Quantitative Ground-Motion Estimates[a]

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INTRODUCTION

Estimates of ground motion in eastern North America (ENA) are hampered by a lack of data. Because of this, most estimation schemes have been based, at least in part, on data obtained from the more seismically active and better-instrumented western North America (WNA). In view of the different geologic structures and tectonic settings in the two regions, however, it is not clear *a priori* that data from WNA can be exported to ENA. A theoretical model has been developed in the last few years that does not require WNA data for the estimation of ground motions in ENA. This model constructs the ground motion from filtered random Gaussian noise, for which the filter parameters are determined by a seismological model of both the source and the wave propagation. Many of the parameters in the model can be determined from independent seismological investigations in ENA or in other regions with similar tectonic characteristics. Crucial ingredients of this model are the shape of the radiated energy spectrum and the relation between the seismic moment of the earthquake and the corner frequency of the spectrum (usually referred to as the "scaling law"). In two recent papers, predictions of ENA ground motions using a scaling law characterized by a constant stress parameter were in reasonable agreement with the sparse observed data at rock sites, most of which come from earthquakes near moment magnitude 4.5. Subsequent to these studies, however, two variable-stress scaling laws have been proposed. All the laws lead to similar motions for moderate earthquakes ($M = 4.5$), but for larger events the estimates diverge (the range in predicted motions is a factor of 6 for an $M = 7.5$ earthquake, the estimates from the constant stress scaling being between the other two). The new model can be used to gain insight into similarities and differences between ground motions for ENA and WNA earthquakes. The calculations suggest that the motions would be the same at distances within about 60 km for ground motions with frequencies less than about 10 to 15 Hz. At greater distances the differences in regional attenuation of seismic waves leads to larger ground motions in ENA (although these motions would probably not cause much damage), and at higher frequencies the generally more competent rock in ENA will allow higher frequencies to propagate to the site than would be the case for typical rock sites in WNA.

STOCHASTIC MODEL

The stochastic model for estimating ground motions is best described with reference to FIGURE 1; more complete descriptions can be found in papers published by Boore,[1] Boore and Atkinson,[2] and Toro and McGuire,[3] and the refer-

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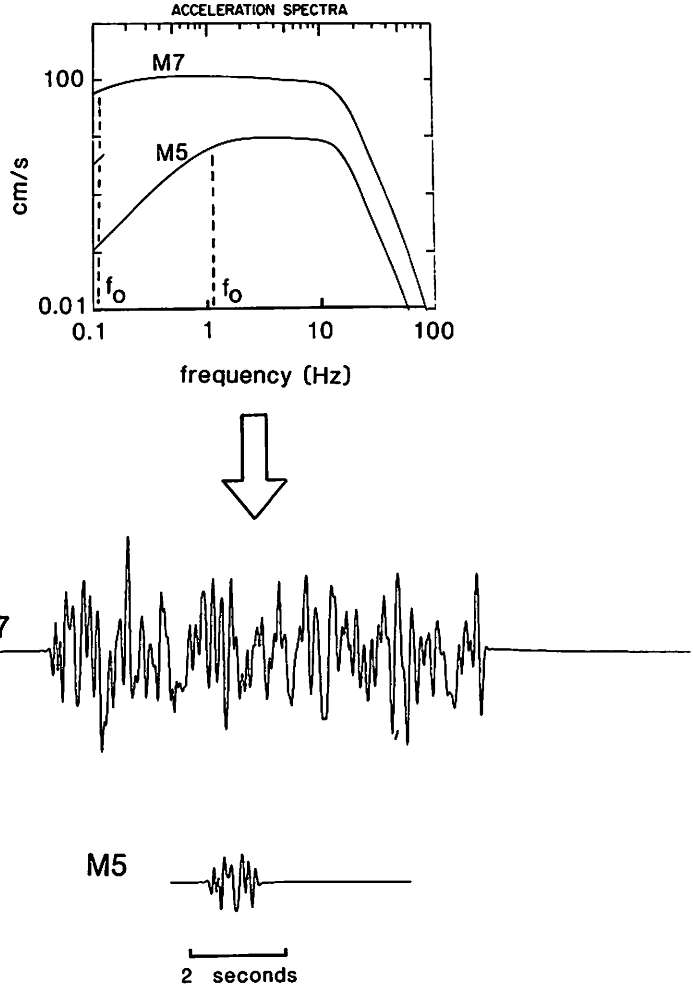

FIGURE 1. Basis of stochastic model. Radiated energy described by spectra in *upper part* of figure is assumed to be distributed randomly over a duration equal to the inverse of the lower frequency corner (f_0). Time series is one realization of a random process. The levels of the low-frequency part of the spectra are directly proportional to the logarithm of the seismic moment and thus, by definition of Hanks and Kanamori,[15] to the moment magnitude **M**. Unless specifically noted otherwise, all magnitudes in this paper refer to moment magnitude.

ences therein. The spectra of the radiated motion is specified by a seismological model (in this case, the ω^2 spectrum with constant stress parameter), and the motion is assumed to be spread out in a stochastic manner over a specified duration (in this case, the inverse of the corner frequency). The peak motions can be determined either by a suite of time-domain simulations or, more conveniently, by random process theory. Boore and Atkinson[2] (hereafter referred to as BA87) used this model with a 100-bar stress parameter to predict pseudo-relative velocity spectra (*PSV*) as well as peak acceleration for hard-rock sites in eastern North America (ENA). Note that the spectra and time series shown in FIGURE 1 have not been sketched by hand; they were computed for the magnitudes shown.

