Bulletin of the Seismological Society of America, Vol. 96, No. 6, pp. 1978–1994, December 2006, doi: 10.1785/0120050176

Comparison of the Historical Record of Earthquake Hazard with Seismic-Hazard Models for New Zealand and the Continental United States

by Mark Stirling and Mark Petersen

Abstract We compare the historical record of earthquake hazard experienced at 78 towns and cities (sites) distributed across New Zealand and the continental United States with the hazard estimated from the national probabilistic seismic-hazard (PSH) models for the two countries. The two PSH models are constructed with similar methodologies and data. Our comparisons show a tendency for the PSH models to slightly exceed the historical hazard in New Zealand and westernmost continental United States interplate regions, but show lower hazard than that of the historical record in the continental United States intraplate region. Factors such as non-Poissonian behavior, parameterization of active fault data in the PSH calculations, and uncertainties in estimation of ground-motion levels from historical felt intensity data for the interplate regions may have led to the higher-than-historical levels of hazard at the interplate sites. In contrast, the less-than-historical hazard for the remaining continental United States (intraplate) sites may be largely due to site conditions not having been considered at the intraplate sites, and uncertainties in correlating ground-motion levels to historical felt intensities. The study also highlights the importance of evaluating PSH models at more than one region, because the conclusions reached on the basis of a solely interplate or intraplate study would be very different.

Introduction

In the past decade there have been considerable advances in the field of probabilistic seismic-hazard analysis (PSHA) and application of PSHA methodology around the world. Arguably some of the most important applications of PSHA have been in the development of national seismic-hazard models for countries like the United States, Canada, and New Zealand (e.g., Basham *et al.*, 1997; Frankel *et al.*, 2002; Stirling *et al.*, 2002). The probabilistic seismic-hazard (PSH) maps have been the benchmark for numerous applications, most importantly for the building codes in these countries (e.g., International Code Council, 2003; Standards New Zealand, 2005). PSH models give estimates of the strength of earthquake shaking that can be expected for any given return period, and the models utilize seismicity catalogs, paleoseismic (active fault) data, and ground-motion attenuation relationships. However, efforts to validate PSH models to date have been limited to evaluating components of the models, for example, comparing local slip rates with Global Positioning System (GPS) models and historical seismicity rates. It also makes fundamental sense to validate the entire PSH model if possible, which would involve examining the actual hazard estimates. PSH models that underestimate the hazard of an area may result in engineers and planners being unprepared for the effects of a major earthquake, and overestimates of hazard may result in unnecessary expense in building construction.

The challenge in developing a test for a PSH model is to provide estimates of the strength and return period for ground motions with data that have not already been used in the PSH model. One such dataset for some countries is the historical record of Modified Mercalli intensities (MMIs). Such data have only been used indirectly and intermittently in the national PSH models for New Zealand and the continental United States (Frankel *et al.*, 2002; Stirling *et al.*, 2002), such as for assigning magnitudes to some of the older (i.e., preinstrumental) events in a historical seismicity catalog. These events are few relative to the abundant instrumental record of small-to-moderate earthquakes, so they have less influence on the background seismicity parameters than the small-to-moderate events for New Zealand and the continental United States (e.g., Stirling *et al.*, 2002). Although the MMI levels assigned to a given earthquake are commonly considered to be too subjective and unreliable to apply to seismic-hazard studies (the various criticisms relate to the subjectivity of the MMI scale and uncertainties in equating MMI with more quantitative measures of earthquake shaking), they nevertheless represent a large independent dataset that should at least be compared with PSH models to see whether any large discrepancies exist between the MMI data and PSH model.

In this article, we compare the predicted frequency of exceedance for ground-motion levels from the New Zealand PSH model (Stirling *et al.*, 2002) with the one to two-century record of ground motions derived from MMI data at 26 New Zealand towns and cities (referred to as sites from hereon) (Fig. 1). The New Zealand analysis builds on, and MMI data are derived from, an earlier analysis by Dowrick and Cousins (2003). Similarly, we compare the U.S. Geological Survey (USGS) PSH model (Frankel *et al.*, 2002) with the historical record of MMI data for 52 sites distributed more or less uniformly across the continental United States (although 26 sites are within southern California) (Fig. 1). While not yet constituting a formal test of the PSH models, our analysis is focused on observing the extent of agreement or disagreement between the PSH models and the historical record of MMI at numerous sites from diverse physiographic, seismotectonic, historical, and demographic settings. Although our tests are limited by the short historical record of New Zealand and the continental United States, they have a major advantage in being able to be simultaneously applied to numerous sites from different seismotectonic environments. The shortcomings of the historical record are, to an extent, compensated for by the ability to make comparisons at a large number and great diversity of sites.

Procedure

Our general procedure is to utilize the historical record of MMI levels experienced at a suite of sites around New Zealand and the continental United States (Fig. 1) to calculate the annual rates of exceedance for those MMI levels, and then compare these historically based hazard curves with the hazard curves calculated for the sites from the relevant PSH models. The generally uniform distribution of sites across the two regions therefore encompasses areas of very high to very low seismotectonic activity and seismic hazard, and samples the spectrum of sites, from small towns to very large cities (Fig. 1).

For the New Zealand sites we searched historical databases on the web and in the literature (primarily relying on the analysis of Dowrick and Cousins, 2003). Specifically, Dowrick and Cousins's calculated rates of exceedance for given MMI levels for New Zealand towns and cities are used directly in our analysis, their rates based on the MMI record for the period 1840–1997. For all of the continental United States sites, the National Oceanic and Atmospheric Administration (NOAA) web site (www.ngdc.noaa.gov/seg/hazard/int_srch.shtml) and USGS SHAKEmap web site (www.trinet.org/shake/) are utilized. Here, we use the MMI record to calculate rates of exceedance for three distinct MMI "subcatalogs" identified in the data (Margaret Hopper, USGS, personal comm., 2002). The subcatalogs are said to contain a complete record of the following: (1) MM7 and greater from the incorporation (founding) year of each town/city to the end of 1930; (2) MM6 and greater from 1931 to the end of 1985 (the main period covered by the NOAA database), and (3) MM6 and greater from 1986 to the present day for some of the sites (mainly derived from the SHAKEmap web site).

The lack of attenuation relations available in the PSH models to derive hazard curves for MMI requires that we first convert the historical MMI levels to the equivalent estimates of peak ground acceleration (PGA) to allow direct comparison of historical data to PSH model. For the continental United States sites, the MMIs are converted to the equivalent mean estimates of PGA by way of the relevant equation used in SHAKEmap $\mathrm{MMI} = 3.66 \log \mathrm{PGA} - 1.66$, in which PGA is in units of cm/sec^2 (Wald *et al.*, 1999). A newly developed relationship relevant to sites in the central and eastern United States is also applied later in the article. Though the Wald *et al.* (1999) relationship is largely based on westernmost continental United States data, it is used routinely across the United States for SHAKEmap. The hazard curves for the sites are calculated from the USGS PSH model by way of the OpenSHA software (www.opensha.org) and via a hazard-curve calculator on the USGS web site (http://eqint.cr.usgs.gov/eq/html/lookup.shtml).

For New Zealand, the MMI-to-PGA conversion is achieved by way of the equations of Davenport (2003) for New Zealand ($\mathrm{MMI} = 1.102 \log \mathrm{PGA} + 2.56$, with PGA in units of mm/sec^2), and the hazard curves are derived from the Stirling *et al.* (2002) PSH model. The New Zealand-based hazard curves are calculated according to the ground class most relevant to the site (site class definitions from Cousins *et al.*, 1996), and the southern California hazard curves are calculated according to the Wills *et al.* (2000) site class map. Other continental United States hazard curves are calculated for soft-rock site conditions, the one site condition available on the USGS hazard-curve calculator. No earthquakes less than the minimum magnitudes considered in the PSH models (M_W 5.0 in the continental United States, and M_W 5.25 in New Zealand) are considered in the construction of the historically based rates of exceedance. The rationale for exclusion of earthquakes less than about M_W 5.0 in PSHA is that they generally do not produce significant damage. Both the New Zealand and continental United States PSH calculations incorporate aleatory uncertainty in the ground-motion estimates from the attenuation models to the 3-sigma level, consistent with the methodology used to calculate the national maps for the two countries (Frankel *et al.*, 2002; Stirling *et al.*, 2002).

Our initial comparisons of the historically based rates of exceedance to the PSH models is accomplished simply by plotting both PSH hazard curve and historical exceedance rates on the same graph (Fig. 2). Later in the article the extent of agreement or disagreement between PSH model and historical data is assessed statistically.

