Some Comparisons Between Recent Ground-Motion Relations

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ABSTRACT

We provide an overview of new ground-motion relations for eastern North America (ENA) developed over the last five years. The empirical-stochastic relations of Atkinson and Boore (1995) are compared to relations developed by the Electric Power Research Institute (EPRI, 1993; also Toro *et al.*, 1994), Frankel *et al.* (1996), and the consensus ENA ground-motion values as reported by SSHAC (1996). The main difference between our relations and those of EPRI or Frankel is in the low-frequency amplitudes ($f < 2$ Hz, all magnitudes). We predict lower amplitudes (by more than a factor of two) at 1 Hz, largely due to our use of an empirical source model rather than a single-corner-frequency Brune source model; the use of the empirical source model is motivated by the desire to match the ENA ground-motion database as closely as possible.

We also compare our new ENA relations to empirical relations for California. The comparison is complicated by the need to adjust the ENA hard-rock motions to obtain equivalent motions for typical California soil conditions. Two alternative methods of making this correction lead to somewhat different conclusions. One possible conclusion is that our ENA relations predict similar low-frequency amplitudes to those predicted by Boore *et al.* (1993, 1994) and Abrahamson and Silva (1996) for California, but our predicted ENA amplitudes are much higher (factor > 2) than California values at high frequencies. The alternative soil correction leads to the conclusion that our ENA relations are moderately lower (factor<2) than the California relations at low frequencies, and moderately higher at high frequencies. Both of these conclusions imply that ground-motion relations or time series for earthquakes in one region cannot be simply modified for use in engineering analyses in another region.

INTRODUCTION

During the last five years, significant effort has been expended towards the development of improved ground-motion relations for earthquakes in eastern North American (ENA) (*e.g.*, Ou and Herrmann, 1990; Atkinson and Mereu, 1992; Boatwright and Choy, 1992; Atkinson, 1993a,b; EPRI, 1993; Toro *et al.*, 1994; Boatwright, 1994; Atkinson and Somerville, 1994; Atkinson and Boore, 1995; Horton, 1994; SSHAC, 1996). The effort was partly motivated by the occurrence of the 1988 *M* 5.8 Saguenay, Quebec earthquake. The Saguenay earthquake occurred, perversely enough, just following an earlier and more limited period of research into ENA ground-motion relations (Atkinson, 1984; Herrmann, 1985; Boore and Atkinson, 1987; Toro and McGuire, 1987). This earlier research produced relations (Boore and Atkinson, 1987; Toro and McGuire, 1987) that underpredicted the high-frequency ground motions experienced during the Saguenay earthquake by factors of two to five. The Saguenay earthquake was the largest event to have occurred in the east in the last 50 years and is the only well-recorded large ENA event; the gross underprediction was, to put it mildly, a source of concern. It highlighted how little was actually known about ENA source and propagation processes.

There have been two major directions to ENA ground-motion research in the 1990s. One of these has been to improve the empirical basis of our knowledge of ENA source and propagation processes, and provide better empirical validation of ENA ground-motion relations. These efforts culminated with new empirically-based stochastic ground-motion relations for ENA (Atkinson and Boore, 1995). A second approach has been to use improved modeling techniques to gain insight into ENA ground-motion processes and their variability (Ou and Herrmann, 1990; EPRI, 1993; Atkinson and Somerville, 1994; Toro *et al.*, this volume). This effort culminated with the new engineering ground-motion relations of EPRI (1993), as summarized by Toro *et al.* (1994).

The purpose of this paper is to make some comparisons between the new Atkinson and Boore (1995) and EPRI (1993) relations for ENA and to illuminate the reasons for their differences. The new relations proposed for national hazard mapping by Frankel *et al.* (1996), which are very similar to the EPRI relations, are also discussed. The consensus values arrived at during the ground-motion workshop of the

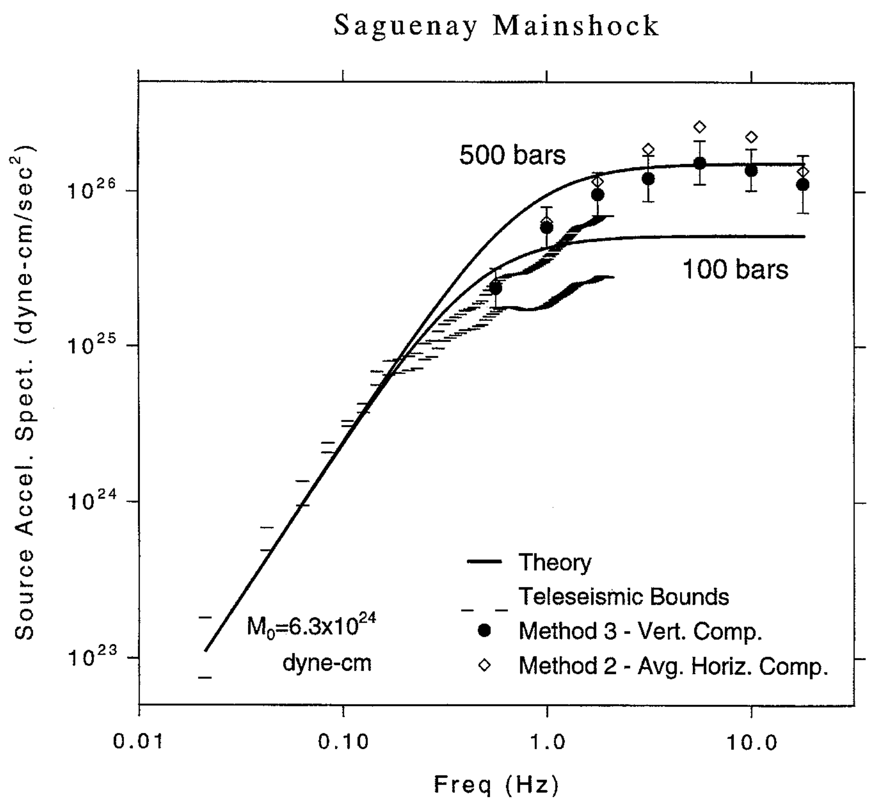
Senior Seismic Hazard Analysis Committee (SSHAC, 1996) are presented in the light of these comparisons. Comparisons between ENA and California ground-motion relations are also presented.

OVERVIEW OF RECENT ENA GROUND-MOTION RELATIONS

In recent years, ground-motion relations for eastern North America (ENA) have been based on a stochastic model (Atkinson, 1984; Boore and Atkinson, 1987; Toro and McGuire, 1987; EPRI, 1988; Atkinson and Boore, 1990; Atkinson and Boore, 1995; Frankel *et al.*, 1996). The model has its origins in the work of Hanks and McGuire (1981), who showed that observed high-frequency ground motions can be characterized as finite-duration bandlimited Gaussian noise, with an underlying amplitude spectrum specified by a simple seismological model of source and propagation processes.

For California, it has been shown that the Brune (1970) source model, with a stress parameter of about 50 to 100 bars, provides reasonable estimates of average ground motions when used in conjunction with the stochastic model (Hanks and McGuire, 1981; Boore, 1983; Boore *et al.*, 1992; Silva and Darragh, 1995), although there is some tendency to overpredict motions at frequencies of 1 Hz and less (Schneider *et al.*, 1993; Silva and Darragh, 1995; Atkinson and Silva, 1997). For ENA, applications of the stochastic model in the 1980s (Atkinson, 1984; Boore and Atkinson, 1987; Toro and McGuire, 1987; EPRI, 1988; Atkinson and Boore, 1990) all assumed a 100-bar Brune source model. This assumption was based on limited observations from a few moderate ENA events (Atkinson, 1989), coupled with inferences based on modeling of teleseismic data (Somerville *et al.*, 1987). The 1988 Saguenay earthquake, by contrast, differed dramatically from the predictions of the simple Brune model, as shown in Figure 1. Boatwright and Choy (1992) used teleseismic data to show that the source spectra of large intraplate events generally depart from the Brune model; most intraplate earthquakes appear to have two "corner frequencies" (*i.e.*, two changes in slope in Figure 1).

The Saguenay earthquake also highlighted the importance of wave-propagation effects in determining ground-motion amplitudes. Several of the stations in the distance range near 100 km recorded particularly strong motions. At this distance the direct wave is joined by the first postcritical reflection from internal crustal interfaces and the Moho discontinuity (Burger *et al.*, 1987). It was therefore suggested that the "Moho bounce" may have been at least partly responsible for the large motions (Somerville *et al.*, 1990).



▲ **Figure 1.** Near-source acceleration spectrum of the Saguenay earthquake (symbols), compared to the theoretical Brune spectra for stress drops of 100 and 500 bars (lines). The data for the source-spectral estimates include analysis of teleseismic data (Boatwright and Choy, 1992) and analysis of strong-motion and regional seismographic data using several methods (from Boore and Atkinson, 1992).

