Final Technical Report

Analysis of "Did You Feel It?" Intensity Data to Determine Ground Motion Characteristics for the Central/Eastern United States

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Non-technical Summary

This study uses earthquake ground-motion information that is being collected by the "Did You Feel It?" (DYFI) online citizen response program initiated by the U.S. Geological Survey to determine ground motion characteristics for earthquakes in the Central and Eastern United States. The DYFI data offer the potential to resolve long-standing issues in earthquake ground motion science, due to their volume and widespread regional coverage. They are particularly powerful when calibrated against instrumental ground motion data. This calibration is done using California data, because in California there are both abundant DYFI data and abundant instrumental data. (By contrast, instrumental data in the CEUS are sparse.) In this study, the calibrated DYFI data from the CEUS are used to examine ground-motion prediction models. The study concludes that DYFI data generally support ground-motion prediction models used in engineering studies in the CEUS, and point to the importance of soil response in controlling the strength of ground-motion effects.

Introduction

Uncertainty in the ground motion amplitudes that will be caused by future large earthquakes in the central and eastern United States (CEUS) is the largest source of uncertainty in evaluating seismic hazards in the region, and a significant impediment to mitigating future earthquake losses. It is also an impediment to public and engineering acceptance of seismic hazard results that suggest large ground motions are appropriate for engineering design in areas of the Central United States that will be affected by the next New Madrid-type earthquakes. The main reason why uncertainties are so high is that large earthquakes in the CEUS are rare and the distribution of strong motion and seismographic stations is sparse, leading to relatively few instrumental records for moderate CEUS events and essentially no instrumental records for large events. Thus empirical data to develop or test strong ground motion relations are lacking. Furthermore, there is considerable controversy regarding source characteristics for large CEUS events, and whether or not large California events can be used as 'analogs' in understanding CEUS source processes and the resulting ground motions. For example, stress drop is typically assumed to be a factor of two higher for CEUS events than those in California based on the work of Atkinson (1993), and this assumption is often built in

to CEUS ground-motion relations (eg. Frankel et al., 1996; Campbell, 2003). The work of Atkinson and Wald (2007), which shows that intensities are higher in the CEUS than in California at near-source distances, for events of the same magnitude, would tend to support this view. However, existing uncertainties also allow the interpretation that the stress drop is about the same for the two regions (Beresnev and Atkinson, 2002), at least when we consider just the sparse instrumental data. This issue heightens our uncertainty in CEUS ground motion relations.

This study utilizes a vast new database of ground motions for the CEUS that are directly relevant to earthquake hazards, with potential that has not yet been tapped. These are the intensity data collected by the U.S.G.S. "Did You Feel It?" (DYFI) program. The DYFI program compiles thousands of citizen responses submitted over the internet shortly after an earthquake occurs to map in detail the felt effects of moderate to large earthquakes. This program has been remarkably successful, with nearly 1 million responses being collected within the last few years. Analyses of these data show that they are of surprisingly high quality, capable of distinguishing propagation and source effects, and of highlighting differences in source and propagation characteristics between the CEUS and California (Atkinson and Wald, 2007). These data are, practically by definition, directly applicable to seismic hazard estimation and mitigation. In this study, the comparative analysis of DYFI data for CEUS and California events, calibrated using instrumental ShakeMap data (and other seismological data) for both regions, is used to infer source and attenuation characteristics of damaging CEUS earthquakes relative to those in California. Specifically, intensity data are used to evaluate recent ground-motion prediction equations (GMPEs) for the CEUS, with a focus on the GMPEs proposed by Atkinson and Boore (2006).

Relationship of MMI to Instrumental Ground-Motion Parameters

A study by Atkinson and Kaka (2007) developed empirical relations between intensity (Modified Mercalli Intensity – MMI or Did You Feel It? Intensity) and instrumental ground motion parameters for both the CEUS and California. The instrumental measures considered were peak ground acceleration (PGA), velocity (PGV) and response spectral pseudo-acceleration (5% damped) at three frequencies: PSA1hz, PSA3.3hz and PSA0.5hz (all horizontal component). The data included ENA (eastern North American) broadband seismographic data from dozens of moderate events (M2 to 4.5) occurring in the central to eastern U.S. and Canada, plus California data from both moderate and some larger events. In that study, individual ground motion observations were assigned individual MMI values based on proximity. It was determined that ENA and California show the same relationship between MMI and ground motions, as can be seen in Figure 1 by comparing the red and blue symbols. It was also noted that older strong-motion datasets from California (brown symbols) appear to be biased in the relationship they suggest at low intensities, probably due to bias towards larger motions in compiling such datasets.

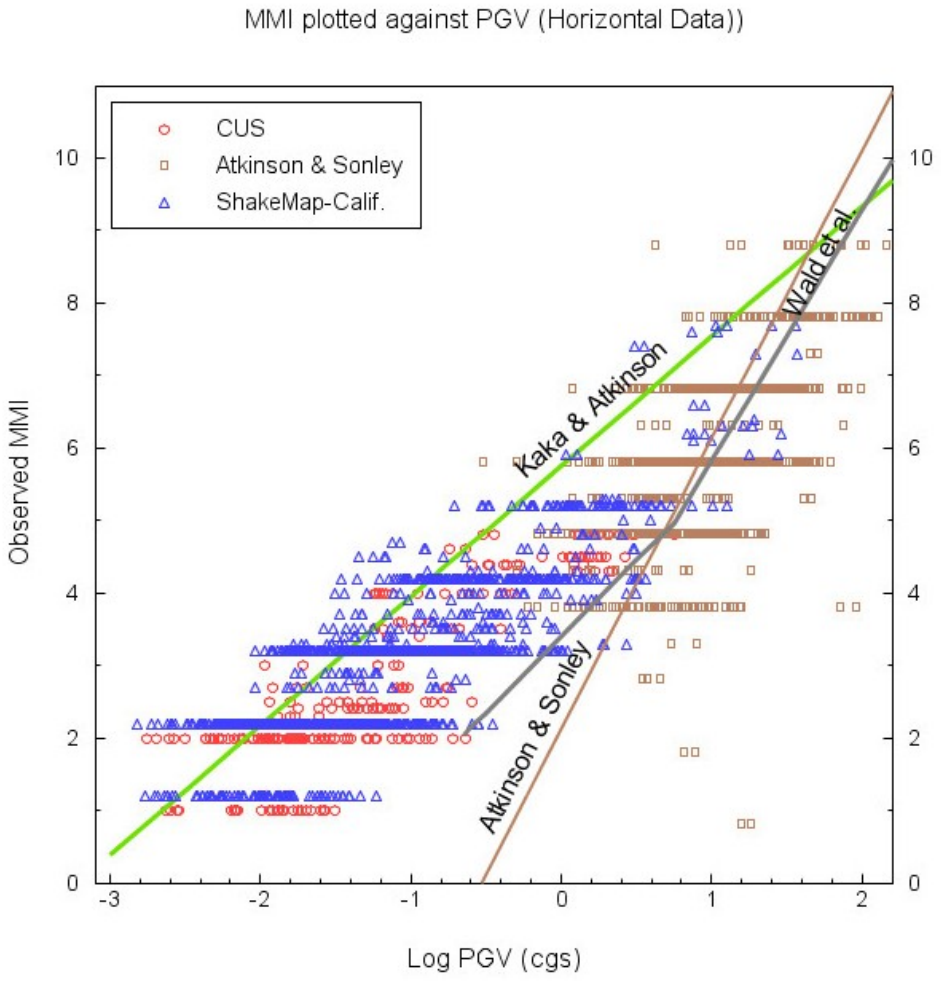

Figure 1 – Relationship between intensity (MMI) and PGV (in log cm/s units) for earthquakes in the CEUS (red circles), in California based on moderate events (blue triangles), and California based on legacy strong-motion data (brown squares). Older proposed empirical relationships between the parameters are also shown (Kaka and Atkinson, 2004; Atkinson and Sonley, 2000; Wald et al., 1999). Figure from Atkinson and Kaka (2007).

It was concluded that we can combine the data from both the east and west to develop a predictive relationship for MMI from ground motion, or vice versa. An example is shown in Figure 2, for the relationship between intensity and response spectra at 3.3 Hz.

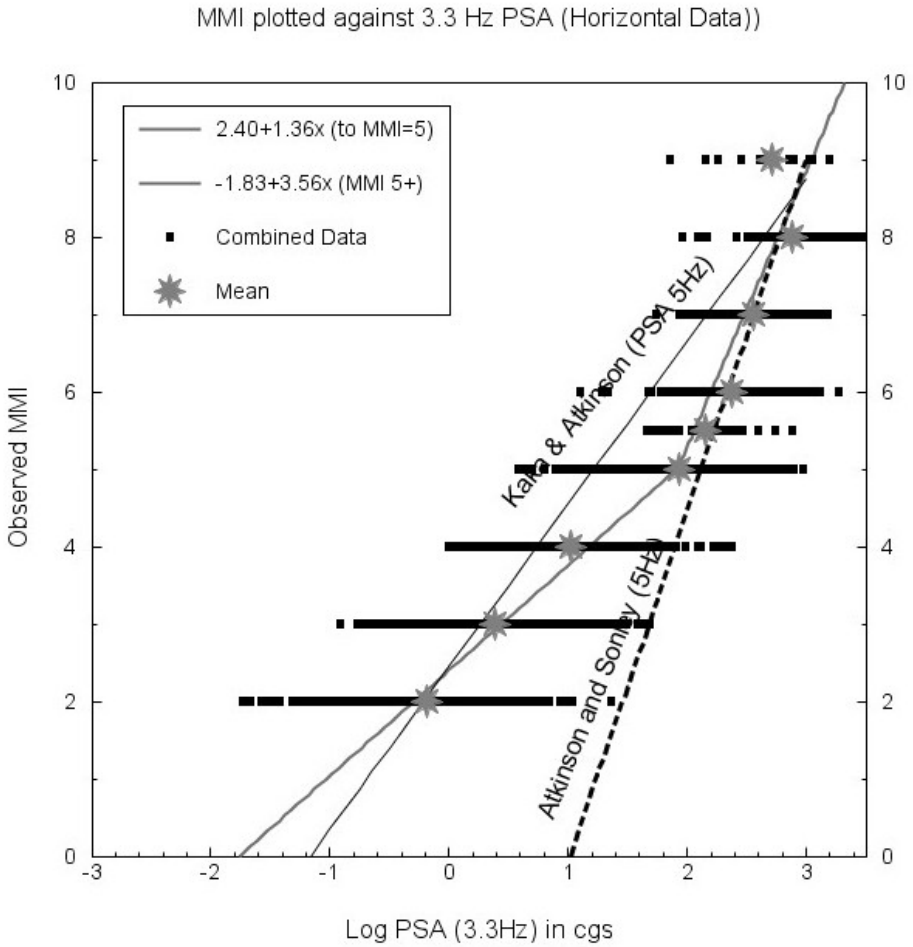

Figure 2 – Observed relationship between mean MMI and PSA at 3.3 Hz (log cm/s^2 units), considering data from both the CEUS and California. Solid gray lines show fit given by Atkinson and Kaka (2007); older relations of Kaka and Atkinson (2004) and Atkinson and Sonley (2000) are also shown. Note the older relations are biased at low intensities. (from Atkinson and Kaka, 2007)

Atkinson and Kaka (2007) noted that the relationship between intensity and ground motion has significant magnitude and distance trends. A good illustration of the magnitude and distance dependence of the relationship is provided in Figure 3, which plots the parameter (MMI – log Y) (where MMI is intensity and log Y is the log of an instrumental ground motion measure) in magnitude-distance space. This plot was compared by compiling both DYFI and ShakeMap data in California, for events with good datasets for both, and examining the average behavior of both log Y and MMI versus distance. Observations for each event were binned by distance to bring out the underlying trends in average amplitudes. It is clear that if we want to estimate the level of ground motion (log Y) that is implied by a given intensity value, we must know the magnitude and distance of the observation, as well as the observed intensity.

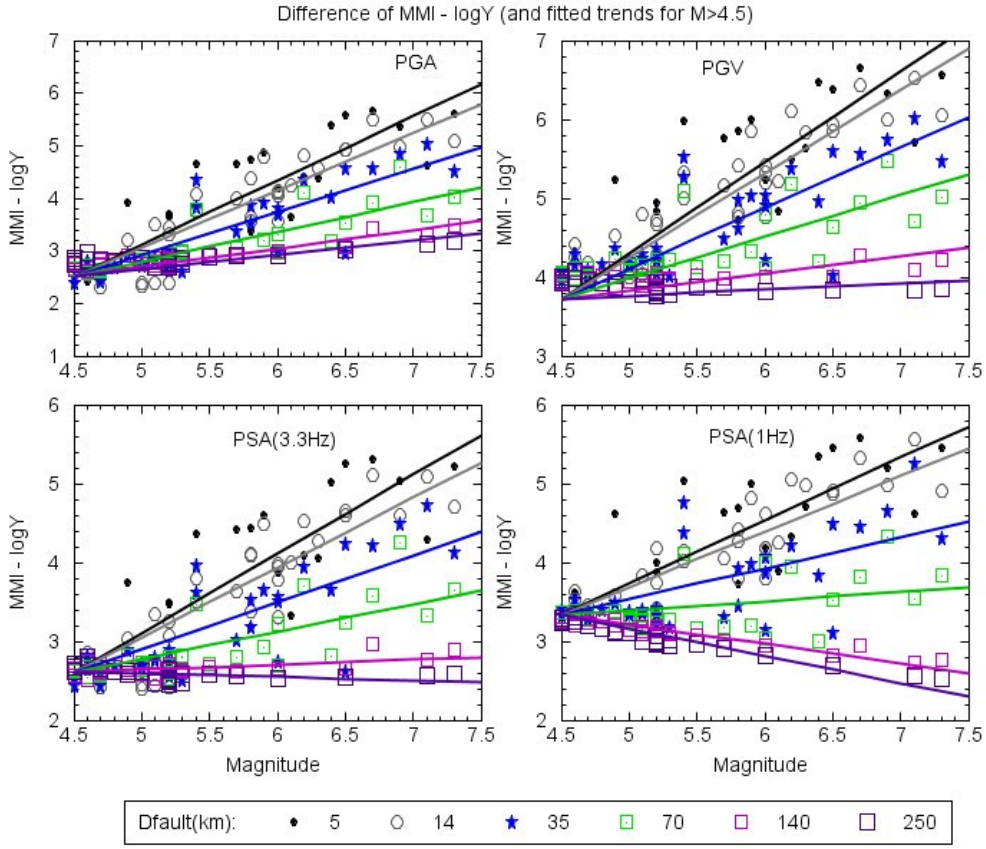

Figure 3 – Difference between intensity (MMI) and measured ground motion (log Y) based on ShakeMap and DYFI data from California, at various distances (5 to 250 km from the fault) and magnitudes. Approximate fit lines highlight observed trends.

Magnitude and distance trends in the relationship between intensity and ground motion have been reported for decades (eg. McGuire, 1984), but are often overlooked in empirical correlations. However, it is crucial to include these tendencies to avoid major biases in interpretation of intensity data. It is because of these trends that an earlier study by Kaka and Atkinson (2004) found a different relationship between intensity and ground motion for ENA than had been determined for California, by either Wald et al. (1999) or Atkinson and Sonley (2000). Both the Wald et al. and Atkinson and Sonley equations are appropriate for large-magnitude events at relatively near distances, but are biased for small magnitudes, and at large distances (the effects of which are seen in Figure 1). By including magnitude and distance as predictive variables, we can develop a predictive equation for ground motion from MMI that is applicable to all regions. This was illustrated by Atkinson and Kaka (2007), who produced equations relating intensity to ground motion, magnitude and distance, which are in good agreement with data from events in both the CEUS and California. Their equations are given in Table 1.

An application of the Atkinson and Kaka (2007) relationships is as a predictive tool to estimate ground motion from intensity (assuming we also know the magnitude and location for the intensity observations). This can be done by simply inverting the Table 1

equations to derive log Y given MMI, M (moment magnitude) and D (distance to fault). It may be noted that an alternative would be to refit the database using log Y as the dependent variable. This would require a fundamentally different approach, as it is the mean log Y value that was originally associated with each MMI level; associating a mean MMI with each value of log Y would not be optimal for these data as MMI is quantized by its integer representation in older databases. Thus we initially assume that a simple inversion can be used to predict log Y from Table 1, given M and D. However it must be recognized that an inversion of this type can result in a biased relationship, so we must test this approach for potential bias. Furthermore, not that this approach results in a prediction of multiple ground-motion parameters (PGA, PSA3.3Hz, PSA1Hz and PGV) from a each intensity value, implying that a spectrum is being predicted from a single intensity (aided by its magnitude and distance). There is an inherent assumption of a fixed spectral shape as a function of magnitude and distance, that is simply scaled up or down by the corresponding intensity. This seems like a reasonable approximation, but it should be kept in mind that not all ground motion parameters may be equally well predicted by the approach, particularly if intensity is dominated by a certain spectral band.

Table 1 – Relationship between ground motion and MMI from Atkinson and Kaka (2007).

$MMI = c1 + c2 \log Y + c5 + c6\, M + c7 \log D$ $\quad (\log Y \leq \log Y(I5))$

$MMI = c3 + c4 \log Y + c5 + c6\, M + c7 \log D$ $\quad (\log Y \geq \log Y(I5))$

Coefficient	PGA	PSA(3.3Hz)	PSA(1Hz)	PGV
c1	2.65	2.4	3.23	4.37
c2	1.39	1.36	1.18	1.32
c3	-1.91	-1.83	0.57	3.54
c4	4.09	3.56	2.95	3.03
c5	-1.96	-0.11	1.92	0.47
c6	0.02	-0.2	-0.39	-0.19
c7	0.98	0.64	0.04	0.26
logY(I5)	1.69	1.92	1.5	0.48

Validation of Inferred ground motions from MMI for California

To test whether the Atkinson and Kaka (2007) equations (Table 1, denoted AK07) can be used to provide estimates of ground motion, I apply the equations to predict log Y (for Y = PGA, PGV, PSA1hz, PSA3.3hz) from MMI for well-recorded California events that also have a good DYFI intensity database. I treat the instrumental data, downloaded from ShakeMap (http://www.cisn.org/shakemap.html), in the same manner as the DYFI data, downloaded from the DYFI site (http://earthquake.usgs.gov/eqcenter/dyfi/). Each ground-motion parameter is binned in distance bins 0.1 log units in width, to provide an estimate of mean amplitude (and its standard deviation) at fixed distance intervals. The mean intensity values at each distance are also binned, and weighted such that zip codes with more reports receive more weight in the average than do zip codes in the same distance bin with few reports. The weighted mean intensities are then used to predict the corresponding log Y using Table 1. Figures 4 to 8 show comparisons of the observed

spectral parameters at 1 and 3.3 Hz (with standard deviation) and those predicted from the DYFI intensities through Table 1. The agreement between observed and predicted spectral parameters is generally good. There is a tendency for the 3.3Hz PSA to be better-predicted than the 1-Hz PSA, though this does not hold for all events. The prediction equations of Boore and Atkinson (2007) for shallow earthquakes in active regions such as California, for B/C boundary (760 m/s) and E (150 m/s) site conditions, are also shown for reference; the observations would be expected to lie somewhere between the B/C and E predictions, but probably closer to the E predictions as intensities tend to be based largely on observations on soil. Interestingly, the agreement of the instrumental ground-motion data with BA07 is often not very good for individual events. Note that these data are not necessarily the same as those in the PEER-NGA database from which BA07 was derived; for example, the ShakeMap data used here may contain more distant data, and some events such as Parkfield were not in the PEER-NGA database.

