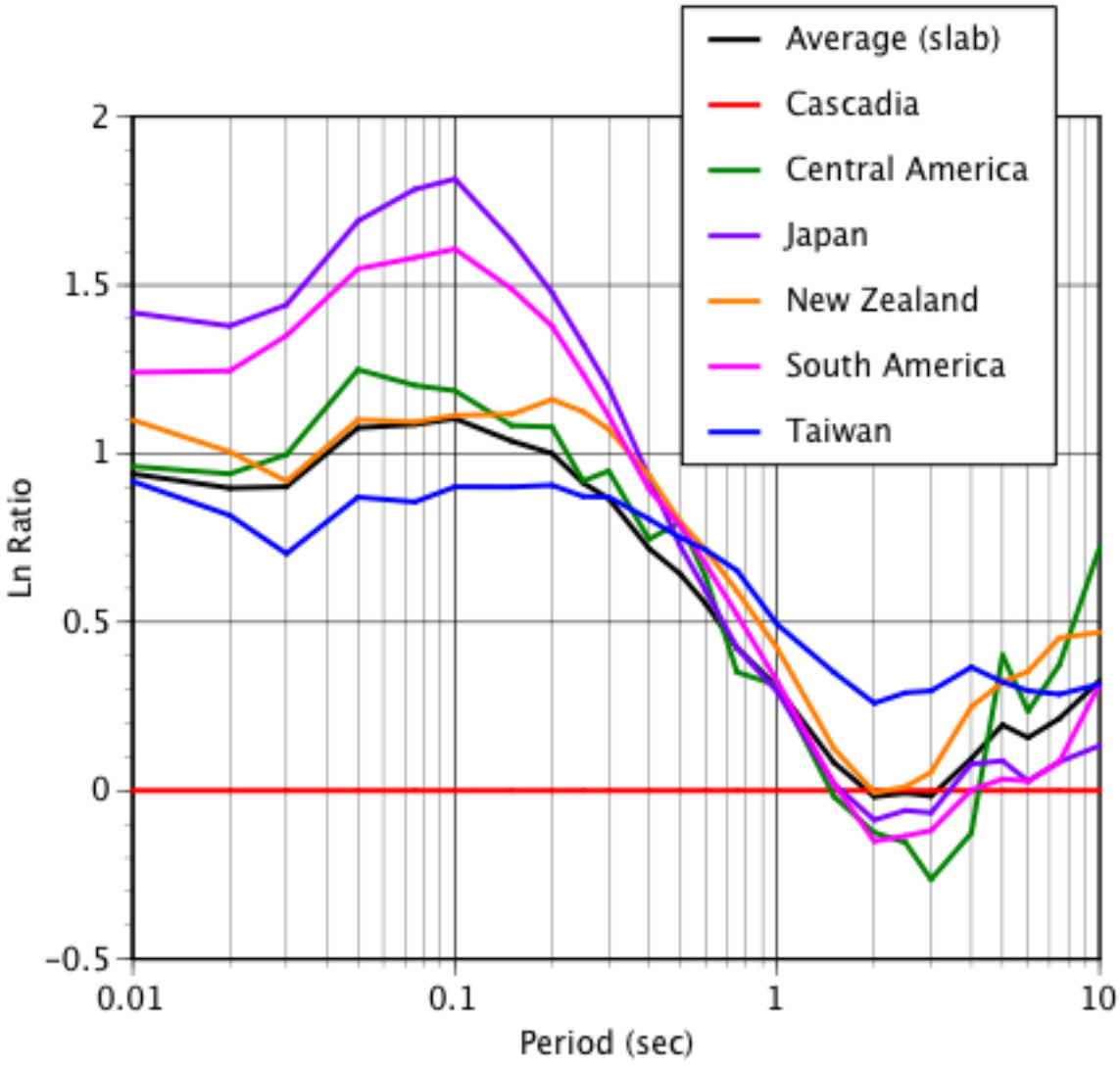

Figure 4.3 Adjustment to the constant term for Cascadia for intraslab earthquakes.

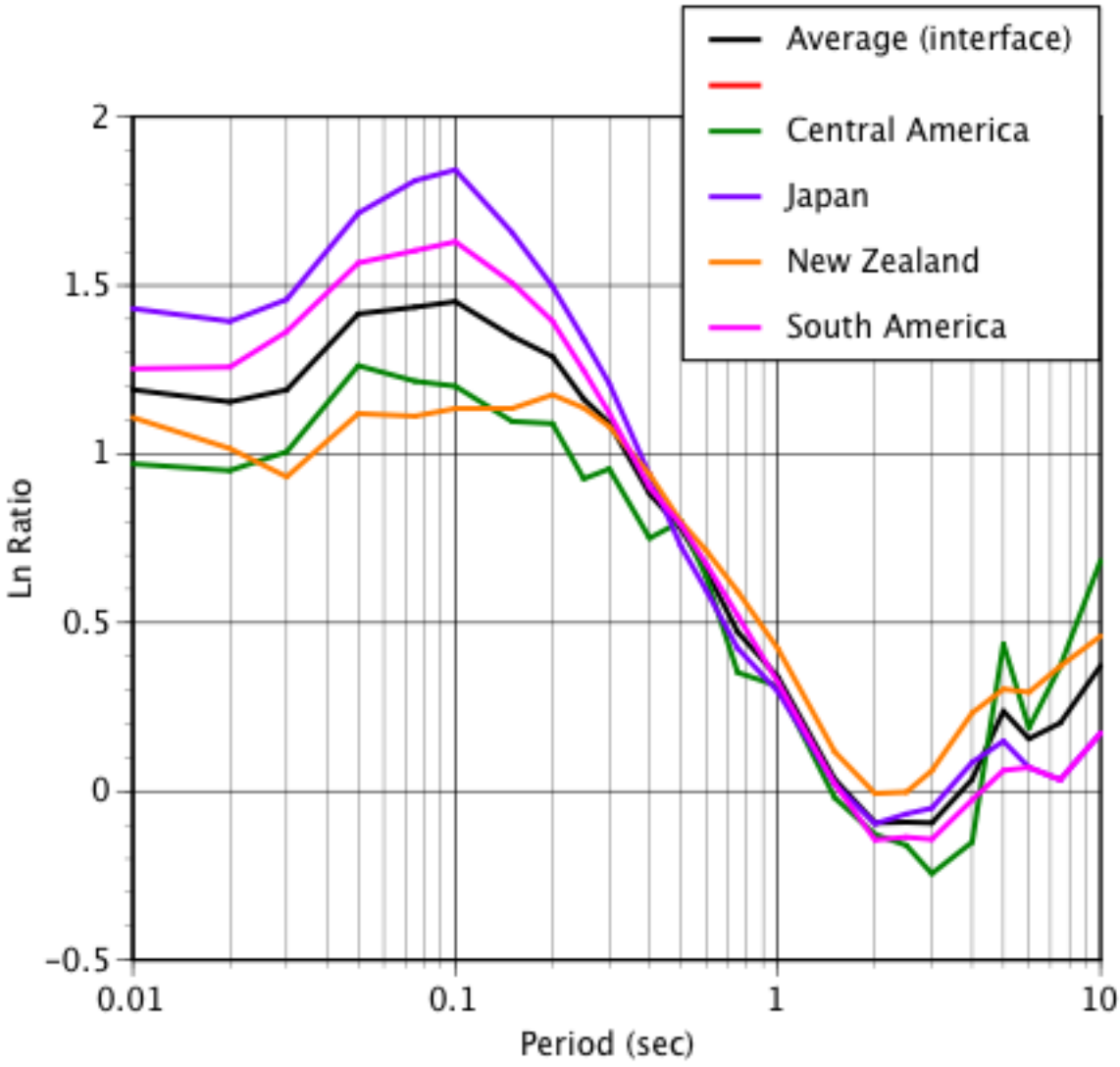

Figure 4.4 **Adjustment to the constant term for Cascadia for interface earthquakes.**

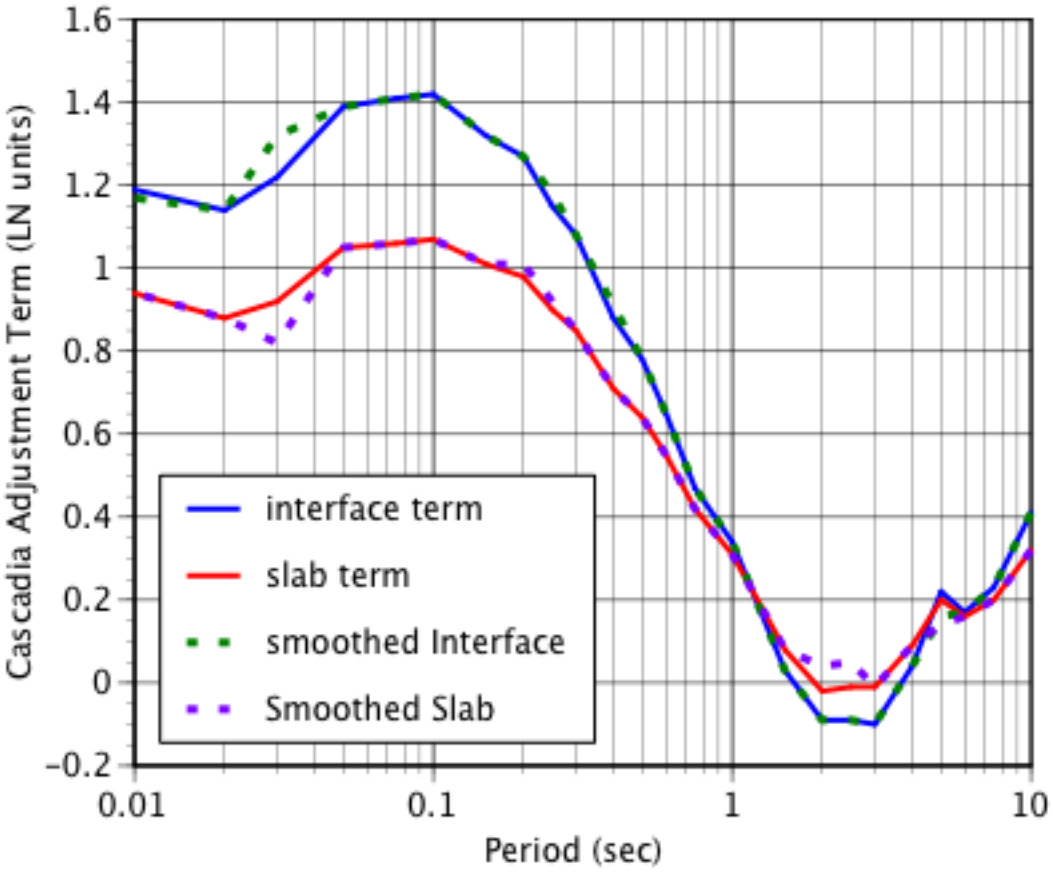

Figure 4.5 Smoothed adjustment for the constant term for Cascadia.

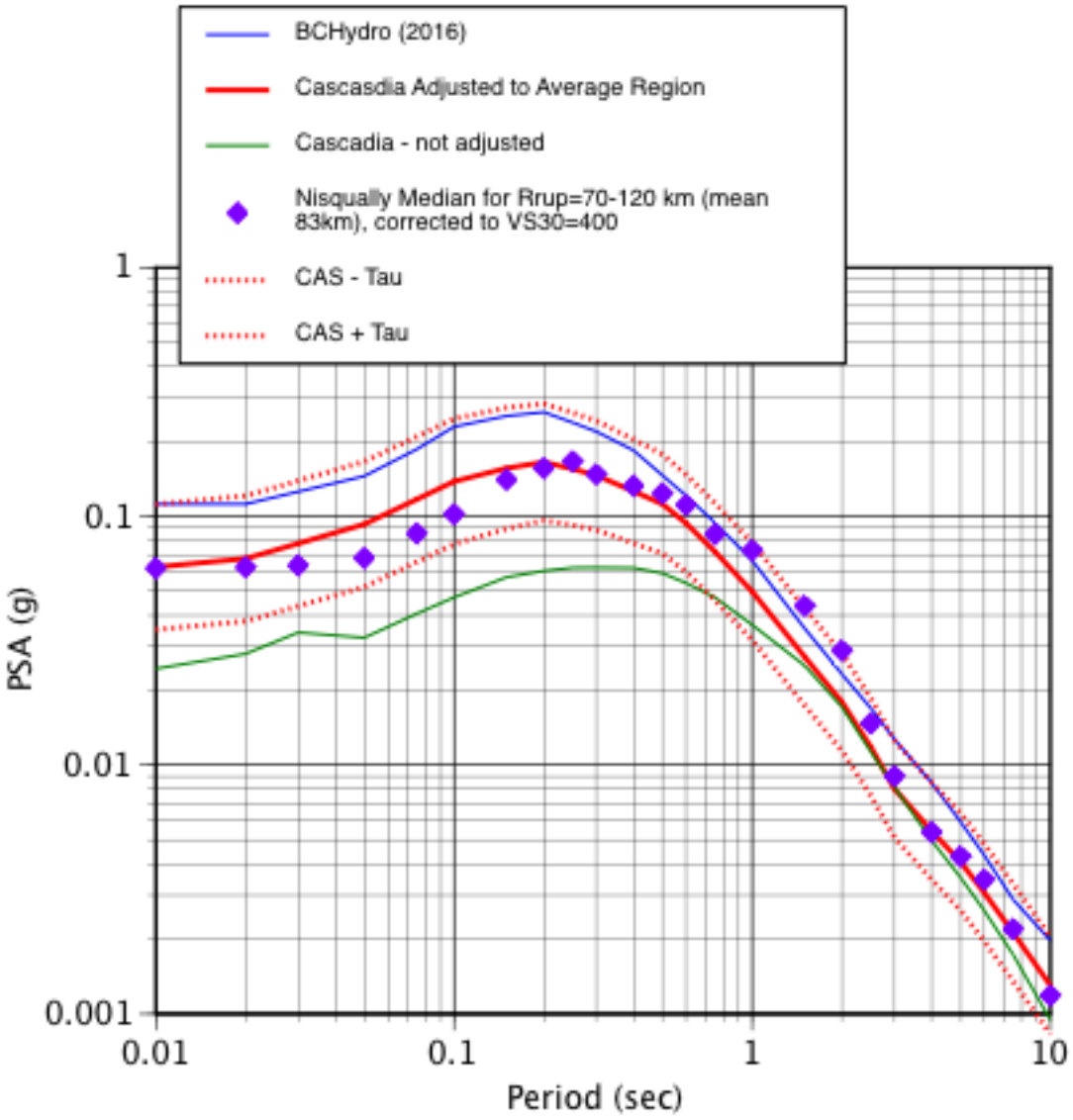

Figure 4.6 Comparison of adjusted Cascadia median for M6.8, V_{S30} = 400 m/sec, R_{rup}=83 km.

4.2 MODEL COEFFICIENTS

The model coefficients for the adjusted Cascadia ground-motion model are listed in Tables 4.1, 4.2, and 4.3. Examples of the magnitude, distance, and ZTOR scaling of the median spectral values are shown in Figures 4.7 to 4.9. Figure 4.7 shows the spectra for M5 to M9 or a rupture distance of 80 km and a V_{S30} of 760 m/s. Figure 4.8 shows the spectra for distances of 50 to 1000 km an M9 interface earthquake and for a V_{S30} of 760 m/s. The dips in the short-period spectra ($T<0.4$ sec) at a distance of 1000 km reflects the difficulties of applying a simple parametric form to a wide range of magnitudes and distances. Figure 4.9 shows the spectra for Z_{TOR} values of 30 to 100 km. For $Z_{TOR}>$ 100 km, there is a cap on the scaling.

Table 4.1 Period-independent coefficients.

Coefficient	Period-independent values
n	1.18
c	1.88
C_4	10 km
a_3	-0.10
a_5	0.0
a_9	0.40
a_{10}	1.73

Table 4.2 Period-dependent coefficients for the Cascadia model.