(a)

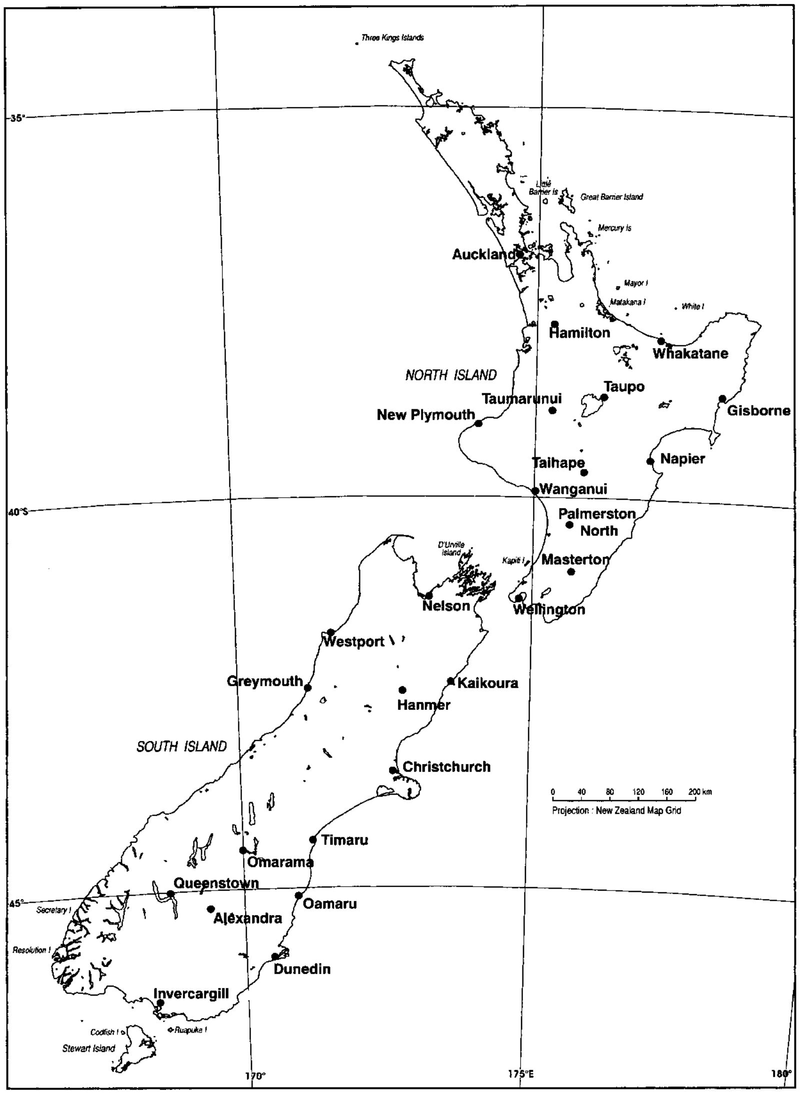


Figure 1. The 26 New Zealand sites (a), 26 southern California sites (b), and the other 26 continental United States sites (c) examined in this study. (*continued on facing page*)

Comparisons

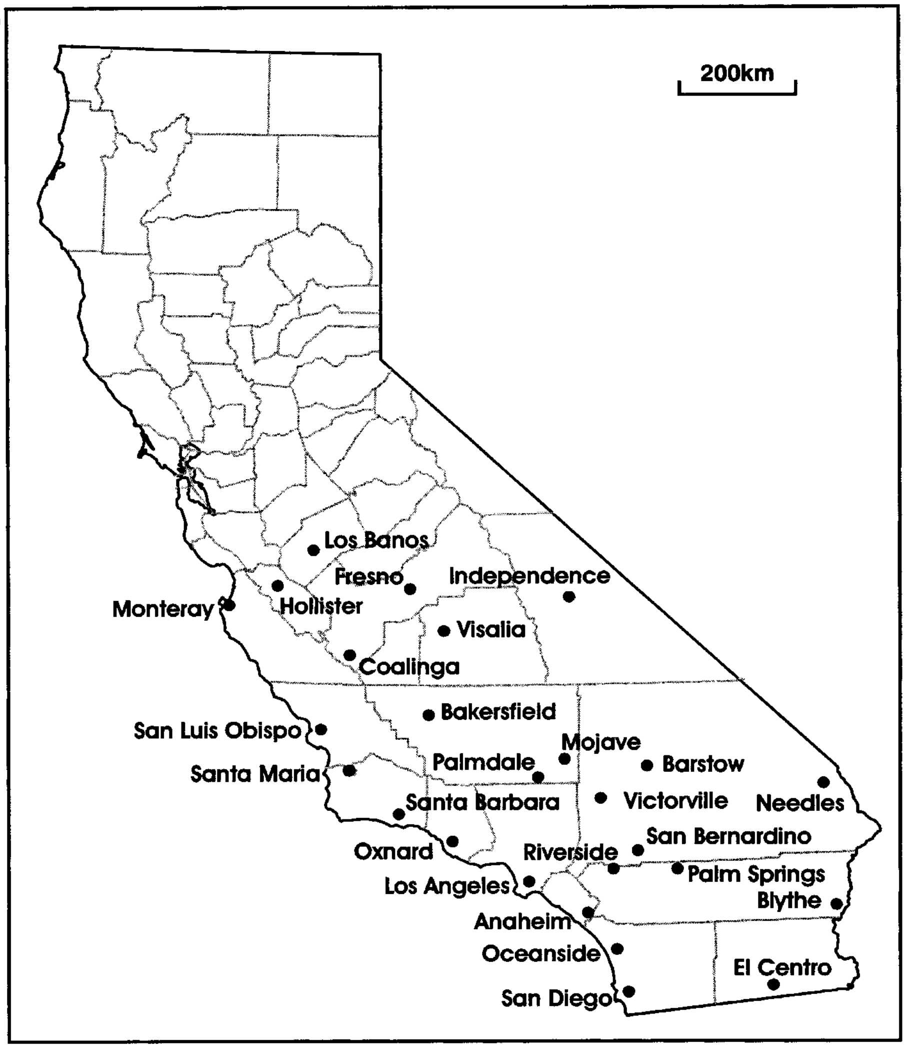
The graphs in Figure 2 show the comparisons made at the New Zealand and continental United States sites. The graphs show the historically based rates of exceedance for various levels of PGA (symbols) along with hazard curves derived from the New Zealand and USGS PSH models (solid lines). For the New Zealand sites the tendency is for the historical rates of exceedance to be approximately equivalent to the PSH model for PGAs of less than about $0.2g$ (less than MMI7). The historical rates appear to be significantly higher than the PSH model at higher PGAs (equivalent to MMI >7), but these PGAs are not considered further in our analysis, based on Davenport's assertion that his MMI-to-PGA relationship is unstable at MMI >7 (Davenport, 2003).

Unlike New Zealand, the continental United States graphs generally show a tendency for the historical rates to exceed the rates derived from the PSH model. For the continental United States sites we find the historical rates for PGAs of about 0.1 and $0.2g$ to be on average about five times greater than the PSH model across the subset of 26 southern California sites, and more than two orders of magnitude greater, than the PSH model for the remaining continental United States sites (Fig. 2). The greatest discrepancies therefore appear to be at intraplate sites where earthquake rates are moderate to low, and hazard is dominated by background earthquake sources (e.g., "Denver" in Fig. 2, located in low-seismicity central United States), and least in the interplate high-hazard areas dominated by fault sources (e.g., "San Bernardino" in Fig. 2, located in an area of high seismicity and close to the junction of three major active faults in southern California). The marked discrepancies for most of the continental United States sites as compared with the New Zealand sites is surprising, given that the two PSH models have similar methodology.

Refinements to and Statistics of Comparisons

Our results show that the USGS PSH model produces lower estimates of hazard than the historical hazard at most

(b)


200km
Los Banos
Fresno
Independence
Monteray
Hollister
Visalia
Coalinga
Bakersfield
San Luis Obispo
Mojave
Palmdale
Barstow
Santa Maria
Santa Barbara
Victorville
Needles
San Bernardino
Oxnard
Riverside
Palm Springs
Los Angeles
Blythe
Anaheim
Oceanside
El Centro
San Diego

(c)


Canada
Seattle
Washington
Helena
Montana
North Dakota
Minnesota
Oregon
Boise
Idaho
Wyoming
Casper
South Dakota
Sioux Falls
St. Paul
Wisconsin
Michigan
Maine
New York
Vt.
Portland
New Hampshire
Massachussetts
Rhode Island
Connecticut
New York
New Jersey
Pennsylvania
Ohio
Iowa
Chicago
Nebraska
Reno
Nevada
Salt Lake City
Utah
Denver
Colorado
San Francisco
California
Illinois
Indiana
Cincinnati
West Virginia
Virginia
Delaware
Maryland
Roanoke
Kansas
Kansas City
Missouri
Kentucky
Knoxville
Tennessee
North Carolina
Memphis
So. Carolina
Arizona
Tulsa
Phoenix
Albuquerque
Amarillo
Oklahoma
Arkansas
New Mexico
Birmingham
Georgia
Charleston
Atlantic Ocean
Alabama
Mississippi
Texas
Louisiana
Austin
Florida
New Orleans
Pacific Ocean
Mexico
Gulf of Mexico
The Bahamas

