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Douglas, John and Ulrich, Thomas and Bertil, Didier and Rey, Julien (2014) Comparison of the ranges of uncertainty captured in different seismic-hazard studies. Seismological Research Letters, 85 (5). pp. 977-985. ISSN 1938-2057 , http://dx.doi.org/10.1785/0220140084

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Comparison of the Ranges of Uncertainty Captured in Different Seismic-Hazard Studies

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INTRODUCTION

The inclusion of epistemic uncertainties, generally via logic trees (Kulkarni *et al.*, 1984), within probabilistic seismic-hazard assessments (PSHAs) is becoming standard for all types of studies (commercial, governmental, or research; site specific, national, regional, or global). Consequently many studies publish expected ground motions for a given annual frequency of exceedance (AFE) or return period derived from the hazard curves for the mean, median, and various fractiles (percentiles). The spread of these values represents the uncertainty captured in the results (the greater the spread the higher the uncertainty). For example, Figure 1 shows the distribution of AFE for a peak ground acceleration (PGA) of 0.25*g* obtained in the study for the Washington Nuclear Plant (WNP)-2 nuclear power plant (Hanford Reservation, Washington State) reported by Kulkarni *et al.* (1984). Distributions of ground-motion levels for a given AFE are now most commonly reported in recent PSHAs rather than distributions of AFEs for a certain ground-motion level.

Woo (2002) calls for the epistemic uncertainty to be overlaid on seismic hazard maps, although this is rarely, if ever, done. Giardini *et al.* (2004, their fig. 34) present the relative uncertainty in the Swiss National Seismic Hazard Map showing that parts of the map are associated with considerable uncertainty (more than 40%) because of doubts over the seismic source zones and *b*-values. A recent detailed study of epistemic uncertainties in a PSHA is by Bradley *et al.* (2012), who rank the impact of various uncertainties on hazard results for two New Zealand cities (Wellington and Christchurch). There are, however, no studies to our knowledge in which these distributions are compared among PSHAs. As we seek to show in this brief article, such comparisons can provide useful insights into the suitability of the distributions of the input parameters within the logic trees. For example, if the range of uncertainty of a study is much narrower than the uncertainty present in comparable PSHAs for a similar location then it could indicate that the uncertainties in the input parameters (e.g., seismic source characterization) have not been completely captured. Additional data collection and analysis can significantly reduce epistemic uncertainty, and this should be done when possible—all remaining uncertainties should be accounted for within the final PSHA.

SELECTED STUDIES AND UNCERTAINTY MEASURES

In this study, we consider various published PSHAs for rock sites that report expected PGAs and pseudospectral accelerations (PSAs) for a structural period of 1 s and 5% of critical damping for the mean[1], median (50th percentile), and 15th (or 16th) and 85th (or 84th) percentiles for return periods of 475 (10% chance of exceedance in 50 years, AFE of $1/475 = 2.1 \times 10^{-3}$) and 2475 years (2% chance of exceedance in 50 years, AFE of $1/2475 = 4.0 \times 10^{-4}$). Examining the relationships between these ground-motion levels will allow an assessment of the reported uncertainty in the hazard results to be made. These ground-motion measures and AFEs were considered because they are the results most commonly reported in PSHAs for standard infrastructure. For facilities such as nuclear power plants, lower AFEs (or longer return periods) and a wider range of percentiles (e.g., 5th and 95th) are often published, but these are not considered here. The only component of the PSHA that differs when considering PGA, PSA(1 s), or PSA at another structural period is the intensity measure (IM) for which the ground-motion prediction equations (GMPEs) are evaluated. Douglas (2010) shows that the epistemic uncertainty associated with GMPEs are comparable for PSA (considering a natural period of 1 s as an example) and PGA. Long-period PSAs can, however, be more sensitive to uncertainties in the recurrence rates of large earthquakes (e.g., through the M_{max} used in the magnitude–frequency relations) than short-period intensity measures, such as PGA (Julian Bommer, written comm., 2014). Hence, the period dependency of the uncertainty is examined here.

The selected PSHAs comprise various regional, national, and site-specific studies in which the required information for such a comparison is freely available from published hazard curves, which may have required digitization or interpolation, or tables. Despite using detailed logic trees the hazard results of

[1]Bommer and Scherbaum (2008) note that the two methods used to compute this parameter (either calculation of the mean ground motion at each AFE or, correctly, that based on statistics of the AFEs for each ground-motion amplitude) can lead to different results. Here, we simply use the values reported by the authors irrespective of which method they use, which is very rarely stated.