Period (sec)	a_1	a_2	a_4	a_6	a_{11}	a_{12}	a_{13}	a_{14}
0.01	2.340	-1.044	0.59	-0.00705	0.0170	0.818	-0.0135	-0.223
0.02	2.360	-1.044	0.59	-0.00707	0.0170	0.857	-0.0135	-0.196
0.03	2.384	-1.080	0.59	-0.00710	0.0170	0.921	-0.0135	-0.128
0.05	2.446	-1.110	0.59	-0.00725	0.0180	1.007	-0.0138	-0.130
0.075	2.751	-1.110	0.59	-0.00758	0.0180	1.225	-0.0142	-0.130
0.10	3.019	-1.110	0.59	-0.00788	0.0180	1.457	-0.0145	-0.130
0.15	3.349	-1.084	0.59	-0.00820	0.0175	1.849	-0.0153	-0.156
0.20	3.284	-1.027	0.62	-0.00835	0.0170	2.082	-0.0162	-0.172
0.25	3.211	-0.983	0.64	-0.00835	0.0160	2.240	-0.0172	-0.184
0.30	3.145	-0.947	0.66	-0.00828	0.0152	2.341	-0.0183	-0.194
0.40	2.997	-0.890	0.68	-0.00797	0.0140	2.415	-0.0206	-0.210
0.50	2.839	-0.845	0.68	-0.00770	0.0130	2.359	-0.0231	-0.223
0.60	2.658	-0.809	0.68	-0.00740	0.0122	2.227	-0.0256	-0.233
0.75	2.346	-0.760	0.68	-0.00698	0.0113	1.949	-0.0296	-0.245
1.0	1.851	-0.698	0.68	-0.00645	0.0100	1.402	-0.0363	-0.261
1.5	1.216	-0.612	0.68	-0.00570	0.0082	0.329	-0.0493	-0.285
2.0	0.649	-0.550	0.68	-0.00510	0.0070	-0.487	-0.061	-0.301
2.5	0.082	-0.501	0.68	-0.00465	0.0060	-0.770	-0.0711	-0.313
3.0	-0.369	-0.460	0.68	-0.00430	0.0052	-0.700	-0.0798	-0.323
4.0	-1.034	-0.455	0.68	-0.00390	0.0040	-0.607	-0.0935	-0.282
5.0	-1.520	-0.450	0.73	-0.00370	0.0030	-0.540	-0.098	-0.250
6.0	-1.810	-0.450	0.78	-0.00357	0.0022	-0.479	-0.098	-0.250
7.5	-2.173	-0.450	0.84	-0.00340	0.0013	-0.393	-0.098	-0.250
10.0	-2.712	-0.450	0.93	-0.00327	0.0000	-0.350	-0.098	-0.250

Table 4.3 Period-dependent coefficients for the Cascadia model (cont).

Period (sec)	V_{lin}	b	C_{1_inter}	C_{1_slab}	Adjustment term for interface	Adjustment term for intraslab
0.01	865.1	-1.186	8.2	7.2	1.04	0.83
0.02	865.1	-1.219	8.2	7.2	1.05	0.79
0.03	907.8	-1.273	8.2	7.2	1.23	0.71
0.05	1053.5	-1.346	8.2	7.2	1.34	0.98
0.075	1085.7	-1.471	8.2	7.2	1.32	0.99
0.1	1032.5	-1.624	8.2	7.2	1.32	1.00
0.15	877.6	-1.931	8.2	7.2	1.21	0.92
0.2	748.2	-2.188	8.2	7.2	1.14	0.88
0.25	654.3	-2.381	8.2	7.2	1.05	0.81
0.3	587.1	-2.518	8.2	7.2	0.95	0.75
0.4	503	-2.657	8.2	7.2	0.79	0.62
0.5	456.6	-2.669	8.2	7.2	0.66	0.54
0.6	430.3	-2.599	8.2	7.2	0.54	0.46
0.75	410.5	-2.401	8.15	7.2	0.36	0.33
1.0	400	-1.955	8.1	7.2	0.24	0.23
1.5	400	-1.025	8.05	7.2	-0.08	-0.01
2.0	400	-0.299	8.0	7.2	-0.21	-0.09
2.5	400	0	7.95	7.2	-0.21	-0.05
3.0	400	0	7.9	7.2	-0.22	-0.02
4.0	400	0	7.85	7.2	-0.06	0.06
5.0	400	0	7.8	7.2	0.06	0.06
6.0	400	0	7.8	7.2	0.09	0.10
7.5	400	0	7.8	7.2	0.14	0.13
10.0	400	0	7.8	7.2	0.31	0.24

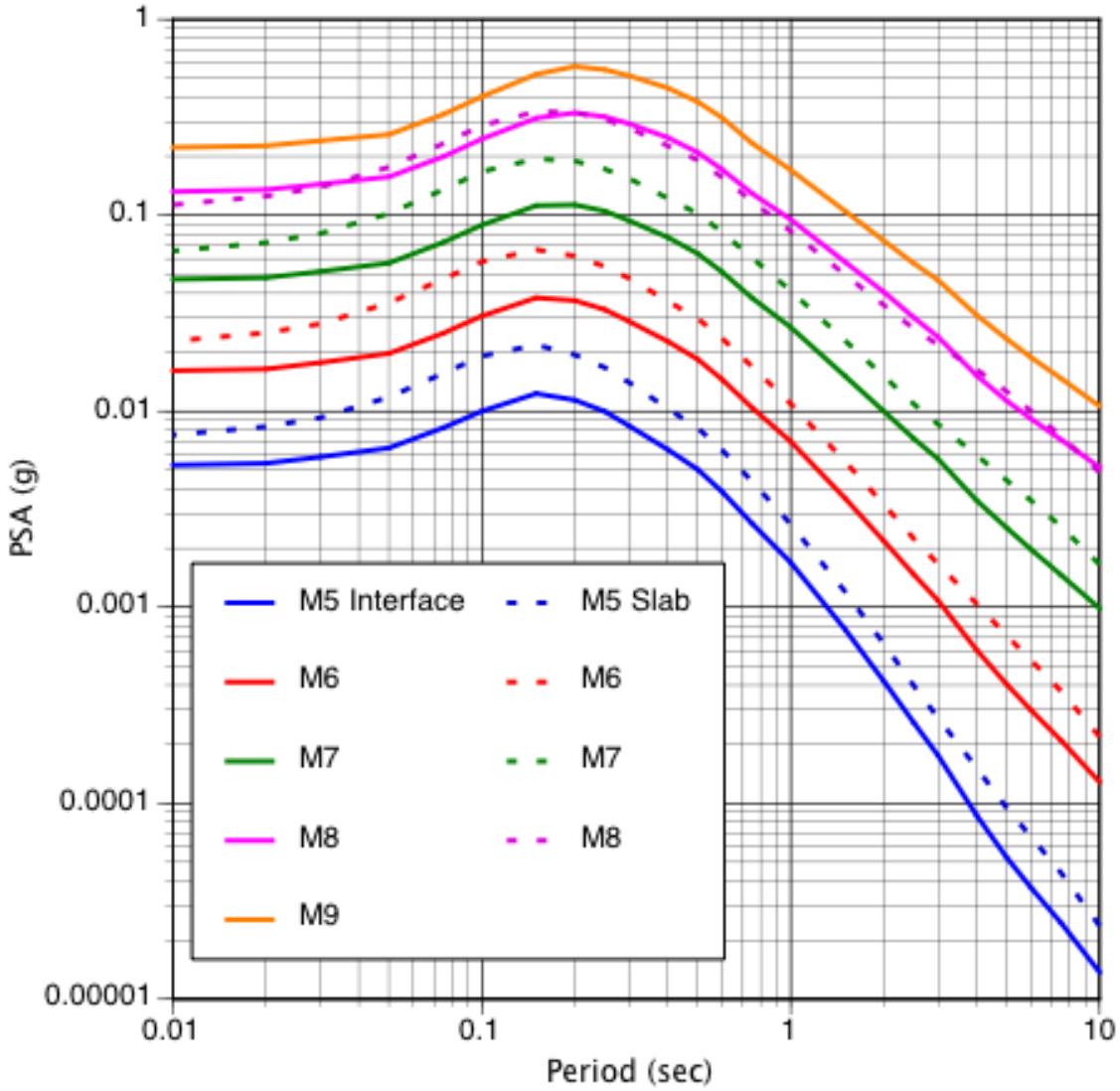

Figure 4.7 Magnitude scaling of spectra for Rrup=80 km and VS30=760 m/s.

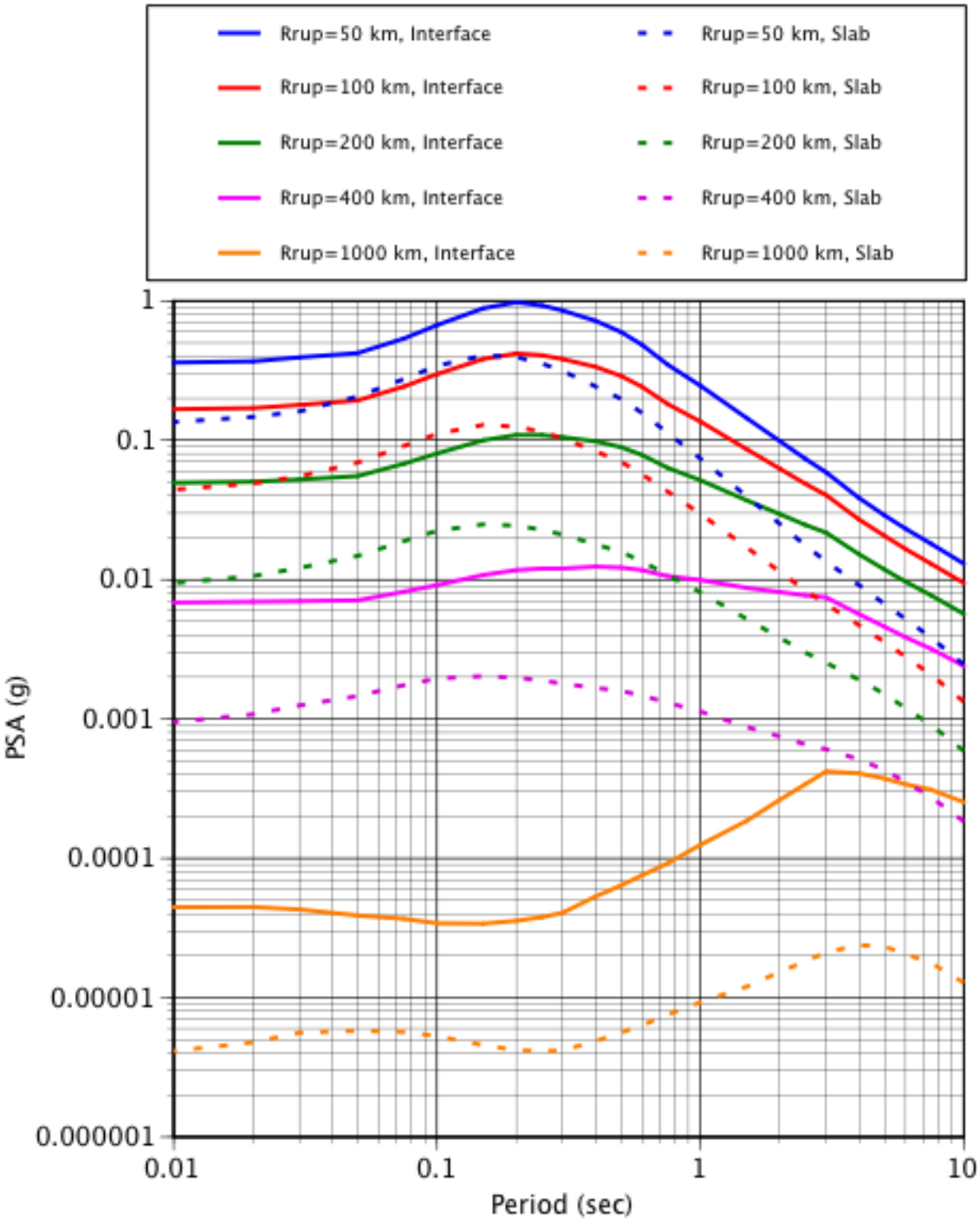

Figure 4.8 **Distance scaling of spectra for M=9 interface earthquakes and VS30=760 m/s.**

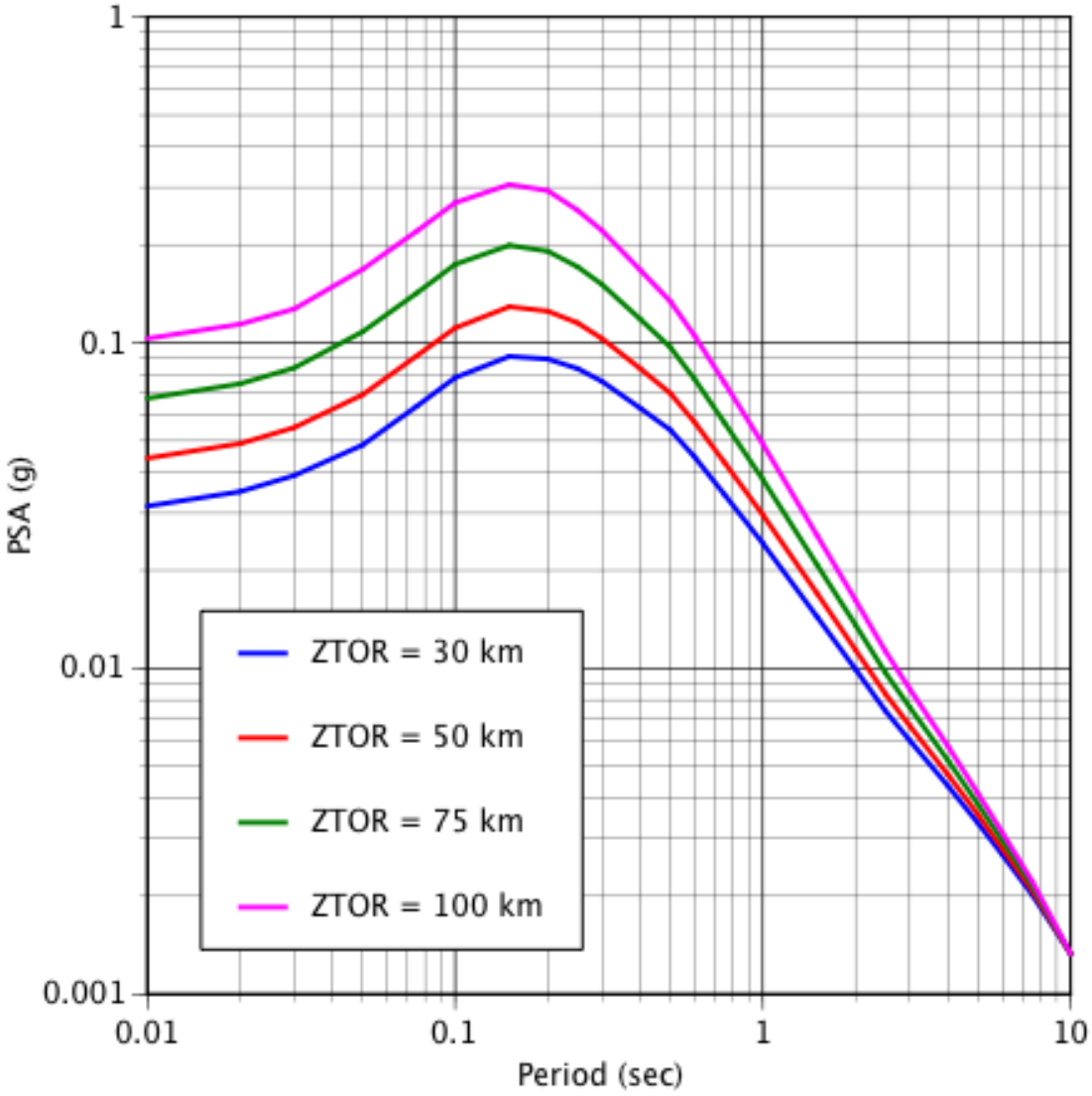

Figure 4.9 ZTOR scaling of spectra for M=7 intraslab events and VS30=760 m/s.

4.3 EPISTEMIC UNCERTAINTY

The epistemic uncertainty is modelled using the scaled backbone approach. The scale factor for the scaled backbone model is based on the range of average ground motions between the different regions. The range is shown in Figures 4.10 and 4.11 for intraslab events and interface events, respectively. The recommended high and low epistemic uncertainty range is shown by the heavy black lines in these figures. At short periods, the recommended epistemic uncertainty does not capture the lower range of the Cascadia events.

While a reduction in the epistemic uncertainty range for the interface at long periods could be justified by the range of the models shown in Figure 4.11, preliminary results using random effects for the constant scale factor between regions leads to a standard deviation at long periods

that is similar for interface and intraslab events and is also larger than indicated by the range of the interface models shown in Figure 4.11. The epistemic range shown in Figure 4.10 and 4.11 are generally consistent with the preliminary random-effects results if a three-point distribution (±1.65 sigma) is used. The epistemic uncertainty is listed in Table 4.4. For this range, epistemic weights of 0.2, 0.6, and 0.2 are appropriate for the low, central, and high models.

This epistemic uncertainty is a minimum uncertainty that only reflects the epistemic uncertainty in the adjustment factor applied to the Cascadia model. It does not capture the epistemic uncertainty in the magnitude and distance scaling. Other published ground-motion models can be used to capture the alternative magnitude and distance scaling.

Table 4.4 Epistemic uncertainty in the adjustment term (in LN units).

