DT# 47748 QA:NA 5/10/06

LESSONS LEARNED – THE USE OF FORMAL EXPERT ELICITATION IN PROBABILISTIC SEISMIC HAZARD ANALYSIS

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SUMMARY

Probabilistic seismic hazard analyses provide the opportunity, indeed the requirement, to quantify the uncertainties in important inputs to the analysis. The locations of future earthquakes, their recurrence rates and maximum size, and the ground motions that will result at a site of interest are all quantities that require careful consideration because they are uncertain. The earliest PSHA models [Cornell, 1968] provided solely for the randomness or aleatory variability in these quantities. The most sophisticated seismic hazard models today, which include quantified uncertainties, are merely more realistic representations of this basic aleatory model. All attempts to quantify uncertainties require expert judgment. Further, all uncertainty models should endeavor to consider the range of views of the larger technical community at the time the hazard analysis is conducted. In some cases, especially for large projects under regulatory review, formal structured methods for eliciting expert judgments have been employed. Experience has shown that certain key elements are required for these assessments to be successful, including: 1) experts should be trained in probability theory, uncertainty quantification, and ways to avoid common cognitive biases; 2) comprehensive and user-friendly databases should be provided to the experts; 3) experts should be required to evaluate all potentially credible hypotheses; 4) workshops and other interactions among the experts and proponents of published viewpoints should be encouraged; 5) elicitations are best conducted in individual interview sessions; 6) feedback should be provided to the experts to give them insight into the significance of alternative assessments to the hazard results; and 7) complete documentation should include the technical basis for all assessments. Case histories are given from seismic hazard analyses in Europe, western North America, and the stable continental region of the United States.

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1. INTRODUCTION

Quantification of uncertainties is an essential component of probabilistic hazard assessments. For probabilistic seismic hazard analyzes (PSHA) the locations of future earthquakes, their recurrence rates and maximum size, and the ground motions that will result at a site of interest are all quantities that require careful consideration because they are uncertain. The earliest PSHA model developed by Cornell [1968] provided for a single interpretation of seismic source geometries and characteristics, a single ground motion attenuation relationship, and resulted in a single seismic hazard curve. With time, we have come to recognize more fully the uncertainties in alternative models to explain seismic source and ground motion predictions, and uncertainties in the parameter values for those models. The quantification and incorporation of those uncertainties leads to a probability distribution defined by a family of hazard curves.

Expert elicitation is a formal, structured and documented process for identifying and quantifying uncertainties. It has a goal of representing the views of the informed scientific community. Expert judgment is used in any technical assessment, but often is implicit and undocumented. Formal expert elicitation explicitly includes judgments of multiple experts to represent the range of scientific views and documents the reasoning on which the judgments are based. Expert elicitation provides a means for properly and fully incorporating the uncertainties represented by diverse technical interpretations, as well as providing transparency through the complete documentation of the process and results. For these reasons, expert elicitation has gained increasing acceptance within the regulatory community for dealing with seismic hazard analyses for critical facilities.

Two major PSHA projects conducted in the mid-1980's represent significant landmarks in the development of formal expert elicitation and the systematic, explicit incorporation of the diversity of expert interpretations. Conducted by the Lawrence Livermore National Laboratory (LLNL) [Bernreuter et al., 1989] and the Electric Power Research Institute (EPRI) [EPRI, 1989], both projects were focused on developing seismic hazard curves for the large region of the central and eastern United States to develop a basis for assessing hazard at the 69 nuclear power plant sites east of the Rocky Mountains. Although the two studies each utilized large numbers of technical experts and were similar in many technical and procedural ways, the results of the studies – specifically, the mean seismic hazard curves – differed significantly for most sites in the eastern U.S.

Based on the differing results obtained from the two large PSHA studies conducted by EPRI and LLNL, it eventually became clear that the process used to conduct an expert elicitation was equally as important as the technical content of the interpretations. Accordingly, a methodology for conducting a PSHA using expert elicitation was developed in a project jointly sponsored by the U.S. Department of Energy (DOE), the U.S. Nuclear Regulatory Commission (NRC) and EPRI. Known as the "SSHAC" study, after the Senior Seismic Hazard Analysis Committee who conducted the project, the final guidelines resulting from the study were published in 1997 in U.S. Nuclear Regulatory Commission's NUREG/CR-6372 [SSHAC, 1997], and have been used subsequently for large studies, including case studies described in this paper. The descriptions in this paper of the key elements required for successful probabilistic hazard assessments are based on both the SSHAC guidance and the experience of the authors, who participated in developing and implementing the expert elicitation processes in the case studies described.