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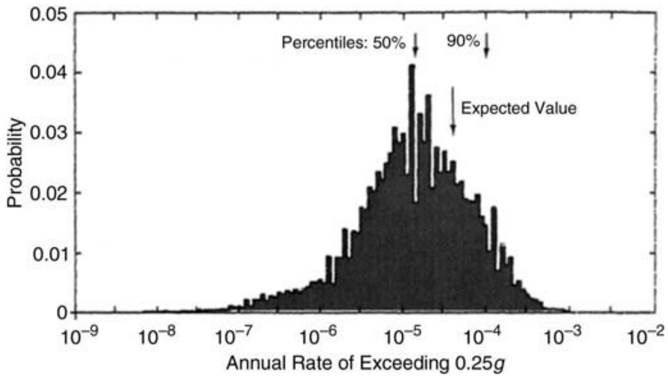


▲ **Figure 1.** Example distribution of annual frequency of exceedance (AFEs) for a considered peak ground acceleration (PGA) of 0.25*g* for the WNP-2 nuclear power plant (Hanford Reservation, Washington State) (Kulkarni *et al.*, 1984, Reprinted with permission from Earthquake Engineering Research Institute).

the U.S. National Seismic Hazard Mapping Project (e.g. Petersen *et al.*, 2008) are only published for the mean ground motion, and hence this study is not included here. The Global Seismic Hazard Assessment Program (Giardini, 1999) also only published results for the mean ground motion. The recent SHARE project (Giardini *et al.*, 2013), which provides a harmonized seismic-hazard model for Europe, provides the results for the mean and various fractiles, and hence this study is selected as an example of a recent regional PSHA. This project could be considered as following a Senior Seismic Hazard Analysis Committee (SSHAC) 2 philosophy. SSHAC (Budnitz *et al.*, 1997; United States Nuclear Regulatory Commission [USNRC], 2012) sought to formalize the procedures used to consider expert judgments within PSHAs, particularly those conducted for critical infrastructure (e.g., nuclear power plants). It defined four types of study ranging from level 1, which corresponds to analyses conducted by a small team of analysts using publicly available information and without seeking outside expert advice, to level 4, which corresponds to a large-scale study with many participants with clearly defined roles and a highly formalized procedure. Coppersmith and Bommer (2012) discuss the differences between these levels of study. As the only two examples of PSHAs following the SSHAC level 4 procedure to date, the results of the Yucca Mountain (Stepp *et al.*, 2001) and Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites (PEGASOS; National Cooperative for the Disposal of Radioactive Waste [NAGRA], 2004) projects are included here. As examples of site-specific SSHAC levels 1, 2, and 3 studies, some recent public service and commercial projects of Bureau de Recherches Géologiques et Minières (BRGM) are included as well as recent studies for: a proposed nuclear waste repository at Bruce (Canada), a planned nuclear power plant at Thyspunt (South Africa), and the city of Cologne (Germany), and the Italian seismic building code. Brief summaries of the selected studies are provided in Table 1 along with their SSHAC level; Figure 2 indicates the locations of the European sites (the three non-European locations are not plotted).

Three metrics to measure the uncertainty in the expected IM [here either PGAs or PSA(1 s)] for a given AFE were originally considered: ratio of the 85th (or 84th) percentile IM (IM_{85}) and median IM; ratio of median IM and 15th (or 16th) percentile (IM_{15}); and $100 \log(IM_{85}/IM_{15})$, which is used by Giardini *et al.* (2004) in their report on the Swiss National Seismic Hazard Map (they call it the relative uncertainty). When the distribution of the logarithm of the ground-motion level for a given AFE is symmetrical about the median then these measures lead to the same conclusions. This is not the case for asymmetric hazard distributions, such as those for Rome (Istituto Nazionale di Geofisica e Vulcanologia [INGV]) where the median is much closer (in logarithmic space) to the 85th percentile than the 15th, which are due to the input parameters to the PSHA being skewed in logarithmic space. For simplicity, and because in most cases considered here the hazard distributions are roughly symmetric, we choose to report only the third of these measures, that is, $100 \log(IM_{85}/IM_{15})$.

COMPARISONS

In this section, various hypotheses on observations that one would expect to see when examining the uncertainties of hazard results are tested using the selected studies. A discussion of the observations and their implications for PSHAs are given in the following section.