Period (sec)	Interface Low	Interface High	Slab Low	Slab High
0.01	-0.3	0.3	-0.5	0.5
0.02	-0.3	0.3	-0.5	0.5
0.03	-0.3	0.3	-0.5	0.5
0.05	-0.3	0.3	-0.5	0.5
0.075	-0.3	0.3	-0.5	0.5
0.1	-0.3	0.3	-0.5	0.5
0.15	-0.3	0.3	-0.5	0.5
0.2	-0.3	0.3	-0.5	0.5
0.25	-0.3	0.3	-0.46	0.46
0.3	-0.3	0.3	-0.42	0.42
0.4	-0.3	0.3	-0.38	0.38
0.5	-0.3	0.3	-0.34	0.34
0.6	-0.3	0.3	-0.3	0.3
0.75	-0.3	0.3	-0.3	0.3
1.0	-0.3	0.3	-0.3	0.3
1.5	-0.3	0.3	-0.3	0.3
2.0	-0.3	0.3	-0.3	0.3
2.5	-0.3	0.3	-0.3	0.3
3.0	-0.3	0.3	-0.3	0.3
4.0	-0.3	0.3	-0.3	0.3
5.0	-0.3	0.3	-0.3	0.3
6.0	-0.3	0.3	-0.3	0.3
7.5	-0.3	0.3	-0.5	0.5
10.0	-0.3	0.3	-0.5	0.5

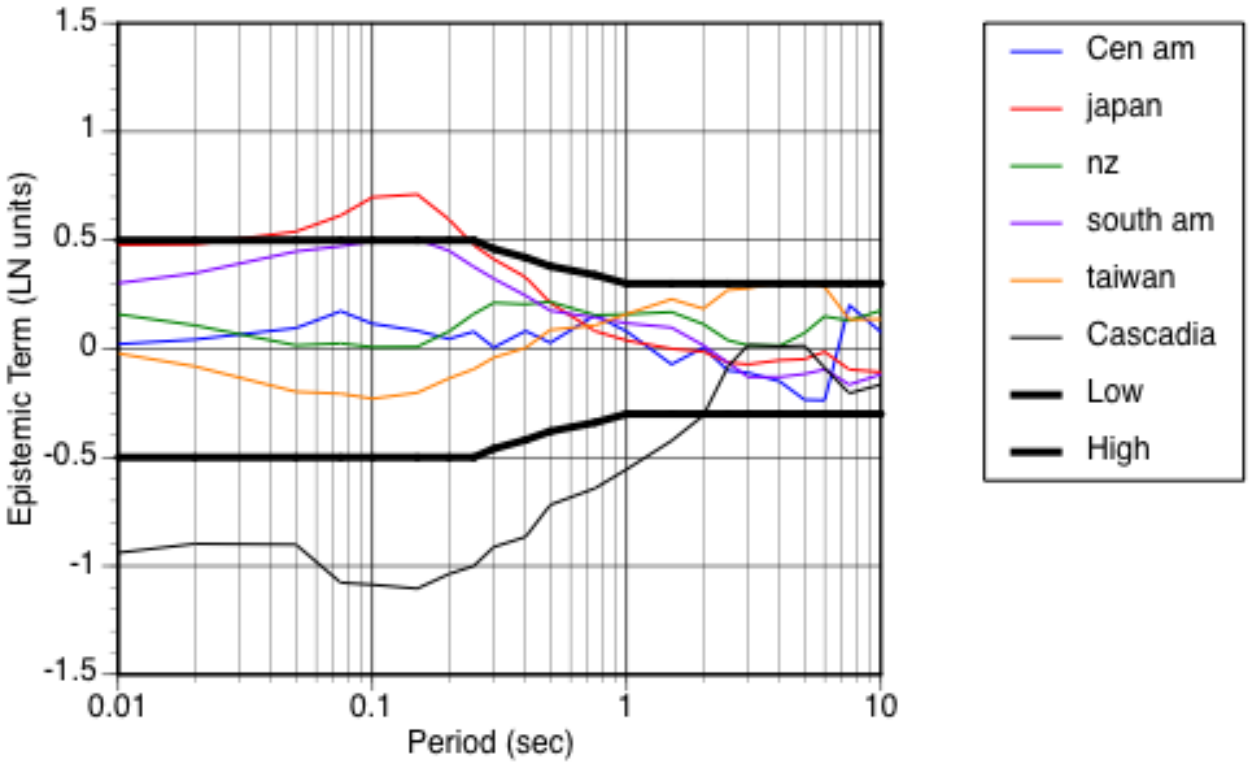

Figure 4.10 **Recommended epistemic uncertainty in the Cascadia adjustment term for intraslab earthquakes.**

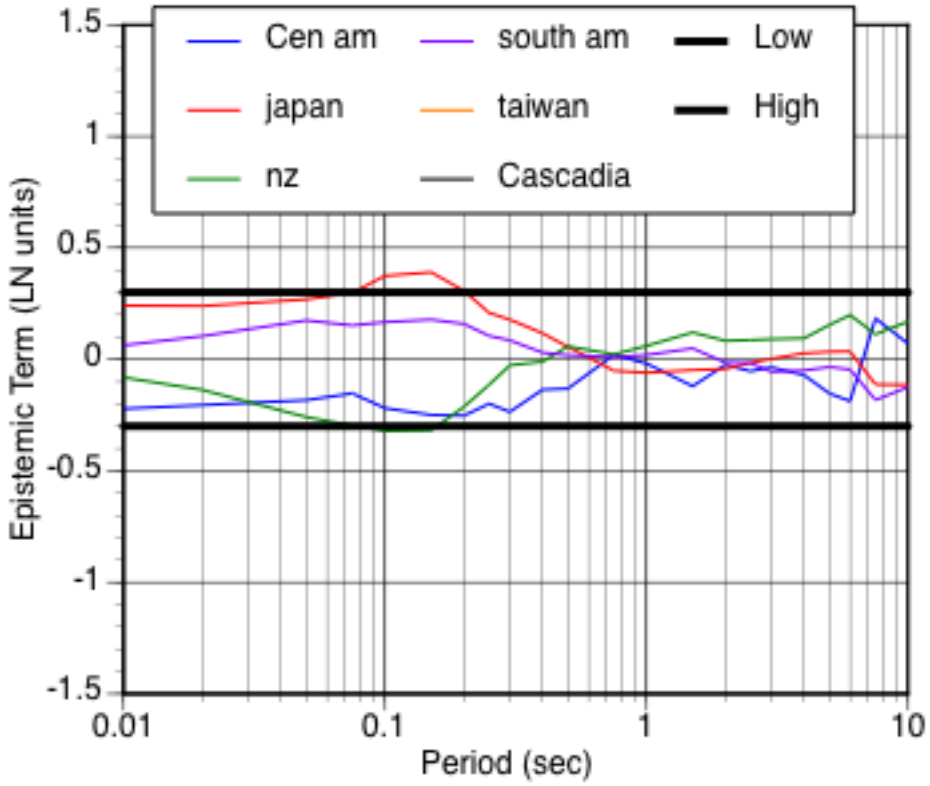

Figure 4.11 **Recommended epistemic uncertainty in the Cascadia adjustment term for interface earthquakes.**

4.4 MEDIAN MODEL COMPARISONS

The updated BCHydro model is compared with several current GMMs for subduction earthquakes in this section:

GMM	Abbreviation in plots
Zhao et al [2006]	Z06
Zhao et al [2016]	Z16
Atkinson and Boore [2003,2008] class B	AB, B
Atkinson and Boore [2003,2008] class C	AB, C
Atkinson and Boore [2003,2008] Cascadia, class B	AB-Cas, B
Atkinson and Boore [2003,2008] Cascadia, class C	AB-Cas, C
Atkinson and Macias [2009]	AM
Gregor et al [2006]	G06
Abrahamson et al [2016] central mag break	BCH-Cen
Abrahamson et al [2016] lower mag break	BCH-Low
Abrahamson et al [2016] higher mag break	BCH-Low
Updated BCHydro central model	BCH-381
Updated BCHydro high model	BCH-382
Updated BCHydro low model	BCH-383

The two Zhao models are based on Japanese ground motion data. The Atkinson and Boore models and the Abrahamson et al [2016] models are global models. The Atkinson and Macias [2009] and Gregor [2006] models are based on numerical simulations for interface earthquakes in Cascadia.

Figures 4.12a to 4.12d compare the distance scaling for **M**9 interface earthquakes for four spectral periods (PGA, T=0.2 sec, T=1 sec, and T=3 sec). Figures 4.13a to 4.13d compare the distance scaling for **M**7 intraslab earthquakes for these same four spectral periods. The Gregor et al (2006) and Atkinson and Macias (2009) models are only for interface and are not plotted in the intraslab scaling comparison. For both interface and intraslab events, the distance scaling of the updated BCHydro model is similar to the scaling of the Zhao et al. model [2006] (for Japan). Compared to the 2016 BCHydro model, the updated BCHydro model has steeper distance scaling at short periods (PGA), similar distance scaling at intermediate periods (T = 1 sec), and flatter distance scaling at long periods (T = 3).

Figures 4.14a to 4.14d compare the magnitude scaling for interface earthquakes and Figures 4.15a to 4.15d compare the magnitude scaling for intraslab earthquakes. The magnitude scaling for the updated BCHydro model is similar to the scaling in the Zhao et al (2006) model.

Figures 4.16 to 4.19 compare the response spectra for **M**8 and **M**9 interface earthquakes at distances of 75 and 300 km. At 75 km distance, the spectral shapes of the updated BCHydro model are similar to the spectral shapes of the 2016 BCHydro model; however, at 300 km distance, the spectral content is very different, with the updated model showing a shift to longer spectral periods due to the greater attenuation in the Cascadia model.

Figures 4.20 to 4.23 compare the response spectra for **M**6.5 and **M**7.5 intraslab earthquakes at distances of 75 and 300 km. At both 75 km and 300 km distance, the spectral shape of the updated BCHydro model is similar to the 2016 BCHydro model at long periods, but show lower short-period ground motions.

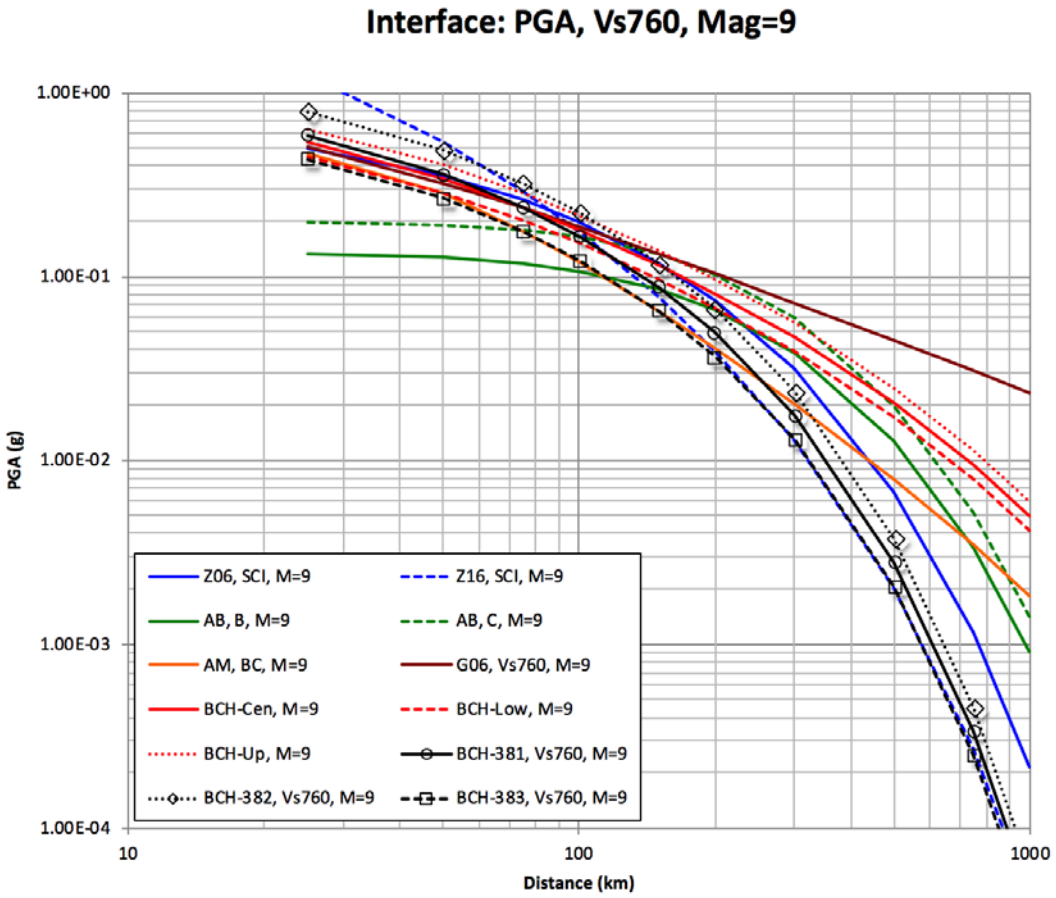

Figure 4.12(a) Median attenuation comparison for PGA for M9, V_{S30} = 760 m/sec. The symbols are shown on the updated BCHydro model to make these models stand out on the plot.

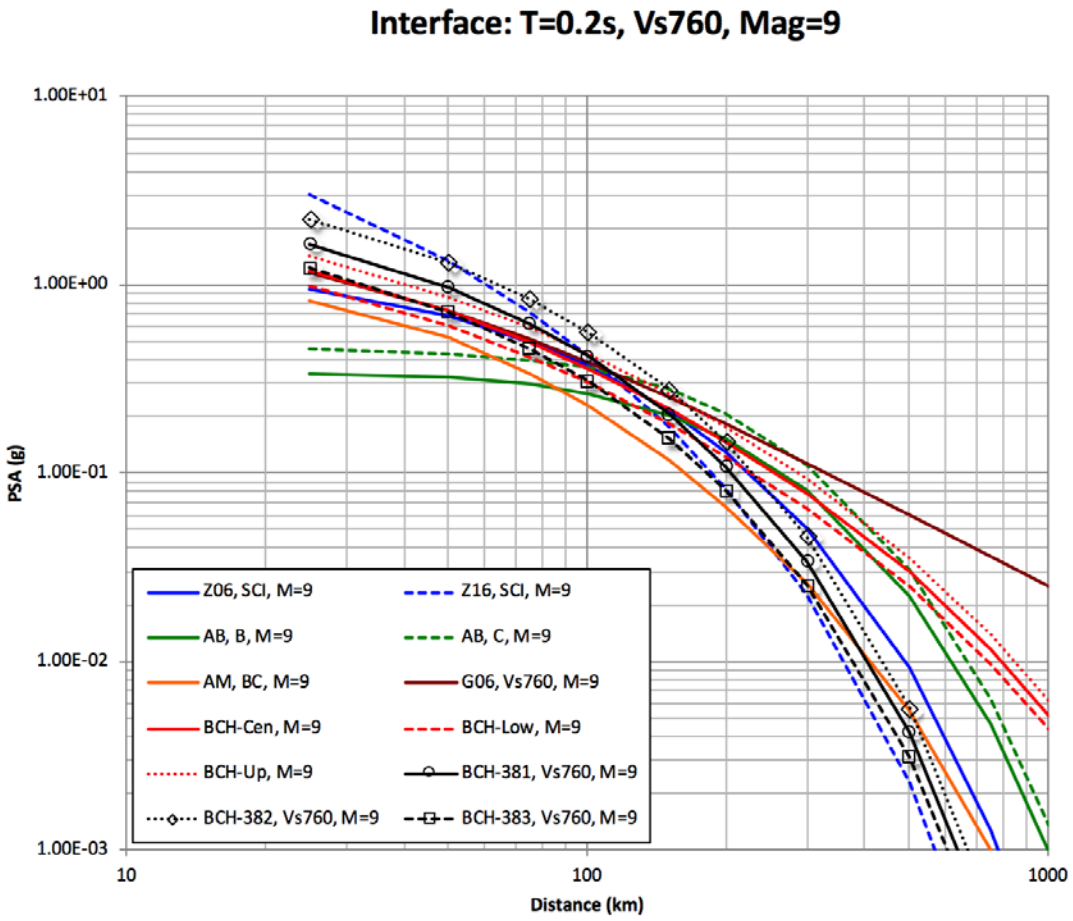

Figure 4.12(b) Median attenuation comparison for T = 0.2 sec for M9, V_{S30} = 760 m/sec.