SOURCE SCALING

Crucial to the ground-motion predictions is the specification of the source spectrum. This usually comprises two parts: the shape of the spectrum, and the way in which the spectral corners depend on seismic moment (this dependence is usually referred to as the "scaling law"). At the time BA87 was written, the only scaling law offered for ENA earthquakes was that of Nuttli[4] (referred to hereafter as N83). BA87 considered this scaling law, but found it to lead to ground motions significantly lower than the few available recordings (mainly for earthquakes around M4.5). BA87 found that scaling with a constant stress parameter of 100 bars gave reasonable predictions of the available data. Since publication of BA87, Nuttli *et al.*[5] (referred to hereafter as N87) and Boatwright and Choy[6] (referred to hereafter as B&C) have published scaling laws for ENA and intraplate earthquakes. FIGURE 2 compares the magnitude scaling of the high-frequency level of

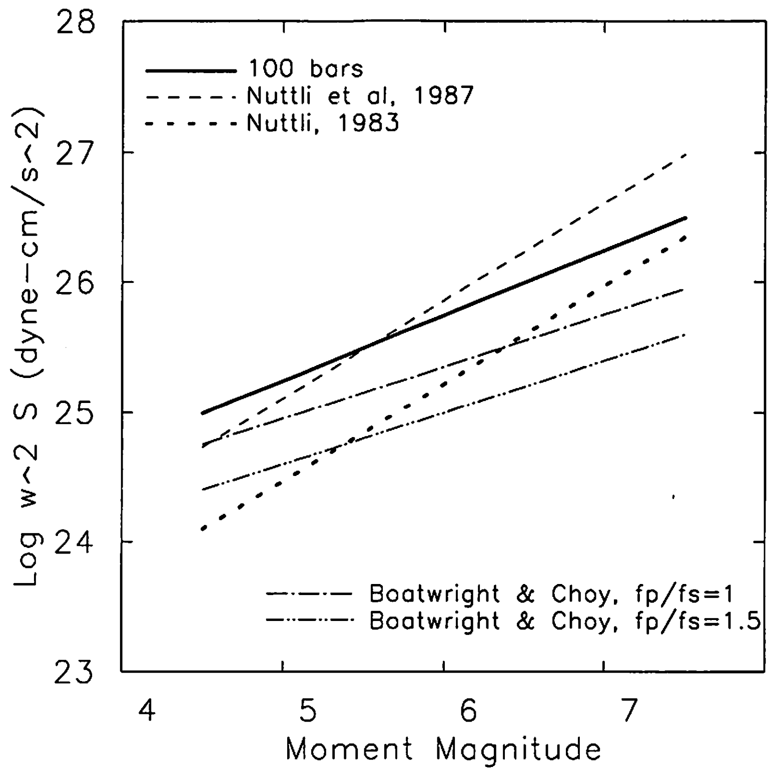

FIGURE 2. High-frequency acceleration spectral levels predicted by various scaling laws.

$(2\pi f)^2$ times the moment rate spectrum (in effect this is the acceleration spectrum normalized such that the long period level of the corresponding displacement spectrum is equal to the seismic moment) for the various scaling laws.

Boatwright and Choy[6] used teleseismic P waves to derive their source spectra. In order to apply their results to the radiation of S waves, I have assumed that the shape of the source spectra is the same for both P and S waves, with a specified ratio between the P- and S-wave corner frequencies. A frequency-independent multiplicative factor accounted for the radiation pattern and seismic velocity differences. The high-frequency spectral level of the S wave depends on this