First, because uncertainties should compound as return period increases (or AFE decreases), it would be expected that the hazard curves for the different fractiles would spread out and the uncertainty metric defined above would increase. This is checked by comparing the hazard results for AFE $= 1/475$ and AFE $= 1/2475$ in the selected studies (Figs. 3 and 4, compare gray and black error bars from the same study). For the selected studies and AFEs, the hazard results do not always show this expected behavior; often the spread of fractiles is similar for 1/475 and 1/2475, and in some cases (e.g., for Gösgen from SHARE for PGA) the spread is much lower for an AFE of 1/2475. A possible explanation for this apparent contradiction is that an uncertain seismic source is dominant for higher AFEs, but a better known source becomes important as the AFE decreases. Another possible reason (Julian Bommer, written comm., 2014) could be that the dominant earthquakes for higher AFEs are smaller than for lower AFEs and predicted IMs from small earthquakes ($M_w \sim 5$) show greater dispersion than for moderate magnitudes ($M_w \sim 6.5$) (e.g., Douglas, 2010, compare his figs. 2 and 4).

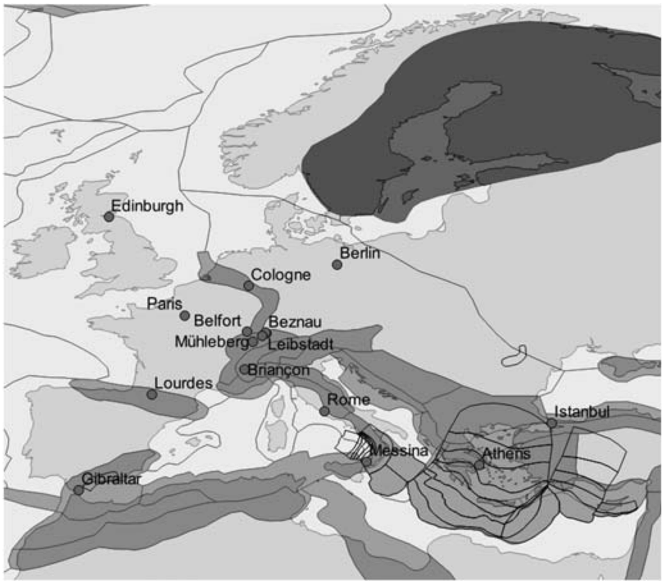
Second, because the earthquake rate in stable areas is much lower (and consequently available observations, both in terms of events and ground motions, fewer) than in active areas it would be expected that the uncertainties in hazard estimates in those areas would be higher, provided that similar rigor is applied to the assessment and capturing of uncertainties in the two cases. This is checked by comparing the SHARE results for sites in the stable continental crust (the hazard, according to SHARE, in the Scandinavian shield is lower, and hence this regime is not considered here) and active areas in Figures 3

Table 1
Summary of Probabilistic Seismic-Hazard Assessments (PSHAs) Selected Here for Comparisons

Sites (References)	SSHAC Level	Brief Description
Belfort (Rey *et al.*, 2011), Lourdes (ISARD; Secanell *et al.*, 2008), and Briançon (Le Goff *et al.*, 2009)	Level 1	These projects were supported by the French government, the European Interreg program or commercial clients, to assess hazard for various parts of France. They were conducted during a period of a few months by a small team based on data and knowledge available in the literature. The AFEs of interest were 1/2475 or greater
Cologne (Grünthal and Wahlström, 2006)	Level 1	This research study, conducted by a two-person team, computed the seismic hazard in a small area enclosing the cities of Cologne and Aachen (western Germany). It was part of a wider research project. The authors paid particular attention to accounting for uncertainties in the input parameters. The AFEs of interest were 1/2475 or greater
Rome and Messina (INGV; Montaldo *et al.*, 2007)	Level 2	This large-scale project was conducted by INGV to produce the Italian seismic hazard map for use with a new building code. It involved inputs from many experts and included a review by a scientific board. The AFEs of interest were 1/2475 or greater
Athens, Berlin, Beznau, Edinburgh, Gibraltar, Gösgen, Istanbul, Leibstadt, Mühleberg, Paris, Rome, and Messina (SHARE; Giardini *et al.*, 2013)	Level 2	This three-and-a-half-year project, supported by the European Commission, produced a harmonized seismic-hazard model for the wider European area. It involved 18 partner institutes and sought data and expertise from many dozens of experts outside the consortium, as well as being extensively reviewed. The AFEs of interest were 1/5000 or greater
Bruce (AMEC Geomatrix, Inc., 2011)	Level 2	This project assessed the seismic hazard at the site of a proposed deep geological repository for the permanent storage of low- and intermediate-level nuclear waste for Ontario Power Generation at Bruce (Municipality of Kincardine, Ontario, Canada). It involved correspondence with external experts to obtain unpublished data and an external review. The AFEs of interest ranged from 10^{-2} to 10^{-8}
Thyspunt (Bommer *et al.*, 2014)	Level 3	This two-and-a-half-year project assessed the seismic hazard at the site of a proposed nuclear power plant in Eastern Cape (South Africa). It was the first application of the SSHAC 3 approach outside North America and involved many experts in a wide variety of roles. The AFEs of particular interest were 1/10000 and lower
Beznau, Gösgen, Leibstadt, and Mühleberg (PEGASOS; NAGRA, 2004)	Level 4	This three-year project reassessed the seismic hazard at the four existing nuclear power plants in Switzerland. It was the second application of the SSHAC 4 approach. The AFEs of particular interest were 1/10000 and lower
Yucca Mountain (CRWMS M&O; Stepp *et al.*, 2001)	Level 4	This four-year project assessed the seismic hazard for a planned nuclear waste repository beneath Yucca Mountain (Nevada). It was the first application of the SSHAC 4 process. The AFEs of particular interest were 1/10000 and lower