Summary of Atkinson and Boore (1995) Ground-Motion Relations

The approach that we took to improving our ground-motion relations of 1987 in light of these developments was largely empirical. We analyzed a wide variety of data sources to define each of the input parameters to the stochastic model, then validated the resulting model against the ENA ground-motion database. The input parameters to our 1995 stochastic ground-motion relations were constructed from the following elements:

1. the analysis of over 1,500 ENA seismograms from small-to-moderate events, recorded on hard-rock sites of the Eastern Canada Telemetered Network (ECTN), to determine regional attenuation and source characteristics (Atkinson and Mereu, 1992; Atkinson, 1993a, b; Boatwright, 1994), the duration of motion and the horizontal-to-vertical (*H/V*) component ratio for rock (Atkinson, 1993b);
2. analysis of teleseismic spectra from intra-plate events (Somerville *et al.*, 1987; Boatwright and Choy, 1992); and
3. estimation of source parameters for large historic ENA events, based on regional seismographic data and calibration of felt areas to spectral parameters (Atkinson, 1993a).

This information spans thousands of records from hundreds of ENA earthquakes in the magnitude range from 3 to 7 at distances from <10 to 1,000 km. The digital data used are all from hard rock sites. No distinction of focal mechanism type is made; based on the regional faulting style the predominant mechanism is believed to be thrust.

The data were used to define the parameters of the following basic model for the earthquake spectrum, as a function of moment magnitude (M), hypocentral distance (r_{hypo}) and frequency (f):

$$A(M, r_{hypo}, f) = E(M, f) D(R_{hypo}, f) P(f) I(f) . \qquad (1)$$

$E(M,f)$ is the earthquake source spectrum (*i.e.*, Fourier spectrum of the ground acceleration at a distance of 1 km). Our source spectral model is empirical (Atkinson, 1993a); it differs from the previous Brune model in that it uses two corner frequencies to describe a spectral shape similar to that indicated by the Saguenay data in Figure 1. $D(r_{hypo},f)$ is a diminution function that models the geometric and anelastic attenuation of the spectrum as a function of distance. It is also defined empirically (Atkinson and Mereu, 1992) and includes the effect of the "Moho bounce" on the shape of the attenuation curve. $P(f)$ is a high-cut filter that rapidly reduces amplitudes at very high frequencies (f>> 10 Hz); we use the f_{max} model (Hanks, 1982), with f_{max} = 50 Hz for hard rock sites. This is roughly equivalent to the kappa model (Anderson and Hough, 1984) with kappa = 0.002. $I(f)$ is a filter used to shape the spectrum to correspond to the particular ground-motion measure of interest. For example, for the computation of response spectra I is the response of an oscillator to ground acceleration.

The final input element of the stochastic predictions is the duration of motion. The duration model generally has two terms:

$$T = T_o + T_b(r_{hypo}) \qquad (2)$$

where T_o is the source duration and $T_b(r_{hypo})$ represents a distance-dependent term which accounts for scattering and dispersion. For the source duration, we assume that

$$T_o = \frac{1}{2f_A}$$

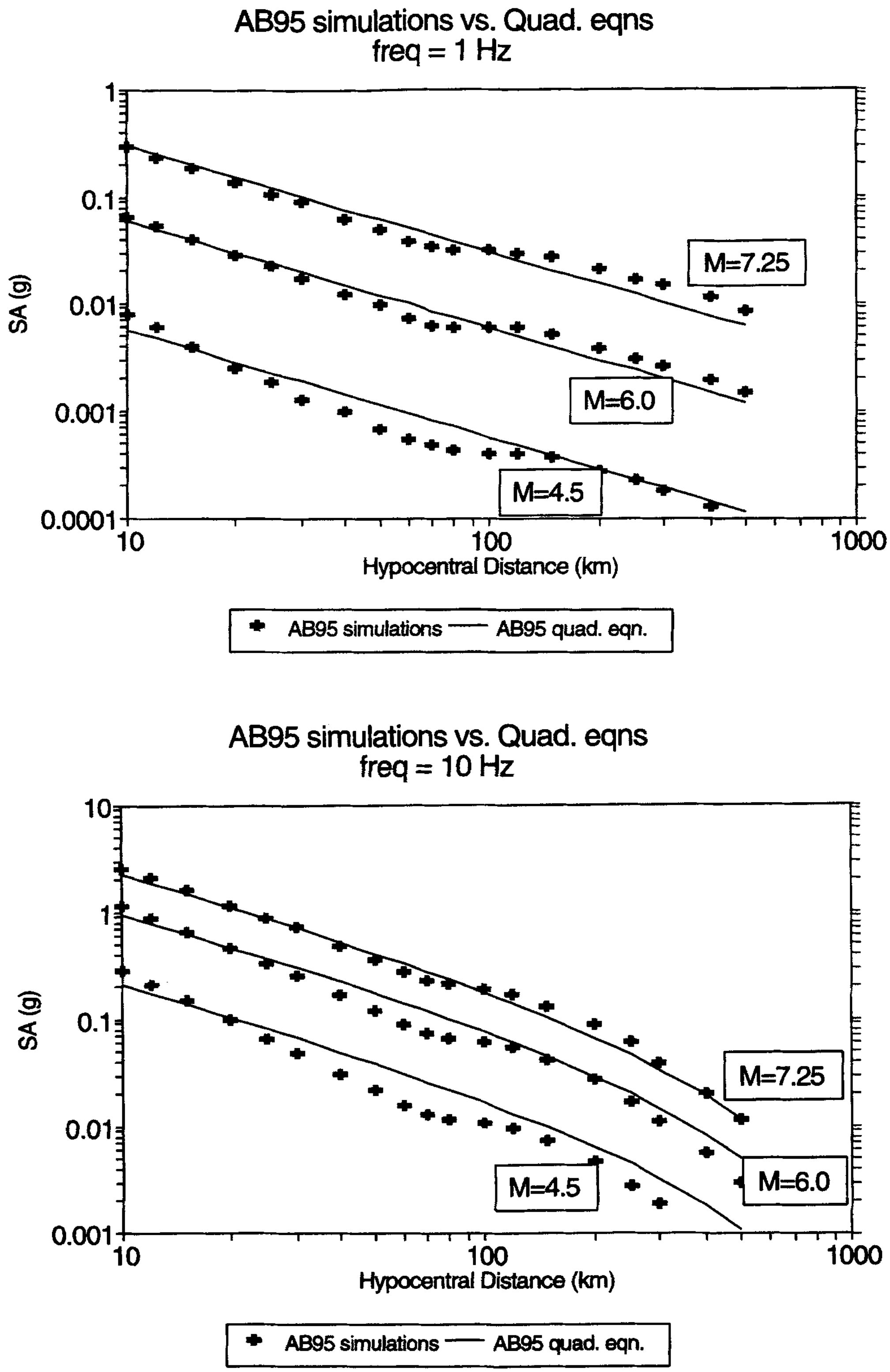
(Boatwright and Choy, 1992), where f_A is the lowest corner frequency in the source spectrum. The empirical basis for the distance-duration term is the ECTN seismogram collection used to define the attenuation function. As shown in Atkinson and Boore (1995), the duration increases with distance, steeply at first, then more gradually at larger distances. Our distance-duration term differs significantly from the approach used in other studies (*e.g.*, EPRI, 1993) and is a principal factor in discrepancies between alternative relations, particularly at distances from about 50 to 150 km.

Using the inputs described above, response spectra (5% damped pseudo-absolute-acceleration, SA) for frequencies of 0.5 Hz to 20 Hz and peak ground acceleration (PGA) and velocity (PGV) were simulated for $4.0 \leq M \leq 7.25$ in 0.25 magnitude-unit increments from r_{hypo} = 10 km to r_{hypo} = 500 km, in increments of 0.1 log units. Fifty trials were used for each magnitude-distance combination. The median ground motions for the random horizontal component at hard rock sites are summarized in the Appendix table.

Quadratic-Equation Form of Atkinson and Boore Relations

Figure 2 plots the attenuation of SA for frequencies of 1 and 10 Hz, based on the simulation results tabulated in the Appendix. The figure also shows simple quadratic equations that approximate the estimates for the purposes of seismic hazard calculations. The coefficients of the plotted quadratic prediction equations are listed in Table 1.

The quadratic equations were obtained by regression of a subset of the simulated ground-motion data. The subset included all distances ($r_{hypo} \leq$ 500 km) for large events ($M > 6.5$) but only near distances ($r_{hypo} \leq$ 25 km) for small events. This constrains the attenuation to match the relatively slow decay of motions that is applicable for large earthquakes. In Figure 2 it is clear that the quadratic equations do not adequately match the shape of the attenuation curve for small-to-moderate events ($M < 5.5$), resulting in gross overprediction of the simulated amplitudes at distances greater than 30 km. This was deliberate. The objective was to fit the complex magnitude-dependent shape of the results with a



▲ **Figure 2.** Predicted response spectral values (SA for 5% damping) for frequencies of 1 and 10 Hz for *M* 4.5, 6.0, and 7.25 as a function of hypocentral distance. Symbols show ground-motion predictions. Lines show quadratic equations of Table 1.