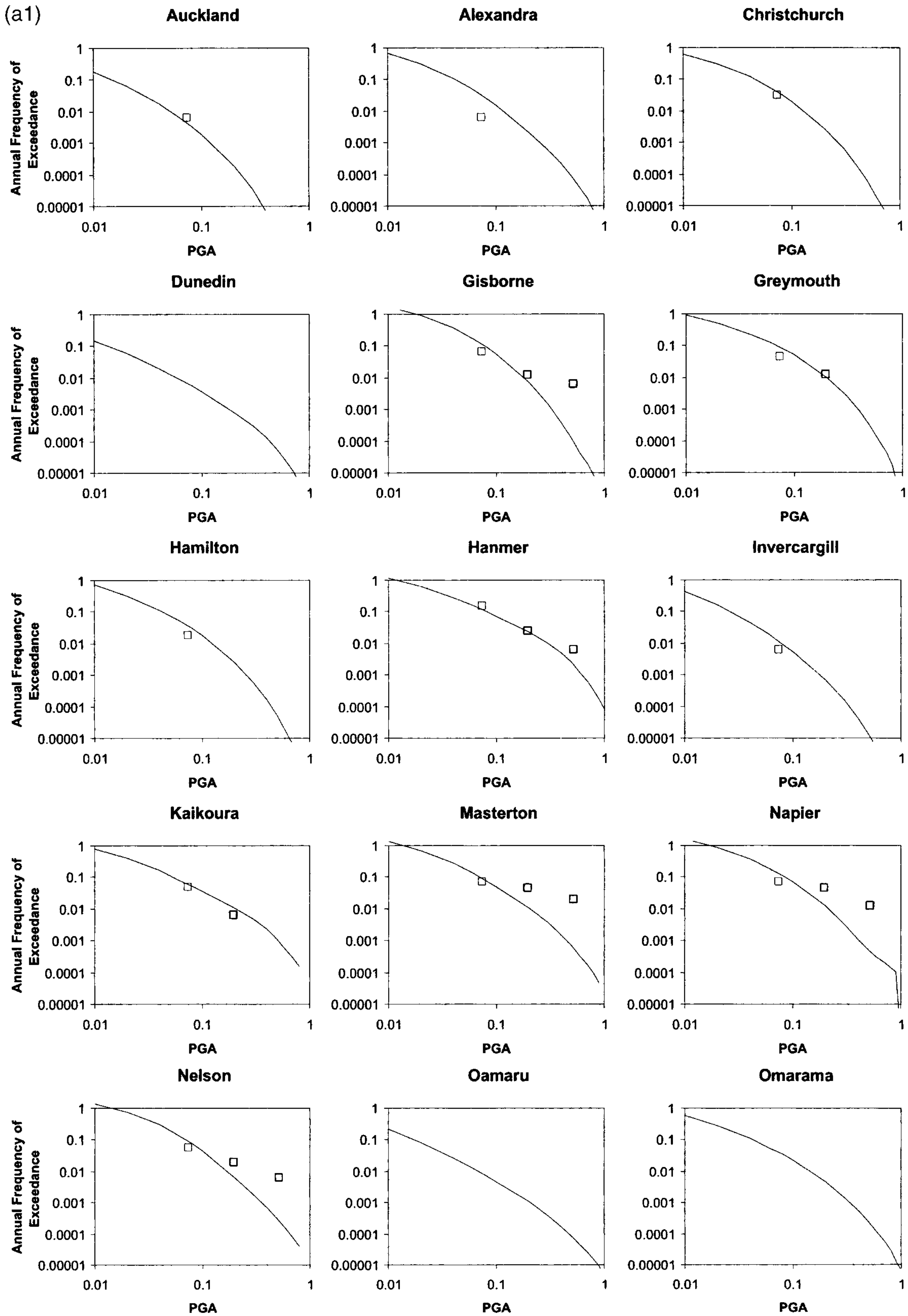


Figure 2. (a) New Zealand sites; (b) southern California sites; (c) continental United States sites. The New Zealand and continental United States sites, showing historical rates of exceedance for PGA levels (converted from MMI via the relevant relationship of Wald *et al.*, 1999; see text) compared with the PGA hazard curves derived from the PSH models for each country (the solid lines on each graph; see text). (*continued*)

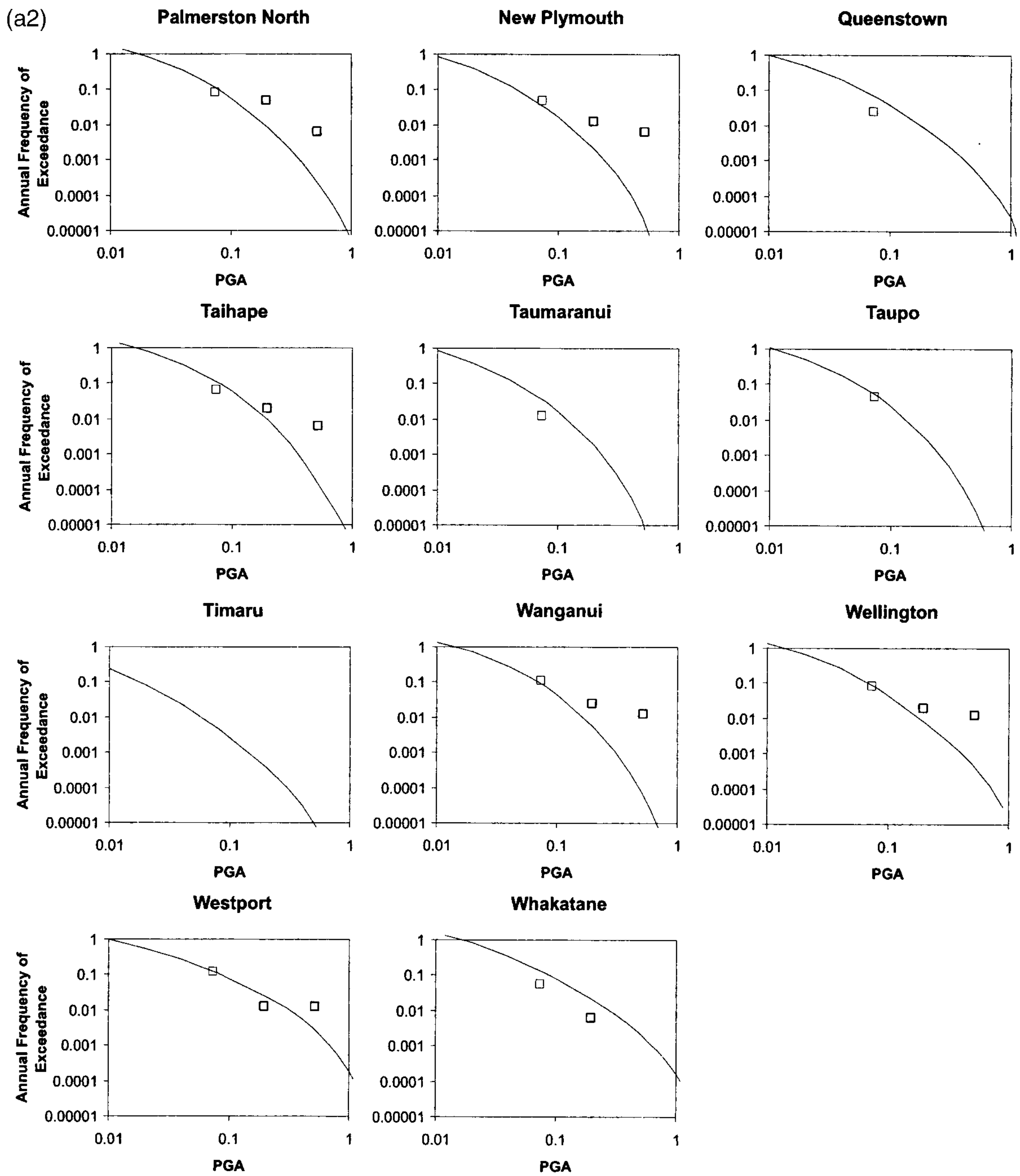


Figure 2. (*continued*) For the New Zealand graphs the squares represent observations from the period 1840–1997. For the continental United States graphs the diamonds represent observations from the incorporation (founding) year to 1930, the squares represent the observations for 1931–1985, and the triangles represent observations for the period 1986–2002. (*continued*)

of the continental United States sites. This discrepancy is not observed in the New Zealand analysis, despite the similarity of PSH methodology for the two countries, and similar plate boundary settings in the southern California subset of the United States sites. A possible explanation for the United States discrepancies is that the historical data have somehow been recorded differently than in New Zealand. In support of this suggestion is the fact that the NOAA web site states that the "The Earthquake Intensity Database (1638–1985) includes the maximum intensity for each city (or locality) that felt a particular earthquake. For later years, the USGS National Earthquake Information Center provides maximum intensities for each event" (www.ngdc.noaa.gov/seg/hazard/int_srch.shtml). In contrast, the New Zealand-based MMIs are an ensemble of actual felt reports and interpolated estimates between isoseismals (Dowrick and Cousins, 2003), so