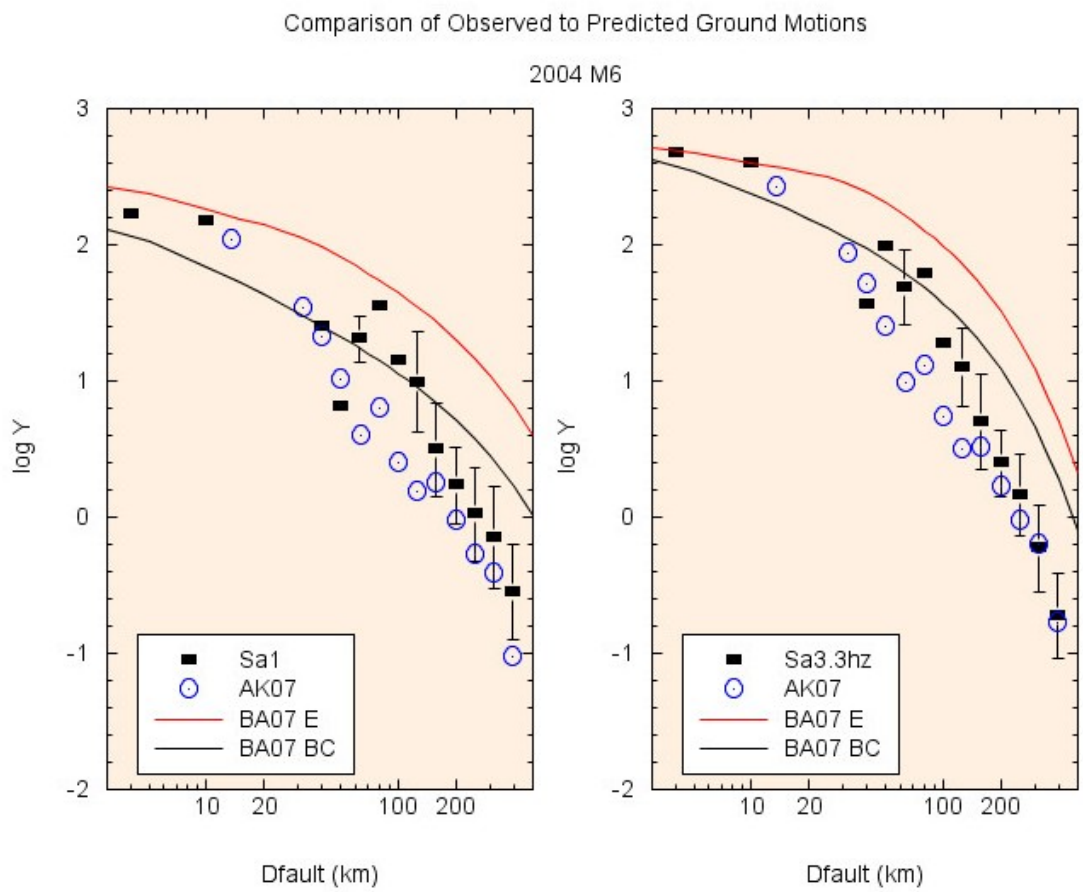

*Figure 4 – Comparison of observed spectral acceleration at 1 and 3.3 Hz (mean and standard deviation) with predictions of Atkinson and Kaka (2007): 2004 Parkfield earthquake of **M**6.0. Prediction equations of Boore and Atkinson (2007) for B/C and E site conditions also shown.*

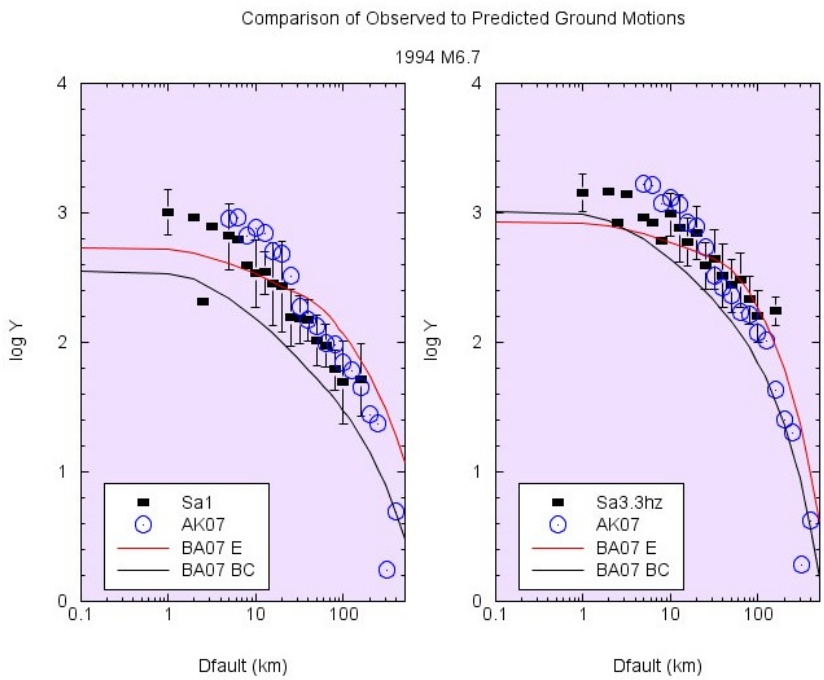

*Figure 5 – Comparison of observed spectral acceleration at 1 and 3.3 Hz (mean and standard deviation) with predictions of Atkinson and Kaka (2007): 1994 Northridge earthquake of **M**6. Prediction equations of Boore and Atkinson (2007) for B/C and E site conditions also shown.*

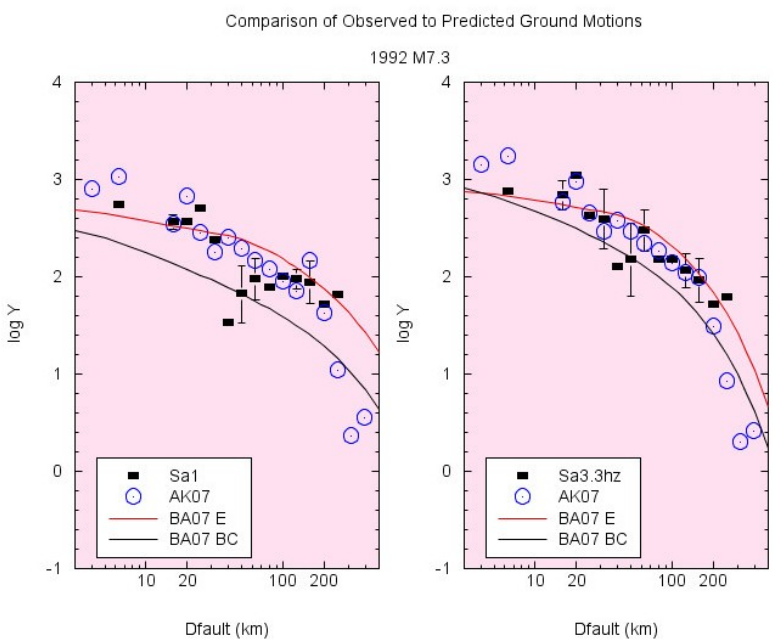

*Figure 6 – Comparison of observed spectral acceleration at 1 and 3.3 Hz (mean and standard deviation) with predictions of Atkinson and Kaka (2007): 1999 Landers earthquake of **M**7.3. Prediction equations of Boore and Atkinson (2007) for B/C and E site conditions also shown.*

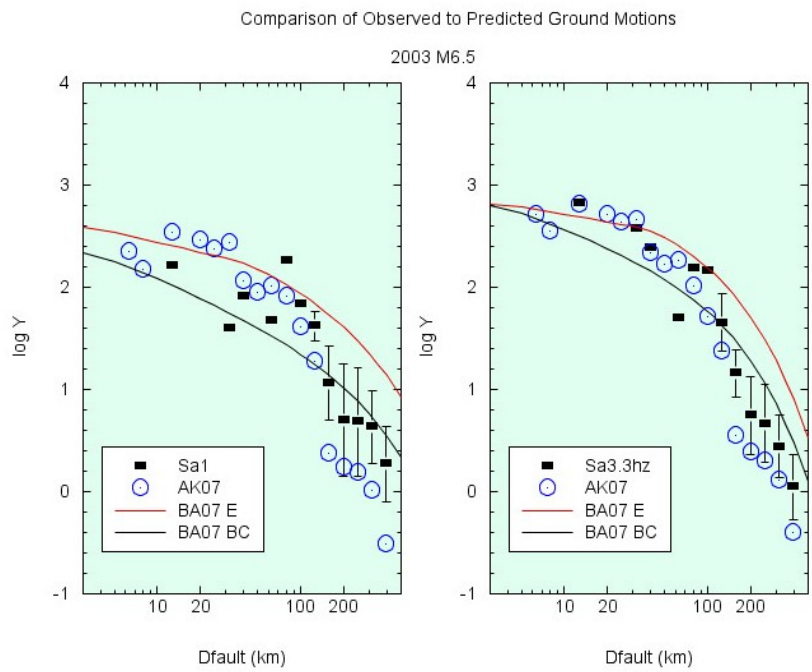

*Figure 7 – Comparison of observed spectral acceleration at 1 and 3.3 Hz (mean and standard deviation) with predictions of Atkinson and Kaka (2007): 2003 San Simeon earthquake of **M**6.5. Prediction equations of Boore and Atkinson (2007) for B/C and E site conditions also shown.*

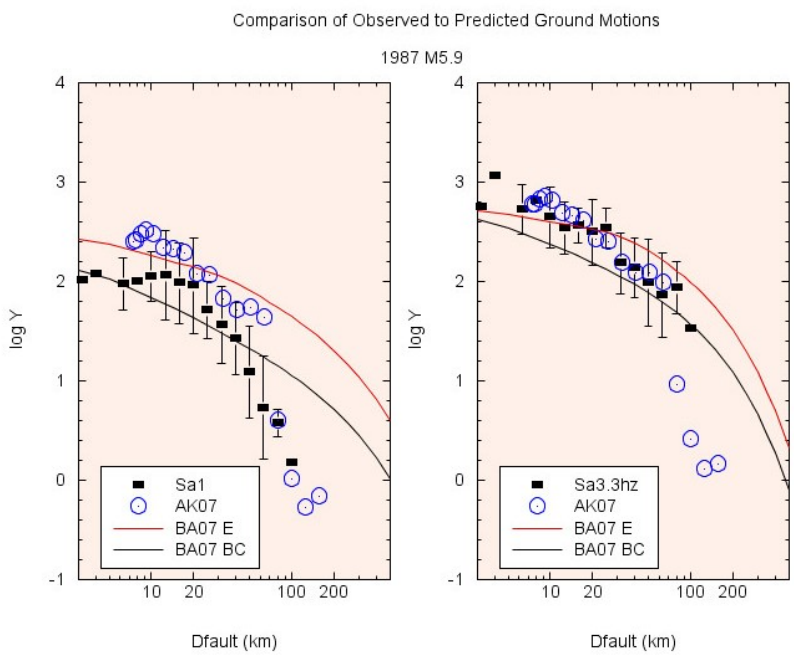

*Figure 8 – Comparison of observed spectral acceleration at 1 and 3.3 Hz (mean and standard deviation) with predictions of Atkinson and Kaka (2007): 1987 Whittier Narrows earthquake of **M**5.9. Prediction equations of Boore and Atkinson (2007) for B/C and E site conditions also shown.*

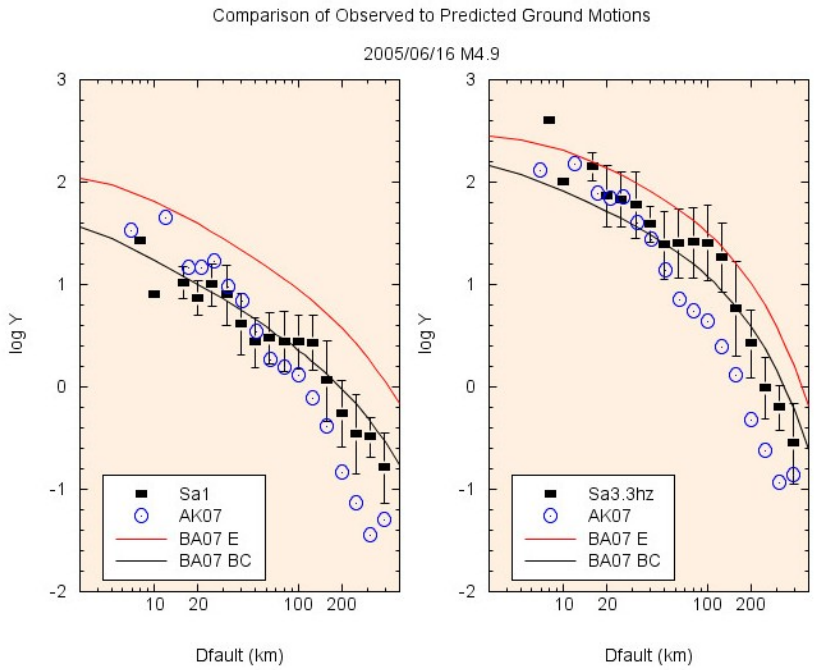

*Figure 9 – Comparison of observed spectral acceleration at 1 and 3.3 Hz (mean and standard deviation) with predictions of Atkinson and Kaka (2007): 2005/06/16 event of **M**4.9. Prediction equations of Boore and Atkinson (2007) for B/C and E site conditions also shown.*

Figures 10 to 15 show similar comparisons for PGA and PGV. On these figures, the relationships by Wald et al. (1999) that are used in ShakeMap to predict intensity from instrumental data are also shown; both the PGA and PGV relations are shown, though Wald et al. recommend using the PGA relation for lower intensities (<5) and the PGV relation for larger intensities (>5). The Wald et al. predictions are very similar to those of Atkinson and Kaka (2007) for large events at distances less than 100 km; at larger distances, the relationships diverge, as the Wald et al. relations do not include magnitude and distance effects. The Wald et al. relations generally work well for the purpose for which they are intended (ShakeMap applications in California, which focus on large events within 100 km), but can be improved upon for more general applications over a wider range of magnitudes and distances. There is a tendency for PGV to be better-predicted from intensity than PGA. Overall, I conclude that the Atkinson and Kaka (2007) relations provide a reasonable estimate of ground motion parameters, especially PSA at 3.3 Hz and PGV, for moderate to large events (**M**5. to 7.5) in California, at all felt distances. Events for which one or two ground motion parameters show amplitudes that match the intensities well, while other parameters match poorly, may be indicative of a spectral shape that is not typical for that magnitude and distance.

It is important to note from these plots that there is a general shape discrepancy between the MMI-based ground-motion predictions and the shape implied by recent ground-motion prediction equations (Boore and Atkinson, 2007). At larger distances, the BA07 equations appear to be overpredicting both the MMI-based and recorded ShakeMap ground-motion data, especially for moderate events. This may be because the ShakeMap database used here contains more large-distance observations, while the PEER-NGA database used by Boore and Atkinson (2007) contains more near-source data, especially from large events. Furthermore, the PEER-NGA database contains records from shallow crustal earthquakes in active tectonic zones around the world, not just California. This discrepancy needs to be kept in mind when interpreting the data.

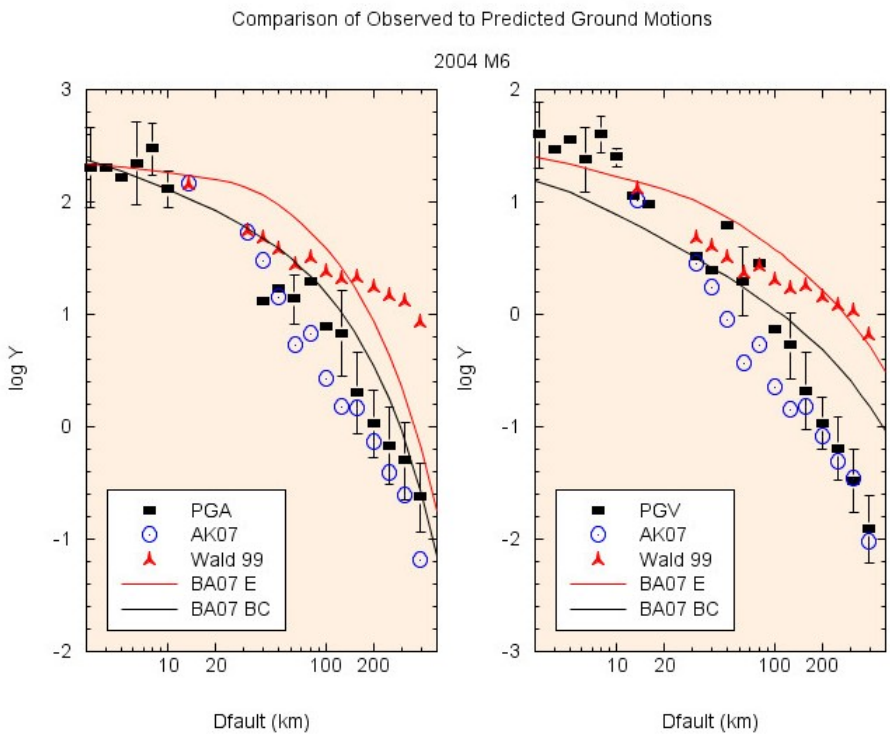

*Figure 10 – Comparison of observed PGA and PGV (mean and standard deviation) with predictions of Atkinson and Kaka (2007): 2004 Parkfield earthquake of **M**6.0. Predictions of Wald et al. (1999) also shown. Prediction equations of Boore and Atkinson (2007) for B/C and E site conditions also shown.*

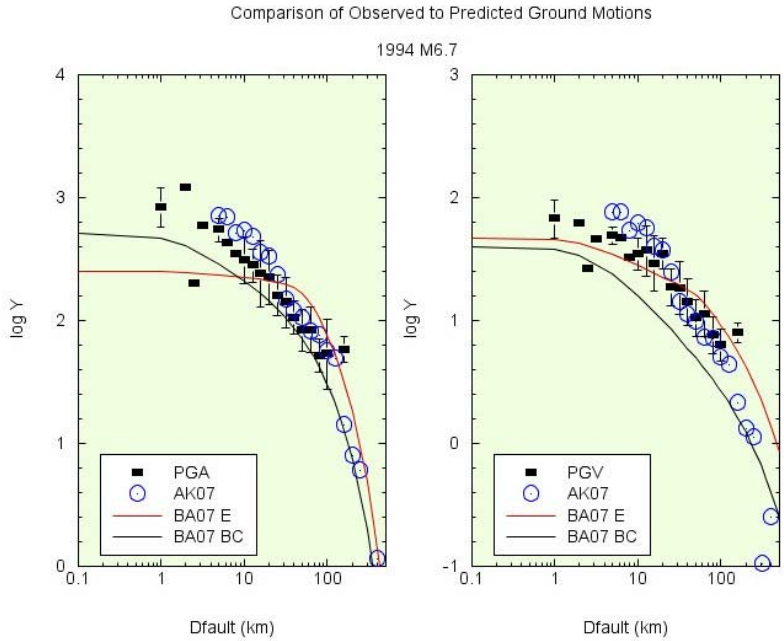

*Figure 11 – Comparison of observed PGA and PGV (mean and standard deviation) with predictions of Atkinson and Kaka (2007): 1994 Northridge earthquake of **M**6.7. Predictions of Wald et al. (1999) also shown. Prediction equations of Boore and Atkinson (2007) for B/C and E site conditions also shown.*

