"Did You Feel It?" Intensity Data: A Surprisingly Good Measure of Earthquake Ground Motion

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ABSTRACT

The U.S. Geological Survey is tapping a vast new source of engineering seismology data through its "Did You Feel It?" (DYFI) program, which collects online citizen responses to earthquakes. To date, more than 750,000 responses have been compiled in the United States alone. The DYFI data make up in quantity what they may lack in scientific quality and offer the potential to resolve longstanding issues in earthquake ground-motion science. Such issues have been difficult to address due to the paucity of instrumental ground-motion data in regions of low seismicity. In particular, DYFI data provide strong evidence that earthquake stress drops, which control the strength of high-frequency ground shaking, are higher in the central and eastern United States (CEUS) than in California. Higher earthquake stress drops, coupled with lower attenuation of shaking with distance, result in stronger overall shaking over a wider area and thus more potential damage for CEUS earthquakes in comparison to those of equal magnitude in California—a fact also definitively captured with these new DYFI data and maps.

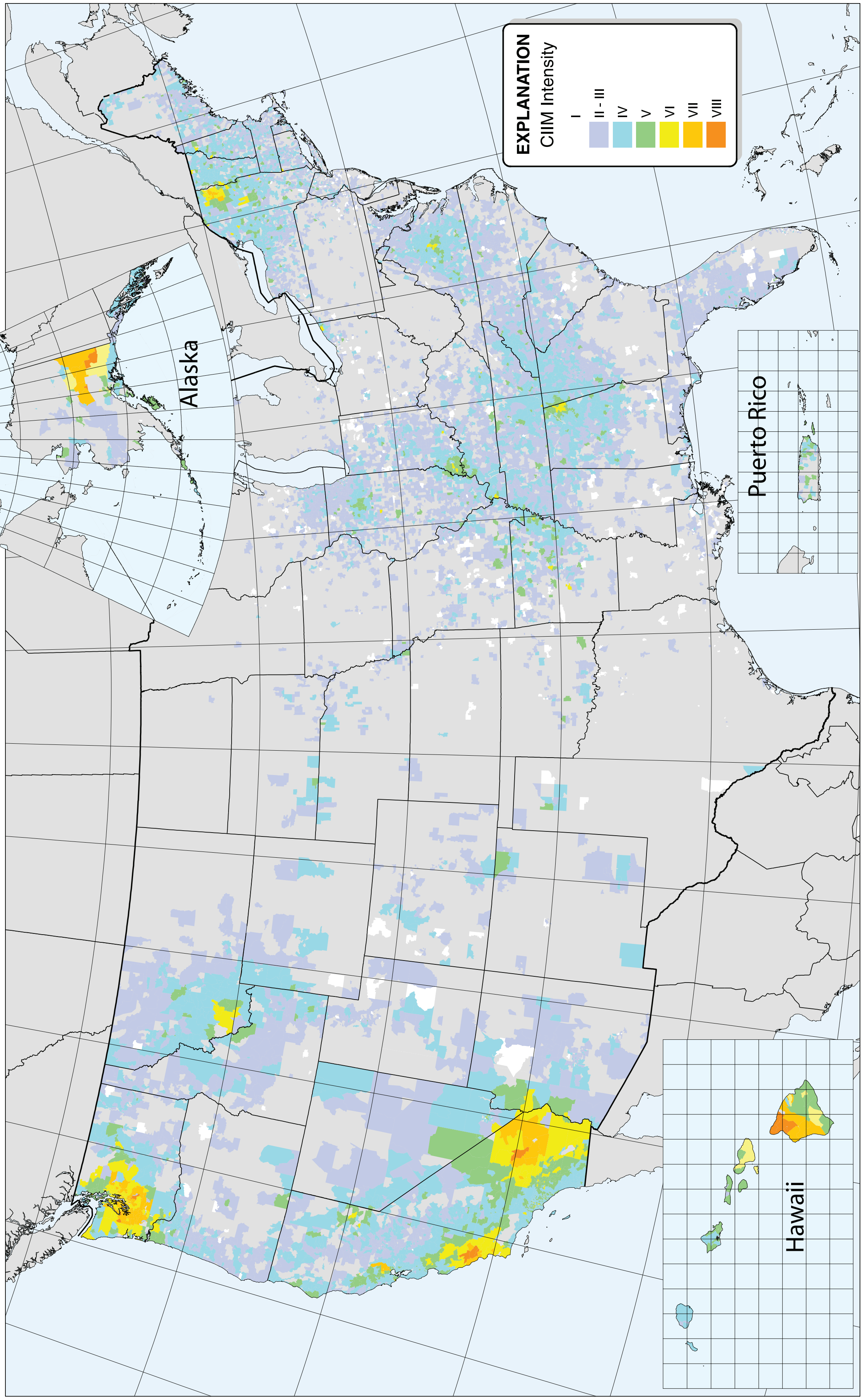
INTRODUCTION

The "Did You Feel It?" (DYFI) program developed by the U.S. Geological Survey (Wald *et al.* 1999a) is collecting a large and important new source of engineering seismology data. The idea of the DYFI program is that citizens use an Internet Web site (http://earthquake.usgs.gov/dyfi/) to report their experiences and observations for any earthquakes that they have felt (or not felt) by answering a simple multiple-choice questionnaire. The questions are designed to be diagnostic of the Modified Mercalli Intensity (Wood and Neumann 1931; Dewey *et al.* 1995) at the observer's location, via application of a simple algorithm to relate the citizen responses to MMI (Wald *et al.* 1999a; Dewey *et al.