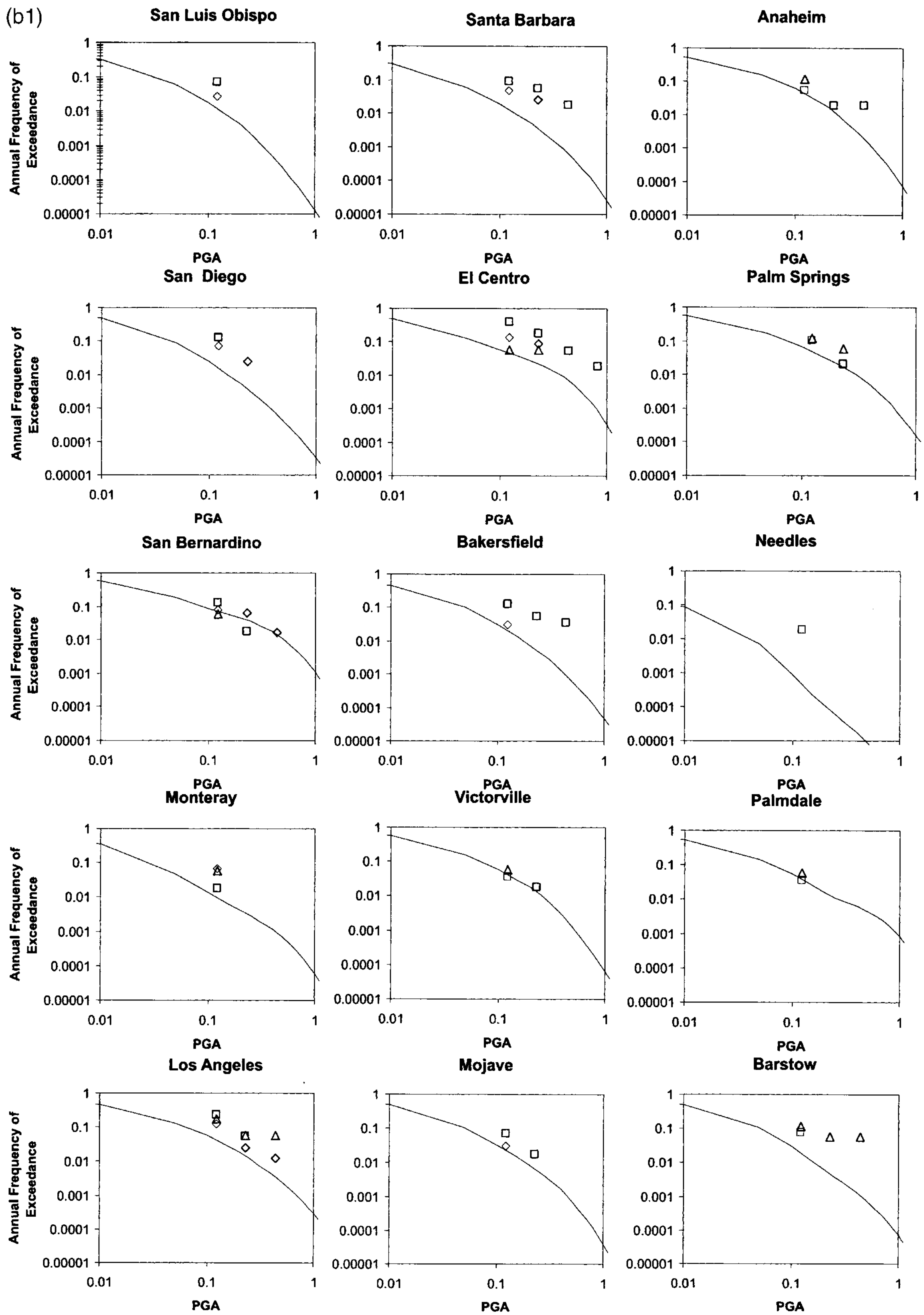


Figure 2. Continued.

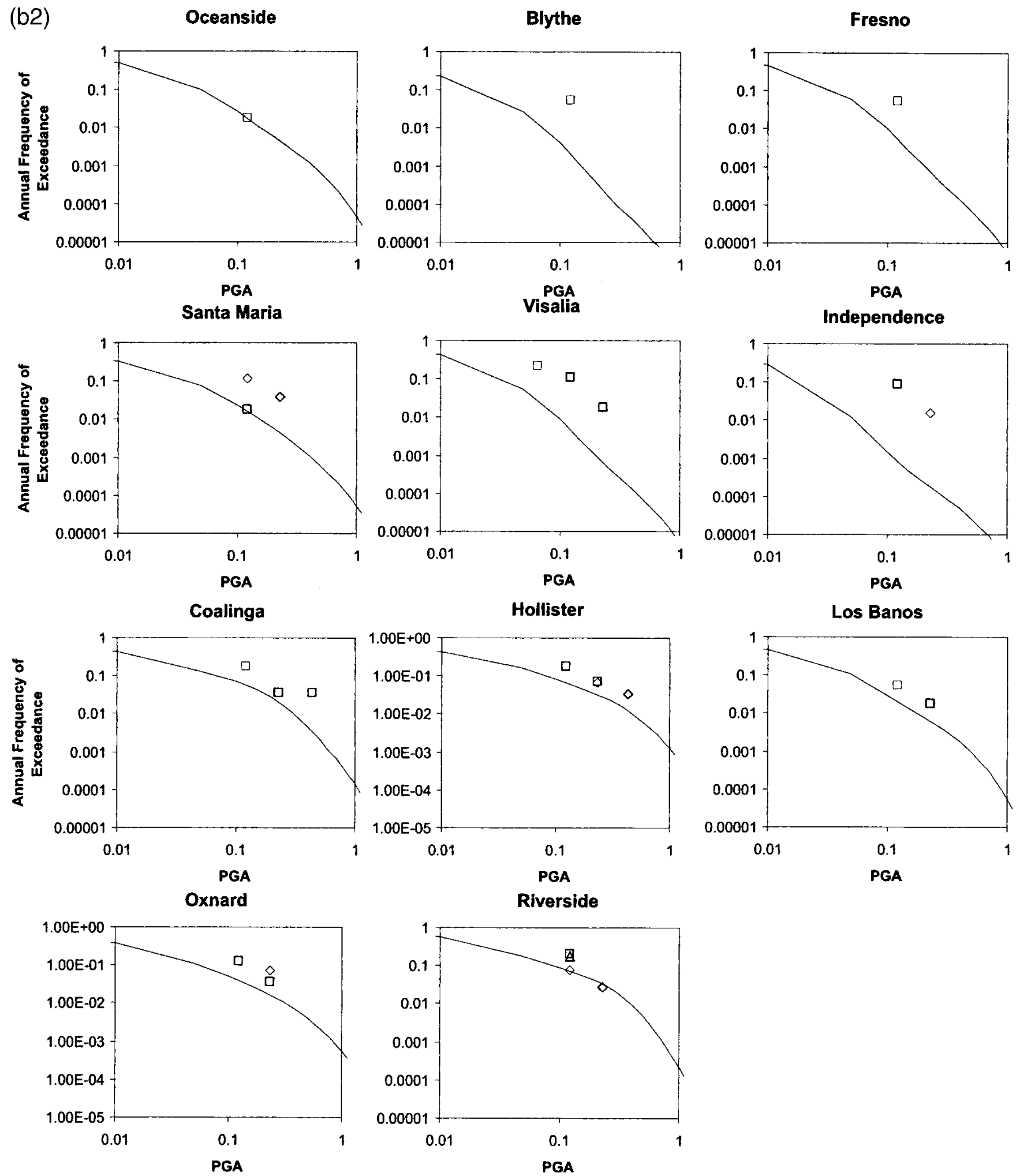


Figure 2. Continued.

are less likely to be maximum estimates of MMI for a given earthquake at a site. Discussions with USGS scientists familiar with the NOAA database (Margaret Hopper, USGS, personal comm., 2002) further confirmed that the continental MMI data represent a selection of the most reliable maximum estimates for a given site and earthquake.

A method that assists in assessing whether the continental United States MMI data represent maximum estimates is to compare the historical MMIs used to construct the graphs in Figure 2 with the MMIs predicted from the modern SHAKEmap attenuation equations for the same magnitudes and earthquake-to-site distances as those of the historical earthquakes. Because the SHAKEmap-derived MMIs are calculated as mean estimates of MMI for a site (see Wald *et al.*, 1999, and/or www.OpenSHA.org), there should be a systematic difference between the historical and SHAKEmap-derived estimates of MMI if the NOAA data do indeed represent the maximum MMIs experienced at the United States sites. Our relevant comparison is shown for the southern California subset of sites in Figure 3. We limit this part of the analysis to the southern California subset because the Wald *et al.* (1999) equations are most relevant to California,

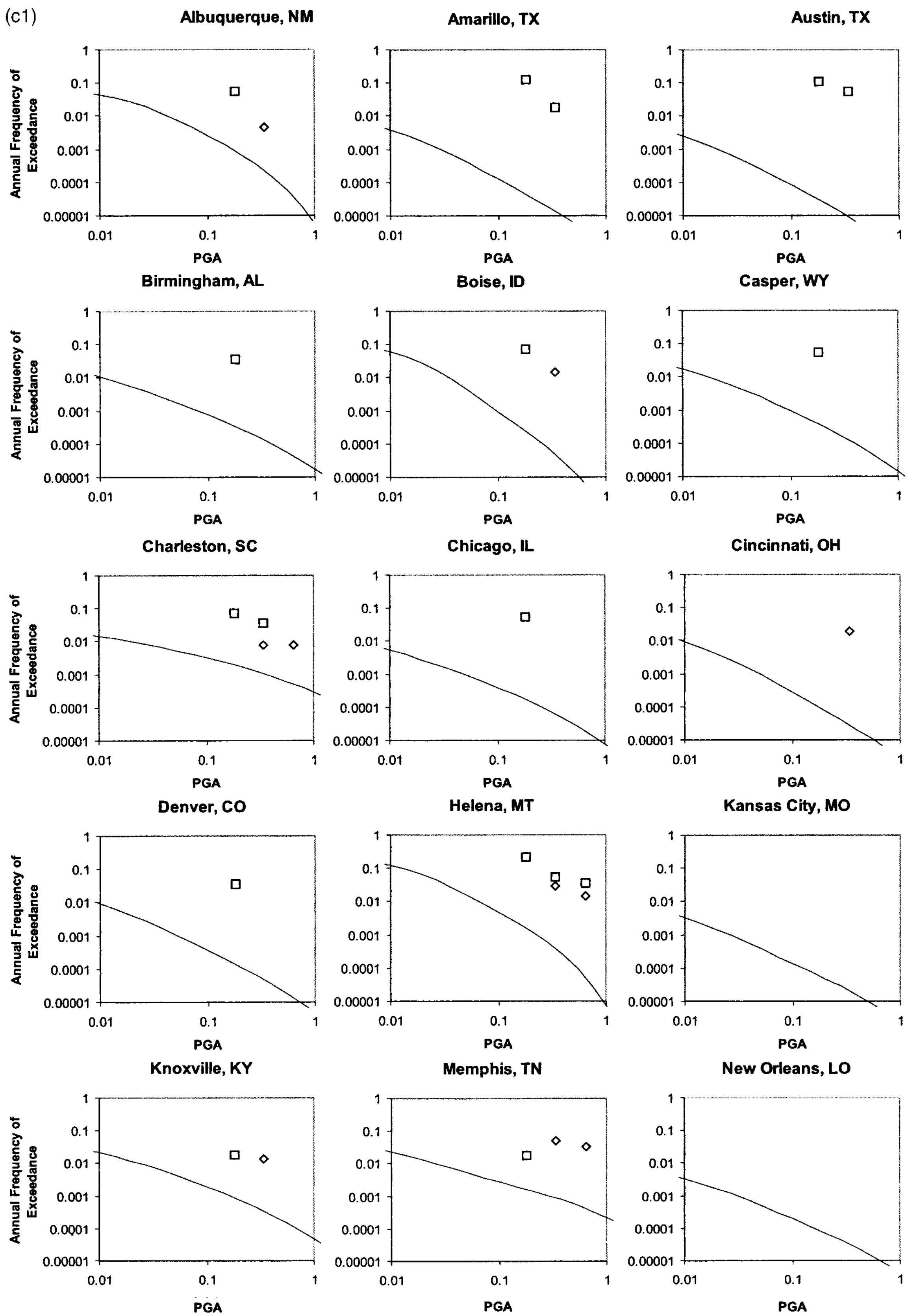


Figure 2. Continued.