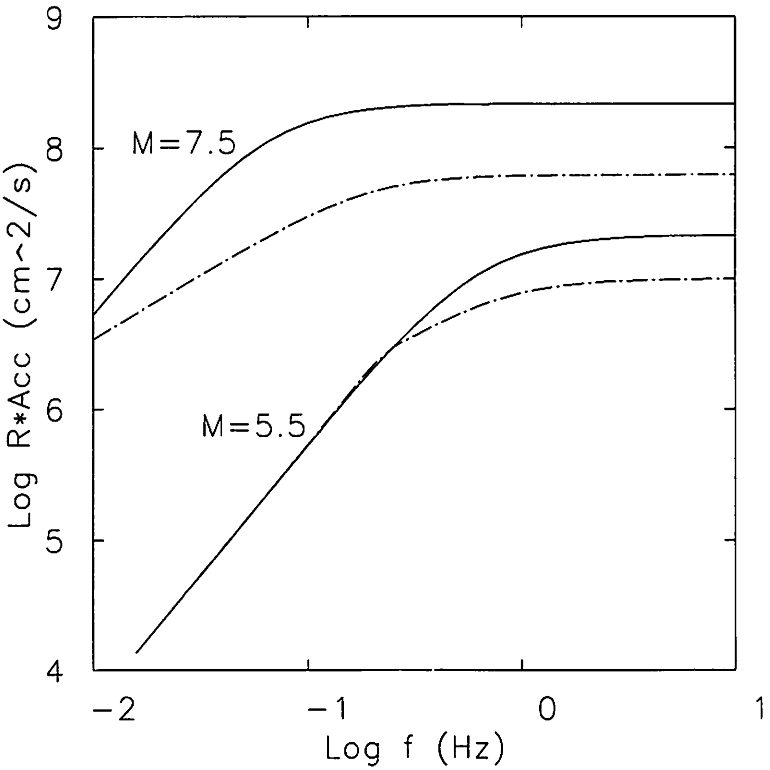

FIGURE 3. Distance-corrected acceleration spectra for 100-bar (*solid line*) and Boatwright and Choy (*dot-dash line*) scalings. The ratio of P-wave to S-wave corner frequencies was 1.0.

multiplicative factor and on the ratio of corner frequencies. In most of the computations presented here, the corner frequency ratio has been taken to be unity. This produces a result that is consistent with Choy and Boatwright's derivation of high-frequency S-wave spectral amplitudes from their P-wave scaling.[7] For comparative purposes, FIGURE 2 also contains results for a corner frequency ratio of 1.5.

From FIGURE 2 alone, we can see that all other things being equal, the N83 scaling will lead to much lower ground motions than the 100-bar scaling, and that for earthquakes less than about M 6.5 the revised scaling given by N87 will lead to motions similar to those given by the 100-bar relation used by BA87. The B&C

relation with a corner frequency ratio of 1.5 leads to low motions, as will their relation with a ratio of 1.0 (except for events near M = 4.5).

The spectral shapes assumed for the constant stress (100 bar) and B&C scalings, for earthquakes of magnitudes 5.5 and 7.5, are shown in FIGURE 3. The B&C spectra are characterized by two corner frequencies. The higher of the two corners is determined by a least-square line fit to B&C observations of corner frequency versus moment magnitude; the lower corner is found by intersection of the low-frequency part of the spectrum, determined by moment, and a line of unit slope between the observationally determined high-frequency corner and spectral level.

COMPARISON WITH ENA GROUND MOTIONS

FIGURE 4, patterned after Figure 7 in BA87, shows the predicted *PSV* as a function of distance for the various scaling laws. The symbols are available data from rock sites in ENA. Coincidentally, the N87 and B&C (with corner frequency ratio of unity) laws give virtually identical motions (see the previous figure also). It would be difficult to choose between the 100-bar, N87, and B&C laws based on a comparison of the predictions to the observations.

The scaling with magnitude of *PSV* for the various scaling laws, at a fixed distance of 10 km, is shown in FIGURE 5. It is clear that although the 100-bar, N87, and B&C laws lead to similar motions at M = 4.5 (see previous figure also), the predictions diverge for the large earthquakes of most importance for engineering design. Data from these large events are needed to distinguish between the models. B&C based their study on teleseismic recordings of earthquakes greater than M = 5, and so preference should perhaps be given to their law. On the other hand, the 100-bar relation gave a reasonable prediction of m_{Lg} values for larger ENA earthquakes,[2,8] and Somerville *et al.*[9] found an average stress drop of 100 bars in their analysis of teleseismic recordings of large earthquakes in eastern North America.

COMPARISON WITH NAHANNI EARTHQUAKE DATA

The M = 6.5 December 23, 1985, Nahanni, Northwest Territories earthquake was recorded on three nearby SMA stations. For several reasons, including similarities of types of faulting and geologic conditions, the event is considered by Wetmiller *et al.*[10] to be representative of events that might occur in ENA. The strong motion recordings then take on particular significance for the estimation of seismic hazard in ENA. The aftershock locations and instrument locations are shown in FIGURE 6, which was taken from Weichert *et al.*[11]

Observed and predicted pseudo-relative velocity spectra at the three stations are shown in FIGURE 7. The *PSV* at station 1 was computed using the first 7 seconds of record, thereby eliminating the large burst of energy late in the record (this prominent burst of energy is not seen on the records from the other stations and may not be representative of the overall fault rupture). The open circles are predictions using equations in BA87, with two distance measures—closest distance, and distance to the center of aftershocks; the ×'s are predictions from Joyner and Boore's analysis of records from western North America.[12] The agreement between observed and predicted values is reasonable, especially in view of