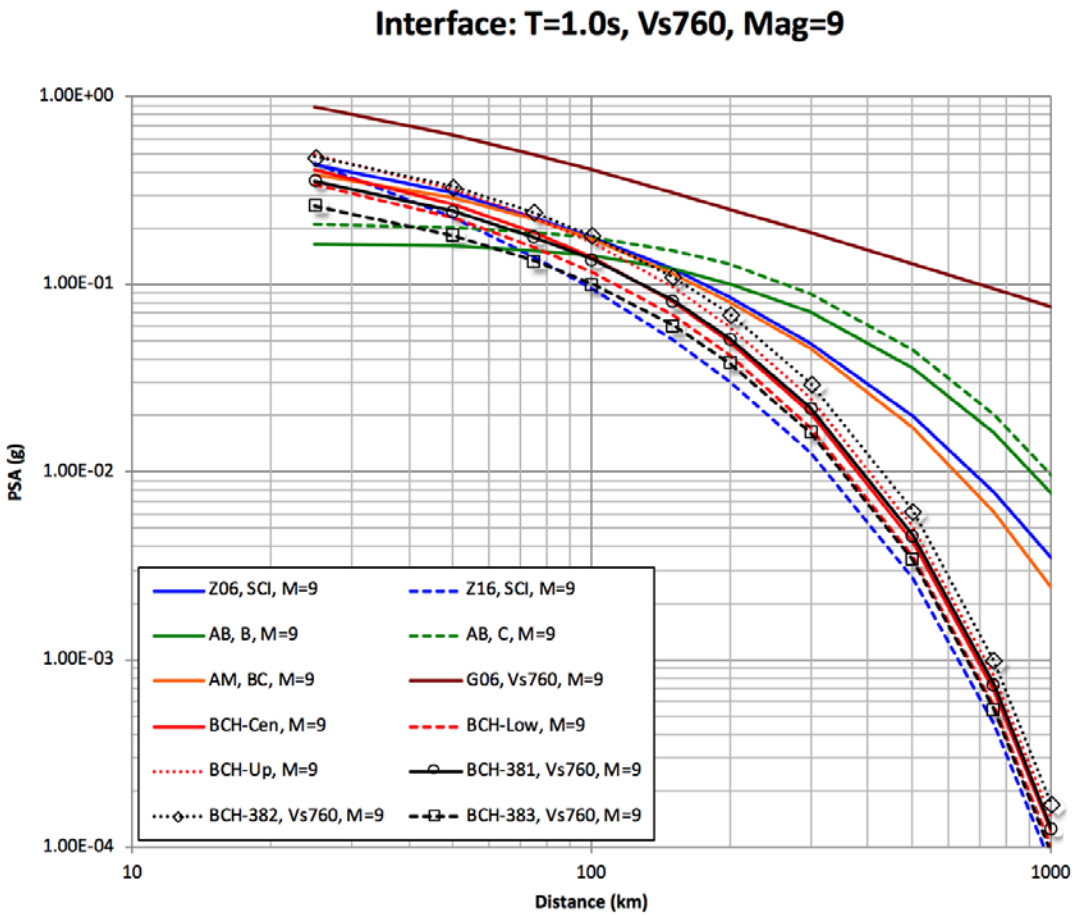

Figure 4.12(c) Median attenuation comparison for T = 1 sec, for M9, V_{S30} = 760 m/sec.

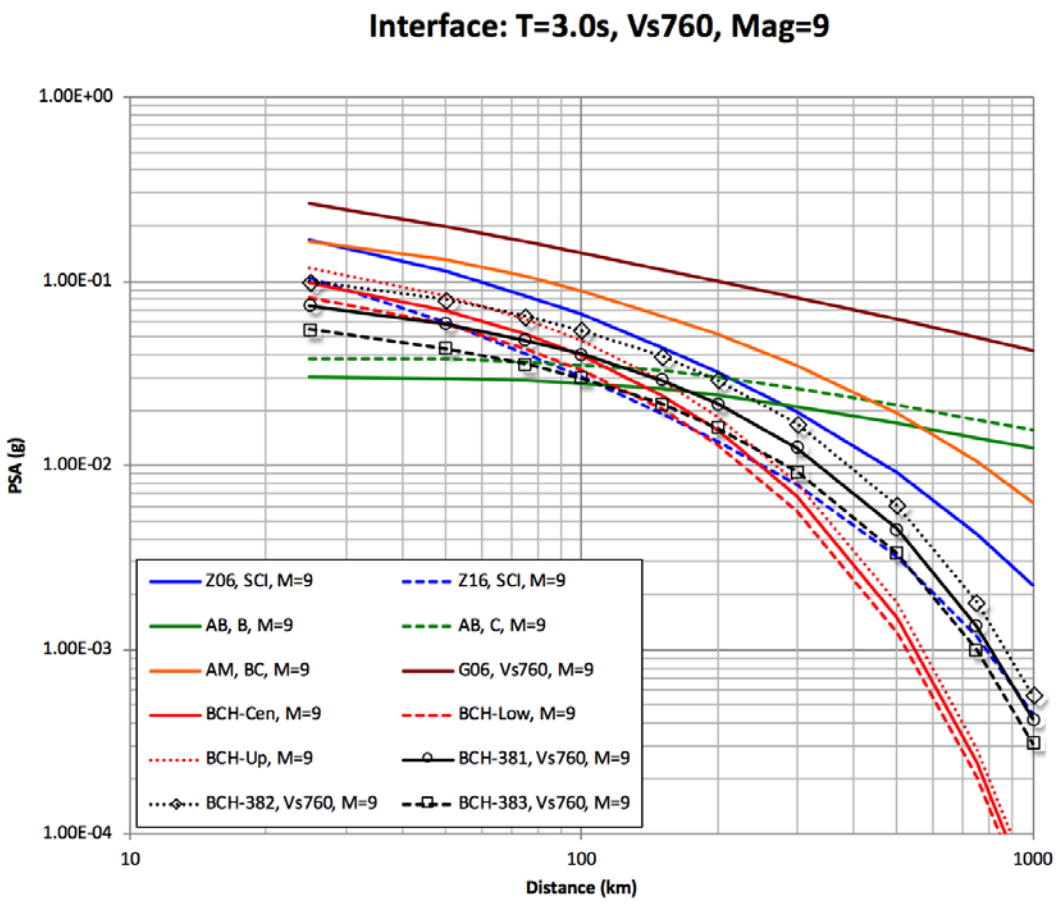

Figure 4.12(d) Median attenuation comparison for T = 3 sec, for M9, V_{S30} = 760 m/sec.

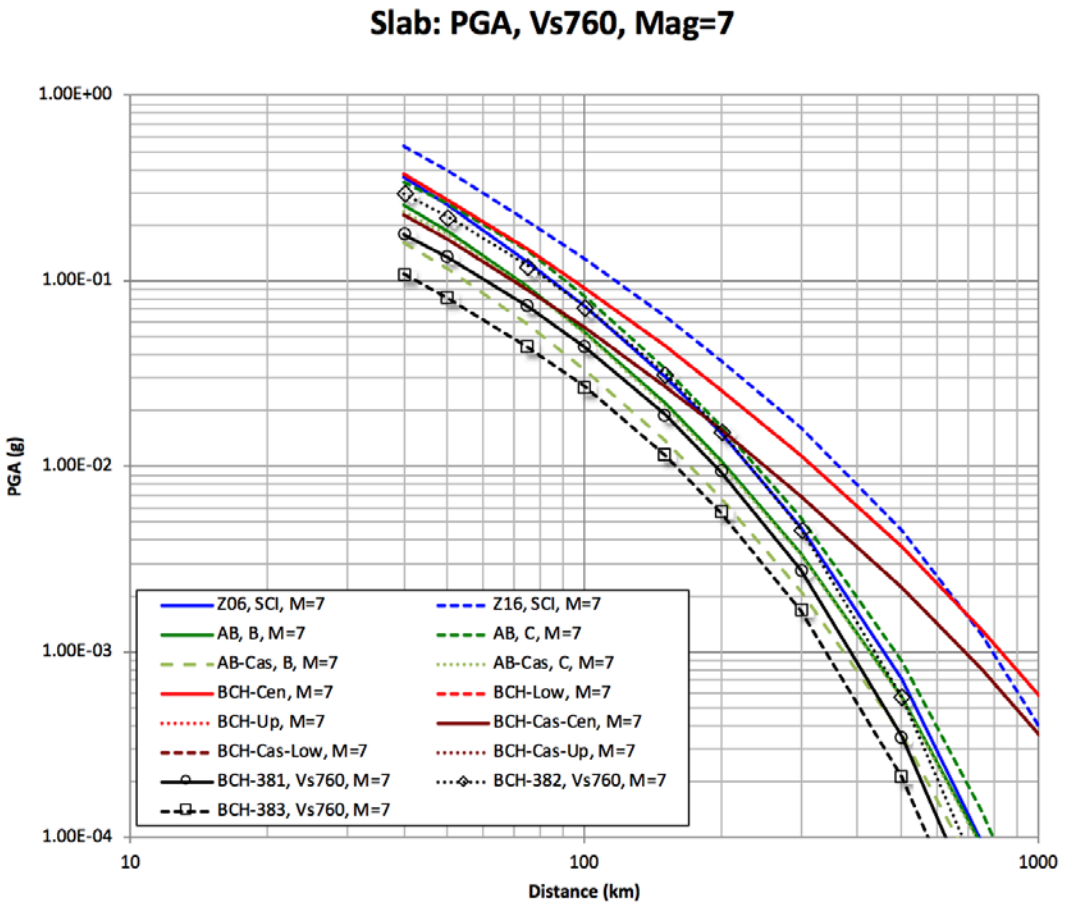

Figure 4.13(a) Median attenuation comparison for intraslab events, PGA, for M7, V_{S30} = 760 m/sec.

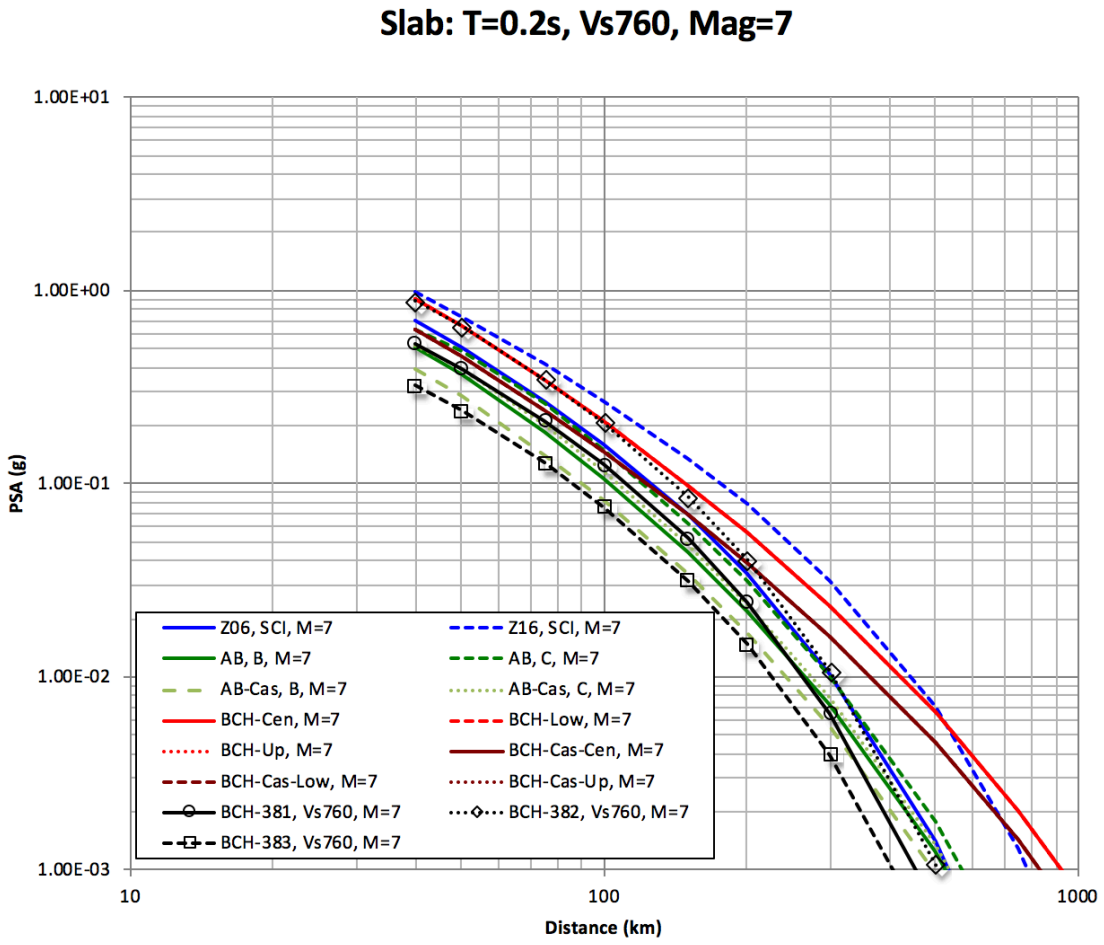

Figure 4.13(b) Median attenuation comparison for intraslab events, T = 0.2, for M7, V_{S30} = 760 m/sec.

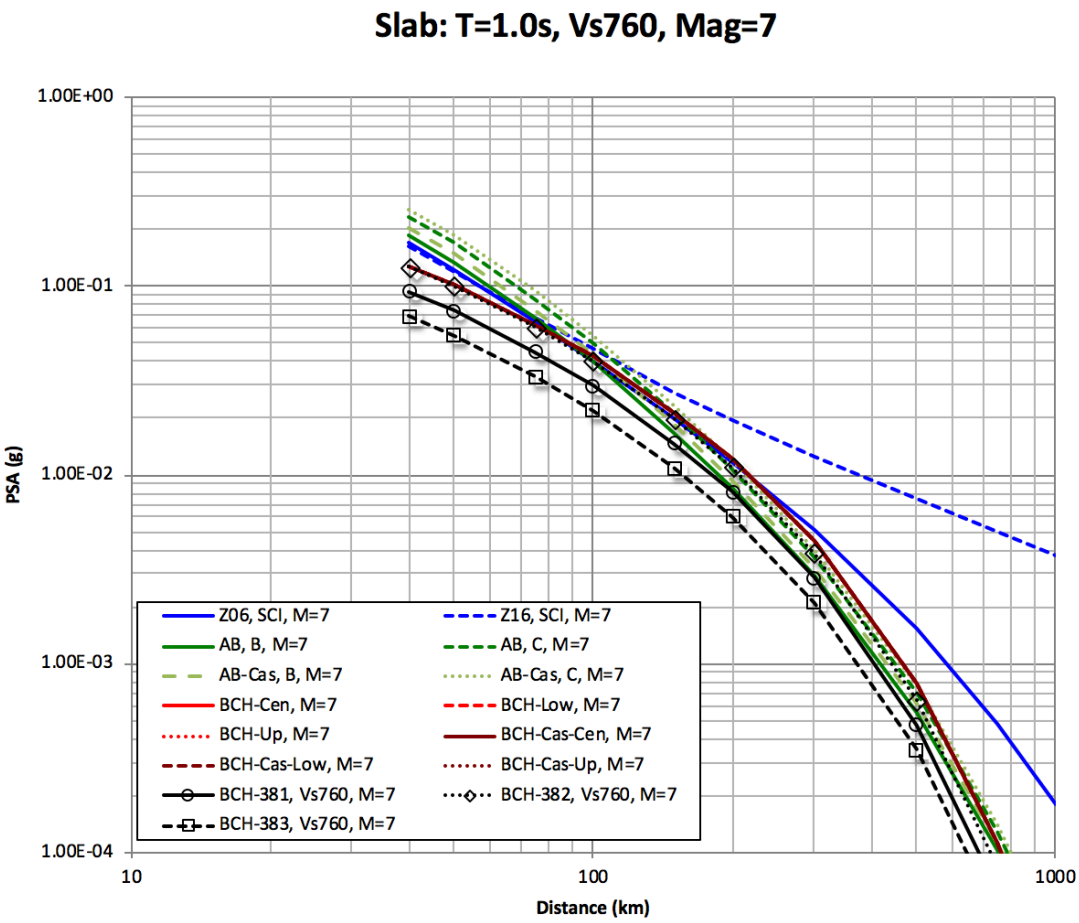

Figure 4.13(c) Median attenuation comparison for intraslab events, T = 1, for M7, V_{S30} = 760 m/sec.