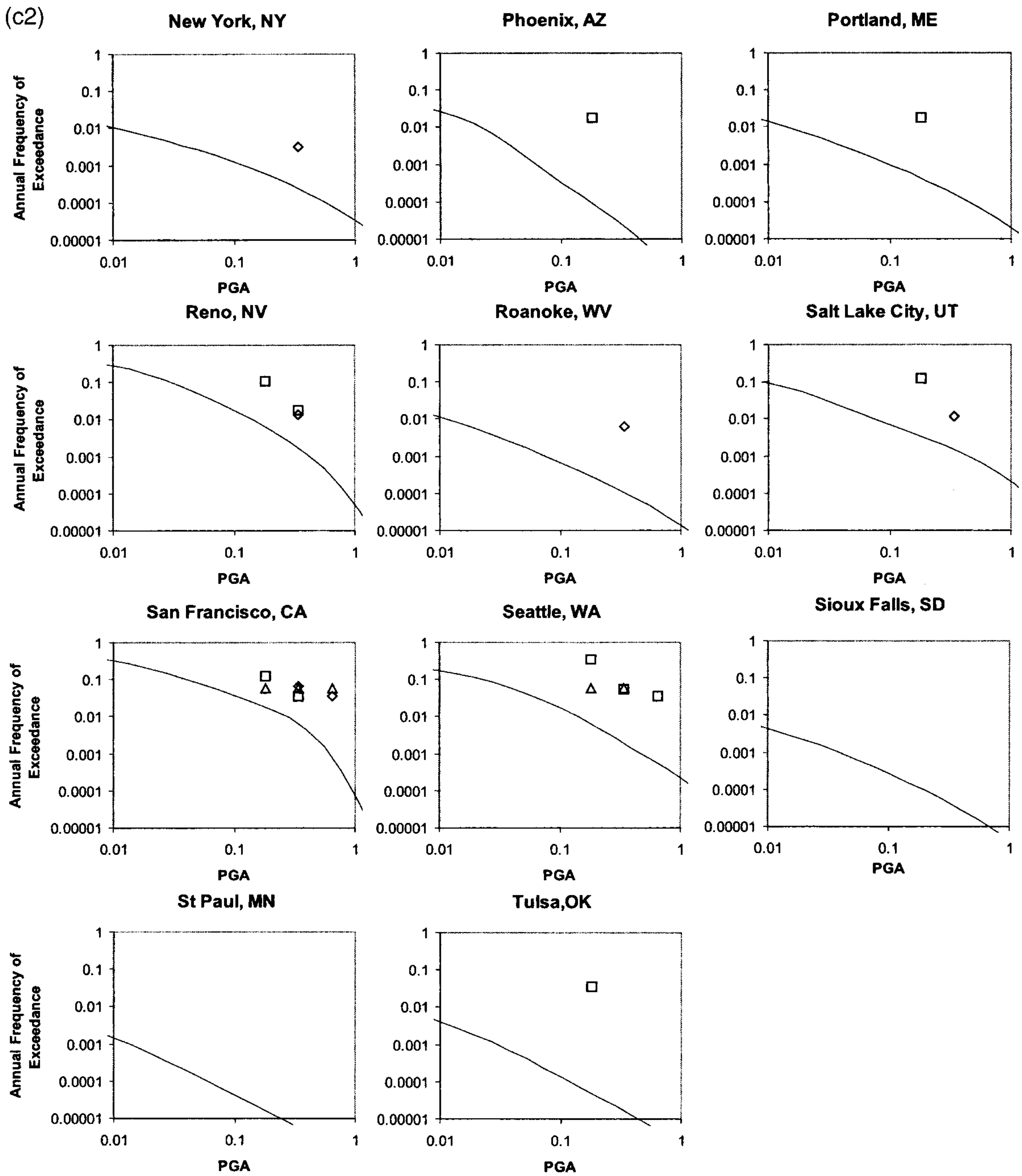


Figure 2. Continued.

and the southern California comparisons have considered the site geology. Almost without exception, the historical MMI data exceed the MMIs predicted from the SHAKEmap attenuation equations, and a mean difference of 1.7 MMI units is calculated for all of the 26 sites (Fig. 3). This discrepancy is statistically significant, given that the Wald *et al.* (1999) relationship has a standard deviation of 1.08 MMI units.

We verify that subtracting the mean discrepancy of 1.7 MMI units from the historical MMIs for southern California sites (Fig. 2) removes the discrepancies with the hazard curves. The graphs in Figure 4 show the historical rates of MMI-derived PGAs to be very similar to the rates predicted from the hazard curves for the USGS PSH model across the 26 southern California sites after this adjustment is performed. For the remaining continental United States sites, we subtract the 1.7 MMI units from the historical MMI levels but also recalculate the equivalent PGAs with a new MMI-PGA relationship developed specifically for central and eastern United States sites (MMI $= 2.31 + 1.32x + 0.372x^2$, in which x is log PGA in units of cm/sec^2; Atkinson and Kaka, 2006). We do not perform the latter conversion for the Seattle and San Francisco sites as we assume that the

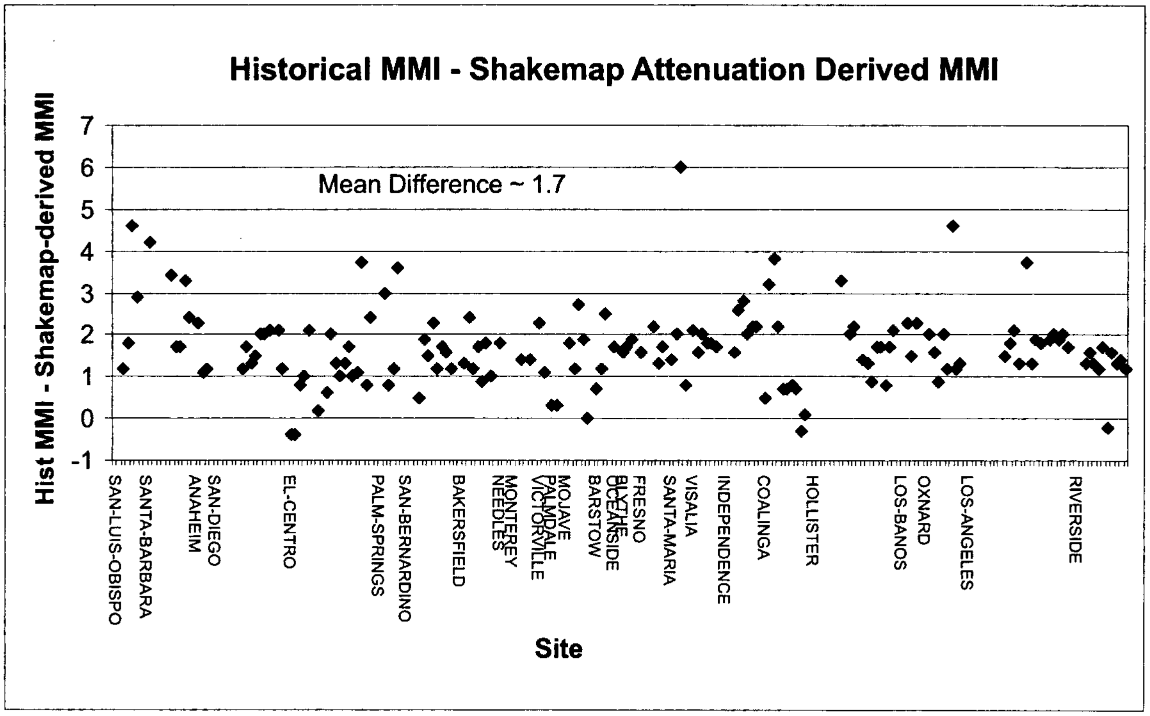


Figure 3. Comparison of southern California historical MMI observations with the MMI levels estimated for the same earthquake magnitudes and distances with the Wald *et al.* (1999) SHAKEmap methodology. The former is on average 1.7 MMI units larger than the latter.

Wald *et al.* (1999) relationship will be better suited to these sites. The resulting graphs (Fig. 5) show agreement between the historical data and the hazard curves for more than half of the sites.

Statistical assessment of the differences between the historically based hazard and PSH estimates for New Zealand, southern California, and remaining continental United States sites is possible by first converting the PSH-model-derived rates of exceedance of MMI-equivalent PGAs to the equivalent number of times the PGAs would be exceeded in the historical period, and then comparing the predicted number to observed number of exceedances for a given PGA level. Comparison between historical data and model is therefore done with the data and model in the same temporal context, and statistical significance is assessed by assuming that the predicted number of exceedances from the PSH model is described by a Poisson distribution, in which the standard deviation is equivalent to the square root of the predicted number of exceedances. The statistical significance of the difference between PSH model derived and historically observed number of events is therefore able to be quantified in terms of the number of standard deviations (DeltaNsigma = (historicalN − PSHmodelN)/sigma)), in which "DeltaNsigma" is the difference in terms of the number of standard deviations, "historicalN" is the historical number of events, "PSHmodelN" the PSH model-derived number of events, and "sigma" is the standard deviation for the PSH model-derived number of events. For this analysis we restrict our attention to the 1931–1985 subcatalog of the continental United States sites, because this generally contains the greatest number of observations of all the available subcatalogs.