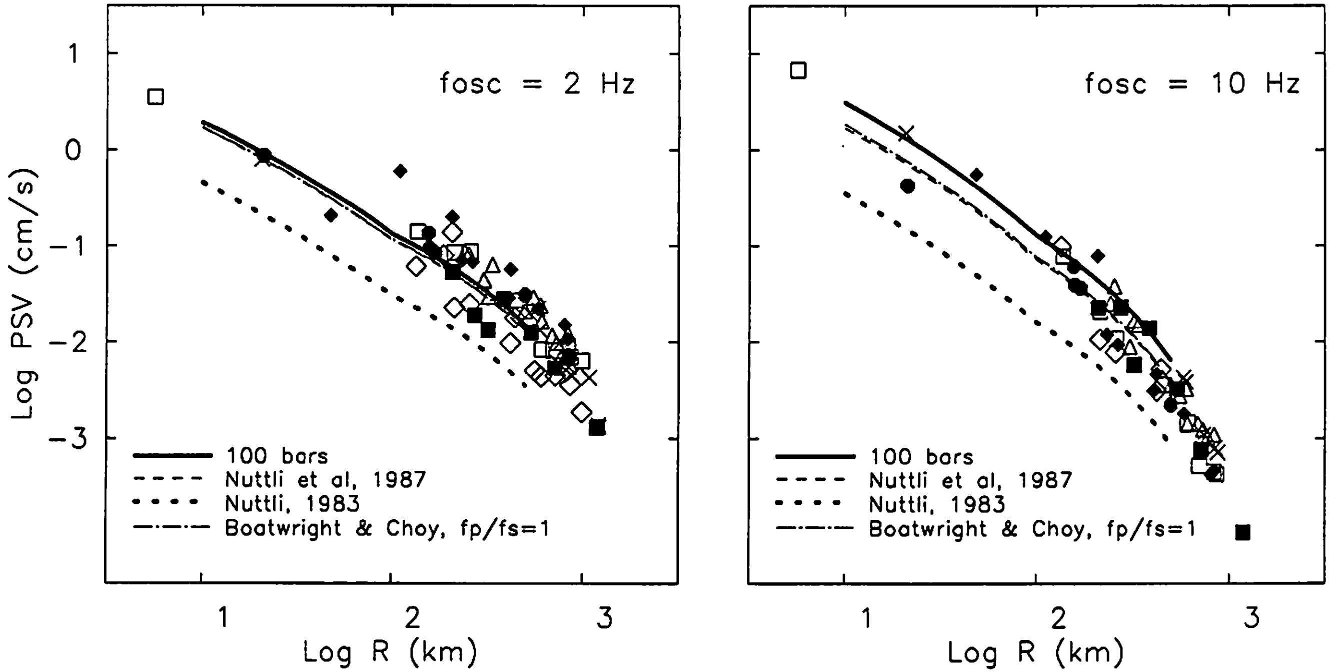

FIGURE 4. Comparison of observed (*symbols*) and predicted (*lines*) 5 percent damped pseudo-velocity response spectra (*PSV*) for 2- and 10-Hz oscillators. Data have been normalized to M = 4.5 by means of scaling obtained from the theoretical predictions using 100-bar scaling. (See Figure 7 in Boore and Atkinson[2] for key to symbols.)

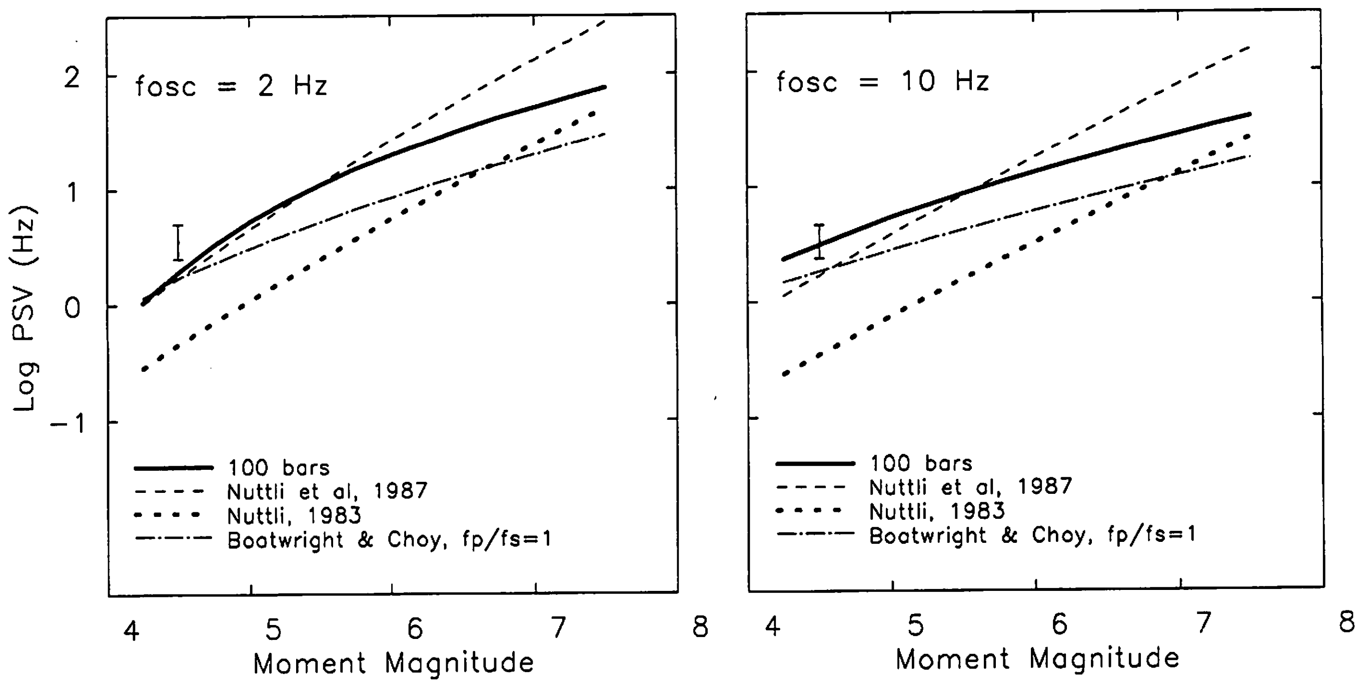

FIGURE 5. Scaling of *PSV* with moment magnitude (M) at 10-km distance for 2- and 10-Hz oscillators. The scant data suggest *PSV* values indicated by the bar at M = 4.5.