2. A BRIEF OVERVIEW OF THE SSHAC GUIDANCE

The objective of the SSHAC project was to provide methodological guidance on how to perform a PSHA, with particular emphasis on approaches to dealing with uncertainties. PSHA is an analytical methodology that estimates the likelihood that various levels of earthquake-caused ground motion will be exceeded during a given future time period for a given location. Such estimates, however, can be attained only with significant uncertainty as there are major gaps in our understanding of the mechanisms that cause earthquakes and the effects of earthquakes at specific locations. Significantly, there are often wide differences of legitimate scientific opinion on key inputs into a PSHA. The SSHAC probabilistic formulation for dealing with seismic hazards specifically embeds uncertainties in the core of the methodology. Two different classes of uncertainties are defined: epistemic and aleatory. Epistemic uncertainties are lack-of-knowledge uncertainties that occur at the present time but in principle are reducible through further research and additional data collection. The randomness in a physical process is called aleatory uncertainty (often termed aleatory variability); this randomness cannot be known in detail nor reduced. For example, recurrence rates for various magnitude earthquakes reflect the degree of epistemic uncertainty, but the exact location and magnitude of a future large-magnitude earthquake is an aleatory uncertainty.

The SSHAC guidance provides advice for four "study levels," which are differentiated as a function of the importance, complexity, diversity of views and contentiousness of an issue. The level of study required for a PSHA is related to factors such as the regulatory framework, the resources (money and time) available to conduct the study, perceptions of the importance of the project, and scheduling constraints. Regardless of the level of study, the goal is the same: to provide a representation of the informed scientific community's view of the important components and issues, and, finally, the seismic hazard. "Informed" in this sense assumes, hypothetically perhaps, that the community of experts was provided with the same data and level of interaction as that of the experts. In more modest studies (SSHAC Study Levels 1 – 3), a Technical Integrator (TI) utilizes interpretations found in the published literature supplemented by conversations or workshops with individuals conducting relevant research. The TI then evaluates the viability and credibility of various hypotheses with an objective of capturing the range of alternative interpretations and their uncertainties to provide an overall assessment that represents the informed scientific community's view of the subject (hazard). In these studies, the TI is the "owner" of the seismic hazard results. When resources and sophistication are high – typically for issues that are highly contentious, significant to hazard, and highly complex – the assessments needed for a PSHA can be made by multiple experts (called "evaluator experts"), who evaluate alternative models and parameters in a process that involves a series of workshops and individual elicitation meetings. This is called SSHAC Study Level 4 and is the subject of this paper. Consistent with the SSHAC guidance, a Technical Facilitator/Integrator (TFI; this can be a single individual or a team) is responsible for facilitating the interactions among the experts and integrating the judgments of the expert panel to develop the composite distribution that reflects the informed technical community. For SSHAC Study Level 4, the "ownership" of the seismic hazard results is shared between the TFI and the experts.

3. PSHA CASE STUDIES

Expert elicitation has been used to conduct PSHAs over the past twenty years in a wide variety of seismotectonic environments. Although sharing some common attributes, each study is unique in its implementation. Further, each study has lead to an evolution of methods and approaches that have been successful. The salient elements of some of these studies are summarized in this section, followed by a discussion of the key elements of the lessons learned from expert elicitations for PSHA.

