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Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts

Appendices

Prepared by
Senior Seismic Hazard Analysis Committee (SSHAC)
R. J. Budnitz (Chairman), G. Apostolakis, D. M. Boore, L. S. Cluff, K. J. Coppersmith, C. A. Cornell, P. A. Morris

Lawrence Livermore National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission
U.S. Department of Energy
Electric Power Research Institute

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ABSTRACT

Probabilistic Seismic Hazard Analysis (PSHA) is a methodology that estimates the likelihood that various levels of earthquake-caused ground motion will be exceeded at a given location in a given future time period. Due to large uncertainties in all the geosciences data and in their modeling, multiple model interpretations are often possible. This leads to disagreement among experts, which in the past has led to disagreement on the selection of ground motion for design at a given site.

In order to review the present state-of-the-art and improve on the overall stability of the PSHA process, the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy (DOE), and the Electric Power Research Institute (EPRI) co-sponsored a project to provide methodological guidance on how to perform a PSHA.

The project has been carried out by a seven-member Senior Seismic Hazard Analysis Committee (SSHAC) supported by a large number other experts.

The SSHAC reviewed past studies, including the Lawrence Livermore National Laboratory and the EPRI landmark PSHA studies of the 1980's and examined ways to improve on the present state-of-the-art.

The Committee's most important conclusion is that differences in PSHA results are due to procedural rather than technical differences. Thus, in addition to providing a detailed documentation on state-of-the-art elements of a PSHA, this report provides a series of procedural recommendations.

The role of experts is analyzed in detail. Two entities are formally defined—the Technical Integrator (TI) and the Technical Facilitator Integrator (TFI)—to account for the various levels of complexity in the technical issues and different levels of efforts needed in a given study.

Disclaimer

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SPONSOR'S PERSPECTIVE

Probabilistic Seismic Hazard Analysis (PSHA) has become an increasingly important tool for aiding design and decision making at all levels in both the private sector and government. The level of sophistication applied to PSHA has increased dramatically over the past 27 years since the technique was first introduced in the literature. As more and more people and groups implemented and used PSHA in different forms, it became clear to the sponsors of the Senior Seismic Hazard Analysis Committee (SSHAC) report that the time had arrived to establish more uniform and up-to-date guidelines for future PSHA studies.

The need for such guidelines is threefold:

1. As the situation stands today, it is often the case that multiple PSHA studies are available for the same geographic region. However, due to differences in implementation, results of these studies often differ by substantial amounts for the same physical location. Further, because of the amount of technical information and complex combination of techniques utilized, it is not always simple to determine the source of these differences and which answer should be used.

2. Potential sponsors of a PSHA study are faced with the difficulty of determining the appropriate level of a proposed PSHA to ensure stable results that meet the sponsor's needs.

3. The cost to perform a PSHA study can be quite large. The sponsors of this report expected that a suitable set of guidelines could be developed to assist the potential user in choosing the appropriate level of analysis consistent with the overall goals and resources available. Given the need to conserve resources, issuing such guidelines to optimize future PSHA studies in accordance with the sponsor's need takes on added importance.

Overall, the sponsors saw a need for more stability in the PSHA process, both for nuclear and non-nuclear applications, in dealing with future needs for using PSHA to establish seismic hazard levels throughout the United States.

Comparative evaluations have shown that the differences between PSHA studies are often not technical, but due to the information gathering and assembly process used in the study. The integration of the different types of information required in a PSHA (geologic, seismotectonic, probability and statistics, information theory, and decision making) presents significant inter-disciplinary challenges and requires a project structure and process that assure proper integration. The skills required to be a good integrator and evaluator are not necessarily the same skills needed to be a good scientist. Our observation is that although many PSHA practitioners are trained experts in one or more fields, the PSHA divergence issue can partly be explained by a lack of integration and evaluation skills so important to the PSHA product. We believe this is true at all levels of PSHA, and these skill requirements may be most acute at the simpler levels of seismic hazard analysis not associated with critical facility assessments where typically the PSHA analysts must complete their work.

This report addresses the integration and evaluation issues that should be considered and focuses on the process of integration required in a PSHA. The SSHAC's investigations have led to the conclusion that technical facilitation and integration is a necessary component for the proper implementation of a PSHA in some instances. In most of these cases, it is anticipated that following the approaches outlined in the report will bring about more consistent interpretations that are supported by the data or bulk of scientific thought. However, if an outlier interpretation persists, it is our firm belief—in agreement with the SSHAC—that the approaches outlined will allow for essential downweighting of that interpretation. This is preferable to the stiff adherence to an equal weighting scheme, which can result in the final seismic hazard being driven by a single outlier input.

The issues that are raised and discussed in the SSHAC report, especially but not exclusively the process issues, apply in varying degrees to any PSHA project, and should be at least considered by sponsors and analysts before undertaking a PSHA. While the primary focus of SSHAC was on siting critical facilities, it is believed that all PSHA projects should attempt to achieve several primary objectives: 1) proper and full incorporation of uncertainties, 2) inclusion of the range of diverse technical interpretations that are supported by available data, 3) consideration of site- specific knowledge and data sets, 4) complete documentation of the process and results, 5) clear responsibility for the conduct of the study, and 6) proper peer review. Regardless of the level of the study, the goal in the various approaches 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.

For these reasons, the sponsors believe that the SSHAC report is complete in terms of outlining the process a principal investigator should follow to complete a PSHA. Indeed, the report provides for technical flexibility where such flexibility is needed and, at the same time, encourages standardization of technical approaches and procedures as much as is feasible.

The future utility of PSHA in decision making depends to a large degree on our ability to implement the process in a meaningful and cost-effective way. Development of the SSHAC guidelines was planned with this goal in mind.

EXECUTIVE SUMMARY

Probabilistic seismic hazard analysis (PSHA) is a methodology that estimates the likelihood that various levels of earthquake-caused ground motions will be exceeded at a given location in a given future time period. The results of such an analysis are expressed as estimated probabilities per year or estimated annual frequencies. The objective of this project has been to provide methodological guidance on how to perform a PSHA. The project, co-sponsored by the U.S. Nuclear Regulatory Commission, the U.S. Department of Energy, and the Electric Power Research Institute, has been carried out by a seven-member Senior Seismic Hazard Analysis Committee (SSHAC), supported by a large number of other experts working under the Committee's guidance, who are named in the following "Acknowledgments" section.

The members of the Senior Seismic Hazard Analysis Committee (SSHAC) are:

Dr. Robert J. Budnitz (Chairman)	President Future Resources Associates, Inc.
Professor George Apostolakis	Massachusetts Institute of Technology previously at University of California, Los Angeles
Dr. David M. Boore	Seismologist U.S. Geological Survey
Dr. Lloyd S. Cluff	Manager, Geosciences Department Pacific Gas & Electric Company
Dr. Kevin J. Coppersmith	Vice President Geomatrix
Professor C. Allin Cornell	C. A. Cornell Company
Dr. Peter A. Morris	Applied Decision Analysis, Inc.

The scope of the SSHAC guidance is intended to cover both site-specific and regional applications of PSHA (more broadly, applications in both low-seismicity and high-seismicity regions) in both the eastern U.S. and western U.S. Although the sponsors' primary objective is guidance for applications at nuclear power plants and other critical facilities, the methodological guidance applies in whole or in part, on a case-by-case basis, to a broad range of applications.

The SSHAC guidance involves both technical guidance and procedural guidance, with a strong emphasis on the latter for reasons explained below. Therefore, the audience for the report includes not only analysts who will implement the methodology and earth scientists whose expertise will support the analysts, but also PSHA project sponsors—those decision-makers in organizations such as private firms or government agencies who have a need for PSHA information and are in a position to sponsor a PSHA study.

Note that our guidance is not intended to be "the only" or "the standard" methodology for PSHA to the exclusion of other approaches; there are other valid ways to perform a PSHA study. Likewise, our formulation should not be viewed as an attempt to "standardize" PSHA in the sense of freezing the science and technology that underlies a competent PSHA, thereby stifling innovation. Rather, our guidance is intended to represent SSHAC's opinion on the best current thinking on performing a valid PSHA.

The most important and fundamental fact that must be understood about a PSHA is that the objective of estimating annual frequencies of exceedance of earthquake-caused ground motions can be attained only with significant uncertainty. Despite much recent research, major gaps exist in our understanding of the mechanisms that cause earthquakes and of the processes that govern how an earthquake's energy

propagates from its origin beneath the earth's surface to various points near and far on the surface. The limited information that does exist can be—and often is—legitimately interpreted quite differently by different experts, and these differences of interpretation translate into important uncertainties in the numerical results from a PSHA.

The existence of these differences of interpretation translates into an operational challenge for the PSHA analyst who is faced with (1) how to use these different interpretations properly, and (2) how to incorporate the diversity of expert judgments into an analytical result that appropriately captures the current state-of-knowledge of the expert community, including its uncertainty.

The SSHAC studied a large number of past PSHAs, including two landmark studies from the late 1980s known as the "Lawrence Livermore (LLNL)" study and the "Electric Power Research Institute (EPRI)" study, both of which broke important new methodological ground in attempting to characterize earthquake-caused ground motion in the broad region of the U.S. east of the Rocky Mountains. Most important, the mean seismic hazard curves presented in the reports for most sites in the eastern U.S. differed significantly. However, the median hazard results did not differ by nearly as much. We now understand that differences in both the inputs and the procedures by which the two studies dealt with the inputs were among the key reasons for the differences in the mean curves. At the time this was not understood, and the differences between the mean curves caused not only considerable consternation, but launched several efforts to understand what might underlie the differences and attempts to update the older work.

Ultimately, the inability to understand all of the differences between the LLNL and EPRI hazard results—and the concomitant need for an improved methodology going beyond the late-1980s state-of-the-art—led directly to the formation of the SSHAC to perform this project. However, although the Committee studied both the LLNL and EPRI projects carefully to obtain methodological insights (both positive and negative), it did not undertake a forensic-type review to identify past "errors." Rather, it attempted to draw more broadly upon the entire body of PSHA literature and experience, including of course the LLNL and EPRI projects along with many others, to formulate the guidance herein.

In the course of our review, we concluded that many of the major potential pitfalls in executing a successful PSHA are procedural rather than technical in character. One of the most difficult challenges for the PSHA analyst is properly representing the wide diversity of expert judgments about the technical issues in PSHA in an acceptable analytical result, including addressing the large uncertainties. This conclusion, in turn, explains our heavy emphasis on *procedural* guidance.

This also explains why we believe that *how a PSHA is structured* is as critical to its success as the technical aspects—perhaps more critical because the procedural pitfalls can sometimes be harder to avoid and harder to uncover in an independent review than the pitfalls in the technical aspects. Finally, this also explains why *one of the key audiences for this report is the project sponsor*, who needs to understand the procedural/structural aspects in order to initiate and support the desired PSHA project appropriately.

This Executive Summary will conclude with a brief overview of what the SSHAC believes are its most important findings, conclusions, and recommendations in the procedural area. Because we recognize that several very important pieces of technical guidance concerning the earth-sciences aspects of PSHA will not be discussed in this Executive Summary, the SSHAC requests that readers turn to the full report to review the technical guidance. The key procedural points follow:

1) SSHAC identifies and describes several different *roles for experts* based on its conclusion that confusion about the various roles is a common source of difficulty in executing the aspect of PSHA involving the use of experts. The roles for which SSHAC provides the most extensive guidance

include the expert as *proponent* of a specific technical position, as an *evaluator* of the various positions in the technical community, and as a *technical integrator* (see the next paragraph).

2) SSHAC identifies four different types of consensus, and then concludes that one key source of difficulty is failure to recognize that 1) there is not likely to be "consensus" (as the word is commonly understood) among the various experts and 2) no single interpretation concerning a complex earth-sciences issue is the "correct" one. Rather, SSHAC believes that the following should be sought in a properly executed PSHA project for a given difficult technical issue: (1) a representation of the legitimate range of technically supportable interpretations among the entire informed technical community, and (2) the relative importance or credibility that should be given to the differing hypotheses across that range. As SSHAC has framed the methodology, this information is what the PSHA practitioner is charged to seek out, and seeking it out and evaluating it is what SSHAC defines as *technical integration*.

3) SSHAC identifies a hierarchy of complexity for technical issues, consisting of four *levels* (representing increasing levels of participation by technical experts in the development of the desired results), and then concentrates much of its guidance on the most complex level (level 4) in which a panel of experts is formally constituted and the panel's interpretations of the technical information relevant to the issues are formally elicited. To deal with such complex issues, SSHAC defines an entity that it calls the Technical Facilitator/Integrator (TFI), which is differentiated from a similar entity for dealing with issues at the other three less-complex levels, which SSHAC calls the Technical Integrator (TI). Much of SSHAC's procedural guidance involves how the TI and TFI functions should be structured and implemented. (Both the TI and TFI are envisioned as roles that may be filled by one person or, in the TFI case, perhaps by a small team).

4) The role of *technical integration* is common to the TI and TFI roles. What is special about the TFI role, in SSHAC's formulation, is the *facilitation* aspect, when an issue is judged to be complex enough that the views of a panel of several experts must be elicited. SSHAC's guidance dwells on that aspect extensively, in part because SSHAC believes that this is where some of the most difficult procedural pitfalls are encountered. In fact, the main report identifies a number of problems that have arisen in past PSHAs and discusses how the TFI function explicitly overcomes each of them.

5) For most technical issues that arise in a typical PSHA, the issue's complexity does not warrant a panel of experts and hence the establishment of a TFI role. Technical integration for these issues can be accomplished—indeed, is usually best accomplished—by a TI. In fact, SSHAC has structured its recommended methodology so that even the most complex issues *can* be dealt with using the less expensive TI mode, although with some sacrifice in the confidence obtained in the results on both the technical and the procedural sides.

6) One special element of the TFI process is SSHAC's guidance on sequentially using the panel of experts in different roles. Heavy emphasis is placed on assuring constructive give-and-take interactions among the panelists throughout the process. Each expert is first asked, based on his/her own knowledge (yet cognizant of the views of others as explored through the information-exchange process), to act as an *evaluator*; that is, to evaluate the range of technically legitimate viewpoints concerning the issue at hand. Then, each expert is asked to play the role of *technical integrator*, providing advice to the TFI on the appropriate representation of the composite position of the community as a whole.

   Contrasting the classical role of experts on a panel acting as individuals and providing inputs to a separate aggregation process, the TFI approach views the panel as a team, with the TFI as the team leader, working together to arrive at (i) a composite representation of the knowledge of the group, and then (ii) a composite representation of the knowledge of the technical community at large. (Neither of these representations necessarily reflects panel consensus—they may or may not, and their validity does *not* depend on whether a panel consensus is reached.)

The SSHAC guidance to the TFI emphasizes that a variety of techniques are available for achieving this composite representation. SSHAC recommends a blending of behavioral or judgmental methods with mathematical methods, and in the body of the report several techniques along these lines are described in detail. A key objective for the TFI is to develop an aggregate result that can be endorsed by the expert panel both technically and in terms of the process used.

7) The TFI's integrator role should be viewed not as that of a "super-expert" who has the final say on the weighting of the relative merits of either specific technical interpretations or the various experts' interpretations of them; rather, the TFI role should be seen as charged with characterizing both the commonality and the diversity in a set of panel estimates, each representing a weighted combination of different expert positions. SSHAC thus sees the TFI as performing an integration assisted by a group of experts who provide integration advice.

8) Thus, the TFI as facilitator structures interaction among the experts to create conditions under which the TFI's job as integrator will be simplified (e.g., either a consensus representation is formed or it is appropriate to weight equally the experts' evaluations of the knowledge of the technical community at large). In the rare case in which such simple integration is not appropriate, additional guidance is provided. In the main report, guidance is presented on two possible approaches involving (i) explicit quantitative but unequal weights (when it becomes obvious that using equal weighting misrepresents the community-as-a-whole); and (ii) "weighing" rather than "weighting", in cases when the experts themselves, acting as evaluators and integrators, find fixed numerical weights to be artificial, and when it is appropriate to represent the community's overall distribution in a less rigid way.

9) The SSHAC guidance gives special emphasis to the importance of an independent peer review. We distinguish between a participatory peer review and a late-stage peer review, and we also distinguish between a peer review of the process aspects and of the technical aspects for the more complex issues. We strongly recommend a participatory peer review, especially for the process aspects for the more complex issues. This paper details the pitfalls of an inadequate peer review.

ACKNOWLEDGMENTS

This project has been jointly supported by the U. S. Department of Energy (DOE), the U. S. Nuclear Regulatory Commission (NRC), and the Electric Power Research Institute (EPRI). The project managers for the three sponsors, whose participation went far beyond managerial support to include technical input as well, and without whom the project could not have been successfully completed, were Jeffrey Kimball and Ann Bieniawski (DOE), Andrew J. Murphy and Ernst G. Zurflueh (NRC), and J. Carl Stepp and John Schneider (EPRI). They were ably supported administratively by Michael P. Bohn of Sandia National Laboratories (DOE) and Jean B. Savy of Lawrence Livermore National Laboratory (NRC), both of whom made technical contributions as well.

Although the intellectual responsibility for the report rests solely with the seven SSHAC members, the task could not have been accomplished without the diligent and very capable contributions of a large number of others who worked in a collaborative mode under the SSHAC Committee's overall direction. These other experts, some of whom ghost-wrote entire subsections or appendices of the report, were:

Don L. Bernreuter, Lawrence Livermore National Laboratory

Michael P. Bohn, Sandia National Laboratories (DOE Project Manager; lead author for the Glossary)

Auguste C. Boissonnade, Lawrence Livermore National Laboratory

Martin W. McCann, Jack Benjamin & Associates Inc. (lead author for Chapter 7)

Robin K. McGuire, Risk Engineering Inc. (author of Appendix G)

Richard W. Mensing, Logicon-RDA (lead author for Chapter 6; author of Appendix D; contributor to Chapter 4 and Appendix A)

Jean B. Savy, Lawrence Livermore National Laboratory (NRC Project Manager)

Gabriel R. Toro, Risk Engineering Inc. (major contributor to Chapter 5; author of Appendices F and I; contributor to Chapter 4 and Appendices A and B)

The SSHAC project organized four different workshops that were attended by a large number of experts representing a variety of disciplines. The participants, who are all listed in the workshop descriptions (see Appendices A, B, C, and H), deserve our thanks for contributing so significantly to the project.

We would also like to thank Norman Abrahamson for contributing an excellent piece of guidance that we have taken the liberty to incorporate herein as Appendix E.

The National Academy of Sciences/National Research Council (NAS/NRC) organized a special "Panel on Seismic Hazard Evaluation" under its Committee on Seismology with the charter to review our report. This review was supported by the U.S. Nuclear Regulatory Commission. The Panel's review comments on our draft report of November 11, 1994 were especially helpful in focusing the SSHAC on key issues that needed extra attention. Besides the NAS/NRC Panel's review, we had the benefit of informal review comments on the November draft from about a dozen other specialists and organizations for which we are very grateful. The comments of the NAS/NRC Review Panel, which were published separately by the National Academy Press, are included in this report as an Appendix to Volume 1.

Finally, the logistical work of pulling the report together, based on input from many different authors typing on many different word processors, was accomplished in an outstanding manner by Rosa I. Yamamoto of LLNL, whose skill and dedication the SSHAC gratefully acknowledges.

GROUND MOTION WORKSHOPS I & II

Appendices A & B

APPENDIX A

GROUND-MOTION WORKSHOP I
MARCH 17-18, 1994
BOULDER, COLORADO

A.1 INTRODUCTION

As the SSHAC deliberations progressed, it became clear that expert elicitation would be one of the main topics of the final report. SSHAC decided to hold several workshops dealing with ground-motion issues to test some of the ideas regarding elicitation that emerged from the deliberations. The primary purpose of the workshops was to test the concept of integration and facilitation by an Integrator, one entity responsible for representing the composite state of information of the community of ground-motion experts (later, we renamed this entity "Technical Facilitator/Integrator," or TFI). The Integrator process to be tested was explicitly contrasted with the alternative approaches of using models (including using one and only one model), using multiple models with explicit numerical weights, and using one core model with other models for support. One of the hypotheses we wished to test was that the Integrator process, based explicitly on the principle that there is "no one correct model," would reduce the participants' tendencies to view themselves as advocates or "proponents" and would accentuate their role as scientists with different scientific hypotheses (this, in fact, is just what happened in the second workshop). In addition, we believed that the process of structured interaction among the experts could be improved beyond what was done in previous ground-motion elicitation efforts. The workshop also helped test and strengthen the distinction between the "proponent" and "evaluator" roles of the experts (see Chapter 3).

A second purpose of the workshop was to capture the current state of thinking regarding the issues in predicting ground motions in central and Eastern North America (CENA) for use in PSHA, and hopefully in providing specific guidance about these issues.

We originally planned two workshops, each of which focussed on a different ground-motion issue: the first on uncertainty and the second on central estimates of ground-motion amplitudes. As planning for the first workshop progressed, we came to the realization that uncertainty is intimately tied to the underlying ground-motion model, and therefore we should concentrate on these models rather than on the uncertainty in the elicitation. We planned two workshops. Workshop I examined the general methods for ground-motion prediction and presented SSHAC's views about uncertainty. This first workshop set the stage for the second workshop, which was focussed on elicitation of central estimates and uncertainties in ground-motion amplitude for specific magnitudes and distances. This appendix discusses Workshop I; Workshop II is covered in Appendix B.

A.2 DESIGN AND ORGANIZATION

The design of Workshop I evolved from seven planning meetings that involved a core planning group composed of D. Boore, C.A. Cornell, R. Mensing, P. Morris, and G. Toro. This unusually large number of meetings is explained by the evolution of the focus of the workshop described above. The first meeting was held about five months before the workshop.

After careful deliberation, a list of invited attendees was prepared by the planning committee. As usual, the committee had to grapple with the competing factors of too large a group stifling discussion and too small a group not encompassing the range of views about the subject. The final list represents a compromise that we feel struck a good balance between the two conflicting requirements. The list of attendees is given in Table A-1. The attendees included the integrators (discussed below), invited participants, and observers.

In this workshop, the Integration Team was comprised of four individuals with a combination of ground-motion and elicitation expertise. The group interaction was led by two facilitators, one with ground-motion expertise (D. Boore) and one with elicitation expertise (P. Morris). Two other Integrators (C.A. Cornell and R. Mensing) aided in questioning and interpreting the

TABLE A-1
ATTENDEES AT SSHAC GROUND-MOTION WORKSHOP I

Integrators:

David M. Boore, SSHAC
C. Allin Cornell, SSHAC
Peter Morris, SSHAC
Richard Mensing, Logicon-RDA

Invited Participants:

Norman A. Abrahamson, Consultant
Gail M. Atkinson, Consultant
Don Bernreuter, Lawrence Livermore National Laboratory
Kenneth W. Campbell, EQE
Robert B. Herrmann, Saint Louis University
Klaus Jacob, Lamont-Doherty Earth Observatory
William Joyner, U.S. Geological Survey
Chandan Saikia, Woodward-Clyde Consultants
Walter J. Silva, Pacific Engineering and Analysis
Paul Somerville, Woodward-Clyde Consultants (via telephone)
Gabriel R. Toro, Risk Engineering, Inc.
Mihailo Trifunac, University of Southern California
Daniele Veneziano, Massachusetts Institute of Technology
Robert Youngs, Geomatrix Consultants

Observers:

George Apostolakis, SSHAC
Ann Bieniaswski, U.S. Department of Energy
Mike Bohn, Sandia National Laboratory
Auguste Boissonnade, Lawrence Livermore National Laboratory
Nilesh Chokshi, U.S. Nuclear Regulatory Commission
Tom Hanks, National Academy of Sciences
Jean B. Savy, Lawrence Livermore National Laboratory
John F. Schneider, Electric Power Research Institute

experts and in performing the final integration. The Integrator team was responsible for the following functions:

- Structuring and facilitating complete information and judgment exchange among the experts
- Ensuring consistent databases and terminology
- Staging interactive debates among experts in critical areas
- Eliciting from the experts the strengths and weaknesses of different methods for ground-motion prediction
- Obtaining agreement on a <u>representative set</u> of state of the art methods.
- Deciding on which methods to consider explicitly in Workshop II.

Specific questions the workshop was designed to address regarding the Integrator process included:

- Would it be possible to have a useful structured discussion focused on basic ground-motion prediction methods rather than on individual expert opinions?
- Would the "active listening" process work in the ground-motion expert community?
- Would the explicit de-emphasis on choosing the "best" model and not numerically weighting different models promote an enhanced, less emotional information exchange?
- Would the meeting, with its heavy emphasis on information exchange and structured interaction, provide useful information to the Integrators; i.e., how hard wi it be for the Integrators to integrate?

The meeting was held in the Hotel Boulderado in Boulder, Colorado on March 17 and 18, 1994. The participants were sent a short set of instructions (Attachment A-1) as well as a paper on uncertainty prepared by G. Toro (a revised version of which is given in Appendix F) to help them prepare for the meeting. Five of the participants were asked to give oral presentations on ground-motion prediction methods. The methods and presenters were identified by the planning committee. The presenter for each method had been closely involved in the development and application of that method. These presenters were sent an additional set of instructions (Attachment A-2). The intent was for a broad overview rather than a detailed exposition of the method. Unfortunately, some of the presenters apparently did not understand the charge to them, and therefore not all presentations fulfilled the goal of the planning committee. The lesson is that more verbal communication with each presenter is required, to make sure they understand what is being asked of them.

The Agenda (Attachment A-3) contained three SSHAC presentations (introduction, discussion of elicitation, and characterization of uncertainty), followed by the five reviews of methods for obtaining ground-motion values for use in PSHA. The Integrators then led several discussions of the methods. On the second day, the participants were asked to complete a survey (Attachment A-4). While the survey was being completed, the Integrators met to discuss what had taken place in the workshop; their conclusions were presented to the participants in the closing session, which also allowed for feedback from the participants. After the workshop, a detailed analysis of the survey was completed by one of the Integrators (P. Morris).

A.3 SUMMARY OF PRESENTATIONS

The following is a summary of the formal presentations by SSHAC members and invited presenters. In addition, this summary contains two brief presentations by D. Veneziano.

A.3.1. Introduction (D.Boore)

This presentation outlined the purposes of Workshop I, which were as follows:

- (Main) Examine and compare various methods (classes of models) available for prediction of ground motion in the central and eastern United States for use in seismic hazard analysis.

- (Second) Describe and elicit feedback about a different procedure for eliciting information from ground-motion experts.

- (Third) Present and discuss a proposed framework for the characterization of uncertainty in ground-motion predictions.

A.3.2. Elicitation: Past, Present, Future (P. Morris)

This presentation provided a summary of the approaches used in past efforts at ground-motion elicitation and integration, and described the approach proposed by SSHAC.

The two most significant past elicitation efforts were those of EPRI and LLNL in the late 1980's and LLNL in 1992. In the EPRI study, a limited number of ground motion models were selected for use in seismic hazard analysis. This approach included extensive discussions and interactions between members of a working group and with outside experts, but the ultimate selection of ground-motion models was made by a small group of analysts/experts. The advantage of this approach is that there is significant interaction within the working group. The drawback of this approach is that there is a negative perception because the final choice of models was not made directly by multiple experts.

In the latest LLNL study, a group of approximately six experts were asked to provide estimates of ground-motion amplitudes and associated aleatory and epistemic uncertainties, at selected magnitudes and distances. These estimates were in the form of joint probability distributions, not necessarily lognormal or independent, for the aleatory and epistemic uncertainties. The advantage of this approach is that the final ground-motion estimate (in this case, expressed in non-parametric form) is derived directly from the experts. The drawbacks of this approach are that relatively little effort was made to have the experts "defend" their estimates, and there was relatively little interaction between experts about their interpretations and estimates.

The elicitation and integration approach proposed by SSHAC will take place in two phases, and will be led by a small group of Integrators who will take an active role in guiding and focusing discussions, eliciting information, and integrating the information. Morris described the two phases as follows:

1. **Initial Elicitation: Estimation Approaches (Workshop 1).** This phase contains extensive discussion and interaction about ground-motion estimation methods by experts representing the principal classes of models, e.g., intensity models, empirical models, stochastic models, and semi-empirical models. Discussion, as guided by the Integrators, is intended to focus on the methods, not the work/inputs of individual experts or on model-specific parameter values or details; its goals are to isolate sources of disagreements between methods and the attributes of the various methods and to identify areas of agreements between experts. Discussions are designed to be based on active listening and to foster constructive feedback by participants.

   Integrators formulate, based on the discussions from the first workshops and their collective judgement, a position on which classes of models are to be pursued in the second phase, based on their given state of development.

2. **Final Elicitation: Ground-Motion Predictions (Workshop 2).** Using the results of the first workshop, Integrators develop a process for eliciting the appropriate ground-motion information based on the methods selected. Inputs to be elicited include

estimates of median amplitudes at specified magnitude-distance pairs, aleatory uncertainty, and epistemic uncertainty.

Finally, the Integrators aggregate information derived from the elicitations into a composite model. Details of the aggregation procedure are to be presented at the second workshop.

Several panelists expressed strong opinions about the need to be informed about how their inputs are to be used. They would like to know what difficulties are encountered with their inputs, and what are the results of their inputs. They stated that such feedback was absent from past ground-motion elicitation efforts.

A.3.3. Proposed Framework for Characterizing Ground-motion Uncertainties (G.Toro)

This presentation provided a framework for the treatment of uncertainty. This framework partitions uncertainty using a two-way classification: epistemic versus aleatory and parametric versus modeling. This partition is particularly useful in the context of models having physical parameters, because it helps in capturing all sources of uncertainty. An expanded version of this presentation is contained in Appendix F.

A.3.4. Reflections in the Nature of Uncertainty in PSHA (D. Veneziano)

This presentation discussed the partition of uncertainty and presented a series of examples to illustrate the arguments presented. The following is a short list of the key arguments.

1. With respect to a specific model, one may separate epistemic and aleatory uncertainty. With respect to nature, all uncertainty in PSHA is epistemic because the underlying physical processes are deterministic, albeit complex.

2. Although there is no need to differentiate among components of uncertainty, it may be useful to differentiate during the intermediate steps of PSHA in order to ensure that all components of uncertainty are captured.

3. A finer differentiation of components of uncertainty and the separate propagation of these components may lead to additional complexity and lack of transparency in PSHA results. This additional complexity should be avoided. Moreover, there should be an effort to streamline PSHA.

A.3.5. Intensity Methods (M. Trifunac)

The main reason for using Intensity-based methods for predicting ground motions is that most of the earthquake-size data in seismicity catalogs is in the form of (or is based on) epicentral-intensity (I_0) measurements. This was true in the past and it is still true in many parts of the world. Another reason is that site intensity (I_S) is directly related to damage.

The most serious difficulty in using intensity-based methods is that there are few data for the development of relations to predict instrumental ground-motion amplitudes (e.g., peak acceleration, spectral acceleration) from site intensity and site conditions. Although it is recognized that these relationships should also include magnitude and distance for theoretical reasons (i.e., they should be of the form $\ln A=f[I_S$, site conditions, $m, r])$, magnitude and distance terms are not included for lack of data and because those terms would make the relationships non-transportable from one region to another.

Another difficulty is that there are many intensity scales in use throughout the world and that the assignment of intensities contains a subjective element.

Examples were presented showing graphs and equations for peak acceleration, peak velocity, peak displacement, and Fourier amplitude, given I_S and site category.

Another application was presented using intensity data from eastern Europe, showing the data used, the relationship among the various intensity scales used, and the procedure to compute the distribution of distance to isoseismals. Results from the intensity-attenuation analysis are in the form of probability distributions of distance to the isoseismal for I_S, given I_0; they should be applied in this form in seismic-hazard analysis.

Another application compares two seismic-hazard maps for 0.9-sec spectral velocity and 100-year return period in the Los Angeles area. One map was obtained working directly with attenuation equations for spectral velocity; the other was obtained using intensity attenuation relations and relationships between intensity and spectral velocity. The two hazard maps are similar but not identical, with the latter map showing slightly higher amplitudes at some locations.

A.3.6. Notes on Intensity Methods and on the Joint use of Intensity Methods, Instrumental Data, and Physical Models (D. Veneziano)

This presentation illustrated the proper mechanics of deriving attenuation equations for instrumental ground motions in CENA (or any region where there is intensity data and there is little or no instrumental data) as a function of magnitude and distance, using intensity-attenuation relationships. This process requires knowledge of three probabilistic relationships for the region of interest. These three relationships may be written as conditional probability distributions; i.e., $(I_S|I_0,R)_E$, $(I_0|M)_E$, and $(Y|I_S,M,R)_E$, where subscript E (East) refers to CENA and Y denotes instrumental ground-motion amplitude. Difficulties arise because the relationship $(Y|I_S,M,R)_E$ is not available. The conventional practice has been to assume that $(Y|I_S,M,R)_E=(Y|I_S,M,R)_W$, where subscript W (West) denotes western North America, thereby assuming that differences between east and west are limited to the first two relationships.

Two approaches were proposed to alleviate this difficulty. The first approach would derive $(Y|I_S,M,R)_E$ using physical models. The second approach would transform an empirically derived $(Y|I_S,M,R)_W$ into $(Y|I_S,M,R)_E$ using physical models. Finally, a unified approach was sketched, which combines the above two approaches and also makes use of instrumental data from eastern North America.

A.3.7. Empirical Methods (K. Campbell)

Two approaches are possible for the empirical prediction of ground motion for CENA (or for any region where there is limited instrumental data). The first one is direct empirical regression using data from CENA. This approach is not satisfactory at present because the data are limited, particularly in the magnitude-distance region of interest. Several graphs were used to illustrate this point.

The second approach consists of modifying attenuation equations obtained using data from western North America (WNA), to account for known differences between CENA and WNA. This approach rests on the assumption that ground motions at short distances are the same in both regions. This second approach was the focus of the presentation.

The modifications must take into account the following factors:

1. Magnitude. Depending on which magnitude scale is used to characterize seismicity, it may be required to convert the attenuation equations from moment magnitude to m_{bLg}. Magnitude modification was not required in the application presented as an example.

2. Stress Drop. Based on the current thinking that stress-drop differences are not large, no modification for stress drop is applied.

3. Differences in geometric and anelastic attenuation. These differences are important, except at short distances and require the use of modification factors.

4. Differences in distance measure. Most WNA attenuation equations use some form of minimum distance to the rupture or projection of the fault. Because magnitudes are typically lower in CENA and because most PSHA studies in CENA use area sources, hypocentral or epicentral distance is often used. Differences in the distance measure affect the attenuation equation and the residual standard deviation.

5. Differences in site conditions. Most strong-motion data in WNA come from soil sites and the more robust WNA attenuation equations are those for soil. Most CENA attenuation equations are derived for rock site conditions, because most CENA data come from seismograph stations founded on rock.

The modification for site conditions uses the amplification factors recently proposed by Roger Borcherdt (USGS) for use in building codes. These factors are used to convert the WNA soil predictions to rock.

The modification for geometric and anelastic attenuation effects is obtained by applying a stochastic ground-motion model, making predictions for rock site conditions in both CENA and WNA and then computing their ratio as a function of frequency, magnitude, distance. This ratio is then used as a modification factor that multiplies the WNA empirical attenuation equations.

The modification for differences in distance measures assumes that both the attenuation equations in terms of rupture and hypocentral distance predict the same amplitudes for some pre-specified magnitude-distance combination. This resulting modification may be different for different WNA attenuation equations.

Epistemic uncertainty is introduced by considering multiple WNA attenuation equations, thereby obtaining multiple CENA attenuation equations. Epistemic uncertainty in the modification factors is not considered.

One advantage of this approach is that extended-source effects and other effects that may cause saturation are automatically captured.

Examples were presented showing the attenuation equations obtained for a particular site and comparing the predicted response spectra to those obtained using a stochastic method.

A.3.8. Stochastic Methods (G.Atkinson)

The basic assumptions of most stochastic models are that ground motions may be represented as a finite-duration segment of a stationary gaussian random process and that we know enough about earthquakes (particularly in CENA, where these methods are used the most) to be able to predict the expected Fourier power spectrum and duration of the ground motion for any magnitude-distance combination of interest.

The Fourier amplitude spectrum is generally written in the form $A(\mathbf{M},R,f)=E(\mathbf{M},f)\times D(R,f)$, where E represents the source spectrum, D represents attenuation effects, **M** is moment magnitude, R is hypocentral distance, and f is frequency. Specification of duration $T(\mathbf{M},R)$ is also required in order to calculate root-mean-square (rms) and peak time-domain amplitudes.

The most controversial piece of the model is the source spectrum E(**M**,f) and its dependence on **M**. Information on the source spectrum of CENA earthquakes comes from various sources as follows:

1. At low frequencies (<< 1 Hz): from estimates of seismic moment.

2. Near 1 Hz: from Street and Turcotte's compilation of regional recordings, from Boatwright and Choy's analyses of teleseismic recordings of the larger intraplate events, and from records obtained using strong-motion instruments at distances within 200 km.

3. At higher frequencies (above the event's corner frequency): Eastern Canada Telemetered Network (ECTN) records, records obtained using strong-motion instruments at distances within 200 km, and from intensity data (felt area exhibits high correlation with the high-frequency Fourier amplitude).

The ECTN data set, which is the largest of these data sets, is composed in large part of earthquakes with $\mathbf{M} \leq 5$ and $R > 100$ km.

Traditionally, E(**M**,f) has been characterized by a Brune spectrum with stress drop of approximately 100 bars. As more data have been collected, it has become apparent that the spectral shapes predicted by the Brune model deviate systematically from the observed spectral shapes. Figures were shown indicating that 1-Hz Fourier amplitudes are consistent with a 50-bar Brune model, whereas 10-Hz amplitudes are consistent with a 200-bar Brune model. Another example is provided by the Fourier spectra of the station S-16 recordings from the 1988 Saguenay earthquake.

Based on these observations, a model with two corner frequencies was proposed by Atkinson. The dependence of the two corner frequencies on **M** was derived empirically from the data listed above. This model is not too different from the Brune model for $\mathbf{M} \cong 5$. For larger earthquakes and for frequencies lower than 0.5 Hz, this model predicts significantly lower Fourier amplitudes than the Brune model.

The attenuation effects D(R,f) are generally divided into three physical mechanisms, as follows:

1. Geometric attenuation, representing elastic wave-propagation effects, the simplest form of which is R^{-1}.

2. Crustal anelastic attenuation, represented by the quality factor Q, which may be frequency-dependent.

3. Phenomena controlling the shape of the Fourier spectra at frequencies of 10 Hz and higher, generally explained as near-site anelastic attenuation and characterized by the cutoff frequency f_{max} and the attenuation parameter κ.

The available data are sufficient to determine the combined effect of geometric attenuation and Q, with little uncertainty at all distances greater than 15 km. These data are not sufficient to resolve between the two mechanisms.

Fewer data are available for determining the spectral shape at high frequencies (represented by f_{max} or κ), due to bandwidth limitations of the instruments and to lack of records at R<100 km. In addition, there is considerable site-to site variability: some records suggest κ<0.003 sec, others suggest κ=0.03 sec (typical of WNA).

Duration increases with distance due to wave-propagation effects. This tendency is seen even at distances shorter than the distance of the first Moho reflection. The following expression has been used to represent duration as a function of magnitude and distance:

$T(M,R)=T_{src}(M)+0.05R$, where T has units of sec, R has units of km, and T_{src} is the source duration.

In summary, the strengths of the stochastic method are its conceptual simplicity and its versatility (e.g., can accommodate a variety of model assumptions, is amenable to a formal treatment of uncertainty). The limitations of the method relate to the uncertainty in model parameters, due to limitations in the data. In particular, there are no data to verify the predictions for large **M**. These limitations are common to any methods that are used to predict ground motions in CENA.

A.3.9. Empirical Source Function Method (C. Saikia and P. Somerville)

In the current form of this method, empirical source functions (ESF's) are used to simulate the portion of the ground motion above 1 Hz and a deterministic method is used to simulate the portion below 1 Hz. In the discussion that follows, the term "ESF method" will refer to this hybrid approach.

For both portions of the simulation, the rupture plane is divided into a number of rectangular sub-faults. The slip in each sub-fault is given by a pre-specified slip distribution. The total ground motion is generated as the sum of the ground motions from the various sub-faults.

In the ESF portion of the simulation, the effects of source radiation and scatter are captured empirically by using recorded ground motions from small earthquakes, corrected for path effects. Path effects are quantified using generalized ray theory or frequency-wavenumber integration. Site effects are introduced in the form of a frequency-domain correction to account for differences in parameter kappa.

In the deterministic portion of the simulation, source effects are represented by means of theoretical source functions, using a pre-specified spatial and temporal distribution of slip. Path effects are quantified using frequency-wavenumber integration.

In the final step, the ESF and deterministic time histories are combined by using matched filters.

The validity of this method has been demonstrated by comparisons to data in California and in CENA. Some comparisons are in terms of amplitudes as a function of distance for a given event, other comparisons are in terms of observed and modeled time histories for a given record.

The ESF method requires specification of the following parameters:

1. Rupture dimensions for a given seismic moment. Typically, the Somerville et al. (1987) relationship is used.
2. Rupture geometry (strike angle, dip angle, depth range) and location of the site.
3. Spatial distribution of slip along the rupture (or an algorithm to generate artificial slip distributions) and rake angle.
4. Layered crustal structure (layer thicknesses, seismic velocities, densities, and Q values). The EPRI (1993) crustal regionalization of CENA may be used to obtain these data.
5. Site kappa value.

The ESF method has been extensively validated by comparing predicted to observed amplitudes. Results shown using the ESF-deterministic method for 16 near-fault Loma Prieta stations show no significant bias over the 0.2-30 Hz frequency range (bias arises below 1 Hz if only time histories simulated using empirical source functions are used for the entire frequency range). The standard deviation of the residuals (representing modeling uncertainty) is approximately 0.45 (natural-log units) over the entire frequency range. Predictions made by Saikia (1993) for a **M** 7 thrust earthquake in the Elysian thrust system are consistent with observed peak accelerations from the 1994 Northridge earthquake. The ESF method is applicable to all magnitudes, distances, and frequencies of engineering interest.

The strengths of the ESF method are as follows:

1. It uses the same wave-propagation methods that are used by seismologists to invert for the source characteristics of past earthquakes.
2. It can make use of data to be obtained by the new broadband stations of the National Seismic Network.
3. It has been extensively validated against strong-motion data from California and against some CENA data.
4. It predicts CENA motions with slightly lower bias and standard error than the stochastic method.
5. It is especially useful for CENA locations where crustal-structure and source data are available but no ground-motion data are available.

The weaknesses of the ESF methods are as follows:

1. Green's functions do not include the effects of scattering and of non-planar structures. These effects may be important at high frequencies. Scattering effects are included implicitly in the empirical source functions. This does not allow adjustments for regional differences in scattering or for the effect of distance.
2. Requires knowledge of the crustal structure and substantial computational effort.

A.4. OBSERVATIONS AND LESSONS

Workshop I had two positive outcomes. First, we were able to test each of our hypotheses about ground-motion elicitation to some degree. Second, the Integrator process appeared to be very successful. Its credibility was strengthened as a candidate for the SSHAC-recommended elicitation process, at least in the ground-motion arena. Here are some of the more pertinent results:

- Workshop I brought together many experts, helping to draw in, for broad consideration, very diverse points of view. This format proved useful for identifying methods and issues that should receive further consideration. A workshop of this type is not sufficient, in and of itself, and it must be followed by a more focused workshop.

- The approach of conditioning the conversation on different fundamental methods for ground-motion prediction proved to be extremely successful. From a facilitation perspective, the discussions naturally focused on technical debates rather than on personal disagreements.

- There was remarkable agreement on the relative strengths and weaknesses of the various models. Dave Boore summarized observations about the strengths and weaknesses of the models, and the group accepted the summaries without apparent reservation, even those who supported the less popular models.

- There was also remarkable agreement among the experts regarding the following issues: 1) unequal weights for the various methods are appropriate, 2) these weights may vary as a function of magnitude and distance, and 3) the values of the weights for the different approaches. It was clear in the group interaction that most of the experts preferred certain models over others, and that this preference depended on the application (characterized by magnitude, distance, and spectral frequency). The survey results presented below quantify this observation, but it was also a clear qualitative signal from the structured interaction.

- A consensus developed on the set of ground-motion models that define the current state of the art. While there are many flavors of each basic model form, the Integrators proposed an initial list, and the group refined the list into five ground-motion models (direct empirical, hybrid empirical, empirical source function, intensity-based, stochastic [single corner], and stochastic [two corner]). The group agreed that these five methods define a representative set.

- There was apparent clear group understanding about the details of each method except for the Empirical Source Function method. (The Integrators were briefed by N. Abrahamson at a later meeting in order to help them understand the details of this method. Abrahamson also prepared Appendix E.)

- While there was clear group understanding at a conceptual level about the models, it was also clear that the group format is not appropriate for complete and detailed information exchange. To obtain a more complete understanding of the implications of the models, one must assemble a much smaller group of experts and one must stage discussions focused on specific model estimates and on the effects of model assumptions and parameter values. This was the motivation for Workshop II.

- The information provided was indeed useful for the Integrators. The structured discussion and the survey were directly useful in designing the next, more detailed, elicitation stage (Workshop II and the mail exchanges that preceded it). Even if there had been no follow-on workshop, the information developed would have been useful in helping the Integrators make a final numerical ground-motion assessment at this stage.

- The experts did not appear to have problems assigning weights to the various methods (as opposed to assigning weights to other experts). All experts but one assigned explicit weights in the survey, and the expert who did not provide weights refused on general principles, not because he regarded the weights as a stigma in any sense. This is a very positive result, because, in general, there is a great deal of empirical evidence that experts are very reluctant to assign weights to one another.

- The workshop also validated the notion that the Integrator should be minimally a team that consists of someone with functional knowledge of the subject matter (in this case, ground motion) and someone with experience and knowledge in elicitation methods. The functional knowledge was especially valuable in clarifying the scientific interchange and in summarizing points on which there appeared to be clear points of group agreement or disagreement. The elicitation expertise was useful in designing the structure for expert interchange, formulating the expert survey, and setting the "tone" and format for the interaction.

- Discussions during the workshop highlighted the practical and philosophical difficulties in defining and quantifying uncertainty, particularly epistemic uncertainty. Generally, experts are most comfortable at specifying their "best-shot" models. Aleatory uncertainty is easily grasped if it can be related to scatter in observations, but it becomes more difficult if it involves propagation of parameter uncertainties. The partition of uncertainty into four categories is helpful for some experts but not for others.

Because of time and resource limitations, the workshop explicitly did not include some elements that are likely to be part of any final elicitation process. We did not conduct individual interviews, which would have helped to make sure that the methods were described in a common format and language. The presentations were not as focused and pre-structured as they could have been -- e.g., a common format would have been useful, graphical communication schemes such as influence diagrams would have streamlined communication, and prescribing common terminology would also have helped. Finally, there was not much time for the experts to reflect and iterate. Some of these aspects that were left out were the motivation for holding a later follow-up workshop (described in Appendix B).

A.5 RESULTS OF THE INTEGRATOR SURVEY

The survey that was handed out to the thirteen ground-motion experts is included as Attachment A-4[1]. This section summarizes the overall results of the survey, focusing on the summary data provided in Tables A-2, A-3 and A-4. A great deal of additional interesting and useful information is provided in Attachments A-5 through A-8, whose contents are briefly described here:

Attachment A-5: Expert Inputs on Comparison of Methods. These tables summarize the experts' ratings on method logic, use of data, parameter estimation, and credibility of the various methods. These tables help explain the overall ratings in Table A-2.

Attachment A-6: Experts' Written Comments on Comparison of Methods. The experts provided a great deal of supporting information in the form of written comments that explain their inputs. This information is crucial for a detailed understanding of the relative credibility each expert assigned to each method.

Attachment A-7: Detailed Expert Inputs on Using the Various Methods for Forecasting. This is the raw input, expert-by-expert, application-by-application, that formed the basis for the aggregated data shown in Table A-3.

[1]In attachments A-4 through A-8, the Empirical Source Function (ESF) method is referred to as the "Advanced Numerical" method.

Attachment A-8: Detailed Expert Inputs on Preferences of the Overall Expert Community.

This is the raw input, expert-by-expert, application-by-application, that formed the basis for the aggregated data shown in Table A-4.

The basic results of the survey are most easily understood by reviewing Tables A-2, A-3 and A-4, which are discussed below.

Overall Rating (Table A-2). Table A-2 shows rather dramatically that the experts do not regard the five methods as equally attractive. The numbers in the figure were derived by assigning a 0-10 scale (0 = "poor, low" and 10 = "excellent, high") to the expert ratings on the first page of the survey. While the numbers are somewhat arbitrary, nevertheless there is a striking, remarkably consistent pattern of preference towards the stochastic and empirical source function methods and a lack of preference for the intensity-based method. This is also demonstrated by the two rows at the bottom of the table, which indicate--for each method--the number of experts that rated that method the highest among the five methods and the number of experts that rated that method the lowest among the five methods. For example, nine out of the thirteen experts rated the stochastic model at least as highly as any of the others, and none of the experts rated the stochastic model the lowest. In contrast, only one expert rated the intensity-based method highest, while nine out of the thirteen experts rated it lowest.

It is important to note from other parts of the survey that the relative attractiveness of the five methods depends in some cases heavily on the magnitude, distance, and structural frequency. Further, it is very clear that the approach of assigning equal weights to the various methods would not capture the sense of the ground-motion community, as represented by these thirteen experts.

Using the Methods for Forecasting (Table A-3). Probably the most interesting results of the survey are presented in Table A-3. This table averages the weights for each of the models over the thirteen experts in each application (the expert-by-expert weights are presented in Attachment A-7). Once again, the most striking observation is that *the weights are definitely unequal.* In fact, a close examination of the detailed expert inputs in Attachment A-5 reveals a good amount of consistency among the bulk of experts in how they weight the methods for each application (although there are clearly a few outlier opinions).

A number of interesting observations can be made about the weights in Table A-3, including:

- Consistent with Table 1, the stochastic and empirical source function methods tend to get the highest weights, while the intensity-based and hybrid empirical tend to get the lowest weights.

- The weights are, in some cases, heavily a function of the application. For example, the direct empirical method gets much more weight at 5.5 magnitude than at 7.0 magnitude, clearly because this is where data are available. The empirical source function method gets relatively higher weight for the higher magnitude, as does the hybrid empirical method.

- It is important to note that the weights, as well as the overall ratings in Table A-2, are consistent with the expert discussion.

Preferences of the Overall Expert Community (Table A-4). Table A-4 shows the average weights, averaged over thirteen experts, indicating how the experts feel the overall expert community would rate the five methods. The most relevant observation about this table is that, in aggregate, the percentages in this table are roughly consistent with the weights in Table A-3, which indicates that the thirteen experts generally feel that they are representative of the overall ground-motion expert community. However, there are at least a couple of interesting differences between the two tables:

- The experts apparently feel that the overall ground-motion expert community would be even less positive about the intensity-based method than themselves.

- For some reason, the thirteen experts felt that the overall ground-motion community would rate the direct empirical method higher for frequency 1 Hz and magnitude 7.0 than the thirteen experts rated it (18, 16, 10 versus 4, 4, 3). This is true to a lesser extent for the 10 Hz frequency applications.

TABLE A-2

INTEGRATOR SURVEY: OVERALL RATINGS

(Scale: 0=poor, low; 10=excellent, high)

Expert	Stochastic	Empirical Src. Funct.	Direct Empirical	Hybrid Empirical	Intensity Based
1	8	8	10	8	0
2	8	10	10	5	5
3	8	8	0	5	2
4	10	×	×	×	×
5	10	8	0	5	0
6	8	8	5	2	0
7	8	8	5	8	0
8	10	8	10	5	0
9	8	6	5	5	0
10	8	8	0	2	2
11	10	8	5	2	0
12	5	2	×	×	8
13	8	8	10	2	0
Average	**8.4**	**7.5**	**5.5**	**4.5**	**1.4**
High Rank[1]	**9**	**5**	**4**	**1**	**1**
Low Rank[1]	**0**	**1**	**3**	**1**	**9**

[1] High Rank (Low Rank) indicates the number of experts that gave this method the highest (lowest) score. If two methods are tied for the highest (lowest) score, both methods are counted as highest (lowest).

TABLE A-3

INTEGRATOR SURVEY: USING THE APPROACHES FOR FORECASTING

How would you expect to weight the results if all five approaches were applied to a specific site application? (weights averaged over 13 experts)

Frequency	1	1	1	1	1	1	10	10	10	10	10	10
Magnitude	5.5	5.5	5.5	7.0	7.0	7.0	5.5	5.5	5.5	7.0	7.0	7.0
Distance	5	70	200	5	70	200	5	70	200	5	70	200
	WEIGHTS											
Stochastic	38	38	38	41	42	45	38	41	42	45	47	50
Empirical Src. Funct.	22	20	22	28	29	32	18	18	19	27	25	29
Direct Empirical	26	29	28	4	4	3	27	29	28	4	4	3
Intensity Based	10	8	9	13	12	11	9	8	8	13	12	10
Hybrid Empirical	4	4	3	13	13	9	9	4	3	12	12	8

TABLE A-4

INTEGRATOR SURVEY: PREFERENCES OF THE OVERALL EXPERT COMMUNITY

What percentage of the ground-motion community would you expect to favor each method if they could only choose one?
(percentages averaged over 13 experts)

Frequency	1	1	1	1	1	1	10	10	10	10	10	10
Magnitude	5.5	5.5	5.5	7.0	7.0	7.0	5.5	5.5	5.5	7.0	7.0	7.0
Distance	5	70	200	5	70	200	5	70	200	5	70	200
	PERCENTAGE											
Stochastic	41	41	43	44	42	48	39	43	46	47	49	51
Empirical Src. Funct.	21	21	23	26	29	31	20	19	20	29	29	29
Direct Empirical	28	28	27	18	16	10	27	28	26	11	9	9
Intensity Based	6	5	4	6	5	5	6	5	4	6	6	5
Hybrid Empirical	4	6	3	8	8	7	9	5	3	7	8	6

ATTACHMENT A-1

GROUND-MOTION WORKSHOP I

WRITTEN INSTRUCTIONS MAILED TO INVITED EXPERTS

SSHAC FIRST GROUND-MOTION ELICITATION WORKSHOP
March 17 and 18, 1994

INSTRUCTIONS FOR EXPERTS

You have been asked to attend the first SSHAC Ground Motion Elicitation Workshop, in the capacity of Ground Motion Expert.

SSHAC (Senior Seismic Hazard Analysis Committee) is a panel of engineers, seismologists, and geologists with experience in seismic-hazard analysis and in risk analysis in general. Its task is to develop a new, more stable, methodology for seismic hazard analysis, drawing on the experience from the EPRI and LLNL seismic-hazard studies and from other major seismic-hazard studies performed in the last five years. The SSHAC effort is sponsored by DOE, EPRI, and NRC.

The main objective of this workshop is to examine and compare the various approaches available for the prediction of ground-motions in the central and eastern United States for the purposes of seismic hazard analysis. The term "approach" is used here in a broad sense, representing a whole class of methods and including variants proposed by other authors. The following approaches will be presented and examined:

- Advanced numerical modeling (empirical Green's functions)
- Empirical regressions
- Intensity based approach
- Stochastic (source-spectrum based) approach

The second objective of the workshop is to test a different procedure for the elicitation of information from ground-motion experts. The proposed procedure will differ from past elicitations in three main aspects, as follows: (1) there will be more interaction, in order to clarify--and hopefully resolve--differences among experts, (2) a small group of integrators will take an active role in guiding and focusing the discussion, and (3) the integrators will formulate, based on the discussions and on their collective judgment, a position on which approaches are to be pursued, given their current state of development.

The third objective of the workshop is to present and discuss SSHAC's proposed framework for the characterization of uncertainty in ground-motion predictions. To meet this objective it is important that you read and study the paper entitled "Characterization of Uncertainty in Ground-Motion Predictions," which will be mailed to you in the next few days. You should be prepared to critique and discuss the paper at the workshop.

You will be asked to discuss the technical and practical merits of the four approaches. The discussion should focus on the scientific bases for the various approaches and on their ability to predict ground motions for future earthquakes of engineering interest. More specifically, the parameters of interest are as follows:

Geographic area:	Central and eastern United States (east of the Rockies)
Ground-motion measures:	PGA and spectral accelerations in the 0.5 to 35-Hz range.
Magnitudes:	**M** 5 to 8, or m_{Lg} 5 to 7.5
Distances:	0 to 500 km, with emphasis on the following: a) 0 to 100 km, all magnitudes and frequencies b) 100 to 500 km, f<2.5 Hz, M>6
Site conditions:	Hard rock

After the presentations and discussions, you will be asked to provide brief written comments on your opinions about the various approaches. These comments, together with the discussions, will be used by the integrators to formulate their conclusions.

Your contributions to the discussions and your written comments should be aimed at giving the SSHAC members[2] who will act as integrators--and other ground-motion experts--a clear picture of the strengths and limitations of various approaches. Detailed discussions on parameter values, minor differences among variants of the various approaches, implementation details, and predictions for specific magnitude-distance values will be the subject of a second workshop.

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[2]Most of these SSHAC members are not experts in ground-motion estimation but have considerable expertise in seismic-hazard analysis, general probabilistic methods, and expert elicitation.

ATTACHMENT A-2

GROUND-MOTION WORKSHOP I

WRITTEN INSTRUCTIONS MAILED TO PRESENTERS

SSHAC FIRST GROUND-MOTION ELICITATION WORKSHOP
March 17 and 18, 1994

INSTRUCTIONS FOR PRESENTERS

You have been asked to make a presentation on one of the approaches for ground-motion prediction listed below, before the SSHAC Ground-Motion Subcommittee and other ground-motion experts like yourself, during the first SSHAC Ground Motion Elicitation Workshop.

SSHAC (Senior Seismic Hazard Analysis Committee) is a panel of engineers, seismologists, and geologists with experience in seismic-hazard analysis and in risk analysis in general. Its task is to develop a new, more stable, methodology for seismic hazard analysis, drawing on the experience from the EPRI and LLNL seismic-hazard studies and from other major seismic-hazard studies performed in the last five years. The SSHAC effort is sponsored by DOE, EPRI, and NRC.

The main objective of this workshop is to examine and compare the various approaches available for the prediction of ground-motions in the central and eastern United States for the purposes of seismic hazard analysis. The term "approach" is used here in a broad sense, representing a whole class of methods and including variants proposed by other authors. The following approaches will be presented and examined:

- Advanced numerical modeling (empirical Green's functions) - Chandan Saikia

- Empirical regressions - Ken Campbell

- Intensity based - Mihailo Trifunac

- Stochastic (source-spectrum based) - Gail Atkinson

The second objective of the workshop is to test a different procedure for the elicitation of information from ground-motion experts. The proposed procedure will differ from past elicitations in three main aspects, as follows: (1) there will be more interaction, in order to clarify--and hopefully resolve--differences among experts, (2) a small group of integrators will take an active role in guiding and focusing the discussion, and (3) the integrators will formulate, based on the discussions and on their collective judgment, a position on which approaches are to be pursued, given their current state of development.

The third objective of the workshop is to present and discuss SSHAC's proposed framework for the characterization of uncertainty in ground-motion predictions. To meet this objective it is important that you read and study the paper entitled "Characterization of Uncertainty in Ground-Motion Predictions," which will be mailed to you in the next few days. You should be prepared to critique and discuss the paper at the workshop.

The presentation should focus on the ability of the approach you are presenting to predict ground motions for future earthquakes of engineering interest. More specifically, the parameters of interest are as follows:

Geographic area:	Central and eastern United States (east of the Rockies)
Ground-motion measures:	PGA and spectral accelerations in the 0.5 to 35-Hz range.
Magnitudes:	**M** 5 to 8, or m_{Lg} 5 to 7.5
Distances:	0 to 500 km, with emphasis on the following: a) 0 to 100 km, all magnitudes and frequencies b) 100 to 500 km, f<2.5 Hz, M>6
Site conditions:	Hard rock

Your presentation should be aimed at giving the SSHAC members[3] who will act as integrators--and other ground-motion experts--a clear picture of the basic assumptions, strengths, and limitations of the approach. The presentation should be broad enough to include other authors' variants of the approach you are presenting. The following is a list of topics that you should cover in your presentation (this is intended as guidance, not as a prescribed outline):

1. Brief description of the approach, emphasizing its basic elements. This exposition should cover only the basic elements that define the approach you are presenting and differentiate it from the other three approaches being presented by others. The exposition should also include a brief description of the main differences among investigators using the approach you are presenting.

2. Scientific/technical basis for the approach. This exposition should cover the basic assumptions of the approach you are presenting.

3. Required Data and Parameters. Describe the types of data or parameters required for

[3]Most of these SSHAC members are not experts in ground-motion estimation but have considerable expertise in seismic-hazard analysis, general probabilistic methods, and expert elicitation.

application of the approach you are presenting to the region, magnitudes, distances, and frequencies of interest. This discussion should focus on the types of data and parameters, including the availability and quality of the data, confidence in the parameter values, and the impact of the various and parameters on the final predictions.

4. Summary of Validation Studies. This exposition should summarize studies that serve to give confidence in the approach you are presenting. Studies that validate the approach as a whole (rather than its parts), and studies relevant to central and eastern North America and to ground-motions of engineering interest, should be emphasized (if feasible).

5. Applicability to the Various Magnitude-Distance-Frequency Ranges of Engineering Interest. For this discussion, we ask you to put yourself in the role of a seismic-hazard analyst who is trying to select attenuation equations to predict ground-motions for the various frequencies of interest. Discuss the parameter combinations for which the predictions obtained using the approach you are presenting are most reliable, and those for which they are less reliable. To help focus your discussion, we ask you to consider the following specific combinations of magnitude, distance (to the rupture), and frequency:

m_{Lg} 5.5	m_{Lg} 7.0
5 km (1 Hz, 10 Hz, and PGA)	5 km (1 Hz, 10 Hz, and PGA)
70 km (1 Hz, 10 Hz, and PGA)	70 km (1 Hz, 10 Hz, and PGA)
200 km (1 Hz and 10 Hz)	200 km (1 H, 10 Hz, and PGA)

You are not being asked to provide ground-motion predictions for these magnitude-distance combinations, only to comment on the adequacy of the approach for these combinations.

6. Areas of Strength and Weakness. Discuss the strengths and weaknesses of the approach you are presenting for the magnitude-distance-frequency combinations of interest. This should not be a critique of other approaches (there will be time for this elsewhere in the agenda).

Your presentation should focus on the basic scientific and technical issues relating to the approach you are presenting and its applicability to the problem of interest. Detailed discussions on parameter values, minor differences among variants of the approach, implementation details, and predictions for specific magnitude-distance values will be the subject of a second workshop.

You will be given 45 minutes for your presentation. You should allow some time for clarifications.

You are also asked to participate in all other discussions planned for the workshop. See the enclosed agenda and "Instructions to Participants" for more details.

ATTACHMENT A-3

GROUND-MOTION WORKSHOP I

AGENDA

SSHAC FIRST GROUND-MOTION ELICITATION WORKSHOP

March 17 and 18, 1994

AGENDA

Thursday, March 17

9:00-9:30	Introduction	David Boore
9:30-10:00	Elicitation: Past, Present and Future	Peter Morris
10:30-11:00	Break	
11:00-1:00	Characterization of Uncertainty in Ground Motions (presentation & discussion)	Gabriel Toro
1:00-2:00	Lunch	
2:00-3:30	Approaches to Ground-Motion Prediction	
	Intensity-based approach (2:00-2:45)	Mihailo Trifunac
	Empirical regression approach (2:45-3:30)	Ken Campbell
3:30-4:00	Break	
4:00-5:30	Approaches to Ground-Motion Prediction (continued)	
	Stochastic approach (4:00-4:45)	Gail Atkinson
	Advanced numerical modeling (4:45-5:30)	Chandan Saikia
5:30-6:00	Do we span the space of models with this set of basis vectors? (Is the shopping list complete?)	Discussion led by David Boore

Friday, March 18

8:30-10:30	Pros and Cons of Each Method	Discussion led by Integrators
10:30-11:00	Break	
11:00-12:30	Applicability of the various approaches to the (magnitude, distance, frequency) values of engineering interest	Discussion led by Integrators
12:30-1:00	Preparation of written comments to Integrators	Experts (individually)
1:00-2:00	Lunch	
2:00-3:00	Preliminary Integration	
	Presentation	Integrators
	Feedback	Experts
	Wrap-up	Integrators

ATTACHMENT A-4

GROUND MOTION WORKSHOP 1

INTEGRATOR SURVEY

PURPOSE OF SURVEY

- GUIDANCE FOR INTEGATORS
- FOR COMPARING APPROACHES, NOT EXPERTS
- ANONYMOUS

CONTEXT OF SURVEY

ALL QUESTIONS SHOULD BE ADDRESSED FOR:

- CENTRAL AND EASTERN UNITED STATES ONLY
- 1 TO 10 HERTZ FREQUENCY RANGE ONLY
- HARD ROCK SITE ONLY

COMPARISON OF APPROACHES

Use the key below to rate the various approaches in terms of how it deals with each issue. All four approaches should be rated for each issue:

A	=	**ADVANCED NUMERICAL**	**I**	=	**INTENSITY BASED**
E	=	**EMPIRICAL**	**S**	=	**STOCHASTIC**

	Poor Low				**Excellent High**
Example: **APPROACHE'S NAME** - Characterizes approach accurately	**A**	______	**I S**	______	**E**
MODEL LOGIC - Theoretically sound - Based on solid science - Reasonable underlying assumptions	______	______	______	______	______
USE OF DATA - Based on relevant data - Does not use questionable data	______	______	______	______	______
PARAMETER ESTIMATION - Sound estimation methods - Adequate sample size	______	______	______	______	______
CREDIBILITY OF APPROACH - Well-established, non-controversial - Time-tested, well-understood by expert community	______	______	______	______	______
OVERALL RATING	______	______	______	______	______

Please list the key assumptions that make each approach attractive or unattractive. Which assumptions or hypotheses are especially essential or undesirable? (use back of page if necessary):

Advanced numerical:

Empirical:

Intensity Based:

Stochastic:

USING THE APPROACHES FOR FORECASTING

Assign a weight (0 to 100) to each approach based on how you would expect to weight the results of all your approaches were applied to a specific site application characterized by frequency, magnitude, and distance. The weights should sum to 100.

Frequency: 1 Hz

Magnitude: / Distance:	m_{Lg} 5.5 / 5 km	m_{Lg} 5.5 / 70 km	m_{Lg} 5.5 / 200 km	m_{Lg} 7.0 / 5 km	m_{Lg} 7.0 / 70 km	m_{Lg} 7.0 / 200 km
Advanced Numerical	______	______	______	______	______	______
Empirical	______	______	______	______	______	______
Intensity Based	______	______	______	______	______	______
Stochastic	______	______	______	______	______	______
Total	100%	100%	100%	100%	100%	100%

Frequency: 10 Hz

Magnitude: / Distance:	m_{Lg} 5.5 / 5 km	m_{Lg} 5.5 / 70 km	m_{Lg} 5.5 / 200 km	m_{Lg} 7.0 / 5 km	m_{Lg} 7.0 / 70 km	m_{Lg} 7.0 / 200 km
Advanced Numerical	______	______	______	______	______	______
Empirical	______	______	______	______	______	______
Intensity Based	______	______	______	______	______	______
Stochastic	______	______	______	______	______	______
Total	100%	100%	100%	100%	100%	100%

Please summarize your reasons for the judgments by approach (use back of page if necessary):

Advanced numerical:

Empirical:

Intensity Based:

Stochastic:

PREFERENCES OF THE OVERALL EXPERT COMMUNITY

Consider the entire community of ground motion experts. What percentage would you expect to favor each approach of they could only choose one for each application. The percentages should add to 100 in each column.

Note: This should *not* reflect your own rating, only what you believe about the preferences of the overall group of experts.

Frequency: 1 Hz

Magnitude: / Distance:	m_{Lg} 5.5 / 5 km	m_{Lg} 5.5 / 70 km	m_{Lg} 5.5 / 200 km	m_{Lg} 7.0 / 5 km	m_{Lg} 7.0 / 70 km	m_{Lg} 7.0 / 200 km
Prefer Adv. Numerical						
Prefer Empirical						
Prefer Intensity Based						
Prefer Stochastic						
Total	100%	100%	100%	100%	100%	100%

Frequency: 10 Hz

Magnitude: / Distance:	m_{Lg} 5.5 / 5 km	m_{Lg} 5.5 / 70 km	m_{Lg} 5.5 / 200 km	m_{Lg} 7.0 / 5 km	m_{Lg} 7.0 / 70 km	m_{Lg} 7.0 / 200 km
Prefer Adv. Numerical						
Prefer Empirical						
Prefer Intensity Based						
Prefer Stochastic						
Total	100%	100%	100%	100%	100%	100%

Please summarize your reasons for the judgments (use back of page if necessary):

ATTACHMENT A-5

GROUND MOTION WORKSHOP 1

EXPERT INPUTS ON DIFFERENT ASPECTS OF THE GROUND MOTION MODELS

			GROUND MOTION WORKSHOP I		
MODEL LOGIC			INTEGRATOR SURVEY		
		Advanced	Direct	Hybrid	Intensity
Expert	Stochastic	Numerical	Empirical	Empirical	Based
1	8	10	10	5	0
2	10	10	8	8	5
3	8	10	8	5	2
4	10	x	x	x	x
5	10	10	8	8	5
6	8	10	5	2	2
7	8	8	10	8	2
8	10	8	10	5	2
9	10	10	5	5	0
10	5	8	8	2	2
11	10	8	10	2	0
12	2	2	x	x	8
13	x	x	x	x	x
Average	8.3	8.5	8.2	5.0	2.5
Hi Rank	6	7	5	0	1
Lo Rank	1	1	0	2	9

GROUND MOTION WORKSHOP I

USE OF DATA — *INTEGRATOR SURVEY*

Expert	Stochastic	Advanced Numerical	Direct Empirical	Hybrid Empirical	Intensity Based
1	8	10	10	10	5
2	8	10	10	8	5
3	10	10	10	8	2
4	10	x	x	x	x
5	10	10	5	5	0
6	10	8	5	5	2
7	8	8	5	5	2
8	10	10	10	5	8
9	8	8	5	5	2
10	x	8	10	5	2
11	8	5	10	2	5
12	x	x	x	x	8
13	8	8	10	2	0
Average	**8.9**	**8.6**	**8.2**	**5.5**	**3.4**
Hi Rank	**7**	**7**	**6**	**1**	**1**
Lo Rank	**0**	**1**	**0**	**1**	**9**

			GROUND MOTION WORKSHOP I		
CREDIBILITY OF APPROACH			INTEGRATOR SURVEY		
		Advanced	Direct	Hybrid	Intensity
Expert	Stochastic	Numerical	Empirical	Empirical	Based
1	8	8	10	8	0
2	10	10	10	8	0
3	8	8	10	2	2
4	10	x	x	x	x
5	5	5	10	5	0
6	8	5	5	2	0
7	8	8	8	8	0
8	8	5	10	2	5
9	8	2	2	2	0
10	8	8	8	2	2
11	10	5	10	2	0
12	5	2	x	x	8
13	10	8	8	2	0
Average	8.2	6.2	8.3	3.9	1.4
Hi Rank	8	3	8	1	1
Lo Rank	0	1	0	4	10

			GROUND MOTION WORKSHOP I		
PARAMETRIC ESTIMATION			INTEGRATOR SURVEY		
		Advanced	Direct	Hybrid	Intensity
Expert	Stochastic	Numerical	Empirical	Empirical	Based
1	8	8	x	8	2
2	10	10	10	10	10
3	5	5	0	8	2
4	10	x	x	x	x
5	x	x	x	x	x
6	10	5	5	2	8
7	8	8	2	5	0
8	8	5	10	x	0
9	8	5	5	5	0
10	5	5	0	2	2
11	8	5	2	2	0
12	5	5	x	x	5
13	8	8	10	2	0
Average	7.8	6.3	4.9	4.9	2.6
Hi Rank	9	4	3	3	2
Lo Rank	1	1	2	0	7

ATTACHMENT A-6

GROUND MOTION WORKSHOP 1

EXPERTS' WRITTEN COMMENTS

GROUND MOTION WORKSHOP I — INTEGRATORS SURVEY
COMPARISON OF APPROACHES

Experts who signed their surveys:
Expert 4 — Bill Joyner
Expert 12 — Mike Trifunac
Expert 13 — Bob Hermann

ADVANCED NUMERICAL:

Expert 1: Can include details in source and propagation (A); Difficult to implement (D).

Expert 2: I rate A as exceptional, because it handles everything.

Expert 3: Best captures physical process/requires too many parameters.

Expert 4: Too complex — Too many parameters.

Expert 5: Advantages: rigorous treatment of wave propagation, captures elements of natural variability in source functions, favorably compares to extant data; Disadvantages: too many poorly determined parameters, computationally cumbersome.

Expert 6: No comments

Expert 7: Requires that fairly detailed knowledge of source and earth structure are known. This makes this method attractive for very specific applications but less attractive for generalizing to regional attenuations.

Expert 8: Requires many (source) parameters. Correlations between source parameters not well known. Distributions of additional source parameters are uncertain.

Expert 9: Clarification: Refers to an application of A where one has randomized over all epistemic (as of the present) and aleatory uncertainties.
Unattractive: complexity, need for very detailed data, empirical modeling of seismic source is cumbersome.
It is not clear how much is gained by using a very detailed physical model when parameters are not well known and have to be integrated over. One has to integrate over some parameters (e.g., crustal structure) because they have epistemic uncertainty and over others because they have aleatory uncertainty (fault dip, azimuth/distance, rake angle, slip distribution, etc.). This is where I see the stochastic model as a useful compromise.
Attractive: most complete physical model; especially useful for 1Hz at 500 km.

Expert 10: Allows for good physical modeling etc. Main problems: do not have good source functions. Must extrapolate from small earthquakes and/or WUS data for small earthquakes. Also iffy on how to distribute over fault.

Expert 11: Useful for understanding past earthquakes and extrapolating to crustal structures without empirical data.

Expert 12: Cannot go beyond 1-3Hz.

Expert 13: Attractive: Permits theoretically based extrapolation of data set
Unattractive: time-consuming to consider all possible source time functions.

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EMPIRICAL:

Expert 1: Direct: Based on data (A); Not dependent on models (A); No large M data (D)

Hybrid: Based on data (A); Less dependent on Models (A); Large uncertainty (D); Cannot be used at long distances (D)

Expert 2: They are good methods, probably the best, provided we have data. In east and central United States this may be a limitation.

Expert 3: Least number of assumptions/too few data (D); Makes good use of UCUS data/calibration to EVS problematic (H)

Expert 4: Direct: Inadequate data above M_{eq} =5

Hybrid: No advantage over stochastic if scaling is the same E and W and inadequate if the scaling is not the same

Expert 5: Direct: Limited data

Hybrid: Advantage: uses WNA data; Disadvantage: uncertainty in shifting to ENA

Expert 6: No comments

Expert 7: Direct: General form of relationships is well known from studies of empirical data and modeling — problem is lack of data to refine estimate

Hybrid empirical: Key assumption is that one can identify the key differences between EUS & WUS and adjust for them. To the extent that this can be done with the stochastic model, then the HE method may not bring much information on the mean, but it can bring a lot of information on sigma.

Expert 8: Direct: When data is available, this is the best method

Hybrid: No comments

Expert 9: Direct:
Advantages: Conceptually simple (straightforward), would be preferred if there were more data (S. Calif.)
Disadvantage: Not sufficient data (M dependence is very poorly constrained).

Hybrid:
Advantage: Brings some of the WUS information to bear (e.g., M scaling, extended source, short-distribution attenuation)
Disadvantages: Does not use CEUS data as much as it should. It is not a clean procedure, affected by uncertainties about parameters in both east and west. Except for extended source effects, the structure of the stochastic model may be a better way to transfer knowledge from west to east (except for extended-source effects).

Expert 10: Direct: Excellent but no data: not useful except at M≅5.

Hybrid: Have to make assumption that M scales the same in WUS as in EUS. Corrections a bit iffy but then no more so than the results from the stochastic model.

EMPIRICAL (cont'd):

Expert 11: Direct: Useful for ≈M5 earthquakes. Can't be extrapolated to M≥6.

Hybrid: Not useful due to uncertainty in "adjustments" except possibly as a consistency check.

Expert 12: No adequate data for EUS

Expert 13: Attractive: Data cannot be denied, but extrapolation to larger distances, magnitudes must be model-based.

INTENSITY-BASED:

Expert 1: Tied to intensity data (A); Poor relationship with ground motion (D)

Expert 2: We do not have much data except for the data in the old BSSA papers. An evaluation of these data by the experts is relevant.

Expert 3: Uses data from large ENA earthquakes/poor quality, non-engineering data

Expert 4: Intensity data can be better used in the stochastic model. Intensity data should be used in the form of isoseismal areas.

Expert 5: Limited data; High uncertainty in translating to engineering parameter

Expert 6: No comments

Expert 7: Key assumption is translation from I_s to ground motion parameter — this is a weak correlation and implies large uncertainties.

Expert 8: Poor reliability going from site intensity to ground motion. Useful for M_{eq} estimation.

Expert 9: Clarification: Refers to the LLNL Expert-5 approach, as documented by LLNL and by Trifunac-Lee NRC reports (ca. 1988) (this characterization may be out of date). Trifunac presentation did not help at all.
[Footnote #1 to I under Parameter Estimation:] Parameter estimation method is very poor. Sample size is large.

Expert 10: Generally not useful because we lack the key information of GM=f(I_s, size, d) for region of interest. However, it is actual data from the large EUS earthquakes that reflect the ground motion and actual source. Therefore useful in M~7-8 range out to about 150 Km.

Expert 11: Useful for limited purposes only: Use felt area to determine high-frequency level.

Expert 12: Good, simple and direct.

Expert 13: Unattractive: Should compare Fourier amplitude spectra estimates in WUS to EUS data.

STOCHASTIC:

Expert 1: Can include basic source and propagation parameters (A); May not adequately predict long periods (D)

Expert 2: I like this and apply this myself. I know its inherent limitation. We may say those limitations do not matter, but they are limitations. Parameters that properly [sic] depth-related and crustal structure-related attenuation are quite average. In east, this is our chance to include them correctly so that we do not have to come back later and spin the wheel again. I see a strong interaction between stochastic and Advanced numerical method because I am a believer and doer of both.

Expert 3: Good physical basis, computational expedient/in part still under development

Expert 4: No comments

Expert 5: Advantages: simple with easy-to-measure parameters therefore robust, predictions compare favorably with extant data; Disadvantage: highly sensitive to one parameter, delta sigma.

Expert 6: No comments

Expert 7: Gross properties of earthquakes can be represented in "simple" physical models (validated in WUS) and that these can be estimated for the east

Expert 8: Simple enough to keep the number of source parameters small. Better known source parameter distributions.

Expert 9: Advantages: Contains (or mimics) most significant physical processes affecting ground motions, yet simple enough, moderate number of parameters.

Disadvantages: There is still significant uncertainty about source spectrum of large CEUS quakes (given Mo or MLg). Handling of extended-source effects is not well established. Wave propagation: geometric attenuation and duration modeling need some improvement.

Expert 10: Generally most useful in M range of most interest. Can be calibrated with existing data. Has problems with large earthquakes close-in. Some uses exist. Overall the most useful method as it requires the fewest empirical parameters and yet keeps some physics

Expert 11: Useful for these predictions. Emphasis on model validation with data is required.

Expert 12: No comments

Expert 13: Attractive: Permits theoretically based extrapolation of data set.

ATTACHMENT A-7

GROUND MOTION WORKSHOP 1

DETAILED EXPERT INPUTS ON USING THE APPROACHES FOR FORECASTING

GROUND MOTION WORKSHOP I — INTEGRATORS SURVEY
USING THE APPROACHES FOR FORECASTING

ADVANCED NUMERICAL:

Expert 1: [refers to list of advantages/disadvantages under "Comparison of Approaches"]

Expert 2: Advanced numerical modeling helps to include the source complexity, path effects including scattering and site. It is stable and also helps us to understand the variation of ground motions due to known parameters at least in east and central United States.

Addendum:

- It has super predictive power
- To integrate the parameter effects, you have to know first these effects in real situations.
- Note: it could predict the ground motion of Northridge event. You cannot rule out this kind of power of this method in the ground motion prediction.
- Please do not [sic] do the exercise and see how stochastic prediction did against the Northridge data just as an exercise, at least to evaluate the method.

Events that cannot be modeled should not be discarded. They may give inputs to real hazard estimation.

Expert 3: The above [i.e., the numbers on same sheet] reflect rough a priori estimates. I am sure I would revise the weights based on the results and uncertainties of the various methods.

Expert 4: I would use the stochastic method in all cases for reasons given on the back page [transcribed here]:

I am not very good at checking boxes. I believe that the stochastic point source model is the best approach for all of the magnitudes and distances except possibly for the M_{eq} =5.0, where the direct empirical might be preferred. M_{eq} =5.0 earthquakes are not, however, a significant part of the hazard and the advantages of using one method across the magnitude range favor the use of the stochastic point source model even for M_{eq} =5.0. There is simply not enough data to use the direct empirical methods for magnitudes higher than M_{eq} =5.0. As for the hybrid empirical method, there is no advantage over the point-source stochastic method if the magnitude scaling is the same in the east as the west, except that the hybrid method might represent finite source effects better. Walt Silva's comparisons of point-source stochastic models with data in the west suggest that the deficiencies of the point-source models for representing extended sources are small and would not have much effect on eastern US hazard. If the ground-motion scaling is different in the east, then the point-source stochastic model is superior.

I believe that intensity data should be incorporated as suggested by Gail Atkinson, that is by using felt areas (or isoseismal areas) to determine the high-frequency spectral levels. Isoseismal areas could also be used in methods such as proposed by Art Frankel to check the parameters (e.g., Q) of the point-source stochastic model. The direct use of intensity requires the use of ground-motion vs. intensity relationships which I don't understand very well, but which make me very uneasy. As I understand it, their use results in large increases in uncertainty. In any case, if they are used they should be scrutinized very carefully.

There are a number of different advanced methods (which I interpret as finite-source methods). Some of them I don't like very much; one of them I am the author of. I believe they all are too complex and involve too many parameters for the eastern US problem. The only possible advantage I see is in taking account of finite source effects for the M_{eq} =7.0 earthquake at 5.0 km. As I stated earlier, however, it does not seem to me that the deficiencies of the point-source stochastic model in accounting for finite-source effects would have much impact on eastern US hazard.

Expert 5: Both Stochastic and Advanced Numerical match extant data about equally well. Because stochastic requires fewer parameters, it is more robust and therefore warrants slightly higher weight.

Expert 6: Logic, complete, when used together with "empirical" scattering functions it is globally applicable. Difficulty lies in constraining ''geophysical" parameter space for input. Easy to use sensitivity studies to explore dependence of sigma on various input parameters. Difficulty how to test output against observable data.

Expert 7: The model requires too much additional information that is not known to give it an advantage over the S method in the east.

Expert 8: In its current form, I would not use the advanced numerical results. I've assumed that a sufficient number of parameter variations have been run with a simplified presentation of results (e.g., attenuation relation has been removed or table of mean and standard error of ground motions for each magnitude and distance is given). Requires a lot of runs before I'm confident that the results are robust.

Expert 9: No comments

Expert 10: For small earthquakes (M=5.5) I don't see much difference between A and S, so I put weight on S. For other cases I have down-weighted A because of complexity in use and in the need for source function. I'm not sure about the percentage between A and S here. I need to look a bit more closely at A to see where it has significant (if any) advantages over S. In this case I'm assuming that S includes extended source model "S". If not, then my weights would change accordingly.

Expert 11: Approach is good, especially at low frequencies, but needlessly complex. Parameters hard to determine.

Expert 12: Cannot be used beyond 1-3 Hz

Expert 13: [see General Comments below]

EMPIRICAL:

Expert 1: [refers to list of advantages/disadvantages under "Comparison of Approaches"]

Expert 2: Useful when data is available, also even when we use hybrid method in a less expensive manner

Expert 3: The above [i.e., the numbers on same sheet] reflect rough a priori estimates. I am sure I would revise the weights based on the results and uncertainties of the various methods.

EMPIRICAL (cont'd):

Expert 4: I would use the stochastic method in all cases for reasons given on the back page [transcribed above, under "Advanced Numerical"]

Expert 5: Direct: Limited data.
Hybrid: Useful approach, but uncertainty in shifting to ENA

Expert 6: Direct: Limited data sets make uncertainties high at short distances and for large magnitudes.

Expert 7: Direct: Data available for small magnitudes by magnitude scaling not known well enough provides a basis for estimating uncertainties

Expert 8: Direct: Only have data for M < 5.
Hybrid: No comments

Expert 9: No comments

Expert 10: Direct: Good for M=5.5 but no good elsewhere other than a check — too little data.
Hybrid: No point using at M=5.5 — of some value for larger events as you get the source function in.

Expert 11: Direct: Method good but data lacking at large M.
Hybrid: I don't think the method is useful due to unknown source differences between east and west.

Expert 12: OK. but no adequate data

Expert 13: Direct: Direct empirical is limited by distance/magnitude range of data sets and the extent to which observations are extrapolated.
Hybrid: Hybrid empirical is affected by lack of knowledge of variability (regional) of controlling factors. However, this may provide a plausible constraint for large-magnitude, short-distance motions.

INTENSITY-BASED:

Expert 1: [refers to list of advantages/disadvantages under "Comparison of Approaches"]

Expert 2: Should use it as a check. Many times you have intensity information at a site where you do not have ground motion. For such a scenario, it can be tool (supportive at least)

Expert 3: The above [i.e., the numbers on same sheet] reflect rough a priori estimates. I am sure I would revise the weights based on the results and uncertainties of the various methods.

Expert 4: I would use the stochastic method in all cases for reasons given on the back page [transcribed above, under "Advanced Numerical"]

Expert 5: Useful approach, large uncertainty

Expert 6: Poor quality of "original" data (site geology-dependent, construction-dependence make these data uncertain, but should be used at high M and at short distances to check results on other methods where these are highly uncertain because of poor or non-existent instrumental data

INTENSITY-BASED (cont'd):

Expert 7: Too much uncertainty in the translation to ground motion parameters of interest

Expert 8: I have no confidence in this method to predict ground motions.

Expert 9: No comments

Expert 10: Good for checking — of value for very large events out to 70km as only actual data from such events which is the actual source effects

Expert 11: Intensity data generally unreliable for making direct ground motion predictions; no credible methods.

Expert 12: OK

Expert 13: No comments

STOCHASTIC:

Expert 1: [refers to list of advantages/disadvantages under "Comparison of Approaches"]

Expert 2: It is sound process and as good as numerical modeling. I have not seen their time-series and fit at long period. So at present, I am critical (I am open to change my opinion when I see it).

Expert 3: The above [i.e., the numbers on same sheet] reflect rough a priori estimates. I am sure I would revise the weights based on the results and uncertainties of the various methods.

Expert 4: I would use the stochastic method in all cases for reasons given on the back page [transcribed above, under "Advanced Numerical"]

Expert 5: Both Stochastic and Advanced Numerical match extant data about equally well. Because stochastic requires fewer parameters, it is more robust and therefore warrants slightly higher weight.

Expert 6: Probably the most versatile, particularly when combined in an upgraded hybrid form together with advanced numerical methods. There are some problems with duration i.e., beyond 100 km. At short distances the source randomness (and finite source size) may cause difficulties. The source model (Brume, 1-corner, 2-corner, multicorner spectral shape) may cause epistemic uncertainties, but whose σ can be readily determined by applying alternative source models.

Expert 7: Does a good job of matching observations in the WUS with a simple set of parameters that can be estimated for the east.

Expert 8: Well developed model. I have confidence that results are robust. Maybe (but I don't think so) troubles at 1 Hz.

Expert 9: No comments

Expert 10: Generally the best, except around M=7 or greater close in there are problems.

Expert 11: Applicable to predictions, requiring a minimum of parameters, and well-accepted.

Expert 12: Problem at ≤ 1 Hz.

Expert 13: No comments

ATTACHMENT A-8

GROUND MOTION WORKSHOP 1

DETAILED EXPERT INPUTS ON PREFERENCES OF THE OVERALL EXPERT COMMUNITY

GROUND MOTION WORKSHOP I — INTEGRATORS SURVEY
PREFERENCES OF OVERALL EXPERT COMMUNITY

SUMMARY OF "YOUR REASONS FOR THE JUDGMENTS":

Expert 1: Above estimates are highly speculative and will depend on the makeup of the experts. Seismologists will prefer the numerical methods (S-bias), engineers will prefer the empirical methods (E-bias), and a small minority of primarily engineers and other disciplines will prefer the intensity methods (I-bias). Assigning values in above table has a very large uncertainty, but since the community of ground motion experts in the east is biased towards seismologists, the numerical methods (Advanced and Stochastic) will be the preferred models as a percentage of total.

Expert 2:
1. Stochastic and Advanced Numerical methods are useful and have predictive powers, except at long period where Advanced Numeric wins.
2. Empirical and Hybrid may be useful at 5.5 by extrapolating 5.0.
3. Intensity data may not be transportable because it depends on the site condition.

Expert 3: Some of the techniques are newer and less well established than others (e.g., Hybrid Empirical may be hardly known and Advanced Numerical is, I believe, fast gaining popularity). I cannot break the percentages down by M_{Lg}, R, or f.

Expert 4: I don't really think I have a good sense of the views of the entire community.

Expert 5: Stochastic and Advanced Numerical have track record in WNA and are perceived as reliable models. Intensity is still favored by some. Indirect Empirical has attractive elements.

Expert 6: No comments

Expert 7: Community still likes to consider intensity because of presence of data.
Community likes Advanced Numerical modeling because of its conceptual advantages.
Community beginning to recognize that much of what AN offers can be captured in S.

Expert 8: No comments

Expert 9: No comments

Expert 10: No comments

Expert 11: I think most people are comfortable with the stochastic approach and appreciate its simplicity. Numerical models are also favored, but I think to a lesser degree due to complexity. But for large events at low frequencies, numerical models are often preferred. I sense no support for intensity-based ground motion predictions because no credible method has been presented. Empirical <u>methods</u> are favored by data are lacking.

Expert 12: No comments, except quotes were added around the word "expert"

Expert 13: I presume that the experts know the inherent difficulties of prediction for Eastern North America. I would also assume that they are optimistic about data sets, and hence inclined or prejudiced toward empirical data of any time and that they distrust complicated numerical techniques.

PREFERENCES OF OVERALL EXPERT COMMUNITY — Page 2

GROUND MOTION WORKSHOP I — INTEGRATORS SURVEY GENERAL COMMENTS

Expert 13:

- One general comment is that prediction models must agree with observations, where those observations exist. If there is no agreement, then model parameters for advanced numerical, stochastic must be carefully modified.
- Given my extensions to stochastic, Silva's work for finite fault stochastic, stochastic is really a hybrid, advanced numerical technique. A difference between the two is that one is tied to a specific waveform and the other to a specific spectrum and duration. Stochastic encompasses time domain modeling ensembles.
- Because of uncertainty about large earthquakes, a distribution of source models must be considered for large magnitudes, primarily to incorporate reasonable fault length/width aspect ratio, and high-frequency asperities typically seem in large (M >6) earthquakes.
- Advanced numerical has practical, computational limits at high frequency. At lower frequency it is a good extrapolator.
- In general, empirical data are required for calibration of all models, especially stochastic/advance numerical. The real advantage of these two latter techniques is that sensitivity analysis can be performed to:

a) Estimate the effect of "epistemic" error on motion estimates. For example, for a given M_{Lg}, measured at large distance, the effect will be to increase uncertainty at short distance.

b) The second aspect is that such a sensitivity analysis would define the most crucial source parameters and thus drive research to reduce the "epistemic" uncertainty for future analysis. Estimation of uncertainty may be as important as estimating the mean ground motion value.

GROUND MOTION WORKSHOP I

INTEGRATOR SURVEY: EXPERT INPUTS

USING THE APPROACHES FOR FORECASTING

		Freq.		1				Freq.		1				Freq.		1				Freq.		1		
		Mag.		5.5				Mag.		5.5				Mag.		5.5				Mag.		7		
		Dist.		5				Dist.		70				Dist.		200				Dist.		5		
Exp	AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE	
1	5	85	0	5	5	100	5	85	0	5	5	100	5	85	0	5	5	100	50	0	20	15	15	100
2	50	20	20	10	0	100	35	30	0	35	0	100	50	0	0	50	0	100	40	15	0	25	20	100
3	35	15	5	35	10	100	35	15	5	35	10	100	35	15	5	35	10	100	30	5	15	30	20	100
4	0	0	0	100	0	100	0	0	0	100	0	100	0	0	0	100	0	100	0	0	0	100	0	100
5	40	0	0	50	10	100	40	0	0	50	10	100	40	0	0	50	10	100	40	0	0	50	10	100
6	30	15	5	50	0	100	35	15	5	45	0	100	40	15	5	40	0	100	20	10	10	40	20	100
7	10	20	0	60	20	100	10	20	0	60	20	100	10	35	0	60	5	100	10	0	0	60	30	100
8	35	25	0	40	0	100	20	50	0	30	0	100	25	50	0	25	0	100	35	0	0	50	15	100
9	20	20	0	60	0	100	20	30	0	50	0	100	20	30	0	50	0	100	10	20	0	50	20	100
10	0	70	0	25	5	100	0	70	0	25	5	100	0	70	0	30	0	100	40	0	25	20	15	100
11	30	30	0	40	0	100	30	30	0	40	0	100	30	30	0	40	0	100	50	0	0	50	0	100
12	5	3	90	2	0	100	5	3	90	2	0	100	0	0	100	0	0	100	5	3	90	2	0	100
13	30	30	5	30	5	100	30	30	5	30	5	100	25	40	5	25	5	100	40	5	5	40	10	100
Avg	**22**	**26**	**10**	**38**	**4**	**100**	**20**	**29**	**8**	**38**	**4**	**100**	**22**	**28**	**9**	**38**	**3**	**100**	**28**	**4**	**13**	**41**	**13**	**100**

GROUND MOTION WORKSHOP I

INTEGRATOR SURVEY: EXPERT INPUTS

USING THE APPROACHES FOR FORECASTING

		Freq.		1					Freq.		1					Freq.		10					Freq.	
		Mag.		7					Mag.		7					Mag.		5.5					Mag.	
		Dist.		70					Dist.		200					Dist.		5					Dist.	
Exp	AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE	
1	50	0	10	20	20	100	50	0	10	20	20	100	5	85	0	5	5	100	5	85	0	5	5	100
2	35	10	0	35	20	100	50	0	0	50	0	100	25	40	10	25	0	100	35	30	0	35	0	100
3	30	5	15	30	20	100	30	5	15	30	20	100	35	15	5	35	10	100	35	15	5	35	10	100
4	0	0	0	100	0	100	0	0	0	100	0	100	0	0	0	100	0	100	0	0	0	100	0	100
5	40	0	0	50	10	100	40	0	0	50	10	100	40	0	0	50	10	100	40	0	0	50	10	100
6	30	10	10	35	15	100	40	10	10	30	10	100	20	10	10	60	0	100	25	15	10	50	0	100
7	10	0	0	60	30	100	20	0	0	60	20	100	10	20	0	50	20	100	10	20	0	50	20	100
8	35	0	0	60	5	100	40	0	0	60	0	100	25	25	0	50	0	100	15	50	0	35	0	100
9	10	20	0	50	20	100	10	20	0	50	20	100	15	15	0	8	70	108	15	25	0	60	0	100
10	40	0	25	20	15	100	50	0	0	40	10	100	0	70	0	30	0	100	0	70	0	30	0	100
11	50	0	0	50	0	100	50	0	0	50	0	100	25	30	0	45	0	100	25	30	0	45	0	100
12	5	3	90	2	0	100	0	0	100	0	0	100	0	5	90	5	0	100	0	5	90	5	0	100
13	40	5	5	40	10	100	40	10	5	40	5	100	30	30	0	35	5	100	30	30	5	30	5	100
Avg	**29**	**4**	**12**	**42**	**13**	**100**	**32**	**3**	**11**	**45**	**9**	**100**	**18**	**27**	**9**	**38**	**9**	**101**	**18**	**29**	**8**	**41**	**4**	**100**

Fourth case parameters: Freq. 10, Mag. 5.5, Dist. 70

GROUND MOTION WORKSHOP I

INTEGRATOR SURVEY: EXPERT INPUTS

USING THE APPROACHES FOR FORECASTING

		Freq.		10				Freq.		10				Freq.		10				Freq.		10		
		Mag.		5.5				Mag.		7				Mag.		7				Mag.		7		
		Dist.		200				Dist.		5				Dist.		70				Dist.		200		
Exp	AN	DE	IB	S	HE		AN	DE	IB	S	HE	0	AN	DE	IB	S	HE		AN	DE	IB	S	HE	
1	5	85	0	5	5	100	25	0	25	25	25	100	30	0	10	30	30	100	30	0	10	30	30	100
2	50	0	0	50	0	100	60	15	0	20	15	110	35	10	0	35	20	100	50	0	0	50	0	100
3	35	15	5	35	10	100	30	5	15	30	20	100	30	5	15	30	20	100	30	5	15	30	20	100
4	0	0	0	100	0	100	0	0	0	100	0	100	0	0	0	100	0	100	0	0	0	100	0	100
5	40	0	0	50	10	100	40	0	0	50	10	100	40	0	0	50	10	100	40	0	0	50	10	100
6	30	10	10	50	0	100	40	5	15	40	0	100	35	10	15	40	0	100	40	5	15	40	0	100
7	10	35	0	50	5	100	10	0	0	60	30	100	10	0	0	60	30	100	20	0	0	60	20	100
8	15	50	0	35	0	100	35	0	0	50	15	100	35	0	0	60	5	100	30	0	0	70	0	100
9	15	25	0	60	0	100	10	15	0	70	5	100	10	15	0	70	5	100	10	15	0	70	5	100
10	0	70	0	30	0	100	25	0	25	25	25	100	25	0	25	25	25	100	50	0	0	40	10	100
11	25	30	0	45	0	100	40	0	0	60	0	100	40	0	0	60	0	100	40	0	0	60	0	100
12	0	0	90	10	0	100	0	5	90	5	0	100	0	5	90	5	0	100	0	0	90	10	0	100
13	25	40	5	25	5	100	30	5	5	45	15	100	35	5	5	45	10	100	40	10	5	40	5	100
Avg	**19**	**28**	**8**	**42**	**3**	**100**	**27**	**4**	**13**	**45**	**12**	**101**	**25**	**4**	**12**	**47**	**12**	**100**	**29**	**3**	**10**	**50**	**8**	**100**

GROUND MOTION WORKSHOP I

INTEGRATOR SURVEY: EXPERT INPUTS

PREFERENCES OF THE OVERALL EXPERT COMMUNITY

		Freq.		1				Freq.		1				Freq.		1				Freq.		1		
		Mag.		5.5				Mag.		5.5				Mag.		5.5				Mag.		7		
		Dist.		5				Dist.		70				Dist.		200				Dist.		5		
Exp	AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE	
1	22	50	1	22	5	100	22	50	1	22	5	100	22	50	1	22	5	100	22	50	1	22	5	100
2	30	30	10	30	0	100	30	20	0	30	20	100	50	0	0	50	0	100	60	0	0	30	10	100
3	25	5	10	50	10	100	25	5	10	50	10	100	25	5	10	50	10	100	25	5	10	50	10	100
4	x	x	x	x	x	0	x	x	x	x	x	0	x	x	x	x	x	0	x	x	x	x	x	0
5	30	0	10	50	10	100	30	0	10	50	10	100	30	0	10	50	10	100	30	0	10	50	10	100
6	20	10	0	70	0	100	20	10	0	70	0	100	20	10	0	70	0	100	20	10	0	70	0	100
7	40	10	10	40	0	100	40	10	10	40	0	100	40	10	10	40	0	100	40	5	10	40	5	100
8	30	30	5	30	5	100	30	30	5	30	5	100	30	30	5	35	0	100	10	0	10	75	5	100
9	20	20	0	60	0	100	20	30	0	50	0	100	20	30	0	50	0	100	10	20	0	50	20	100
10	0	70	0	25	5	100	0	70	0	25	5	100	10	80	0	10	0	100	10	80	0	10	0	100
11	20	20	0	55	5	100	20	20	0	55	5	100	20	20	0	55	5	100	50	0	0	45	5	100
12	10	5	20	60	5	100	10	5	20	60	5	100	0	5	10	80	5	100	10	5	20	60	5	100
13	5	80	5	5	5	100	5	80	5	5	5	100	5	80	5	5	5	100	20	40	5	20	15	100
Avg	21	28	6	41	4	100	21	28	5	41	6	100	23	27	4	43	3	100	26	18	6	44	8	100

GROUND MOTION WORKSHOP I

INTEGRATOR SURVEY: EXPERT INPUTS

PREFERENCES OF THE OVERALL EXPERT COMMUNITY

		Freq.		1				Freq.		1				Freq.		10				Freq.		10	
		Mag.		7				Mag.		7				Mag.		5.5				Mag.		5.5	
		Dist.		70				Dist.		200				Dist.		5				Dist.		70	
Exp	AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE	
1	22	50	1	22	5	100	22	50	1	22	5	100	22	50	1	22	5	100	22	50	1	22	5	100
2	50	0	0	35	15	100	50	0	0	50	0	100	35	20	10	35	0	100	30	20	0	30	20	100
3	25	5	10	50	10	100	25	5	10	50	10	100	25	5	10	50	10	100	25	5	10	50	10	100
4	x	x	x	x	x	0	x	x	x	x	x	0	x	x	x	x	x	0	x	x	x	x	x	0
5	30	0	10	50	10	100	30	0	10	50	10	100	30	0	10	50	10	100	30	0	10	50	10	100
6	20	10	0	70	0	100	20	10	0	70	0	100	20	10	0	70	0	100	20	10	0	70	0	100
7	40	5	10	40	5	100	40	5	10	40	5	100	40	10	10	40	0	100	40	10	10	40	0	100
8	50	0	5	45	0	100	40	0	0	60	0	100	10	25	5	60	0	100	10	25	5	60	0	100
9	10	20	0	50	20	100	10	20	0	50	20	100	15	15	0	8	70	108	15	25	0	60	0	100
10	10	80	0	10	0	100	50	0	10	30	10	100	10	80	0	10	0	100	10	80	0	10	0	100
11	50	0	0	45	5	100	50	0	0	45	5	100	15	20	0	60	5	100	15	20	0	60	5	100
12	10	5	20	60	5	100	0	5	10	80	5	100	10	5	20	60	5	100	10	5	20	60	5	100
13	30	20	5	30	15	100	30	20	5	30	15	100	5	80	5	5	5	100	5	80	5	5	5	100
Avg	29	16	5	42	8	100	31	10	5	48	7	100	20	27	6	39	9	101	19	28	5	43	5	100

GROUND MOTION WORKSHOP I

INTEGRATOR SURVEY: EXPERT INPUTS

PREFERENCES OF THE OVERALL EXPERT COMMUNITY

		Freq.		10				Freq.		10				Freq.		10				Freq.		10		
		Mag.		5.5				Mag.		7				Mag.		7				Mag.		7		
		Dist.		200				Dist.		5				Dist.		70				Dist.		200		
Exp	AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE	
1	22	50	1	22	5	100	22	50	1	22	5	100	22	50	1	22	5	100	22	50	1	22	5	100
2	50	0	0	50	0	100	60	0	0	30	10	100	50	0	0	35	15	100	50	0	0	50	0	100
3	25	5	10	50	10	100	25	5	10	50	10	100	25	5	10	50	10	100	25	5	10	50	10	100
4	x	x	x	x	x	0	x	x	x	x	x	0	x	x	x	x	x	0	x	x	x	x	x	0
5	30	0	10	50	10	100	30	0	10	50	10	100	30	0	10	50	10	100	30	0	10	50	10	100
6	20	10	0	70	0	100	20	10	0	70	0	100	20	10	0	70	0	100	20	10	0	70	0	100
7	40	10	10	40	0	100	40	5	10	40	5	100	40	5	10	40	5	100	40	5	10	40	5	100
8	10	25	5	60	0	100	10	0	10	75	5	100	10	0	10	75	5	100	20	0	5	75	0	100
9	15	25	0	60	0	100	10	15	0	70	5	100	10	15	0	70	5	100	10	15	0	70	5	100
10	10	80	0	10	0	100	50	0	10	30	10	100	50	0	10	30	10	100	50	0	10	30	10	100
11	15	20	0	60	5	100	45	0	0	50	5	100	45	0	0	50	5	100	45	0	0	50	5	100
12	0	5	10	80	5	100	10	5	20	60	5	100	10	5	20	60	5	100	0	5	10	80	5	100
13	5	80	5	5	5	100	20	40	5	20	15	100	30	20	5	30	15	100	30	20	5	30	15	100
Avg	20	26	4	46	3	100	29	11	6	47	7	100	29	9	6	49	8	100	29	9	5	51	6	100

APPENDIX B

GROUND MOTION WORKSHOP II

JULY 28-29, 1994

MENLO PARK, CALIFORNIA

B.1 INTRODUCTION

As discussed in the introduction to Appendix A, two ground-motion workshops were held to test a way of eliciting information that SSHAC felt was an improvement over previous elicitation methods. The first workshop, discussed in Appendix A, dealt with the broad issues of what methods should be considered in ground-motion estimation for ENA and was attended by 26 individuals. The second workshop, discussed in this Appendix, was smaller and more intense. In it, specific values of ground motion were elicited and specific differences in data, assumptions and estimates were addressed.

The experts were asked to provide ground-motion estimates at three different times; namely, before, during, and after the workshop. Intensive information exchange and directed interaction took place before and between these times. This Appendix starts with a discussion of the workshop planning and organization, and then proceeds to discuss the Pre-, Co-, and Post-workshop results in sequence. Following this, we discuss the integration performed by the Integrators. Because of time and budget limitations, this integration is not yet complete. In spite of that, however, we feel that the integration process was adequate to allow useful recommendations for future integrations, and that the ground-motion estimates themselves will prove to be useful to the scientific and engineering community.

Many attachments accompany this Appendix. All of the questionnaires and documentation from the experts are included, as well as various graphical presentations of the ground-motion values. In addition, a description of the database prepared for comparison with the ground-motion estimates is included (one lesson from Workshop I was that this database should have been prepared prior to the first workshop; as it happened, the database discussed here was prepared after the second workshop, for use in the integration process).

B.2 DESIGN AND STRUCTURE

The planning for Workshop II was carried out by the core integrator team, composed of D. Boore, A. Cornell, R. Mensing, P. Morris, and G. Toro, during 6 meetings. The first meeting took place 4 months prior to the workshop.

The participants included the integrator team, proponents, experts, and observers (see Table B-1 for a list of the attendees). Each proponent was specifically asked to provide estimates using only one model. The experts were asked to provide estimates of ground motions using any or all methods and information that they considered appropriate, including the estimates provided by the proponents. The role of the experts in this workshop was typical of what SSHAC calls the "evaluator" role, in contrast to the role of the "proponent" (see Chapter 3). The proponents assumed the role of experts after fulfilling their proponent role. This was done for reasons of economy and efficiency. One open question was whether the same person could successfully change from a role of proponent to one of expert. The nature of Workshop I was such that a large number of participants were welcomed and desired. For Workshop II, however, this was not the case. In order not to dampen the discussions at the workshop, the Integrator team made a substantial effort to keep the number of participants to a minimum (among other things, by limiting the number of observers). The number that attended was just about right, with enough different realms of expertise represented to have fruitful technical discussions and not so many as to discourage open discussion by all experts present.

The Integrator team first chose the methods of estimating ground motion that would be represented by proponents, and then identified proponents who would apply a specific model to the selected prediction problems. The choice of methods was largely based on the results

TABLE B-1
ATTENDEES AT SSHAC GROUND-MOTION WORKSHOP II

Integrators:

David M. Boore, SSHAC
C. Allin Cornell, SSHAC
Peter Morris, SSHAC
Richard Mensing, Logicon-RDA
Gabriel R. Toro, Risk Engineering, Inc.

Invited Participants:

Norman A. Abrahamson, Consultant
Gail M. Atkinson, Consultant
Don Bernreuter, Lawrence Livermore National Laboratory
Kenneth W. Campbell, EQE
William Joyner, U.S. Geological Survey
Walter Silva, Pacific Engineering and Analysis
Paul Somerville, Woodward-Clyde Consultants

Observers:

Tom Hanks, National Academy of Sciences
Robert Rothman, U.S. Nuclear Regulatory Commission
Jean B. Savy, Lawrence Livermore National Laboratory
John F. Schneider, Electric Power Research Institute
Ernst Zuerflueh, U.S. Nuclear Regulatory Commission

of the first workshop. Included were the stochastic method, the hybrid-empirical method, and the empirical source function method. Because of its widespread use and because of some fundamental differences in the model parameters, two proponents were used for the stochastic method. Based on the strong guidance from Workshop I, no intensity-based methods were included (this does not preclude experts from using such information, of course). The proponents were chosen because of their intimate familiarity with a particular model for predicting ground motion, and they were asked to base their estimates solely on that model. An important advantage to having the proponents provide estimates rather than relying on an analyst to do so is that the chance of an erroneous application of a model was eliminated and furthermore, the proponents could provide reliable sensitivity studies. The experts were made up of the proponents and several generalists who have a broad knowledge of ground-motion estimation. Although all the proponents assumed the role of experts, this is not necessary.

The Integrator team was responsible for the following tasks:

- Setting up cases on which model runs by proponents were to be based.
- Providing detailed instructions to both proponents and experts.
- Disseminating results of initial model runs and expert assessments to all participants prior to the workshop.
- Guiding the interchange among experts at the workshop.
- Focusing debates on key points of disagreements.
- Summarizing the key points of agreement or disagreement and the key quantitative results, at various times during the workshop.
- Assessing the strengths and weaknesses of different modeling approaches and expert positions.
- Integrating the results, i.e., forming an integrated position regarding the median and the standard deviation of ground motion for each application.

Specific questions the workshop was designed to address regarding the Integrator process included the following:

- Would it be possible to maintain the effective interchange observed in Workshop I, even when the discussion is focused on specific model details or ground-motion estimates? In particular, would it be possible for the Integrators to focus debate on the key issues and have all the experts participate actively in this debate?

- Would it be feasible and meaningful for proponents and experts to develop, not only median ground-motion estimates, but also probabilistic descriptions of the epistemic and aleatory uncertainties?
- Would the distinction between the proponent and expert roles promote information exchange among experts and focus the experts on the task of evaluating the merits of the various models and then arriving at estimates that are representative of the expert community? Is this distinction useful to the integration process?
- Would experts' estimates and uncertainty bands display more or less agreement than the estimates and uncertainty bands provided by the proponents?
- Would the workshop develop sufficient information for the Integrator team to formulate specific Integrator estimates?
- Would the Integrator estimates be defensible and reasonably easy to articulate, and how would the experts respond to the Integrator estimates?

The most important consideration in designing the workshop was that there be ample opportunity and time for interaction amongst the experts and that adequate opportunity was given the experts to study intermediate results and to alter their ground-motion estimates. The Integration team felt that previous ground-motion elicitation exercises did not have sufficient interaction and feedback. To accomplish this, the elicitation was divided into three stages -- Pre-, Co-, and Post-Workshop. The content and results from each stage are discussed below.

B.3 CONTENT AND RESULTS

B.3.1 Pre-Workshop Stage

In the Pre-Workshop stage, four proponents provided ground-motion estimates, obtained using four separate models, for a specified set of magnitudes and distances, for specified measures of ground motion at a very-hard rock site in eastern North America. The distances and magnitudes were chosen so that data was available for some magnitude-distance combinations and not for others. Also, the magnitude was specified in terms of m_{bLg}, because this is the current standard for the specification of seismicity in PSHA and we wanted to include the conversion of m_{bLg} to **M** in the elicitation. In particular, we specified $m_{bLg} = 7.0$ because the lack of data for earthquakes this large introduces some uncertainty in the relation between the two magnitudes. The proponents were also asked to document the model used to obtain their estimates, to provide sensitivity results for the most important model parameters (so that an experts could easily modifiy a proponent's results if he or she felt that a different parameter value was more appropriate), to discuss the pros and cons of the model used, and to discuss the required modifications for use of the model in other geographic regions. The actual magnitudes, distances, and ground-motion measures are included in the Instructions to Proponents. These instructions and the responses from the proponents, including their written documentation explaining the processes used in arriving at their estimates, are given in Attachment B-1. In addition, Attachment B-1 contains plots of the ground motions made by the Integrator team.

The proponent results were sent to the experts well before the workshop. The experts then estimated the ground motions at the same set of magnitudes and distances for which the proponents provided values. The experts were asked to act as "mini-Integrators", basing their estimates on the proponents results as well as any other models, methods, or information that they considered appropriate (and were willing to defend during the workshop). The instructions to the experts, their results (referred to as "Experts 1"), and plots of their results are contained in Attachment B-2.

The Experts 1 results were collated and plots comparing the estimates were made before the workshop; the estimates and the plots were sent to the experts before the workshop. The cover letter for the transmission of the results is contained in Attachment B-3; for the sake of comparison between the various stages of ground motion, these initial results will be discussed later.

B.3.2 Co-Workshop Stage

The meeting for Workshop II was held from July 28--29, 1994, in Menlo Park, California, at the headquarters of Applied Decision Analysis, Inc.

The workshop was divided into the consideration of median ground-motion estimates, the consideration of uncertainties in ground motion (both epistemic and aleatory), and the completion of an Integrator's survey. The working agenda, made up before the workshop, is given in Attachment B-4. As expected, the agenda was changed somewhat as the workshop proceeded. Overall, however, the deviations from the agenda were minor. Each topic was introduced by a member of the Integrator team, who summarized the results of the proponents and experts and then conducted an informal--but guided--discussion of the results, with an emphasis on interaction amongst the participants. The experts were encouraged to challenge the bases for the ground-motion estimates of the other experts, and were also expected to be prepared to explain the reasoning behind their own choices. The Integrators made sure that the discussion moved from topic to topic, made oral summaries of what they heard before moving to the next topic, and kept the experts from dwelling on issues not important to the end result. These discussions were very fruitful and were carried out at a high intellectual level. The Integrator team believe that the experts were truly trying to do the best job possible of estimating ground motions and were not just trying to defend their territories.

After the first day, the experts were asked to reconsider their ground-motion estimates and to provide new estimates by the start of the second day, if they desired to do so. New plots comparing the ground-motion estimates were made while the meeting was in progress, and these new plots were then discussed by the participants. The new results are termed "Expert 2", and the responses are collected in Attachment B-5.

B.3.2.1 Ground-Motion Estimates. To facilitate discussion, plots were made of the various results, with care given to using common scales, symbols, and so on. Overhead transparencies were used so that comparisons between results and editing of results could easily be made. Not having the means to include transparencies in this appendix, we have shown the comparisons by using two levels of a gray scale to differentiate between results.

(Also, the various estimates at a particular distance were offset horizontally around the specified distance in order to reduce overlap.)

A comparison of selected Proponents, Experts 1, and Experts 2 results are given in Figures B-1 through B-8. Please note that the ordering of the figures follows the order of the workshop, with all the Proponent-Expert 1 comparisons before the Experts 1-Experts 2 comparisons. The results are for 1 and 10 Hz oscillator frequencies. To save space, comparison plots are not given for the 2.5 Hz, 25 Hz, and PGA estimates.

It should also be noted that the meaning of the shortest distance (5 km) was interpreted differently by the different participants, and therefore the ground-motion estimates for 5 km should be treated with caution or ignored. (Somerville and Saikia provided numbers at 12 km as proponents rather than 5 km; the other participants variously interpreted the distance of 5 km as closest distance to the fault and as horizontal distance to the surface projection of the fault). In hindsight, the distance should have been stated as being directly over the earthquake source. In this way the experts would have to grapple with the way to handle the depth extent of faulting and the associated uncertainty that the depth parameter introduces into the estimates. The lesson learned by the Integrators is that greater care must be given in the specification of the elicitation to avoid ambiguity.

The experts utilized a variety of procedures to arrive at their estimates. For instance, several experts used weighted combinations of the proponents' results. Some experts used weights that are magnitude- and distance-dependent. Some experts used these weights in a formal (quantitative) manner, others used them to guide their reasoning for obtaining ground-motion estimates. One expert identified correlation between models as a factor in assigning weights to the proponents' models. Another expert used a subjective combination of modified proponent results and data. A third expert used a single model, which was a modification of a proponent's model. The experts' Pre-Workshop documentation (Attachment B-2, part b) and Co- and Post-Workshop comments (Attachment B-5, part a, and B-7, part b) provides further insights into the experts' reasoning.

The first thing to note in the median amplitudes is that the spread in the 1 Hz estimates is greater than in the 10 Hz estimates. For that reason, the following discussion concerns the 1 Hz estimates. The trend in going from the Proponents to the Experts 1 results was for the range of estimates to be reduced. This is easily seen in Figures B-1 and B-2. In the written documentation (Attachment B-2), the experts who had also acted as proponents clearly stated that they attempted to be "mini-Integrators" (this is consistent with the ideas in Chapter 3 and Appendix J). In particular, note that Atkinson's and Somerville and Saikia's low proponent values increased when they acted as experts, and Campbell's and Silva's high proponent values decreased when they acted as experts.

Reasons for proponent differences were discussed at the workshop. In particular, the low results of Atkinson are due to her source spectral model and to her increase of duration with distance. In view of her low estimates relative to those of the other proponents, as an expert she increased her values. At the workshop, however, there were no challenges to her parameters. (In fact, Joyner considered all the proponent results and decided that the scientific evidence favored the Atkinson model, with a modification to her source spectra. As a result, Joyner did not provide an assessment of the community's best estimate [e.g., see Chapter 3], nor was he asked to[1]. His estimates were derived after careful consideration of all the proponent results). As a result of the discussion during day 1 of the workshop, Atkinson altered her estimates downward (Figures B-5 and B-6). Somerville and Saikia were persuaded by the discussion to give more weight to the Atkinson proponent model and as a result, lowered their estimates for m_{bLg} 5.5 at 1 Hz. In addition, the discussion of Somerville and Saikia's estimates revealed that the moment magnitude associated with their conversion of m_{bLg} 7 was much lower (6.4) than those of the other experts (7.0 to 7.2). The difference lies in the weight given to model extrapolations vs. empirical extrapolations in a region for which few data exist (and this problem is precisely why the Integrators chose m_{bLg} 7 and why they did not specify moment magnitudes). Appendix C contains some plots illustrating

[1]At the time of Workshop II, the elicitation scheme of Chapter 3 and Appendix J had not fully crystallized. Hence, the Integrators did not emphasize the distinction between an expert's own opinions and an expert as a mini-Integrator representing the whole community of experts. In fact, many of the ideas in Chapter 3 grew out of the experience from Workshop II.

the problem. As a result of the discussion, Somerville and Saikia modified their m_{bLg} 7 values upward in their Expert 2 estimates (Figures B-6 and B-8).

B.3.2.2 Uncertainty Estimates. The uncertainty estimates did not vary as much from Proponent to Experts 1 or between Experts 1 and Experts 2, as did the median ground motion values (the same is true between the Experts 2 and Experts 3 estimates; the latter will be discussed in Section B.3.3 and shown in Figures B-14 through B-17). In other words, the experts did not feel as much of a need to resolve differences in the uncertainty estimates. Discussions revealed misunderstandings about what the epistemic uncertainty represents, about the difference between epistemic and aleatory uncertainty, and about how to compute epistemic uncertainty. There was also a misunderstanding about how the experts were asked to report epistemic uncertainty in the input forms (initially, some experts reported the quantity ln[Amplitude, 90-percentile] – ln[Amplitude, median], rather than the epistemic standard deviation). Some experts relied on formal procedures for the quantification of epistemic uncertainty, while others used a subjective approach.

B.3.2.3 Integrator's Survey. The survey that was handed out to the seven ground-motion experts is included as Attachment B-6, part a. This section summarizes the overall results of the survey, focusing on the summary data provided in Tables B-2 through B-5. Additional interesting and useful information also is provided in Attachment B-6, whose contents are briefly described here:

Attachment B-6, part b: Experts' Written Comments. The experts provided supporting information in the form of written comments that explain their Experts 1 inputs. This information is important in understanding how each expert evaluated each model.

Attachment B-6, part c: Detailed Expert Inputs on Weighting the Forecasts. This is the raw data, expert-by-expert, application-by-application, that formed the basis for the aggregated data shown in Table B-3.

Attachment B-6, part d: Detailed Expert Inputs on Relative Forecasting Uncertainty. This is the raw input, expert-by-expert, application-by-application, that formed the basis for the aggregated data shown in Table B-4.

The basic results of the survey are most easily understood by reviewing Tables B-2 through B-5, which are described below.

Basis for Experts' Estimates (Table B-2). Table B-2 illustrates that all seven experts used weights either implicitly or explicitly as the basis for determining their own Experts 2 estimate based on the model results. This supports both an expert interaction process and an Integrator process that uses model weights, at least for guidance, if not for formal mathematical combination.

No expert did <u>not</u> weight informally or formally. In the ground-motion arena, weighting appears to be a natural mode in which experts think. This lends more credence to the model-based elicitation process in which Integrators focus on the models like the experts do and use the experts for guidance as to how to weight the models.

Weighting the Forecasts (Table B-3). Each expert was asked to assign numerical weights to the Proponent models, even if the expert had used informal weighting to derive his estimates. Table B-3 shows, for six different applications,[2] the weights for the four Proponent models averaged over seven experts (the expert-by-expert weights are presented in Attachment B-6, part c). Several observations are pertinent:

- The weights are definitely **not** equal. While the relative weights assigned by the experts are reasonably diverse, the experts very clearly do not equally weight each modeling approach. This is true despite the initial association between models and specific proponents prior to and during the early stages of the workshop (recall that, in the past, experts have shown reluctance to weight

[2]We refer to one frequency-magnitude-distance combination as one "application".

other experts). This suggests that, in the later stages of the workshop, experts (even those who had acted as proponents) are able to de-couple models from individuals for the purpose of assigning numerical weights. This confirms the same observation of the more general survey of Workshop I.

- The average weights are remarkably consistent across the different applications–more consistent than they were in Workshop I. The stochastic model with empirical attenuation consistently gets the greatest weight, while the hybrid empirical model consistently gets the lowest weight. The stochastic model with ray theory attenuation and the empirical-source-function methods fall in between.

Relative Forecasting Uncertainty (Table B-4). This table needs to be interpreted only roughly because a number of experts stated that they were somewhat confused over the meaning of the question. One of the homework assignments for the Integrator team from the workshop is to construct a more meaningful measure for assessing forecasting error. The table shows:

- The relative forecasting of each model is seen to vary, sometimes rather dramatically, with application. For example, the hybrid empirical model is judged to be almost 50% less accurate for magnitude 5.5 applications than for a frequency 1 Hz, 7.0 magnitude application.

- The stochastic model with empirical attenuation tended to be judged as having the least forecasting error, and the hybrid empirical judged as having the most forecasting error. In general, however, there is a fairly high degree of similarity among all the numbers. This indicates, again, that the experts see the models as all providing useful information.

Correlation Among Model Forecasts (Table B-5). This table is perhaps most easily understood by looking at the average correlation among model pairs, shown on the left portion of the table. This indicates that for the six experts who responded, there is a correlation or overlap of 22% to 56%, for an average of 39%, among pairs of models. This supports the observation made by the Integrator team during the group interaction that there is clearly a reasonable amount of overlap among all four of these models. Some specific observations are:

- The empirical-source-function method is seen to have the least overlap with the other models, as evidenced by the lowest average percent correlation demonstrated in the small table to the right, and as evidenced by the generally smaller correlations with the other models shown in the larger table to the left.

- The experts show significant diversity in their assessments of the correlation among the different model forecasts. This indicates that, prior to integration, these disagreements need to be explored to find out whether they are unintentional or based on true differences.

- The survey also revealed that there is substantial disagreement about the relative correlation among the different model forecasts. Part of this disagreement may be unintended, due to confusion about the interpretation of the question and about the correlation measure, but part of this disagreeement may be due to actual substantive differences. Prior to final integration, it would be useful to explore the source of the diversity and opinion in this area.

B.3.2.4 List of Contributors to Uncertainty. The experts were asked to discuss and catalog the different factors that contribute to total uncertainty in ground-motion prediction, whether they contribute to aleatory or epistemic uncertainty, and which factors are the most important. The result of this exercise is Table B-6. It would have been useful to devote more time to these issues, in order to elicit each expert's quantitative estimates of the various contributors to aleatory and epistemic uncertainty.

B.3.3 Post-Workshop Stage

Following the workshop, the experts were given another chance to change their estimates. Most of the experts responded (the instructions and response are contained in Attachment B-7; the results are referred to as "Experts 3"). Because of time and budget constraints only a few experts modified their estimates, although more would have liked to do so. Those who did not provide revised estimates, however, indicated that the changes would probably not be major. The Expert 3 estimates of median ground-motion amplitude for all magnitudes, distances, and oscillator frequencies are contained in Figures B-9 through B-13.

The Expert 3 estimates of epistemic and aleatory uncertainty are contained in Figures B-14 through B-17. The epistemic uncertainties are greater for m_{bLg} 7 than for m_{bLg} 5.5 (Figures B-14 and B-15) , which makes sense in terms of the data available to constrain the estimates and calibrate the models. On the other hand, there is a large spread among the experts' estimates. This spread may be due, in part, to the following causes: the misunderstandings described in Section B.3.2.2 (which may have remained after the Workshop), and differences in the way the experts estimated epistemic uncertainty (formally vs. subjectively). In contrast, the aleatory uncertainty showed surprisingly little variation among experts (Figures B-16 and B-17). The lesson is that it is much harder to elicit and estimate epistemic uncertainty than it is aleatory uncertainty. Subject to the caveat that several of the experts would have revised their estimates somewhat if resources had permitted, Figures B-9 through B-17 can be considered to exhibit the final estimates of the individual experts.

B.4 INTEGRATION

After receiving the Post-Workshop results, the Integrator team met several times for the purpose of providing their integration of the various estimates into the final estimates. To aid in the integration of the median ground-motion estimates, some effort was made in preparing figures showing the data and the various median estimates. This effort is discussed in Attachment B-8 (as noted earlier, if this elicitation exercise were done over, the data preparation would have been the initial task of Workshop I). It was not at all clear how the integration should proceed, but after some time a strategy arose. Basically, it was decided to produce two estimates of the median ground motions, one by equally weighting the seven Experts 3 results, and the other by unequally weighting the four proponent results. In the latter case, the weights were strongly guided by the results of the Integrator's survey completed during the workshop (see Table B-3), except that Joyner's Experts 3 results were to be substituted for those of the Atkinson proponent estimates, because in the view of the Integrators, Joyner's spectral shape deviated less from the conventional Brune shape in the region between the two corner frequencies. These weights are given in Table B-6 (note that different weights are used for the median amplitudes and for the uncertainties). Both approaches produced similar results. Unfortunately, the figures showing the estimates obtained by applying unequal weights to the proponents' results were not prepared for all magnitudes and oscillator frequencies; they are given here for magnitude 5.5 and 1 Hz only. Integration results for all magnitudes and oscillator frequencies are provided only in tabular form in Tables B-8 and B-9.

The results for the mean amplitude and and epistemic uncertainty are contained in Figures B-18 through B-23 (except for Figure B-19, which shows results for unequal weights on the proponents' results). The mean shown is the geometric mean of the seven individual estimates. The upper and lower bars show the Integrators estimates of the epistemic uncertainty. These were computed by averaging the variances of the Experts 3 log uncertainties, giving zero weight to the Silva epistemic uncertainties, which the Integrator team judged to be unrealistically low in view of the spread of estimates shown in the median estimates. The upper and lower bars should also have contained a contribution from the expert-to-expert variation in the median ground motions, but the need for this additional term was discovered after the resources for the project were exhausted. It is expected that the increase in spread of the upper and lower bars would be small, since the new value would be given by the sum of the squares of the uncertainties, and the individual epistemic uncertainties are larger than the spread between the median estimates.

Tables B-8 and B-9 provide summaries of the estimates obtained for all magnitudes and distances elicited, using the two approaches for integration, and Table B-10 compares these estimates (estimates of the aleatory standard deviation will be discussed below). The median estimates obtained using equal weights on experts are somewhat lower than those obtained using unequal weights on the proponents' results. The difference between the two sets of median estimates is at most 26%, which is not large given the epistemic uncertainties.

The estimates of epistemic uncertainty in the median are generally consistent between the two integration approaches. The only exception is 1 Hz, for which the weighted proponent estimates has a lower value. In general, the epistemic uncertainty is higher for m_{bLg} 7 than for m_{bLg} 5.5, as one would expect (due to the lack of data and to uncertainty about source scaling and the relationship between seismic moment and m_{bLg} at high magnitudes).

For the aleatory uncertainty, the proponents and experts were asked to provide both the median aleatory standard deviation (we will call this quantity $\bar{\sigma}$) and the epistemic uncertainty in the aleatory standard deviation (we will call this quantity σ_σ). Calculations show that σ_σ values of 0.2 or lower have only a minor effect on the ground-motion distribution within $\pm 2\bar{\sigma}$ and that this effect may be represented by replacing $\bar{\sigma}$ with the slightly larger quantity $[\bar{\sigma}^2+\sigma_\sigma{}^2]^{1/2}$ (we will call this quantity the aleatory standard deviation, or σ). Table B-11 lists the Experts 3 values of $\bar{\sigma}$ and σ_σ for a distance of 20 km and shows that only one expert used values of σ_σ greater than 0.2. Thus, it is appropriate to represent the integration results in terms of σ, without having to represent $\bar{\sigma}$ and σ_σ separately.

The integrated aleatory standard deviation was estimated in the same way as was the epistemic uncertainty, by combining the variances of the individual estimates. The results are shown in Figures B-24 through B-28 and in Tables B-8 and B-9. These figures indicate that the aleatory standard deviations are in rough agreement with the scatter in the data.