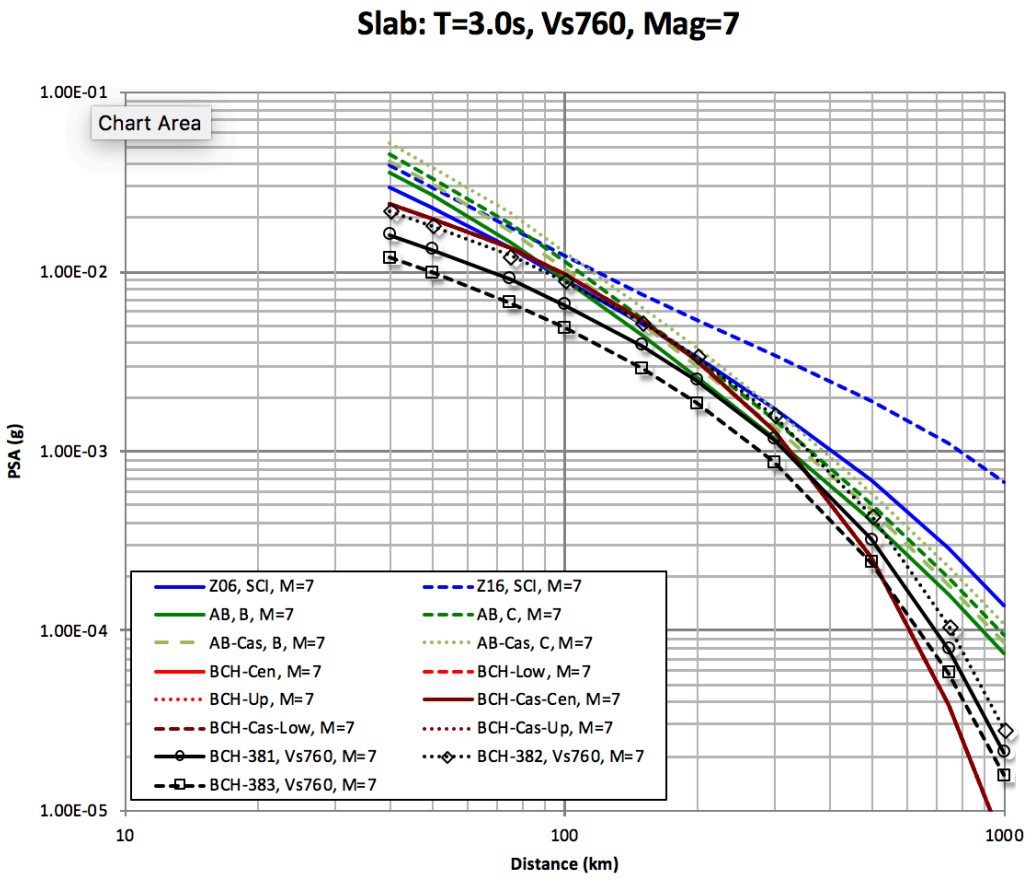

Figure 4.13(d) Median attenuation comparison for intraslab events, T = 3, for M7, V_{S30} = 760 m/sec.

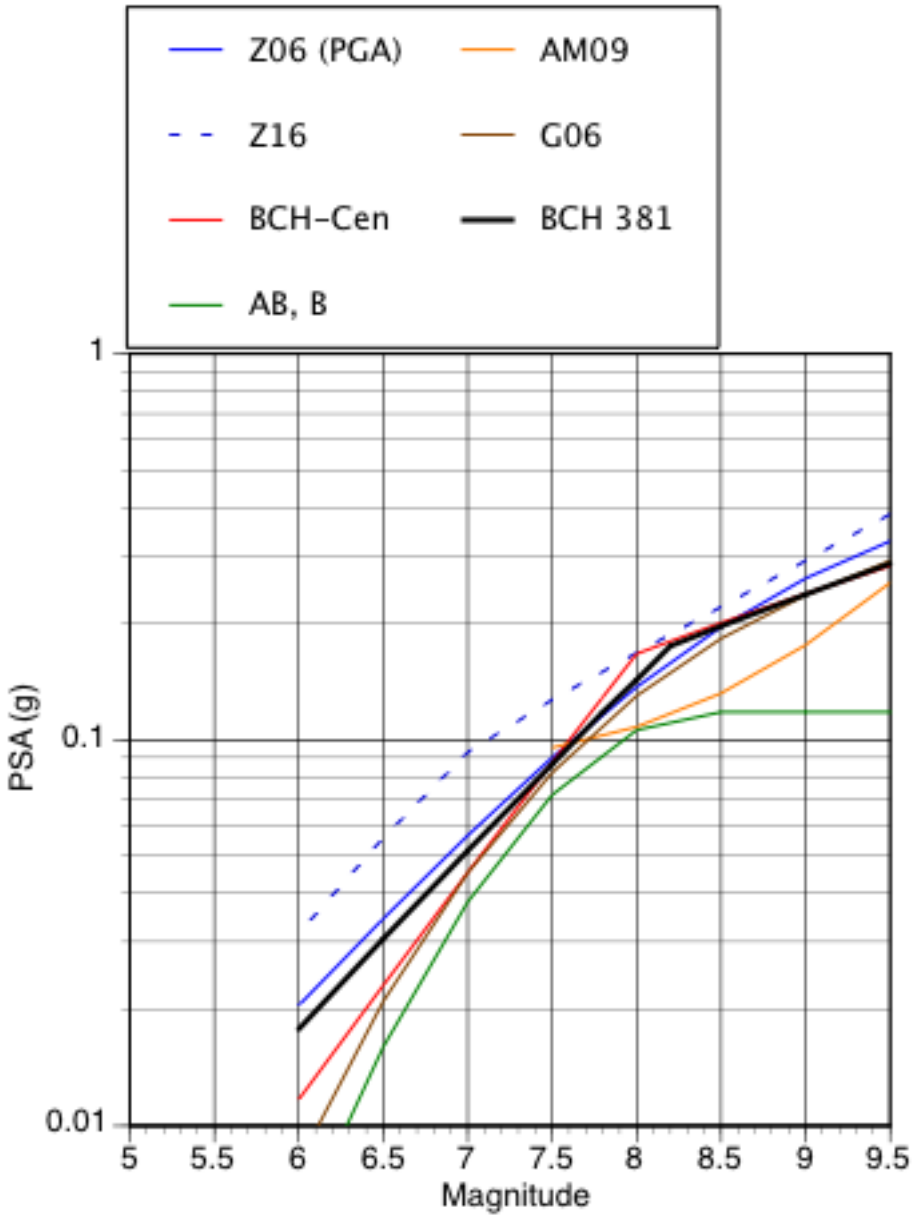

Figure 4.14(a) Magnitude scaling for PGA for interface earthquakes. (R_{rup}=75 km, V_{S30}=760 m/s)

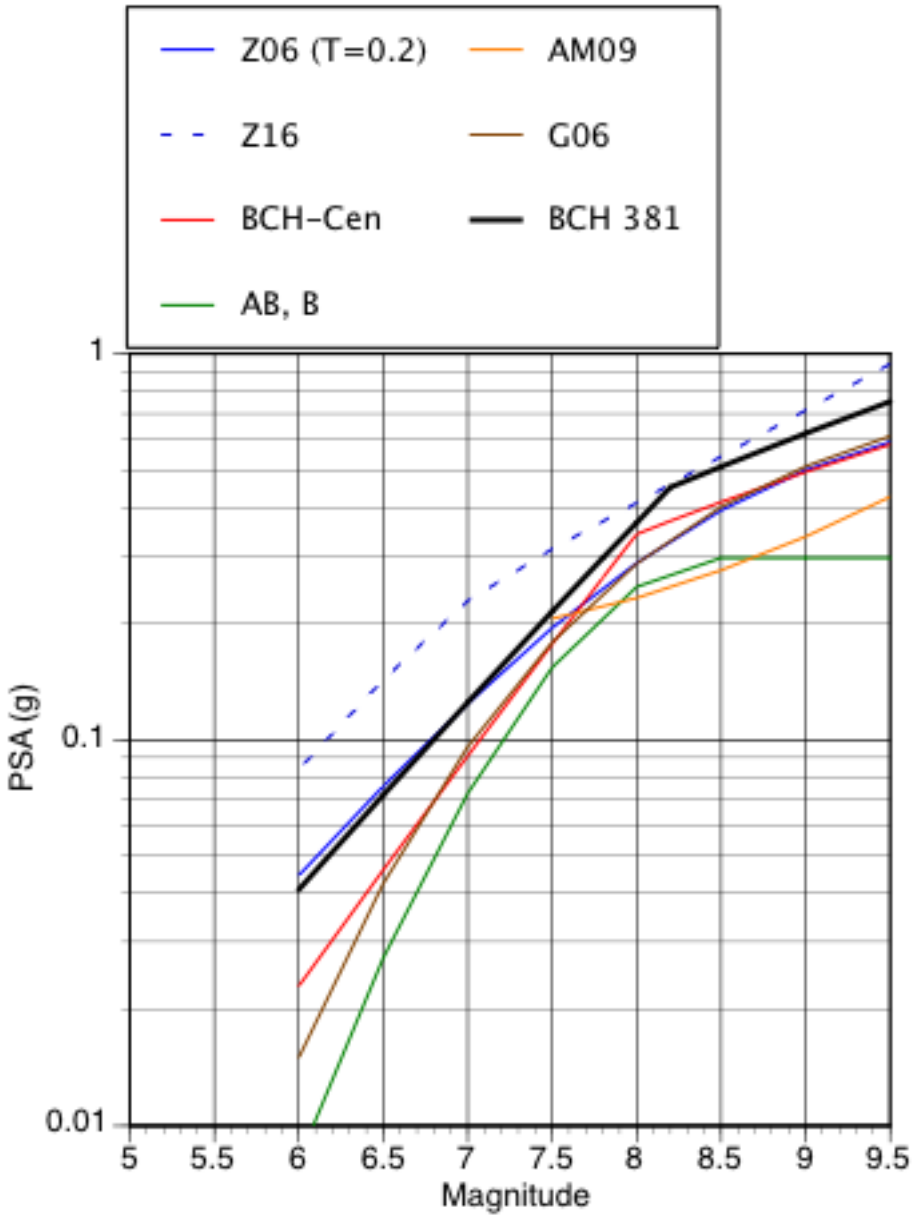

Figure 4.14(b) Magnitude scaling for T=0.2 sec for interface earthquakes. (R_{rup}=75 km, V_{S30}=760 m/s)

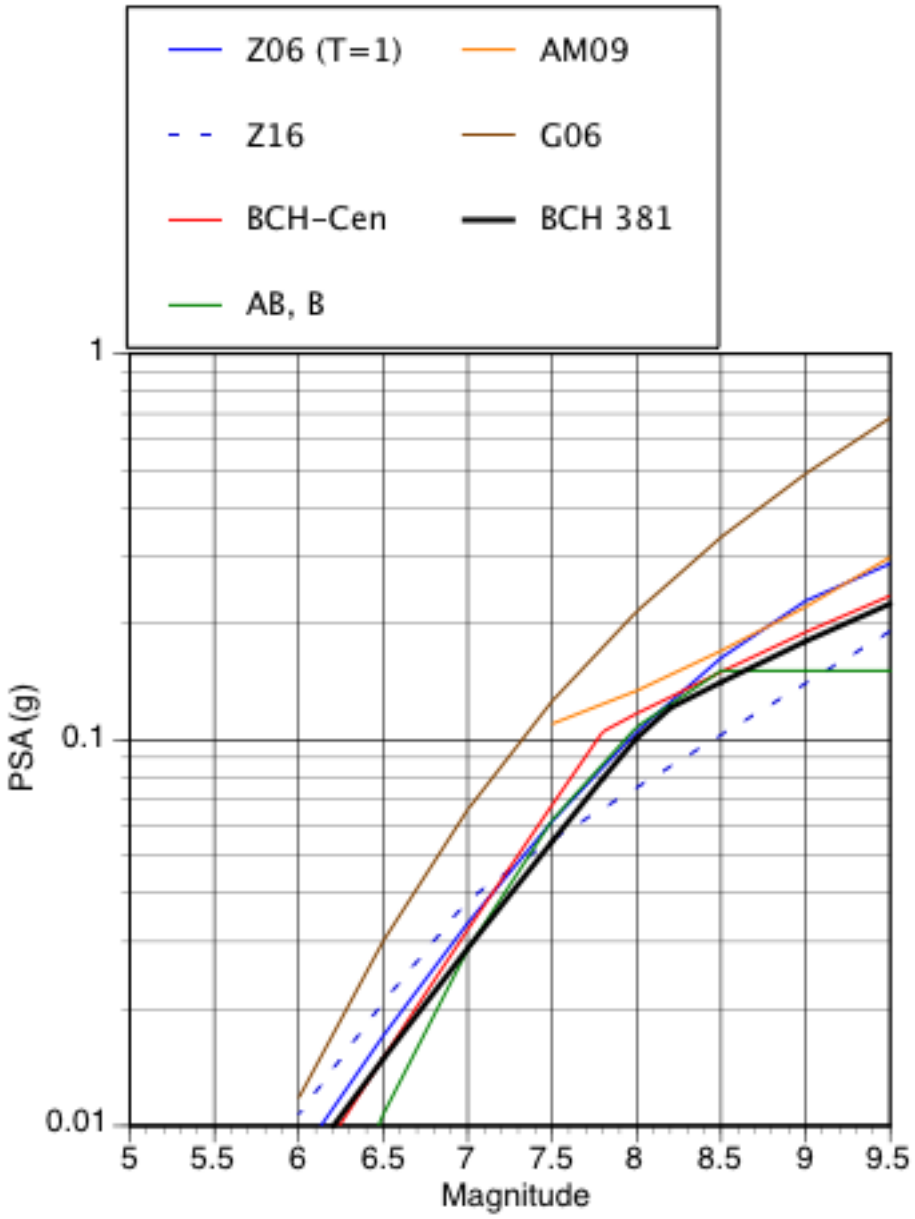

Figure 4.14(c) Magnitude scaling for T=1 sec for interface earthquakes. (R_{rup}=75 km, V_{S30}=760 m/s)

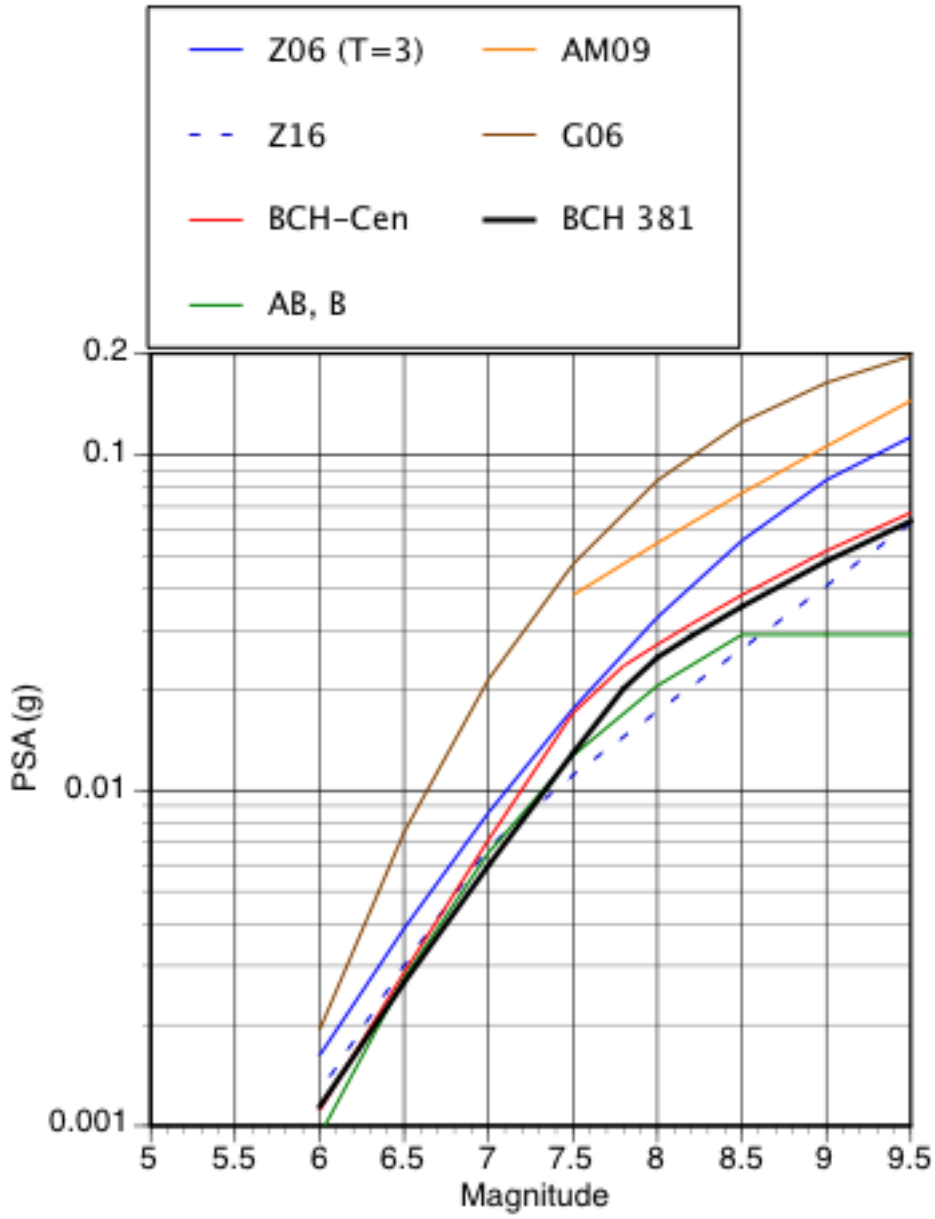

Figure 4.14(d) Magnitude scaling for T=3 sec for interface earthquakes. (R_{rup}=75 km, V_{S30}=760 m/s)