and 4, using the seismotectonic zonation of Delavaud *et al.* (2012, see fig. 2). As expected, the uncertainties at sites in stable continental crust are much higher than those in active areas. For the SHARE results this higher uncertainty in stable regions is probably due in great part to the ground-motion logic tree branches, although the uncertainties in the seismic source characterization are considerable. The ground-motion branches for stable regions combined ground-motion models for active regions with models selected for the shield, thereby leading to a large spread in the predicted ground motions for a given magnitude and distance.

Third, because the uncertainty in conducting hazard analyses for a large area (e.g., Europe or a country) is higher than conducting it for a well-known site (e.g., a critical infrastructure) the logic tree for the large area should, in theory, model a higher spread in the inputs than the logic tree for the individual site. This is studied by comparing results for various sites from the national hazard map for Italy, SHARE, and some site-specific studies (compare results in Differing geographical extents shown in Figs. 3 and 4). No systematic dependence on the geographical extent and the uncertainty can be seen from this comparison. For some sites (e.g., Messina) the more local study shows lower uncertainty than the analysis for the wider region (as expected), whereas for other locations (e.g., Rome and Briançon for PGA) the uncertainty from the local study is higher than in the PSHA for the broader region. This could be due to the local and national/regional study making different levels of effort to capture the uncertainties in the seismic sources. Computational limitations and time and resource constraints means that it is doubtful that studies covering a large



▲ **Figure 2.** Locations of the selected sites in Europe (Bruce, Canada; Thyspunt, South Africa; and Yucca Mountain, Nevada, are outside the map) overlying the subdivisions of the Euro-Mediterranean area into its main tectonic regimes developed for the SHARE project (Delavaud *et al.*, 2012) in which dark gray, shield; mid-gray, active areas; light gray, stable continental crust; and black lines, subduction zones and areas of deep-focus nonsubduction earthquakes (Vrancea).

area could use the type of complex logic trees often developed and evaluated for site-specific analyses. That being said, it may be possible to develop simple logic trees that roughly capture the uncertainties in inputs to regional/national PSHAs so that the hazard fractiles reflect, to a first order, the uncertainties inherent in conducting such analyses. For a site-specific study or low AFEs, such simple logic trees, however, are unlikely to be appropriate.