TABLE 1 Regression Coefficients for Quadratic Equation				
freq(Hz)	c_1	c_2	c_3	c_4
0.5	–1.660	1.460	–0.039	0.00000
0.8	–0.900	1.462	–0.071	0.00000
1.0	–0.508	1.428	–0.094	0.00000
1.3	–0.094	1.391	–0.118	0.00000
2.0	0.620	1.267	–0.147	0.00000
3.2	1.265	1.094	–0.165	0.00024
5.0	1.749	0.963	–0.148	0.00105
7.9	2.140	0.864	–0.129	0.00207
10.0	2.301	0.829	–0.121	0.00279
13.0	2.463	0.797	–0.113	0.00352
20.0	2.762	0.755	–0.110	0.00520
PGA	1.841	0.686	–0.123	0.00311
PGV	4.697	0.972	–0.0859	0.0

Notes: Equation gives SA, PGA in g, PGV in cm/s, where SA is the pseudo-acceleration (5% damped) for the random horizontal component on rock. $\ln SA = c_1 + c_2(M-6) + c_3(M-6)^2 - \ln R - c_4 R$

simple functional form that is convenient to use in hazard analyses and is sufficiently accurate in the magnitude-distance ranges that are most significant to seismic hazard analysis in the east. We are willing to accept a large margin of conservatism for small, distant earthquakes because these will not contribute significantly to the seismic hazard.

We tested how well the simple quadratic equations meet this goal by performing some example probabilistic hazard calculations for areas of low, moderate, and high seismic activity rates (see Atkinson and Boore, 1995 for details). We compared the seismic hazard curves obtained using the quadratic ground-motion relations of Table 1 to those obtained using our "exact" ground-motion relations (Appendix table). The latter relations are implemented by building a look-up table into the program that performs the hazard computations; for each magnitude-distance step considered by the hazard program, the appropriate ground-motion value is obtained by interpolation from the table of ground-motion results. We found that for cases where the expected motions are relatively large (PGA > 0.25 g), the quadratic equations predict the results obtained using the "exact" ground-motion relations accurately (to within 5% to 10%). For cases where the expected ground motions are moderate (PGA 0.1 g to 0.2 g), the use of the quadratic equations will give ground-motion estimates that are conservative by 20% to 40% at high frequencies. Small expected ground motions (PGA ≤ 0.05 g) are grossly overpredicted, but this has no practical significance since these motions would not influence design. It is important to keep these effects in mind when using the quadratic equations. To avoid conservatism in low-seismicity regions, we recommend referring to the table of results given in the Appendix. We will mail a diskette with our unabridged table of results, with a subroutine for implementing the look-up table approach described above, to anyone who requests one (please send a blank formatted diskette and a self-addressed envelope).

The ground-motion estimates given in the Appendix table, and by the quadratic equations, apply to bedrock sites. For very stiff, deep ENA soil sites (depth > 60 m; average shear-wave velocity ~500 m/s in the top 30 m, similar to Boore *et al.* Class B), linear analyses indicate that the bedrock values would be amplified by a factor of 1.4 to 2 over most of the frequency range from 0.5 to 10 Hz, as shown in Table 2. Table 2 was produced by comparing the ground-motion equations derived by Boore and Joyner (1991) for deep soil sites to the equivalent relations derived by Boore and Atkinson (1987) for rock sites. Both sets of relations used the stochastic method with the same parameter values. The factors are thus relative amplifications; they do not depend significantly on the specific parameter values of the ground-motion simulations. The frequency dependence of the amplification is attributable to the depth of the soil column. As a general statement for stiff soil sites of unknown depth, the bedrock values should be multiplied by a factor of about two. This does not account for any decreases in amplification that may be observed at large amplitudes due to nonlinear effects.

For many soil sites (*e.g.*, Class C of Boore *et al.*, 1993 and all soft soils), the amplification factor would be significantly larger than two, particularly at frequencies near 1 Hz. The amount of amplification to be applied can be determined either analytically for a specific soil profile or empirically based on an assumed average shear-wave velocity in the top 30 m (Boore *et al.*, 1994). Under the latter approach, it

TABLE 2
Soil-amplification factor to be applied to ground motion relations for rock to obtain relations for deep soil sites

Frequency (Hz)	log factor*	Multiplicative factor
0.5	0.27	1.9
1.0	0.27	1.9
2.0	0.29	2.0
5.0	0.24	1.7
10.	0.15	1.4
20.	-0.03	0.93

* Amplification factor is given in log units.
$\log SA_{soil} = \log SA_{rock} + \log \text{factor}$

should be noted that the reference near-surface shear-wave velocity for ENA hard rock sites is considered to be about 2.8 km/s (see Silva and Darragh, 1995).

In comparing hazard estimates made with our new relations to those made with our 1987 and 1990 relations, we have found that high-frequency ($f > 5$ Hz) ground-motion estimates have increased significantly. This reflects new knowledge of the potential for enhanced high-frequency radiation, such as observed from the 1988 Saguenay, Quebec and 1990 Mont Laurier, Quebec earthquakes. Intermediate-frequency ($f \leq 1$ Hz) motions have decreased, in some cases dramatically, as a consequence of the new source model shape. The relative shift in expected ground motions towards higher frequencies has important implications for seismic hazard evaluations thoughout ENA. It may be that the eastern earthquake hazard is mostly restricted to high-frequency structures.