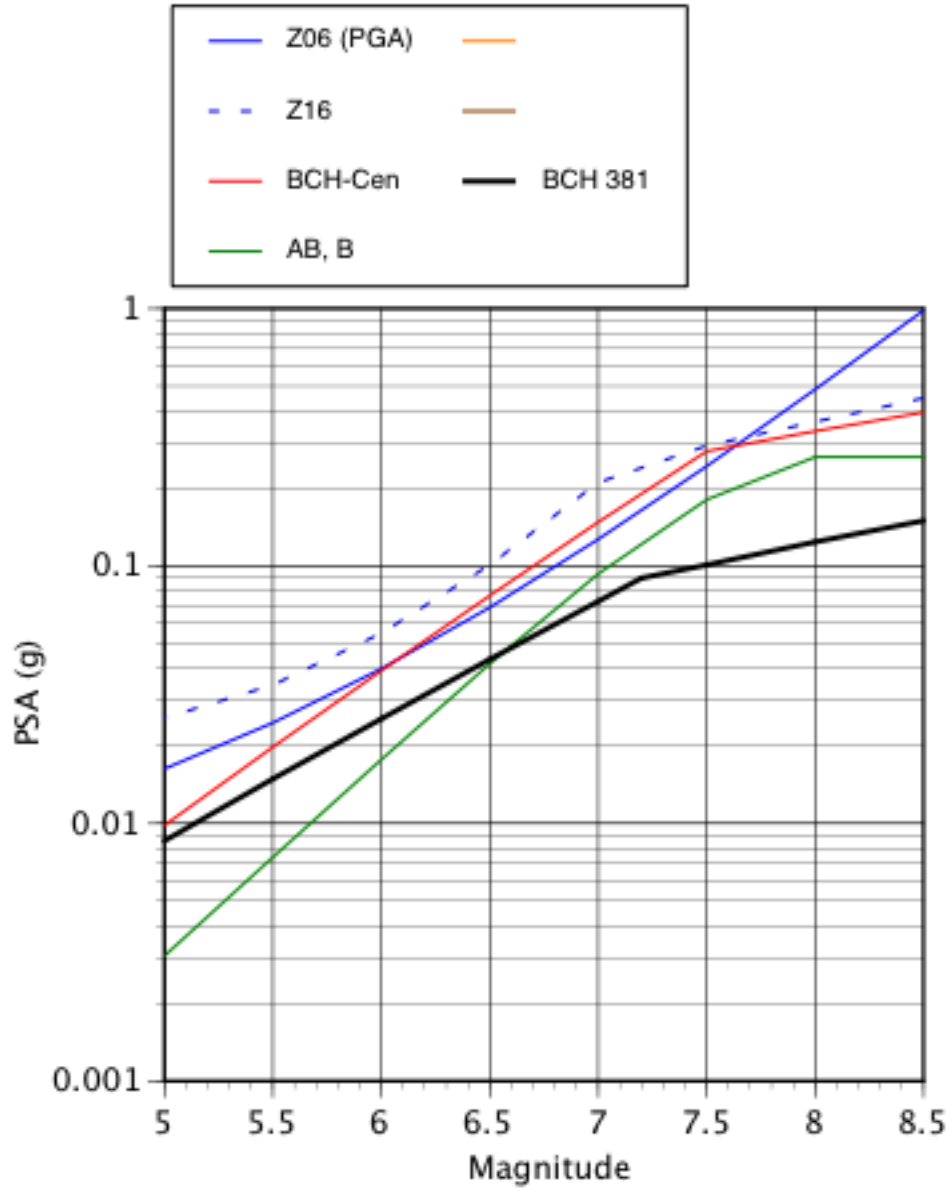

Figure 4.15(a) Magnitude scaling for PGA for intraslab earthquakes. (R_{rup}=75 km, V_{S30}=760 m/s, Z_{TOR}=50 km)

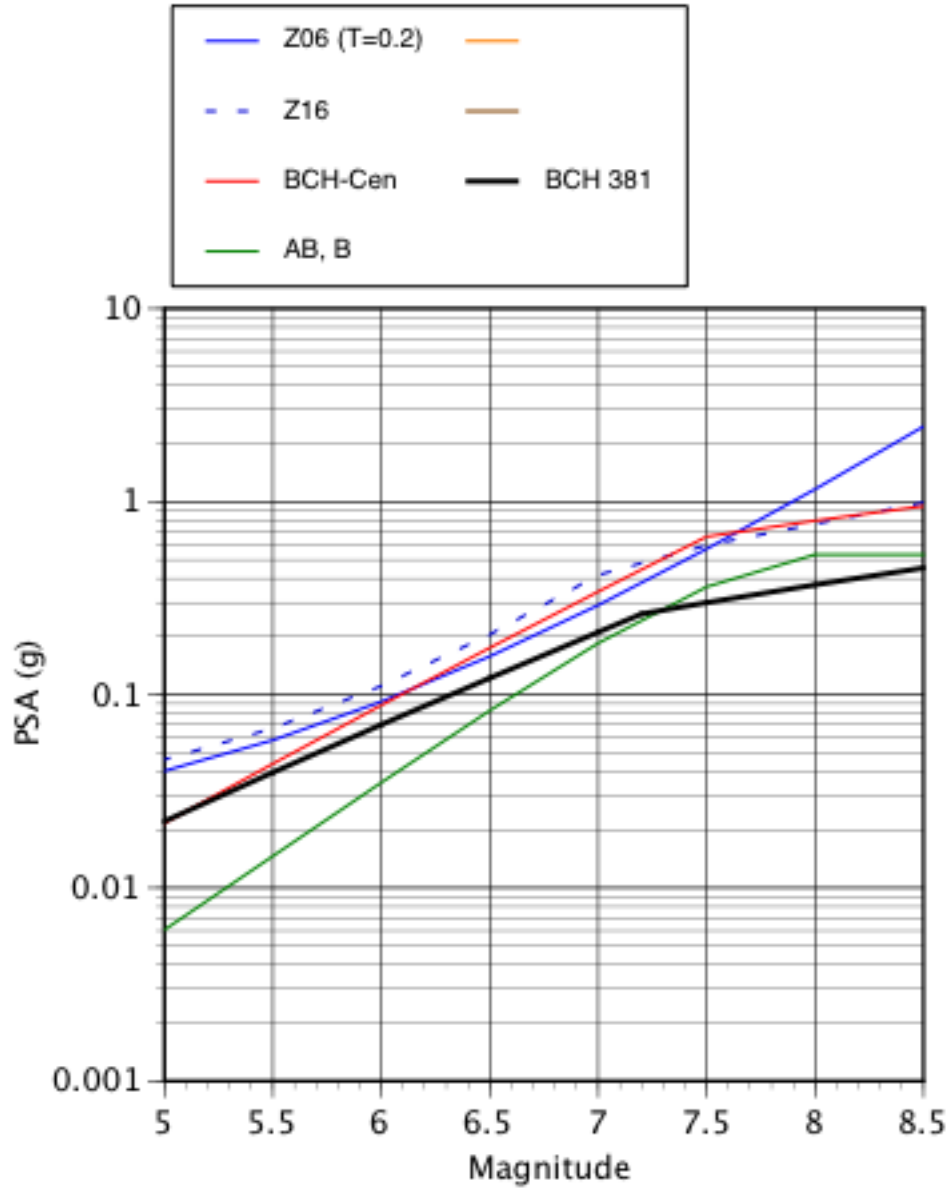

Figure 4.15(b) Magnitude scaling for T=0.2 sec for intraslab earthquakes. (R_{rup}=75 km, V_{S30}=760 m/s, Z_{TOR}=50 km)

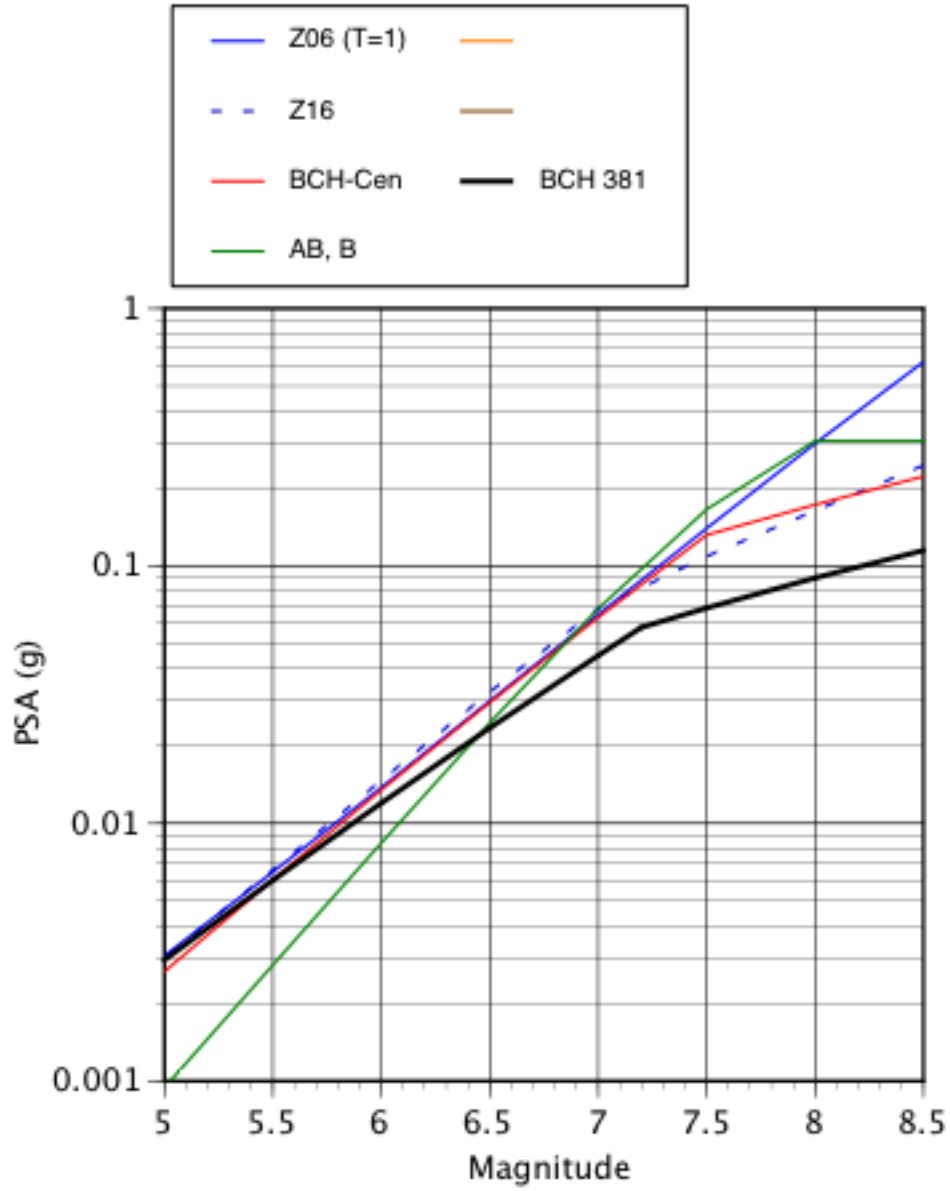

Figure 4.15(c) Magnitude scaling for T=1 sec for intraslab earthquakes. (R_{rup}=75 km, V_{S30}=760 m/s, Z_{TOR}=50 km)

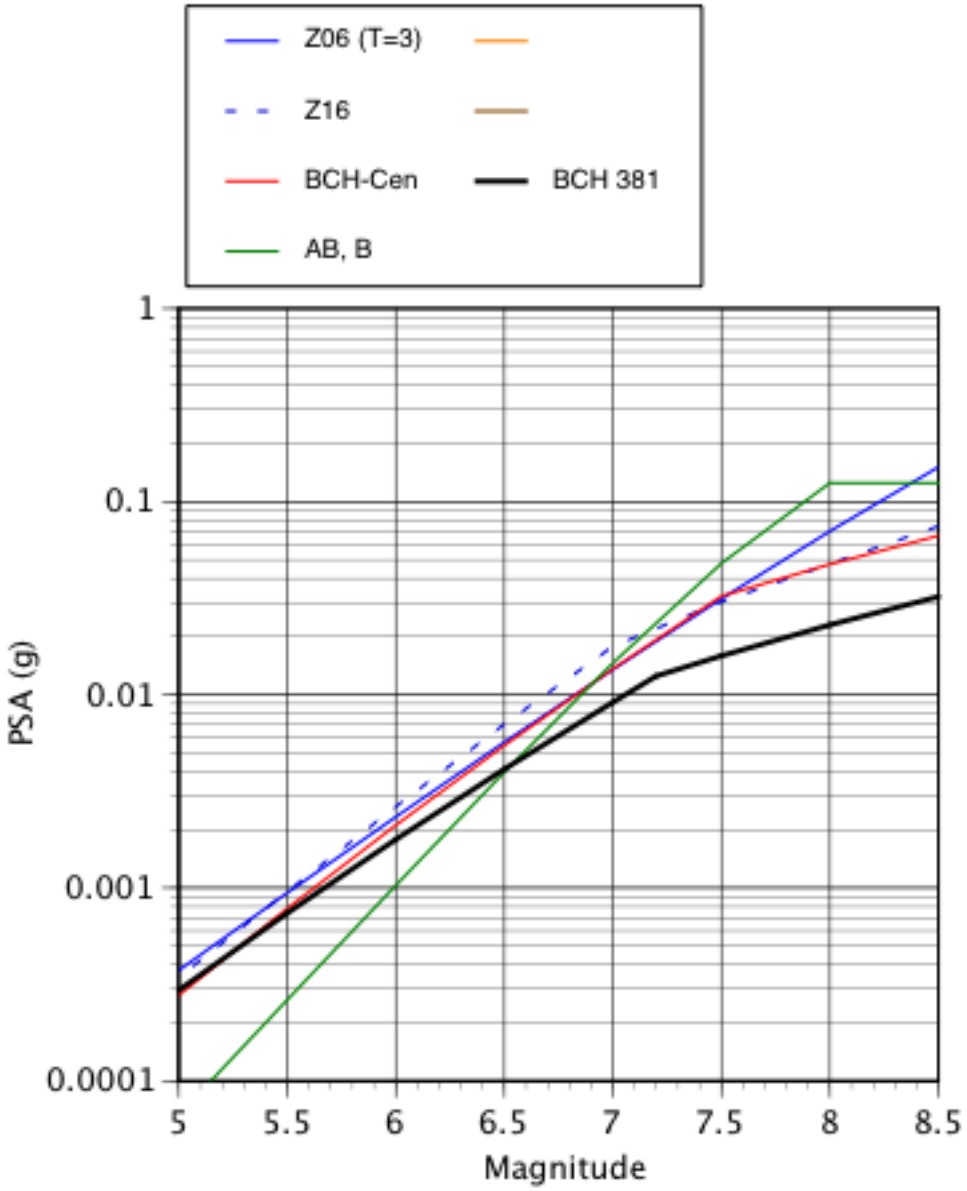

Figure 4.15(d) Magnitude scaling for T=3 sec for intraslab earthquakes. (R_{rup}=75 km, V_{S30}=760 m/s, Z_{TOR}=50 km)

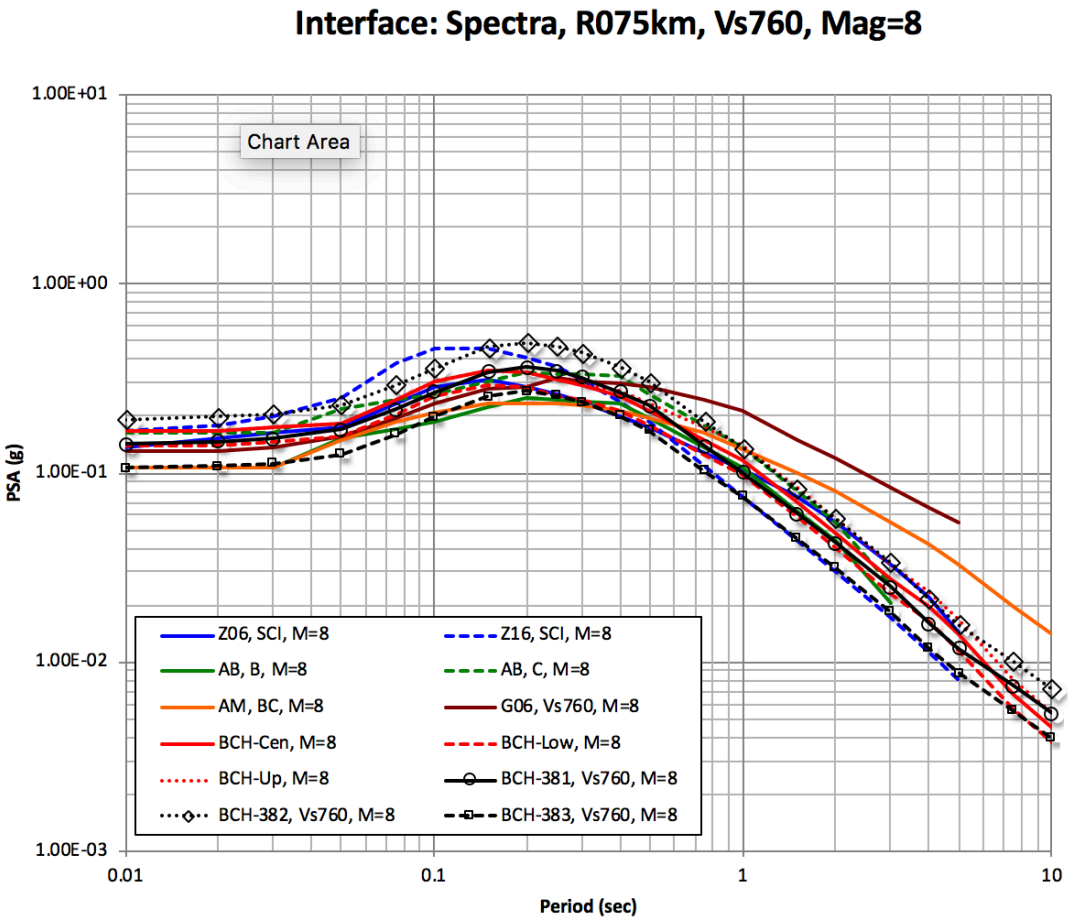

Figure 4.16 **Median spectrum comparison for interface events, R_{rup} = 75 km, for M8, V_{S30} = 760 m/sec.**

