Observations on regional variability in ground-motion amplitudes for small-to-moderate earthquakes in North America

Gail M. Atkinson and Mark Morrison, University of Western Ontario

For submission to BSSA

Revised Jan. 2009

Abstract

The regional variability in earthquake ground-motion amplitudes for a given magnitude and distance in western North American environments was examined using ShakeMap data from small-to-moderate events. The abundance of data for small-to-moderate events in California allows average ground-motion levels, as a function of magnitude and distance, to be resolved with a high level of confidence. Ground-motion amplitudes in northern California are lower on average than those for southern California, for events of the same magnitude, at distances in the range from 120 – 250 km, over all frequencies. The observed regional variations could be indicative of regional differences in attenuation effects or site effects.

An unexpected result of the study is the finding that ground motions for events of **M**<5.5 in California attenuate more rapidly with distance than predicted by the recent PEER-NGA ground-motion prediction equations for shallow crustal earthquakes in active tectonic regions (Boore and Atkinson, 2008; Chiou and Youngs, 2008; Abrahamson and Silva, 2008 and Campbell and Bozorgnia, 2008). It appears that the limited **M**<5.5 data used in the PEER-NGA study are not representative of ground motions from **M**<5.5 events in California in general. (At larger magnitudes, however, the California ShakeMap observations converge with expectations based on the PEER-NGA equations.) By contrast, the California ground motions for **M**<5.5 at distances less than 100 km appear consistent with those that would be predicted by the ground-motion model of Atkinson and Boore (2006) for eastern North America, if an adjustment is made for a factor of two difference in stress drop between eastern and western North America. This attests to the need to include a broad range of magnitudes and distances in the development of comprehensive ground-motion prediction models.

Introduction

Standard practice in the assessment of seismic hazards requires the use of ground-motion prediction equations (GMPEs) that quantify the expected peak ground motion and response spectral parameters. The main predictive variables for GMPEs are earthquake magnitude and distance, with other parameters such as site condition, fault mechanism, directivity and so on playing a lesser role in modifying the prescribed motions. GMPEs are typically developed using empirical regression techniques to characterize a ground-motion database (though theoretical methods are sometimes used to extend or supplementa sparse database). Recently, for example, the PEER-NGA (Pacific Earthquake Engineering Research Center – Next Generation Attenuation) project has produced several alternative equations to describe the motions for shallow crustal earthquakes in active tectonic regions around the world (Power et al., 2008; Boore and Atkinson, 2008; Chiou and Youngs, 2008; Abrahamson and Silva, 2008 and Campbell and Bozorgnia, 2008). Empirical equations have also been developed on a global basis for both in-slab and interface subduction earthquakes (Youngs et al., 1997; Atkinson and Boore, 2003).

The motivation to combine data from different regions in developing GMPEs is strong, as few regions have sufficient data in the magnitude-distance range of engineering interest to develop robust local empirical GMPEs. The PEER-NGA equations, for example, benefit greatly in their robustness from the inclusion of data from large well-recorded earthquakes in Taiwan and other regions, in addition to the California data used in previous generations of such equations (Power et al., 2008). A critical implicit assumption in this approach is that ground motion data from different regions are sufficiently similar in terms of their embedded source and attenuation properties to warrant their combination into a single database. The resulting equations may be biased in the median in their applicability to certain regions, and may overestimate variability in the median (sigma), if there is significant regional variability in earthquake source and attenuation effects, or in average regional site amplifications for a given site class variable.

The regional variability of ground motions has been addressed in several previous studies. Wang et al. (2004) studied ground motions from aftershocks of the 1999 Chi Chi Taiwan earthquake, in comparison to prediction equations derived largely from California data. They showed that the motions for aftershocks in Taiwan of **M**5.8 to **M**6.3 agreed with prediction equations based on California data (Abrahamson and Silva, 1997; Campbell, 1997; Sadigh et al., 1997; Boore et al., 1997) at close distances, but decayed more rapidly with distance, indicating greater regional attenuation in Taiwan than in California. Douglas (2004) performed an analysis of variance to show that there is little evidence of regional variability of ground motions in Europe, in regions including the Caucasus, Italy, Greece and Iceland. Furthermore, Stafford et al.(2008) have shown that the PEER-NGA ground-motion prediction equations, developed from a global database of shallow crustal earthquakes, are a good predictive model for application to the Euro-Mediterranean strong-motion database. Thus it appears that shallow crustal earthquakes in Europe produce motions similar to those predicted by global relationships, while there may be some evidence for attenuation differences between California and Taiwan. On a continental scale, it has long been known that seismic waves propagate more efficiently at regional distances in eastern North America than in the west, resulting in lesser attenuation in the east, at least at large distances (Nuttli, 1973; Benz et al., 1997).

The original aim of this note was to examine regional variability in earthquake ground-motion amplitudes for a given magnitude and distance in western North American environments, from California to British Columbia (B.C.). Data sources are the seismographic data collected by ShakeMap in California and the Pacific Northwest, supplemented by data compiled from the Canadian Seismographic Network in B.C. The data are from small-to-moderate magnitudes, as such events are sufficiently abundant to allow robust statistical conclusions as to whether motions in different regions are the same for a given magnitude and distance. The investigation initially focused on evaluating systematic differences in amplitudes between crustal earthquakes in southern and northern California, as the ground-motion database is richest in these regions. Systematic differences were indeed found, as is described below. We also found that the attenuation rate of small-to-moderate California earthquakes is steeper than that predicted by the PEER-NGA ground-motion prediction equations. This finding was unexpected, and has important implications which we also explore in this note.

Database

The key to identifying regional variability in ground-motion characteristics with confidence is a large database that allows conclusions of statistical significance to be drawn. To distinguish regional differences, we require databases having common magnitude-distance attributes; the attributes must be in common over multiple recordings to average out station site effects, and over multiple events to average out event source effects. Furthermore, the recording stations should be distributed in space (as opposed to multiple stations in a single locality). These conditions are only met for small-to-moderate events, in well-instrumented regions having relatively high levels of seismicity. ShakeMap in the western U.S. is a good source of such data (see Data and Resources section). Figure 1 shows the locations of the events and stations used in this study. We downloaded ShakeMap data from events of **M**≥3.5 that occurred over the last 5 years in California and the Pacific Northwest (PNW) (Morrison, 2008); the period of 5 years was selected to obtain well-sampled data, as ShakeMap coverage has improved over time, while allowing a reasonable scope (as data compilation is time-consuming). ShakeMap data were supplemented with seismographic data compiled by Atkinson (2005) for events of **M**>4 in British Columbia (B.C.), updated to include newer events of **M**>3.5. We distinguish between the ShakeMap data compiled primarily for the Seattle region of the PNW, and the B.C. data. The ShakeMap PNW data are largely from the Puget Sound basin region, while the B.C. data are for hard rock sites. Thus the ShakeMap PNW and B.C. amplitude characteristics may differ from each other. The compiled data parameters are peak ground acceleration and velocity, and response spectral acceleration (5% damped) at 0.3s and 1 s, all for the log-averaged horizontal component (the geometric mean). (Note: ShakeMap spectral parameters are available at 0.3, 1 and 3 sec, but longer period motions are very weak for the low magnitude range used in this study and thus not reliable.)

To facilitate direct comparisons of ground motion amplitudes as a function of magnitude and distance, we binned the data to compute log-average ground motion amplitudes, in magnitude bins 0.3 units in width, and distance bins 0.1 log units in width. Thus we compute the average observed amplitude for events within a region for, say, **M**3.6 (±0.1) at log Fault Distance (in km) = 0.1, 0.2, 0.3, etc. Note that due to the small magnitudes of the events used, the fault distance is approximately equal to the hypocentral distance. The magnitude scale used is believed to be moment magnitude (**M**) or equivalent throughout. We did not determine magnitudes for any events specifically for this study, but relied on the values provided by others. For California and the PNW, the ShakeMap documentation indicates that all magnitudes are moment magnitude or equivalent. For B.C., we used the moment magnitude values provided by Atkinson (2004). Figure 2 shows the number of records included in each magnitude-distance bin for each region, for **M** 3.6 to 5.1. In California, the number of events included in each magnitude range is generally >20 for **M**≤4.5, although there will not necessarily be >20 events represented in each distance bin. Events of **M**>5.1 are not considered in detail in this study, because the number of events that could be included within the magnitude bin is less than five, even in California; for larger magnitudes, we often have many recordings within a distance bin, but they represent only a few events at best. For crustal or in-slab events in the PNW or B.C., the data are sparse even at low magnitudes, with only a few magnitude-distance bins having >10 records, and these generally originating from only a few events. This limits our ability to draw definitive conclusions on differences between PNW or B.C. ground motions and those in California.

A challenge in interpreting comparisons between regions involves the physical and statistical significance of observed differences in ground-motion amplitudes. The typical standard deviation of ground-motion amplitudes for a given magnitude and distance (sigma) is about a factor of two (eg. Boore and Atkinson, 2008), or 0.3 log(10) units. Statistically, if we have 10 independent observations from within a magnitude-distance bin, the standard error of the mean would then be of the order of 0.3/√10, or about 0.1 log units, which should be a sufficiently small error to allow detection of regional differences in amplitude. However, the observations are not generally independent as they come from a limited number of events, and may sample a limited geographical space. Furthermore, the physical significance of observed differences is questionable if they do not persist over a broad or consistent range of the magnitude-distance bins available. Thus we can only be sure of the significance of apparent amplitude differences between regions if the observed trends show a consistent pattern over magnitude and distance, and if they are derived from bins that represent not only multiple observations, but at multiple locations, and from multiple events. This suggests a much larger number of records per bin is needed – perhaps of the order of 100 instead of 10. Based on these considerations, we should be able to draw robust conclusions on regional variability of motions in southern California versus northern California over a limited range of magnitudes and distances (**M**3.6-4.5 at 50-400 km). For the PNW and B.C., we cannot draw robust conclusions, but can at least note some apparent general trends.