* 2000). MMI measures the intensity of ground motions from the perspective of human and structural response on a qualitative scale from 1 (not felt) to 10 (very heavy damage) or sometimes 12 (total destruction), based on descriptions such as "felt indoors" (MMI = 3) to "felt by all, windows, dishes, glassware broken, weak plaster cracked" (MMI = 6) to "some structures with complete collapse" (MMI = 9) (see Dewey *et al.* 1995 for current use of the scale; the scale was defined using Roman numerals, which are used interchangeably with the corresponding numbers in this paper). The MMI values assigned to individual responses are averaged by the DYFI program within a postal zip code (alternative geographical measures are used outside the United States) to provide an average measure of MMI and its variability across the affected region.

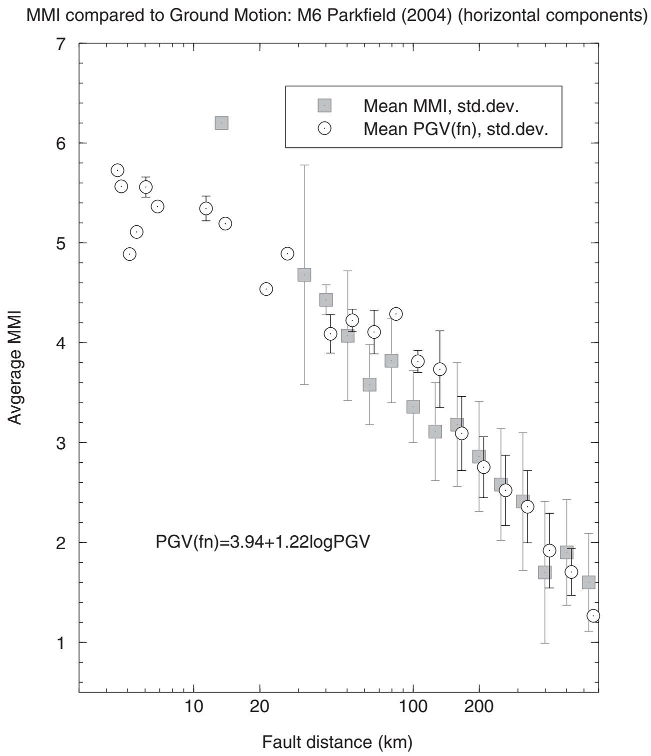
The DYFI program has been remarkably successful since its inception about seven years ago. More than 750,000 individual responses have been compiled for earthquakes in the United States, and the program is rapidly expanding internationally. Figure 1 is a compilation of the U.S. responses to date. It provides an interesting snapshot of seismicity and felt earthquake effects on a national scale over the past few years. Intensity maps for individual earthquakes are typically based on thousands of responses, collected over hundreds of zip codes. For example, the **M** 6 2004 Parkfield, California, earthquake generated more than 14,000 responses from 838 zip codes, illustrating the strength of citizen support and involvement. The Internet makes it possible to gather larger and more comprehensive data sets than ever, with much quicker turnaround and at minimal cost. Prior to this system, intensity maps were rarely made for U.S. earthquakes of magnitude less than about 5.5; now intensities as low as magnitude 2.0. are routinely reported for the smallest felt earthquakes nationwide. In addition, thousands of reports are available for moderate to large events—often tens of thousands for those in densely populated areas. The greatly expanded data sets allow for post-processing and analysis in ways that were not previously possible.