The central and eastern United States is characterized generally by a 200-year historical record of low to moderate levels of seismicity and virtually no geologic information on recent faulting, punctuated by infrequent large magnitude earthquakes (e.g., the M~7 to 8 New Madrid earthquakes of 1811 and 1812; the M~7 Charleston earthquake of 1886). These conditions present significant challenges for assessments of seismic hazard because of the considerable uncertainties associated with key inputs. The large EPRI project [EPRI, 1986, 1989], in which seismic hazard was assessed for 69 nuclear power plant sites in the central and eastern U.S., was important for developing methodologies and procedures on the conduct of a formal expert elicitation utilizing multiple experts. This study focused on developing a methodology for PSHA that included a highly structured procedure for interpreting the tectonics of an area to define the seismic source zones and utilized statistical analyses of a historical earthquake catalog to develop earthquake size and rate parameters. An initial part of the study involved compilations of comprehensive geophysical and seismological databases. These databases were then distributed to six earth science teams, composed of individuals representing the fields of seismology, geology, and geophysics. The teams independently developed seismic source zones and associated seismicity parameters for the area of focus, explicitly accounting for uncertainties in the evaluations using alternative, weighted interpretations for individual zones or features. To implement the methodology numerous and extensive workshops and meetings with project participants were convened, and the methodology team worked directly with the participants to elicit their scientific judgments and to format those judgments to be suitable for hazard calculations.

Considerable uncertainty exists regarding the earthquake potential of the Cascadia subduction zone in the Pacific Northwest of the United States due to the historically aseismic nature of the interface between the Juan de Fuca and North American plates (see Figure 1). A PSHA involving expert elicitation of multiple experts was conducted in this region for the Satsop nuclear power plant site in western Washington state [Coppersmith and Youngs, 1990]. To develop a complete seismic source characterization spanning the range of interpretations regarding the earthquake potential of Cascadia, a group of 14 experts was selected based on their experience in the region as well as convergent margins worldwide. These experts assessed source characteristics, including

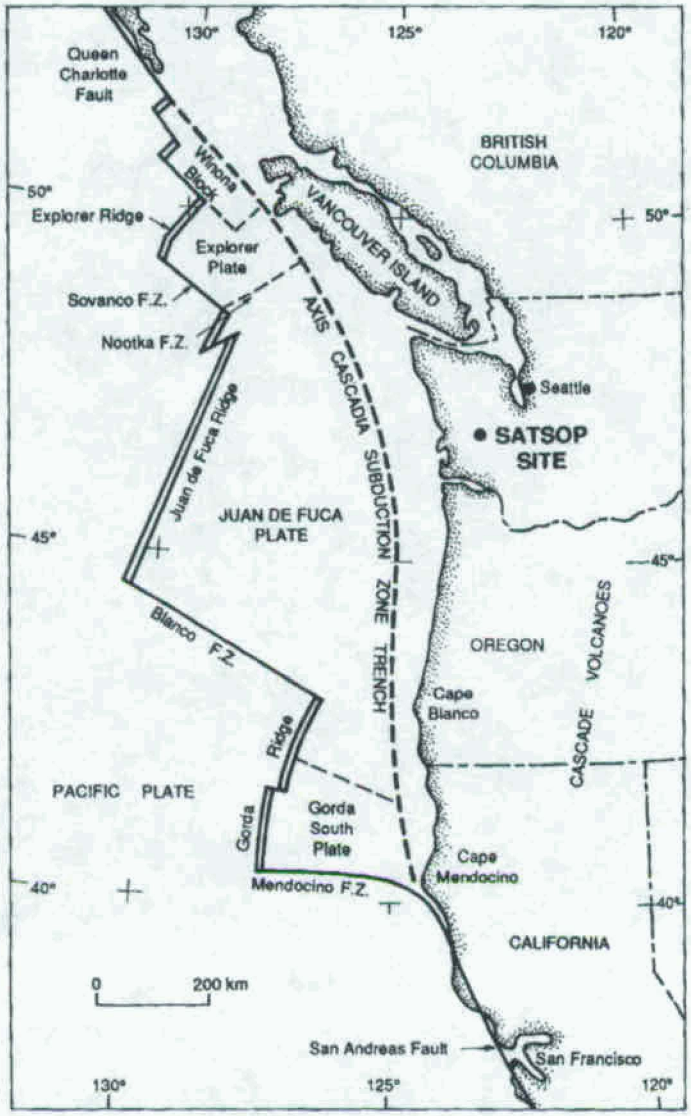

Figure 1: Tectonic setting of Cascadia subduction zone and location of Satsop site [Coppersmith and Youngs, 1990]