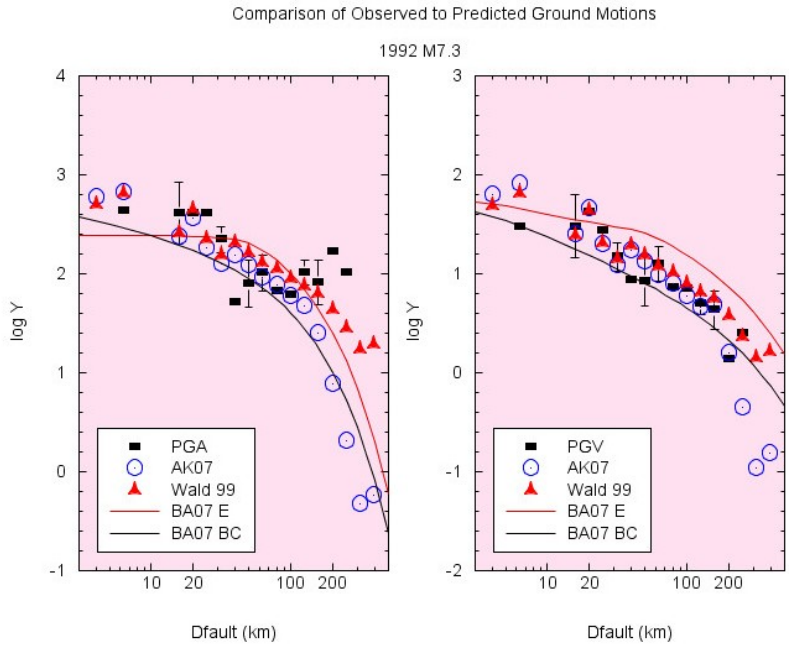

*Figure 12 – Comparison of observed PGA and PGV (mean and standard deviation) with predictions of Atkinson and Kaka (2007): 1999 Landers earthquake of **M**7.3. Predictions of Wald et al. (1999) also shown. Prediction equations of Boore and Atkinson (2007) for B/C and E site conditions also shown.*

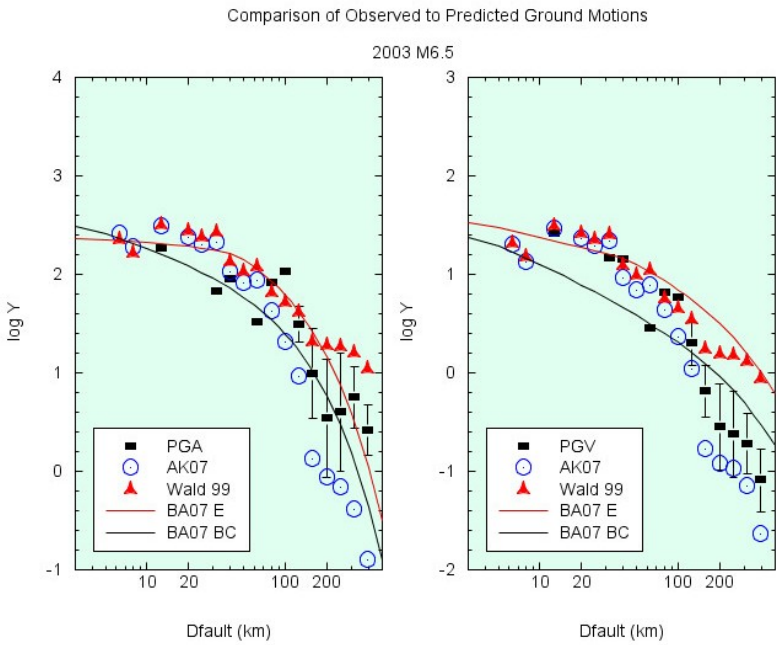

*Figure 13 – Comparison of observed PGA and PGV (mean and standard deviation) with predictions of Atkinson and Kaka (2007): 2003 San Simeon earthquake of **M**6.5. Predictions of Wald et al. (1999) also shown. Prediction equations of Boore and Atkinson (2007) for B/C and E site conditions also shown.*

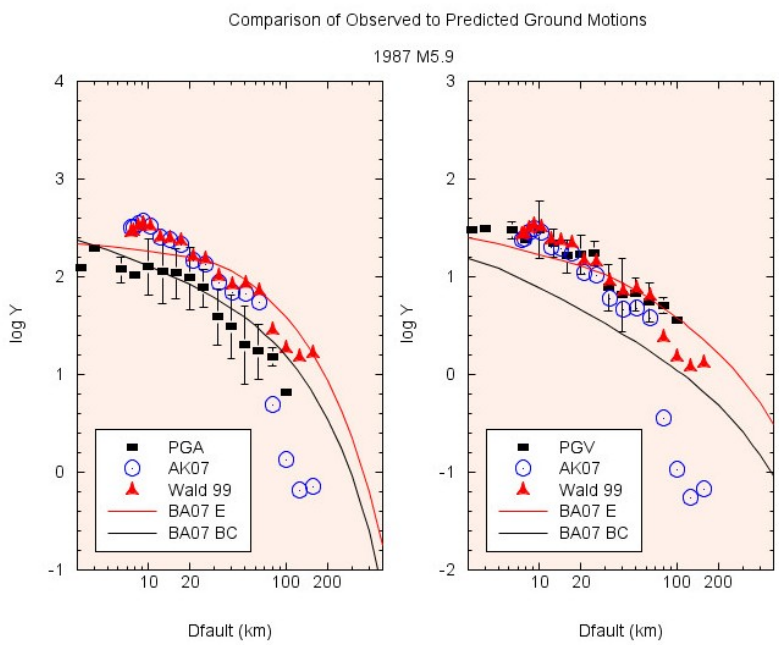

*Figure 14 – Comparison of observed PGA and PGV (mean and standard deviation) with predictions of Atkinson and Kaka (2007): 1987 Whittier Narrows of **M**5.9. Predictions of Wald et al. (1999) also shown. Prediction equations of Boore and Atkinson (2007) for B/C and E site conditions also shown.*

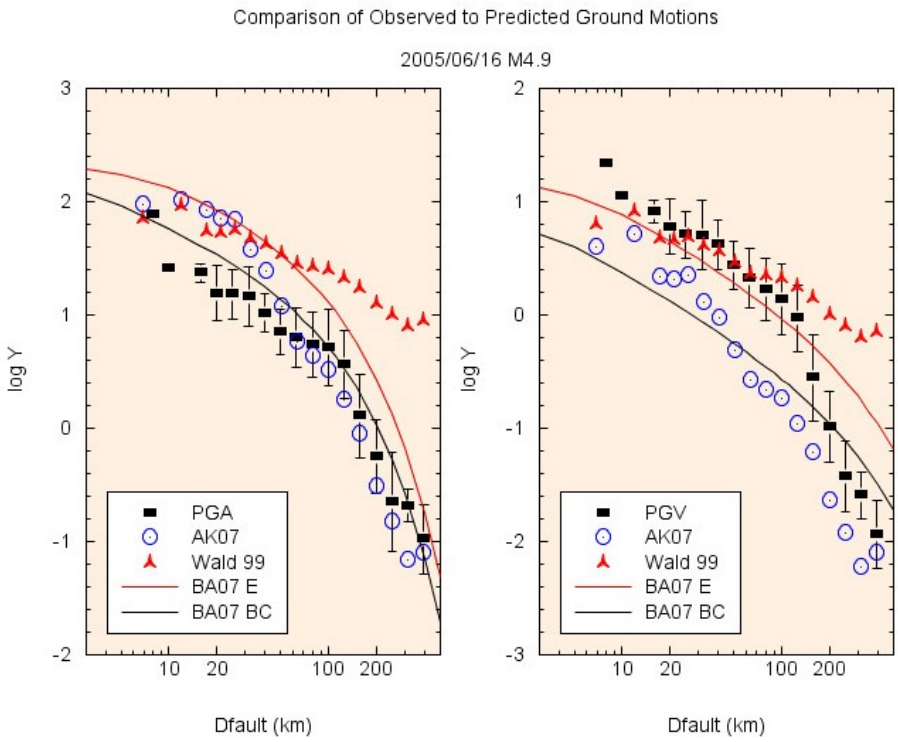

*Figure 15 – Comparison of observed PGA and PGV (mean and standard deviation) with predictions of Atkinson and Kaka (2007): 2005/06/16 event of **M**4.9. Predictions of Wald et al. (1999) also shown. For this event, PGA is overpredicted, while PGV is underpredicted. Prediction equations of Boore and Atkinson (2007) for B/C and E site conditions also shown.*

Validation of Inferred ground motions from MMI for ENA

It would be useful to validate the application of the Atkinson and Kaka equations to the prediction of ground motion specifically for ENA. There are a limited number of events for which such a validation can be performed. These are the 1988 **M**5.8 Saguenay earthquake, the 2002 **M**5.0 Au Sable Forks earthquake, and the 2005 **M**5.0 Riviere du Loup earthquake. Each of these events had both a good intensity dataset and a good ground-motion dataset (by eastern standards). However, there are complications in the interpretation. Unlike the California events, the instrumental data for the eastern events were recorded on hard rock sites, while the intensity data generally reflect typical moderate to soft soil conditions (by contrast, in California both the instrumental and intensity data reflect typical soils). Furthermore, the instrumental data are sparse for all events, and the intensity data for the Saguenay and Riviere du Loup events are poor, as Canada does not have an organized DYFI program. We thus expect to see: (i) more scatter in the comparisons of measured ground motions with those predicted by intensity; and (ii) a bias of the intensity-based predictions towards larger ground motions, due to the soil effects.

Figures 16 to 18 compare recorded ground motions at 1 and 3.3 Hz (rock sites) to those inferred from intensity data (soil sites), for the Saguenay, Au Sable Forks and Rivieres du Loup earthquakes. Note that individual ground-motion observations are shown, as the data are relatively sparse for binning (however the intensity data are binned). On these plots, the ground-motion prediction equations of Atkinson and Boore (2006) for two site conditions – B/C boundary and NEHRP E – are also shown, as are the Atkinson (2008) Referenced Empirical predictions for B/C conditions for ENA. The following observations can be made:

- For the Saguenay and Au Sable Forks earthquakes, the intensity-inferred motions generally match the observations well at 3.3 Hz, despite the suspected systemic differences in site conditions. At 1 Hz, the intensity-inferred motions significantly exceed the recorded motions, which is consistent with significant site amplification of lower frequency motions. There are almost no instrumental observations at distances less than 50 km, so the fit in close is difficult to assess
- For the Rivieres du Loup earthquake, the intensity-inferred motions generally exceed the recorded ground motions at both 1 and 3.3 Hz, consistent with expectations based on soil amplification. Unlike other events, this earthquake has instrumental data at relatively close distances (coverage good for $R \geq 20$ km).
- The intensity-inferred motions show a faster decay with distance than either the ground-motion prediction equations or the instrumental data. The observed trends suggest that the intensity-based ground motions may be too high at close distances, and too low at large distances, due to this trend.

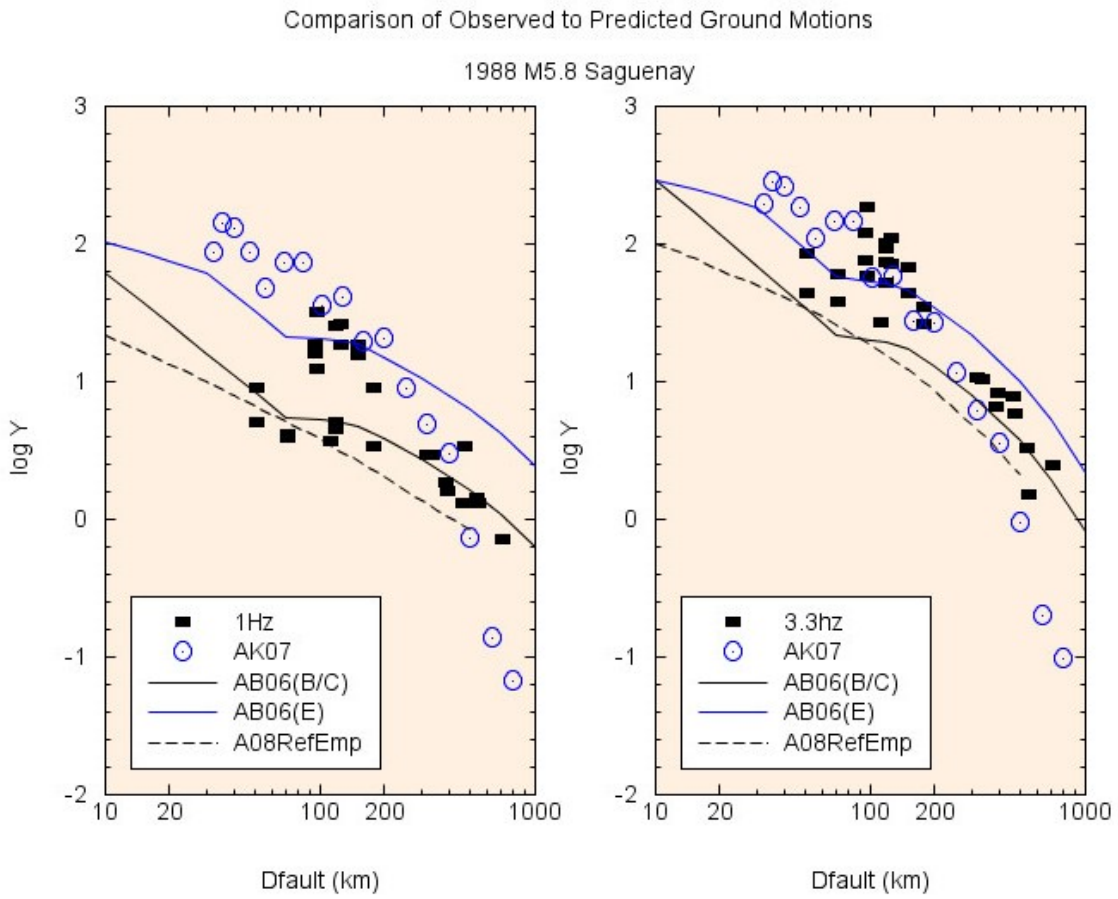

*Figure 16 – Comparison of observed spectral acceleration at 1 and 3.3 Hz (individual observations) with predictions of Atkinson and Kaka (2007): 1988 Saguenay earthquake of **M**5.8. Ground-motion prediction equations of Atkinson and Boore (2006) for B/C and E site conditions, and those of Atkinson (2008) for B/C conditions, are also shown. AK07 likely corresponds to soil, recorded motions are on rock.*

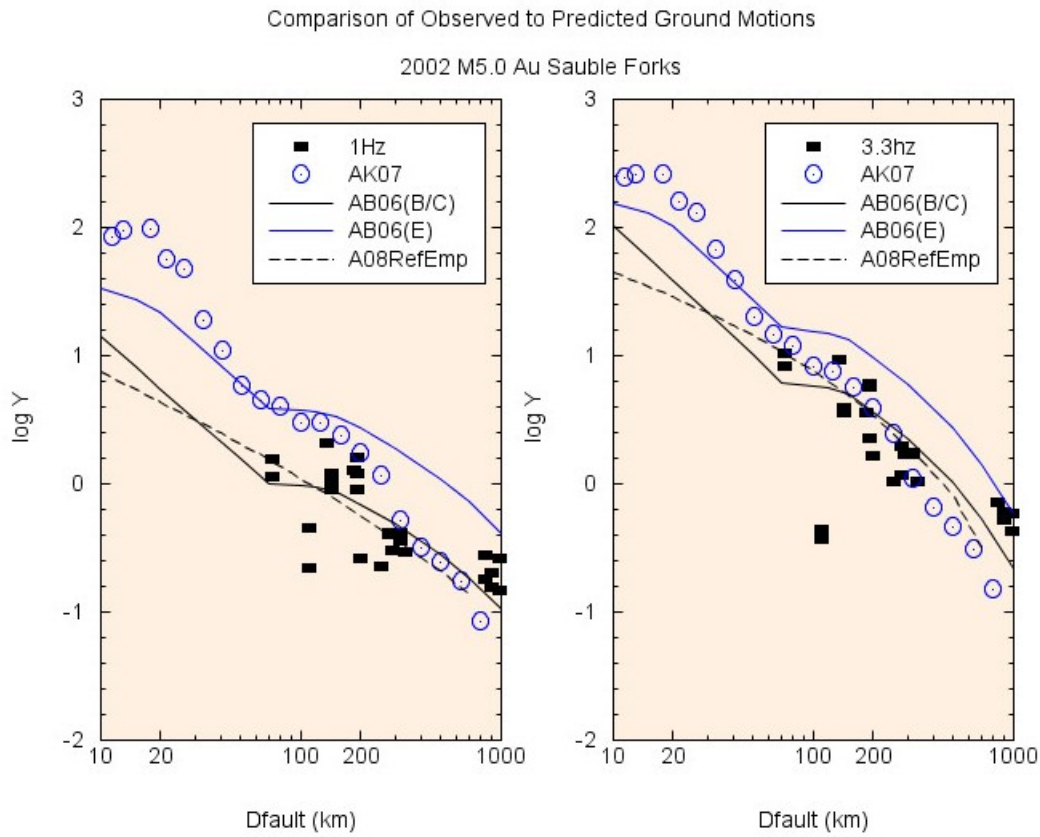

*Figure 17 – Comparison of observed spectral acceleration at 1 and 3.3 Hz (individual observations) with predictions of Atkinson and Kaka (2007): 2002 Au Sable Forks earthquake of **M**5.0. Ground-motion prediction equations of Atkinson and Boore (2006) for B/C and E site conditions, and those of Atkinson (2008) for B/C conditions, are also shown. AK07 likely corresponds to soil, recorded motions are on rock.*

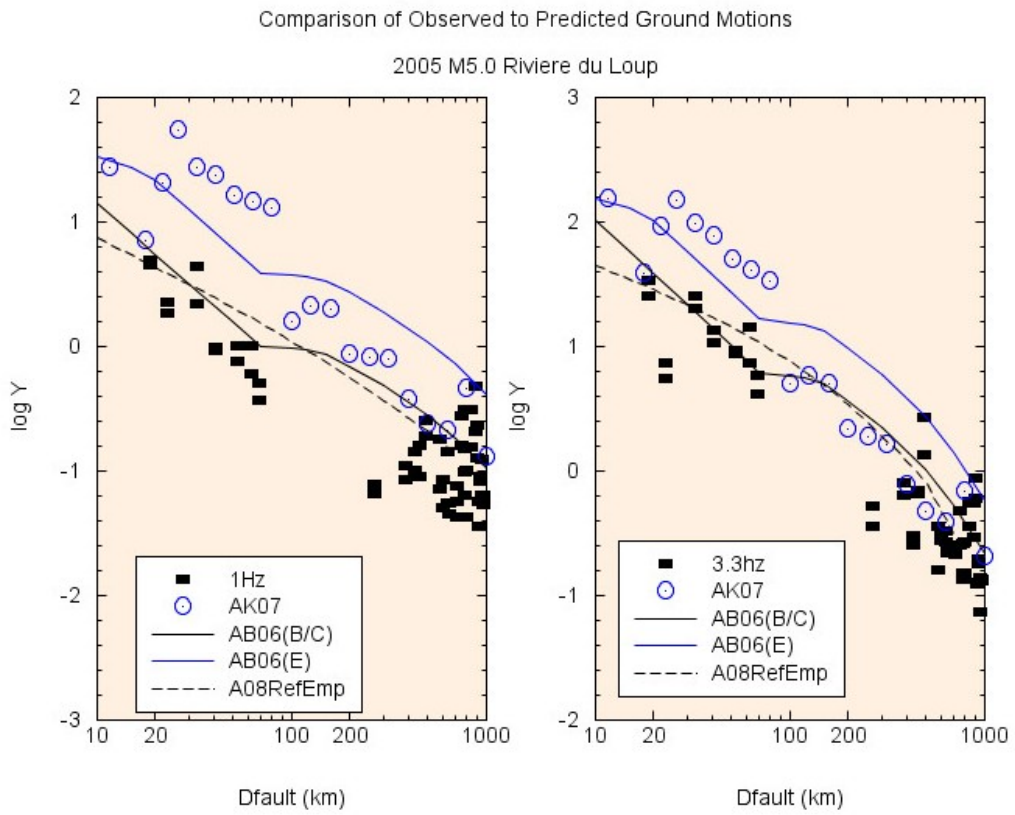

*Figure 18 – Comparison of observed spectral acceleration at 1 and 3.3 Hz (individual observations) with predictions of Atkinson and Kaka (2007): 2005 Rivieres du Loup earthquake of **M**5.0. Ground-motion prediction equations of Atkinson and Boore (2006) for B/C and E site conditions, and those of Atkinson (2008) for B/C conditions, are also shown. AK07 likely corresponds to soil, recorded motions are on rock.*

On Figures 19-20, similar comparisons of intensity-inferred and recorded ground motions are made for PGA and PGV. (Note: the Au Sable Forks event is not included in this series as it does not have PGA, PGV data in the AB06 database). On these graphs, the prediction curves of Wald et al. (1999) are also shown, though it should be noted that they should not be expected to be applicable except at close distances since the motions are generally weak. The following observations are made:

- Recorded PGA values on rock are generally consistent with those inferred from intensity on soil; this may be because rock sites preserve high-frequency information well. It is interesting that this holds for the Saguenay earthquake, for which PGA values are regarded as very high for an event of this magnitude (particularly strong high-frequency content).
- Recorded PGV values on rock are significantly lower than those inferred from intensity on soil. This could be because PGV is substantially amplified by soil, or could be because the intensity is controlled more by PGA than PGV in these events.