RELATIONSHIP BETWEEN DYFI DATA AND EARTHQUAKE GROUND MOTIONS

An important finding of recent analyses of the DYFI data is that in addition to being extremely useful for rapid post-earthquake information, they are also robust and of surprisingly high utility. They appear to offer the potential to not only describe ground-motion effects qualitatively, but to be used in quantitative scientific studies. They may even resolve longstanding issues in earthquake ground-motion science. The key to the usefulness of the data is simply this: They make up in quantity what they



▲ **Figure 1.** Summary of DYFI responses over seven years, 2000–2006.



▲ **Figure 2.** MMI amplitudes compared to instrumental ground-motion amplitudes for the **M** 6 Parkfield earthquake of 2004. Symbols show mean and standard deviation of observations, for data grouped in bins 0.1 log distance units in width. Slight offset of distance values used for PGV dataset for plotting clarity.

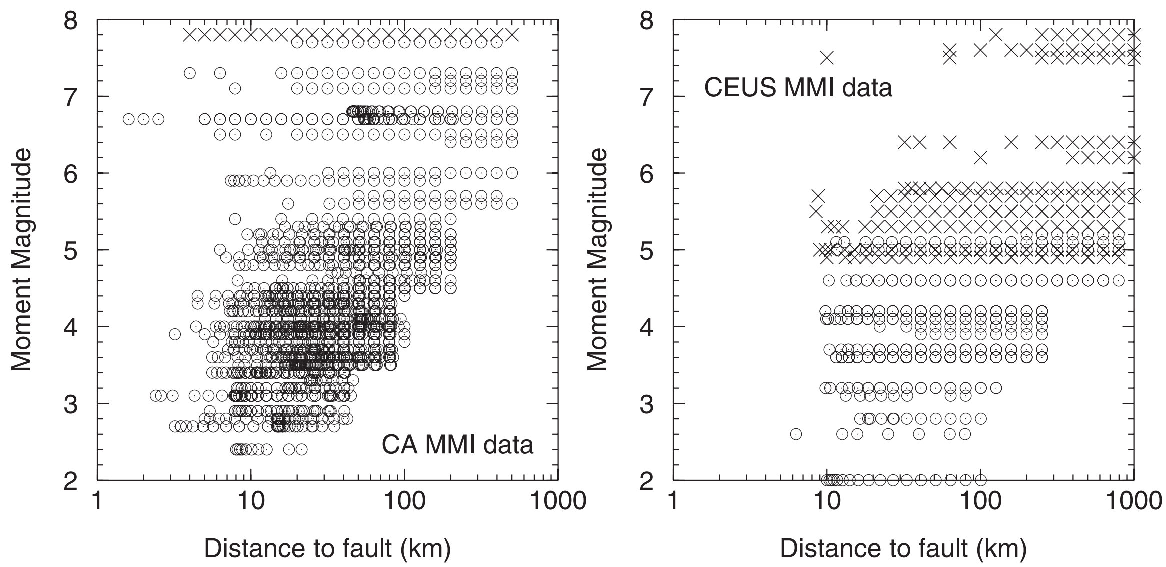
may lack in quality. Because there are so many responses, stable statistics on average effects are produced, illuminating ground-motion trends and allowing effective correlation and calibration with more-quantitative ground-motion measures. This is illustrated in figure 2, which provides an overview of MMI observations from the DYFI responses in comparison to measured earthquake ground motions from digital strong-motion instruments, as cataloged by the U.S. Geological Survey's ShakeMap Web-based database (http://earthquake.usgs.gov/shakemap/), for a single earthquake (2004 Parkfield). The figure plots the mean and standard deviation of the DYFI zip code MMI values in distance bins that are 0.1 log units in width as we move away from the causative earthquake fault. The intensity values show a well-behaved progression of decreasing intensity with increasing distance. Overlaid on the intensity data are the instrumental ground-motion data for the same event, binned and plotted in the same way. The ground-motion measure plotted is based on the recorded peak ground velocity (PGV), which has been transformed via a linear function (determined by regression of the MMI versus PGV data), $fn(\mathrm{PGV}) = 3.94 + 1.22 \log_{10} \mathrm{PGV}$. The transformation is used so that the PGV data will plot on the same scale as the MMI data for ease of comparison. We observe that the MMI and PGV data track each other closely, suggesting that the MMI observations are actually providing reliable data on ground-motion amplitudes, albeit with somewhat larger variability (as noted by the larger error bars for MMI observations in comparison to those for PGV). This means that MMI observations, properly calibrated with instrumental observations, can be used to make inferences about earthquake ground motions. Even subtle features can be seen in the DYFI observations, such as a flattening of attenuation in the distance range from 70 to 150 km, where direct-arrival seismic phases are joined by postcritical reflections off the Moho (Burger *et al.* 1987). This is an important finding because there are many regions, such as the eastern United States, where instrumental data are sparse but human populations are dense; citizen responses provide "human seismometers" that can effectively fill gaps in earthquake ground-motion observations and potentially resolve important issues in earthquake ground-motion science.