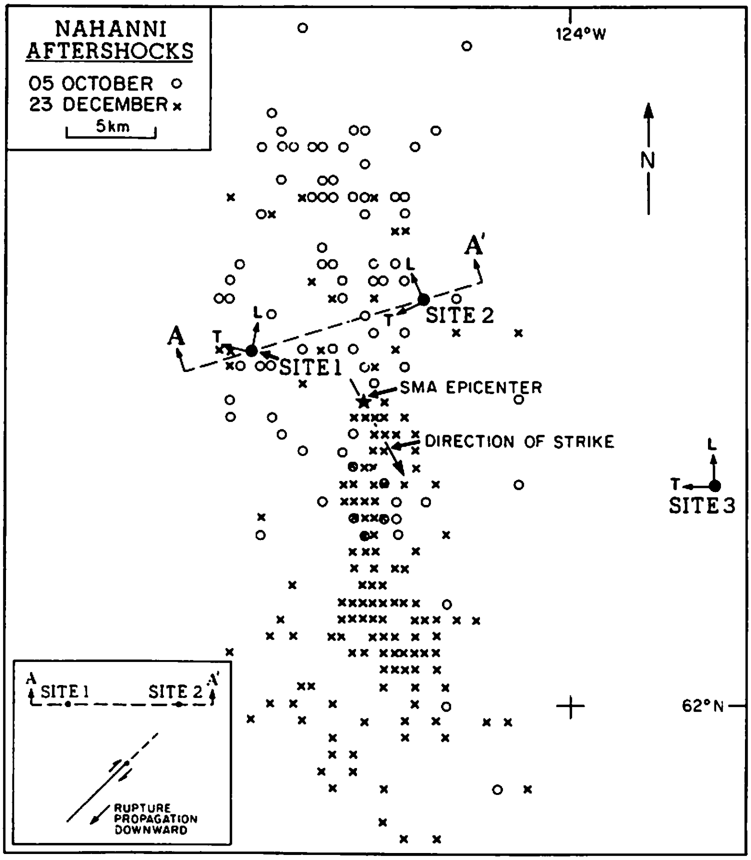

FIGURE 6. Station locations of SMA instruments (*solid circles*) and aftershocks of Nahanni earthquakes. (From Weichert *et al.*[11] Reprinted by permission.)

the large scatter of individual observations that exists in any attempt to predict inean values of ground motion.

The comparison in FIGURE 7 was between *PSV* derived from observations and previously published predictions of the *PSV*. The relation between the data and theoretical predictions using B&C's scaling, as well as the 100-bar stress parameter model, are shown in FIGURES 8 and 9. The comparison is in terms of Fourier amplitude spectra (*FAS*) rather than *PSV* (the relative agreement of observations and predictions should be similar for both quantities, however). The observations are given by heavy lines (where, as with *PSV*, only the first 7 seconds were used in computing the *FAS* for station 1). In FIGURE 8, the predictions used the distances and radiation pattern terms used by Choy and Boatwright.[7] The predictions in FIGURE 9 use my estimates of distances (closest distance and distance to center of aftershocks) and the radiation pattern term used in BA87. B&C give a better fit to the observations when using their parameters, and as expected from the comparison in FIGURE 7, the 100-bar prediction is reasonable for stations 1 and 2 when using the BA87 parameters. B&C, however, consistently have a better fit to the station 3 acceleration spectrum than that given by the 100-bar model. Some cautions are necessary before drawing any firm conclusions from these comparisons. First, the BA87 predictions are for the mean value of motion, and the motions from any one earthquake could be systematically higher or lower than the mean value. Second, radiation pattern and geometrical spreading terms, as well as directivity and partition of energy into various components, affect the overall amplitude level, but are somewhat uncertain, especially close to large faults. For this reason, a firm conclusion that one scaling model is better than another should not be reached solely on the basis of the Nahanni data.