subduction-zone geometry; potential interplate, intraslab, and crustal seismic sources; probability that each potential source is seismogenic; expected locations and dimensions of rupture; maximum earthquake magnitude; earthquake recurrence models; geologic recurrence intervals; plate convergence rate; and seismic coupling. Important sources of uncertainty included alternative conceptual models regarding the nature and rate of seismogenic convergence across a plate interface that has shown no historical evidence of moderate to large earthquakes. At the time of the elicitation, new geologic evidence of episodic coastal subsidence had become available, which was interpreted by some as evidence for prehistorical seismogenic coupling along the plate interface. The results of the seismic hazard analysis were submitted by the electric utility to the NRC as part of licensing activities.

Assessing hazard for a nuclear waste repository presents unique technical challenges and significant uncertainties. Probabilistic seismic hazard analyses were conducted to estimate both ground motion and fault displacement hazards at the proposed geologic repository for spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nevada in the United States [CRWMS M&O, 1998; Stepp et al., 2001]. The methodology followed in the three-year study was consistent with SSHAC recommendations for a Level 4 PSHA as well as guidelines established by the NRC for expert elicitations [Kotra, et al., 1996]. Six teams of three experts performed the seismic source and fault displacement evaluations, and seven individual experts provided ground motion evaluations. State-of-the-practice expert elicitation processes were implemented including dissemination of a common database, structured workshops, field trips to visit sites of paleoseismic investigations, participation of "resource" experts to share data gathered at analogue locations, and open exchanges about alternative conceptual models. Site-specific ground motions were characterized for a given site condition in

order to allow for subsequent use in site response studies. The major emphasis of the study was on quantification of epistemic uncertainty. The results of the PSHA are being used to establish seismic design bases for surface facilities and to evaluate the performance of the repository during the regulatory period following closure (10,000 to 1,000,000 years). The NRC, other oversight groups, and participatory peer reviewers were closely involved in the review of the project throughout its course.

Although Switzerland is generally considered to have a low to moderate level of seismicity, the Swiss Federal Nuclear Safety Inspectorate (HSK) identified seismic hazard as a potentially significant contributor to the risk at four nuclear power plant sites (Mühleberg, Gösgen, Beznau, and Leibstadt). The HSK identified the need to update the seismic hazard analyses at the sites and requested that the Swiss electric utilities conduct a PSHA following SSHAC Level 4 expert elicitation methodologies. Under the direction of National Cooperative for the Disposal of Radioactive Waste (NAGRA), a PSHA was conducted for Swiss nuclear power plant sites. The study has since become known under the name of the 'PEGASOS Project' (Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-StandOrte in der Schweiz) [NAGRA, 2004]. The objective of the project was to assess the relevant earthquake-induced ground motions at the building foundation levels of the four sites, which would be used subsequently for probabilistic safety analyses. A full-scope expert elicitation process was used, including dissemination of a comprehensive database, multiple workshops for identification and discussion of alternative models and interpretations, elicitation interviews, feedback to provide the experts with the implications of their preliminary assessments, and full documentation of the assessments. The study brought together experts from all over Europe. Four teams consisting of three experts conducted the seismic source characterization, five individual experts addressed ground motion characterization, and four experts characterized the site effects. The entire study was subject to participatory peer review by an HSK Review Team, which monitored and provided feedback on the procedural and technical aspects of the project, as well as provided a review of the final report.

4. KEY ELEMENTS OF FORMAL EXPERT ELICITATION

Key process elements of importance for formal expert elicitations have been identified by the authors, based on their experience in each of the PSHA case studies described above, as well as in hazard assessments that utilized formal expert elicitations for other technical issues (e.g., a probabilistic volcanic hazard analysis for the proposed nuclear waste repository at Yucca Mountain, Nevada).

4.1 Experts should be trained in probability theory, uncertainty quantification, and ways to avoid common cognitive biases

Many experts who have knowledge relevant to seismic hazard assessments are not necessarily experienced at developing probability distributions that reflect their state of knowledge. Accordingly, training in the language of probability and quantifying uncertainties (including recognizing the distinction between aleatory variability and epistemic uncertainty) should be provided. Possible biases may also unknowingly be expressed by the experts unless they have been educated to recognize and minimize such biases. These include cognitive biases such as overconfidence, anchoring and the reporting of narrower-than-justified probability distributions. Motivational biases may occur if an expert is a strong proponent of a particular alternative. The TFI must be aware of this possibility and attempt to eliminate such bias by stressing the importance of having each expert act as an evaluator who represents the larger technical community.