The estimates of aleatory uncertainty are generally consistent between the two integration approaches, although the value from weighted proponent estimates is slightly higher. The aleatory uncertainty is slightly higher for low frequencies than for high frequencies and is also slightly higher for m_{bLg} 5.5 than for m_{bLg} 7. These trends with frequency and magnitude are consistent with the trends observed in empirical attenuation studies using WNA strong-motion data. The estimated values of aleatory uncertainty for 10 Hz and PGA are, however, significantly higher than values obtained using WNA strong-motion data, especially for large magnitudes. There are several possible explanations for these higher values. For instance, much of the CENA data come from small earthquakes (~ m_{bLg} 5) and from rock sites (both of these conditions are believed to produce higher scatter), the fact that the magnitude is specified in terms of m_{bLg} rather than moment magnitude, or the experts' difficulty in separating aleatory and epistemic uncertainties. This is another issue that would have benefited from additional Post-Workshop interaction with the experts.

B.4.1 Preferred Ground-Motion Estimates

The estimates obtained by combining the Experts 3 estimates using equal weights (Table B-8) are selected as the preferred estimates from this integration exercise. The main reason for this selection is that the Experts 3 estimates directly incorporate the feedback from all the exchanges of information that took place during Workshop II. The consistency between these results and the results obtained using unequal (expert-selected) weights to the proponents estimates (see Tables B-9 and B-10) suggests that the integration process is robust.

Potential users of these results are cautioned that the the estimates of aleatory uncertainty in Table B-8 for high-frequency ground motions may be too high, as was discussed above, and should be considered tentative.

B.4.2 Interpolation

The integration results in Table B-8 may be used in a PSHA by applying a suitable interpolation scheme over magnitude, distance, and frequency. Because the elicited magnitudes, distances, and frequencies are sparse[3], interpolation of the median estimates must

[3]The number of magnitude, distance, and frequency combinations for which to elicit ground-motion estimates was deliberately kept small. The Integrators felt that it was preferable to focus

be done very carefully. For instance, one may use an existing functional form (e.g., Atkinson and Boore, 1995, Toro et al., 1995) and adjust a small number of coefficients to match or approximate the estimates obtained here. Particular case must be used at short distances, with due consideration for the definition of distance being used.

Interpolation of the epistemic and aleatory standard deviations is less critical, as these quantities do not show a strong dependence on magnitude, distance, or frequency.

An additional issue is the epistemic correlation among magnitude-distance pairs (for a given frequency; see Chapter 6 for a discussion of this issue). The default assumption is perfect correlation (i.e., one can represent epistemic uncertainty using a family of attenuation equations that do not intersect each other). This assumption does not affect the mean hazard, gives a conservative estimate of the epistemic uncertainty, and it is a good approximation if uncertainty in the mean stress drop dominates the epistemic uncertainty in ground motion.

An alternative to the interpolation scheme discussed above is to represent the Integration results as a weighted combination of model predictions (for instance, in terms of the proponents' models). This alternative has the following two drawbacks: one must allow for weights that depend on magnitude and distance (requiring interpolation of the weights, and thereby negating some of the conceptual simplicity of the approach), and it may increase the proponents' visibility at the expense of the experts' (contrary to the tendency observed in the workshop). One advantage of this approach is that the epistemic correlation among magnitude-distance pairs is automatically built into the Integration results.

B.5 CONCLUDING OBSERVATIONS AND DISCUSSION

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the experts' efforts into obtaining high-quality estimates for a limited number of cases, rather than diluting the experts' efforts.

In general, the workshop was very successful. It substantiated a number of our beliefs about positive aspects of the Integrator process. It also pointed out several weaknesses in the process design; however, the good news is that the weaknesses suggested specific mechanisms for improvement.

Here we list the overall results of the Expert and Proponent interchange and the Integration Process. Specific results related to the survey were provided in an earlier section.

- The Proponents and Experts exhibited a striking amount of agreement, considering the range of different approaches and philosophies used to generate the numbers. Moreover, as the interaction progressed, the agreement increased (experts were asked to reassess over-night and after the workshop and those that did tended to bring their estimates and uncertainty ranges closer to the group average).

- The most heartening result of the workshop was the success of the information interchange that was engendered by the Integrator-facilitated proponent/expert process. In the process of isolating sources of disagreement, many common points of agreement were established and a number of points of unintended disagreement were revealed. The response of the experts, when queried about their feelings about the workshop, were summarized by one participant: "It is astonishing how much everyone agrees." The workshop seemed to generate a great deal of clarity and new understanding among the ground motion community on matters ranging from data to methodology to philosophy.

- The model median estimates and the rationale for them appeared to be well understood by the group. However, there appeared to be less clear understanding of the uncertainty ranges supplied by the Proponents and Experts. Several experts misinterpreted the questions (e.g., at least two experts supplied ten-ninety percentiles when asked for standard deviations), and there was clearly some confusion concerning how to classify uncertainties as either aleatory or epistemic.

- The above observation makes it clear that, consistent with observations in other similar exercises, uncertainty elicitation needs to be done individually, at least until each expert is thoroughly familiar with the meaning and implications and subtleties of the uncertainty estimates. Written instructions are inadequate even for experts who are trained in probability and statistics. In order to provide reasonable judgments, experts need to be trained and the elicitation needs to be carefully structured to remove any possible biases.

- The proponent/expert distinction worked quite well. It solidified the conclusion from Workshop I that it is advantageous to focus discussion and debate on models, rather than individual experts. Viewing the individuals as expert interpreters of models that provide insights to the Integrators appears to be a very attractive alternative compared to the view of experts as advocates of their own models or assessments.

- Experts' estimates, after observing the model estimates, tended to be more tightly grouped than the model estimates themselves. This indicates that the experts are willing to take a broad view in which most or all approaches are viewed as providing some useful information.

- The largest changes in the median ground-motion estimates occurred before the workshop took place (Proponents to Experts 1); subsequent changes were less pervasive. This confirms that much valuable elicitation can and should be done prior to any group meeting, when the experts have time to think, study, and calculate. The experts should be provided with sufficient guidance and information (e.g., proponents' estimates, data).

- One view of the process used is that it puts the experts in the role of Integrators themselves. The experts' willingness to use information from different points of view would appear to be a good sign about the future viability of the Integrator process. An interpretation of the elicitation process is that the experts are actually being asked to provide the Integrator with their best assessment of how to integrate.

- It was highly useful to have the experts as a group generate the list of uncertain factors that lead to overall uncertainty in ground motion. It was also extremely useful as both a teaching exercise and in developing useful information to have the group categorize the different factors in terms of whether they contribute to aleatory uncertainty or epistemic uncertainty or both. This appears to be a far better idea than having the Integrators suggest a list of such factors prior to the workshop.

- The integration process was, for several reasons, necessarily incomplete:

  - The biggest impediment to the integration process was that it became clear that the Integrators did not understand explicitly enough the database on which the different model estimates and expert judgments were predicated. The lesson here is clear: future workshops should explicitly focus on the different databases in at least as much detail and as structured a way as Workshop I and Workshop II focused on modeling approaches. One idea is to try to design common formats for representing the raw data in a form that experts can compare easily.

  - The integration process was hampered to a lesser extent by a lack of understanding about the reasons underlying some of the experts' uncertainty bands. It is important to know explicitly, if an expert's epistemic uncertainty band is smaller than the range of model estimates, whether this represents an explicit down-weighting of the other model estimates or is simply a misunderstanding of what the uncertainty band is intended to represent. Similarly, if an expert's uncertainty band is far wider than the range of model estimates, it is important to understand why. This suggests that there should be additional interaction between Integrators and experts, after the Integrators have fully digested the experts' estimates. This interaction may be in the form of conference calls (some plenary, some with each individual expert) and written communications.

- In spite of the above difficulties, and in spite of the short time available at the workshop itself (two hours), the Integrators were able to come up with tentative, but specific, median estimates and uncertainty bands about those estimates. Contributing to the ease of the integration process was the large amount of agreement among the experts; however, the promising observation is that even when the experts disagreed, the workshop had developed a reasonably clear picture of why they disagreed. Thus, the Integrators were able to address clearly defined ground-motion issues rather than having to guess why experts disagreed.

- The response of the experts to the Integrators preliminary estimates was fairly benign. Several factors probably contributed to this: 1) the integration was performed on estimates that were not final. At the workshop, we decided that another iteration of estimates was necessary, based on the information generated at the workshop; 2) Since there was a good deal of agreement among the experts, the Integrator position, which is fairly close to most of the individual experts' positions, was not controversial; and 3) the experts, by essentially playing the role of Integrators themselves in the workshop process, were probably psychologically much more prepared to accept the results of an integrated estimate than they would have been had they not had to go through the exercise themselves.

TABLE B-2

GROUND MOTION WORKSHOP II
INTEGRATOR SURVEY
BASIS FOR EXPERTS' ESTIMATES

EXPERT	Explicit Weights	Informal Weights	No Weights
Abrahamson		XXX	
Atkinson		XXX	
Bernreuter		XXX	
Campbell	XXX		
Joyner	XXX		
Silva	XXX		
Somerville		XXX	

TABLE B-3

GROUND MOTION WORKSHOP II
INTEGRATOR SURVEY
WEIGHTING THE FORECASTS

How would you weight the results if all four approaches were applied to a specific site application? (weights averaged over 7 experts)						
Frequency (Hz)	1	1	10	10	PGA	PGA
Magnitude (m_{bLg})	5.5	7.0	5.5	7.0	5.5	7.0
Distance (km)	20	20	20	20	20	20
Method	**AVERAGE WEIGHTS**					
Stochastic with Empirical Attenuation	46	42	42	41	42	41
Stochastic with Ray Theory Attenuation	19	19	23	22	23	22
Hybrid Empirical	14	13	14	16	14	16
Empirical Source Functions	22	25	22	22	22	22
Total	100	100	100	100	100	100

TABLE B-4

GROUND MOTION WORKSHOP II
INTEGRATOR SURVEY
RELATIVE FORECASTING UNCERTAINTY

How would you judge the relative forecasting error band assuming 100 for the approach that has the least error? (weights averaged over 7 experts)							
Frequency (Hz)	1	1	10	10	PGA	PGA	
Magnitude (m_{bLg})	5.5	7.0	5.5	7.0	5.5	7.0	
Distance (km)	20	20	20	20	20	20	AVG
Method	**RELATIVE ERROR BANDS**						
Stochastic with Empirical Attenuation	100	118	100	113	105	113	108
Stochastic with Ray Theory Attenuation	117	112	110	108	115	115	113
Hybrid Empirical	153	112	157	128	158	135	140
Empirical Source Functions	129	140	122	128	115	133	128
Average	125	120	122	119	123	124	122

TABLE B-5

GROUND MOTION WORKSHOP II
INTEGRATOR SURVEY -- EXPERT INPUTS:
CORRELATION AMONG MODEL FORECASTS

	Percent Correlation for Each Model Pair*								Avg. Percent Correlation for Each Model			
Expert	SE SR	SE HE	SE ESF	SR HE	SR ESF	HE ESF	AVG		SE	SR	HE	ESF
Abrahamson	50	25	10	25	20	0	22		28	32	17	10
Atkinson	33	33	33	67	33	33	**39**		30	44	44	33
Bernreuter	66	33	0	33	0	0	22		33	33	22	0
Campbell	33	33	67	67	33	33	**44**		44	44	44	44
Joyner	X	X	X	X	X	X	**X**		X	X	X	X
Silva	33	33	33	100	67	67	**56**		33	67	67	56
Somerville	67	33	67	33	33	67	**50**		56	44	44	56
AVERAGE	**47**	**32**	**35**	**54**	**31**	**33**	**39**		**38**	**44**	**40**	**33**

* Assumes for data display that: "0" = 0 "+" = 33 "++" = 67 "+++" = 100

SE: Stochastic with empirical attenuation (Atkinson)
SR: Stochastic with ray-theory attenuation (Silva)
HE: Hybrid empirical (Campbell)
ESF: Empirical source function (Somerville and Saikia)

TABLE B-6

FACTORS THAT CONTRIBUTE TO UNCERTAINTY IN GROUND MOTIONS
(prepared by Experts)

FACTOR	Dominant	Epistemic P.S.	Epistemic F.S.	Aleatory P.S.	Aleatory F.S.
PARAMETRIC					
Source					
m_{bLg} - M relationship (for predictions in terms of m_{bLg})	√large mag.	√	√	√	√
Stress Parameter (pt. source only)	√	√	×	√	×
Focal Depth	√small dist.	O	O	√	√
Rupture dimensions	√large mag.	×	√	×	√
Slip Distribution		×	O	×	O
Rise Time		×	O	×	O
Source Spectral Shape	√ 1 Hz	√	O	√	O
Rupture Velocity (Duration)		×	O	×	O
Source Mechanism		O	O	O	√
Path					
Geometric Attenuation		O	O	O	O
Anelastic Attenuation	√ large dist.	O	O	√	√
Duration vs. Distance (assumes no RVT for finite src.)	√ sm. mag	O	×	O	×
Crustal Structure	√ mod. dist.	O	O	O	×
Site					
Kappa	√ WNA, H. Freq.	O	O	√	√
Near-surface velocity structure		O	O	O	O
MODELING					
Performance vs. data, data quality, horiz. vs. vertical	√	√	√	√	√

Notes: P.S., Point Source; F.S, finite source; √ done; × not done; O could do, should do, or not used

TABLE B-7

WEIGHTS USED IN INTEGRATION

Method	Proponent	Weight for Median	Weight for Uncertainty
Hybrid Empirical	Campbell	0.14	0.17
Stochastic (2-corner, empirical geometric attenuation)	Atkinson (modif. by Joyner)	0.46	0.56
Stochastic (Brune spectrum, ray-theory geometric attenuation)	Silva	0.19	0
Empirical Source Function	Somerville and Saikia	0.22	0.27

TABLE B-8

INTEGRATION RESULTS:
EQUAL WEIGHTS ON EXPERTS' ESTIMATES

f (Hz)	mbLg	R (km)	Median Amplitude (g)	Epistemic Std. Dev.	Aleatory Std. Dev.
1	5.5	20	1.09E-02	0.48	0.80
	5.5	70	2.27E-03	0.46	0.80
	5.5	200	9.36E-04	0.37	0.80
	7.0	20	1.67E-01	0.66	0.78
	7.0	70	4.50E-02	0.71	0.78
	7.0	200	1.82E-02	0.73	0.79
2.5	5.5	20	4.17E-02	0.34	0.77
	7.0	20	3.67E-01	0.53	0.73
10	5.5	20	1.55E-01	0.32	0.73
	5.5	70	2.58E-02	0.32	0.75
	7.0	20	8.45E-01	0.52	0.70
	7.0	70	1.88E-01	0.53	0.72
25	5.5	20	2.13E-01	0.34	0.73
	7.0	20	1.07E+00	0.51	0.70
PGA	5.5	70	1.28E-02	0.41	0.75
	7.0	70	9.36E-02	0.51	0.70

TABLE B-9

INTEGRATION RESULTS: UNEQUAL WEIGHTS ON PROPONENTS' ESTIMATES

f (Hz)	mbLg	R (km)	Median Amplitude (g)	Epistemic Std. Dev.	Aleatory Std. Dev.
1	5.5	20	1.01E-02	0.50	0.80
	5.5	70	2.07E-03	0.36	0.82
	5.5	200	9.10E-04	0.41	0.82
	7.0	20	1.67E-01	0.56	0.78
	7.0	70	4.16E-02	0.58	0.79
	7.0	200	1.65E-02	0.64	0.80
2.5	5.5	20	3.69E-02	0.39	0.80
	7.0	20	3.56E-01	0.67	0.78
10	5.5	20	1.24E-01	0.36	0.76
	5.5	70	1.90E-02	0.27	0.78
	7.0	20	7.31E-01	0.55	0.74
	7.0	70	1.61E-01	0.57	0.76
25	5.5	20	1.69E-01	0.36	0.75
	7.0	20	1.04E+00	0.55	0.73
PGA	5.5	70	9.77E-03	0.44	0.76
	7.0	70	8.07E-02	0.56	0.75

TABLE B-10

INTEGRATION RESULTS: COMPARISON OF INTEGRATION RESULTS - UNEQUAL WEIGHTS ON PROPONENTS VS. EQUAL WEIGHTS ON EXPERTS

f (Hz)	mbLg	R (km)	Median Amplitude (% diff.)	Epistemic Std. Dev. (diff.)	Aleatory Std. Dev. (diff.)
1	5.5	20	-8	0.02	0.00
	5.5	70	-9	-0.10	0.02
	5.5	200	-3	0.04	0.02
	7.0	20	-0	-0.09	-0.01
	7.0	70	-7	-0.13	0.01
	7.0	200	-9	-0.09	0.01
2.5	5.5	20	-12	0.05	0.03
	7.0	20	-3	0.14	0.05
10	5.5	20	-20	0.04	0.02
	5.5	70	-26	-0.05	0.03
	7.0	20	-13	0.03	0.03
	7.0	70	-14	0.05	0.04
25	5.5	20	-21	0.02	0.02
	7.0	20	-3	0.04	0.03
PGA	5.5	70	-24	0.04	0.02
	7.0	70	-14	0.05	0.05

Notes: diff.= Weighted Proponents - Experts
% diff.= (Weighted Proponents - Experts) / Experts

TABLE B-11

EXPERTS' ESTIMATES OF ALEATORY UNCERTAINTY

(Distance: 20 km)

mbLg	Expert	f (Hz)	σ	σ	σ
5.5	Abrahamson	1	0.75	0.10	0.76
5.5	Abrahamson	2.5	0.70	0.10	0.71
5.5	Abrahamson	10	0.70	0.10	0.71
5.5	Abrahamson	25	0.70	0.10	0.71
5.5	Atkinson	1	0.80	0.20	0.82
5.5	Atkinson	2.5	0.80	0.20	0.82
5.5	Atkinson	10	0.80	0.20	0.82
5.5	Atkinson	25	0.80	0.20	0.82
5.5	Bernreuter	1	0.70	0.30	0.76
5.5	Bernreuter	2.5	0.70	0.30	0.76
5.5	Bernreuter	10	0.60	0.30	0.67
5.5	Bernreuter	25	0.65	0.20	0.68
5.5	Campbell	1	0.82	0.15	0.83
5.5	Campbell	2.5	0.76	0.15	0.77
5.5	Campbell	10	0.68	0.15	0.70
5.5	Campbell	25	0.70	0.15	0.72
5.5	Joyner	1	0.80	0.20	0.82
5.5	Joyner	2.5	0.80	0.20	0.82
5.5	Joyner	10	0.80	0.20	0.82
5.5	Joyner	25	0.80	0.20	0.82
5.5	Silva	1	0.92	0.20	0.94
5.5	Silva	2.5	0.74	0.20	0.77
5.5	Silva	10	0.61	0.20	0.64
5.5	Silva	25	0.68	0.20	0.71
5.5	Somerville & Saikia	1	0.80	0.10	0.81
5.5	Somerville & Saikia	2.5	0.70	0.10	0.71
5.5	Somerville & Saikia	10	0.65	0.10	0.66
5.5	Somerville & Saikia	25	0.60	0.10	0.61

TABLE B-11 (continued)

mLg	Expert	f (Hz)	σ	σ	σ
7.0	Abrahamson	1	0.75	0.10	0.76
7.0	Abrahamson	2.5	0.70	0.10	0.71
7.0	Abrahamson	10	0.70	0.10	0.71
7.0	Abrahamson	25	0.70	0.10	0.71
7.0	Atkinson	1	0.80	0.20	0.82
7.0	Atkinson	2.5	0.80	0.20	0.82
7.0	Atkinson	10	0.80	0.20	0.82
7.0	Atkinson	25	0.80	0.20	0.82
7.0	Bernreuter	1	0.80	0.40	0.89
7.0	Bernreuter	2.5	0.70	0.30	0.76
7.0	Bernreuter	10	0.60	0.30	0.67
7.0	Bernreuter	25	0.60	0.30	0.67
7.0	Campbell	1	0.74	0.15	0.76
7.0	Campbell	2.5	0.68	0.15	0.70
7.0	Campbell	10	0.62	0.15	0.64
7.0	Campbell	25	0.64	0.15	0.66
7.0	Joyner	1	0.80	0.20	0.82
7.0	Joyner	2.5	0.80	0.20	0.82
7.0	Joyner	10	0.80	0.20	0.82
7.0	Joyner	25	0.80	0.20	0.82
7.0	Silva	1	0.80	0.20	0.82
7.0	Silva	2.5	0.64	0.20	0.67
7.0	Silva	10	0.51	0.20	0.55
7.0	Silva	25	0.60	0.20	0.63
7.0	Somerville & Saikia	1	0.70	0.15	0.72
7.0	Somerville & Saikia	2.5	0.60	0.15	0.62
7.0	Somerville & Saikia	10	0.55	0.15	0.57
7.0	Somerville & Saikia	25	0.55	0.15	0.57

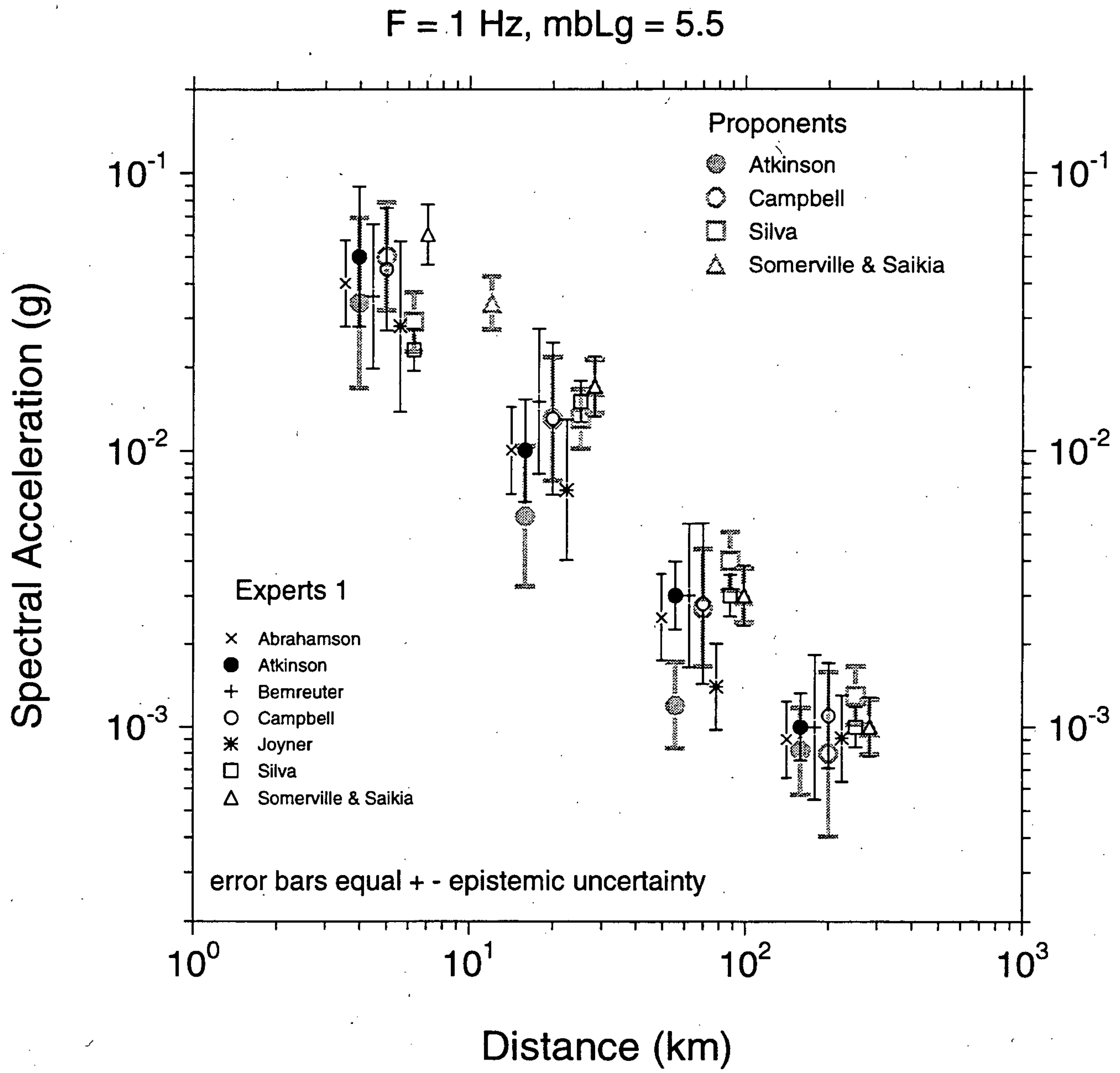

Figure B-1. Comparison of proponents' estimates (gray) to Experts 1 estimates (black) of 1-Hz spectral acceleration for m_{bLg} 5.5. The error bars represent the $\pm\sigma_{epistemic}$ range.

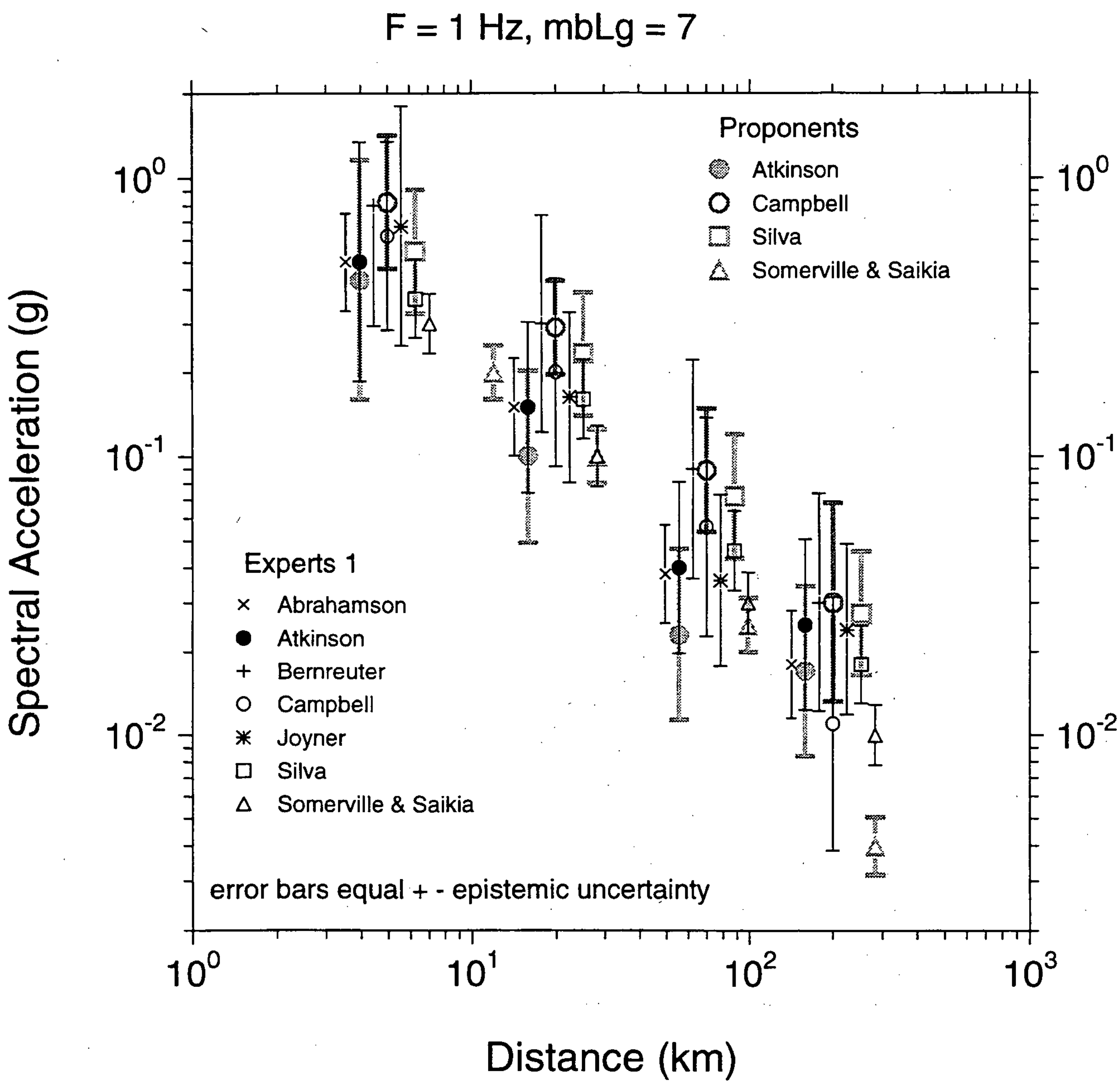

Figure B-2. Comparison of proponents' estimates (gray) to Experts 1 estimates (black) of 1-Hz spectral acceleration for m_{bLg} 7.0. The error bars represent the $\pm\sigma_{epistemic}$ range.

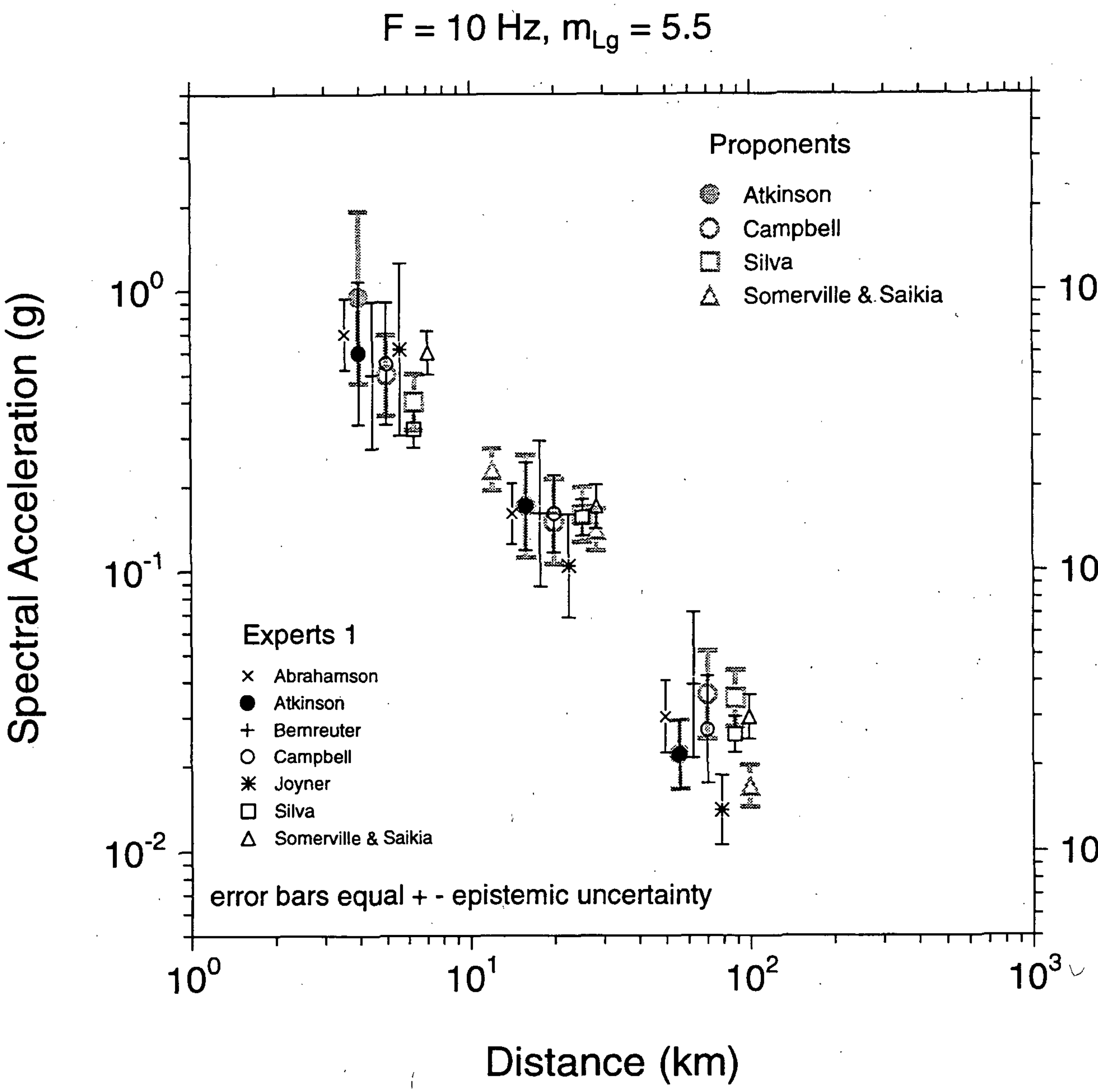

Figure B-3. Comparison of proponents' estimates (gray) to Experts 1 estimates (black) of 10-Hz spectral acceleration for m_{bLg} 5.5. The error bars represent the $\pm\sigma_{epistemic}$ range.

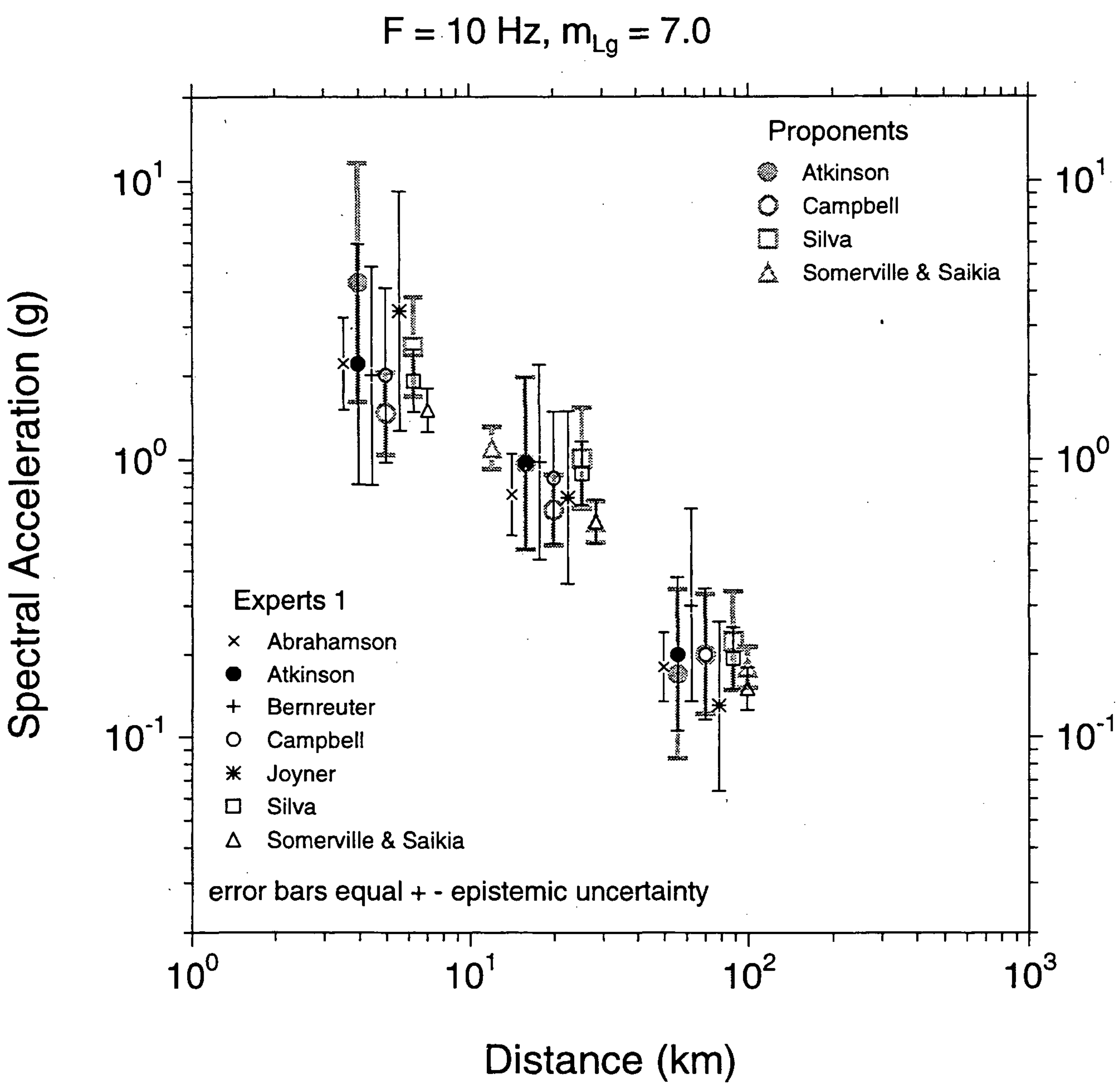

Figure B-4. Comparison of proponents' estimates (gray) to Experts 1 estimates (black) of 10-Hz spectral acceleration for m_{bLg} 7.0. The error bars represent the $\pm\sigma_{epistemic}$ range.

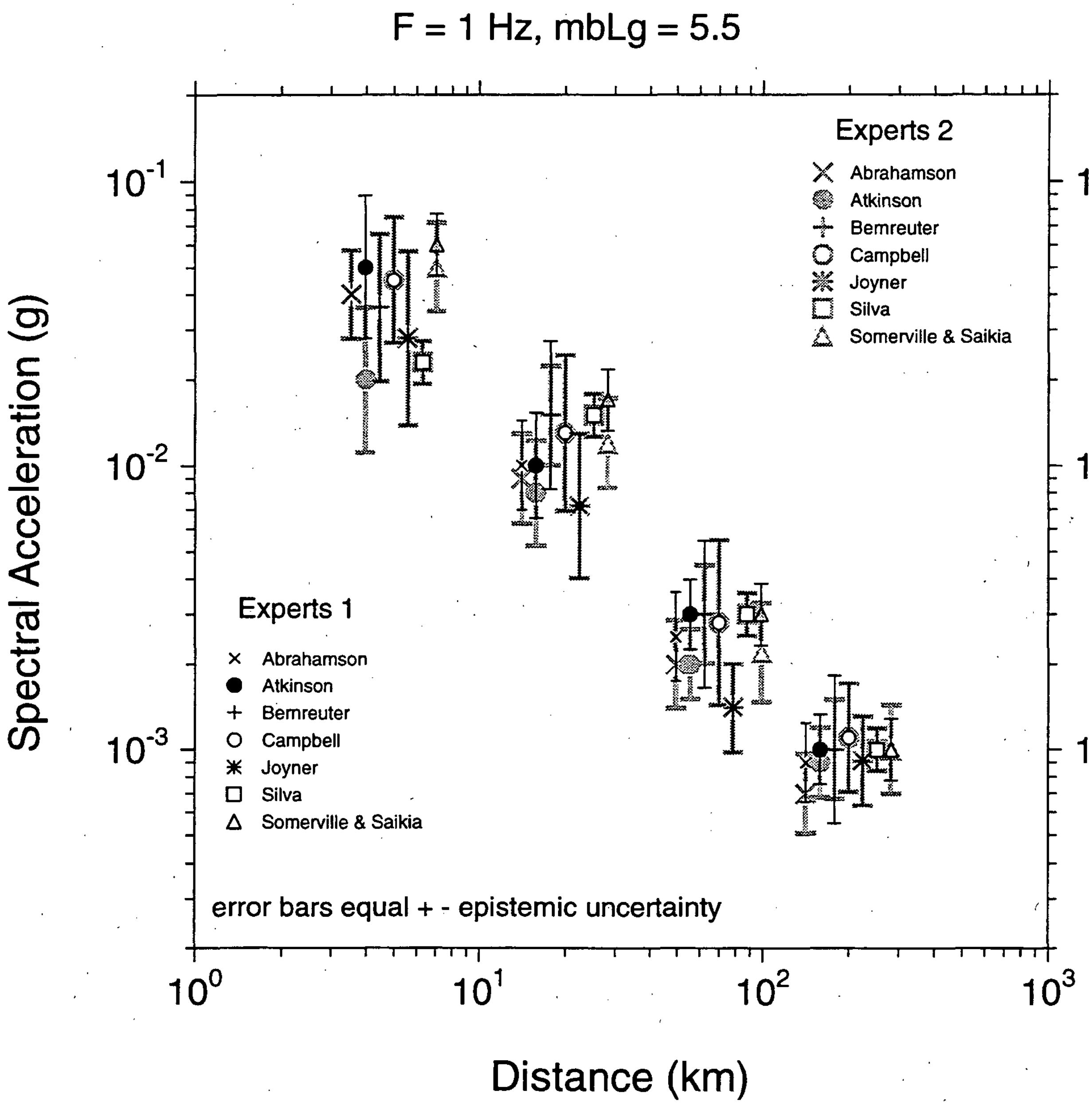

Figure B-5. Comparison of Expert 2 (gray) to Expert 1 (black) estimates of 1-Hz spectral acceleration for m_{bLg} 5.5. The error bars represent the $\pm\sigma_{epistemic}$ range.

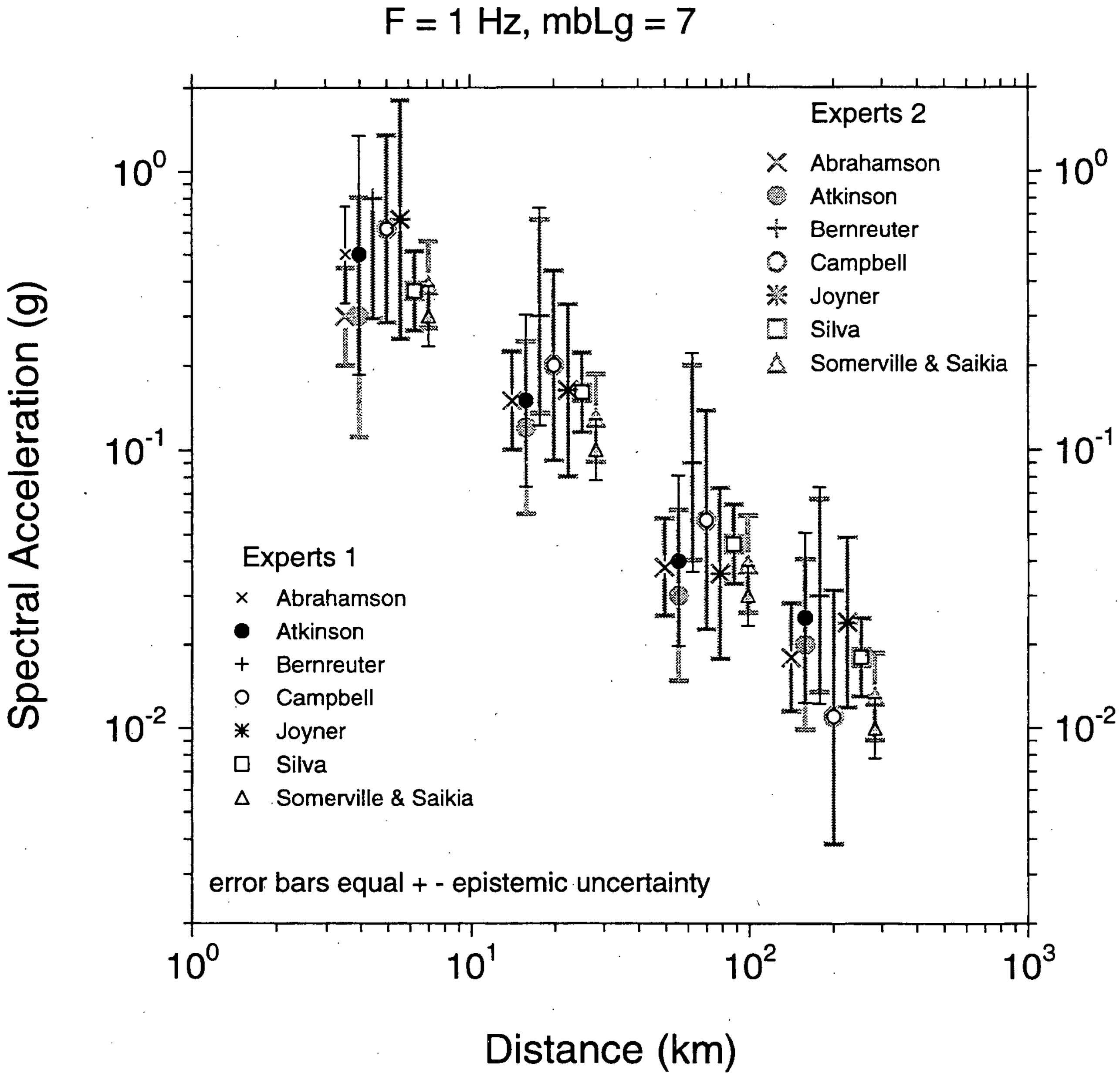

Figure B-6. Comparison of Expert 2 (gray) to Expert 1 (black) estimates of 1-Hz spectral acceleration for m_{bLg} 7.0. The error bars represent the $\pm\sigma_{epistemic}$ range.

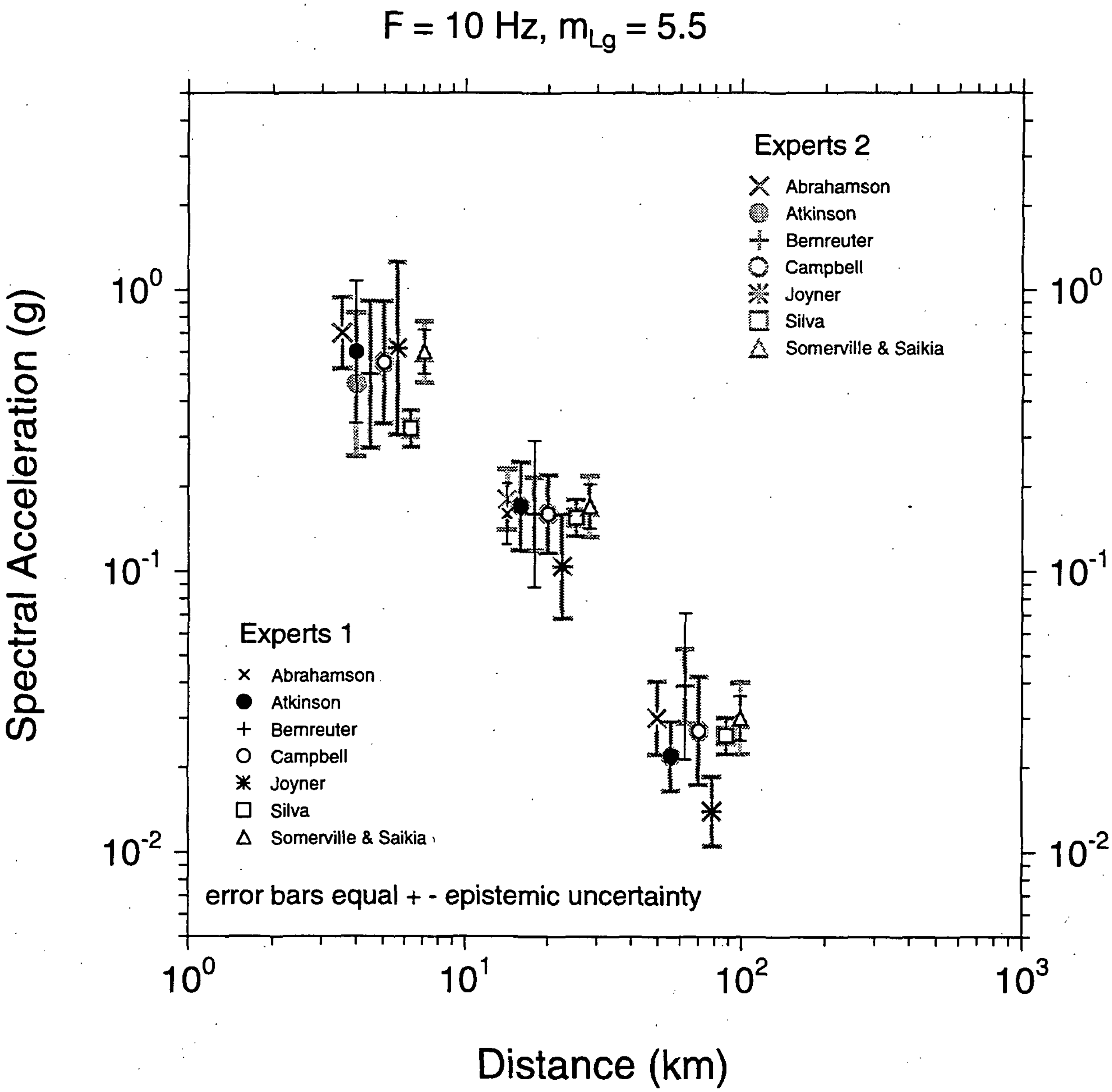

Figure B-7. Comparison of Expert 2 (gray) to Expert 1 (black) estimates of 10-Hz spectral acceleration for m_{bLg} 5.5. The error bars represent the $\pm\sigma_{epistemic}$ range.

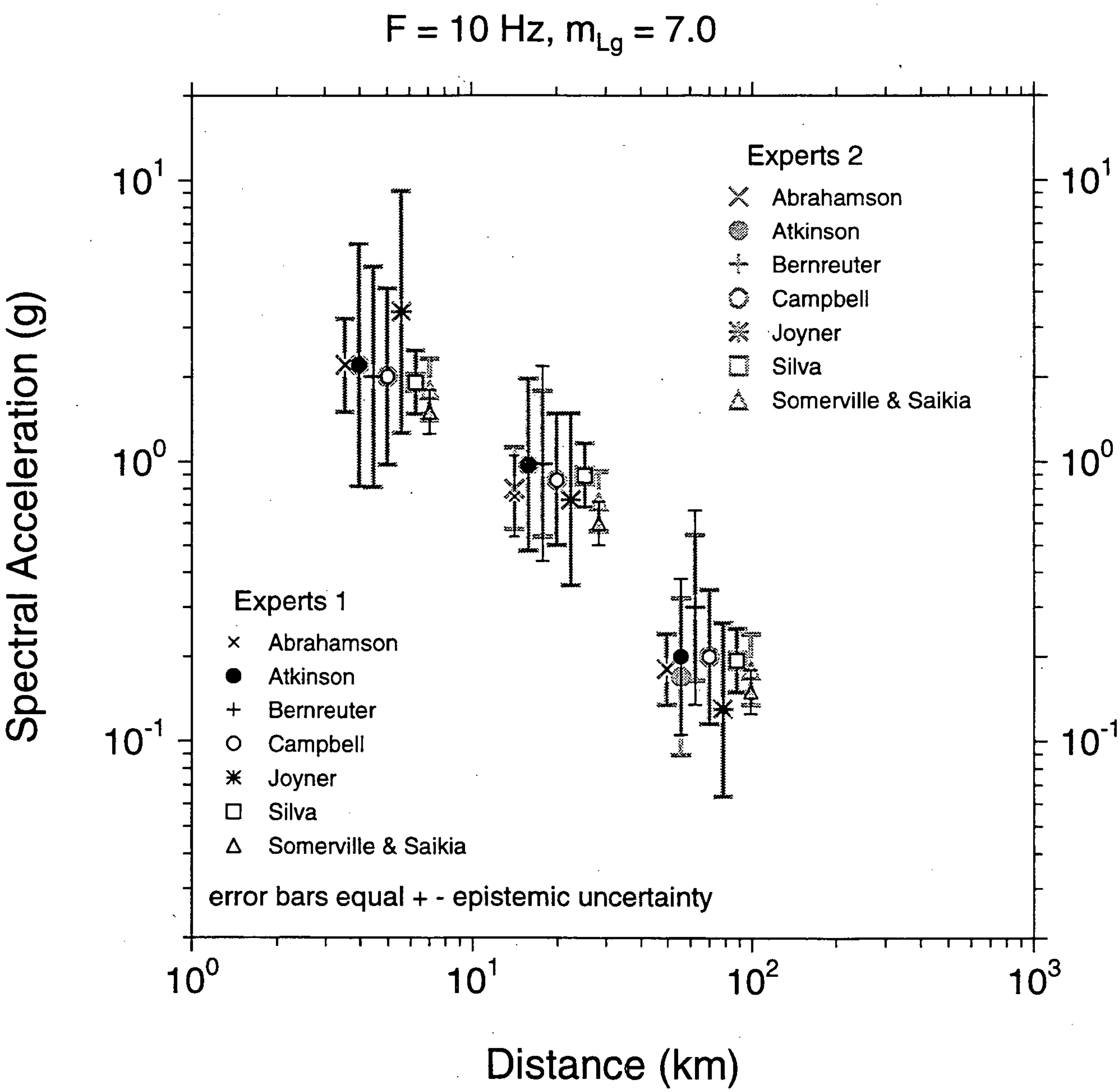

Figure B-8. Comparison of Expert 2 (gray) to Expert 1 (black) estimates of 10-Hz spectral acceleration for m_{bLg} 7.0. The error bars represent the $\pm\sigma_{epistemic}$ range.

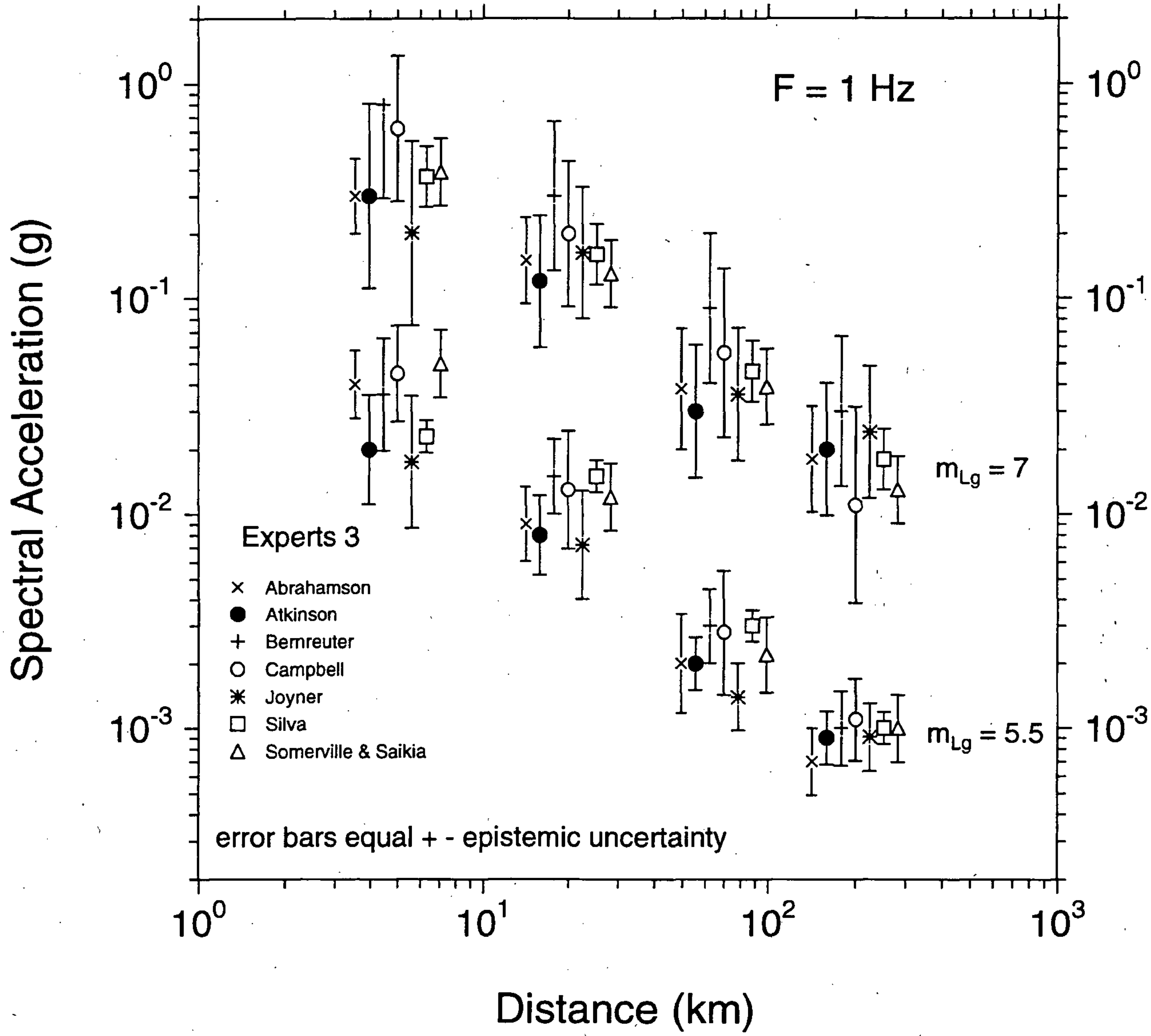

Figure B-9. Experts 3 estimates of 1-Hz spectral acceleration. The error bars indicate the experts' $\pm\sigma_{epistemic}$ range.

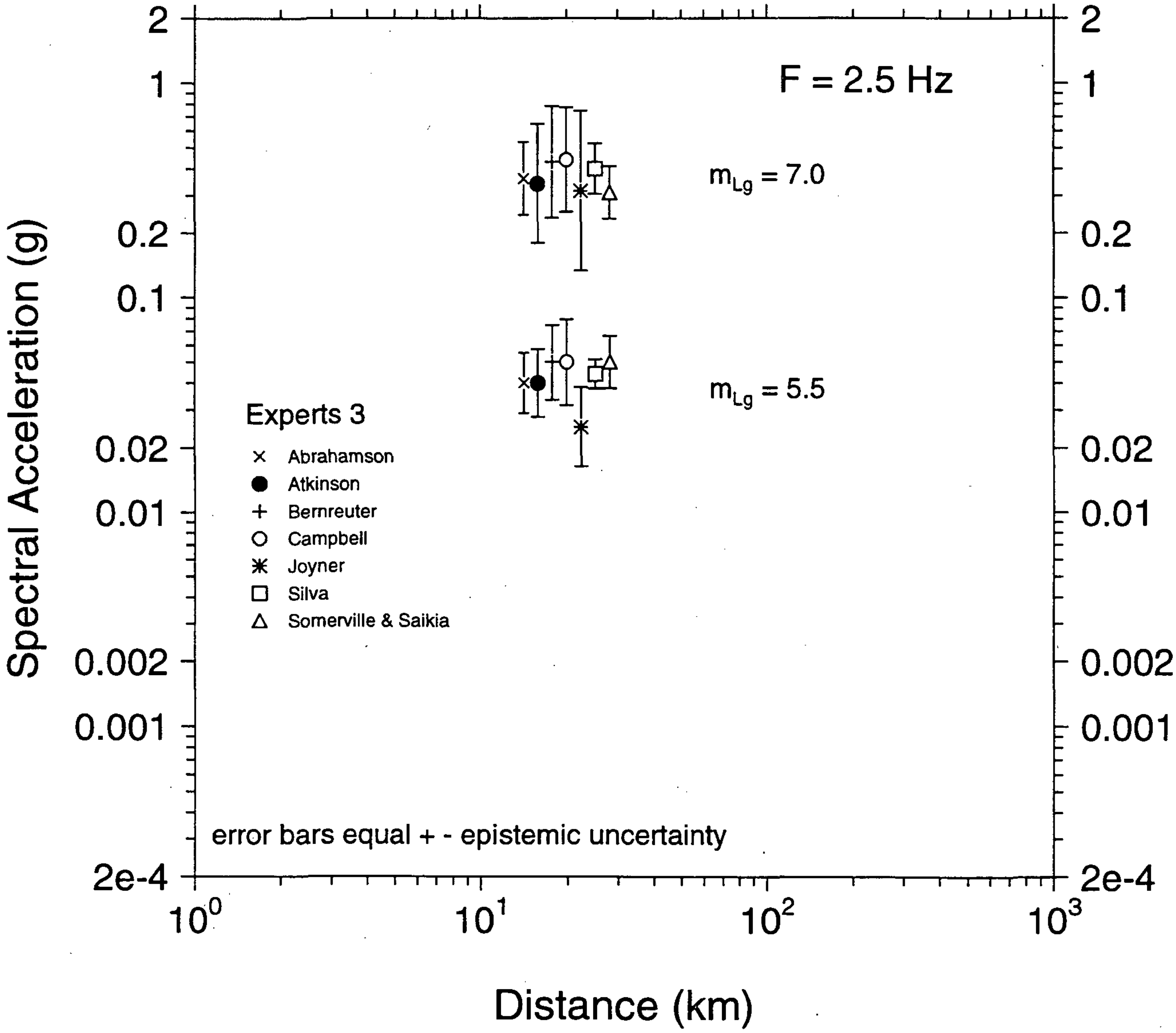

Figure B-10. Expert 3 median estimates of epistemic uncertainty in the median 1-Hz spectral acceleration for m_{bLg} 5.5.

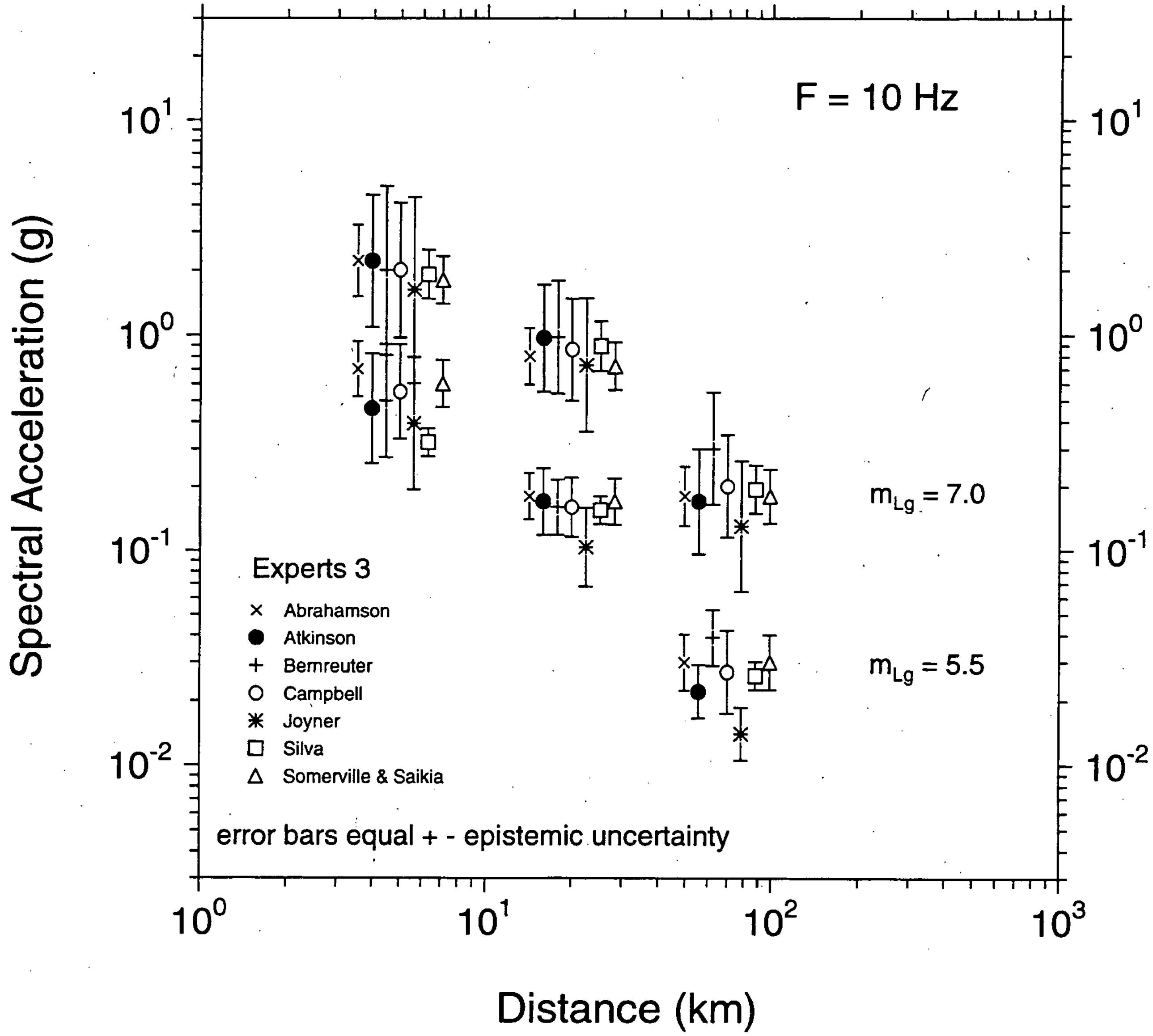

Figure B-11. Expert 3 median estimates of epistemic uncertainty in the median 1-Hz spectral acceleration for m_{bLg} 7.0.

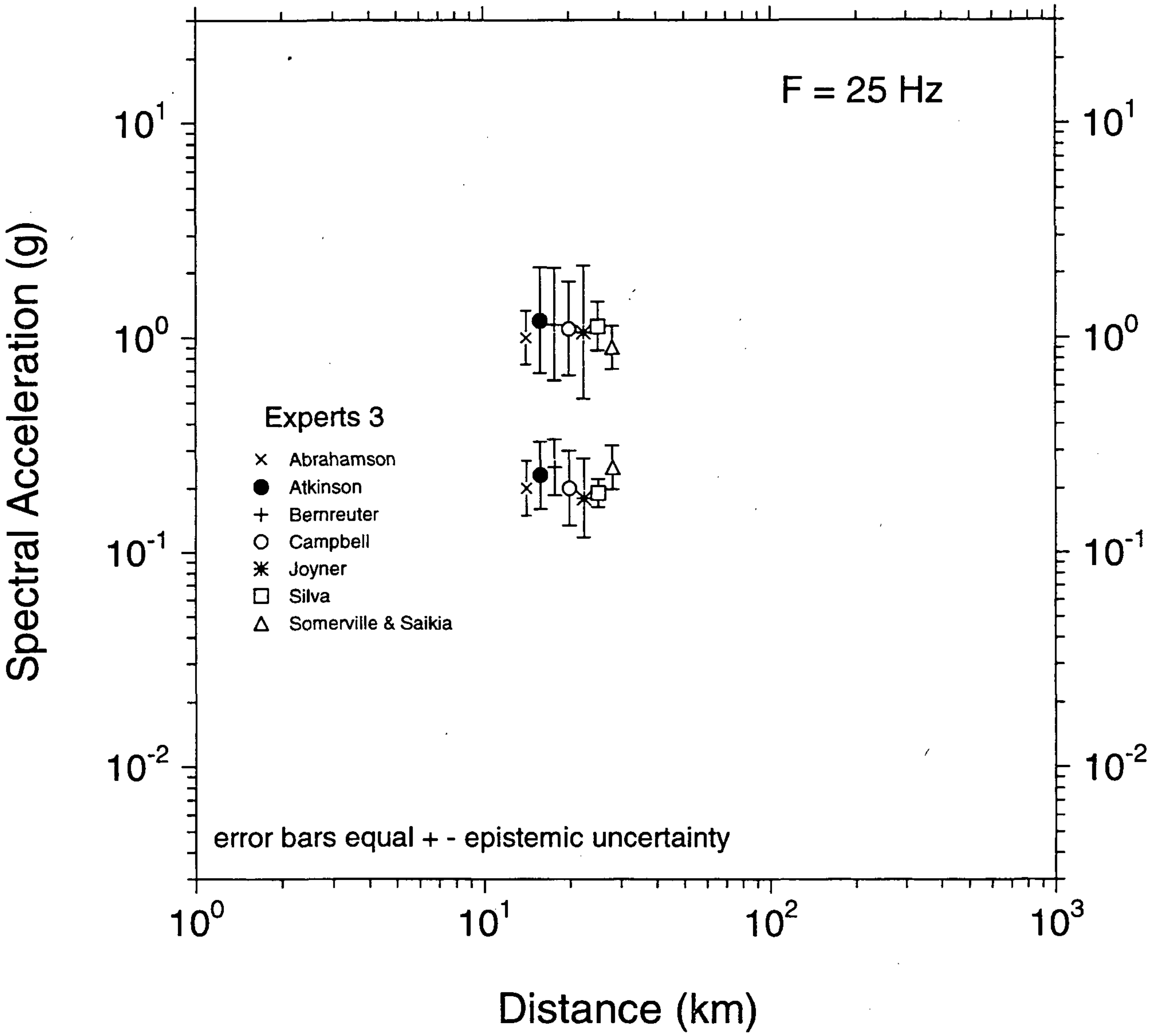

Figure B-12. Expert 3 median estimates of the aleatory uncertainty in 1-Hz spectral acceleration for m_{bLg} 5.5.

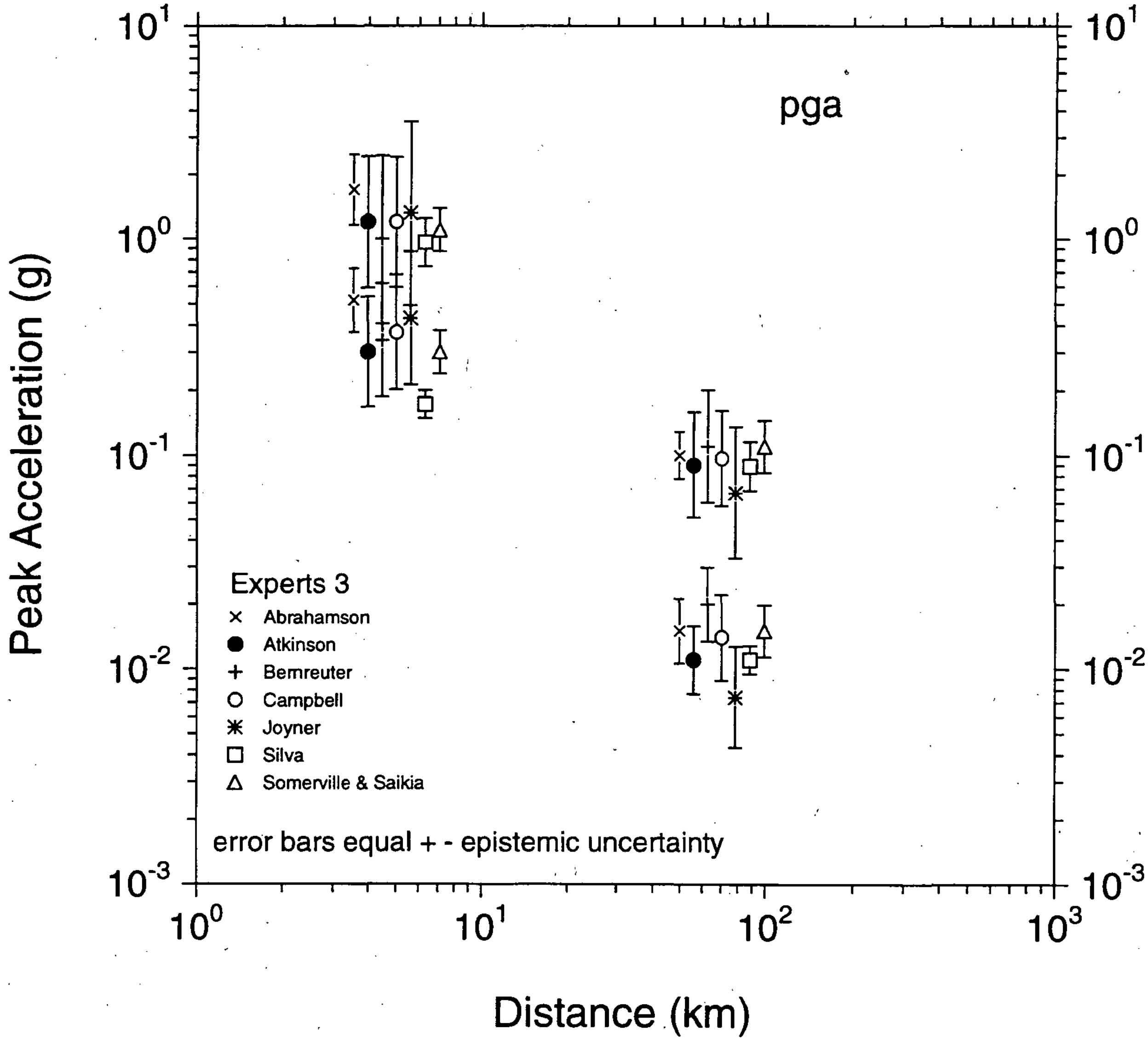

Figure B-13. Expert 3 median estimates of the aleatory uncertainty in 1-Hz spectral acceleration for m_{bLg} 7.0.

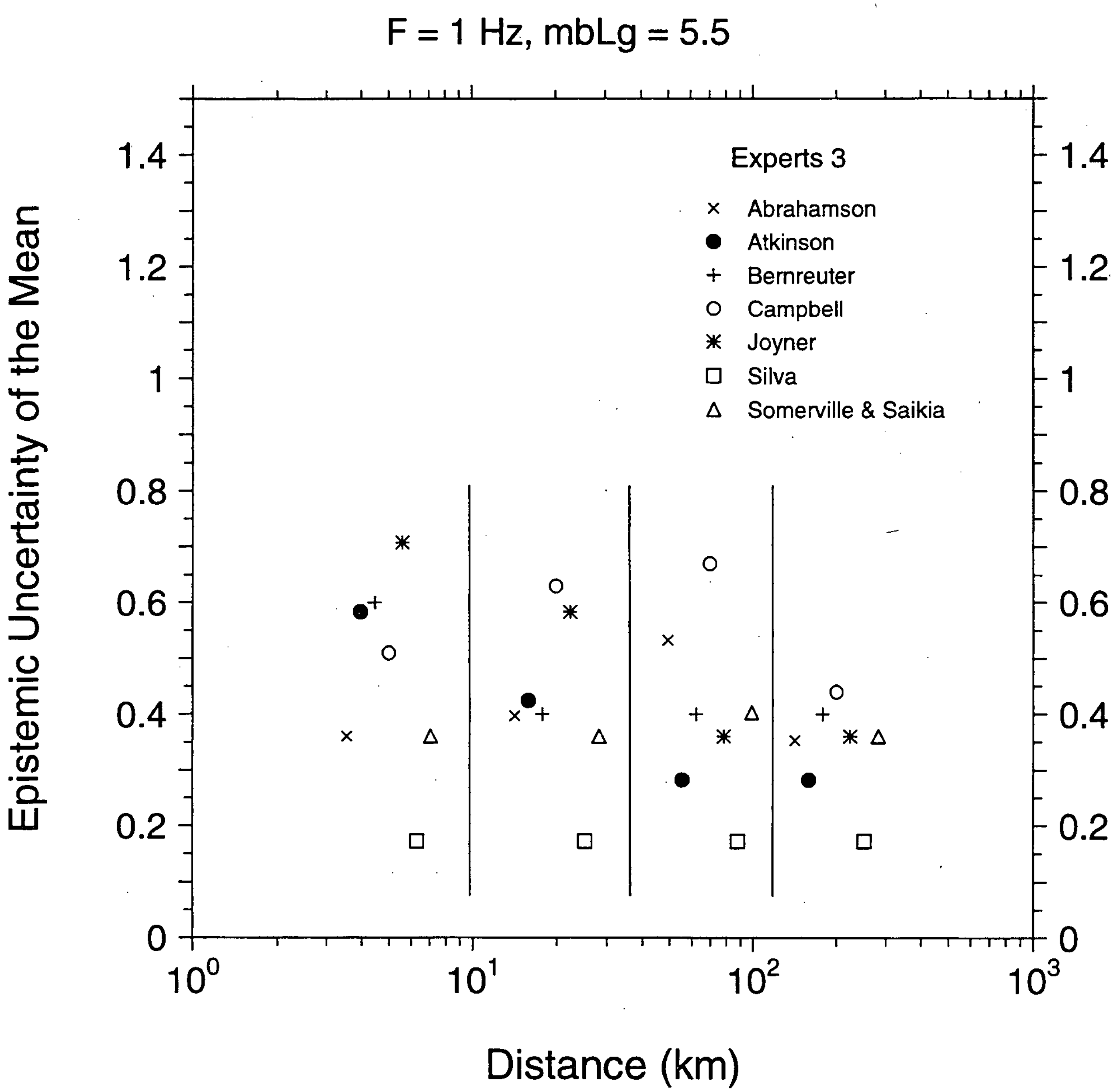

Figure B-14. Experts 3 estimates of 2.5-Hz spectral acceleration. The error bars indicate the experts' $\pm\sigma_{epistemic}$ range.

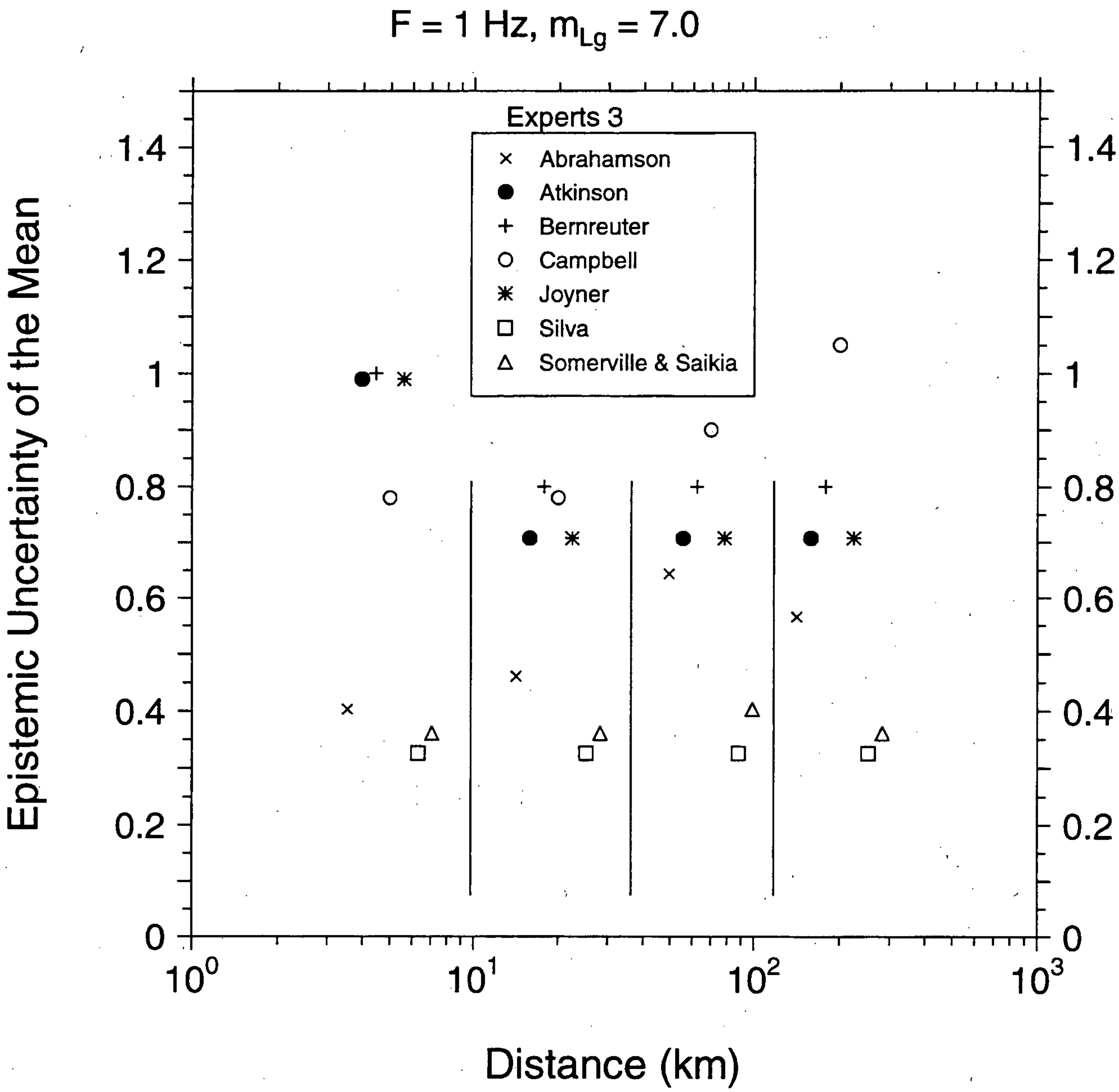

Figure B-15. Experts 3 estimates of 10-Hz spectral acceleration. The error bars indicate the experts' $\pm\sigma_{epistemic}$ range.

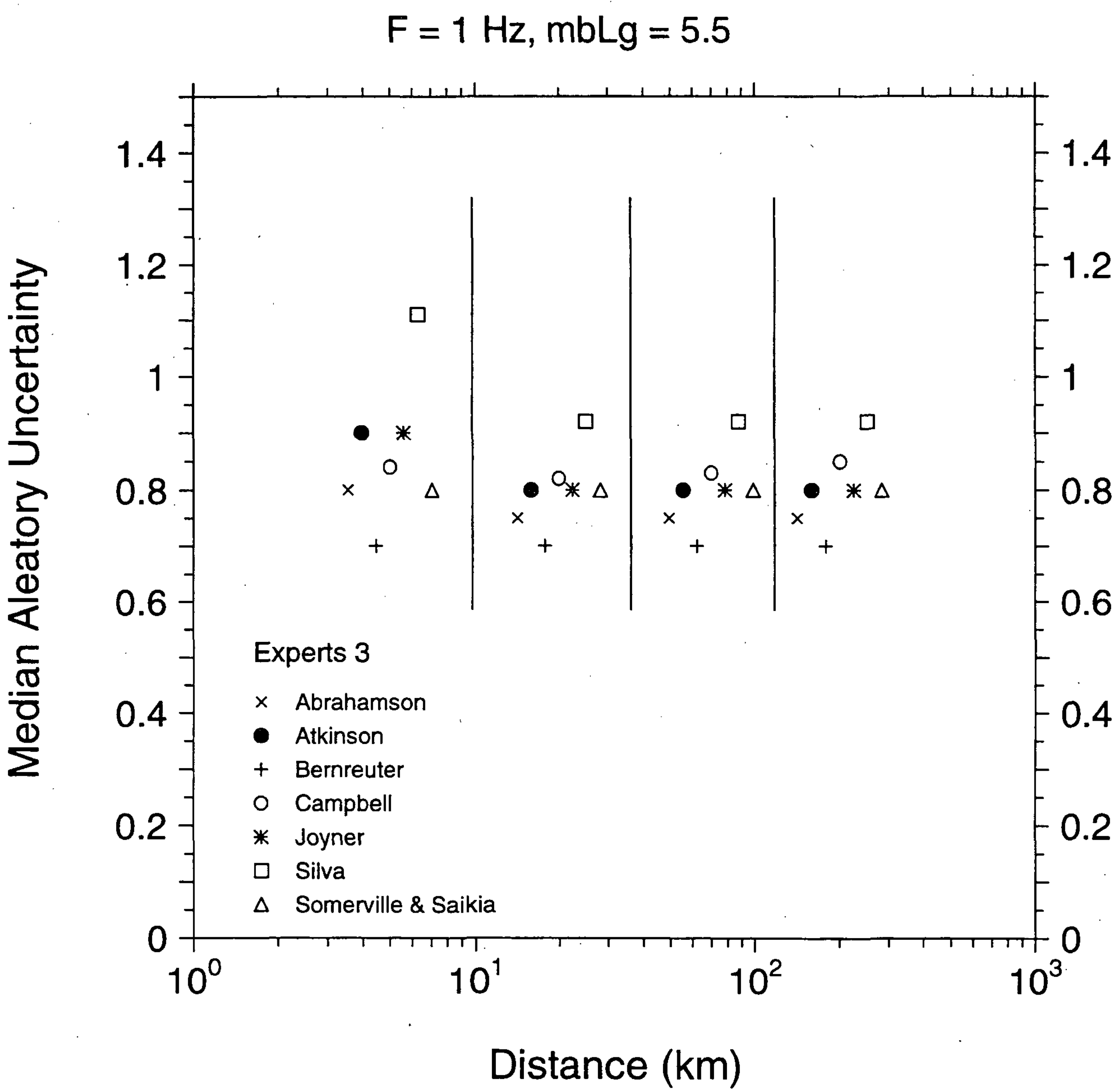

Figure B-16. Experts 3 estimates of 25-Hz spectral acceleration. The error bars indicate the experts' $\pm\sigma_{epistemic}$ range.

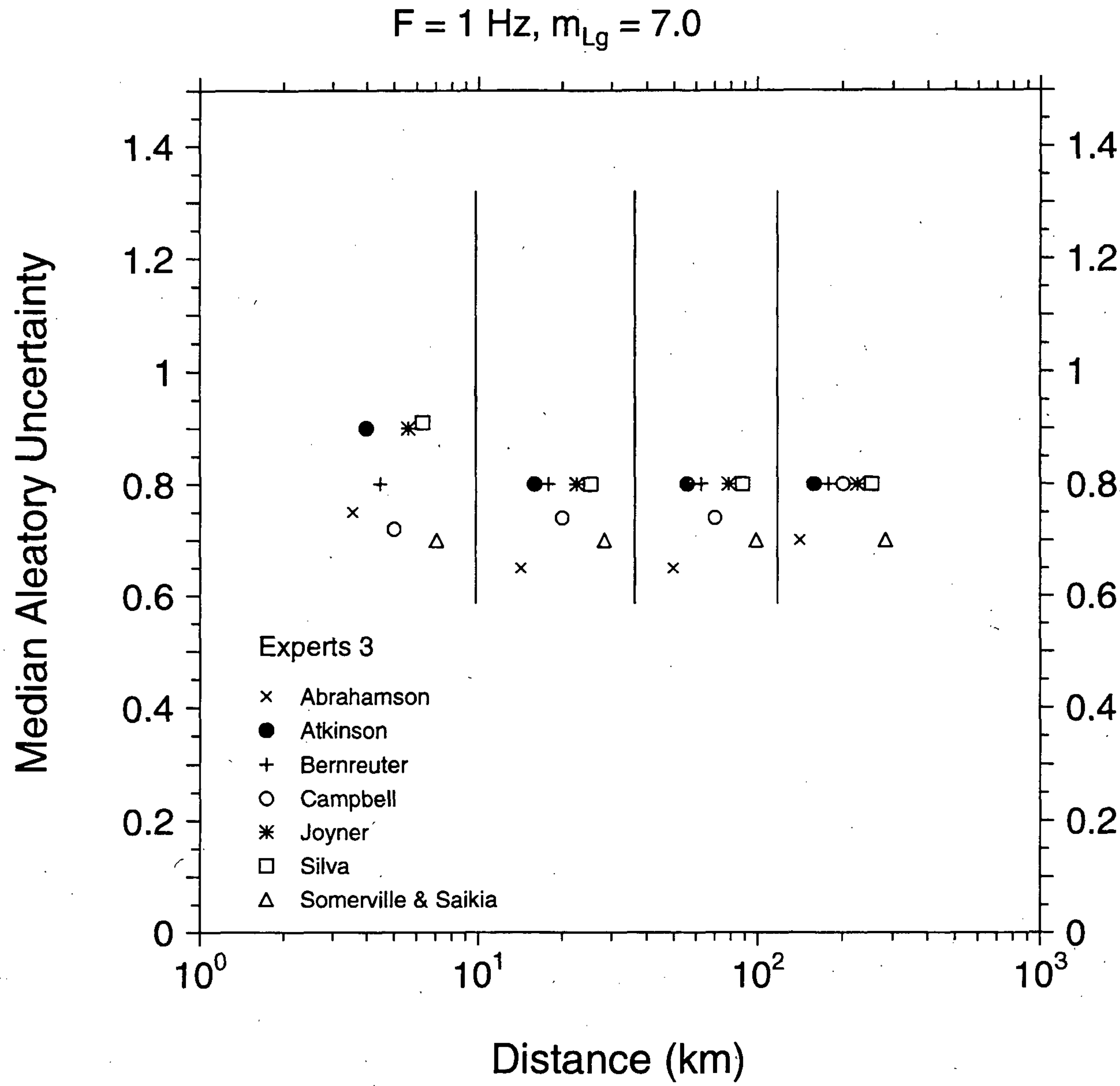

Figure B-17. Expert 3 estimates of PGA. The error bars indicate the experts' $\pm\sigma_{epistemic}$ range.

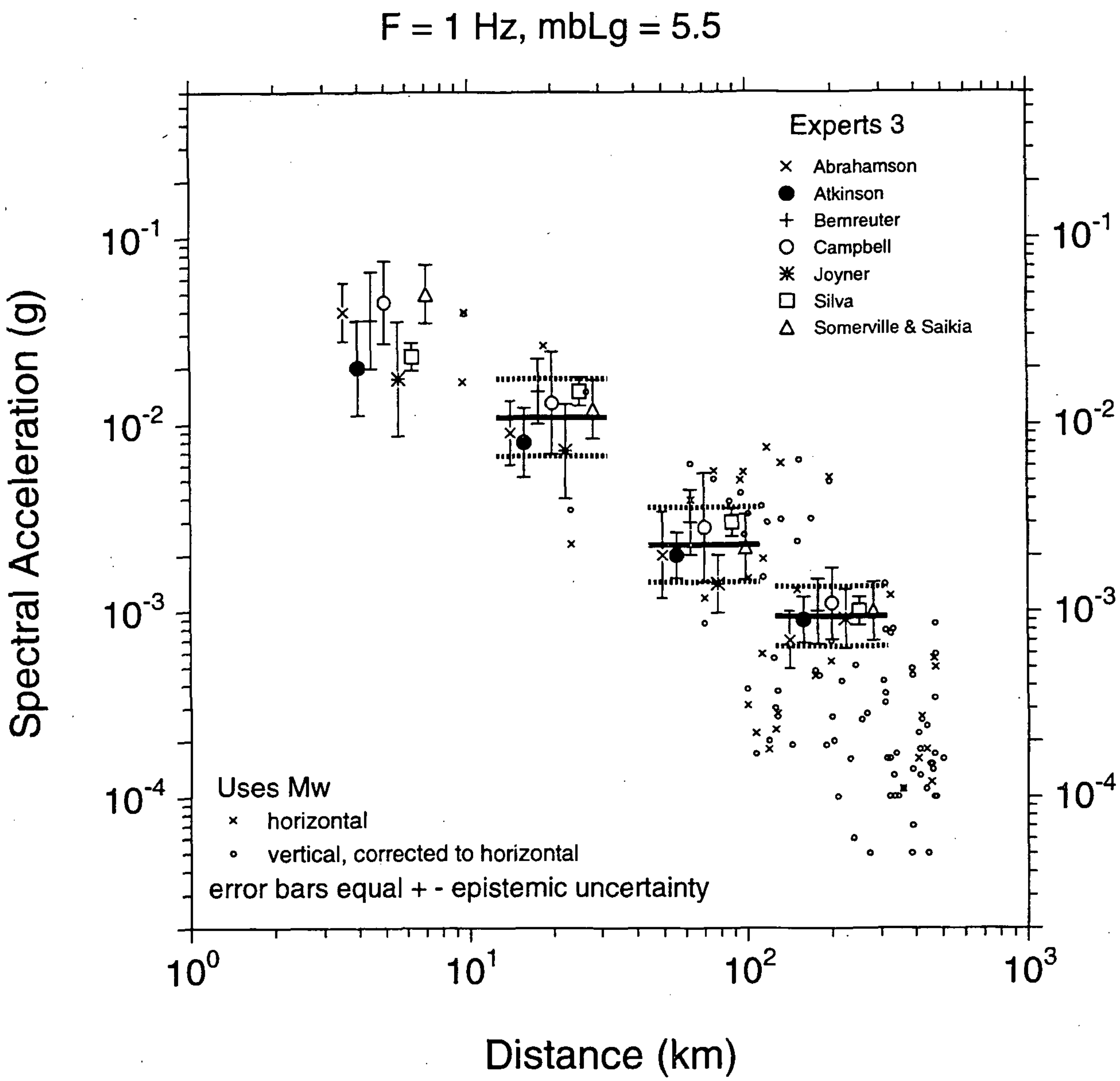

Figure B-18. Comparison of integration results (median amplitude $\pm\sigma_{epistemic}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 1-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

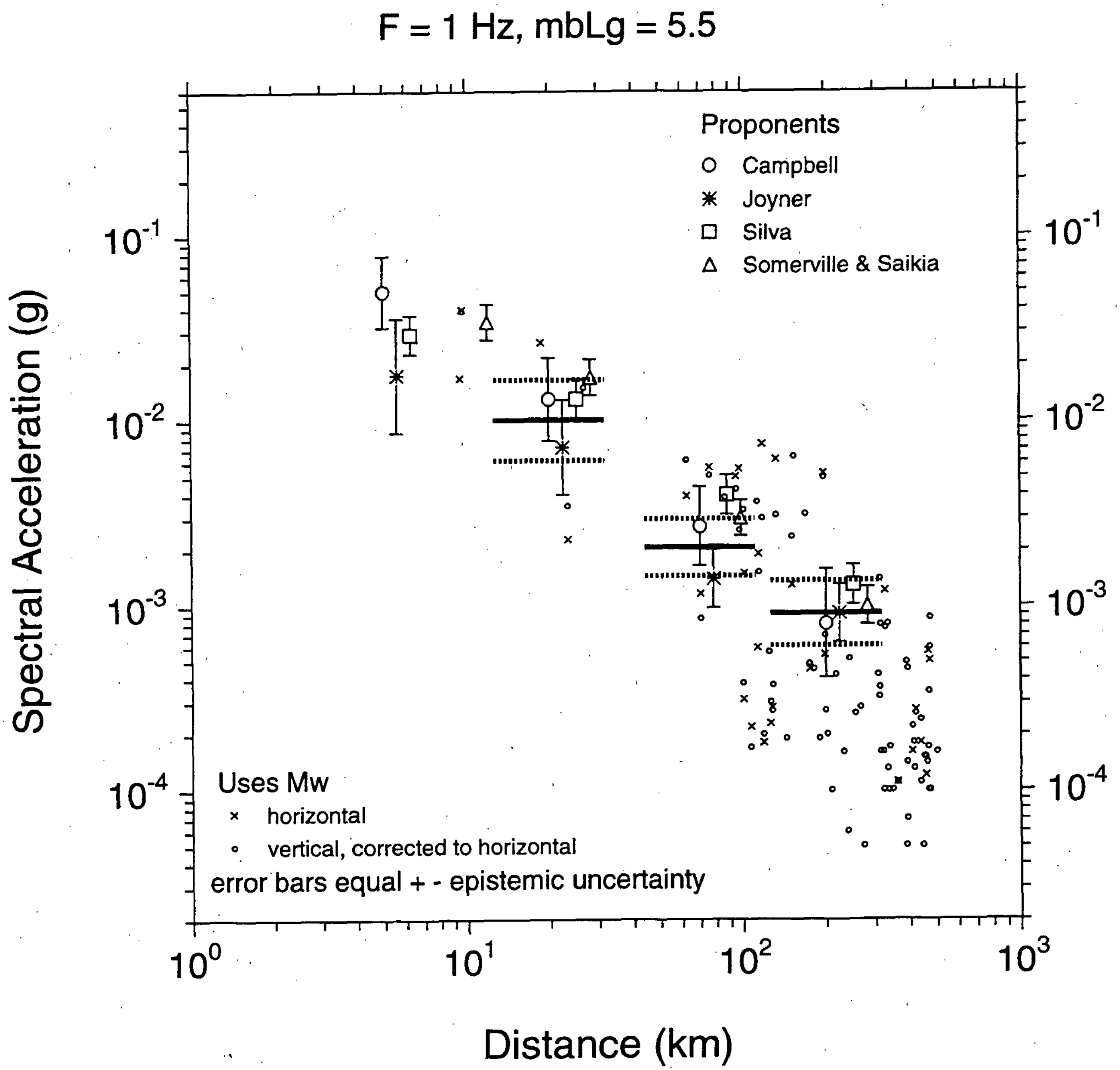

Figure B-19. Comparison of integration results (median amplitude $\pm\sigma_{epistemic}$) using unequal weights on the proponents' estimates of 1-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

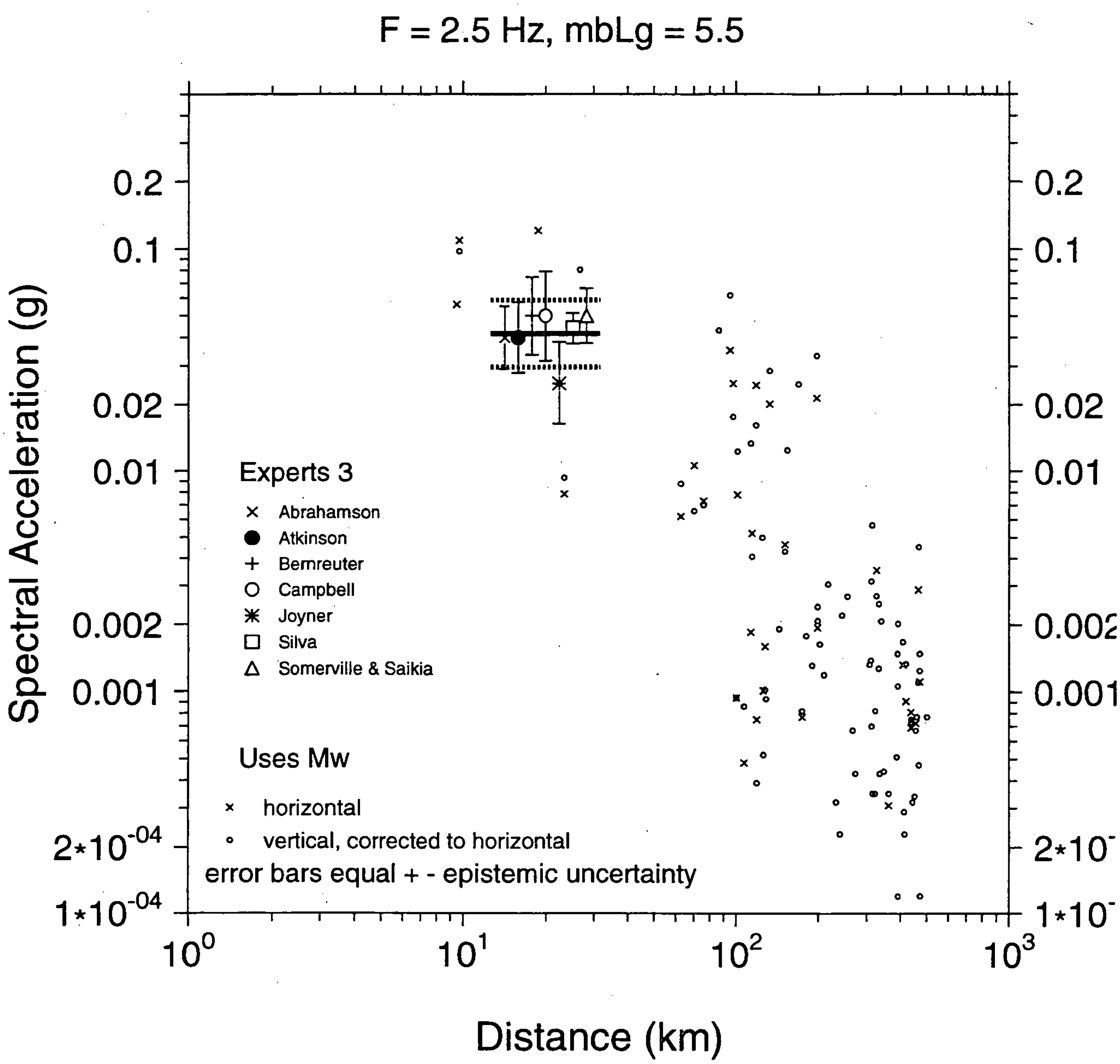

Figure B-20. Comparison of integration results (median amplitude $\pm\sigma_{epistemic}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 2.5-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

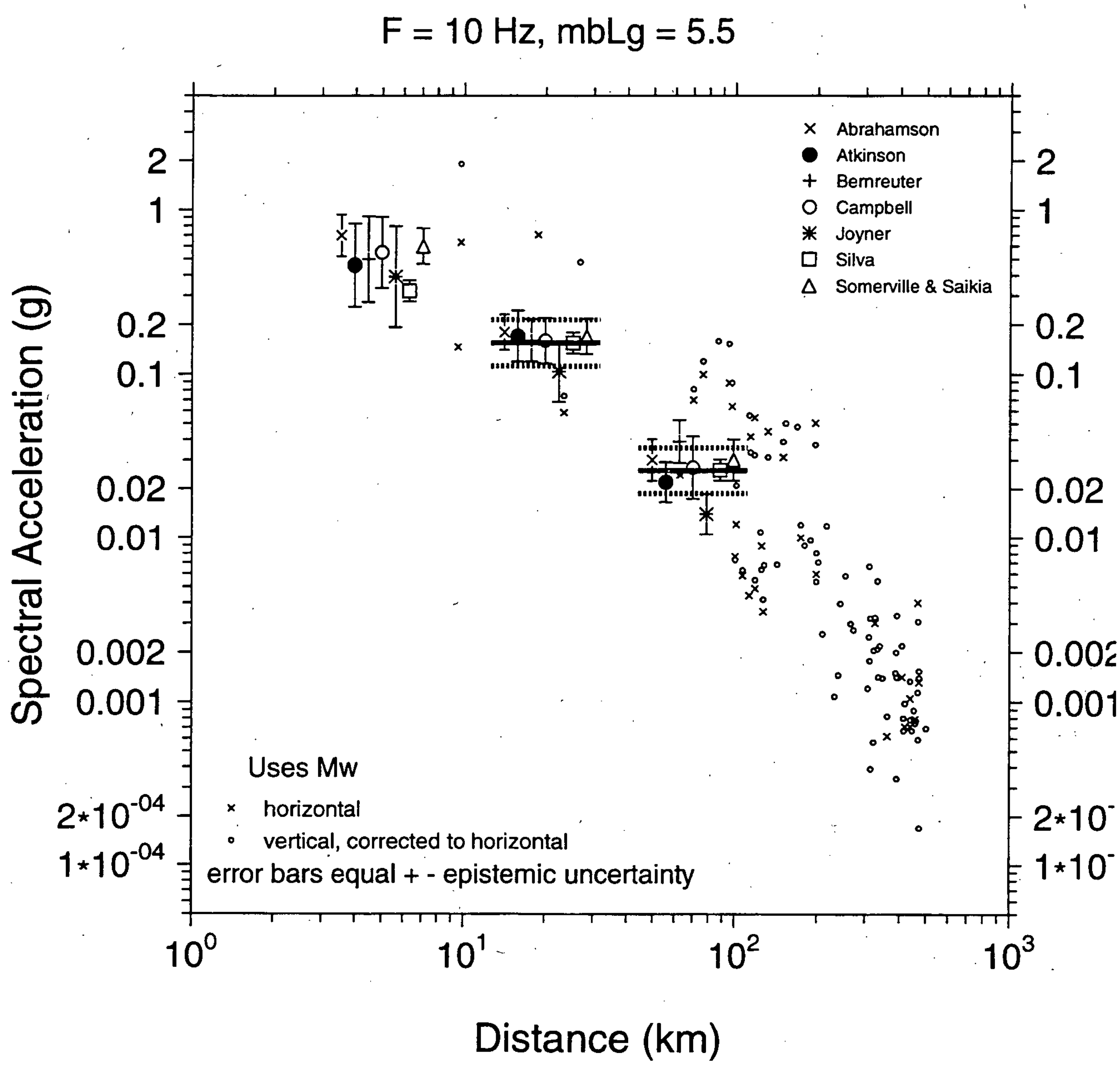

Figure B-21. Comparison of integration results (median amplitude $\pm\sigma_{epistemic}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 10-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

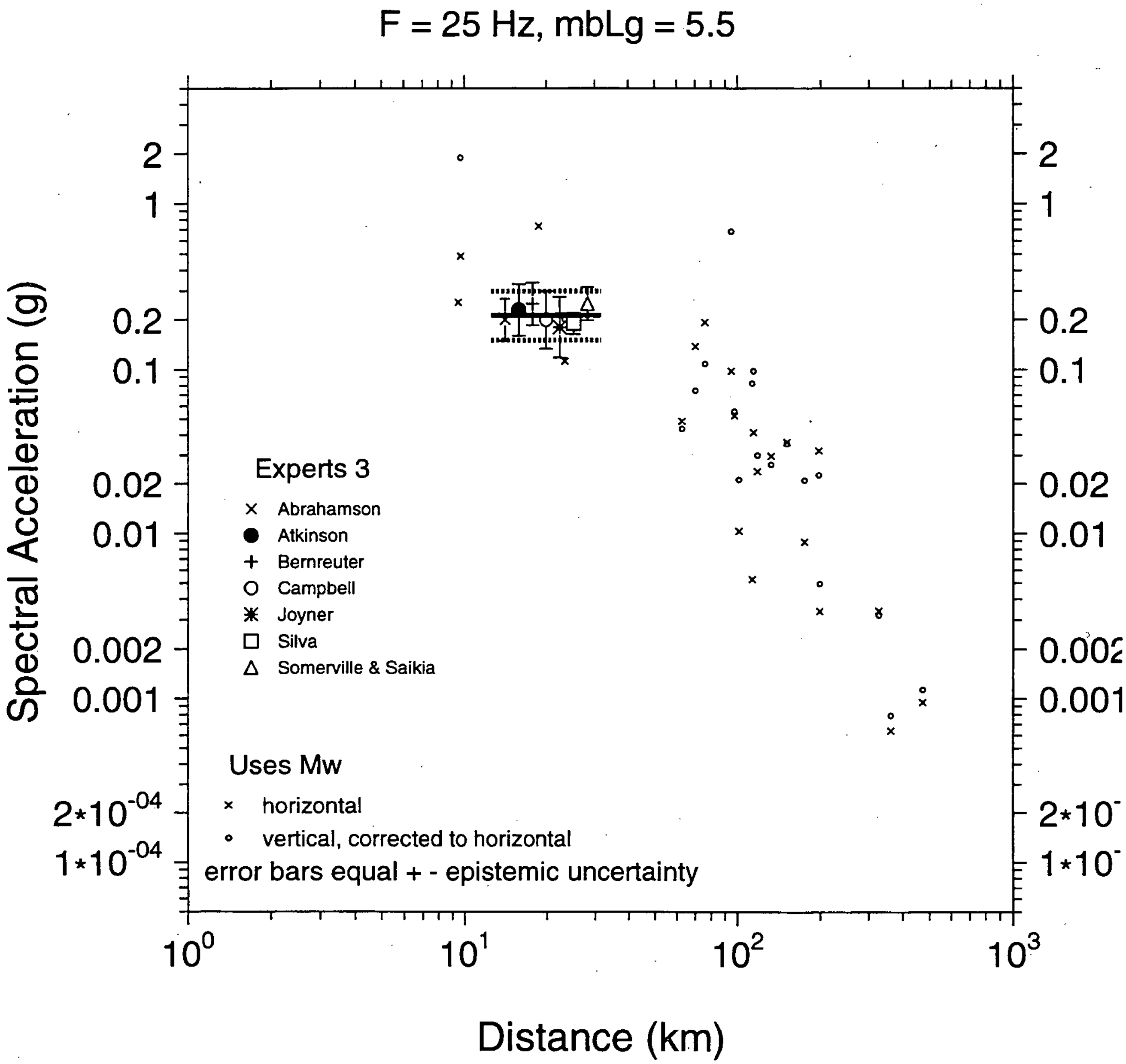

Figure B-22. Comparison of integration results (median amplitude $\pm\sigma_{epistemic}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 25-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

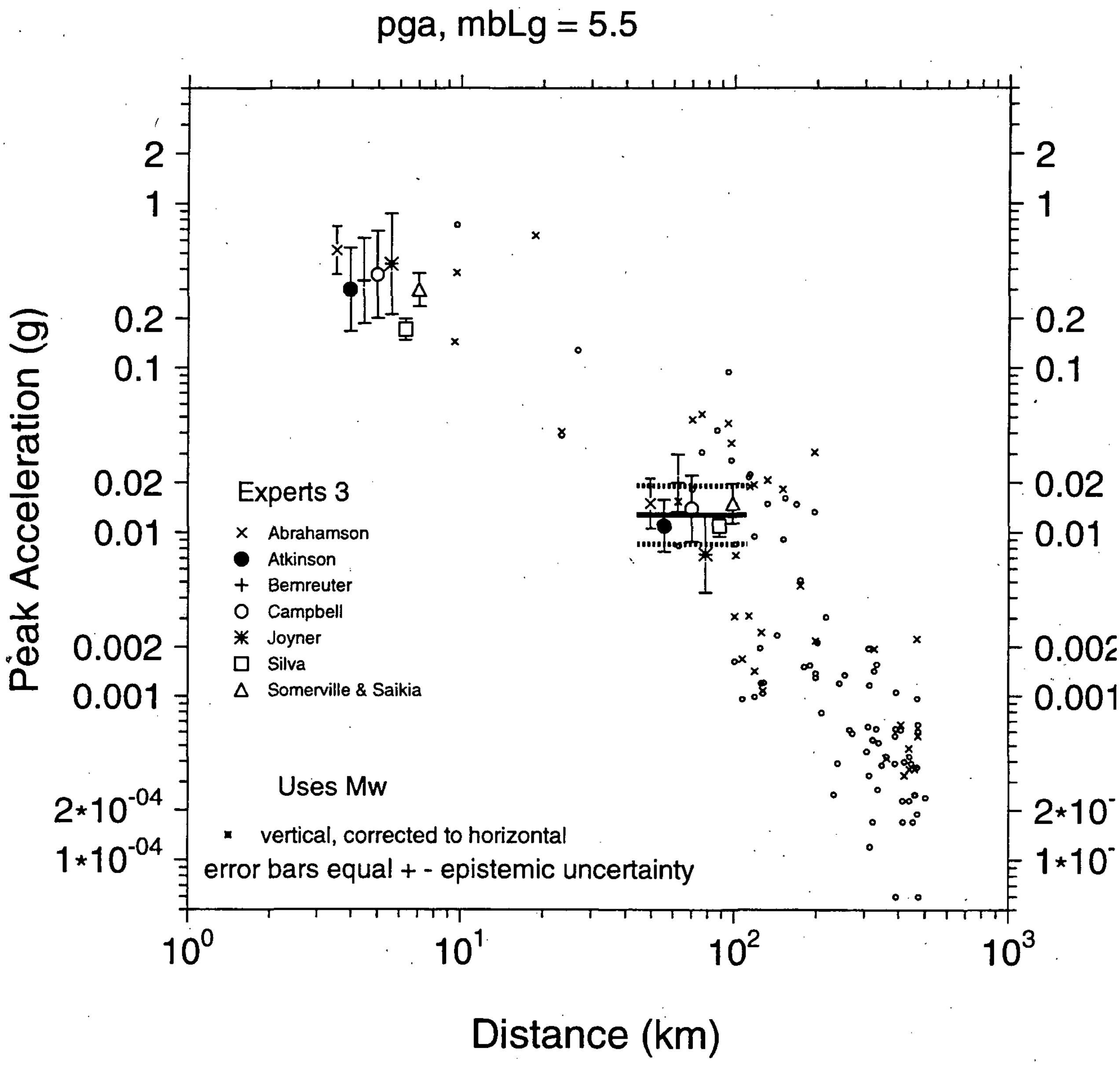

Figure B-23. Comparison of integration results (median amplitude $\pm\sigma_{epistemic}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of PGA for m_{bLg} 5.5. The small symbols represent data.

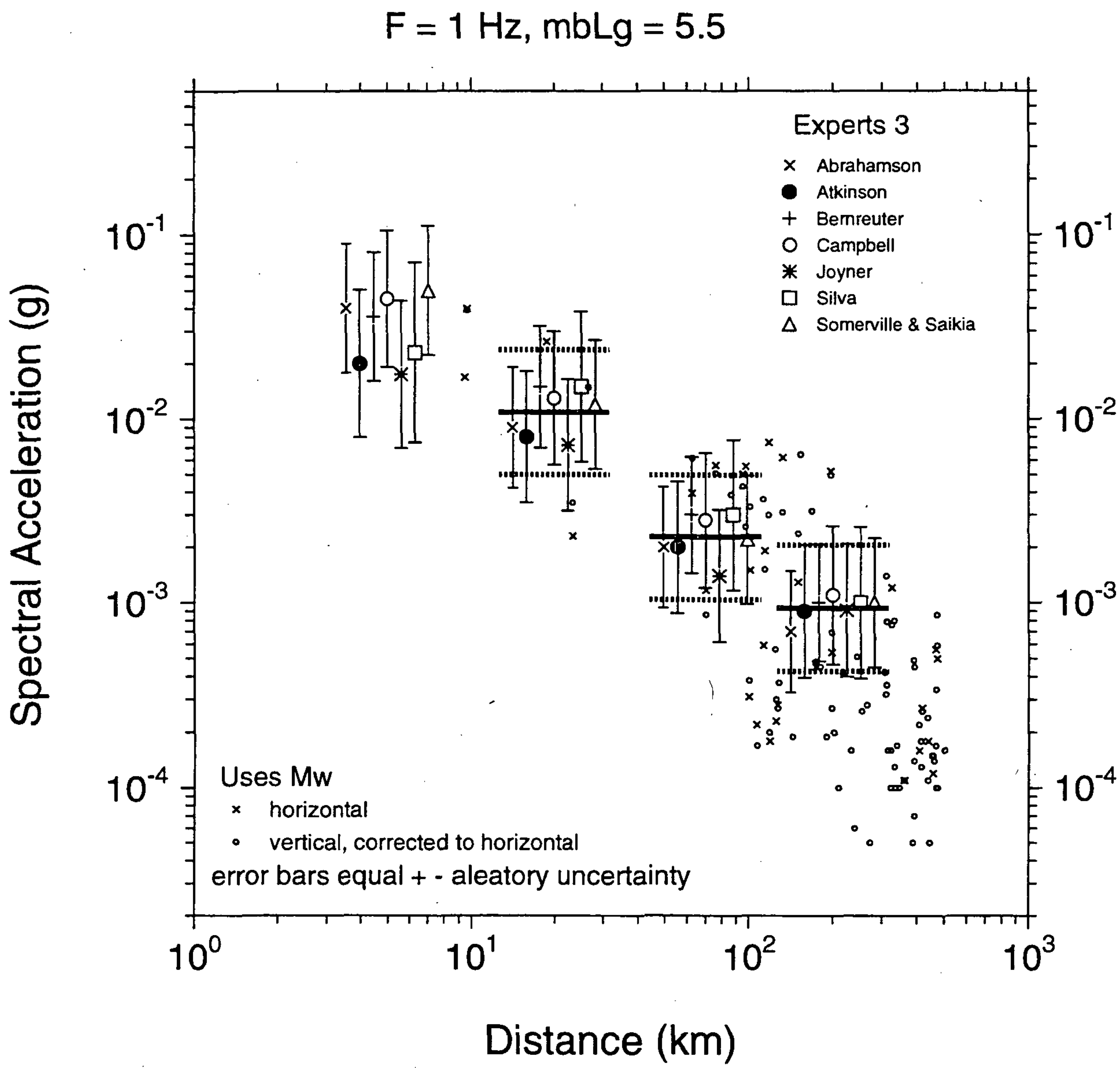

Figure B-24. Comparison of integration results (median amplitude $\pm\sigma_{aleatory}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 1-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

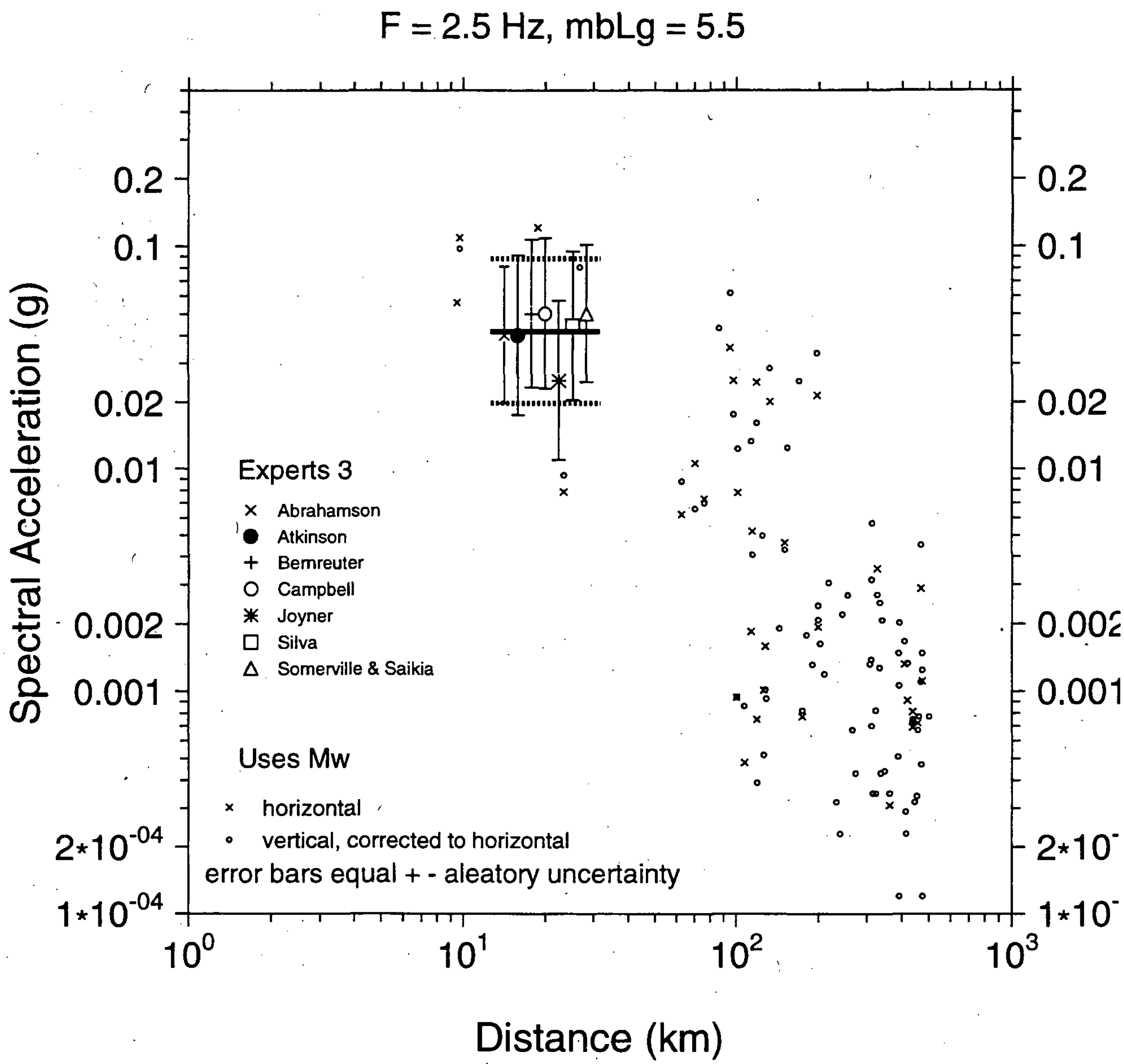

Figure B-25. Comparison of integration results (median amplitude $\pm\sigma_{aleatory}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 2.5-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

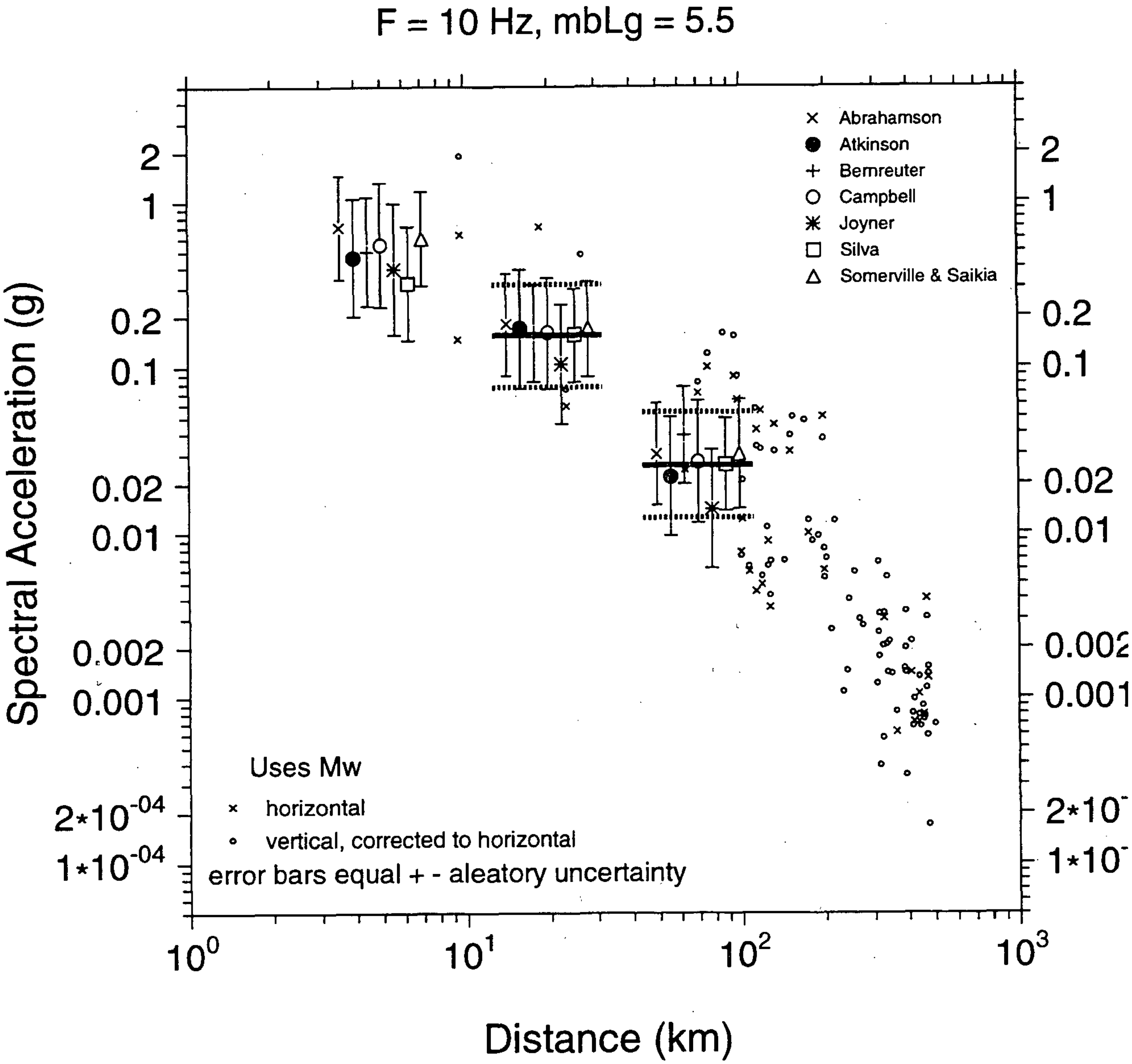

Figure B-26. Comparison of integration results (median amplitude $\pm\sigma_{aleatory}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 10-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

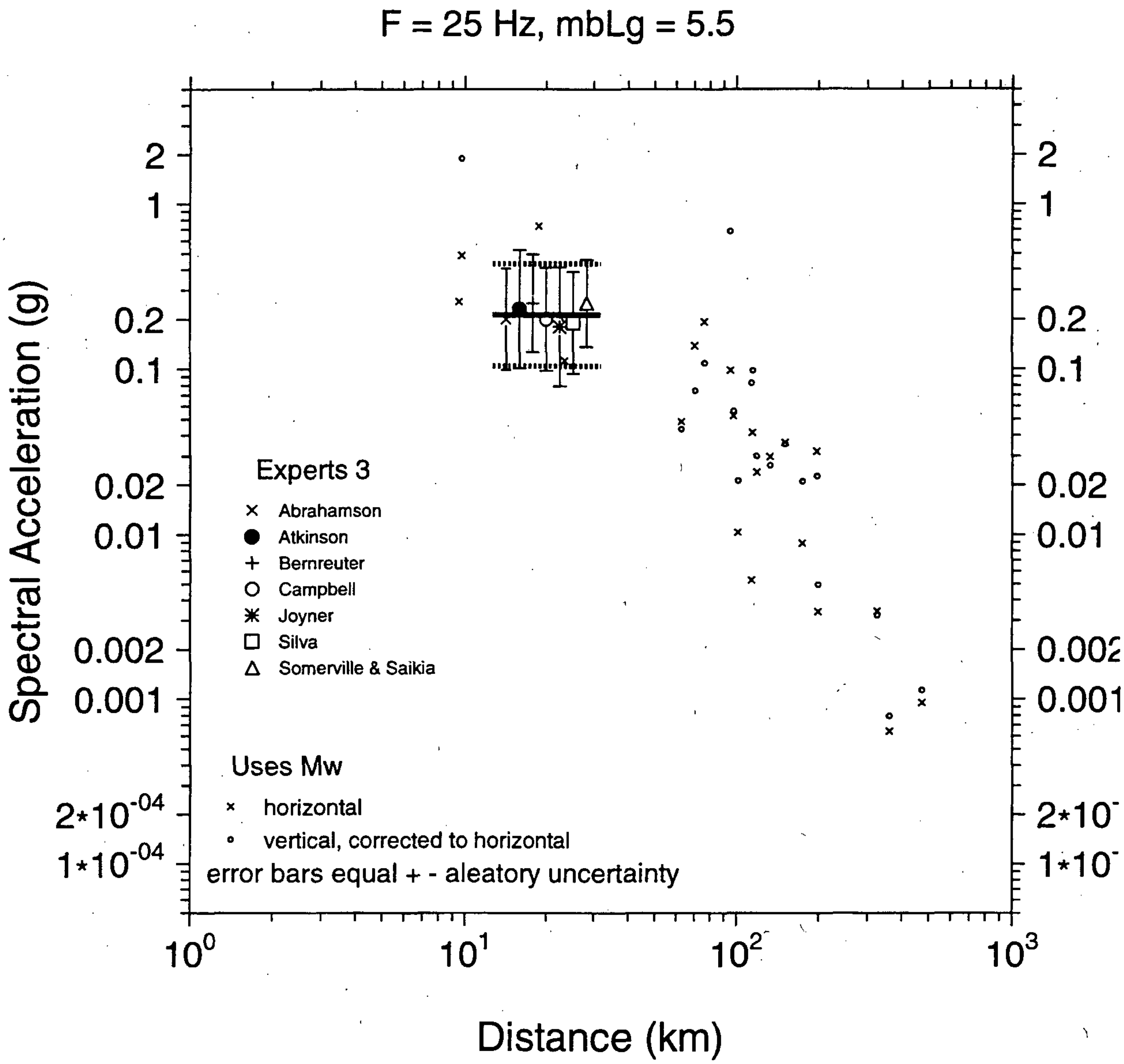

Figure B-27. Comparison of integration results (median amplitude $\pm\sigma_{aleatory}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 25-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

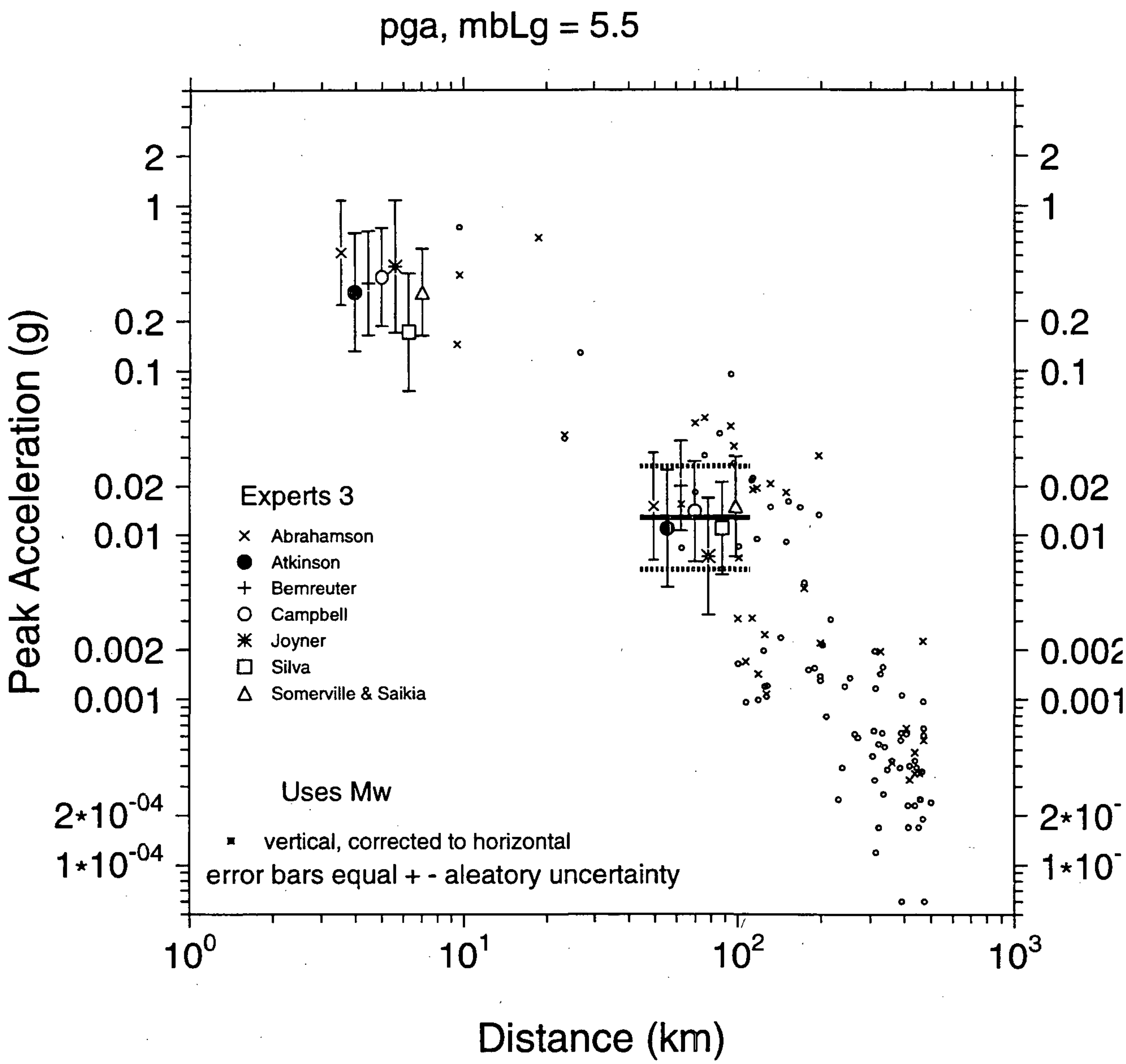

Figure B-28. Comparison of integration results (median amplitude $\pm\sigma_{aleatory}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of PGA for m_{bLg} 5.5. The small symbols represent data.