A limitation of ShakeMap data is that site conditions are not readily available. Over the western U.S. ShakeMap sites (California and the PNW), the site conditions will likely represent a range from rock to soft soil (NEHRP A to E conditions), with most sites being located on soil. The B.C. seismographic data are entirely on hard rock (NEHRP A/B site conditions). Regional variability in what constitutes the "average site condition" is thus one possible source of regional variability in observed ground-motion amplitudes. We would expect regional differences in the average site condition to manifest as a constant offset in amplitudes from one region to another, possibly of a different amount at different frequencies. It should be noted that all of the motions used in this study are weak motions (<10%g), such that nonlinearity of soil response is not an issue in the interpretation of the observations.

There are several other possible explanations for any observed regional differences in ground motions. A regional difference in source properties or magnitude-determination practices could produce a constant offset in observed amplitudes, for example. By contrast, a regional difference in attenuation properties would manifest as a difference in amplitudes between one region and another that depends on distance.

Comparison of Southern California to Northern California Ground Motions

Regional variability in ground-motion amplitudes is most convincingly tested for northern versus southern California, due to the richness of the available datasets. We focus the comparisons on **M**<5, for which the data are plentiful at distances from 20 to 400 km (Figure 2). Data from the events and stations shown on Figure 1 were downloaded from ShakeMap and organized into magnitude groups: **M**3.6±0.1, **M**3.9±0.1, **M**4.2±0.1 and **M**4.5±0.1. Within each magnitude group, data were binned into distance bins 0.1 log units in width, for fault distances of 0.7±0.05 log units (5 km), 0.8±0.05 (6.3 km), 0.9±0.05 (7.9 km), 1.±0.05 (10 km), and so on. The log average amplitudes within each magnitude-distance bin, for each regional dataset, are compared on Figures 3 to 6 (at 0.3 s, 1 s, PGV and PGA), for magnitude-distance bins having at least 10 observations. Typical standard deviations within a bin are about 0.4 log units; this large variability probably reflects the inclusion of a variety of site conditions within each bin. Because of the large number of observations (N>10 at distances >20 km), standard errors of the means (standard deviation/√N) are <0.1 log unit in most magnitude-distance bins, which would suggest that discernable differences in amplitudes on the plots are statistically significant. (This can be readily confirmed by standard t-tests, which indicate that the chances of getting the observed offsets between northern and southern California amplitudes at distances ≥50 km by random chance are negligible, <<1%.) However, as discussed above, the significance of the observed differences requires more careful consideration. If the observations within a bin do not include multiple events, recorded over multiple locations in space, they may be biased and thus not representative of true regional differences. Furthermore, to be physically significant the observed differences should persist in a systematic way over a range of magnitudes and distances.

To focus on differences in amplitudes which are truly significant and persistent, Fiugre 7 plots the observed differences in southern and northern California amplitudes for just those magnitude-distance bins having N>100 observations in both regions. Such bins generally include multiple events that are well recorded in space. The figure shows the log differences in amplitude (southern California minus northern California) versus distance for each magnitude bin, and the mean difference over all magnitudes (for bins with N>100). This figure suggests that differences in spectral amplitudes between the two regions are either small or insignificant (ie. not detectable with confidence) for distances D < 100 km, though interestingly the difference in PGA levels between southern and northern California appears to be significant for D<100 km. There is a distance range between about 120 km and 250 km for which southern California amplitudes are clearly higher than those in northern California, for all ground-motion parameters available. Then at larger distances those differences diminish, with amplitudes in the two regions converging for distances of 300 km or greater. These trends might be due to attenuation differences, possibly caused by crustal structure effects such as a Moho bounce effect that elevates amplitudes in a selective distance range. Alternatively, they could reflect the influence of basin sites in southern California that systematically amplify motions from events that happen to occur in this distance range. For example, the station density is greatest in the Los Angeles Basin region, which records many events that occur on the San Andreas fault system at this distance range (see Figure 1). However, basin site effects are expected to be most significant at low frequencies, while the ground-motion differences observed in our study are of a similar order for PGA, PGV and PSA at 0.3 to 1 s.

To place the observed regional attenuation trends in context, we plotted two ground-motion prediction equations (GMPEs) on Figures 3 to 6 for reference. The comparison of these GMPEs to the observed data in California surprised us. The solid lines in Figures 3 to 6 show the predictions of Boore and Atkinson (2007, 2008) for shallow crustal earthquakes in active tectonic regions, from the PEER-NGA project, for NEHRP B/C boundary site conditions (time-averaged shear-wave velocity of 760 m/s over the top 30 m). The PEER-NGA equations, like most empirical GMPEs, were derived from a strong-motion dataset that includes primarily events of **M**5 and greater, from active tectonic regions including California. Data in the small-to-moderate magnitude range that we used in this study were not included, due to the focus of the PEER-NGA equations on the magnitude-distance range of most interest for seismic hazard analysis (ie. damaging ground motions). The magnitude range of validity for the empirical PEER-NGA equations is **M**>4.5, so we plot the Boore and Atkinson predictions (BA07) only for the **M**4.2 and **M**4.5 magnitude groups, to avoid gross extrapolation. We see immediately that the attenuation slope of the BA07 equations is much less steep than the observed attenuation rate of small-magnitude earthquakes, though the near-source amplitudes appear to agree with those predicted by the BA07 model. This mismatch is not particular to the BA07 GMPE model; it is a general problem for the PEER-NGA equations. We demonstrate this in Figure 8, which compares the alternative PEER-NGA GMPEs for **M**4.5, all for B/C site conditions, for PSA at 1 sec (assuming a strike slip fault placed at a depth of 5 km). It is important to note that the equations are all plotted for B/C boundary conditions, while most of the observations in California are likely on soil (NEHRP C or D), as indicated by the California site-condition map of Wills and Clahan (2006); for this reason, we would expect the equations to underpredict, rather than overpredict, the average data amplitudes. Overall, the PEER-NGA equations feature similar near-source amplitudes and similar rates of attenuation. All of the PEER-NGA equations overpredict the California data for **M**4.5, though the Chiou and Youngs (2008) equations do a noticeably better job than the other equations, as they predict lesser amplitudes at distances beyond 20 km. The mismatch between model predictions and observed small-magnitude data in California exists due to the type of data selected for use in the development of empirical models such as the PEER-NGA equations. The PEER-NGA equations were derived from motions for larger events, and may be significantly biased when applied to small magnitudes (which were not included in the PEER-NGA database). (Note: A check of the PEER-NGA equation predictions against the ShakeMap data for larger California events, made for consistency, indicates that the mismatch disappears between about **M**5.5 and **M**6, though data are too sparse to be definitive).

The steep attenuation of observed amplitudes in California relative to the BA07 model was not expected. This prompted us to also compare the observations to the GMPEs of Atkinson and Boore (2006) developed for eastern North America (ENA) for B/C boundary site conditions. We used the stress drop adjustment factor provided by Atkinson and Boore (2006) to make the predictions for a 70 bar stress drop (typical California value) instead of the default of 140 bars used for ENA (eg. see Atkinson and Boore, 1990). The stress-factor adjustment should make the AB06 predictions reasonable for California at near-source distances, but does not account for differences in attenuation between ENA and California. The AB06 ENA equations match the

California ground motions at distances up to 70 km better than we expected, in view of the significant differences in attenuation processes between ENA and California. The California amplitudes in this distance range are higher than the AB06-predicted values for 70 bars by a constant factor of about 0.2 log units at 0.3 s, increasing to about 0.4 log units at 1 sec and PGV. These differences could be explained by the average site conditions of the recorded ground motions in California. Although we do not know the specific site conditions for each station, we expect that most of the stations are on soil (NEHRP C or D) (see Wills and Clahan, 2006), which would be significantly softer than the B/C reference condition plotted for the GMPEs. Based on the site amplification model of Boore and Atkinson (2008), we would expect amplification of about 0.2 log units from B/C to D at 0.3s, increasing to 0.4 log units at periods near 1 s (for the weak motions of this study). For PGA, the observed amplitudes fall below the AB06-based predictions, perhaps because of the effects of kappa (Anderson and Hough, 1984), which attenuates high frequencies more steeply in California than in ENA (Atkinson and Boore, 1990). However, the main point of interest is that the shape of the AB06 attenuation curve is a good fit to the apparent attenuation rate for the California data, at distances out to 70 km – and a noticeably better fit than is provided by most of the PEER-NGA equations. At larger distances, the AB06 attenuation model predicts lesser attenuation, as would be expected due to the more efficient propagation of regional phases in ENA as compared to California (Atkinson and Boore, 1990).