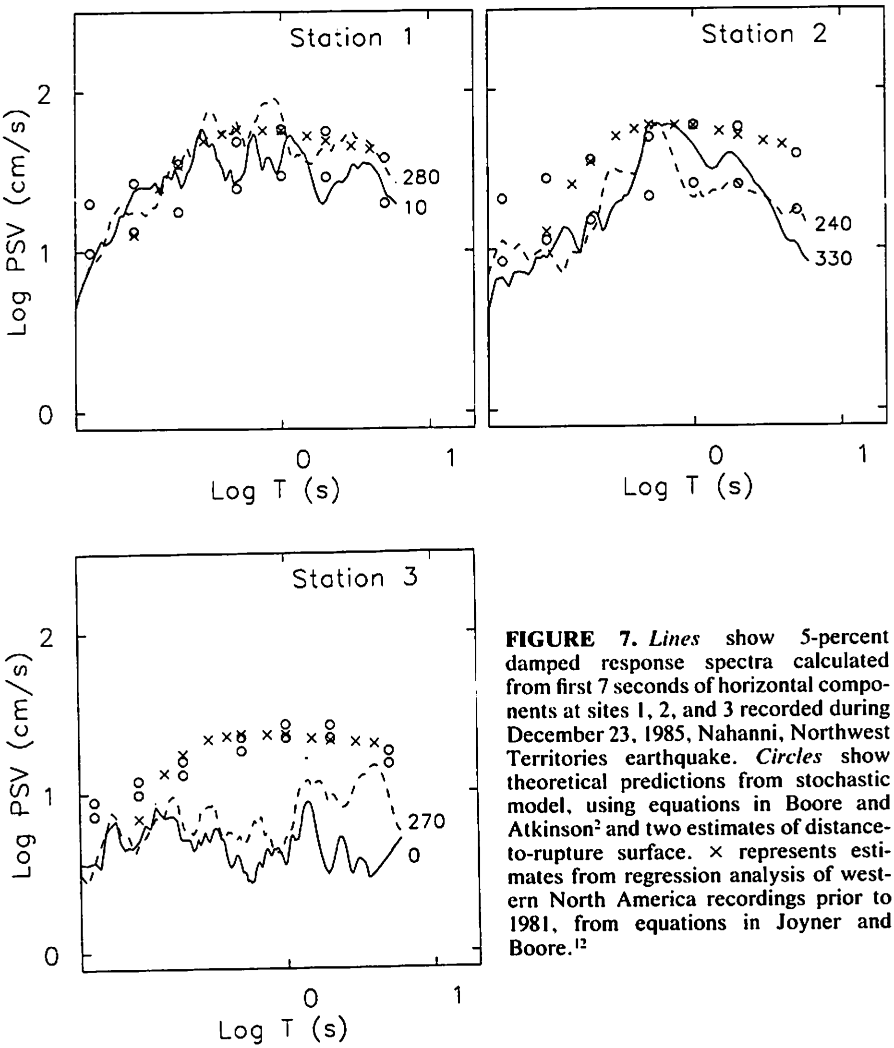

FIGURE 7. *Lines* show 5-percent damped response spectra calculated from first 7 seconds of horizontal components at sites 1, 2, and 3 recorded during December 23, 1985, Nahanni, Northwest Territories earthquake. *Circles* show theoretical predictions from stochastic model, using equations in Boore and Atkinson[2] and two estimates of distance-to-rupture surface. × represents estimates from regression analysis of western North America recordings prior to 1981, from equations in Joyner and Boore.[12]

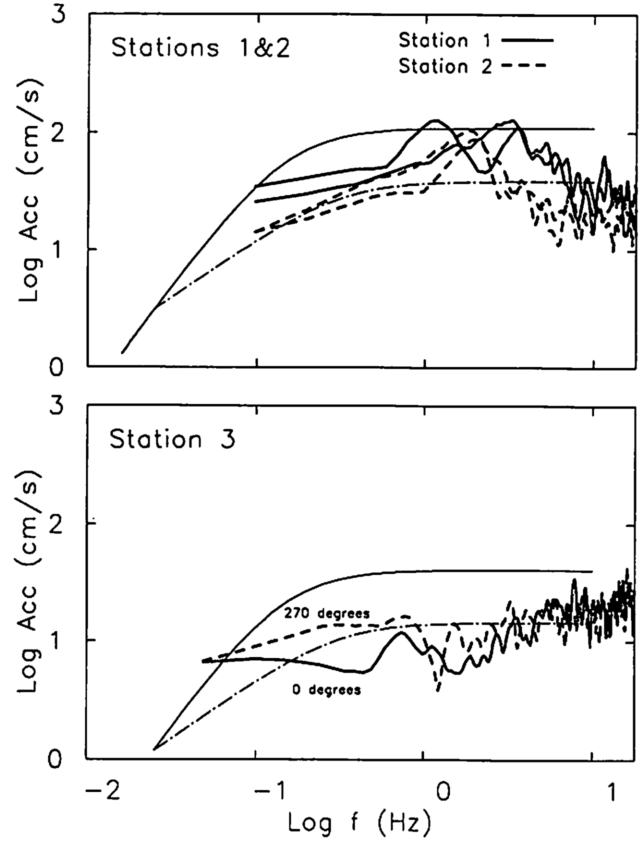

FIGURE 8. *Heavy lines* show acceleration from first 7.5 seconds of horizontal components at sites 1, 2, and 3 recorded during the 23 December 1985 Nahanni earthquake. *Light lines* show estimated spectra, using 100-bar model (*solid line*) and Boatwright and Choy model (*dash-dot*: P- to S-wave corner frequency ratio = 1.0). Distances and radiation patterns are from Choy and Boatwright.[7]