ATTACHMENTS

ATTACHMENT B-1

PROPONENTS' RESULTS

SSHAC SECOND GROUND-MOTION WORKSHOP

INSTRUCTIONS FOR PROPONENTS

Gabriel R. Toro
Risk Engineering, Inc.
May27, 1994

As part of the preparations for the second SSHAC Ground Motion Workshop, we are asking you to prepare and document ground-motion estimates for a specific tectonic province and for a suite of magnitudes, distances, and frequencies of engineering interest. We are testing a format for these estimates that is somewhat different from those used in past ground-motion elicitation efforts. Your estimates, along with the estimates prepared by other proponents, will be distributed to other participating ground-motion experts. This set of results will be a key input in the development of a composite ground-motion model.

The definition of the problem is as follows:

- Site location: northeastern United States or southeastern Canada
- Site conditions Eastern United States Rock (2800 m/s average shear-wave velocity over the top 30 m)
- Magnitudes, distances (to closest point on rupture), and oscillator frequencies as given below:

Distance to closest point on rupture (km)	m_{Lg} 5.5	m_{Lg} 7
5	1 Hz, 10 Hz, PGA	1 Hz*, 10 Hz*, PGA
20	1 Hz*, 2.5 Hz*, 10 Hz*, 25 Hz*	1 Hz*, 2.5 Hz, 10 Hz*, 25 Hz*
70	1 Hz, 10 Hz, PGA	1 Hz, 10 Hz, PGA
200	1 Hz	1 Hz*

where the asterisks denote debating points (i.e., predictions on which we will focus the comparisons and discussions).

For each magnitude-distance-frequency combination, you are asked to provide the following information:

1 an estimate of the median ground-motion amplitude (5% damped spectral acceleration or PGA),

2 an estimate of the epistemic uncertainty associated with that estimate of the median (you are also asked to partition this epistemic uncertainty into its parametric and modeling components)

3 a central estimate of the aleatory uncertainty (about the true median) anticipated in future observations of ground motions under the same conditions (i.e., same magnitude, distance, geographic region, and site conditions; this aleatory uncertainty is typically represented by the standard deviation σ, which we will call $\sigma_{\ln[\text{amplitude}],\ \text{aleatory}}$ for the sake of clarity),

4 epistemic uncertainty associated with the aleatory uncertainty (i.e., uncertainty about the true value of $\sigma_{\ln[\text{amplitude}],\ \text{aleatory}}$),

5 parametric sensitivities.

The definition of epistemic and aleatory uncertainties follows the "white paper" distributed prior to the first workshop, and are repeated below:

> Epistemic Uncertainty. Uncertainty that is due to incomplete knowledge and data about the physics of the earthquake process. In principle, epistemic uncertainty can be reduced by the collection of additional information.
>
> Aleatory Uncertainty. Uncertainty that is inherent to the unpredictable nature of future events. It represents unique details of source, path, and site response that cannot be quantified before the earthquake occurs. Given a model, one cannot reduce the aleatory uncertainty by collection of additional information.

The epistemic uncertainty about the median amplitude is further sub-divided into two components: parametric and modeling. The parametric component represents, for example, uncertainty about the median amplitude due to uncertainty about the median stress drop for the eastern U.S. (e.g., is it 120 bars?, does it increase with seismic moment?). The modeling component relates to uncertainty about the model's systematic bias (i.e., $\ln[\text{Amplitude}]_{\text{true}} - \ln[\text{Amplitude}]_{\text{predicted}}$). Such bias may be introduced by the model's functional form or by parameters that are not treated explicitly as uncertain. Uncertainty about the size of the bias arises because the data available for model validation are few and are often outside the magnitude-distance range of engineering interest. The Appendix to these instructions, and the white paper distributed prior to the first workshop, contain examples on these distinctions. In addition, you may contact David Boore, Allin Cornell, or myself, if you have any question about these distinctions or if you wish to discuss their validity or usefulness.

In the evaluation of epistemic and aleatory uncertainties, you should use whichever method you think is appropriate (e.g., propagation of parameter and modeling uncertainties, use of empirical data from ENA or other regions, and/or direct subjective assessments). Your assessment of aleatory uncertainty should be conditional on the independent variables given (i.e., m_{Lg}, closest distance, geographic region, and site conditions). If your model contains additional independent variables (e.g., stress drop, focal depth, rupture dimensions, depth to basement), you should incorporate the effect of uncertainty in these variables on the total aleatory uncertainty requested above.

The parametric sensitivity results will help other experts modify your estimates if they wish to use your model but they wish to make some modifications in the model parameters. You should indicate the sensitivity of your estimate to the three most important model parameters (you should try to anticipate the parameters that another expert would be most likely to change).

Format of Results and Documentation

Estimates of Median and Uncertainties. Your results for the prescribed magnitudes, distances, and frequencies should be provided in the attached forms 1 through 5. Debating points are identified by thick rectangles; magnitude-distance-frequency combinations for which no input is required are shaded. You may wish to submit, in addition, graphical results, tables, and/or equations that cover a wider magnitude-distance-frequency range; we encourage but do not require such results. The functional forms you provide may prove helpful because, ultimately, we shall have to provide predictions over a continuous range of magnitude and distance.

Each component of the epistemic uncertainty may be represented adequately by lognormal distributions (in which case you would enter the logarithmic standard deviation [using natural logs]), or by discrete, triangular, uniform, or other distributions. We encourage you to concentrate your attention on the extent of the spread (as measured, for example, by the logarithmic standard deviation of the median; i.e., $\sigma_{\ln[\text{median}]\text{epistemic}}$), rather than on the fine details of the distribution shape (i.e., lognormal vs. triangular).

The aleatory uncertainty may also be represented by any distribution, but the lognormal distribution is expected to be adequate (so, you would simply specify $\sigma_{\ln[\text{Ampl}],\text{aleatory}}$). You should also specify truncation, if appropriate. To specify the epistemic uncertainty about the proper value of $\sigma_{\ln[\text{Ampl}],\text{aleatory}}$, you may use multiple values of $\sigma_{\ln[\text{Ampl}],\text{aleatory}}$ with associated weights or, again, any other simple measure of "spread".

Parametric Sensitivity Results. Please report the sensitivity of the median estimate to changes in the median values of the three most important (and likely to change) parameters, using forms 1S to 5S. The following are three possible formats for the sensitivity to a parameter:

1. For a scalar parameter, such as stress drop, report the quantity $\partial \ln[\text{Amplitude}] / \partial \text{Parameter}$, evaluated with all parameters set at their median or base-case values.

2. For a scalar parameter, report the estimates obtained by changing the parameter of interest to an "interesting" value (e.g., the logarithmic mean+σ value of stress drop), report the parameter value and the corresponding estimate of the median ground-motion amplitude.

3. For a non-scalar parameter whose uncertainty is represented by a moderate number of discrete alternatives with associated weights (e.g., crustal velocity structure), describe the alternatives and their weights and report the median predictions obtained with each alternative.

Alternatively, you may wish to use another format for representing parametric uncertainties. Your sensitivity results should, however, allow another expert to adjust your median estimates without extensive calculations or any software.

Documentation. Please provide three to ten pages of documentation, summarizing the approach and parameters used to generate your predictions, including how the two uncertainty estimates were obtained. In addition, you should briefly discuss the following three topics:

1. strengths and weaknesses of your approach, applicability of your approach to each of the magnitude-distance-frequency ranges of interest;

2. qualitative discussion of whether the hard-rock site considered here is representative of rock sites in CEUS

3. qualitative discussion of how your results would be different for other regions within CEUS.

You may wish to include relevant papers and reports as appendices.

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page __ of __

Proponent: ____________________

Approach: ____________________

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

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GROUND MOTION WORKSHOP

Form 2: Page __ of __

Proponent: ____________________

Approach: ____________________

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: ____________________

Approach: ____________________

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Proponent: ____________________

Approach: ____________________

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 5: Page __ of __

Proponent: ______________________________

Approach: ______________________________

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: ______________________________

Approach: ______________________________

Sensitivity Results: Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km			
70 km			
200 km			

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Proponent: ____________________

Approach: ____________________

Sensitivity Results: Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km			
70 km			
200 km			

Comments/footnotes:

Proponent: ______________________________

Approach: ______________________________

Sensitivity Results: Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km			
70 km			
200 km			

Comments/footnotes:

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SSHAC SECOND GROUND MOTION WORKSHOP

Form 4S: Page __ of __

Proponent: ______________________________

Approach: ______________________________

Sensitivity Results: Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km			
70 km			
200 km			

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Form 5S: Page __ of __

Proponent: ______________________________

Approach: ______________________________

Sensitivity Results: Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km			
70 km			
200 km			

Comments/footnotes:

APPENDIX

THE PARTITION AND ESTIMATION OF UNCERTAINTY

In the "white paper" on uncertainty, we developed a two-way partition of uncertainty, as follows:

a) Is this uncertainty that can be reduced with the collection of additional data? (epistemic vs. aleatory)

b) Is this uncertainty due to a parameter of the model that is explicitly treated as uncertain? (parametric vs. modeling)

The table that follows contains examples of the four types of uncertainty resulting from this partitioning.

	Epistemic	Aleatory
Modeling	Uncertainty about the true model bias (i.e, to what extent model has a tendency to over- or under-predict observations)	Unexplained scatter due to physical processes not included in the model
Parametric	Median stress drop for ENA, depth distribution, etc.	Event-to-event variation in stress drop or focal depth, etc

In this exercise, we are asking you to report the two components of epistemic uncertainty and the combined (parametric+modeling) aleatory uncertainty. The example that follows should clarify these definitions.

Assume that there are thousands of records from earthquakes in the region of interest, all having the magnitude (m_x), same distance (r_x), and same site category (s_x) for the prediction at hand. Given these data, we can compute the true value of the median[1] ground-motion amplitude at a certain frequency as

$$\ln[Amplitude]_{\text{true median}} = \frac{1}{n}\sum_{i=1}^{n} \ln[Amplitude]_{\text{observed},\,i} \tag{1}$$

where n is the number of records.

Assume also that we have a deterministic predictive model (e.g., a physical model, a stochastic model, or an empirical attenuation function) of the form:

$$\ln[Amplitude]_{\text{pred}} = f(m, r, \text{ site category; } \boldsymbol{P}) \tag{2}$$

where $\boldsymbol{P}$ is a vector of explicit model parameters (e.g., stress drop, focal depth, slip distribution, etc.) and that we know the parameter values $\boldsymbol{P}_i$ for each record. By comparing predictions (for the same magnitude, distance, and site category of interest) to observations, we can quantify the model bias

$$\frac{1}{n}\sum_{i=1}^{n} \left(\ln[Amplitude]_{\text{observed},\,i} - f(m_x, r_x, s_x;\ \boldsymbol{P}_i)\right) \tag{3}$$

or

$$\ln[Amplitude]_{\text{true median}} - \frac{1}{n}\sum_{i=1}^{n} f(m_x, r_x, s_x;\ \boldsymbol{P}_i) \tag{3a}$$

One can also compute the associated aleatory uncertainty (which is due to aleatory variations in all source, path, and site factors other than region, magnitude, distance, and site category) from the observed scatter as

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \left(\ln[Amplitude]_{\text{observed},\,i} - \ln[Amplitude]_{\text{true median}}\right)^2} \tag{4}$$

In reality, the number of available records for the desired magnitude, distance, and site category is small at best. Thus, there is statistical uncertainty about the true value of the model bias in Equation 3 (this is epistemic modeling uncertainty) and about the standard

[1]We are using the term median in a loose sense. Strictly speaking, the quantity in Equation 1 is the logarithmic-mean amplitude, which is equal to the median amplitude only if the amplitude follows a log-normal distribution.

deviation $\sigma_{\ln[Amplitude],\text{aleatory}}$ in Equation 4 (this is epistemic uncertainty, containing both model and parametric components).

Limitations in the data also introduce a parametric component of epistemic uncertainty in physical ground-motion models. This uncertainty is due to uncertainty about the true distributions of model parameters. In the hypothetical situation where one has many records and one knows $\boldsymbol{P}_i$ for each record, one would know the median stress drop exactly (though one would not know the stress drop for the next event). The extent of this uncertainty depends on the uncertainty in the median stress drop and on the sensitivity of $f(m_x, r_x, s_x;\ \boldsymbol{P})$ to stress drop.

In practice, the data are so limited that one is required to use data from other magnitudes, distances, and site categories to estimate the bias, epistemic modeling uncertainty, epistemic parametric uncertainty, and aleatory uncertainty. In doing this, there is the implicit assumption that the predictive model $f(m,r,\text{site category};\ \boldsymbol{P})$ is equally good, and has the same bias, for (m_x, r_x, s_x) and for the magnitudes, distances, and site categories represented in the data. This assumption introduces additional epistemic uncertainty, which may quantified by considering alternative models.

Some Possible Approaches

The following is a brief description of some of the techniques available for the estimation of bias, epistemic uncertainty, and aleatory uncertainty. Additional details are found in the White Paper on Uncertainty that was distributed prior to the first workshop.

Physical and Stochastic Models. The 1993 EPRI study provides an example of the Abrahamson et al. (1991) formulation of uncertainty. Modeling uncertainty is calculated by comparing observed spectral accelerations to predictions obtained using parameters $\boldsymbol{P}_i$ appropriate to each event and site. These comparisons yield estimates of the bias

$$\mu=\frac{1}{n}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\,i}-f(m_i,r_i,s_i;\ \boldsymbol{P}_i)\right) \tag{5}$$

and the standard error

$$\text{std. error}=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\,i}-f(m_i,r_i,c_i;\boldsymbol{P}_i)-\mu\right)^2} \tag{6}$$

The standard error serves as an estimate of the aleatory modeling uncertainty (i.e., physical process and parameters not included in the predictive model, which cause seemingly random scatter). The epistemic modeling uncertainty (i.e., uncertainty in the bias) should be estimated as (std. error)/$(n')^{1/2}$, where n' is the equivalent number of independent observations (this number is smaller than n because of correlation among records from the same event). In the

EPRI study, additional epistemic modeling uncertainty was introduced by site-specific correction terms. Additional epistemic modeling uncertainty may arise due to the existence of competing models.

The epistemic and aleatory uncertainty in the model parameters $\boldsymbol{P}_i$ (e.g., uncertainty in the median stress drop and uncertainty in the stress drop for the next event) introduce epistemic parametric and aleatory parametric uncertainties in the predictions. The contributions of stress drop to the epistemic parametric and aleatory parametric uncertainties are approximately[2] equal to

$$\left[\frac{\partial f(m,r,\text{site category}; \boldsymbol{P})}{\partial \ln\Delta\sigma}\right]_{\boldsymbol{P}=\boldsymbol{P}_{\text{median}}} \times \sigma_{\overline{\ln\Delta\sigma}} \tag{7}$$

and

$$\left[\frac{\partial f(m,r,\text{site category}; \boldsymbol{P})}{\partial \ln\Delta\sigma}\right]_{\boldsymbol{P}=\boldsymbol{P}_{\text{median}}} \times \sigma_{\ln\Delta\sigma} \tag{8}$$

where $\sigma_{\overline{\ln\Delta\sigma}}$ is the logarithmic standard deviation representing epistemic uncertainty in the median stress drop (i.e., how well do we know the median stress drop that we would observe if we studied earthquakes in the region for thousands of years) and $\sigma_{\ln\Delta\sigma}$ is the logarithmic standard deviation representing aleatory uncertainty (i.e., the event-to-event scatter in ln[$\Delta\sigma$] that we would observe if we studied earthquakes in the region for thousands of years). Assuming that the uncertainties about all explicit model parameters in $\boldsymbol{P}$ are independent (i.e., no trade-offs), the total epistemic parametric and aleatory parametric uncertainties are approximately equal to

$$\sqrt{\sum_j \left\{\left[\frac{\partial f(m,r,\text{site category}; \boldsymbol{P})}{\partial \ln p_j}\right]_{\boldsymbol{P}=\boldsymbol{P}_{\text{median}}} \times \sigma_{\overline{p_j}}\right\}^2} \tag{9}$$

and

where the summations extend over all model parameters. Alternatively, one may use logic-trees to calculate the parametric uncertainties, as was done in the EPRI study.

The aleatory uncertainty (modeling+parametric) may also be calculated directly using records from the same region or from other regions. If the magnitudes and distances in the differ substantially from the magnitude and distance for which a prediction is being made, there is a

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[2] The result is approximate because it involves linearization of f(m,r, site category; $\boldsymbol{P}$) with respect to one of the parameters in $\boldsymbol{P}$.

$$\sqrt{\sum_j \left\{ \left[\frac{\partial f(m,r,\text{site category}; \boldsymbol{P})}{\partial \ln p_j} \right]_{\boldsymbol{P}=\boldsymbol{P}_{\text{median}}} \times \sigma_{p_j} \right\}^2} \tag{10}$$

problem with different sensitivity to a parameter (such as Q) at different magnitudes and distances. If residual standard deviations from another region are being used to estimate the aleatory uncertainty in a region with limited data, one should keep in mind the following considerations: (1) if the regression contained additional explanatory variables (e.g., focal depth, style of faulting), these variables should be treated as uncertain parameters and integrated over in order to obtain a revised estimate of aleatory uncertainty; and (2) the residual standard deviation may contain some effects other than aleatory uncertainty (e.g., lack of fit, undetected regional variations in the data set).

Empirical Attenuation Equations. In empirical attenuation equations, the empirically derived coefficients take the role of parameters. These coefficients have no aleatory uncertainty (i.e., they are assumed to be the same for all events and sites). The calculated statistical uncertainty in these coefficients is typically very small and not representative of the true epistemic uncertainty. Differences among empirical models developed by different investigators (using somewhat different data sets and functional forms) is a better representation of epistemic uncertainty.

Modeling uncertainty is characterized by the residual standard deviation σ. This standard deviation contains both aleatory and epistemic components, but it is typically taken as all aleatory.

If empirical attenuation equations are used in a hybrid mode (i.e., the empirical attenuation equations are modified to account for regional differences in source scaling, magnitude definition, path effects, or site effects), such corrections introduce epistemic parametric uncertainty, which should be considered.

If the attenuation equations contain explanatory variables other than magnitude, distance, and site category, one must treat these explanatory variables as uncertain parameters (as was done with physical models). Thus, one must integrate over these parameters, considering the appropriate distribution of the parameter in the region of interest. For instance, if parameter Z represents faulting style in the attenuation equation

$$\ln[\text{Amplitude}] = g(m,r,\text{site category},Z) \tag{11}$$

and the probability of distribution of faulting styles in the region of interest is given by $p_Z(z_1)$, $p_Z(z_2)$, ... $p_Z(z_m)$, then the attenuation equation without Z is equal to
and the aleatory parametric uncertainty due to Z is characterized by a standard deviation equal to

$$g^*(m_x, r_x, s_x) = \sum_{k=1}^{m} p_Z(z_k)\ g(m_x, r_x, s_x, z_k) \tag{12}$$

$$\sqrt{\sum_{k=1}^{m} p_Z(z_k)\ \left(g(m_x, r_x, s_x, z_k) - g^*(m_x, r_x, s_x)\right)^2} \tag{13}$$

This standard deviation, and other parametric standard deviations, should be combined with the residual standard deviation (using a square root of the sum of the squares formula), to obtain the total aleatory uncertainty associated with g*(m,r,s) (i.e., for predictions in terms of magnitude, distance, and site category).

Changes in the definition of magnitude or distance can be treated in a similar manner. For instance, if the original attenuation equation uses distance definition R_1 and one wants to change to R_2, one may perform calculations similar to those in Equations 12 and 13 (but in integral form), using the conditional probability density function $f_{R_1|R_2,m,r}(r_1;\ r_2, m, r)$. If distance definition R_2 is superior to R_1, this approach will yield a higher residual standard deviation for R_2, because it ignores dependence between the regression residuals and $R_1|R_2,m,r$.

DOCUMENTATION OF GROUND MOTION ESTIMATES FOR ENA

Gail M. Atkinson, June 13, 1994

This note documents the ground motion estimates prepared for the SSHAC Ground Motion Workshop (July 1994). My estimates were prepared using the stochastic ground motion model, with methodology and parameter values as described in Atkinson and Boore (1994), and attached as Appendix A. Unfortunately the actual numerical values of the predicted motions given in the paper in Appendix A are in error, due to a programming error. However the methodology and input parameters are correct as stated, and the ground motion values given here are correct. The key parameters of the model, as described in Appendix A, are an empirical source model for ENA earthquakes, as a function of moment magnitude (**M**) (Atkinson, 1993a), an empirical attenuation form (Atkinson and Mereu, 1992), and an empirical duration model (Atkinson, 1993b). These three input components to the model were obtained largely from analysis of recent seismological data (over 1500 records from earthquakes in southeastern Canada and the northeastern U.S., of $3<\mathbf{M}<6$), supplemented with analyses of regional and teleseismic data from historical ENA earthquakes (Street and Turcotte, 1977; Ebel et al., 1986; Somerville et al., 1987), and MMI intensity data (Hanks and Johnston, 1992). The aim of the empirical analyses was to bring together relevant data from a variety of sources, and use it to define the essential building blocks of the stochastic model. A calibration study (Atkinson and Somerville, 1994) provided confidence that the stochastic model can provide unbiased ground motion estimates for frequencies of 1 to 10 Hz, provided that these essential building blocks can be defined.

The target events of m_N 5.5 and m_N 7.0 have been assumed to have moment magnitudes of 5.0 and 7.0, respectively. Because of the uncertainty in these **M** values, the aleatory uncertainty in the predictions is large (ie. use of m_N in specifying source spectrum leads to large inter-event variability). I based the median aleatory uncertainty on empirical analysis of ENA response spectra data, as described in Appendix B. (The uncertainty in 1-Hz amplitudes for m_N-based predictions was assumed to be somewhat lower than given in Appendix B for 1 Hz, but higher than given in B for 10 Hz. The reason is that the m_N values in Appendix B are for ECTN instruments, whereas I assume that the U.S. catalogue m_N would be WWSSN where available.) Note in Appendix B that if the estimates had been for either moment or high-frequency magnitude, the aleatory uncertainty would have been much lower (0.55 versus 0.8). My estimated uncertainty in the aleatory sigma is subjective, based on examination of the data from Appendix B, and knowledge of typical sigma values for other (ie. California) data sets.

The epistemic uncertainty features zero median bias, based on comparisons of our predictions the data listed in Appendix B. The uncertainty in the bias is a guesstimate, based on the limitations of the data used to estimate the median bias, as well as the limitations of the data used to constrain the model parameters. The parametric epistemic uncertainty is also a guesstimate, and is also based on limitations of the database used to constrain model parameters. These uncertainties must vary in some fairly sophisticated fashion with magnitude, distance and frequency. But in the time frame provided a detailed analysis of these uncertainties was not feasible. I have therefore used rather arbitrary values of either 0.2, 0.3, 0.5, or even 0.7 (ln units), in each of these boxes, according to whether I believe each uncertainty to be 'low', 'medium', 'high', or 'very high'. My apologies to those that favor partial differential equations, HP calculators, 50 ways to partition your table, and so on.

For the parametric sensitivity results, I have focused on the most 'interesting' parameters for each frequency. For 1 to 2.5 Hz, I think that the shape of the source spectrum (Brune versus empirical) merits attention. For 10 Hz I have examined stress drop. For 25 Hz and PGA I have looked at kappa. Duration is important for all frequencies, but I have shown its influence just at 1 Hz and 2.5 Hz.

I must note that I am uncomfortable with the estimates at R=5 km, particularly for **M** 7. I would not normally apply these estimates to R<10 km, since the model does not treat the many near-source effects that may significantly affect motions very close to the source.

Regarding the specified rock condition, EUS rock with β = 2.8 km/s, I have assumed that this is comparable to the conditions at ECTN seismometer sites in southeastern Canada. Since my input parameters implicitly assume zero average amplification for such sites, I have not amplified the ground motion predictions for surficial rock response. Any such amplification would be small in any case; the maximum amplification due to impedance contrast would be a factor of about 1.16 ($\sqrt{3.8/2.8}$, where 3.8 is the assumed value of β at midcrustal depths).

Proponent: G.M. Atkinson

Approach: Stochastic with empirical inputs

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.034	0.43
	epistemic uncertainty	parametric (ln)	0.5	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.0058	0.10
	epistemic uncertainty	parametric (ln)	0.5	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.0012	0.023
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude		0.00082	0.017
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2

Comments/footnotes:

m_N 5.5 ≃ M 5.0
m_N 7.0 ≃ M 7.0

Aleatory uncertainty based on m_N.
If M/m had been used, I would give σ_{tot} = 0.55 for all frequencies.
Uncertainty in σ for M/m would be 0.1

Proponent: G.M. Atkinson

Approach: Stochastic

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.032	0.34
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: G.M. Atkinson

Approach: Stochastic

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.95	4.3
	epistemic uncertainty	parametric (ln)	0.5	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.17	0.97
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.022	0.17
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: Gail Atkinson

Approach: Stochastic

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.26	1.3
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: G.M. Atkinson

Approach: Stochastic

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.77	2.8
	epistemic uncertainty	parametric (ln)	0.5	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.011	0.084
	epistemic uncertainty	parametric (ln)	0.5	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: G.M. Atkinson

Approach: Stochastic

Sensitivity Results: Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km	Base Case	0.034	0.43
	Brune shape	0.041	1.0
	Alt. durn	0.026	0.52
20 km	Base	0.0058	0.10
	Brune	0.010	0.26
	Alt. Durn	0.0078	0.13
70 km	Base	0.0012	0.023
	Brune	0.0022	0.056
	Alt. Durn	0.0014	0.027
200 km	Base	0.00082	0.017
	Brune	0.0016	0.034
	Alt. Durn	0.00077	0.015

Comments/footnotes:

Brune has $\Delta\sigma = 180$ bars, with source durn. $1/f_0$.

Alt. Durn is $1/f_0$ for $R < 50$ km
then $1/f_0 + 0.05R$ for $R \geq 70$ km.

Proponent: G.M. Atkinson

Approach: Stochastic

Sensitivity Results: Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km	Base Case	0.032	0.34
	Brune shape	0.051	0.54
	Alt. durn	0.030	0.41
70 km			
200 km			

Comments/footnotes:

Brune shape has $\Delta\sigma$=180 bars

Proponent: G. M. Atkinson

Approach: Stochastic

Sensitivity Results: Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km	Base Case	0.95	4.3*
	Brune 180 bars	1.1	6.0*
	Brune 500 bars	2.0	12.*
20 km	Base Case	0.17	0.97
	Brune 180 bars	0.16	1.1
	Brune 500 bars	0.35	2.5
70 km	Base Case	0.022	0.17
	Brune 180 bars	0.022	0.18
	Brune 500 bars	0.045	0.42
200 km			

Comments/footnotes:

* I don't believe values would be this high; near-source effects for M7 should be considered. I would normally use R≥10 km, which would reduce these by a factor of 2.

Proponent: G. M. Atkinson

Approach: Stochastic

Sensitivity Results: Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km	Base Case	0.26	1.3
	Kappa = 0.006	0.16	0.84
70 km			
200 km			

Comments/footnotes:

Proponent: G. M. Atkinson

Approach: Stochastic

Sensitivity Results: Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km	Base Case	0.77	2.8
	kappa=0.006	0.51	1.8
20 km			
70 km	Base Case	0.011	0.084
	kappa=0.006	0.0079	0.062
200 km			

Comments/footnotes:

GROUND MOTION RELATIONS FOR EASTERN NORTH AMERICA

GAIL M. ATKINSON AND DAVID M. BOORE

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ABSTRACT

Predictive relations are developed for ground motions from eastern North American earthquakes of $4.0 \leq \mathbf{M} \leq 7.25$ at distances of $10 \leq R \leq 500$ km. The predicted parameters are response spectra at frequencies of 0.5 Hz to 20 Hz, and peak ground acceleration and velocity. The predictions are derived from an empirically-based stochastic ground-motion model. The relations differ from previous work in the improved empirical definition of input parameters, and empirical validation of results. The relations are in demonstrable agreement with ground motions from earthquakes of **M** 4 to 5. There are insufficient data to adequately judge the relations at larger magnitudes, although they appear to be consistent with data from the Saguenay (**M** 5.8) and Nahanni (**M** 6.8) earthquakes. The underlying model parameters are well-constrained by empirical data for events as large as **M** 7.

INTRODUCTION

Ground-motion relations describing peak ground motions and response spectra as functions of earthquake magnitude and distance are of paramount importance in the assessment of earthquake hazard to engineered structures. In recent years, ground-motion relations for eastern North America (ENA) have been based on a stochastic model (eg. Boore and Atkinson, 1987; Toro and McGuire, 1987; EPRI, 1988; Atkinson and Boore, 1990). The model has its origins in the work of Hanks and McGuire (1981), who showed that observed high-frequency ground-motions can be predicted by assuming the motion is bandlimited Gaussian noise, whose amplitude spectrum is given by a simple seismological model of the source and propagation processes. Their model has fundamentally changed the way in which ground motion relations are developed, in providing a simple physical framework by which to interpret empirical observations.

For western North America (WNA), it has been shown that the Brune (1970) source model, with a stress parameter of about 100 bars, provides accurate estimates of average ground motions when used in conjunction with the stochastic model (Hanks and McGuire, 1981; Boore, 1983; Boore et al., 1992). For ENA, previous applications (referenced above) have also assumed the 100-bar Brune source model. This assumption was justified based on inferences from a few moderate (**M** 4 to 5) ENA events (Atkinson, 1989) and teleseismic data from larger historical earthquakes (Somerville et al., 1987). The 1988 Saguenay, Quebec earthquake (**M** 5.8), by contrast, differed dramatically from the predictions of the simple Brune model (Boore and Atkinson, 1992), raising questions concerning the validity of the underlying source model for large events and the adequacy of our knowledge concerning ENA source spectra. These concerns were heightened by the work of Boatwright and Choy (1993), who showed that the teleseismic spectra of large intraplate events generally depart from the Brune model; intraplate earthquakes appear to have two corner frequencies.

Recent earthquakes have also highlighted wave-propagation issues that were not addressed in the development of previous ENA ground-motion relations. Specifically, theoretical studies of wave propagation in a layered crust indicate that the decay of ground-motion amplitudes may be depth dependent, and that the decay pattern may be significantly disrupted in the distance range from about 60 to 120 km; in this distance range the direct wave is joined by the first postcritical reflections from internal crustal interfaces and the Moho discontinuity (Burger et al., 1987). It has been suggested that this phenomenon was at least partly responsible for the large ground-motion amplitudes observed at distances near 100 km during the Saguenay (Somerville et al., 1990) and Loma Prieta (Fletcher and Boatwright, 1991; Campbell, 1991) earthquakes.

Recent empirical studies of over 1500 seismograms from ENA earthquakes in the magnitude range from 3.5 to 7 have provided significant new information on ENA ground-motion processes. The recent studies show that: (i) source spectra for ENA earthquakes of **M** > 4 deviate significantly from the Brune 100-bar model

(Atkinson, 1993a); (ii) the attenuation of spectral amplitudes is slightly disrupted by the transition from direct-wave to Lg-wave spreading, suggesting a hinged trilinear form for the attenuation curve (Atkinson and Mereu, 1992); (iii) the duration of motion increases with distance in a complex manner (Atkinson, 1993b); and (iv) the ratio of horizontal-to-vertical component ground motions is frequency-dependent, but independent of distance (Atkinson, 1993b). These studies were based on data derived largely from earthquakes in southeastern Canada and the northeastern United States. Detailed simulation studies (EPRI, 1993) suggest that ground-motion relations should show little regional variability over most of ENA, with the exception of the Gulf Coast region. Therefore ground-motion relations derived from data in southeastern Canada and the northeastern U.S. should be applicable over most of ENA.

In this paper, we use the new information on ENA source and attenuation processes to revise our 1987 ground-motion relations. The method used to develop the ground-motion relations is briefly reviewed, with emphasis on the data defining each of the input parameters. Predictive relations are developed for peak ground motion and response spectra for rock sites, and compared to available ground-motion data.

APPROACH

Review of the Basic Method. The ground-motion predictions are based on the stochastic model, including both the random-process theory and time-domain implementations. In both approaches, ground motion is modeled as bandlimited Gaussian noise; the radiated energy is assumed to be evenly-distributed over a specified duration. The method is quite general and can be used to predict many amplitude and instrument-response parameters.

The method begins with the specification of the Fourier amplitude spectrum of ground acceleration as a function of seismic moment and distance, $A(M_o,R,f)$, which can be represented by:

$$A(M_o,R,f) = E(M_o,f)\ D(R,f)\ P(f)\ I(f). \qquad (1)$$

$E(M_o,f)$ is the earthquake source spectrum for a specified seismic moment (ie. Fourier spectrum of the ground acceleration at a distance of 1 km). $D(R,f)$ is a diminution function that models the geometric and anelastic attenuation of the spectrum as a function of hypocentral distance (R). $P(f)$ is a high-cut filter that rapidly reduces amplitudes at very high frequencies ($f>>10$ Hz); it may be based on either the f_{max} model (Hanks, 1982) or the kappa model (Anderson and Hough, 1984). $I(f)$ is a filter used to shape the spectrum to correspond to the particular ground-motion measure of interest. For example, for the computation of response spectra I is the response of an oscillator to ground acceleration. For free-field ground-motion parameters, I is simply

$$I(f) = 1/(2\ \pi\ f)^p \qquad (2)$$

where $p = 0$ for acceleration, 1 for velocity, or 2 for displacement.

The time-domain implementation of the stochastic method (Boore, 1983) begins with the generation of a windowed acceleration-time-series, comprised of random Gaussian noise with zero mean amplitude; the variance is chosen such that the spectral amplitude is unity on average. The duration of the window is specified as a function of magnitude and distance. The spectrum of the windowed time series is multiplied by the desired amplitude spectrum ($A(M_o,R,f)$ from equation (1)). The filtered spectrum is then transformed back into the time domain to yield a simulated earthquake record for that magnitude and distance.

The random-process approach uses Parseval's theorem to relate the spectral amplitudes ($A(M_o,R,f)$) to root-mean-square (rms) amplitudes in the time domain. Equations from random-process theory are used to obtain expected values of peak amplitudes from the rms amplitudes. For details of these methods, refer to Hanks and McGuire (1981), Boore (1983), and Boore and Atkinson (1987).

Input Parameters. The input parameters for the method include all terms of equation (1), and the duration of motion. The simulations will apply to the random horizontal component of the shear phase of ground motion.

The earthquake source spectrum ($E(M_o,f)$) for the horizontal component of ground motion is given by a functional form which represents the addition of two Brune spectra (Atkinson, 1993a):

$$E(M_o,f) = C\ (2\pi f)^2\ M_o\ \{(1-\epsilon)/[1+(f/f_A)^2] + \epsilon/[1+(f/f_B)^2]\} \qquad (3)$$

where $C = R_p\ F\ V\ /\ (4\pi \rho \beta^3\ R)$, with $R = 1$ km, R_p = average radiation pattern (=0.55), F = free surface amplification (=2.0), V = partition onto two horizontal components (=0.71), ρ = crustal density (=2.8 gm/cm^3), and β = shear wave velocity (=3.8 km/sec).

The values for the crustal constants are based on the seismic reflection/refraction data of Mereu et al. (1986) for southeastern Canada, for the average focal depth of events in the region (10 km). The choice of reference depth for β is not critical because there is little dependence of shear wave velocity on depth for ENA hard-rock sites; this also implies that near-surface amplification due to impedance contrasts is negligible for hard-rock sites (Boore and Atkinson, 1987). The parameters ϵ, f_A and f_B are functions of seismic moment, given for $4 \leq \mathbf{M} \leq 7$ by:

$$\log \epsilon = 2.52 - 0.637\ \mathbf{M} \tag{4}$$

$$\log f_A = 2.41 - 0.533\ \mathbf{M} \tag{5}$$

$$\log f_B = 1.43 - 0.188\ \mathbf{M} \tag{6}$$

Equation (3) was derived by combining analysis of spectral data in the frequency range from 1 to 10 Hz (22 ENA earthquakes of $4 \leq \mathbf{M} \leq 7$, with moments and corner frequencies (f_A and f_B) inferred from spectral data and teleseismic models (Somerville et al., 1987; Boatwright and Choy, 1992). The use of equation (3) for magnitudes as large as 7.25 represents a slight extrapolation.

Figure 1 compares the new source model to the 100-bar Brune model used in our 1987 ground-motion relations. The complexity of shape is required in order to reconcile observations over the 1 to 10 Hz frequency band with the seismic moment of the events. Equation (3) is the simplest functional form that could be found to match both spectral amplitudes and corner frequencies. It is an empirical representation rather than a theoretical model. The rather dramatic reduction of spectral amplitudes at intermediate frequencies, relative to the Brune model, is an important implication of equation (3). This feature is a consequence of the spectral-amplitude and corner-frequency data; it is not an artifact of the selected functional form. The sag in spectral amplitudes at intermediate frequencies is largely driven by the observation that 1-Hz spectral amplitudes are low, relative to those that would be inferred by a simpler interpolation between the moment-end of the spectrum and its high-frequency end. The amplitudes predicted by equation (3) are well-constrained by data for frequencies of 1 Hz and greater, for $4 \leq \mathbf{M} < 7$. Examination of strong-motion data from the Saguenay (**M** 5.8) and Nahanni (**M** 6.8) earthquakes suggests that the shape is appropriate for frequencies at least as low as 0.5 Hz; for these earthquakes the observed ratio of 1 Hz to 0.5 Hz spectral amplitudes is well-predicted by equation (3). The amplitudes cannot be verified for lower frequencies, and therefore the ground-motion predictions are restricted to $f \geq 0.5$ Hz.

The attenuation of spectral amplitudes with distance (D(R,f)) is given by the hinged trilinear form of Atkinson and Mereu (1992). Based on 1500 seismograms from 100 earthquakes of magnitude m_N 3 to 6.5, they found that spectral-amplitude decay due to geometric spreading is approximately independent of frequency. The observed decay is given by $R^{-1.1}$ for distances from R=10 to R=70 km. From R=70 to R=130 km, there is no apparent geometric spreading. For R>130 km, spectral amplitude decay due to geometric spreading can by modeled as $R^{-0.5}$. The associated Q model is $Q = 670 f^{0.33}$, where the anelastic attenuation of spectral amplitudes is then given by $\exp(-\pi f R / \beta Q(f))$. The overall attenuation is obtained as the product of the geometric and anelastic attenuation terms. (Note: For distances R<10 km, the geometric spreading is assumed to be given by R^{-1}; this assumption was also made in deriving the source spectra from the empirical observations.) No apparent dependence of the attenuation on focal depth was observed. The empirical attenuation is applicable for distances large enough to allow the source to be treated as a point. Finite-fault effects might alter the observed attenuation in the near-source region, but this would only be significant for large (**M**>6.5) earthquakes.

For the high-cut filter we use (Boore, 1986):

$$P(f) = [1 + (f/f_{max})^8]^{-1/2} \quad (7)$$

where f_{max} is the high-frequency cut-off proposed by Hanks (1982). For ENA we have assumed a value of f_{max} = 50 Hz based on a review of very limited data. An alternative would be to use the kappa filter suggested by Anderson and Hough (1984):

$$P(f) = \exp(-\pi k f) \quad (8)$$

where k is the high-frequency decay-slope on plots of log spectra versus frequency (for near-source distances for which anelastic attenuation is negligible). The kappa filter is not as abrupt as the f_{max} filter; it represents a gradual diminution of spectral amplitudes with increasing frequency, rather than an upper limit on frequency. Many of the ENA spectra that we have reviewed are apparently flat out to frequencies of 20 Hz, above which there are no data (we approach the upper corner-frequency of the recording instruments). In this case a meaningful estimate of either kappa or f_{max} is not really possible. This is illustrated for several typical ECTN records (at R<100 km) in Figure 2. We have therefore chosen to use the f_{max} filter with a high cut-off value (50 Hz), to avoid artificially diminishing high-frequency amplitudes. Beware that predictions for frequencies above 20 Hz, and peak ground acceleration, depend critically on this parameter. If very high frequencies are of interest, more information is needed on P(f). For the present application, we assume that frequencies above 20 Hz are not of engineering interest.

The final input element of the stochastic predictions is the duration model. The duration model generally has two terms:

$$T = T_o + b\ R \tag{9}$$

where T_o is the source duration and b R represents a distance-dependent term which accounts for dispersion. For the source duration, we assume that $T_o = 1/(2f_A)$ (Boatwright and Choy, 1992), where f_A is the lowest corner frequency in the source spectrum, as given by equation 5. This source-duration estimate is compatible with the ENA source-duration data of Somerville et al. (1987). The source durations given by $1/(2f_A)$ are within 10% of those used in our previous (1987) study. (In 1987 we assumed a source duration of $1/f_o$, where f_o was the corner frequency of the Brune model; note $f_A<f_o<f_B$).

The empirical basis for the distance-duration term is the collection of 1500 ECTN seismographs used to define the attenuation function. Atkinson (1993b) computed, for each record, the duration which matches the observed relationship between the peak ground velocity (PGV) and the Fourier spectrum, using random-process-theory equations. For this study we have taken a closer look at these duration data. Because most of the earthquakes in the ECTN database are small, the distance-dependent term of equation (9) dominates the duration; the bR term can therefore be determined with confidence by subtracting a simple estimate of T_o from the total duration. For this purpose, we assume $T_o = 1/f_o$, rather than $1/(2f_A)$, since most events in the duration dataset are too small (M<4) for the two-corner model to be applicable. These distance-dependent duration terms ($T-T_o$) are averaged within narrow distance bins in Figure 3. The distance-dependence of duration is modeled as trilinear, using the transition distances 70 and 130 km for consistency with the attenuation model; the slope b is 0.16 for $10 \leq R \leq 70$ km, -0.03 for $70 < R \leq 130$ km, and 0.04 for $130 < R < 1000$ km. The negative slope in the transition zone from direct-wave to Lg-phase (70 to 130 km) reflects the fact that, as more rays arrive, additional energy is being injected within the time-window of the signal. The random-process model requires a decrease in duration in order to correctly predict the enhanced time-domain amplitudes which result.

Choice of Magnitude Scale. The above equations provide all the information needed to simulate the horizontal component of ground motion for hard-rock sites as a function of moment magnitude and hypocentral distance. We choose to develop the ground-motion equations in terms of moment magnitude, rather than the more widely-catalogued (but more ambiguously defined) Nuttli magnitude

(m_N). We prefer **M** because it has a simple physical interpretation (Hanks and Kanamori, 1979), and because there is some hope of being able to specify **M** for a future expected earthquake based on geological evidence. **M** has been estimated for most of the large historical ENA earthquakes from special studies. For moderate ($m_N \leq 6$) catalogued events for which no estimates of **M** are available, **M** can be estimated from the empirical relationship shown on Figure 4 (Atkinson, 1993a):

$$\mathbf{M} = -0.39 + 0.98\, m_N \quad ; \quad m_N \leq 6 \tag{10}$$

The standard error of an estimate is 0.15. This relationship should not be extrapolated to $m_N > 6$, since theoretically there is significant curvature to the m_N versus **M** relation at large magnitudes (Boore and Atkinson, 1987). This curvature cannot be defined by the empirical data due to the paucity of large events and the large uncertainties in estimated values of both **M** and m_N for a few critical historical earthquakes (1925 Charlevoix, 1935 Timiskaming). It can be defined theoretically, but only by making particular assumptions regarding the instrument type and distance at which m_N is measured. One such theoretical relation is (Boore and Atkinson, 1987):

$$\mathbf{M} = 2.715 - 0.277\, m_N + 0.127\, m_N^2 \tag{11}$$

We suggest using equation (10) for $m_N \leq 5.5$, and equation (11) for $m_N > 5.5$.

It is straightforward and practical to conduct seismic hazard analyses based on **M** rather than m_N. In fact, the ability to predict **M** from m_N, or vice-versa, is implicit in any process that converts the **M**-based predictive model to an equivalent m_N-

based model. It may be argued that the use of m_N should result in lower variability of high-frequency ground motions, since m_N is measured at higher frequencies than **M**. Contrary to this expectation, Atkinson (1993a) found that the standard error of the common logarithm of the estimated high-frequency spectral amplitude is 0.17 for predictions based on **M**, and 0.19 for predictions based on m_N. This suggests that intermediate-frequency magnitude (m_N) does not predict high-frequency amplitude with any greater precision than does low-frequency magnitude (**M**). Thus there appears to be no advantage to using m_N.

If it is desired to make ground-motion predictions based on a magnitude scale which more closely describes high-frequency motions, the high-frequency magnitude scale (**m**) proposed by Atkinson and Hanks (1994) can be used. **m** can be defined for modern events based on seismographic data, or for historical events based on felt area. Since **M** = **m** on average, by definition, separate ground-motion relations in terms of **m** are not required; simply use the observed **m** in place of **M** in the predictive relations, for frequencies above f_B. For example, referring to the list of **m** values in Table 4, the high-frequency (f>2 Hz) amplitudes from the Saguenay earthquake could be predicted from our ground-motion relations using a magnitude of 6.5.

NOTE: The rest of the paper is not included since results contain a programming error.

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FIGURE CAPTIONS

FIGURE 1 - Comparison of horizontal-component source spectra (R = 1 km) for the ENA empirical model with those of the 100-bar Brune model, for **M** 5, 6 and 7. (from Atkinson, 1993a)

FIGURE 2 - Typical plots of acceleration spectra versus frequency for ENA events near the source, showing the apparent lack of high-frequency decay (kappa).

FIGURE 3 - Mean of the rms duration minus the source duration, averaged by 15-km distance bins. Vertical bars show 90% confidence limits on the estimate of the mean. Trilinear line is that used in the stochastic simulations. Simple straight line is 0.05 R, the distance-duration term used in previous (1990) simulations.

FIGURE 4 - Relationship between Lg magnitude (m_N) and moment magnitude (**M**). Data are from the ECTN (**M** values of Atkinson, 1993a; m_N values from Geophysics Division, Geological Survey of Canada), and from Boore and Atkinson (1987). Dotted line is the least-squares fit to the data (see equation (10)). Solid line is the theoretical relation of Boore and Atkinson (1987). Line connecting empty to filled square shows alternative **M** estimates for the Timiskaming earthquake. (from Atkinson, 1993a)

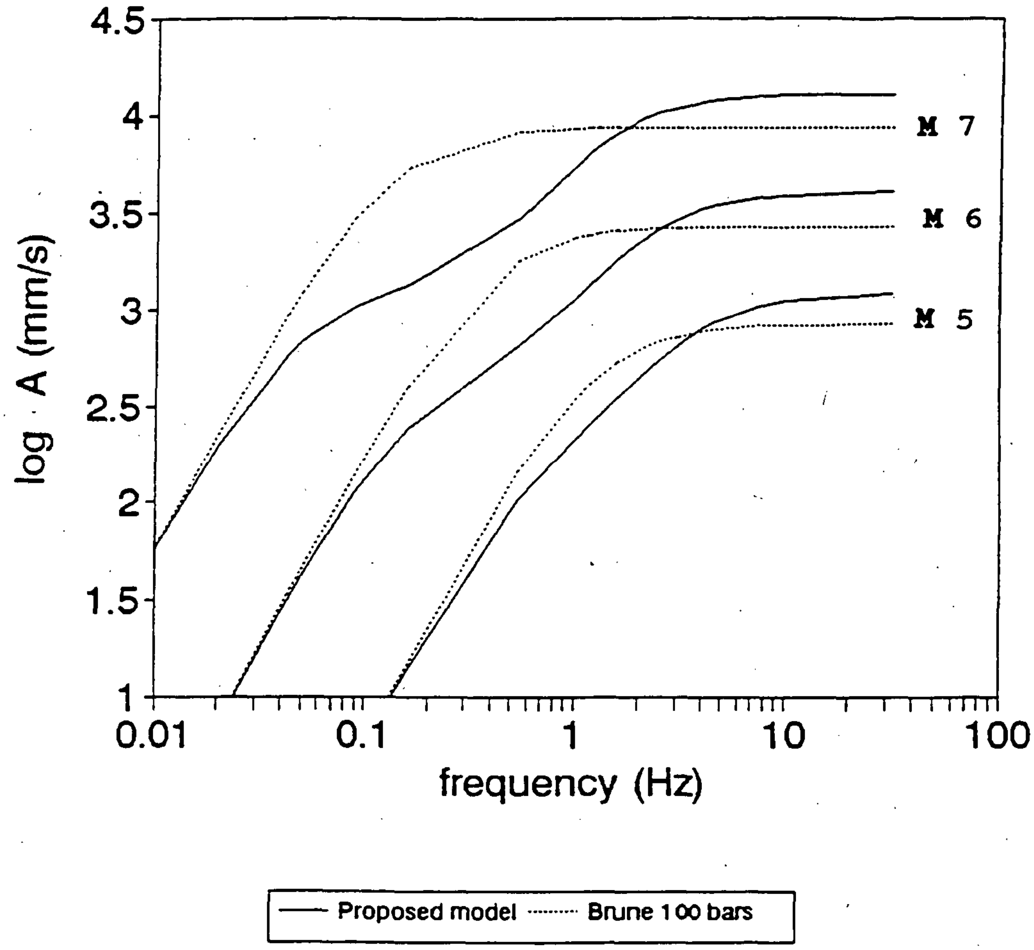
FIGURE 5 - Predicted response spectral values (PSA for 5% damping) for four frequencies and peak ground acceleration (PGA) and velocity (PGV), for **M** 4.0 ( ), 5.5 (+), and 7.0 (*). Symbols show ground motion predictions. Lines show quadratic equations of Table 1.

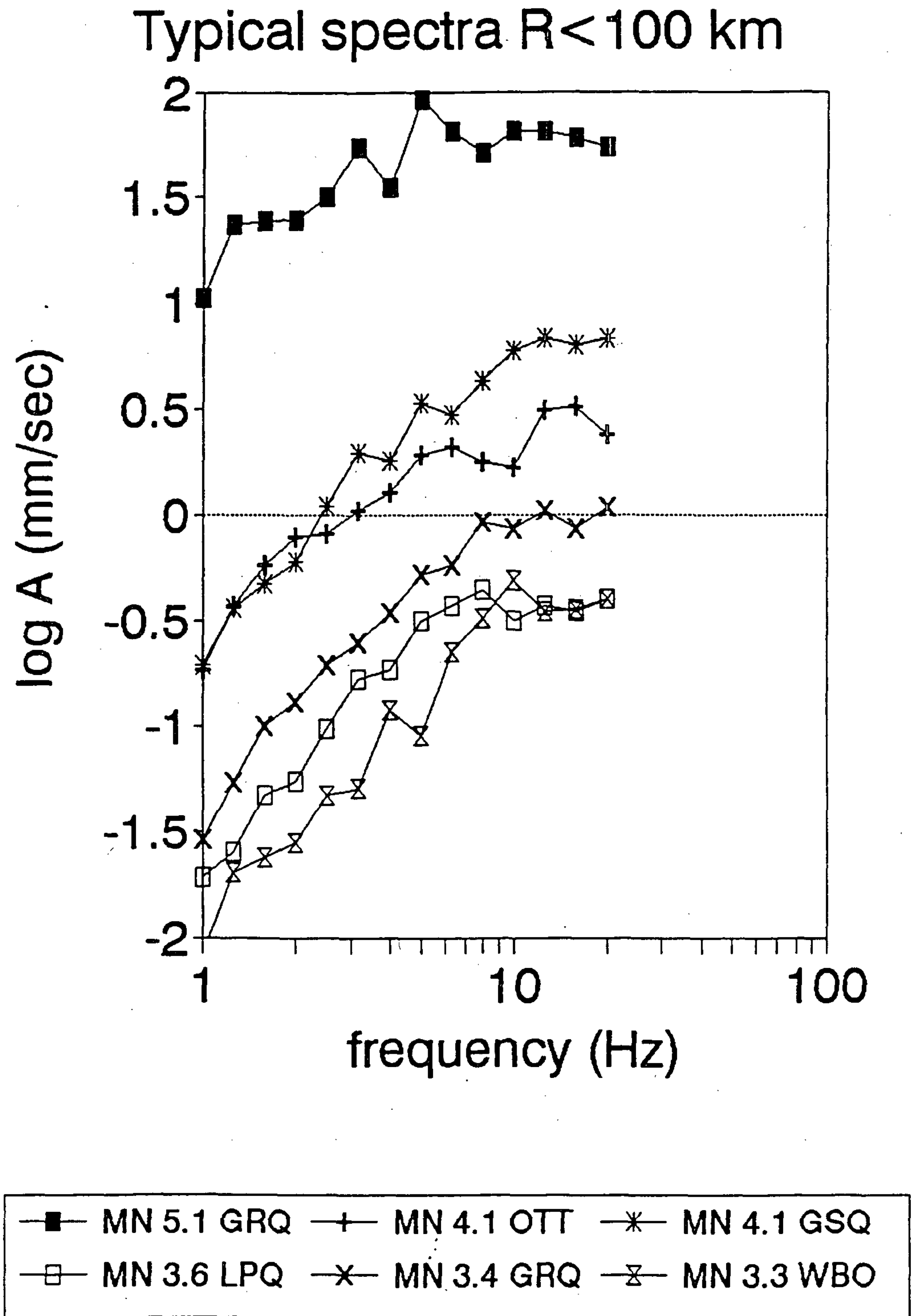
FIGURE 6 - Comparison of results of probabilistic hazard analysis, for probabilities of 0.002 p.a. (lower lines) and 0.0001 p.a. (upper lines), obtained using 'exact' ground motion relations (heavy solid), new quadratic approximation (light solid), and the Atkinson and Boore (1990) relations (dotted). Comparisons are provided for areas of low, moderate and high hazard. The expected PGA is plotted for reference at an arbitrary frequency of 100 Hz, with an arbitrary straight-line connection between the 20-Hz PSA and the PGA.

FIGURE 7- Differences (residuals in log units) between observed and predicted ground motions as a function of **M**, for oscillator frequencies of 1, 2, 5 and 10 Hz (mainshocks only).

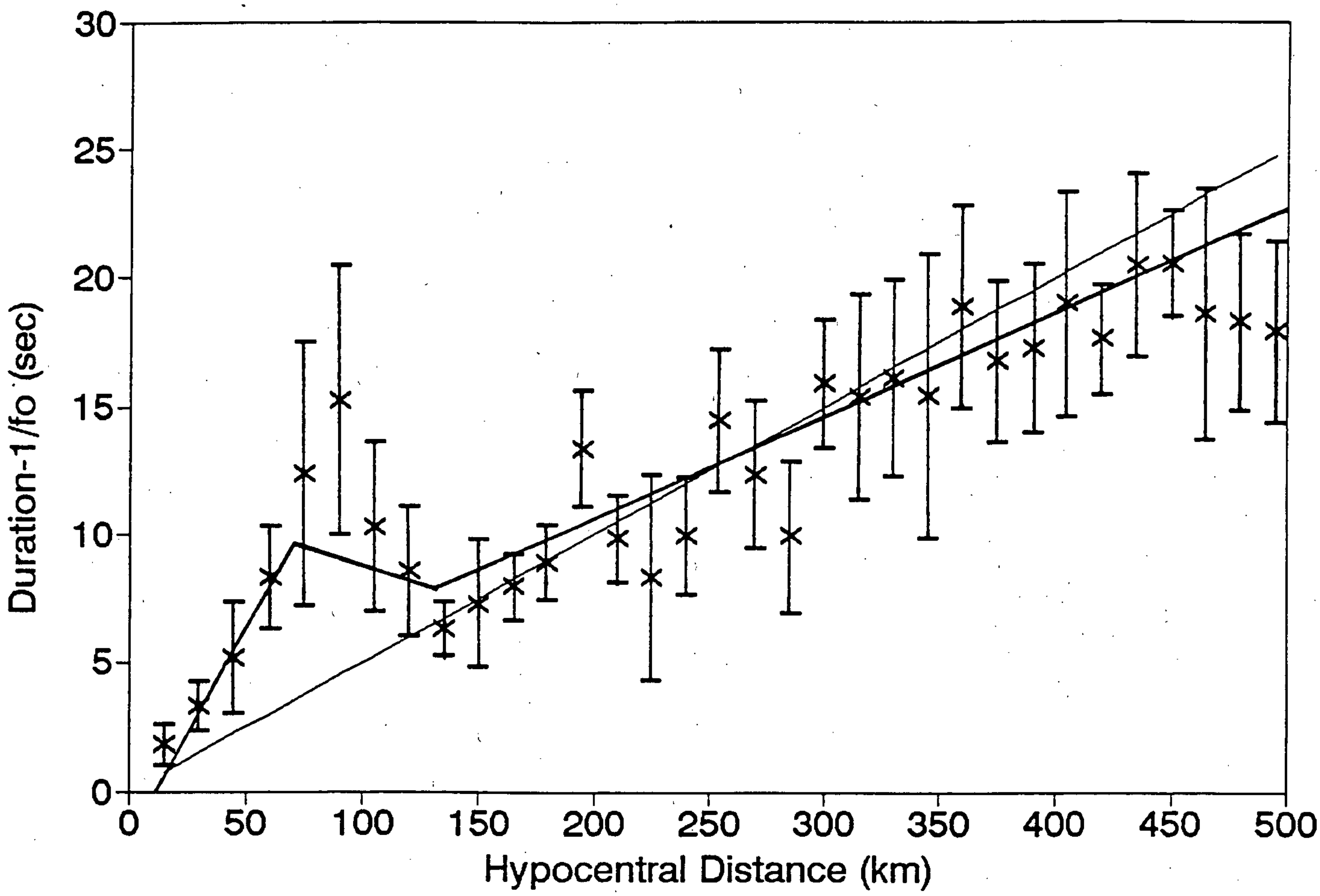
FIGURE 8 - Differences (residuals in log units) between observed and predicted ground motions as a function of distance, for oscillator frequencies of 1, 2, 5 and 10 Hz.

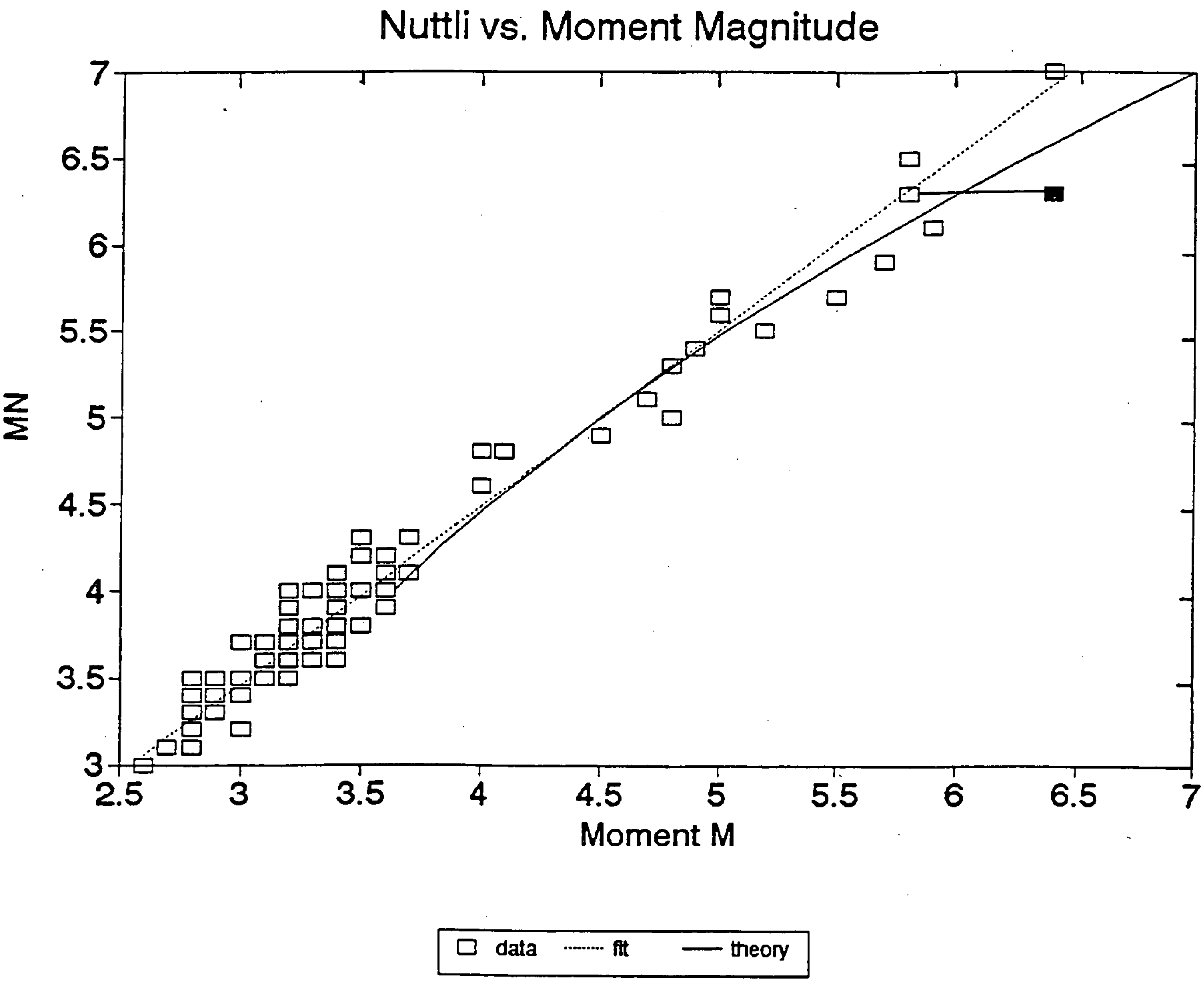
ENA Model vs. Brune 100 bars
M = 5, 6, 7




Typical spectra R<100 km
log A (mm/sec)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1
10
100
frequency (Hz)
MN 5.1 GRQ
MN 4.1 OTT
MN 4.1 GSQ
MN 3.6 LPQ
MN 3.4 GRQ
MN 3.3 WBO

(Duration - source duration)




Nuttli vs. Moment Magnitude
MN
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
Moment M
data
fit
theory

OPTIMAL CHOICE OF MAGNITUDE SCALES FOR SEISMIC HAZARD ESTIMATES IN EASTERN NORTH AMERICA

by Gail Marie Atkinson: Draft 2 - June 10, 1994

For Submission to Seism. Res. Letters as a Short Note.

INTRODUCTION

There are currently several magnitude scales that are used to describe the size of earthquakes in eastern North America (ENA). These include **M** (moment magnitude; Hanks and Kanamori, 1979), m_N (Nuttli or Lg magnitude; Nuttli, 1973) and, most recently, **m** (Atkinson and Hanks, 1994). Each of these scales measures ground motion amplitude in a different frequency band: **M** is a low-frequency measure, m_N typically measures amplitudes in the 1 to 2 Hz frequency band (although this depends on the instrumentation), and **m** measures high-frequency (5 to 10 Hz) motions.

The choice of magnitude scale is an important issue for seismic hazard analysis. It implicitly dictates the physical underpinning of the most fundamental building block of any seismic hazard analysis: the earthquake catalogue. In a typical probabilistic hazard analysis (ie. Cornell, 1968; McGuire, 1977), the choice of magnitude scales enters the analysis in two ways: (i) through the magnitude recurrence relations, which describe the frequency of occurrence of earthquakes as a function of magnitude, within each seismic source zone; and (ii) through the ground motion relations, which are used to estimate the severity of ground shaking at a site, as a function of earthquake magnitude and distance.

Current ground motion relations for ENA (Boore and Atkinson, 1987; Toro and McGuire, 1987; EPRI, 1993; Atkinson and Boore, 1994; Toro et al., 1995) specify the earthquake source spectrum based on magnitude. Consequently, the ability of each magnitude scale to estimate the source spectrum has significant implications for the uncertainty involved with the use of the ground motion relations. This uncertainty is currently a controversial issue; it is being carefully studied by major research organizations such the Electric Power Research Institute, Lawrence Livermore National Laboratory, and a special panel convened by the National Academy of Science.

The purpose of this note is to discuss the pros and cons of each of the above three choices of magnitude scales. I propose an optimal solution for seismic hazard analyses: the best choice is to use **M** for estimating low-frequency ground motions ($f<2$ Hz) and **m** for high-frequency ground motions ($f>2$ Hz). If only one magnitude scale is to be used, the choice should be based on the most-critical frequency range for the application.

The note is motivated by the importance of this choice for the reduction of aleatoric uncertainty (ie. randomness) in ground motion estimation. Aleatoric uncertainty is characterized by the standard deviation (sigma) of median ground motion predictions (illustrated in Figures 1 and 2). This random uncertainty has a significant impact on probabilistic seismic hazard estimates. Specifically, a large degree of random scatter in the median ground motion relations leads to larger expected ground motions, for any probability level, than does a small degree of scatter. This situation is a consequence of the nature of the distributions; simply stated, the number of small earthquakes that might produce larger-than-average ground motions outweighs the number of large earthquakes that might produce smaller-than-average ground motions.

REVIEW OF MAGNITUDE ALTERNATIVES FOR HAZARD COMPUTATIONS

Moment Magnitude

Moment magnitude has the advantage of conceptual simplicity. It is a physically-based measure of the size of an earthquake. This means that there is some hope of being able to estimate **M** for future events from geologic constraints on the size of the fault plane. Moreover, seismic moment is the fundamental measure of earthquake source strength upon which current ENA ground motion models (Boore and Atkinson, 1987; Toro and McGuire, 1987; EPRI, 1993; Atkinson and Boore, 1994) are based. The use of moment magnitude therefore removes the need to convert the ground motion predictions to another magnitude scale. **M** is fairly-well determined for ENA earthquakes. Most large historic earthquakes have **M** values that have been determined by studies of teleseismic or regional records (eg. Ebel et al., 1986). Moment magnitudes have also been published for many recent small events (eg. Atkinson, 1993). For small-to-moderate earthquakes ($3.0 \leq \mathbf{M} \leq 5.5$) with unknown **M**, a well-constrained empirical relationship can be used to estimate **M** from the more widely-catalogued m_N values (Atkinson, 1993): $\mathbf{M} = -0.39 + 0.98\ m_N$.

A final advantage of using **M** in ENA is that it simplifies comparisons with the west, since **M** is routinely catalogued for California earthquakes.

An oft-cited disadvantage of **M** is that it is a long-period measure, whereas for engineering purposes we are most interested in predicting the high-frequency amplitudes of ground motion. High-frequency ground-motion predictions based on **M** would tend to have greater uncertainty than predictions based on other magnitude measures, obtained at higher frequencies. (As will be shown in the following section, this is only partially true.) Another disadvantage is that **M** is not yet widely-catalogued in ENA, so that a somewhat laborious catalogue conversion is required. Finally, the relationship between **M** and MMI shows a large degree of scatter (Hanks and Johnston, 1992). Consequently there is large uncertainty in **M** estimates for large pre-instrumental earthquakes.

Nuttli Magnitude

Nuttli magnitude is the most widely-catalogued measure of the size of ENA earthquakes. Considerable effort has gone into developing reliable catalogues of past events in terms of m_N. Observatory procedures for determining m_N for contemporary events are well-developed and work smoothly. In short, m_N has the considerable advantage of inertia. It typically measures ground motions in the 1 to 2 Hz frequency band, which is a relevant frequency range for many engineered structures.

The problem with m_N is that its physical interpretation, in terms of the models upon which ground motion predictions are based, is ambiguous. The relationship between m_N and the earthquake source spectrum depends on the instrumentation and distance at which the measurements were made, as well as the stress drop of the event (eg. Atkinson and Boore, 1987; EPRI, 1993). Also, m_N measures only a narrow frequency band of the ground motion, which may not be predictive of the motion at higher or lower frequencies. These factors introduce much uncertainty into the prediction of ground motion amplitudes from m_N, since current methods use earthquake magnitude to estimate the entire earthquake source spectrum.

High-frequency Magnitude

High-frequency magnitude measures the level of the earthquake source spectrum at frequencies above the corner frequency. Since the corner frequency decreases with increasing magnitude, the bandwidth of this measure increases with increasing magnitude. For damaging earthquakes, say those with $\mathbf{M} > 5$, the frequency range for m is about 2 to 10 Hz. **m** is therefore a good predictor of the earthquake source spectrum in the frequency range of engineering interest, by definition. This makes it particularly well-suited to ground motion predictions based on current methods. It is related to seismic moment in a fairly simple manner, since **m** = **M** for events of average stress drop (Atkinson and Hanks, 1994).

m has the considerable advantage of being well-determined by the felt area of an earthquake (Atkinson and Hanks, 1994). The use of **m** thus reduces the uncertainty in estimating ground motions from the large pre-instrumental earthquakes that are so important to seismic hazard in ENA.

There are significant disadvantages to using **m** in seismic hazard analyses at this time. It is a new scale and is therefore almost completely uncatalogued. Developing new catalogues in terms of **m** is a straightforward task but would entail considerable effort. It will likely be several years before reliable catalogues for old events are compiled. Changing observatory practices to include computation of **m** for modern events is also not a trivial process. Finally, uncertainty in the relationship between **m** and spectral amplitude grows as frequency decreases. Therefore **m** is not a particularly good magnitude measure for predicting ground motion amplitudes at frequencies less than 2 Hz, except for large (**M**>6) earthquakes.

UNCERTAINTIES IN GROUND MOTION PREDICTION

The pros and cons of each magnitude scale for the prediction of ground motion amplitudes are best appreciated through data comparisons. Table 1 lists ENA earthquakes for which we have response spectra data. Only mainshock data are included because aftershocks tend to have lower stress drops (Boore and Atkinson, 1989; Atkinson, 1993), and thus have systematically lower ground motion amplitudes. Only rock sites are included since the predictive ground motion relations are for rock. Figures 1 and 2 convey some appreciation for the distribution of the data in magnitude and distance.

The data set of Table 1 should be considered a biased sample in terms of stress drop. The 1988 Saguenay and 1990 Mont Laurier earthquakes both had stress drops of about 500 bars. Analysis of seismographic data indicates that such high-stress events represent about 15% to 20% of ENA earthquakes (Atkinson, 1993). By contrast, these two events represent about half of the records listed in Table 1 (and 25% of the events). The potential bias is a factor that should be kept in mind in interpreting these data. For example, Atkinson and Boore (1994) found that 1-to-10 Hz PSA data from the events of Table 1 are on average about 25% higher than their predictions, made in terms of **M**, if all *records* are weighted equally. However if all *events* are weighted equally, then this apparent bias disappears. This is because the equal-record weighting implicitly gives the high-stress earthquakes a weight of ½, whereas the equal-event weighting gives them a weight of ¼; the latter weight is more consistent with the percentage of high-stress events within the broader seismological database for ENA.

Current ground motion relations should be capable of predicting the ENA ground motion data correctly on average (ie. zero mean residual), provided that the sample bias is adequately accounted for, regardless of which magnitude scale is selected. However the random scatter of the data about the mean relations, as characterized by the standard deviation of the residuals (sigma), will vary according to how well the magnitude scale predicts the source spectrum. In this section I examine the implications of each magnitude scale for 'sigma'.

The random scatter of the ground motion relations has two components: intra-event (1) and inter-event (2). These components are illustrated in Figures 1 and 2, respectively. The total random variability is determined by $\sigma_t = \sqrt{(\sigma_1^2 + \sigma_2^2)}$ (Joyner and Boore, 1981). The intra-event component was determined to be 0.20 log units (Atkinson, 1993), independent of distance and frequency (1-10 Hz), based on examination of over 1000 ENA Fourier spectra. This value is applicable to the response spectral data of Table 1 on average (Figure 1), although some events (in particular Mont Laurier) appear to have a higher degree of scatter. This component of scatter is, of course, independent of the magnitude scale.

The inter-event component of scatter can be estimated from the Table 1 data, for predictions based on each magnitude scale. For each frequency, I calculate the average residual for each of the eight earthquakes, by comparing the data to ground motion predictions made using the Atkinson and Boore (1994) model, for the particular magnitude scale (Figure 2). The standard deviation of these eight residuals is then an estimate of the inter-event variability. Combining the inter-event variability with the intra-event variability of 0.20, by the addition rule shown above, gives the total random variability as a function of frequency for each magnitude scale, as shown in Table 2.

Table 2 indicates that **M** provides estimates with the least amount of random uncertainty for frequencies less than or equal to 2 Hz. **m** provides the lowest uncertainty for frequencies greater than 2 Hz. m_N-based predictions have the highest amount of uncertainty at all frequencies. This is a good reason *not* to choose m_N for ground motion predictions.

It is important to keep in mind that the figures quoted in Table 2 are based on a set of only eight earthquakes, and that the values quoted are therefore uncertain. Furthermore, the average magnitude of the eight events is only 5.0. For larger magnitudes, which are particularly critical for seismic hazard estimation, the frequency range for which **m** provides the lowest uncertainty would extend to lower frequencies. The frequency range over which **M** is superior would also shift to lower frequencies. Consequently, for large events, **m** would be expected to have less uncertainty than **M** over the entire 1 to 10 Hz frequency band.

CONCLUSION

The optimal choice of magnitude scale for seismic hazard computations is that which reduces random uncertainty in ground motion predictions to the lowest possible level. For moderate earthquakes, **M** is optimal for frequencies of 2 Hz or less, while **m** is optimal for greater frequencies. m_N is not an optimal choice in any frequency band. If a single magnitude scale is to be used, then **m** will be the best choice in most cases, for two reasons: (i) for large (**M**>6) events, it will yield the lowest uncertainty in predicted ground motions over the major frequency band of engineering interest (1 to 10 Hz); and (ii) it is the only magnitude that can be reliably determined for both modern and pre-instrumental earthquakes.

Using the optimal magnitude scale has a significant impact on seismic hazard estimates. Of course, the effect will vary from site-to-site. For many cases, though, the magnitude-recurrence parameters in terms of **m** will not differ significantly from those in terms of **M**, because **m** = **M** on average. For such cases there will be a reduction in computed ground motion when **m** is used for high-frequency parameters; the reduction is associated entirely with the lower sigma for **m** as opposed **M**. Sample calculations suggest that the reduction could be about 20% to 30%, for estimated ground motions at probabilities of 0.001 to 0.0001 per annum. Is this a sleight of hand ? It might appear that way, but actually the lower estimate is a real consequence of reduced uncertainty in the levels of high-frequency ground motion experienced during past earthquakes. This reduction in uncertainty comes from gathering and utilizing the information that is most closely correlated with high-frequency ground motion levels. Much of this data is available for past ENA events, and can certainly be catalogued if we are willing to expend the effort. So if we are serious about reducing uncertainty in ground motion predictions, we should go ahead and *just do it.*

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TABLE 1 - Summary of data for comparison with ground motion predictions

Event		M	M_N	m	stress(bars)	No. obs.	dist.(km)
Gaza	82/01/19	4.0	4.8	4.0	86	5	200 -1000
Goodnow	83/10/07	5.0	5.6	4.8	113	13	200 - 800
Nahanni	85/12/23	6.8	6.1	6.2	53	6	8 - 23
Painesville	86/01/31	4.8	5.3	4.8	149	9	20 -1000
Ohio	86/07/12	4.5	4.9	4.5	154	5	700 -1000
Saguenay FS	88/11/23	4.1	4.6	4.2	190	10	100 - 500
Saguenay	88/11/25	5.8	6.5	6.5	517	29	50 - 700
Mt. Laurier	90/10/19	4.7	5.1	5.4	517	14	30 - 500

Notes: Only mainshocks are included. All records were obtained from the Geophysics Division of the Geological Survey of Canada. High-frequency magnitude is defined as: $\mathbf{m} = 2 \log a_{hf} + 3$, where a_{hf} is the amplitude of the Fourier spectrum of acceleration (cm/s, horizontal component, on rock), at a distance of 10 km from the source. It may be estimated for ENA earthquakes from PGV (horizontal component of peak ground velocity, on rock, in cm/s) using the following, for R≤630 km (Atkinson and Hanks, 1994):

$\mathbf{m} = 2.85 + 1.48 \log PGV_1$ for $\mathbf{M} \geq 4.2$

$\mathbf{m} = 3.34 + 0.902 \log PGV_1$ for $\mathbf{M} < 4.2$

where $\log PGV_1 = \log PGV + \log R + 0.00131 R$, and R is hypocentral distance.

TABLE 2 - Total random variability in ground motions for ENA

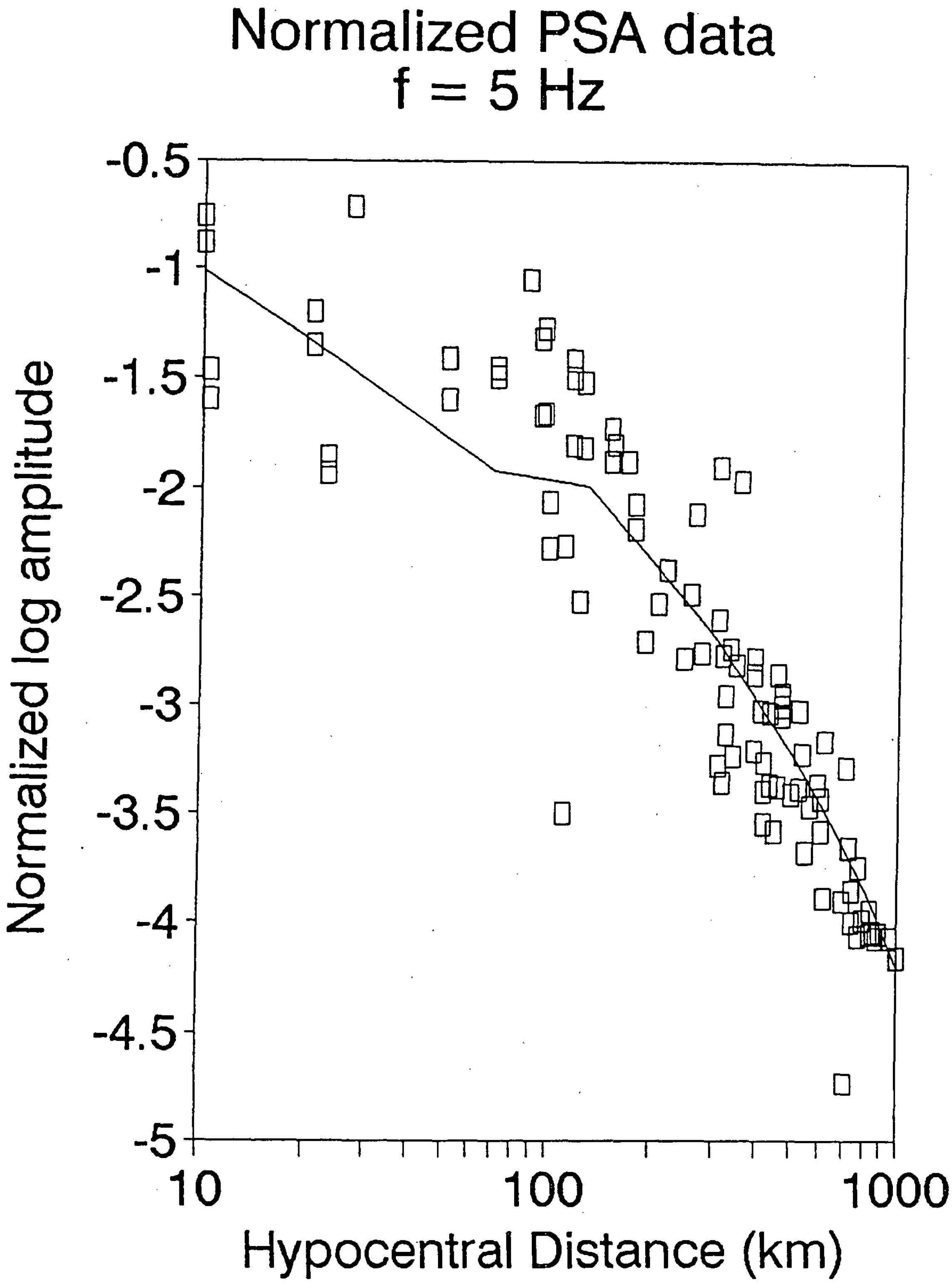
MAGNITUDE SCALE	Standard deviation of residuals for PSA:			
	1 Hz	2 Hz	5 Hz	10 Hz
m_N	0.43	0.34	0.31	0.29
M	0.24	0.24	0.26	0.27
m	0.31	0.30	0.23	0.24

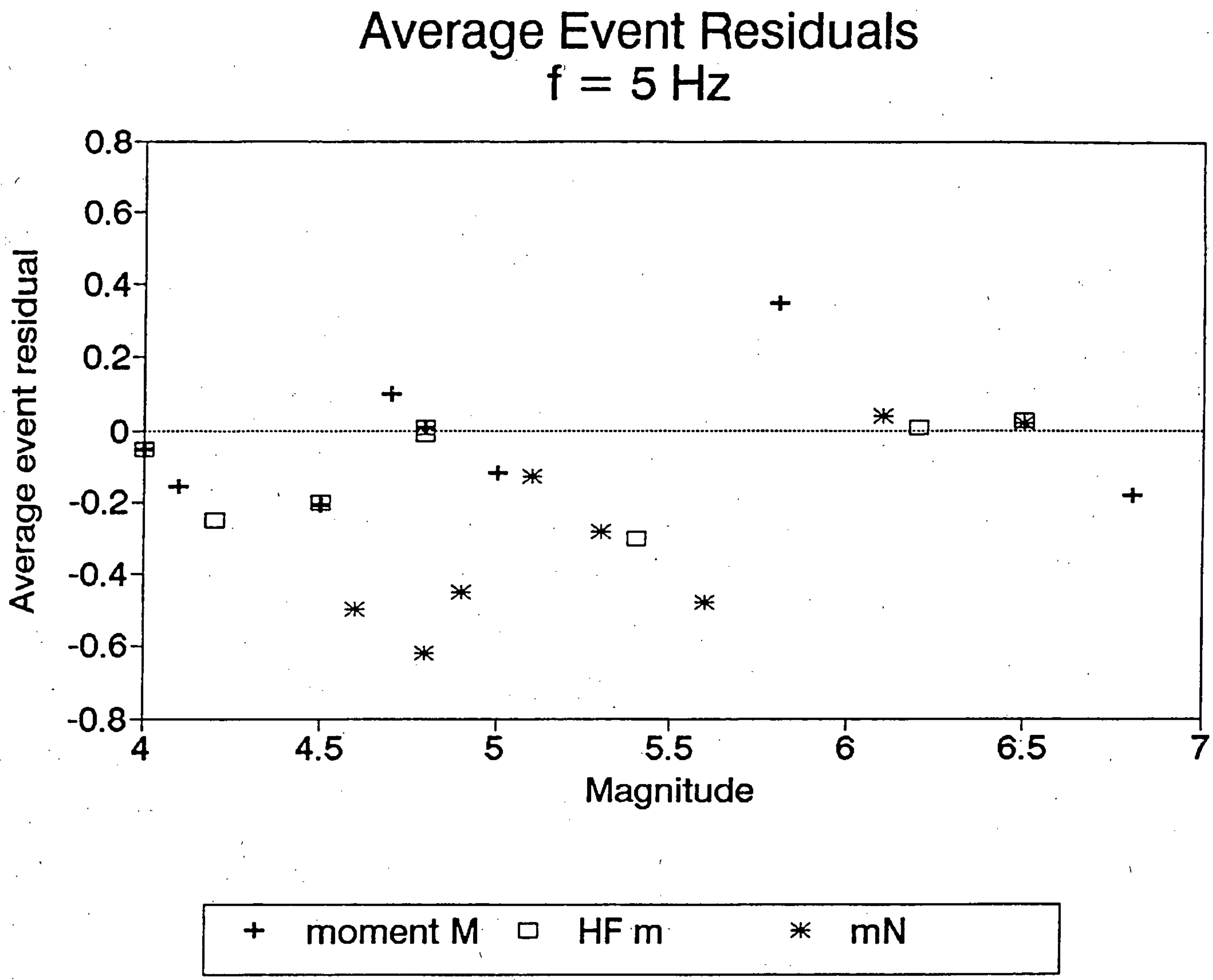
Notes: PSA is the 5% damped pseudo-acceleration. Residuals apply to rock sites, for mainshocks only. The variability (standard deviation of residuals, σ_t) was obtained as $\sigma_t = \sqrt{(\sigma_1^2 + \sigma_2^2)}$, where the intra-event variability (σ_1) is 0.20 for all cases. All numbers are log (base 10) units.

FIGURE CAPTIONS

FIGURE 1 - Illustration of intra-event variability for the data listed in Table 1. Symbols show the normalized 5-Hz pseudo-acceleration values; line shows the average attenuation with distance. The normalization was done by subtracting, from each (log) 5-Hz PSA value, the average (log) 5-Hz source amplitude for the event.

FIGURE 2 - Inter-event variability for the data listed in Table 1. Symbols show the average (log) 5-Hz PSA residual for each event, as a function of magnitude. Residuals are shown for ground motion predictions based on **M** (plus symbols), **m** (squares), and m_N (asterisks).


Normalized PSA data
f = 5 Hz
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
10
100
1000
Normalized log amplitude
Hypocentral Distance (km)



Average Event Residuals
f = 5 Hz
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
Average event residual
4
4.5
5
5.5
6
6.5
7
Magnitude
+ moment M
□ HF m
∗ mN

SUMMARY OF HYBRID EMPIRICAL APPROACH FOR ESTIMATING GROUND MOTIONS IN THE CENTRAL AND EASTERN UNITED STATES

SECOND SSHAC GROUND-MOTION WORKSHOP
Palo Alto, California
July 27-28, 1994

Kenneth W. Campbell
EQE *International*, Inc.
Evergreen, Colorado

INTRODUCTION

The Hybrid Empirical approach for estimating ground motions in the Central and Eastern United States (CEUS) was developed as an alternative to the theoretical models that have become the *de facto* standard for the region. The method takes estimates of ground motion from empirical attenuation relationships developed for the Western United States (WUS) and adjusts them to account for differences in the source, path, and site effects between the two regions.

The method is a hybrid of the true empirical approach in that it uses empirical estimates from a region other than that for which the estimates are being made, and as applied, uses theoretical models for both regions to develop factors for making the necessary regional adjustments.

As stated in the instructions for the second SSHAC Ground Motion Workshop, the estimates were made for a hypothetical site located in the northeastern United States and southeastern Canada. The site conditions are described as Eastern United States Rock (i.e., a site having an average shear-wave velocity of 2800 m/sec over the top 30 m). The magnitudes, distances, and ground-motion parameters for which estimates were provided are shown on the attached tables and figures.

METHODOLOGY

Median Ground Motion

The following steps were used to develop the median ground-motion estimates provided in the attached tables and figures.

1. Empirical attenuation relationships developed by Sadigh et al. (1986), Joyner and Boore (1988), and Campbell (1989) were used to estimate median ground-motion parameters for a hypothetical site on WUS Soil. For this purpose, each model was given equal weight. Estimates on Soil rather than Rock were used because the Rock relationships are based on a significantly smaller number of recordings, and a significant number of these recordings are located on abutments of dams and are subject to potential topographic and dam-abutment interaction effects. Although it was not possible for the current effort, attenuation relationships for WUS Rock could be used as an alternative method of developing empirical ground-motion estimates.

2. Empirical estimates for WUS Soil were adjusted to approximate those expected on WUS Rock using the amplitude and frequency dependent site amplification factors that have been recently developed for inclusion in an upcoming revision of the NEHRP *Recommended Provisions for the Development of Seismic Regulations for New Buildings* (e.g., Borcherdt, 1994). For this purpose, WUS Soil was assigned to either Site Class SC-III (0.8 weight) or SC-II (0.2 weight) and WUS Rock was assigned to either Site Class SC-II (0.8 weight) or SC-Ib (0.2 weight), based on a preliminary assessment of the site conditions of recordings in the WUS empirical database.

3. Empirical estimates for WUS Rock were adjusted to approximate those expected on CEUS Rock using the ratio between theoretical ground motions calculated for the two regions. The model used for this purpose was based on the band-limited white noise stochastic simulation method originally proposed by Boore (1983). The model was used with median source, path, and site parameters recommended by EPRI (1993) for Mid-continent CEUS Rock and by W. Silva (written comm., 1993) for WUS Rock. Although beyond the scope of this project, this procedure could be generalized to incorporate alternative source, path, and site characterization models as well as alternative theoretical models for estimating ground motions in the two regions.

Uncertainty

As requested, I have provided estimates of both the epistemic and aleatory uncertainty associated with the median predictions. Due to limitations in the empirical attenuation relationships as well as budget and time constraints, it was not possible to partition the epistemic uncertainty into its parametric and modeling components, nor was it possible to provide an estimate of the epistemic uncertainty associated with the aleatory uncertainty. Additional effort would be required in order to estimate these uncertainties.

The following steps were used to develop the uncertainties in the median ground-motion estimates provided in the attached tables and figures.

1. Aleatory uncertainty was estimated from the standard errors of regression associated with the attenuation relationships used to develop the median ground motions for WUS Soil, assuming equal weight for the three relationships. These standard errors include both true aleatory as well as parametric modeling uncertainty, but there has been no attempt to separate these two components of uncertainty. For the time being, the standard errors are treated as all aleatory uncertainty and a concerted effort was made not to double count the parametric modeling component of this uncertainty in estimating epistemic uncertainty.

2. The parametric component of the epistemic uncertainty was assumed to be zero, since it was inherently included in the aleatory uncertainty..

3. The modeling component of the epistemic uncertainty was estimated from the following three sources of variability: (1) uncertainty associated with the median estimates of ground motion on WUS Soil (approximated by the variability in the median estimates provided by the three empirical attenuation relationships), (2) uncertainty in the median amplification factors used to adjust median estimates of ground motion on WUS Soil to those on WUS Rock (approximated by the uncertainty associated with assigning the generic Soil and Rock sites to one of the Site Classes defined by Borcherdt, 1994), and (3) uncertainty in the models used to adjust the median estimates of ground motion for WUS Rock to those on CEUS Rock (approximated as the epistemic modeling uncertainty associated with the CEUS model developed by EPRI, 1993, since it was assumed that epistemic modeling uncertainty associated with the WUS model is already included in the aleatory uncertainty).

Sensitivity

There was insufficient time in which to perform a sensitivity analysis. It is hoped that this analysis will be completed prior to the workshop.

RESULTS

Estimates of the median ground motions, the epistemic uncertainty, and the aleatory uncertainty for the magnitudes, distances, and ground-motion parameters of interest in this study are summarized in the attached tables. A comparison of the median estimates with those based on the Mid-continent ground-motion model for the CEUS developed by EPRI (1993) are shown on the attached figures.

DISCUSSION

The methodology developed in this study is intended to be a prototype of a proposed alternative model for estimating ground motions in the CEUS. Due to the limited budget and time constraints of this study, it was not possible to fully develop or implement this procedure. The fully developed procedure could perceivably include additional empirical attenuation relationships, additional site-amplification models, and/or additional models to account for regional differences in source, path, and site effects that would make the method considerably more robust.

Because of the constraints of the project, I simply adopted the Mid-continent model developed by EPRI (1993) for the CEUS. Although this model appears to meet the general description for site location and site conditions for which the ground-motion estimates were to be made, there might be refinements to this model that would make it more applicable to the northeastern United States and southeastern Canada.

The hard rock site for which estimates were made in this study is not typical of sites in the CEUS that are located on sediments (e.g., the Mississippi Valley). For these sites, these hard-rock ground motions would have to be adjusted for the response of local site conditions. Since the estimates provided by the Hybrid Empirical approach are intended to be used only for the higher ground motions associated with relatively large magnitudes and short distances (see below), I do not believe that estimates based on this method would be significantly different for other regions in the CEUS. The biggest difference in the estimated ground motions are likely to be caused by differences in local site conditions, which will result in large site-to-site differences in both observed and calculated ground motions both within as well as between regions.

The inherent strength in the Hybrid Empirical method is that it relies on ground-motion models that are well constrained by actual ground-motion recordings. As a result, the attenuation and magnitude scaling characteristics of the models are based on observation rather than theoretical assumptions. This is particular significant for near-source estimates, which are strongly affected by the complex geometric, kinematic, and dynamic characteristics of the rupture process — effects that are not easily predicted theoretically.

The inherent weakness in the method is its potential inclusion of unknown source, path, and site characteristics that are unique to the WUS and not accounted for in the models used to adjust for regional differences in these characteristics. An additional weakness, at least in the current application of the method, involves the procedure used to adjust the ground-motion estimates on WUS Soil to those expected on WUS Rock. Estimates on WUS Rock, especially if it is characterized as Site Class SC-II, may still incorporate some nonlinear site effects that are not accounted for in the theoretical models used to adjust these estimates to CEUS Rock. If this is true, the higher ground-motions associated with near-source estimates at large magnitudes would be somewhat underestimated by this procedure. It might, however, be possible to overcome this weakness with additional studies. Finally, the method incorporates a weakness inherent in the WUS empirical attenuation relationships: these relationships become unreliable and should not be used to estimate ground motions for distances beyond of about 100 km and for magnitudes less than about moment magnitude 5.

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SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page __ of __

Proponent: Ken Campbell

Approach: Hybrid Empirical

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.050	0.82
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.45	0.55
	aleatory uncertainty	median σ	0.74	0.57
		uncertainty in σ		
20 km	median amplitude		0.013	0.29
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.51	0.39
	aleatory uncertainty	median σ	0.74	0.57
		uncertainty in σ		
70 km	median amplitude		0.0027	0.089
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.49	0.51
	aleatory uncertainty	median σ	0.74	0.57
		uncertainty in σ		
200 km	median amplitude		0.00080	0.030
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.68	0.82
	aleatory uncertainty	median σ	0.74	0.57
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 2: Page __ of __

Proponent: Ken Campbell

Approach: Hybrid Empirical

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.051	0.43
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.48	0.35
	aleatory uncertainty	median σ	0.69	0.52
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 3: Page __ of __

Proponent: Ken Campbell

Approach: Hybrid Empirical

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.50	1.46
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.33	0.34
	aleatory uncertainty	median σ	0.64	0.49
		uncertainty in σ		
20 km	median amplitude		0.15	0.66
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.35	0.29
	aleatory uncertainty	median σ	0.64	0.49
		uncertainty in σ		
70 km	median amplitude		0.036	0.20
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.36	0.50
	aleatory uncertainty	median σ	0.64	0.49
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Proponent: Ken Campbell

Approach: Hybrid Empirical

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.22	0.90
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.34	0.29
	aleatory uncertainty	median σ	0.65	0.48
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 5: Page __ of __

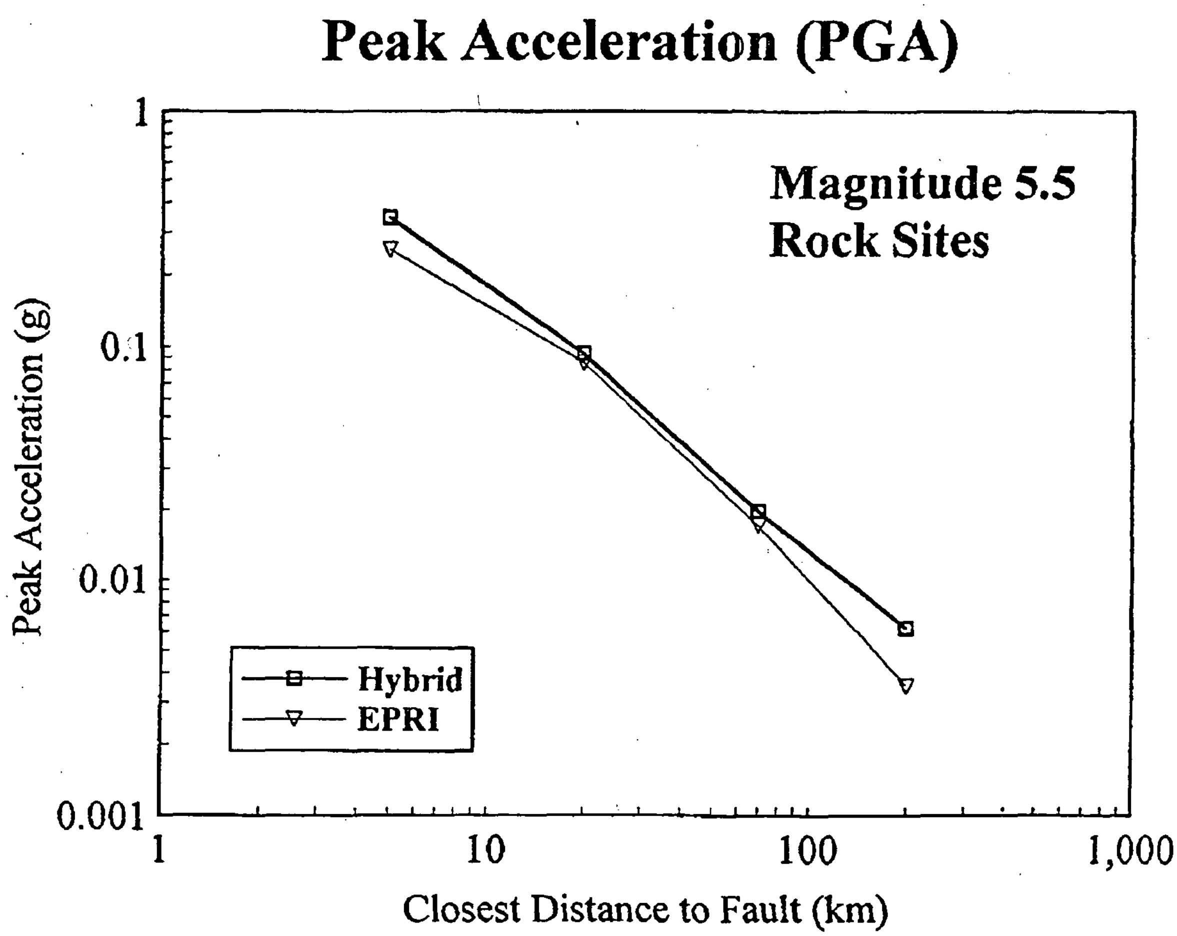
Proponent: Ken Campbell

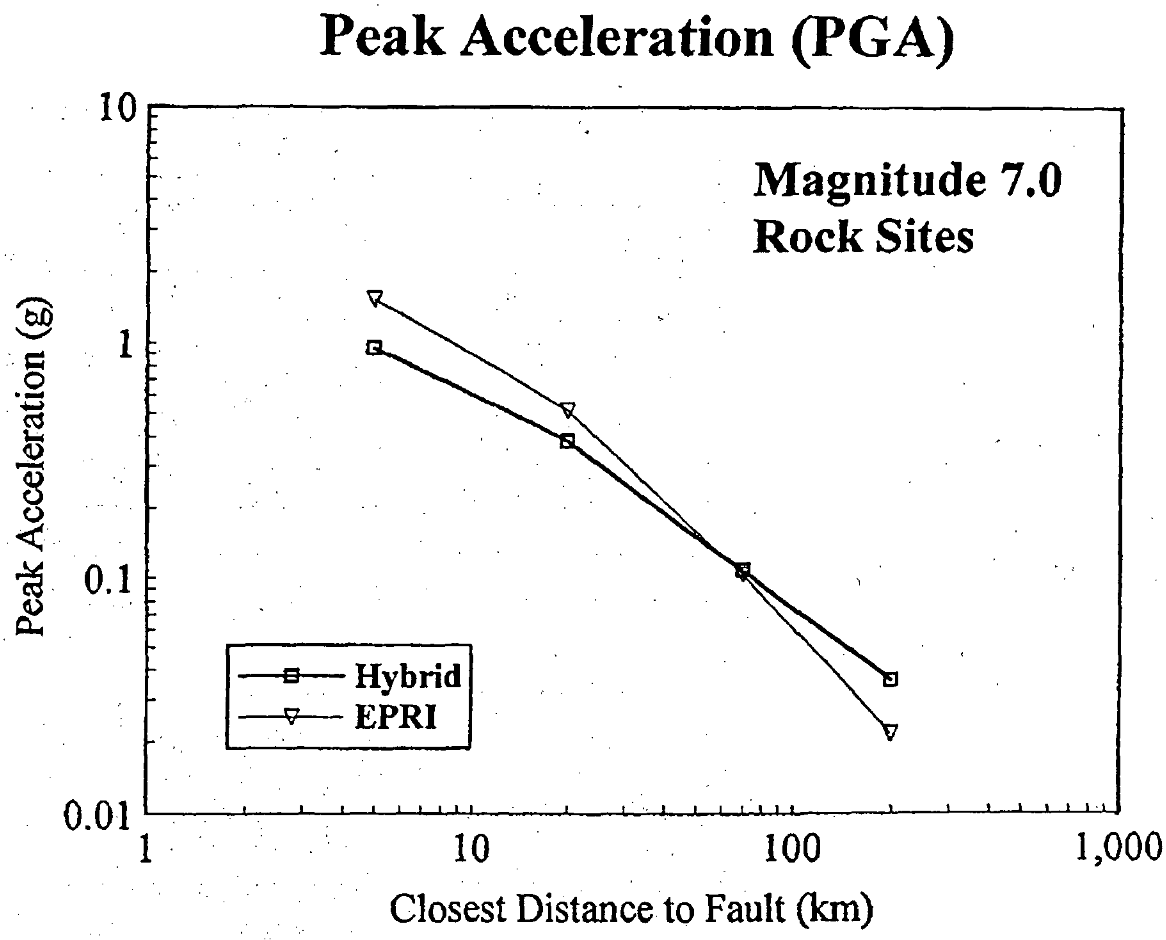
Approach: Hybrid Empirical

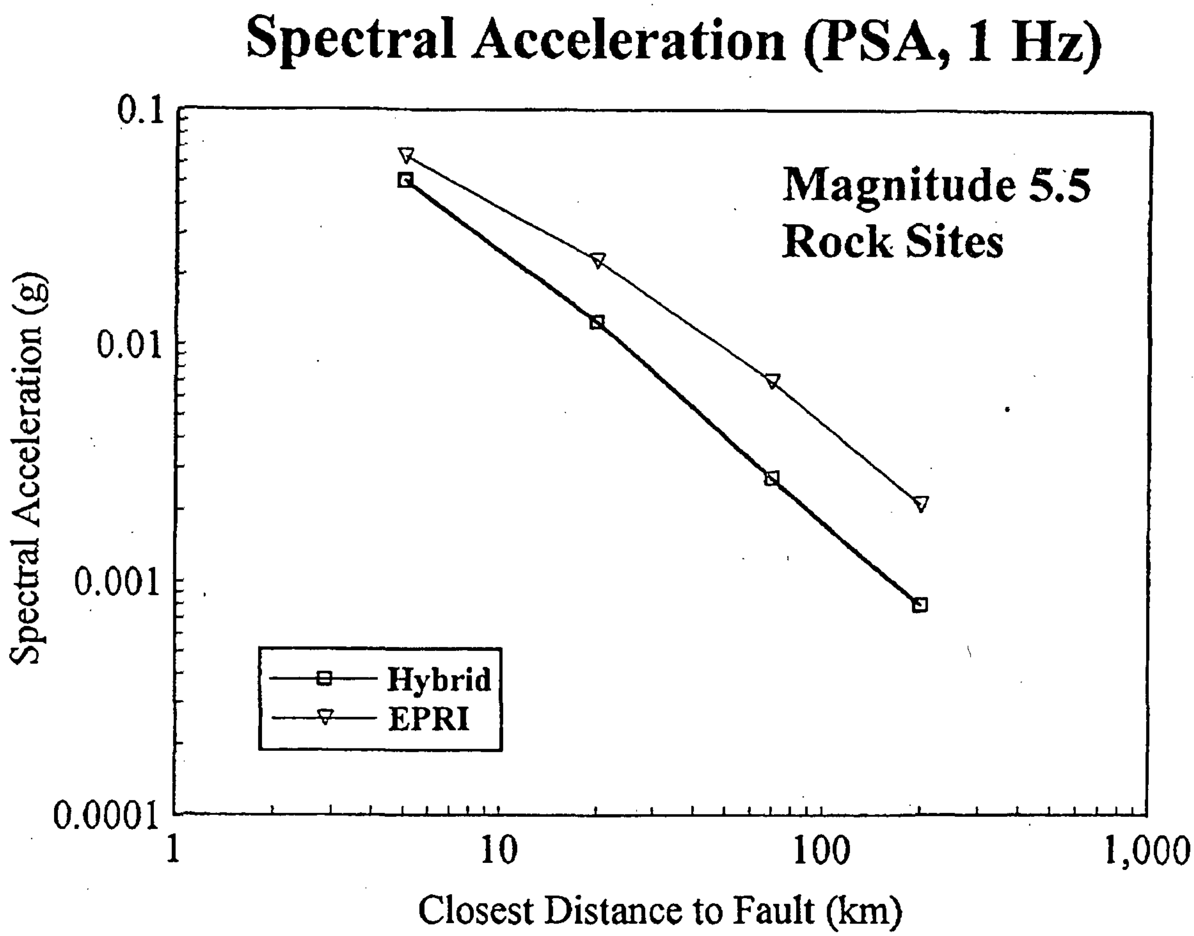
Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.35	0.95
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.38	0.33
	aleatory uncertainty	median σ	0.57	0.48
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.020	0.11
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.41	0.39
	aleatory uncertainty	median σ	0.57	0.48
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

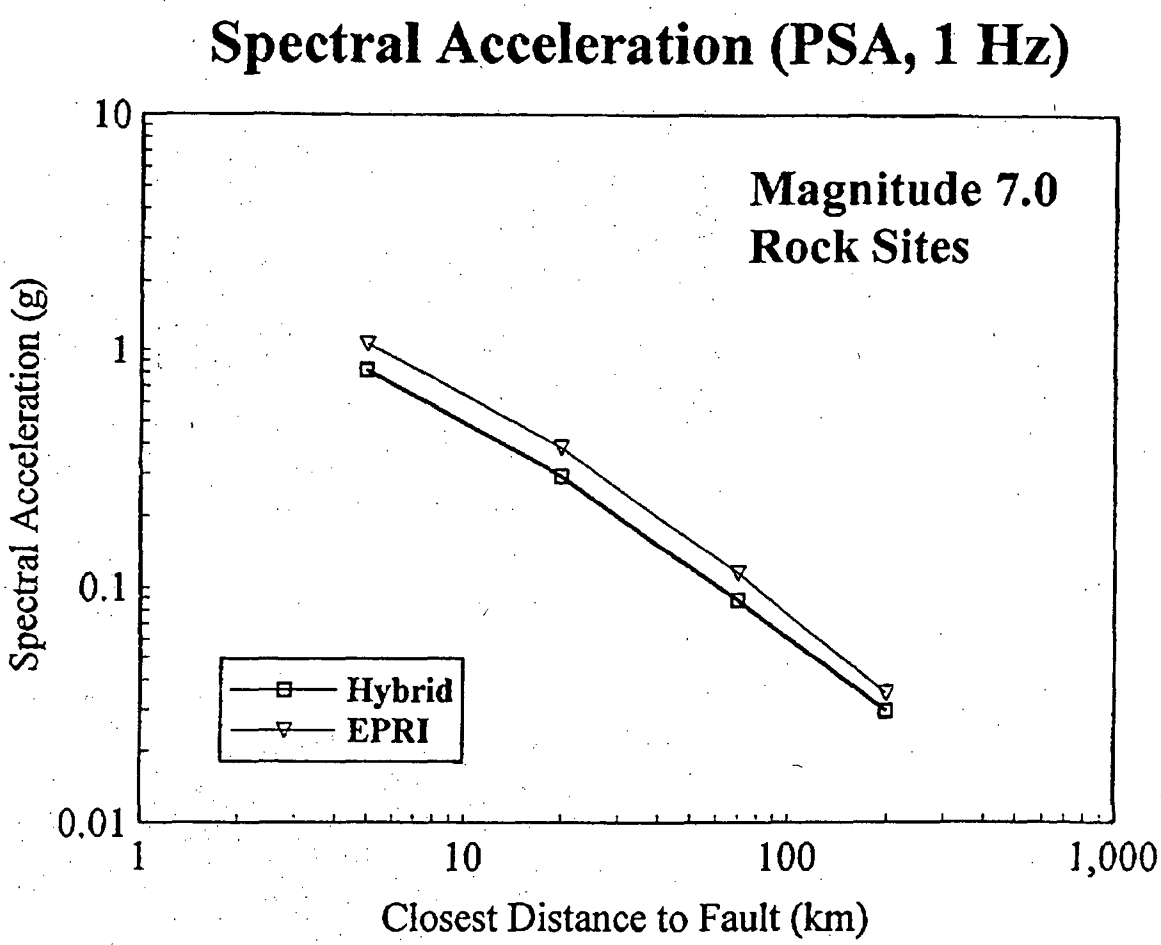
Comments/footnotes:

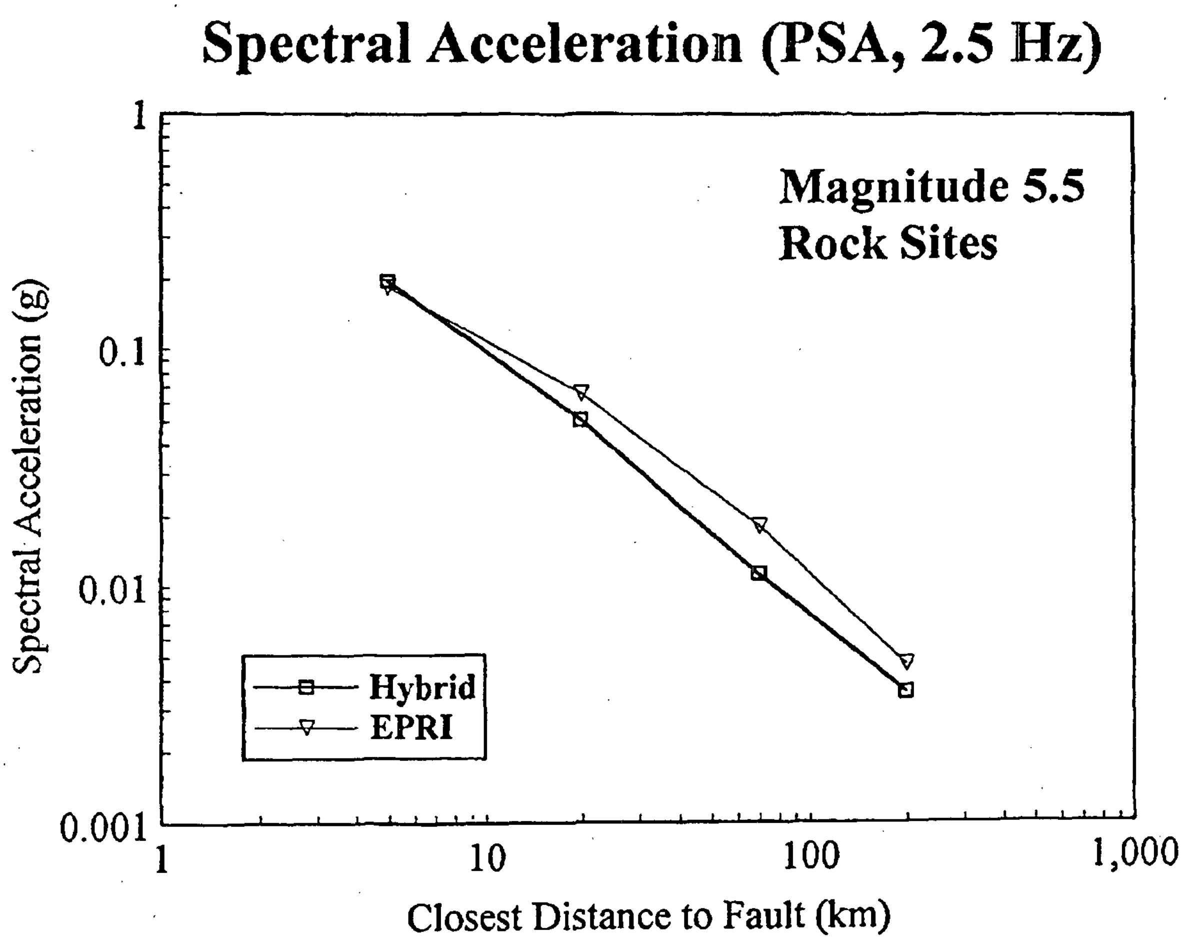

Peak Acceleration (PGA)
Magnitude 5.5
Rock Sites
Peak Acceleration (g)
1
0.1
0.01
0.001
1
10
100
1,000
Closest Distance to Fault (km)
Hybrid
EPRI


Peak Acceleration (PGA)
Magnitude 7.0
Rock Sites
Peak Acceleration (g)
10
1
0.1
0.01
1
10
100
1,000
Closest Distance to Fault (km)
Hybrid
EPRI

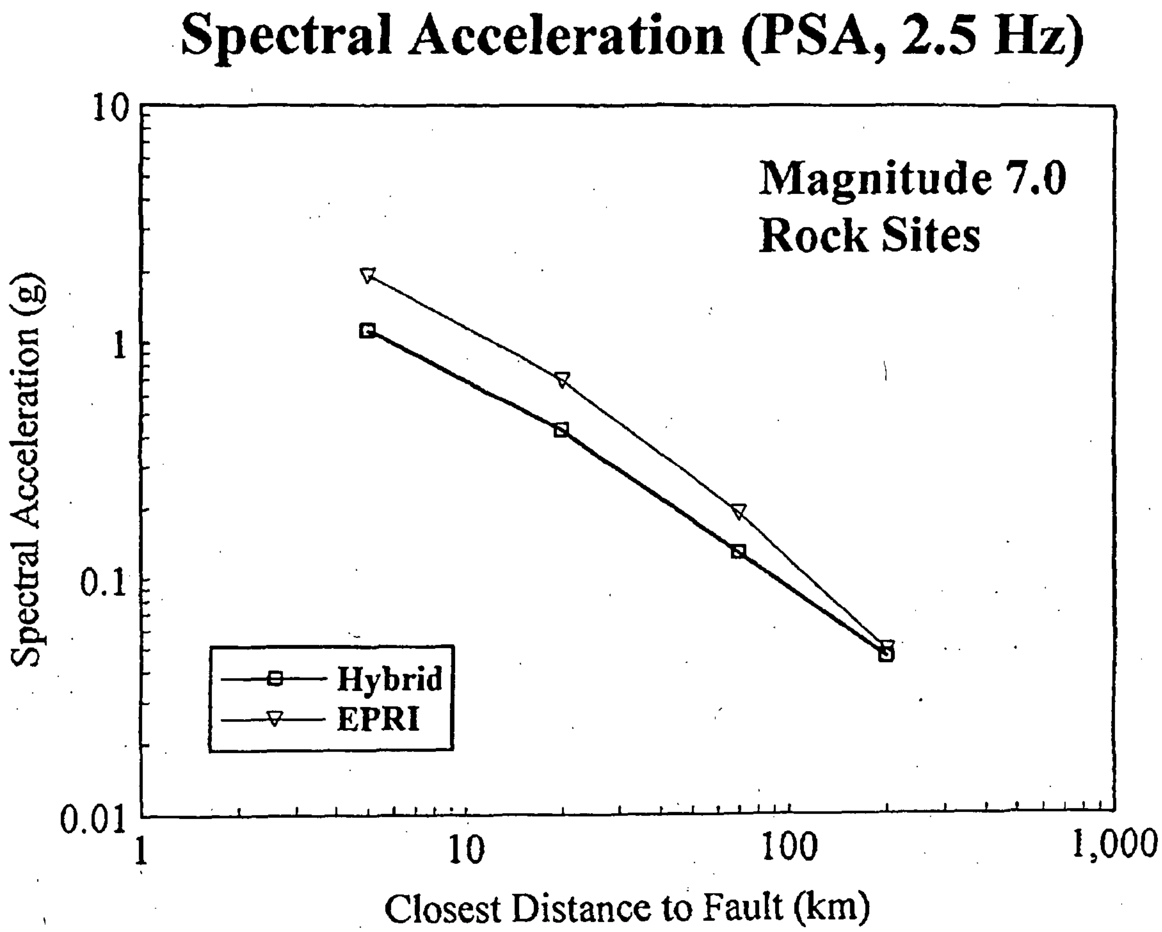


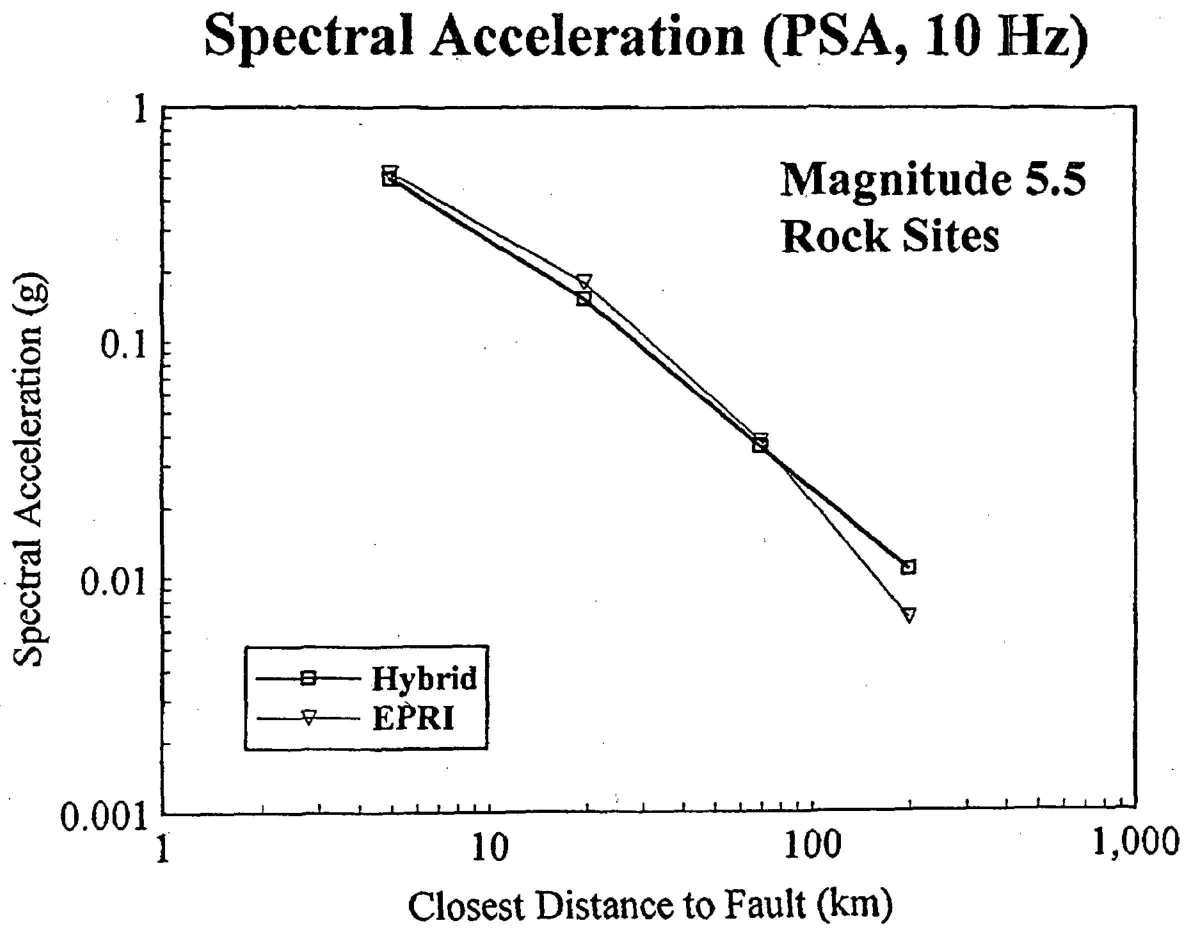
Spectral Acceleration (PSA, 1 Hz)
Magnitude 5.5
Rock Sites
Spectral Acceleration (g)
0.1
0.01
0.001
0.0001
1
10
100
1,000
Closest Distance to Fault (km)
Hybrid
EPRI


Spectral Acceleration (PSA, 1 Hz)
Magnitude 7.0
Rock Sites
Hybrid
EPRI
Spectral Acceleration (g)
10
1
0.1
0.01
1
10
100
1,000
Closest Distance to Fault (km)

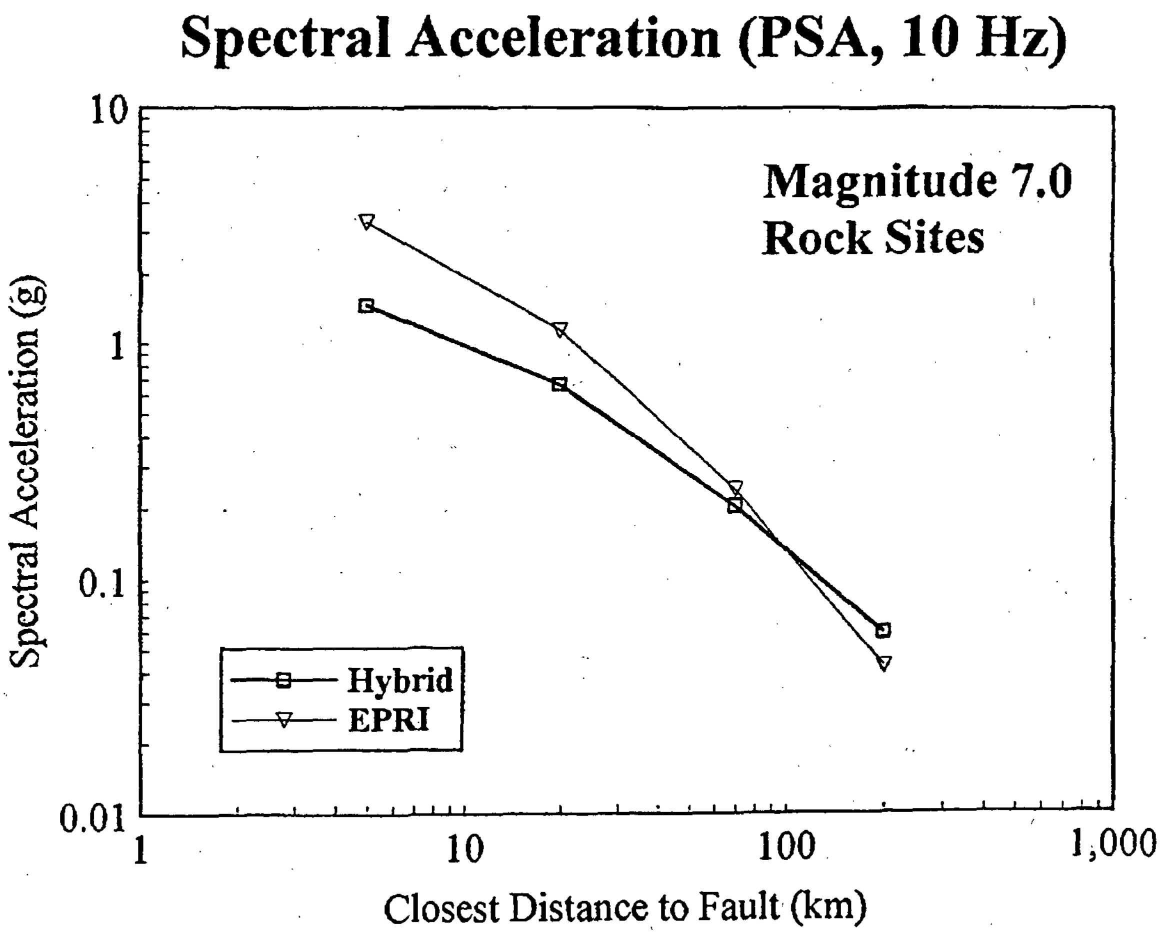


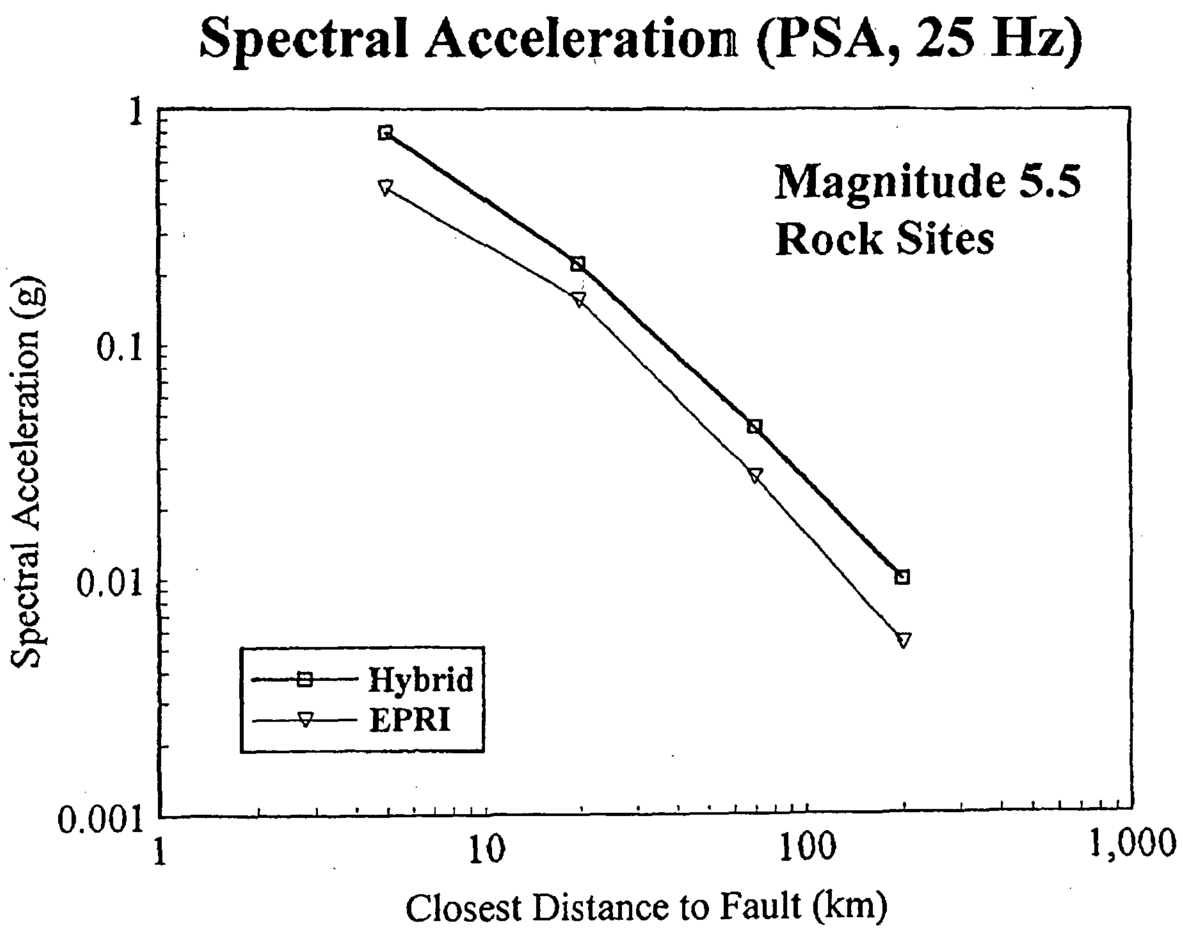
Spectral Acceleration (PSA, 2.5 Hz)
Magnitude 5.5
Rock Sites
Spectral Acceleration (g)
1
0.1
0.01
0.001
1
10
100
1,000
Closest Distance to Fault (km)
Hybrid
EPRI


Spectral Acceleration (PSA, 2.5 Hz)
Magnitude 7.0
Rock Sites
Spectral Acceleration (g)
10
1
0.1
0.01
Hybrid
EPRI
1
10
100
1,000
Closest Distance to Fault (km)

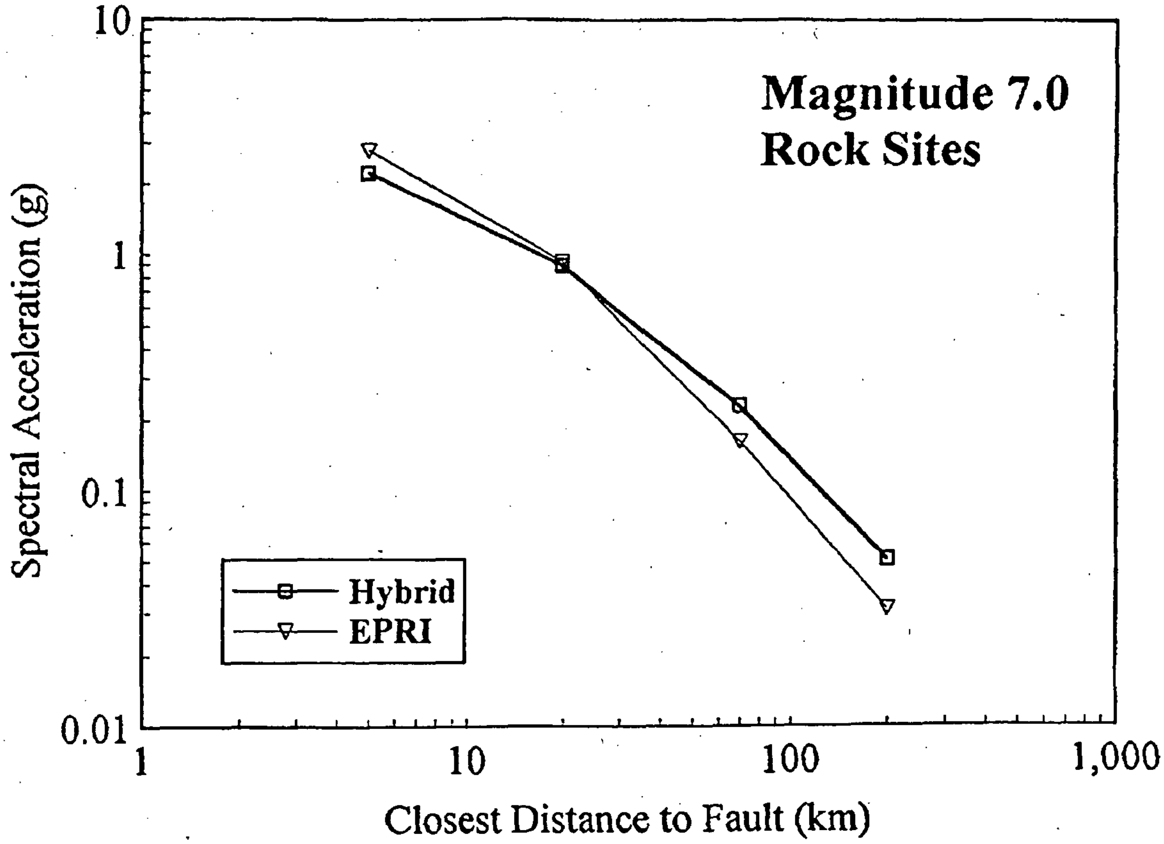

Spectral Acceleration (PSA, 10 Hz)
Magnitude 5.5
Rock Sites
Hybrid
EPRI
Spectral Acceleration (g)
1
0.1
0.01
0.001
1
10
100
1,000
Closest Distance to Fault (km)

JUN-30-1994


Spectral Acceleration (PSA, 10 Hz)
Magnitude 7.0
Rock Sites
Spectral Acceleration (g)
10
1
0.1
0.01
1
10
100
1,000
Closest Distance to Fault (km)
Hybrid
EPRI


Spectral Acceleration (PSA, 25 Hz)
Magnitude 5.5
Rock Sites
Spectral Acceleration (g)
1
0.1
0.01
0.001
1
10
100
1,000
Closest Distance to Fault (km)
Hybrid
EPRI

Spectral Acceleration (PSA, 25 Hz)



SSHAC SECOND GROUND-MOTION WORKSHOP

GROUND MOTION ESTIMATES AND DOCUMENTATION

by

Walter J. Silva
Pacific Engineering and Analysis
July 5, 1994

Proponent: WALT SILVA

Approach: EPRI 1993

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.044 g	0.814 g
	epistemic uncertainty	parametric (ln)	0.14	0.47
		median bias	-0.4	-0.4
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	1.11	0.91
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.019 g	0.348 g
	epistemic uncertainty	parametric (ln)	0.14	0.47
		median bias	-0.4	-0.4
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.92	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.006 g	0.107 g
	epistemic uncertainty	parametric (ln)	0.14	0.47
		median bias	-0.4	-0.4
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.92	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude		0.002 g	0.041 g
	epistemic uncertainty	parametric (ln)	0.14	0.47
		median bias	-0.4	-0.4
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.92	0.8
		uncertainty in σ	0.2	0.2

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Proponent: WALT SILVA

Approach: EPRI, 1993

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.056 g	0.667 g
	epistemic uncertainty	parametric (ln)	0.12	0.38
		median bias	-0.3	-0.3
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.74	0.64
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Proponent: Walt Silva

Approach: EPRI, 1993

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.443 g	2.801 g
	epistemic uncertainty	parametric (ln)	0.11	0.36
		median bias	-0.1	-0.1
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.77	0.69
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.176 g	1.116 g
	epistemic uncertainty	parametric (ln)	0.11	0.36
		median bias	-0.1	-0.1
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.61	0.51
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.039 g	0.248 g
	epistemic uncertainty	parametric (ln)	0.11	0.36
		median bias	-0.1	-0.1
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.61	0.51
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: WALT SILVA

Approach: EPRI, 1993

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.196	1.169
	epistemic uncertainty	parametric (ln)	0.11	0.36
		median bias	-0.1	-0.1
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.68	0.60
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Proponent: WALT SILVA

Approach: EPRI, 1993

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.2099 g	1.264 g
	epistemic uncertainty	parametric (ln)	0.11	0.36
		median bias	-0.1	-0.1
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.79	0.72
		uncertainty in σ	0.2	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.016 g	0.099 g
	epistemic uncertainty	parametric (ln)	0.11	0.36
		median bias	-0.1	-0.1
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.62	0.52
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

INFLUENCE MATRIX, mblg = 5.5,7.5
ENA(see note)

1 Hz

	5(km)	20(km)	70(km)	200(km)
median depth	100	5	0	0
stress drop	60	60	60	60
kappa	1	1	1	1
crust	30	30	50	50

2.5 HZ

	5(km)	20(km)	70(km)	200(km)
median depth	100	5	0	0
stress drop	60	60	60	60
kappa	10	10	10	10
crust	30	30	50	50

10 HZ

	5(km)	20(km)	70(km)	200(km)
median depth	100	5	0	0
stress drop	60	60	60	60
kappa	30	30	30	30
crust	30	30	50	100

25 HZ(AND PGA, see table 1)

	5(km)	20(km)	70(km)	200(km)
median depth	100	5	0	0
stress drop	60	60	60	60
kappa	60	60	60	60
crust	30	30	50	100

note:Matrix values represent a maximum median % change in 5% damped spectral acceleration or pga values for a 100 % change in parameter median value. The difference between small and large magnitudes is much less than the uncertianities and is neglected.