The good match of California data to the ENA GMPE model of Atkinson and Boore (2006) at small magnitudes has important implications, and we take this paper on a tangent for the next few paragraphs to explore them. A controversial feature of the AB06 equations is the relatively steep geometric attenuation adopted for the model within 70 km. Specifically, AB06 embed a geometric spreading rate of $R^{-1.3}$ at $R<70$ km, based on empirical analyses of Fourier amplitude data for ENA earthquakes at small magnitudes (Atkinson, 2004). This is steeper than the R^{-1} used in many past models for ENA, and typically assumed to apply in California. It has been suggested that this steep attenuation in AB06 may lead to a decay of spectral amplitudes in the first 70 km that is too rapid. But we see that this rapid rate of decay is observed for small earthquakes not only in ENA, but also in California. This is highlighted in Figure 4, in which an attenuation rate of $R^{-1.3}$ is drawn on the figure for reference (at a level such that the reference-rate curve crosses the AB06 line at 10 km). We may not expect the slope of -1.3 to match that of the AB06 equations exactly, for two reasons: (i) the slope of -1.3 is for Fourier spectra - the observed rate for response spectra may deviate from this due to subtle differences in the nature of these ground-motion parameters; and (ii) the AB06 equations include anelastic attenuation as well as geometric spreading effects. The latter point warrants additional discussion. In general, it is difficult to separate geometric and anelastic attenuation effects. At close distances, however, attenuation will be dominated by the geometric spreading effects, especially for longer periods. For example, for a typical anelastic decay rate at long periods of $10^{(-0.001R)}$ (Benz et al., 1997), the anelastic amplitude decay from 10 to 70 km would be <0.1 log(10) units, compared to the geometric decay of 1.1 log units (for $R^{-1.3}$) over this distance interval. (This is why we have chosen to plot the geometric attenuation slope on the 1-s response spectra figure.) The close agreement between the AB06 model curve that embeds a geometric spreading rate of $R^{-1.3}$, and the $R^{-1.3}$ reference curve, indicates that the underlying apparent geometric spreading rate can be readily inferred from the observed spectral decay rate for PSA at 1 s. It is clear from inspection of Figure 4 that the attenuation rate due to geometric spreading in California, for $R<70$ km, must be close to $R^{-1.3}$. We do not try to formally fit a spreading rate, as that is not the purpose of this paper, and the compiled data are not well-suited for such a purpose. To obtain the actual geometric spreading rate for California events, a detailed study of a more comprehensive seismographic database from weak-motion instruments should be conducted.

The steep attenuation rate that we observe for California in this study applies to small events, which are effectively point sources. It is well known that for large events, the effects of fault finiteness alter the shape of the attenuation curve as the fault is approached, causing saturation effects that flatten the attenuation curve, and make the underlying geometric spreading rate difficult to discern. These effects have been well documented in empirical GMPEs (eg. Boore and Atkinson, 2008; Chiou and Youngs, 2008; Abrahamson and Silva, 2008 and Campbell and Bozorgnia, 2008). What we have shown here is that at small-to-moderate magnitudes, the attenuation of amplitudes in California is quite steep – consistent with a geometric spreading rate of the order of $R^{-1.3}$

based on inspection.   Furthermore, the PEER-NGA equations overestimate amplitudes from California events of **M**<5.5, especially at larger distances; this overestimation may apply to many other GMPEs by implication, as they are all derived from larger-magnitude datasets using similar methodologies. This may not be of direct consequence for most engineering applications of the GMPEs, but such biases distort our interpretation of ground motions in general, especially if we are comparing GMPEs developed for one region to those developed for another. The problem is particularly pronounced in North America, where western GMPEs calibrated to large-magnitude data are compared to eastern GMPEs calibrated to small-magnitude data. To enable valid inter-regional comparisons, we need comprehensive ground-motion prediction models that span a large range of magnitudes and distances, which overlap between regions.

Comparison of Ground-Motion Amplitudes from California to those in the Pacific Northwest and British Columbia

The data on ground-motion amplitudes in the Pacific Northwest (PNW) and British Columbia (BC) are sparse, so comparisons of ground-motion properties are less definitive than those for California. Furthermore, the site conditions of the stations are poorly known. The PNW stations are likely a mix of rock and soil sites, while the B.C. stations are all sited on hard rock. In. B.C., typical hard-rock velocities are about 1500 m/s (Hunter et al., 1997), making them NEHRP A/ B. On Figures 9 to 12, binned ground motions for the PNW and B.C. are compared to those for California. The magnitudes plotted are from 3.6 to 5.1, to allow the maximum range of the data to be seen. Data are plotted for all bins with at least 3 observations (compared to the minimum of 10 used for California, where we can afford to be more selective). The GMPEs of BA07 for B/C boundary conditions are plotted for reference, along with GMPEs proposed by Atkinson (2005) for rock sites (NEHRP A/B boundary) in B.C., for crustal earthquakes. On the figures, we distinguish between crustal and in-slab events in the PNW and B.C.; offshore events are not included in this study.

Due to the paucity of observations, we cannot reach compelling conclusions. However a general observation is that ground motions in the PNW and B.C. appear to be less than those for California for the same magnitude and distance, although the PNW and B.C. amplitude data represent few events. There do not appear to be readily-discernable differences in ground-motion amplitudes between in-slab and crustal events in most plots, though again the paucity of data prohibit robust conclusions. As noted for California, amplitudes at distances >20 km are significantly less than would be predicted by traditional GMPEs for western North America – likely because such equations are biased for low-magnitude events.

Conclusions

Analysis of small-magnitude earthquake data demonstrates that ground-motion amplitudes in northern California are lower on average than those for southern California, for events of the same magnitude, in the distance range from about 120-250 km; the difference is about a factor of two. The abundance of data for California allows these regional differences to be resolved with a high level of confidence, but does not point to their origin. The most likely explanations appear to be either (i) regional differences in attenuation due to crustal structure effects, such as a Moho bounce effect, that elevate amplitudes in a selective distance range; or (ii) regional differences in site amplification effects, perhaps due to the abundance of basin recording sites in the Los Angeles region, recording events along the San Andreas fault at this distance range.

For other regions of western North America, the paucity of data limits the strength of conclusions that can be drawn. We need to compile more data, perhaps by considering even lower magnitude levels, to resolve outstanding issues. In particular, analysis of more data could verify the following conclusions, which are suggested but not proven by the data presented in this study:

1. Ground motions in the PNW and B.C. are apparently less than those for California, for events of the same magnitude and distance.
2. Crustal and in-slab events appear to produce similar amplitudes for the same magnitude and distance.

An additional conclusion reached in this study is that empirical GMPEs for California (Boore and Atkinson, 2008; Chiou and Youngs, 2008; Abrahamson and Silva, 2008 and Campbell and Bozorgnia, 2008) may be biased for events of **M**<5.5; observed attenuation for small events is much steeper than that predicted by most GMPEs. (Amongst the recent PEER-NGA equations, those of Chiou and Youngs (2008) appear to have the least bias for **M**<5.) The bias arises from the magnitude range that is used in the development of empirical GMPEs, which is larger than the magnitude range examined in this study. The bias may not be important for seismic hazard applications, but is significant when comparing GMPEs for western North America, developed from large-magnitude data, to those for eastern North America, developed from small-magnitude data. It is important to include a broad range of magnitudes and distances in the development of comprehensive ground-motion prediction models, in order to enable regional comparisons.

Data and Resources

Data for the western United States were downloaded from ShakeMap at http://earthquake.usgs.gov/eqcenter/shakemap/. Data for British Columbia were obtained from the Geological Survey of Canada at www.earthquakescanada.nrcan.gc.ca using their autodrm facility.

Acknowledgements

This study was funded by the Natural Sciences and Engineering Research Council. Andrea Darlington and Karen Assatourians assisted with processing data for recent events in B.C. We are grateful to two anonymous referees and Associate Editor Art McGarr for constructive criticisms which greatly improved the manuscript.

References

Abrahamson, N. and W. Silva (1997). Empirical response spectral attenuation relations for shallow crustal earthquakes. Seism. Res. L., **68**, 94-127.

Abrahamson, N. and W. Silva (2008). Summary of the Abrahamson & Silva NGA ground-motion relations. Earthquake Spectra, **24**, 67-97.

Anderson, J. and S. Hough (1984). A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies. Bull. Seism. Soc. Am., **74**, 1969-1993.

Atkinson, G. (2004). Empirical attenuation of ground motion spectral amplitudes in southeastern Canada and the northeastern United States. Bull. Seism. Soc. Am.,**94**, 1079-1095.

Atkinson, G. (2005). Ground Motions for Earthquakes in southwestern British Columbia and northwestern Washington: Crustal, In-Slab and Offshore Events. Bull. Seism. Soc. Am., **95**, 1027-1044.

Atkinson, G., and D. Boore (1990). Recent trends in ground motion and spectral response relations for North America. Earthquake Spectra, **6**, 15-36.

Atkinson, G. and D. Boore (2003). Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions. Bull. Seism. Soc. Am., **93**, 1703-1729.

Atkinson, G. and D. Boore (2006). Ground motion prediction equations for earthquakes in eastern North America. Bull. Seism. Soc. Am., **96**, 2181-2205.

Benz, H., A. Frankel and D. Boore (1997). Regional Lg attenuation for the continental United States using broadband data. Bull. Seism. Soc. Am., **87**, 606-619.

Boore, D. and G. Atkinson (2007). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped SA at spectral periods between 0.01s and 10.0 s. PEER-NGA Report (April 30, 2007). http://peer.berkelely.edu

Boore, D. and G. Atkinson (2008). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped SA at spectral periods between 0.01s and 10.0 s. Earthquake Spectra, **24**, 99-138.

Boore, D. W. Joyner and T. Fumal (1997). Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work. Seism. Res. L., **68**, 128-153.

Campbell, K. W. (1997). Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra, Seism. Res. L., **68 ,**154 –179.

Campbell, K. and Y. Bozorgnia (2008). NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped elastic response spectra for periods ranging from 0.01 s and 10.0 s. Earthquake Spectra, **24**, 171-215.

Chiou, B. and R. Youngs (2008). An NGA model for the average horizontal component of peak ground motion and response spectra. Earthquake Spectra, **24**, 67-97.

Douglas, J. (2004). An investigation of analysis of variance as a tool for exploring regional variability of ground motions. Journal of Seismology, **8**, 485-496.

Hunter, J., J. Harris and J. Britton (1997). Compressional and shear wave interval velocity data for Quaternary sediments in the Fraser River delta from multichannel seismic reflection surveys. Geol. Surv. of Canada Open-file report 97-3325, Ottawa.Morrison, M. (2008). Regional comparisons of earthquake ground motion based on ShakeMap Data. B.Sc. Thesis, University of Western Ontario, April, 2008.