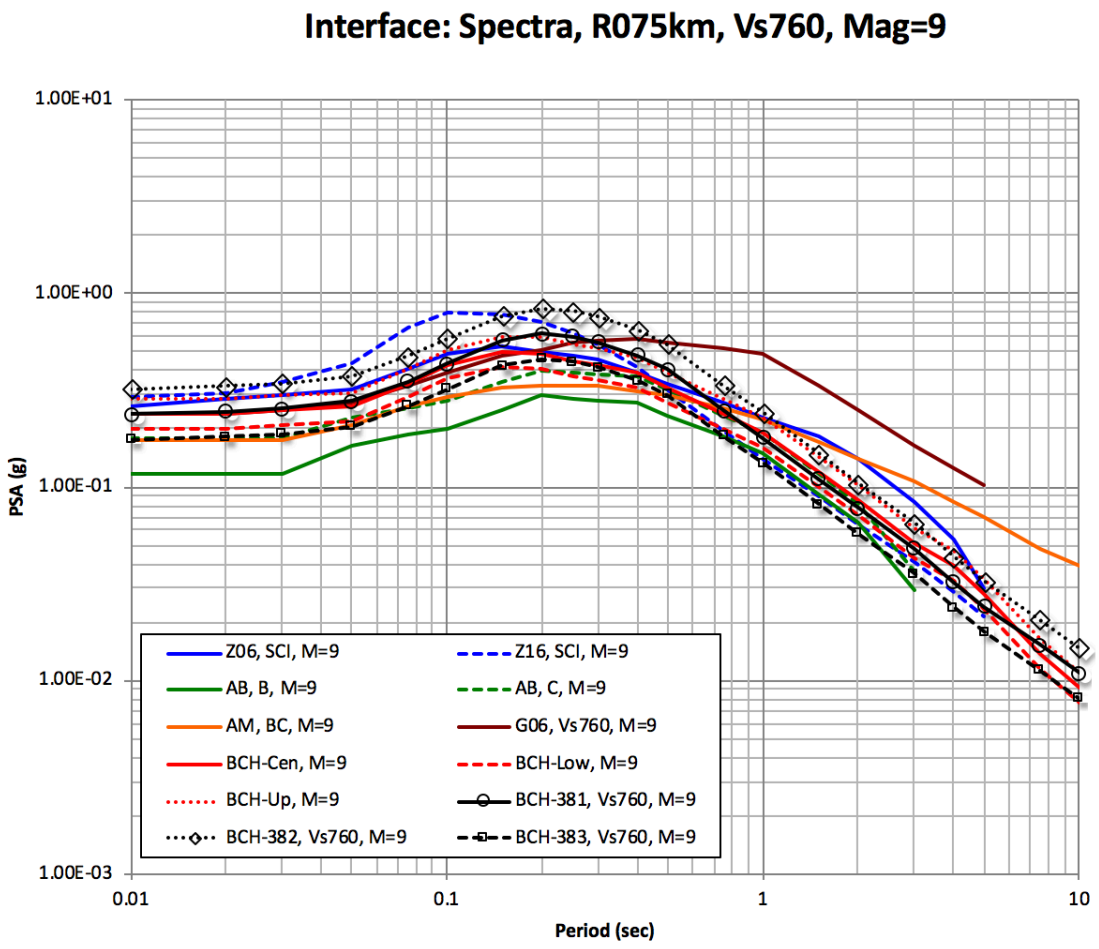

Figure 4.17 **Median spectrum comparison for interface events, R_{rup} = 75 km, for M9, V_{S30} = 760 m/sec.**

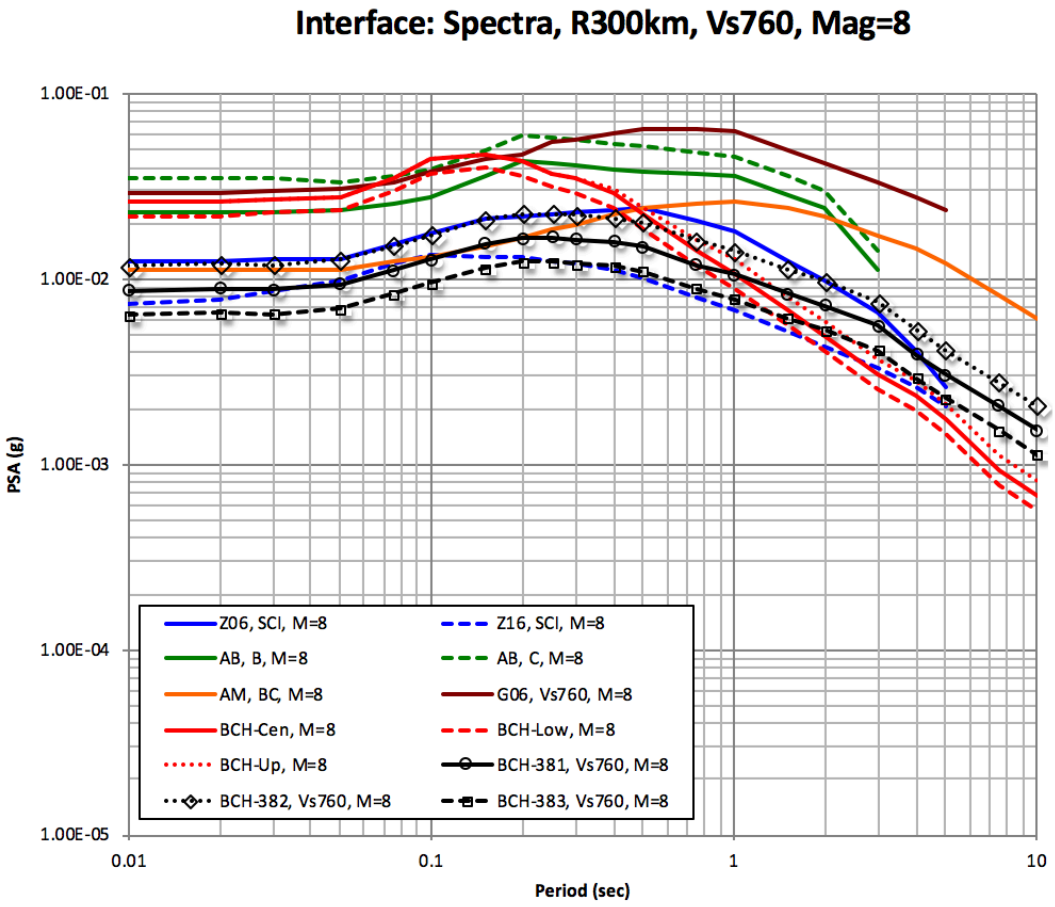

Figure 4.18 **Median spectrum comparison for interface events, R_{rup}= 300 km, for M8, V_{S30} = 760 m/sec.**

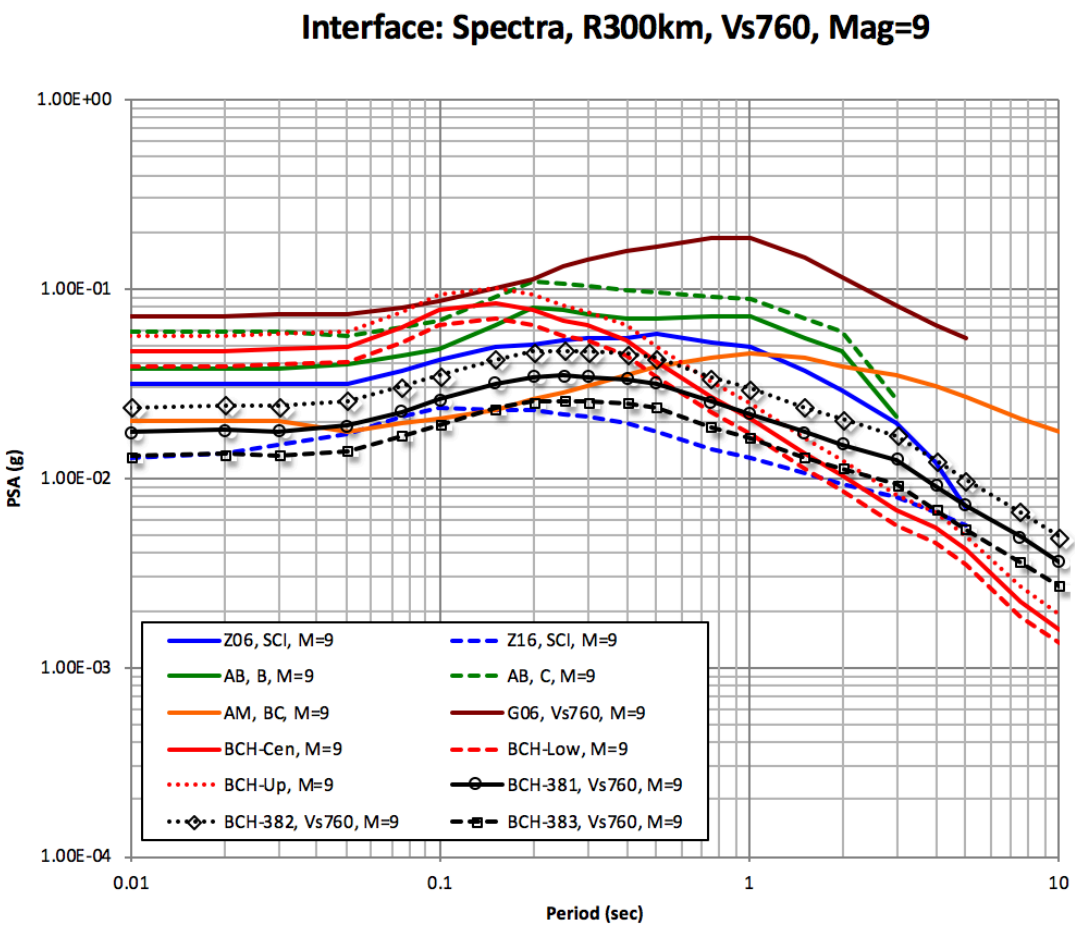

Figure 4.19 **Median spectrum comparison for interface events, R_{rup} = 300 km, for M9, V_{S30} = 760 m/sec.**

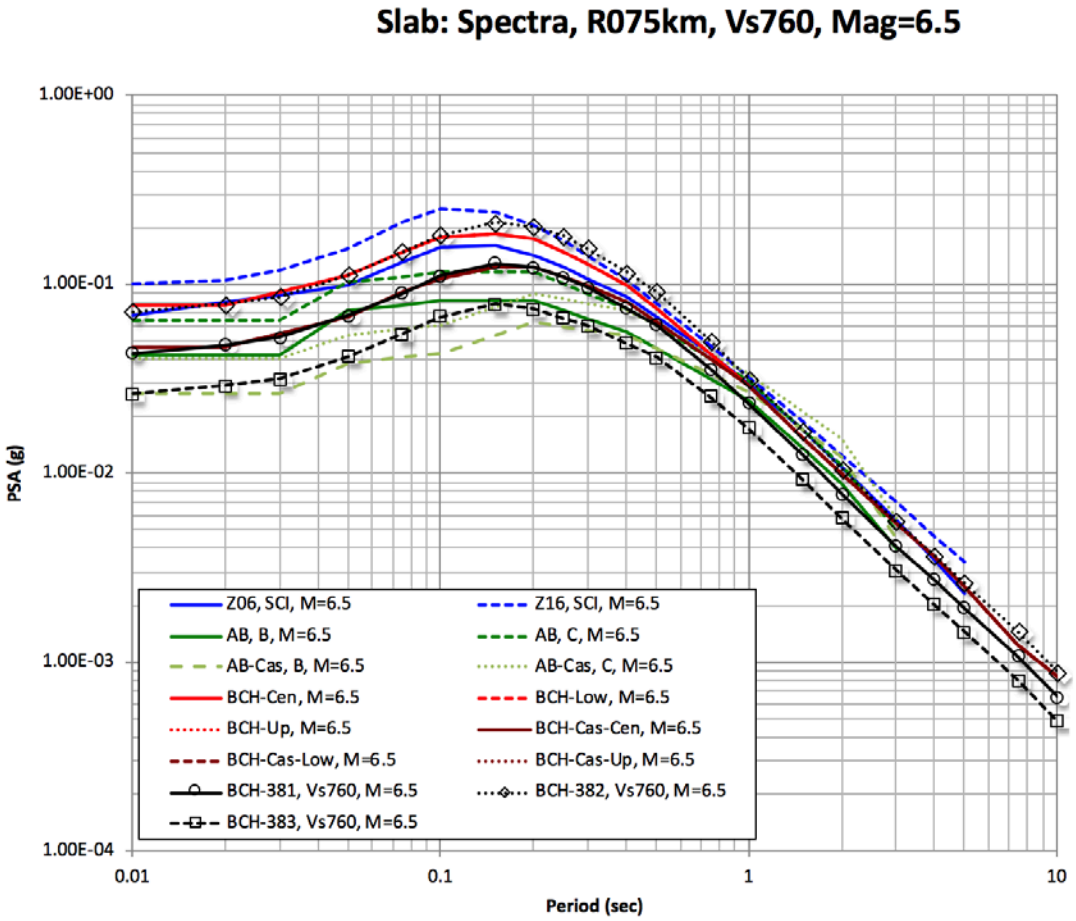

Figure 4.20 **Median spectrum comparison for intraslab events, R_{rup}=75 km, for M6.5, V_{S30} = 760 m/sec.**

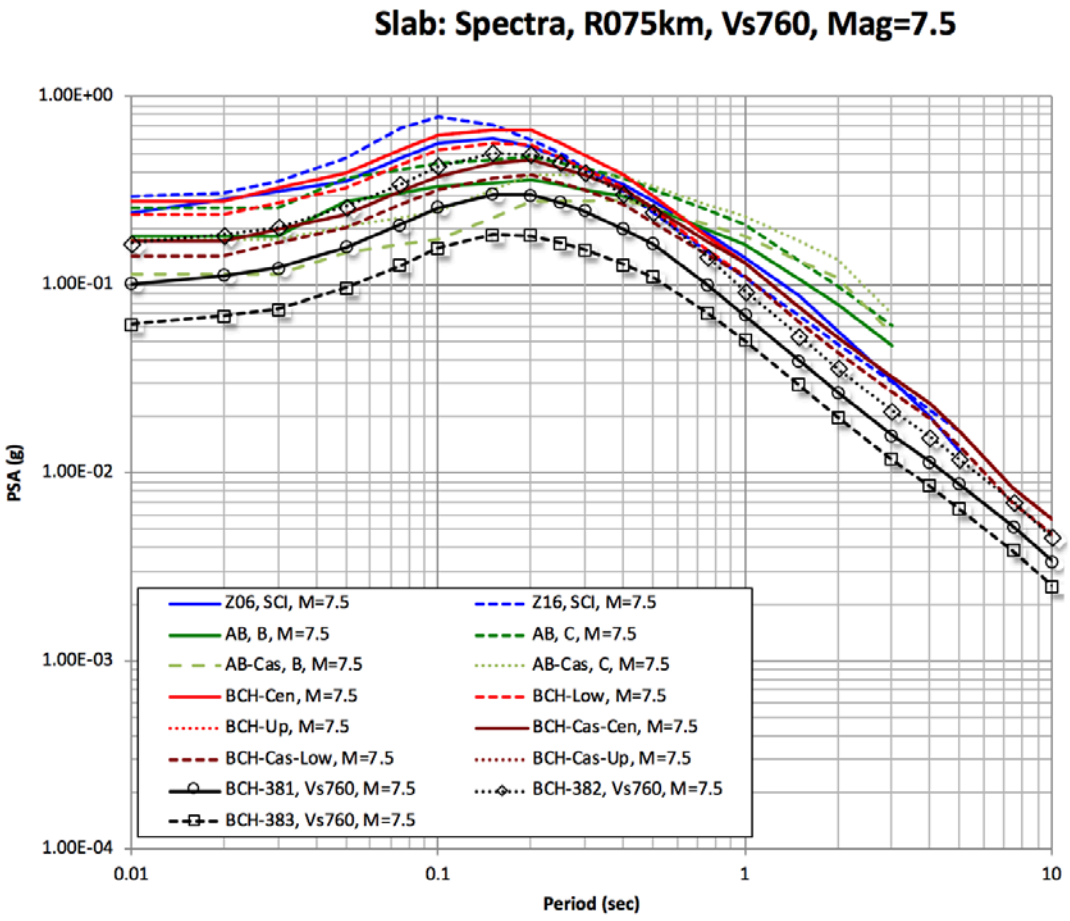

Figure 4.21 **Median spectrum comparison for intraslab events, R_{rup} = 75 km, for M7.5, V_{S30} = 760 m/sec.**