APPLICATION OF DYFI DATA TO ENGINEERING SEISMOLOGY

Uncertainty in the ground-motion amplitudes that will be caused by future large earthquakes in the central and eastern United States (CEUS) is one of the largest sources of uncertainty in evaluating seismic hazards in the region and a significant impediment to mitigating future earthquake losses. Some argue that because the uncertainties are so large (approaching an order of magnitude), it makes little sense to design new structures or retrofit existing structures to resist the earthquake ground motions that have been estimated for recent versions of the national seismic hazard maps (*e.g.*, see Stein *et al.* 2003; Frankel 2003, 2004). It is thus a high priority to reduce uncertainty in CEUS ground motions for both scientific and policy reasons relating to engineering confidence in seismic hazard estimates.

The main reason why uncertainties are so high is that large earthquakes in the CEUS are rare and the distribution of strong motion and seismographic stations is sparse, leading to relatively few instrumental records for moderate CEUS events and essentially no instrumental records for large events. The lack of recordings is particularly pronounced at near distances (< 100 km). As a result, there are also significant questions concerning whether the source characteristics that control strong motion are the same for the CEUS as they are for California (CA). For example, the earthquake stress drop, which controls the strength of high-frequency ground motions, is typically assumed to be a factor of two higher for CEUS events than those in CA (Atkinson 1993), and this assumption is built into many CEUS ground-motion models and hazard maps (*e.g.*, Frankel *et al.* 1996, 2002; Campbell 2003). However, existing uncertainties due to the paucity of near-source ground-motion data also allow the interpretation that the stress drop is about the same for the two regions (Beresnev and Atkinson 1999). The controversy regarding source characteristics for large CEUS events heightens our uncertainty in CEUS ground-motion models and seismic hazard.