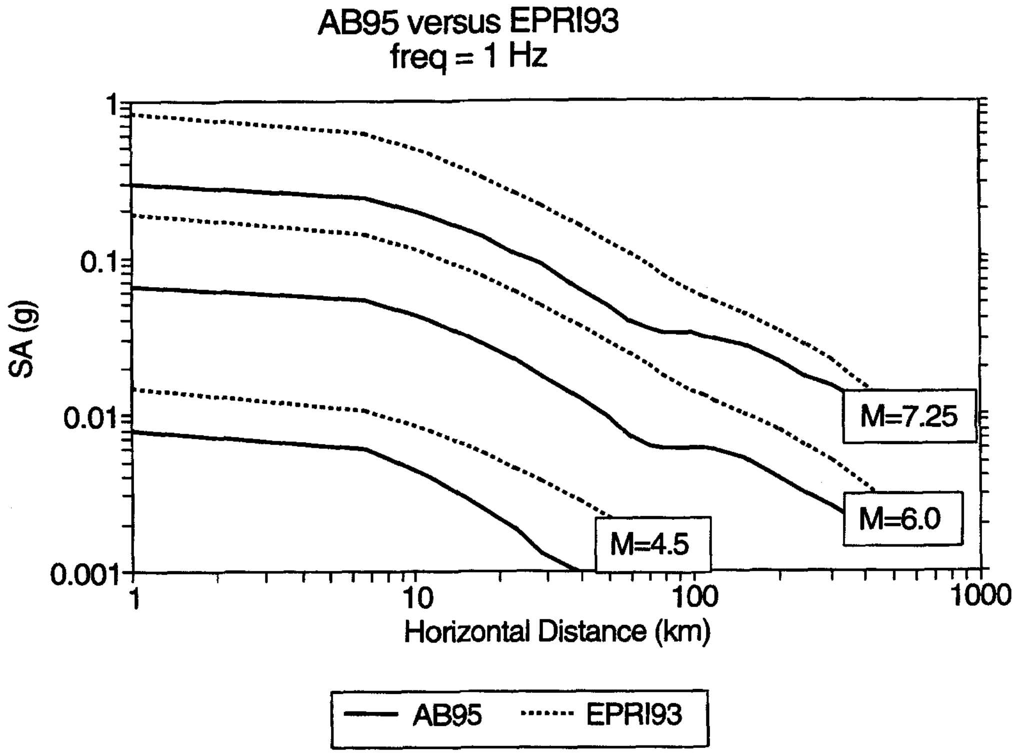
Comparison to Other Relations

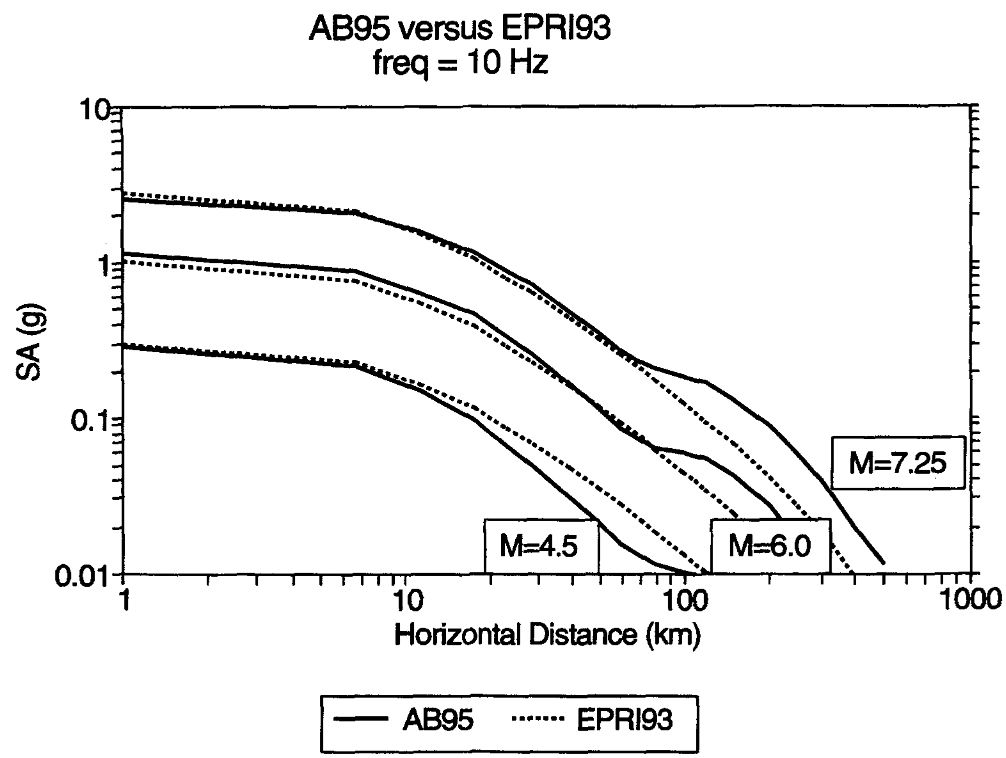
In this section we compare our 1995 relations to other recent relations for ENA. We concentrate on comparisons with the relations developed by the Electric Power Research Institute (EPRI, 1993; also Toro *et al.*, 1994), to be used in siting studies for nuclear power plants in the eastern United States. The reason for this focus is that the EPRI relations are the most comprehensive and best-documented alternative ENA ground-motion relations. We make more limited comparisons with the relations of Frankel *et al.* (1996) and SSHAC (1996). The Frankel *et al.* (1996) relations are similar to those of EPRI, while the SSHAC results give motions at several specified magnitudes and distances, but no generalized relations.

The approach taken by EPRI (1993) was to model the variability of ground-motion amplitudes that results from variability in ENA source and propagation parameters. A stochastic ground-motion model was used, with a single-corner Brune source and attenuation defined by modeling of regional crustal structure effects. The aim was to obtain engineering estimates of not only the median ground motions but also of model variability (epistemic uncertainty) and random variability (aleatory uncertainty).

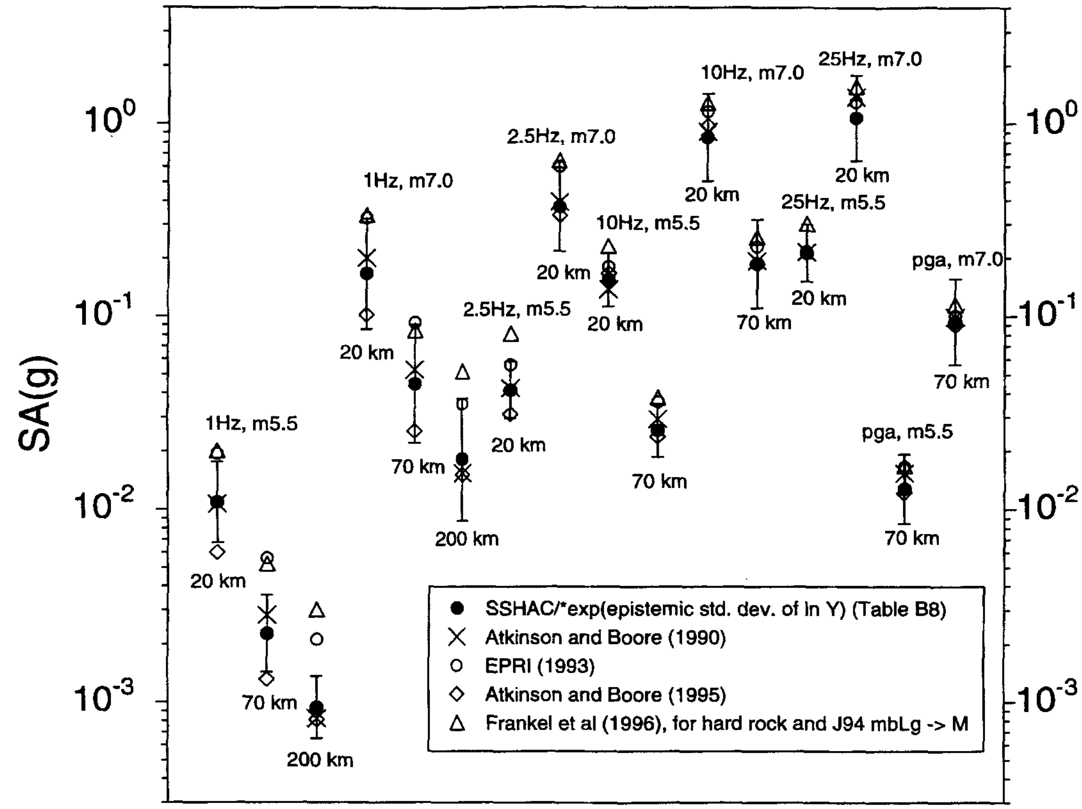
Figure 3 compares the median relations developed for the midcontinent region by the EPRI study (denoted EPRI93) to our median relations (denoted AB95). Both relations are for ENA hard rock sites. For these comparisons, we have used the average ENA focal depth of 10 km to convert our relations from hypocentral distance to the horizontal distance measure used by EPRI (equivalent to epicentral distance for small ruptures). We have plotted the "table" form of our relations rather than the quadratic equations, for accuracy. The apparent differences in the shape of the attenuation curve between AB95 and EPRI93 arise mainly from the smooth functional form of the EPRI93 relations. In the EPRI relations, the leveling of the attenuation curve in the 100 km distance range, which occurs as a consequence of Moho reflections, is smoothed by the range of midcontinent crustal structures and focal depths included in the modeling. By contrast, the empirical data for the somewhat more concentrated region of southeastern Canada and the northeastern United States display the "Moho bounce" effect quite noticeably (Atkinson and Mereu, 1992). This may be a regional difference, since the EPRI model is averaging effects over a broader region. Of course, our quadratic equations also smooth the "Moho bump" in the curve, following the tops of the bumps as shown on Figure 2.

At low frequencies ($f < 3$ Hz) the EPRI93 predictions dramatically exceed the AB95 predictions over all magnitudes and distances, by factors ranging from 1.4 to 2.6. At frequencies of about 10 Hz, the two sets of relations predict approximately equal ground-motion amplitudes at near-source distances, but the AB95 relations predict larger amplitudes from large ($M > 6$) earthquakes at distances greater than 100 km. At very high frequencies ($f > 10$ Hz), and for peak ground acceleration (PGA), the AB95 relations predict significantly larger amplitudes than do the EPRI93 relations for nearly all magnitudes and distances; as a generalization, the AB95 high-frequency amplitudes are typically about 40% higher.





▲ **Figure 3.** Comparison of Atkinson and Boore (1995) ground-motion relations (solid lines) with those of EPRI (1993) (dotted lines), for moment magnitudes 4.5, 6.0 and 7.25, for oscillator frequencies of 1.0 and 10 Hz. Both sets of relations are for hard rock sites in ENA. Note the use of the horizontal distance measure for the x-axis in this comparison.



▲ **Figure 4.** Comparisons of ground motion estimates of various proponents, for specified combinations of m_N, distance and frequency, from the SSHAC workshop, as well as several recent ground-motion predictions for very hard rock sites in ENA.

The frequency-dependent differences in the relations represent the combined effects of differences in the input parameters: the underlying stochastic methodology is essentially the same. The most important differences in input parameters concern the source model and the duration of motion. The EPRI relations assume a Brune source model, while the AB95 relations adopt the empirical source model of Atkinson (1993a). The difference between these two source models is frequency-dependent. The EPRI study did examine variability in source parameters, but within the context of the Brune model. Thus they simulate the variability in ground-motion levels that results from variability in the value of the Brune stress parameter, in the range from 20 to 600 bars, but do not address uncertainty in source spectrum shape. The median stress parameter for the EPRI relations is 120 bars, while the high-frequency level of the empirical source model is equivalent to a Brune stress of 180 bars. The effect of the differences in source model is that their predictions will tend to be higher than ours at low frequencies and lower than ours at high frequencies. This trend is apparent in Figure 3.