Nuttli, O. (1973). Seismic wave attenuation and magnitude relations for eastern North America. J. Geophys. Res., **78**, 876-885.

Power, M., Chiou, B., Abrahamson, N, Y. Bozorgnia, T. Shantz and Roblee, C. (2008). An overview of the NGA project. Earthquake Spectra, **24**, 3-21.

Sadigh, K., C. Chang, J. Egan, F. Makdisi and R. Youngs (1997). Attenuation relationships for shallow crustal earthquakes based on California strong motion data. Seism. Res. L., **68**, 180-189.

Stafford, P., F. Strasser and J. Bommer (2008). An evaluation of the applicability of the NGA models to ground-motion prediction in the Euro-Mediterranean region. Bull. Earthquake Eng. **6**, 149-177.

Wang, G., D. Boore, H. Igel and X. Zhou (2004). Comparisons of ground motions from five aftershocks of the 1999 Chi Chi Taiwan earthquake with empirical predictions largely based on data from California. Bull. Seism. Soc. Am., **94**,

Wills, G. and K. Clahan (2006). Developing a map of geologically defined site-condition categories for California. Bull. Seism. Soc. Am., **96**, 2198-2212.

Youngs, R., S. Chiou, W. Silva and J. Humphrey (1997). Strong ground motion attenuation relationships for subduction zone earthquakes. Seism. Res. L., **68**, 58-73.

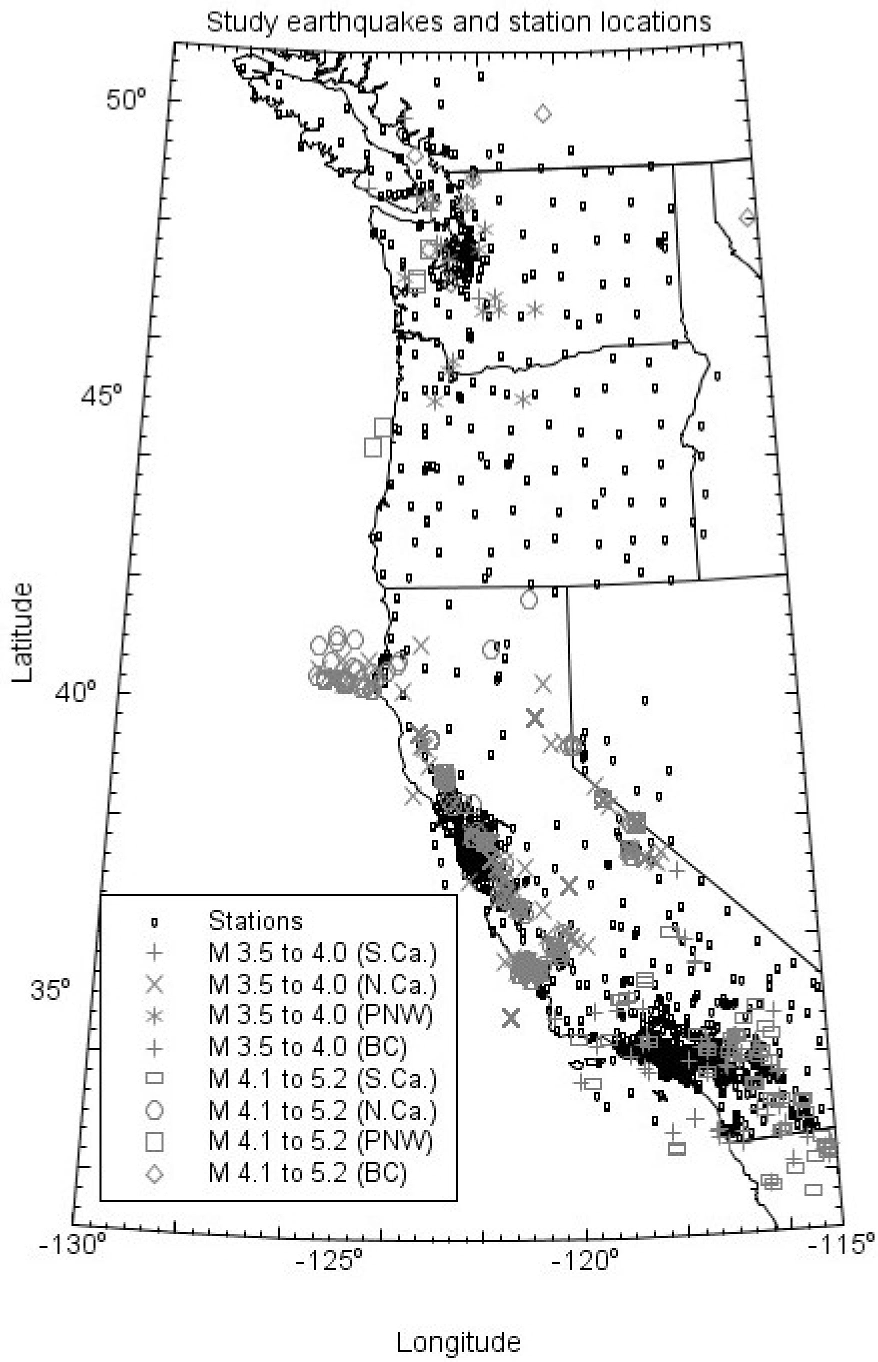

Figure 1 – Map of events (M3.5-5.2 in the last 5 years) and station locations.

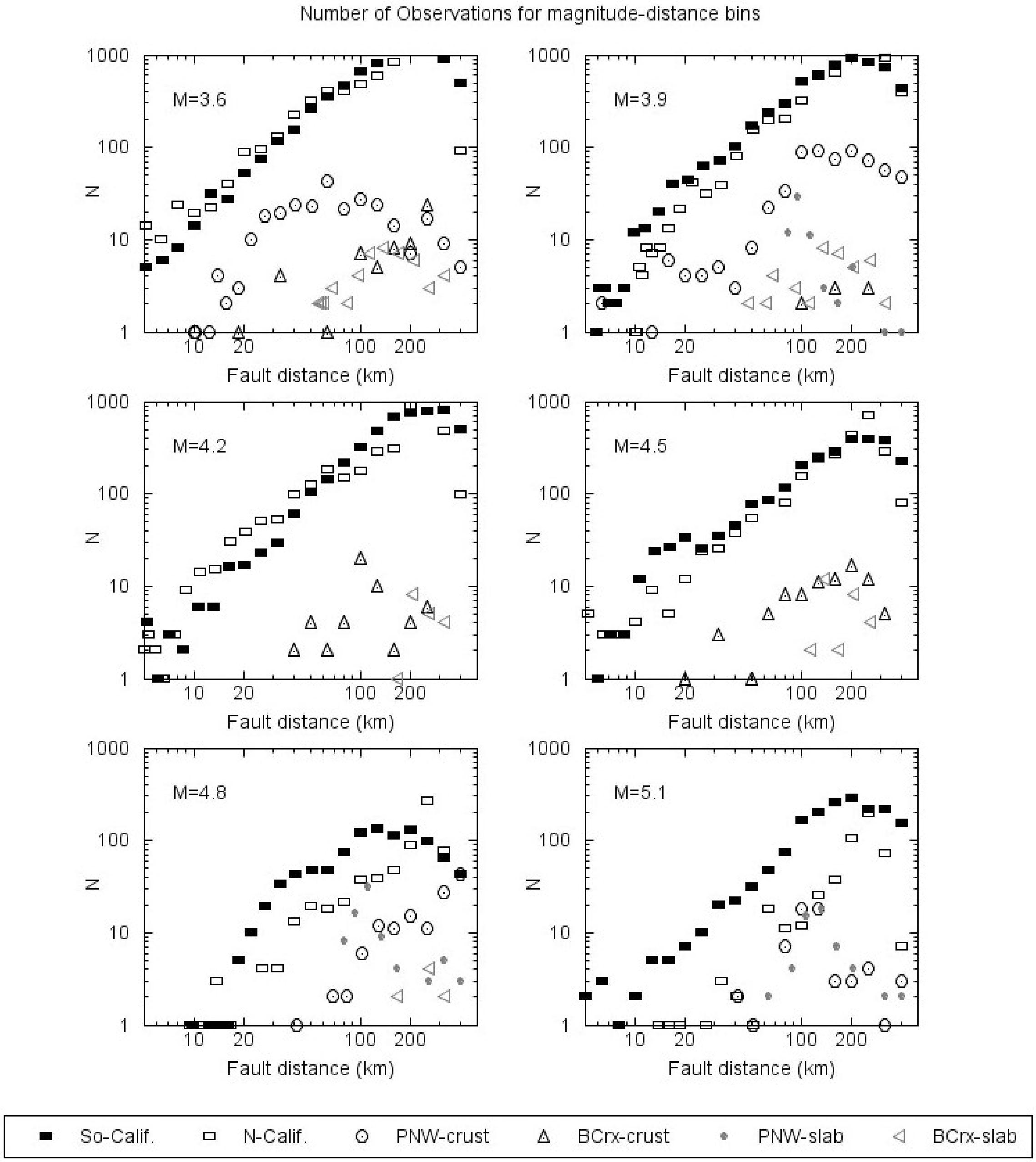

Figure 2 – Number of records in each magnitude-distance bin for southern and northern California (So-Calif., N-Calif.), B.C. rock sites for crustal and in-slab events (BCrx-crust and BCrx-slab), and the Pacific Northwest for crustal and in-slab events (PNW-crust, PNW-slab).