Median Parameter Values(EPRI, 1993)
source depth = 10 km
stress drop = 120 bars
kappa = 0.006 sec
crust = Midcontinent

Stress drop: Source of influence is Figure 1

Kappa: These influence values depend strongly on the median kappa value. If the median kappa value doubles the effect of kappa approximately doubles. See Figure 2.

Crust: For the crust a 100% change would represent a substantially different structure as represented, for example, by the Gulf Coast structure where large differences exist in shallow velocities which affect amplification at 1 Hz and above and in Q(f) which affects higher frequnecies and at large distances. The maximum median effect refers to the average result after considering variation in structure(velocity and Q) and in source depth. After considering reasonable variation the effects of post critical reflections become rather subtle and is reflected in the smooth increase in crustal influence with distance. This effect is also seen in the EPRI(1993) attenuation curves for the Midcontinent and Gulf Coast structres.

PROPONENT: Walt Silva

Approach: EPRI(1993), stochastic point-source model

Epistemic Parametric: Eq. 9-3
Median Bias: Figure 3-6a
Uncertainty in Bias: Figure 3-6a 90% limit

Aletory Uncertainty: Eq. 9-3
Uncertainty of Uncertainty: Taken from range in standard errors of several empirical attenuation relations.

Strength of Approach

1) Accurate: comparable modeling variability and bias compared to more computationally rigorous approaches,
2) Simplicity: minimum of free parameters results in simplest physically plausable model and therefore more robust than more sophisticated models with a larger number of parameters and associated uncertainities to constrain,
3) Controlling parameters can be determined from small earthquakes,
4) Computationally attractive: easily able to generate the large number of synthetic data required to accomodate parametric uncertainities(anyone can code and run the model),
5) Transparency: simplicity of model allows easy assessment(by examining equations) of parametric effects. An important consideration in a regulatory environment. Simplicity is appealing to regulators as parameters (sources of uncertainty) can't be hidden. This results in a greater confidence in validation exercises.

Weakness of Approach

1) Point-source: Neglects saturation effects due to source finiteness.
2) Wave propagation: Uses asymptotic ray theory which is strickly correct at high frequencies.

Applicability
The approach is applicable to the prescribed conditions.

Site conditions
The prescribed site conditions(vs=2800 m/s over top 30 m, k=0.006 sec) represent very hard rock and consequently minimize site effects (except at 25hz where a 100% increase in kappa decreases ground motions by about 60%). These conditions may not represent average rock sites in the larger CEUS. Table 2 lists velocities averaged over 30m at nuclear power stations located in the CEUS and founded on rock. The average is closer to 2000 m/sec(6000 ft/sec) which, according to Figure 2, might be associated with a kappa value of about 0.01 sec. For such sites kappa would have a much greater influence.

From the influence matrix, the maximum average parametric effect is 100% and from Figure 3 the average soil site effect can exceed 100%(factor of 2). Site variability is a significant factor in the variability of strong ground motions. At rock sites, for higher kappa values(> 0.006 sec), the shallow velocities are lower(Figure 4) resulting in amplification. At rock sites the same process exists as at soil sites: amplification due to a velocity gradient and deamplification due to damping(material and scattering). The result is a large component of variability. If SSHAC does not consider site effects it is difficult to see how variability can be addressed to a more refined extent than in the EPRI work. The significant aspect of the EPRI analysis of variability is that the variability is dominated by randomness (aletory).The epistemic variability is small suggesting that we have confidence in our models. The shortcoming in the EPRI study is that it did not include an analysis of uncertainty of site effects in the context of the total model. It seems to me that a reasonably definitive assessment of variability and its partition into aletory and epistemic parts awaits resolution of the uncertainity associated with site effects.I do believe that the total uncertainty arrived at in the EPRI study is probably about right. The site part is buried somewhere and we need to dig it out.

Other regions within CEUS
Following EPRI only the Gulf Coast region would have significantly different motions than the rest of the CEUS(EPRI Midcontinent model). The motion for the Gulf Coast are larger in close due to the lower velocity in the shallow crust but crossover at distance due to the lower Q(f).

TABLE 1

MOMENT MAGNITUDE, CORNER FREQUENCY, PEAK ACCELERATION, AND PEAK PARTICLE VELOCITY AT R = 10 KM FOR STANDARD WNA AND ENA PARAMETERS

WNA

M	f_C (Hz)	A_P (g)	f_P** (Hz)	V_P(cm/s)	f_P(Hz)	V_P/A_P(cm/s/g)
2.5	17.594	0.003	15.03	0.05	9.93	15.73
3.5	5.563	0.020	10.47	0.43	6.37	21.46
4.5	1.759	0.072	7.84	2.50	3.91	34.80
5.5	0.556	0.178	6.86	9.73	2.45	54.52
6.5	0.176	0.378	6.56	32.17	1.55	85.00
7.5	0.056	0.756	6.48	87.95	1.13	116.40

ENA

M	f_C (Hz)	A_P (g)	f_P(Hz)	V_P(cm/s)	f_P** (Hz)	V_P/A_P(cm/s/g)
2.5	19.244	0.017	38.70	0.09	25.54	5.49
3.5	6.084	0.055	31.15	0.51	14.55	9.28
4.5	1.924	0.133	27.43	2.17	7.92	16.37
5.5	0.608	0.283	25.98	8.22	4.32	29.07
6.5	0.192	0.567	25.47	28.63	2.44	50.46
7.5	0.061	1.104	25.32	81.76	1.67	74.03

**Predominant frequencies estimated from random process theory

NUCLEAR POWER PLANT ROCK SITE VELOCITIES
AVERAGES OVER 100 FT OF ROCK

Plant	S-wave Velocity (fps)	P-wave Velocity (fps)
Arkansas	5350	12250
Bellefonte	9227	17584
Braidwood	3583	7930
Byron	4138	10531
Catawba	5910	10140
Comanche Peak	5940	10820
Davis-Besse	6700	12700
Dresden	4817	8122
Fermi	6634	12160
Ginna	7200	12800
Haddam Neck	----	12500
Limerick	5950	12500
Yankee	7000	14000
McGuire	7200	12044
Millstone	6500	13267
Nine Mile Pt	7000	14000
North Anna	5750	14500
Oconee	----	9669
Peach Bottom	----	11500
Perry	4450	9700
Quad Cities	6300	10400
Seabrook	9000	16455
Sequoyah	6860	13019
Shearon Harris	5352	11480
Summer	7120	14750
Susquehanna	6363	13253
Three Mile Island	----	9750
Vermont Yankee	6500	13500
Watts Bar	6285	11406
Average	6285.16	12163.10

$$\frac{\overline{Vp}}{\overline{Vs}} = 1.935$$

$$\sigma = 0.318$$

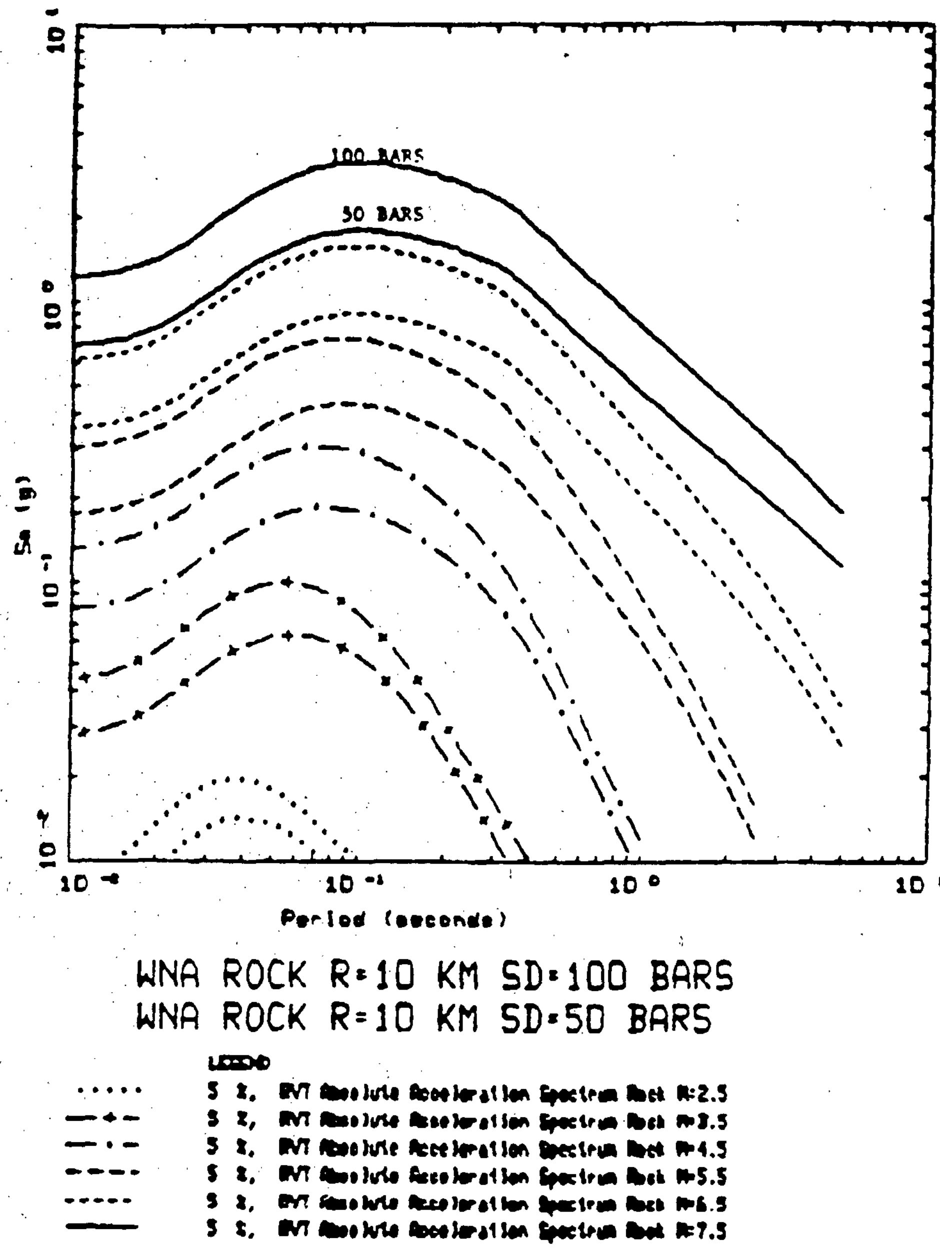
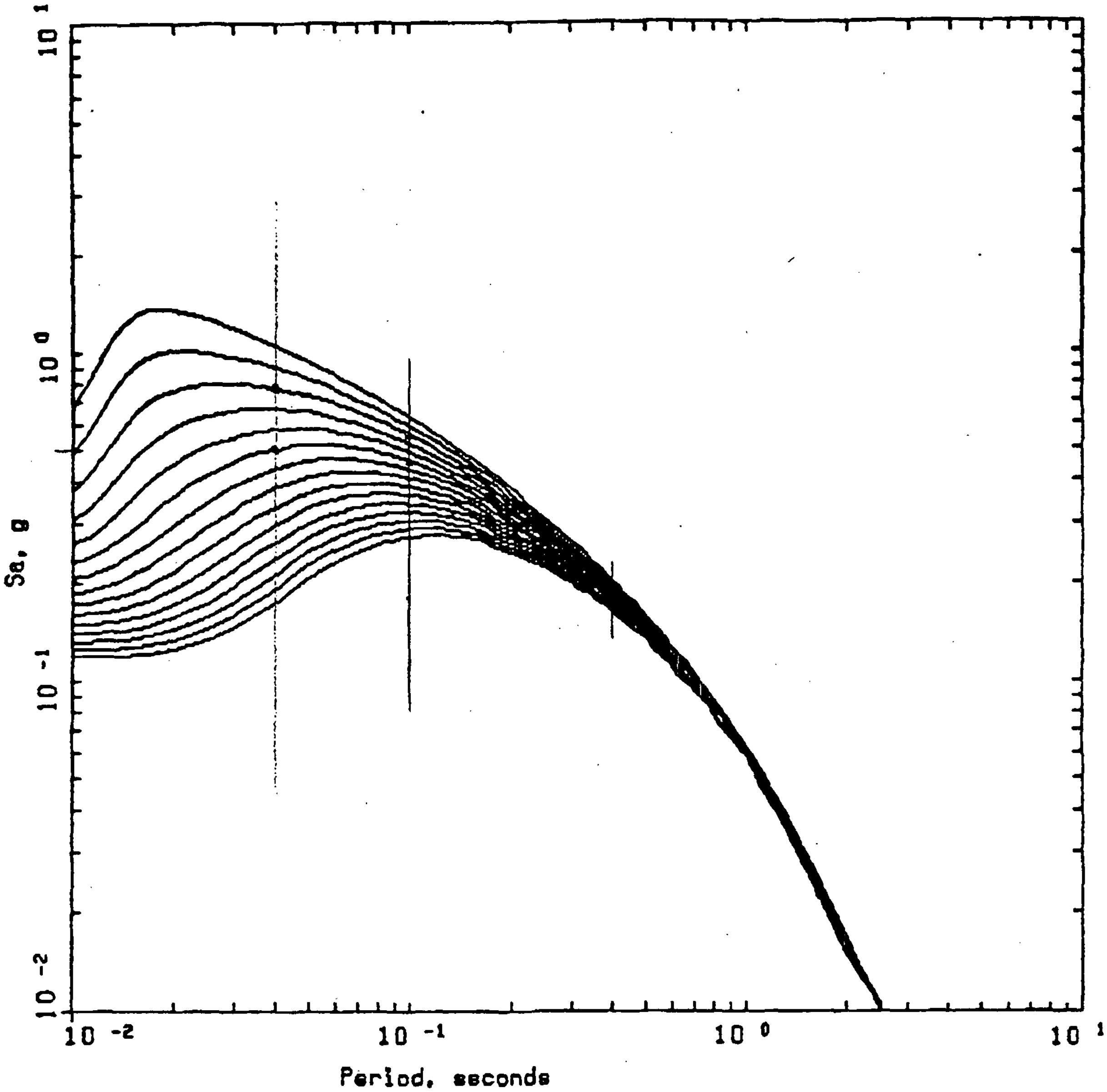


Figure 1 Comparisoin of 5% absolute acceleration response spectra (Sa) computed for WNA parameters (Table 2) for stress parameters of 50 and 100 bars.



ENA ROCK R=10 KM Mw=5.5
FILTER=75.0Hz (5) 10 SEC (5)

LEGEND

RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.002 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.004 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.006 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.008 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.010 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.012 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.014 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.016 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.018 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.020 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.022 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.024 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.026 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.028 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.030 SEC

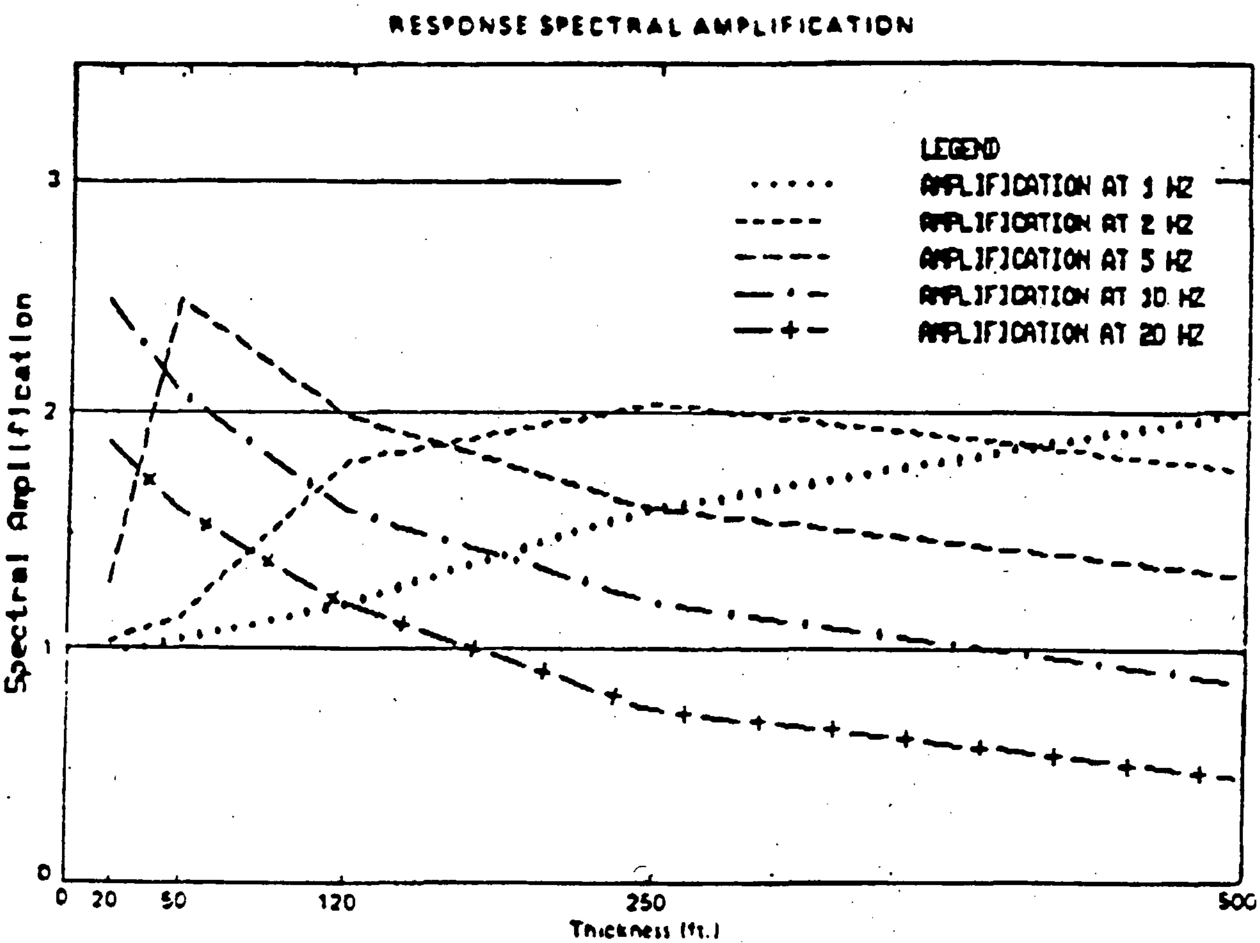
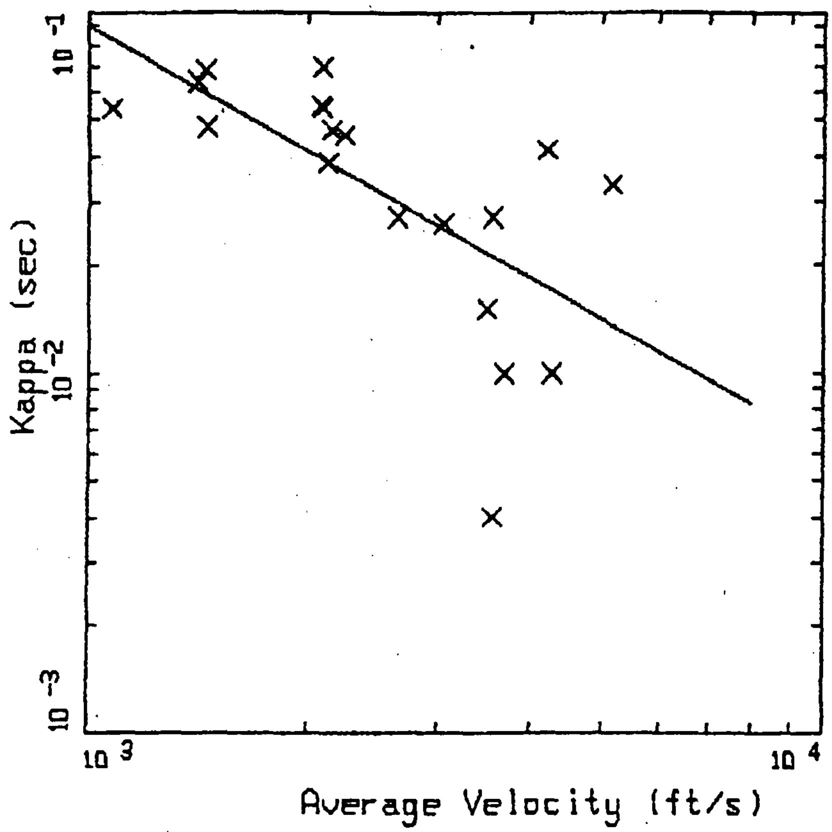


Figure3 . Plot of computed 5% response spectral amplification factors for five site categories (Figure 22) for a 0.5 g level of input (rock outcrop) motion. Curves represent frequencies of 1, 2, 5, 10 and 20 Hz.



ROCK SITES (WNA)

KAPPA VS AVERAGE (OVER 100 FT) VELOCITY

LEGEND

X DATA

—— LOG(KAPPA) = 2.40939 - 1.15099 * LOG(VELOCITY IN FT/S)

SSHAC SECOND GROUND MOTION WORKSHOP

Menlo Park July 28-29 1994

DOCUMENTATION OF GROUND MOTION ESTIMATES

Prepared June 29, 1994

PROPONENTS: Paul Somerville and Chandan Saikia, Woodward-Clyde

APPROACH: Advanced Numerical Modeling

PART 1. METHOD

The advanced numerical modeling method is described in Appendix 1, which is taken from Section 3.3 of EPRI Report TR-102293-V1. The method, termed the semi-empirical ground motion model in that report, is described in Section 3.3.1, and its validation against recorded data is described in Section 3.3.2. The modeling variability and bias derived from the validation are described in Part 2.2, and Parts 3.2 and 3.3 of this documentation, respectively.

PART 2. PROCEDURE FOR ESTIMATION OF ALEATORY UNCERTAINTY

2.1 ALEATORY PARAMETRIC UNCERTAINTY

The base case parameters and their assumed distributions used in the estimation of aleatory parametric uncertainty are summarized in the tables in Appendix 2.

2.1.1. Crustal Structure and Focal Depth

Crustal structure and focal depth are treated together because they are coupled.

Depth distribution: median 11 km; 0.5 sigma lognormal

We assume equal weighting of four different crustal structures within the Northern Grenville - Superior region, shown in Figure 5-23 of EPRI Report TR-102293-V1 which is reproduced in Appendix 2 as Figure 2.1.

Resulting uncertainty in ground motions: Standard error is distance and frequency dependent, as given by the Grenville curves in EPRI Report TR-102293-V1 Figure 5-27, reproduced in Appendix 2 as Figures 2.2 through 2.4. For 1 Hz, the standard errors for 10, 20, 70 and 200 km distance are 0.30, 0.24, 0.35, and 0.38 respectively. For higher frequencies, the corresponding standard errors are 0.30, 0.24, 0.44, and 0.24 respectively.

2.1.2 Stress Drop

The stress drop is used solely to fix the fault rupture area for a given seismic moment. The median value, estimated from the source duration of 14 ENA events (updated from Somerville et al., 1987), is 100 bars. The standard error in $\log_e$stress drop derived from the estimated rupture areas and seismic moments of twelve crustal events is 0.7 (Somerville and Abrahamson, 1991); this relationship is shown in Appendix 2, Figure 2.5. We use this value of 0.7 to represent the variability in $\log_e$stress drop due to variability in rupture area.

Uncertainty in ground motions due to 0.70 uncertainty in $\log_e$stress drop = 0.28; this does not have significant distance and period dependence, as shown in Appendix 2, Figure 2.6.

2.1.3. Seismic Moment M_o

In our model, earthquake size is specified by seismic moment M_o, so we need to convert from m_{blg} to M_o. We use a relation between $\log_{10}M_o$ and m_{blg} based on 13 ENA events updated from Somerville et al., 1987, shown in Appendix 2, Figure 2.7, where data are well modeled by a linear relation:

$$\text{Log}_{10} M_o = 1.2\, m_{blg} + 17.2$$

standard error of $\log_e M_o$ = 0.26
standard error of mean of $\log_e M_o$ = 0.07

Uncertainty in ground motions due to 0.26 uncertainty in $\log_e$Mo: 0.11 (1 Hz); 0.09 (other periods). This should be removed from aleatory uncertainty when predicting ground motions from seismic moment M_o or moment magnitude M_w. Note that:

m_{blg} of 7.0 corresponds to M_o of 4.0×10^{25} dyne-cm and M_w of 6.4
m_{blg} of 5.5 corresponds to M_o of 6.3×10^{23} dyne-cm and M_w of 5.2

There is no significant correlation evident in the relationship between the m_{blg} residuals from this relationship and stress drop, as indicated in Appendix 2, Figure 2.8. This means that we cannot offset this additional source of aleatory uncertainty.

2.1.4. Q_o

The median value of Q_o is taken to be 750, and its uncertainty is assumed to be lognormal with a standard error of 0.4 The effects of this uncertainty are both distance and frequency dependent.

2.1.5. Kappa

The median value of kappa is taken to be 0.006 sec, and its uncertainty is assumed to be lognormal with a standard error of 0.4 The effects of this uncertainty are frequency dependent.

2.1.6. Other source parameters

Variability in source parameters other than stress drop, seismic moment and focal depth considered above contribute to variability in estimated ground motions. One of these is focal mechanism, but we expect most earthquakes in the northeastern United States and southeastern Canada to have thrust mechanisms (Somerville et al., 1987), so variation in focal mechanism may not have a large effect. Other causes of variability in source effects include the distribution of slip on the fault surface, and the location of the hypocenter on the fault surface. The uncertainty in ground motions due to variations in these source parameters is estimated to be 0.20, independent of distance and period.

2.1.7. Overall Aleatory Parametric Uncertainty

Overall aleatory parametric uncertainty is calculated by combining the above six components.

2.2. MODELING UNCERTAINTY

The modeling uncertainty is derived from the standard error in goodness of fit between recorded and simulated acceleration time histories, as described in EPRI Report TR-102293-V1, Ch. 3. Section 3.3.2. The modeling uncertainty is documented in Section 3.3.3 and shown in Figure 3-15b, which is reproduced in Appendix 2, Figure 2.9. The standard error is period dependent but not distance dependent.

2.3. OVERALL ALEATORY UNCERTAINTY

This is calculated by combining the parametric uncertainty and the modeling uncertainty following the procedure of Abrahamson et al. (1990).

2.4. EPISTEMIC UNCERTAINTY IN OVERALL ALEATORY UNCERTAINTY

This is estimated to be 0.1 based on judgment.

PART 3. PROCEDURE FOR ESTIMATION OF EPISTEMIC UNCERTAINTY

3.1. EPISTEMIC PARAMETRIC UNCERTAINTY

3.1.1. Stress drop

Standard error of mean of $\log_e$stress drop derived from rupture area = 0.2

Effect on ground motion amplitudes = 0.08 (1 Hz); 0.07 (other frequencies)

3.1.2. Seismic Moment

Standard error of mean of $\log_e$ seismic moment for a given m_{blg} = 0.07

Effect on ground motion amplitudes = 0.10 (1 Hz); 0.08 (other frequencies)

3.1.3. Overall Parametric Uncertainty

Esttimated by combining the effect of stress drop and seismic moment: 0.13 (1 Hz); 0.10 (other frequencies)

3.2. MEDIAN BIAS

Derived from bias in goodness of fit between recorded and simulated acceleration time histories for a total of 39 recordings of the Loma Prieta, Whittier Narrows, Nahanni and Saguenay earthquakes. This is documented in EPRI, Report TR-102293-V1, Ch. 3. Section 3.3.3, and illustrated in figure 3-15a which is reproduced in Appendix 3 as Figure 3.1. The bias is not significantly different from zero for frequencies of 2.5, 10, 25Hz and pga. An underprediction by 20% was removed from the predicted motions for 1 Hz, so the bias for all frequencies is reported to be zero.

3.3. UNCERTAINTY IN MEDIAN BIAS

The uncertainty in the median bias is derived from the 90% confidence intervals shown in Figure 3.1 of Appendix 3. It ranges from 0.18 at 1 Hz to 0.12 for pga.

PART 4. DISCUSSION

4.1 STRENGTHS

The advanced numerical modeling method that we use for strong motion prediction is based on standard time-domain methods for estimating earthquake source parameters and analyzing seismic wave propagation. It can therefore be readily applied using standard parameterizations of the earthquake source and crustal structure. The method can be made broadband by the incorporation of long-period contributions using synthetic seismograms, which makes it accurate from very long periods (including DC) to high frequencies.

The advanced numerical modeling method has a large potential for development because the new broadband stations of the National Seismic Network provide data that allow us to significantly improve our source and wave propagation models for eastern North America.

The advanced numerical modeling method has been extensively validated against strong motion data from California, and has been validated against most of the available data from eastern North America.

In the advanced numerical modeling method, the attenuation function is determined by the crustal structure and the source depth using standard wave propagation models. It has predictive power in many locations in eastern North America where knowledge of crustal structure and source depth is available but no strong ground motion data exist.

The Green's functions used by the method need only be calculated once for a given crustal structure. They can then be archived on the INTERNET for use by multiple investigators in ground motion modeling and seismic source inversion.

4.2 WEAKNESSES

Green's functions could but currently do not include scattering and the effects of local non-planar structure, which may be important at high frequencies.

The methodology for including scattering is to represent it in the empirical source functions that we use, which we do not correct for scattering effects. At present, we do not have a large number of strong motion recordings from which to derive empirical source functions. Instead, we use empirical source functions from western North American events with kappa corrections. The scattering conditions represented by these may not be optimal for eastern North America.

4.3 APPLICABILITY TO MAGNITUDE/DISTANCE/FREQUENCY RANGES

The Advanced Numerical Modeling method is applicable for all of the combinations of the magnitude, distance and frequency values specified in the Instructions to Proponents.

4.4 REPRESENTATIVENESS OF HARD ROCK SITE

The hard rock site (2.8 km/sec average shear wave velocity over the top 30 m) is probably representative of unweathered crystalline rock sites in the northeastern United States and southeastern Canada. It may not be representative of sedimentary rock sites in the Central and Eastern United States.

4.5 HOW RESULTS WOULD DIFFER IN OTHER REGIONS WITHIN CEUS

The ground motion estimates presented here are for the northeastern United States or southeastern Canada (region 10 in our regionalization of crustal structure) as requested in the instructions for proponents. The variability of median ground motions (5 Hz response spectral acceleration at 5% damping) for a moment magnitude 6.5 earthquake calculated using the crustal structure models for all 16 regions of eastern North America is illustrated in Figure 5-46 from EPRI TR-102293-V1, which is reproduced as Figure 4.1 in Appendix 4. The intra-region variability about the median ground motions due to uncertainty in crustal structure may be different in different regions. This is illustrated in Figures 2.2 through 2.4 in Appendix 2, where the intra-region variability for the Grenville and New Madrid regions are compared. The variability in the Grenville region is largest for distances around 100 km and is produced by variability in the depth of the Moho. In contrast, the variability in the New Madrid region is largest for distances around 60 km, and is produced by variability in the depth of the Conrad.

PART 5. BIBLIOGRAPHY

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PART 6. ESTIMATES OF MEDIAN AND UNCERTAINTIES

Estimates of median ground motion values and their uncertainties are given in Tables 1 through 5 that follow. Explicit calculations have been done for uncertainties in the ground motion estimates for m_{blg} = 7. While complete explicit calculations have not been done for the uncertainties for m_{blg} = 5.5, all of the available calculations indicate that to a first approximation the uncertainties for these two magnitudes can be assumed to be equal.

Estimates for a closest distance of 5 km are not available. In their place, estimates for a closest distance of 12 km are given.

The breakdown of the aleatory uncertainty into parametric and modeling components, and the breakdown of the parametric component into contributions from individual model parameters, is given in Tables 1S through 5S that follow.

The reported aleatory uncertainty is for predicting ground motions given an earthquake size expressed as m_{blg}. The uncertainty due to seismic moment should be removed from the aleatory uncertainty when predicting ground motions from seismic moment M_o or moment magnitude M_w.

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
12 km	median amplitude		0.034	0.20
	epistemic uncertainty	parametric (ln)	*	0.13
		median bias	*	0
		uncert. in bias (ln)	*	0.18
	aleatory uncertainty	median σ	*	0.81
		uncertainty in σ	*	0.1
20 km	median amplitude		0.017	0.10
	epistemic uncertainty	parametric (ln)	*	0.13
		median bias	*	0
		uncert. in bias (ln)	*	0.18
	aleatory uncertainty	median σ	*	0.79
		uncertainty in σ	*	0.1
70 km	median amplitude		0.003	0.025
	epistemic uncertainty	parametric (ln)	*	0.13
		median bias	*	0
		uncert. in bias (ln)	*	0.18
	aleatory uncertainty	median σ	*	0.84
		uncertainty in σ	*	0.1
200 km	median amplitude		0.001	0.004
	epistemic uncertainty	parametric (ln)	*	0.13
		median bias	*	0
		uncert. in bias (ln)	*	0.18
	aleatory uncertainty	median σ	*	0.85
		uncertainty in σ	*	0.1

Comments/footnotes:

* assumed to be the same as for m_{Lg} 7.0

SSHAC SECOND
GROUND MOTION WORKSHOP

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.07	0.32
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.18
	aleatory uncertainty	median σ	*	0.82
		uncertainty in σ	*	0.1
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

* assumed to be the same as for m_{Lg} 7.0

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
12 ~~5~~ km	median amplitude		0.23	1.10
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.14
	aleatory uncertainty	median σ	*	0.68
		uncertainty in σ	*	0.1
20 km	median amplitude		0.14	0.60
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.14
	aleatory uncertainty	median σ	*	0.66
		uncertainty in σ	*	0.1
70 km	median amplitude		0.017	0.18
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.14
	aleatory uncertainty	median σ	*	0.76
		uncertainty in σ	*	0.1
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

* assumed to be the same as for m_{Lg} 7.0

SSHAC SECOND
GROUND MOTION WORKSHOP

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity			m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude				
	epistemic uncertainty	parametric (ln)			
		median bias			
		uncert. in bias (ln)			
	aleatory uncertainty	median σ			
		uncertainty in σ			
20 km	median amplitude			0.13	1.1
	epistemic uncertainty	parametric (ln)		*	0.10
		median bias		*	0
		uncert. in bias (ln)		*	0.12
	aleatory uncertainty	median σ		*	0.64
		uncertainty in σ		*	0.1
70 km	median amplitude				
	epistemic uncertainty	parametric (ln)			
		median bias			
		uncert. in bias (ln)			
	aleatory uncertainty	median σ			
		uncertainty in σ			
200 km	median amplitude				
	epistemic uncertainty	parametric (ln)			
		median bias			
		uncert. in bias (ln)			
	aleatory uncertainty	median σ			
		uncertainty in σ			

Comments/footnotes:

* assumed to be the same as for m_{Lg} 7.0

SSHAC SECOND
GROUND MOTION WORKSHOP

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
12 km	median amplitude		0.13	0.71
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.12
	aleatory uncertainty	median σ	*	0.64
		uncertainty in σ	*	0.1
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.01	0.10
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.12
	aleatory uncertainty	median σ	*	0.73
		uncertainty in σ	*	0.1
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

* assumed to be the same as for mLg 7.0

PART 7. PARAMETRIC SENSITIVITY RESULTS

The ground motion sensitivities to three model parameters: focal depth and crustal structure; stress drop; and seismic moment are listed on Forms 1S through 5S that follow. All are expressed as the standard error of the natural logarithm of the ground motion parameter corresponding to the standard error in the model parameter. Explicit calculations have been done for m_{blg} = 7. While complete explicit calculations have not been done for m_{blg} = 5.5, all of the available calculations indicate that to a first approximation the sensitivies for these two magnitudes can be assumed to be equal.

Estimates for a closest distance of 5 km are not available. In their place, estimates for a closest distance of 12 km are given.

In the Comments/footnotes section, we show calculations of the total aleatory uncertainty including the sensitivities given above. The subtotal of parametric uncertainty for the three listed parameters is shown first, followed by that due to Qo and Kappa and that estimated for other source parameters. These are then combined to give total parametric uncertainty. This is combined in turn with the modeling uncertainty to yield the total aleatory uncertainty, which is reported on Forms 1 through 5.

The reported total aleatory uncertainty is for predicting ground motions given an earthquake size expressed as m_{blg}. The uncertainty due to seismic moment should be removed from the aleatory uncertainty when predicting ground motions from seismic moment M_o or moment magnitude M_w.

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Sensitivity Results: Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
12 ~~8~~ km	Focal Depth + Crustal Struct	*	0.30
	Stress Drop	*	0.28
	Seismic Moment	*	0.11
20 km		*	0.24
	"	*	0.28
		*	0.11
70 km		*	0.35
	"	*	0.28
		*	0.11
200 km		*	0.38
	"	*	0.28
		*	0.11

Comments/footnotes:

Subtotal – parametric	0.42	0.38	0.46	0.48
Q_0 and K	0.01	0.01	0.03	0.10
other parametric	0.20	0.20	0.20	0.20
Total Parametric	0.47	0.43	0.50	0.53
Modeling	0.67	0.67	0.67	0.67
Total Aleatory	0.81	0.79	0.84	0.85

* assumed to be the same as for m_{Lg} 7.0

SSHAC SECOND
GROUND MOTION WORKSHOP

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Sensitivity Results: Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km	Focal Depth + Crustal Struct	*	0.24
	Stress Drop	*	0.28
	Seismic Moment	*	0.09
70 km			
200 km			

Comments/footnotes:

Subtotal - parametric	*	0.38
Q_o and K	*	0.0
other parametric	*	0.20
Total Parametric	*	0.43
Modeling	*	0.70
Total Aleatory	*	0.82

* assumed to be the same as for m_{Lg} 7.0

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Sensitivity Results: Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
~~12~~ 8 km	Focal Depth + Crustal Struct	*	0.30
	Stress Drop	*	0.28
	Seismic Moment	*	0.09
20 km		*	0.24
	"	*	0.28
		*	0.09
70 km		*	0.44
	"	*	0.28
		*	0.09
200 km			

Comments/footnotes:

Subtotal - parametric	*	0.42	0.38	0.53
Q_0 and K	*	0.05	0.05	0.11
other parametric	*	0.20	0.20	0.20
Total Parametric	*	0.47	0.43	0.58
Modeling	*	0.50	0.50	0.50
Total Aleatory	*	0.68	0.66	0.76

* assumed to be the same as for m_{Lg} 7.0

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Sensitivity Results: Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km	Focal Depth + Crustal Struct	*	0.24
	Stress Drop	*	0.28
	Seismic Moment	*	0.09
70 km			
200 km			

Comments/footnotes:

Subtotal - parametric	*	0.38
Q_o and K	*	0.15
other parametric	*	0.20
Total Parametric	*	0.45
Modeling	*	0.46
Total Aleatory	*	0.64

* assumed to be the same as for m_{Lg} 7.0

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Sensitivity Results: Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
12 ~~8~~ km	Focal Depth & Crustal Struct	*	0.30
	Stress Drop	*	0.28
	Seismic Moment	*	0.09
20 km			
70 km		*	0.44
		*	0.28
		*	0.09
200 km			

Comments/footnotes:

Subtotal - parametric	*	0.42	0.53
Q_o and K	*	0.15	0.18
other parametric	*	0.20	0.20
Total Parametric	*	0.49	0.59
Modeling	*	0.42	0.42
Total Aleatory	*	0.64	0.73

* assumed to be the same as for m_{Lg} 7.0

APPENDIX 1.

DESCRIPTION OF THE ADVANCED NUMERICAL MODELING METHOD

3.3 Semi-Empirical Ground Motion Model

At frequencies below about 2 Hz, the principal features of strong ground motions can be modeled using deterministic models of the earthquake source. The ability of synthetic seismograms to match recorded strong ground motions at low frequencies has been clearly demonstrated during the past decade; a summary of events studied is given in Mendoza at Hartzell (1988) and Heaton (1990). However, at the higher frequencies of interest for this study, strong ground motions are highly affected by stochastic processes. The modeling procedure described below combines empirical and theoretical approaches to modeling ground motion effects in order to capture the essence of both deterministic and stochastic elements of ground motion. The combined semi-empirical model is used in this study to quantify path effects or, more precisely, contributions to ground motion variability made by wave propagation in the earth's crust (Section 5).

3.3.1 Model Description

In the semi-empirical ground motion modeling approach, near-source recordings of small earthquakes are used as empirical source functions to provide a realistic representation of effects such as source radiation that are difficult to deterministically model at high frequencies due to their stochastic behavior. Wave propagation effects are modeled using simplified transfer functions or Green's functions that are designed to transfer empirical source functions from their recording sites to those required for use in simulations at a specific site. The details of the simulation procedure are described by Wald et al. (1988a) and Somerville et al. (1991), and are summarized in Appendix 3.B.

The procedure is illustrated schematically in Figure 3-7. The fault is divided into discrete elements, and the motions from these elements are lagged and summed across the fault to simulate the propagation of rupture over the fault surface. A stochastic component is included in the speeds of fault slip and rupture propagation to simulate heterogeneity in rupture dynamics. Large scale asperities (areas of concentrated slip and high-frequency radiation) are introduced by varying the slip distribution over the fault surface.

The Green's functions are calculated using the method of generalized rays (Helmberger and Harkrider, 1978). Rays corresponding to the direct P and S waves and to the primary reflection (and head wave beyond critical angle) from each interface below the source are included, as shown schematically in Figure 3-8. The overall seismogram is produced by summing these various rays, which generally arrive at the site at different times. The amplitude and time relationships between these arrivals change with distance, producing seismograms whose amplitudes and durations change with distance. In a homogeneous half space, the rate at which ground motion decays with distance is the inverse source distance, 1/R. At source-site distances less than the critical distance (the distance beyond which all seismic energy is reflected back to the surface from a given boundary), the interference between the upgoing wave and waves reflected due to the velocity gradient below the source causes attenuation more rapid that 1/R. Beyond the critical distance, however, critical reflections cause the

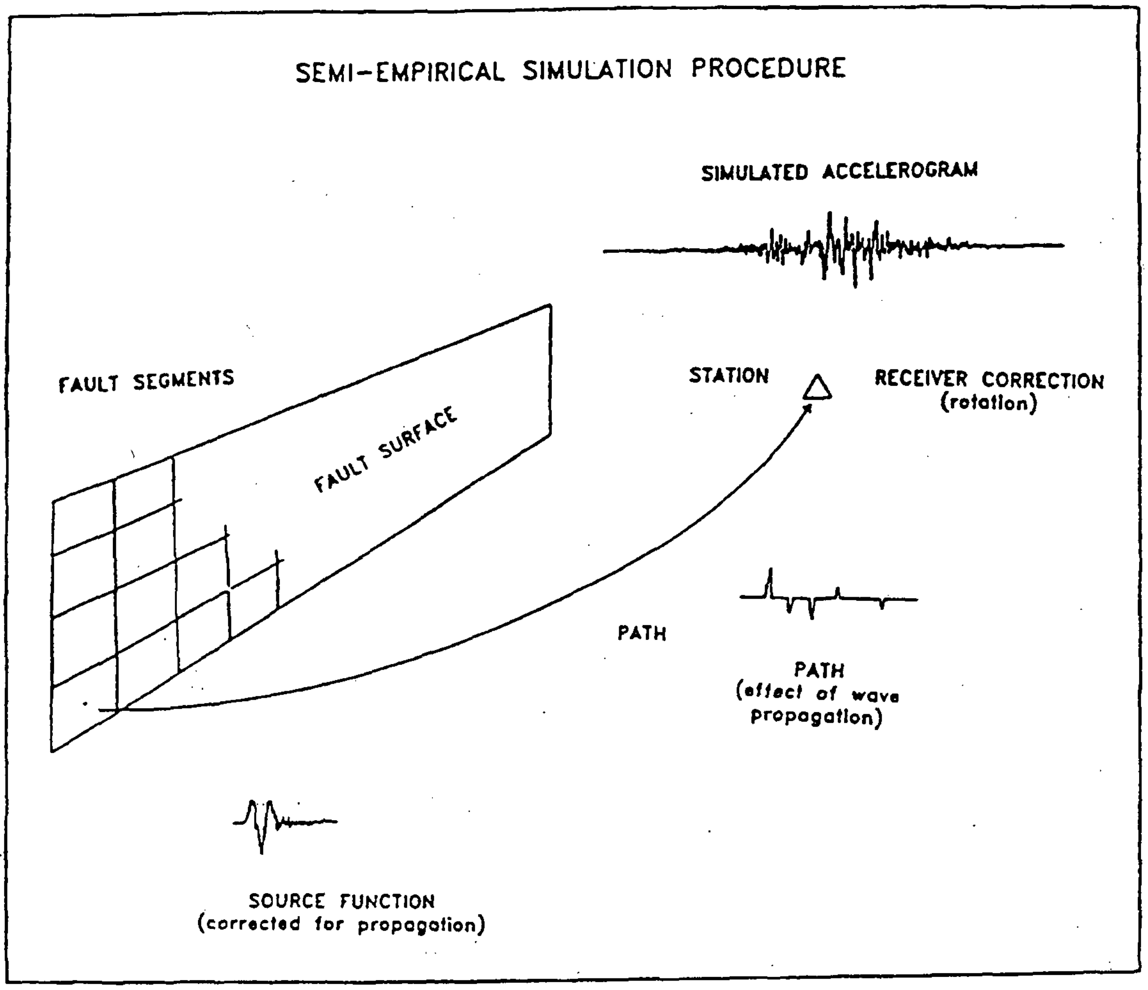


Figure 3-7. Schematic diagram of the ground motion simulation procedure. Source: Somerville et al., 1990.

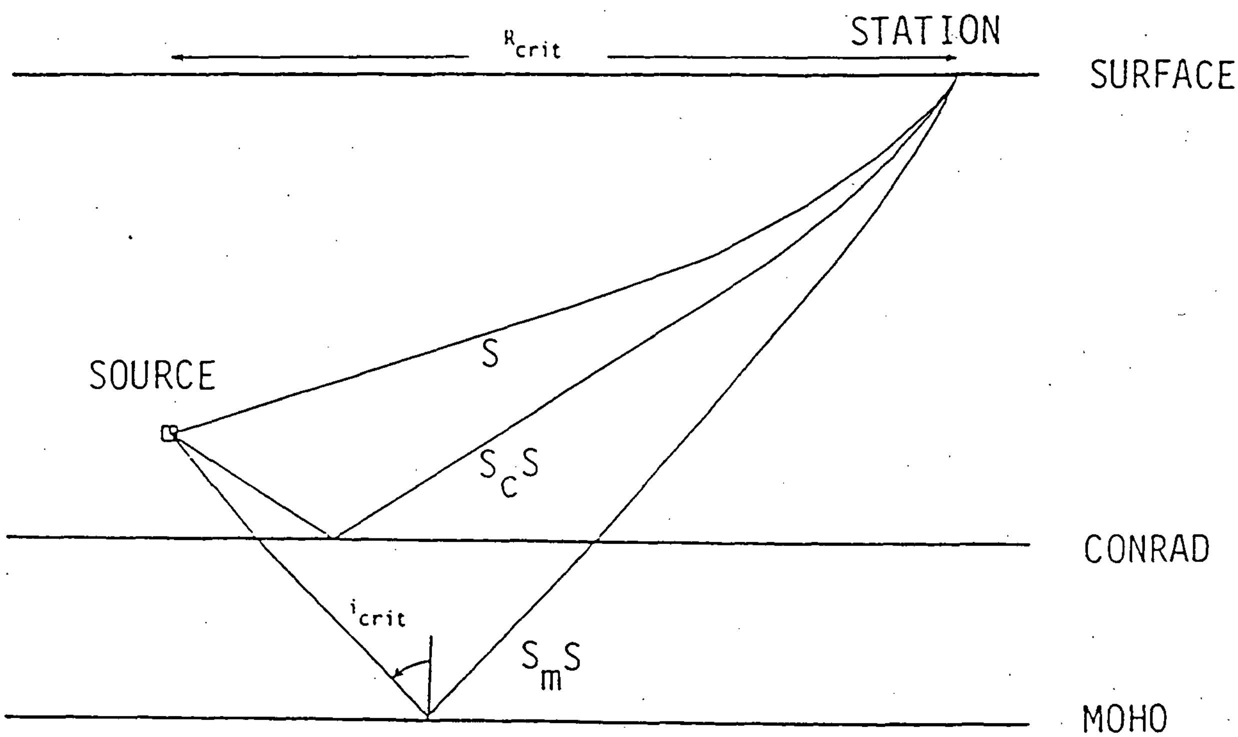


Figure 3-8. Schematic diagram of the wave propagation model, with direct waves (S) and waves S_cS and S_mS reflected from the Conrad and Moho layers. At the critical angle (i_{crit}), the incident wave is totally reflected back to the surface at distances starting at the critical distance R_{crit}.

attenuation to be less rapid than 1/R. Thus the peak amplitudes and duration of the seismogram are a function of the crustal structure and focal depth.

The simplified Green's functions that are used, described further by Somerville et al. (1991), are the response of the crust for P, SV and SH potentials. The receiver function is represented empirically, as described below, and the radiation pattern is assigned an average value. At high frequencies, the small set of rays that used are expected to contain most of the important arrivals out to distances of 200 km. To realistically model the wave propagation at greater distances, it would be necessary to include a much larger set of rays, or use the frequency-wavenumber integration method in place of the generalized ray method. In this application, then, ground motion modeling is not extended beyond 200 km distance.

3.3.2 Model Validation

The semi-empirical ground motion model has been validated against strong motion records of several earthquakes. These include the 1979 Imperial Valley earthquake (Wald et al., 1988a); the 1987 Whittier Narrows earthquake ((Wald et al., 1988b); Saikia, 1992), the 1988 Nahanni earthquake (Somerville et al., 1990); the 1989 Loma Prieta earthquake (Somerville et al., 1992a,b), and the 1985 Michoacan, Mexico and Valparaiso, Chile earthquakes (Somerville et al., 1991).

For the purposes of this study, a validation of the method was performed using a standard set of procedures for four earthquakes: the 1989 Loma Prieta earthquake (55 stations); the 1987 Whittier Narrows earthquake (37 stations); the 1988 Nahanni earthquake (3 stations); and the

Table 3-7

Source Parameters of Earthquakes Used in Validation of Semi-Empirical Simulation Method

Earthquake	Seismic Moment (x 10^{25} dyne cm)	Depth to Top Center (km)	Fault Length (km)	Fault Width (km)	Strike	Dip	Rake	Rupture Velocity (km/sec)	Rise Time (sec)
1985 Nahanni	17.6	3.56	32	15	180	22	110	2.7	0.96
1987 Whittier Narrows	1.0	12.35	12	9	280	30	110	2.5	0.40
1988 Saguenay	0.5	23.14	4	6	323	65	78	3.0	0.40
1989 Loma Prieta	29.5	3.38	40	18	128	70	140	2.7	1.14

1988 Saguenay earthquake (9 stations), for a total of 104 recordings. All available digital strong motion data at source-site distances of less than about 200 km were used in the validation, regardless of site conditions. The simulation method is described in Section 3.3.1 and Appendix 3.B. The standard procedures were as follows. For each event, published slip models were used to characterize the source, and published crustal structure models were used to characterize the wave propagation path. The source and path models are described by Hartzell and Iida (190) and Wald et al. (1989) respectively for the Whittier Narrows earthquake; Somerville et al. (1990) for the Saguenay earthquake; EPRI (1992) for the Nahanni earthquake; and Wald et al. (1992) for the Loma Prieta earthquake. Where these slip models included multiple time windows, a slip model was derived having a single time window. The source models of the four events are summarized in Table 3-7. The stations used in the validation of the four events are listed in Tables 3-8 through 3-11.

The empirical source functions were derived from the October 15, 1979 Imperial Valley aftershock. These empirical source functions represent a seismic moment of 0.6×10^{24} dyne-cm and a fault element size of 4km x 3km. For the Saguenay and Nahanni events, these source functions were modified for eastern North American source conditions to have a kappa value of 0.006 sec, while for the Whittier Narrows and Loma Prieta events the source functions were unmodified and retained an average kappa value of 0.055 sec. Unlike the stochastic model, the semi-empirical model does not include the Brune stress-drop as a specified parameter (from which the corner frequency and high-frequency spectral level are derived). Instead, the stress drop and ground motion levels at high frequencies are a function of the high-frequency ground motion levels embodied in the empirical source functions and the source duration of the finite rupture.

APPENDIX 2.

DOCUMENTATION OF ALEATORY UNCERTAINTY

Table 1. Base Case for Sensitivity Studies

Parameter	Value
Stress-Drop	100 bars
Focal Depth	11 km
Mechanism	45° dip, 90°rake
Kappa	0.006 sec
$Q = Q_0 f^{\eta}$	750 $f^{0.5}$
Crustal Velocity Structure	Grenville
Mw	6.5

Table 2. Sensitivity Runs for Rock Sites

Parameter	Distribution	Median	S.E.
Stress-Drop	lognormal	100 bars	0.7
Focal Depth	lognormal	11 km	0.5
Kappa - Hard Rock	lognormal	0.006 sec	0.4
Kappa - Soft Rock	lognormal	0.04 sec	0.4
Q_0	lognormal	750	0.4
η	normal	0.50	0.3
Crustal Velocity Structure	uniform	-	-
A. West Quebec			
B. Gradient			
C. Charlevoix			
D. Berry			

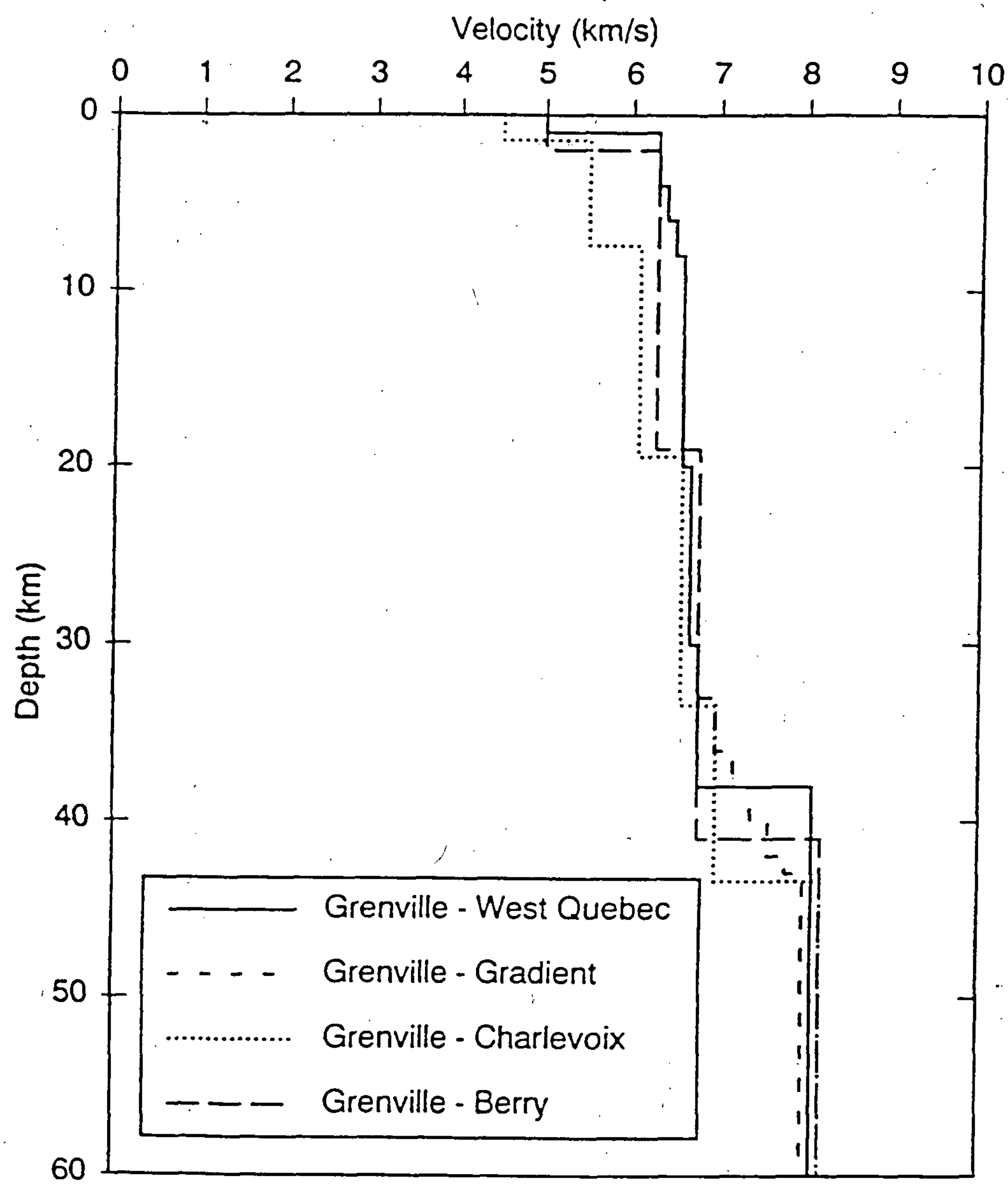


Figure 5-23. Four velocity models used for the Grenville region to represent variability of the velocity model within a region.

The West Quebec model for the Central Metasedimentary Belt near Mont Laurier, Quebec was derived from the profile for Point C in Line CD in Mereu et al. (1986). The Gradient model for the Central Metasedimentary Belt was derived from Point C (the same point as in the West Quebec model) in the intersecting Line CB in the same study. The Gradient model is identical to the West Quebec model above 30 km, but below 30 km has a velocity gradient to a deeper Moho in place of a step change in velocity at the Moho. The Charlevoix model for the north shore of the St. Lawrence River in Quebec was derived by Somerville et al. (1990) using data from the Saguenay earthquake sequence of 1988. The Berry model for northeast Quebec was derived by Berry and Fuchs (1973).

The four crustal models for the New Madrid Rift region are listed in Table 5-11 and shown in Figure 5-24. The

the maximum standard error is shifted to distances of 80 to 120 km again associated with the variation in Moho depth. The depth of the Moho affects the distance range at which the maximum standard error occurs. In general, the deeper the Moho, the larger the distance at which the maximum occurs.

In Figures 5-25 and 5-26 the variation of ground motion for a given crustal structure is shown for three depths. To account for the variability in focal depth, the ground motion variability is computed using a weighted average over focal depths where the weights are given by the EAA generic depth distribution (Table 5-9). The standard errors of the mean spectral acceleration are shown in Figures 5-27a,b,c for 1, 5, and 15 Hz.

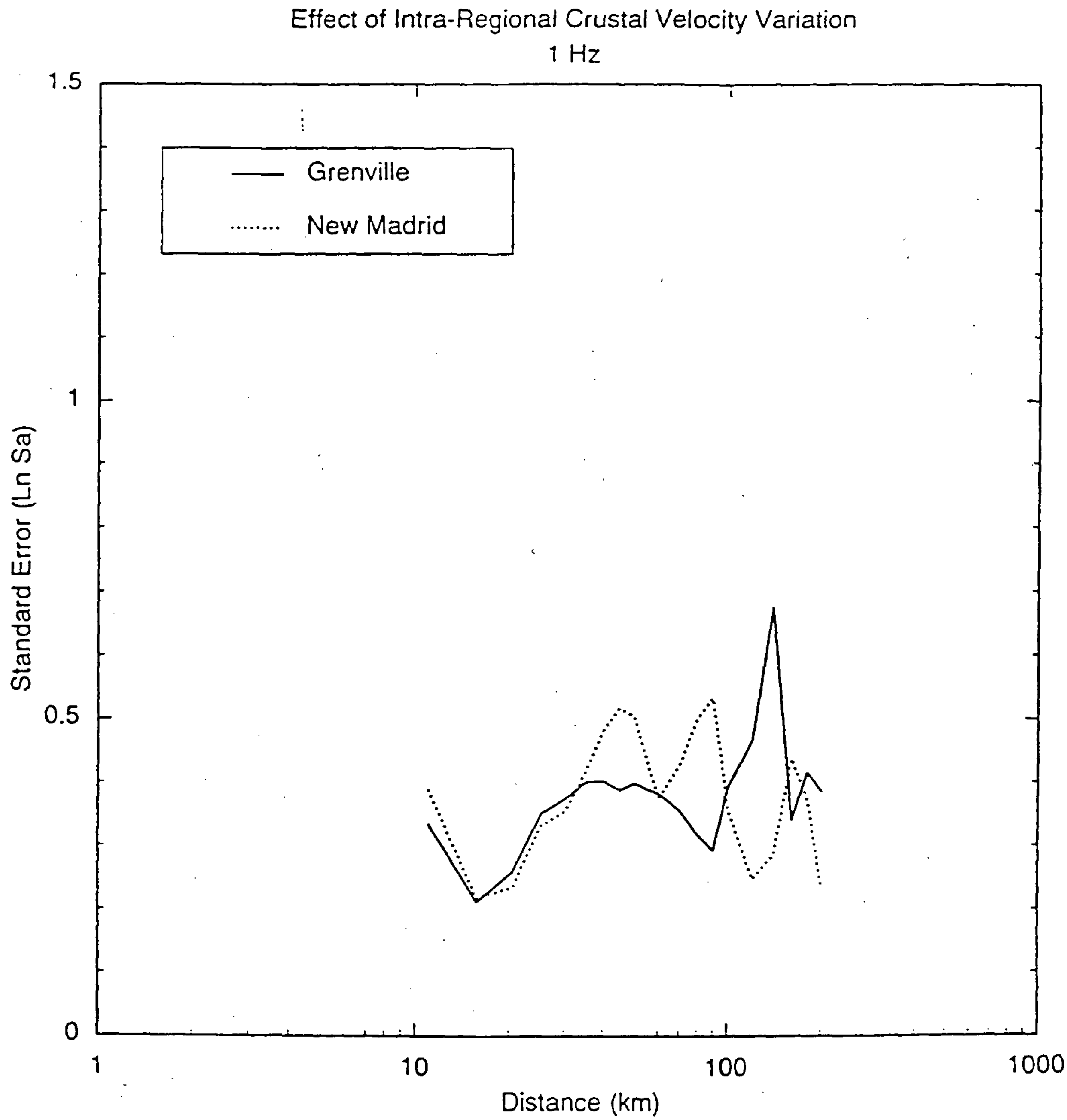


Figure 5-27a. Variability of spectral acceleration at 1 Hz due to crustal velocity uncertainty within the Grenville and New Madrid region. The variability includes variability in focal depth.

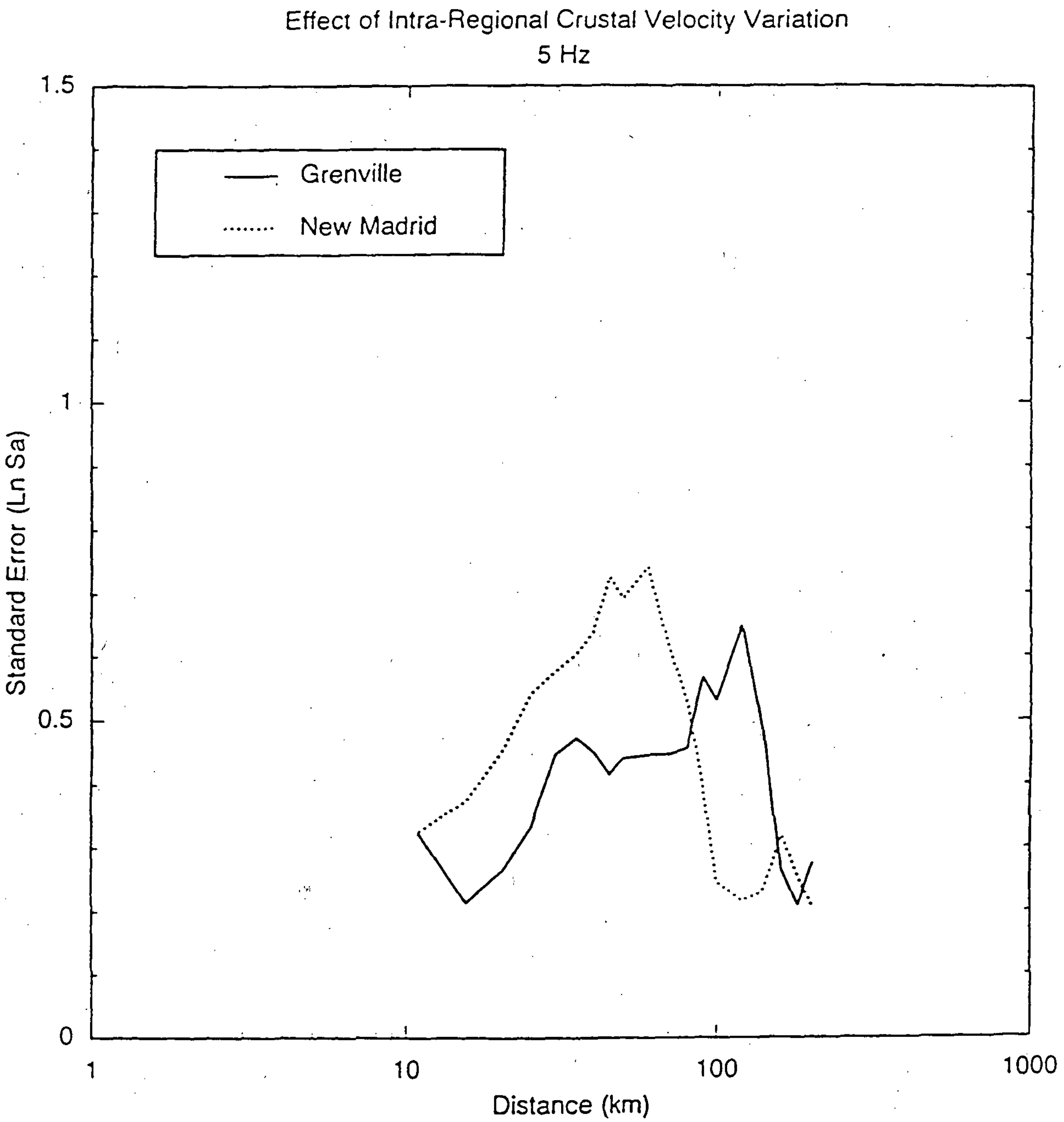


Figure 5-27b. Variability of spectral acceleration at 5 Hz due to crustal velocity uncertainty within the Grenville and New Madrid region. The variability includes variability in focal depth.

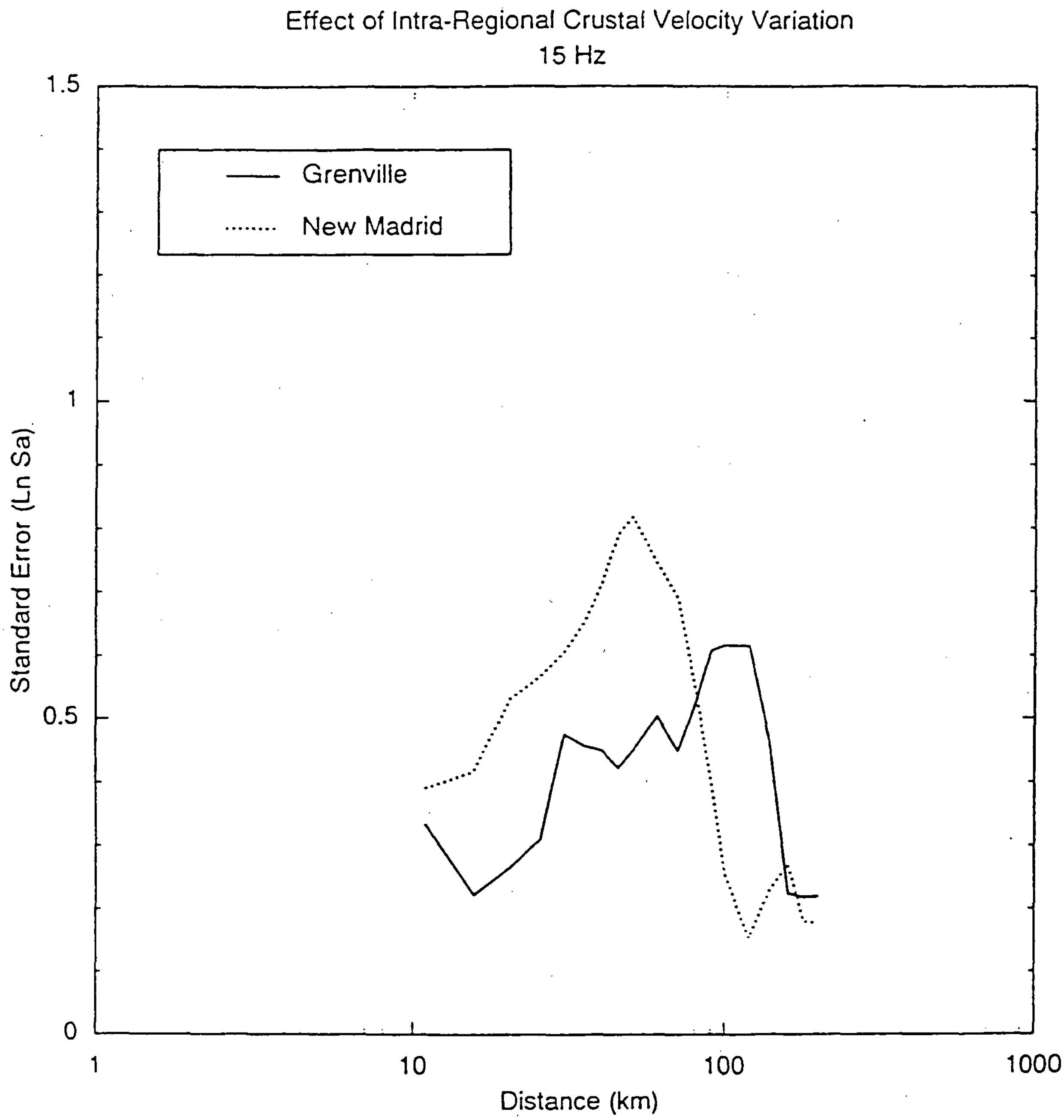
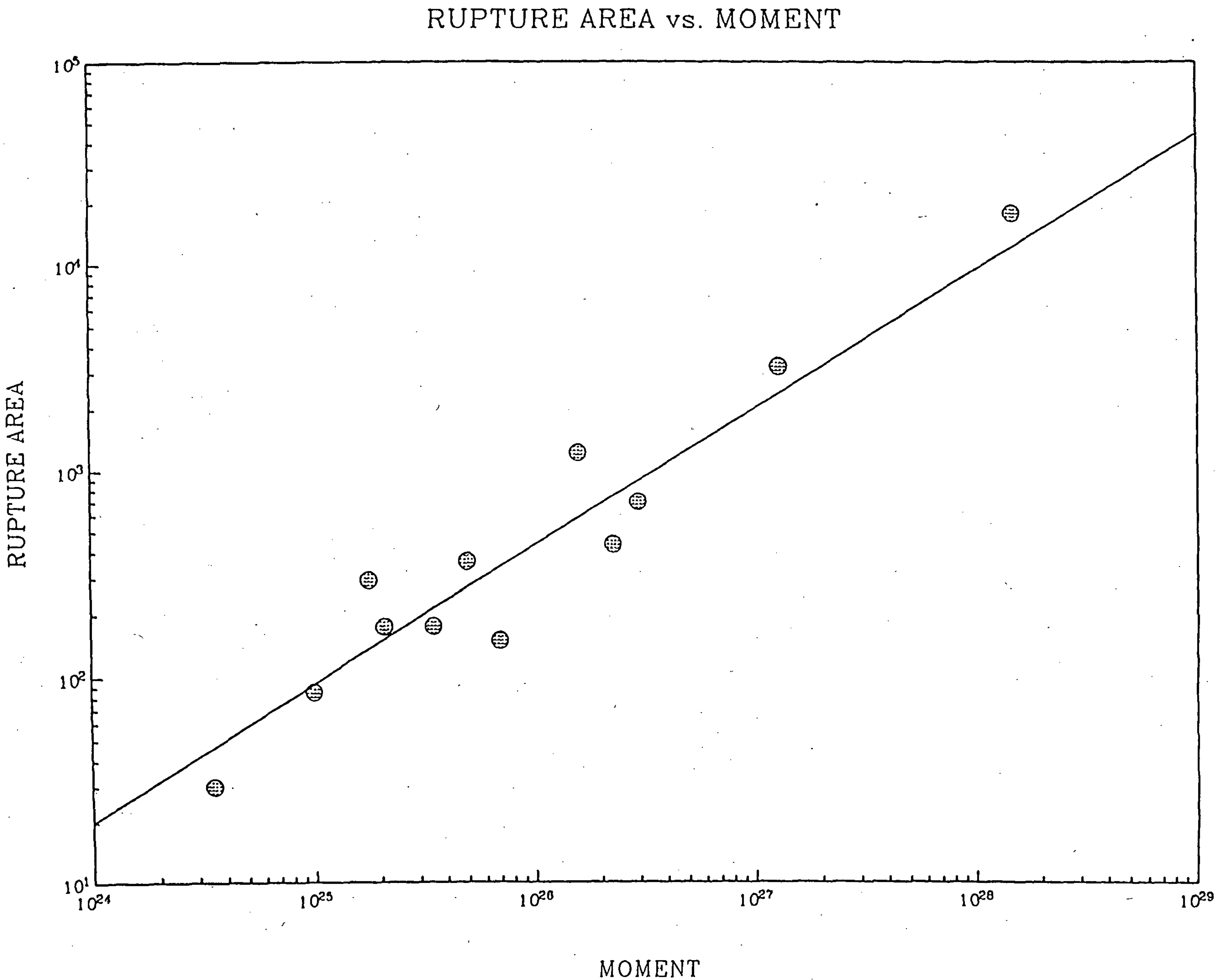
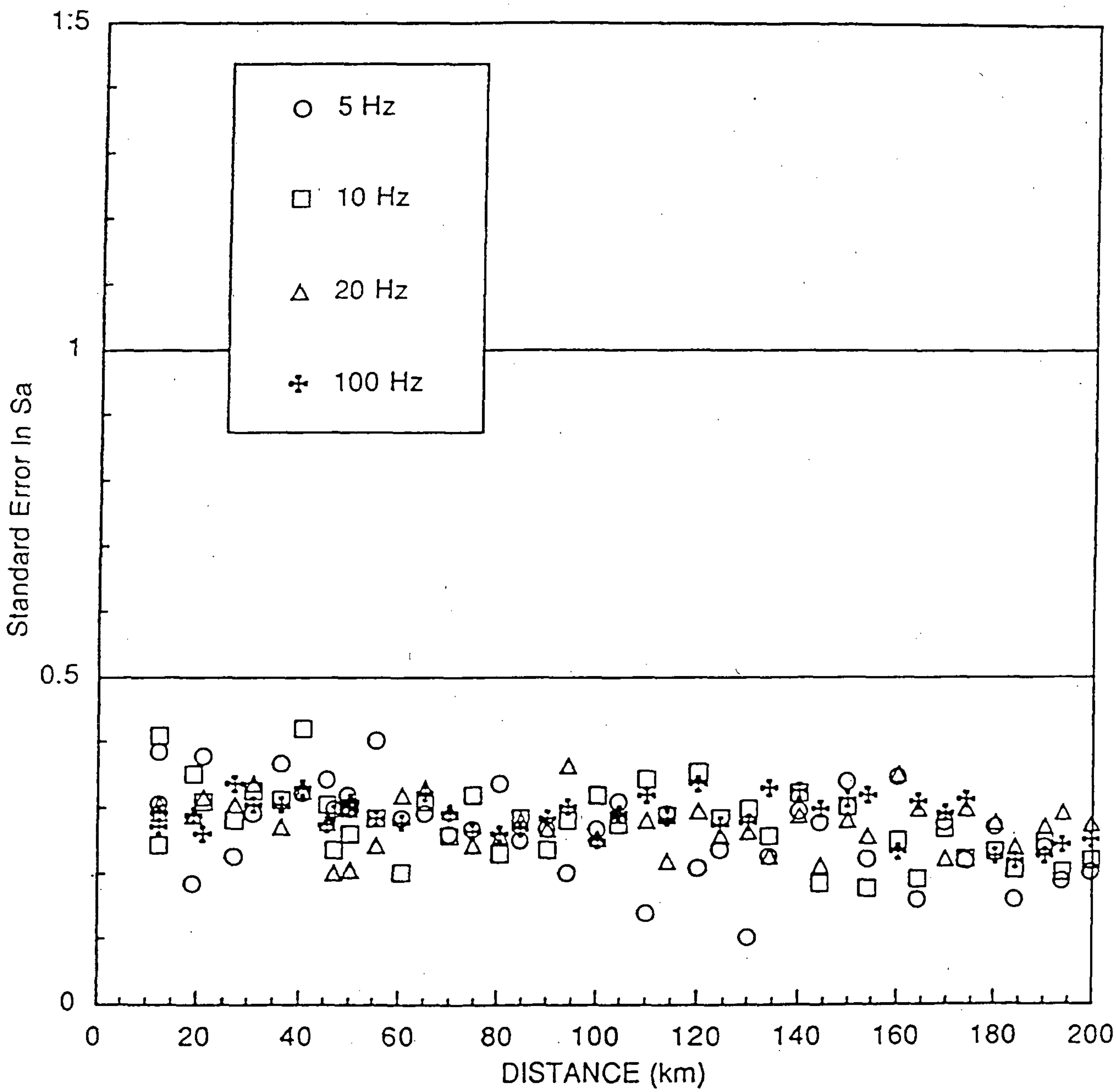


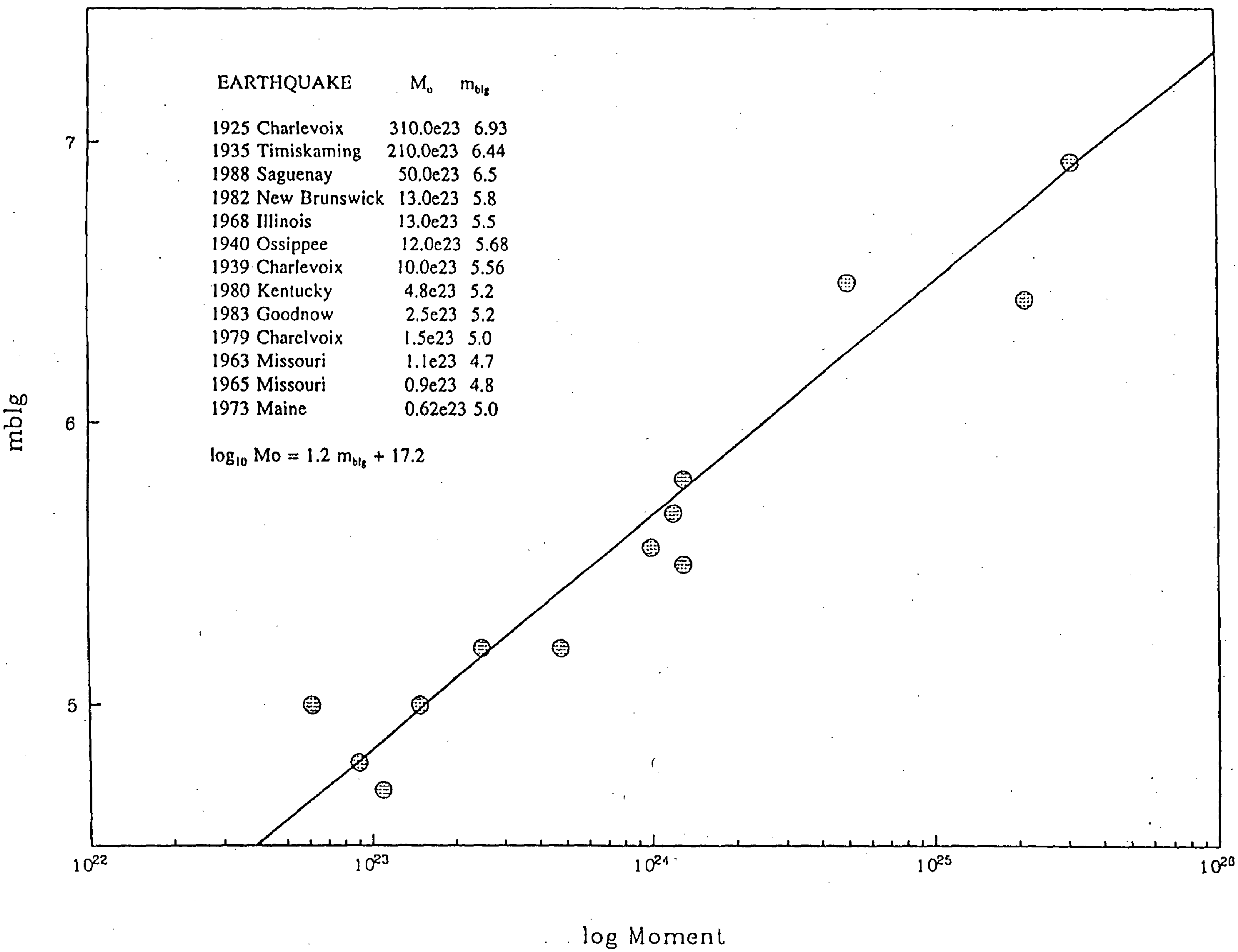
Figure 5-27c. Variability of spectral acceleration at 15 Hz due to crustal velocity uncertainty within the Grenville and New Madrid region. The variability includes variability in focal depth.

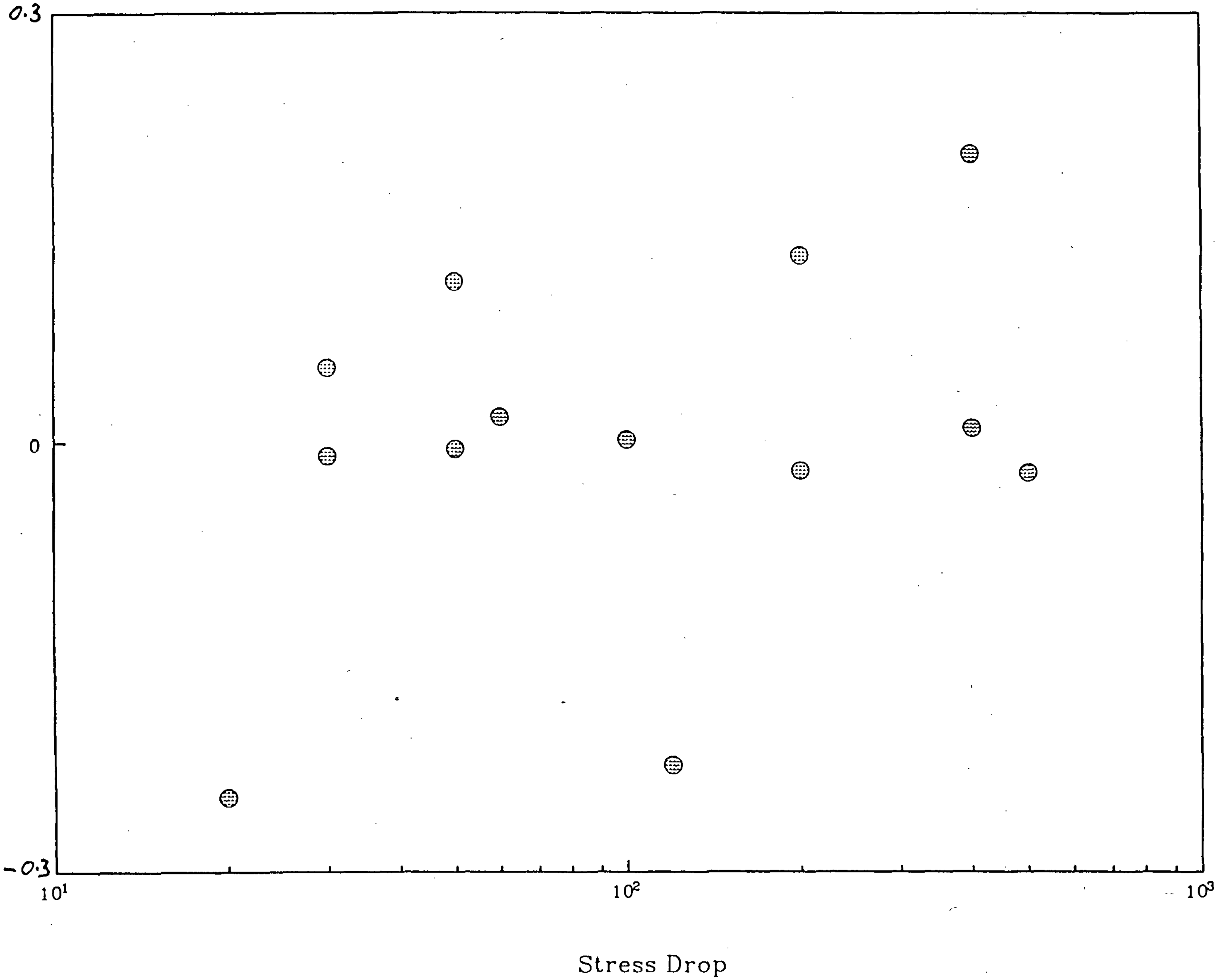


Relation between rupture area and seismic moment. Dots represent individual events, and the line is a least-squares fit under the constraint of self-similarity (slope = 2/3).

WCC Sensitivity: Stress-Drop




EARTHQUAKE Mo mblg
1925 Charlevoix 310.0e23 6.93
1935 Timiskaming 210.0e23 6.44
1988 Saguenay 50.0e23 6.5
1982 New Brunswick 13.0e23 5.8
1968 Illinois 13.0e23 5.5
1940 Ossippee 12.0e23 5.68
1939 Charlevoix 10.0e23 5.56
1980 Kentucky 4.8e23 5.2
1983 Goodnow 2.5e23 5.2
1979 Charelvoix 1.5e23 5.0
1963 Missouri 1.1e23 4.7
1965 Missouri 0.9e23 4.8
1973 Maine 0.62e23 5.0
$\log_{10} Mo = 1.2\, m_{blg} + 17.2$
mblg
7
6
5
10^{22}
10^{23}
10^{24}
10^{25}
10^{26}
log Moment


0.3
0
-0.3
mblg residual
10^1
10^2
10^3
Stress Drop

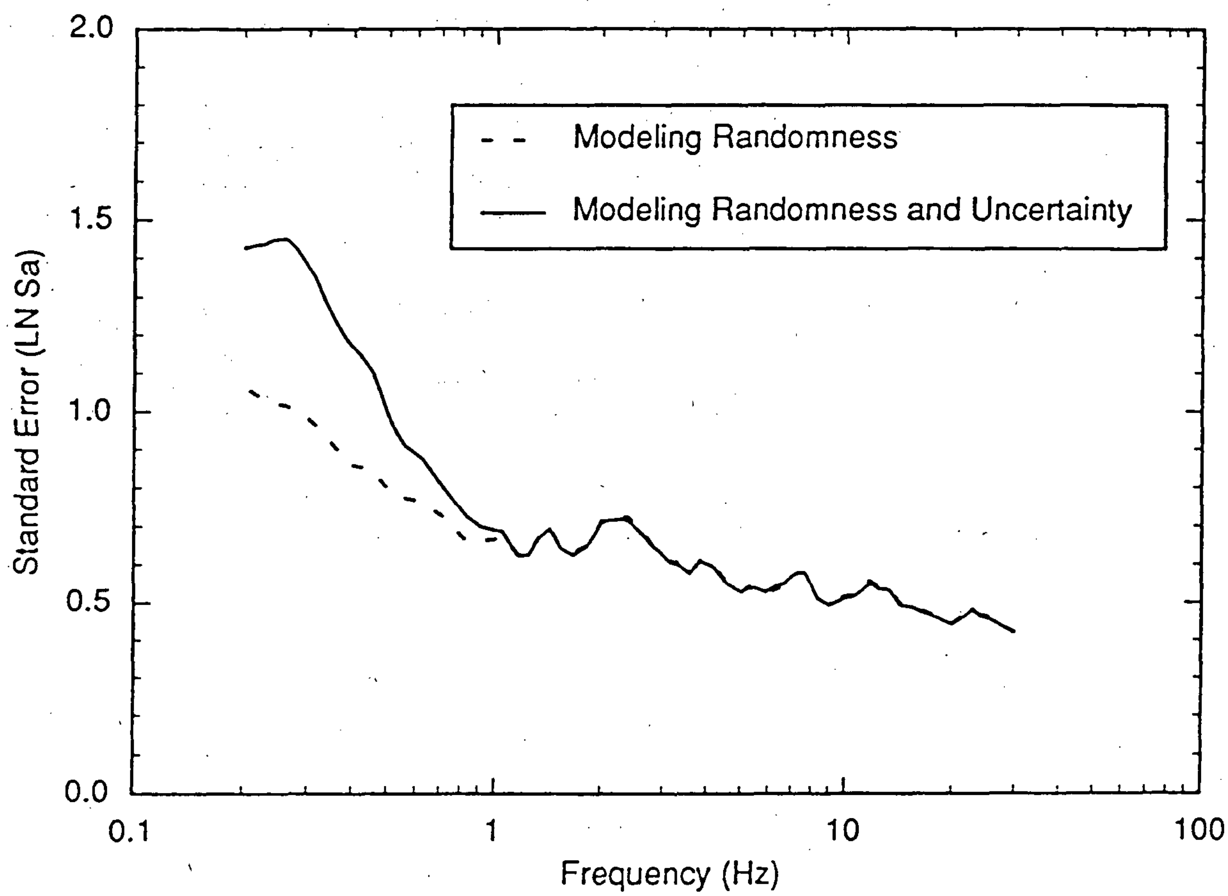


Figure 3-15b. Modeling variability (natural log) computed from recordings at the subset of 39 stations for the Loma Prieta, Whittier Narrows, Nahanni, and Saguenay earthquakes using the semi-empirical ground motion model. Dashed line, total variability (modeling uncertainty plus randomness); solid line, corrected for model bias.

APPENDIX 3.

DOCUMENTATION OF EPISTEMIC UNCERTAINTY

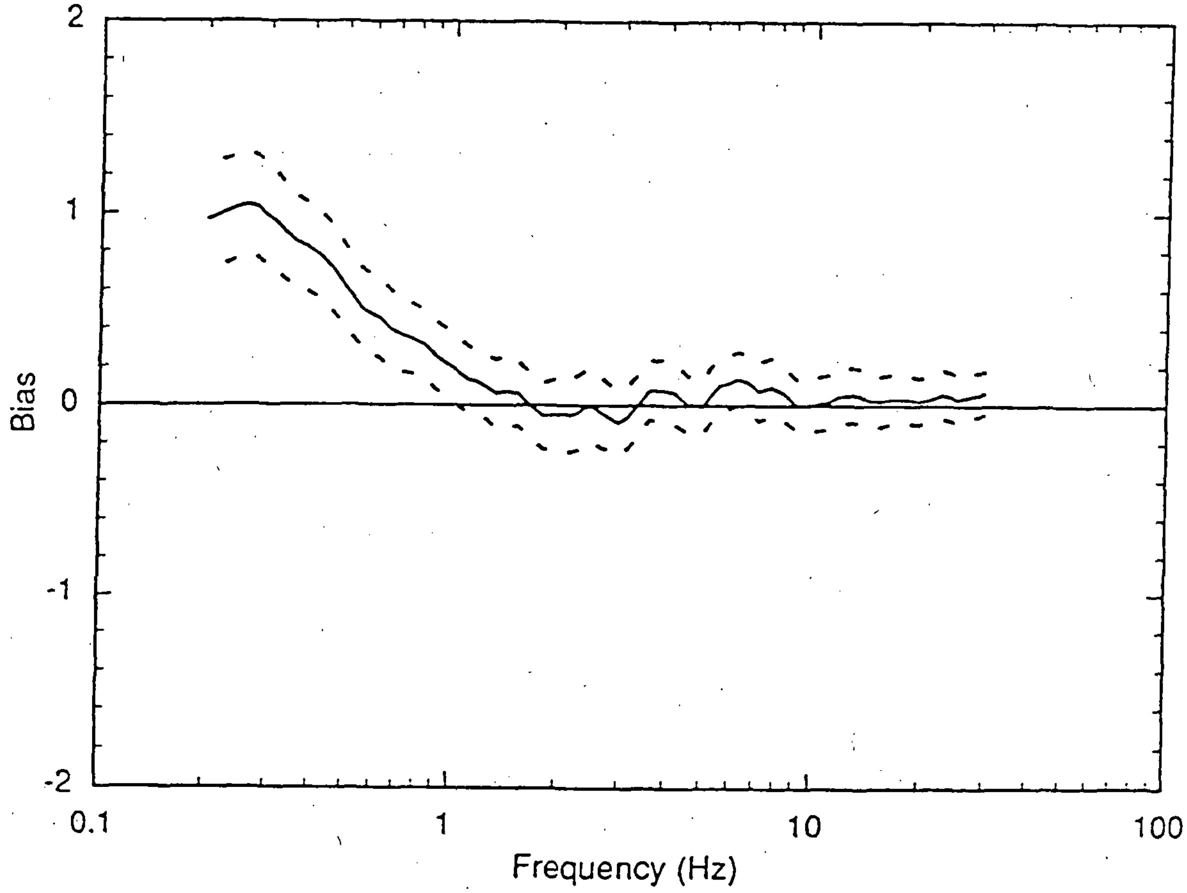


Figure 3-15a. Modeling bias computed from recordings at the subset of 39 stations for the Loma Prieta, Whittier Narrows, Nahanni, and Saguenay earthquakes using the semi-empirical ground motion model. Dashed lines represent 90% confidence limits.

APPENDIX 4.

DOCUMENTATION OF INTER-REGIONAL VARIATIONS

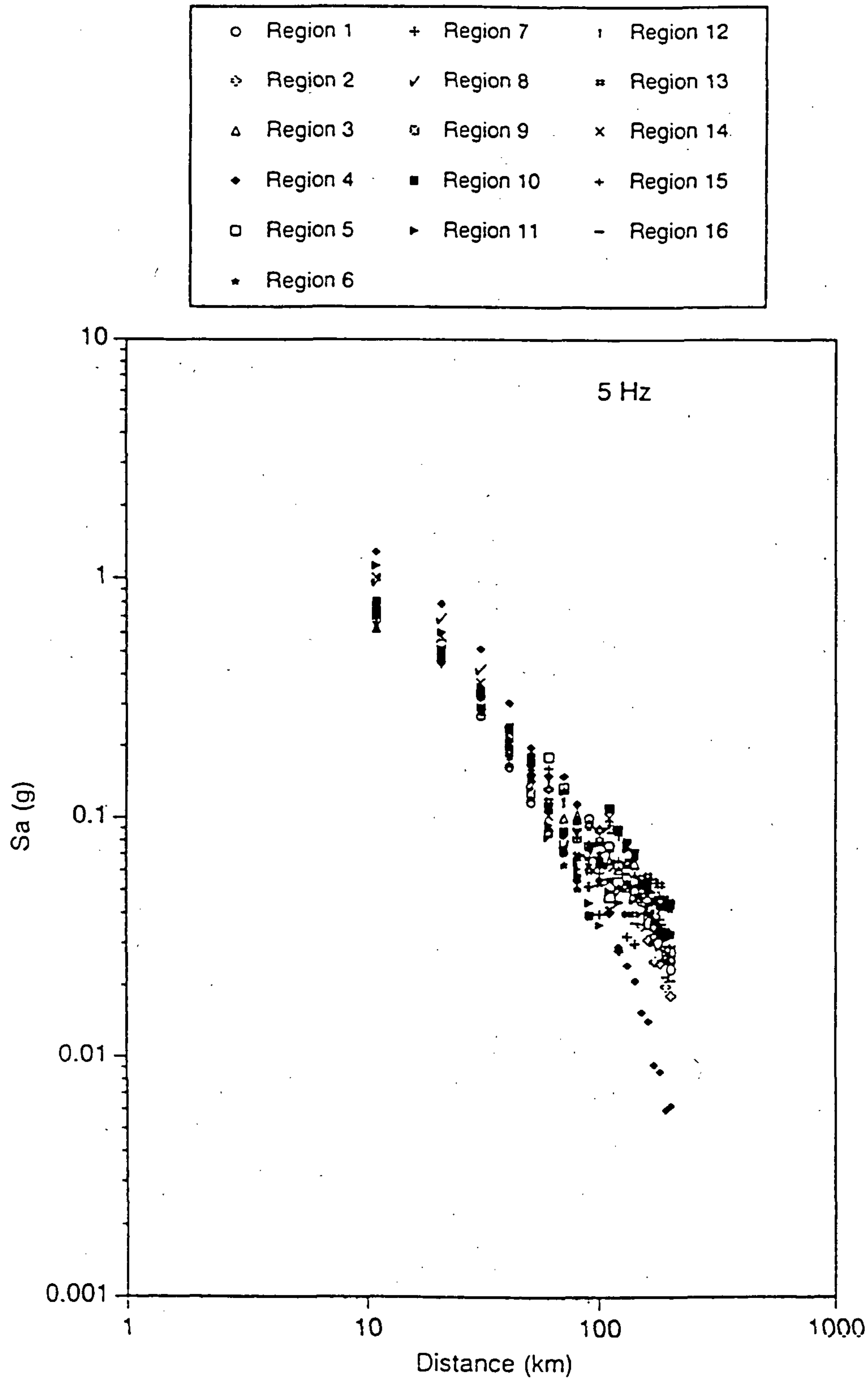
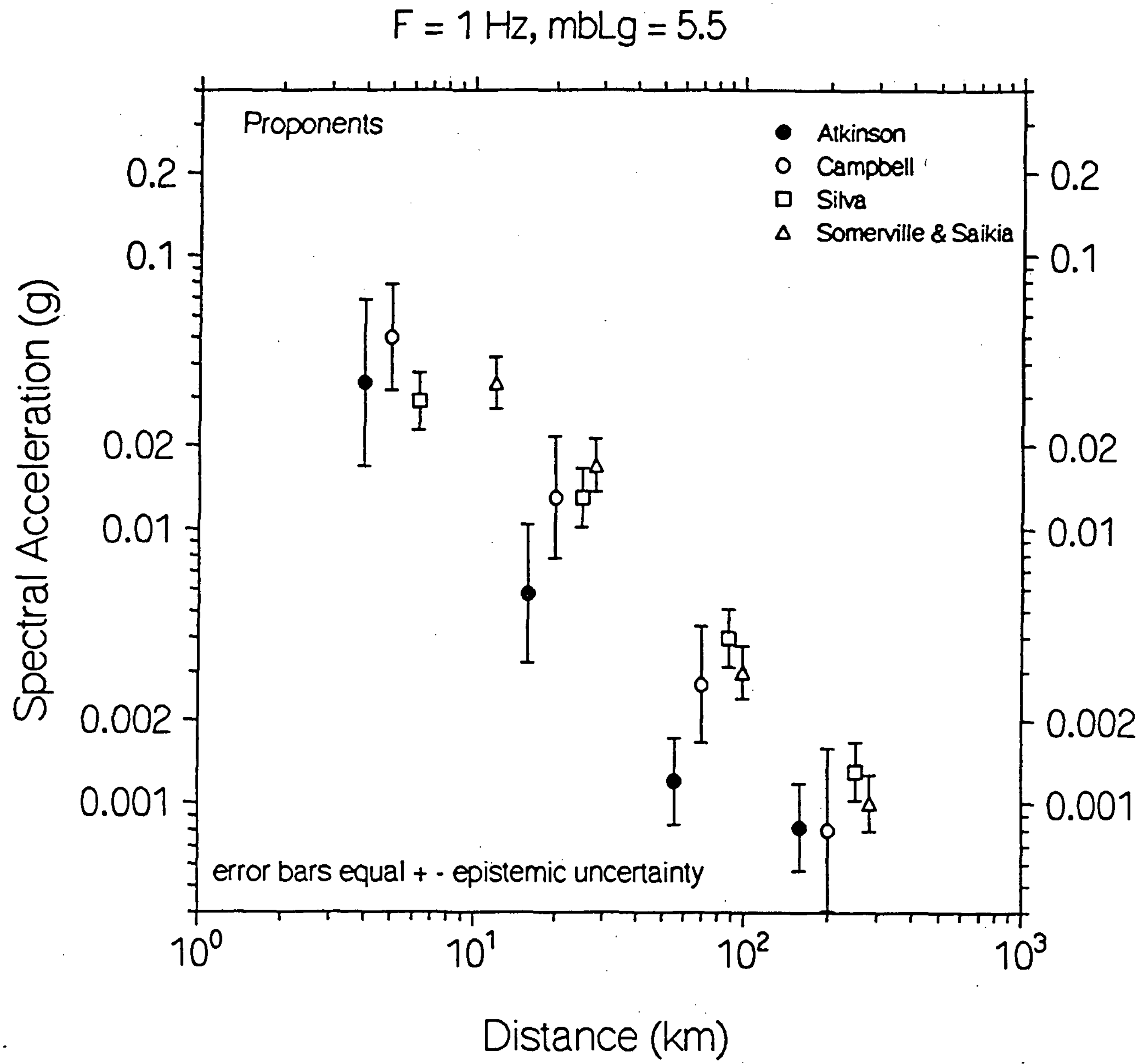
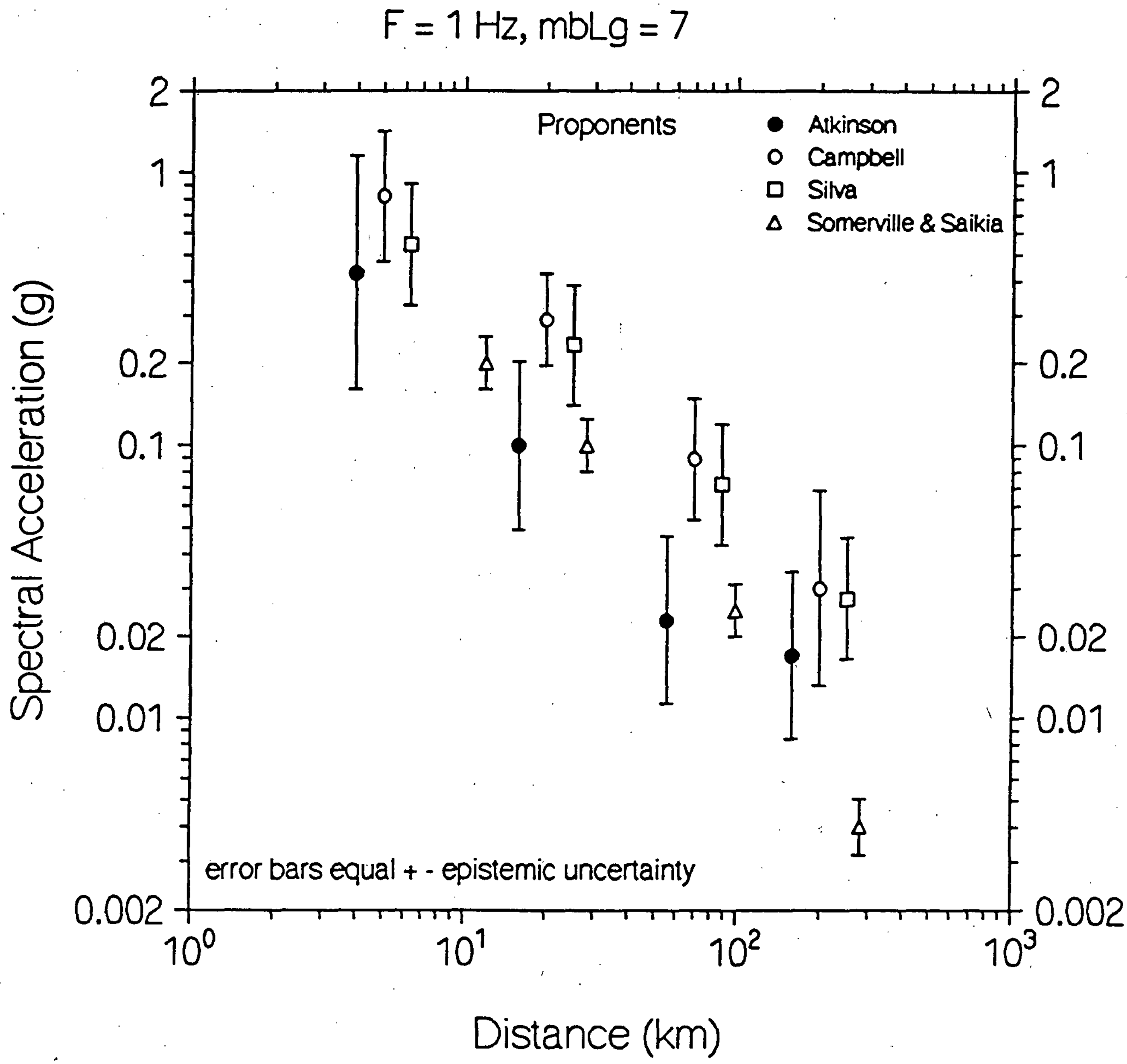
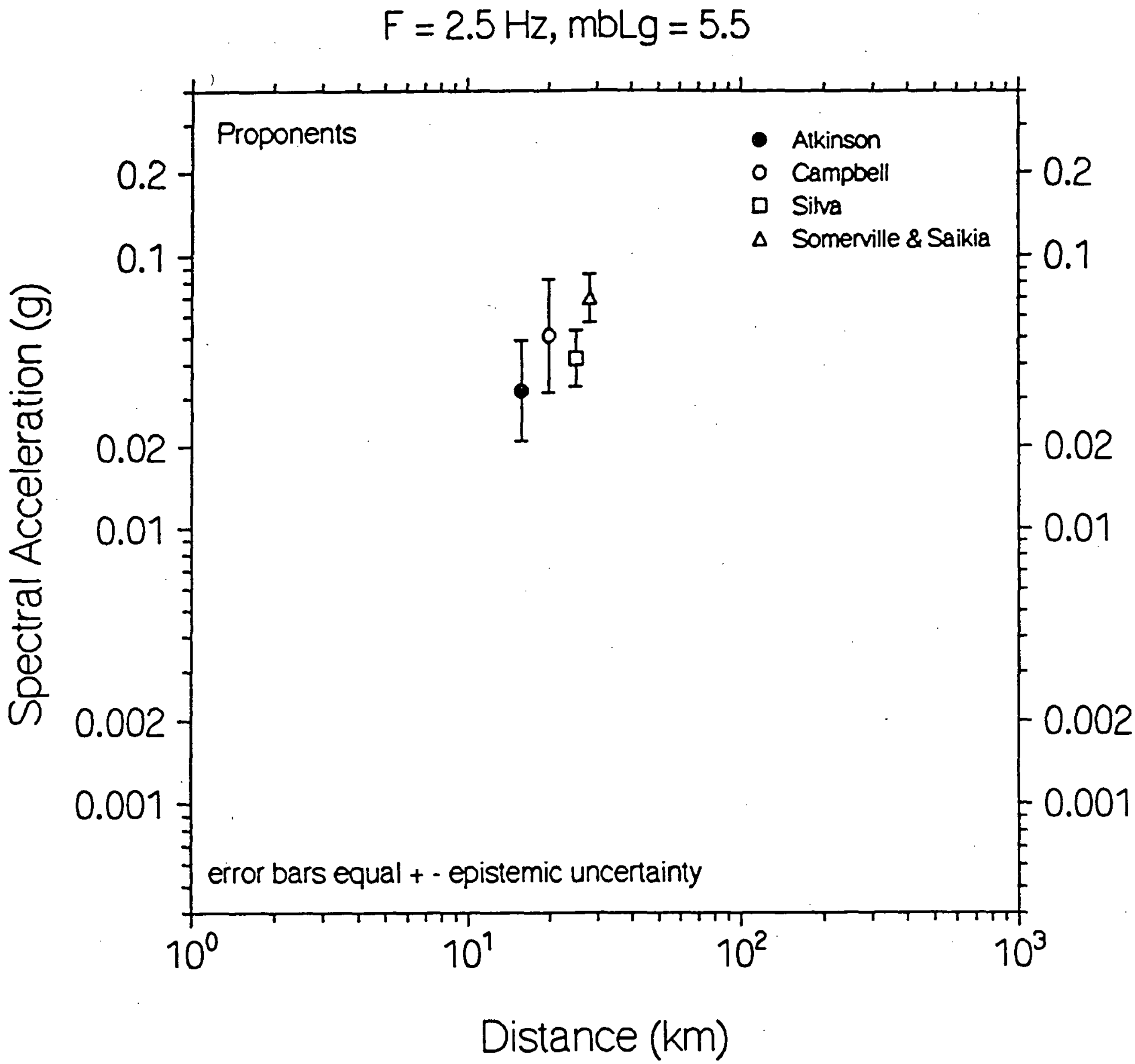


Figure 5-46. Comparison of median ground motion attenuation of spectral acceleration at 5 Hz for the 16 regions.



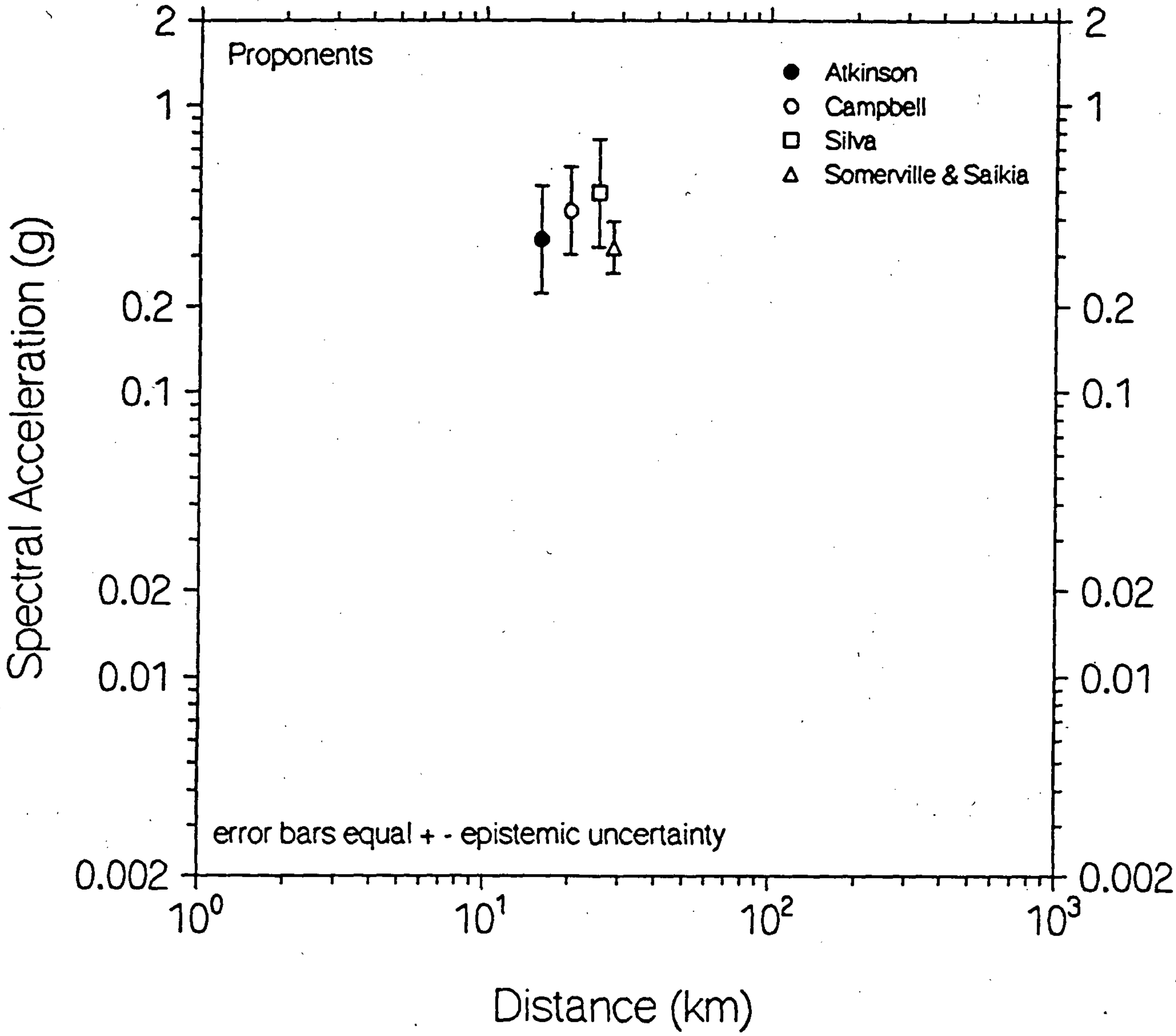
F = 1 Hz, mbLg = 5.5
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
0.2
0.1
0.02
0.01
0.002
0.001
Spectral Acceleration (g)
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)

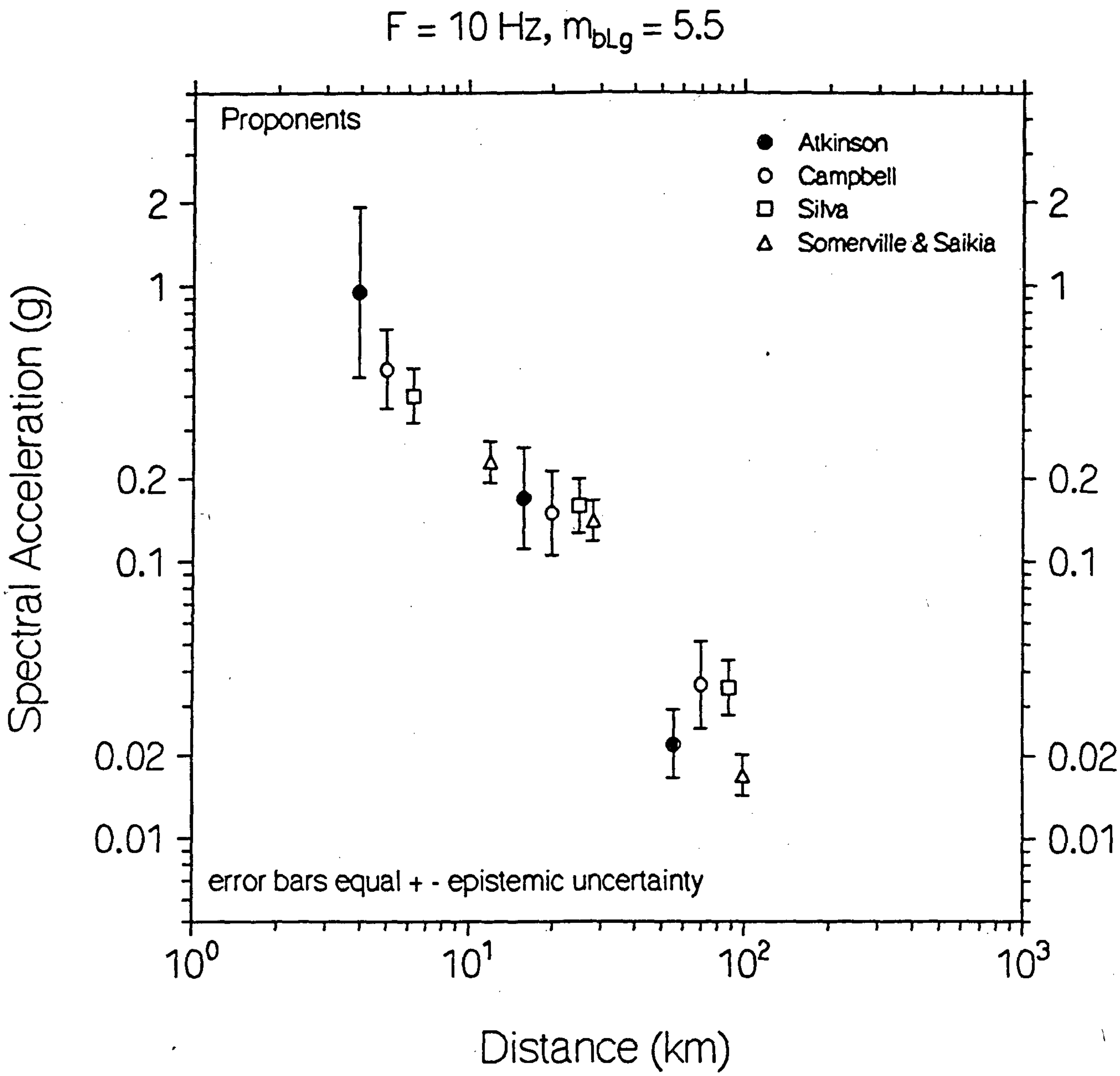

F = 1 Hz, mbLg = 7
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
Distance (km)
2
1
0.2
0.1
0.02
0.01
0.002
10^0
10^1
10^2
10^3

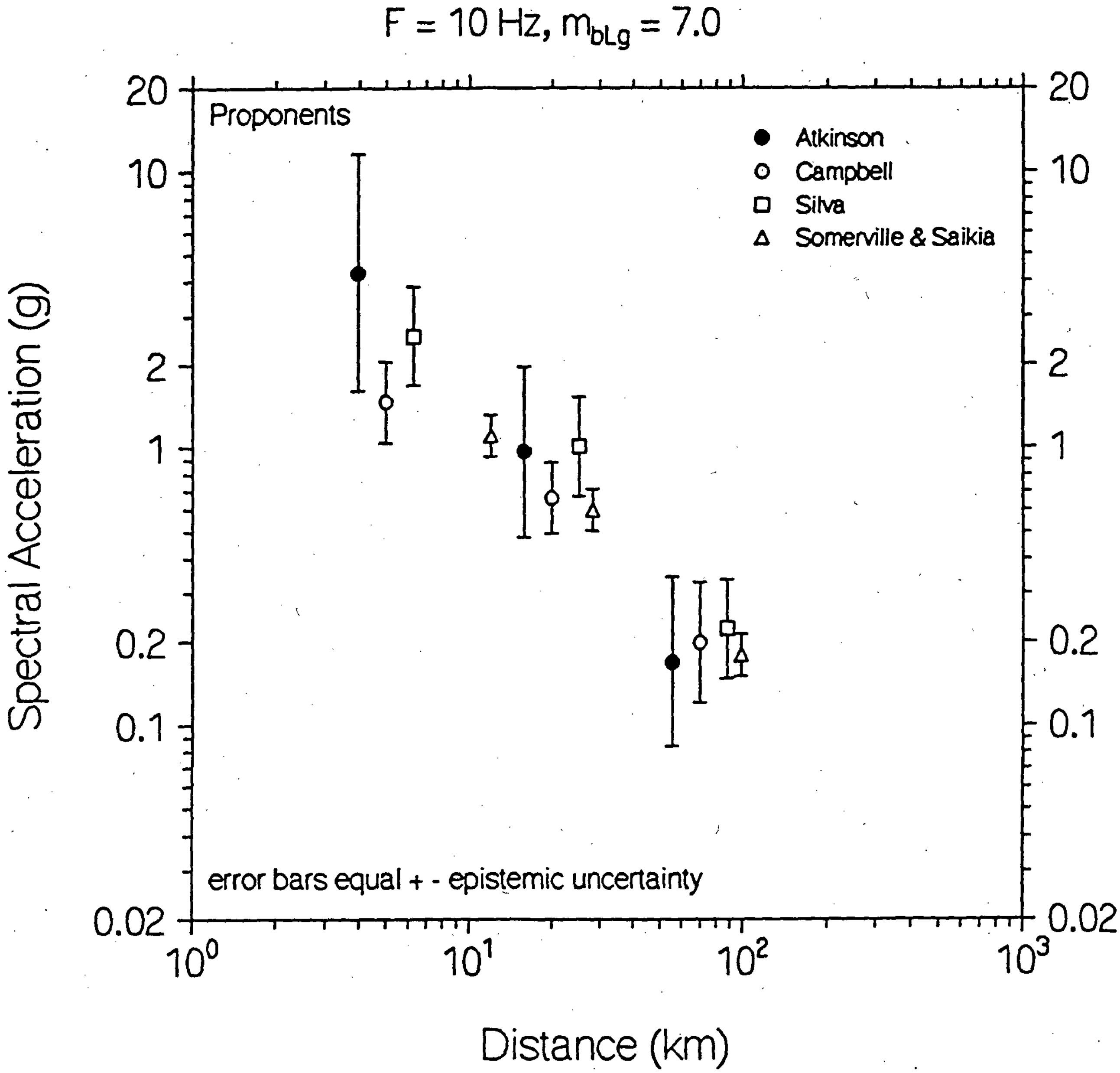


F = 2.5 Hz, mbLg = 5.5
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
0.2
0.1
0.02
0.01
0.002
0.001
Spectral Acceleration (g)
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)

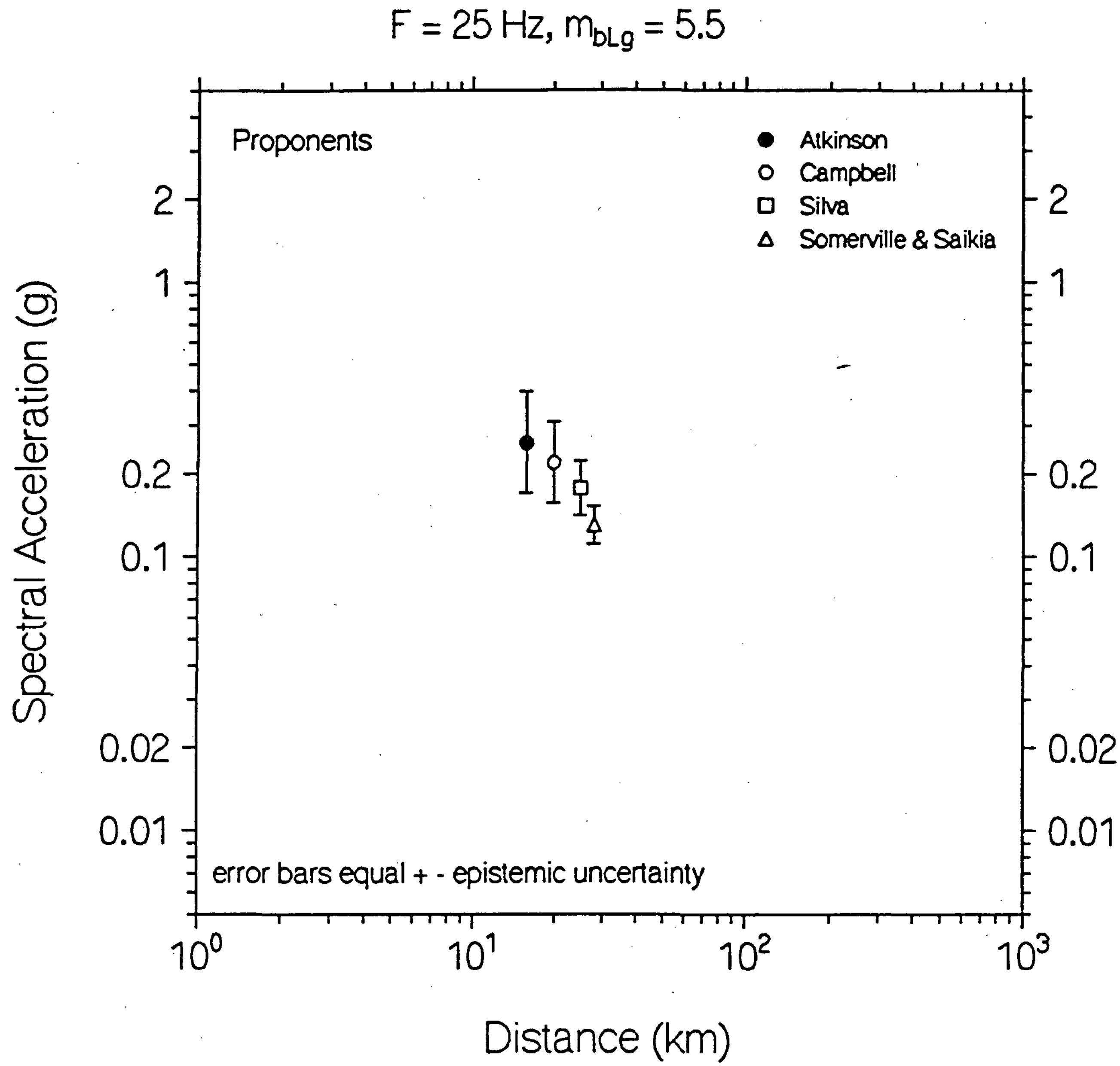
F = 2.5 Hz, mbLg = 7.0

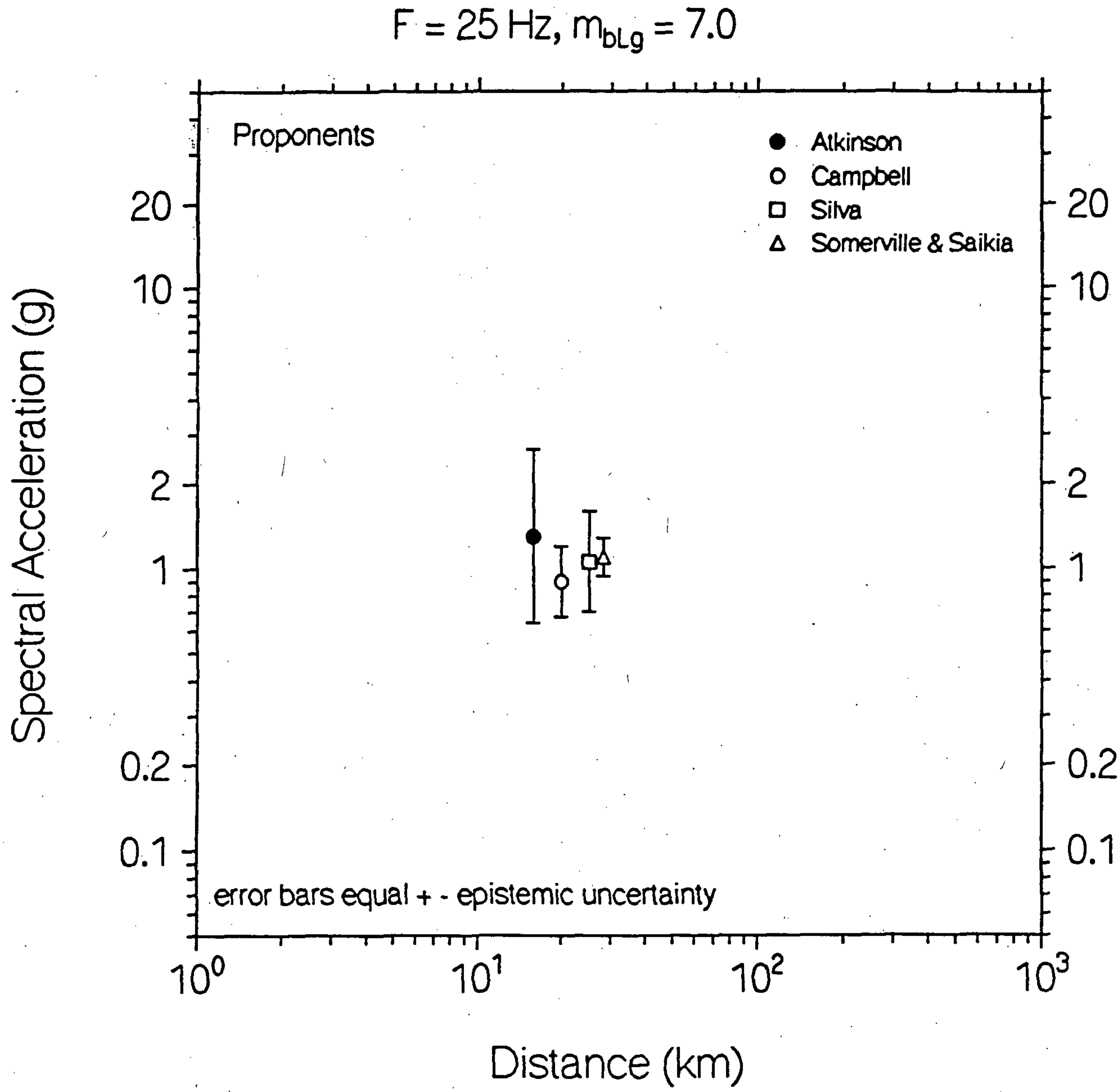



F = 10 Hz, m_{bLg} = 5.5
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3
Distance (km)



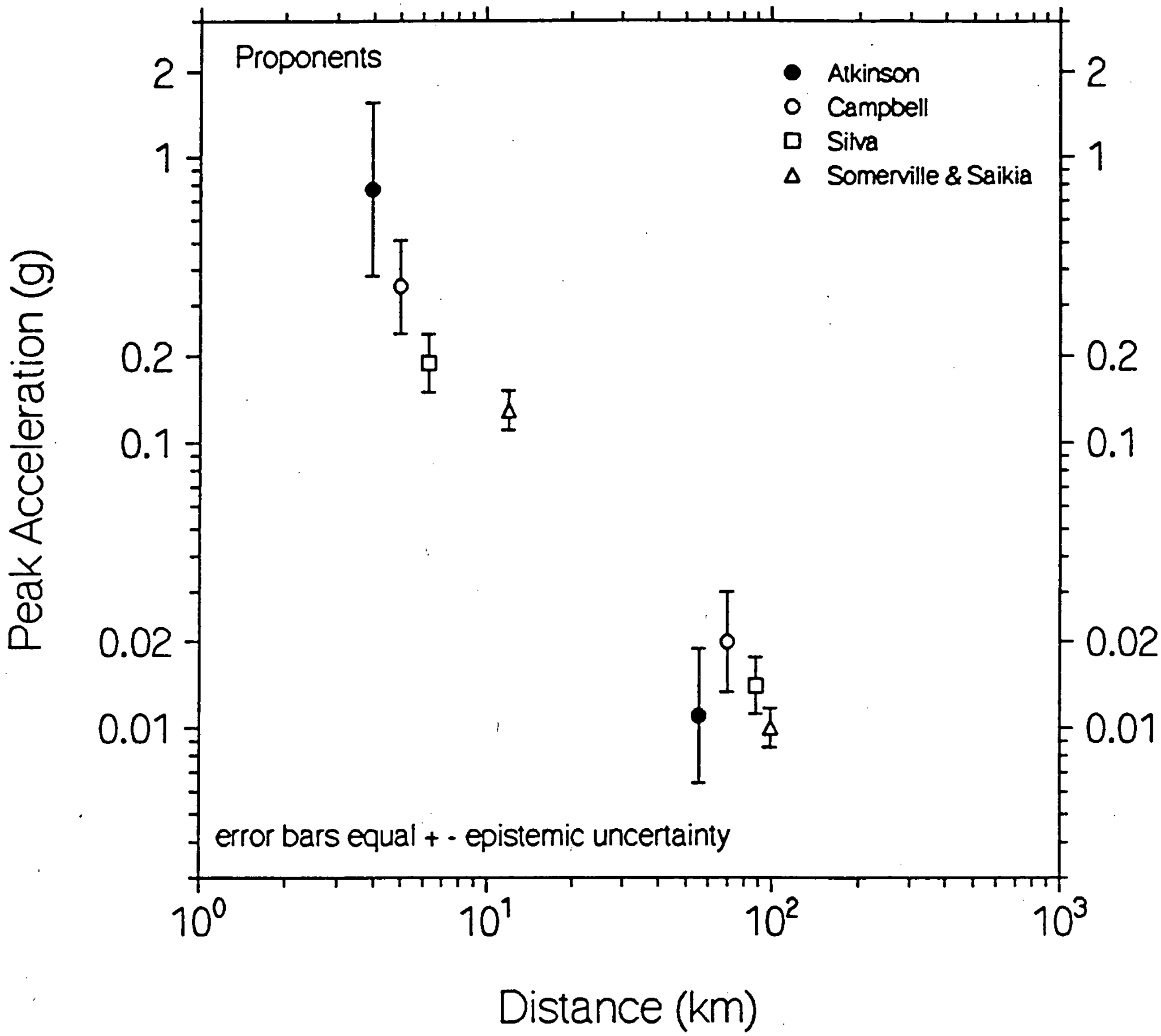
F = 10 Hz, m_{bLg} = 7.0
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3


F = 25 Hz, m_{bLg} = 5.5
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)

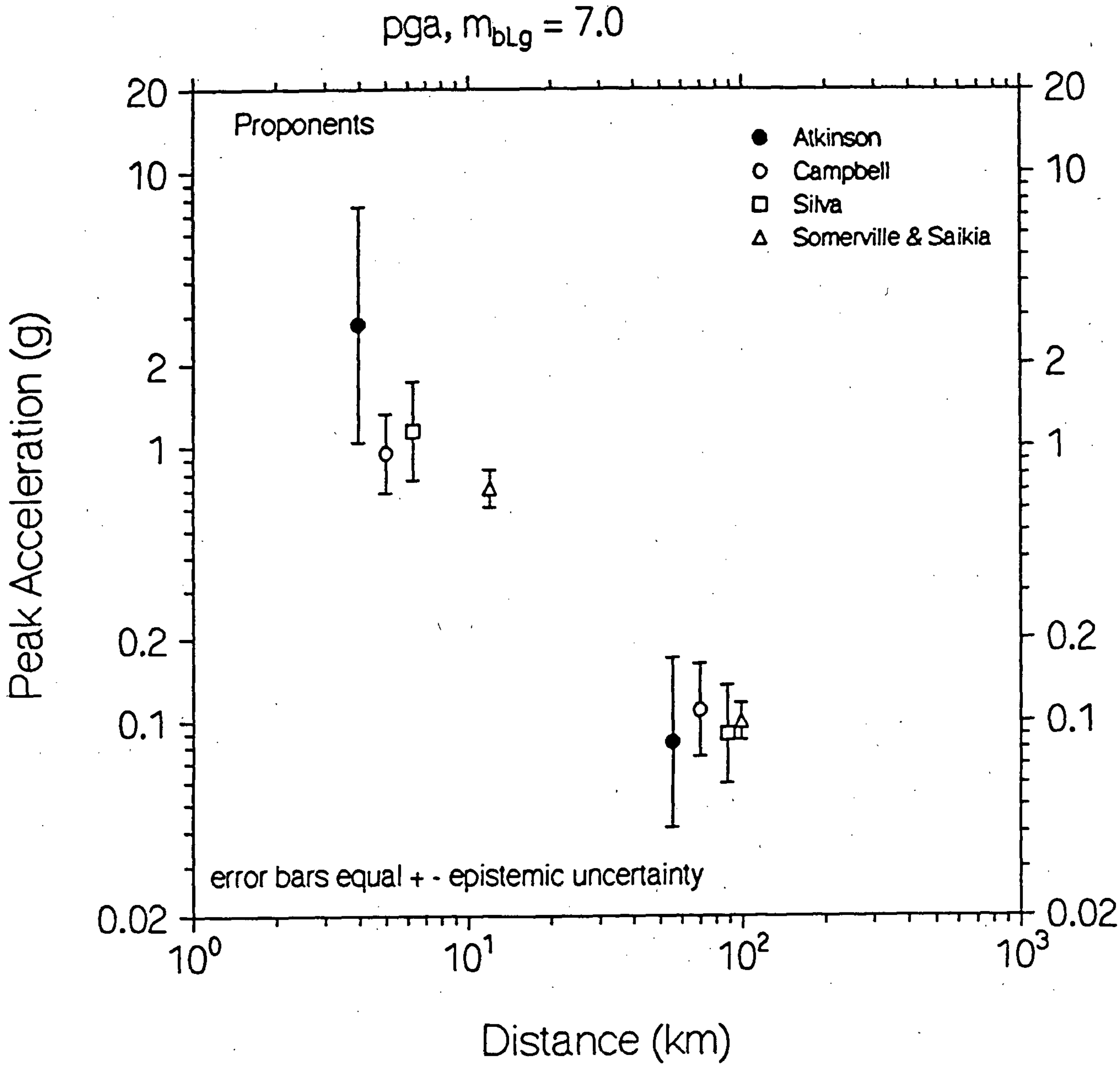


F = 25 Hz, m_{bLg} = 7.0
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
Spectral Acceleration (g)
20
10
2
1
0.2
0.1
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)

pga, $m_{bLg} = 5.5$



Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
2
1
0.2
0.1
0.02
0.01
error bars equal + - epistemic uncertainty
Peak Acceleration (g)
10^0
10^1
10^2
10^3
Distance (km)


pga, m_{bLg} = 7.0
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Peak Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3

ATTACHMENT B-2

EXPERTS 1 (PRE-WORKSHOP) RESULTS

SSHAC SECOND GROUND-MOTION WORKSHOP

INSTRUCTIONS AND QUESTIONNAIRE FOR EXPERTS

Gabriel R. Toro
Risk Engineering, Inc.
July 8, 1994

As part of your participation in the second SSHAC Ground Motion Workshop, we are asking you to prepare and document ground-motion estimates for a specific tectonic province and for a suite of magnitudes, distances, and frequencies of engineering interest. We are testing a format for these estimates that is somewhat different from those used in past ground-motion elicitation efforts. Your estimates, and the data and arguments supporting these estimates, will be important inputs in the development of a composite ground-motion model. Please return your estimates and documentation so that I receive them by July 20, 1994. We need this material for a meeting on July 21.