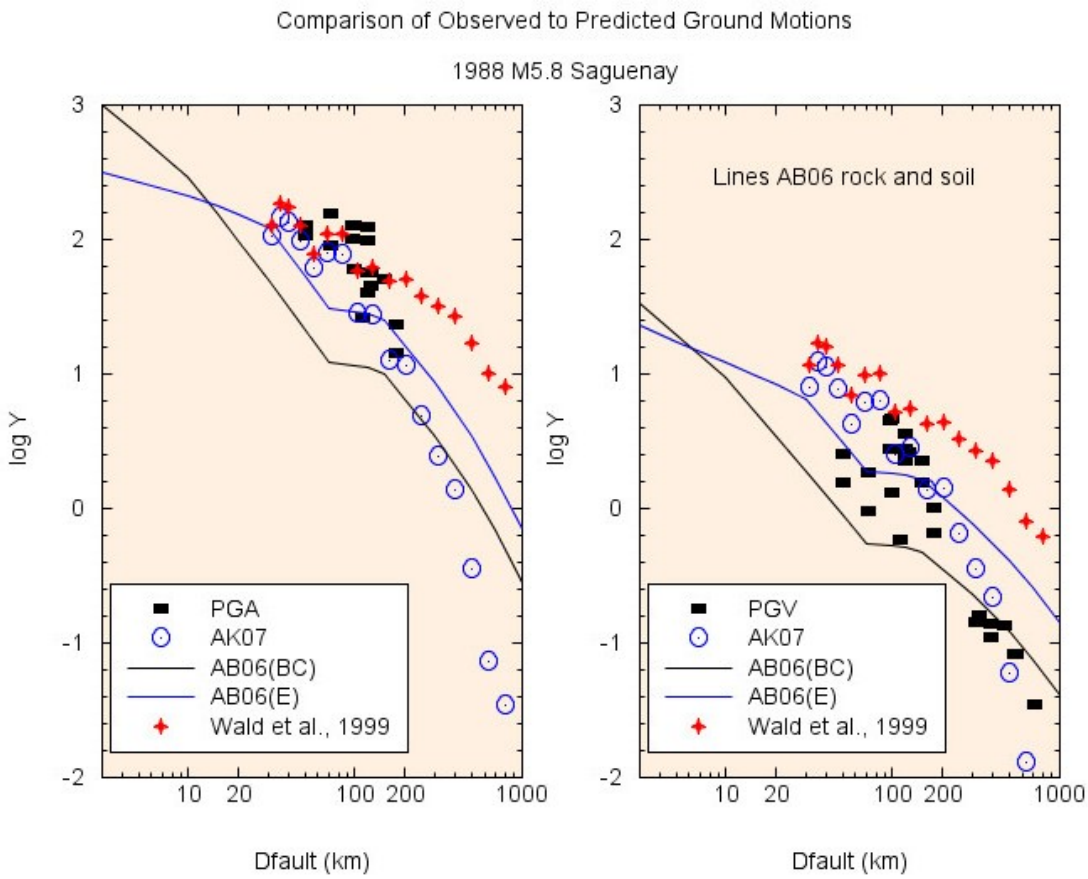

*Figure 19 – Comparison of observed PGA and PGV (individual observations) with predictions of Atkinson and Kaka (2007): 1988 Saguenay event of **M**5.8. Ground-motion prediction equations of Atkinson and Boore (2006) for B/C and E site conditions are also shown. AK07 likely corresponds to soil, recorded motions are on rock. Predictions for Wald et al. (1999) intensity equations also shown.*

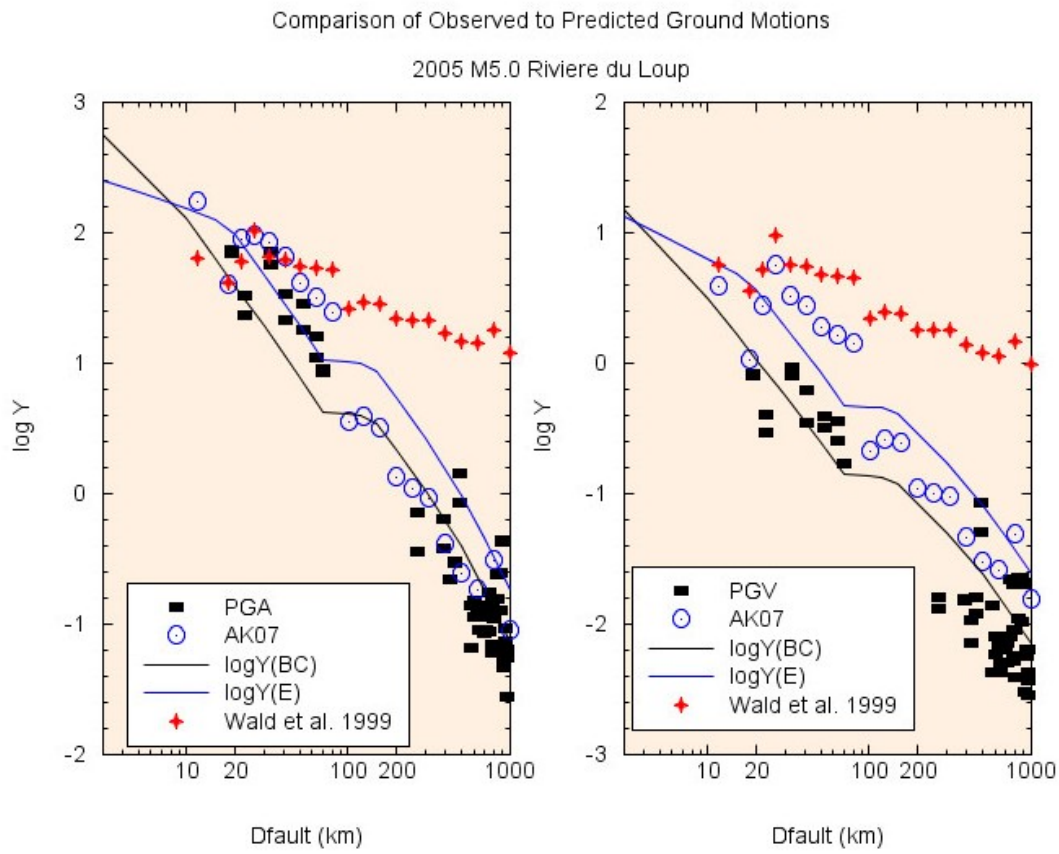

*Figure 20 – Comparison of observed PGA and PGV (individual observations) with predictions of Atkinson and Kaka (2007): 2005 Rivieres du Loup event of **M**5.0. Ground-motion prediction equations of Atkinson and Boore (2006) for B/C and E site conditions are also shown. AK07 likely corresponds to soil, recorded motions are on rock. Predictions for Wald et al. (1999) intensity equations also shown.*

An overall conclusion reached from these comparisons for ENA events is that the intensity-inferred ground-motions are fairly consistent with observations, if one considers that low frequencies (and PGV) are likely to be amplified more by local soils than are high frequencies (and PGA). It may be that ground motions at some frequencies are more closely predicted by the KA07 equations than are others. This could be a consequence of different spectral shape for ENA events for a given magnitude and distance, in comparison to the corresponding spectral shapes for California.

Implications of MMI observations for ENA ground-motion prediction equations

I now consider the implications of MMI observations in ENA for the validation of ENA ground-motion prediction equations. There are three aspects to consider, as described in the following sections.

Historical Events

I first evaluate, briefly, whether intensity observations for a few large historical ENA earthquakes are consistent with recent ENA GMPEs, focusing on the equations of Atkinson and Boore (2006) and the Referenced-Empirical alternative proposed by Atkinson (2008). Figures 21 and 22 compare the inferred ground motions at 1 and 3.3 Hz (based on intensities and KA07 equations) with GMPEs for the 1925 **M**6.4 Charlevoix earthquake and the 1811-1812 **M**7.5 (approx.) New Madrid earthquakes. Assuming that observed intensities reflect soft soil conditions, the Charlevoix intensities are reasonably consistent with the AB06 equations. For the New Madrid events, implied ground motions at distances less than 200 km based on the intensities seem unreasonably large (spectral accelerations >1g at 100 km), perhaps because of biases in the intensity data, which are very poor for this event, especially at close distances. For this reason it is difficult to draw any conclusions, other than the obvious conclusion that the New Madrid intensities at distances out to 100 km imply very large ground motions.

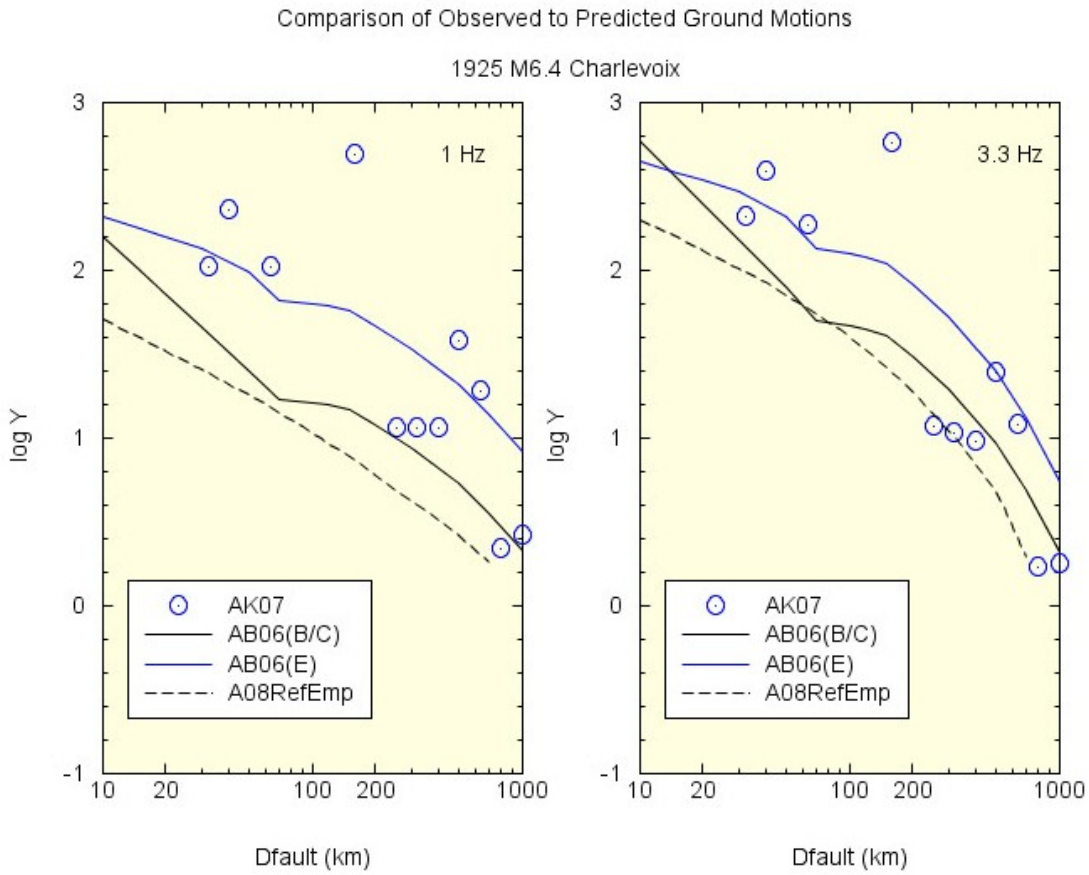

*Figure 21 – Comparison of inferred spectral acceleration at 1 and 3.3 Hz (binned intensity observations, using AK07): 1925 Charlevoix earthquakes of **M**6.4. Ground-motion prediction equations of Atkinson and Boore (2006) for B/C and E site conditions, and those of Atkinson (2008) for B/C conditions, are also shown.*

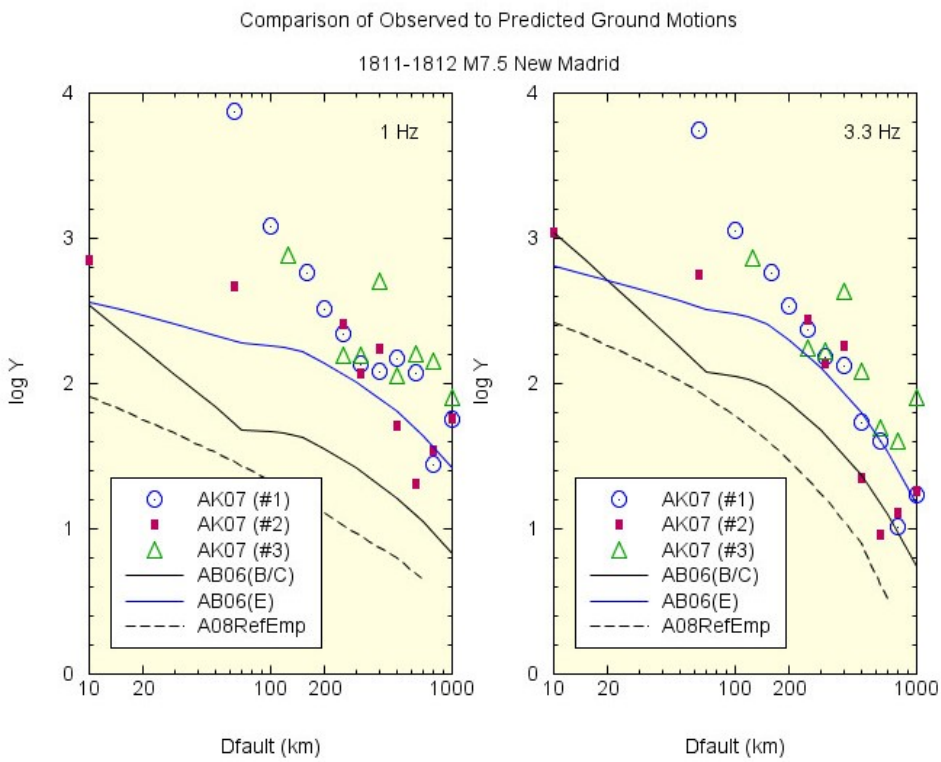

*Figure 22 – Comparison of inferred spectral acceleration at 1 and 3.3 Hz (binned intensity observations, using AK07): 1811-1812 New Madrid earthquakes of **M**7.5 (approx). Ground-motion prediction equations of Atkinson and Boore (2006) for B/C and E site conditions, and those of Atkinson (2008) for B/C conditions, are also shown.*

<u>*Ground-motion prediction equations compared to implications of Intensity Data*</u>

A more systematic way to evaluate the intensity observations against GMPEs is to use the binned MMI values vs. distance from relatively well-recorded ENA earthquakes to characterize ENA intensities for each magnitude level, converting these to inferred ground motions using the KA07 equations as described above. But first we must evaluate and adjust the applicability of this technique using the more plentiful California data, against which validation to recorded ground-motion data can be made. This allows biases to be identified and quantified. Binned weighted mean MMI data versus distance for events with plentiful felt reports (generally >1000) are obtained from the DYFI database for California, and converted to implied ground motion levels – PSA(1Hz), PSA(3.3Hz), PGA and PGV using the KA07 equations. Figures 23 – 29 plot the inferred amplitudes in comparison to the GMPEs of Boore and Atkinson (BA07) for B/C boundary (760 m/s) and E (150 m/s) site conditions, for **M** 4.5 to 7.5, in 0.5 magnitude-unit intervals (1 plot for **M**4.5±0.2, etc.). (Notes: (1) it is implicitly assumed that closest distance to fault and Joyner-Boore distance are approximately equal for Dfault>5 km; (2) the intensities from the 1906 earthquake of **M**7.8 have been included on the **M**7.5 plot.) We would expect the inferred amplitudes to scatter about the GMPE lines of BA07, being perhaps closer to the line for E site conditions as intensities tend to be dominated by the poorest site conditions in a locality. What is seen in these plots is surprising. The BA07

equations appear to systematically overestimate the inferred motions at larger distances for small-to-moderate earthquakes. The inferred motions are consistent with BA07 at all magnitudes at close distances (<20 km), but inferred amplitudes are grossly over-estimated by BA07 at larger distances (30-200 km) for events of **M**≤6.0. As a check on this finding, the inferred motions from the intensity prediction equations of Atkinson and Wald (2007) for California are also plotted, and are clearly self-consistent with the MMI data. It may be noted that the predicted shape from the AW07 equations has some peculiar-looking lack of smoothness with distance at some magnitudes. This arises from the interplay between the bilinear attenuation shape in AW07 and the distance dependence in the KA07 relations; it has no actual physical significance and the AW07 line should be considered a smoothed interpretation of that plotted.