The resulting comparisons are shown for each site in Table 1. Across all 78 sites the historically observed number of exceedances is only slightly greater than the PSH model (mean difference, 0.14 sigma), suggesting that overall the PSH methodology embodied in the New Zealand and continental United States models is consistent with the historical hazard. However, if the sites are sorted into interplate and intraplate classes, the results can be interpreted somewhat differently. Table 1 shows that the historically observed number of exceedances are about one standard deviation less than the PSH model-derived number for interplate New Zealand. The mean difference of −1.37 is consistent with the results of Dowrick and Cousins (2003) who found a similar discrepancy between the historical data and PSH model. For the interplate westernmost United States sites the mean difference is −0.7, and for the intraplate sites the difference is more than two standard deviations (mean difference, 2.75). The San Francisco and Seattle sites are included with the southern California sites in Table 1 as they are interplate sites. The results indicate that the PSH methodology slightly overestimates historical hazard at interplate sites and apparently underestimates historical hazard at intraplate sites. The reasons for such a trend and how the results should be eval-

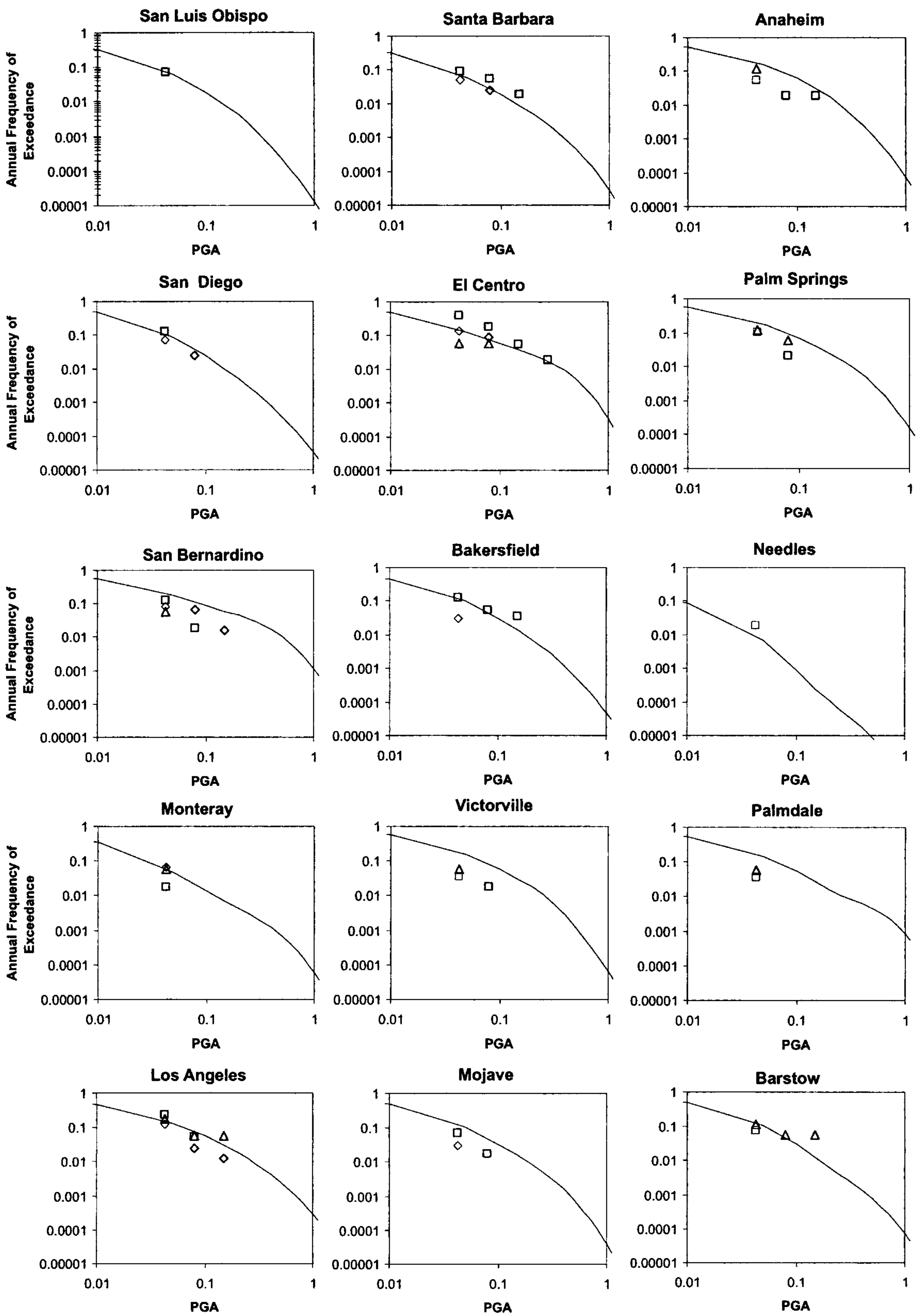


Figure 4. The 26 southern California sites, showing the historical rates of exceedance for PGA levels (after being reduced by 1.7, and then converted from historical MMIs via the relevant relationship of Wald *et al.*, 1999) compared with the hazard curves from the United States PSH model. See Figure 2 for explanation of the symbols. (*continued*)

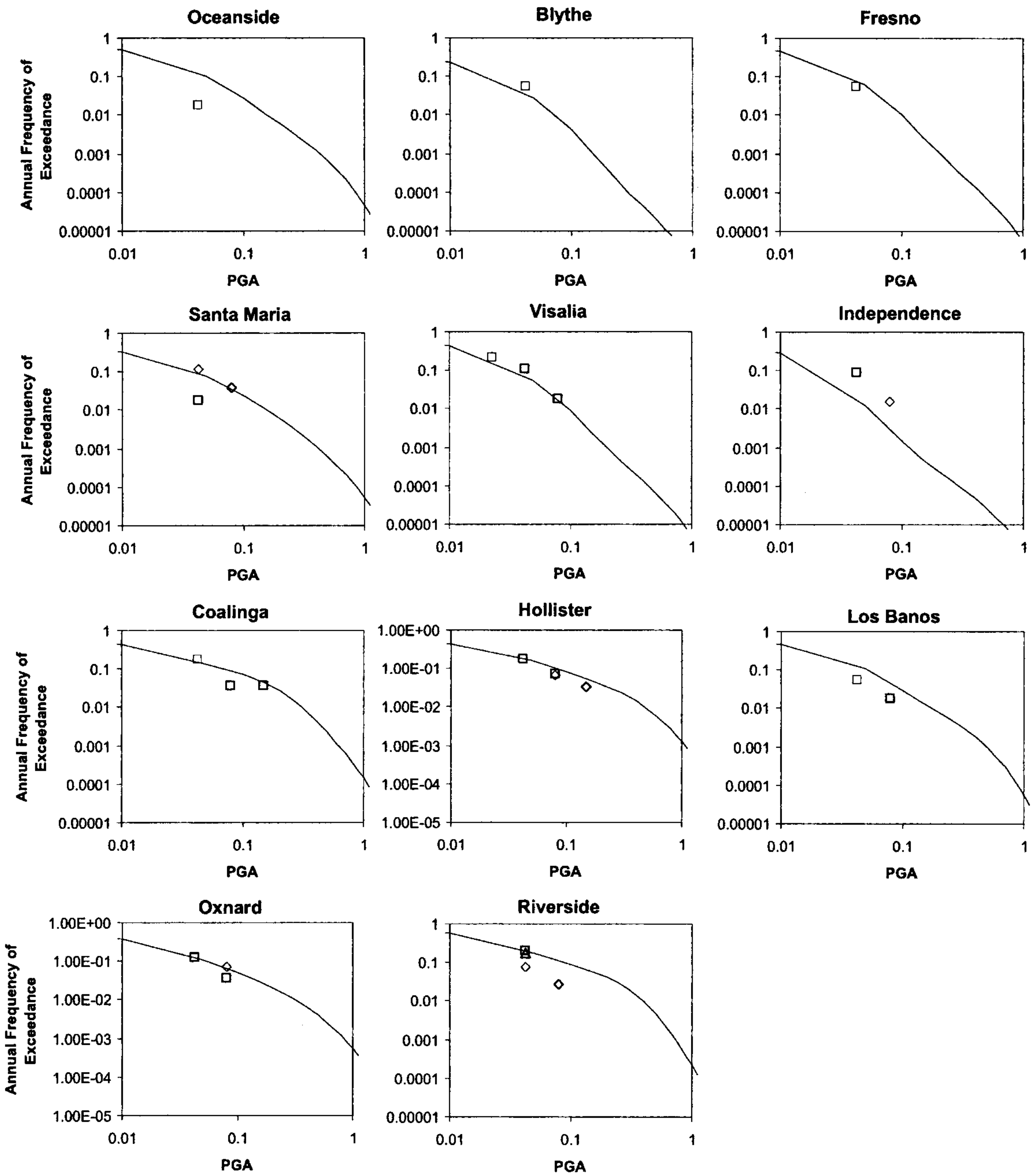


Figure 4. Continued.

uated in the context of a test of the PSH methodology embodied in the New Zealand and United States PSH models are the focus of the following discussion.