The new ground-motion relations of Frankel *et al.* (1996) are very similar to the EPRI relations, as can be seen in the comparisons shown in Figure 4. They are based on a stochastic model with a single-corner 150-bar Brune source. The Frankel *et al.* relations thus show a very similar discrepancy with the AB95 relations at low frequencies. They match or exceed the AB95 relations at high frequencies, because the lower stress parameter (150 bars versus 180 bars) is offset by a lower crustal shear wave velocity (3.6 km/sec versus 3.8 km/sec).

A second significant difference between models concerns the duration of motion. Our model uses an empirical duration function. There is a wealth of data in ENA to show that duration increases markedly with distance from the source (Atkinson, 1993b; Atkinson and Boore, 1995; Horton, 1994); this is due to the effects of scattering, and the arrivals of reflected and refracted phases. The EPRI duration model features an increase in duration with distance due to reflected and refracted phases but does not include a scattering component. Therefore the duration in their model is constant within about 50 km of the source until the arrival of the first reflected or refracted phase. The Frankel *et al.* (1996) relations use a duration of 0.05 r_{hypo}, which nearly equals the AB95 duration at large distances but is much less than the AB95 duration at $r_{hypo} < 150$ km. It should be noted that a constant near-source duration is a "conservative" assumption in that shorter durations will result in larger peak amplitudes because the energy of the spectrum is packed into a shorter time window.

A third difference in input parameters, involving the high-frequency slope of the Fourier spectrum (kappa), affects only high-frequency amplitudes ($f \geq 10$ Hz and PGA). The EPRI study uses a gradual high-frequency decay, as characterized by a median kappa (Anderson and Hough, 1984) of 0.006 for ENA hard rock sites. Frankel *et al.* (1996) also use the kappa model, with kappa = 0.01. Our relations use a sharper cut-off, characterized by f_{max} (Hanks, 1982) of 50 Hz (with no spectral decay until that point). Consequently we predict higher PGA values than does the EPRI study. In our examinations of ENA data (see also Atkinson, 1995a), we have found little evidence to support any general spectral decay of high-frequency amplitude out to frequencies as high as 50 Hz. The data on this parameter are very limited, though, and there are certainly ENA rock sites that have a marked non-zero kappa (especially in the Charlevoix region; see Boore and Atkinson, 1992; Atkinson, 1995a).

From the foregoing discussion it is apparent that recent ENA ground-motion relations predict different ground motions due to different input assumptions regarding the source and path effects. In an effort to shed light on the underlying differences in opinion, there was a significant debate on the information and ideas summarized above through a workshop process referred to as SSHAC (1996). The Senior Seismic Hazard Analysis Committee (SSHAC) set out to produce guidelines for the elicitation of expert opinions. SSHAC's ideas on this topic were tested in the specific topic of ground-motion estimation. The process involved two workshops, the first being a general workshop to identify possible ground-motion models and, if possible, to identify those that should be given careful scrutiny in the elicitation process. Based on the results of the first workshop, a second, intensive workshop was held that focused on ground motions from a specific set of magnitudes, distances, and oscillator periods for a very hard rock site (2.8 km/s in the upper 30 m).

Prior to the second workshop, proponents were selected for each of the four major models identified in the first workshop (G. Atkinson: stochastic 1; K. Campbell: semi-empirical; W. Silva: stochastic 2; P. Somerville: theoretical modeling). These model proponents provided written estimates of the ground motions based on their model, including documentation of the method and assumptions used. This material was then distributed to a group of 7 experts (4 proponents and N. Abrahamson, D. Bernreuter, and W. Joyner), who were asked to provide ground motions for the same magnitudes, distances, and oscillator periods, using whatever methods or information they cared to employ in their estimations. It was implicitly understood that the experts would consider and evaluate the range of opinions and resulting ground-motion values represented by the four proponent documents in arriving at their estimates, but there was no formal requirement to do so.

The group of proponents and experts then met for an intensive two-day workshop in which detailed evaluations, discussion, feedback, and interactions focusing on differences in the ground motions were conducted by a small team of integrators (D. Boore, A. Cornell, R. Mensing, P. Morris and G. Toro). The experts had an opportunity to modify their estimates after the first day of the workshop, as well as after returning home. The team of integrators evaluated all of the information obtained and decided on mean ground motions and associated uncertainties. In this case, they decided that the best approach to obtaining the means was to give equal weight to the final ground-motion estimates (*i.e.*, as revised by the workshop process) of the 7 experts. These results, known as the SSHAC model, are given in Table B-8 of the SSHAC (1996) report. It is important to realize that the SSHAC results are in the form of ground-motion estimates for a limited number of magnitude-distance combinations; there are no equations to generalize the results for hazard computations, and there is no single model to which the estimates can be attributed.

In Figure 4, we compare the mean ground-motion estimates of SSHAC, and their estimate of epistemic uncertainty, to our 1995 relations, the EPRI relations (1993) and the Frankel *et al.* (1996) relations, for the m_N (Nuttli magnitude, also referred to as m_{bLg}) and distance combinations specified by SSHAC. For this comparison the computer code that Frankel *et al.* (1996) used to generate motions for soft rock sites (β = 760 m/s) was rerun for hard rock site conditions (β = 2800 m/s); this involved replacing his soft-rock amplifications with the generic ENA hard-rock amplifications of Boore and Joyner (1997) and replacing their soft-rock kappa of 0.01 with a hard-rock kappa of 0.006. Figure 4 illustrates that the new relations proposed by Frankel *et al.* (1996) for use in national seismic hazard maps are practically identical to the EPRI relations; for this reason subsequent discussions applying to the EPRI relations are also applicable to the Frankel *et al.* (1996) relations. Interestingly, the SSHAC consensus values are practically indistinguishable from our earlier ground-motion relations (Atkinson and Boore, 1990), although these did not enter into the SSHAC discussions. This suggests that one way of representing the SSHAC results in equation form would be to simply use our 1990 equations as an approximation.

It is apparent in Figure 4 that the main difference in opinion among different investigators is at low frequencies, specifically 1 Hz. This difference, nearly a factor of four for events of m_N = 5.5, bears closer scrutiny with the existing ENA data.

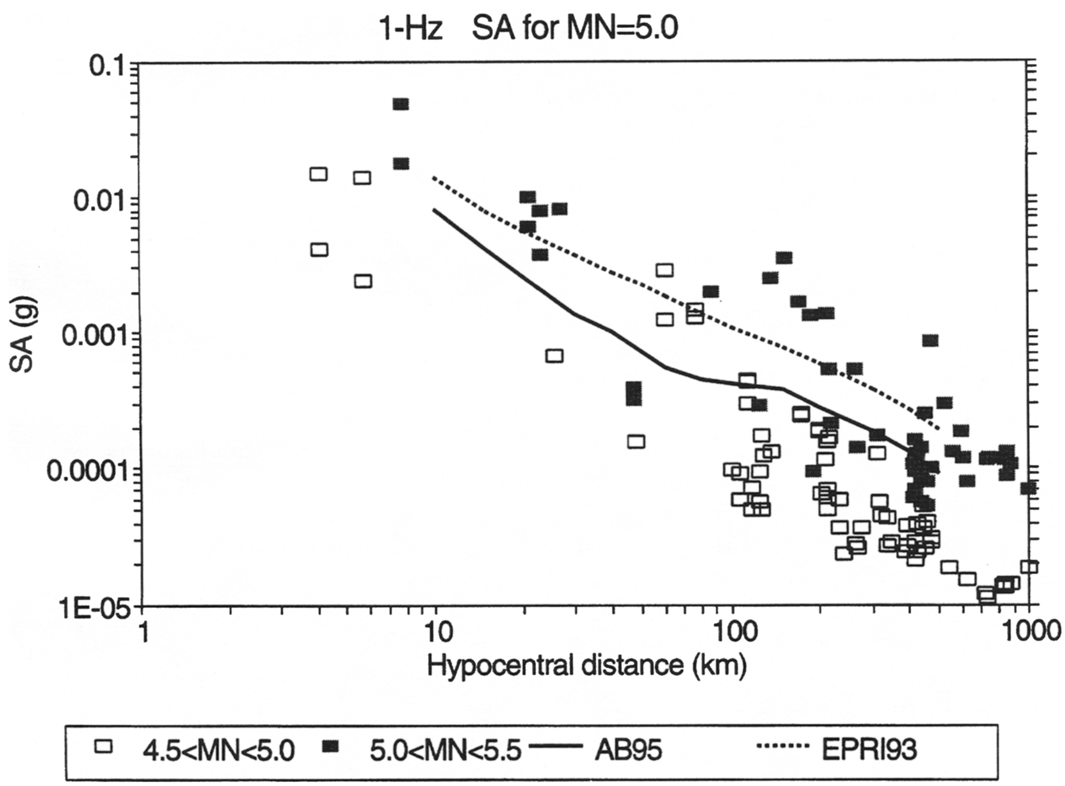
Comparisons of Relations with Data

The total ENA ground-motion database for rock recordings of $M \geq 4$ is summarized in Table 3. In Figure 5, the median AB95 and EPRI93 1-Hz relations for m_N = 5.0 are compared to these data (the AB95 relations are for M, but a relation that converts from M to m_N is provided). Open symbols plot 1-Hz ENA amplitudes for events of $4.5 \leq m_N < 5.0$, while filled symbols plot amplitudes for events of $5.0 \leq m_N < 5.5$. A similar comparison is provided in Figure 6 for the 1-Hz relations for m_N = 6.0. No scaling of the data is done for these plots, except to convert vertical-component data to the equivalent horizontal-component value (relation of