Typically, training of the experts in these areas occurs during the first workshop on the project and is followed by reminders and facilitation throughout the project. Support from the TFI may need to be provided to assist earth scientists with statistical and probabilistic calculations, as long as the expert is fundamentally responsible for the expression of uncertainty. Usually, a careful expert selection process will mitigate the potential for motivational bias in the assessments. Simple awareness of potential cognitive biases and reminders throughout the project are typically adequate for mitigating this source of bias.

4.2 Comprehensive and user-friendly databases should be provided to the experts

From the time of the first large PSHA expert elicitations twenty years ago, there has been an explosion in tools to compile, display, and evaluate complex geologic and geophysical datasets. Further, the range of information that is used to characterize seismic sources and ground motions has expanded. It is important that all experts on a

panel have equal access to data that are most pertinent to the assessments that need to be made. Relevant data, as defined by the experts themselves, should be provided to all experts in the form of a comprehensive and uniform database. Any processing of "raw" data that is made at the request of one expert should also be provided to other experts who wish to review the processed data. The effort to compile and disseminate the data can be significant. For example, in the PEGASOS project, a dedicated database contractor was responsible for compiling geologic maps, geophysical data, seismotectonic data, etc., in various formats specified by the experts. In many cases, multiple GIS layers were combined to form maps for use by the experts (see Figure 2). Likewise, on the Yucca Mountain PSHA, a wealth of site-specific data gathered over many years were distributed to the experts, including seismicity catalogs, paleoseismic trench logs, Quaternary geologic maps, and other data.

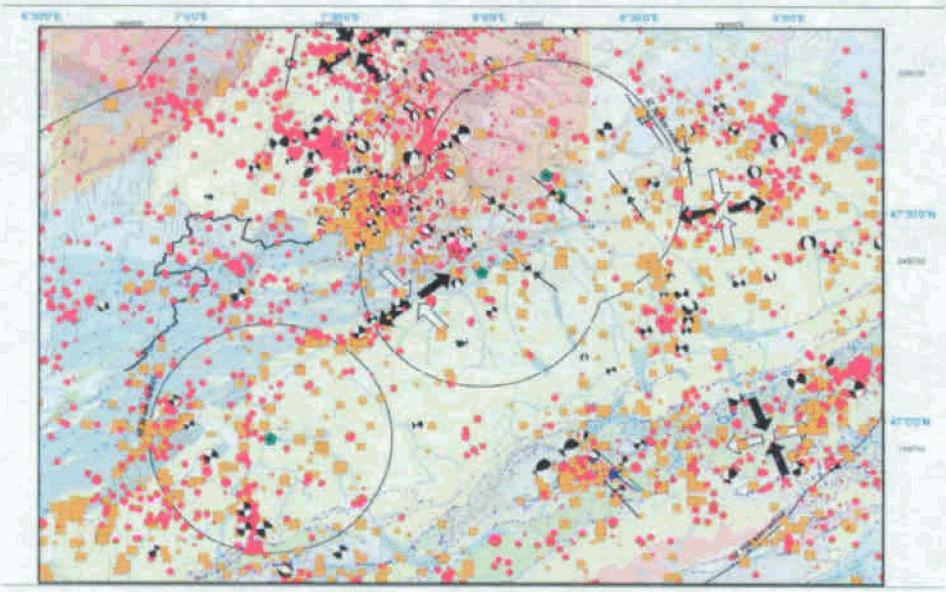

Figure 2: Example of a map developed for the PEGASOS seismic source characterization experts. GIS layers include seismicity (instrumental shown by red circles; historical by yellow boxes), regional stress orientations (large arrows), focal mechanisms, and regional geology. The four nuclear power plant sites are marked as green pentagons. Circular black lines indicate 25-km distance ranges from the sites. [NAGRA, 2004]