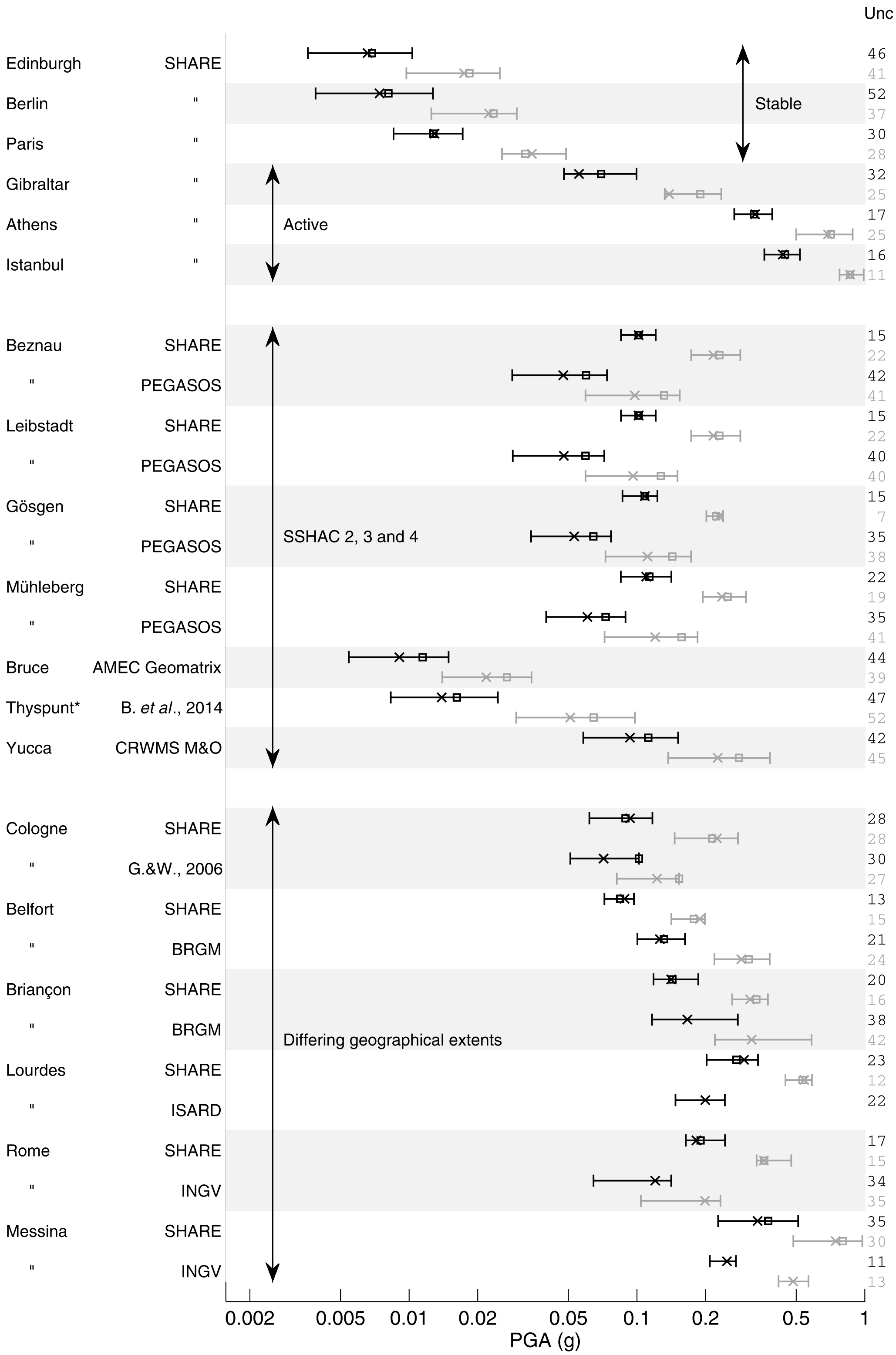
Fourth, because, as noted above, uncertainties in GMPEs appear to be only weakly dependent on response spectral period, it would be expected that the uncertainties in the PSHA would also not show strong period dependency. This is examined by comparing Figure 3 (for PGA) and Figure 4 [for PSA(1 s)] and particularly by examining the ratios between the uncertainty measures for PSA(1 s) and PGA for each study (see right-most column on Fig. 4). In general, the uncertainties in the expected PSA(1 s) values are slightly higher (ratios larger than unity) than the spreads in the expected PGAs and in some cases (e.g., many of the SHARE results) much higher (ratios of more than 1.5). These observations could be explained by, as noted above, PSA(1 s) being more sensitive to uncertainties in the recurrence rates of large earthquakes than are PGAs. Based on disaggregation results, hazard for PSA(1 s) often shows greater influence of more distant sources than does PGA. Consequently, higher uncertainties at longer periods could be due to consideration of more sources, the activity rates of which are poorly constrained. For some sites and studies, the uncertainties for PSA(1 s) are lower than those for PGA. For Thyspunt this can be attributed to large uncertainties in the estimates of the near-surface attenuation (kappa) at this site, which greatly affects the estimates of the short-period response spectral accelerations but has no impact at 1 s (Bommer *et al.*, 2014, their fig. 15).