Using the large DYFI database, MMI observations can be used to evaluate differences in earthquake source and propagation characteristics between the CEUS and CA. Figure 3 shows the intensity database that has been compiled for the CEUS



▲ **Figure 3.** Intensity data distribution for California (left) and the CEUS (right). Gray circles are DYFI data, the black x marks are historical MMI.

and CA (based on the data summarized in figure 1), where the data are again grouped in distance bins as in figure 2. Binning the data is a process that sharpens the underlying image, similar to "stacking" multiple images in reflection seismology. All magnitudes are moment magnitude (**M**) or equivalent. Studies have shown that the DYFI information is equivalent to earlier postal questionnaire–based intensity observations (Dewey *et al.* 2000), and thus we have augmented the data at larger magnitudes with historical MMI observations (NOAA catalog at http://www.ngdc.noaa.gov/seg/hazard/int_srch.shtml). The equivalence of traditional and DYFI MMI values has been reconfirmed for several earthquakes having both types of MMI data. The MMI data for the two regions have been used in empirical regression analyses to determine the dependence of MMI on **M** and distance from the fault, D (which is equivalent to hypocentral distance for small to moderate events). The regression analysis is based on the maximum likelihood method of Joyner and Boore (1983). By analyzing the residuals (defined as observed-predicted MMI for the given **M** and D) from various trial functional forms as a function of magnitude and distance, it was determined that the MMI data can be described, with an average error of 0.4 MMI units (standard deviation of residuals), by an equation of the following form:

$$\mathrm{MMI} = c_1 + c_2(\mathbf{M}-6) + c_3(\mathbf{M}-6)^2 + c_4 \log R + c_5 R + c_6 B + c_7 \mathbf{M} \log R \quad (1)$$

where $R = \sqrt{D^2 + h^2}$

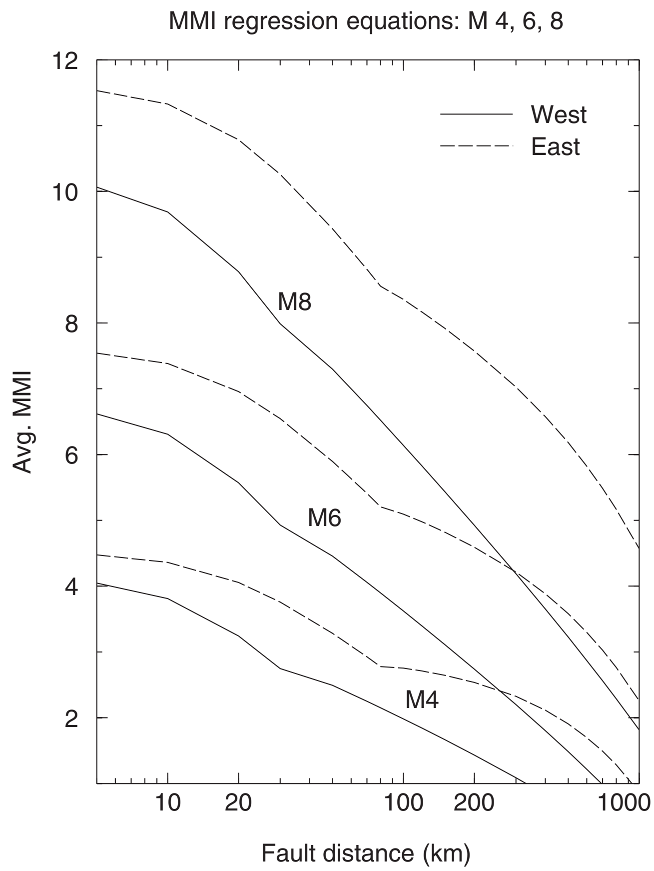
$$B = \begin{cases} 0 & R \le R_t \\ \log(R/R_t) & R > R_t \end{cases}.$$

The coefficients to be determined are c_1 through c_7, an effective depth term (h), and the transition distance in the attenuation shape (R_t). The form allows flexibility in modeling both magnitude and distance dependencies in the amplitude and attenuation of intensity and follows a typical form used in empirical regressions of instrumental ground-motion data (*e.g.*, Boore and Atkinson 2006). Residuals for this functional form have no trends in magnitude or distance in either region. Coefficient values are given in table 1.