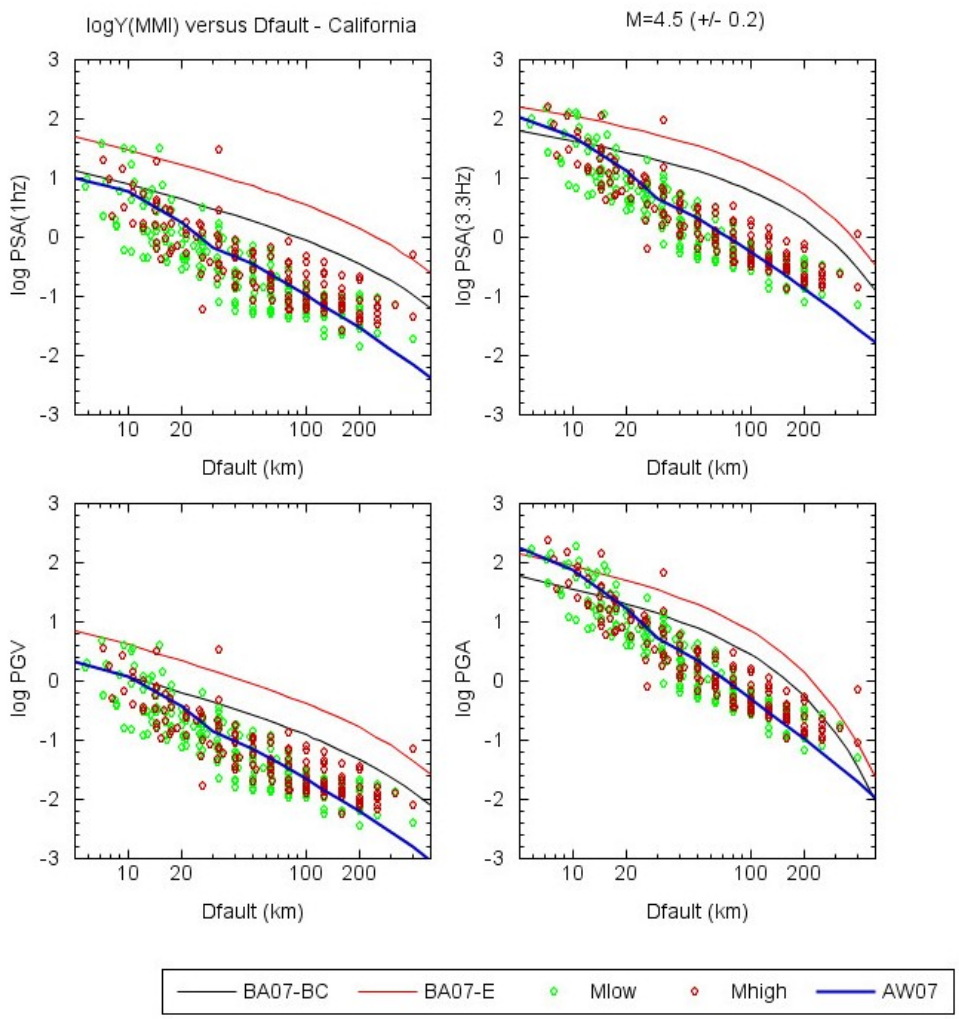

Figure 23 – Ground motions inferred from California intensity data (using KA07) in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. ***M*** *= 4.5 ± 0.2*

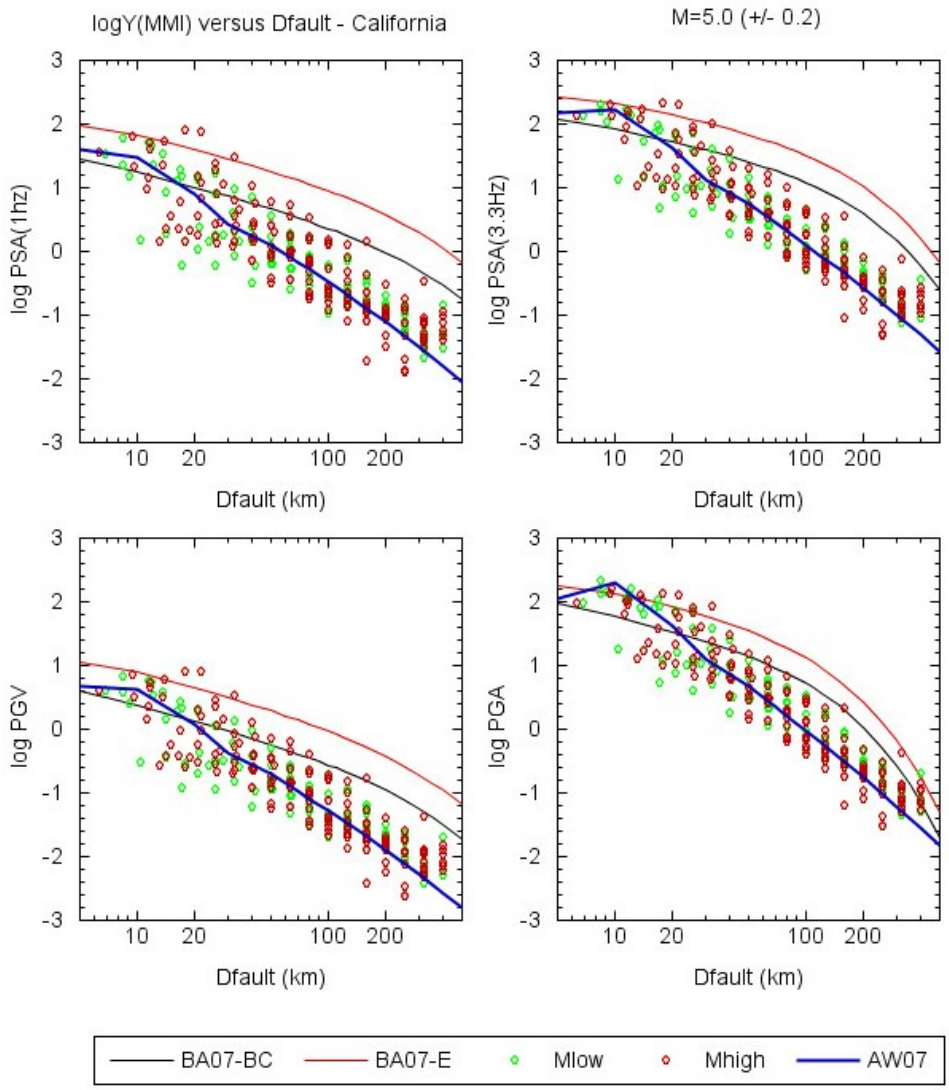

Figure 24 – Ground motions inferred from California intensity data (using KA07) in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. ***M*** *= 5.0 ± 0.2*

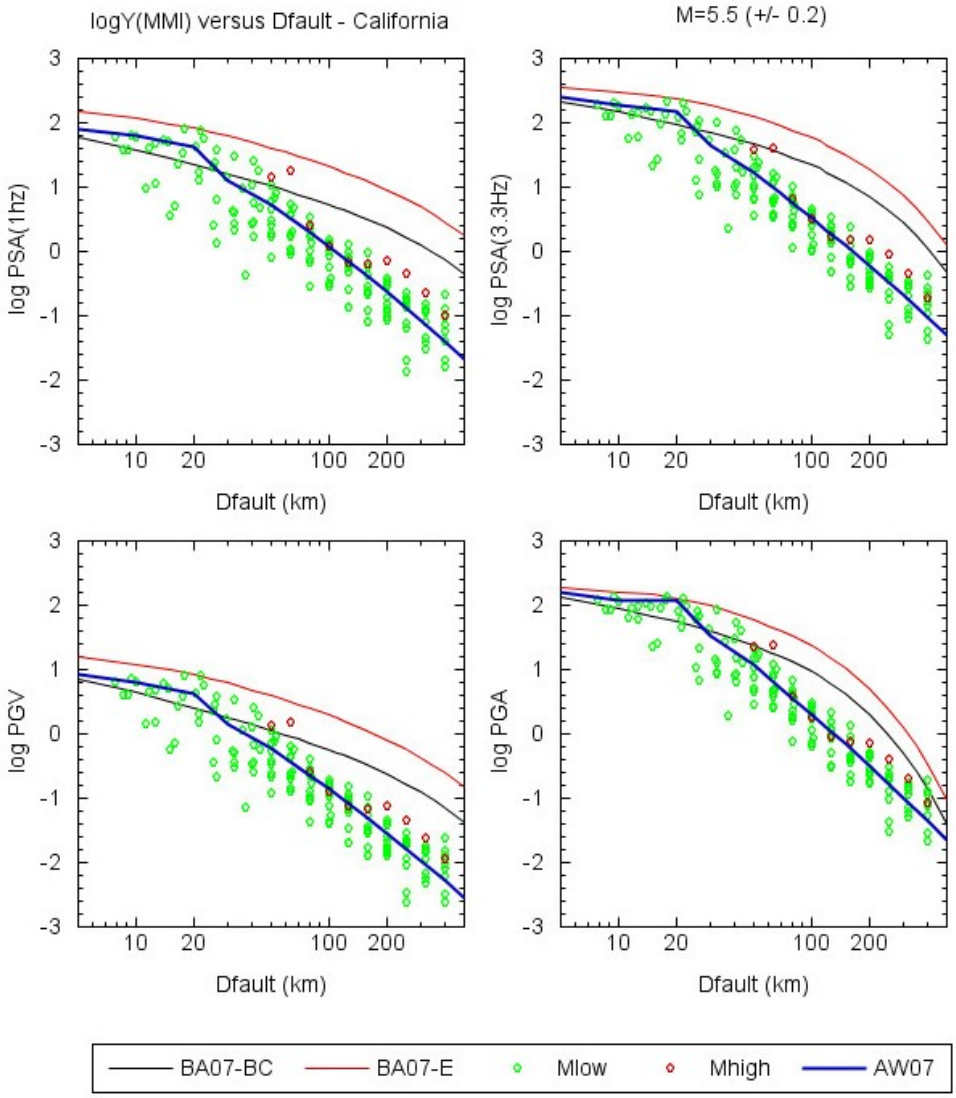

Figure 25 – Ground motions inferred from California intensity data (using KA07) in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. ***M*** *= 5.5 ± 0.2*

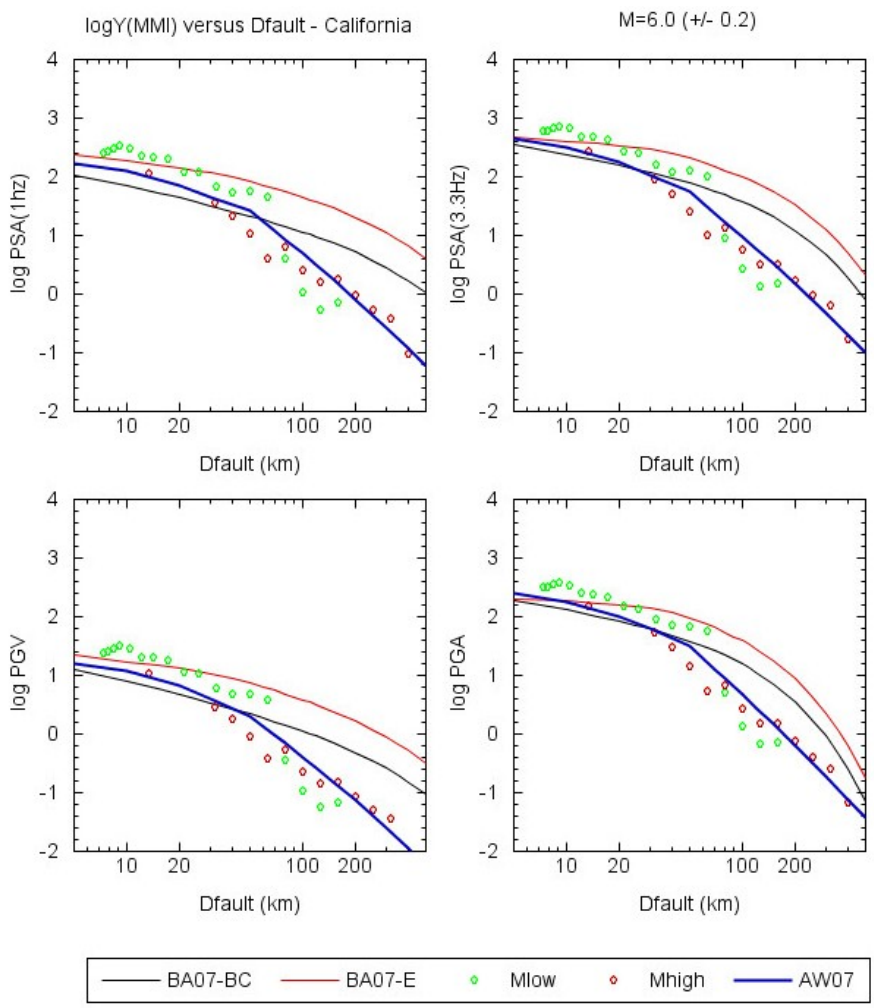

Figure 26 – Ground motions inferred from California intensity data (using KA07) in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. ***M*** *= 6.0 ± 0.2*

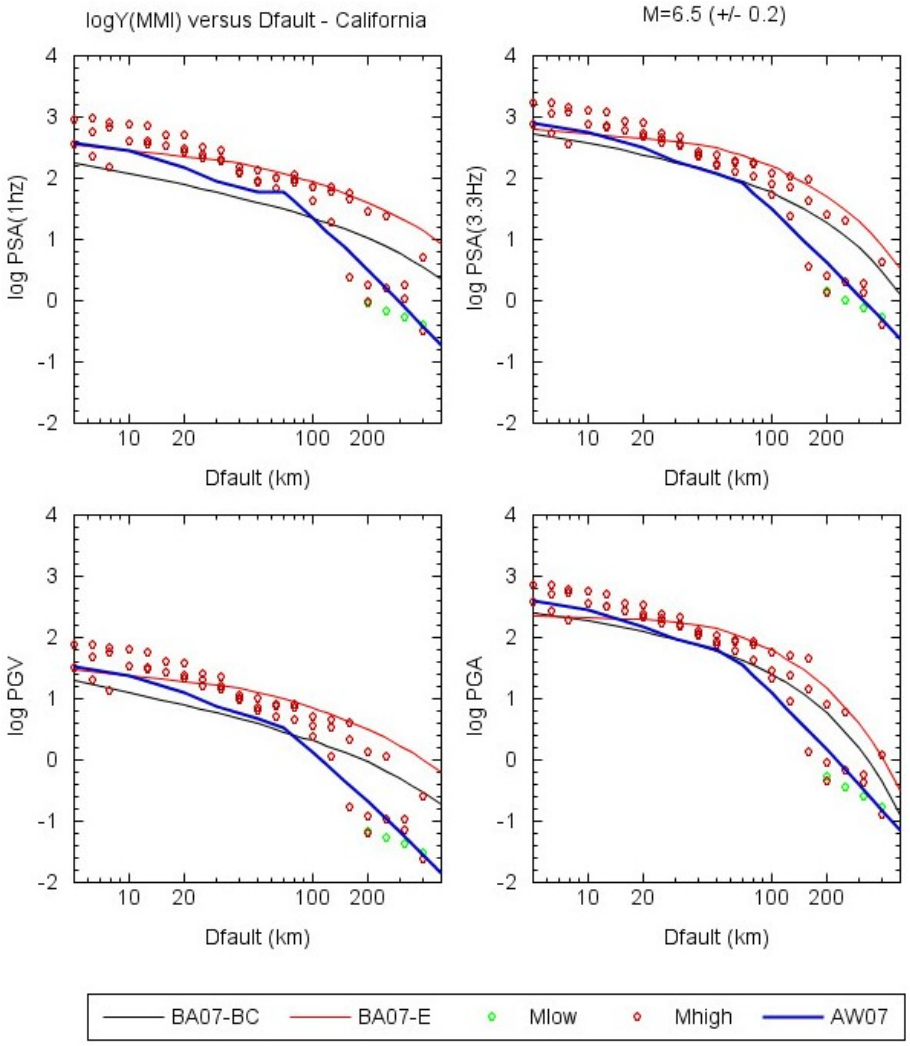

Figure 27 – Ground motions inferred from California intensity data (using KA07) in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. ***M*** *= 6.5 ± 0.2*

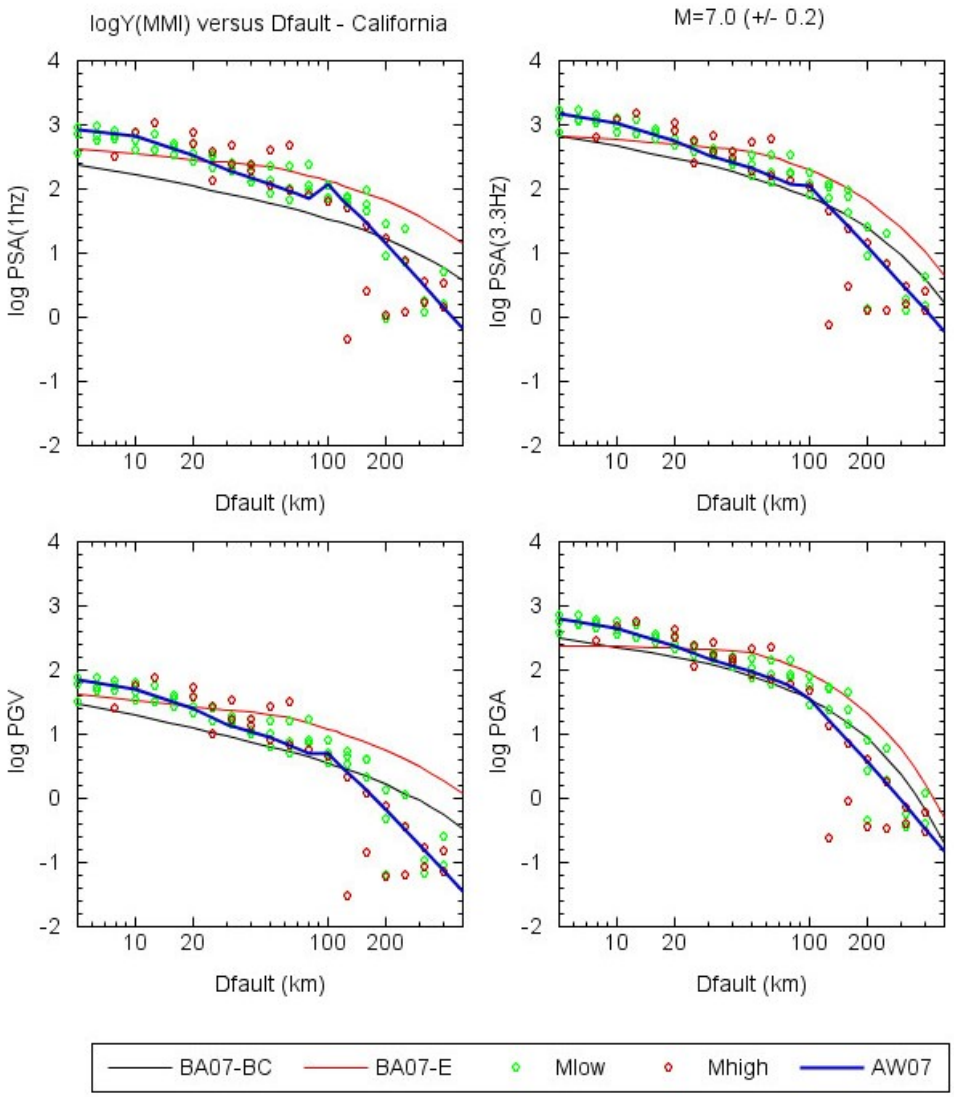

Figure 28 – Ground motions inferred from California intensity data (using KA07) in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. ***M*** *= 7.0 ± 0.2*