The definition of the problem is as follows:

- Site location: northeastern United States or southeastern Canada
- Site conditions Eastern United States Rock (2800 m/s average shear-wave velocity over the top 30 m)
- Magnitudes, distances (to closest point on rupture), and oscillator frequencies as given below:

Distance to closest point on rupture (km)	m_{Lg} 5.5	m_{Lg} 7
5	1 Hz, 10 Hz, PGA	1 Hz*, 10 Hz*, PGA
20	1 Hz*, 2.5 Hz*, 10 Hz*, 25 Hz*	1 Hz*, 2.5 Hz, 10 Hz*, 25 Hz*
70	1 Hz, 10 Hz, PGA	1 Hz, 10 Hz, PGA
200	1 Hz	1 Hz*

where the asterisks denote debating points (i.e., predictions on which we will focus the comparisons and discussions).

For each magnitude-distance-frequency combination, you are asked to provide the following information (ordered by priority):

1a an estimate of the median ground-motion amplitude (5% damped spectral acceleration or PGA),

1b a central estimate of the aleatory uncertainty (about the true median) anticipated in future observations of ground motions under the same conditions (i.e., same magnitude, distance, geographic region, and site conditions; this aleatory uncertainty is typically represented by the standard deviation σ, which we will call $\sigma_{\ln[\text{amplitude}],\ \text{aleatory}}$ for the sake of clarity),

2a an estimate of the epistemic uncertainty associated with your estimate of the median,

2b epistemic uncertainty associated with the aleatory uncertainty (i.e., uncertainty about the true value of $\sigma_{\ln[\text{amplitude}],\ \text{aleatory}}$),

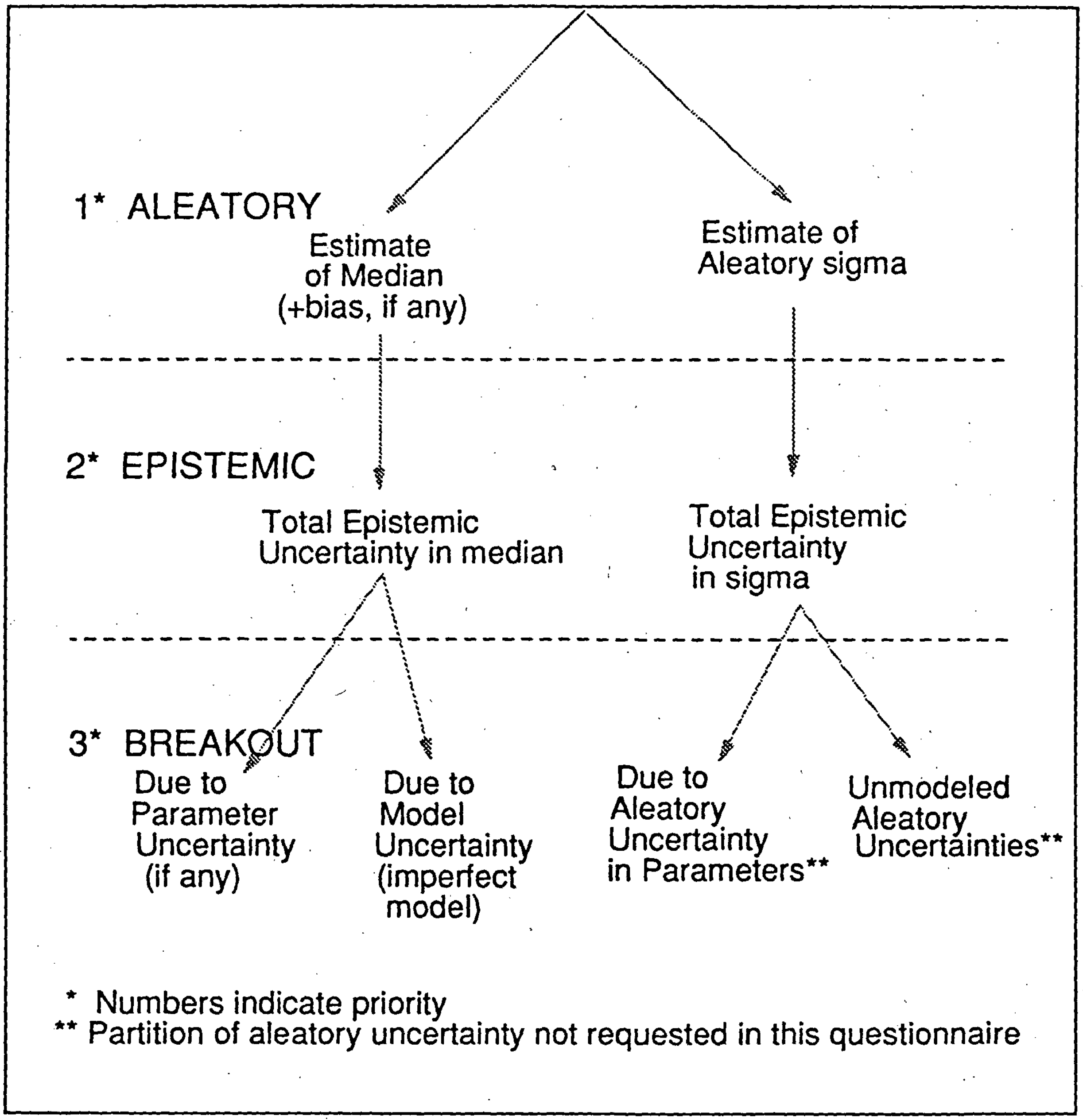
3 partitioning of the epistemic uncertainty into its parametric and modeling components, if applicable.

The definition of epistemic and aleatory uncertainties follows the "white paper" distributed prior to the first workshop, and are repeated below:

> Epistemic Uncertainty. Uncertainty that is due to incomplete knowledge and data about the physics of the earthquake process. In principle, epistemic uncertainty can be reduced by the collection of additional information.
>
> Aleatory Uncertainty. Uncertainty that is inherent to the unpredictable nature of future events. It represents unique details of source, path, and site response that cannot be quantified before the earthquake occurs. Given a model, one cannot reduce the aleatory uncertainty by collection of additional information.

The epistemic uncertainty about the median amplitude is further sub-divided into two components: parametric and modeling. The parametric component represents, for example, uncertainty about the median amplitude due to uncertainty about the median stress drop for the eastern U.S. (e.g., is it 120 bars?, does it increase with seismic moment?). The modeling component relates to uncertainty about the model's systematic bias (i.e., $\ln[\text{Amplitude}]_{\text{true}} - \ln[\text{Amplitude}]_{\text{predicted}}$). Such bias may be introduced by the model's functional form or by parameters that are not treated explicitly as uncertain. Uncertainty about the size of the bias arises because the data available for model validation are few and are often outside the magnitude-distance range of engineering interest. The Appendix to these instructions, and the white paper distributed prior to the first workshop, contain examples on these distinctions. In addition, you may contact David Boore, Allin Cornell, or myself, if you have any question about these distinctions or if you wish to discuss their validity or usefulness.

In the evaluation of epistemic and aleatory uncertainties, you should use whichever method you think is appropriate (e.g., propagation of parameter and modeling uncertainties, use of empirical data from ENA or other regions, and/or direct subjective assessments). Your assessment of aleatory uncertainty should be conditional on the independent variables given (i.e., m_{Lg}, closest distance, geographic region, and site conditions). If your model contains additional independent variables (e.g., stress drop, focal depth, rupture dimensions, depth to basement), you should incorporate the effect of uncertainty in these variables on the total aleatory uncertainty requested above.The following graph illustrates the relationships among the quantities that you are asked to provide, and their relative priorities.



Enclosed with these instructions are the ground-motion estimates and documentation prepared by four "model proponents." The four models represented by the proponents were selected as the four models more appropriate for ground-motion prediction in the CEUS, based on the feedback received during the first Workshop. You should use these estimates and documentation as background information when preparing your estimates. You are not required to (1) choose from among the proponent's estimates, or (2) submit your estimate as a weighted sum of the proponent's estimates. You are free to use any approach or combination of approaches, including the proponents', to arrive at your estimates. Also, the sensitivity results provided by the proponents should also help you if you would like to use a proponent's model but do not agree with the median values or parametric uncertainties used by that proponent.

You should take the broader perspective of an integrator rather than that of a scientist defending his or her preferred model. If you think that a model other than your preferred model is a credible model, you should consider that model's estimates when arriving at your estimates of median values and uncertainties.

Format of Results and Documentation

Estimates of Median and Uncertainties. Your results for the prescribed magnitudes, distances, and frequencies should be provided in the attached forms 1 through 5. Debating points are identified by thick rectangles; magnitude-distance-frequency combinations for which no input is required are shaded. You may wish to submit, in addition, graphical results, tables, and/or equations that cover a wider magnitude-distance-frequency range; we encourage but do not require such results. The functional forms you provide may prove helpful because, ultimately, we shall have to provide predictions over a continuous range of magnitude and distance.

The aleatory uncertainty may be represented adequately by a lognormal distribution (so, you would simply specify $\sigma_{\ln[Amp],aleatory}$). If you feel that this is not the case, provide an alternative distribution. You should also specify truncation, if appropriate. We encourage you to concentrate your attention on the extent of the spread (as measured, for example, by the logarithmic standard deviation of the median; i.e., $\sigma_{\ln[Amp]aleatory}$), rather than on the fine details of the distribution shape (i.e., lognormal vs. triangular).

Each component of the epistemic uncertainty may also be represented adequately by lognormal distributions (in which case you would enter the logarithmic standard deviation [using natural logs]), or by discrete, triangular, uniform, or other distributions. If you do not think that the partitioning of epistemic uncertainty into parametric and modeling components is not appropriate or practical, enter your estimate of the total epistemic uncertainty in the box labeled "uncert. in bias (ln)."[1]

[1]We left the format of the tables unchanged for the sake of consistency between the tables used by the proponents and those used by the larger group of experts. We recognize that it may not always be practical to break-up the epistemic uncertainty into its modeling and parametric components. It is more important that you concentrate on the median estimate and on the total aleatory and epistemic uncertainties.

To specify the epistemic uncertainty about the proper value of $\sigma_{\ln[Amp],aleatory}$, you may use multiple values of $\sigma_{\ln[Amp],aleatory}$ with associated weights or, again, any other simple measure of "spread" such as the epistemic standard deviation of $\sigma_{\ln[Amp],aleatory}$.

Documentation. Please provide three to ten pages of documentation, summarizing and justifying the approach (or approaches) and parameters used to generate your estimates, including how the two uncertainty estimates were obtained. In addition, you should briefly discuss the following three topics:

1. strengths and weaknesses of the approach (or approaches) used or considered, and applicability to each of the magnitude-distance-frequency ranges of interest;

2. qualitative discussion of whether the hard-rock site considered here is representative of rock sites in CEUS

3. qualitative discussion of how your results would be different for other regions within CEUS.

Your discussion of the various approaches used should consider the inner elements and parameters in each approach used or considered. If you like one element of a certain approach but think other elements of that approach are weak, you should state that.

You may wish to include relevant papers and reports as appendices to your documentation.

Expert: ______________________________

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: ____________________

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: ______________________________

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

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Expert: ______________________________

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 5: Page __ of __

Expert: ______________________________

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

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APPENDIX

THE PARTITION AND ESTIMATION OF UNCERTAINTY

(rev. July 11, 1994)

In the "white paper" on uncertainty, we developed a two-way partition of uncertainty, as follows:

a) Is this uncertainty that can be reduced with the collection of additional data? (epistemic vs. aleatory)

b) Is this uncertainty due to a parameter of the model that is explicitly treated as uncertain? (parametric vs. modeling)

The table that follows contains examples of the four types of uncertainty resulting from this partitioning.

	Epistemic	Aleatory
Modeling	Uncertainty about the true model bias (i.e, to what extent model has a tendency to over- or under-predict observations)	Unexplained scatter due to physical processes not included in the model
Parametric	Uncertainty about median stress drop for ENA, depth distribution, etc.	Event-to-event variation in stress drop or focal depth, etc

In this exercise, we are asking you to report the two components of epistemic uncertainty and the combined (parametric+modeling) aleatory uncertainty. The example that follows should clarify these definitions.

Consider first the hypothetical situation in which there are thousands of records from earthquakes in the region of interest, all having the magnitude (m_x), same distance (r_x), and same site category (s_x) for the prediction at hand. Given these data, we can compute the true value of the median[2] ground-motion amplitude at a certain frequency as

$$\ln[Amplitude]_{\text{true median}} = \frac{1}{N}\sum_{i=1}^{N} \ln[Amplitude]_{\text{observed}, i} \tag{1}$$

where N is the number of records. One can also compute the true standard deviation associated with aleatory uncertainty (which is due to aleatory variations in all source, path, and site factors other than region, magnitude, distance, and site category) from the observed scatter as

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(\ln[Amplitude]_{\text{observed}, i} - \ln[Amplitude]_{\text{true median}}\right)^2} \tag{2}$$

Assume also that we have a deterministic predictive model (e.g., a physical model, a stochastic model, or an empirical attenuation function) of the form:

$$\ln[Amplitude]_{\text{pred}} = f(m,r,\ \text{site category};\ \boldsymbol{P}) \tag{3}$$

where $\boldsymbol{P}$ is a vector of explicit model parameters (e.g., stress drop, focal depth, slip distribution, etc.) and that we know the parameter values $\boldsymbol{P}_i$ for each record. This model can be used to predict the amplitude for a given set of parameters $\boldsymbol{P}_0$, as

$$\ln[Amplitude]_{\text{pred},\boldsymbol{P}_0} = f(m,r,\ \text{site category};\ \boldsymbol{P}_0) \tag{4}$$

The predictive model can also be used to predict the median amplitude for the magnitude, distance and site conditions of interest as

$$\ln[\text{Ampl.}]_{\text{pred. median}} = \frac{1}{N}\sum_{i=1}^{N} f(m_x, r_x, s_x;\ \boldsymbol{P}_i) \tag{5}$$

which is equivalent to

[2]We are using the term median in a loose sense. Strictly speaking, the quantity in Equation 1 is the logarithmic-mean amplitude, which is equal to the median amplitude only if the amplitude follows a log-normal distribution.

$$\ln[\mathrm{Ampl.}]_{\mathrm{pred.\ median}} = E_P\left[f(m_x, r_x, s_x;\ P)\right] \tag{6}$$

where E_P denotes expected value (i.e., averaging) over the distribution of the parameter vector $\boldsymbol{P}$. In the hypothetical situation considered here, we know the probability distribution of the parameters in $\boldsymbol{P}$ (i.e., we know the median, mean, standard deviation, distribution type, etc, for all parameters in $\boldsymbol{P}$) because we have a very large number of records and we know the parameter values $\boldsymbol{P}_i$ for each record.

Because the predictive model does not include all physical processes and parameters affecting ground motions, the predicted median value is likely to differ from the true median value. The bias in the predictive model can be evaluated by comparing observations and predictions for the available recordings for the same magnitude, distance, and site category of interest; i.e.,

$$\mu = \frac{1}{N}\sum_{i=1}^{N}\left(\ln[Amplitude]_{\mathrm{observed},\ i} - f(m_x, r_x, s_x;\ \boldsymbol{P}_i)\right) \tag{7}$$

or

$$\mu = \ln[Amplitude]_{\mathrm{true\ median}} - \frac{1}{N}\sum_{i=1}^{N} f(m_x, r_x, s_x;\ \boldsymbol{P}_i) \tag{8}$$

Because we know the model bias for the magnitude, distance, and site conditions of interest, we can use bias-corrected model predictions of the true median amplitude.

The aleatory uncertainty defined in Equation 3 can be decomposed into uncertainty due to uncertainty in the parameter vector $\boldsymbol{P}$ (aleatory parametric uncertainty) and uncertainty due to un-modeled physical processes and missing parameters (aleatory modeling uncertainty). Equation 2 is re-written as[3],

$$\sigma_{\ln[Amplitude],\mathrm{aleatory}} = \sqrt{\begin{array}{l}\frac{1}{N}\sum_{i=1}^{N}\left(f(m_x, r_x, s_x; \boldsymbol{P}_i) + \mu - \ln[Amplitude]_{\mathrm{true\ median}}\right)^2 + \\ \frac{1}{N}\sum_{i=1}^{N}\left(\ln[Amplitude]_{\mathrm{observed},\ i} - f(m_x, r_x, s_x; \boldsymbol{P}_i) - \mu\right)^2\end{array}} \tag{9}$$

[4]where the first summation represents aleatory parametric uncertainty and the second summation represents aleatory modeling uncertainty. In a manner analogous to the step of

[3]We assume that the predictive model's dependence on the parameters in vector $\boldsymbol{P}$ is correct.

4

going from Equation 5 to Equation 6, the parametric term may be written as an expectation over the parameter values, obtaining

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\begin{array}{l} E_P\left[\left(f(m_x, r_x, s_x; P) + \mu - \ln[Amplitude]_{\text{true median}}\right)^2\right] + \\ \dfrac{1}{N}\displaystyle\sum_{i=1}^{N}\left(\ln[Amplitude]_{\text{observed}, i} - f(m_x, r_x, s_x; P_i) - \mu\right)^2 \end{array}} \tag{10}$$

This partitioning of aleatory uncertainty is not necessary, but some investigators consider it useful when applying models with physically based parameters.

In reality, the number of available records for the desired magnitude, distance, and site category is small at best. Assume, for the moment, that we have a small number n of records with the magnitude, distance, and site conditions of interest. We can apply an equation analogous to Equation 7 (but with the smaller sample size) to estimate the model bias; i.e.,

$$\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed}, i} - f(m_x, r_x, s_x;\ \boldsymbol{P}_i)\right) \tag{11}$$

but this estimate of the bias has statistical uncertainty because n is small. This uncertainty is epistemic modeling uncertainty.

Limitations in the data also introduce a parametric component of epistemic uncertainty in physical ground-motion models. This uncertainty is due to uncertainty about the true distributions of model parameters. Thus, epistemic parametric uncertainty arises when we apply Equation 6 to predict the median amplitude $\ln[\text{Amplitude}]_{\text{est.,median}}$, being uncertain about the distribution of the parameters (particularly about their central tendencies, i.e., median or mean). Returning to the example of stress drop, the extent of this uncertainty depends on the uncertainty in the median stress drop and on the sensitivity of $f(m_x, r_x, s_x;\ \boldsymbol{P})$ to stress drop.

The aleatory uncertainty may be estimated using equations analogous to Equations 2 or 9; i.e.,

$$\hat{\sigma}_{\ln[Amplitude],\text{aleatory}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed}, i} - \ln[Amplitude]_{\text{est. median}} - \hat{\mu}\right)^2} \tag{12}$$

or

$$\hat{\sigma}_{\ln[Amplitude],\text{aleatory}} = \sqrt{\begin{array}{l} E_P\left[\left(f(m_x, r_x, s_x; P) + \hat{\mu} - \ln[Amplitude]_{\text{est. median}}\right)^2\right] \quad + \\ \frac{1}{n}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\, i} - f(m_x, r_x, s_x; P_i) - \hat{\mu}\right)^2 \end{array}} \tag{13}$$

There is also epistemic uncertainty associated with the estimated $\sigma_{\ln[\text{Ampl.}],\text{aleatory}}$ because of the limited sample size and uncertainty in the distribution of $\boldsymbol{P}$.

In practice, the data are so limited that one is required to use data from other magnitudes, distances, and site categories to estimate the bias, epistemic uncertainty, and aleatory uncertainty. In doing this, there is the implicit assumption that the predictive model $f(m,r,\text{site category}; \boldsymbol{P})$ is equally good, and has the same bias, for (m_x, r_x, s_x) as for the magnitudes, distances, and site categories represented in the data. This assumption introduces additional epistemic uncertainty, which may quantified by considering alternative models.

Some Possible Approaches

The following is a brief description of some of the techniques available for the estimation of bias, epistemic uncertainty, and aleatory uncertainty. Additional details are found in the White Paper on Uncertainty that was distributed prior to the first workshop.

Physical and Stochastic Models. The 1993 EPRI study provides an example of the Abrahamson et al. (1991) formulation of uncertainty. Modeling uncertainty is calculated by comparing observed spectral accelerations to predictions obtained using parameters $\boldsymbol{P}_i$ appropriate to each event and site. These comparisons yield estimates of the bias

$$\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\, i} - f(m_i, r_i, s_i;\ \boldsymbol{P}_i)\right) \tag{14}$$

and the standard error

$$\text{std. error} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\, i} - f(m_i, r_i, c_i; \boldsymbol{P}_i) - \mu\right)^2} \tag{15}$$

The standard error serves as an estimate of the aleatory modeling uncertainty (i.e., physical process and parameters not included in the predictive model, which cause seemingly random scatter). The epistemic modeling uncertainty (i.e., uncertainty in the bias) should be estimated as (std. error)/$(n')^{1/2}$, where n' is the equivalent number of independent observations (this number is smaller than n because of correlation among records from the same event). In the EPRI study, additional epistemic modeling uncertainty was introduced by site-specific correction terms. Additional epistemic modeling uncertainty may arise due to the existence of competing models.

The epistemic and aleatory uncertainty in the model parameters P_i (e.g., uncertainty in the median stress drop and uncertainty in the stress drop for the next event) introduce epistemic parametric and aleatory parametric uncertainties in the predictions. The contributions of stress drop to the epistemic parametric and aleatory parametric uncertainties are approximately[5] equal to

$$\left[\frac{\partial f(m,r,\text{site category};\, \boldsymbol{P})}{\partial \ln\Delta\sigma}\right]_{\boldsymbol{P}=\boldsymbol{P}_{\text{median}}} \times \sigma_{\overline{\ln\Delta\sigma}} \tag{16}$$

and

$$\left[\frac{\partial f(m,r,\text{site category};\, \boldsymbol{P})}{\partial \ln\Delta\sigma}\right]_{\boldsymbol{P}=\boldsymbol{P}_{\text{median}}} \times \sigma_{\ln\Delta\sigma} \tag{17}$$

where $\sigma_{\overline{\ln\Delta\sigma}}$ is the logarithmic standard deviation representing epistemic uncertainty in the median stress drop (i.e., how well do we know the median stress drop that we would observe if we studied earthquakes in the region for thousands of years) and $\sigma_{\ln\Delta\sigma}$ is the logarithmic standard deviation representing aleatory uncertainty (i.e., the event-to-event scatter in $\ln[\Delta\sigma]$ that we would observe if we studied earthquakes in the region for thousands of years). Assuming that the uncertainties about all explicit model parameters in $\boldsymbol{P}$ are independent (i.e., no trade-offs), the total epistemic parametric and aleatory parametric uncertainties are approximately equal to

$$\sqrt{\sum_j \left\{\left[\frac{\partial f(m,r,\text{site category};\, \boldsymbol{P})}{\partial \ln p_j}\right]_{\boldsymbol{P}=\boldsymbol{P}_{\text{median}}} \times \sigma_{\overline{p_j}}\right\}^2} \tag{18}$$

and

$$\sqrt{\sum_j \left\{\left[\frac{\partial f(m,r,\text{site category};\, \boldsymbol{P})}{\partial \ln p_j}\right]_{\boldsymbol{P}=\boldsymbol{P}_{\text{median}}} \times \sigma_{p_j}\right\}^2} \tag{19}$$

where the summations extend over all model parameters. Alternatively, one may use logic-trees to calculate the parametric uncertainties, as was done in the EPRI study.

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[5] The result is approximate because it involves linearization of f(m,r, site category; $\boldsymbol{P}$) with respect to one of the parameters in $\boldsymbol{P}$.

The aleatory uncertainty (modeling+parametric) may also be calculated directly using records from the same region or from other regions (i.e., using Eq. 12). If the magnitudes and distances in the differ substantially from the magnitude and distance for which a prediction is being made, there is a problem with different sensitivity to a parameter (such as Q) at different magnitudes and distances. If residual standard deviations from another region are being used to estimate the aleatory uncertainty in a region with limited data, one should keep in mind the following considerations: (1) if the regression contained additional explanatory variables (e.g., focal depth, style of faulting), these variables should be treated as uncertain parameters and integrated over in order to obtain a revised estimate of aleatory uncertainty; and (2) the residual standard deviation may contain some effects other than aleatory uncertainty (e.g., lack of fit, undetected regional variations in the data set).

Empirical Attenuation Equations. In empirical attenuation equations, the empirically derived coefficients take the role of parameters. These coefficients have no aleatory uncertainty (i.e., they are assumed to be the same for all events and sites). The calculated statistical uncertainty in these coefficients is typically very small and not representative of the true epistemic uncertainty. Differences among empirical models developed by different investigators (using somewhat different data sets and functional forms) is a better representation of epistemic uncertainty.

Modeling uncertainty is characterized by the residual standard deviation σ. This standard deviation contains both aleatory and epistemic components, but it is typically taken as all aleatory.

If empirical attenuation equations are used in a hybrid mode (i.e., the empirical attenuation equations are modified to account for regional differences in source scaling, magnitude definition, path effects, or site effects), such corrections introduce epistemic parametric uncertainty, which should be considered.

If the attenuation equations contain explanatory variables other than magnitude, distance, and site category, one must treat these explanatory variables as uncertain parameters (as was done with physical models). Thus, one must integrate over these parameters, considering the appropriate distribution of the parameter in the region of interest. For instance, if parameter Z represents faulting style in the attenuation equation

$$\ln[\text{Amplitude}] = g(m, r, \text{site category}, Z) \tag{20}$$

and the probability of distribution of faulting styles in the region of interest is given by $p_Z(z_1)$, $p_Z(z_2)$, ... $p_Z(z_m)$, then the attenuation equation without Z is equal to

$$g^*(m_x, r_x, s_x) = \sum_{k=1}^{m} p_Z(z_k)\, g(m_x, r_x, s_x, z_k) \tag{21}$$

and the aleatory parametric uncertainty due to Z is characterized by a standard deviation equal to

$$\sqrt{\sum_{k=1}^{m} p_Z(z_k)\left(g(m_x, r_x, s_x, z_k) - g^*(m_x, r_x, s_x)\right)^2} \tag{22}$$

This standard deviation, and other parametric standard deviations, should be combined with the residual standard deviation (using a square root of the sum of the squares formula), to obtain the total aleatory uncertainty associated with g*(m,r,s) (i.e., for predictions in terms of magnitude, distance, and site category).

The distribution of Z above may be magnitude and distance dependent (e.g., the distribution of style of faulting and focal depth may depend on magnitude; the distribution of azimuth may be magnitude and distance dependent). In those cases, distributions of Z for the appropriate values of m_x and r_x must be used.

Changes in the definition of magnitude or distance can be treated in a similar manner. For instance, if the original attenuation equation uses distance definition R_1 and one wants to change to R_2, one may perform calculations similar to those in Equations 12 and 13 (but in integral form), using the conditional probability density function $f_{R_1|R_2,m,r}(r_1;\ r_2,m,r)$. Even if distance definition R_2 is superior to R_1, this approach will yield a higher residual standard deviation for R_2, because it ignores dependence between the regression residuals and $R_1|R_2,m,r$.

Ground Motion Estimates by N. Abrahamson

Distance Definition:
There is a discrepancy in the distance definitions for the models provided to the experts. The instructions specify that rupture distance is used, but Walt's model (the EPRI model) uses a horizontal distance (e.g. Joyner and Boore type distance). This creates a problem for the 5 km distance estimate for both the median value and the aleatory uncertainty (the focal depth variability increases the aleatory uncertainty).

In addition, Gail's model uses a point source. She has located the point source at the rupture distance. As pointed out by Gail, this is not appropriate for a magnitude 7 at 5 km.

In interpreting these models, I made a rough correction to the distances for the 5 km case. For Walt's model I based the correction on the depth distribution used in the EPRI model. The median depth is about 12 km. Therefore for M=5.5, I used 13 km. For the large magnitude event, I also considered the depth of the asperity since the point source model has been validated against WUS large event data by putting the point source at the closest point of the fault but at the depth of the asperity. In the EPRI model, the mean asperity depth is located at 60% down dip. Using a weighting of 2/3 for 45 degree dips and 1/3 for 90 degree dips, I computed a rupture distance of 8.5 km for Walt's 5 km distance estimates.

For Gail's model, I also assumed that the point source should be located at the closest distance but at the depth of the asperity. If the asperity is at a depth of 5 km, then I assumed that the rupture reaches the surface. Again using a weighting of 2/3 for 45 degree dips and 1/3 for 90 degree dips, I computed a closest distance of 2.5 km for Gail' model. I should note that I don't think that an event with an asperity disatance of 5 km is likely to occurr.

Additional Models
In making the ground motion estimates, I considered some additional models.

First, I developed estimates for a new model that is a modification of the EPRI model but using a magnitude dependent high-frequency stress-parameter for M>6 (see Figure V.5-5). I did this to account for variability in a more rational way.

In the EPRI model, a constant median high-frequency stress-parameter was used (120 bars). However, this constant value exceeds the stress-parameter for M>6. Therefore, the model has a bias (although with a large uncertainty). The median stress-parameter for large magnitude earthquakes has more uncertainty than the median stress-parameter for moderate earthquakes. Therefore, the epistemic uncertainty for the larger magnitude events should be higher. Having a negative bias coupled with a larger epistemic uncertainty would overestimate the ground motions for large magnitude events at the 84th percentile. To avoid this, the aleatory uncertainty for the large magnitude events was reduced. This reduction is consistent with the trend magnitude dependent aleatory uncertainty observed in WUS data.

As an alternative model, I've used a magnitude dependent stress-parameter model that removes the bias at large magnitude and coupled this with a larger epistemic uncertainty. The ground motions for the new model were estimated using Walt's sensitivity of 60% change in ground motion for a 100% change in stress-parameter. I estimated that the epistemic uncertainty due to the magnitude dependent stress-parameter is 0.25 natural log units for a magnitude 7 event. (I assume that moment magnitude 7 and MLG 7 are the same)

In addition, I've considered the empirical data for rock sites shown in the EPRI report (Figures 2-3, 2-5, 2-7,and 2-9). This is not a formal regression, but rather a rough estimate of the median ground motions. I also considered a WUS rock empirical ground motion model (Geomatrix, 1991) for reference. For the WUS attenuation relation, I used a moment magnitude of 5 for the MLG 5.5 event and a moment magnitude of 7.0 for the MLG 7.0 event.

Approach Used to Develop Ground Motion Estimates

My approach to developing the ground motion estimates was to first plot up the various model predictions (using a consistent distance). I then looked at the discrepancies and evaluated the models based on my estimate of their strengths and weaknesses for the particular magnitude, distance, frequency combination.

Separating modeling uncertainty and parametric uncertainty

I have assumed that the difference between the one-corner and two-corner models for the stochastic approaches is a difference in the model parameters and not in the models. Therefore, I have put the uncertainty associated with the one vs two corner models under parametric epistemic uncertainty. I'm not sure this is right and I need to think about it some more.

I have not had time to develop a formal procedure for computing the uncertainties, so I just estimated the uncertainties based on the plotted results. The partitioning of the epistemic uncertainty into parametric and modeling used the following guidelines:

Variability of the median of the median predictions is combined with the specified parametric epistemic uncertainties to estimate the composite parametric epistemic uncertainty. That is, I increased the average parametric epistemic uncertainty to account for variability between the median predictions for the alternative models. This assumes that the models could be made to give the same predictions if the parameter distributions in the models were modified.

The modeling epistemic uncertainty is based on validation of the models to previous earthquake recordings. For this, I used the listed values. The modeling epistemic uncertainty should be increased as the model is applied to events outside of the magnitude and distance range used in the validation. For the specified events, (MLG=5.5 and MLG=7.0) the models have been validated for this magnitude range. As a result, I have not increased the modeling epistemic uncertainties.

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.040	0.50
	epistemic uncertainty	parametric (ln)	0.30	0.35
		median bias	0	0
		uncert. in bias (ln)	0.20	0.20
	aleatory uncertainty	median σ	0.80	0.75
		uncertainty in σ	0.10	0.15
20 km	median amplitude		0.010	0.15
	epistemic uncertainty	parametric (ln)	0.30	0.35
		median bias	0	0
		uncert. in bias (ln)	0.20	0.20
	aleatory uncertainty	median σ	0.84	0.75
		uncertainty in σ	0.10	0.15
70 km	median amplitude		0.0025	0.038
	epistemic uncertainty	parametric (ln)	0.30	0.35
		median bias	0	0
		uncert. in bias (ln)	0.20	0.20
	aleatory uncertainty	median σ	0.85	0.77
		uncertainty in σ	0.10	0.18
200 km	median amplitude		0.0009	0.018
	epistemic uncertainty	parametric (ln)	0.25	0.40
		median bias	0	0
		uncert. in bias (ln)	0.20	0.20
	aleatory uncertainty	median σ	0.85	0.80
		uncertainty in σ	0.10	0.18

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: N. Abrahamson

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.040	0.36
	epistemic uncertainty	parametric (ln)	0.25	0.30
		median bias	0	0
		uncert. in bias (ln)	0.20	0.20
	aleatory uncertainty	median σ	0.73	0.65
		uncertainty in σ	0.10	0.15
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 3: Page __ of __

Expert: N. Abrahamson

? GRT

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.16	2.2
	epistemic uncertainty	parametric (ln)	0.25	0.35
		median bias	0	0
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.72	0.65
		uncertainty in σ	0.10	0.15
20 km	median amplitude		0.16	0.75
	epistemic uncertainty	parametric (ln)	0.20	0.30
		median bias	0	0
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.72	0.65
		uncertainty in σ	0.10	0.15
70 km	median amplitude		0.030	0.18
	epistemic uncertainty	parametric (ln)	0.25	0.25
		median bias	0	0
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.72	0.65
		uncertainty in σ	0.10	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 4: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity			m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude				
	epistemic uncertainty	parametric (ln)			
		median bias			
		uncert. in bias (ln)			
	aleatory uncertainty	median σ			
		uncertainty in σ			
20 km	median amplitude			0.18	1.0
	epistemic uncertainty	parametric (ln)		0.25	0.25
		median bias		0	0
		uncert. in bias (ln)		0.15	0.15
	aleatory uncertainty	median σ		0.72	0.60
		uncertainty in σ		0.10	0.15
70 km	median amplitude				
	epistemic uncertainty	parametric (ln)			
		median bias			
		uncert. in bias (ln)			
	aleatory uncertainty	median σ			
		uncertainty in σ			
200 km	median amplitude				
	epistemic uncertainty	parametric (ln)			
		median bias			
		uncert. in bias (ln)			
	aleatory uncertainty	median σ			
		uncertainty in σ			

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

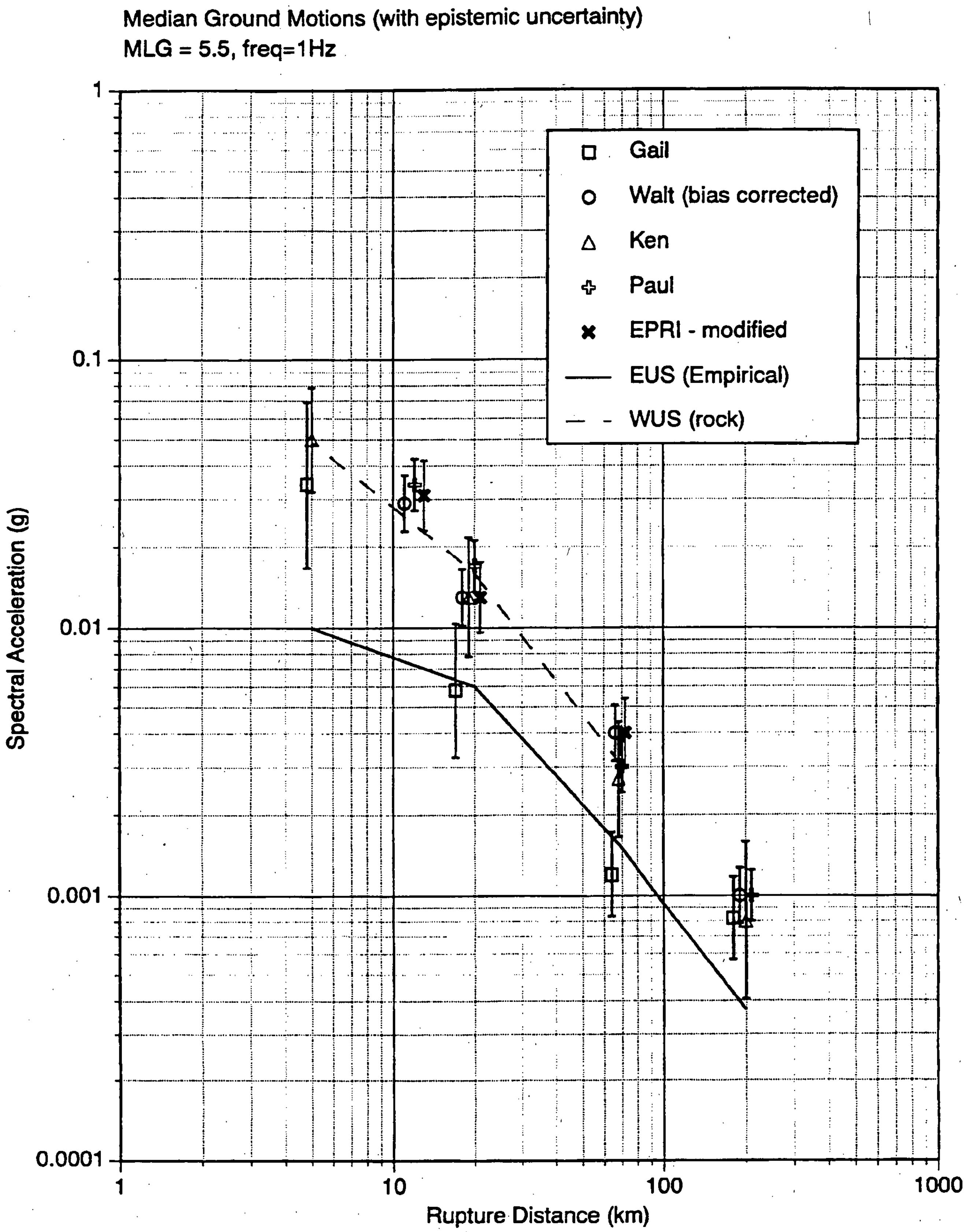
Form 5: Page __ of __

Expert: N. Abrahamson

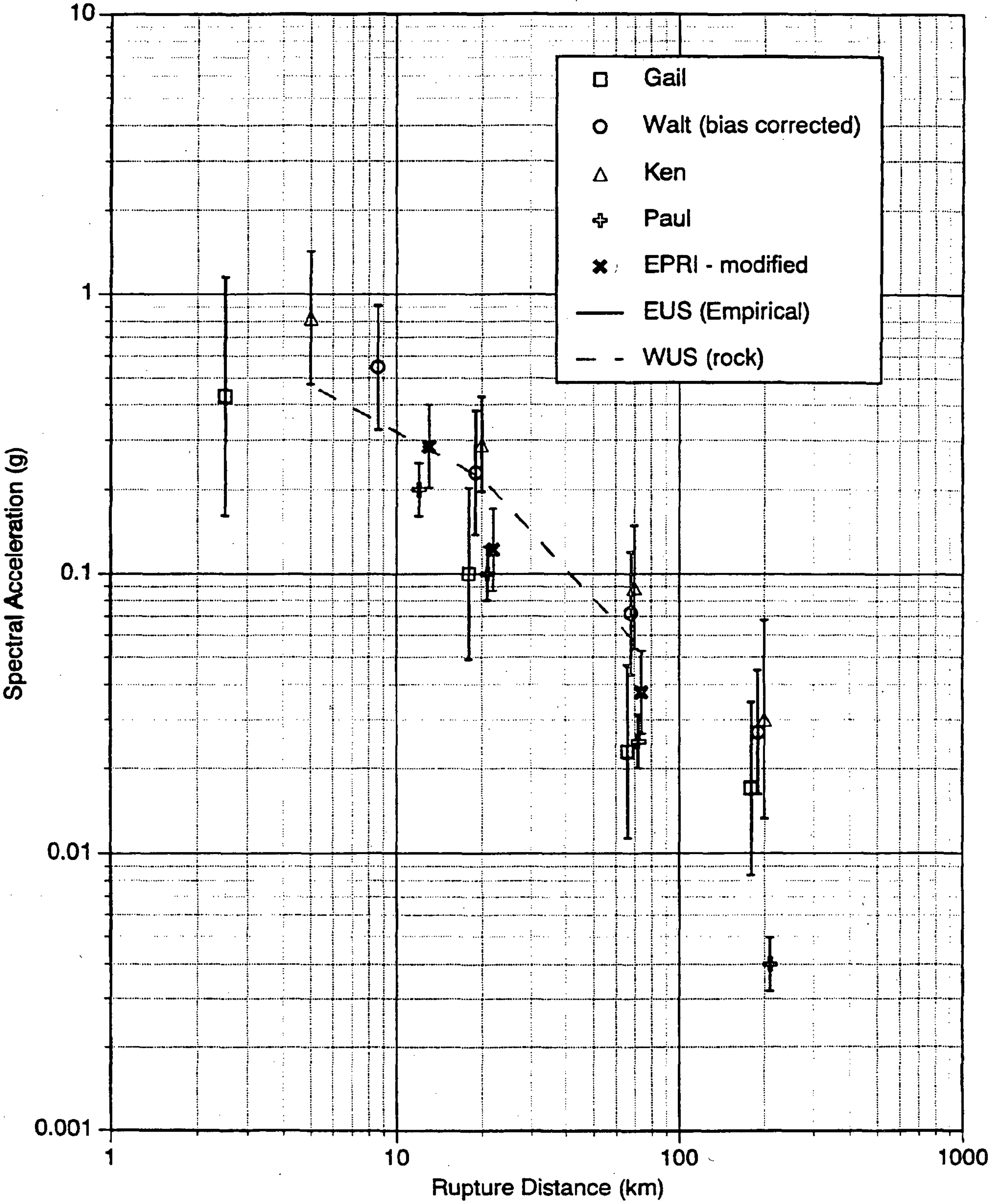
Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.52	1.7
	epistemic uncertainty	parametric (ln)	0.30	0.35
		median bias	0	0
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.72	0.60
		uncertainty in σ	0.10	0.15
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.013	0.090
	epistemic uncertainty	parametric (ln)	0.25	0.20
		median bias	0	0
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.75	0.60
		uncertainty in σ	0.10	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

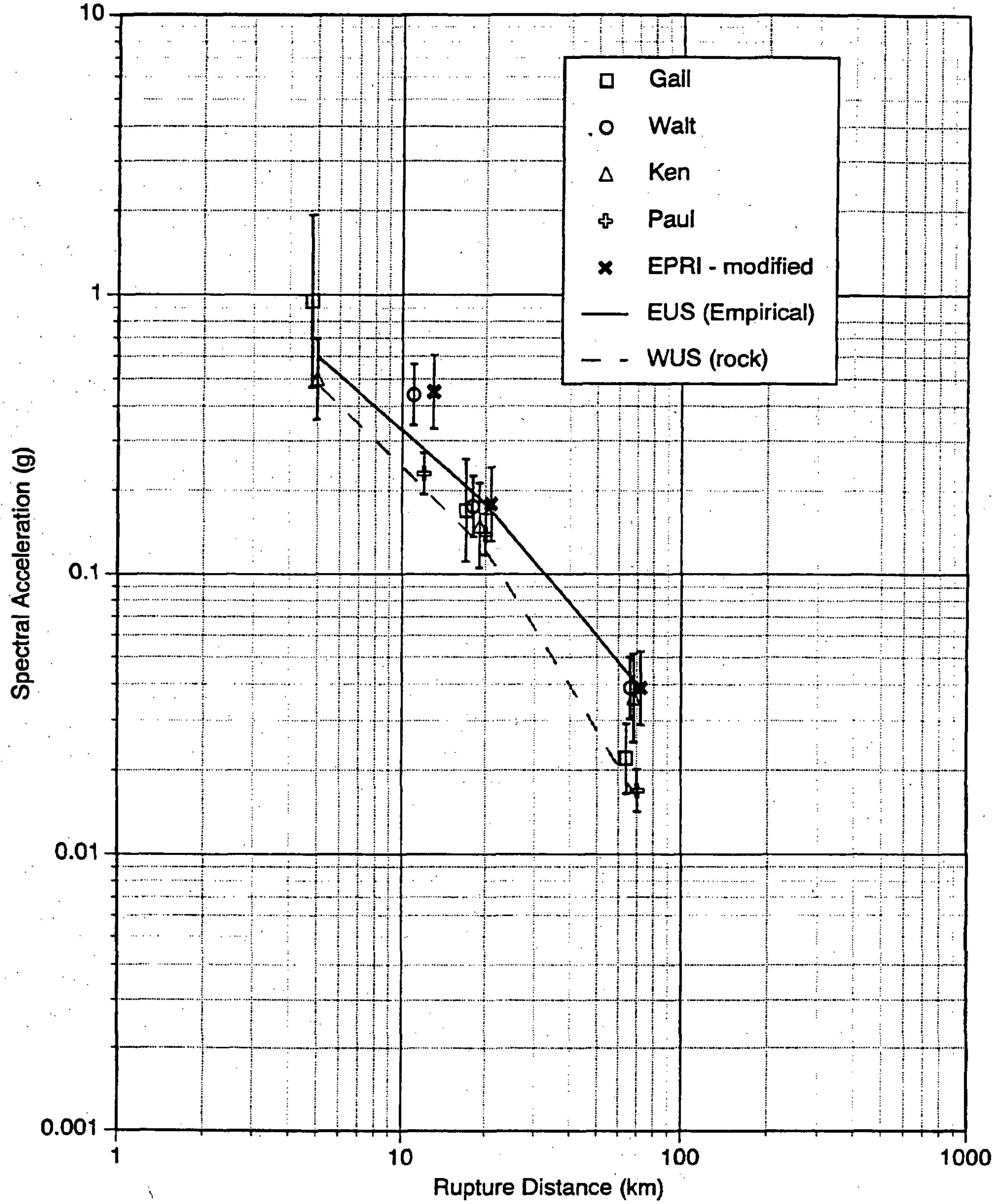
Comments/footnotes:

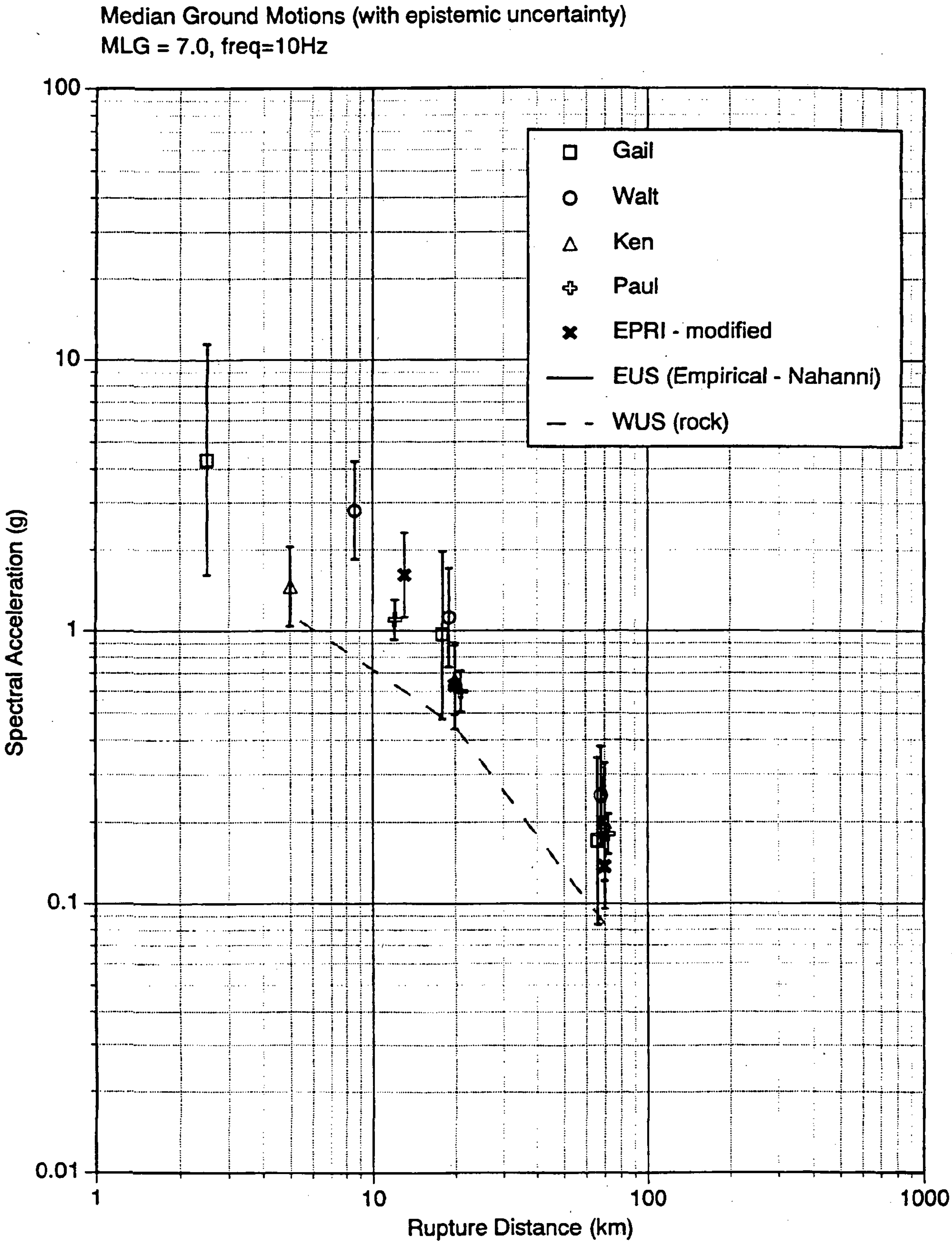

Median Ground Motions (with epistemic uncertainty)
MLG = 5.5, freq=1Hz
Gail
Walt (bias corrected)
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Spectral Acceleration (g)
1
0.1
0.01
0.001
0.0001
1
10
100
1000
Rupture Distance (km)

Median Ground Motions (with epistemic uncertainty)
MLG = 7.0, freq=1Hz



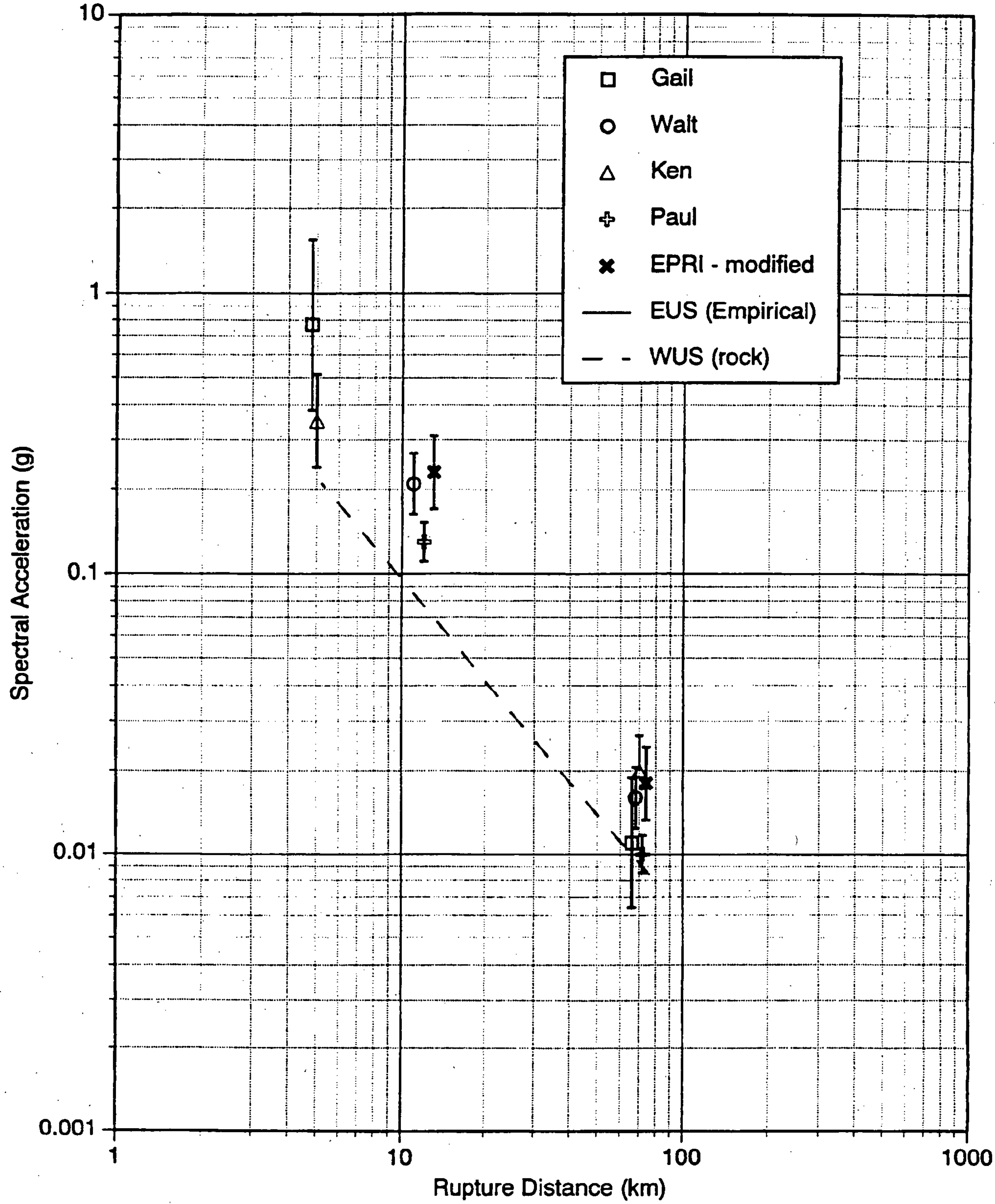
Median Ground Motions (with epistemic uncertainty)
MLG = 5.5, freq=10Hz

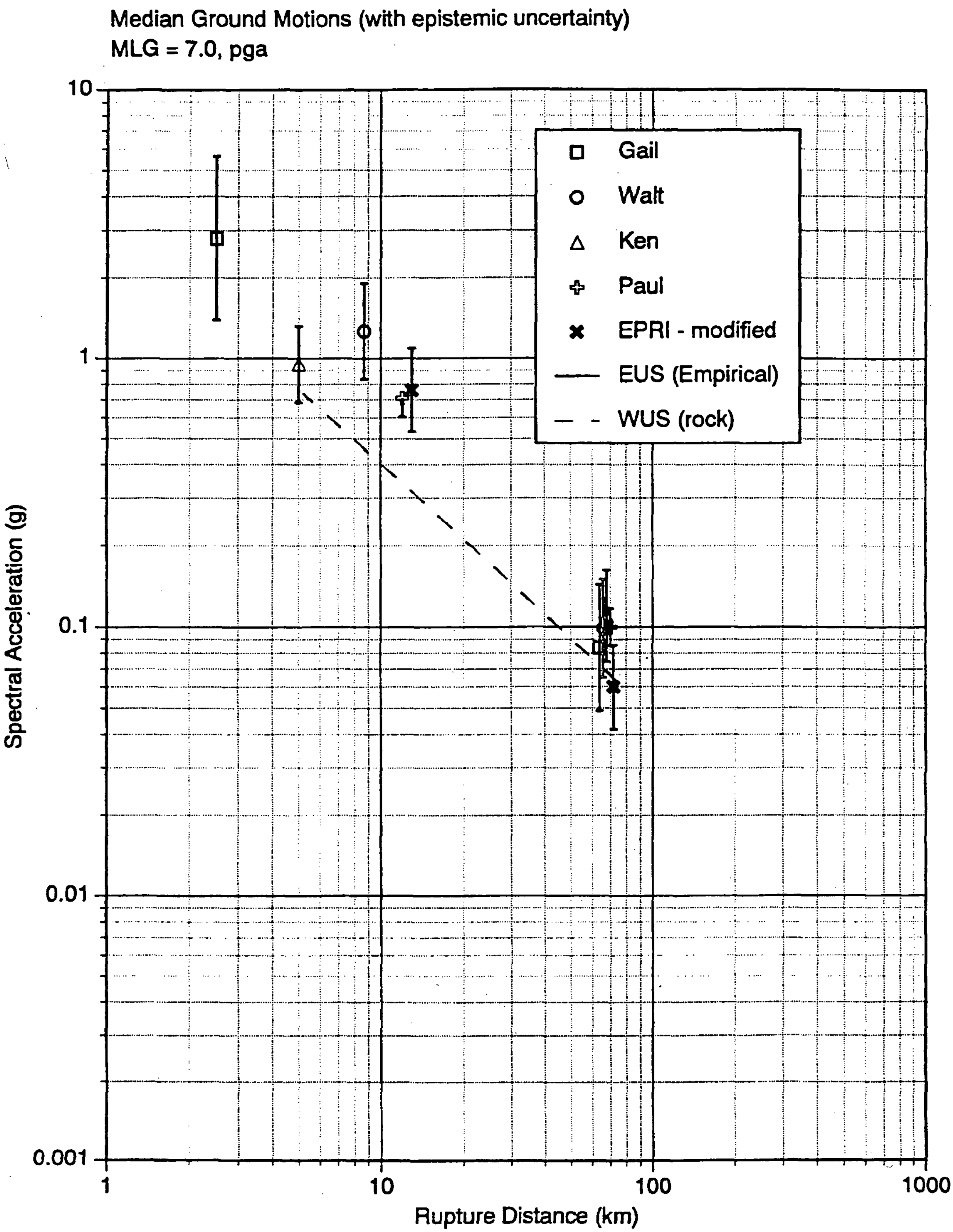




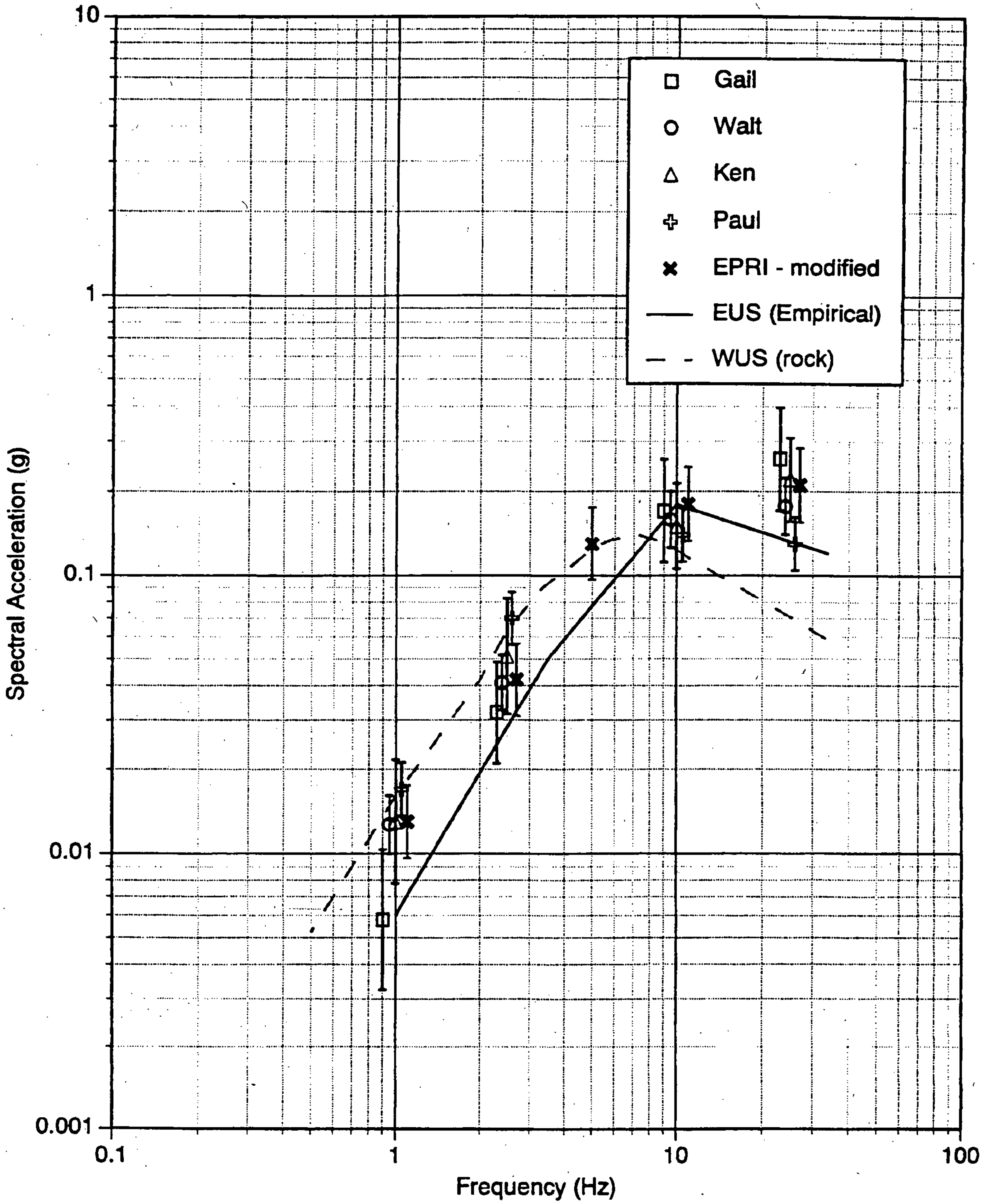
Median Ground Motions (with epistemic uncertainty)
MLG = 7.0, freq=10Hz
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical - Nahanni)
WUS (rock)
Spectral Acceleration (g)
100
10
1
0.1
0.01
1
10
100
1000
Rupture Distance (km)

Median Ground Motions (with epistemic uncertainty)
MLG = 5.5, pga

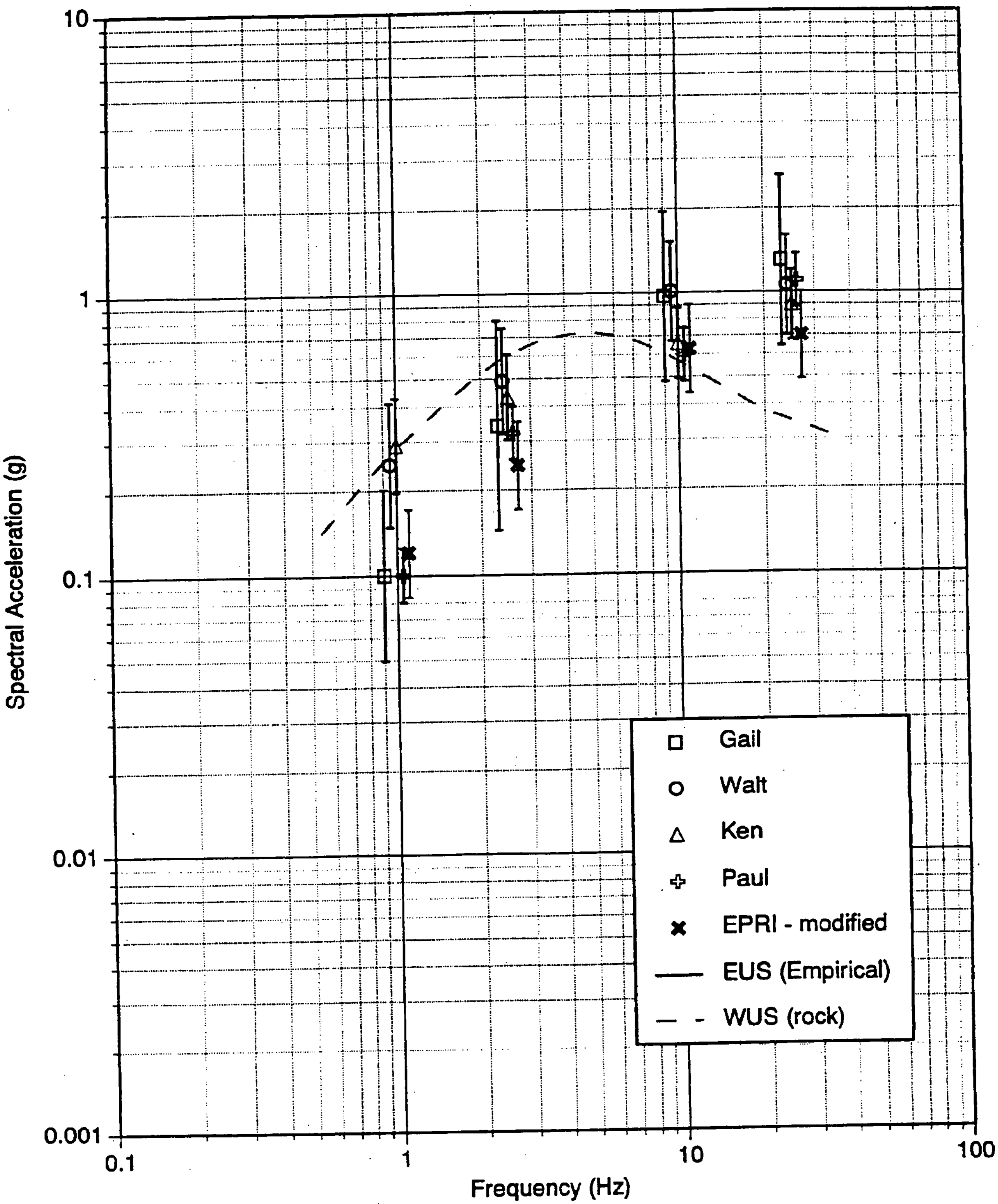


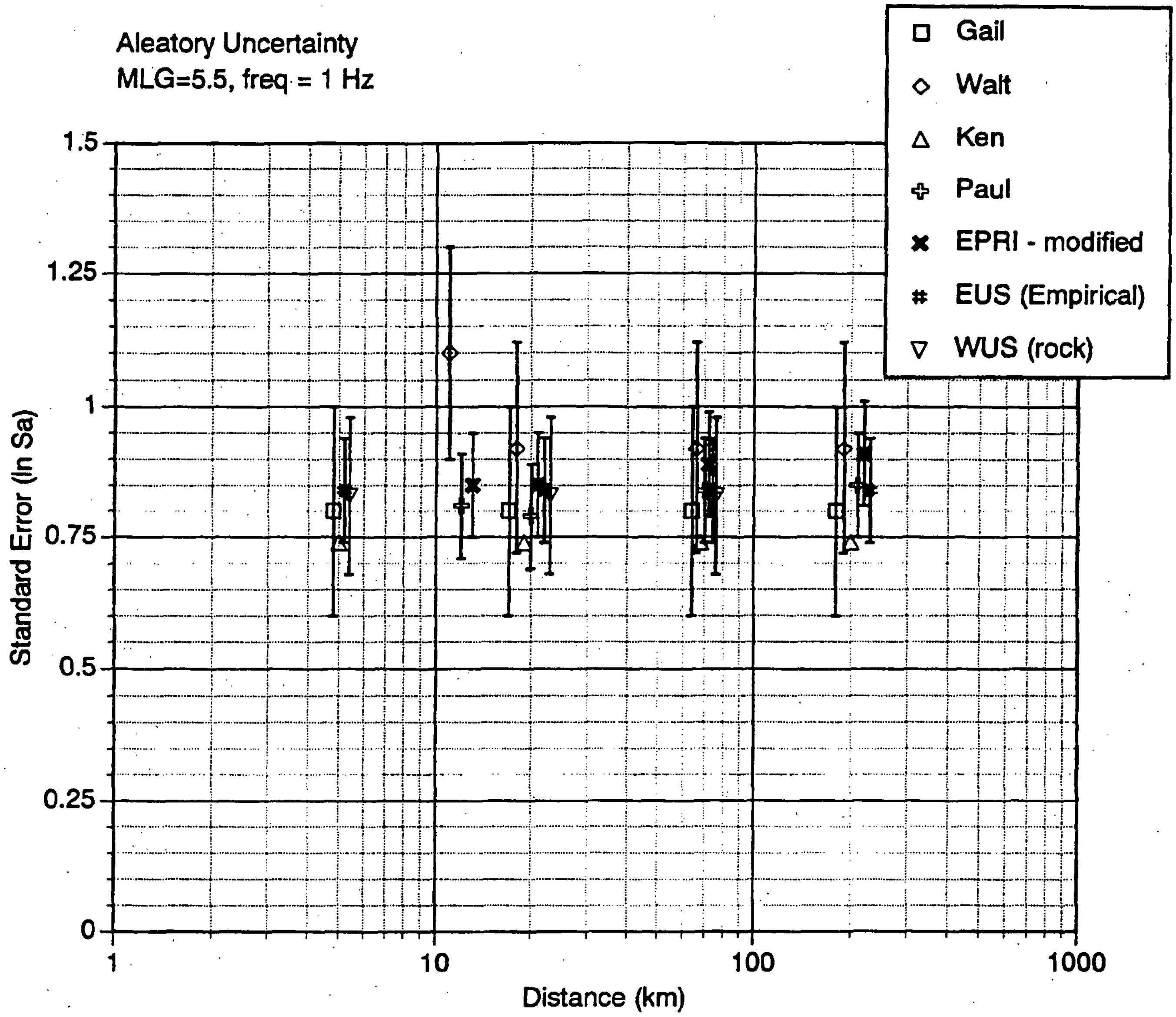

Median Ground Motions (with epistemic uncertainty)
MLG = 7.0, pga
10
1
0.1
0.01
0.001
Spectral Acceleration (g)
1
10
100
1000
Rupture Distance (km)
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)

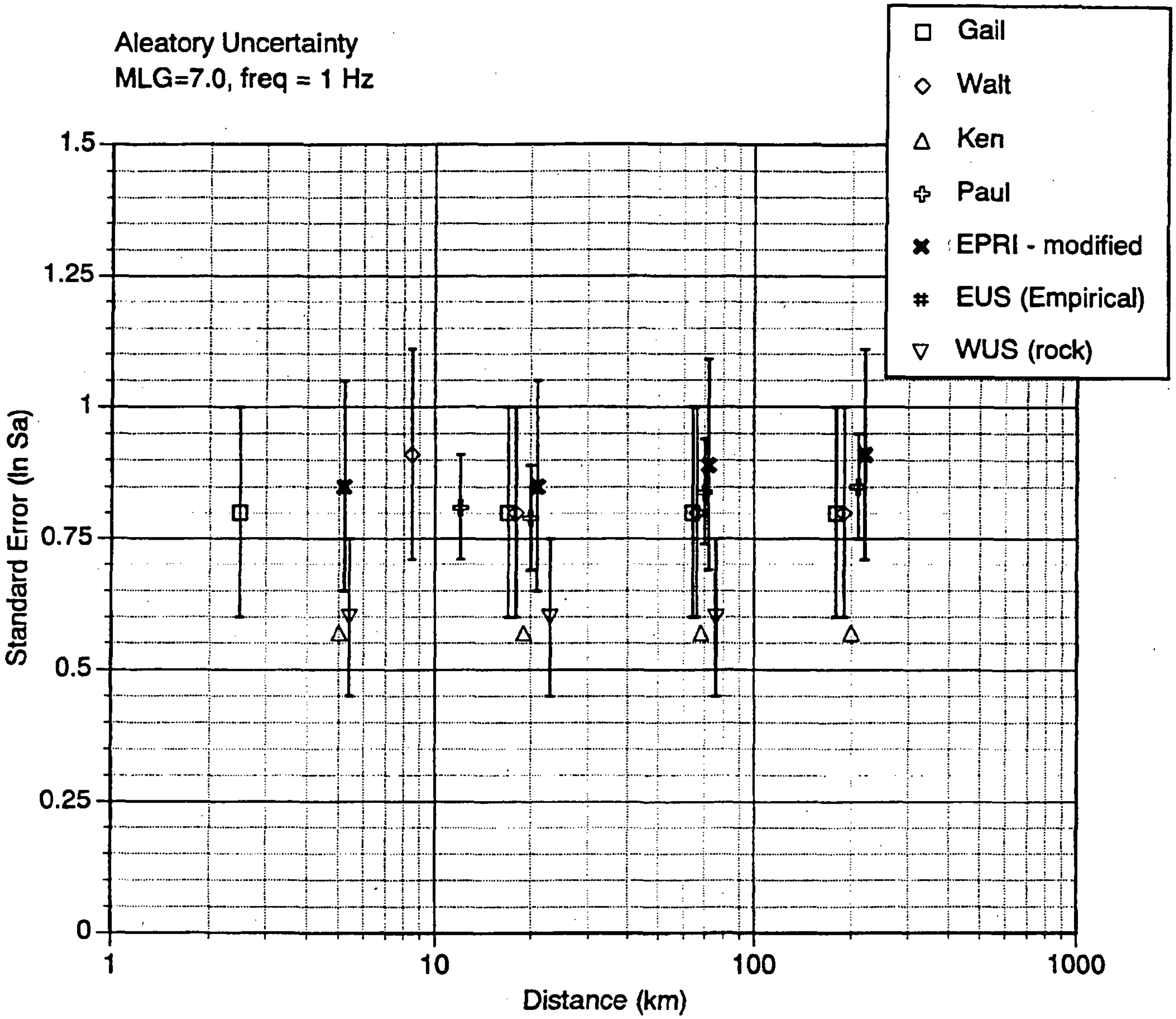
Median Ground Motions (with epistemic uncertainty)
MLG = 5.5, dist = 20 km

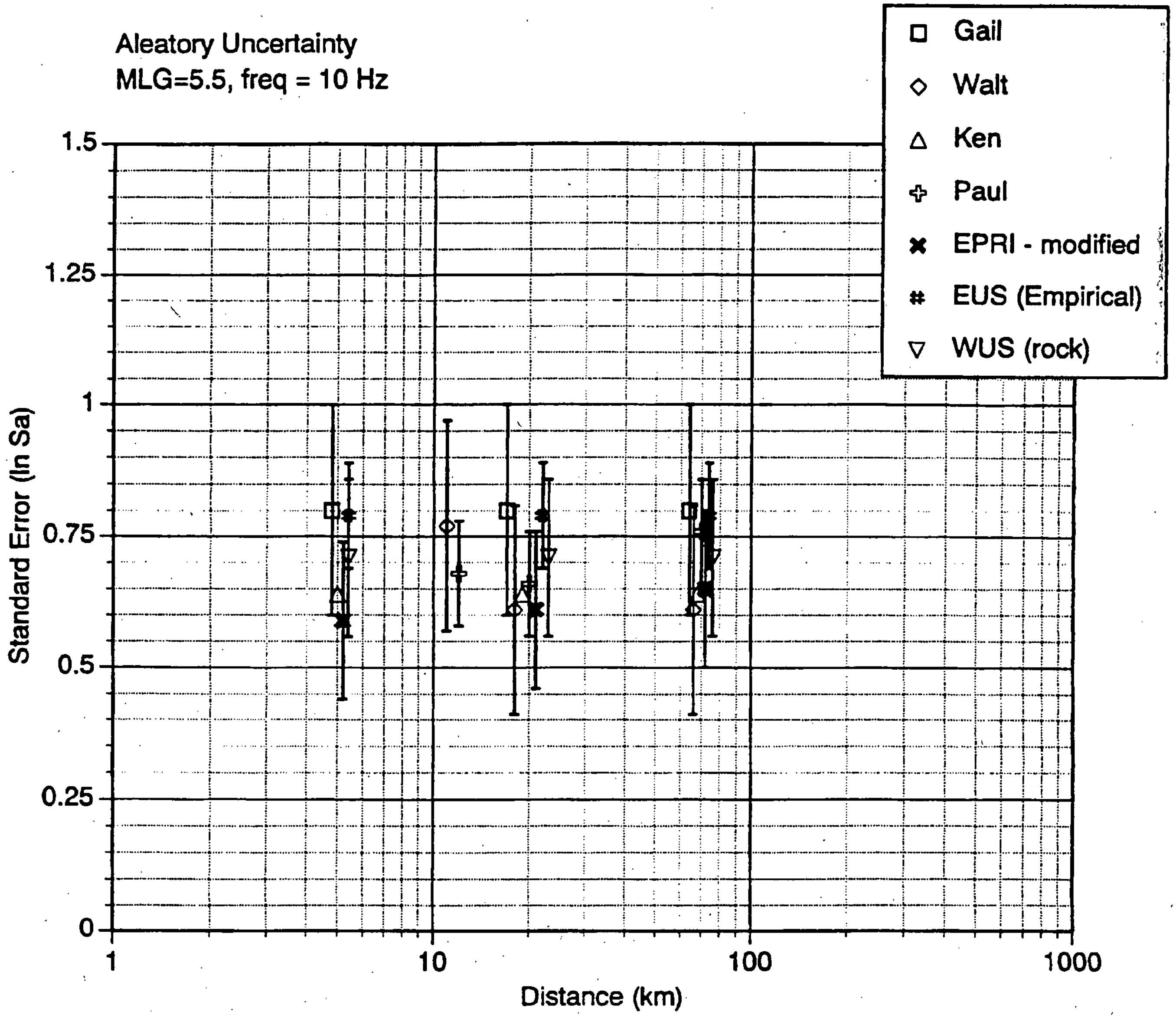


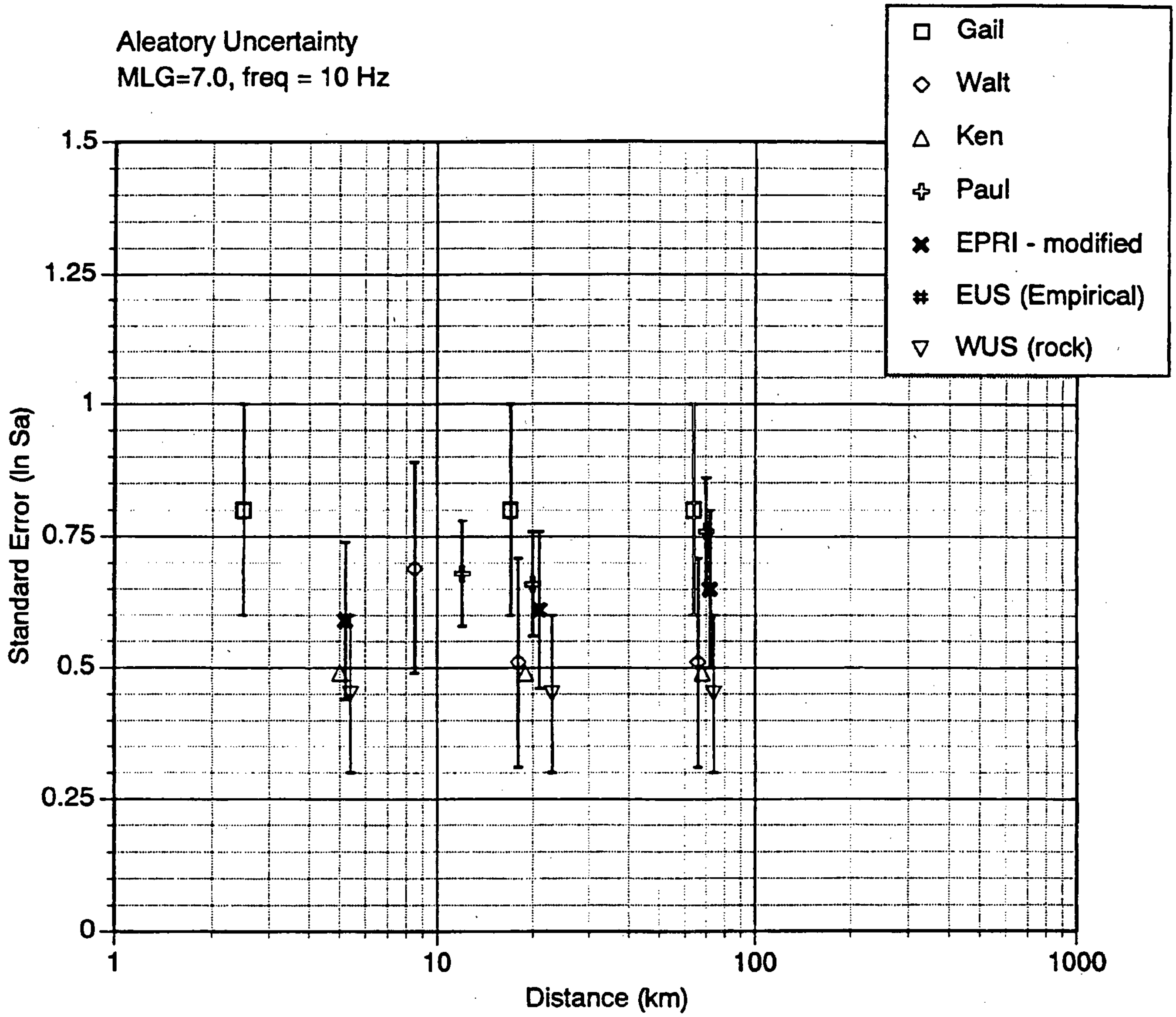
Median Ground Motions (with epistemic uncertainty)
MLG = 7.0, dist = 20 km

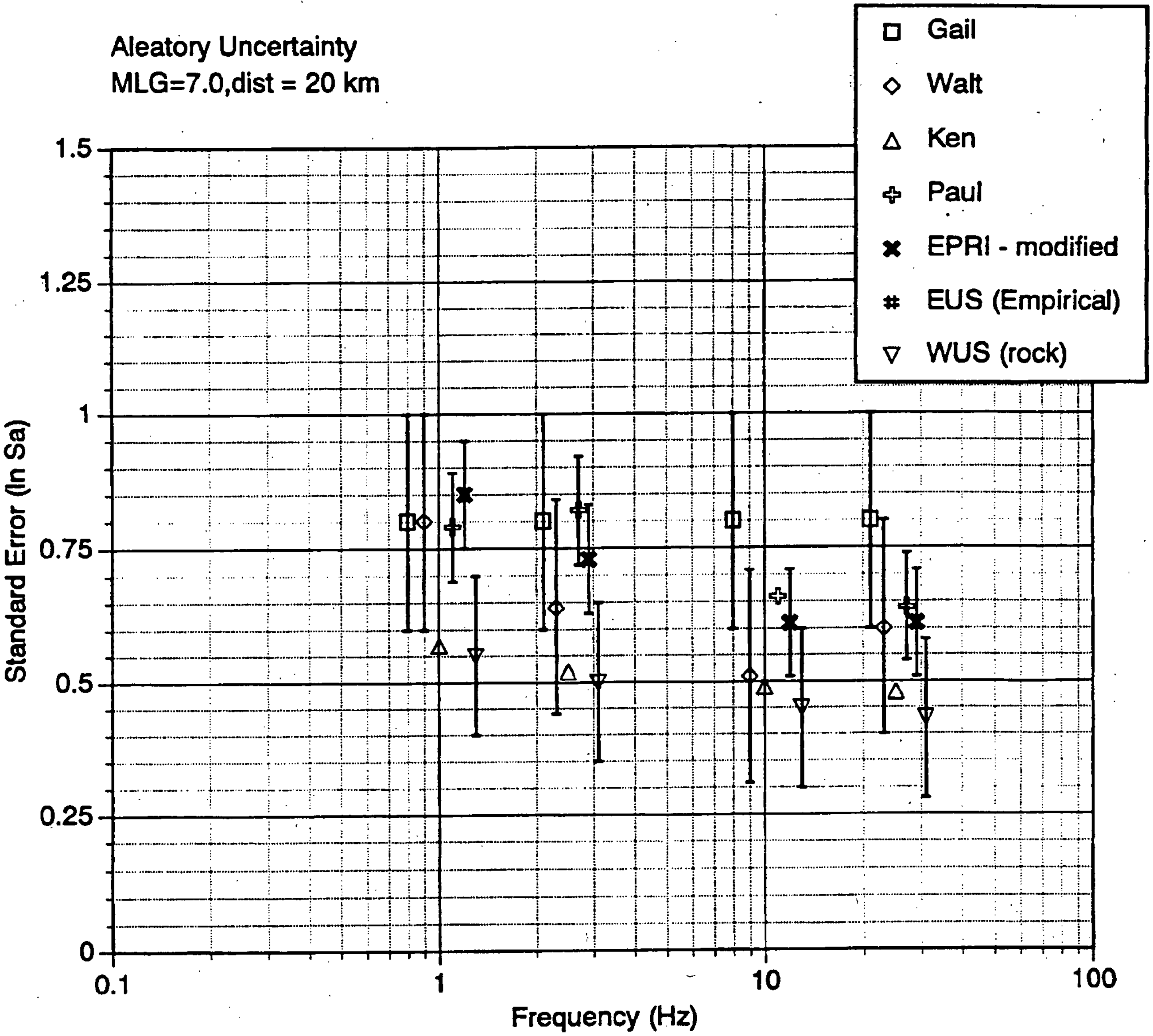


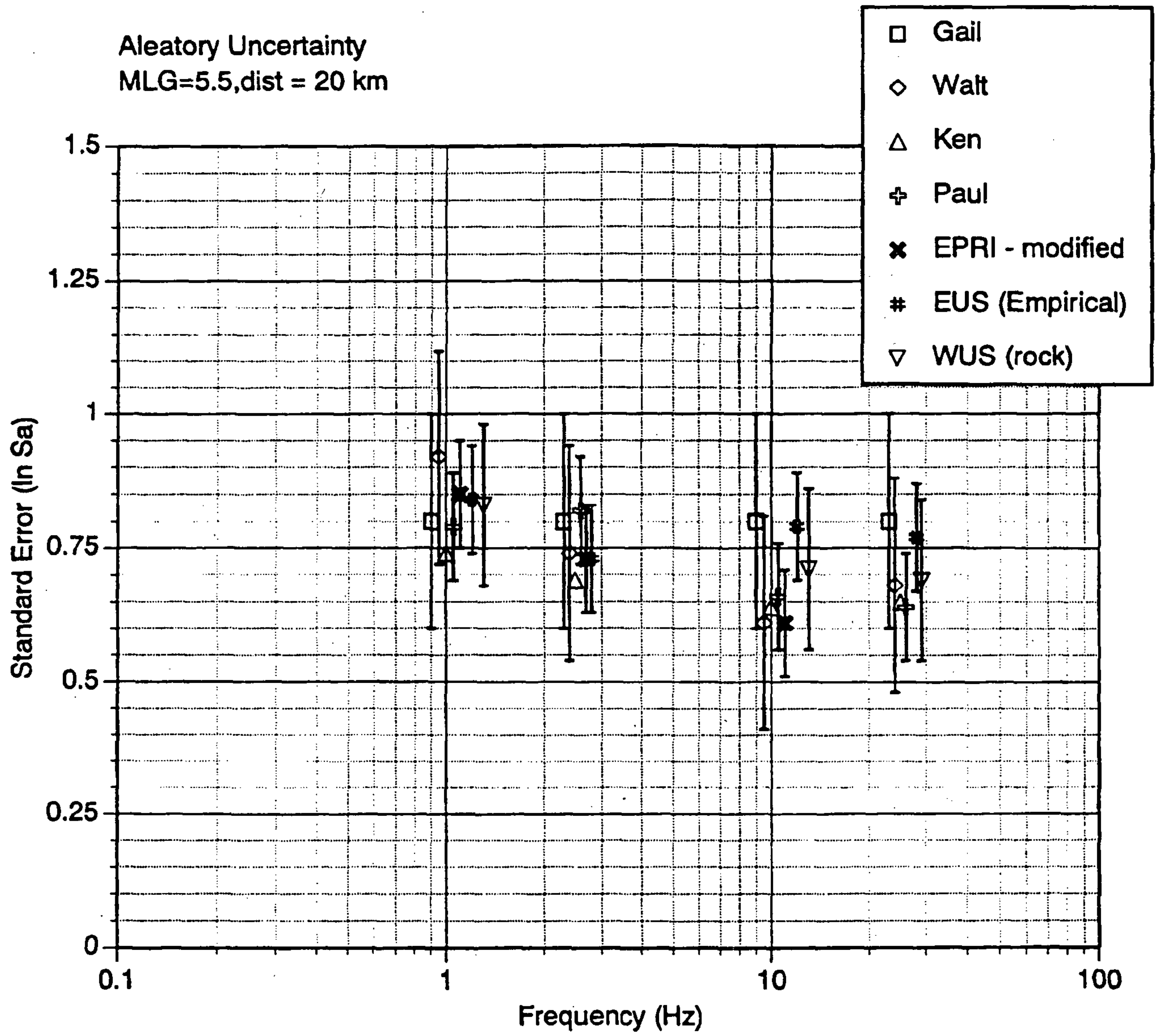

Aleatory Uncertainty
MLG=5.5, freq = 1 Hz
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
1.5
1.25
1
0.75
0.5
0.25
0
Standard Error (ln Sa)
1
10
100
1000
Distance (km)


Aleatory Uncertainty
MLG=7.0, freq = 1 Hz
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Standard Error (ln Sa)
1.5
1.25
1
0.75
0.5
0.25
0
1
10
100
1000
Distance (km)


Aleatory Uncertainty
MLG=5.5, freq = 10 Hz
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Standard Error (ln Sa)
1.5
1.25
1
0.75
0.5
0.25
0
1
10
100
1000
Distance (km)


Aleatory Uncertainty
MLG=7.0, freq = 10 Hz
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Standard Error (ln Sa)
1.5
1.25
1
0.75
0.5
0.25
0
1
10
100
1000
Distance (km)


Aleatory Uncertainty
MLG=7.0,dist = 20 km
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Standard Error (ln Sa)
0
0.25
0.5
0.75
1
1.25
1.5
0.1
1
10
100
Frequency (Hz)


Aleatory Uncertainty
MLG=5.5,dist = 20 km
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Standard Error (ln Sa)
1.5
1.25
1
0.75
0.5
0.25
0
0.1
1
10
100
Frequency (Hz)

because Atkinson assumed a shear wave velocity at the source that is different from the Mid-continent model used in the study. For example, at a depth of 10 km Atkinson used a shear wave velocity of 3.8 km/s, whereas the Mid-continent model has 3.5 km/s. To account for this difference, Atkinson's stress parameter for this focal depth is divided by the factor $(3.8^3/3.5^3)^{1.5}$ which is about 1.45. With this modification, these stress parameters can be used in the stochastic model with the Mid-continent velocity structure to yield high frequency spectral levels that are consistent with the empirical data base.

These high frequency stress parameters are plotted versus moment magnitude in Figure V.5-5. These data show a decrease of stress parameter for magnitudes greater than 6.0; however, a linear least-squares fit of log stress parameter versus magnitude is not statistically significant at the 95% confidence level. The stress parameters range from 37 to 488 bars. The mean natural log stress parameter is 4.79±0.16 (120 bars) with a standard error of a single observation of 0.71 on the natural logarithm of stress parameter.

V.5.2.2 Estimation of Brune Stress Drops

Brune stress drops may be estimated either in the time domain, by measuring the source duration and seismic moment, or in the frequency domain by measuring corner frequency and seismic moment. In a previous study sponsored by EPRI, Somerville et al. (1987) used the time domain approach to estimate median stress drops of 120 bars and 90 bars for large earthquakes in eastern and western North America respectively based on teleseismic data. Comparable values have been estimated in the present study by fitting the Fourier amplitude spectrum of near-source recordings to the omega-square spectral model given in Equation 3.1. The methodology, described below, was applied to both stable continental interiors and tectonically active regions.

V.5.2.2.1 Methodology

In the inversion scheme, earthquake source, path, and site parameters are obtained by using a nonlinear least-squares inversion of Fourier amplitude spectra for the stochastic model parameters in Equation 3.1 (Silva and Stark, 1992). The bandwidth for each amplitude

Used for alternative EPRI model

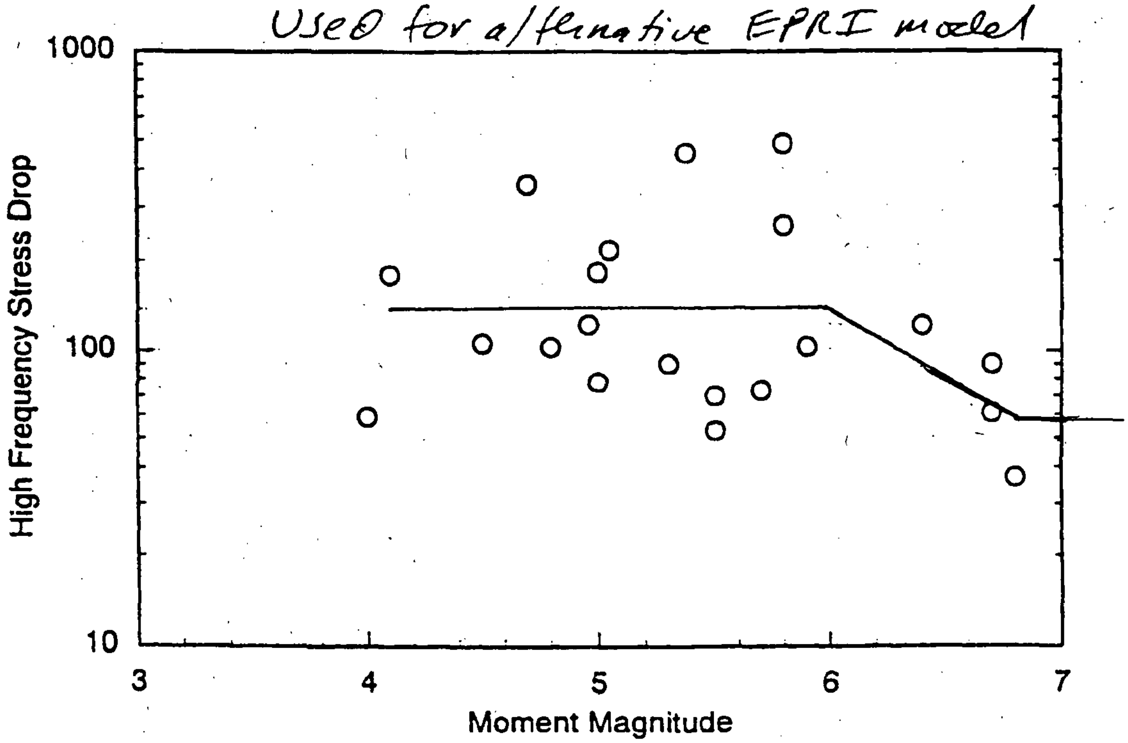


Figure V.5-5. High-frequency stress parameters modified from Atkinson (1993) to be consistent with the Mid-continent velocity structure.

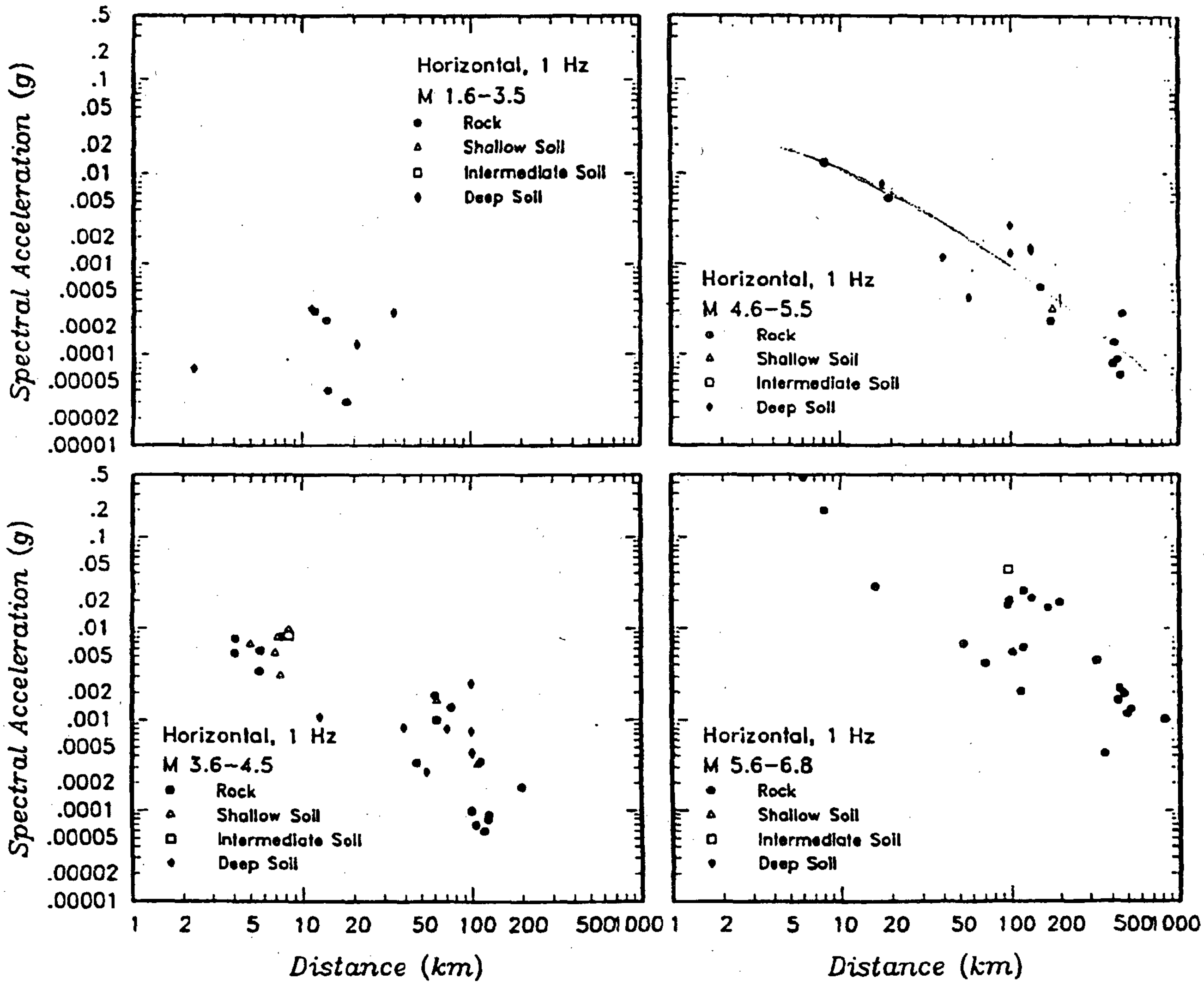


Figure 2-9. Peak horizontal spectral acceleration data for 1 Hz frequency from ENA ground motion data base.

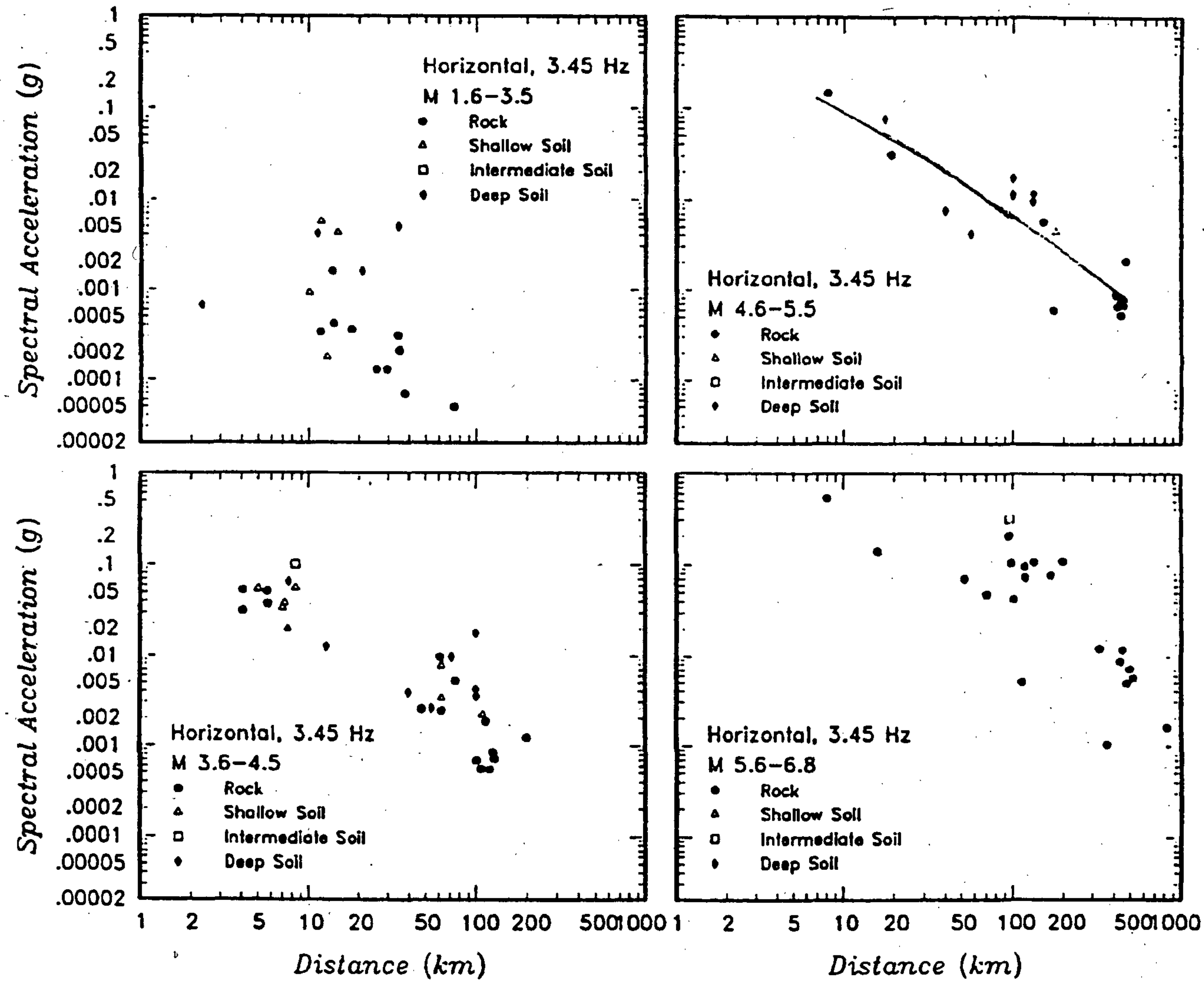


Figure 2-7. Peak horizontal spectral acceleration data for 3.45 Hz frequency from ENA ground motion data base.

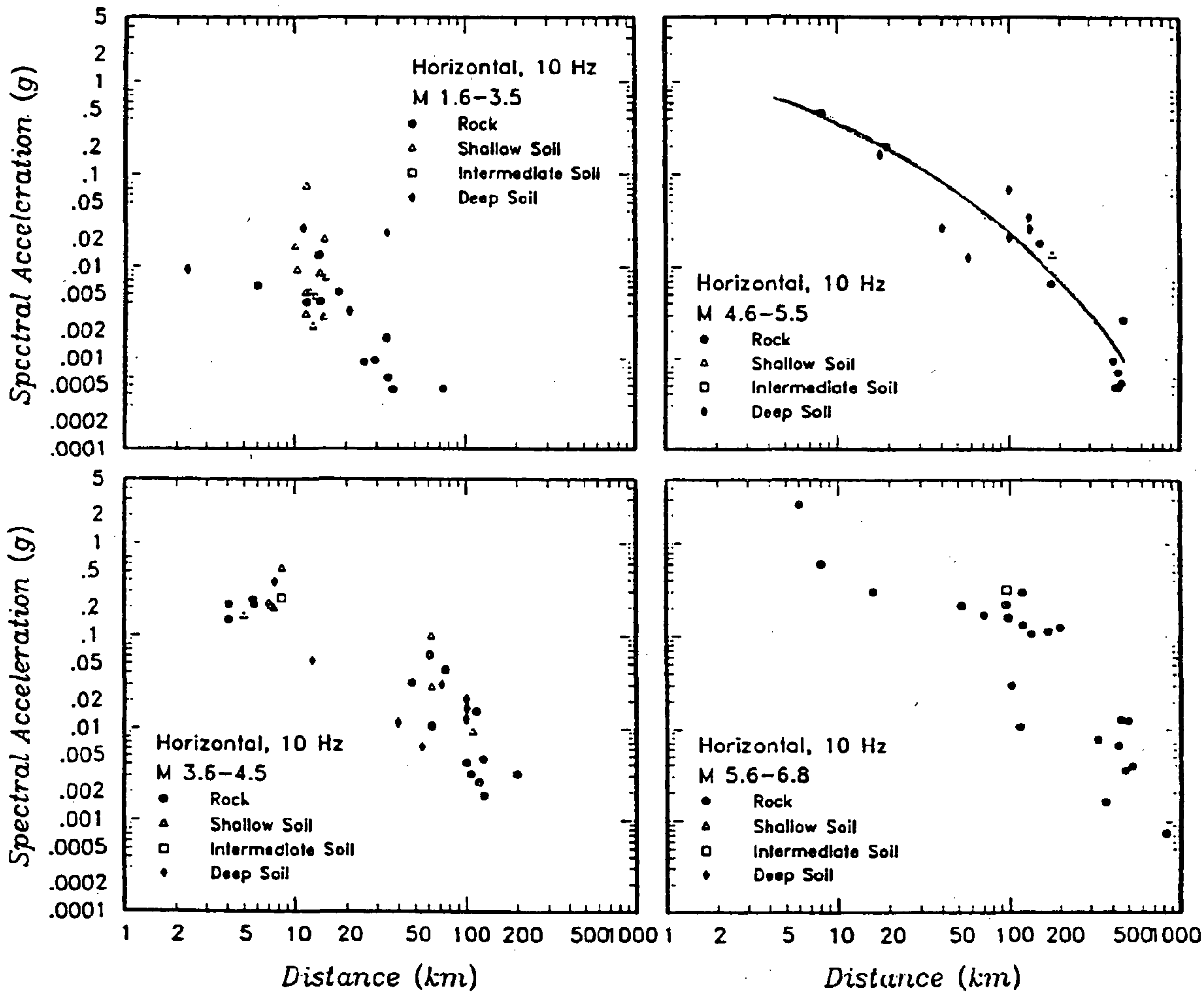


Figure 2-5. Peak horizontal spectral acceleration data for 10 Hz frequency from ENA ground motion data base.

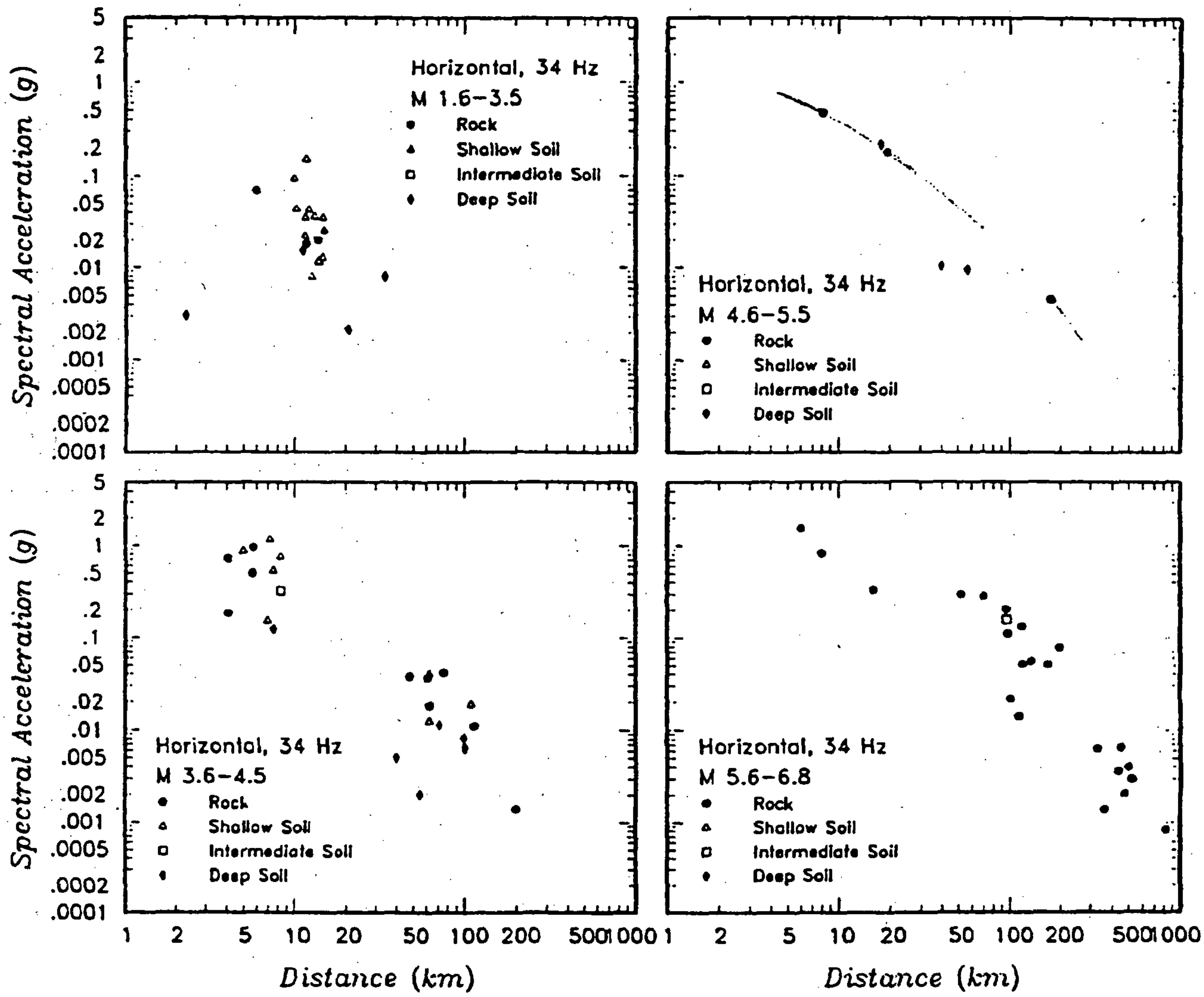


Figure 2-3. Peak horizontal spectral acceleration data for 34 Hz frequency from ENA ground motion data base.

Trouble points:
The magnitude of the events is not consistent between the proponents. In all of the models, the magnitude used in the model is not m_{Lg}, but moment magnitude. The conversion from m_{Lg} to moment magnitude is not consistent.

	Moment Magnitude			
m_{Lg}	Gail	Walt	Ken	Paul
5.5	5.0	5.0		5.2
7.0	7.0	7.0		6.4

I don't know what was used for Ken's model.

Strengths and Weaknesses of Each Model

1. Gail: Stochastic model w/empirical attenuation

Strengths:
The attenuation of the Fourier amplitude spectrum is modelled emprically. This avoids the need for assuming a wave propagation model. This is particulary helpful for the larger distances (100-200 km) for which they may be significant reflected waves.

The site condition is for ENA rock since that is the empirical data base. This avoids the problem of selecting a kappa value.

Weaknesses:
The source is modelled by a point source and it is unclear how this model should be applied to large events at short distances.

The rock sites are assumed to be hard rock (e.g. 2800 ft/sec shear wave velocity) but its not clear to me that they are this hard.

Does not include region specific deterministic crustal effects that may vary in ENA. This is a consquence of the strength of using emprical attenuation. If it is modelled empirically, then the empirical data (whereever it is collected) it assumed to apply to a specific site.

2. Walt: Stochastic model w/ray theory attenuation

Strengths:
Based on a standard model that is well understood by the profession. The small number of source parameters can be evaluated by others.

Attenuation of the Fourier spectrum includes deterministic effects of the crustal structure that can be modeled by 1-D ray theory results.

The model has been tested against earthquake recordings for the magnitude range of interest, including estimates of the modeling uncertainty (often missing in the uncertainty given for numerical simulations)

Weaknesses:
The ray theory results are senstive to source depth location if the source is located near a layer. This makes the attenuation less robust.

The source is modelled by a point source which may not apply to large events at short distances.

Overestimates the ground motion at 1-second by 50%. Forces me to correct for bias (assuming that the model will be wrong for future earthquakes as well) or have a potential significant overprediction. This is most likely a consequence of using a simple source model (e.g. one-corner model) vs a more complex model (e.g. two-corner).

3. Ken: Hybrid empirical

Strengths:
The main strength of this method is that is allows the near-source effects observed in WUS empirical data to be transported to the EUS. Since the modifications are all scale factors, the models used to modifiy the ground motion only need to be accurate in a relative sense (not absolute).

Weaknesses:
The main weakness of this method is the additional transformations that are needed. The WUS soil ground motion is transformed to WUS rock ground motion which is then modified for EUS crustal effects.

The uncertainty of the median values of these transformations was estimated as part of the modeling epistemic uncertainty, but there should be an increase in the aleatriy uncertainty as well due to the aleatory uncertainty of estimating rock ground motions from soil ground motions. I think that this additional aleatory uncertainty is quite large.

No validation of the method is given. How well does this method work for small magnitude (e.g. M=5) events?

Documentation not complete.

4. Paul: Advanced numerical modeling (reduced empirical GF)

Strengths:
The strength of this approach is that it provides a method for transporting empirical Green's functions from a specific site and source to other sites and sources.

The model accounts for deterministic effects of the crustal structure that can be accounted for by 1-D models of the crust.

The model has been tested against earthquake recordings for the magnitude range of interest, including estimates of the modeling uncertainty (often missing in the uncertainty given for numerical simulations)

The radiation pattern is represented empirically so that if the radiation pattern is coherent, then it is included implicity in the model, but if it is not coherent then it excluded implicity. This gets around arguements about whether or not the radiation pattern should be included in the numerical simulation.

The model uses a finite fault source so it should be applicable to large events at short distances (e.g. M=7, R=5 km)

Weaknesses:
The complications in wave propagation (e.g. scattering, 2-D and 3-D structure effects) for the new site are assumed to be captured in the selected empirical source functions, regardless of distance. Since the empirical source functions are from nearby events (< 15 km), scattering effects along a longer distance are not included.

The predicted ground motions depend critically on the selected source functions. The variability of the ground motion due to different source functions is not considered.

This method is more difficult to use and therefore harder to perform independent checks. The main difficulty is in setting up the empirical source functions.

The model has more parameters than the stochastic model. Many of the additional source parameters are fixed, but

The model is also more numerical intensive (e.g. computing the Green's functions).

The model uses a finite fault source so it should be applicable to large events at short distances (e.g. M=7, R=5 km)

Weaknesses:
The complications in wave propagation (e.g. scattering, 2-D and 3-D structure effects) for the new site are assumed to be captured in the selected empirical source functions, regardless of distance. Since the empirical source functions are from nearby events (< 15 km), scattering effects along a longer distance are not included.

The predicted ground motions depend critically on the selected source functions. The variability of the ground motion due to different source functions is not considered.

This method is more difficult to use and therefore harder to perform independent checks. The main difficulty is in setting up the empirical source functions.

The model has more parameters than the stochastic model. Many of the additional source parameters are fixed, but

The model is also more numerical intensive (e.g. computing the Green's functions).

Use of hard Rock

Using hard rock (2800 ft/sec) is reasonable for this comparison, but I think that a better value would be the 2000 ft/sec since this seems to be a better average of the top 30m of rock at nuclear sites in the EUS as noted by Walt.

I would like to know what the velocities are at the sites which recorded the data in Gail's data set. She has assumed that that are applicable to 2800 ft/sec. Are they really that hard?

Applicability to other regions

Based on the EPRI study, the ground motion attenuation in the Gulf coast (region 4 i Figure 5-14) is significantly different from the rest of the EUS. At distances of 80-150 km, there are also some differences in other regions: Central and Western Tennessee, Lake Superior, and Northern Great Plains (regions 6, 7, 11, and 13 in FIgure 5-14). The ground motion may be a factor of 1.5-2 lower at these distances for these regions.

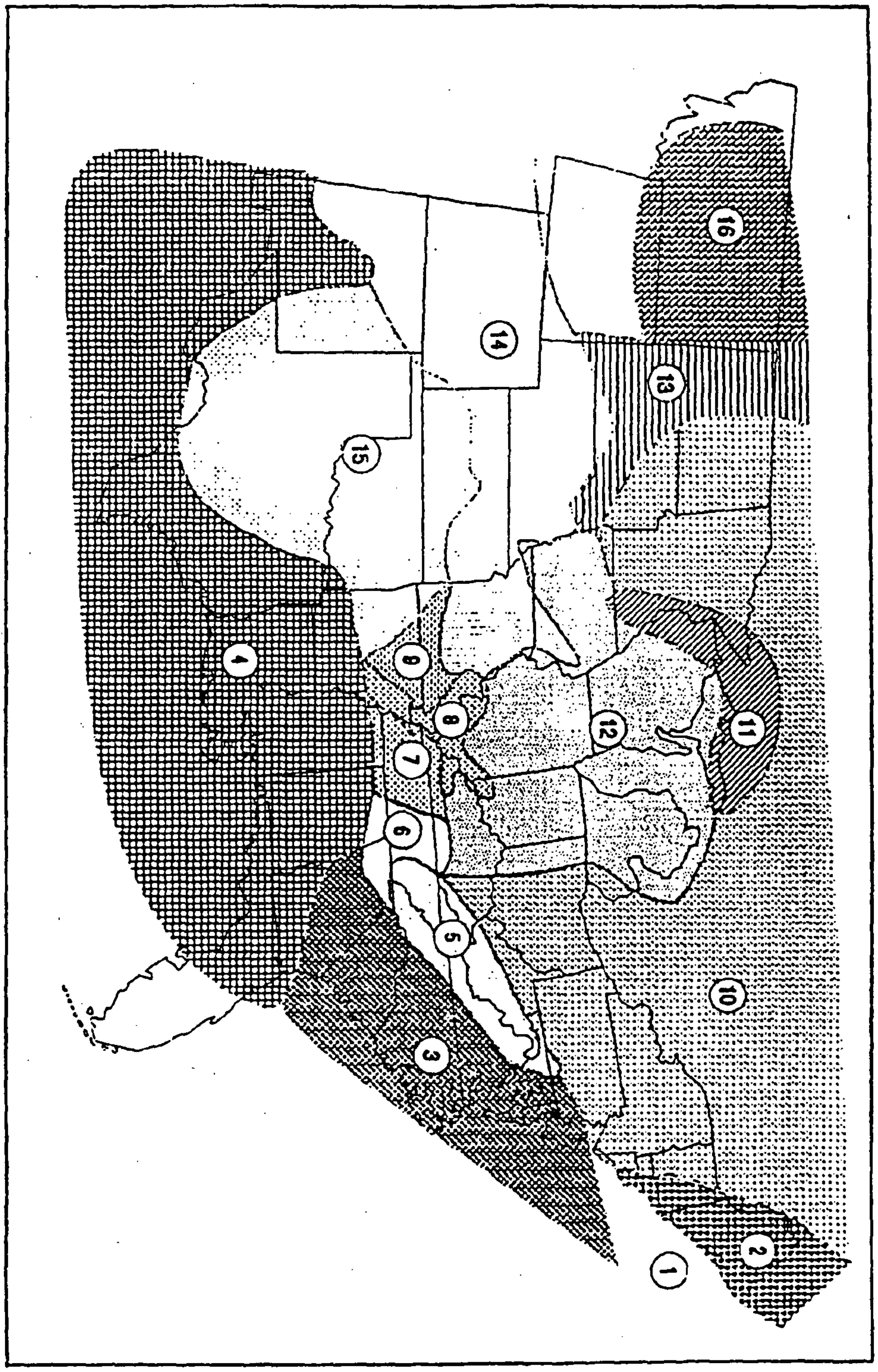


Figure 5-14. Crustal structure regionalizations for the EUS (Woodward-Clyde, 1991).