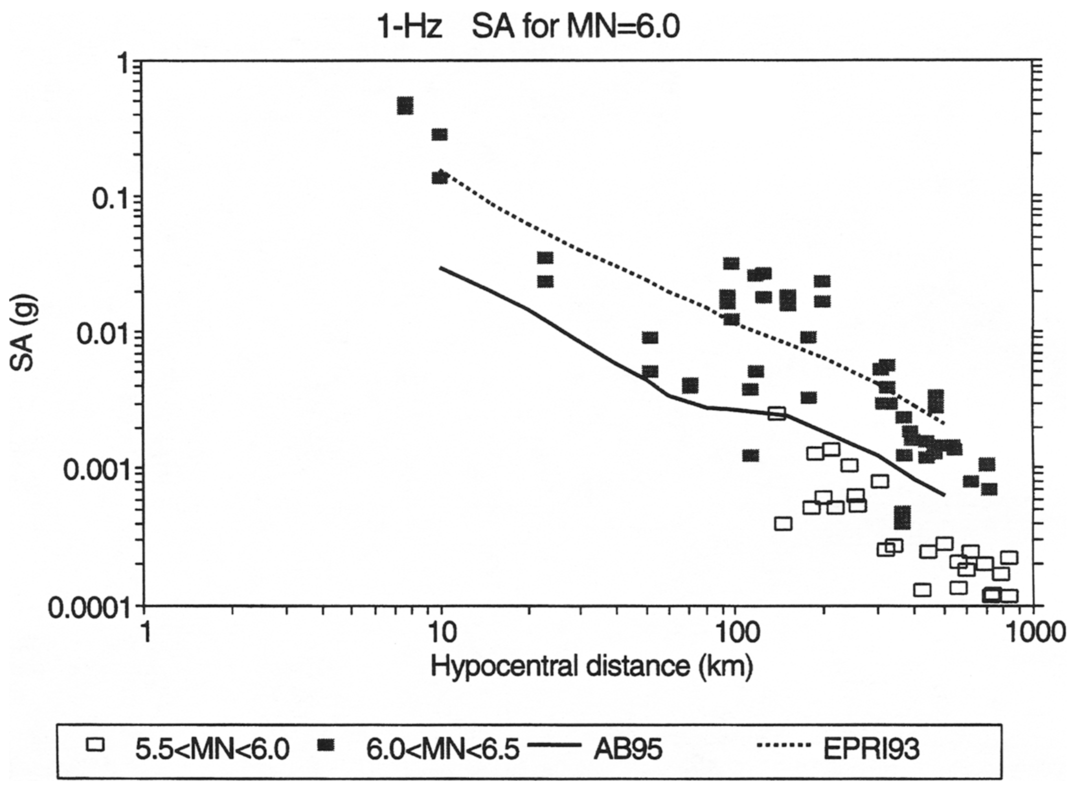
TABLE 3
Summary of Data for Comparison with Ground Motion Predictions

Event		M	M_N	m	No. obs.	Approx. dist.(km)
Miramichi	*82/01/11	5.2	5.5	4.8	13	100–1000
Gaza	82/01/19	4.0	4.8	3.7	12	60–1000
Miramichi	*82/03/31	4.1	4.8	3.5	17	4–1000
Miramichi	*82/06/16	4.0	4.6	3.4	13	50–800
Goodnow	83/10/07	5.0	5.6	4.8	16	100–800
Nahanni	85/12/23	6.8	6.1	6.2	6	8–23
Nahanni	*85/12/25	5.2	5.3	4.4	2	8
Nahanni	*85/12/25	5.2	5.3	4.2	2	23
Painesville	86/01/31	4.8	5.3	4.8	12	20–1200
Ohio	86/07/12	4.5	4.9	4.5	5	700–1000
Saguenay FS	88/11/23	4.1	4.6	4.2	20	100–500
Saguenay	88/11/25	5.8	6.5	6.5	45	50–700
Risco, MO	90/09/26		5.0		2	48
Mt. Laurier	90/10/19	4.7	5.1	5.4	24	30–500
Cape G.	91/05/04	4.4	4.6		2	114

Notes: Aftershock data (indicated by asterisks) may not be applicable at high-frequencies due to apparent differences in stress parameter (as indicated by ($m - M$). Data are from the Geophysics Division of the Geological Survey of Canada and from the EPRI (1993) database. $m = 2 \log A_{hf} + 3$, where A_{hf} is the high-frequency level of the Fourier spectrum of acceleration (horizontal component) in cm/s at a distance of 10 km from the earthquake source (Atkinson and Hanks, 1995).



▲ **Figure 5.** Median 1-Hz SA for an event of $m_N = 5.0$, according to Atkinson and Boore (1995) (solid line) and EPRI (1993) (dotted line). Open symbols show data for events of $4.5 \leq m_N < 5.0$; closed symbols show data for $5.0 \leq m_N < 5.5$.



▲ **Figure 6.** Median 1-Hz SA for an event of $m_N = 6.0$, according to Atkinson and Boore (1995) (solid line) and EPRI (1993) (dotted line). Open symbols show data for events of $5.5 \leq m_N < 6.0$; closed symbols show data for $6.0 \leq m_N < 6.5$.

Atkinson, 1993b); two components are plotted for horizontal-component data, while only a single equivalent horizontal component is plotted for vertical data. Ideally, the ground-motion relation should drive through the middle of the data, with most of the lower-magnitude subset (open symbols) falling below the line and most of the upper-magnitude subset (filled symbols) falling above the line. Based on Figures 5 and 6, we conclude that the apparently-low 1-Hz amplitudes of the AB95 relations appear justified by the data. The EPRI93 relations (also the Frankel *et al.*, 1996 relations) are significantly conservative with respect to the data at 1 Hz, a fact acknowledged in the EPRI report and at the SSHAC workshop.

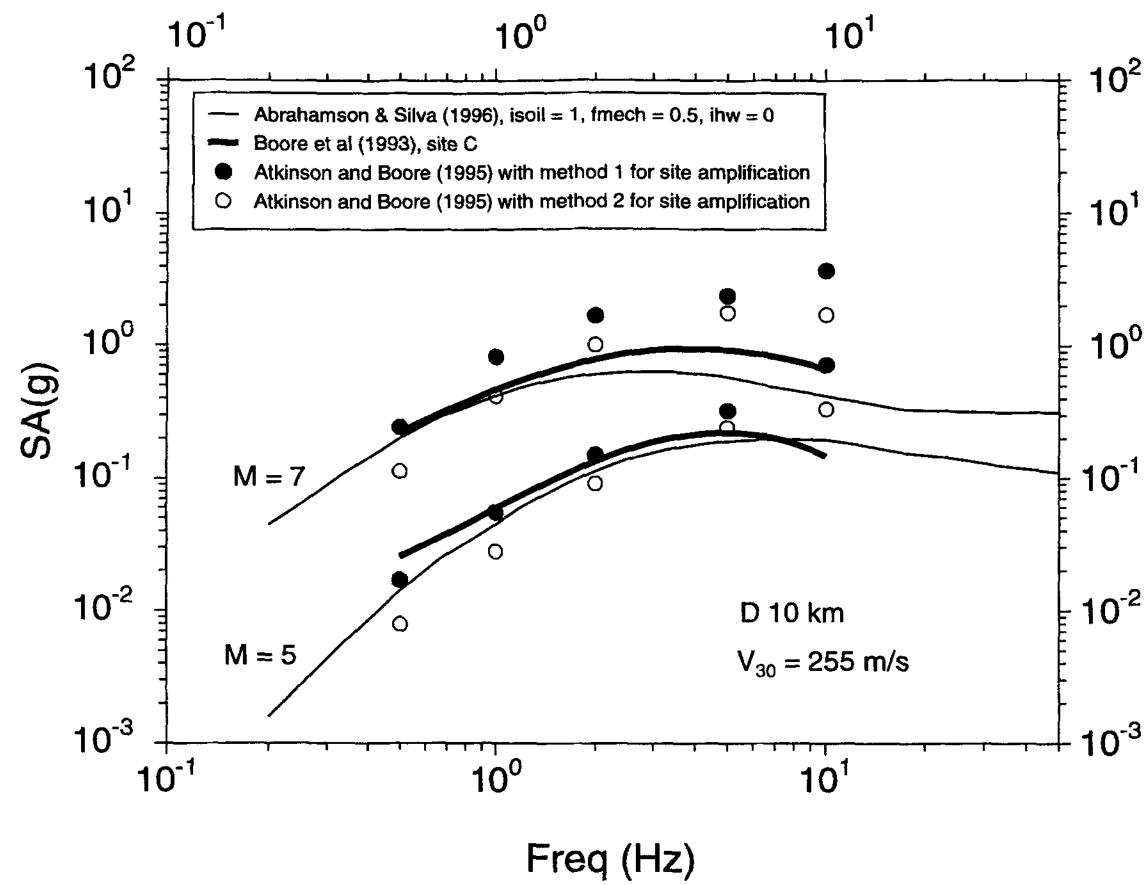
In essence, the current debate over the 1 Hz amplitudes, as discussed at the SSHAC workshop, centers around whether to place most weight on the empirical data or whether to place most weight on the tried-and-true nature of the single-corner Brune source model. The triumph of the SSHAC workshop was that the participants unanimously agreed that the truth is likely to lie somewhere in between.