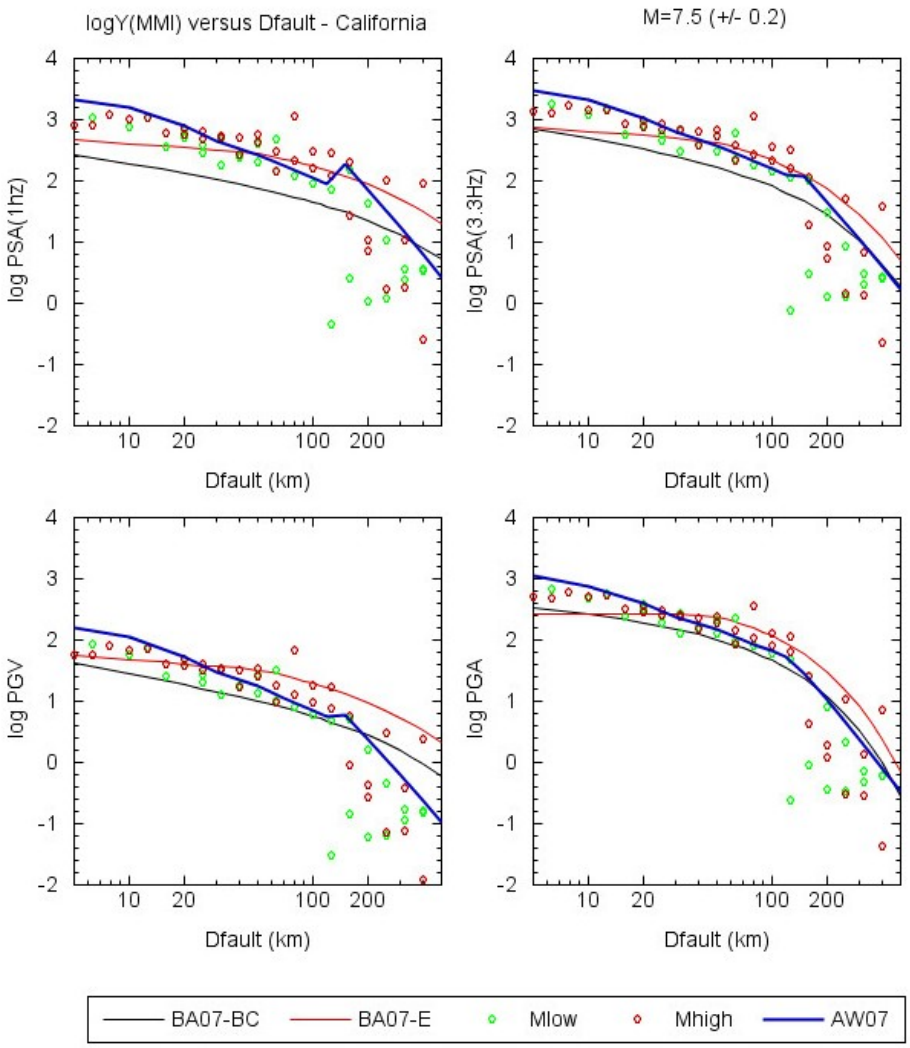

Figure 29 – Ground motions inferred from California intensity data (using KA07) in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. ***M*** *= 7.3 to 7.8.*

A conclusion from Figures 23-29 is that the BA07 equations may over-estimate ground motions from California earthquakes of **M**≤6.0 at distances greater than 20 km. This is quite possible, as the database used in BA07 is biased towards larger-magnitude earthquakes, and includes events from many regions, including California. The emphasis in BA07 is the prediction of amplitudes from larger events, especially at close distances, that are of most engineering interest. For these magnitude-distance combinations, there is no apparent inconsistency, although the MMI data are sparse.

To validate the inference that the BA07 equations may be biased high at large distances for smaller events, Figures 30-33 plot the BA07 GMPEs, and the AW07-inferred GMPEs in comparison to observed California ground-motion amplitudes from ShakeMap for

events of **M**≤6.2, binned with distance for each event in the same way as the MMI data. (Note: plots for **M**≥6.5 from ShakeMap data are consistent with the BA07 predictions, but are not shown as the data are sparse.) These plots confirm that BA07 is indeed over-predicting amplitudes at larger distances for these events (and underpredicting PGV at small distances for **M**4.5 and 5.0). Interestingly, the AW07 inferred GMPEs are underpredicting observed amplitudes at larger distances, except for PGA, which is reasonably well predicted. This suggests that the GMPEs inferred from AW07 are biased low, in contrast to the high bias in BA07.

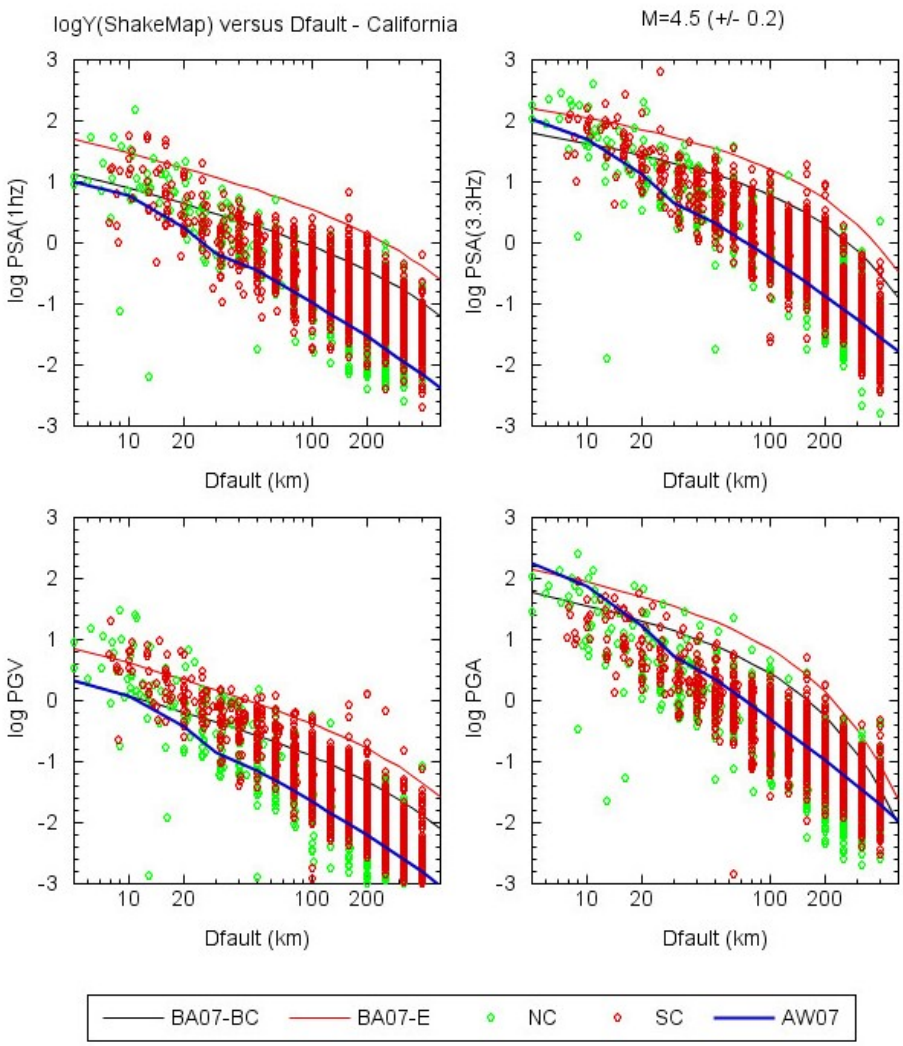

Figure 30 – Ground motions recorded by California ShakeMap, in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. ***M*** *= 4.5±0.2*

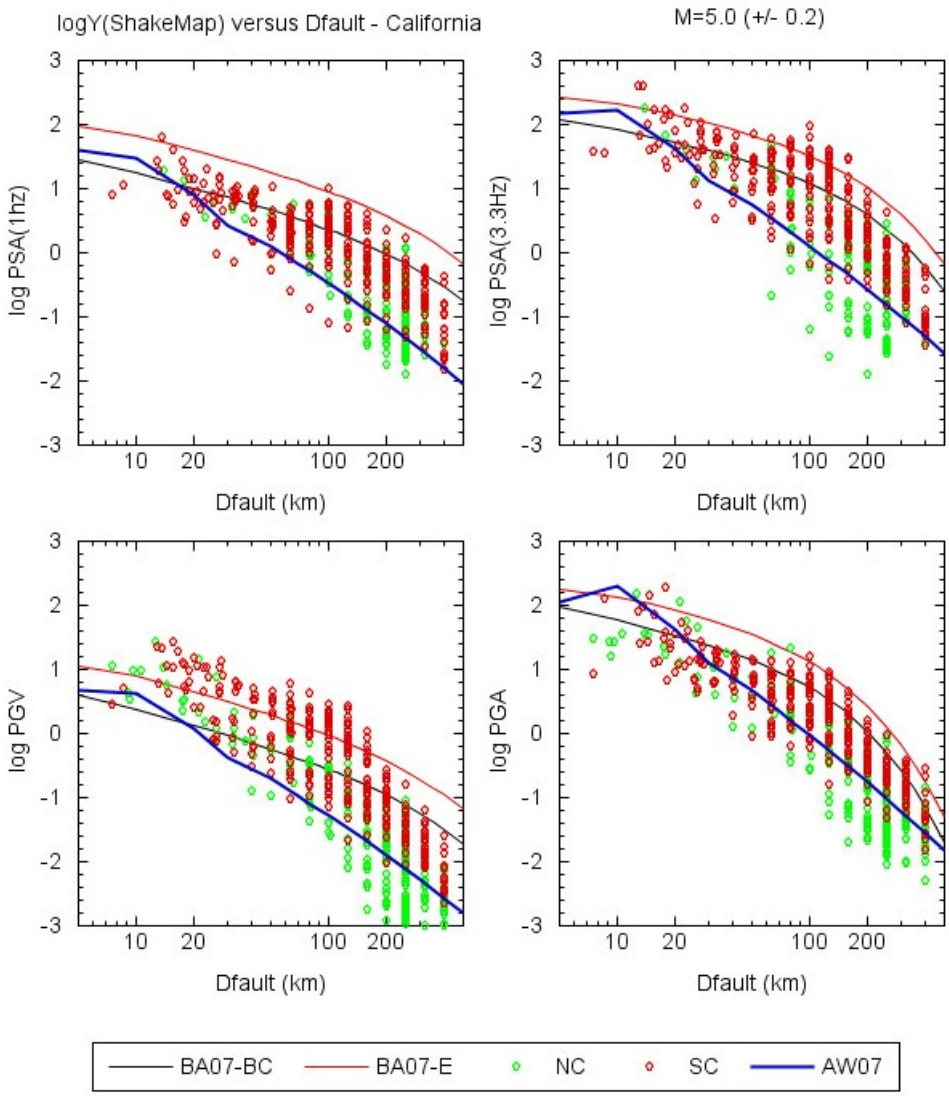

Figure 31 – Ground motions recorded by California ShakeMap, in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. ***M*** *= 5.0±0.2*

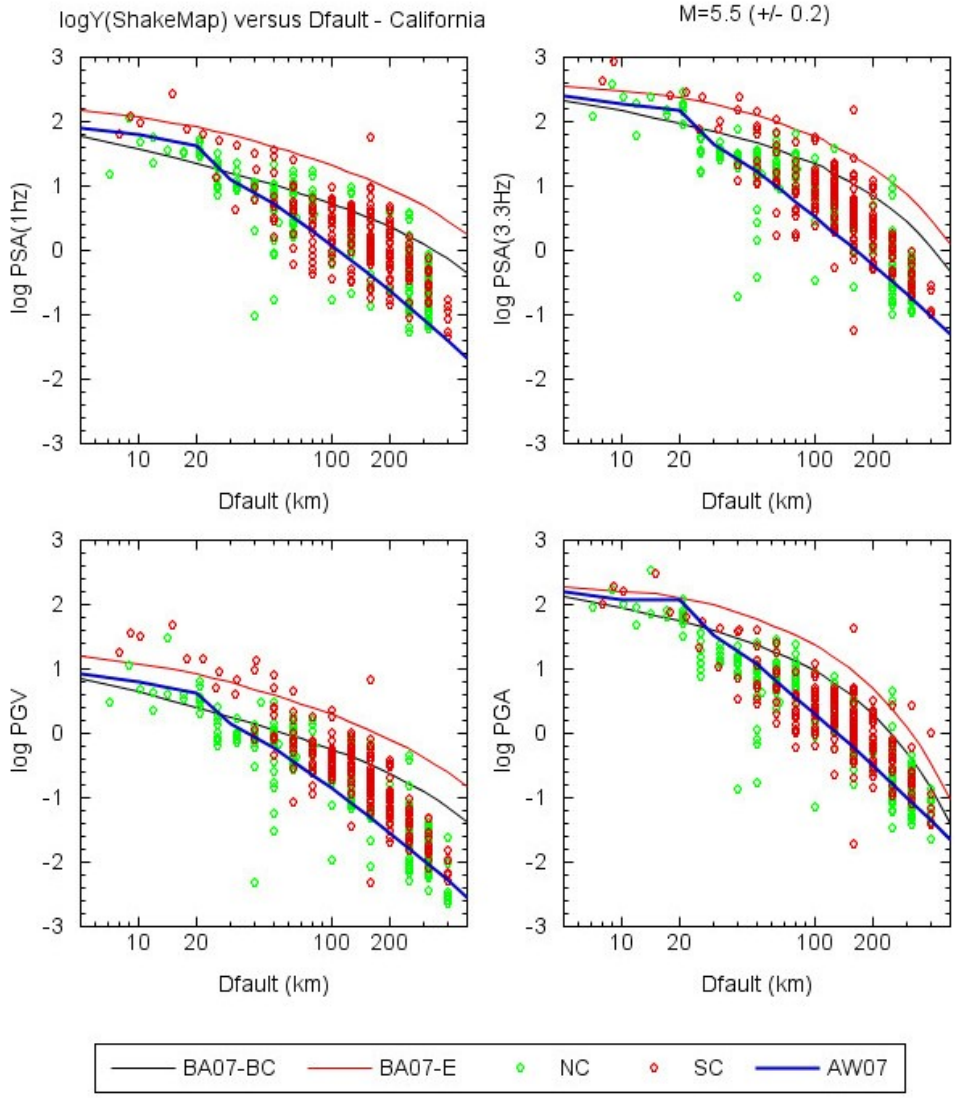

Figure 32 – Ground motions recorded by California ShakeMap, in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. ***M*** *= 5.5±0.2*

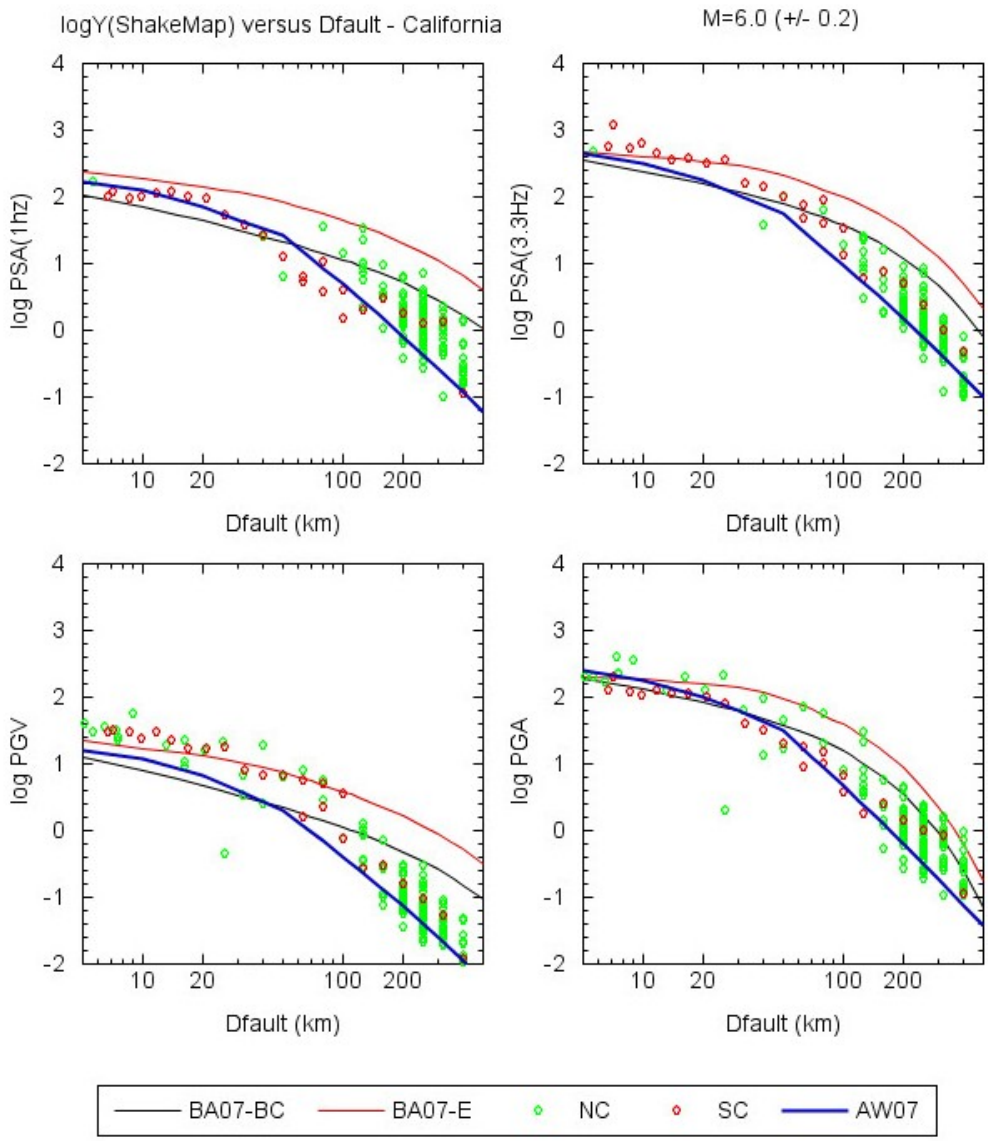

Figure 33 – Ground motions recorded by California ShakeMap, in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. ***M*** *= 6.0±0.2*

To make the intensity-based predictions for California appear consistent with empirical GMPEs, we need to correct the bias in BA07 at lower magnitudes, and similarly correct the bias in the intensity-inferred predictions, so that the two sets of prediction equations will overlie each other, at least approximately. To do this, an ad-hoc adjustment factor (AdjF, in log units) is made to the BA07 equations (**M**≥4) to bring them down to the observed ShakeMap amplitudes overall, at lower magnitudes:

$$\text{Log AdjF(BA07)} = \min((0.004(M-6.5)), 0.) * \min(Rjb, 100) \quad (1)$$

This factor, to be applied to PSA(1Hz), PSA(3.3Hz), PGA and PGV, is *subtracted* from the BA07 equations. The factor goes from 0 at close distance to a maximum value of 1.0 log units for **M**4.0 at 100 km. The maximum value of the factor at 100 km decreases from 1.0 to 0. as magnitude increases from 4.0 to 6.5. At distances greater than 100 km, the factor is constant at its value at 100 km.