TABLE 1
Coefficients of Equation (1)

Coefficient	California	Central and Eastern U.S.
c_1	12.27(± 0.24)	11.72(± 0.36)
c_2	2.270	2.36
c_3	0.1304	0.1155
c_4	–1.30	–0.44
c_5	–0.0007070	–0.002044
c_6	1.95	2.31
c_7	–0.577	–0.479
h	14.0	17.0
R_t	30.0	80.0

Figure 4 shows plots of the the determined relationship for MMI versus distance for **M** 4, 6, and 8 in CA and the CEUS. Figure 5 shows residuals (observed – predicted MMI) as a function of distance; the regression prediction is well-constrained over a wide distance range (10–500 km). MMI values for the CEUS are about one unit larger than those for CA at near-fault distances (< 30 km) for all magnitudes. Due to the large volume of data, these average amplitude levels are robustly determined (standard error 0.3 MMI units at close distances). This strongly implies that the source level of ground motions is higher in the CEUS than in CA. As distance increases, MMI attenuates more

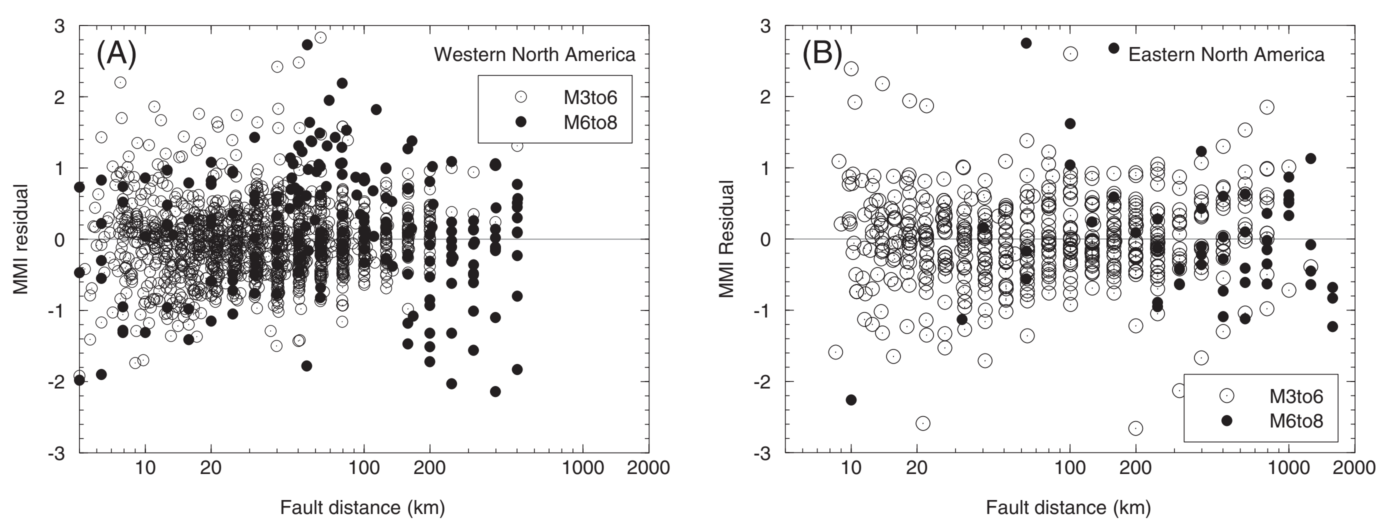


▲ **Figure 4.** Predicted MMI values for events of **M** 4, 6, and 8 for CA (solid) and the CEUS (dashed), based on empirical regression. Note that at 300 km the MMI for a CEUS event of **M** = 4 is similar to that of a CA event of **M** = 6. At 400 km the MMI for a CEUS event of **M** = 6 is similar to that of a CA event of **M** = 8.