COMPARISON OF ENA AND CALIFORNIA GROUND MOTIONS

It has long been known that anelastic attenuation is greater in California than in ENA, resulting in ENA earthquakes being felt to much larger distances than California events of similar magnitude. Numerous studies suggest that there may also be significant regional differences in source parameters. There are even differences in site effects for "rock" sites, with California rock being characterized by lower near-surface shear-wave velocity than glaciated eastern hard rock (Boore and Joyner, 1997). For these reasons, the ground motions for a fixed seismic moment will vary from region to region.

In this section, we examine the differences in ENA versus California ground motions. To simplify comparisons between the regions we focus on near-source motions for the same site conditions. We choose as our reference site condition Class C soil sites (β 180-360 m/s; Boore *et al.*, 1993, 1994), with a median shear-wave velocity of β = 255 m/s in the upper 30 m. The empirical ground-motion relations for California are least uncertain for soil sites, since this is the predominant site condition. To compare the ENA relations to California relations, we must adjust the ENA relations from hard rock to Class C soil. There is significant uncertainty in this step, leading to uncertainty in the implied ENA motions for Class C sites. In these comparisons we show the implications of two alternative site correction procedures.

Both site correction procedures use a frequency-dependent amplification factor. In the first approach, the empirical relations of Boore *et al.* (1994) are used to determine the amplification required to go from β = 255 m/s to the reference California rock velocity of V_A. This is a simple correction factor based on the formula (Boore *et al.*, 1994):



▲ **Figure 7.** Atkinson and Boore (1995) ENA spectra, at a surface distance of 10 km, are adjusted to California Class C site conditions using two alternative soil corrections (open and filled circles) and compared to the empirical relations of Boore *et al.* (1993) (heavy lines) and Abrahamson and Silva, 1996 (light lines) for California, for the same site conditions.

$$\log a_1 = B_V(\log\beta - \log V_A) \quad (3)$$

where B_V and V_A are frequency-dependent coefficients, determined by Boore *et al.* (1994) to describe the soil-amplification effects contained in the California strong-motion database. A small additional correction factor, a_2, converts from the velocity V_A to an assumed near-surface velocity of 2800 m/s for rock sites in ENA. This factor is based on impedance contrast: energy conservation demands an amplification of

$$a_2 = \sqrt{\frac{2800}{V_A}} \quad (4)$$

neglecting any differences in density between California and ENA rocks (Joyner *et al.*, 1981). The total soil-amplification factor to be applied to the ENA hard rock relations for application to Class C sites is $a_1 * a_2$.

Under this approach, an adjustment should also be made to account for relative differences in kappa for California and ENA "rock" sites: ENA near-source rock recordings feature a flat acceleration spectrum above the corner frequency (Atkinson, 1995a), while California rock recordings show a high-frequency decay that is well-described by the exponential decay operator $\exp(-\pi k f)$ (Anderson and Hough, 1984). This difference is believed to be caused by the much larger near-surface velocities of ENA rock sites. By trial-and-error, it is determined that the "kappa effect" on the California rock relations for SA (from Boore *et al.*, 1993, Class A sites) is given by the factor $\exp(\pi f k')$, where $k' = 0.01$ (*e.g.*, multiplication of the California rock SA spectrum by $\exp(\pi f k')$ yields a flat acceleration spectrum above the corner frequency). This effective kappa is applied to the ENA spectra, in addition to the soil-amplification effects above (the net result is referred to as method 1 on Figure 7).

An alternative approach, referred to as method 2, uses simulations to convert the ENA hard rock motions to those for a generic California rock site. The simulations apply Boore and Joyner's (1997) generic rock amplifications, which were computed for a shear-wave velocity profile that was formulated from a compilation of borehole data; the generic western rock has β =620 m/s in the upper 30 m. The empirical California factors of Boore *et al.* (1994) are then used to derive a second (empirical) correction factor to convert from this generic western rock to Class C (*i.e.*, from β = 620 m/s to β = 255 m/s). The total amplification factor is obtained as the product of these two steps.

Method 2 has the advantage that the empirical amplification (from Class B to Class C) is strongly controlled by data. By contrast, the empirical amplification factor used in method 1 (from Class A to Class C) is based on fewer data; the Boore *et al.* (1994) study included 11 Class A sites, 50 Class B sites and 51 Class C sites. On the other hand, the fuller use of the empirical data in the correction in method 1 (Class A to C versus Class B to C) may be considered a strong point of method 1.

In Figure 7 the AB95 ENA relations, adjusted for Class C soil sites using both of the above methods, are compared to the relations of Abrahamson and Silva (1996) and Boore *et al.* (1993, 1994) for such sites in California. The distance used for the comparison is r_{JB} = 10 km, corresponding to the distance from the nearest point on the surface directly above the rupture (this is the epicentral distance for moderate events); a focal depth of 10 km for the ENA events was assumed. If the method 1 soil correction is used, it appears that the ENA and California motions are very similar for M 5 at $f < 5$ Hz, and for M 7 at $f < 1$ Hz. High-frequency ENA motions are enhanced relative to those of California, due to regional differences in source parameters and wave propagation through the crustal velocity gradient. If the method 2 soil correction is used, the ENA motions appear to be somewhat smaller than California motions at low frequencies and somewhat larger at high frequencies (differences are generally less than a factor of 2). Recall that our ENA spectral amplitudes at frequencies less than 2 Hz appear very low relative to earlier models based on a Brune source with a 100-bar stress drop. Interestingly, in Figure 7 it appears that these motions are not necessarily low relative to California experience.

UNCERTAINTY IN GROUND-MOTION RELATIONS

Median ground-motion relations

The uncertainty in ground-motion relations, both aleatory (random scatter) and epistemic (model uncertainty), is a major consideration in earthquake engineering applications. Model uncertainty is particularly critical in ENA given the large differences between alternative ground-motion relations.

Standard Deviation of Residuals (Aleatory Uncertainty)

The standard deviation of the (ln) residuals (σ), expressing the random variability of ground motions, is an important input parameter in probabilistic seismic hazard analysis. In western North America, the observed value of $\ln\sigma$ lies within the range of 0.5 to 0.7 (Boore *et al.*, 1993). In ENA, the random variability depends partly on the magnitude scale used for ground-motion predictions. For predictions from M, it increases slightly with frequency from a value of 0.55 ln units at 1 Hz to 0.62 at 10 Hz (Atkinson, 1995b). Conversely if predictions are based on the proposed high-frequency magnitude scale of Atkinson and Hanks (1995), then variability decreases with frequency from 0.71 at 1 Hz to 0.55 at 10 Hz. The variability for m_N-based predictions is large—about 0.7 to 0.9 ln units. This is a consequence of ambiguity in the relationship between m_N and the source spectrum.

Epistemic Uncertainty in Median Relations

Epistemic uncertainty in the true level of the median ground-motion relations is distinct from the issue of random scatter about the median (aleatory uncertainty), although there is significant interplay between these two types of uncertainty. The AB95 ground-motion relations do not explicitly address the issue of epistemic uncertainty in the median relations. There are several approaches to defining this uncertainty. One approach is to define the range in professional opinion regarding the true level of the median. This is the approach taken by SSHAC (1996), as described above. The disadvantage of this approach is that it involves a subjective interpretation of the meaning of various expert opinions. Another approach is that taken by EPRI (1993), namely to model the variability that results from estimated variability in input parameters to the model. This approach is objective but may ignore a variety of unmodeled uncertainties (source spectral shape, nature of duration, etc.).