The factor to raise the ground motions inferred from the MMI values is:

$$\text{Log AdjF(GM-MMI)} = 0.003 * \min(Dfault, 100) \quad (2)$$

This factor, to be applied to PSA(1Hz), PSA(3.3Hz) and PGV (but **not** PGA, as PGA is well-predicted), is *added* to the ground motions inferred from MMI data. The factor increases with distance from 0, to a maximum value of 0.3 log units at 100 km, then is constant at this value for greater distances. It is constant for all magnitudes, and corrects an apparent bias that arises when the KA07 relationships are inverted to infer ground motion from intensity.

Figures 34-37 show that, when these adjustment factors are applied to the BA07 and AW07 predictions, they are then reasonably self-consistent, and in good agreement with the ground-motion data in California (though the intensity-based PGA values are somewhat under-estimated for **M**5.5 and 6.0 at larger distances). It is acknowledged that these bias corrections are very crude, and should be improved upon in future more detailed studies of these issues. They are applied here simply to allow internal self-consistency between ground motion data and prediction equations derived from both strong-motion data (BA07) and intensity-based methods (AW07 with KA07). This is needed in order to test whether there is an apparent contradiction between MMI observations in ENA and ENA ground-motion prediction equations.

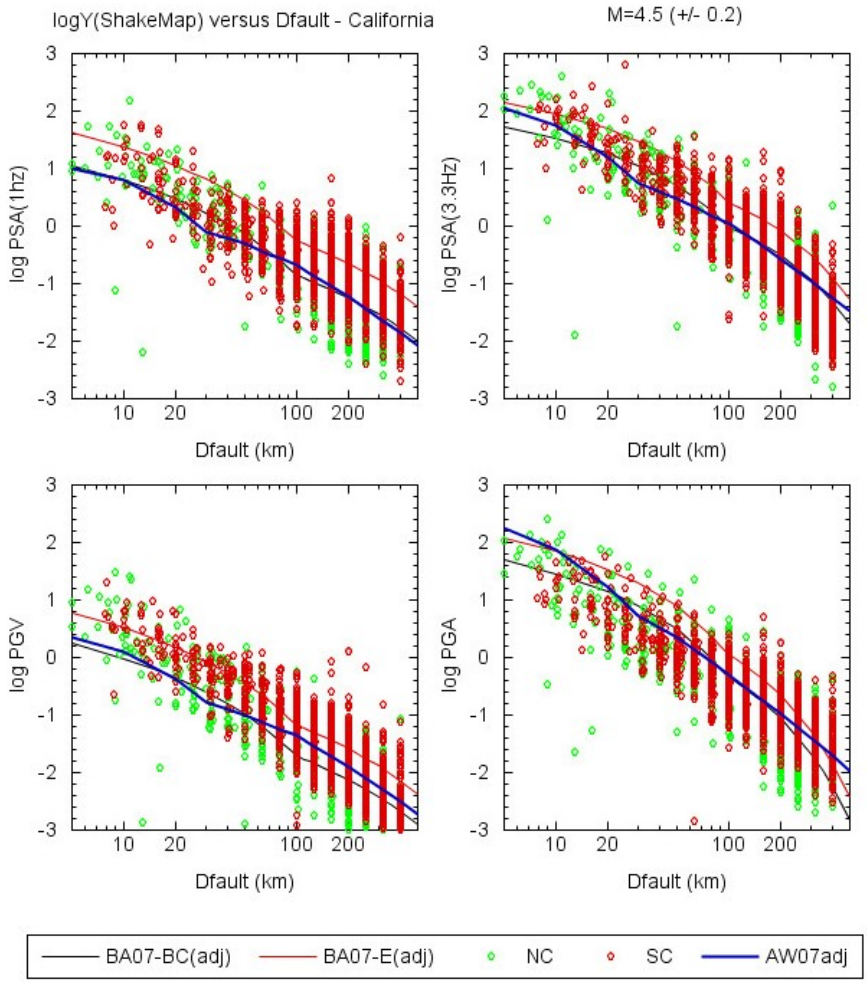

Figure 34 – Ground motions recorded by California ShakeMap, in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. Adjustments for bias (Eqns 1, 2) applied to BA07 and AW07. ***M*** *= 4.5±0.2.*

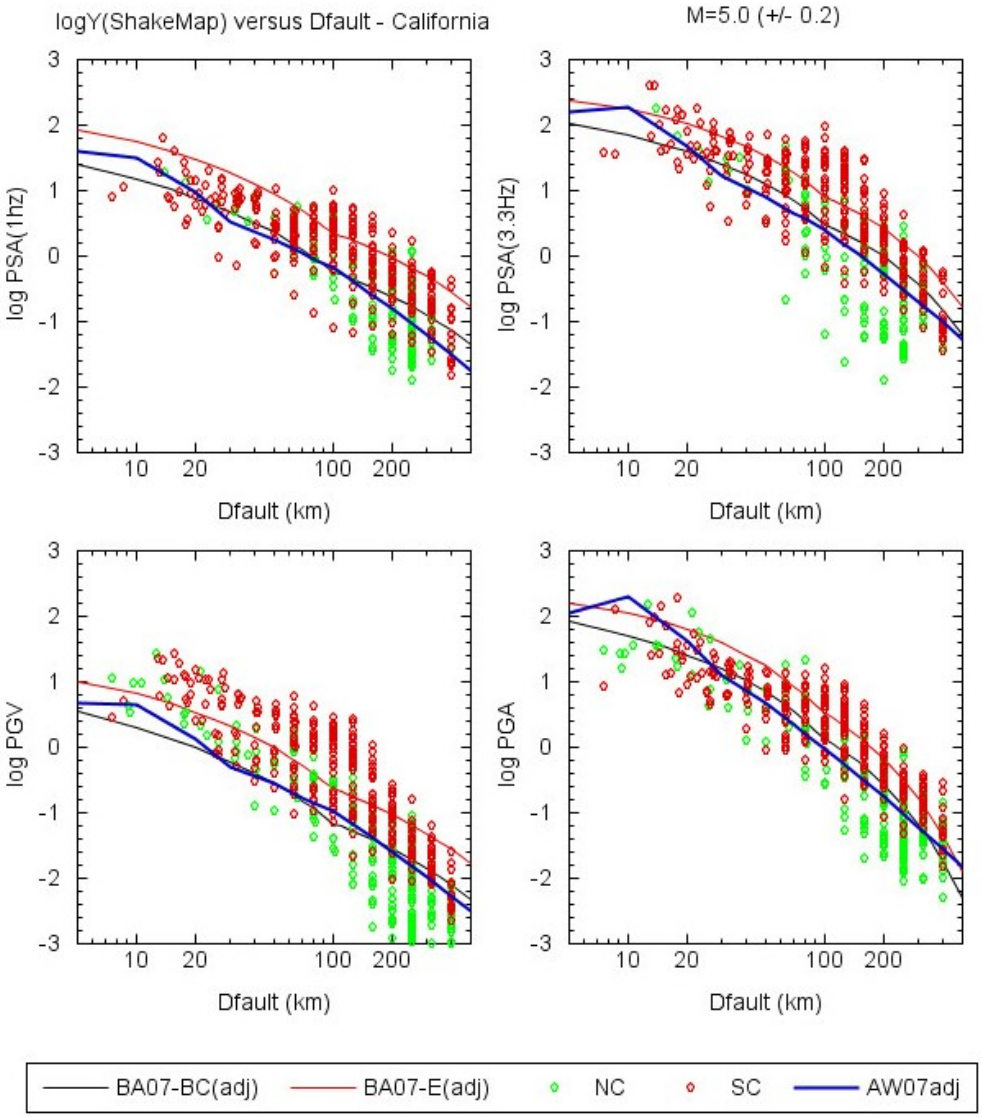

Figure 35 – Ground motions recorded by California ShakeMap, in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. Adjustments for bias (Eqns 1, 2) applied to BA07 and AW07. ***M*** *= 5.0±0.2*

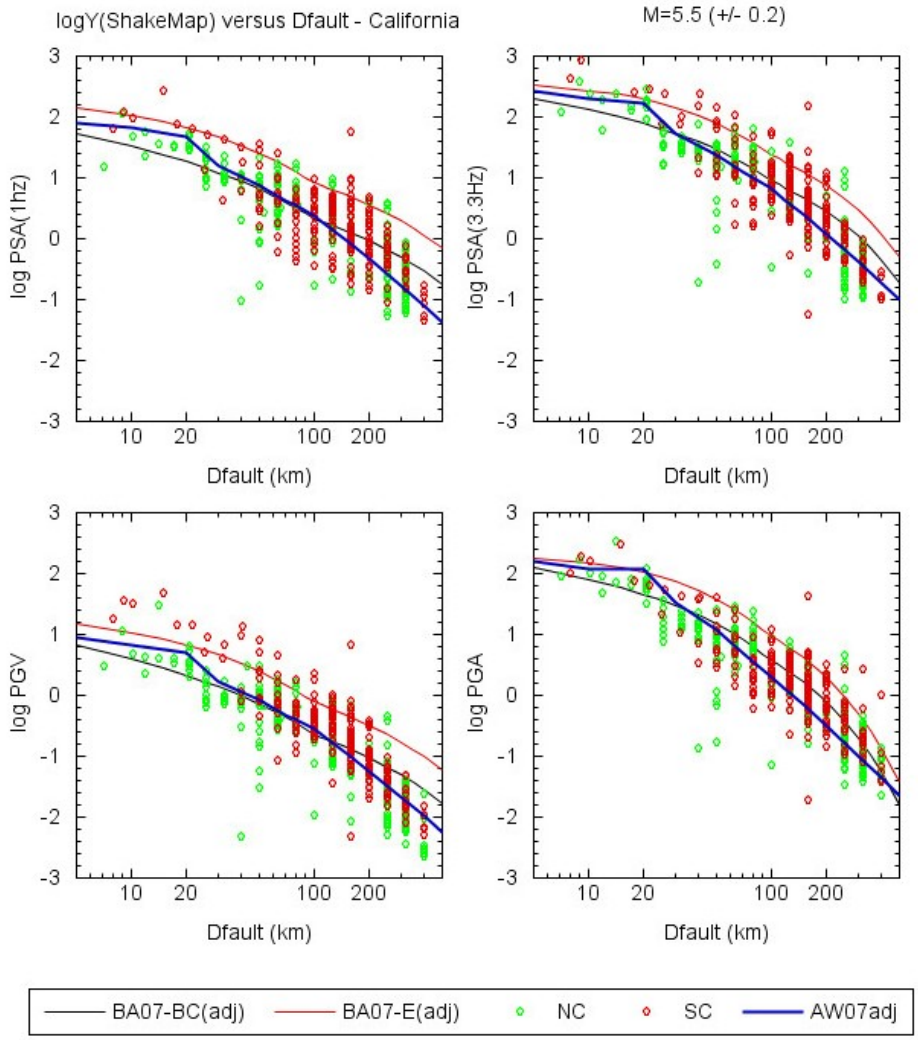

Figure 36 – Ground motions recorded by California ShakeMap, in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. Adjustments for bias (Eqns 1, 2) applied to BA07 and AW07. ***M*** *= 5.5±0.2*

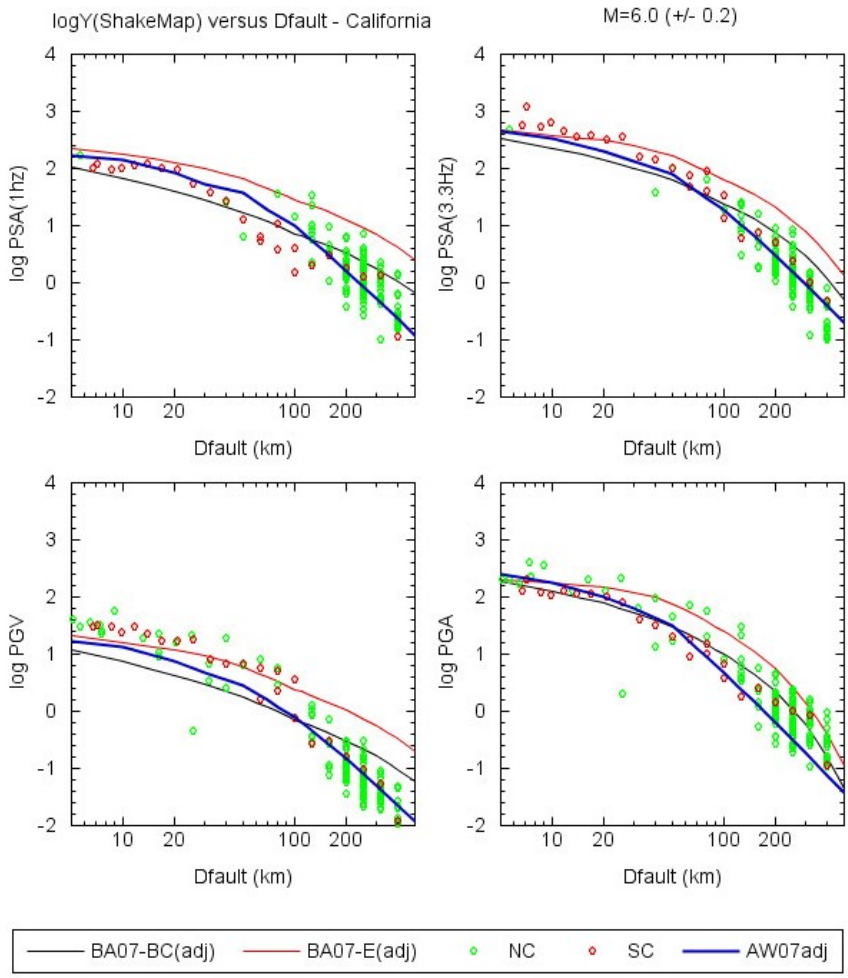

Figure 37 – Ground motions recorded by California ShakeMap, in comparison to GMPEs of Boore and Atkinson (2007) for B/C and E site conditions. Ground motions inferred from intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. Adjustments for bias (Eqns 1, 2) applied to BA07 and AW07. ***M*** *= 6.0±0.2*

Application of Intensity Data to Check ENA GMPEs

The intensity data for ENA can be converted to inferred ground-motion values using the KA07 inverted equations, corrected for bias as described in Equation (2), and compared to the ground-motion values predicted by ENA GMPEs. The intensity data are the binned weighted mean intensities versus distance for well-reported (generally >1000 observations) ENA earthquakes, up to May 2008 (including the April 18, 2008 Illinois earthquake of **M**5.2 and its largest aftershocks). For larger magnitudes, only historical data (as opposed to DYFI data) are available. These data are of lower quality, and are likely biased high due to their reliance on historical media sources (Hough and Pande, 2007); thus I graphically distinguish them from modern MMI-based data in the plots that follow. The GMPEs for comparison are the AB06 equations, for B/C (760 m/s) and E (150 m/s) site conditions.

Figure 38-41 present the comparisons of inferred ground motions in ENA in comparison to the predicted values of AB06, for **M**4.5 to 6.5 (there are insufficient data for comparison at larger magnitudes). The values inferred from MMI should correspond to the predicted soil values from AB06. For comparison, measured instrumental data from ENA, from the database of Atkinson and Boore (2006) are also plotted; these data should correspond to predictions for rock (B/C boundary plotted here for consistency with the California comparisons). The figures also include the ground motions inferred from the Atkinson and Wald (2007) prediction equations for MMI for ENA, corrected for bias as for the California data.

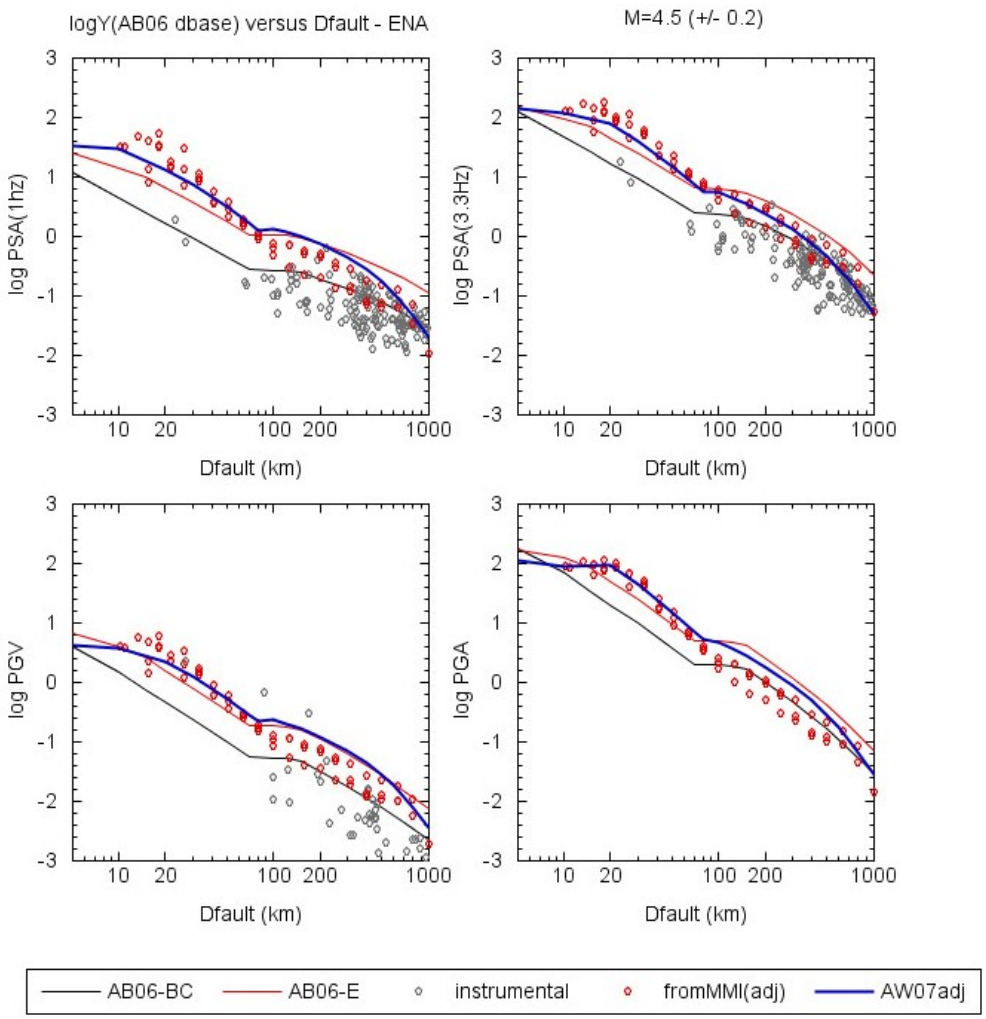

Figure 38 – Ground motions recorded in ENA on rock (gray) and inferred from MMI on soil (red), in comparison to GMPEs of Atkinson and Boore (2006) for ENA, for B/C and E site conditions. Ground motions inferred from ENA intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. Adjustments for bias (Eqns 1, 2) applied to both intensity-based ground-motion data, and AW07. ***M*** *= 4.5±0.2*