COMPARISON OF PREDICTIONS IN EASTERN AND WESTERN NORTH AMERICA

I used the stochastic model to make a comparison of *PSV* at four oscillator periods for the ENA model of BA87 and the WUS model in Boore.[13] The results are shown in FIGURE 10. The two models differ in several ways: in ENA the crustal velocity is slightly higher, f_m is much higher (50 Hz versus 15 Hz), little amplification is expected at hard-rock sites, and a higher stress parameter is required to fit the meager data (100 bars versus 50 bars). These differences are reflected in a complicated way in the comparison shown in FIGURE 10. For example, compared to the WUS, for the 20-Hz *PSV* the ENA motions are considerably higher because of the higher f_m, and for the 5-Hz *PSV* the ENA motions are lower because of the higher crustal velocity and lack of an amplification effect. This

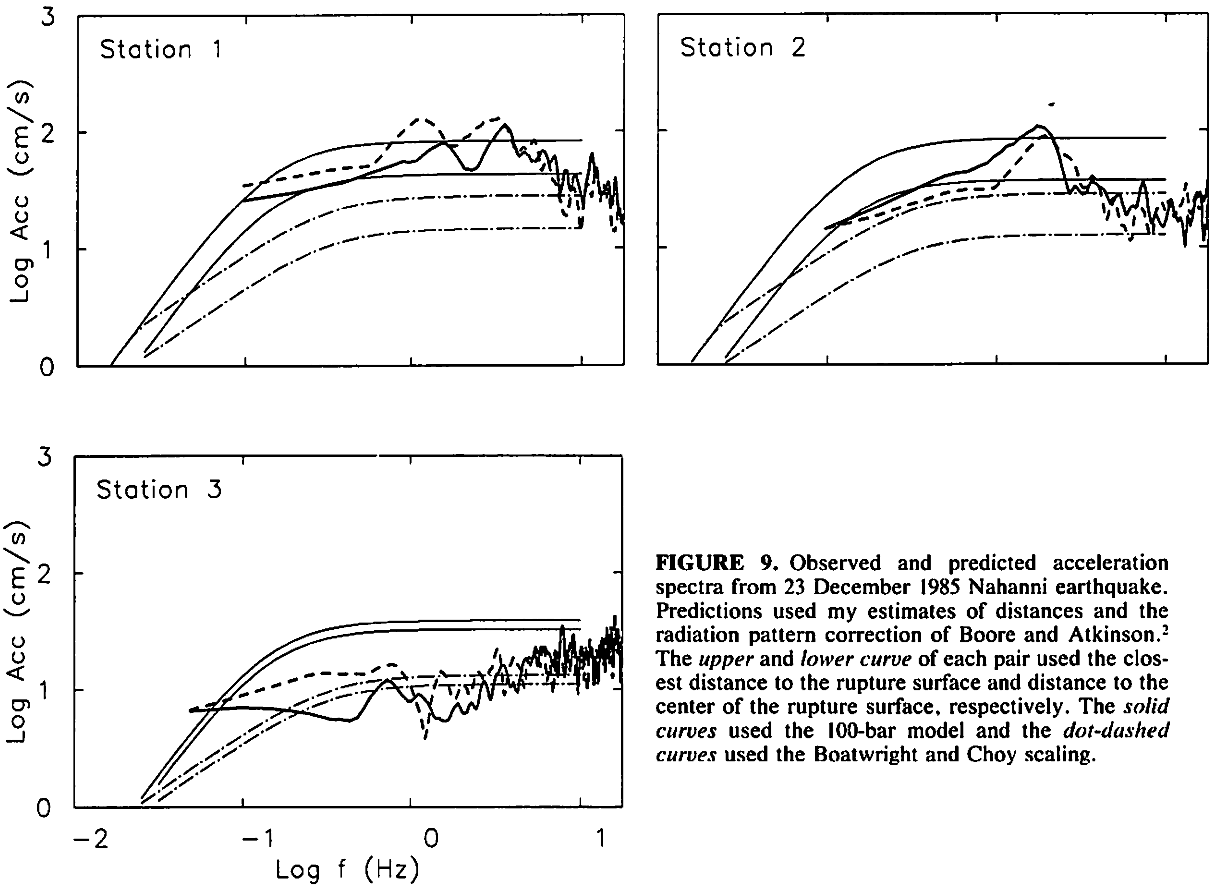

FIGURE 9. Observed and predicted acceleration spectra from 23 December 1985 Nahanni earthquake. Predictions used my estimates of distances and the radiation pattern correction of Boore and Atkinson.[2] The *upper* and *lower curve* of each pair used the closest distance to the rupture surface and distance to the center of the rupture surface, respectively. The *solid curves* used the 100-bar model and the *dot-dashed curves* used the Boatwright and Choy scaling.

amplification effect is frequency-dependent, being near unity for frequencies less than about 1 Hz, and therefore the 1-Hz *PSV* again shows that ENA motions are higher (because of the higher stress parameter). Finally, the 0.2-Hz *PSV* is not very sensitive to the stress parameter, since the corner frequencies of all but the M = 7 event are higher than the oscillator frequency, and therefore the ENA and WUS motions are similar.