4.3 Experts should be required to evaluate all potentially credible hypotheses

For a formal expert elicitation, members of an expert panel are specifically required to be "evaluators" – that is, they are expected to evaluate all potential hypotheses and bases of inputs from available information. This role is distinctly different from the "proponent" role, which is the more common role for scientists. Proponents advocate particular hypotheses and points of view, based on their interpretation of the data. However, "evaluators" are charged with considering alternative interpretations in addition to those that they may advocate, and to arrive at their representation of the community distribution. As such, experts should assign a relative weight or credibility—including zero weight to hypotheses they consider to be non-credible—to alternative hypotheses, recognizing that these are current representations of knowledge and that no single hypothesis is likely to be the "ultimate truth." Examples of alternative assessments of regional seismic sources made by the four PEGASOS seismic source characterization expert teams is given in Figure 3.

A common tool for expressing the relative credibility of alternative conceptual models is a logic tree. The branches of the tree represent alternative credible models or hypotheses and the weights on the branches indicate the relative credibility of the alternatives. Alternatives that are judged by the expert to be non-credible should not be included as branches in the logic tree. For example, the experts in the Satsop PSHA evaluated alternative hypotheses regarding the seismogenic potential of the plate interface of the Cascadia subduction zone. These were given as branches of a logic tree, expressed as the probability that the plate interface is seismogenic (defined as capable of generating a M>5 earthquake). The aggregate distribution across all experts on the panel is shown in Figure 4.

4.4 Workshops and other interactions among the experts and proponents of published viewpoints should be encouraged

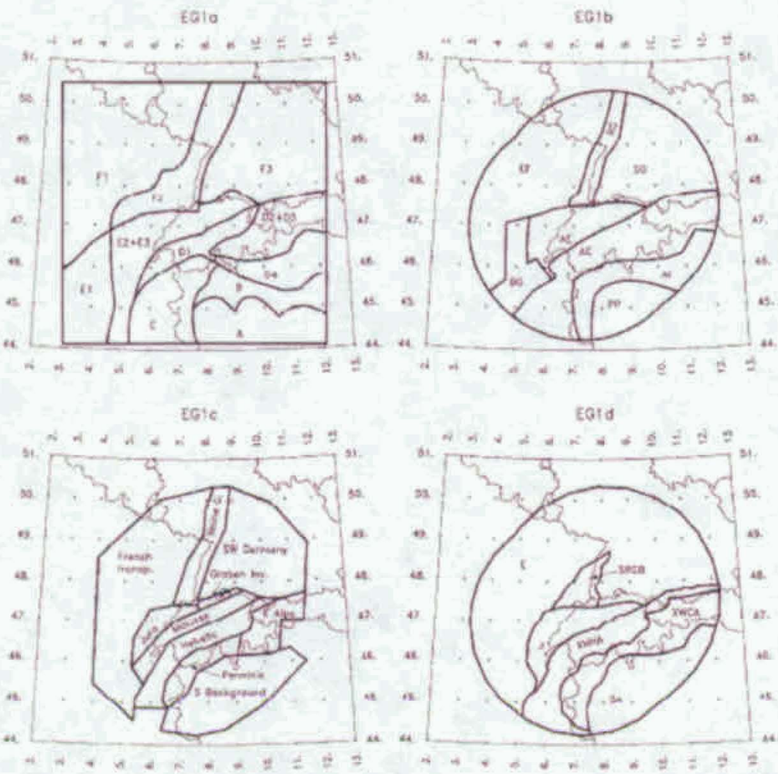

Figure 3: Comparison of the primary seismotectonic regions developed by the four seismic source characterization expert teams [NAGRA, 2004]

Interaction among experts, particularly in facilitated workshops, is a fundamentally important aspect of an expert elicitation process. This is a natural extension of how earth scientists work together to formulate their ideas – typically they rely on common data sets and interact frequently as part of their professional activities. In workshops, the technical issues of greatest importance to PSHA can be identified and the data needed to address