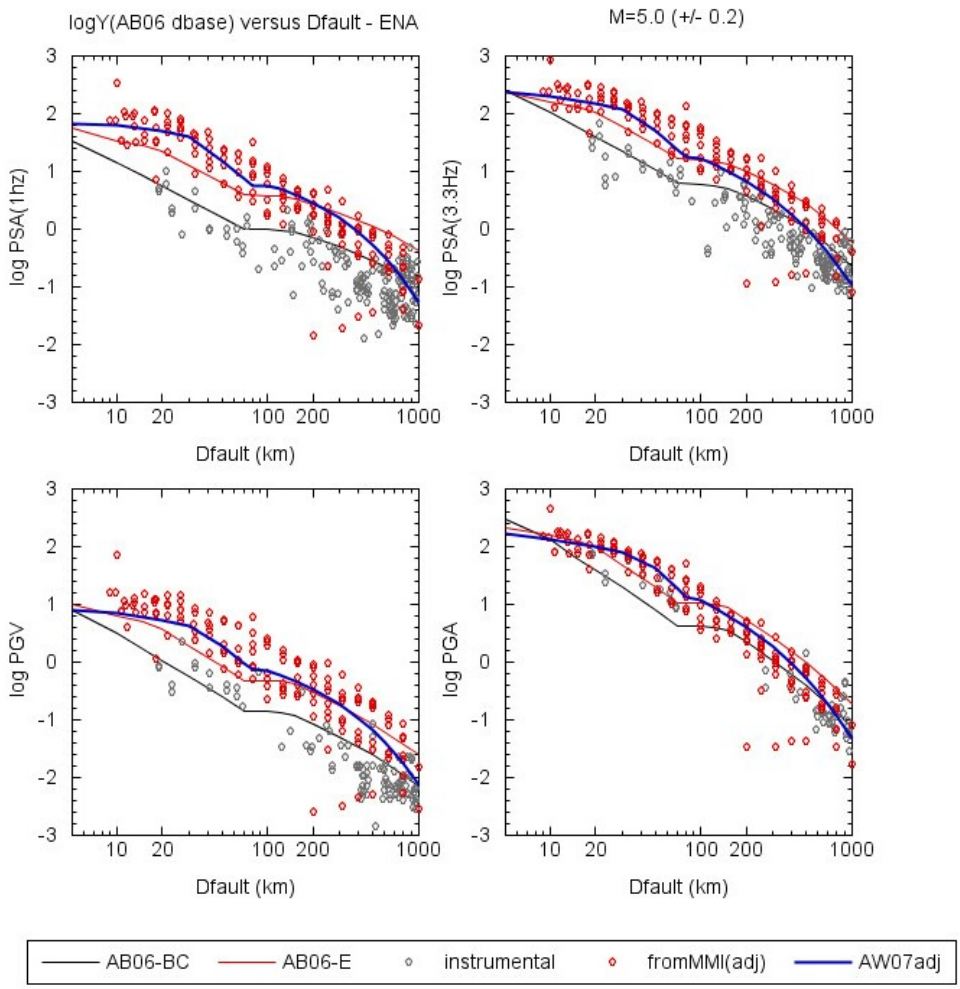

Figure 39 – Ground motions recorded in ENA on rock (gray) and inferred from MMI on soil (red), in comparison to GMPEs of Atkinson and Boore (2006) for ENA, for B/C and E site conditions. Ground motions inferred from ENA intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. Adjustments for bias (Eqns 1, 2) applied to both intensity-based ground-motion data, and AW07. ***M*** *= 5.0±0.2*

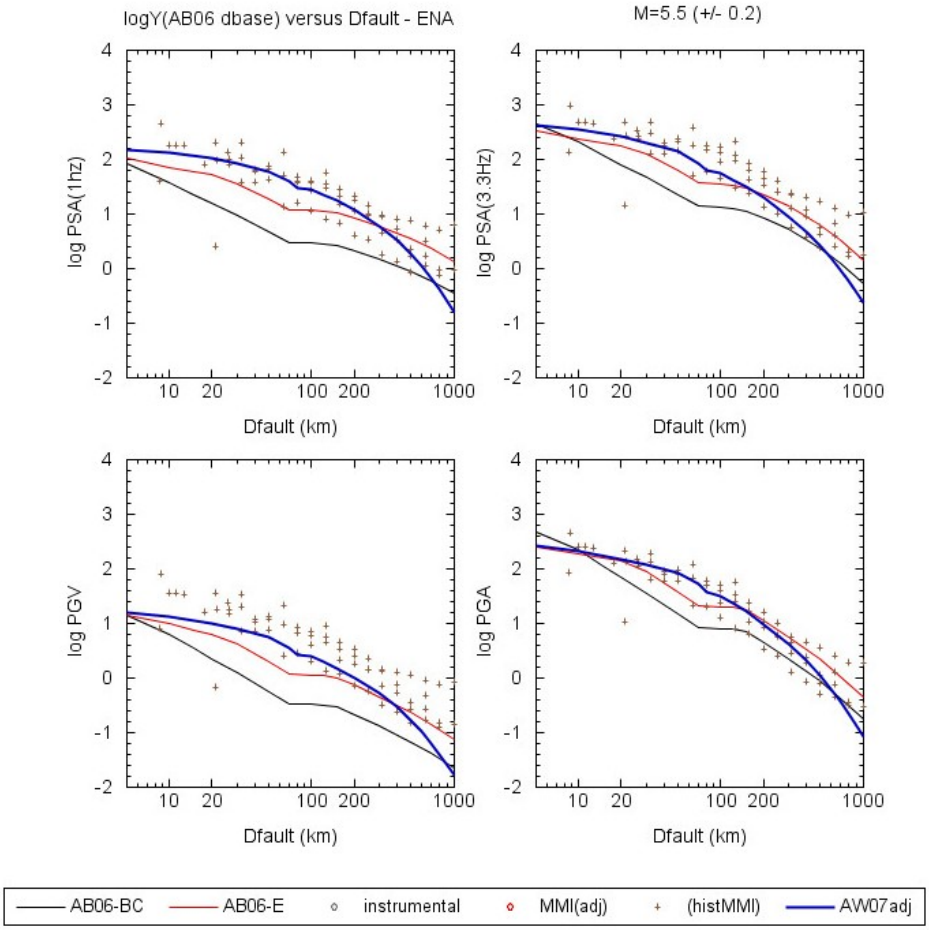

Figure 40 – Ground motions recorded in ENA on rock (gray) and inferred from MMI on soil (red), in comparison to GMPEs of Atkinson and Boore (2006) for ENA, for B/C and E site conditions. Ground motions inferred from ENA intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. Adjustments for bias (Eqns 1, 2) applied to both intensity-based ground-motion data, and AW07. Historical intensity data indicated by + symbols. ***M*** *= 5.5±0.2*

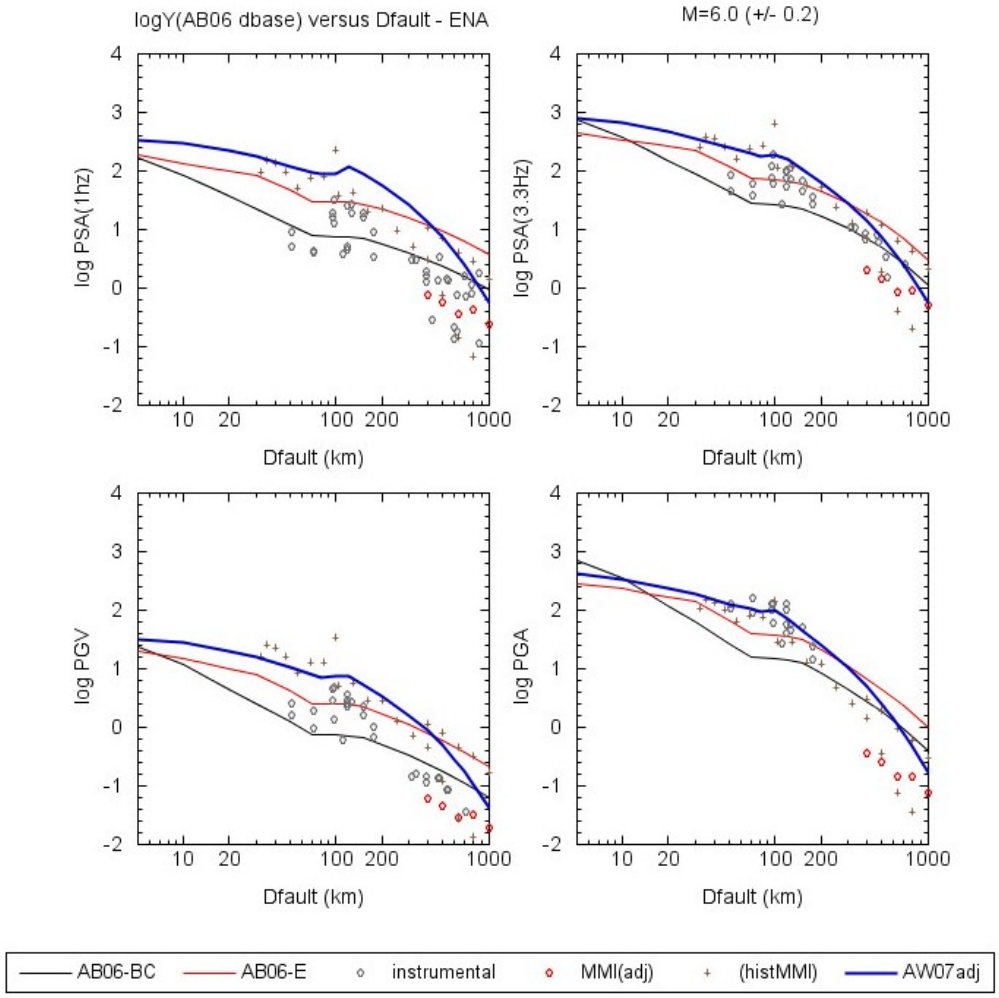

Figure 41 – Ground motions recorded in ENA on rock (gray) and inferred from MMI on soil (red), in comparison to GMPEs of Atkinson and Boore (2006) for ENA, for B/C and E site conditions. Ground motions inferred from ENA intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. Adjustments for bias (Eqns 1, 2) applied to both intensity-based ground-motion data, and AW07. Historical intensity data indicated by + symbols. ***M*** *= 6.0±0.2*

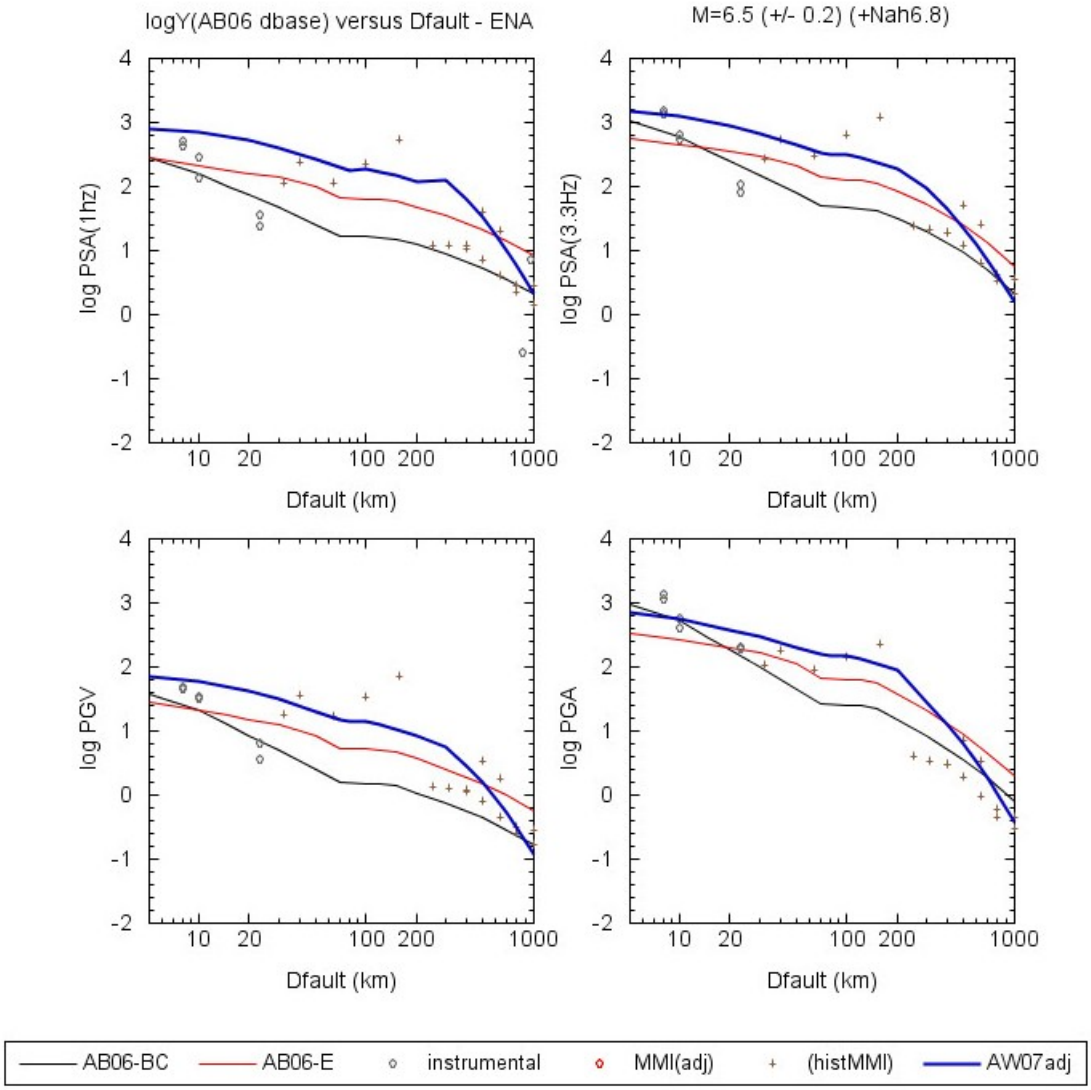

Figure 42 – Ground motions recorded in ENA on rock (gray) and inferred from MMI on soil (red), in comparison to GMPEs of Atkinson and Boore (2006) for ENA, for B/C and E site conditions. Ground motions inferred from ENA intensity prediction equations of Atkinson and Wald (2007), using KA07, are also shown. Adjustments for bias (Eqns 1, 2) applied to both intensity-based ground-motion data, and AW07. Historical intensity data indicated by + symbols. ***M*** *= 6.8±0.2 (plus Nahanni* ***M****6.8)*

A general conclusion that can be reached from these figures is that the ENA GMPEs of Atkinson and Boore (2006) are generally consistent with the intensity-based ground motions at 1 to 3.3 Hz, and PGA, if one assumes the intensities correspond to soft soil conditions (an exception is PGV, which appears to be underpredicted by AB06). There may be a tendency of AB06 to underpredict the intensity-inferred motions at intermediate distances (20 to 50 km), but it is difficult to be conclusive on this point given the rough approximations used to convert intensity to ground motion, and the uncertainty in the soil response factors applied. There may also be a tendency of AB06 to underestimate ground

motions from larger events (**M**6+), based on inferences from intensity, but again this is difficult to verify due to the paucity of quality data, and the likelihood that the historical data used are biased high (Hough and Pande, 2007). Agreement is actually quite remarkable in the magnitude ranges where data are abundant (**M**≤5.5), with the AB06 E prediction equations lying very close to those inferred from the AW07 intensity prediction equations. The differences between instrumental ground motions on rock in ENA, and inferred values on soil based on intensity, are very significant, pointing to the importance of soil amplification effects in interpreting ground motions. Soil response, coupled with bias in historical intensity data, may be responsible for a widely-held suspicion that ENA ground motion prediction equations are inconsistent with intensity observations from past large earthquakes. Further work on refining the relationship between intensity and recorded ground motion, and the influence of site effects, may help resolve these issues more definitively.

Discussion and Conclusions

An interesting and important inference from this study is that the BA07 equations for shallow earthquakes in active tectonic regions are biased high for small-to-moderate magnitudes at distances > 20 km, at least for application to California. This bias has contributed to past conclusions that ENA ground-motion predictions according to Atkinson and Boore (2006) appear to be "too low" relative to GMPEs for California. When this bias in BA07 is corrected, the impression is quite different. This is shown on Figure 43, which compares the bias-corrected BA07 GMPEs (B/C site conditions) to those of AB06 (also for B/C site conditions). (Note: it is implicitly assumed that closest distance to fault and Joyner-Boore distance are approximately equal for Dfault>5 km.) In this plot, predicted ENA and WNA motions are very similar at low frequencies, at distances out to 100 km. At greater distances, ENA motions start to exceed those for WNA, as would be expected from the lower ENA attenuation. At higher frequencies, ENA motions are greater than those in WNA near the source, as would be expected from the higher stress drop. Motions decay more rapidly initially in ENA, due to the higher geometrical spreading rate (1.3 in ENA vs. 1.0 in WNA), but then are much larger than WNA motions at large distances (>100 km), due to the high Q in ENA relative to active tectonic regions.

I conclude that the ENA ground-motion prediction equations of Atkinson and Boore (2006) are generally consistent with expectations based on the predictions of Boore and Atkinson (2007) for active tectonic regions, when bias in the latter due to a sparse database at lower magnitudes is considered. The ENA GMPEs of Atkinson and Boore (2006) are also generally consistent with inferences based on intensity observations, when the effects of soil response are considered.

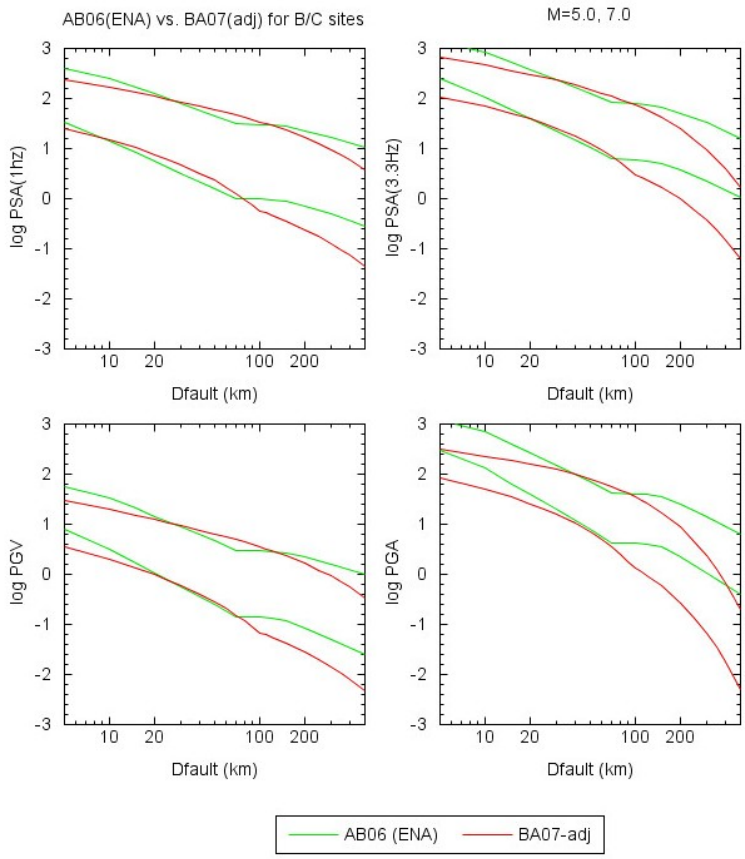

Figure 43 – Comparison of ENA GMPEs of Atkinson and Boore (2006) to GMPEs of Boore and Atkinson (2007) for active tectonic regions, after correcting the latter for low-magnitude bias (Equation 1), for ***M*** *= 5.0 and 7.0. Both for B/C site conditions (760 m/s).*

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