MEMORANDUM

TO: Dave Boore
Gabriel Toro

FROM: Gail Atkinson

DATE: July 21, 1994

RE: Revised SSHAC ground motion estimates

I have reviewed the ENA ground motion estimates submitted by the four model proponents (Atkinson, Campbell, Silva, Somerville/Saikia). Attempting to balance these estimates in some way and arrive at an opinion on the 'correct' values was an exercise in frustration. The approach I would like to take is something like this:

1. 'Calibrate' the various methods for a fixed set of input parameters, so we could first determine if the methods are equivalent. (Based on some comparisons that Somerville and I did, and a bit of blind faith in the other two methods, I am making the assumption that each of these methods will give the right answer if the inputs to the method are correct.)
2. Have each proponent provide brief but systematic (and quantitative) documentation of the data or reasoning behind each input to their model. Do an initial feedback loop on just these inputs, to arrive at appropriate alternative values and weights for the input parameters.
3. Then do ground motion predictions for various required alternatives and weight appropriately.

This approach is not possible with the information at hand. The obvious approach given simply the four sets of ground motion estimates is to weight the values in some way. Assuming that all methods have the potential to give correct answers, and all proponents have the potential to use their favorite method correctly, one might be tempted to use equal weights for the four sets of estimates. I am certain that this would be a mistake. The reason is that the estimates do not each contain independent evaluations of each of the required input parameters.

For example, a major difference in the 1-Hz estimates amongst proponents stems from the source model. My proposed two-corner source model is the wildcard here. The Silva estimates, following EPRI, use the traditional Brune model assumption. The Campbell estimates simply quote the EPRI model. From involvement with the EPRI project, I know that an examination of the shape of the source spectrum was beyond its scope. What I don't know from this material is what Silva or Campbell's opinion on source shape would be, had they specifically examined this issue in the course of developing their estimates. If I had such information, I might be more inclined to change my own opinion. Somerville's source model in not very transparent, in that it has an implicit

California shape, whatever that may be, adjusted for eastern fault dimensions. It may well be closer to my source spectrum, but it is difficult to say.

Another example of overlap between the estimates is the attenuation. The Atkinson attenuation is empirical, while both the Silva and Somerville attenuation, taken from the EPRI study, are based on detailed modeling with a common set of crustal models and focal depths; the Campbell estimates again quote the EPRI study. For kappa values, Silva, Somerville and Campbell all quote the values that Silva derived for the EPRI study.

In my revised estimates, I have tried to weight the alternative input parameters, rather than the proponents. This gets complicated, especially since there are also significant differences in the moments associated with the estimates of the various proponents (Somerville's moments differ significantly from those of Atkinson, Silva, and Campbell (I assume Campbell used the EPRI relations between moment and mLg)). Given the time available, I tried to balance the estimates based on judgement of the merits of their input parameters, using the infamous 'by eye' method. No doubt the results are nauseatingly subjective.

The considerations that went into the attached 'best-guess' ground motions, as derived from the four proponent sets, were as follows:

1. The 'truth' about the source model may lie somewhere in between my source model and the Brune model.
2. The Silva and Somerville models give a robust estimate of the decay of Fourier amplitudes with distance. The corresponding attenuation of response spectral amplitudes is less robust since their duration model does not account for the well-documented effects of scattering on duration, within the first 50 km. These effects are probably important for f>2 Hz. By comparison, the Atkinson attenuation of Fourier amplitudes is not as general, and may not be as applicable over the broader ENA region; however the Atkinson duration model is more appropriate, especially for f>2 Hz, so the time-domain attenuation may be more realistic for high-frequencies, at least within the first 50 km.
3. Based on ECTN records, a kappa of 0.006 is probably too high for truly hard-rock sites.
4. Campbell's use of NEHRP (ie. political) correction factors to de-amplify WUS soil to obtain WUS rock has probably resulted in overestimation of WUS rock. I hope Silva will enlighten us on this point, but my understanding of the NEHRP factors is that they represent the general reluctance of the engineering community to accept the realities of soil amplification. I also think Campbell's uncertainties in the median amplifications used to adjust WUS soil to WUS rock are too low if they are based only on uncertainties in classification.

5. I do not believe that stochastic point-source estimates should be made for distances less than 10 km (median focal depth for ENA), particularly for large magnitudes. Since I see other proponents have taken liberties with the 5 km estimates, I have too. My new 5 km estimates are closer to the 10 km stochastic values.
6. I think some of the proponents (I wouldn't name names, of course, but their initials are PS, WS and KC) have been overly optimistic about our epistemic uncertainties, particularly for large ENA events at close distances.
7. Somerville's mLg 7 event had a much smaller moment than that used by the other proponents.
8. Overall, many of the input assumptions shared by the other proponents, taken from the EPRI study, might be considered more of a 'consensus' view than my own opinions. However my estimates, taken from the Atkinson-Boore study, contain more extensive empirical validation of both input parameters and predictions than does the EPRI study. So I think I have most of the data in my corner, although one might argue with my interpretation of those data.

I look forward to a lively debate at the workshop.

Gail Atkinson

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page __ of __

Expert: Gail Atkinson

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.05	0.5
	epistemic uncertainty	parametric (ln)	0.3	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.9	0.9
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.01	0.15
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.003	0.04
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude		0.001	0.025
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 2: Page __ of __

Expert: Gail Atkinson

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.045	0.4
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 3: Page __ of __

Expert: Gail Atkinson

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.6	2.2
	epistemic uncertainty	parametric (ln)	0.3	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.17	0.97
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.025	0.2
	epistemic uncertainty	parametric (ln)	0.2	0.4
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 4: Page __ of __

Expert: Gail Atkinson

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.23	1.2
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 5: Page __ of __

Expert: Gail Atkinson

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.38	1.4
	epistemic uncertainty	parametric (ln)	0.3	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.014	0.1
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

GROUND MOTION ESTIMATES

Don Bernreuter

Epistemic Uncertainty

My epistemic uncertainty is large, for a number of reasons:

1. Uncertainty about which is the correct source model.

   Generally, I think that the ω^2 model is better than other models, but there are a number of possible variations of ω^2 models. For example:

   i. Brune model (single low frequency corner).

   ii. New model of two corner frequencies proposed by Atkinson & Boore. Seems to have a significant impact on both high and mid-range spectral amplitudes.

   iii. The Joyner two-corner model is also a possibility, but its main impact is to strongly saturate the GM at some critical M.

   iv. For larger events, M>6 and certainly for M>6.75 none of the simple source models (i, ii, or even iii) appear very viable. These all assume only one large dislocation with constant properties, etc. For large events, I see several small strong regions of energy release superimposed on a larger region of lower energy release. I suppose actually model (ii) might represent such a case, but it's not clear how f_A, f_B, and c should be chosen and what is the sensitivity of the GM to variations in these parameters.

   For larger events, the advanced numerical modeling approach is attractive. However, in my view, there is still considerable uncertainty about the source function Somerville uses, how it is distributed over the fault surface, rupture velocities, etc. None of these are discussed by Somerville.

In general, I would expect the results from a simple Brune-like model to be too high for large events. The new Atkinson double-corner model might better represent the complexity of large earthquakes. The problem here for me is that it appears to give even higher spectral amplitudes in the 2 — 50 Hz range than the simpler Brune single-corner model and certainty much higher than Somerville's model.

v. Uncertainty as to the relation between seismic moment and corner frequency — Mo $f_c^a = c$. a is often taken as 3 leading to a constant $\Delta\sigma$ with increasing magnitude. Nuttli and others suggest that a = 3.75 to 4 fits the data better, and leads to an increase in $\Delta\sigma$ with Mo. This can have a significant impact on scaling with magnitude or increasing Mo. Intensity data models suggest a strong scaling with increase Mo. If one includes the data given in Atkinson's for m_{Lg} down to 3.5, which seem to have fc less than 10 Hz, one certainly sees a Mo $f_c^{3.75} = c$ scaling. This relation Mo $f_c^a = c$ implies a strong similarity between earthquakes of increasing size as a result of the simple Brune model. As I noted in (iv), I do not think that this is the true state of nature and the scaling by such a simple law breaks down for larger earthquakes.

2. Uncertainty about the true median value of stress drop.

Its not at all clear to me that $\Delta\sigma$ obtained by different approaches is giving estimates of the parameter needed to compute strong ground motion. In the far-field, we see an averaged scaling parameter. For small earthquakes, this might be okay, but for larger earthquakes, I do not see a uniform release of energy. Thus, closer to the fault we will see considerable variation depending upon the details of the rupture process and energy release. These details control the high-frequency strong ground motion.

In addition, I ask myself if $\Delta\sigma$ has a continuous distribution. Or, are we seeing a bi-modal or tri-modal behavior? Maybe we have a class of earthquakes with $\Delta\sigma$ centered around 100 — 200 bars and a class of earthquakes in an area where the faults are well healed in the 500 bar range. These are two very different models for $\Delta\sigma$.

In Somerville's model, $\Delta\sigma$ is not directly used and is a function of the structure of the dislocation rise time and complexity of the function used to represent the dislocation.

3. Relation between m_{Lg} and Mo.

This leads to a significant uncertainty. I have a problem with the approach of using a body wave spectra to compute a m_{Lg} to relate to Mo. In addition, there is significant differences between m_{Lg} and Mo used by Atkinson, Somerville and Silva. For m_{Lg} of 7, Atkinson has a log Mo = 26.6, whereas Somerville has log Mo = 25.6, or a factor of 10 lower corresponding to a M = 6.4 as compared to M = 7 used by Atkinson. Nuttli developed an empirical relation which would give log Mo = 27.2 for m_{Lg} = 7. Silva appears to have a larger Mo for m_{Lg} = 7 than Atkinson's approximately M = 7.3. At m_{Lg} = 5.5, the estimates for Mo are closer.

4. Uncertainty geometric attenuation and layering effects.

   Some models include layering, etc. in them, in particular Somerville's estimates. Atkinson uses a strong term for geometric attenuation in the first 70 km as —1.1 log r compared to —log r for others. Including layering, or not including it, can have a large impact on the estimates. Personally, I think the models with structure greatly over estimate this effect as compared to the real world.

Values for Sigma

I think the above list covers the most important elements of my epistemic uncertainty. The problem is how to quantify the above. Some of the above uncertainties are related. I will try and factor out this, but naturally, it is hard to do. The various comparisons provided really are not too much help in sorting out the individual factors because they are not for the same case. It would have been nice if Silva, Atkinson and Somerville each modeled the same small Mo and the same large Mo earthquakes, rather than having different Mo's, etc. so we could see the impact of the three different "source" models.

The largest source of epistemic uncertainty appears to be in the Mo — m_{Lg} relation at larger magnitudes. As I look at the various relations, it would appear to lead to about a factor of 10 — 15 in the estimate of Mo, say from low to high or approximately a factor of 3 — 5 or ground motion. This would lead to a σ_M ~ 0.8. The uncertainty is larger for m_{Lg} = 7 than for 5.5 at 5.5 σ_M ~ 0.4.

The Atkinson two-corner model appears about 20% higher in the 10 Hz PGA range than the Brune model and about 20% lower at 1 Hz. It's hard to tell how much difference Somerville's model makes compared to the others. As noted my uncertainty is larger for large events than for smaller events. Variations in the

the definition of duration also adds some uncertainty along with the other parameters (other than stress drop) also add a little uncertainty. Overall I would estimate $\sigma_{SM} \sim 0.25$ excluding stress drop and Mo $f_c^a = c$ for $m_{Lg} \sim 5.5$. For $m_{Lg} \sim 7$ mu uncertainty is much larger because I think all of the models are a poor representation of nature. A factor of 2 or so seems reasonable here but with little justification as it is hard to come by. Hence $\sigma_{SM} = 0.7$ for $m_{Lg} \sim 7$.

How the corner frequency or stress drop scales with Mo is a large potential source of uncertainty for $m_{Lg} \sim 7$. At $m_{Lg} = 7$ it could introduce a factor of 5 difference. However, as I noted I discount this because I do not think the source model is applicable. At $m_{Lg} = 5.5$ the effect is less important — but more real. Yet much of this — at least at $m_{Lg} = 5.5$ may be related to the two corner model or what-have-you.

If I start combining the above sigmas the resultant is much too large. Clearly, they are not all independent. Thus the final Numbers given are based on the above considerations and my judgment as to what seems reasonable. I am also influenced by Campbell and Silva's values for the aleatory uncertainty estimates. My estimates are larger for 1 hz than 10 Hz or PGA because the models are not very good at 1 Hz and for large events.

Aleatory Uncertainty

Based on what I know about ~~E~~WUS data with some increase due to a wider range of stress drops in the EUS. As noted I am also influenced by EPRI's work (Silva) and Campbell's WUS work.

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page __ of __

Expert: BERNREUTER

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.036	0.8
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	1.0
	aleatory uncertainty	median σ	0.7	0.8
		uncertainty in σ	0.4	0.4
20 km	median amplitude		0.015	0.3
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.9
	aleatory uncertainty	median σ	0.7	0.8
		uncertainty in σ	0.3	0.4
70 km	median amplitude		0.003	0.09
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.9
	aleatory uncertainty	median σ	0.7	0.8
		uncertainty in σ	0.2	0.4
200 km	median amplitude		0.001	0.03
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.9
	aleatory uncertainty	median σ	0.7	0.8
		uncertainty in σ	0.2	0.2

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 3: Page __ of __

Expert: BERNREUTER

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.5	2.0
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.9
	aleatory uncertainty	median σ	0.7	0.7
		uncertainty in σ	0.3	0.3
20 km	median amplitude		0.16	0.98
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.8
	aleatory uncertainty	median σ	0.6	0.6
		uncertainty in σ	0.2	0.3
70 km	median amplitude		0.039	0.3
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.8
	aleatory uncertainty	median σ	0.6	0.6
		uncertainty in σ	0.2	0.3
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 4: Page __ of __

Expert: BERNREUTER

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.25	1.15
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.8
	aleatory uncertainty	median σ	0.65	0.6
		uncertainty in σ	0.2	0.3
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 5: Page __ of __

Expert: BERNREUTER

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.34	1.0
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.9
	aleatory uncertainty	median σ	0.7	0.7
		uncertainty in σ	0.2	0.3
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.02	0.11
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.8
	aleatory uncertainty	median σ	0.6	0.6
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

EXPERT EVALUATION OF GROUND MOTIONS IN THE CENTRAL AND EASTERN UNITED STATES

SECOND SSHAC GROUND-MOTION WORKSHOP
Palo Alto, California
July 27-28, 1994

Kenneth W. Campbell
EQE *International*, Inc.
Evergreen, Colorado

INTRODUCTION

I used a weighted estimate of ground motions derived from the Hybrid Empirical Model, the Stochastic Simulation (EPRI) Model, the Stochastic Simulation (Atkinson) Model, and the Advance Numerical Model to produce the recommended median values of PGA and PSA and their associated uncertainty for the Central and Eastern United States (CEUS).

As stated in the instructions for the second SSHAC Ground Motion Workshop, the estimates were made for a hypothetical site located in the northeastern United States and southeastern Canada. The site conditions are described as Eastern United States Rock (i.e., a site having an average shear-wave velocity of 2800 m/sec over the top 30 m). The magnitudes, distances, and ground-motion parameters for which estimates were provided are given in Table 1.

METHODOLOGY

A description of the methodology used to develop the ground-motion and uncertainty estimates is given below.

Weights

I assigned relative weights to each set of models, magnitudes, and distances based on the proponents' and my own opinion on the strengths and weaknesses of each model. A brief explanation of how these weights were assigned is given below. Because of the limited amount of time that was available, these assignments are rather crude and are meant to indicate the general process by which these weights should be determined. The actual weights that I used to develop the estimates are presented in Table 1.

Hybrid Empirical Model

1. I gave this model relatively more weight at 5 km because it is well constrained by near-source recordings. All of the other models were based on a point-source representation of the earthquake, which is not valid at close distances, especially for the larger magnitudes. Relatively more weight was given to this model for the magnitude 7 event than for the magnitude 5.5 event, since the point-source representation is particularly poor for an earthquake of this size.

2. I would have given even more weight to this model at close distances, except that it may have a tendency to underestimate high-amplitude ground motions because of inherent nonlinear soil and soft-rock responses that may have not been completely removed from the original predictions.

3. I gave this model zero weight at 200 km, since the Western United States (WUS) attenuation relationships on which it is based are not reliable beyond about 100 km. Note, however, that the predicted values at this distance are not all that inconsistent with those derived from the other models.

Stochastic Simulation (EPRI) Model

1. I gave relatively less weight to this model at 5 km, especially for the magnitude 7 event, because it is based on a point-source representation of the earthquake.

2. I gave relatively less weight to this model at 200 km because it uses a simplified model to account for enhanced ground motions due to critical reflections that are important at this distance.

Stochastic Simulation (Atkinson) Model

1. I gave relatively less weight to this model at 5 km, especially for the magnitude 7 event, because it is based on a point-source representation of the earthquake.

2. I gave relatively more weight to this model at 200 km because it is based on observed attenuation characteristics at this distance.

Advance Numerical Model

1. Although this model incorporated finite fault effects, I gave it relatively less weight at 5 km, especially for the magnitude 5.5 event, because it appears to have been applied in such a manner that the median closest distance is larger than this target value.

2. I gave this model relatively less weight at magnitude 7 because it used a moment magnitude that was 0.6 to 0.8 units lower than was used by the other proponents and, hence, may be unconservative.

3. I gave this model relatively more weight at 200 km because it incorporates the most comprehensive modeling of the critical reflections that are important at this distance.

Median Ground Motion

I estimated median ground-motions by taking a weighted average of the logarithms of the median estimates (i.e., the geometric mean) provided by the four models. These estimates are summarized on the accompanying forms.

Epistemic Uncertainty

I did not attempt to separate the parametric and modeling components of the epistemic uncertainty. When separate estimates for these two components were provided by the proponents, I simply combined them by adding their variances. I estimated the total epistemic uncertainty by adding the weighted average of the epistemic variances provided by the four models to the weighted average of the variances of the logarithms of the median predictions derived from the four models. These estimates are summarized on the accompanying forms.

Aleatory Uncertainty

I estimated aleatory uncertainty by taking a weighted average of the aleatory variances provided by the four models. These estimates are summarized on the accompanying forms.

Epistemic Uncertainty on the Aleatory Uncertainty

I estimated the epistemic uncertainty on the aleatory uncertainty by adding an estimate of the variance of this uncertainty to the weighted average of the calculated variances of the aleatory variances provided by the four models. The former was estimated to be 0.01 (i.e., a standard deviation of 0.1) based on estimates provided by empirical attenuation relationships for the WUS. These estimates are summarized on the accompanying forms.

DISCUSSION

The hard rock site for which estimates were made in this study is not typical of sites in the CEUS that are located on sediments (e.g., the Mississippi Valley), and may not even be typical of the majority of hard-rock sites in the CEUS based on results given by Walt Silva in his submission. For more typical sites, the ground motions on very hard rock provided in this study should be adjusted for the response of local site conditions.

All of the models depend to some extent on specific source and propagation models. To the extent that these source and propagation models vary significantly from region to region in the CEUS, the results will change accordingly. To accommodate these differences, the models would either have to be applied to a specific region, or sensitivity studies would have to be performed in order to show that the models are appropriate for the region of interest.

TABLE 1
WEIGHTS USED IN THE ANALYSES

Parameter	m_{LG}	Closest Dist. (km)	Hybrid Empirical	Stochastic (EPRI)	Stochastic (Atkinson)	Advance Numerical
PGA	5.5	5	0.6	0.2	0.2	0
	5.5	70	0.25	0.25	0.25	0.25
	7.0	5	0.5	0.2	0.2	0.1
	7.0	70	0.3	0.3	0.3	0.1
PSA (25 Hz)	5.5	20	0.25	0.25	0.25	0.25
	7.0	20	0.3	0.3	0.3	0.1
PSA (10 Hz)	5.5	5	0.6	0.2	0.2	0
	5.5	20	0.25	0.25	0.25	0.25
	5.5	70	0.25	0.25	0.25	0.25
	7.0	5	0.5	0.2	0.2	0.1
	7.0	20	0.3	0.3	0.3	0.1
	7.0	70	0.3	0.3	0.3	0.1
PSA (2.5 Hz)	5.5	20	0.25	0.25	0.25	0.25
	7.0	20	0.3	0.3	0.3	0.1
PSA (1 Hz)	5.5	5	0.6	0.2	0.2	0
	5.5	20	0.25	0.25	0.25	0.25
	5.5	70	0.25	0.25	0.25	0.25
	5.5	200	0	0.2	0.4	0.4
	7.0	5	0.5	0.2	0.2	0.1
	7.0	20	0.3	0.3	0.3	0.1
	7.0	70	0.3	0.3	0.3	0.1
	7.0	200	0	0.2	0.4	0.4

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page 1 of 5

Expert: KEN CAMPBELL

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.045	0.62
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.51	0.78
	aleatory uncertainty	median σ	0.84	0.72
		uncertainty in σ	0.15	0.15
20 km	median amplitude		0.013	0.20
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.63	0.78
	aleatory uncertainty	median σ	0.82	0.74
		uncertainty in σ	0.15	0.15
70 km	median amplitude		0.0028	0.056
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.67	0.90
	aleatory uncertainty	median σ	0.83	0.74
		uncertainty in σ	0.15	0.15
200 km	median amplitude		0.0011	0.011
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.44	1.05
	aleatory uncertainty	median σ	0.85	0.80
		uncertainty in σ	0.15	0.15

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 2: Page 2 of 5

Expert: KEN CAMPBELL

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.050	0.44
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.46	0.56
	aleatory uncertainty	median σ	0.76	0.68
		uncertainty in σ	0.15	0.15
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: KEN CAMPBELL

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.55	2.0
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.50	0.72
	aleatory uncertainty	median σ	0.70	0.62
		uncertainty in σ	0.15	0.15
20 km	median amplitude		0.16	0.86
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.32	0.54
	aleatory uncertainty	median σ	0.68	0.62
		uncertainty in σ	0.15	0.15
70 km	median amplitude		0.027	0.20
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.44	0.55
	aleatory uncertainty	median σ	0.71	0.63
		uncertainty in σ	0.15	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: KEN CAMPBELL

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.20	1.1
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.40	0.50
	aleatory uncertainty	median σ	0.70	0.64
		uncertainty in σ	0.15	0.15
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 5: Page 5 of 5

Expert: KEN CAMPBELL

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.37	1.2
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.61	0.70
	aleatory uncertainty	median σ	0.67	0.62
		uncertainty in σ	0.15	0.15
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.014	0.097
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.46	0.51
	aleatory uncertainty	median σ	0.69	0.63
		uncertainty in σ	0.15	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

GROUND-MOTION ESTIMATES FOR THE NORTHEASTERN U.S. OR SOUTHEASTERN CANADA

W. B. Joyner

The attached estimates were made using a stochastic model based on recent work by Atkinson (1993) and Boatwright and Choy (1992) on source spectra and work by Atkinson and Mereu (1992) on distance attenuation in eastern North America. The principal difference between the model I used and the one described by Atkinson and Boore (1994) is that their two-corner source model is made up of two additive components whereas mine has two multiplicative components. The multiplicative model has fewer free parameters, and the corresponding spectra do not have the prominent sag at 2 to 3 s period that is characteristic of the additive model for large magnitudes. I am not claiming at this stage, however, that the multiplicative model is superior.

I have developed two variations of the multiplicative model. The one I prefer and have used in making the attached estimates is the self-similar model in which both corner frequencies scale as moment to the minus one-third power. The other is the empirical model in which the scaling of the corner frequencies with moment is adjusted to fit the spectral data, subject to the constraint that the high-frequency spectral level scale as moment to the one-third power.

The spectrum for the self-similar model is given by

$$A(f) = CM_0(2\pi f)^2/([1+(f/f_A)^2]^{3/4}[1+(f/f_B)^2]^{1/4}), \tag{1}$$

where $C = \mathcal{R}_\mathcal{P}FV/(4\pi\rho\beta^3R)$, $\mathcal{R}_\mathcal{P}$ is the factor for average radiation pattern (0.55), F is the free-surface amplification factor (2.0), V is the factor for partition into two horizontal components (0.707), ρ is the crustal density (2.8 gm/cc), β is the source-region shear-wave velocity (3.8 km/s), M_0 is the seismic moment (dyne-cm) and R is distance (km). The corner frequencies are given by

$$f_A = 2.272 - 0.5\mathrm{M} \tag{2}$$

and

$$f_B = 3.389 - 0.5\mathrm{M}, \tag{3}$$

where M is moment magnitude ($= \frac{2}{3}\log M_0 - 10.7$). The constant terms in equations (2) and (3) were chosen so tha the high-frequency spectral levels and 1-Hz spectral amplitudes would fit the values given by Atkinson [1993, equations (4) and (5)]. The spectrum of equation (1) has an intermediate slope of $\omega^{1/2}$. A spectrum with an intermediate slope of ω can be developed that fits Atkinson's high-frequency spectral levels and 1-Hz spectral amplitudes, but it calls for f_A values that differ more from hers than the model with the $\omega^{1/2}$ intermediate slope.

There are other, minor, differences between my model and Atkinson and Boore (1994). I have used a κ filter (Anderson and Hough (1984) with a κ value of 0.002 instead of a sharp high-frequency cutoff at $f_{max} = 50Hz$. The choice of 0.002 for κ was governed by the records of Miramichi events that showed flat spectra out to 100 Hz. The use of a κ filter with such a small value of κ required the use of a time step of 0.002 s. At D. M. Boore's suggestion suggestion I have changed the geometric spreading decay so that it is R^{-1} from $R = 0$ to $R = 70$ km, flat from $R = 70$ to $R = 130$ km, and $R^{-1/2}$ beyond $R = 130$ km. The associated Q model is $Q = 680f^{0.36}$. I have introduced a site-amplification filter based on the quarter-wavelength approximation (Boore and Joyner, 1991) and an assumed linear increase in velocity with depth from 2.8 km/s at the surface to 3.8 km/s at a depth of 3.6 km, which is the depth at which the overburden pressure reaches the value of 1 kbar, necessary to close the pores (Press, 1966).

I did not have time for an analysis of uncertainty, so I took as my estimates the values Gail Atkinson gave in her submission as "proponent." This should be appropriate in view of the similarity in the models.

In my view the point-source stochastic model makes the optimum use of available data while retaining simplicity, and I believe that the point-source stochastic model should be used exclusively for estimating ground motion in eastern North America (with possible exceptions in areas such as New Madrid and Charleston). Admittedly, estimates at 5 km for a moment magnitude 7 earthquake do strain the point-source assumption. I am not concerned with changes in magnitude scaling at short distance. We have examined that question with western U.S. empirical data (Boore *et al.*, 1994) and have found no effect. Directivity effects, however, may be preferentially higher at short distances and the point-source estimates thereby too low, but even if that is the case we need not be concerned, because the contribution of moment magnitude 7 earthquakes at 5 km to the hazard in Eastern North America is negligible except perhaps in areas such as New Madrid or Charleston.

The hard-rock site described in the instructions, with the surface shear-wave velocity of 2.8 km, is probably representative of rock sites in eastern North America that were affected by Wisconsin glaciation. Such sites probably require κ values of 0.002 or less. South of the southern limit of Wisconsin glaciation somewhat lower values of shear-wave velocity and higher values of κ would probably be appropriate for rock sites.

The geometric-spreading and Q functions used were obtained from data recorded in southeastern Canada on the Eastern Canada Telemetered Network. Data from the U.S. National Seismic Network suggest that there may be some reconizable differences in geometric-spreading and Q functions over the eastern and central U.S. (Harley Benz, oral communication, 1994).

In closing I wish to register my agreement with Gail Atkinson that moment magnitude (or better still high-frequency magnitude) is preferable to m_{Lg} for purposes of ground-motion estimation.

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SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: W. B. Joyner

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.028 ✓	0.671 ✓
	epistemic uncertainty	parametric (ln)	0.5	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.0072 ✓	0.163 ✓
	epistemic uncertainty	parametric (ln)	0.5	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.0014 ✓	0.036 ✓
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude		0.00091 ✓	0.024 ✓
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Form 2: Page 2 of 5

Expert: W. B. Joyner

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.025 ✓	0.315 ✓
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 3: Page 3 of 5

Expert: W. B. Joyner

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.618	3.40
	epistemic uncertainty	parametric (ln)	0.5	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.104	0.731
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.014	0.130
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 4: Page 4 **of** 5

Expert: W. B. Joyner

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.180 ✓	1.06 ✓
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: W. B. Joyner

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.700 ✓	2.83 ✓
	epistemic uncertainty	parametric (ln)	0.5	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias.		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.0074 ✓	0.067 ✓
	epistemic uncertainty	parametric (ln)	0.5	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND

GROUND MOTION WORKSHOP

SECOND GROUND MOTION ESTIMATES AND DOCUMENTATION

by

Walt Silva

Pacific Engineering and analysis

July 20, 1994

The current ground motion estimates are developed from the viewpoint of a reasonably knowledgeable practitioner rather than proponent. I have included other models but retain a large weight on the EPRI model. In this regard perhaps the proponent lingers although in projects for WNA, I generally weight site specific (using the stochastic model) 0.5-0.6 and 0.5-0.4 weight to WNA empirical or hybrid empirical. Additionally, the EPRI model as implemented here is bias corrected. In my experience with the model in comparisons to data and finite fault modeling, the point source appears to have a stable overprediction of average motions at low frequencies (about 1 Hz and below). This bias results in a large reduction (50%) of motions at low frequencies (1 Hz). On further reflection, I would probably have done this in the initial estimates although I am always sensitive to the task of supporting a reduction in motion to a regulatory panel.

I am curious why PGA is not emphasized since it is used to pin shapes and this procedure is currently and will continue to be used? Also PGV is important because 0098 spectra are used in CENA and V/A ratios are different for CENA and WNA rock motions. Additionally DOE is becoming interested in motions at 2 sec. How would this affect the models being considered?

The specific models and weights are as follows:

Model	Weight
EPRI (1993) bias corrected	0.4
Atkinson (adjusted)	0.3
Advanced Numerical Modeling	0.2
Stochastic 1/R (1/$\sqrt{R}$, R>100 km)	0.1

The following capricious logic documents the choice of models and respective weights.

1) EPRI (1993) with 40% weight: This models represents the most intensive and comprehensive development in terms of parameters and uncertainties as well as validation of all the models considered. It considers effects of source finiteness and observed source depth distributions. It is simplest model with the fewest parameters and when using WNA parameters its predictions compare very favorably with the WNA empirical (see discussion on stochastic model).

2) Atkinson (adjusted) with a 30% weight: I am concerned about the empirical attenuation applied to large magnitudes and was uncertain about the 5 km results (Atkinson has only 1 event within 20 km). To accommodate the closest distance, I ran the point source with the specified parameters but using the Atkinson 2-corner source model (h = 10 km). Figure Set 2 shows the resulting spectra and Table 1 lists the ground motions. To <u>adjust</u> my runs to what Gail might have gotten, I scaled my 2-corner runs down by 1.5. This factor results from correcting R^{-1} to $R^{-1.1}$ at R = 11 km ≈ 1.3 and taking out the amplification in the Midcontinent crustal structure ≈ 1.2. The net result is 1.3 times 1.2 ≈ 1.5. It should be noted my motivation for including this model is primarily the 2-corner source, the attenuation is similar to EPRI (1993) as Figure 3 suggests.

3) Advanced Numerical Modeling was given 20% weight: This model apparently has very similar attenuation characteristics as the Atkinson empirical model for small magnitude earthquakes (Atkinson and Somerville, 1994). It also gave values close to Atkinson's for m_{Lg}

7.0. It seems the epistemic uncertainty is very low for a model with many parameters applied in a region with few opportunities to constrain the parameters. I would not associate such a low epistemic uncertainty with the stochastic finite fault applied in ENA. I am concerned with the large disagreement between the bias corrected EPRI and advanced numerical modeling results. In validation exercises EPRI (1993) both models showed similar values for modeling uncertainty plus randomness for the same earthquakes and nearly the same sites ?

4) Stochastic with 10 % weight: The simple 1/R geometrical attenuation single corner frequency stochastic model predicts WNA ground motions reasonably well. Figure Set 1 shows PGA attenuation for M 5.5, 6.0, 6.5, 7.0, and 7.5 using a point source with 1/R and a stochastic finite source with 1/R compared to WNA empirical attenuation. The point source depth used is 8 km and is taken from Joyner and Boore's (1981) factious depth for PGA attenuation. For all magnitudes, the comparisons between the point source (dashed lines) and the empirical (solid lines) are good. At M 7.5, the point source overpredicts as it does not include saturation effects (log PGA ~ 0.3 M) but up to M 7.0 the point source is not overpredicting. The EPRI 1993 model incorporates this effect of source finiteness. These results suggest that a point source using 1/R is a reasonable model for ground motions due to a finite source in a realistic earth structure. Much of this logic reflects my feelings about the difference between using rigorous wave propagation methods in idealized 1-dimensional earth models and trying to predict strong ground motions in the real earth for engineering design. When all the variabilities are considered, 1/R with a flattening beyond some distance (70-100 km) does a good job on average.

Interestingly, and worth note, the stochastic finite source overpredicts at distance using 1/R and the degree of overprediction is smallest for the **M** 5.5. For **M** 6.5 (the best constrained empirical), the stochastic finite source was run using the Ou and Herrmann formulation for direct plus post-critical rays. The results show larger motions than 1/R in close and a slightly faster attenuation rate at distance and then a change at about 70 km. A plausible interpretation of these results is that a finite source suitably averaged over slip models, nucleation points, crustal structure (not done here), and site azimuth attenuates about like 1/R (compare the dashed line and the crosses for **M** 6.5) out to some distance defined by an average crustal thickness where the slope changes. In other words, a finite source comprised of patches with each patch attenuating with direct waves greater then 1/R has a net effect which attenuates about as 1/R (before the critical distance). This is why the point source works. A finite source with each patch attenuating as 1/R falls off more slowly than 1/R, as Figure Set 1 suggest. Note the attenuation for **M** 5.5 for point and finite sources both using 1/R are nearly identical and match the empirical very well. In this case, the **M** 5.5 source size is essentially a point. The point in all of this is that the EPRI (1993) model used a point source with the Ou and Herrmann formulation and may, as a result, tend to be high in-close and fall off too fast at intermediate distances. I do feel that the point source should be run with 1/R ($1/\sqrt{R}$, $R > R_0$) to emulate a finite fault. These results also suggest that empirical attenuation models based largely on small magnitude data may show more structure in attenuation with distance than would be shown with larger sources. To capture an aspect of the 1/R results and to have some contribution of the stochastic model to the specific magnitudes and distances (rather than the EPRI regression model) I ran the point source with the give parameters with a depth of 10 km (Table 1). The depth was based on the average C_7 terms in the EPRI (1993) midcontinent attenuation model and the hypocenter distribution (EPRI, 1993). These results were bias corrected using the bias estimates listed in the tables from the initial ground motion estimates and given a 10% weight.

5) Hybrid Empirical was given a weight of 0%: Based on comparisons between the stochastic point source and empirical relations for WNA (such as Figure Set 1) I would expect the adjusted empirical to be similar to the stochastic model predictions. The fact that they are support the stochastic model's validity. Weighting it higher would essentially dilute the 2-corner contribution. I suppose the converse argument could be made in giving EPRI 0% weight and the Hybrid Empirical 40%. I don't know what to say about that.

The accompanying reduction in epistemic uncertainty by combining models was assumed to be:

1) 100% reduction in bias uncertainty from 0.2 to 0.1

2) the parametric was left unchanged for m_{Lg} 5 and reduced by 50% for m_{Lg} 7.

For application, the advanced numerical modeling (or an equivalent such as Toro's model, Hutchings' model, or NCEER'S model which is well validated) representing finite fault and more rigorous wave propagation than 1/R and $1/\sqrt{R}$ with larger epistemic uncertainties (reflecting source function variabilities, magnitude area relations, asperity characteristics (size and depth), rise time scaling, etc) needs to be in the form of an attenuation model. I would also feel more comfortable with a demonstration that the Atkinson empirical attenuation form is appropriate for large magnitudes, for higher frequencies, and for PGA, and adjusted for magnitude saturation effects. If EPRI (1993) we redone using 1/R my weights would be revised specific stochastic point source 50-60%, Atkinson 30% (primarily for the 2-corner contribution), and finite fault 20%. For the finite fault, I would use the stochastic finite fault with Ou and Herrmann geometrical spreading. I believe the finite fault is most appropriate for deterministic studies in site-specific cases where you are dealing with a dominate structure with M>6.5 and with the site within about 10 km.

Table 1

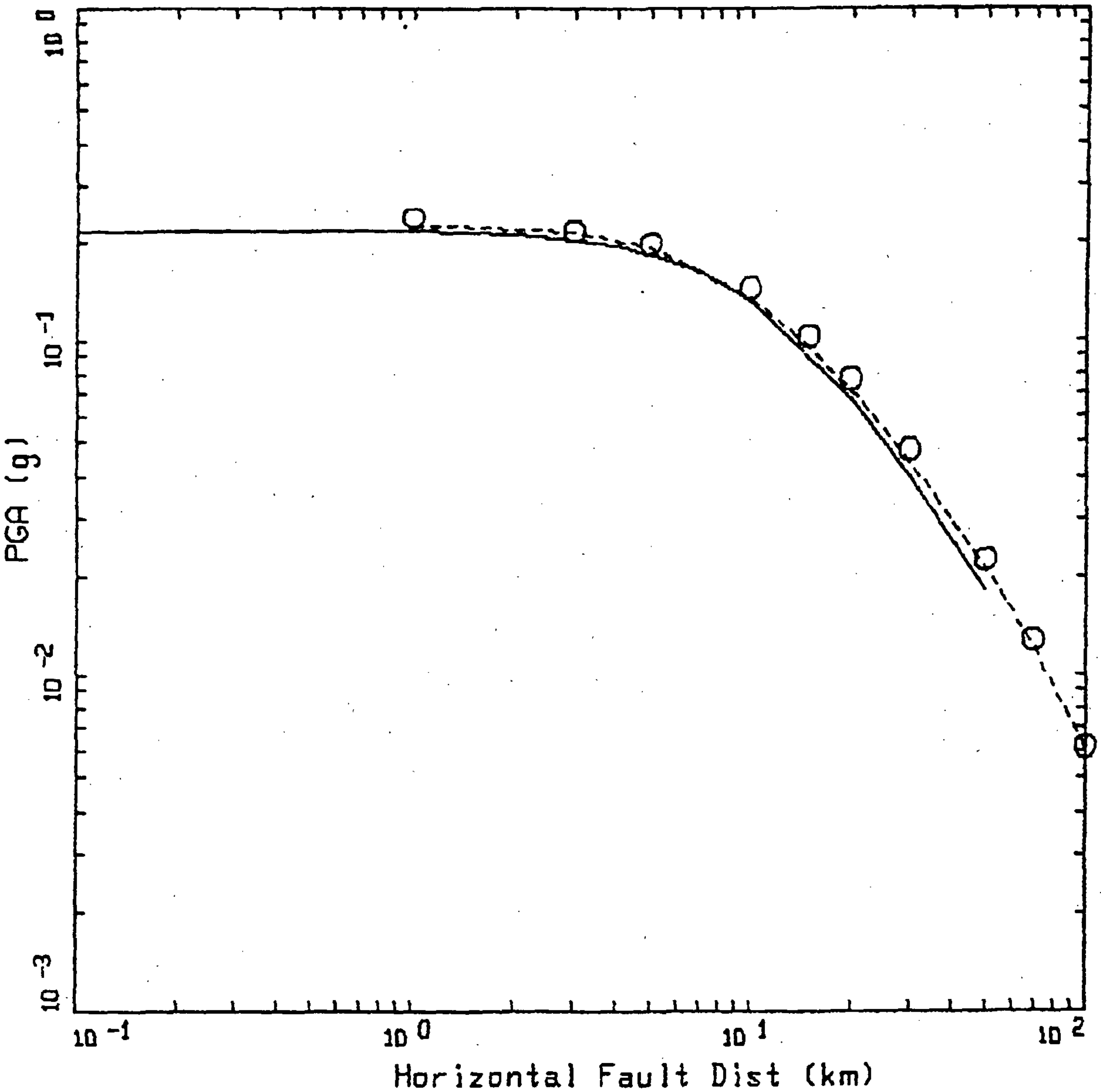
1.0 Hz Spectral Acceleration (g)	M 5.0	M 7.1	R (km)
Atkinson	0.0169 (0.011)*	0.3820 (0.255)	11
Stochastic	0.0243 (0.0163)**	0.5209 (0.3492)	11
	0.0083	0.1856	22
	0.0119 (0.008)	0.2533 (0.169)	22
	0.00231	0.0521	71
	0.00337 (0.0023)	0.0713 (0.048)	71
	0.00081	0.0194	200
	0.00186 (0.0012)	0.0268 (0.0179)	200
2.5 Hz Spectral Acceleration (g)			**R (km)**
	0.04712	0.5810	22
	0.04924 (0.036)	0.4471 (0.3312)	22

*Corrected for $R/R^{1.1}$ where R = 11 km and amplification in Midcontinent crust of about 1.2

**Corrected for bias
Model Parameters: h = 10 km, $\Delta\sigma$ = 120 bars, κ = 0.006 sec, Q(f) = 670 $f^{0.33}$, Midcontinent Crust, Atkinson = 2-corner source, Stochastic = 1-corner source

Table 1 (cont.)

10 Hz Spectral Acceleration (g)			R (km)
	M 5.0	M 7.1	
	0.5214 (0.3342)	2.646 (1.69)	11
	0.3274 (0.2959)	1.867 (1.689)	11
	0.2204	1.350	22
	0.1385 (0.1253)	0.8550 (0.7736)	22
	0.0394	0.2942	22
	0.0249 (0.0225)	0.1873 (0.1695)	22
25 Hz Spectral Acceleration (g)			**R (km)**
	0.3009	1.638	22
	0.1783 (0.1613)	1.024 (0.9266)	22
ap (g)			
	0.2741 (0.183)	1.378 (0.919)	11
	0.1713 (0.155)	0.8989 (0.8133)	11
	0.0160	0.1206	71
	0.0105 (0.0095)	0.0841 (0.0761)	71



M=5.5 SLIP VARIATION
AVERAGE PGA ATTENUATION

LEGEND
O FINITE SOURCE: AVG OVER 11 SLIPS, 11 SITES, NEW RT, RAND FOC, NEW AMPS
----- POINT SOURCE
——— AVERAGE EMPIRICAL (PG&E)

Figure Set 1.

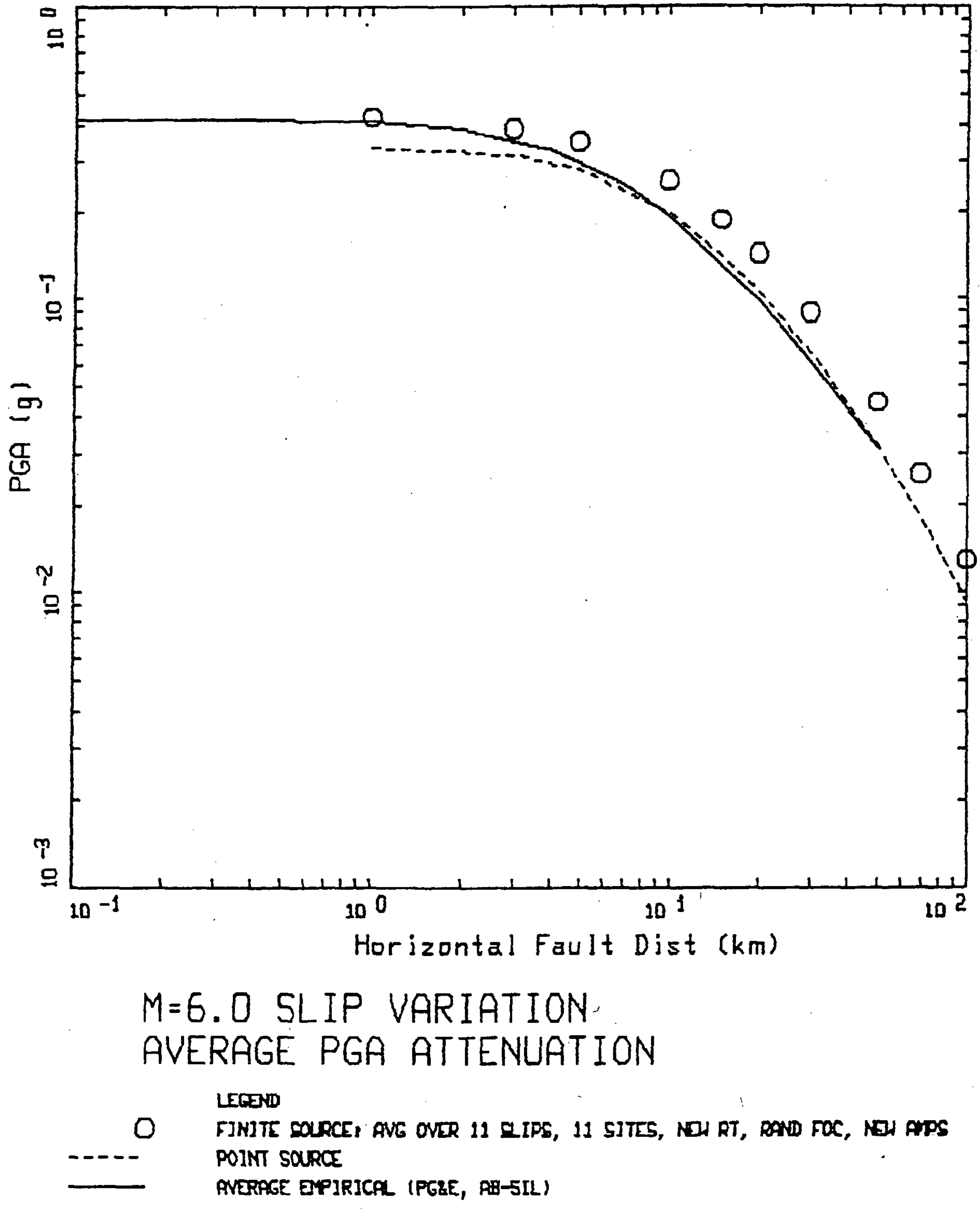
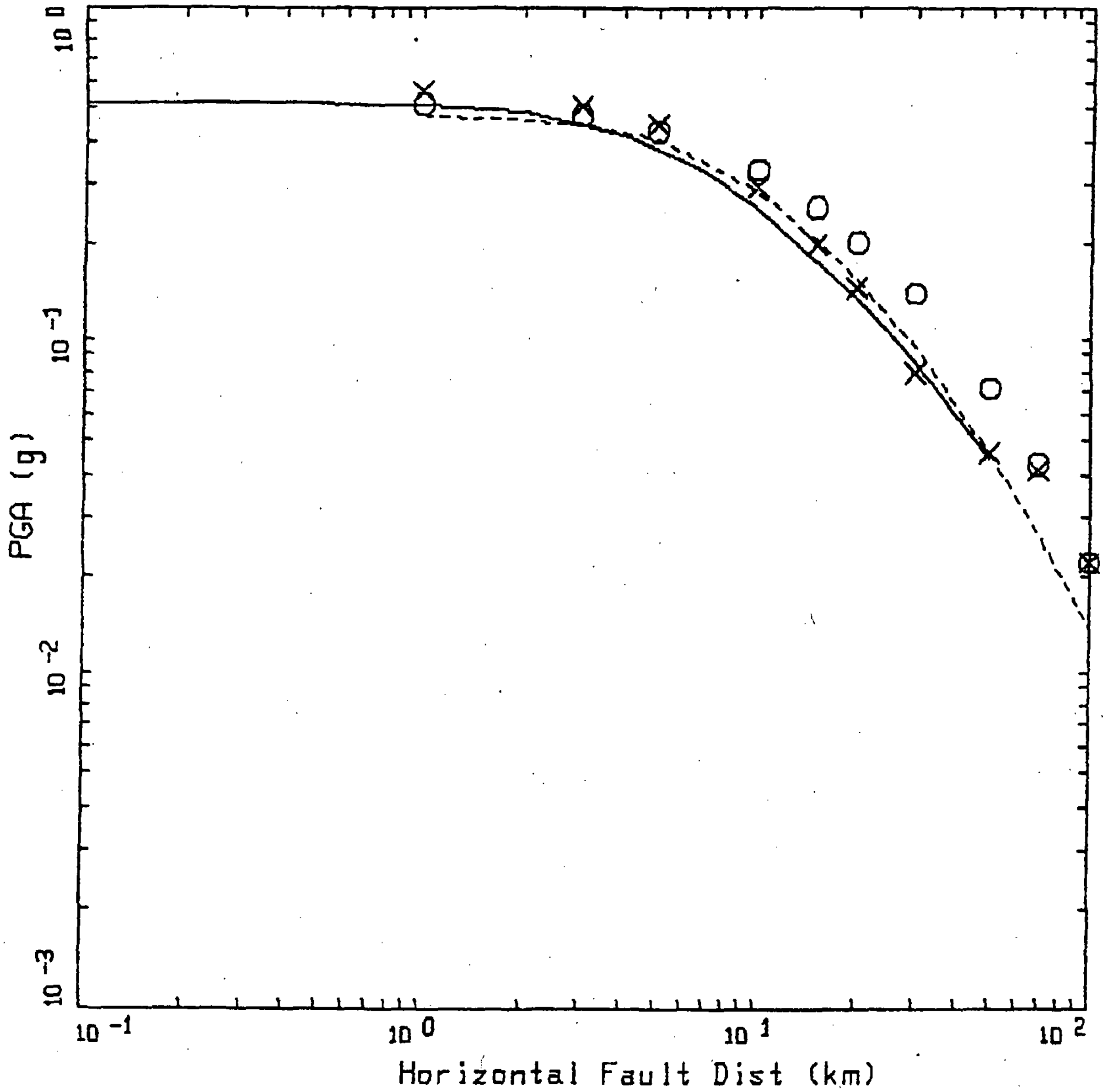


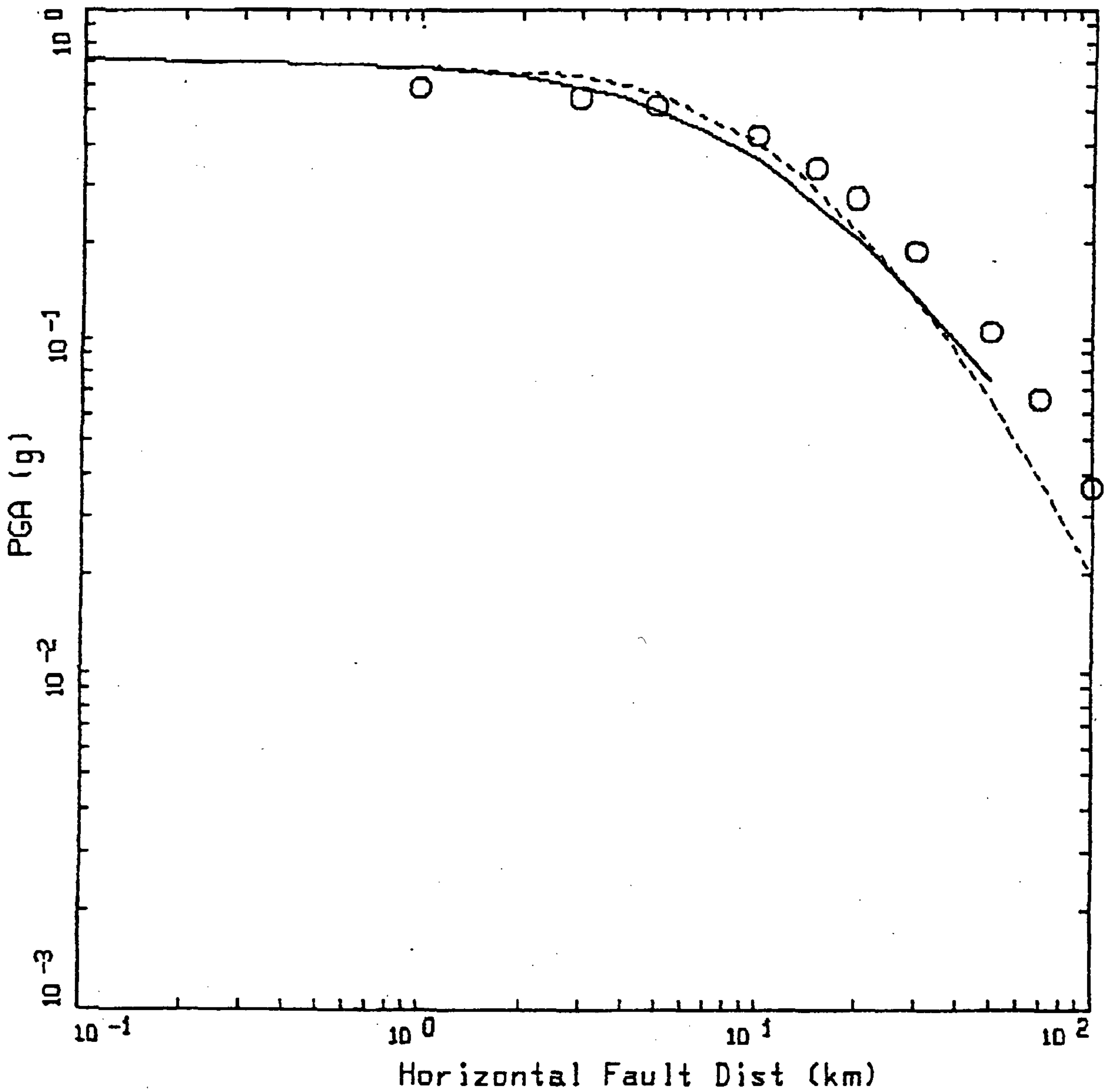
Figure Set 1. (Continued)



M=6.5 SLIP VARIATION
AVERAGE PGA ATTENUATION

LEGEND
O FINITE SOURCE: AVG OVER 11 SLIPS, 11 SITES, NEW RT, RAND FOC, BOORE AMPS
X FINITE SOURCE: AVG OVER 11 SLIPS, 11 SITES, NEW RT, RANFOC, WALD/OH, NEW AMPS
----- POINT SOURCE
——— AVERAGE EMPIRICAL

Figure Set 1. (Continued)



M=7.0 SLIP VARIATION
AVERAGE PGA ATTENUATION

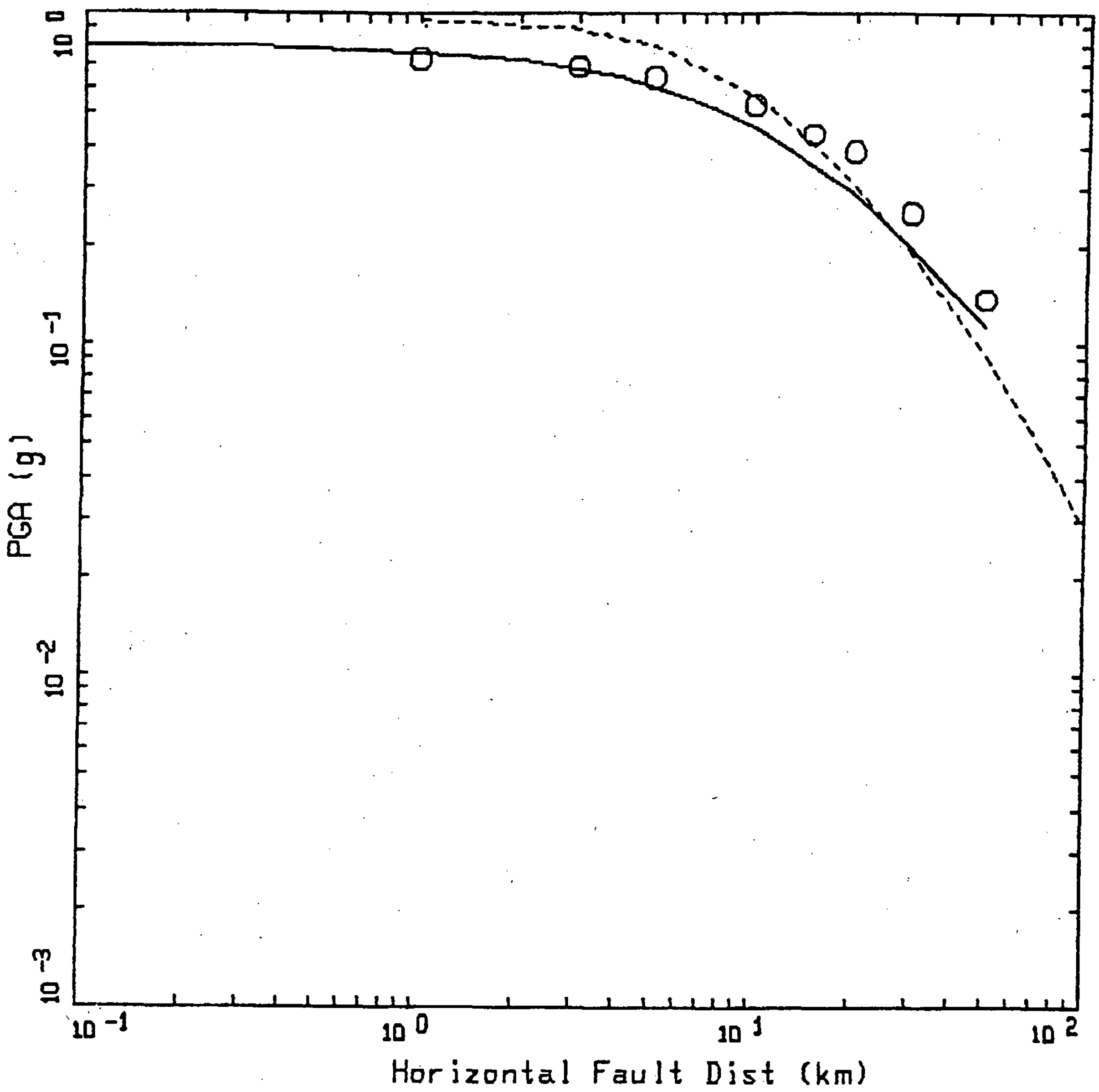
LEGEND

O FINITE SOURCE: AVG OVER 11 SLIPS, 11 SITES, NEW RT, RAND FOC, NEW AMPS

----- POINT SOURCE

—— AVERAGE EMPIRICAL (PG&E, AB-SIL)

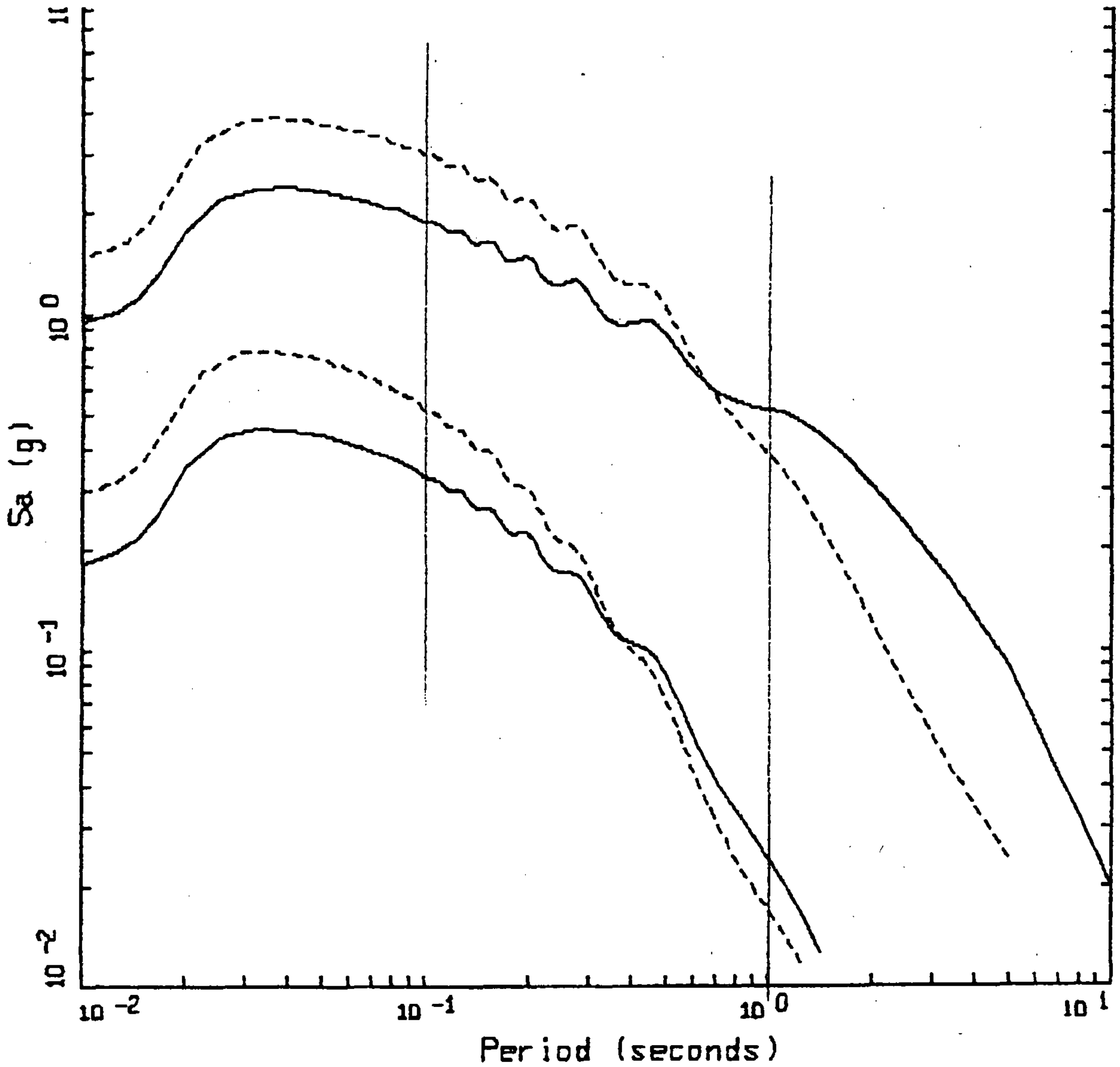
Figure Set 1. (Continued)



M=7.5 SLIP VARIATION
AVERAGE PGA ATTENUATION

LEGEND
O FINITE SOURCE: AVG OVER 11 SLIPS, 11 SITES, NEW RT, RAND FOC, NEW AMPS, NEW AREA
----- POINT SOURCE
——— AVERAGE EMPIRICAL (PG&E, AB-SIL)

Figure Set 1. (Continued)



SSHAC RESPONSE SPECTRA
MIDCONT CRUST, D=5 KM

LEGEND
——— 5 %, M=5.0, SD=120 BARS; PGA=0.171 G
- - - - - 5 %, M=5.0, ATKINSON SOURCE; PGA=0.274 G
——— 5 %, M=7.1, SD=120 BARS; PGA=0.899 G
- - - - - 5 %, M=7.1, ATKINSON SOURCE; PGA=1.378 G

Figure Set 2.

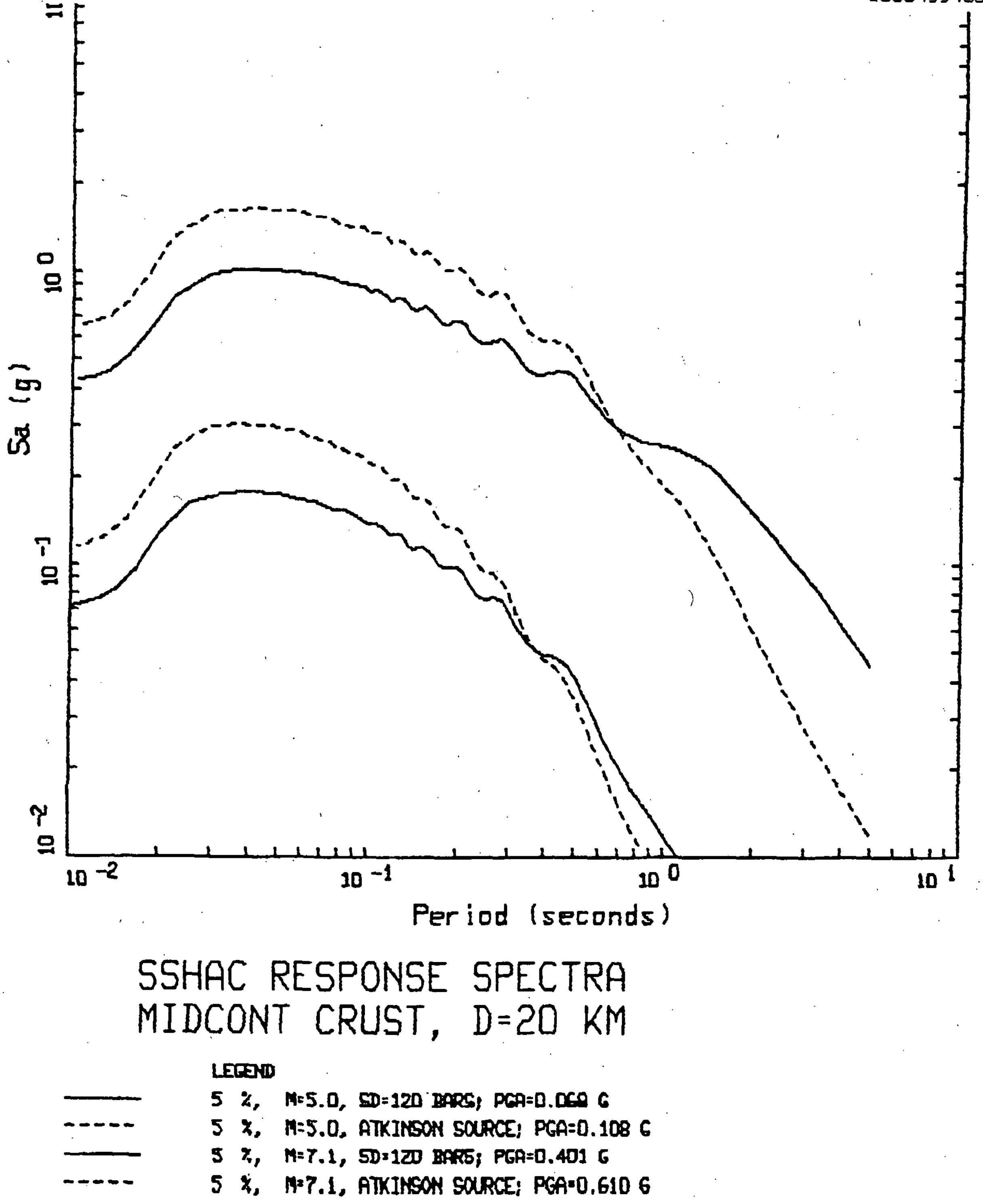
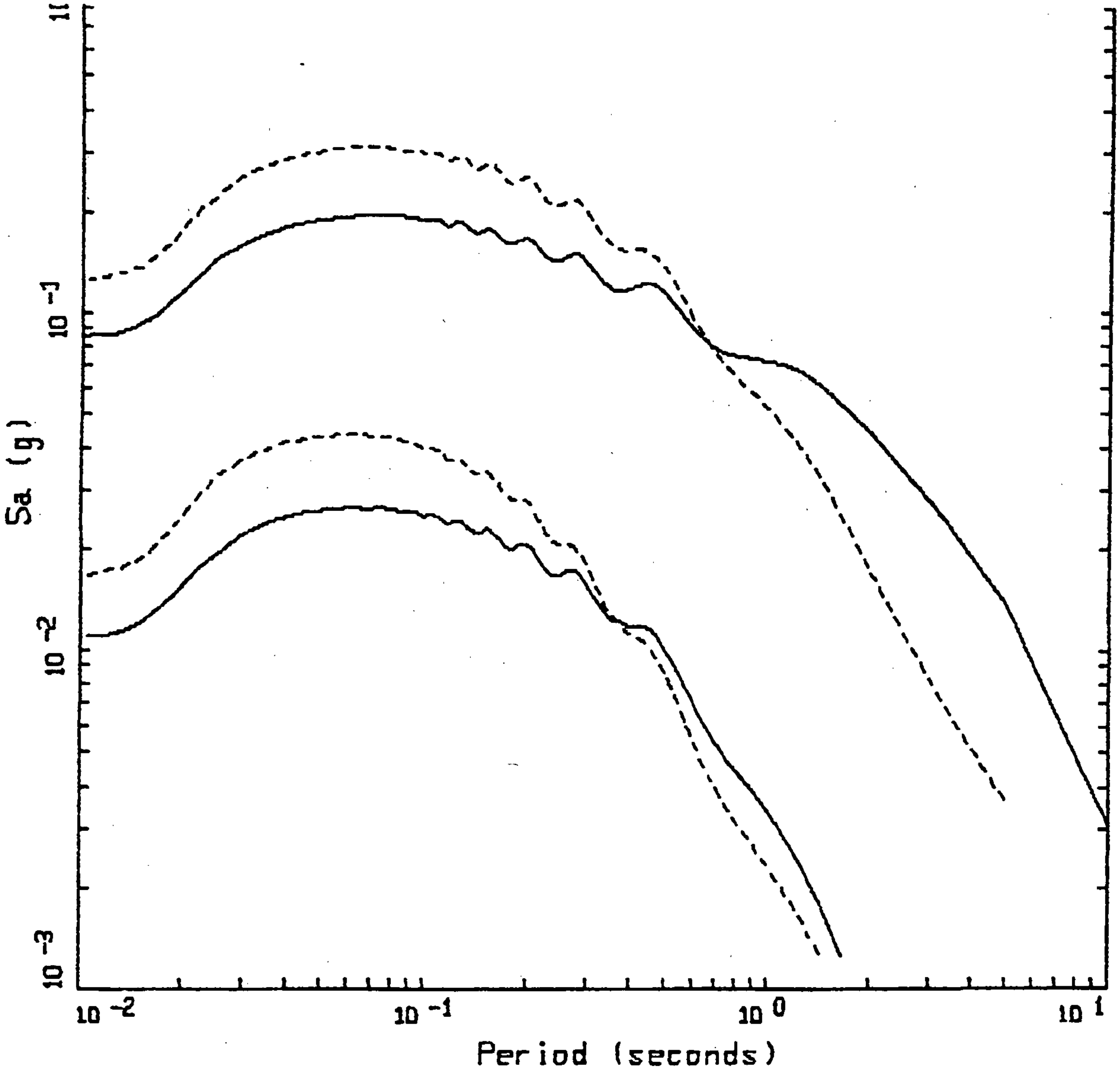


Figure Set 2. (Continued)

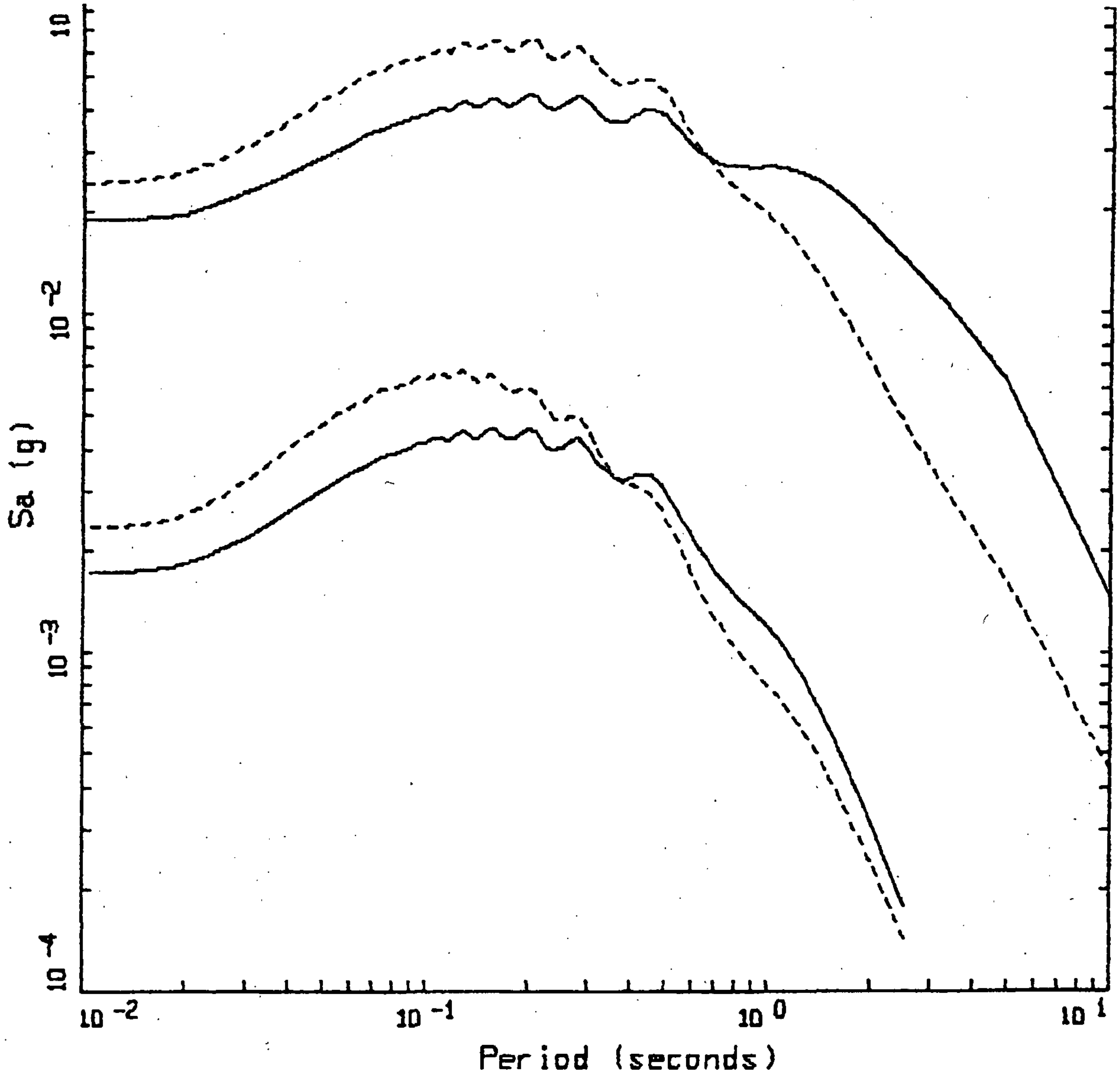


SSHAC RESPONSE SPECTRA
MIDCONT CRUST, D=70 KM

LEGEND

———	5 %, M=5.0, SD=120 BARS; PGA=0.011 G
- - - - -	5 %, M=5.0, ATKINSON SOURCE; PGA=0.016 G
———	5 %, M=7.1, SD=120 BARS; PGA=0.082 G
- - - - -	5 %, M=7.1, ATKINSON SOURCE; PGA=0.121 G

Figure Set 2. (Continued)

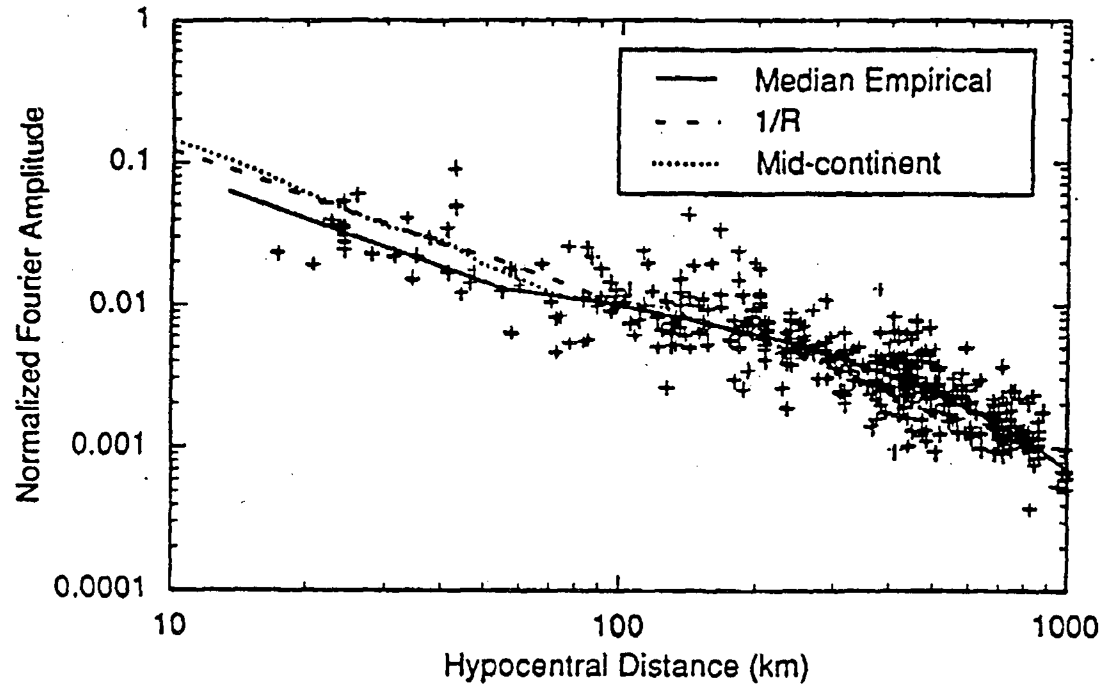


SSHAC RESPONSE SPECTRA
MIDCONT CRUST, D=200 KM

LEGEND

————	5 %, M=5.0, SD=120 BARS; PGA=0.002 G
- - - - -	5 %, M=5.0, ATKINSON SOURCE; PGA=0.002 G
————	5 %, M=7.1, SD=120 BARS; PGA=0.019 G
- - - - -	5 %, M=7.1, ATKINSON SOURCE; PGA=0.024 G

Figure Set 2. (Continued)



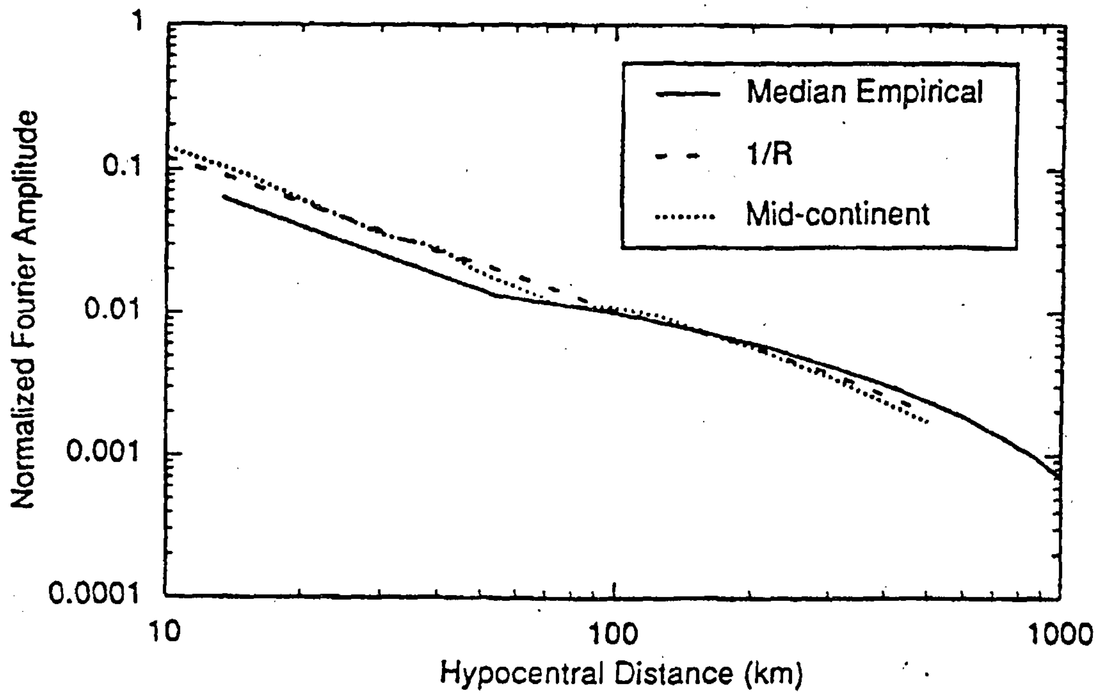


Figure 5-2a. Top frame: Empirical attenuation in southeastern Canada for Fourier amplitude at 2 Hz from Atkinson and Mereu (1992). Station corrections and source corrections have been applied. The solid curve is the regression fit to these data. The dashed and dotted lines are based on the stochastic model described in Section 3.2. Bottom frame: Without data.

Figure 3.

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page 19 of 23

Expert: WALT SILVA

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.023	0.370
	epistemic uncertainty	parametric (ln)	0.14	0.31
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	1.11	0.91
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.015	0.160
	epistemic uncertainty	parametric (ln)	0.14	0.31
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.92	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.003	0.046
	epistemic uncertainty	parametric (ln)	0.14	0.31
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.92	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude		0.001	0.018
	epistemic uncertainty	parametric (ln)	0.14	0.31
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.92	0.8
		uncertainty in σ	0.2	0.2

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Expert: WALT SILVA

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.044	0.400
	epistemic uncertainty	parametric (ln)	0.12	0.25
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.74	0.64
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: WALT SILVA

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.321	1.910
	epistemic uncertainty	parametric (ln)	0.11	0.24
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.77	0.69
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.155	0.892
	epistemic uncertainty	parametric (ln)	0.11	0.24
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.61	0.51
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.026	0.194
	epistemic uncertainty	parametric (ln)	0.11	0.24
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.61	0.51
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: WALT SILVA

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.190	1.13
	epistemic uncertainty	parametric (ln)	0.11	0.24
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.68	0.60
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: WALT SILVA

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.172	0.96
	epistemic uncertainty	parametric (ln)	0.11	0.24
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.79	0.72
		uncertainty in σ	0.2	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.021	0.089
	epistemic uncertainty	parametric (ln)	0.11	0.24
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.62	0.52
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Menlo Park July 28-29 1994

DOCUMENTATION OF GROUND MOTION ESTIMATES DERIVED FROM THE ESTIMATES OF FOUR PROPONENTS

GROUND-MOTION EXPERTS: Paul Somerville and Chandan Saikia, Woodward-Clyde

Prepared July 18, 1994

DERIVATION OF GROUND MOTION ESTIMATES FROM THE ESTIMATES OF FOUR PROPONENTS

PART 1. MEDIAN AMPLITUDES (Topic 1a)

1.1. Magnitude Dependence; Conversion of m_{blg} - M_w

We think that the M_w values of 7.23 used by Campbell and Silva and the M_w value of 7.0 used by Atkinson are inappropriate representations of an m_{blg} 7 earthquake, for the reasons described in Appendix 1. In order to use their estimates for m_{blg} 7, we have adjusted them to represent motions for M_w 6.4. When this is done, the differences among the ground estimates by the different proponents are greatly reduced, as shown in Figures 1-1 through 1-3. We have similarly adjusted the estimates for the m_{blg} 5.5 earthquake by Atkinson, Campbell and Silva, converting their estimates for M_w 5.0 to estimates for M_w 5.2.

1.2. Period Dependence

We think that the source model of Atkinson underpredicts the motions at a period of one second. We assign low weights to these estimates in deriving our best estimates. The predictions of m_{blg} 5.5 motions by Somerville and Saikia have high frequency levels that seem inconsistent with those for m_{blg} 7 motions, suggesting that kappa may have not been treated consistently between these two sets of calculations. Accordingly, the high frequency estimates of Somerville and Saikia for m_{blg} 5.5 are assigned low weights in deriving our best estimates.

1.3. Distance Dependence

We think that the point source stochastic models of Atkinson and Silva overpredict the near fault motions (distances of 5 and 12 km) for magnitude 7.0. We assign low weights to these estimates in deriving our best estimates.

adjusted to Mw 6.4

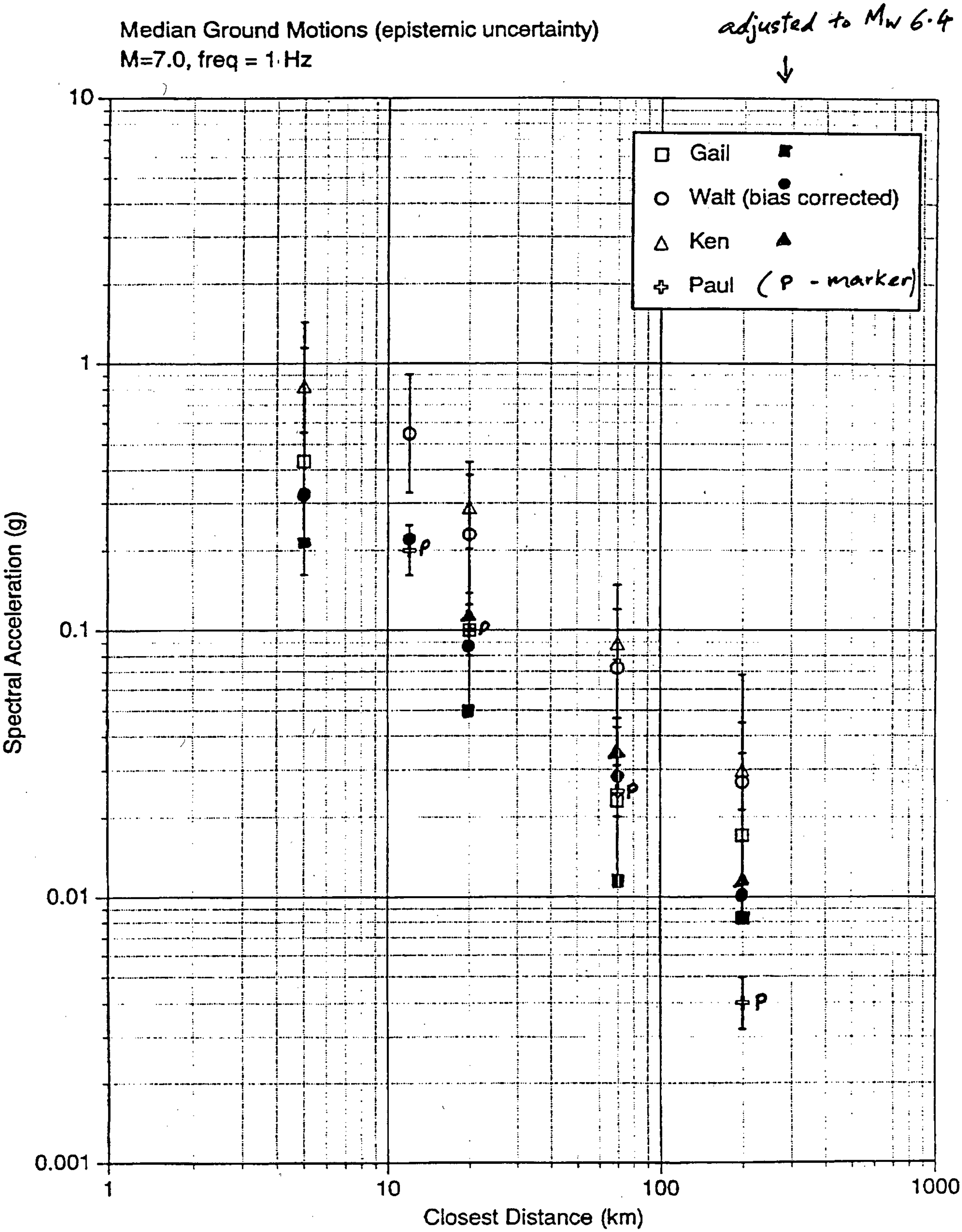


Fig. 1-1

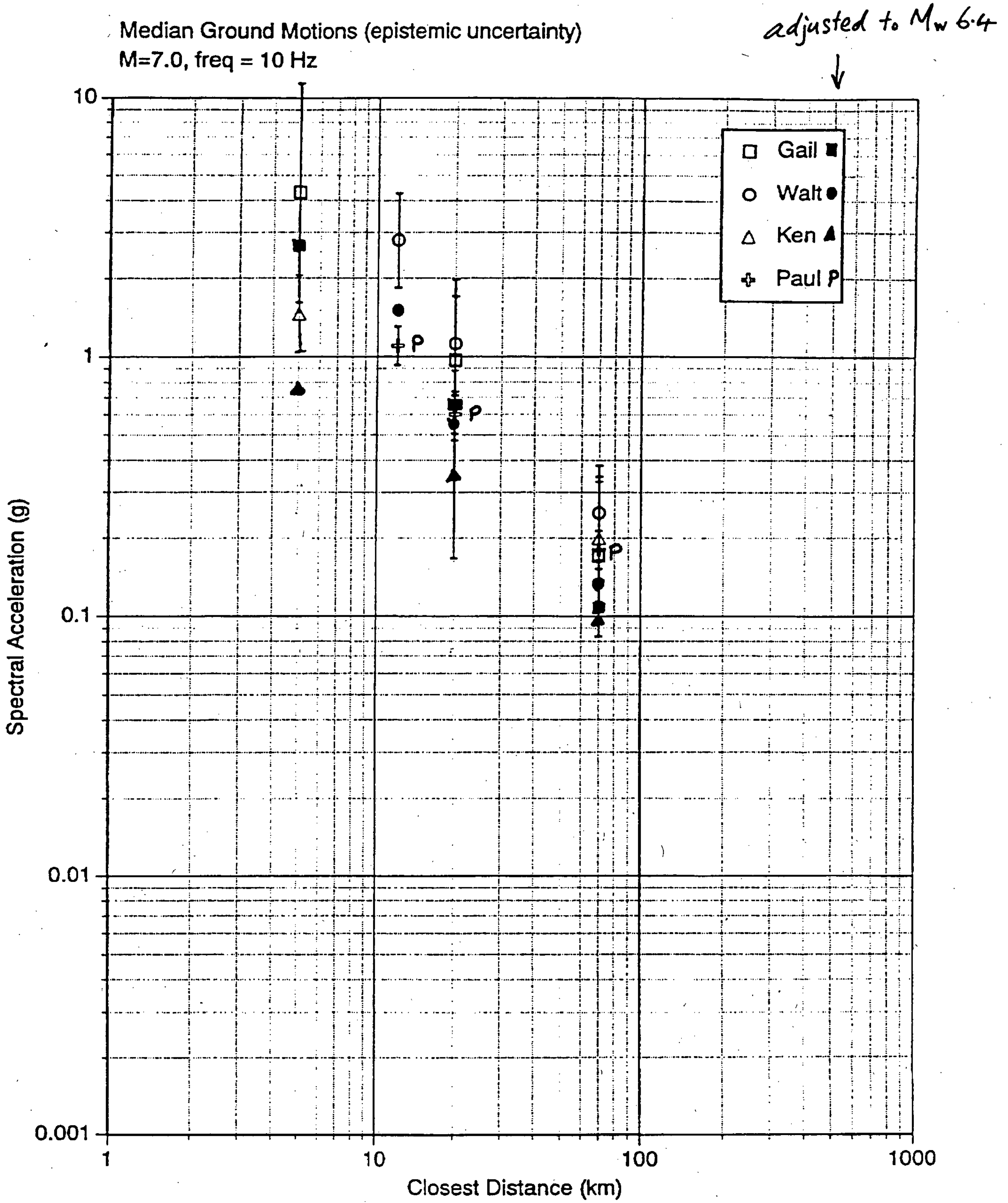

Median Ground Motions (epistemic uncertainty)
M=7.0, freq = 10 Hz
adjusted to Mw 6.4
Gail
Walt
Ken
Paul P
P
P
P
10
1
0.1
0.01
0.001
Spectral Acceleration (g)
1
10
100
1000
Closest Distance (km)

Fig 1.2

Median Ground Motions (epistemic uncertainty)
M=7.0, dist = 20 km adjusted to M_w 6.4

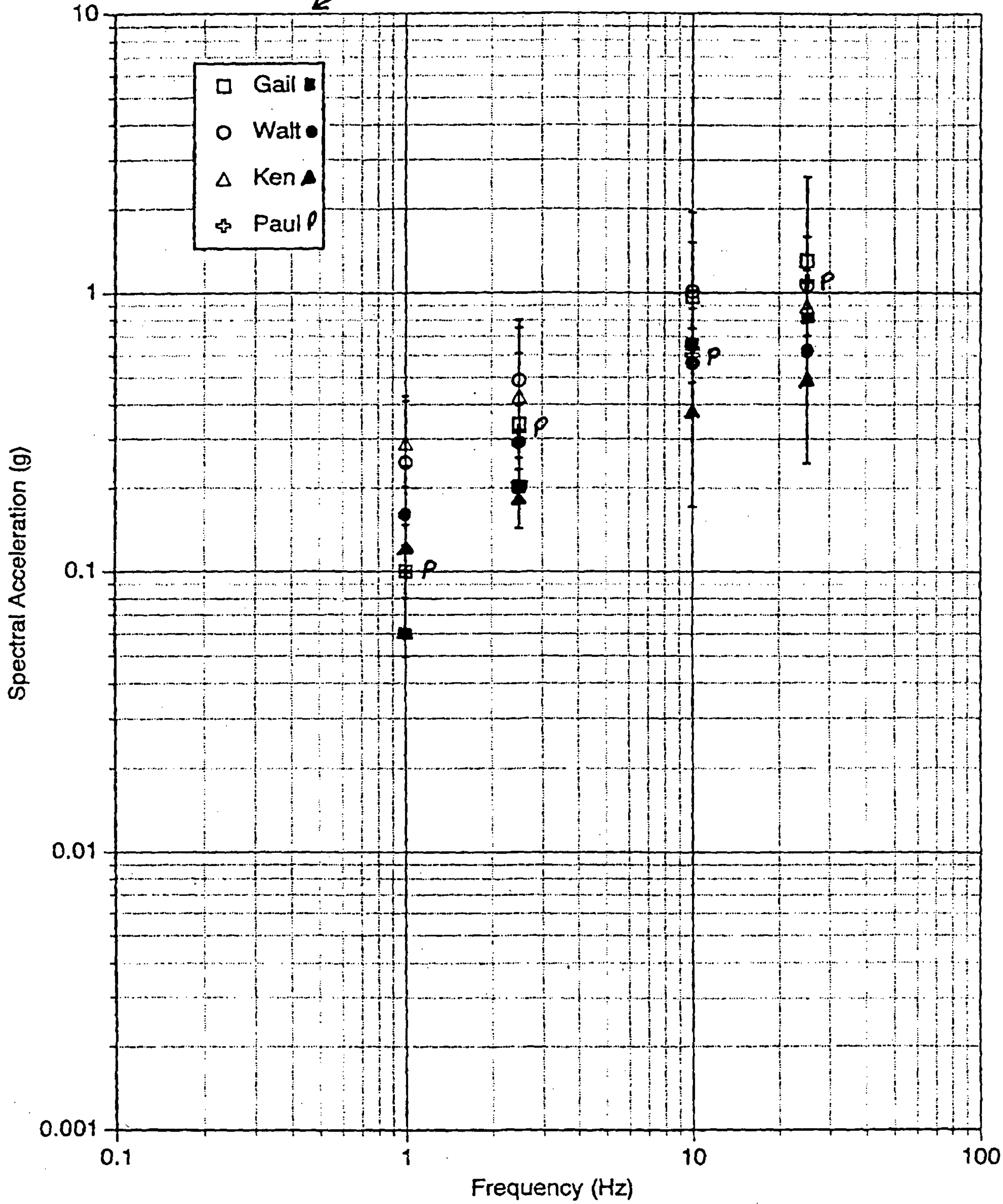


Fig 1-3.

PART 2. ALEATORY UNCERTAINTY (Topics 1b, 2b)

2.1 Specific Comments on Estimates by Individual Proponents.

Atkinson assumed an aleatory uncertainty of 0.8, independent of magnitude, distance and period. However, the values given in Table 2 of her Appendix B range from 0.99 at 1 Hz to 0.67 at 10 Hz. This strong period dependence is compatible with the estimates of other proponents. She does not estimate total aleatory uncertainty by combining parametric and modeling components following the Abrahamson et al. (1990) procedure, as was done by Silva and by Somerville and Saikia. Consequently, we are unable to compare the contribution of parametric uncertainty due to the stress parameter in her model with that of Silva's model.

The aleatory uncertainty in the Silva model shows a higher frequency dependence than that of the other proponents for m_{blg}5.5, and is very large for the longer periods. His aleatory uncertainty is generally less than that of the other proponents (except Campbell) for m_{blg} 7 because most of the uncertainty in the stress parameter is treated as epistemic parametric uncertainty for magnitude 7. As indicated in the preceding paragraph, we do not have an estimate of parametric uncertainty due to the stress parameter in another version of the stochastic model (Atkinson's model) to evaluate the appropriateness of the Silva estimate.

Somerville and Saikia seem to have overestimated their aleatory uncertainty by double counting the contributions from Q and kappa. Since they used fixed assumptions about Q and kappa values in the calculations that were compared with recorded data to estimate modeling uncertainty, it is inappropriate to include parametric uncertainties in Q and kappa in the overall aleatory uncertainty. The practical results of this double counting are not large, and are only significant for the estimates of aleatory uncertainty for 25 Hz and PGA.

The aleatory uncertainty in the Campbell model is lower than that of the other models, especially for m_{blg} 7. Campbell assumed that the strong magnitude dependence of aleatory uncertainty that is observed in strong motion data in the western United States is also applicable in the northeastern United States and southeastern Canada. One issue that he did not address is whether the aleatory uncertainty that he derives from attenuation relations for soil is also appropriate for attenuation relations for rock.

2.2 Magnitude Dependence.

As described above, Campbell assumed that the strong magnitude dependence of aleatory uncertainty that is observed in strong motion data in the western United States is also applicable in the northeastern United States and southeastern Canada. We consider this to be a reasonable assumption, but would prefer that it be supported by some kind of evidence from ground motion data from the northeastern United States and southeastern Canada. Unpublished results of analyses of the empirical data that were performed during the EPRI project may shed light on this. All of the other three proponents use models which have large parametric uncertainties. We think that there is considerable overlap between the parametric uncertainty and the modeling uncertainty (derived from goodness of fit to recorded data), because of the imperfection of the models. The combined aleatory uncertainty in these models therefore probably overestimates the variability that we will see in recorded data. Based on these considerations, we have adopted an intermediate position. We have introduced a magnitude dependence into the aleatory uncertainty that is not present in the estimates derived from the three modeling approaches, giving estimates for m_{blg} 7 that are intermediate between the low values extrapolated from the western United States by Campbell and the high values that come from the three modeling approaches.

2.3 Period Dependence.

There is a tendency for the aleatory uncertainty to decrease with increasing frequency in all of the four proponents' models for both magnitudes evaluated. We think that this is a realistic feature of aleatory uncertainty in ground motions, and have introduced a monotonic decrease in aleatory uncertainty with increasing frequency into our best estimate of the ground motions.

2.4 Distance Dependence.

Taken together, the aleatory uncertainty of the four models does not show a dependence on distance for either magnitude. However, for the Somerville and Saikia calculations for the higher frequencies, there is a pronounced increase in aleatory uncertainty at a distance of 70 km. This results from variations in the critical distance for lower crustal reflections due to variability in crustal structure. There is evidence for this kind of distance dependence in the residuals between recorded motions and those calculated by ray theory in Atkinson and Somerville, 1994 (Figures 10 and 11). We have chosen to reflect this kind of distance dependence in the aleatory uncertainty for the higher frequencies. We also expect it to be present in the aleatory uncertainty for the lower frequencies, but this uncertainty is so large because of the large modeling uncertainty component at the lower frequencies that the distance dependence is not resolved. With the distance measure defined as closest distance to the fault rupture, we do not understand why the uncertainties in the estimates of Silva at close distances are so large.

2.5 Epistemic uncertainty associated with aleatory uncertainty

Two of the proponents (Atkinson and Silva) estimated this to be 0.2, one (Somerville and Saikia) estimated it to be 0.1, and one (Campbell) did not provide an estimate. In our minds, the largest source of this uncertainty is due to uncertainty in whether the aleatory uncertainty decreases with magnitude in northeastern United States and adjacent southeastern Canada, as it does in the western United States. Accordingly, we assign this parameter a value of 0.1 for m_{blg} 5.5 and 0.15 for m_{blg} 7.

PART 3. EPISTEMIC UNCERTAINTY (Topics 2a, 3)

We think that it is appropriate to separate epistemic uncertainty into its parametric and modeling components, and have provided our estimates in this form. The parametric component is entered in the box labelled "parametric," and the modeling component is entered in the box labelled "uncertainty in bias." We consider our best estimate ground motions to be unbiassed and so we report zero bias.

Two of the proponents (Atkinson and Campbell) have very large epistemic uncertainties for both magnitudes, and another (Silva) has large epistemic uncertainites for m_{blg} 7. Atkinson uses "guestimates" of parametric uncertainty that are not documented or justified in detail. In the hybrid approach used by Campbell, there are large modeling uncertainties involved in the conversion from soil to rock conditions in the WUS, and from WUS to CEUS rock conditions, but their sizes are not identified individually or separated from the component due to differences among empirical attenuation relations. Silva's large parametric uncertainty for m_{blg} 7, which is clearly documented in the EPRI report, comes from assigning most of the variability in stress drop for large magnitudes to epistemic uncertainty.

In contrast with these large (and in some cases poorly documented) epistemic uncertainties, the estimates of epistemic uncertainty by Somerville and Saikia are rigorously documented and are quite small. Based on a review of the parametric and modeling uncertainties considered by the other proponents in estimating epistemic uncertainty, we have not identified any aspects that were not taken into account by Somerville and Saikia. This should justify giving larger weights (as amended by weights based on the other considerations discussed in Part 1) to the median ground motion amplitude estimates of Somerville and Saikia than to those of Atkinson and Campbell for m_{blg} 5.5, and to all three of the other proponents for m_{blg} 7, in deriving best estimates for the ground motion amplitudes.

In estimating epistemic uncertainty in the best estimates of ground motions provided here, we consider that the relatively low values of modeling and parametric uncertainty documented by Somerville and Saikia are more realistic than those of the other proponents, and have adopted them as representing the epistemic uncertainty in the best estimates of the ground motion amplitudes.

PART 4. DISCUSSION

4.1 General discussion of strengths and weaknesses of the approaches used

We consider the approaches of all four proponents to be relevant in a general sense for estimating ground motions in northeastern North America. Specific qualifiers to this general statement are discussed in Part 1 above and Part 4.2 below. The approaches are related to physical models and incorporate empirical data in differing ways and to differing degrees, and produce differing estimates of ground motions and their uncertainties.

4.1.1 Considerations based on estimates of uncertainty by the different models

The variations in aleatory uncertainty between the different proponents are fairly well documented and understood. The largest sources of differences relate to the large uncertainty in the stress parameter in the stochastic model for m_{blg} 5.5, and to the assumption of magnitude dependent aleatory uncertainty in the hybrid empirical method for m_{blg} 7. However, there are large differences among the four proponents' estimates of epistemic uncertainty, as described above in Part 3. These estimates are significantly larger for the Atkinson, Campbell and Silva models than they are for the Somerville and Saikia model. Based on a review of the parametric and modeling uncertainties considered by these three proponents in estimating epistemic uncertainty, we have not identified any aspects that were not taken into account by Somerville and Saikia. This may justify giving larger weights to the median ground motion amplitude estimates of Somerville and Saikia than to those of Atkinson and Campbell for m_{blg} 5.5, and to all three of the other proponents for m_{blg} 7, in deriving best estimates for the ground motion amplitudes.

4.1.2 Considerations based on the nature of the different models

The stochastic models used by the proponents are all based on a point source model having a uniform radiation pattern and a random phase spectrum. The assignment of a Brune source spectrum (or two-cornered spectrum) having a finite corner frequency and finite stress parameter to a point source is, strictly speaking, inconsistent since a true point source has infinite corner frequency and infinite stress drop. Obviously, the point source representation is being used as a convenience, but in this mode, the stochastic model is more like a mathematical analog of a physical model than a physically plausible model. Similarly, the approximate methods that are used to represent geometrial spreading in the stochastic model are more like mathematical analogs than true physical models. In the stochastic approach used by Atkinson, all three of the inputs (the source model, the geometrical spreading function, and the ground motion duration model) are estimated from empirical data. Her model is more like a hybrid empirical model than a theoretical model which predicts ground motions from a set of physical laws, but has the flexibility of incorporating empirically based inputs.

The advanced numerical modeling approach used by Somerville and Saikia, in comparison, has a corner frequency that results from finite source dimensions (as in the Brune model), and uses Green's functions (which are a rigorous representation of wave propagation in simplified crustal models) to represent geometrical spreading. While the approach used by Somerville and Saikia contains simplifications and approximations, it is a more physically-based model than the point-source stochastic model. It has more predictive power in regions where data are sparse than does a hybrid empirical model that relies on regional data for the constraint of its input parameters. The advanced numerical modeling method is compatible with methods that are used routinely in the estimation of earthquake source parameters and wave propagation characteristics based on the calculation of synthetic seismograms, and should be comprehensible to this large community of seismologists. The Green's functions used by the method need only be calculated once for a given crustal structure. They can then be archived on the INTERNET for use by multiple investigators in ground motion modeling and seismic source inversion.

One of the features of the stochastic model is its dependence on a key parameter, the stress parameter, that directly scales the ground motion amplitude at frequencies above the corner frequency. This simple model should have an advantage over more complex models in that it is subject to uncertainty in the median values and variabilities of fewer parameters. However, there appears to be considerable epistemic uncertainty in the median value of the stress parameter (Atkinson most recently used 180 bars, while Silva used 120 bars). Moreover, as we saw in the discussion of aleatory uncertainty in Part 2, the variability in the stress parameter gives rise to very large uncertainties in predicted ground motions.

It is possible that this variability in stress parameter is really caused by other factors, such as the inadequate sampling of azimuthal variability in source radiation. Complexities such as this may cause the over-estimation of variability in the stress parameter, as well as contribute to the modeling uncertainty when azimuthally invariant ground motion predictions are compared with data having real azimuthal variation in source radiation. Thus inadequate parameterizations of source and path models, instead of yielding the benefit of minimizing parametric uncertainty, may give rise to the double counting of certain effects in parametric and modeling uncertainty and result in larger overall aleatory uncertainty than more adequate parameterizations of source and path models.

The source radiation strength in the advanced numerical model used by Somerville and Saikia is controlled by the radiation contained in empirical source functions. As implemented in their calculations, a fixed set of empirical source functions is used and so they do not treat the source radiation as a variable. Any inadequacies in this representation of source radiation strength appear as modeling uncertainty derived from goodness of fit to a suite of different earthquakes, and there is no parametric uncertainty involved with the prediction of ground motions for future events. In this sense, the advanced numerical modeling approach is free of a source strength parameter that is difficult to constrain, and is thus simpler to use. However, the empirical source functions that it uses need to be appropriate to the region in which the method is applied. To date, the available evidence indicates that the stress drops of magnitude 5 events (which are used for empirical source functions) are about 100 bars in both eastern and western North America, justifying the use of empirical source functions in the eastern United States that are derived from western United States earthquakes.

In the hybrid empirical approach used by Campbell, there are large modeling uncertainties involved in the conversion from soil to rock conditions in the WUS, and from WUS to CEUS rock conditions. We think that this parametric uncertainty could be reduced, and the hybrid empirical method improved, by starting with empirical attenuation relations for hard rock, even allowing for the difficulties associated with the hard rock data.

4.2 Applicability to magnitude/distance/frequency ranges

For predictions for a specified M_w, we consider the hybrid empirical method of Campbell and the advanced numerical modeling method of Somerville and Silva to be applicable for all of the combinations of magnitude, distance and frequency values specified in the Instructions to Proponents. The point source stochastic models of Atkinson and Silva may not be appropriate at close distances to large earthquakes, and the Atkinson model may not be appropriate for periods around 1 second. For predictions for a specified m_{blg}, the Atkinson, Campbell and Silva methods are not applicable for the larger magnitudes unless corrections (described in Appendix 1) are applied to the relationships between M_w and m_{blg}.

4.3 Representativeness of hard rock site

The hard rock site (2.8 km/sec average shear wave velocity over the top 30 m) is probably representative of unweathered crystalline rock sites in the northeastern United States and southeastern Canada. It may not be representative of sedimentary rock sites in the Central and Eastern United States.

4.4 How results would differ in other regions within the Central and Eastern United States

The ground motion estimates presented here are for the northeastern United States or southeastern Canada (region 10 in the EPRI regionalization of crustal structure). The variability of median ground motions (5 Hz response spectral acceleration at 5% damping) for a moment magnitude 6.5 earthquake calculated using the crustal structure models for all 16 regions of eastern North America is illustrated in Figure 5-46 from EPRI TR-102293-V1, which is reproduced as Figure 4.1. The intra-region variability about the median ground motions due to uncertainty in crustal structure may be different in different regions. This is illustrated in Figures 4.2 through 4.4, where the intra-region variability for the Grenville and New Madrid regions are compared. The variability in the Grenville region is largest for distances around 100 km and is produced by variability in the depth of the Moho. In contrast, the variability in the New Madrid region is largest for distances around 60 km, and is produced by variability in the depth of the Conrad.

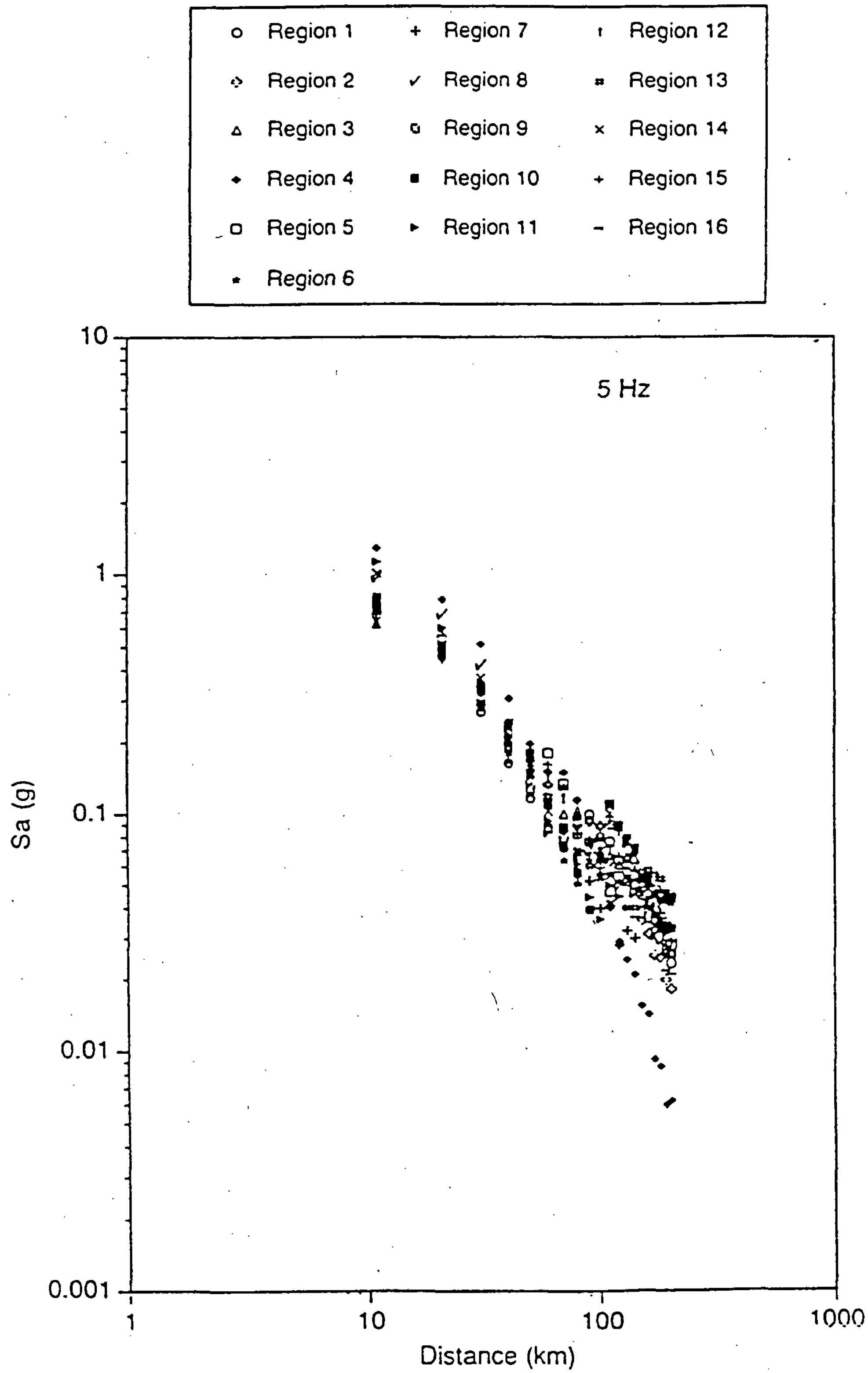


Figure 5-46. Comparison of median ground motion attenuation of spectral acceleration at 5 Hz for the 16 regions.

Fig. 4.1

the maximum standard error is shifted to distances of 80 to 120 km again associated with the variation in Moho depth. The depth of the Moho affects the distance range at which the maximum standard error occurs. In general, the deeper the Moho, the larger the distance at which the maximum occurs.

In Figures 5-25 and 5-26 the variation of ground motion for a given crustal structure is shown for three depths. To account for the variability in focal depth, the ground motion variability is computed using a weighted average over focal depths where the weights are given by the EAA generic depth distribution (Table 5-9). The standard errors of the mean spectral acceleration are shown in Figures 5-27a,b,c for 1, 5, and 15 Hz.

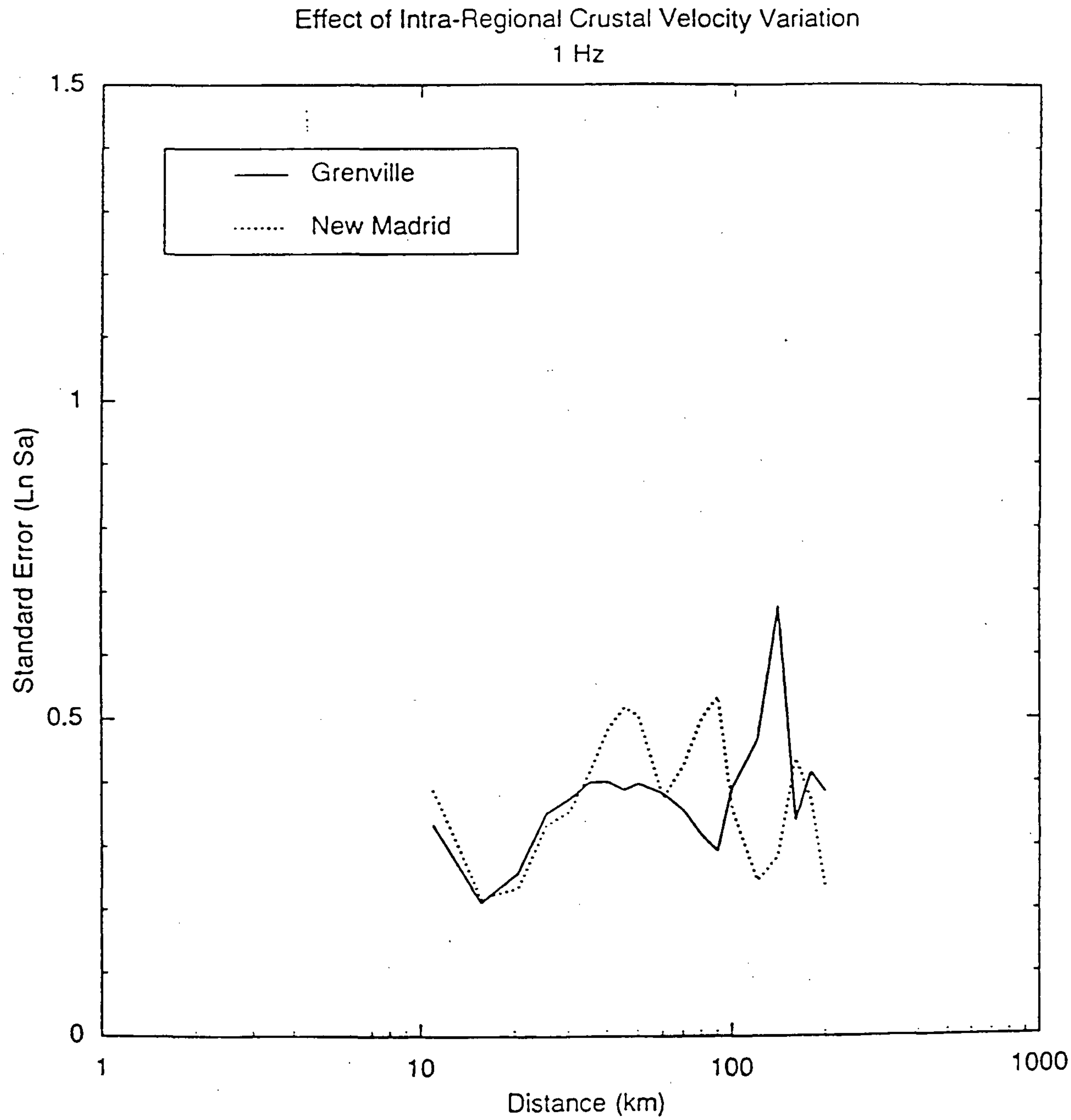


Figure 5-27a. Variability of spectral acceleration at 1 Hz due to crustal velocity uncertainty within the Grenville and New Madrid region. The variability includes variability in focal depth.

Fig. 4 · 2

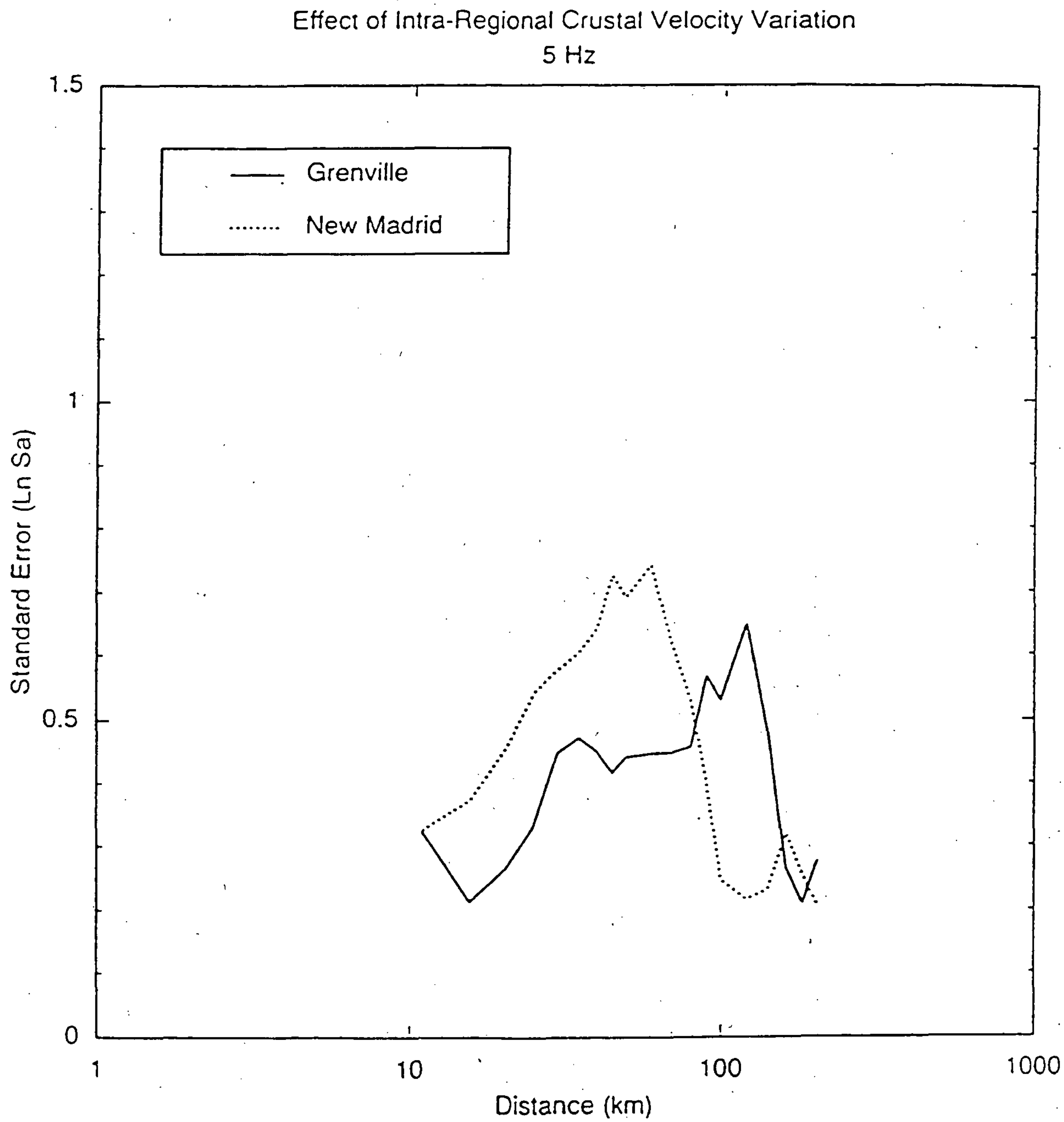


Figure 5-27b. Variability of spectral acceleration at 5 Hz due to crustal velocity uncertainty within the Grenville and New Madrid region. The variability includes variability in focal depth.

Fig. 4.3

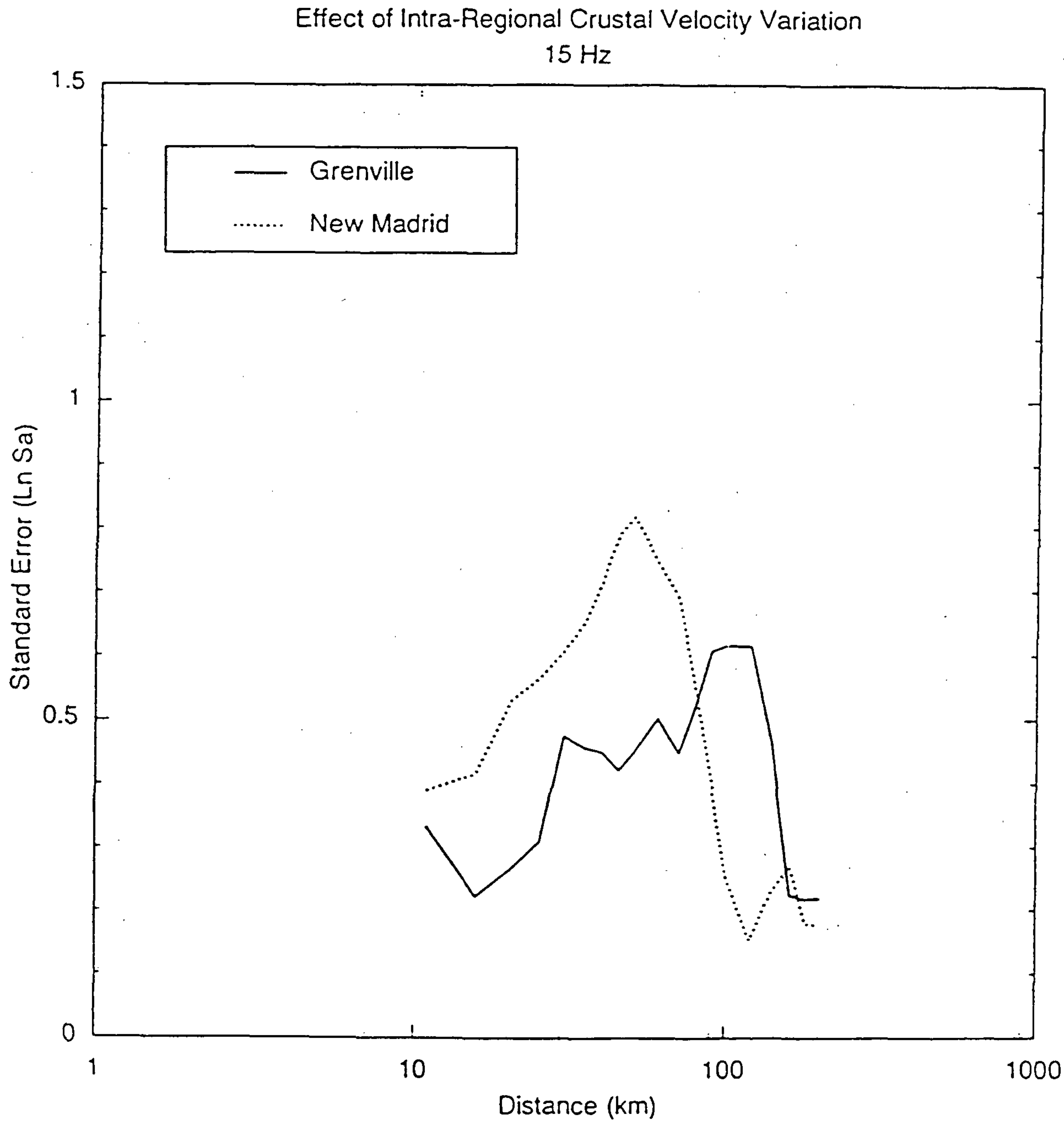


Figure 5-27c. Variability of spectral acceleration at 15 Hz due to crustal velocity uncertainty within the Grenville and New Madrid region. The variability includes variability in focal depth.

Fig. 1.4

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PART 6. ESTIMATES OF MEDIAN AND UNCERTAINTIES

Estimates of median ground motion values and their uncertainties are given in Tables 1 through 5 that follow. The reported aleatory uncertainty is for predicting ground motions given an earthquake size expressed as m_{blg}. The uncertainty due to seismic moment should be removed from the aleatory uncertainty when predicting ground motions from seismic moment M_o or moment magnitude M_w.

Expert: Somerville / Saikia

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.06	0.3
	epistemic uncertainty	parametric (ln)	0.15	0.15
		median bias	-	-
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.8	0.7
		uncertainty in σ	0.1	0.15
20 km	median amplitude		0.17	0.1
	epistemic uncertainty	parametric (ln)	0.15	0.15
		median bias	-	-
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.8	0.7
		uncertainty in σ	0.1	0.15
70 km	median amplitude		0.003	0.03
	epistemic uncertainty	parametric (ln)	0.15	0.15
		median bias	-	-
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.8	0.7
		uncertainty in σ	0.1	0.15
200 km	median amplitude		0.001	0.01
	epistemic uncertainty	parametric (ln)	0.15	0.15
		median bias	-	-
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.8	0.7
		uncertainty in σ	0.1	0.15

Comments/footnotes:

Expert: Somerville / Saikia

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.07	0.25
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	-	-
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.7	0.6
		uncertainty in σ	0.1	0.15
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: Somerville / Saikia

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.6	1.5
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	-	-
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.65	0.55
		uncertainty in σ	0.1	0.15
20 km	median amplitude		0.17	0.6
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	-	-
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.65	0.55
		uncertainty in σ	0.1	0.15
70 km	median amplitude		0.03	0.15
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	-	-
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.75	0.65
		uncertainty in σ	0.1	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: Somerville / Saikia

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.25	0.75
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	-	-
		uncert. in bias (ln)	0.12	0.12
	aleatory uncertainty	median σ	0.60	0.55
		uncertainty in σ	0.1	0.15
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: Somerville / Saikia

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.3	0.9
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	-	-
		uncert. in bias (ln)	0.12	0.12
	aleatory uncertainty	median σ	0.6	0.55
		uncertainty in σ	0.1	0.15
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.015	0.09
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	-	-
		uncert. in bias (ln)	0.12	0.12
	aleatory uncertainty	median σ	0.7	0.6
		uncertainty in σ	0.1	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

APPENDIX 1.

REVIEW OF m_{blg} - M_w RELATIONSHIPS USED BY THE FOUR PROPONENTS

The ground motion estimates provided by the four model proponents for specified m_{blg} values of 5.5 and 7.0 were all generated using M_w (moment magnitude) estimates. The relationships between M_w and m_{blg} that were used differ widely, especially for m_{blg} 7. The M_w values used by each proponent are given in Table 1.

Table 1. M_w values used by proponents to represent m_{blg} values

PROPONENT	M_w for m_{blg} 5.5	M_w for m_{blg} 7.0
Atkinson	5.0	7.0
Campbell	5.0	7.23
Silva	5.0	7.23
Somerville & Saikia	5.2	6.4

Most investigators who have developed empirical m_{blg} - M_w relationships have found that the data are well fit by a linear relationship. Some examples of such relationships are as follows:

$\mathrm{Log}_{10} M_o = 1.2\ m_{blg} + 17.2$	$M_w = 0.80\ m_{blg} + 0.77$	(Somerville and Saikia, 1994)
	$M_w = 0.98\ m_{blg} - 0.39$	(Atkinson, 1993)
$\mathrm{Log}_{10} M_o = 1.37\ m_{blg} + 16.22$	$M_w = 0.91\ m_{blg} + 0.11$	(Patton and Walter, 1992)

These relationships are based on a set of earthquakes whose m_{blg} values range from 3 to 7 and whose M_w values range from 2.6 to 6.4.

The M_w values that they predict for m_{blg} values of 5.5 and 7.0 are listed in Table 2.

Table 2. M_w values calculated from empirical m_{blg} - M_w relationships

AUTHOR	M_w for m_{blg} 5.5	M_w for m_{blg} 7.0
Atkinson, 1993	5.00	6.47
Patton & Walter, 1992	5.12	6.48
Somerville & Saikia, 1994	5.17	6.37

Proponent Atkinson chose not to use her empirical m_{blg} - M_w relationship in converting m_{blg} 7 to M_w, because for larger magnitudes she prefers to use a non-linear relationship derived from her stochastic ground motion model. Similarly, proponents Campbell and Silva used a non-linear m_{blg} - M_w relationship based on the stochastic ground motion model (EPRI, 1993) in converting m_{blg} to M_w. The reasons for using these model-based relationships are that the empirical data are sparse and there is a desire that the relationship used be consistent with the stochastic model.