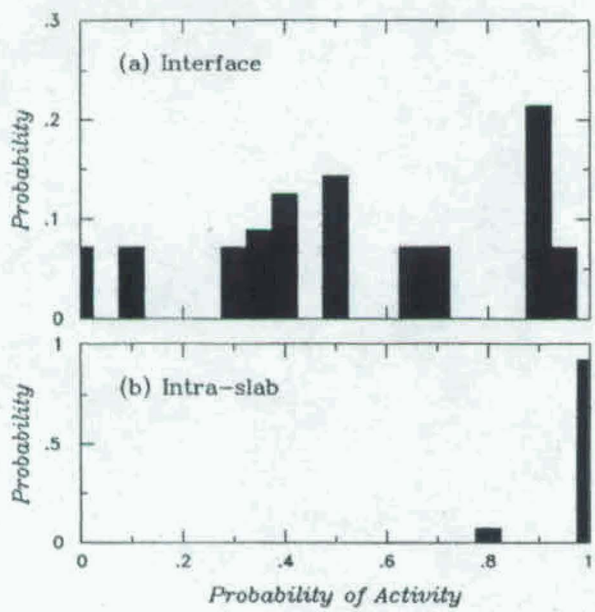

Figure 4: Aggregate distribution of 14 experts' assessments of the probability of activity for (a) the plate interface and (b) the intra-slab source [Coppersmith and Youngs, 1990]

these issues specified. In addition, the methods and procedures available to characterize seismic sources and ground motions can be discussed among the experts to ensure that all are aware of the tools that are available to them. Presentations on available data by resource experts (who themselves are not elicited) may be made and, importantly, proponents of alternative viewpoints can provide their arguments to the expert panel. Such workshops need to be carefully facilitated by the TFI to ensure that the viewpoints are presented and discussed in a balanced manner. Review, technical challenge, and defense of hypotheses and interpretations are important objectives for a workshop. In studies evaluated by SSHAC it was found that unless experts interact and discuss alternative technical interpretations, unintentional disagreements arose because of exposure to different data sets or a lack of understanding of the basis for alternative positions.

4.5 Elicitations are best conducted in individual interview sessions

After the experts have received training in elicitation procedures (see Section 4.1) and after they have been exposed to a full range of data and interpretations in workshops, it is recommended that individual experts be elicited in small interview sessions. The interview should be conducted by the TFI (a TFI team may consist of a technical expert and an elicitation expert with experience in subjective probability assessment; others who can provide specialized knowledge – e.g., of modeling – may also attend the interview sessions). Every effort should be made to put the expert at ease in the elicitation, to maintain flexibility in the questioning and to allow the expert to express his/her interpretations and uncertainties in his/her own way. Commonly, the initial parts of the interview deal with the overall structure of the assessment and the general evaluations of models. From there, more detailed assessments of model specifics and parameter values can be made. It is important to encourage the expert to consider the technical merits of all hypotheses and assess the relative credibility of each. The expert should represent both his/her own range of knowledge and uncertainty as well as provide an assessment of the diversity of views within the larger informed technical community.

In those cases where teams of experts are used (e.g., the EPRI and PEGASOS seismic source experts), each team should be elicited in an interview session. The team as a unit is responsible for developing a consensus interpretation and uncertainty distribution that captures the diversity of their individual views on specific issues. Of course, some members of a team may defer to others who are more familiar with a particular issue on the team, but this is expected and is a primary benefit of creating teams. Developing a range of assessments that effectively captures the thinking of the team as a whole is the objective.

4.6 Feedback should be provided to the experts to give them insight into the significance of alternative assessments to the hazard results

Experience has shown that two rounds of elicitation interviews, separated by feedback, provide an adequate basis for the final expert assessments. After the first interview, the preliminary expert assessments can be used in seismic hazard calculations and sensitivity analyses. They can also be discussed by all expert panel members in a workshop setting. The purpose is to allow each expert to see the preliminary interpretations made by the other experts, to understand the implications that various assessments have to the calculated seismic hazard results and to identify those aspects of their assessments that are most important to the hazard results. This will allow each expert to focus on the important elements of their assessment during the second round. Possible problems or inconsistencies in the first round of assessments can also be identified using this approach. For example, an expert's interpretations of recurrence models and parameter uncertainties might predict that the rate of seismicity (e.g., the number of $M>6$ earthquakes per year) is significantly higher – or lower – than the observed rate from historical seismicity. Correlations between some parameter values, as in the assessment of recurrence parameters, can lead to some unintended combinations and resulting rates, which need to be clearly identified and discussed.