Finally, because of the rigorous approach of SSHAC 3 and 4 studies to fully capture uncertainties in the seismic hazard it would be thought that expected ground motions from this level of study would show a larger spread than results from SSHAC 1 and 2 projects. This is investigated by comparing PEGASOS and SHARE results for four Swiss sites (compare results in SSHAC 2, 3, and 4 studies shown in Figs. 3 and 4). This figure shows that hazard results from PEGASOS (SSHAC 4) have wider fractiles than those from SHARE (SSHAC 2), indicating higher uncertainties. Fractiles from the two SSHAC 4 studies (PEGASOS and Yucca Mountain) and the SSHAC 3 study (Thyspunt) show similar spreads, as do the fractiles from the SSHAC 2 study for Bruce. The AFEs of interest and purpose of SSHAC 3 and 4 studies should be borne in mind when making this comparison. SSHAC 1 and 2 studies generally focus on higher AFEs (1/2475 or higher) than SSHAC 3 and 4 studies (AFEs of 1/10000 and lower), which are conducted for critical facilities that require high regulatory assurance that uncertainties are correctly captured. Another observation that can be made is the large difference between the median and mean IMs in the results from SSHAC 3 and 4 studies; for SHARE they are generally similar. As noted by Abrahamson and Bommer (2005) the mean hazard curve is highly sensitive to the most severe of the alternatives in the logic tree. SSHAC 3 and 4 studies often feature more extreme alternatives in their logic trees, and hence this drift across fractiles is more noticeable than in SSHAC 1 and 2 results.