The different results for interplate and intraplate sites could be due to differences in the long-term representativeness of the historical data for the two classes of region. Specifically, the greater number of exceedances in the historical period for the interplate regions as compared with the intraplate region should translate to greater reliability of the historical period as an indicator of long-term hazard. An explanation that could account for the differences for the intraplate sites (Table 1) is that the hazard curves for these sites do not consider local site conditions. This is because the USGS model only readily provides hazard curves for soft-rock site conditions. In contrast, the hazard curves for southern California sites were able to be calculated with local site conditions included via OpenSHA, and likewise for the New Zealand sites. It is therefore possible that the historical MMIs may be reflecting the influence of strong site effects at the intraplate sites (Table 1). The observation that many of the sites are located on deep alluvial deposits supports this suggestion. Uncertainties in the Atkinson and Kaka (2006) MMI-PGA relationship may also account for the discrepancies. For MMI ≥6 the standard deviation of the relationship

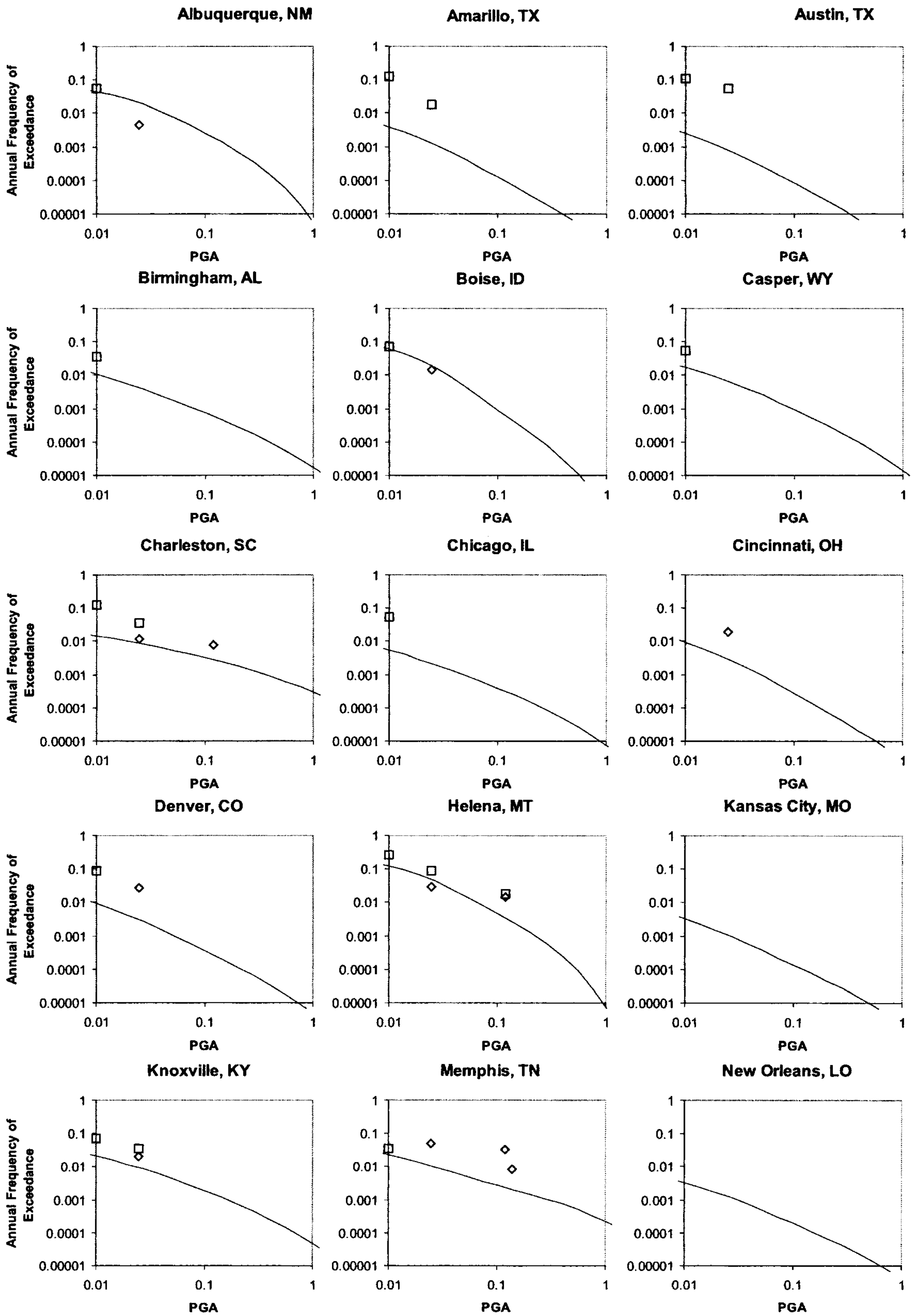


Figure 5. The 26 continental United States sites outside of southern California, in which the historical MMIs are first reduced by 1.7 before converting to PGA via the relevant relationship of Atkinson and Kaka (2006). (*continued*)

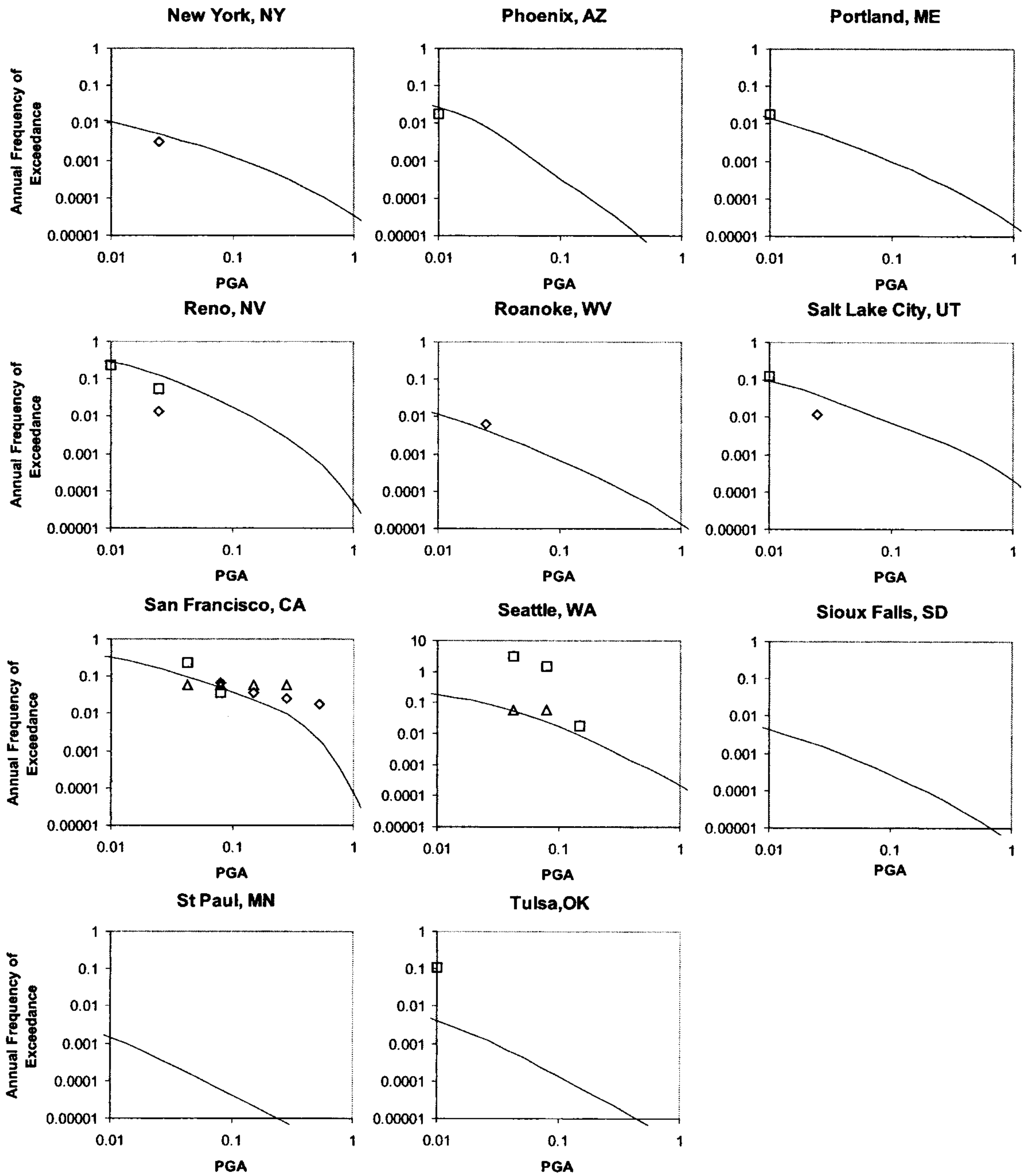


Figure 5. Continued.

is 0.31 to 0.41 in units of log PGA (PGA is in cm/sec^2). This is a large standard deviation, given that it reduces the minus-one-standard-deviation PGA to about half that of the median PGA. Such differences in PGA are of similar magnitude to those of the remaining discrepancies between the historical data and PSH model in Figure 5. However, we have no basis for assuming that the historical PGAs should be reduced by one standard deviation for the applicable sites at the present time, especially since we have not yet been able to assess the effects of local site geology at the intraplate sites.