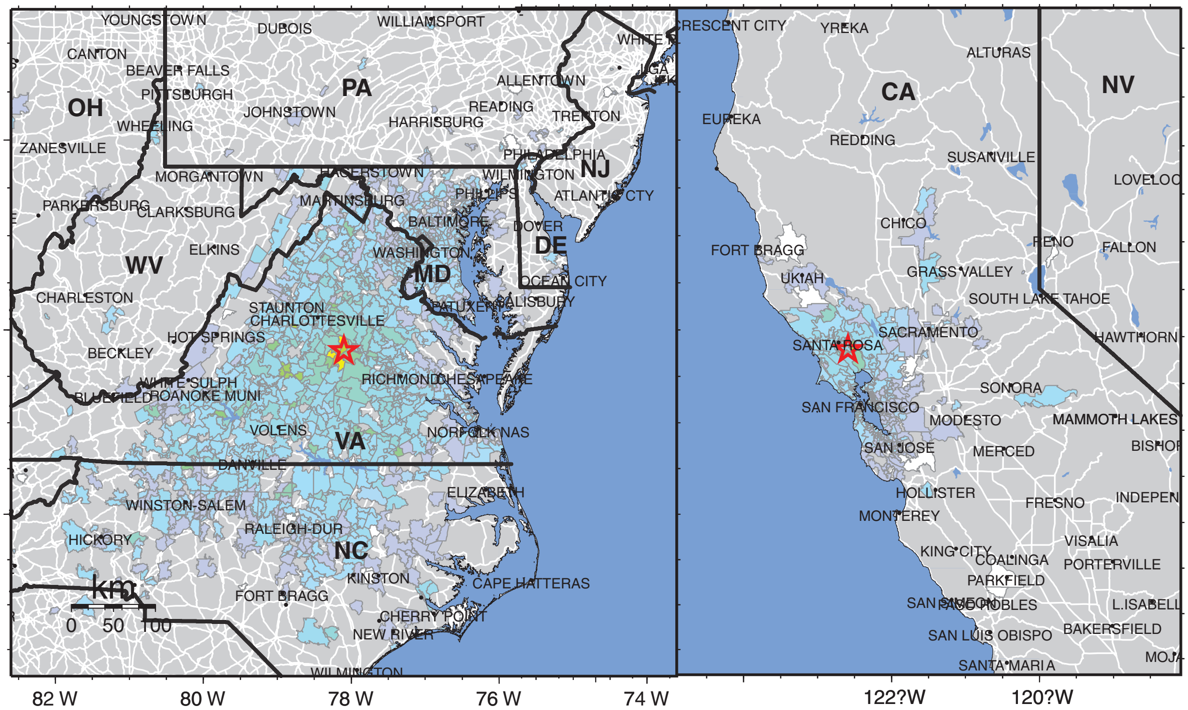
quickly in CA than in the CEUS, due to the well-known phenomenon of greater ground-motion attenuation in CA than in stable tectonic regions (Nuttli 1973, and many others). Hence intensity values are typically 1.5 to 2 units higher for CEUS earthquakes than for CA events of the same magnitude at distances greater than 100–200 km.

These trends can also clearly be seen for individual events of the same magnitude. For example, figure 6 shows the DYFI maps for the 9 December, 2003 **M** 4.2 Columbia, Virginia, earthquake in comparison to that for the 2 August 2006 **M** 4.4 Santa Rosa, California, earthquake. Note the much larger area of the felt intensities for the Columbia event. Figure 7 shows the binned decay of DYFI amplitudes for the two events; the larger epicentral intensity of the Columbia event is quite clear. The larger extent of the felt area for the Columbia event does not show as clearly in this plot as on figure 6, because the Santa Rosa event generated few felt reports beyond about 200 km. However, another interesting observation can be made from figure 7. The attenuation of intensity is more rapid for the Columbia event at close distances in comparison to that for Santa Rosa. Empirical regressions of eastern North America (ENA) ground-motion databases suggest a relatively rapid geometric decay of amplitudes within the first 70 km, $R^{-1.3}$, in comparison to values of near R^{-1} observed for California (Atkinson 2004). At greater distances the slower anelastic attenuation in ENA results in larger amplitudes at large distances, in comparison to that for California. These attenuation trends are apparent on figure 7. However, they are not apparent in the overall regression results of figure 4, which do not appear to show regional attenuation differences as clearly as might be expected; it is likely that such features are obscured by other shape parameters in the prediction equations, such as R_t.