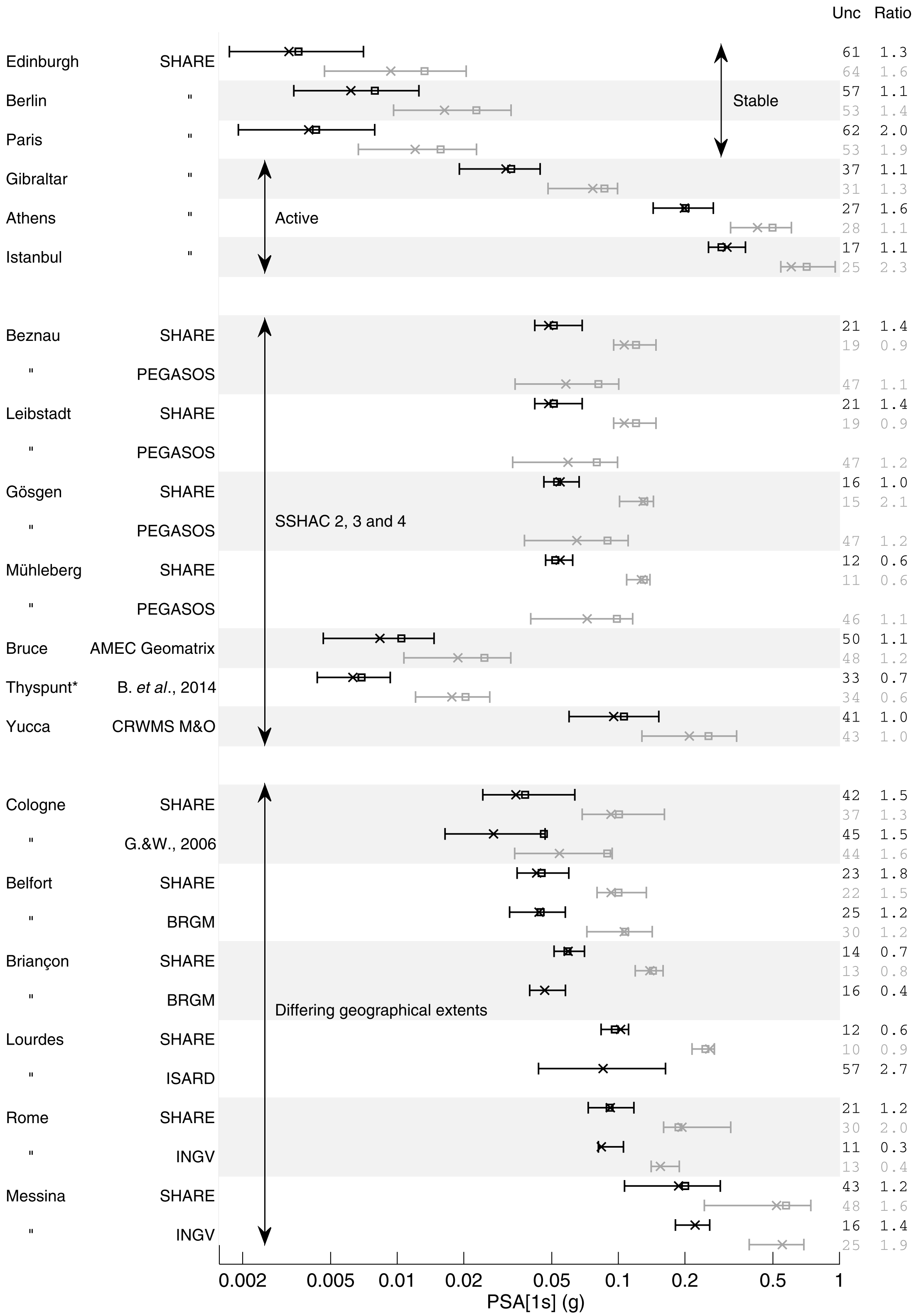
DISCUSSION AND CONCLUSIONS

The aim of state-of-the-art hazard assessments should be to account for the center, body, and range of the technically defensible interpretations (USNRC, 2012) concerning inputs to the analysis. For the center, the best-estimate model (e.g., the ground-motion model that is thought to best represent the median ground motions in the region) or parameter (e.g., the best estimate for the b-value in the Gutenberg–Richter relation) should be used. The body refers to the shape of the alternative interpretations of the available data (e.g., accounting for the uncertainty in the b estimate based on its standard deviation), and the range refers to the tails of the interpretations and limiting credible values (e.g., considering analogs to similar regions).

For the most recent site-specific studies (e.g., the Thyspunt study by Bommer *et al.*, 2014), this objective appears to be reached, but for national, regional, or global studies this does not always appear to be true. This is a question of the geographical scale at which the analysis is conducted: at a small scale the activity of individual faults is considered and various source models may be constructed, whereas at a regional scale the uncertainties in sources may be neglected because there is not the time to look at individual faults. However, the lack of



▲ **Figure 3.** Comparison of expected PGAs (AFEs of 1/475 [black] and 1/2475 [gray] return periods) from different probabilistic seismic-hazard assessments (PSHAs) (bars, 15th–85th fractiles; crosses, medians; and squares, means) and the uncertainty metric $100 \log(PGA_{85}/PGA_{15})$. Note that for Thyspunt (indicated by an asterisk), a low-kappa site, that PGA corresponds to spectral acceleration at a frequency greater than 100 Hz (not computed in the study), and the results for a pseudospectral accelerations for 100 Hz are plotted here (Bommer *et al.*, 2014). The studies are split vertically to help comparisons discussed in the text. Estimates of the mean PGAs are not available for Rome (Istituto Nazionale di Geofisica e Vulcanologia [INGV]), Messina (INGV), Briançon (Bureau des Recherches Géologiques et Minières [BRGM]), and Lourdes (Information Sismique Automatique Régionale de Dommages [ISARD]) which also does not provide ground-motion estimates for AFE of 1/2475.



▲ **Figure 4.** Comparison of expected PSA(1 s) (AFEs of 1/475 [black] and 1/2475 [gray] return periods) from different PSHAs (bars, 15th–85th fractiles; crosses, medians; and squares, means), the uncertainty metric $100\log(PSA_{85}/PSA_{15})$ and the ratio of the uncertainty metrics for PSA(1 s) and PGA. The studies are split vertically to help comparisons discussed in the text. Estimates of the mean PSAs(1 s) are not available for Rome (INGV), Messina (INGV), Briançon (BRGM), and Lourdes (ISARD), which also does not provide ground-motion estimates for a return period of 2475 years; the expected PSA(1 s) for an AFE of 1/475 for the four Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites are not available for the considered fractiles.

knowledge in the regional-scale source zonation should be considered. For the case of the SSHAC 3 and 4 studies (PEGASOS, Yucca Mountain and Thyspunt), which show wide uncertainty ranges in Figure 3, the hazard fractiles would have shown an even wider spread if the extensive data collection and analyses (e.g., geologic investigation of faults, investigations of historical seismicity, and shear-wave velocity measurements) conducted within these studies had not been made.

In the case of GMPEs, site-specific studies (e.g., Bommer *et al.*, 2014) sometimes include additional logic-tree branches to scale up or down a backbone GMPE to increase the spread in the predicted ground motions (Bommer, 2012). This is done because it is believed that the sampling of possible ground motions in the region is sparse, and hence the average stress drop, for example, is poorly known. This is not often done for hazard assessments of large zones (an exception is the U.S. National Hazard Maps). In the Global Earthquake Model's (GEM) Global GMPEs project there were only a few GMPEs selected per tectonic regime (Stewart *et al.*, 2014) despite the large uncertainty in predicting ground motions for all sites globally. It could have been better to increase the spread in the logic tree by, for example, scaling up or down certain models, although this scaling is currently difficult to calibrate, particularly for a project with a global scope such as GEM.