ESTIMATION OF RESPONSE SPECTRA FROM PEAK MOTIONS

A common way of estimating *PSV* is to multiply peak acceleration and/or peak velocity by appropriate factors and to plot the resulting levels on log-log paper (Newmark and Hall;[14] most U.S. and Canadian building codes). When applied to the stochastic model calculations (FIG. 11), this method produces reasonable estimates of *PSV* for magnitude 5 events but overestimates *PSV* for larger earthquakes by as much as a factor of two, for frequencies less than about 10 Hz. For all size events the method consistently underestimates the high-frequency part of

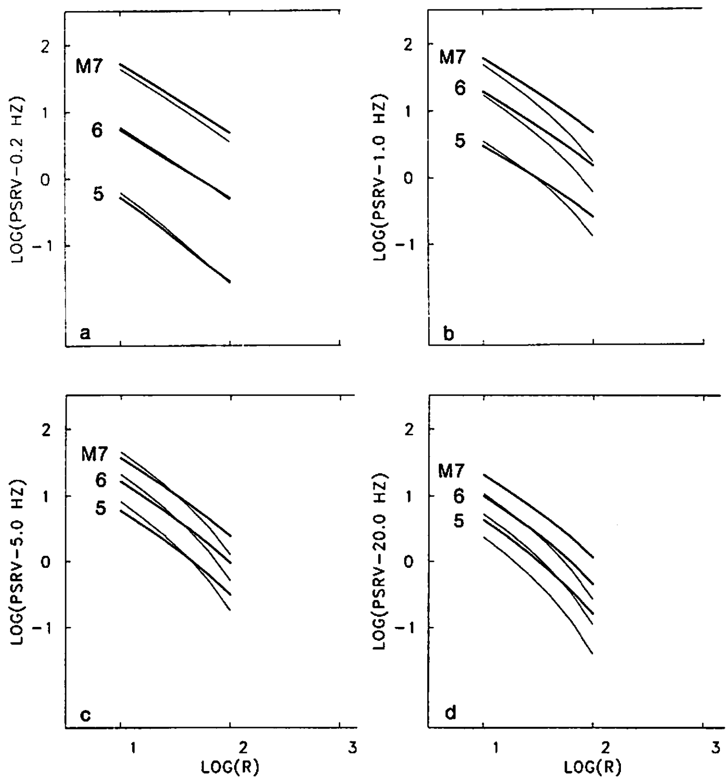

FIGURE 10. log *PSV* versus log *r* for 5-percent-damped oscillators at four frequencies (**a, b, c, d**). In each figure, results are shown for moment magnitudes 5, 6, and 7. The ENA and WUS predictions are given by *heavy* and *light lines*, respectively.

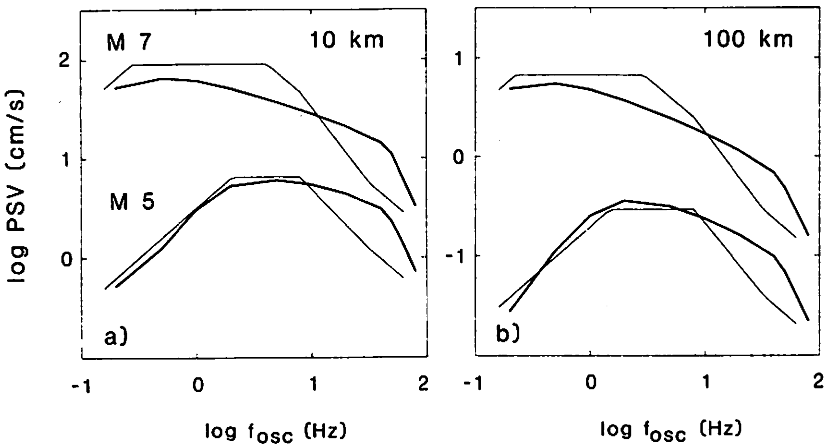

FIGURE 11. Predicted 5-percent-damped pseudo-velocity response spectra (*PSV*) at 10 and 100 km as a function of oscillator frequency (f_{osc}). Predictions from the stochastic model are shown by the *heavy curves*. The *light lines* were obtained from the peak velocity and acceleration predicted from the model by applying median amplification factors from Table 1 in Newmark and Hall,[14] with faring to the high-frequency asymptote beginning at 8 Hz and ending at 33 Hz (see Figure 5 in Newmark and Hall[14]). (From Boore and Atkinson.[2] Reprinted by permission.)

the spectrum, by up to a factor of 3, even though the peak accelerations used in the method were those computed for the ENA ground-motion model. This is in large part due to the much higher frequency content in the theoretical motions (controlled by the choice of f_m = 50 Hz) than exist in the WNA data from which the amplification factors and faring frequencies published by Newmark and Hall[14] were derived. The comparison emphasizes the need to predict expected response spectra directly, rather than through the use of standard spectral shapes. Simply put, the frequency content and attenuation of ENA ground motions preclude the use of standard spectral shapes developed empirically from western data. In particular, the enrichment of ENA motions in higher frequencies means that the relationship between maximum ground acceleration and maximum acceleration response is not a simple constant in the frequency range of engineering interest (less than 30 Hz). The acceleration response spectra, S_a, will increase with increasing frequency until frequencies near f_m (50 Hz) are approached.

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