In the case of the interplate sites it appears that the PSH methodology slightly overestimates historical hazard, perhaps because of the stronger influence of geologically based earthquake parameters in the hazard calculations for these areas (Frankel *et al.*, 2002; Stirling *et al.*, 2002). In New Zealand, this could be due to non-Poissonian earthquake occurrence for the fault-derived earthquakes, because only a small proportion of the more-than-300 fault sources in the country produced large earthquakes during the historical period. Another possible explanation is that the characteristic earthquake sizes may have been underestimated for the PSH models in both interplate regions, which would lead to an

Table 1

The Differences between Historical and PSH Model-Derived Number of Events for the PGA Equivalent to MMI ≥6 at the New Zealand Sites, and MMI ≥4.3 at the Continental United States Sites*

INTER USA	DNsig	INTER NZ	DNsig	INTRA USA	DNsig
Riverside	−0.84	Auckland	0.195	Albuquerque	0.35
SanLuis	−0.9066	Alexandra	−2.07	Amarillo	14.40
SantaBarb	−0.82	Christchurch	−0.94	Austin	15.71
Anahelm	−2.71	Dunedin	−1.1	Birmingham	1.79
San Diego	−0.74	Gisborne	−2.43	Boise	−0.1
El Centro	3.31	Greymouth	−2.29	Casper	2.1
Palm Springs	−2.38	Hamilton	−1.47	Charleston	6.90
San Bernar	−1.92	Hanmer	0.572	Chicago	4.83
Bakersfield	−0.82	Invercargill	−0.83	Cincinnatti	−0.73
Needles	−0.23	Kaikoura	−0.869	Denver	6.14
Monterey	−2.03	Masterton	−1.33	Helena	3.07
Victorville	−3.02	Napier	−2.62	Kansas	−0.43
Palmdale	−2.88	Nelson	−1.96	Knoxville	2.58
Los Angeles	0.56	Oamaru	−1.27	Memphis	0.57
Mojave	−1.98	Omarama	−2.698	New Orleans	−0.43
Barstow	−2.298	PalmerstonN	−1.8	New York	−0.77
Oceanside	−2.84	New Plymouth	0.396	Phoenix	−0.40
Blythe	−0.37	Queenstown	−2.47	Portland, ME	−0.24
Fresno	−1.71	Taihape	−2.23	Reno	−0.66
Santa Maria	−2.28	Taumaranul	−1.87	Roanoke	−0.81
Visalia	−0.497	Taupo	−0.996	Salt Lake	0.85
Independence	0.665	Timaru	−1.06	Sioux Falls	−0.49
Coalinga	−0.184	Wanganul	0.228	St Paul	−0.29
Hollister	−0.66	Wellington	−0.79	Tulsa	12.00
Los Banos	−2.19	Westport	−0.718	Mean	2.75
Seattle	10.195	Whakatane	−3.17		
San Francisco	0.758	Mean	−1.37		
Oxnard	−0.66				
Mean	−0.70				

*MMI 4.3 = MMI 6 − 1.7 unit correction factor for the historical MMIs (see the text for further explanation). The comparisons are for 1931–1985 for interplate United States sites (INTER USA), 1840–1997 for interplate New Zealand sites (INTER NZ), and 1931–1985 for the intraplate United States sites (INTRA USA). The difference is in units of standard deviation for the PSH model-derived number of events (DNsig). See Figure 1 for location of the sites, and the text for further explanation.

overestimation of earthquake rates. Last, the large uncertainties in converting MMI to PGA evident in the Davenport (2003) and Wald *et al.* (1999) relationships (standard deviations of 0.46 and 1.08 MMI units, respectively) could account for the discrepancies between the historical data and the hazard models. Investigation of the preceding possible explanations should form the basis of follow-up studies. Our study also highlights the importance of evaluating PSH methodology with different datasets and models, because our conclusions would be very different if we had restricted our attention to just one of the three regions.

Finally, in an attempt to evaluate the PSHA methodology embodied in the New Zealand and USGS models, the results of the study show that the PSHA methodology produces results that exceed the ground motions experienced in the historical period for a suite of interplate sites (based on the interplate New Zealand and westernmost United States results), but the PSH model produces hazard estimates lower than the historical record at the intraplate United States sites. Any attempts to formally adjust the New Zealand and continental United States PSH models in light of our results should not be carried out until our recommended follow-up work is achieved (see earlier text). These efforts should also be substantiated by (1) a similar analysis of instrumental strong-motion data, and (2) by the use of unstable landform features (precariously balanced rocks) to independently constrain long-term seismic hazard at a suite of sites in the western United States (e.g., Brune, 1996) and New Zealand (Stirling and Anooshehpoor, 2006). The unstable landform studies thus far tend to show that PSH models may overestimate seismic hazard for return periods longer than the historical (10^4–10^5 yr) in the western United States and New Zealand. This is consistent with our results for these two regions.

Conclusions

Our comparisons of the national PSH models for New Zealand and the continental United States with the historical rate of exceedance for specific MMI levels at a suite of 78 sites show a tendency for the PSH models to slightly exceed the historical hazard in New Zealand and westernmost continental United States interplate regions, but show lower hazard than that of the historical record in the continental United States intraplate region. Factors such as non-Poissonian behavior and parameterization of active fault data in the PSH calculations for the interplate regions may have led to the higher-than-historical levels of hazard at the interplate sites. In contrast, the less-than-historical hazard for the remaining continental United States (intraplate) sites may be largely due to site conditions not having been considered in the PSH calculations for the intraplate sites. Uncertainties in the MMI–PGA relationships may also have contributed to the observed discrepancies for all three regions. Adjustments to the PSH models should not be considered unless these issues are addressed. A similar analysis of instrumental strong-motion data, and the use of unstable landform data to constrain seismic hazard in New Zealand and westernmost United States should also be important follow-up work from our study. The comparisons would also benefit from being carried out in a more statistically robust manner by fully accounting for epistemic uncertainty in the PSH models. Finally, the study highlights the importance of evaluating PSH models at more than one region, since the conclusions reached on the basis of a solely interplate or intraplate study would be very different.

Acknowledgments

We thank Jim Cousins, Margaret Hopper, and James Dewey for their assistance with location of MMI data and discussions, and Ned Field, Art Frankel, Graeme McVerry, Matthew Gerstenberger, Paul Somerville, David Jackson and Steven Jaume for discussions. The manuscript benefited from reviews by Jeff Kimball, Roland LaForge, Ivan Wong, John Zhao, and Warwick Smith. This article is the result of collaborative work from 2002 to 2004 when the senior author was the inaugural USGS "Senior Scientist in Residence" award recipient for one month in 2002, and a visiting Southern California Earthquake Center (SCEC) scientist for a further two months at USGS Pasadena from 2003 to 2004. Financial support came from the Foundation for Research, Science and Technology (New Zealand), USGS, and SCEC. SCEC is funded by NSF Cooperative Agreement EAR-0106924 and USGS Cooperative Agreement 02HQAG0008. The SCEC contribution number for this article is 964.

References

Atkinson, G. M., and S. I. Kaka (2006). Relationships between felt intensity and instrumental ground motion for New Madrid earthquakes, Report for USGS NEHRP Award 05HQGR0039.

Basham, P., S. Halchuk, D. Weichert, and J. Adams (1997). New seismic hazard assessment for Canada, *Seism. Res. Lett.* **68,** 722–726.

Brune, J. N. (1996). Precariously balanced rocks and ground motion maps for southern California, *Bull. Seism. Soc. Am.* **86,** 43–54.

Cousins, W., N. D. Perrin, G. H. McVerry, R. T. Hefford, and T. E. Porritt (1996). Ground conditions at strong motion recording sites in New Zealand, Institute of Geological and Nuclear Sciences Science Report 96/33.

Davenport, P. N. (2003). Instrumental measures of earthquake intensity in New Zealand, in *Proceedings of 2003 Pacific Conference on Earthquake Engineering*, Christchurch, February 2003.

Dowrick, D. J., and W. J. Cousins (2003). Historical incidence of Modified Mercalli Intensity in New Zealand and comparisons with hazard models, *Bull. N.Z. Soc. Earthquake Eng.* **36,** 1–24.

Frankel, A. D., M. D. Petersen, C. S. Mueller, C. M. Haller, R. L. Wheeler, E. V. Leyendecker, R. L. Wesson, S. C. Harmsen, C. H. Cramer, D. M. Perkins, and K. S. Rukstales (2002). Documentation for the 2002 update of the National Seismic Hazard Maps, *U.S. Geol. Surv. Open-File Rept. 02-420*.

International Code Council (ICC) (2003). International Building Code, The International Code Council, Falls Church, Virginia.

Standards New Zealand (2005). Structural Design Actions, New Zealand. NZS 1170.5 Supp 1:2004. Part 5: Earthquake Actions with Commentary.

Stirling, M. W., and A. Anooshehpoor (2006). Constraints on probabilistic seismic hazard models from unstable landform features in New Zealand, *Bull. Seism. Soc. Am.* **96,** 404–414.

Stirling, M. W., G. H. McVerry, and K. R. Berryman (2002). A new seismic hazard model for New Zealand, *Bull. Seism. Soc. Am.* **92,** 1878–1903.

Wald, D. J., V. Quitoriano, T. H. Heaton, and H. Kanamori (1999). Relationships between peak ground acceleration, peak ground velocity and Modified Mercalli Intensity in California, *Earthquake Spectra* **15,** 557–564.

Wills, C. J., C. J. Petersen, M. D. Bryant, M. S. Reichle, G. J. Saucedo, S. S. Tan, G. C. Taylor, and J. A. Treiman (2000). A site-conditions map for California based on geology and shear-wave velocity, *Bull. Seism. Soc. Am.* **90,** S187–S208.

GNS Science
P.O. Box 30368
Lower Hutt, 6009 New Zealand
(M.S.)

U.S. Geological Survey
Box 25046, MS996
Denver Federal Center
Denver, Colorado 80255
(M.P.)

Manuscript received 18 August 2005.