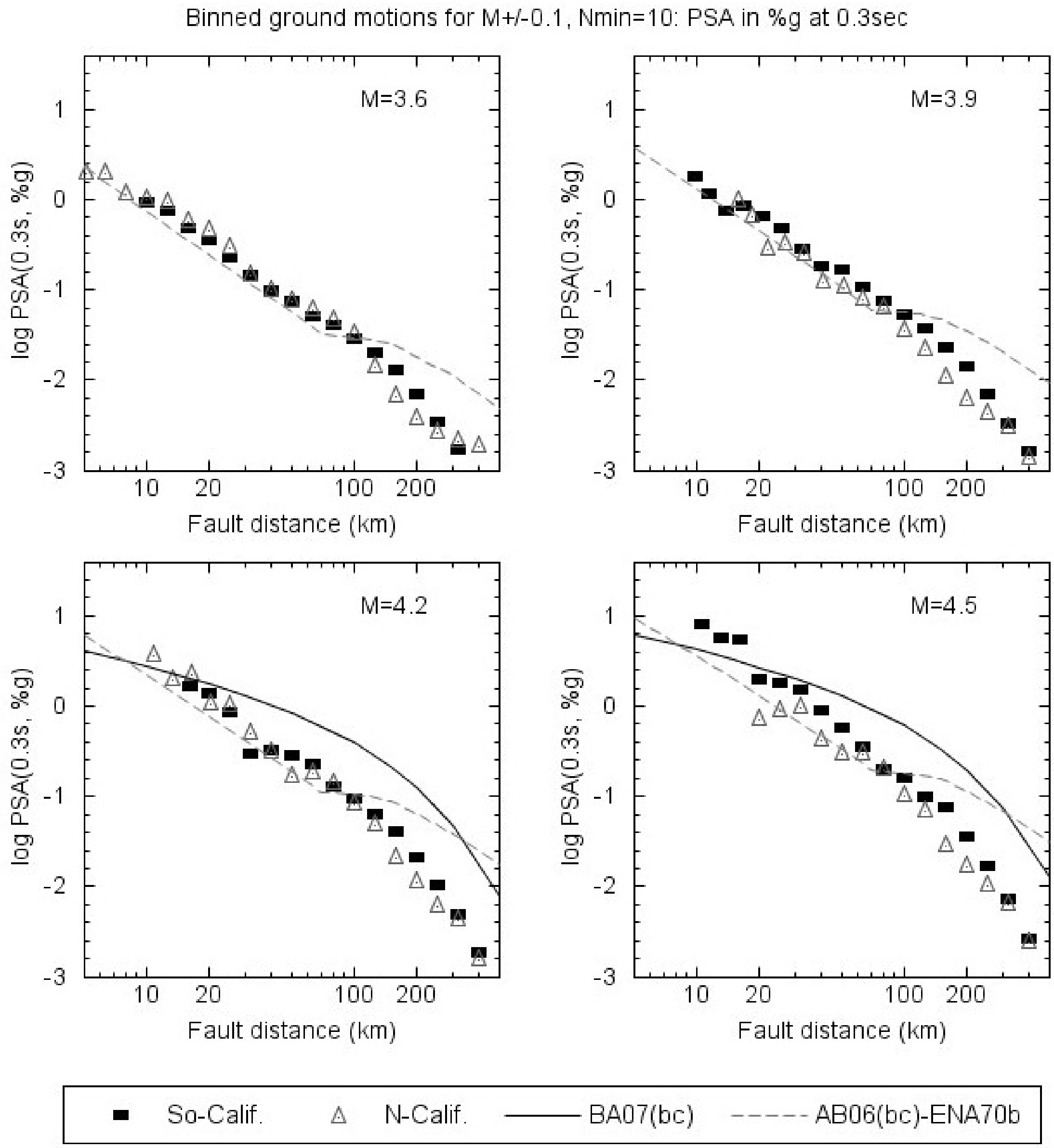

Figure 3 – Comparison of average ground-motion amplitudes (in magnitude-distance bins) for northern California (triangles) versus southern California (squares), at 0.3 s. Prediction equations of Boore and Atkinson (2007, 2008) for active tectonic regions, and of Atkinson and Boore (2006) for ENA (but with a 70 bar stress drop) are also shown, both for B/C boundary site conditions.

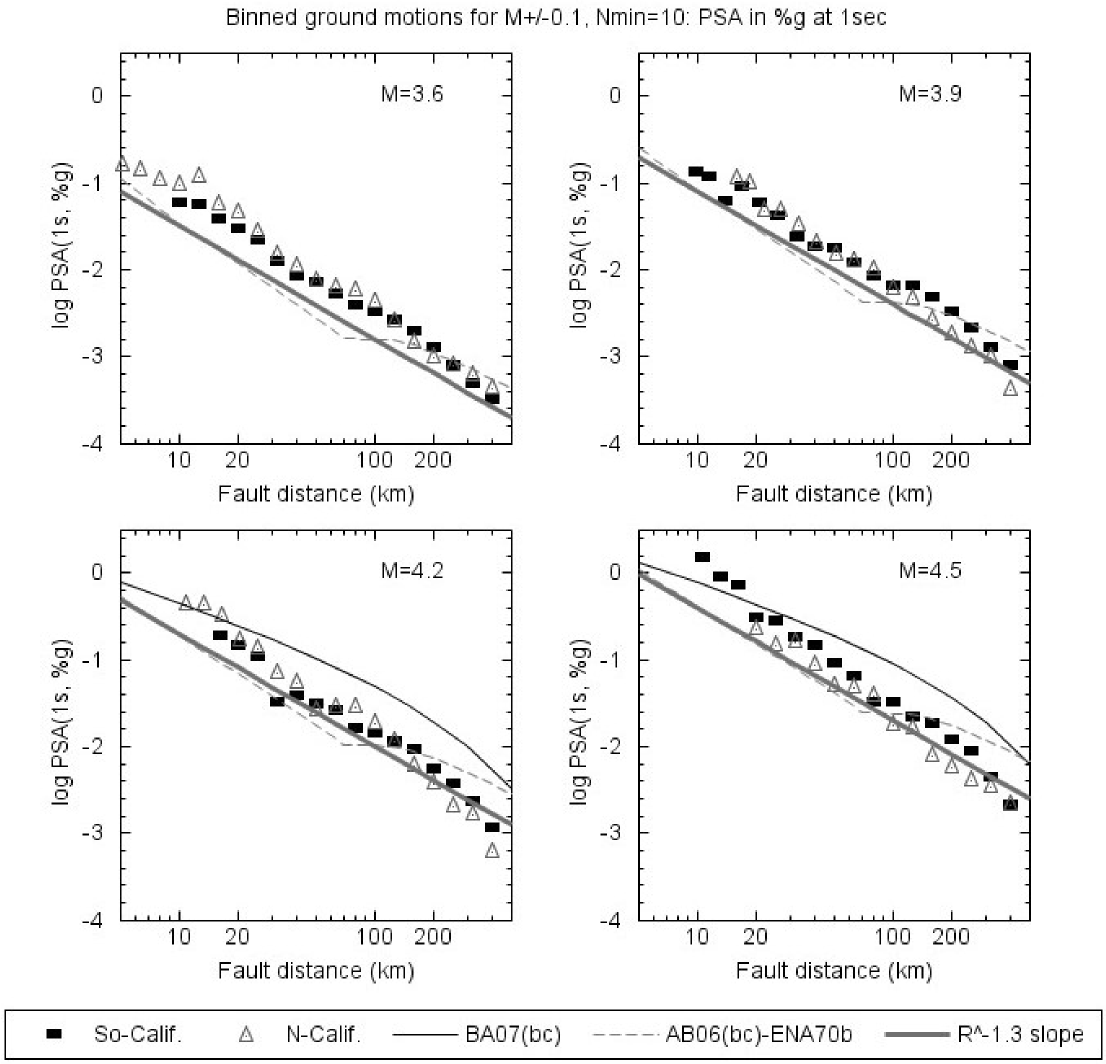

Figure 4 – Comparison of average ground-motion amplitudes (in magnitude-distance bins) for northern California (triangles) versus southern California (squares), at 1 s. Prediction equations of Boore and Atkinson (2007, 2008) for active tectonic regions, and of Atkinson and Boore (2006) for ENA (but with a 70 bar stress drop) are also shown, both for B/C boundary site conditions. Heavy grey line shows a slope of -1.3 (level arbitrarily selected to cross AB06 curve at 10 km).