The fact that ground motions at near-fault distances are larger in the CEUS than in CA suggests that the stress drop of CEUS events is greater, because stress drop is the most important factor controlling ground-motion amplitudes at

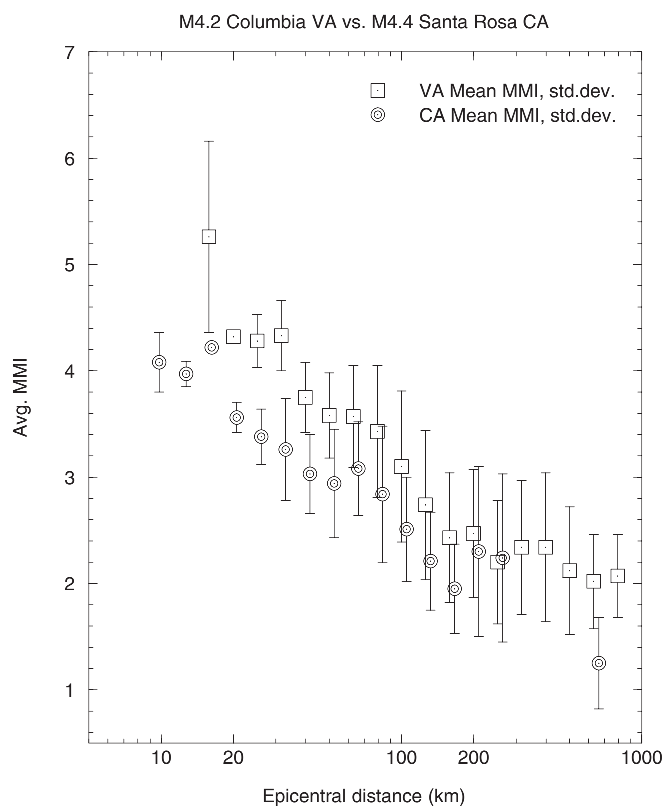


▲ **Figure 5.** Residuals (observed MMI – predicted MMI) of equation 1 versus distance. (A) Western North America (B) Eastern North America.



INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy

▲ **Figure 6.** Comparison of felt area and intensities for the 9 December 2003 **M** 4.2 Columbia, Virginia, earthquake (left) with the 2 August 2006 **M** 4.4 Santa Rosa, California, earthquake (right). Note the dramatic difference in the overall felt area and difference in epicentral intensity (see also figure 6). Maps scales are approximately the same.



intermediate-to-high frequencies. (Alternative explanations are unlikely; these include 1) site amplification effects are systematically higher in the CEUS than in CA, or 2) human and structural responses are systematically higher in the CEUS than in CA.) A rough estimate of the stress-drop difference between the regions can be made based on simple concepts of ground-motion scaling. According to the Brune (1970) source model, high-frequency ground motions, above the corner frequency of an earthquake, are closely related to stress drop, with peak ground acceleration (PGA) scaling as 5/6 log $\Delta\sigma$, where $\Delta\sigma$ is stress drop (Hanks and McGuire 1981; Boore 1983). Empirical correlations between PGA and MMI (*e.g.*, Wald *et al.* 1999b; Atkinson and Sonley 2000) generally show that the increase in the amplitude of log PGA, per unit increase in MMI, is about 0.38 (a factor of 2.4). It follows that a near-source difference of 1 MMI unit would correspond to a stress drop that is, on average, nearly three times larger in the CEUS than in CA ($10^{(0.38\times6/5)} = 2.9$). This is a very rough calculation useful only for illustrating the concept. More detailed analyses as more data

▲ **Figure 7.** Decay of DYFI data with distance for the 9 December 2003, **M** 4.2 Columbia, Virginia, earthquake and the 2 August 2006, **M** 4.4 Santa Rosa, California, earthquake. Symbols show mean and standard deviation. Slight offset of distance values used for California (CA) dataset for plotting clarity.

are collected will enable a better understanding of the differences in CEUS and CA ground-motion properties, based on analyses of correlated MMI and ground-motion databases.

CONCLUSION

The vast amount of new data on earthquake ground motions and effects being collected from online citizen responses with the DYFI program offers a valuable new data resource for both qualitative and quantitative earthquake studies and has the potential to address some longstanding controversies in earthquake science. An important finding to date is that MMI data provide conclusive evidence that earthquake stress drops are higher in the CEUS than in California.

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