Hazard assessments over large geographical regions (e.g., SHARE) require a harmonized earthquake catalog, which often means that its lower magnitude limit is higher than for a national or site-specific study because of limited resources to compile, harmonize, and analyze large catalogs (the number of earthquakes increases roughly by ten times for every decrease by one unit in the minimum magnitude). Consequently, the catalog compiled by SHARE only considers events with $M_w > 3.5$, which for areas of low seismicity, in particular, means that the assessment of the Gutenberg–Richter parameters is associated with lower precision (but not necessarily lower accuracy; Frank Scherbaum, written comm., 2014) than for national or site-specific studies with catalogs that start at smaller magnitudes.

Recent PSHAs appear to have well characterized the center and often the body, because both can be more readily quantified using available models and data, but the range does not appear to be fully accounted for. This is because its assessment requires a quantification of what we do not know rather than just what we do. For areas with limited data and knowledge (high uncertainty), the body and range dominate the logic tree, but these are more difficult to capture (and potentially more subjective), whereas for areas for which data are abundant the center is the most important. As an example of this, the ground-motion logic trees used in SHARE (Delavaud *et al.*, 2012) for active shallow crustal areas has four models, two of which are assigned a total weight of 0.7, whereas the logic tree for stable continental crust has five models all equally weighted. As mentioned above, this demonstrates that the SHARE ground-motion expert group felt that the uncertainty in the estimation of ground motions in stable continental crust is higher than in active areas, which is understandable given the lack of strong-motion data from stable areas and the relative abundance in active zones. Rather than simply considering the number and weights of the selected GMPEs when comparing uncertainties in ground-motion logic trees it would be better to measure the distribution of predicted ground motions using, for example, the composite ground-motion model viewpoint (Scherbaum *et al.*, 2005). For example, five GMPEs may be selected in one study and two in another, which would give the impression that the first study accounted for higher ground-motion uncertainty than the second, but if the five GMPEs all predicted similar PGAs, whereas the two from the other study predicted widely different motions, then the second study would actually model a higher uncertainty.

To more objectively capture uncertainty, the construction of logic trees for PSHA could benefit from the application of innovative procedures to guide expert judgment. A purpose of such methods would be to consolidate the assessments of a pool of experts. To merge all the expert judgments, which occurs in a SSHAC Level 4 study, could possibly lead to disproportionate spread in the integrated answer and, potentially, to some dubious results (Aspinall, 2010). If a group of experts is gathered to get a synthetized position, social influence could be magnified, for example, the expert assessments could converge to the judgment of the most renowned participant (Curtis, 2012), although in a properly run SSHAC 3 or 4 study this should not happen if the NUREG-2117 guidance is followed (USNRC, 2012). Runge *et al.* (2013) present an approach to more rigorously assess expert weights for GMPEs within logic trees for PSHA. The procedure is based on asking an expert a sequence of questions on his/her relative confidence in one GMPE being more appropriate than another. A similar method could be developed to assign weights to other parts of the logic tree, for example, those concerning source activity rates.

A standard step in SSHAC 3 and 4 studies is a sensitivity study examining the influence of the different uncertainties on the hazard results. Such studies, often presented in the form of tornado diagrams (e.g., Porter *et al.*, 2012), allow the most important uncertainties to be identified. Based on this information, additional data collection or analysis may be undertaken to reduce this lack of knowledge.

As a closing remark, we would like to encourage the publication of the uncertainties in hazard studies because this makes studies more transparent and defensible to the wider community, and it would also help guide efforts to reduce the uncertainties. In addition, sensitivity studies on the influence of the different uncertainties in the hazard results should be considered as a standard requirement of all seismic-hazard assessments. It should be the goal of all seismic-hazard studies to reduce the uncertainties as far as possible through collecting and analyzing data and subsequently to characterize the remaining unknowns through the development of an appropriate logic tree.

ACKNOWLEDGMENTS

This study was conducted within a Bureau de Recherches Géologiques et Minières (BRGM) Development Project. We thank hazard analysts and their sponsors for freely publishing the uncertainties in hazard results, without which this study would have been impossible. Julian Bommer kindly provided the hazard results for Thyspunt. In addition, we thank Hilmar Bungum, Julian Bommer, Frank Scherbaum, and Céline Beauval for their detailed and insightful comments on an earlier version of this article, which led to significant improvements. Finally, we thank editors Zhigang Peng and Eric Thompson and two anonymous reviewers for their comments on a previous version of this article.

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