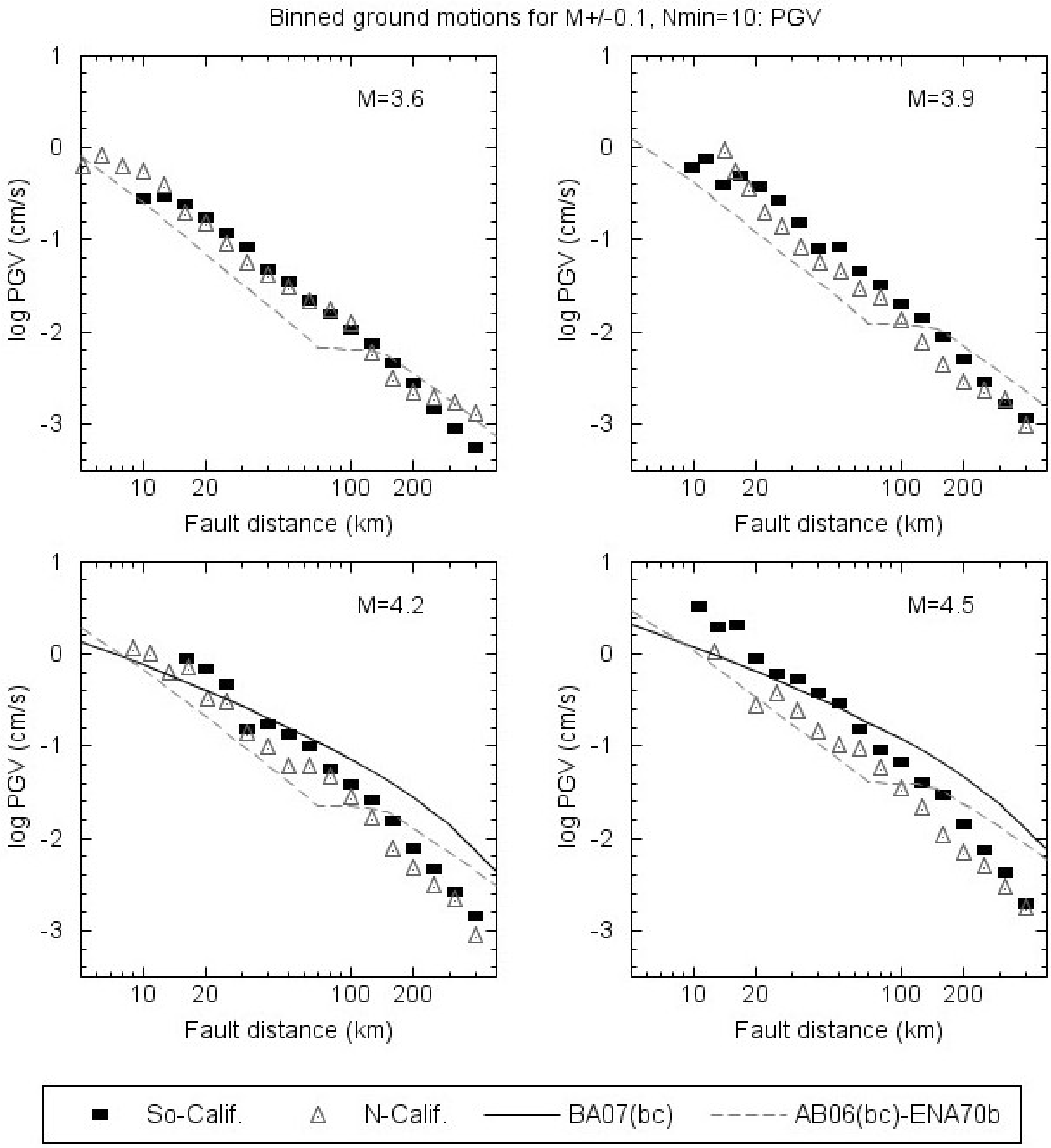

Figure 5 – Comparison of average ground-motion amplitudes (in magnitude-distance bins) for northern California (triangles) versus southern California (squares), for PGV. Prediction equations of Boore and Atkinson (2007, 2008) for active tectonic regions, and of Atkinson and Boore (2006) for ENA (but with a 70 bar stress drop) are also shown, both for B/C boundary site conditions.

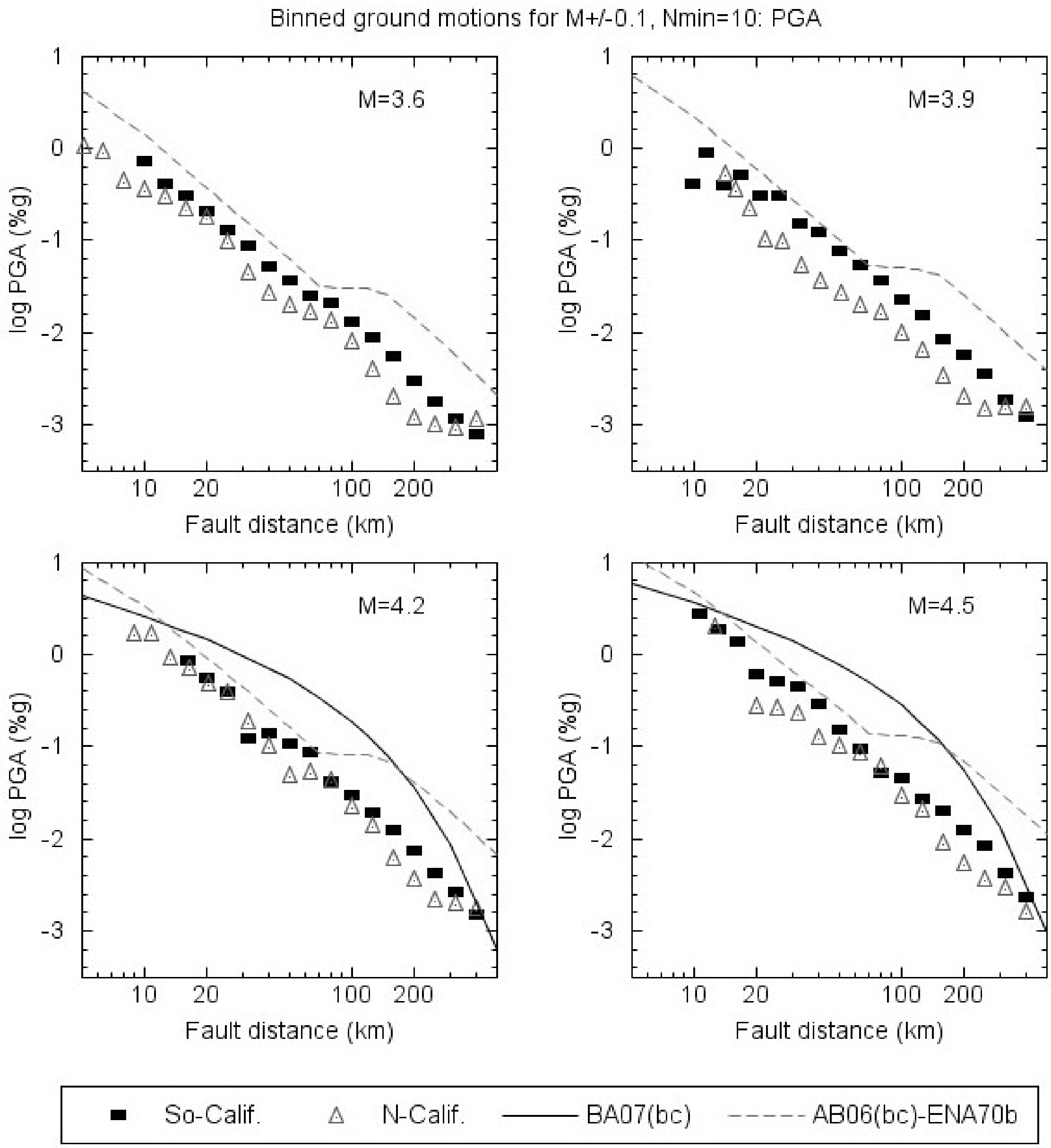

Figure 6 – Comparison of average ground-motion amplitudes (in magnitude-distance bins) for northern California (triangles) versus southern California (squares), for PGA. Prediction equations of Boore and Atkinson (2007, 2008) for active tectonic regions, and of Atkinson and Boore (2006) for ENA (but with a 70 bar stress drop) are also shown, both for B/C boundary site conditions.

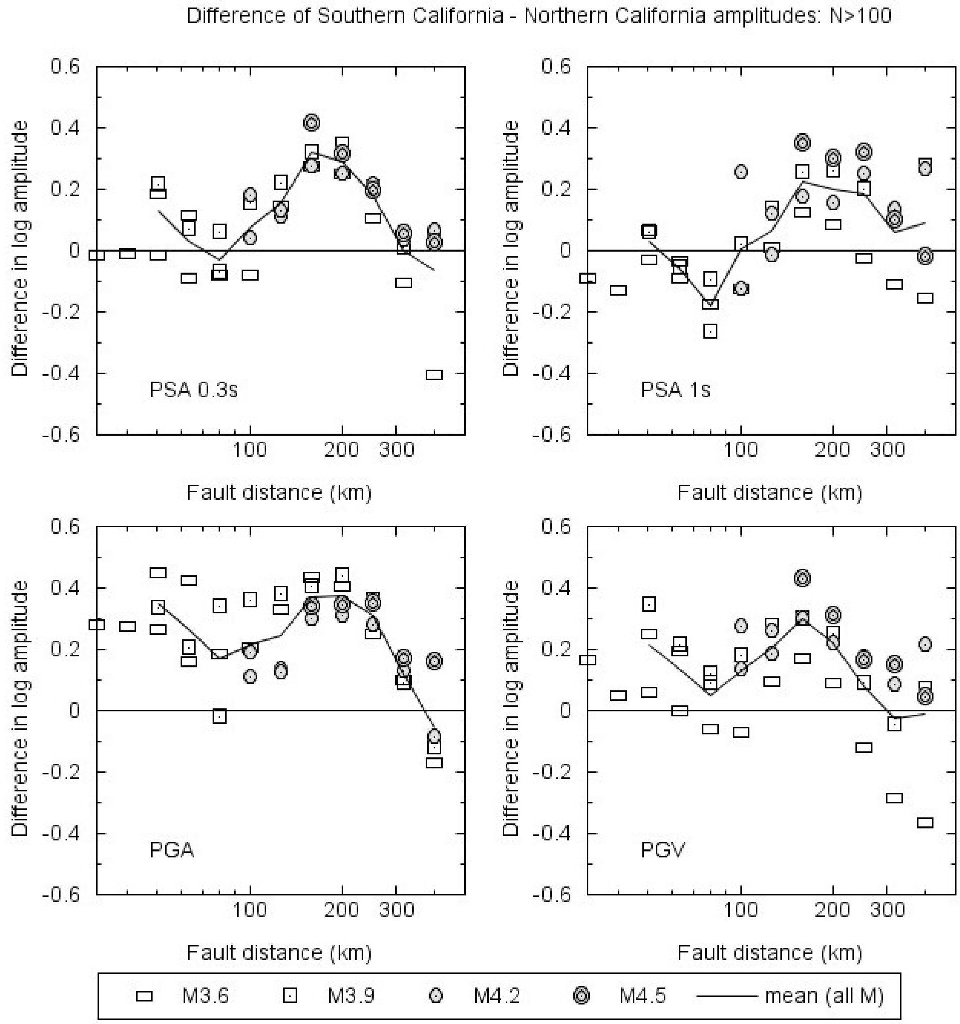

Figure 7 – Mean difference between southern and northern California amplitudes, for distance bins with >100 observations. Symbols show averages for each magnitude range; line shows average over all magnitudes.