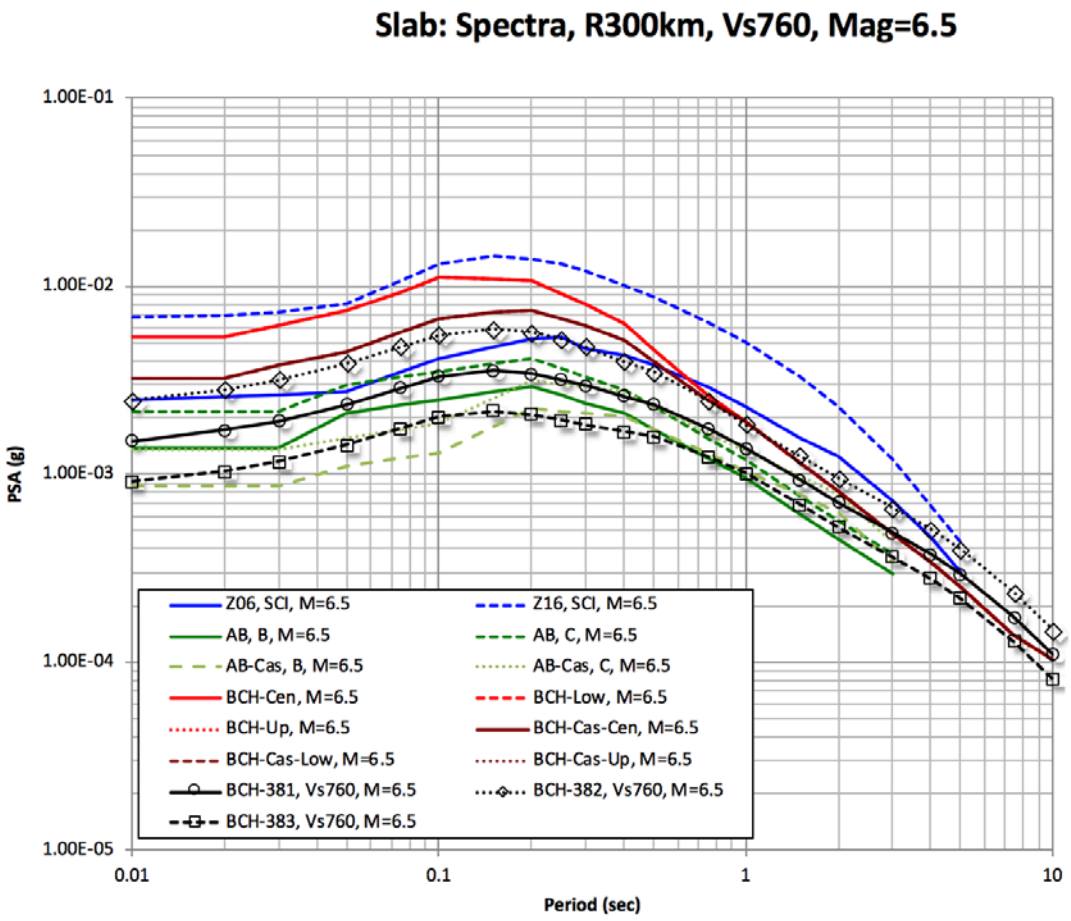

Figure 4.22 **Median spectrum comparison for intraslab events, R_{rup} = 300 km, for M6.5, V_{S30} = 760 m/sec.**

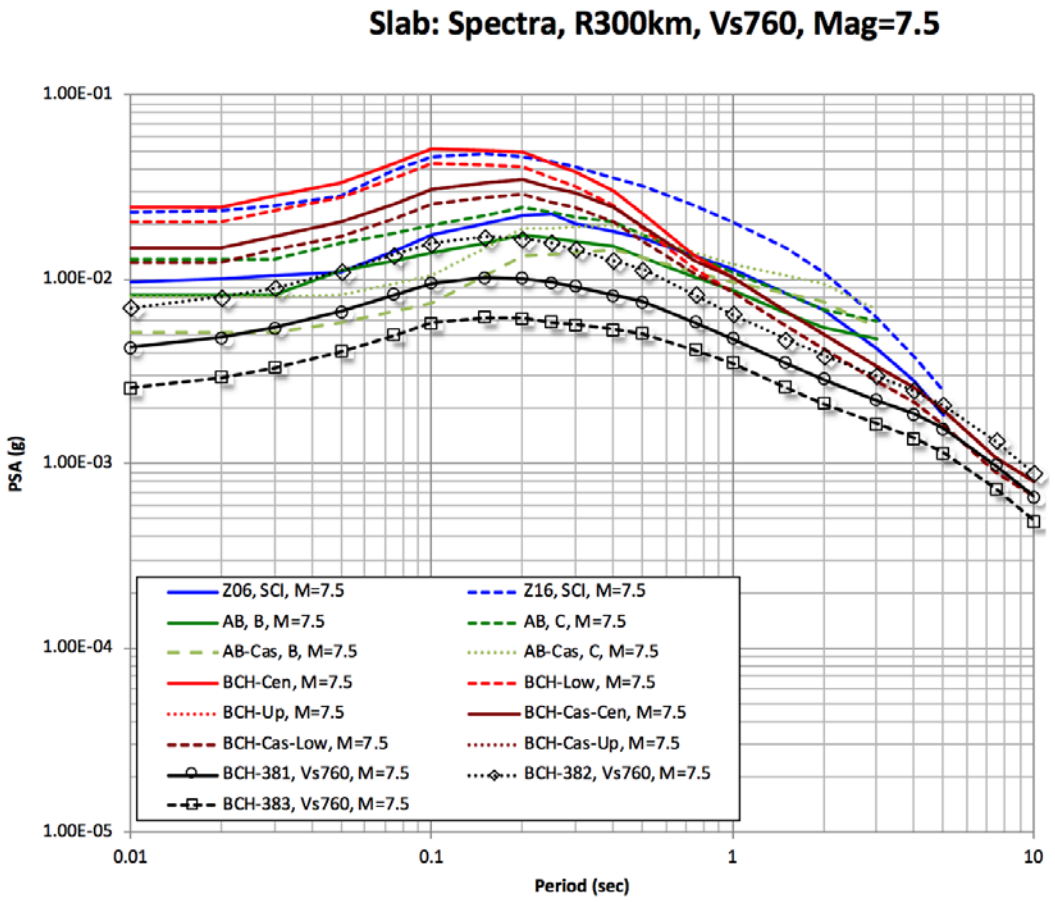

Figure 4.23 Median spectrum comparison for intraslab events, R_{rup} = 300 km, for M7.5, V_{S30} = 760 m/sec.

4.5 STANDARD DEVIATION

The standard deviation of the within-event residuals (phi) and the between-event residuals (tau) from the regression is shown in Figure 4.24. A check of the magnitude dependence of the phi and tau did not show a need for a magnitude-dependent model. A simple model with a period-independent and magnitude-independent phi is used. To avoid unusual shapes in the spectrum at different epsilon levels, the phi and tau are smoothed, as shown in Figure 4.24. The smoothed aleatory terms are listed in Table 4.5.

The nonlinear site response term is set to the PGA_{1000}-based model using in the 2016 BCHydro GMM which was based on the nonlinear site model in Abrahamson and Silva (2008). The effect of the nonlinear site response on the phi and tau is modelled using the approach in Abrahamson and Silva (2008). The nonlinear phi and tau are given below:

$$\varphi\left(T, P\hat{G}A_{1000}, V_{S30}\right) = \varphi_0^2(T) + \left(\frac{\partial ln\left(Amp\left(T, P\hat{G}A_{1000}, V_{S30}\right)\right)}{\partial\left(lnPGA_{1000}\right)}\right)^2 \varphi_B^2(T) + 2\left(\frac{\partial ln\left(Amp\left(T, P\hat{G}A_{1000}, V_{S30}\right)\right)}{\partial\left(lnPGA_{1000}\right)}\right)\varphi_B(T)\varphi_B(PGA)\rho_w(T, PGA)$$

and

$$\tau\left(T, P\hat{G}A_{1000}, V_{S30}\right) = \tau_0^2(T) + \left(\frac{\partial ln\left(Amp\left(T, P\hat{G}A_{1000}, V_{S30}\right)\right)}{\partial\left(lnP\hat{G}A_{1000}\right)}\right)^2 \tau_0^2(T) + 2\left(\frac{\partial ln\left(Amp\left(T, P\hat{G}A_{1000}, V_{S30}\right)\right)}{\partial\left(lnP\hat{G}A_{1000}\right)}\right)\tau_0(T)\tau_0(PGA)\rho_B(T, PGA)$$

where

$$\frac{\partial ln\left(Amp\left(T, P\hat{G}A_{1000}, V_{S30}\right)\right)}{\partial\left(lnP\hat{G}A_{1000}\right)} = \begin{cases} 0 & for\ V_{S30} \geq V_{LIN} \\ \dfrac{-b(T)P\hat{G}A_{1000}}{P\hat{G}A_{1000} + c} + \dfrac{b(T)P\hat{G}A_{1000}}{P\hat{G}A_{1000} + c\left(\frac{V_{S30}}{V_{LIN}}\right)^n} & for\ V_{S30} < V_{LIN} \end{cases}$$

and

$$\varphi_B(T) = \sqrt{\varphi_0^2(T) - \varphi_{amp}^2(T)}$$

Following Abrahamson and Silva (2008), a value of $\varphi_{amp}(T) = 0.3$ natural log units is assumed for all periods. The phi and tau values listed in Table 4.5 are the $\varphi_0(T)$ and $\tau_0(T)$ in the equations for the nonlinear site effects on phi and tau given above.

Table 4.5 Aleatory variability terms (in LN units)

Period (sec)	phi	tau
0.01	0.62	0.58
0.02	0.62	0.58
0.03	0.62	0.58
0.05	0.62	0.58
0.075	0.62	0.58
0.1	0.62	0.58
0.15	0.62	0.56
0.2	0.62	0.54
0.25	0.62	0.52
0.3	0.62	0.505
0.4	0.62	0.48
0.5	0.62	0.46
0.6	0.62	0.45
0.75	0.62	0.45
1.0	0.62	0.45
1.5	0.62	0.45
2.0	0.62	0.45
2.5	0.62	0.45
3.0	0.62	0.45
4.0	0.62	0.45
5.0	0.62	0.45
6.0	0.62	0.45
7.5	0.62	0.45
10.0	0.62	0.45

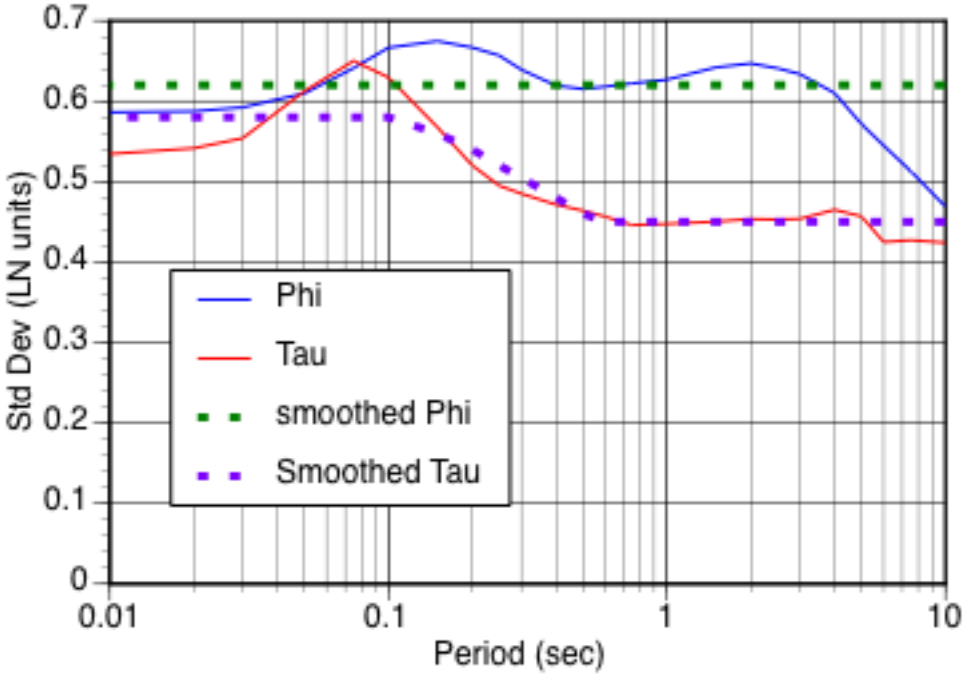

Figure 4.24 Smoothed phi and tau models.

5 Conclusions and Future Work

The updated BCHydro model is based on the expanded and improved NGA-SUB dataset and it includes the first order regional differences in the ground-motion scaling in terms of the V_{S30} scaling, linear R scaling, and a constant term. Due to these two changes, the model represents in an improvement over the 2016 BCHydro GMM. The Updated BCHydro GMM is intended for application to the Cascadia region as part of the 2020 update to the national uniform-hazard maps. The ongoing NGA-SUB project will develop a suite of subduction GMMs that can be applied to other regions. These NGA-SUB GMMs will supersede this BCHydro updated GMM.

In developing this update of the BCHydro ground-motion model for subduction earthquakes, several technical issues were identified that were not resolved and should be addressed as part of the completion of the NGA-SUB project. These issues are listed below.

- On average, the short-period ground motion for the Cascadia earthquakes is much lower than for other regions. In this update, without a clear physical basis for this large reduction, the Cascadia GMM was increased to the global average. There is a need to determine the cause of the lower short-period ground motions in Cascadia.
- Basin effects were not included in the updated BCHydro model. Basin terms from empirical data are correlated with the VS30 scaling in the ground-motion model. The similarity or difference between basin scaling for different regions needs to be evaluated, then basin terms can be developed for Cascadia using either Cascadia data or global data for the basin scaling.
- The updated BCHydro model does not distinguish between forearc and backarc scaling. This is appropriate for Cascadia which did not show a significant difference in the attenuation rates for forearc and backarc stations, but in other regions of the world, this can be a large effect. The approach to modeling this effect in terms of the lengths of ray paths through forearc and backarc regions needs to be addressed.
- The magnitude scaling below the magnitude break point was modeled using the same scaling for interface and intraslab earthquakes. The event terms show that for the **M**5 to **M**6 range, the magnitude scaling for intraslab events is stronger than for interface events. The basis for using either the same magnitude scaling or different magnitude scaling for small magnitude interface and intraslab events should be revisited.

- The large magnitude scaling (above the break point) in the updated BCHydro model is based on finite-fault simulations for large interface earthquakes. This large scaling from the interface simulations was assumed to apply to the intraslab earthquakes as well. The new finite-fault simulations developed for intraslab earthquakes should be evaluated to determine if the large magnitude scaling from interface earthquakes is applicable to intraslab earthquakes.
- Site terms and single-station sigma was not evaluated in the updated BCHydro model. Because the locations of the subduction earthquakes often cover a limited azimuth range, the site terms may be strongly correlated with path terms. An evaluation of the trade-off between site and path terms is needed before developing single-station sigma models.
- The intraslab thickness was used to set the magnitude break for the intraslab scaling. Another approach would be to use the intraslab thickness to scale the difference between intraslab and interface events (the a_{10} term). The best use of the intraslab thickness to constrain the scaling of the intraslab ground motion needs further evaluation.
- Local site response depends on the level of shaking and the frequency content of the input rock motion as well as on the local site characteristics. The nonlinear site response scaling used for the updated BCH GMM was based on frequency content of rock motions generated by crustal events in active regions. The nonlinear site response scaling needs to be reevaluated using rock motions generated by subduction events.
- The analysis of ergodic site response for Cascadia in this study is preliminary and based on limited data. More complete analyses using additional data is needed to evaluate differences between VS30-scaling in Cascadia vs other regions of the United States. This will be considered in future ground motion analyses.

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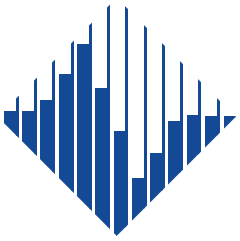

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