Further work in defining the uncertainty in median relations in ENA appears warranted, particularly in light of the differences in the AB95 medians as compared to the EPRI93 medians. These differences, along with the range of estimates put forward by the proponents at the SSHAC workshop, suggest that the epistemic uncertainty in the true median might be as high as a factor of two (for one standard deviation from the median). On the other hand, it was demonstrated at the SSHAC workshop that the epistemic uncertainty may be reduced through constructive exchanges of data and interpretations.

Regional Variability

Regional differences in a wide range of source and propagation parameters indicate that ground-motion relations or time series for earthquakes in one region cannot be simply modified for use in engineering analyses in another region (see Figure 7, for example). This is unfortunate since this has been a convenient and widespread practice in the past.

We do not know the distance scale over which significant differences in fundamental ground-motion parameters appear. The modeling work of the EPRI studies has demonstrated significant variability in path effects even within the ENA region. It is unknown whether there are identifiable variations in source properties within this region. We conclude there is much work to be done in the area of regional and local variability in fundamental ground-motion processes.

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APPENDIX
ENA Median Horizontal Component: Hard Rock Sites
Natural logs of values, in g, are given. Abridged version of Appendix of Atkinson and Boore, 1995.

		SA (5% damped) for frequency (Hz) =					
Moment M	**rhypo(km)**	**1.0**	**2.0**	**3.0**	**5.0**	**10.0**	**PGA**
4.50	10.0	−4.83	−3.66	−2.97	−2.10	−1.25	−1.34
4.50	15.0	−5.52	−4.24	−3.49	−2.74	−1.89	−2.18
4.50	20.0	−5.99	−4.63	−3.90	−3.05	−2.32	−2.72
4.50	30.0	−6.63	−5.26	−4.51	−3.74	−3.02	−3.45
4.50	40.0	−6.94	−5.58	−4.95	−4.18	−3.48	−3.99
4.50	50.0	−7.28	−5.96	−5.21	−4.49	−3.82	−4.40
4.50	60.0	−7.53	−6.21	−5.53	−4.77	−4.17	−4.78
4.50	80.0	−7.73	−6.42	−5.74	−5.07	−4.46	−5.17
4.50	100.0	−7.82	−6.47	−5.86	−5.07	−4.55	−5.32
4.50	150.0	−7.92	−6.64	−5.98	−5.35	−4.90	−5.76
4.50	200.0	−8.19	−6.93	−6.32	−5.70	−5.37	−6.32
4.50	300.0	−8.62	−7.44	−6.90	−6.38	−6.30	−7.28
5.00	10.0	−4.22	−3.01	−2.20	−1.50	−0.77	−0.97
5.00	15.0	−4.68	−3.45	−2.78	−2.12	−1.35	−1.71
5.00	20.0	−5.12	−3.85	−3.16	−2.40	−1.79	−2.17
5.00	30.0	−5.57	−4.33	−3.71	−3.02	−2.42	−2.88
5.00	40.0	−5.96	−4.64	−4.03	−3.49	−2.88	−3.40
5.00	50.0	−6.24	−5.04	−4.47	−3.80	−3.23	−3.80
5.00	60.0	−6.52	−5.33	−4.70	−4.06	−3.55	−4.18
5.00	80.0	−6.69	−5.53	−4.90	−4.33	−3.85	−4.57
5.00	100.0	−6.69	−5.53	−4.96	−4.33	−3.95	−4.70
5.00	150.0	−6.86	−5.73	−5.16	−4.63	−4.25	−5.12
5.00	200.0	−7.12	−6.01	−5.51	−4.98	−4.74	−5.65
5.00	300.0	−7.56	−6.57	−6.08	−5.68	−5.65	−6.62
5.50	10.0	−3.51	−2.28	−1.63	−0.95	−0.29	−0.62
5.50	15.0	−3.92	−2.72	−2.06	−1.44	−0.86	−1.26
5.50	20.0	−4.20	−3.16	−2.49	−1.87	−1.25	−1.69
5.50	30.0	−4.76	−3.64	−3.02	−2.46	−1.84	−2.37

APPENDIX (Continued)
ENA Median Horizontal Component: Hard Rock Sites
Natural logs of values, in g, are given. Abridged version of Appendix of Atkinson and Boore, 1995.

		SA (5% damped) for frequency (Hz) =					
Moment M	**rhypo(km)**	**1.0**	**2.0**	**3.0**	**5.0**	**10.0**	**PGA**
5.50	40.0	–5.11	–3.94	–3.38	–2.84	–2.31	–2.87
5.50	50.0	–5.40	–4.23	–3.73	–3.11	–2.68	–3.27
5.50	60.0	–5.65	–4.52	–3.99	–3.40	–2.98	–3.63
5.50	80.0	–5.86	–4.79	–4.20	–3.67	–3.27	–3.99
5.50	100.0	–5.90	–4.81	–4.24	–3.76	–3.35	–4.15
5.50	150.0	–6.02	–4.98	–4.43	–4.00	–3.69	–4.56
5.50	200.0	–6.27	–5.23	–4.80	–4.41	–4.18	–5.10
5.50	300.0	–6.67	–5.73	–5.34	–5.00	–5.06	–5.95
6.00	10.0	–2.73	–1.54	–1.02	–0.42	.12	–0.33
6.00	15.0	–3.23	–2.04	–1.54	–0.94	–0.44	–0.88
6.00	20.0	–3.56	–2.44	–1.90	–1.30	–0.79	–1.30
6.00	30.0	–4.04	–2.94	–2.40	–1.86	–1.37	–1.91
6.00	40.0	–4.38	–3.28	–2.75	–2.29	–1.79	–2.38
6.00	50.0	–4.64	–3.59	–3.04	–2.60	–2.15	–2.76
6.00	60.0	–4.93	–3.86	–3.35	–2.84	–2.44	–3.09
6.00	80.0	–5.13	–4.05	–3.61	–3.11	–2.75	–3.44
6.00	100.0	–5.10	–4.05	–3.61	–3.16	–2.81	–3.59
6.00	150.0	–5.28	–4.21	–3.81	–3.40	–3.16	–4.00
6.00	200.0	–5.55	–4.58	–4.12	–3.81	–3.60	–4.52
6.00	300.0	–5.93	–5.03	–4.69	–4.41	–4.49	–5.37
6.50	10.0	–2.16	–1.06	–0.57	–0.12	.49	–0.03
6.50	15.0	–2.58	–1.51	–1.00	–0.55	–0.03	–0.51
6.50	20.0	–2.92	–1.87	–1.32	–0.88	–0.40	–0.90
6.50	30.0	–3.37	–2.33	–1.82	–1.38	–0.94	–1.51
6.50	40.0	–3.72	–2.61	–2.16	–1.76	–1.34	–1.92
6.50	50.0	–3.97	–2.97	–2.52	–2.10	–1.65	–2.30
6.50	60.0	–4.19	–3.19	–2.74	–2.33	–1.97	–2.61
6.50	80.0	–4.41	–3.39	–2.98	–2.58	–2.22	–2.96
6.50	100.0	–4.38	–3.45	–3.03	–2.63	–2.32	–3.11
6.50	150.0	–4.57	–3.62	–3.23	–2.89	–2.67	–3.49
6.50	200.0	–4.79	–3.85	–3.57	–3.25	–3.12	–3.99
6.50	300.0	–5.20	–4.41	–4.08	–3.85	–3.97	–4.81
7.00	10.0	–1.52	–0.58	–0.09	.36	.80	.32
7.00	15.0	–1.95	–0.96	–0.54	–0.13	.31	–0.21
7.00	20.0	–2.28	–1.34	–0.91	–0.47	–0.03	–0.58
7.00	30.0	–2.75	–1.76	–1.36	–0.95	–0.52	–1.10
7.00	40.0	–3.02	–2.10	–1.70	–1.30	–0.93	–1.53
7.00	50.0	–3.36	–2.41	–1.93	–1.59	–1.22	–1.89
7.00	60.0	–3.54	–2.62	–2.18	–1.86	–1.49	–2.21

APPENDIX (Continued) ENA Median Horizontal Component: Hard Rock Sites Natural logs of values, in g, are given. Abridged version of Appendix of Atkinson and Boore, 1995.							
		SA (5% damped) for frequency (Hz) =					
Moment M	**rhypo(km)**	**1.0**	**2.0**	**3.0**	**5.0**	**10.0**	**PGA**
7.00	80.0	−3.76	−2.79	−2.46	−2.10	−1.81	−2.54
7.00	100.0	−3.79	−2.83	−2.53	−2.19	−1.88	−2.67
7.00	150.0	−3.96	−3.06	−2.68	−2.42	−2.22	−3.08
7.00	200.0	−4.19	−3.34	−2.98	−2.72	−2.66	−3.53
7.00	300.0	−4.50	−3.72	−3.49	−3.36	−3.49	−4.28