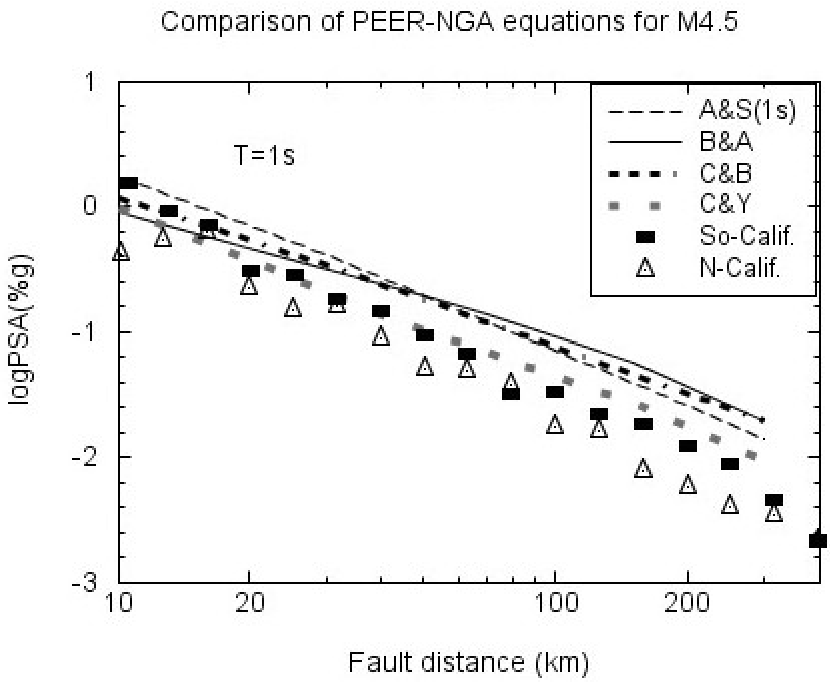

Figure 8 – Comparison of alternative PEER-NGA equation predictions for **M**4.5 (a hypocenter at 5 km depth, with a strike-slip mechanism is assumed), for B/C site conditions, for PSA at 1 sec. A&S=Abrahamson and Silva, 2008; B&A=Boore and Atkinson, 2007, 2008; C&B=Campbell and Bozorgnia, 2008; C&Y=Chiou and Youngs, 2008.

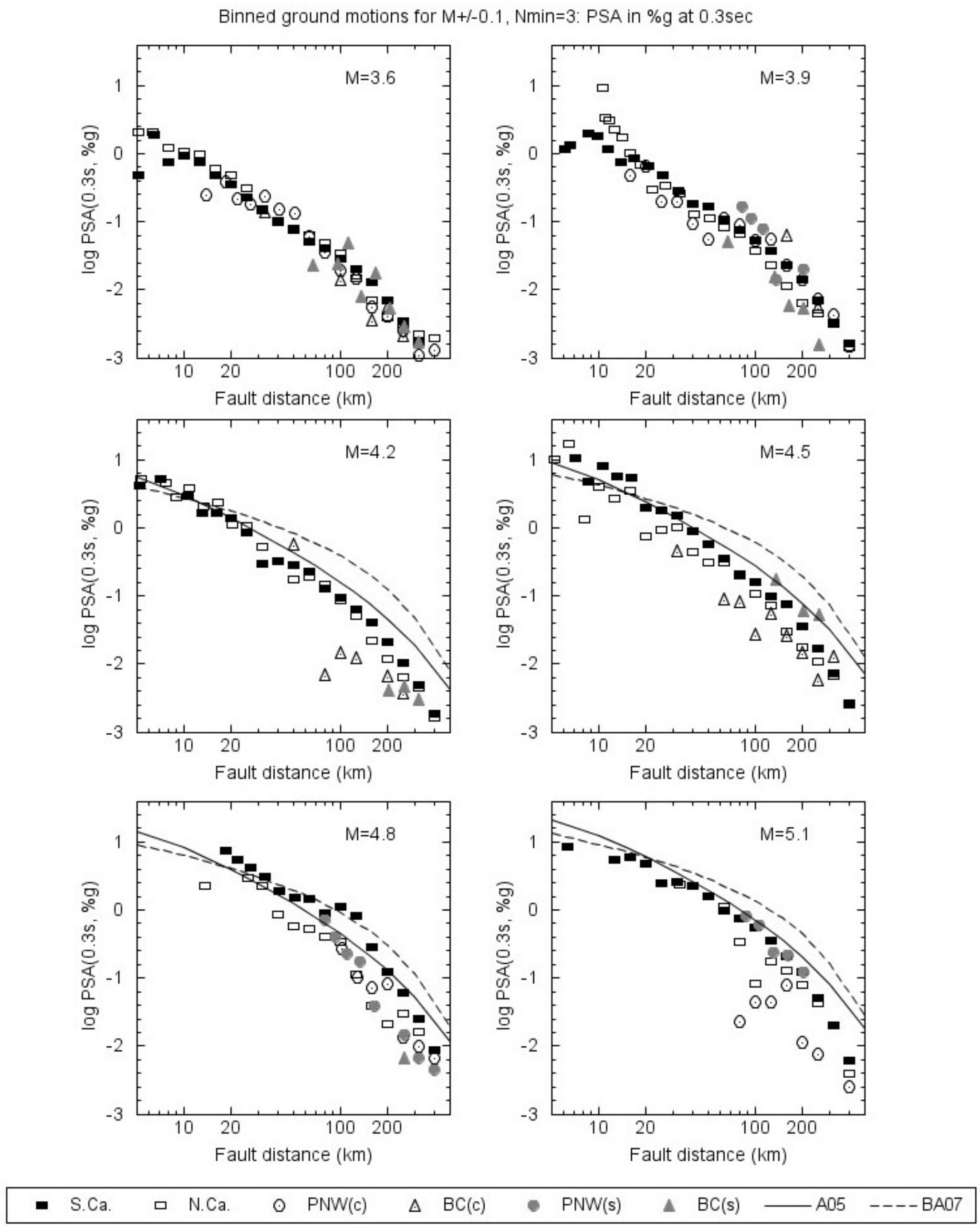

Figure 9 - Comparison of average ground-motion amplitudes (in magnitude-distance bins) for southern California (filled squares), northern California (empty squares), crustal events in the PNW and B.C. (empty circles and triangles), and in-slab events in the PNW and B.C. (filled circles and triangles), for PSA at 0.3 s. Prediction equations of Boore and Atkinson (2007, 2008) for active tectonic regions (B/C boundary), and of Atkinson (2005) for crustal earthquakes in B.C. on rock are also shown.

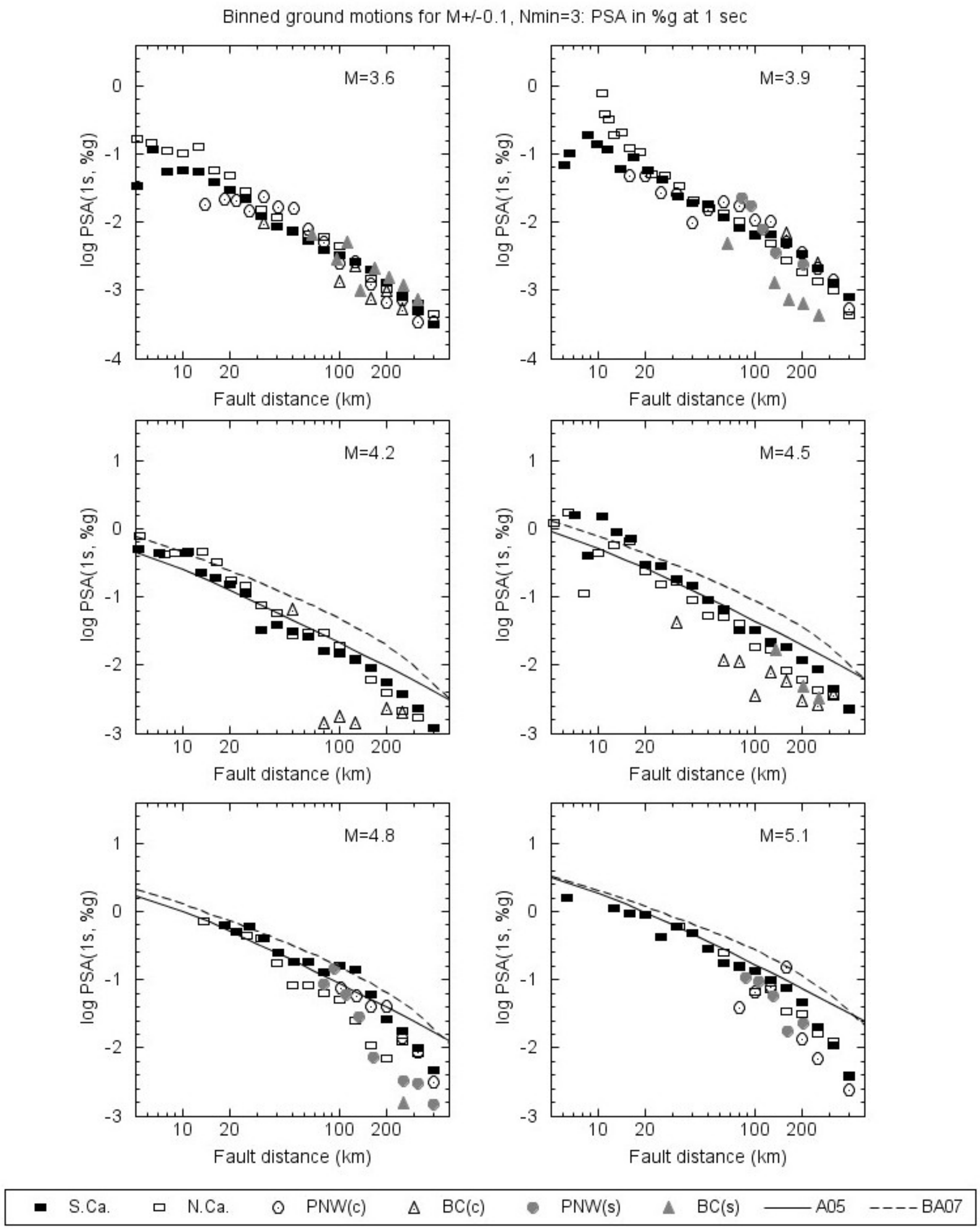

Figure 10 - Comparison of average ground-motion amplitudes (in magnitude-distance bins) for southern California (filled squares), northern California (empty squares), crustal events in the PNW and B.C. (empty circles and triangles), and in-slab events in the PNW and B.C. (filled circles and triangles), for PSA at 1 s. Prediction equations of Boore and Atkinson (2007, 2008) for active tectonic regions (B/C boundary), and of Atkinson (2005) for crustal earthquakes in B.C. on rock are also shown.