A feedback workshop provides each expert the opportunity to discuss interpretations and evaluations with other experts while focusing on the technical bases for the assessments. Constructive scientific debate, while seeking areas of consensus and resolution of misunderstandings or identification of different assumptions, is a valuable component of a feedback workshop. Examples of the feedback provided to the experts on the PEGASOS project are given in Figures 5 and 6.

4.7 Complete documentation should include the technical basis for all assessments

Formal expert elicitations are typically conducted when there is a high level of regulatory and/or public scrutiny. Accordingly, the inputs and results of the hazard assessment will be extensively reviewed, so complete documentation of the elicitation process and the technical bases for all judgments is essential. The elicitation interviews in particular must be carefully documented, as well as the proceedings of the workshops, the methodologies for expert elicitation, and the hazard results and sensitivity analyses. Both the interpretations and uncertainties expressed by the experts and the technical bases for the interpretations must be recorded. It is not sufficient for the documentation to merely record the expert assessments; the technical reasons for the assessments should also be included. Experience has shown that it works well to have the TFI record the elicitation in writing and subsequently provide this text to the expert for his/her use in developing a comprehensive elicitation summary. An expert elicitation for a PSHA occurs at a particular point in time and it is important to capture in the documentation the state of knowledge at that time. This allows reviewers—including those who may examine the study many years hence—a basis for understanding the data, models, and thought processes that drove the assessments.

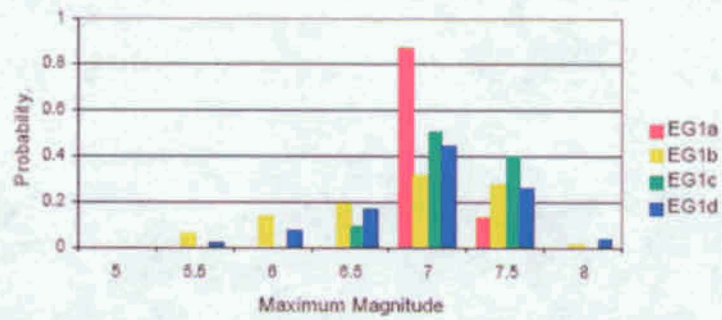

Figure 5: Comparison of maximum magnitude distributions developed by the four seismic source characterization expert teams for the Basel region [NAGRA, 2004]

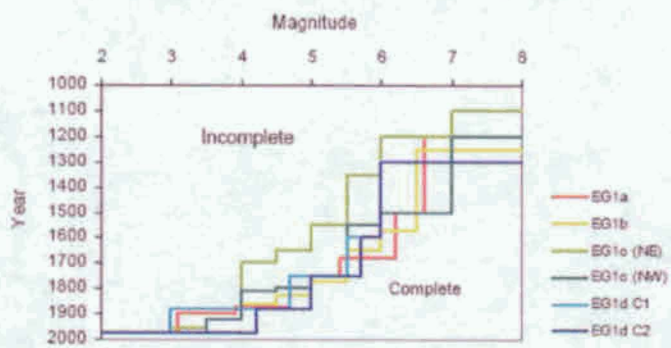

Figure 6: Comparison of earthquake catalogue completeness estimates for Northern Switzerland developed by the four seismic source characterization expert teams [NAGRA, 2004]

5. CONCLUSIONS

Over the past two decades, formal expert elicitation has emerged as an effective tool for capturing the important uncertainties associated with PSHA. Because of the resources required to carry out these projects, they have been reserved for projects under considerable regulatory scrutiny where uncertainties are considerable and significant. The conduct of several elicitations in a variety of tectonic and regulatory environments has provided insights into the key *process* elements that will help lead to successful projects. These elements relate to the training of the experts, the data and information provided to the experts, the manner in which experts are allowed and encouraged to interact, the feedback that is provided to inform their final assessments, and the documentation that is needed to allow for a review by others. The case studies discussed in this paper are from PSHA, but it is important to note that expert elicitation has also been used to characterize other natural hazards, such as volcanic hazard.

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