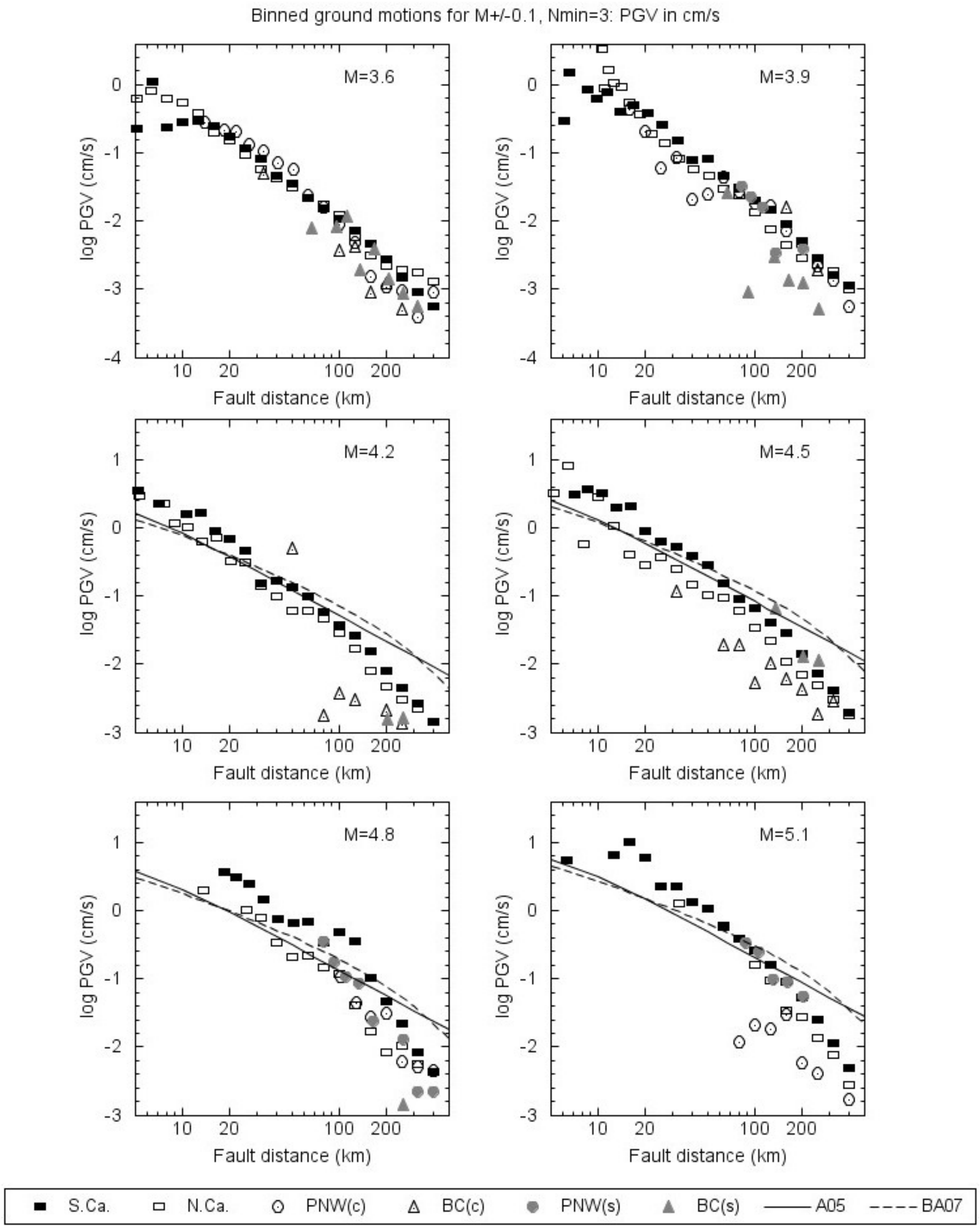

Figure 11 - Comparison of average ground-motion amplitudes (in magnitude-distance bins) for southern California (filled squares), northern California (empty squares), crustal events in the PNW and B.C. (empty circles and triangles), and in-slab events in the PNW and B.C. (filled circles and triangles), for PGV. Prediction equations of Boore and Atkinson (2007, 2008) for active tectonic regions (B/C boundary), and of Atkinson (2005) for crustal earthquakes in B.C. on rock are also shown.

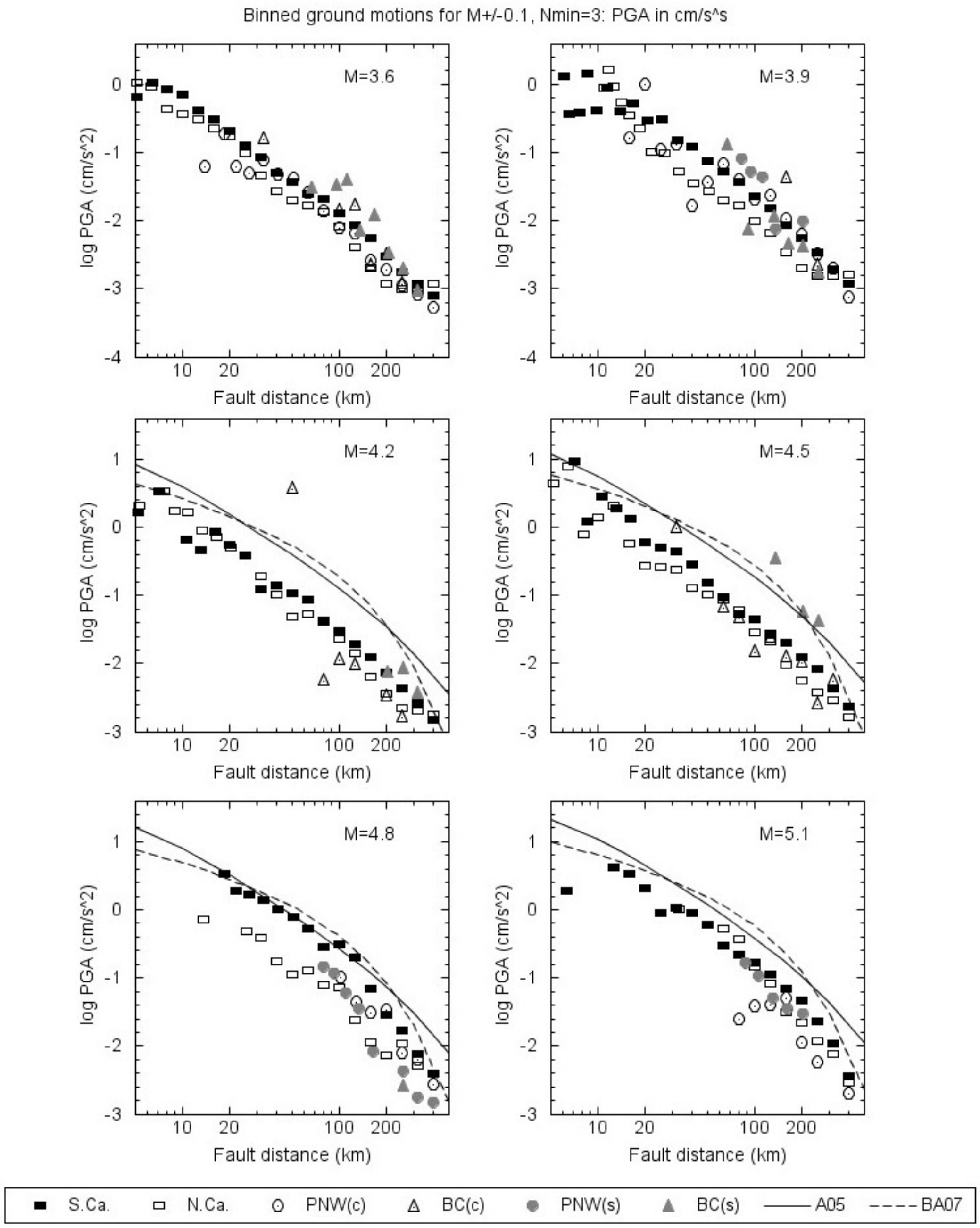

Figure 12 - Comparison of average ground-motion amplitudes (in magnitude-distance bins) for southern California (filled squares), northern California (empty squares), crustal events in the PNW and B.C. (empty circles and triangles), and in-slab events in the PNW and B.C. (filled circles and triangles), for PGA. Prediction equations of Boore and Atkinson (2007, 2008) for active tectonic regions (B/C boundary), and of Atkinson (2005) for crustal earthquakes in B.C. on rock are also shown.