The m_{blg} - M_w relationships based on the stochastic ground motion models of Atkinson (1993) and EPRI (1993) are shown in Figures 1 and 2. Also shown on Figure 2 are revised estimates of the median values and uncertainties in the M_w and m_{blg} of the 1925 Charlevoix earthquake. This earthquake had an m_{blg} of 6.93 +/- 0.14, derived from five stations at less that 15 degrees (derived from Atkinson and Boore, 1987) and an M_w of 6.2 +/- 0.2 (derived from 17 observations including both regional and teleseismic stations by Bent, 1993, Table 3). While the model-based EPRI (1993) m_{blg} - M_w relationship was compatible with the previous estimates of m_{blg} and M_w of the 1925 Charlevoix earthquake, it is not compatible with the revised ones.

Proponents Somerville and Saikia prefer to use a relationship that is consistent with the empirical m_{blg} - M_w data. They do not use the stochastic model and so do not have a need to be consistent with an m_{blg} - M_w relationship based on the stochastic model. They regard the 1925 Charlevoix earthquake as representative of the m_{blg} 7 earthquake addressed in this study, and their empirical relationship is compatible with its m_{blg} of 6.93 and its M_w of 6.2, as shown in Figure 3. It had a stress drop of about 50 bars, which is about half the average of 100 bars for eastern North American events, and its source function does not exhibit any anomalous features. Although there are few events to compare it with in eastern North America, they do not view this event as an outlier in a population of m_{blg} 7 events whose average M_w is 0.6 or 0.83 units larger, i.e. M_w 7.0 or 7.23. This would correspond to seismic moments 8 to 18 times larger, and stress drops of 400 to 900 bars, if we scale up the 1925 earthquake to satisfy these M_w values.

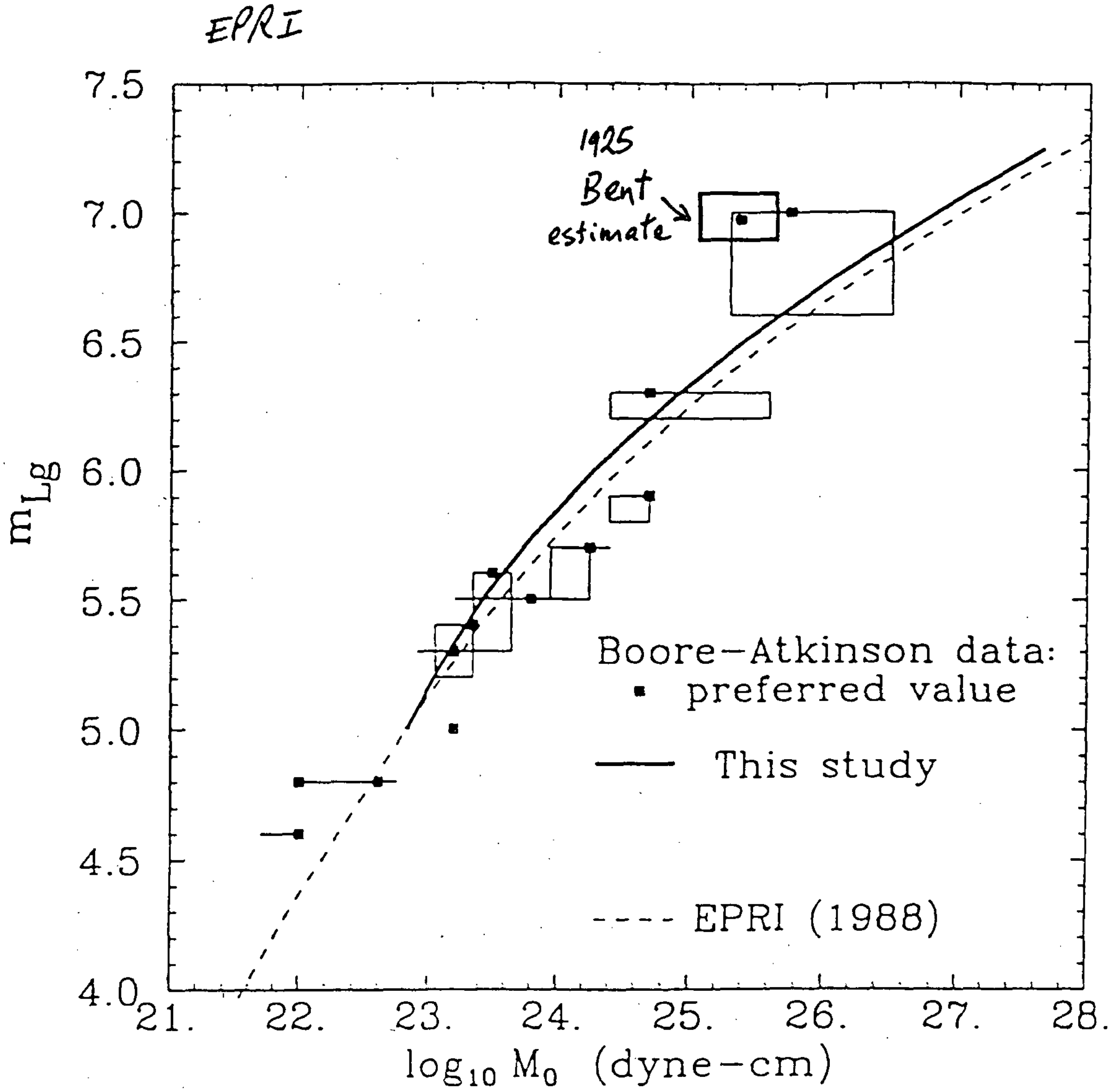


Figure V.5-1. Average predicted M_0–m_{Lg} relationship calculated using the ground-motion model in Section#3 (heavy solid line). Also shown are the relationship obtained by McGuire et al. (1988, dashed line) and the M_0–m_{Lg} data of Boore and Atkinson (1987, rectangles).

Fig A-1

Atkinson

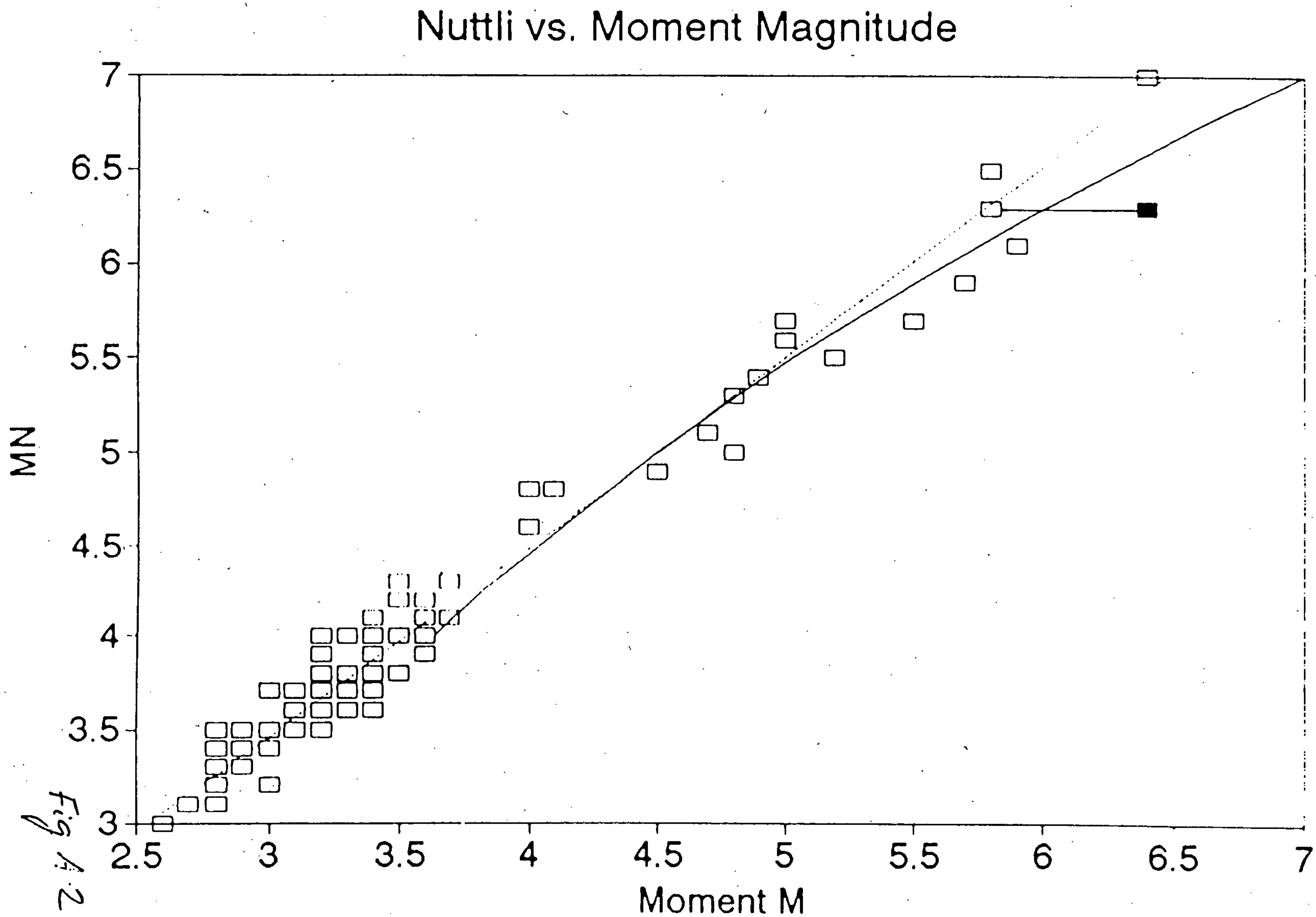


Fig A.2

Somerville /Saikia

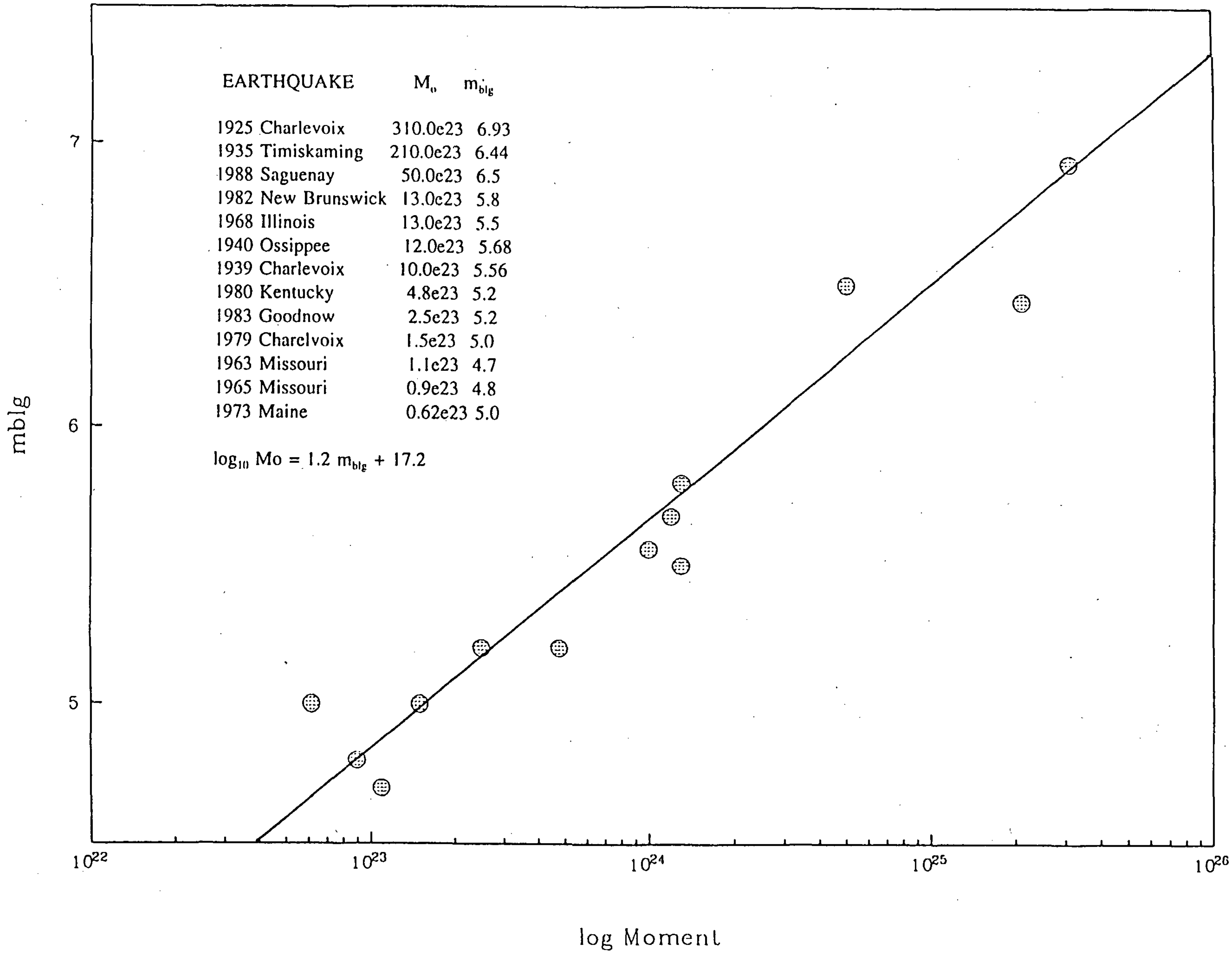
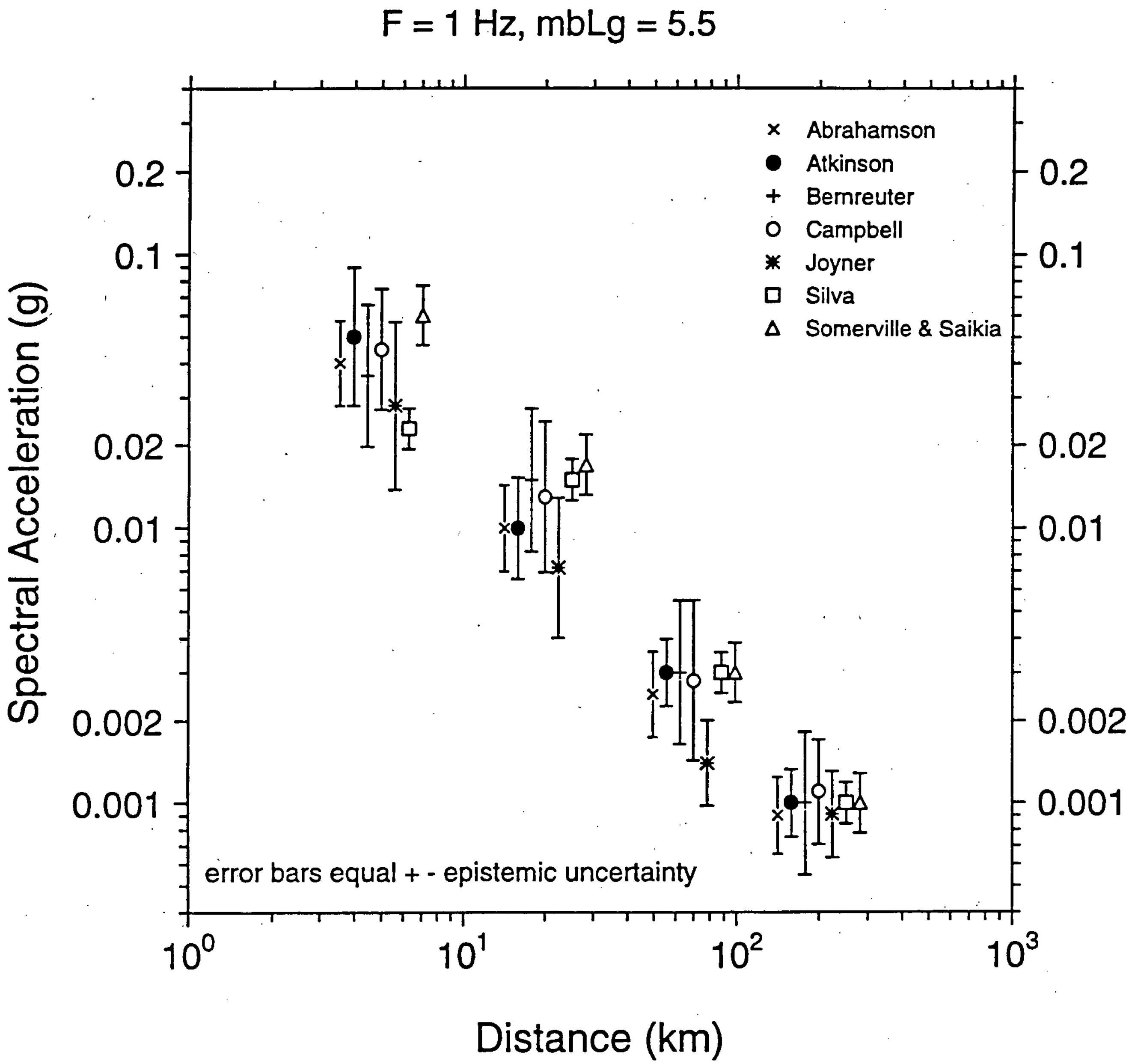
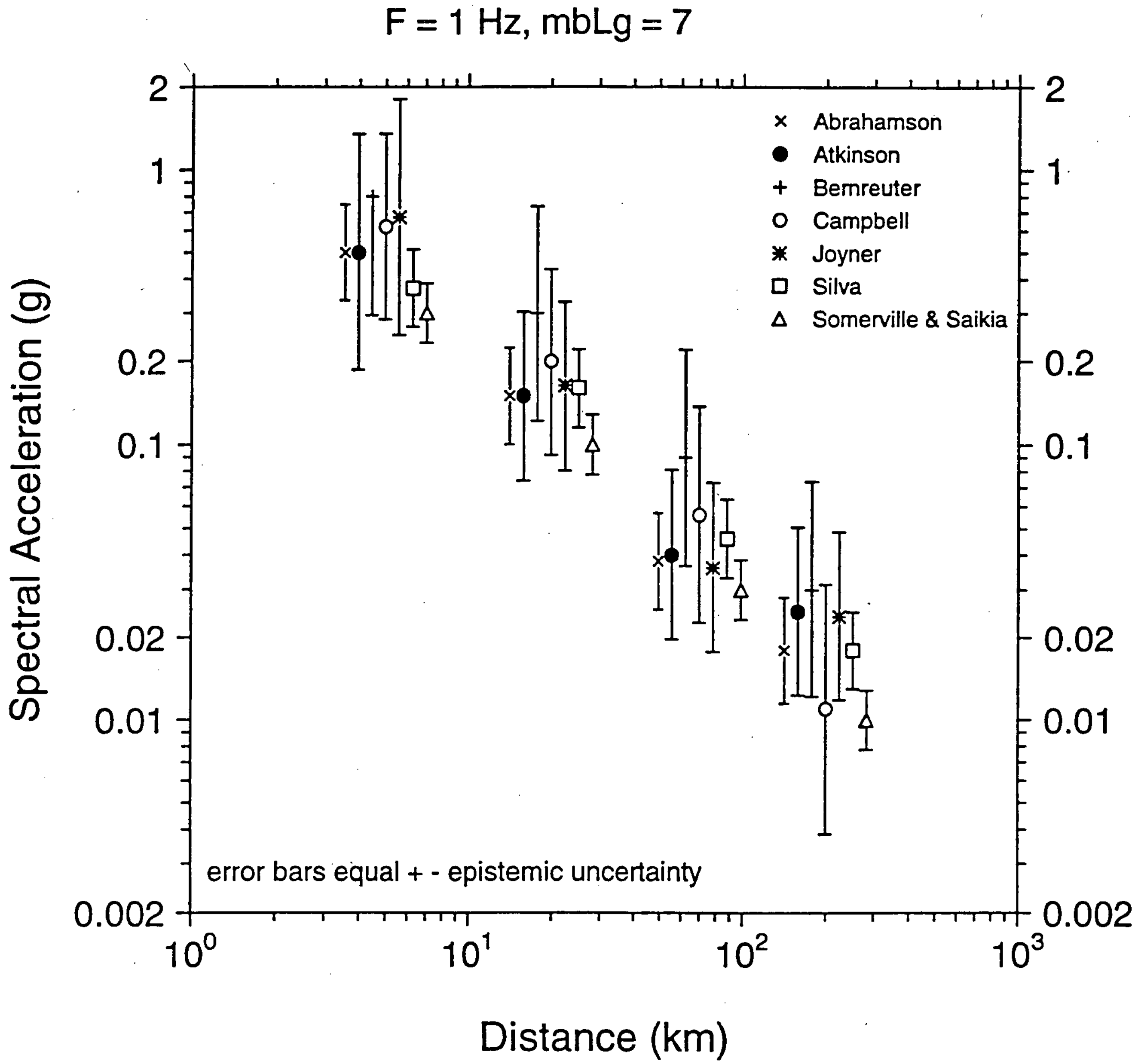


Fig A-3

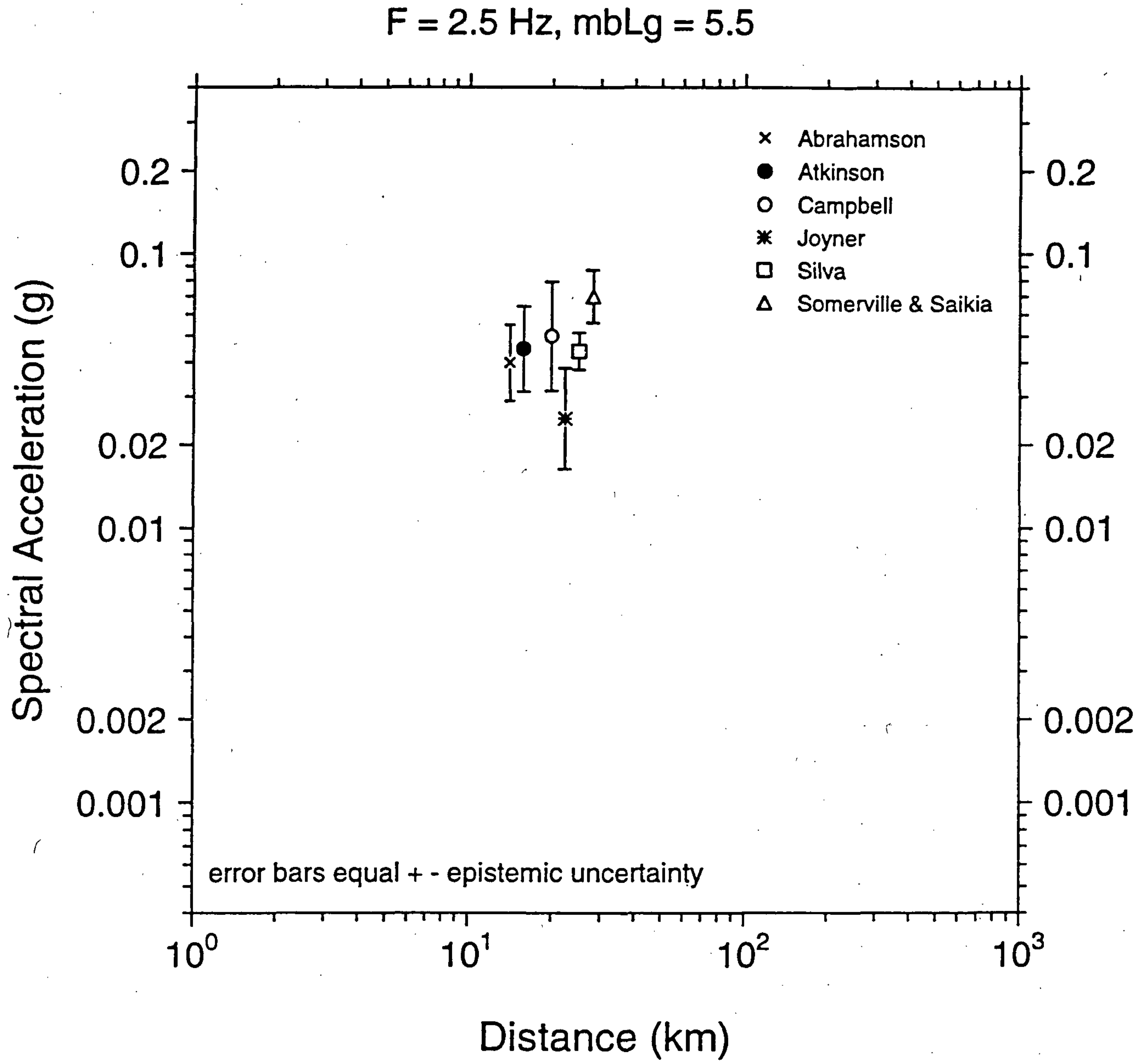
B-361



F = 1 Hz, mbLg = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
0.2
0.1
0.02
0.01
0.002
0.001
Distance (km)
10^0
10^1
10^2
10^3

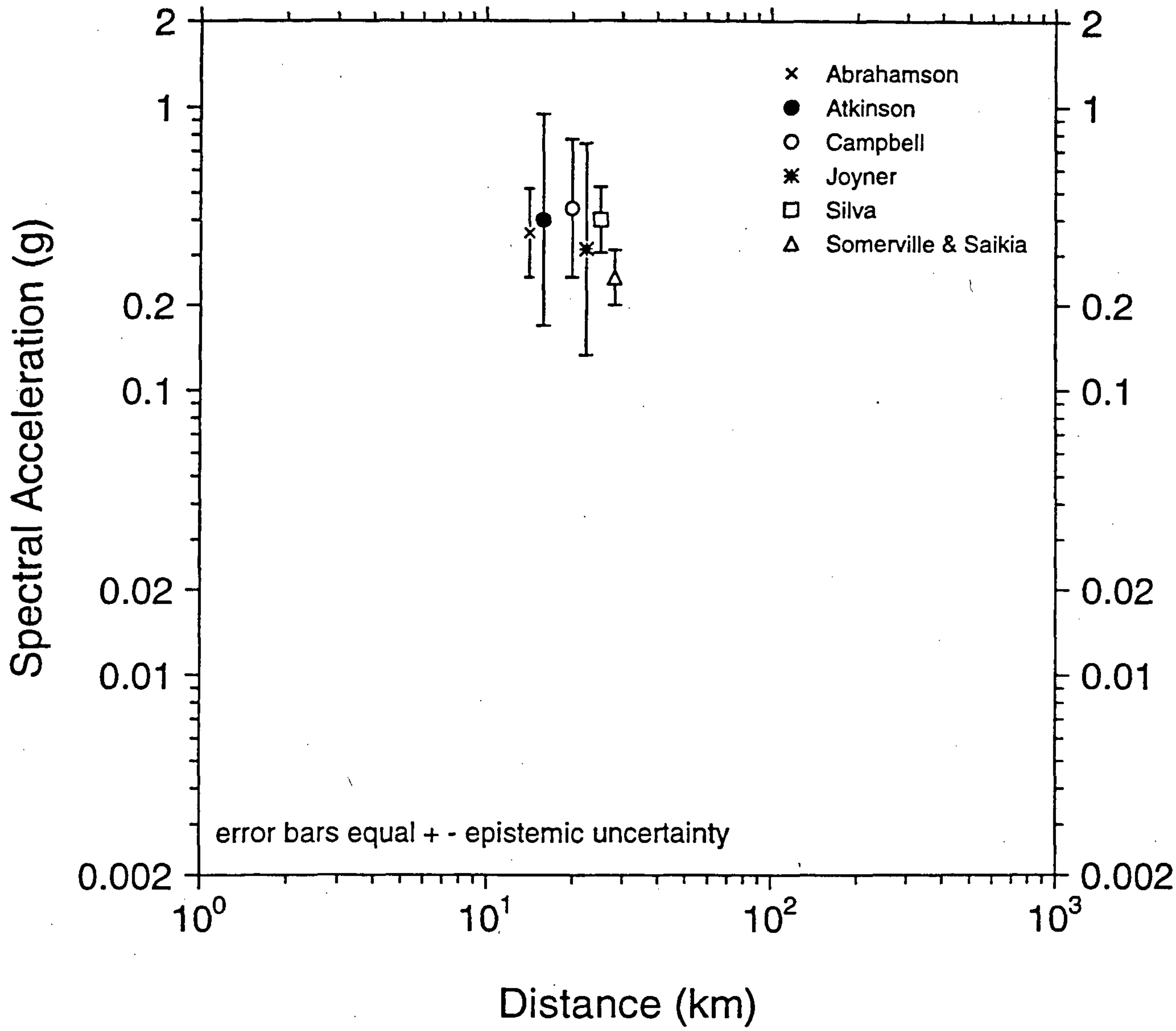


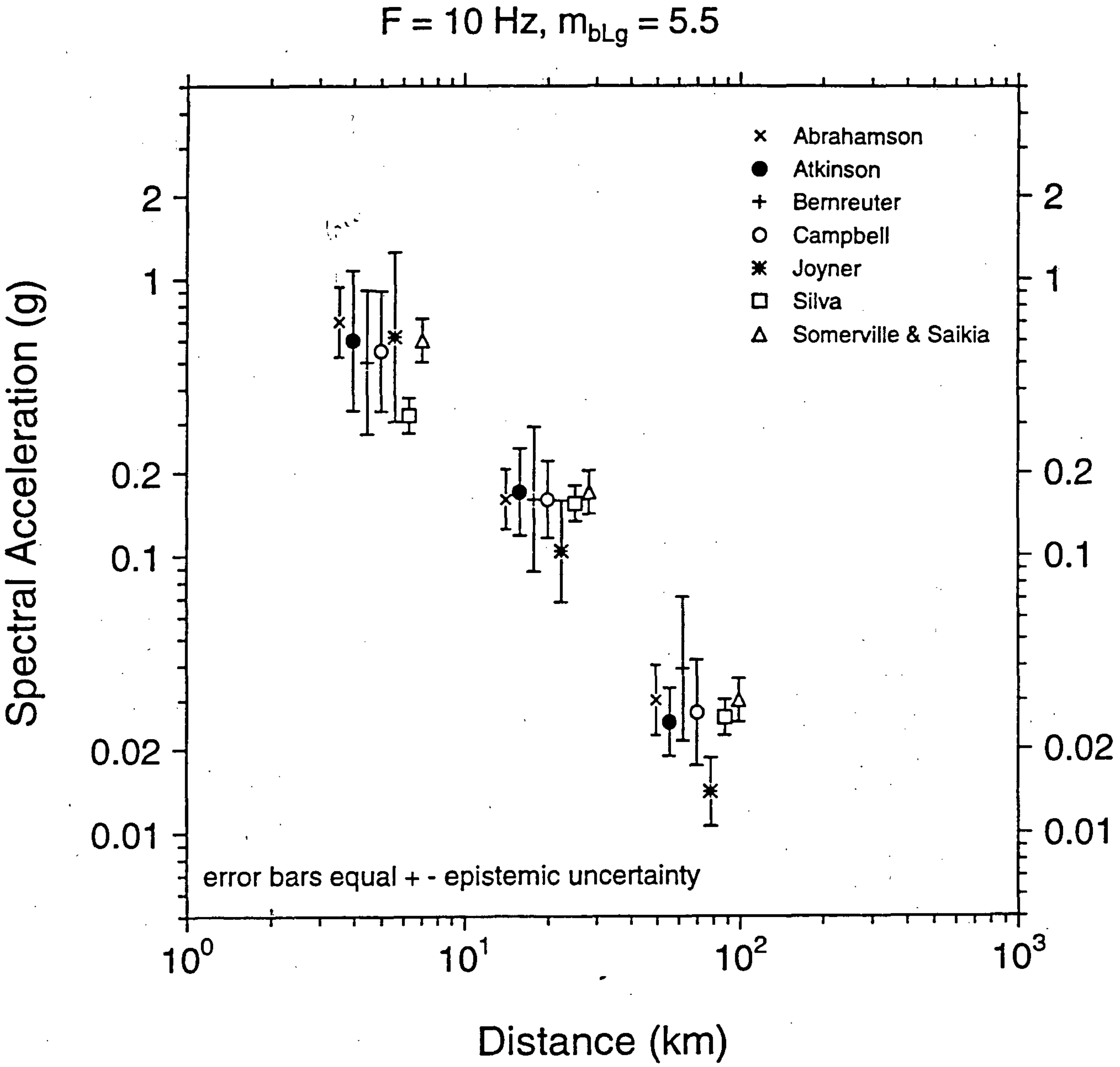
F = 1 Hz, mbLg = 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
0.002
10^0
10^1
10^2
10^3
Distance (km)



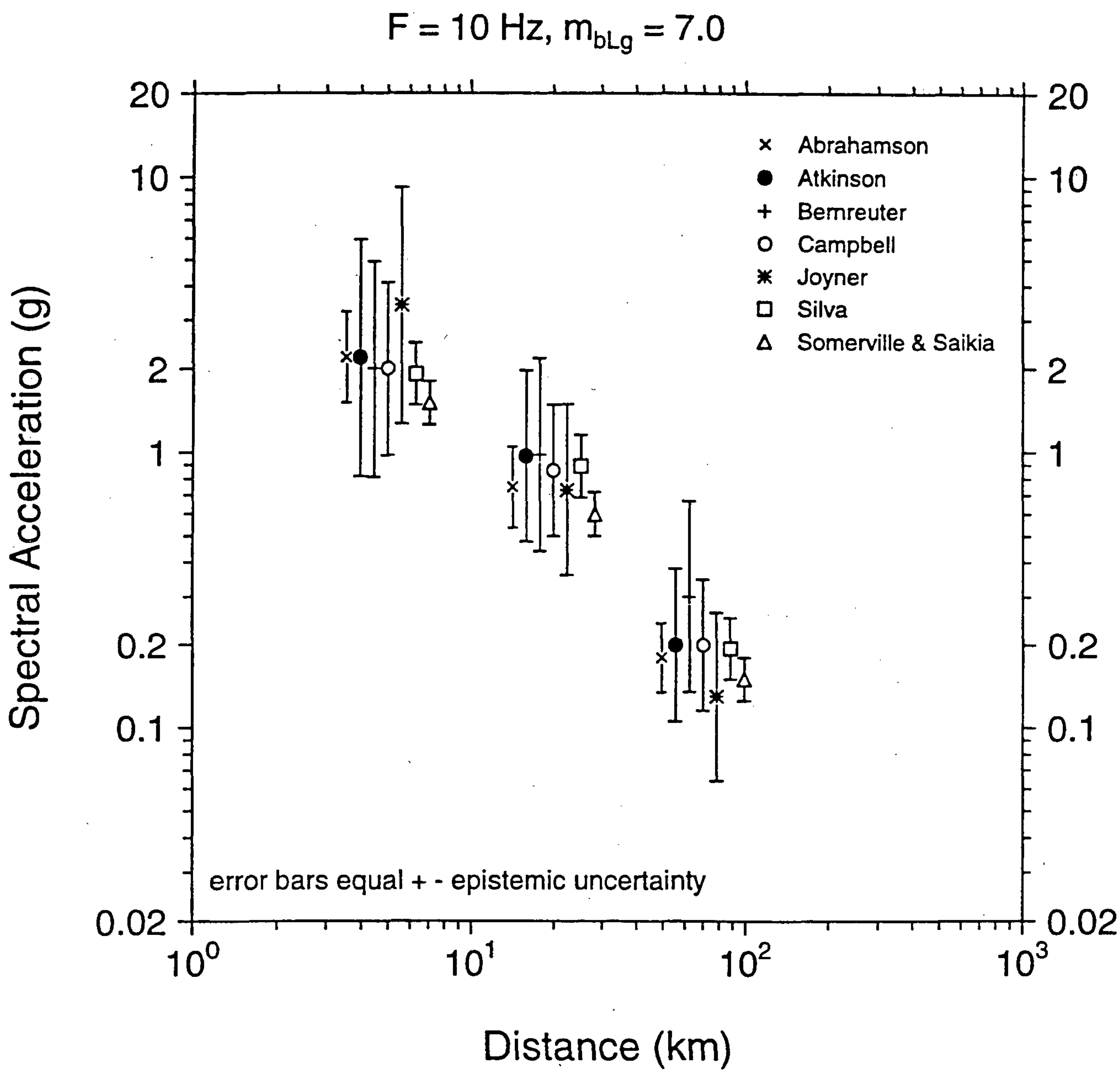
F = 2.5 Hz, mbLg = 5.5
Abrahamson
Atkinson
Campbell
Joyner
Silva
Somerville & Saikia
0.2
0.1
0.02
0.01
0.002
0.001
Spectral Acceleration (g)
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)

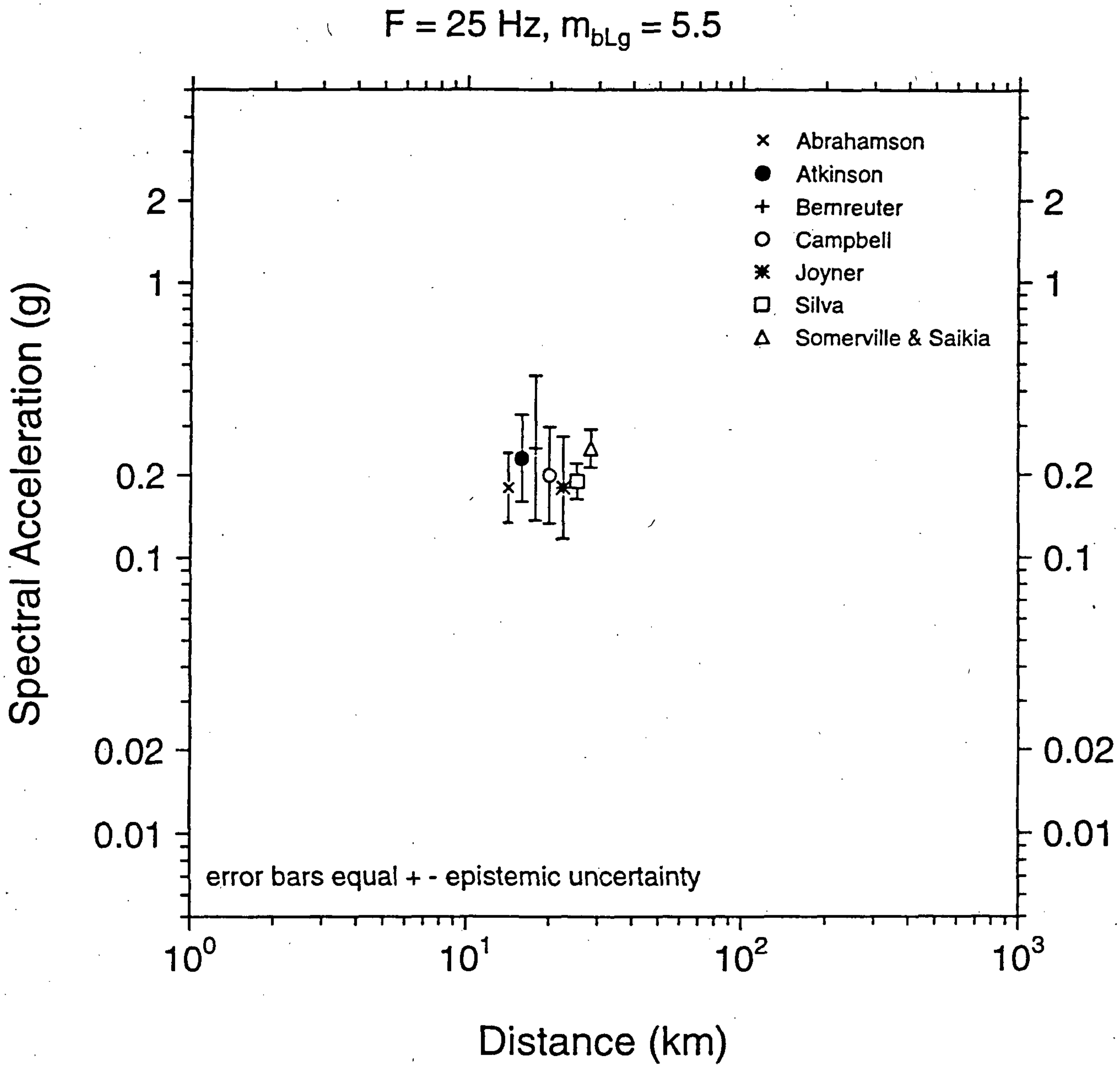
F = 2.5 Hz, mbLg = 7.0

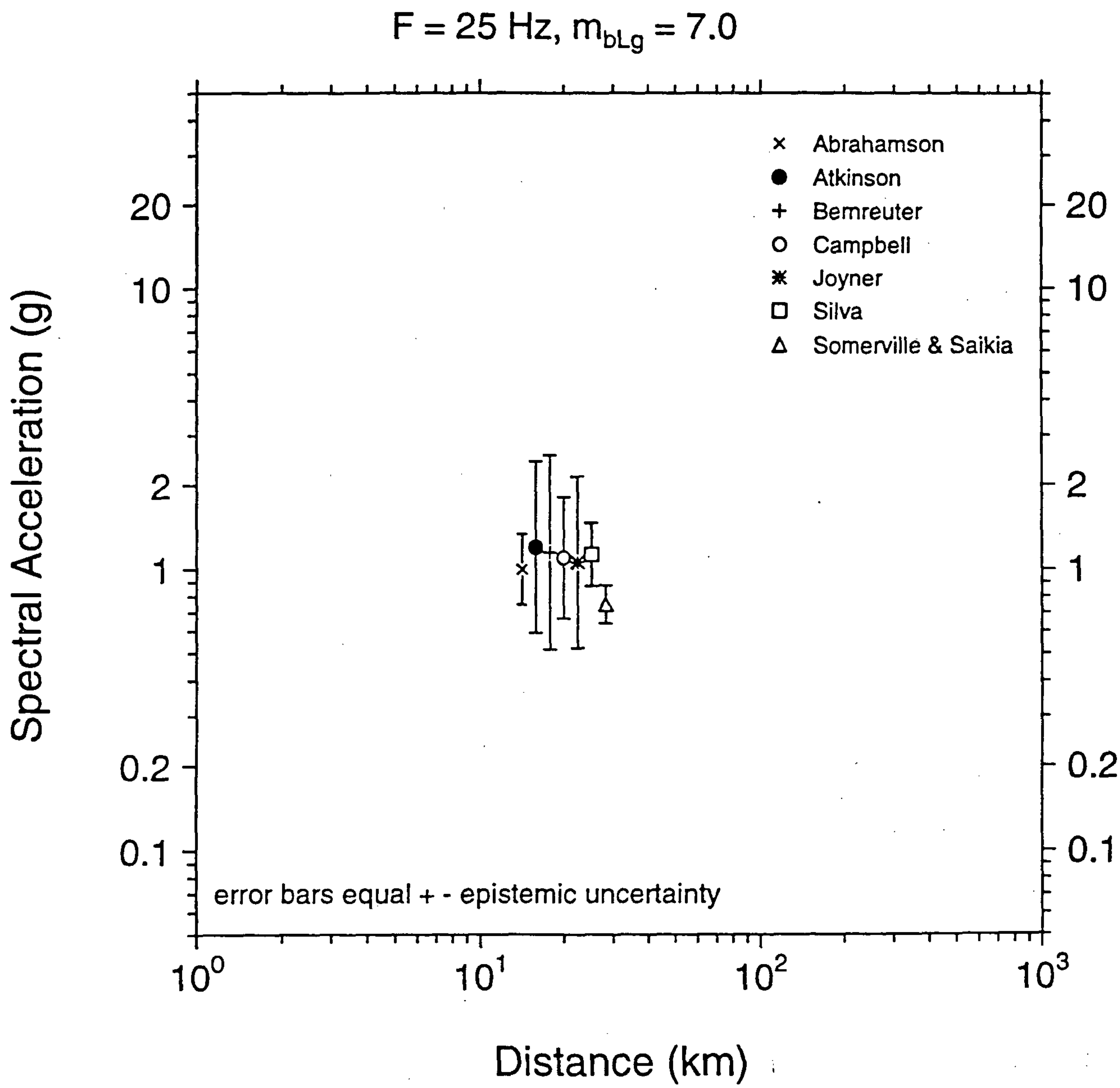


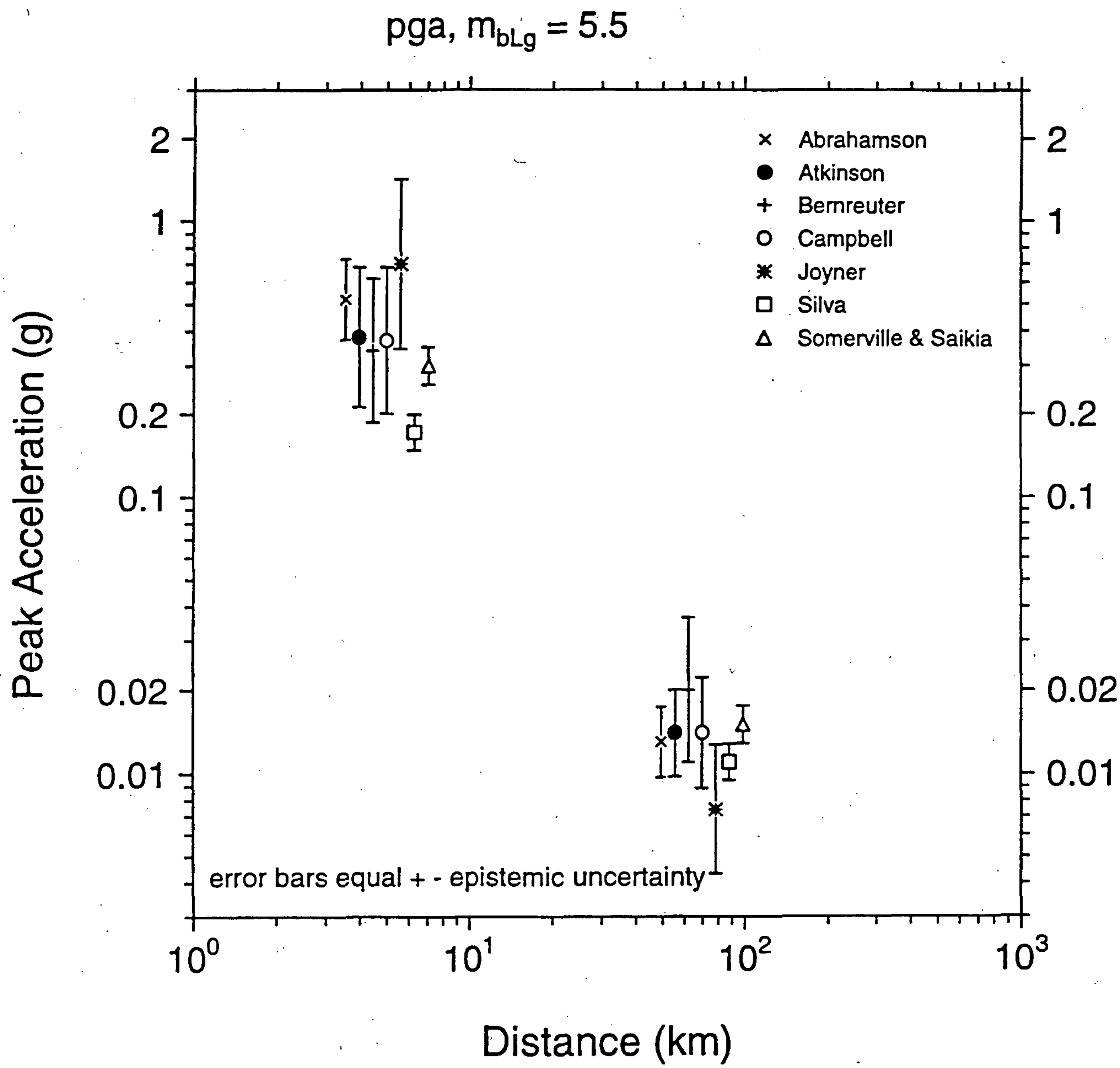


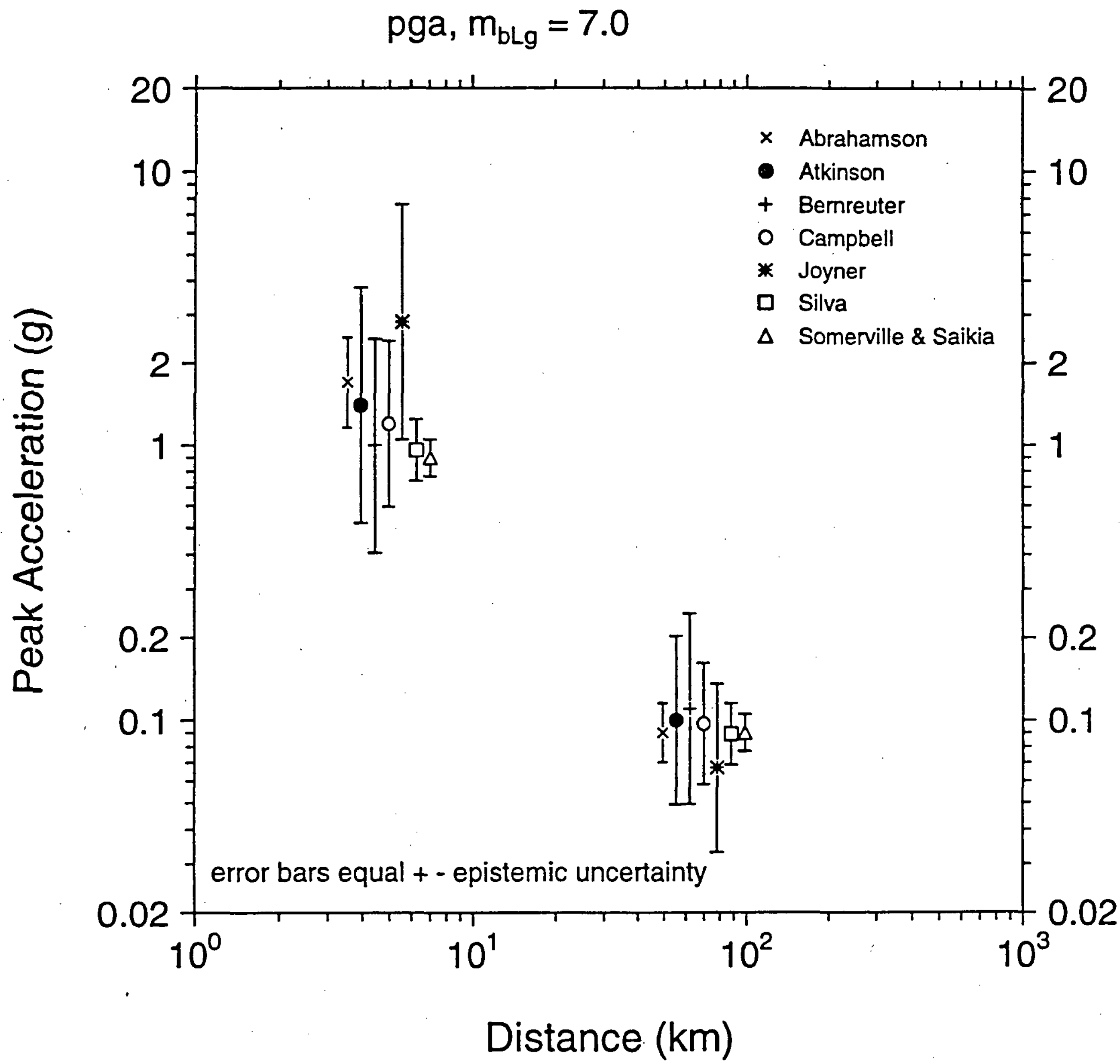
F = 10 Hz, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)


F = 10 Hz, m_{bLg} = 7.0
Spectral Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty

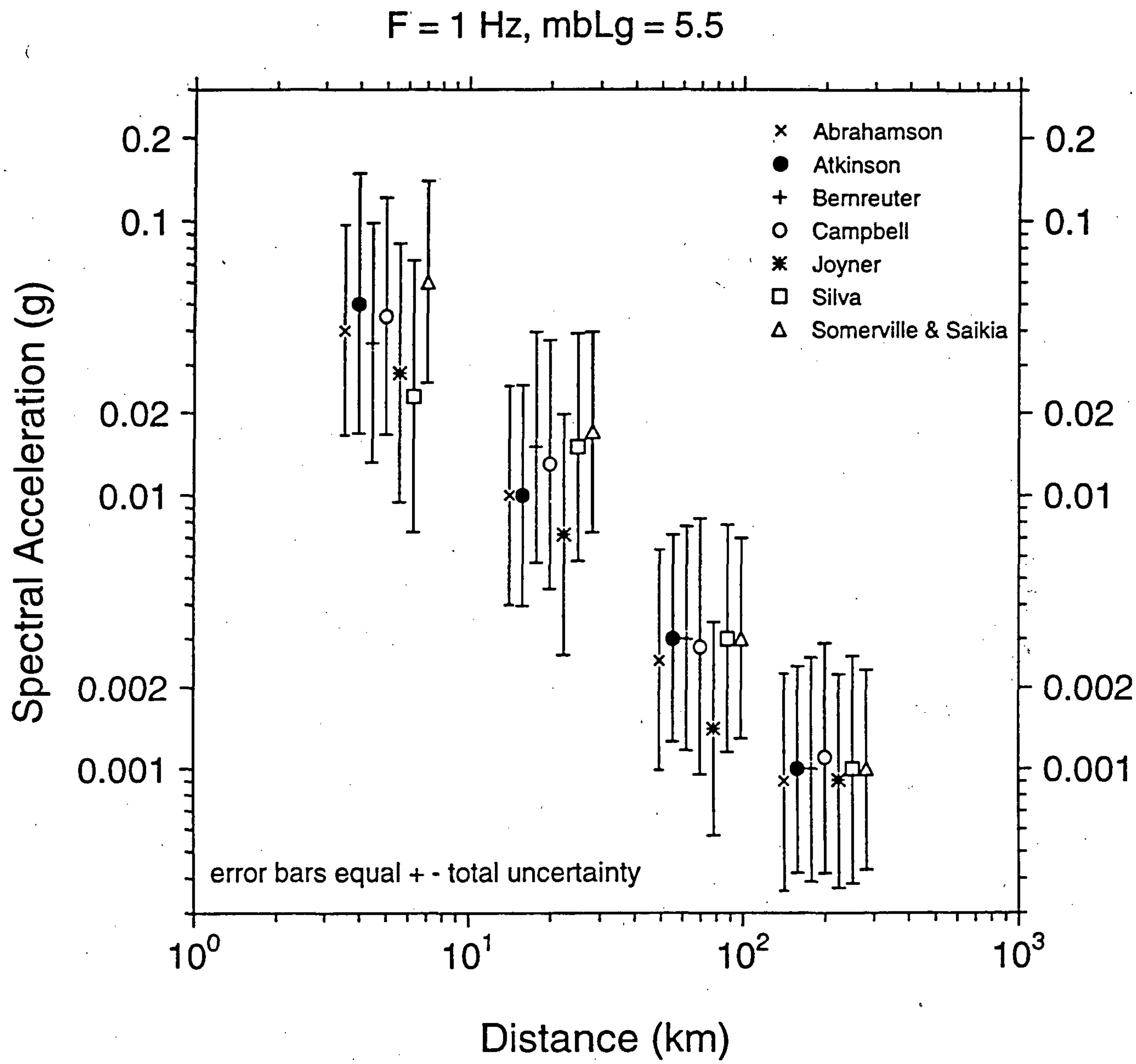

F = 25 Hz, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
2
1
0.2
0.1
0.02
0.01
Spectral Acceleration (g)
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)

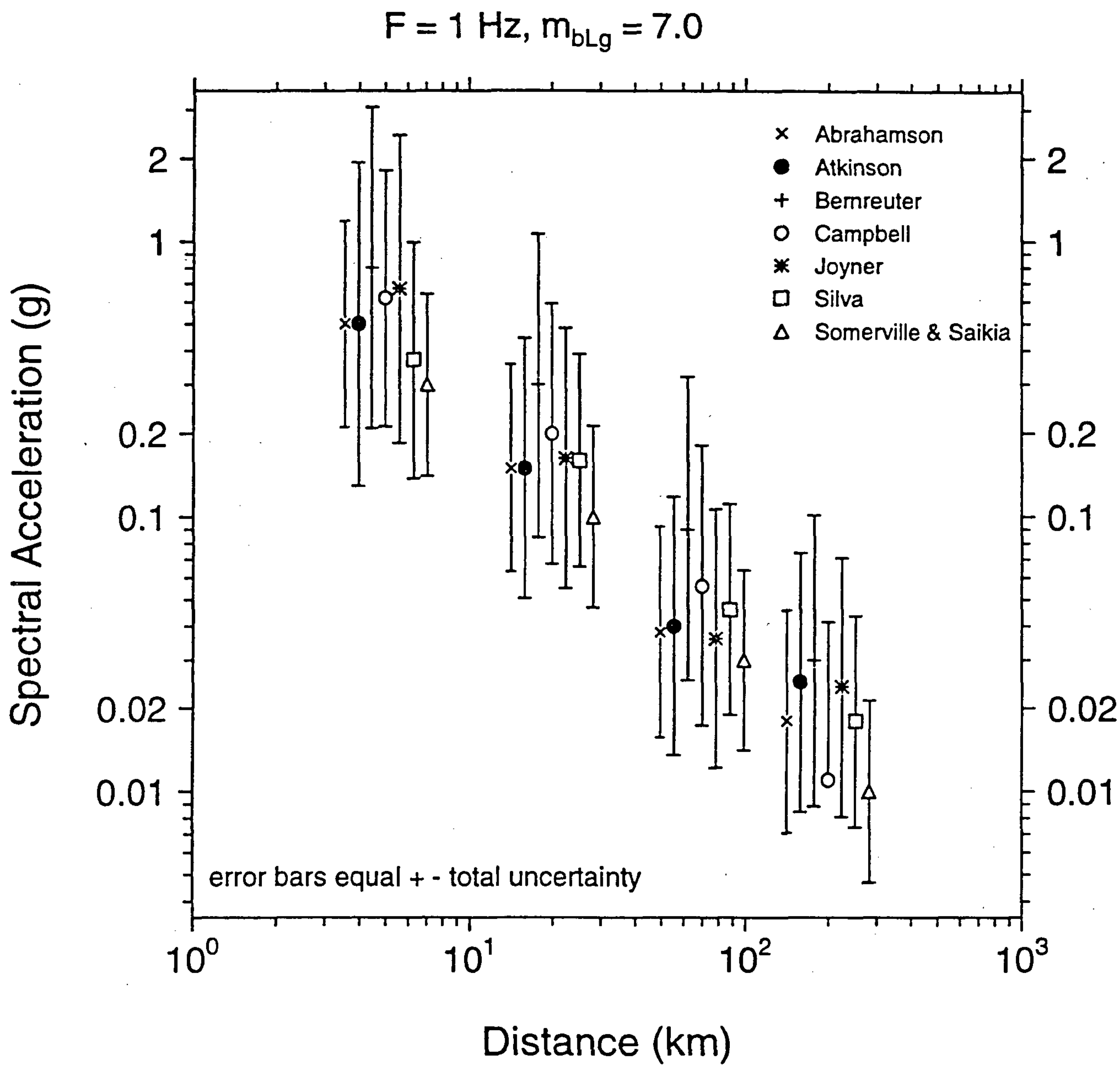

F = 25 Hz, m_bLg = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
10^0
10^1
10^2
10^3


pga, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Peak Acceleration (g)
Distance (km)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3

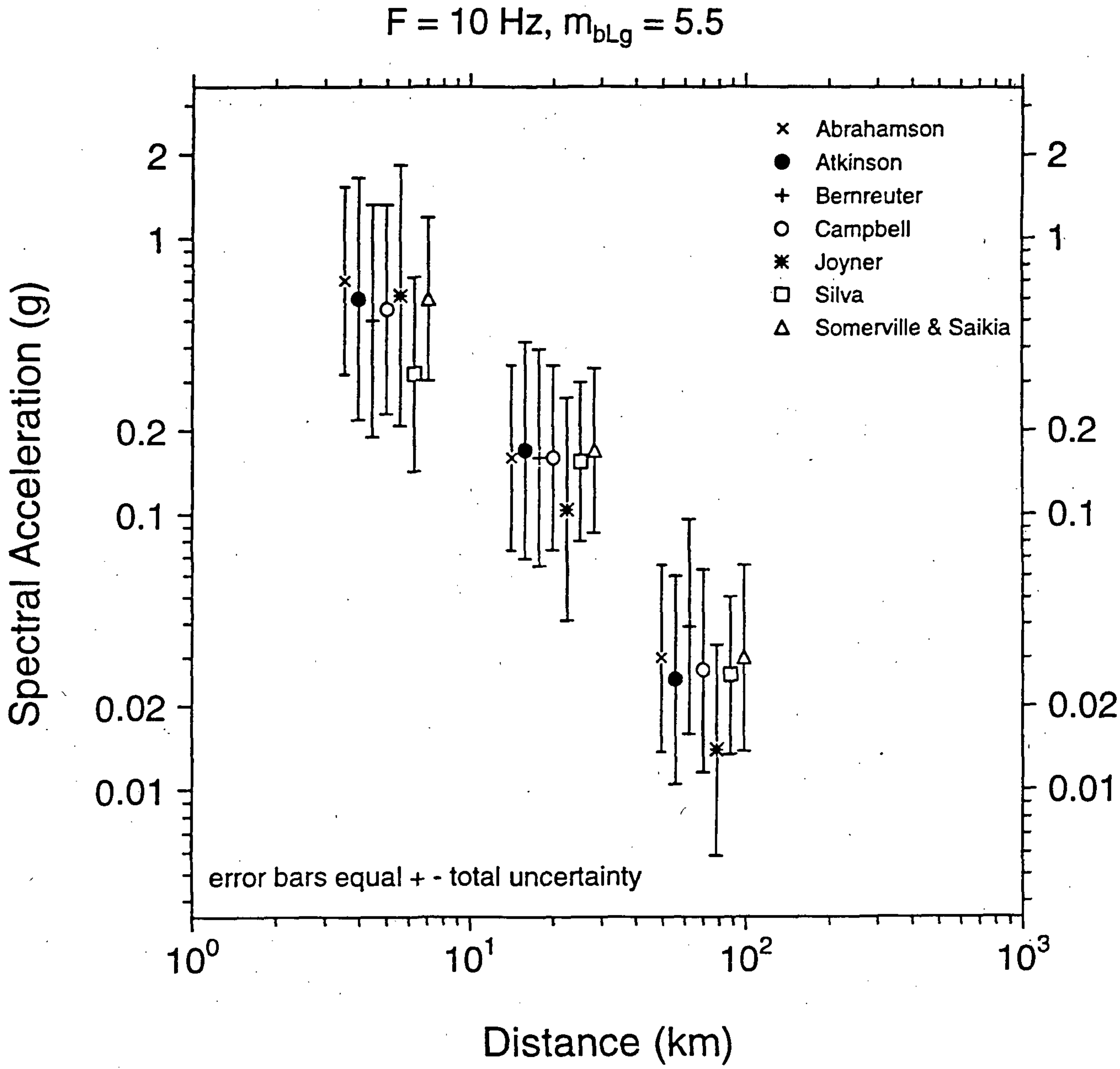


pga, m_{bLg} = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Peak Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3

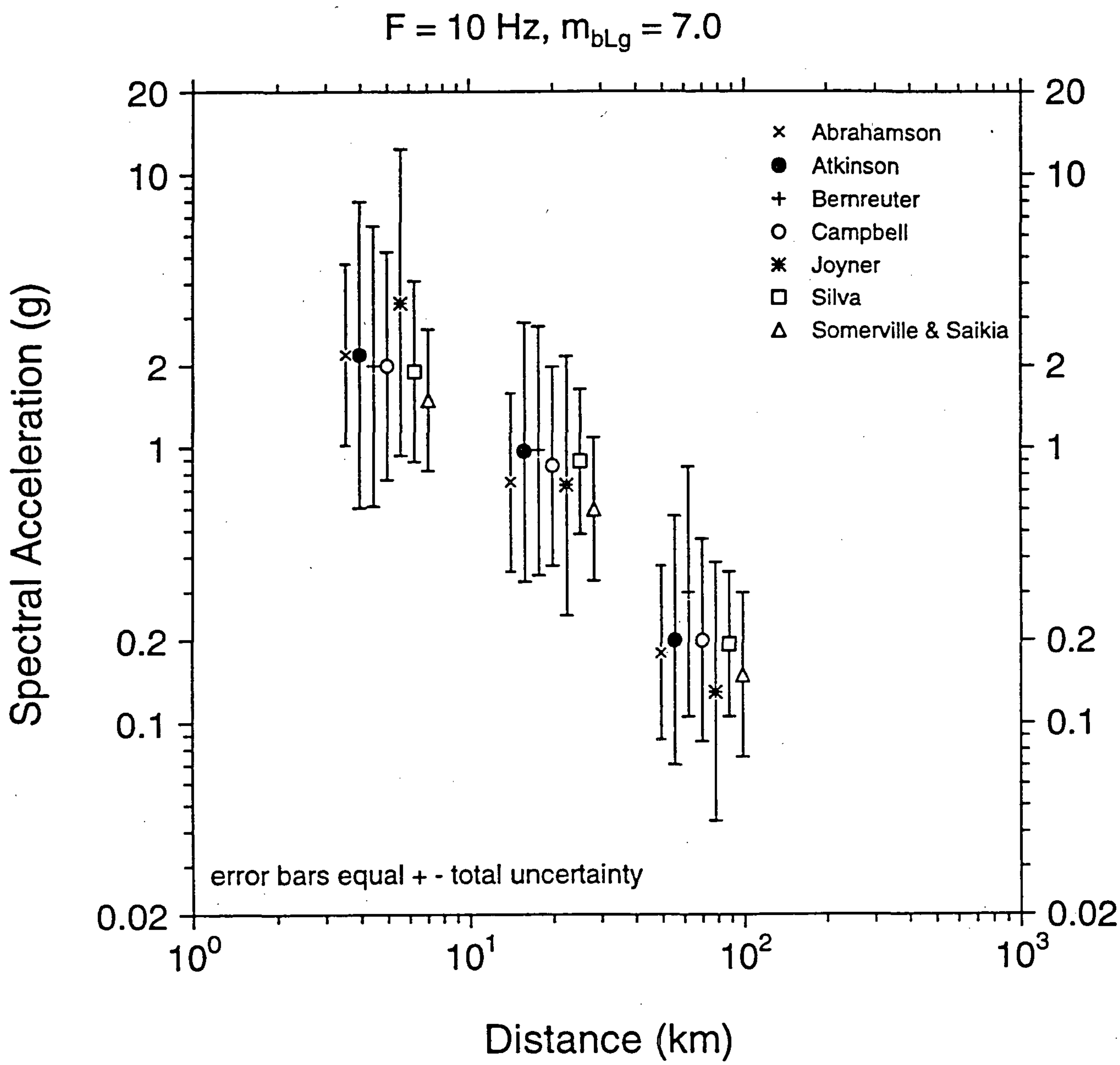

F = 1 Hz, mbLg = 5.5
Spectral Acceleration (g)
Distance (km)
0.2
0.1
0.02
0.01
0.002
0.001
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - total uncertainty

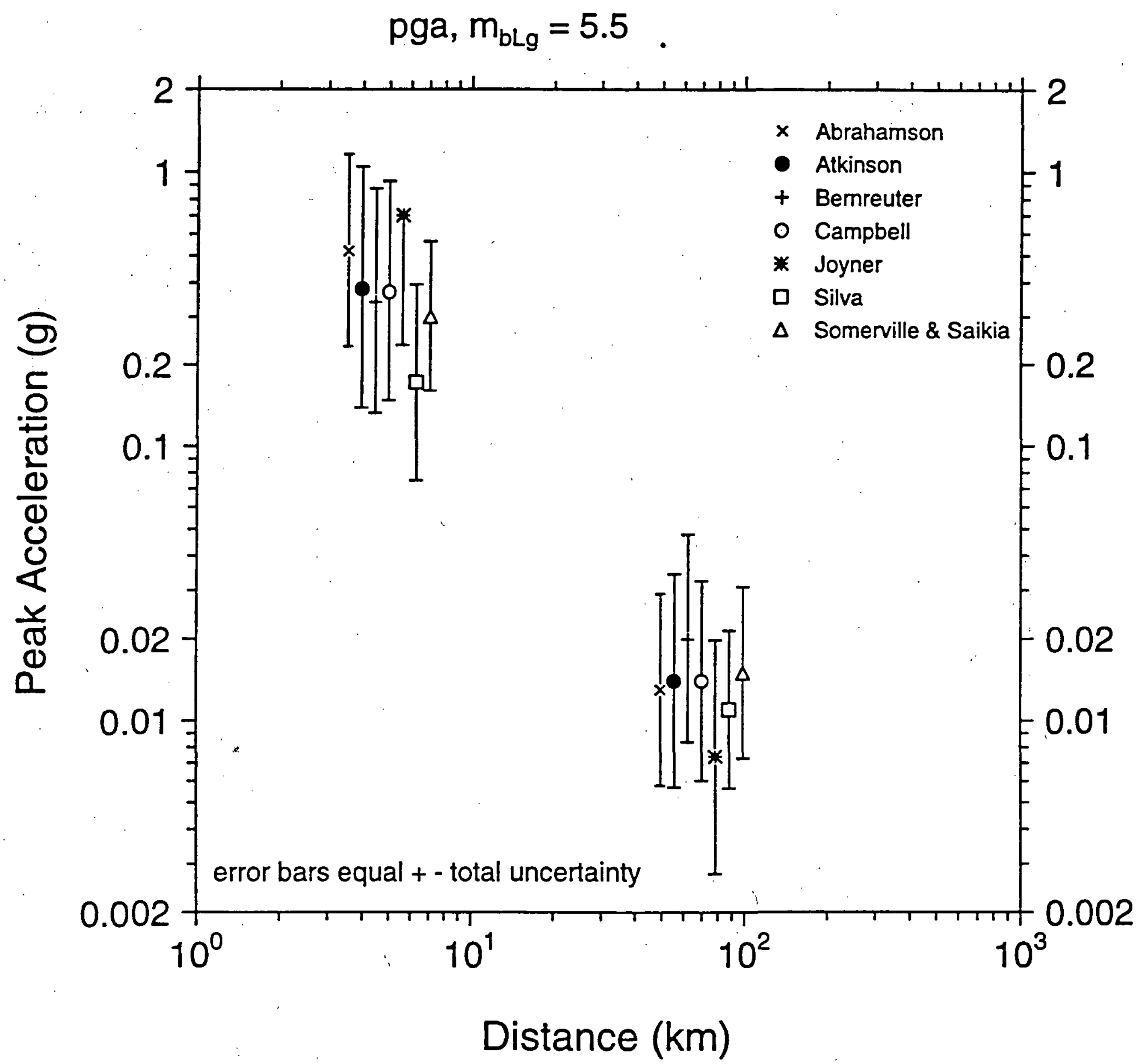


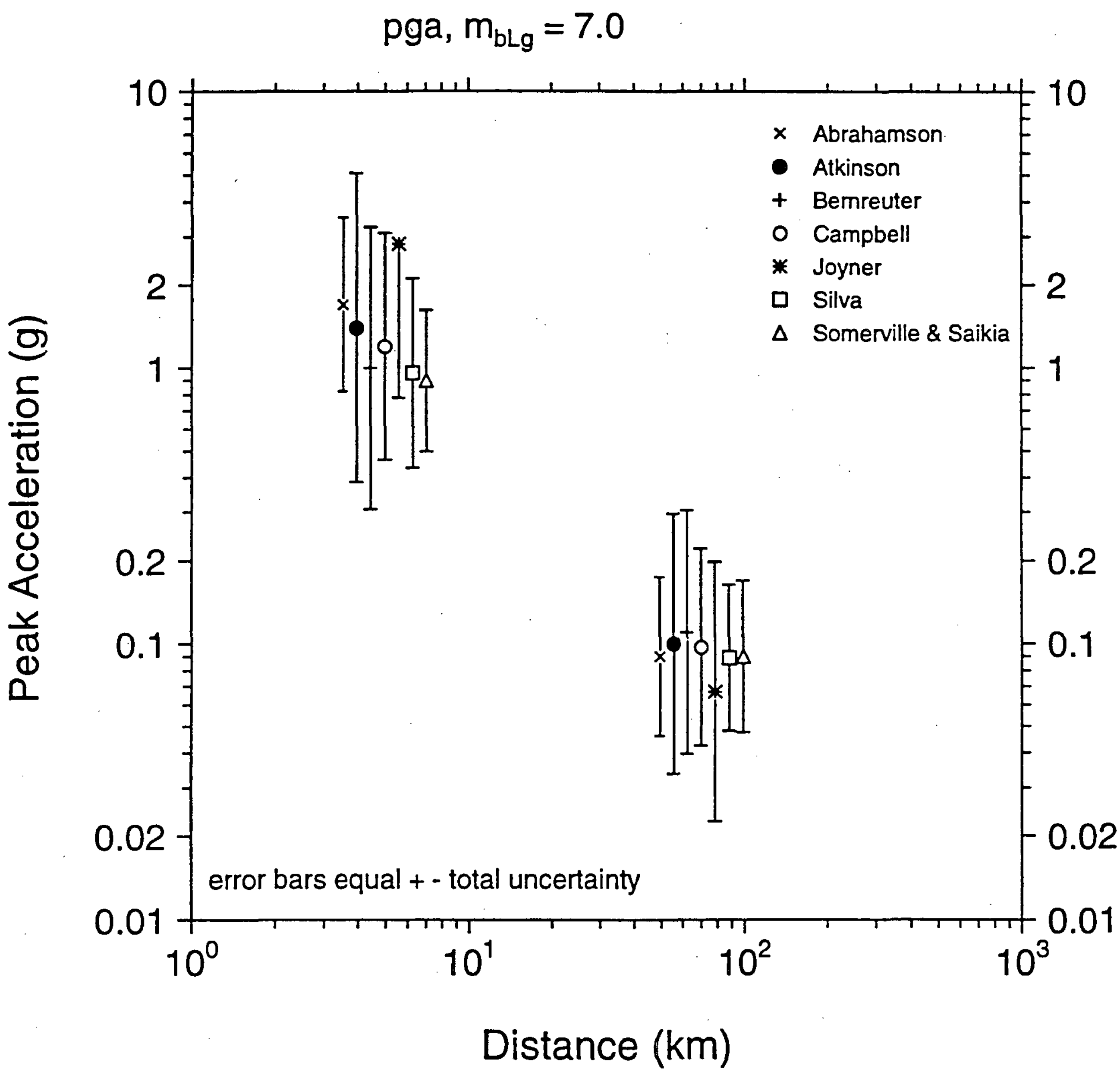
F = 1 Hz, m_{bLg} = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - total uncertainty
Spectral Acceleration (g)
Distance (km)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3

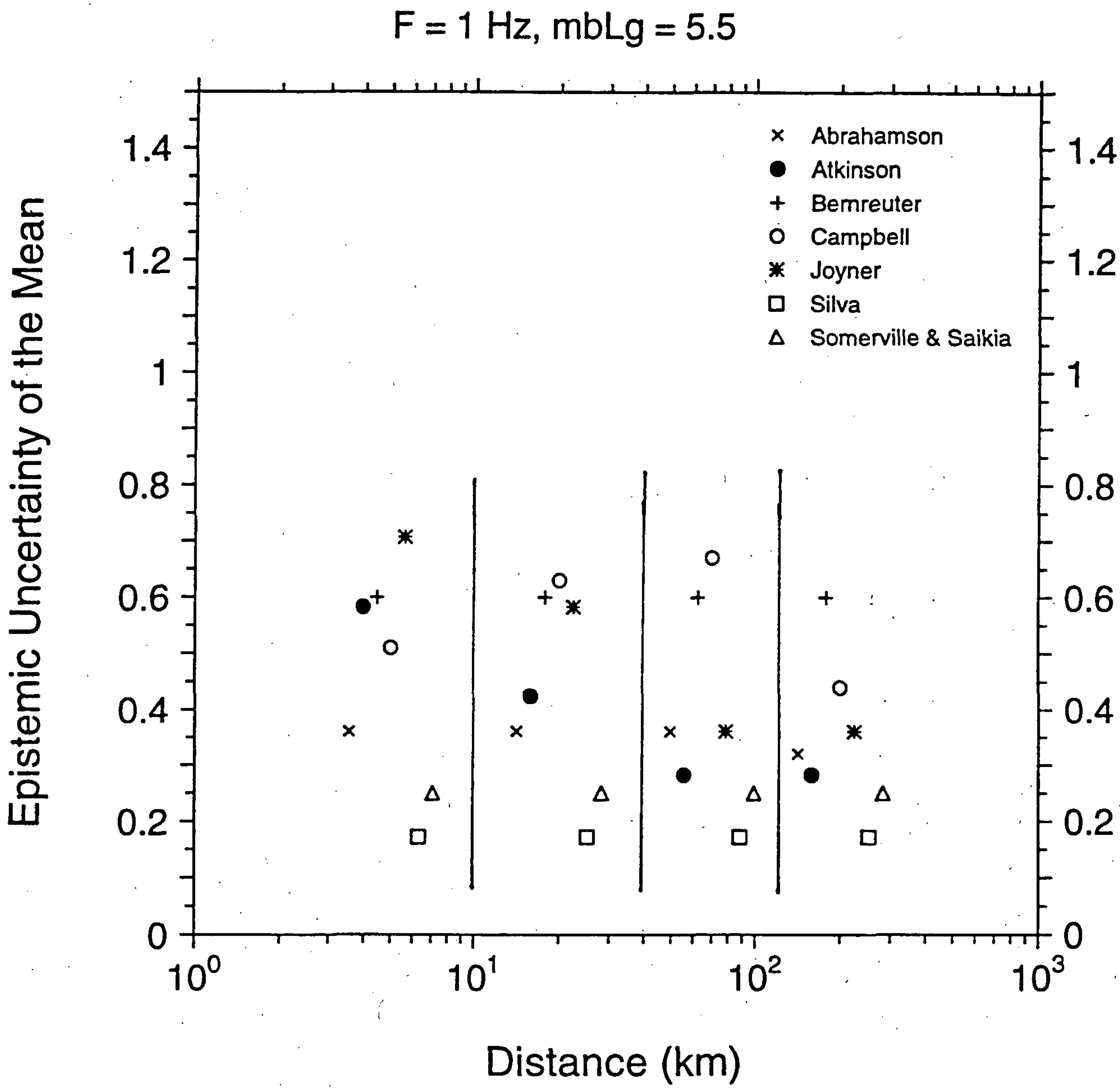


F = 10 Hz, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
error bars equal + - total uncertainty
10^0
10^1
10^2
10^3
Distance (km)

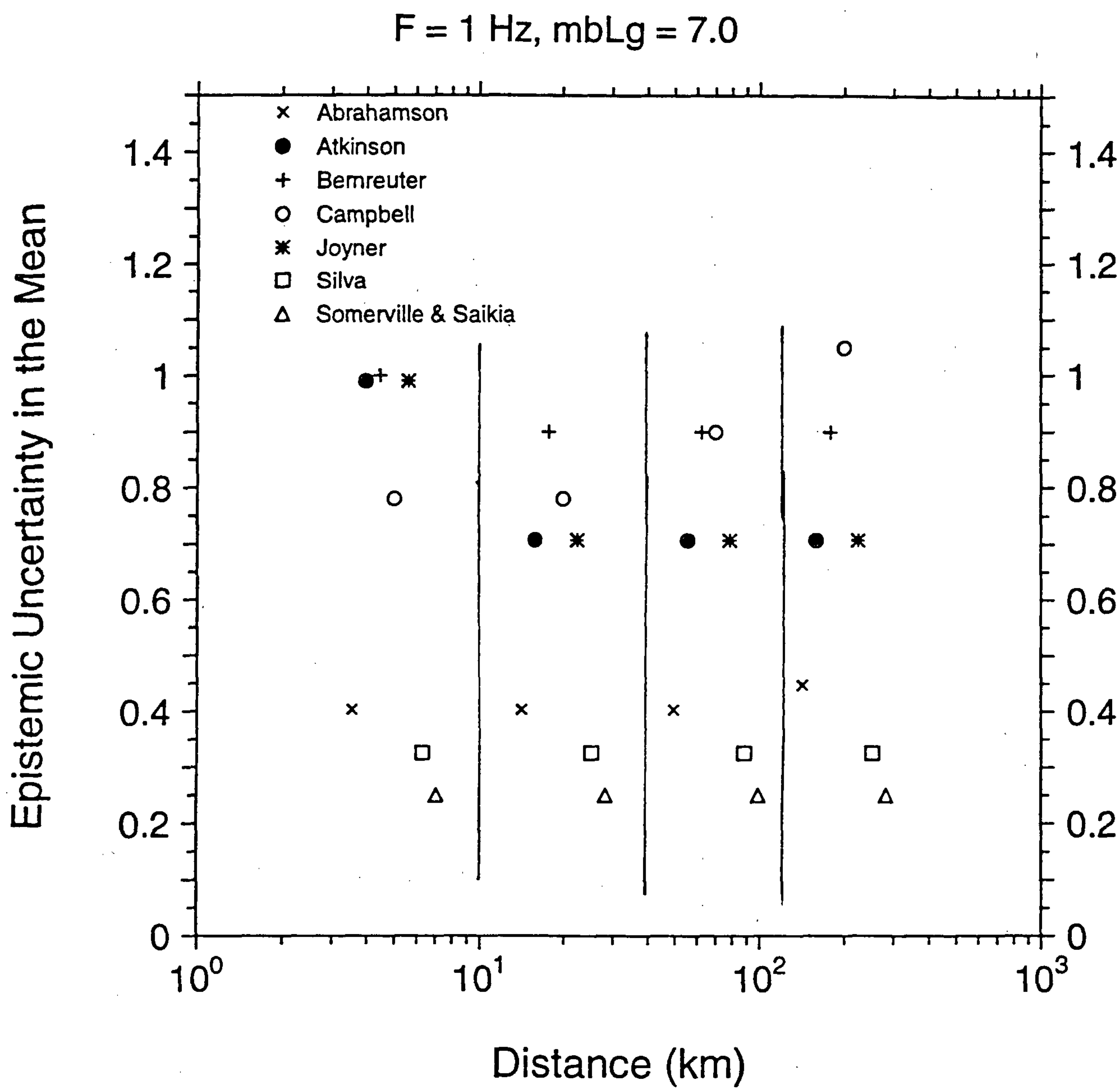

F = 10 Hz, m_{bLg} = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - total uncertainty
Spectral Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3


pga, m_{bLg} = 5.5
Peak Acceleration (g)
Distance (km)
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - total uncertainty
2
1
0.2
0.1
0.02
0.01
0.002
10^0
10^1
10^2
10^3

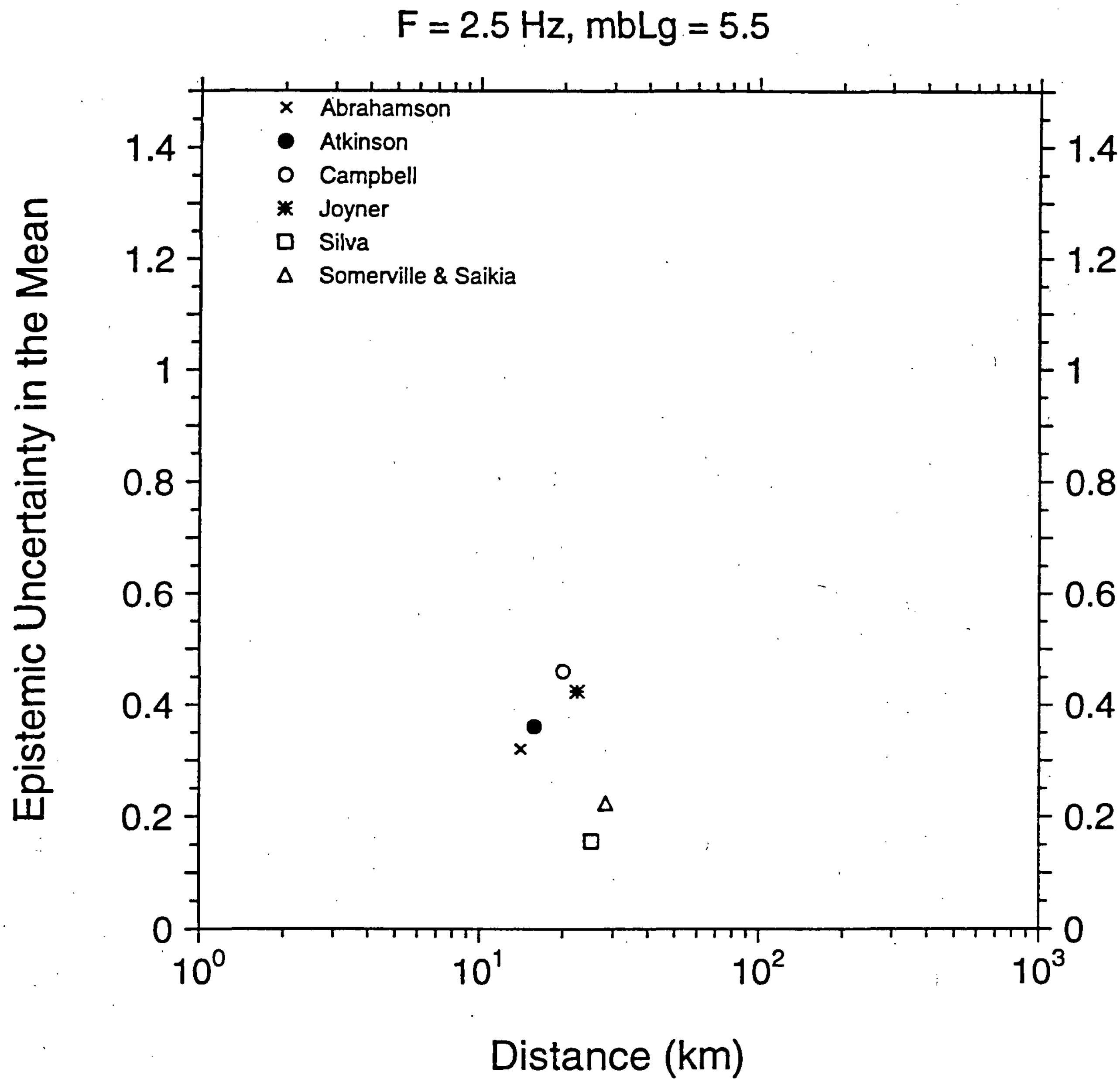

pga, m_{bLg} = 7.0
Peak Acceleration (g)
Distance (km)
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - total uncertainty
10
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3



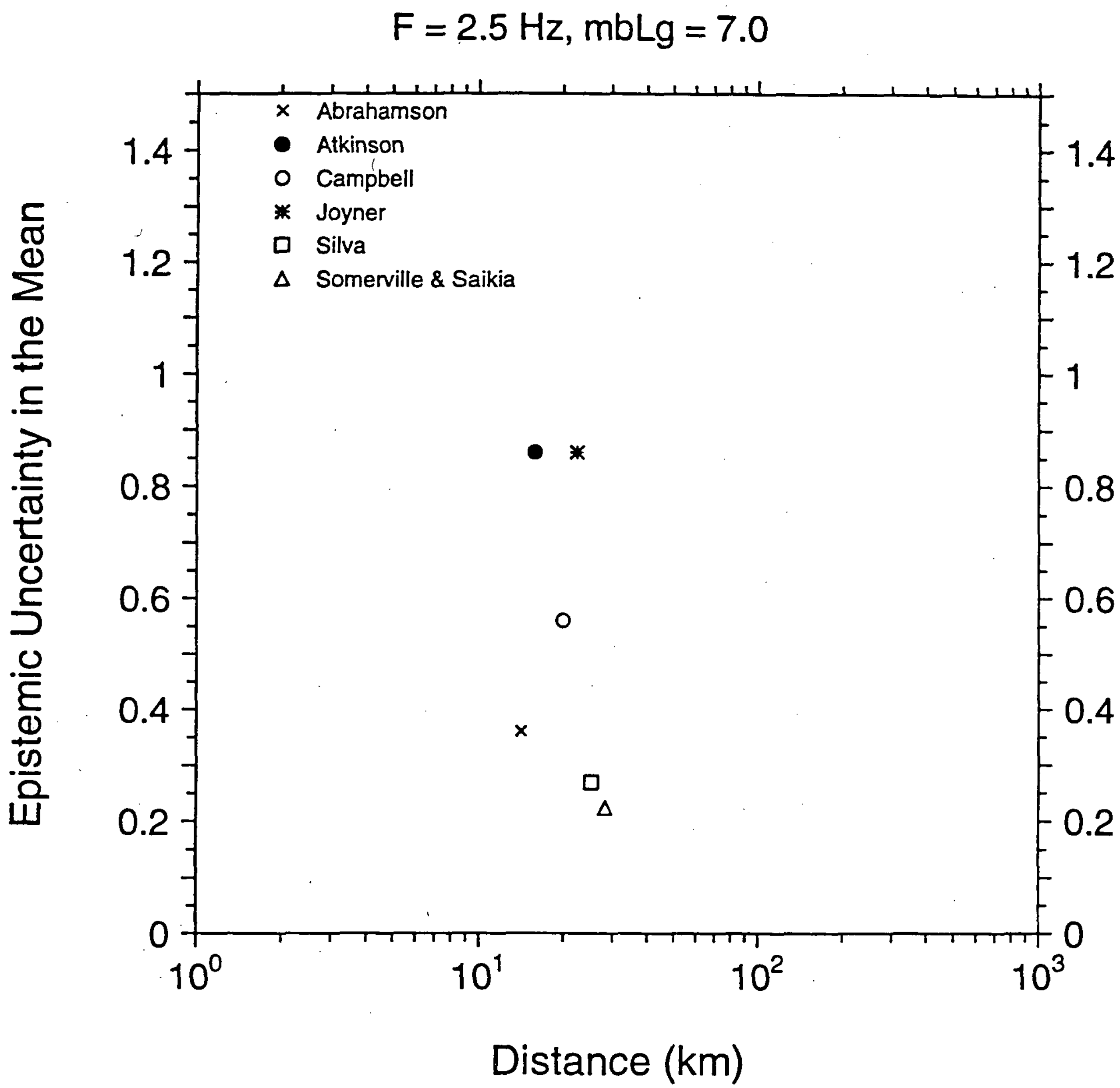
F = 1 Hz, mbLg = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty of the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3



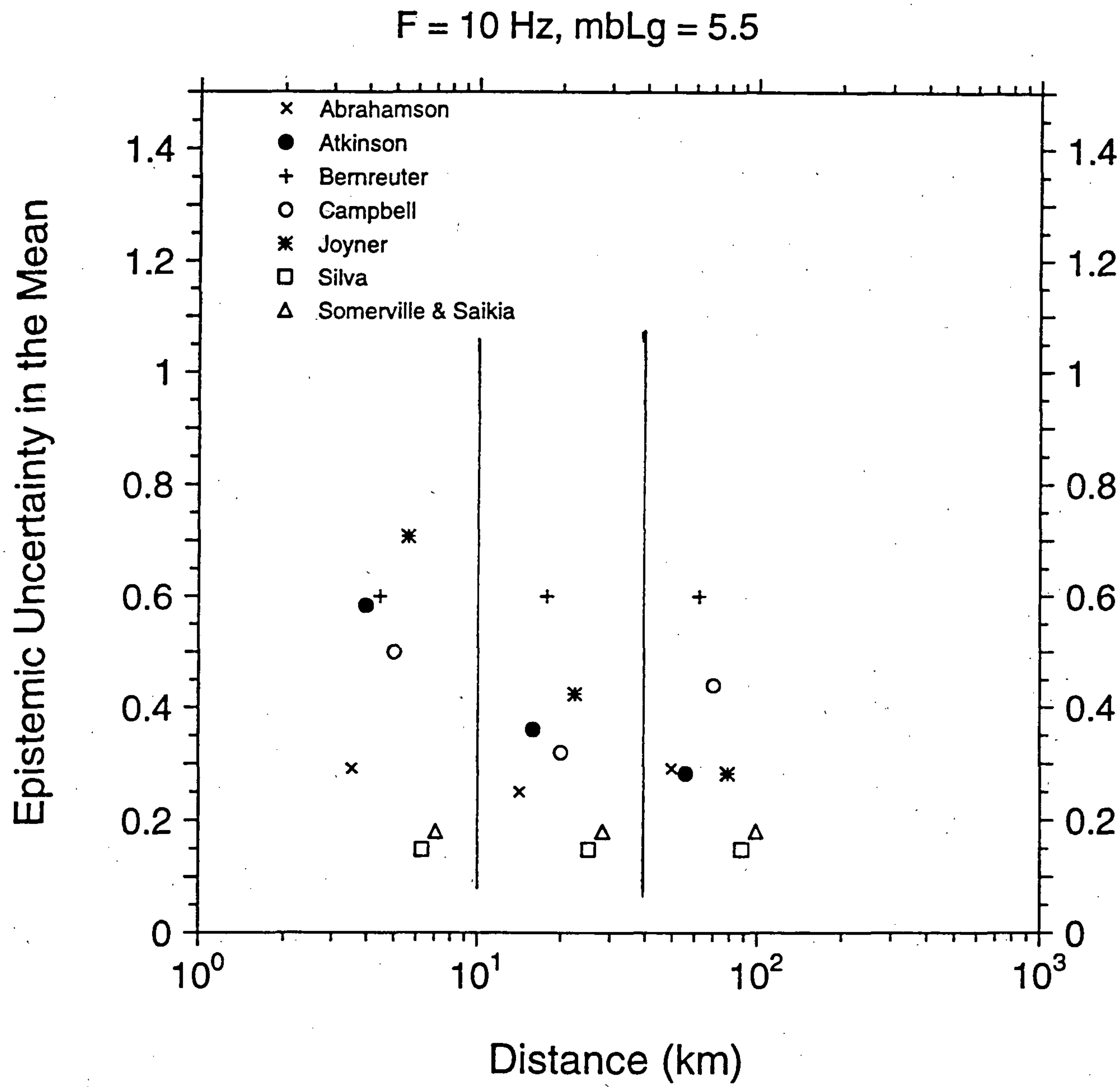
F = 1 Hz, mbLg = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

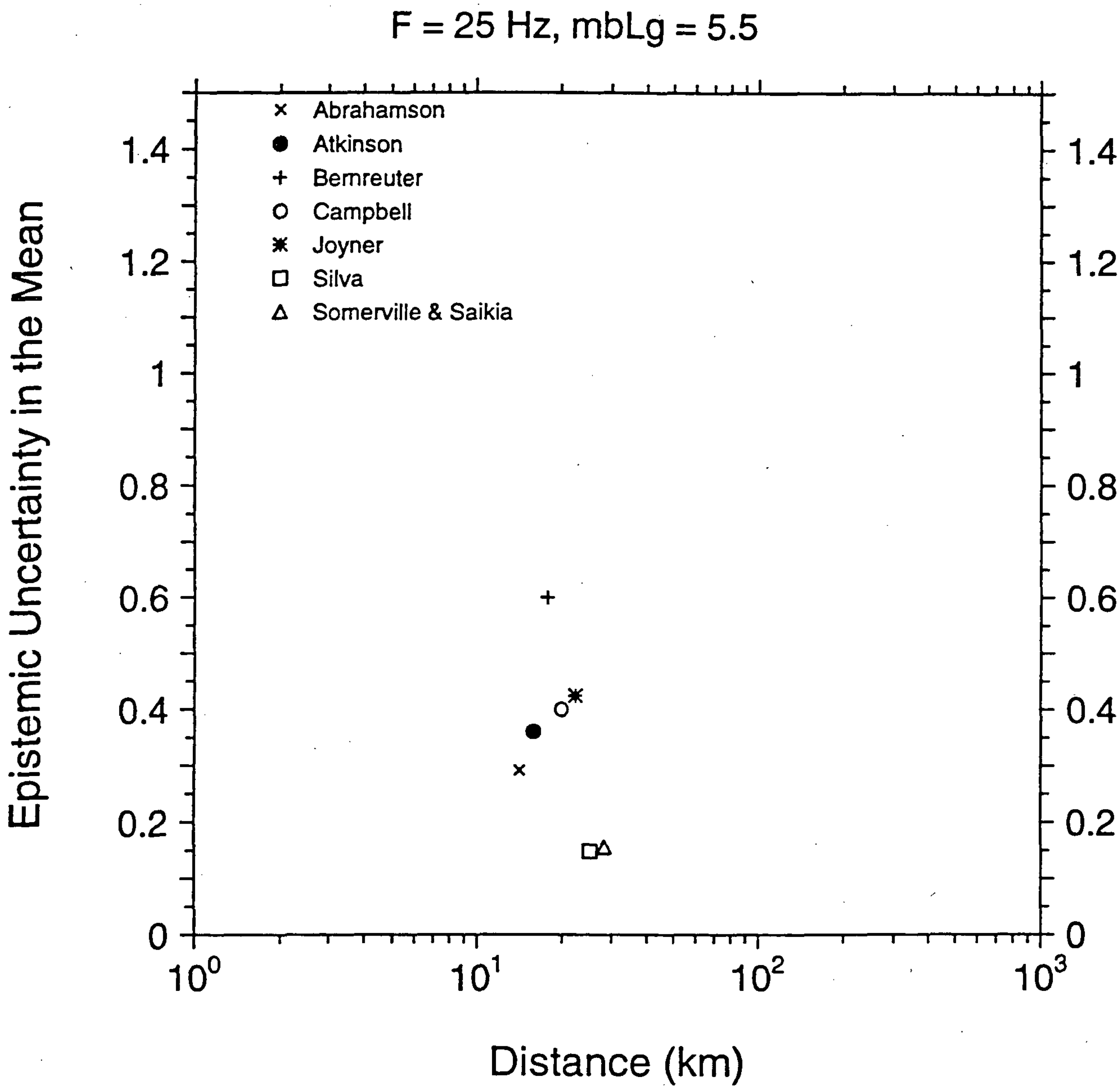


F = 2.5 Hz, mbLg = 5.5
Abrahamson
Atkinson
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)

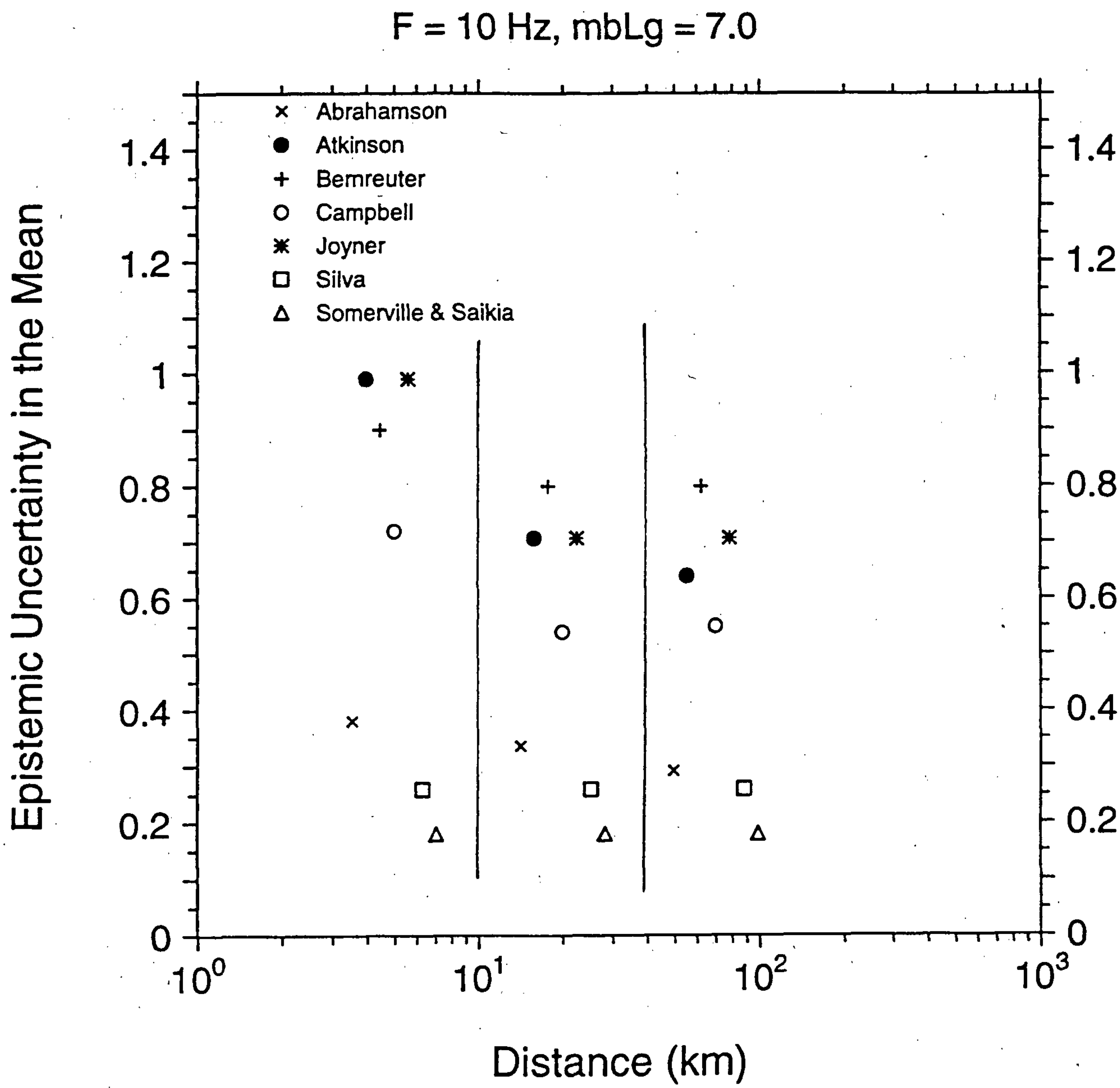


F = 2.5 Hz, mbLg = 7.0
Abrahamson
Atkinson
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

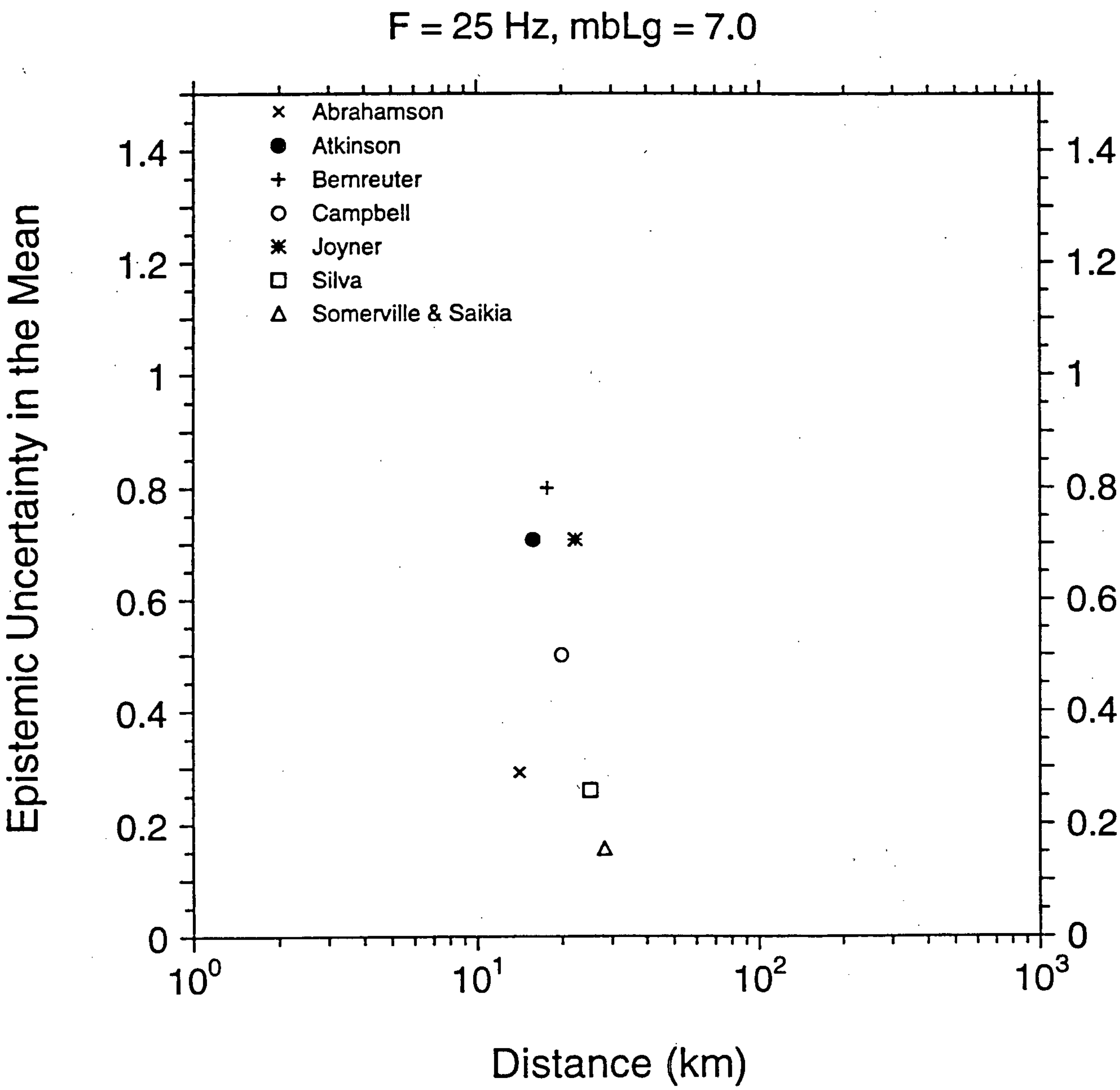

F = 10 Hz, mbLg = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

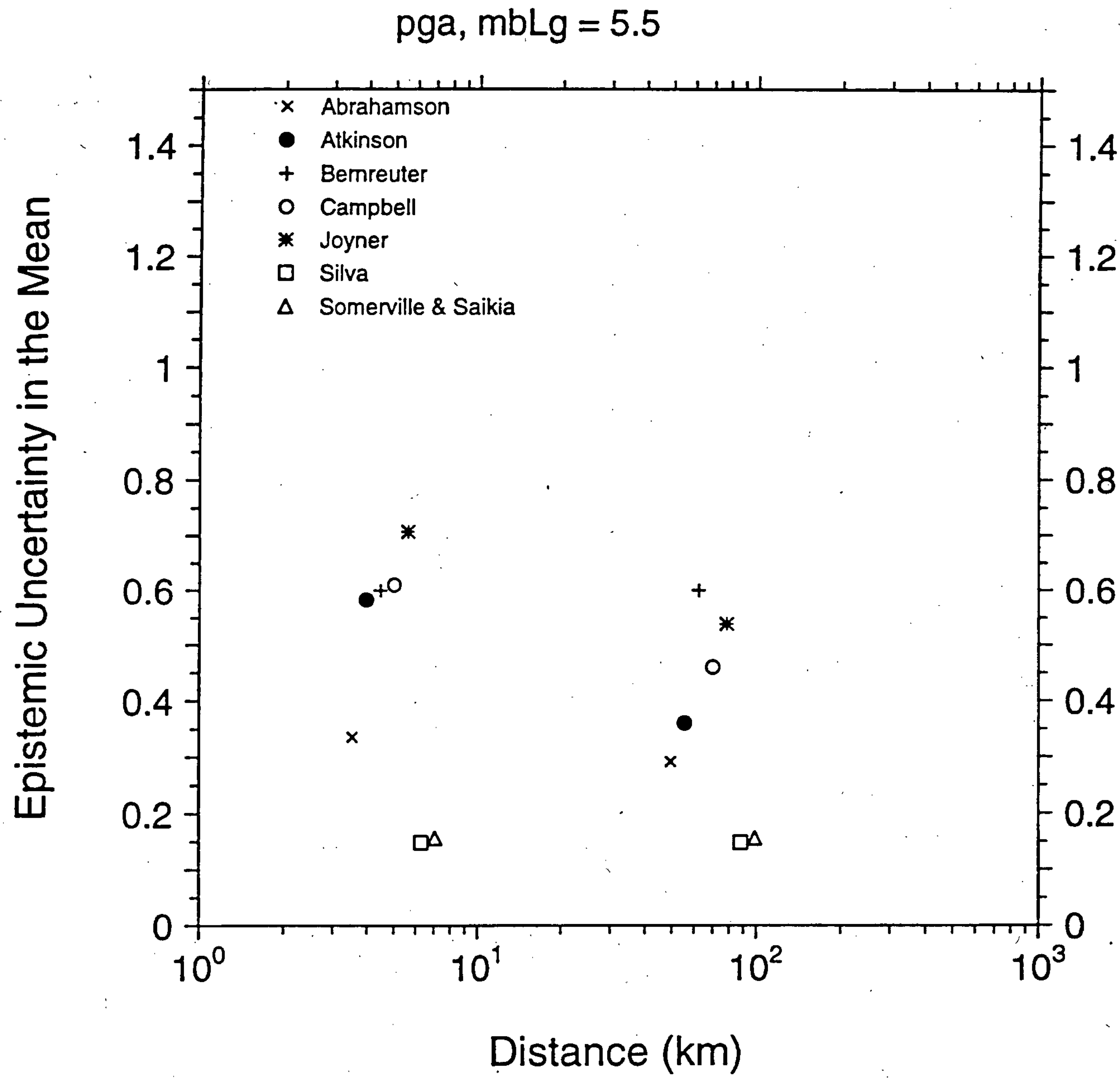


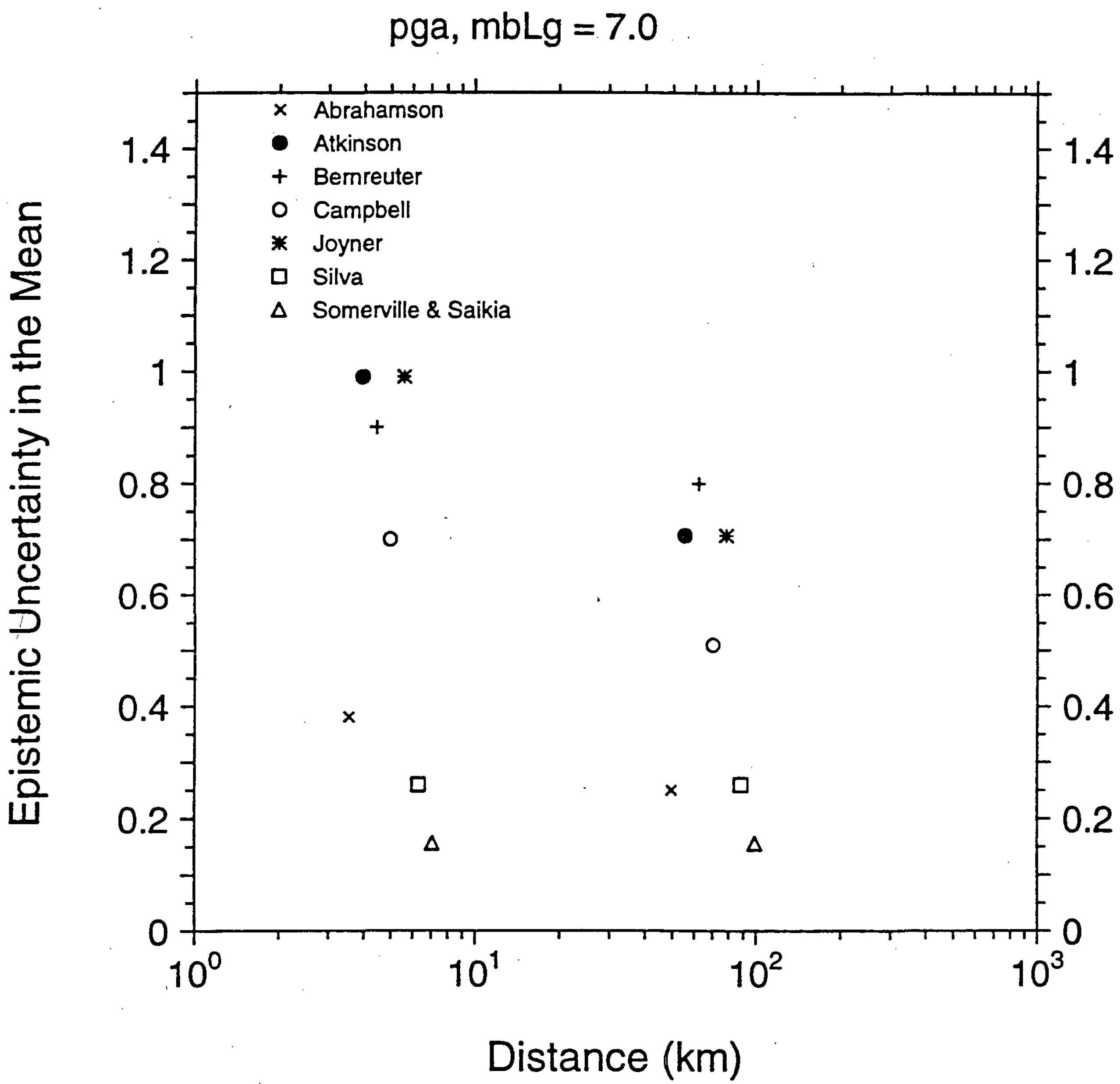
F = 25 Hz, mbLg = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3
Distance (km)

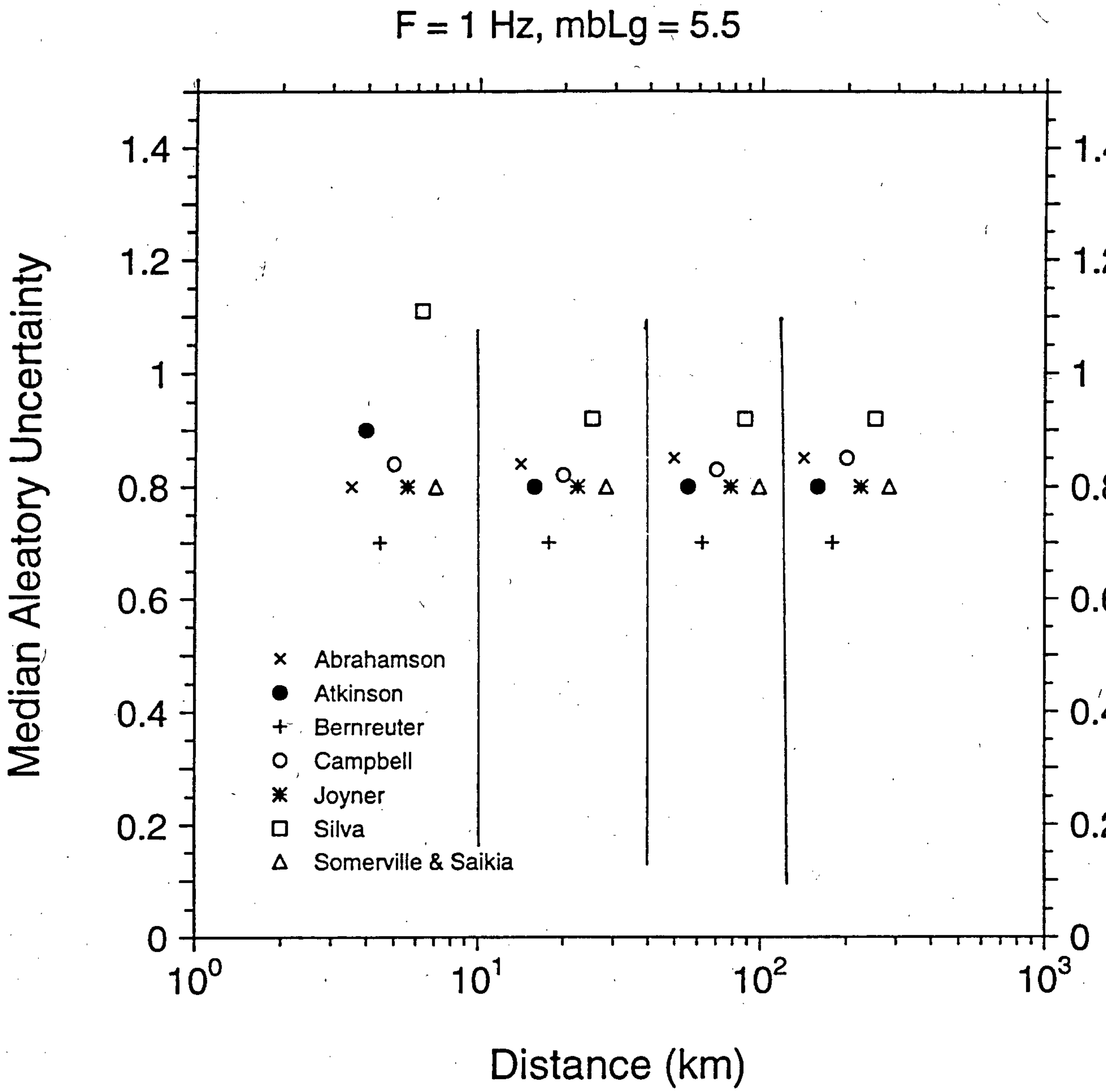


F = 10 Hz, mbLg = 7.0
Abrahamson
Atkinson
Bemreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

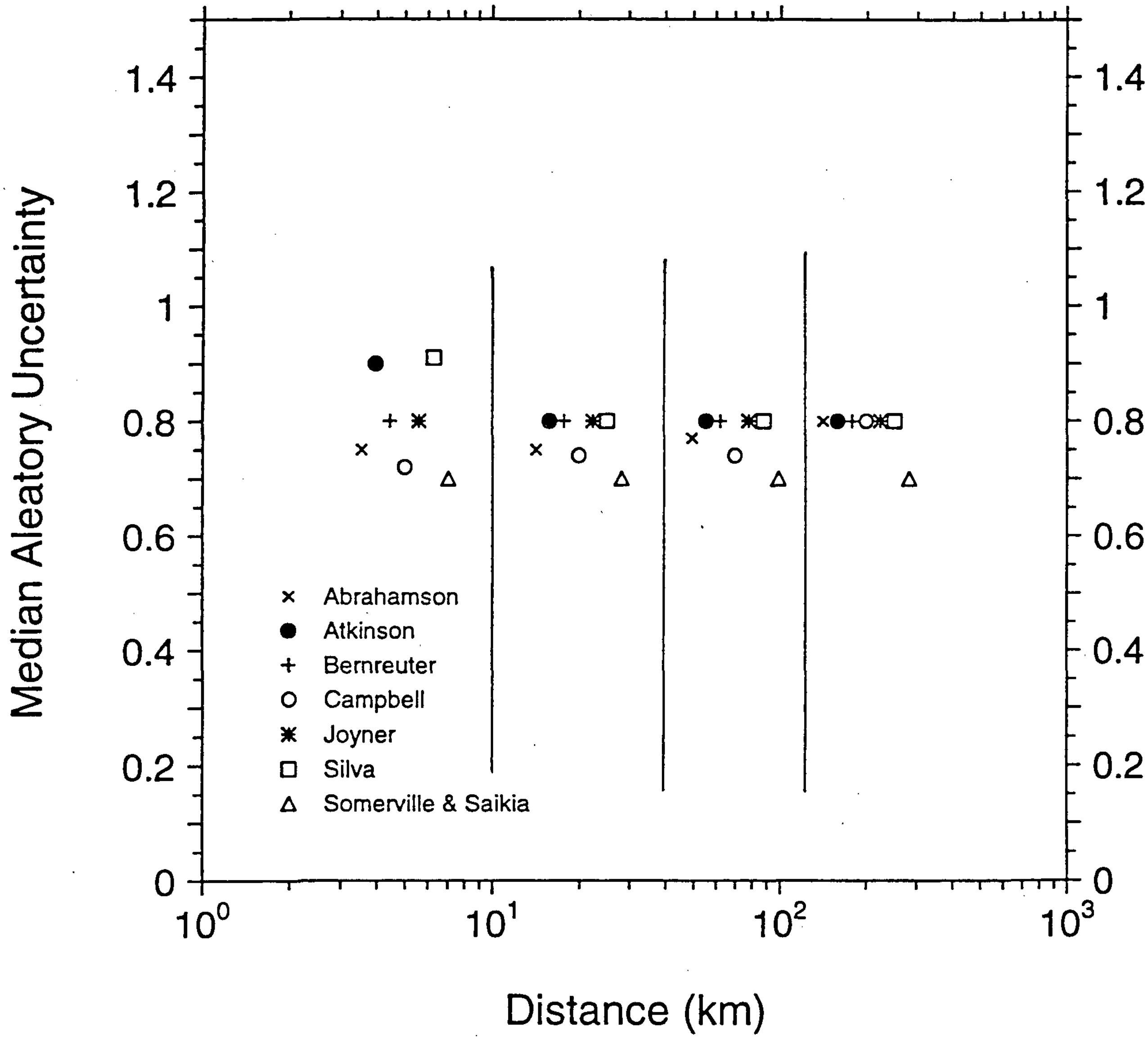

F = 25 Hz, mbLg = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3


pga, mbLg = 5.5
Abrahamson
Atkinson
Bemreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

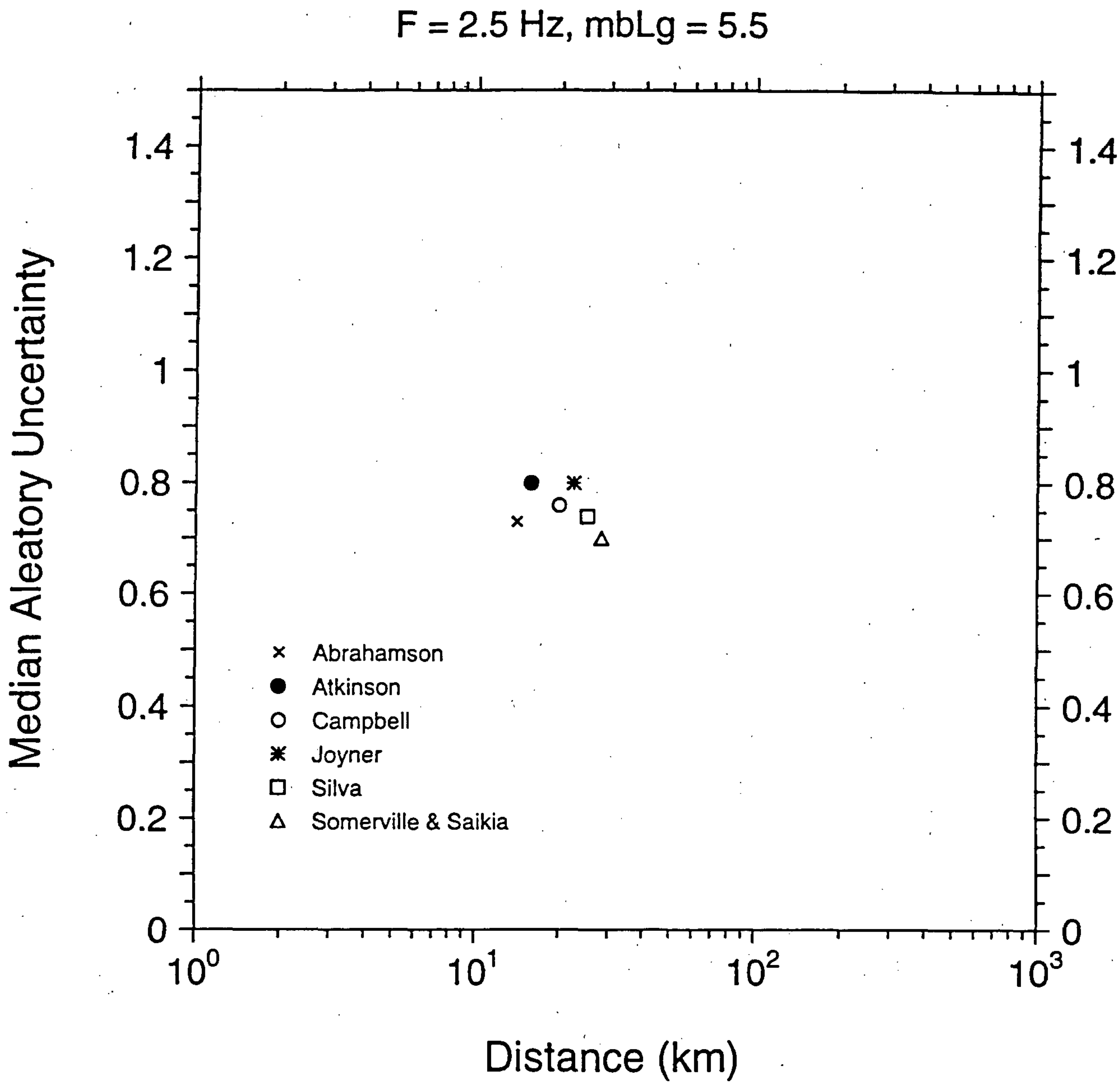

pga, mbLg = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3


F = 1 Hz, mbLg = 5.5
Median Aleatory Uncertainty
Distance (km)
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

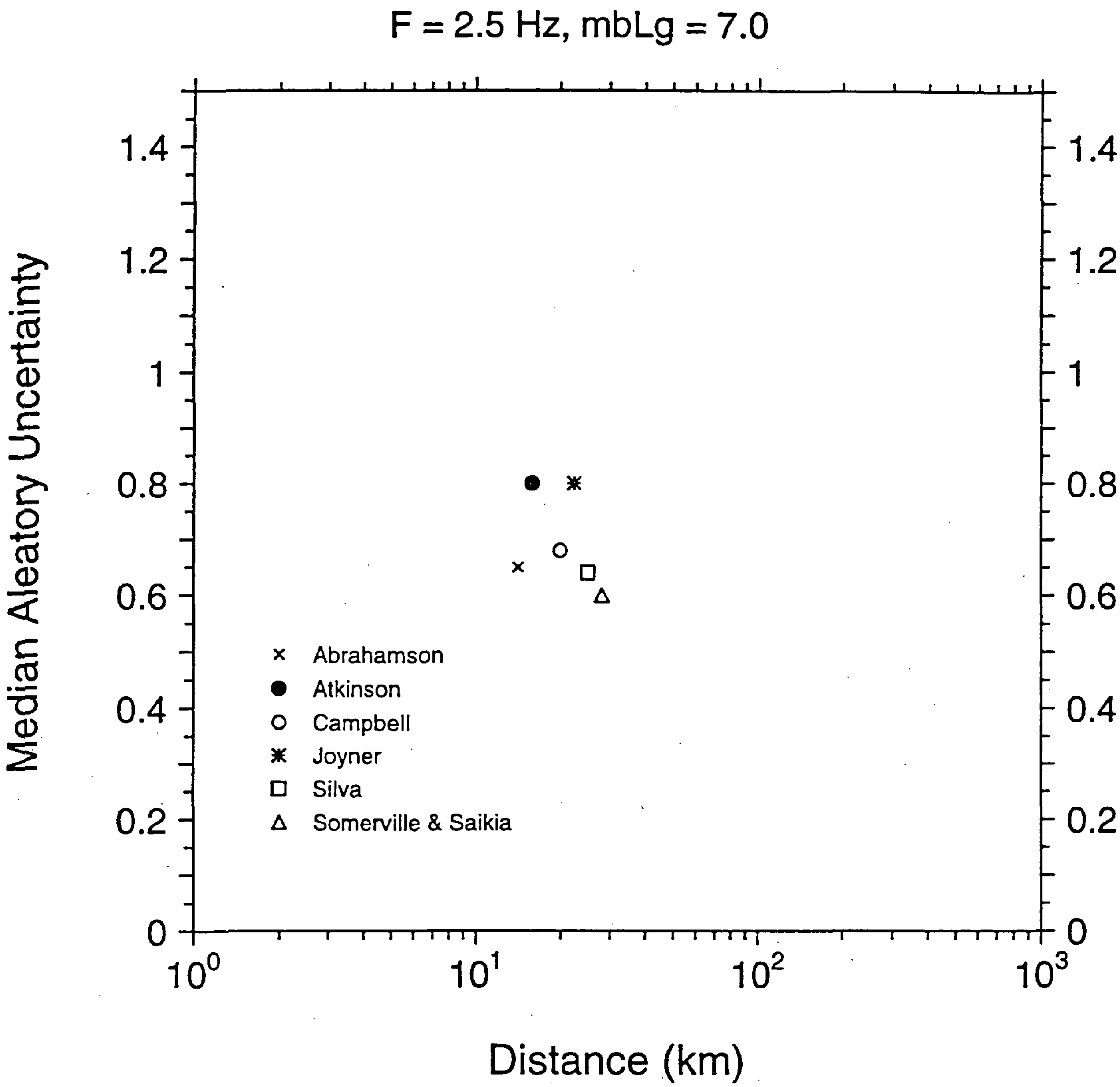
F = 1 Hz, mbLg = 7.0



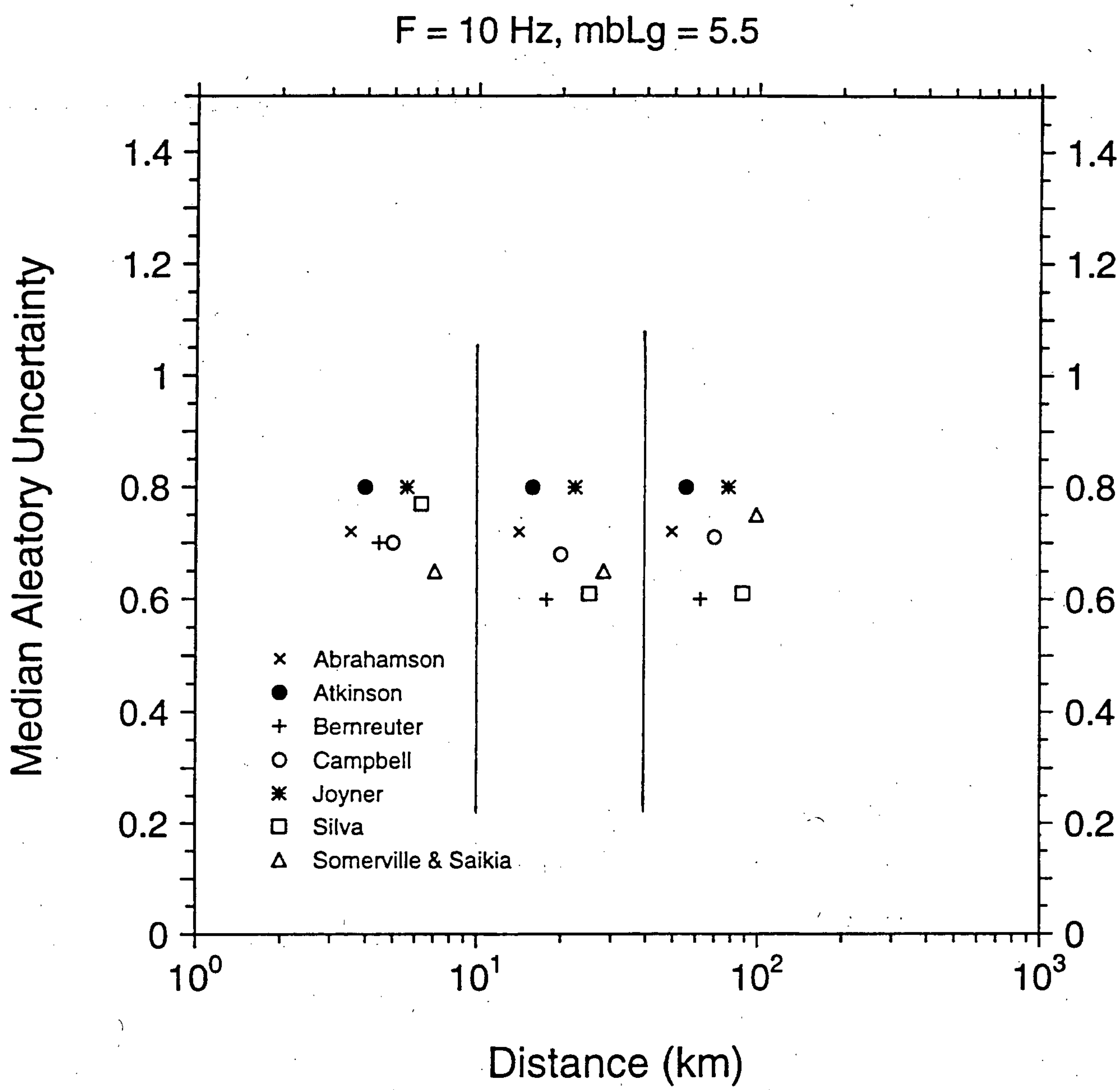
Median Aleatory Uncertainty
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia



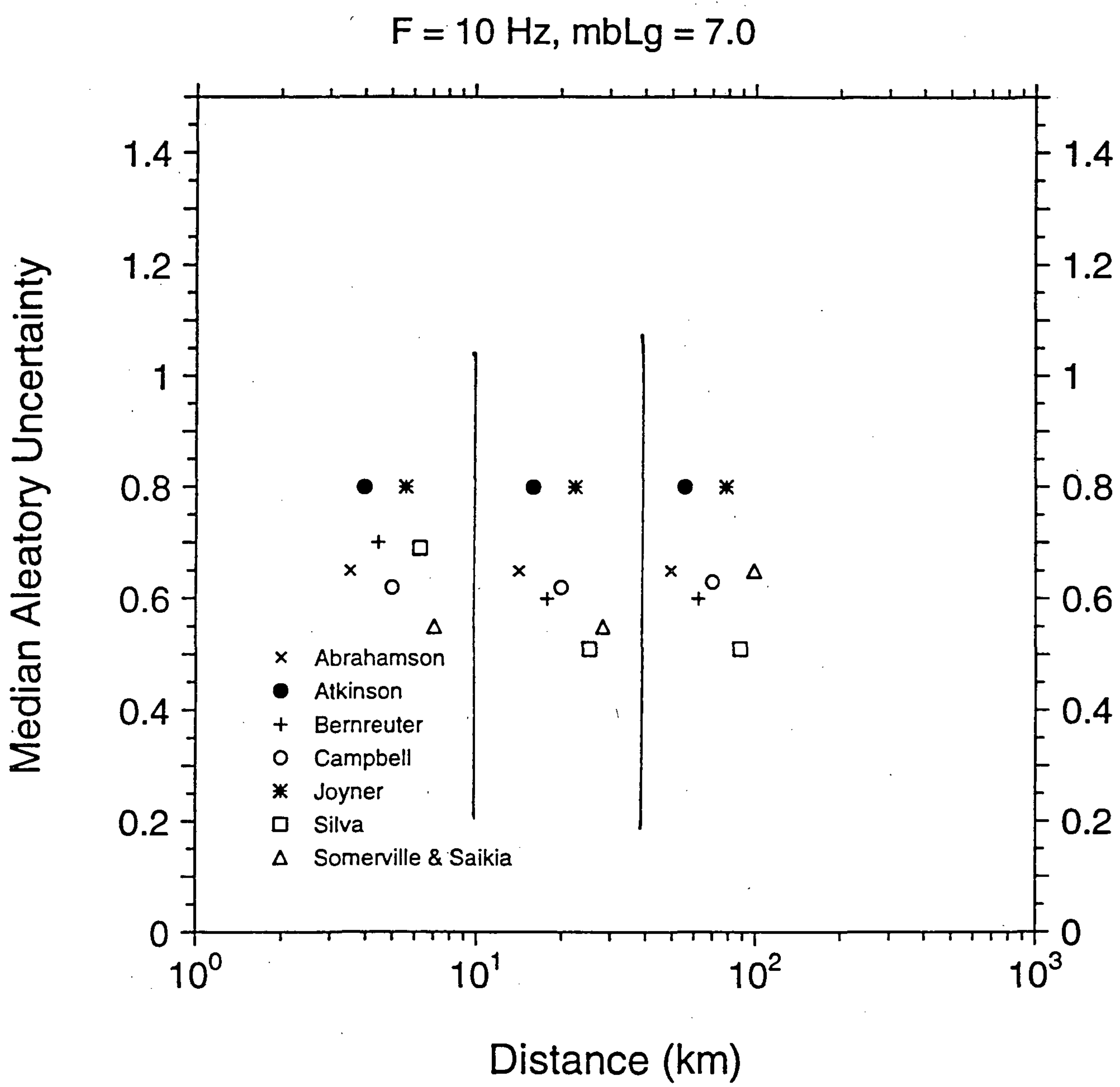
F = 2.5 Hz, mbLg = 5.5
Median Aleatory Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Campbell
Joyner
Silva
Somerville & Saikia

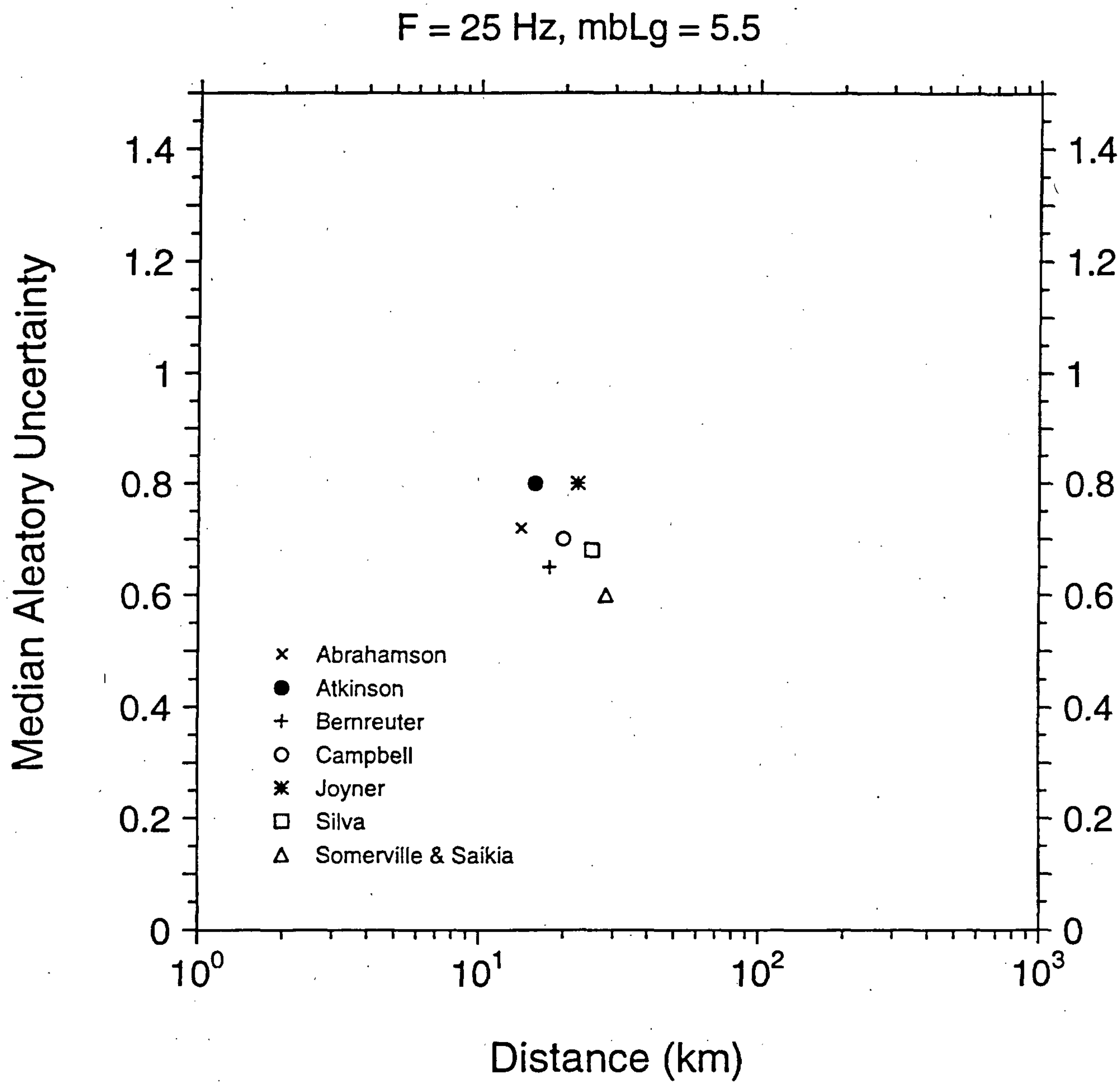


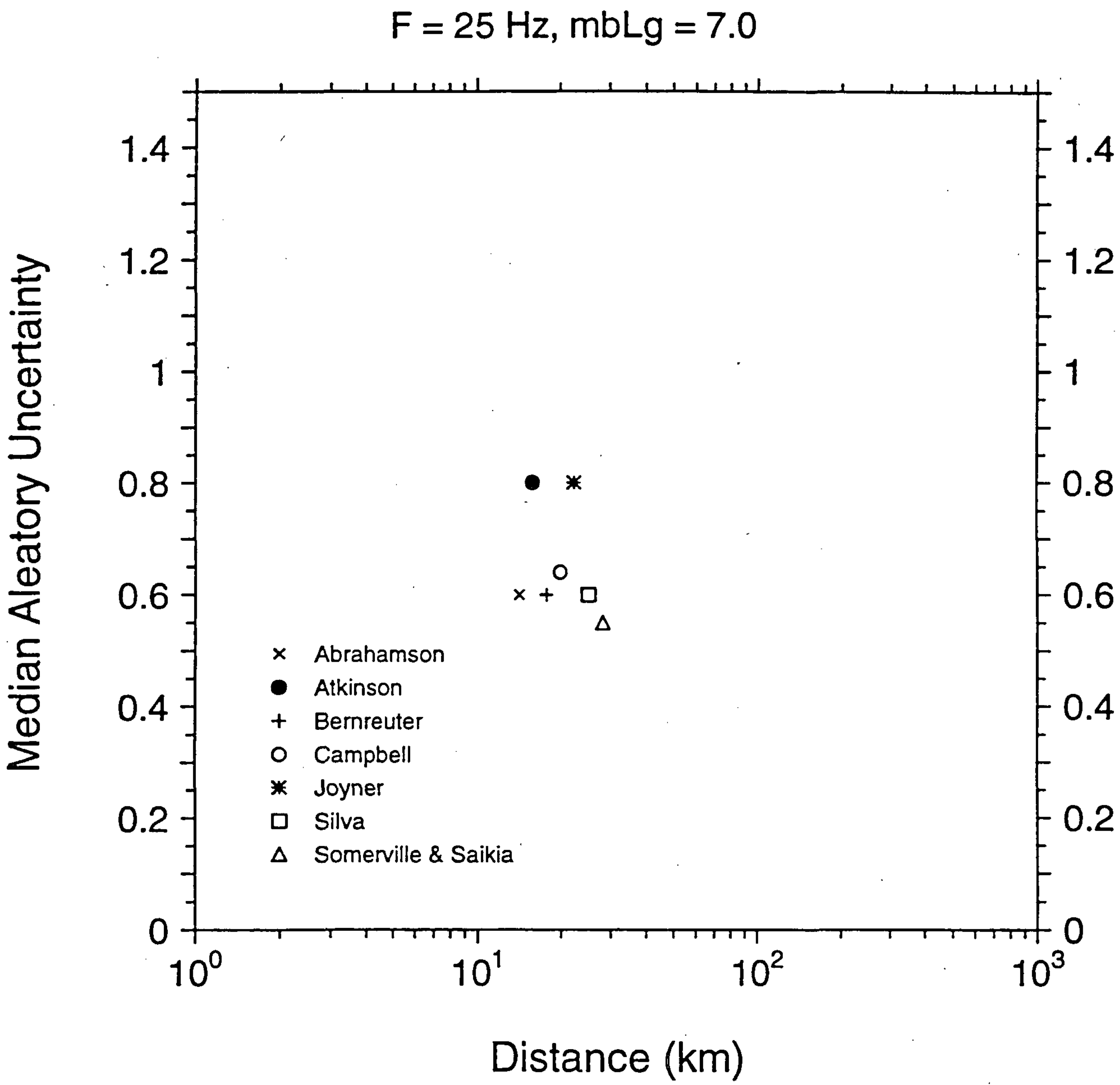
F = 2.5 Hz, mbLg = 7.0
Median Aleatory Uncertainty
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3
Distance (km)
Abrahamson
Atkinson
Campbell
Joyner
Silva
Somerville & Saikia

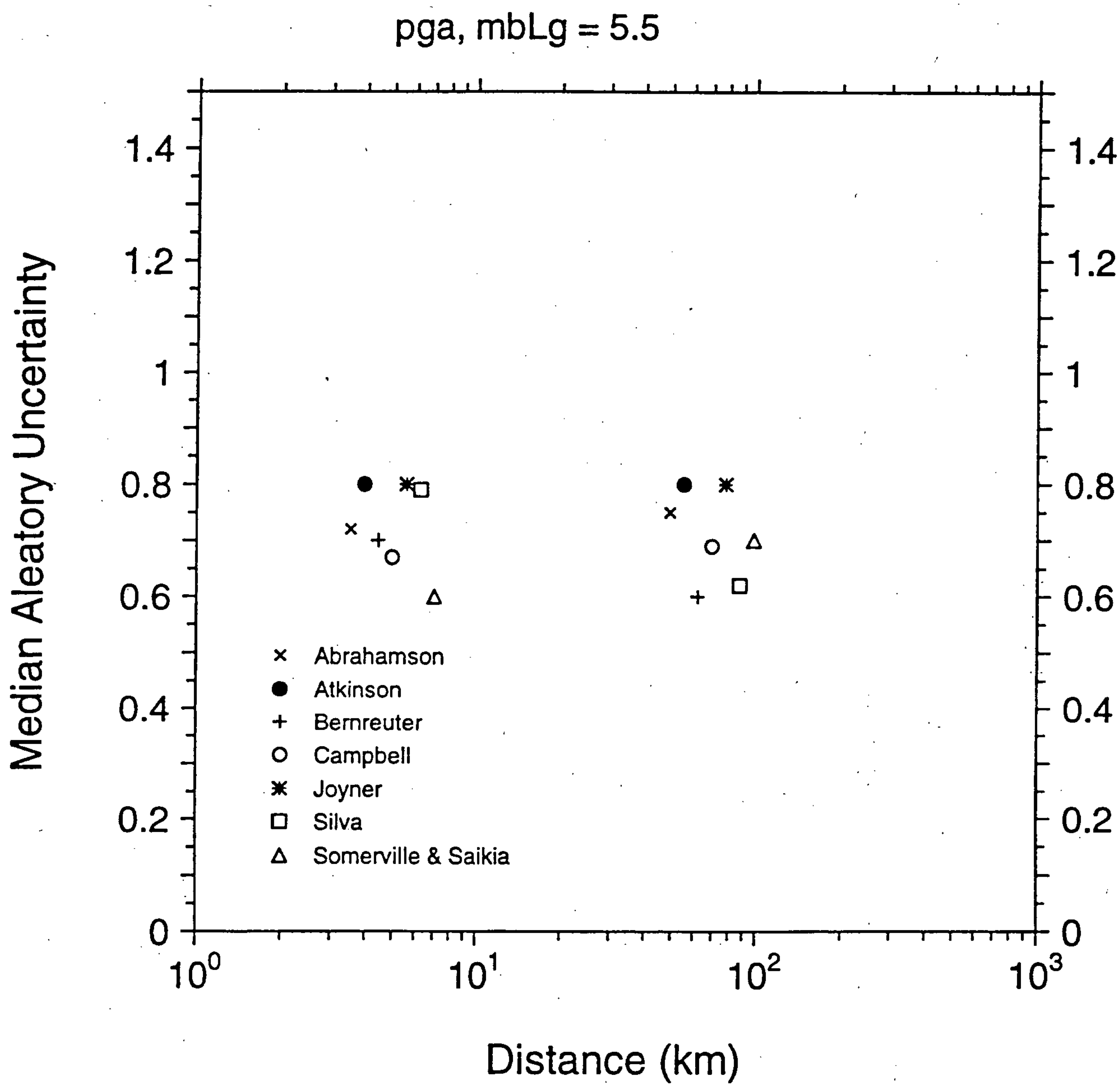


F = 10 Hz, mbLg = 5.5
Median Aleatory Uncertainty
Distance (km)
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

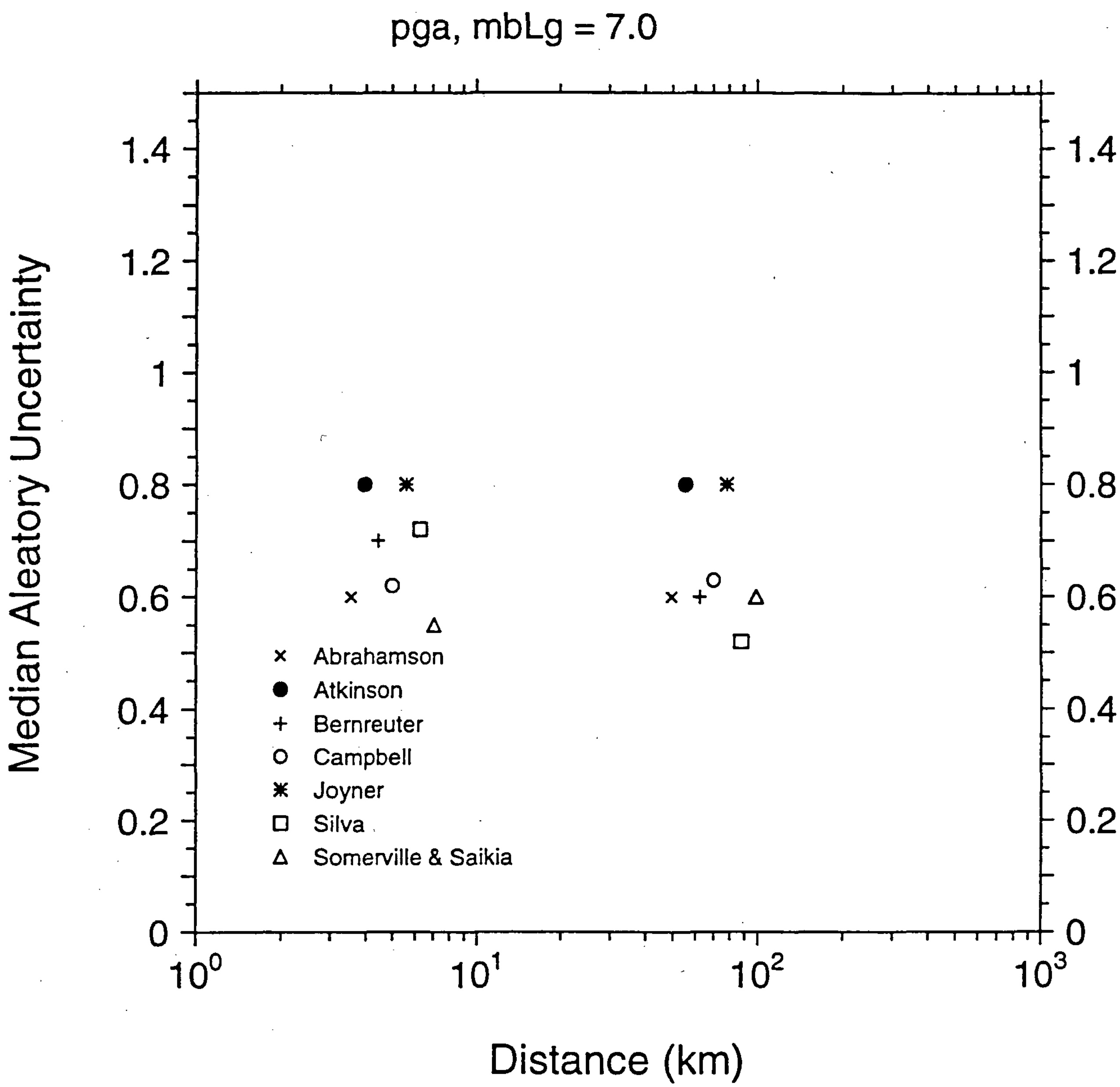

F = 10 Hz, mbLg = 7.0
Median Aleatory Uncertainty
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

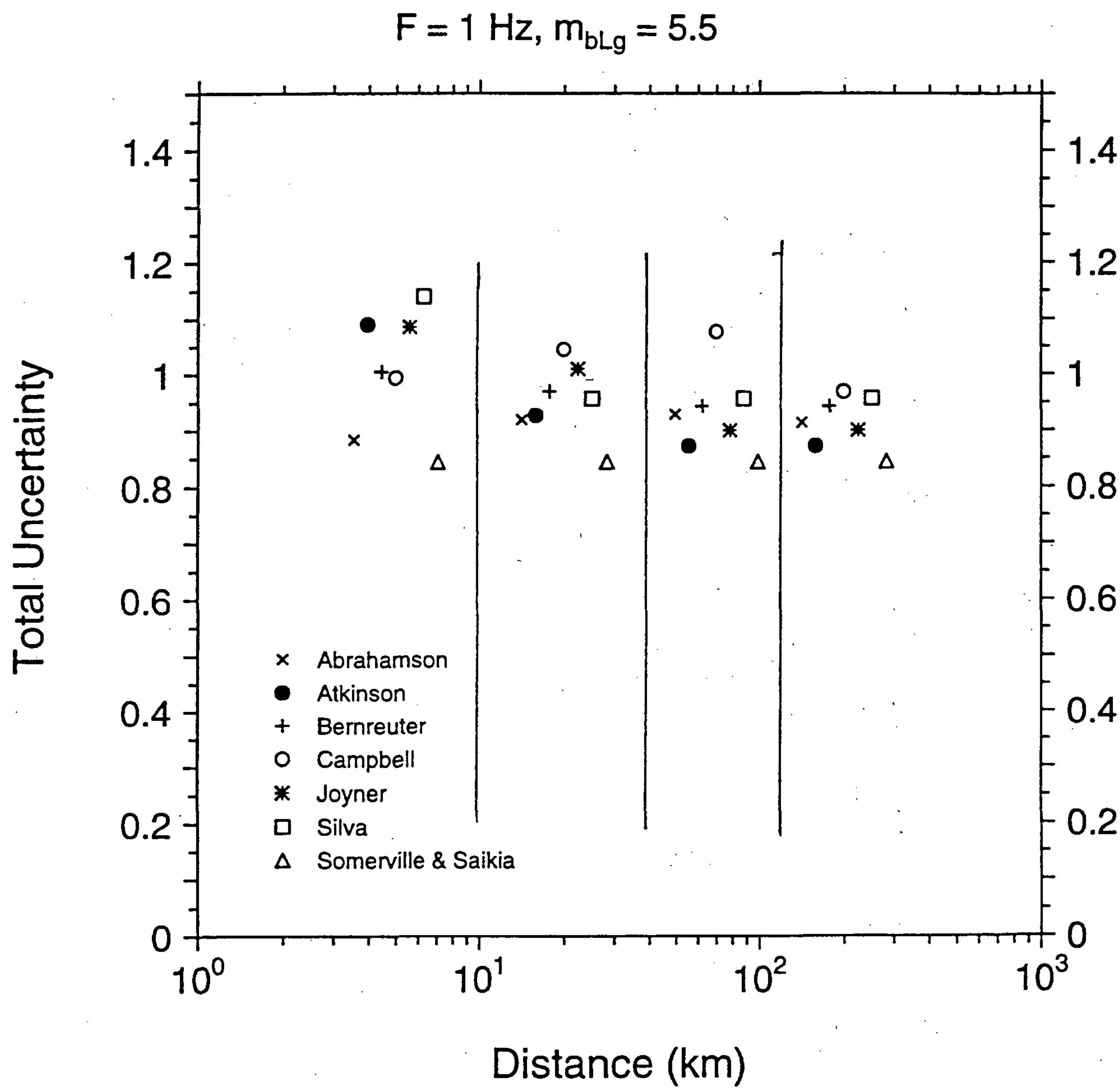

F = 25 Hz, mbLg = 5.5
Median Aleatory Uncertainty
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia


F = 25 Hz, mbLg = 7.0
Median Aleatory Uncertainty
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

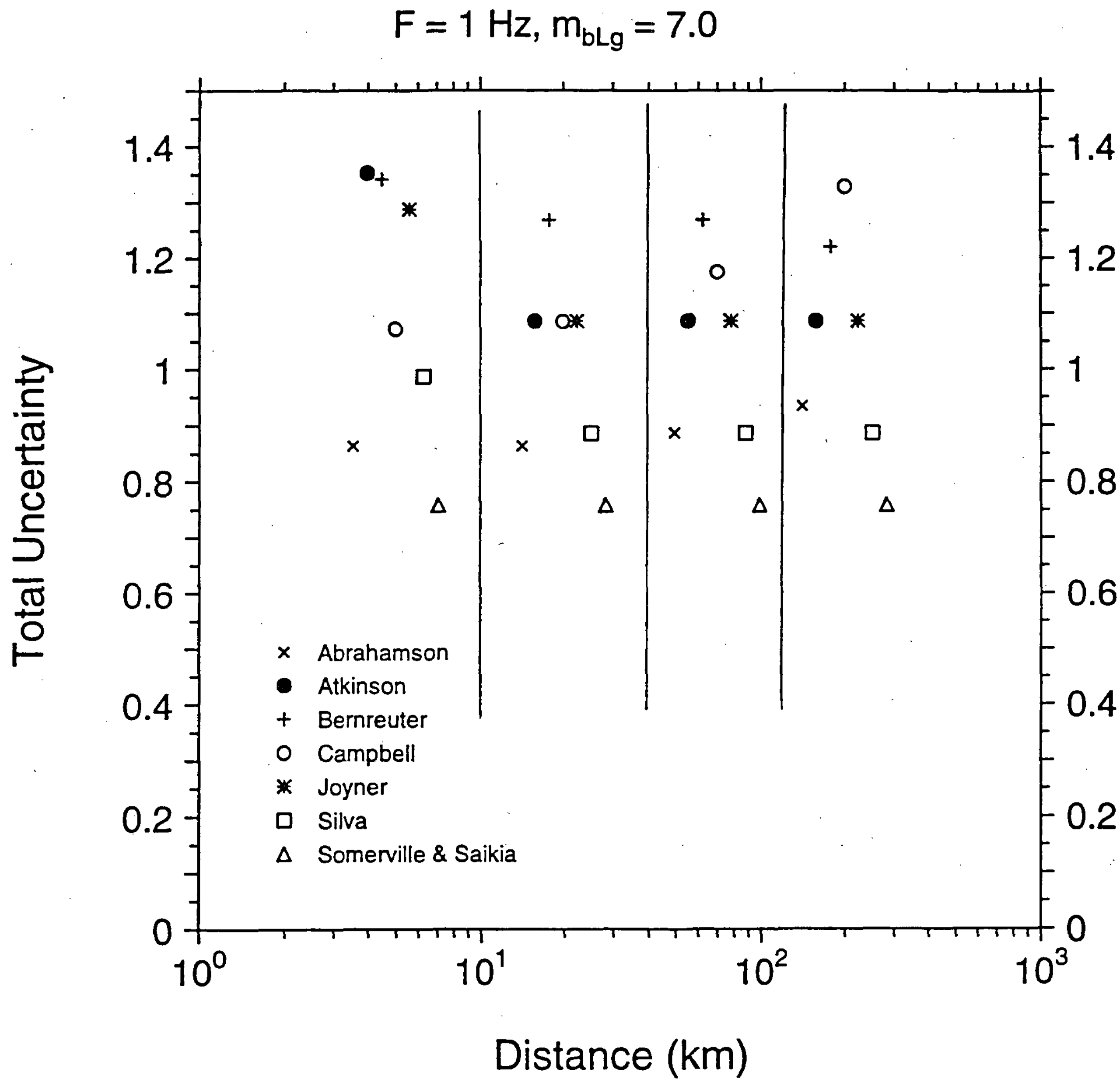


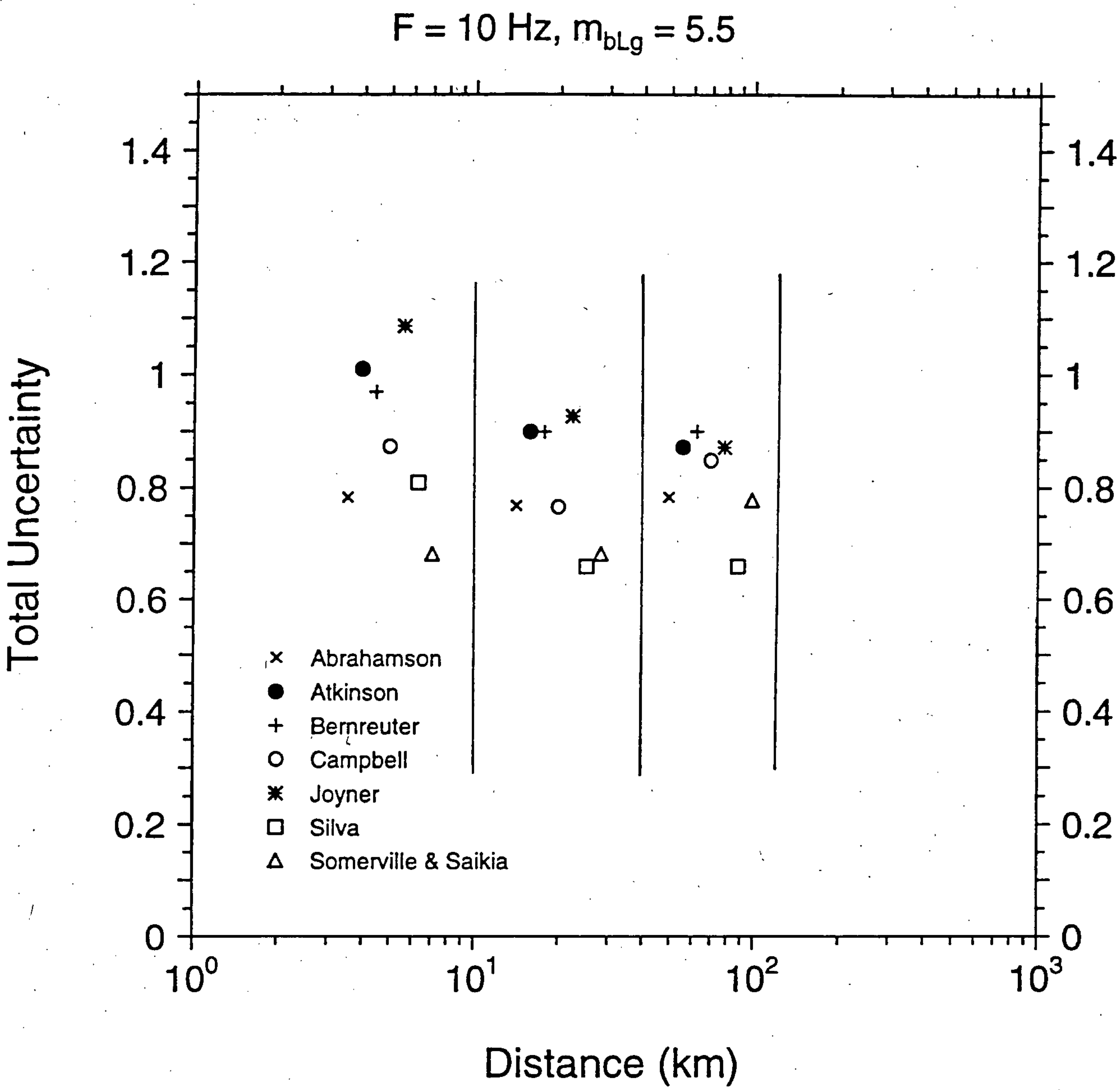
pga, mbLg = 5.5
Median Aleatory Uncertainty
Distance (km)
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia


pga, mbLg = 7.0
Median Aleatory Uncertainty
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

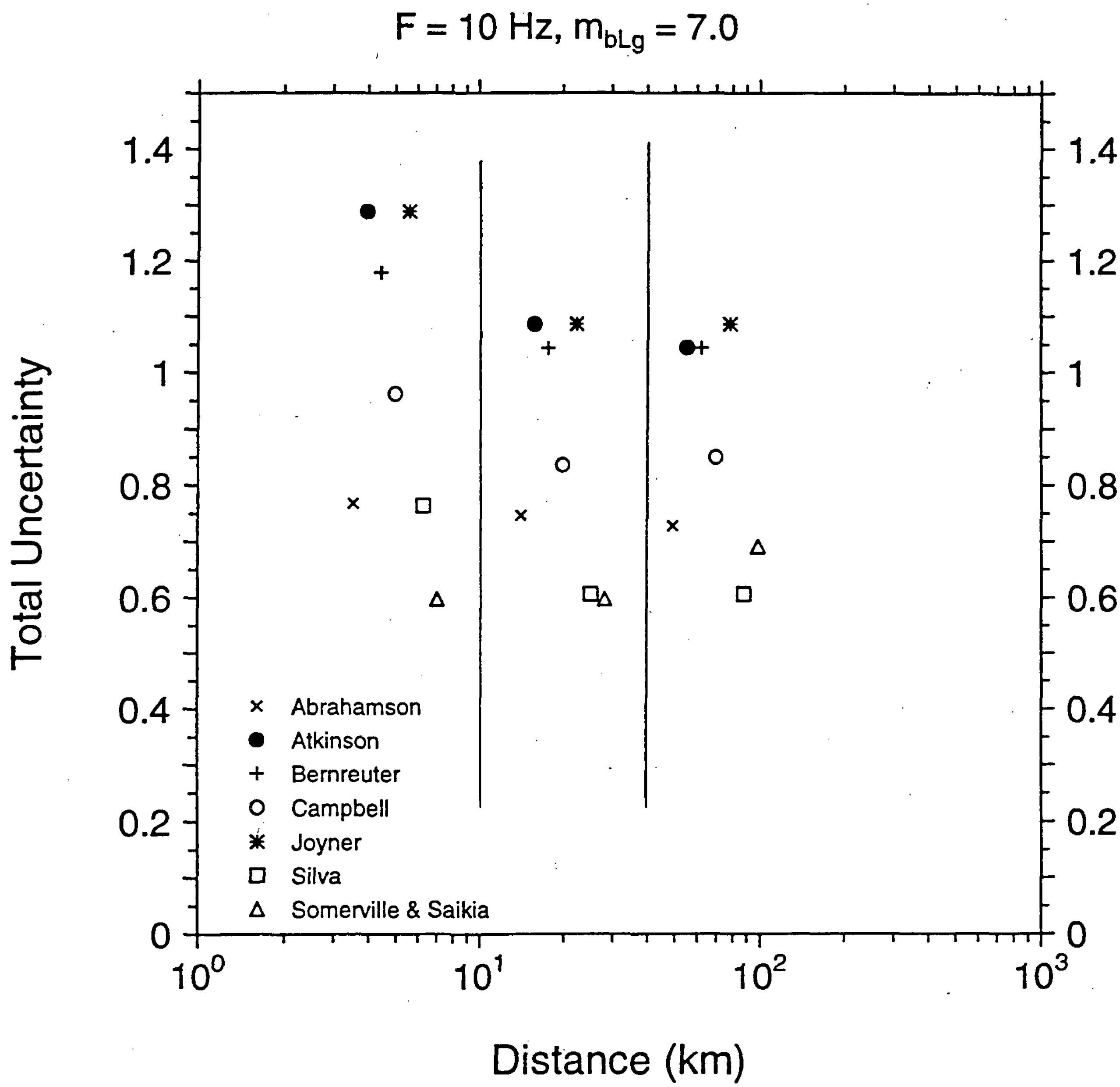


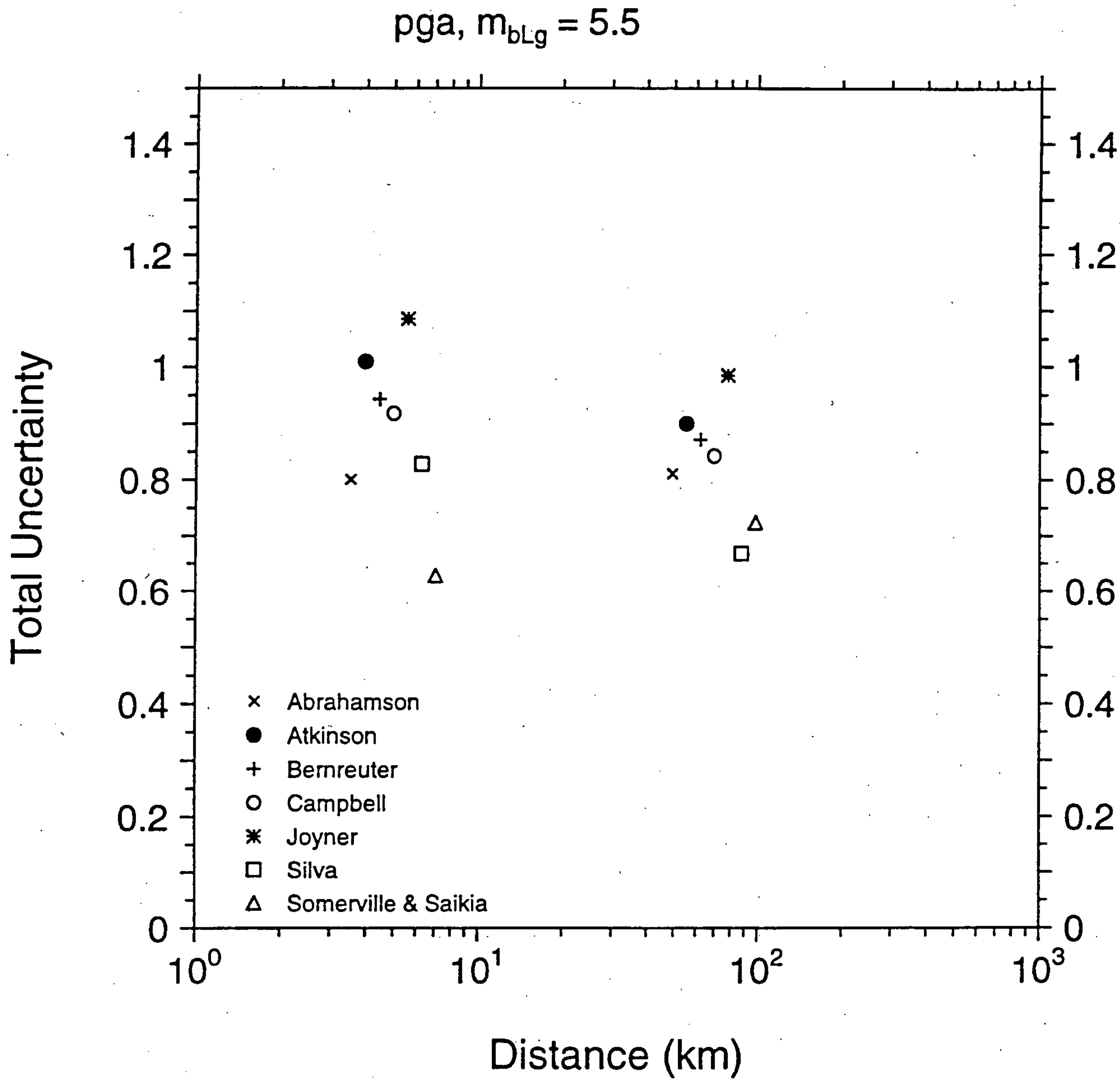
F = 1 Hz, m_{bLg} = 5.5
Total Uncertainty
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

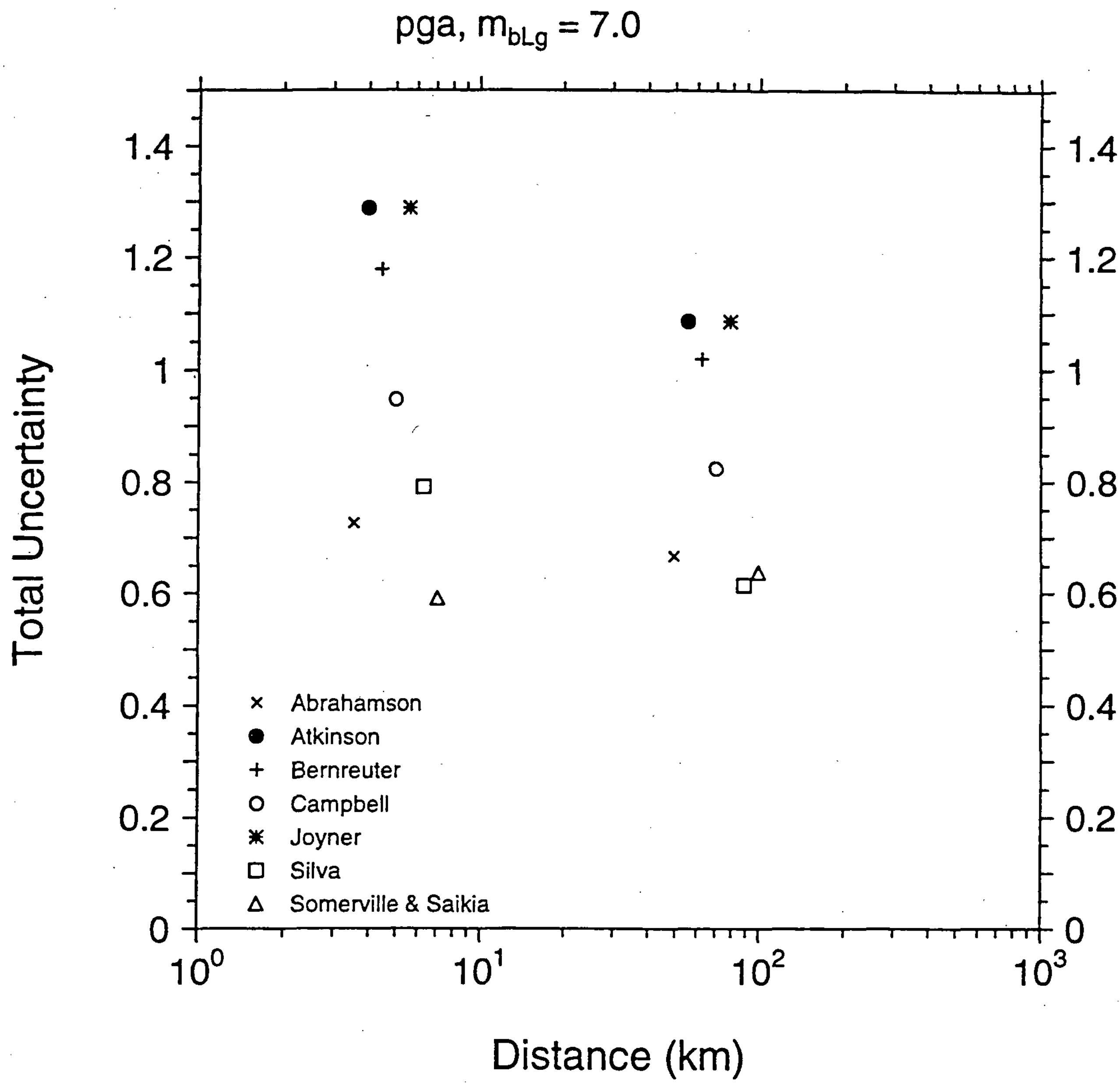

F = 1 Hz, m_{bLg} = 7.0
Total Uncertainty
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia



F = 10 Hz, m_{bLg} = 5.5
Total Uncertainty
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia


F = 10 Hz, m_{bLg} = 7.0
Total Uncertainty
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia


pga, m_{bLg} = 5.5
Total Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia



pga, m_{bLg} = 7.0
Total Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

ATTACHMENT B-3

PRE-WORKSHOP DISTRIBUTION AND COMPARISON OF EXPERTS' RESULTS

Risk Engineering, Inc.
4155 Darley Avenue, Suite A
Boulder, CO 80303 USA
Telephone: (303)499-3000
Fax Number: (303)499-4850

FAX TRANSMITTAL MEMO

To: Gabriel R. Toro (self-copy)	From: Gabriel R. Toro (303)494-1021
Time: 20:16:12	Date: 7/25/94
Pages (including cover): 24	

To: Norm Abrahamson
Gail Atkinson
Don Bernreuter, LLNL
Bill Joyner, USGS
Ken Campbell, EQE
Walt Silva, PEA
Paul Somerville and Chandan Saikia, WCC

From: G. R. Toro

Re: SSHAC Ground Motion Workshop

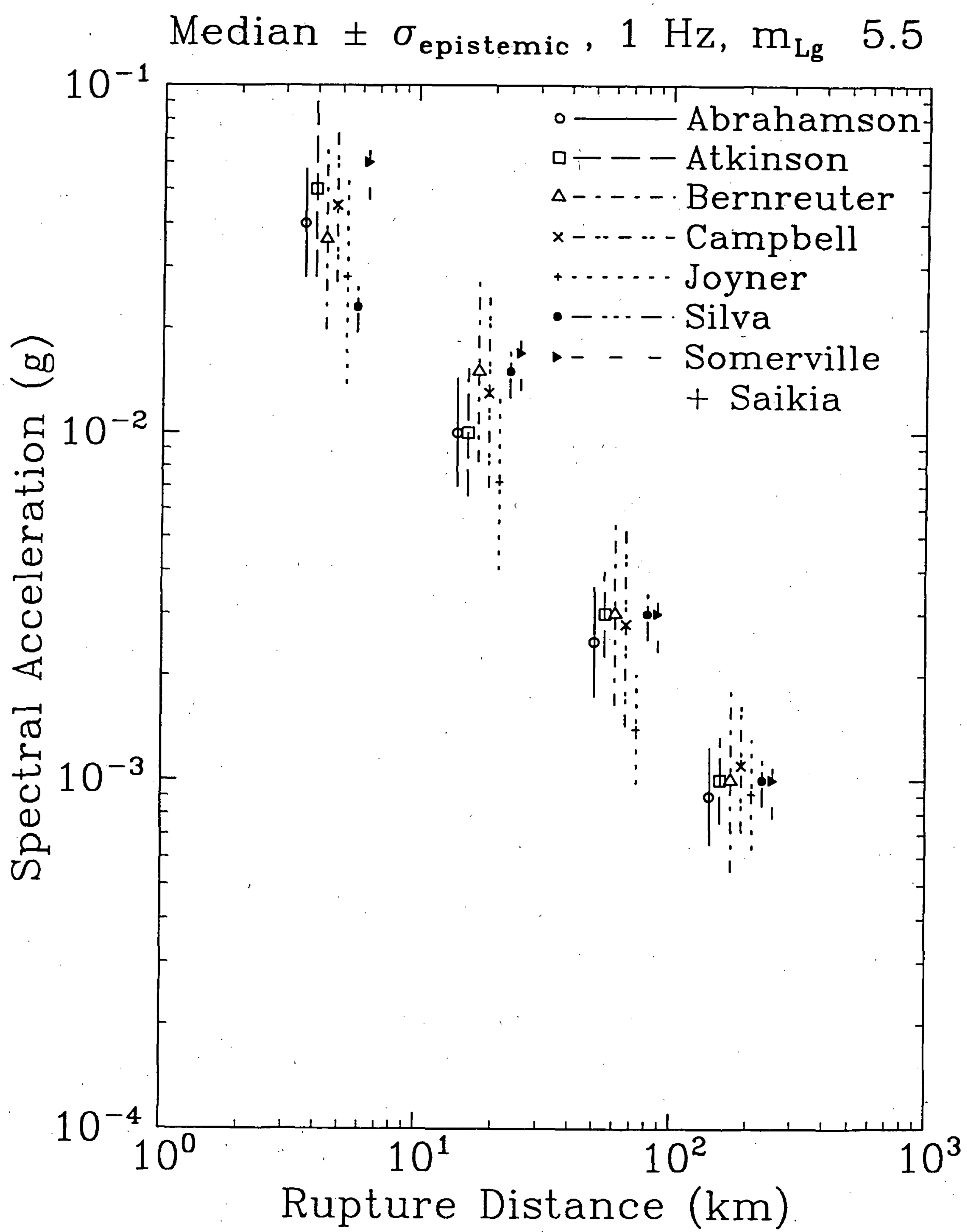
Enclosed are figures comparing the predictions by al ground-motion experts. This set also includes a set of figures showing the median +- total uncertainty (where total uncertainty is sqrt(epistemic**2+sigma**2+sigma(sigma)**2). I will fax Joyner's predictions and documentation later tonight or tomorrow morning.

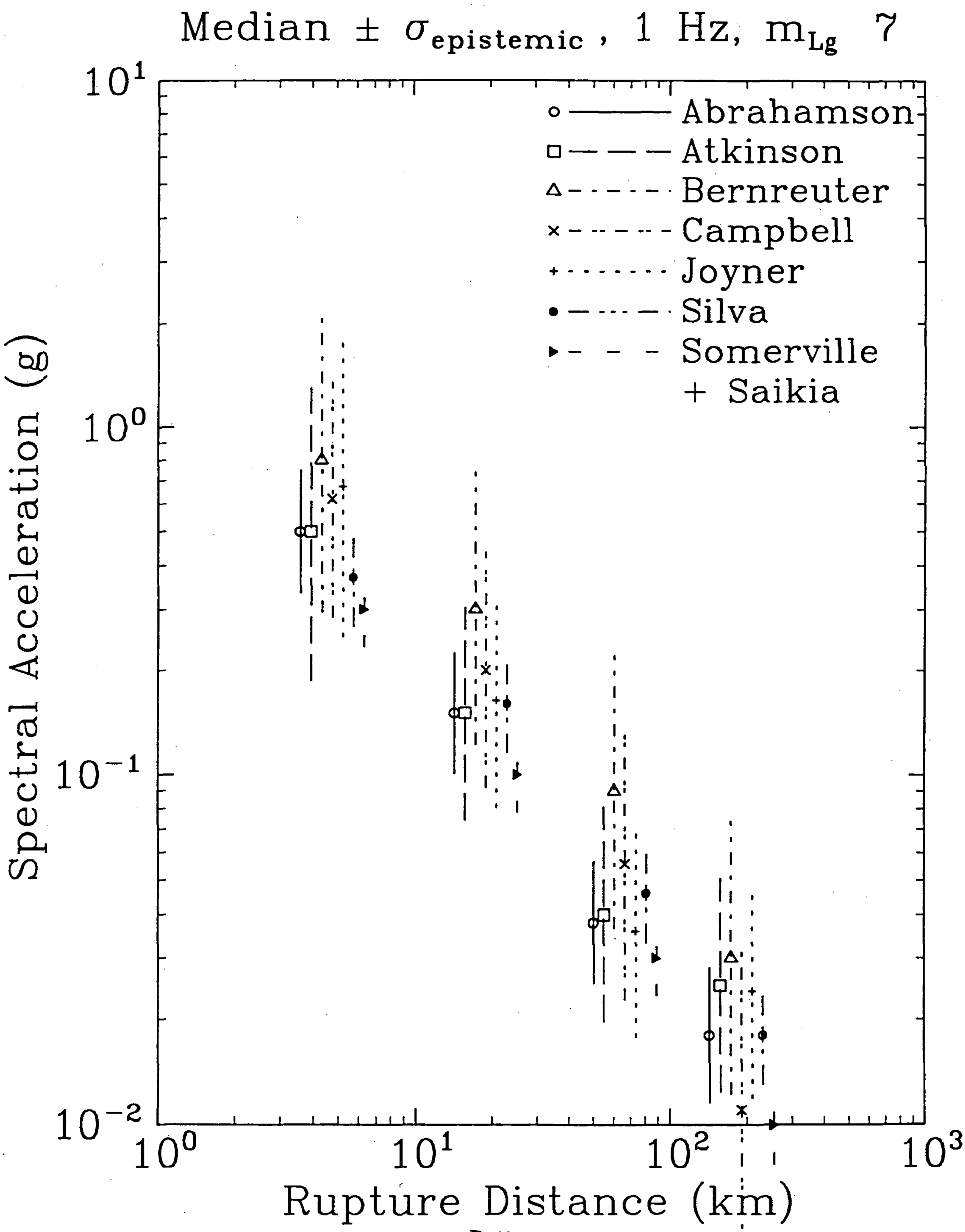
I look forward to very Interesting discussions at the workshop.

cc. Dave Boore, USGS
C. A. Cornell
Peter Morris, ADA
Richard Mensing, Logicon-RDA

(Four figures revised and three figures removed as per fax of July 26, 1995)

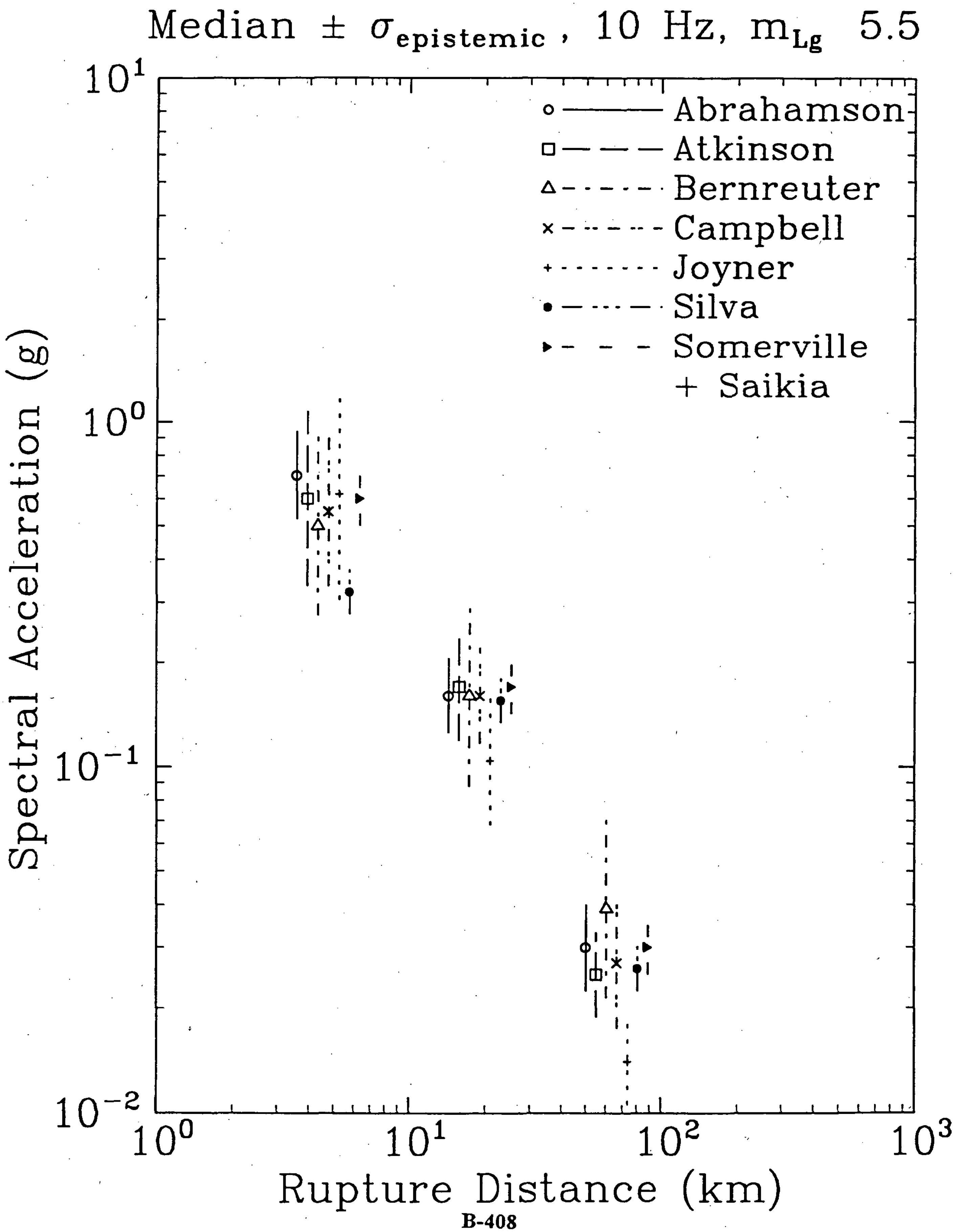
frame 1 $DISK3:[GTOH.9305.WSHOP_2]1_010_55.MET;2

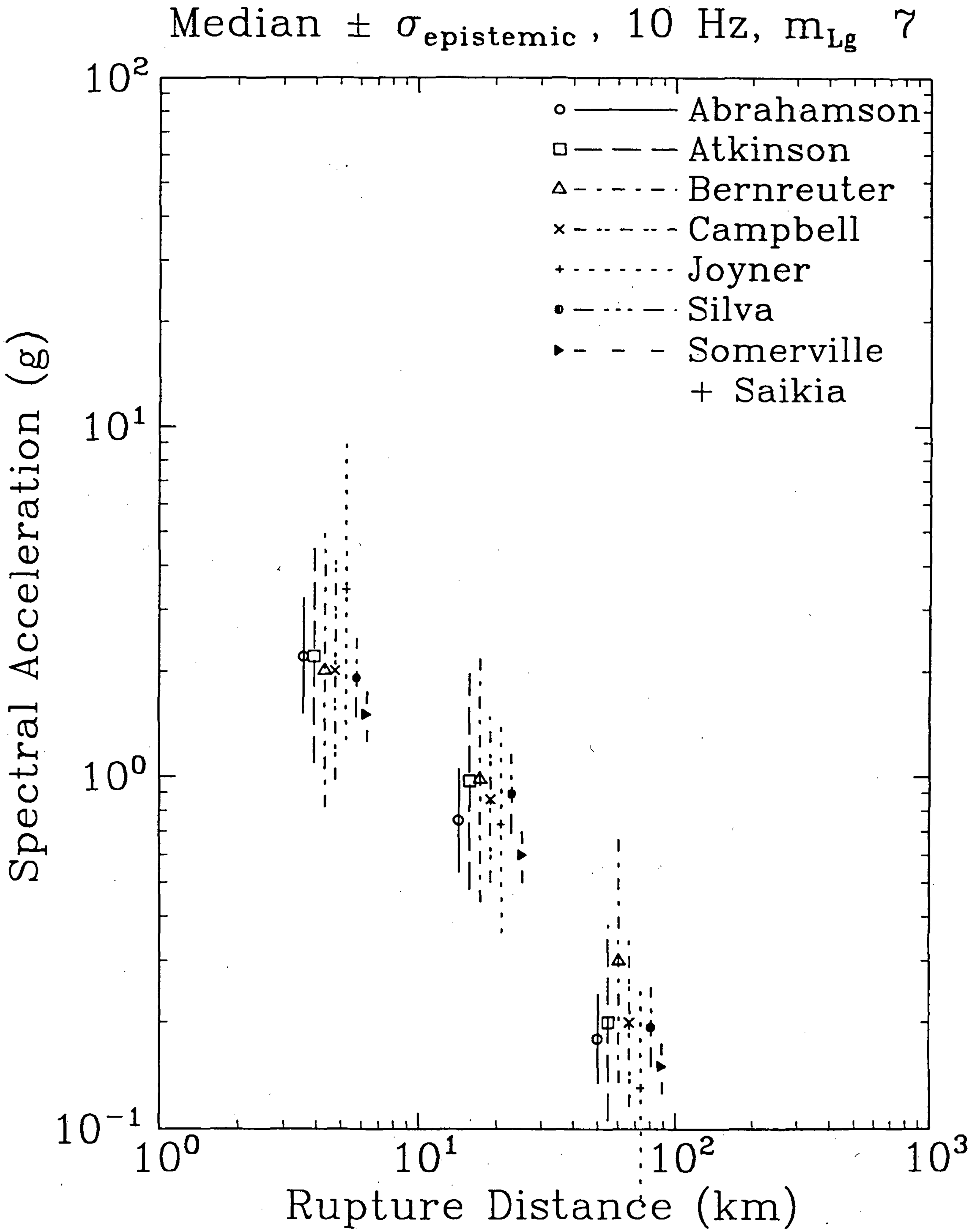




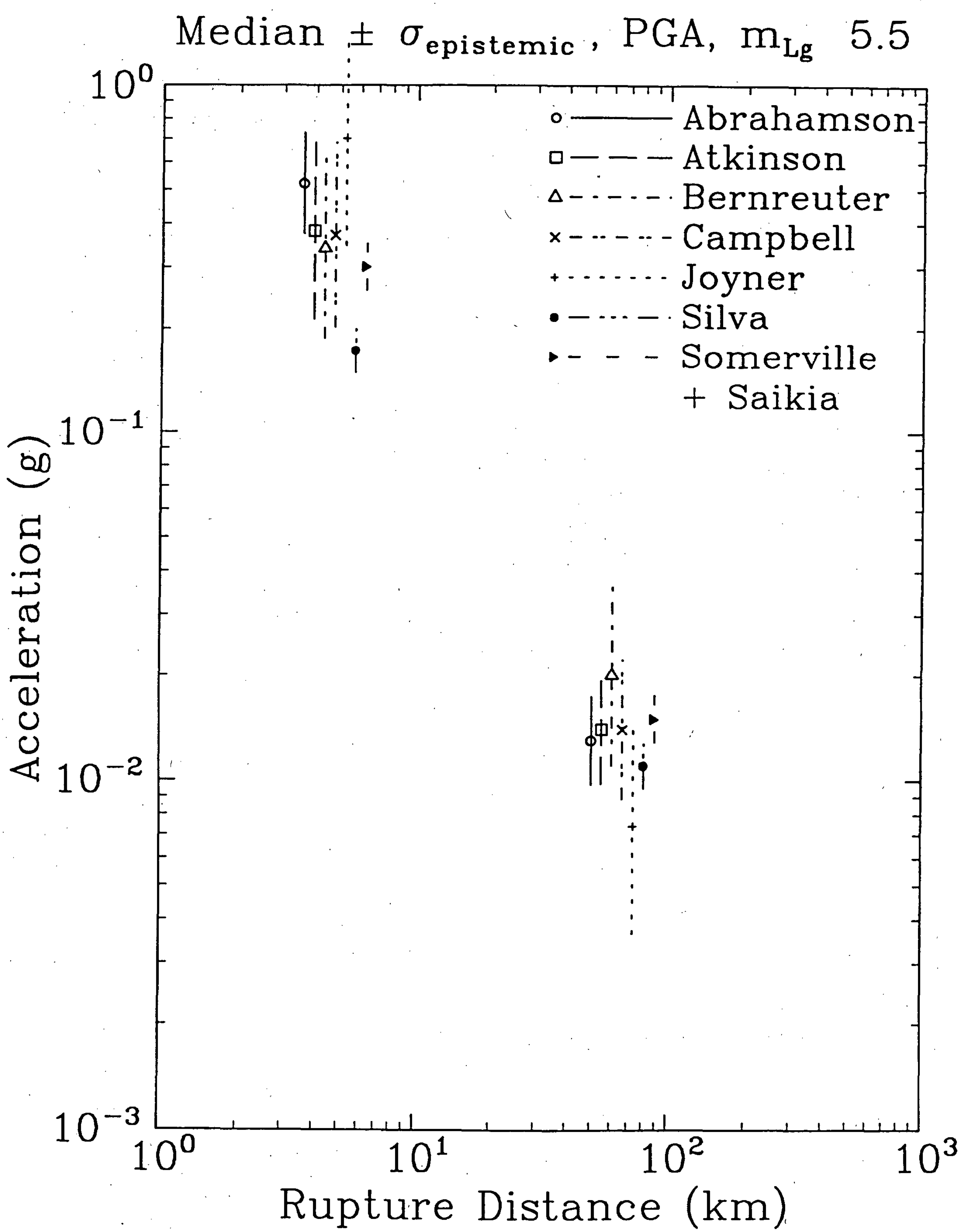
Median ± $\sigma_{epistemic}$, 1 Hz, m_{Lg} 7
Spectral Acceleration (g)
10^1
10^0
10^{-1}
10^{-2}
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
10^0
10^1
10^2
10^3
Rupture Distance (km)

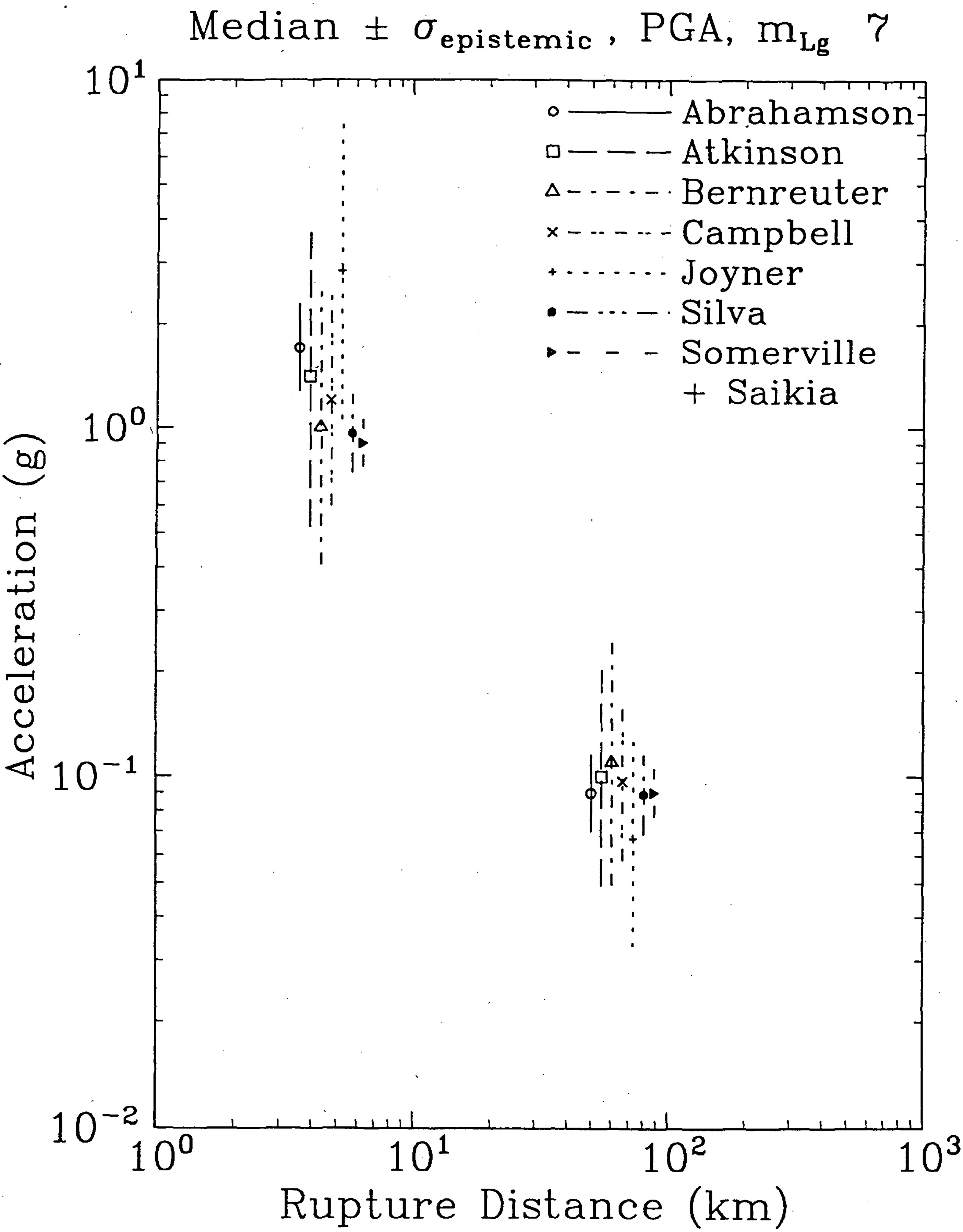
frame 1 $DISK3:[GTOH.9305.WSHOP_2]1_100_55.MET;2

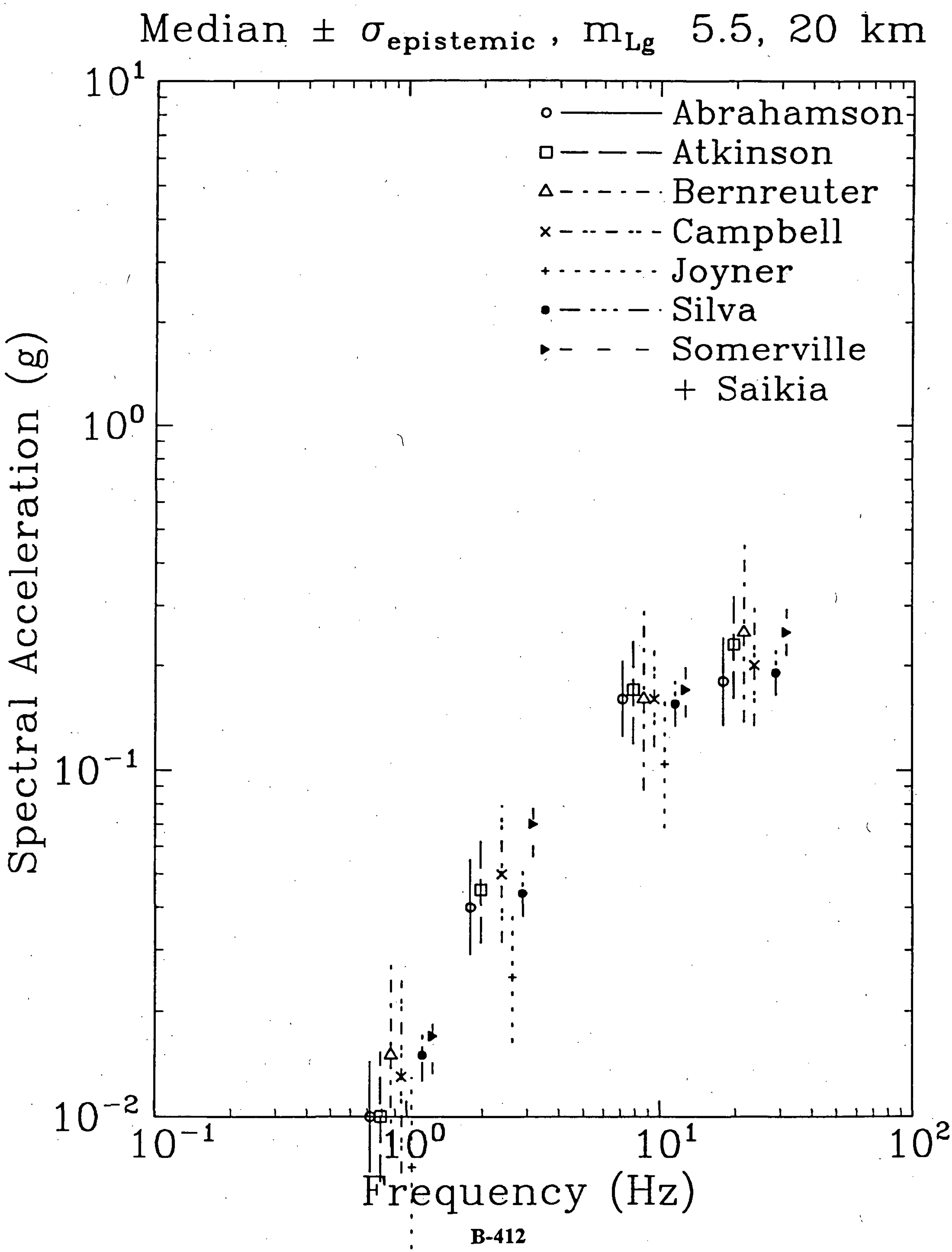


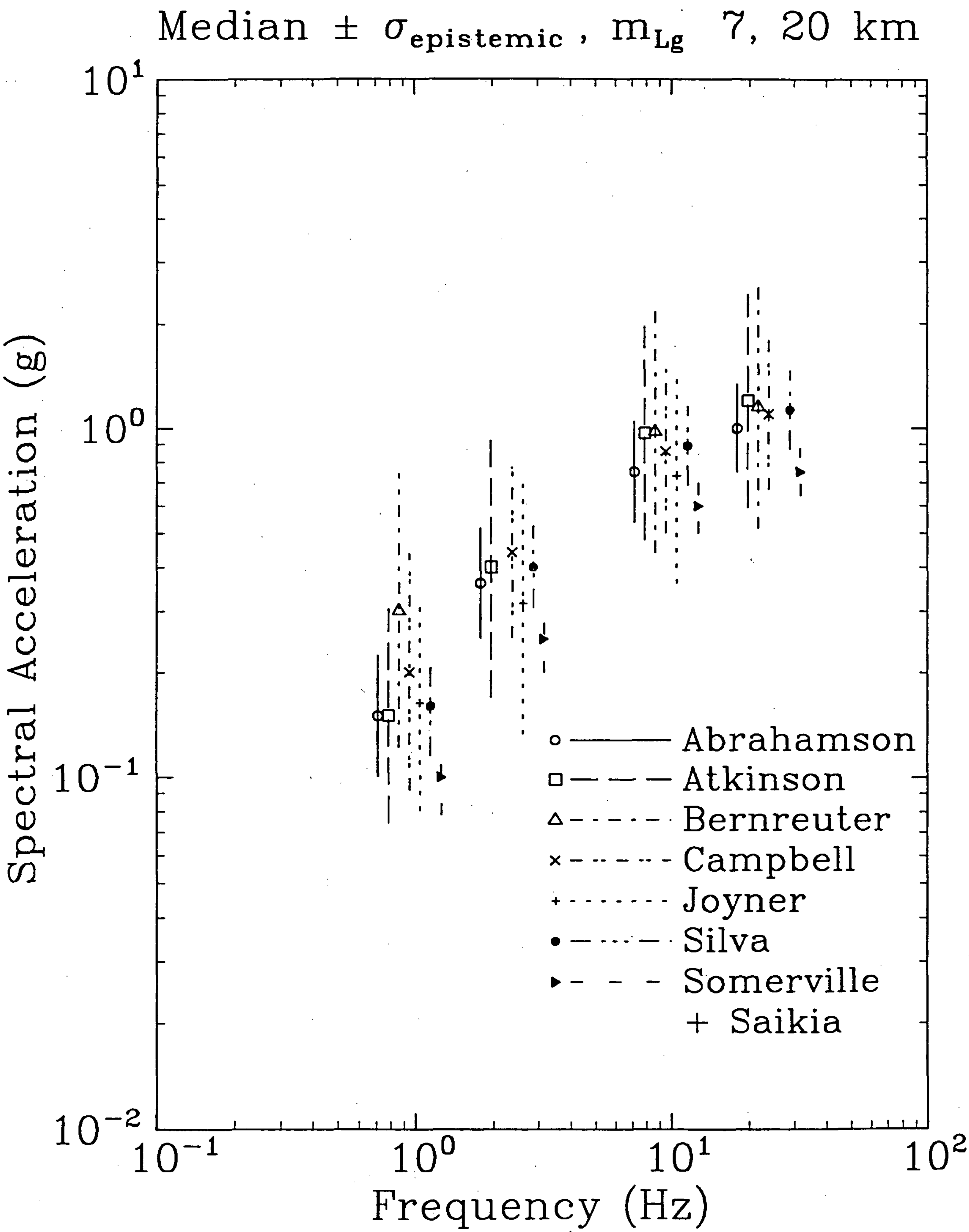


Median ± $\sigma_{epistemic}$, 10 Hz, m_{Lg} 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
10^3
Spectral Acceleration (g)
Rupture Distance (km)

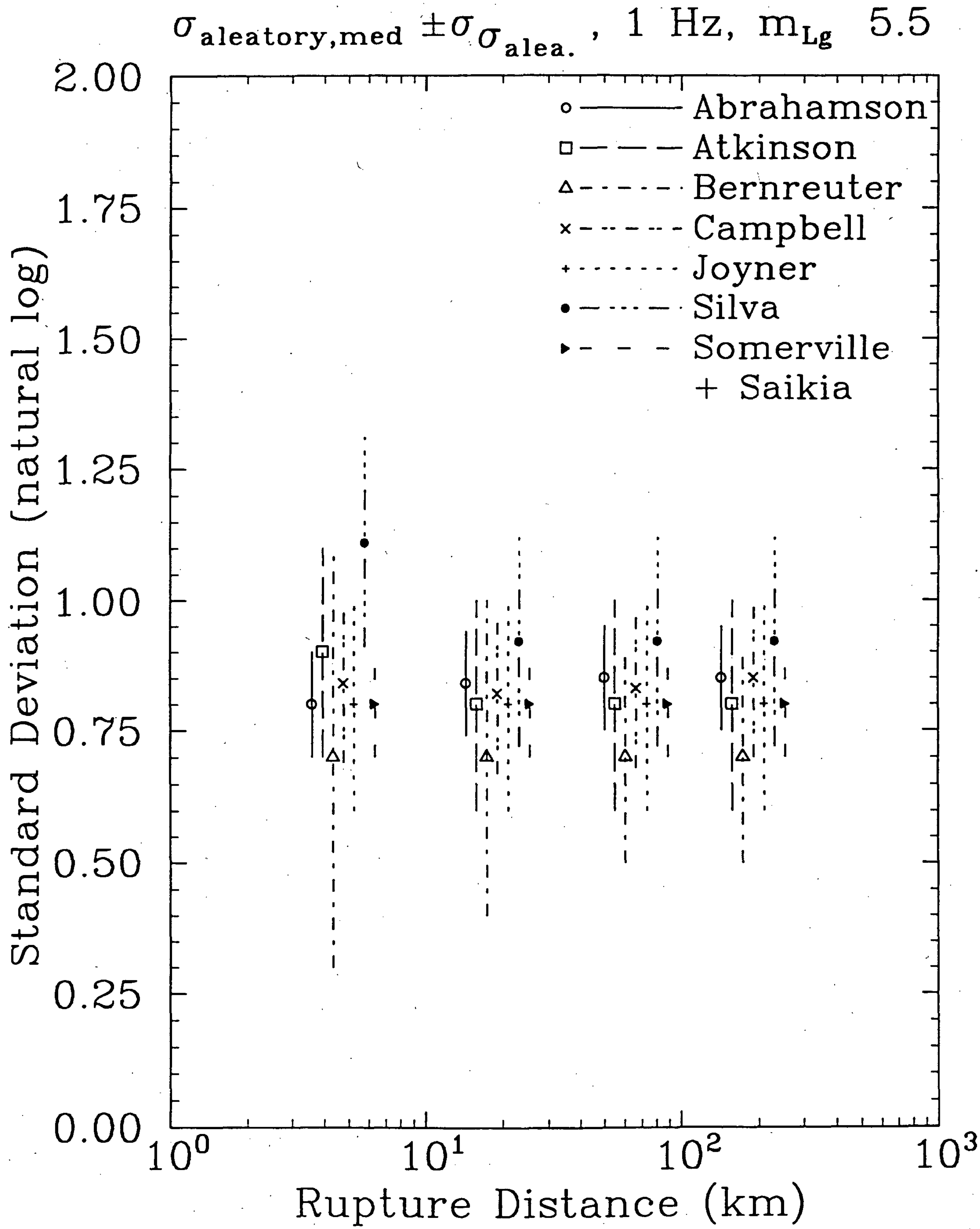

Median ± σepistemic , PGA, mLg 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
Acceleration (g)
10^0
10^-1
10^-2
10^-3
10^0
10^1
10^2
10^3
Rupture Distance (km)

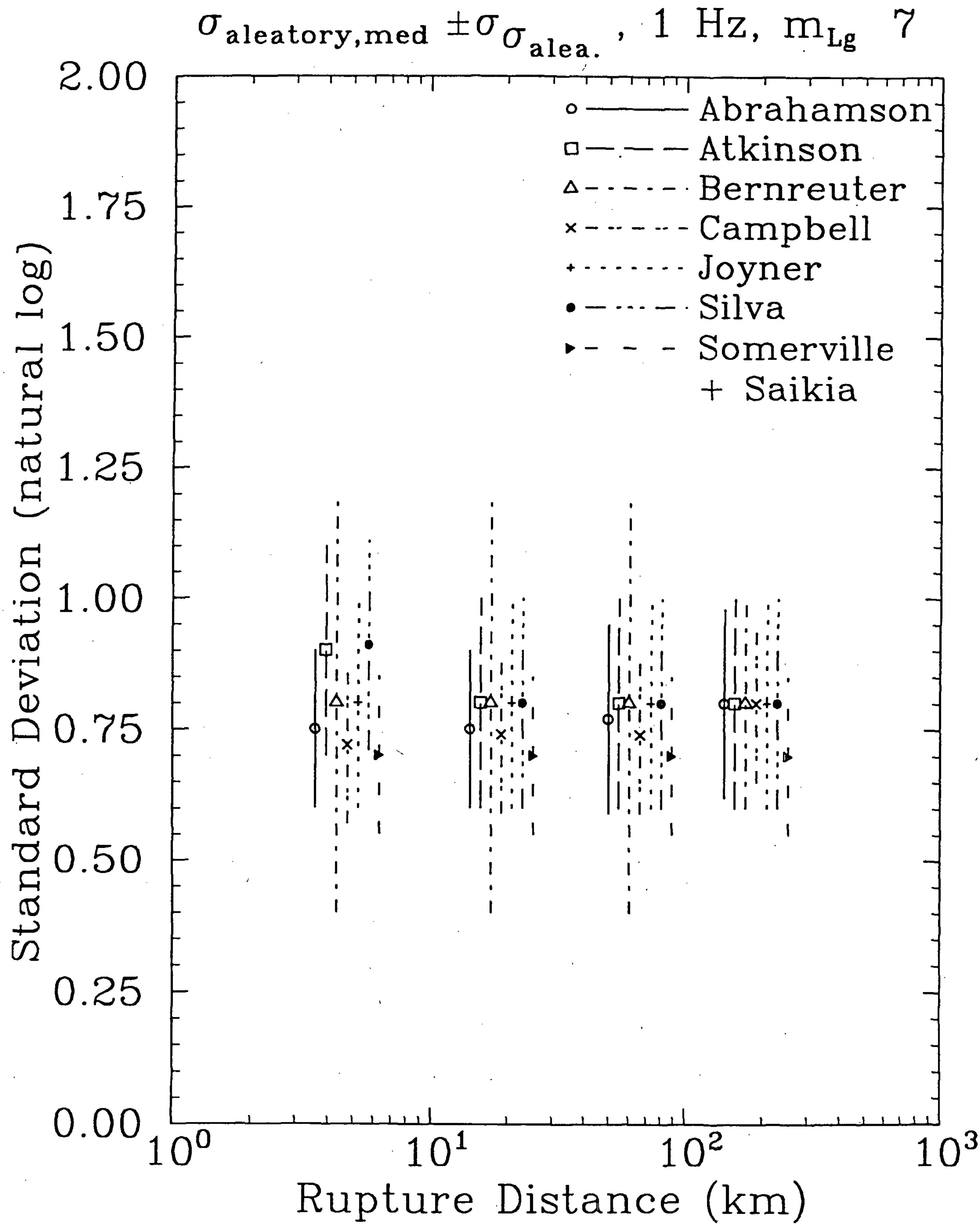

Median ± σ epistemic , PGA, m Lg 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
Acceleration (g)
Rupture Distance (km)
10^1
10^0
10^-1
10^-2
10^0
10^1
10^2
10^3


Median ± $\sigma_{epistemic}$, m_{Lg} 5.5, 20 km
Spectral Acceleration (g)
10^1
10^0
10^{-1}
10^{-2}
Frequency (Hz)
10^{-1}
10^0
10^1
10^2
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia

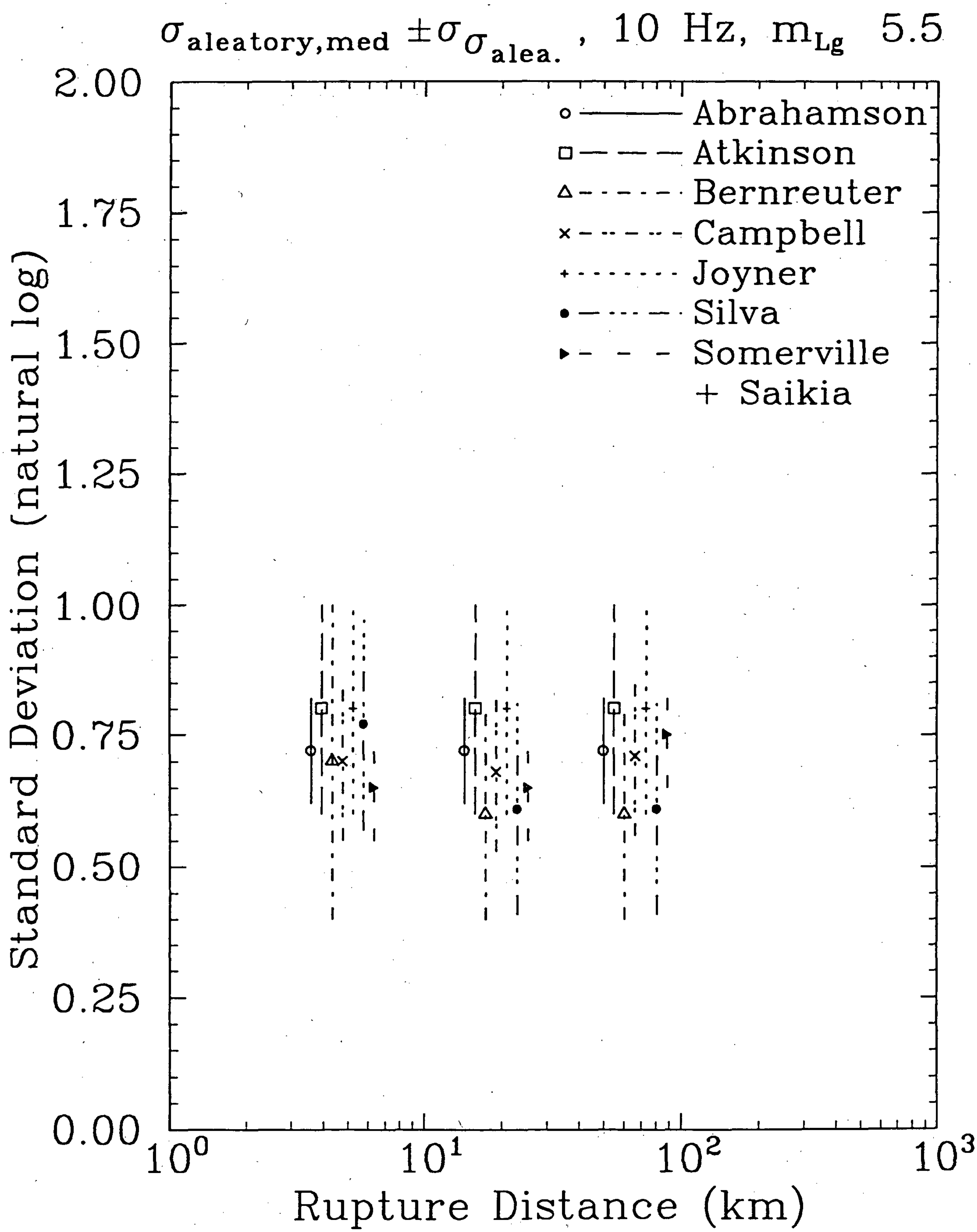


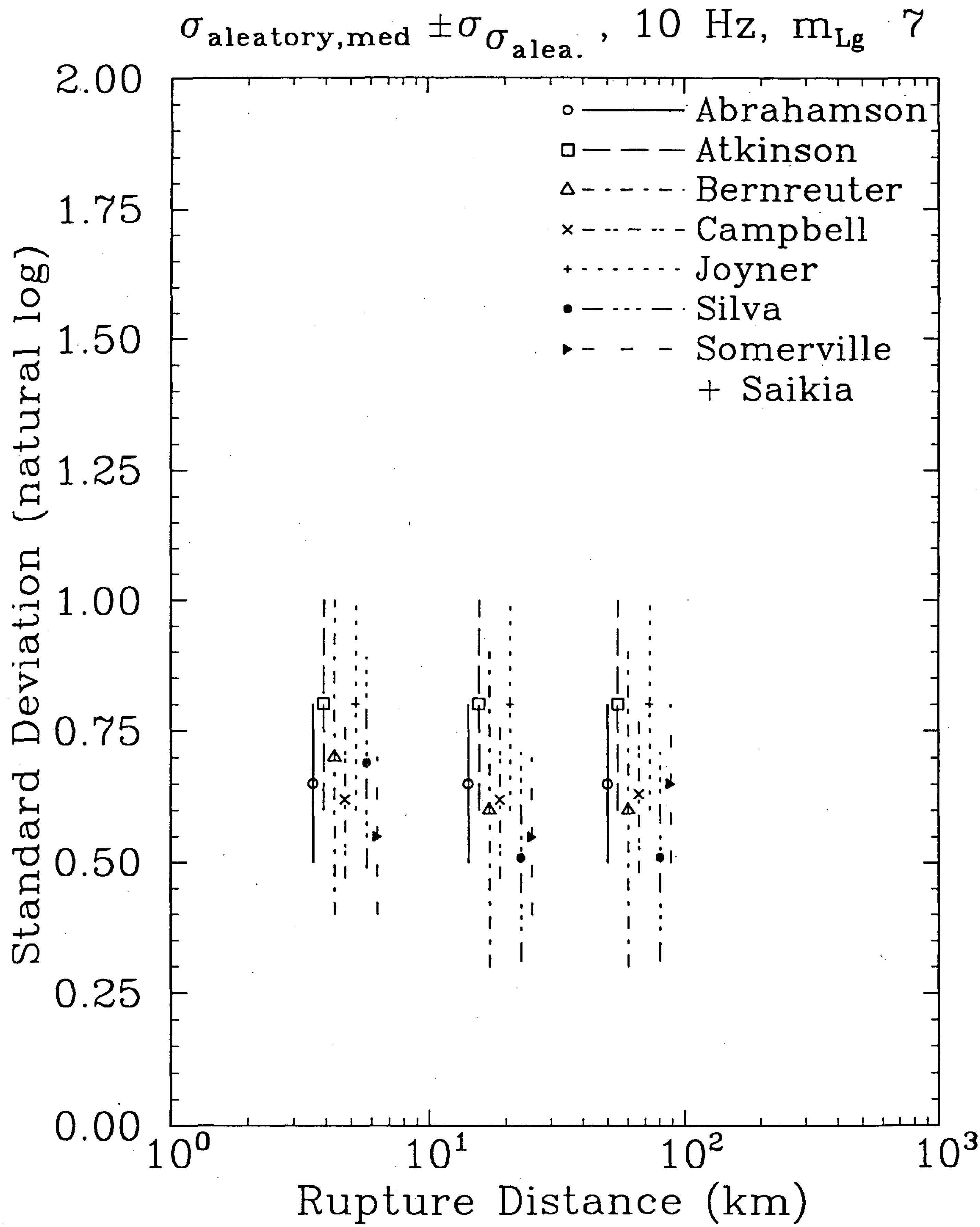
Median ± σepistemic , mLg 7, 20 km
Spectral Acceleration (g)
Frequency (Hz)
10^1
10^0
10^-1
10^-2
10^-1
10^0
10^1
10^2
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia

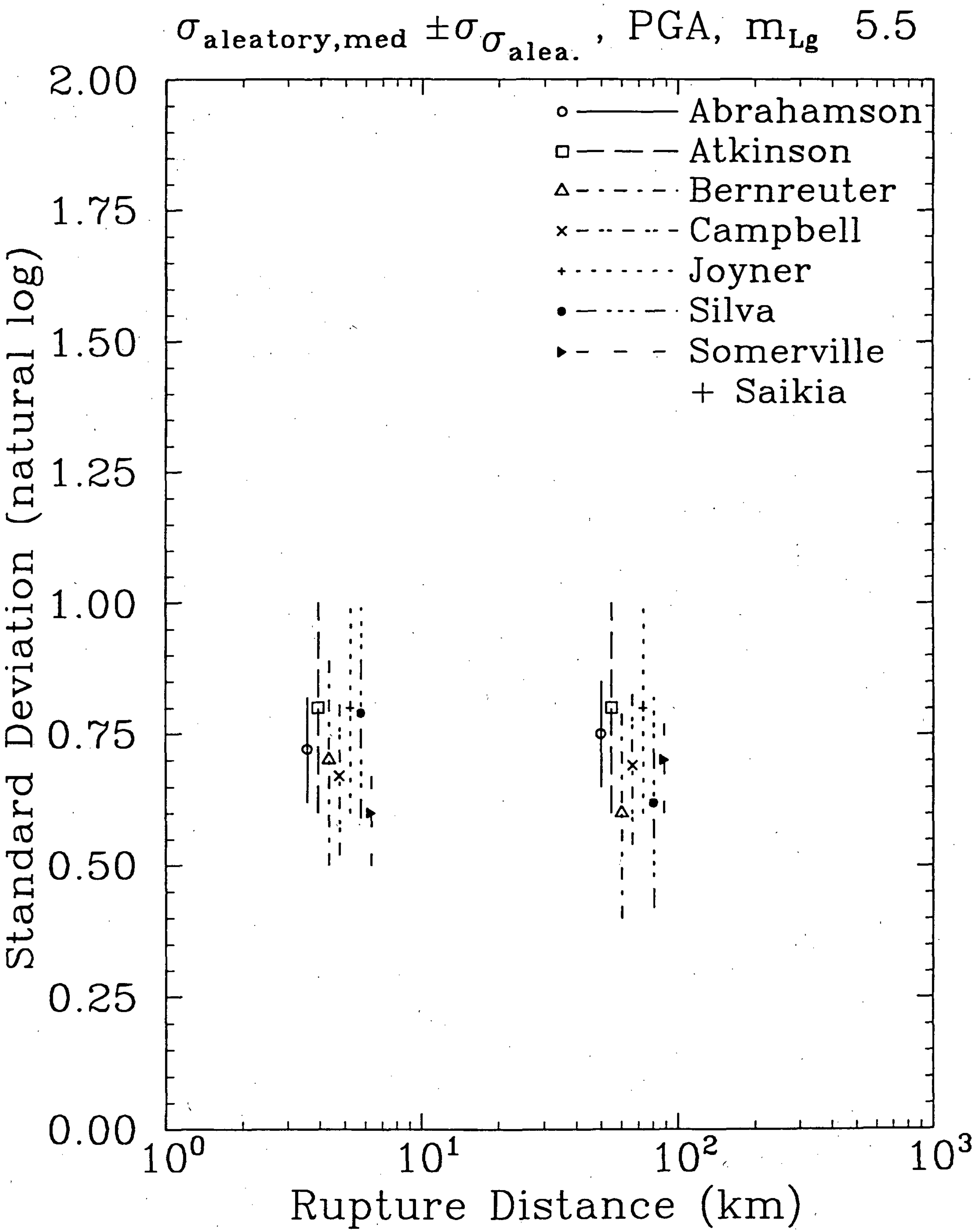

$\sigma_{aleatory,med} \pm\sigma_{\sigma_{alea.}}$, 1 Hz, m_{Lg} 5.5
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Standard Deviation (natural log)
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
10^0
10^1
10^2
10^3
Rupture Distance (km)


$\sigma_{aleatory,med} \pm \sigma_{\sigma_{alea.}}$, 1 Hz, m_{Lg} 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
Standard Deviation (natural log)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^0
10^1
10^2
10^3
Rupture Distance (km)

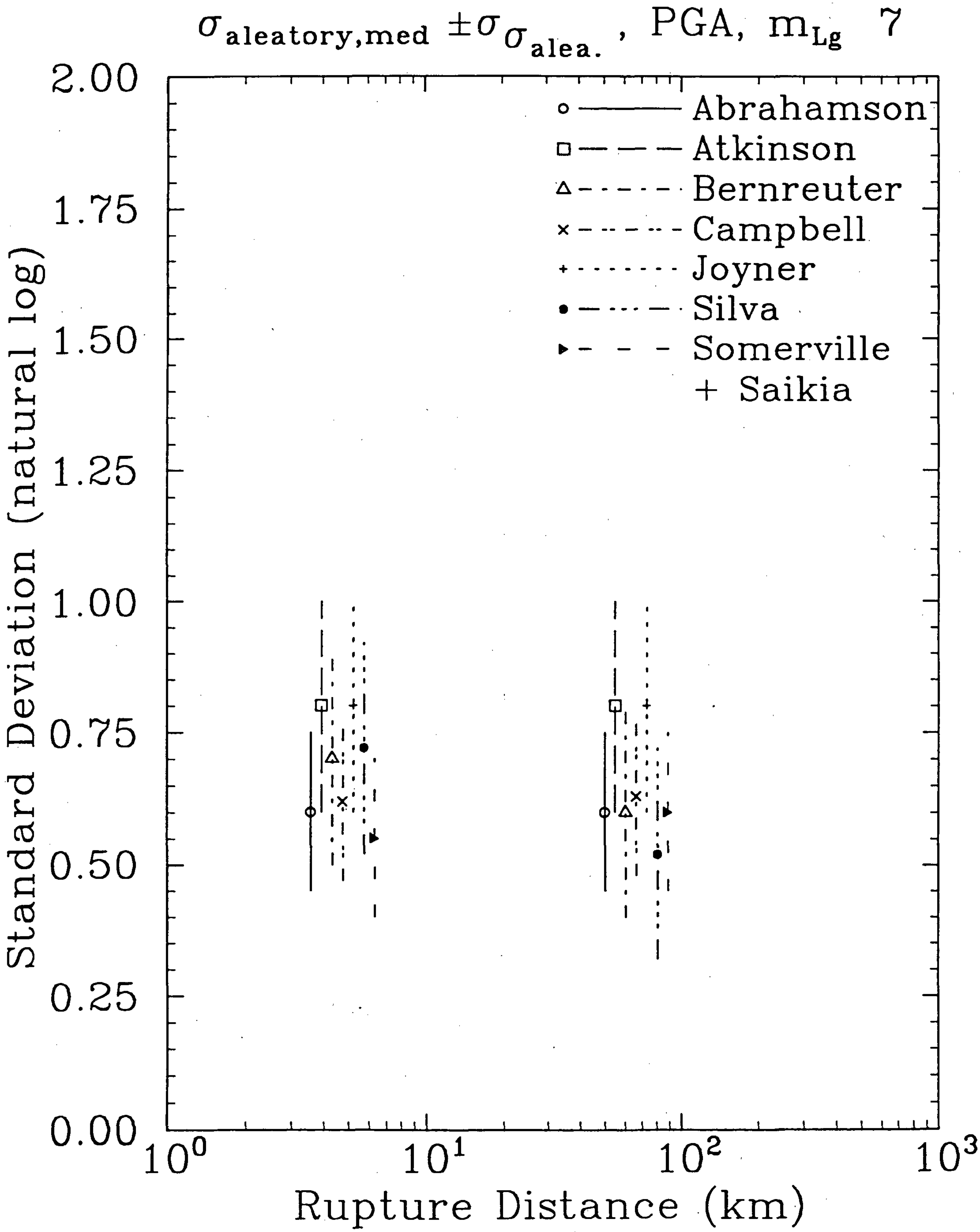
frame 1 $DISK3:[GTOH.9305.WSHOP_2]3_100_55.MET;5

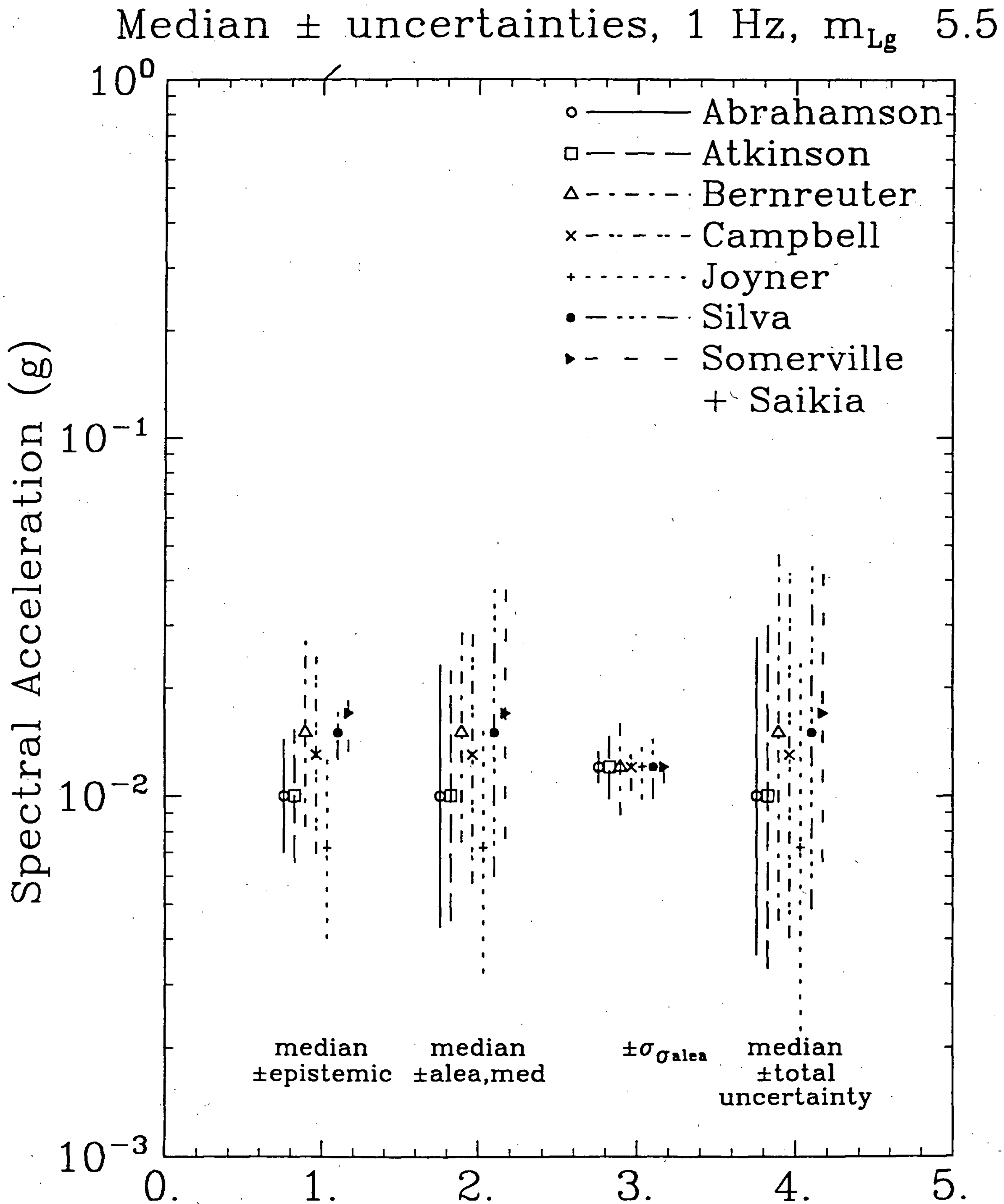



σ aleatory,med ±σ σ alea. , 10 Hz, m Lg 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
Standard Deviation (natural log)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^0
10^1
10^2
10^3
Rupture Distance (km)

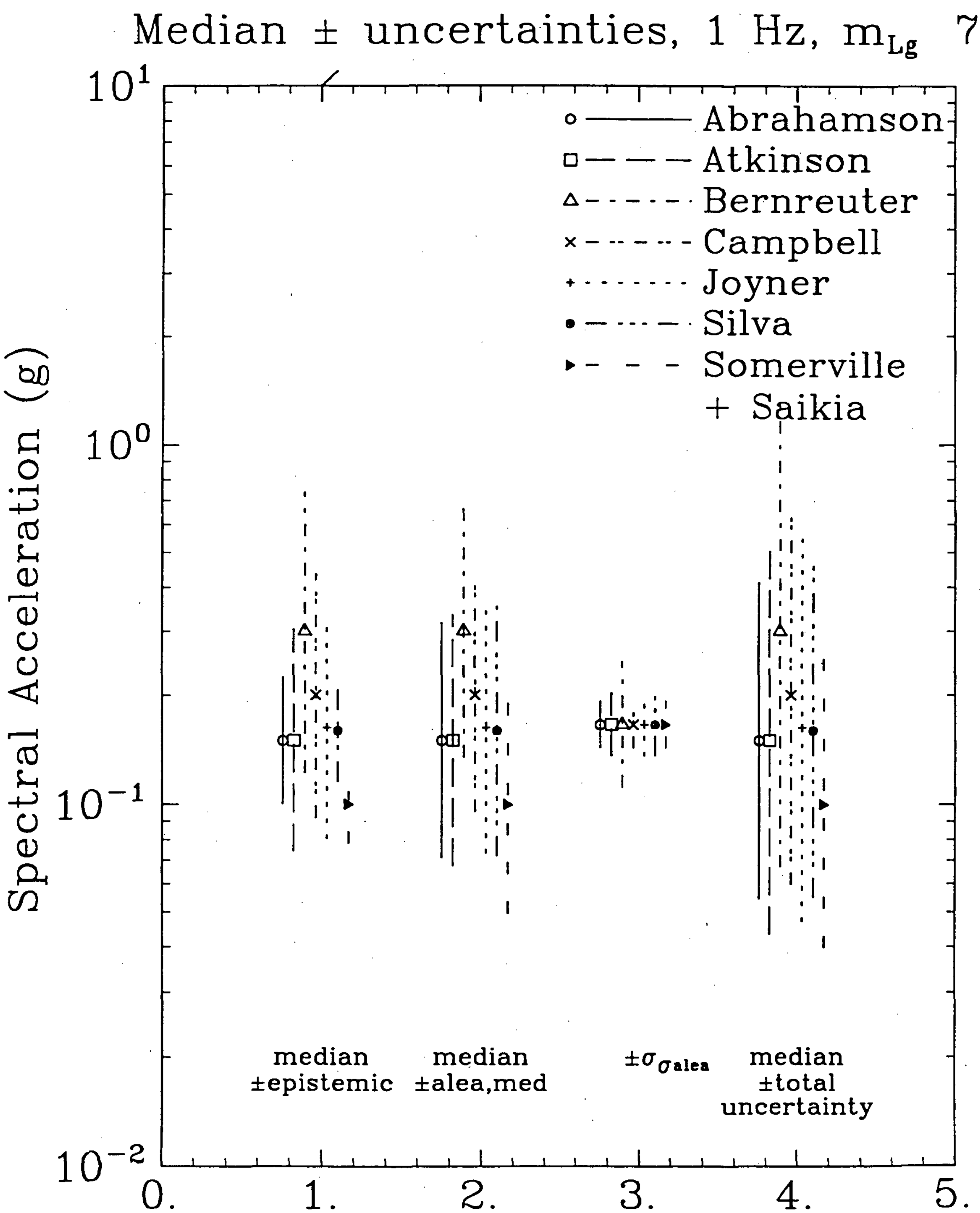


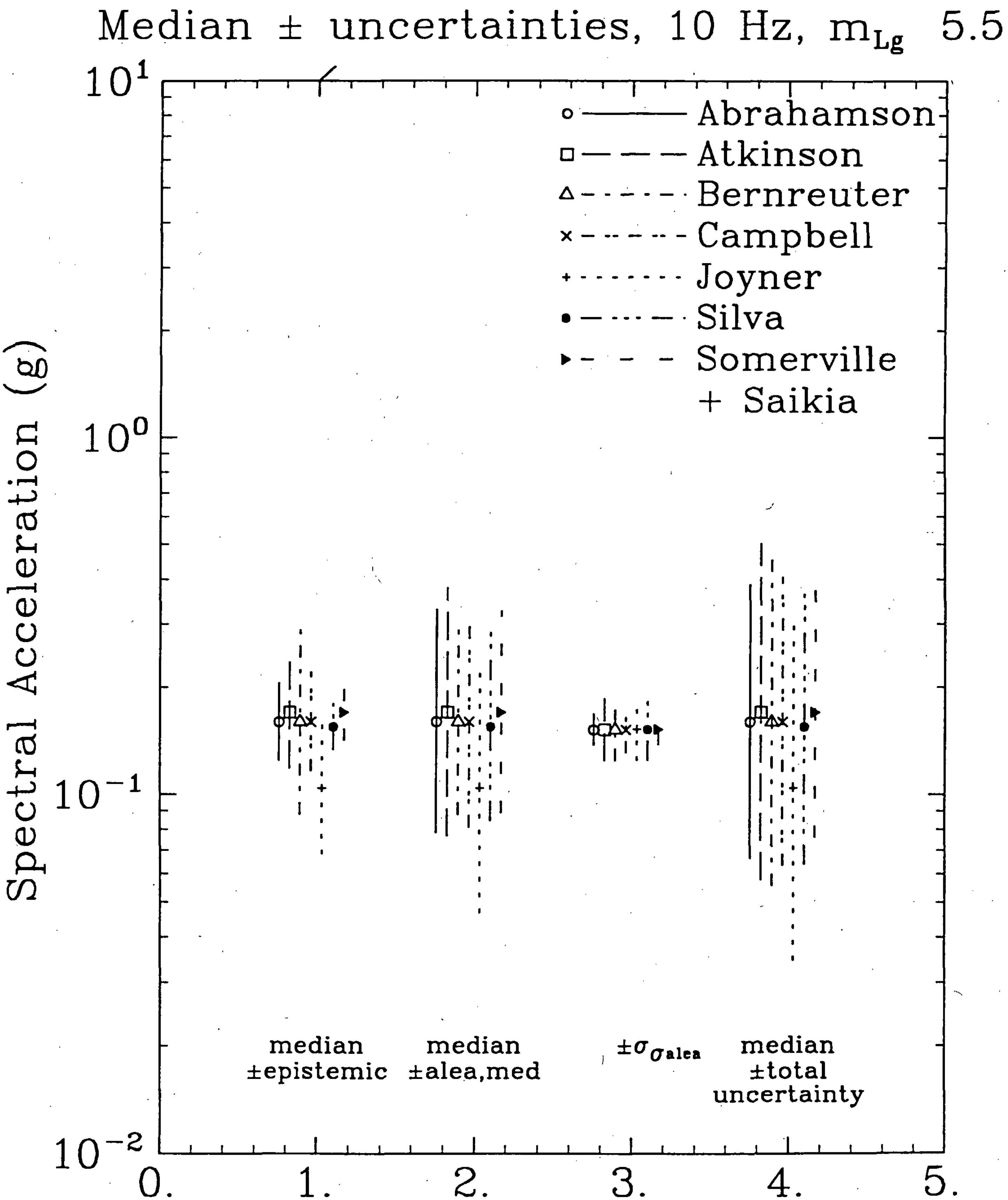
$\sigma_{aleatory,med} \pm \sigma_{\sigma_{alea.}}$, PGA, m_{Lg} 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
Standard Deviation (natural log)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^0
10^1
10^2
10^3
Rupture Distance (km)

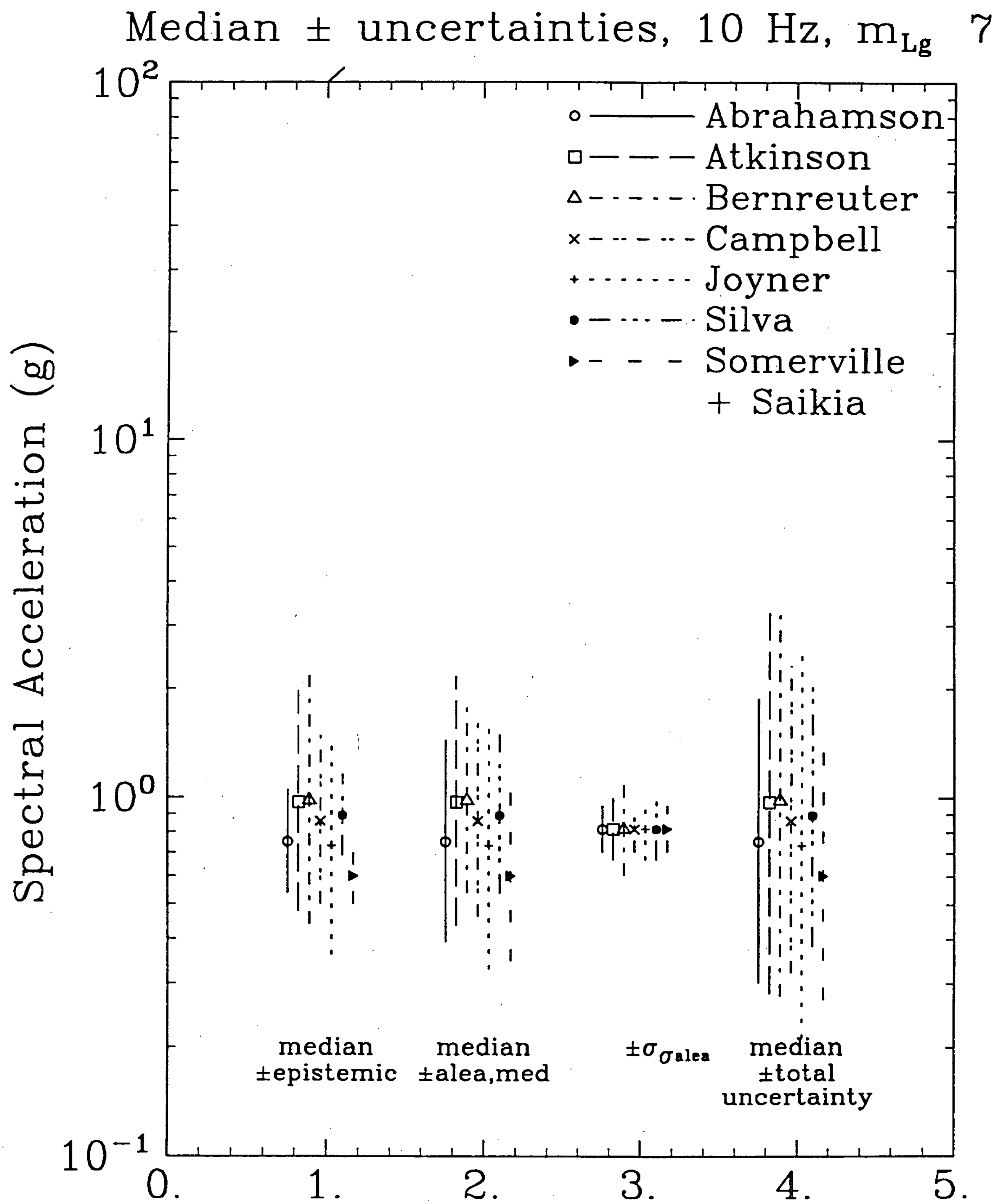

$\sigma_{aleatory,med} \pm \sigma_{\sigma_{alea.}}$, PGA, m_{Lg} 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
Standard Deviation (natural log)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^0
10^1
10^2
10^3
Rupture Distance (km)


Median ± uncertainties, 1 Hz, m_{Lg} 5.5
Spectral Acceleration (g)
10^0
10^{-1}
10^{-2}
10^{-3}
0.
1.
2.
3.
4.
5.
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
median ±epistemic
median ±alea,med
$\pm\sigma_{\sigma alea}$
median ±total uncertainty

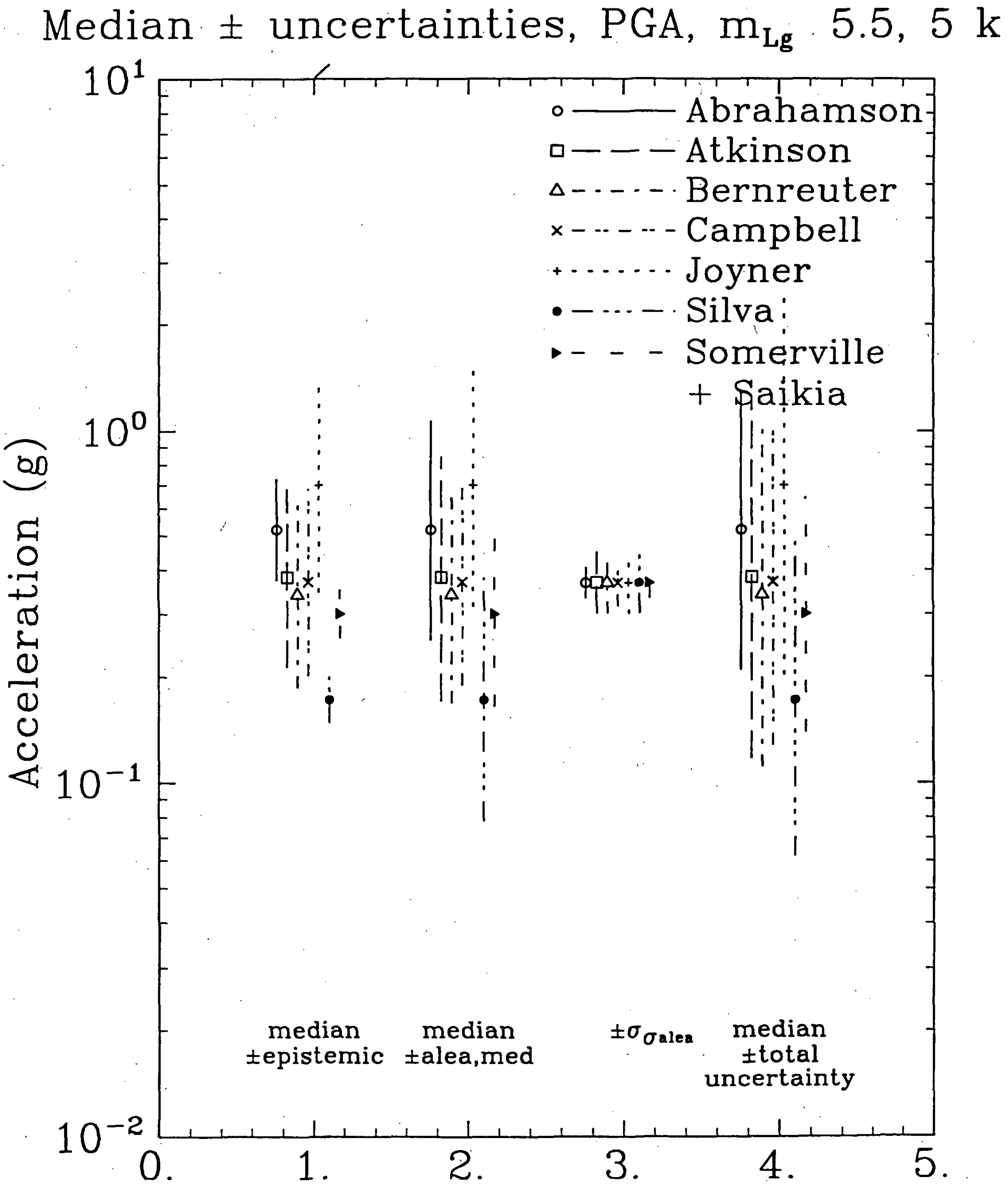
frame 1 $DISK3:[GTOH.9305.WSHOP_2]5_010_70.MET;3

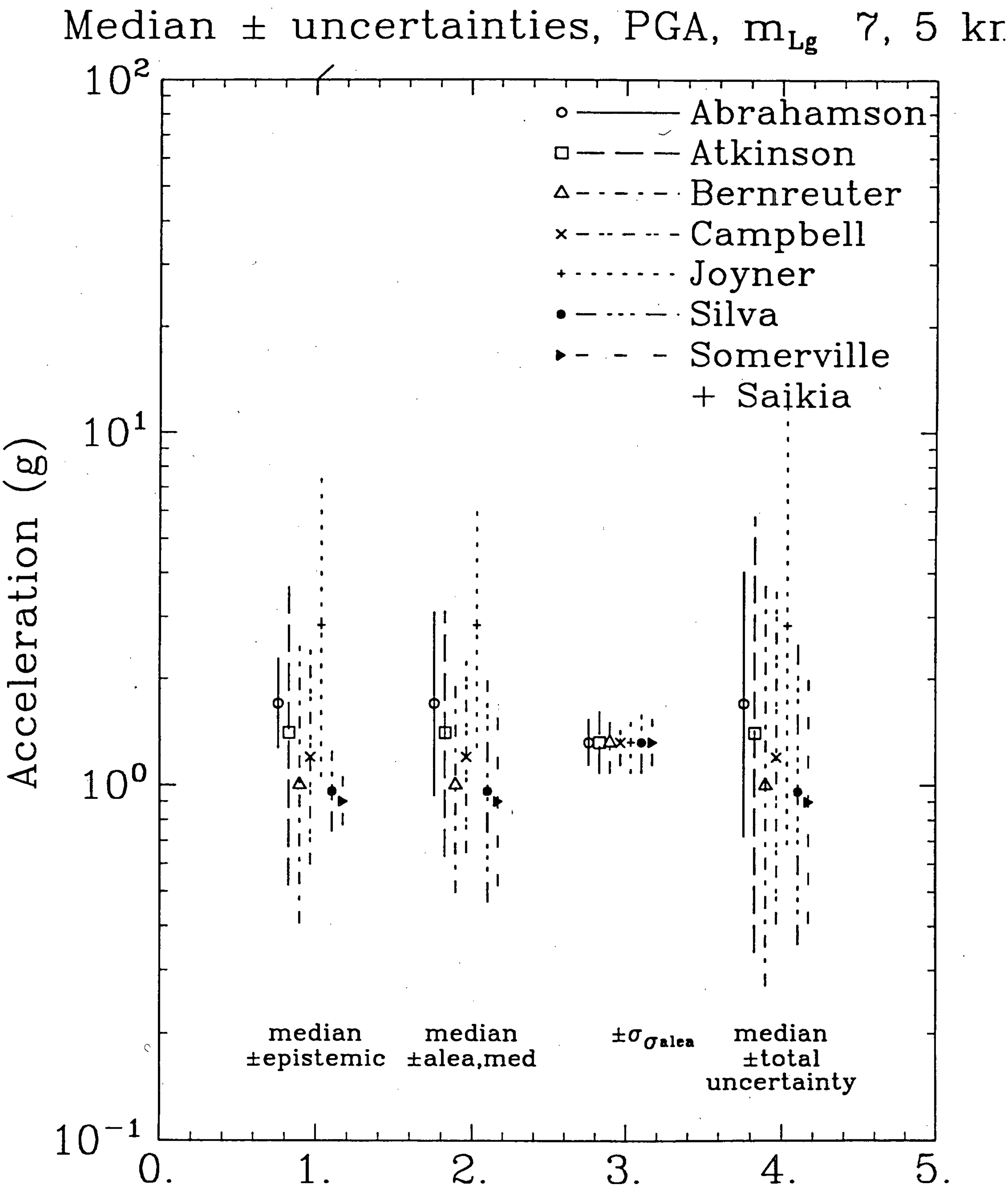



Median ± uncertainties, 10 Hz, m_{Lg} 5.5
Spectral Acceleration (g)
10^1
10^0
10^{-1}
10^{-2}
0.
1.
2.
3.
4.
5.
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
median ±epistemic
median ±alea,med
$\pm\sigma_{\sigma alea}$
median ±total uncertainty


Median ± uncertainties, 10 Hz, m_{Lg} 7
Spectral Acceleration (g)
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
median
±epistemic
median
±alea,med
$\pm\sigma_{\sigma alea}$
median
±total
uncertainty
10^2
10^1
10^0
10^{-1}
0.
1.
2.
3.
4.
5.

frame 1 $DISK3:[GTOH.9305.WSHOP_2]5_PGA_55.MET;3





Median ± uncertainties, PGA, m_{Lg} 7, 5 kr
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
Acceleration (g)
10^2
10^1
10^0
10^{-1}
median
±epistemic
median
±alea,med
$\pm\sigma_{\sigma alea}$
median
±total
uncertainty
0.
1.
2.
3.
4.
5.

ATTACHMENT B-4

WORKSHOP-II AGENDA

SSHAC Ground Motion Workshop Number 2

Applied Decision Analysis, Inc.
Menlo Park, California

July 28 -- 29, 1994

<u>First Day</u>

Welcome & Logistics

Introduction

- Agenda
- Goals of workshop

Median Values: Proponent's Results

- Integrator's summary
- Discussion of model issues

Median Values: Expert's Results

- Integrator's summary
- Brief review of procedures by experts
- Discussion of differences

Epistemic Uncertainty in the Median Values: Expert's Results

- Integrator's summary
- Brief review of procedures by experts
- Discussion of differences

Ground Motion Implications of Elicited Information

Homework Assignment

- (including discussion of truncation elicitation)

SSHAC Ground Motion Workshop Number 2

Applied Decision Analysis, Inc.
Menlo Park, California

July 28 -- 29, 1994

<u>Second Day</u>

Discuss Homework

Aleatory Uncertainty: Expert's Results

- Integrator's summary
- Brief review of procedures by experts
- Discussion of differences

Lunch Assignment

- Experts fill out survey
- Integrator's integrate

Review of Integrator's Integration

ATTACHMENT B-5

EXPERTS 2 (CO-WORKSHOP) RESULTS

Expert: Abrahamson

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			0.30 ↓
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		.0090 ↓	0.15 x
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.0020 ↓	0.038 x
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude		.00070 ↓	0.018 x
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

[illegible] weight on empirical & Atkinson for M_{Lg} = 5.5

Expert: Abrahamson

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.040 x	0.36 x
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: Abrahamson

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.18 ↑	0.80 ↑
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.030 x	.18 x
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Increase @ 20km

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 4: Page __ of __

Expert: Abrahamson

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.20	1.0
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: Abrahamson

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.015 ↑	0.10 ↑
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:
increase to account for lower Kappa.

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: Gail Atkinson July 29 1994

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
~~5 km~~ d=1	median amplitude		0.02	0.30
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.008	0.12
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.002	0.030
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude		0.0009	0.020
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:
① I have not revised epistemic uncertainties but following yesterday's discussion I believe my epistemic uncertainties should be treated as 90% confidence limits rather than ± 1 s.d.
② I have moved my median amplitudes back towards my 'proponent' values in light of perceived agreement that data support my results (at meeting

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: Gail Atkinson July 29

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
~~5 km~~ d=1	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.040	0.34
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: Gail Atkinson July 29 1994

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
~~5 km~~ d=1	median amplitude		0.46	2.2
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.17	0.97
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.022	0.17
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: Gail Atkinson July 29

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.23 ~~0.26~~	~~1.3~~ 1.2
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: Gail Atkinson July 29

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
~~5 km~~ d=1	median amplitude		0.30	1.2
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.011	0.09
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page __ of __

Expert: BERNREUTER

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.4	0.8
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.4	0.8
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.4	0.8
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: Might lower median est 1Hz $M_{blg}=7$ @ 20, 70 and 200 a bit

I lowered my epistemic uncertainties because I think my estimates were more for the 90% or so rather than 85%. I fear I may still have some aleatory uncertainty mixed in — so they might

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 2: Page __ of __

Expert: BERNREUTER

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.05	0.43
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.8
	aleatory uncertainty	median σ	0.7	0.7
		uncertainty in σ	0.3	0.3
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: ______________________

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.4	0.6
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 3: Page __ of __

Expert: ____________________

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.3	0.6
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.3	0.6
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: ____________________

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.3	0.6
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 5: Page __ of __

Expert: ______________________________

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.4	0.6
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page __ of __

Expert: Somerville / Saikia   7/29/94

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5 (Mw 5.2)	m_{Lg} 7.0 (Mw 6.7)
5 km	median amplitude		0.05	0.39
	epistemic uncertainty	parametric (ln)	0.3	0.3
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.012	0.13
	epistemic uncertainty	parametric (ln)	0.3	0.3
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.0022	0.039
	epistemic uncertainty	parametric (ln)	0.35	0.35
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude		0.001	0.013
	epistemic uncertainty	parametric (ln)	0.3	0.3
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: Changes:

1. MLg 5.5 : Atkinson given .5 weight
2. MLg 7.0 : now represented by Mw 6.7
3. epistemic parametric uncertainty increased

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 2: Page __ of __

Expert: Somerville / Saikia 7/29/94

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g) M_w 5.2 M_w 6.7

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.05	0.31
	epistemic uncertainty	parametric (ln)	0.2	0.2
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: Changes:

1. mLg 5.5 : Atkinson given 0.5 weight
2. mLg 7.0 : now represented by Mw 6.7
3. parametric epistemic uncertainty increased.

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: Somerville / Saikia 7/29/94

Ground Motion Measure: 10-Hz Spectral Acceleration (g) M_w 5.2 M_w 6.7

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			1.8
	epistemic uncertainty	parametric (ln)	0.2	0.2
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			0.72
	epistemic uncertainty	parametric (ln)	0.2	0.2
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			0.18
	epistemic uncertainty	parametric (ln)	0.25	0.25
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: Changes:

1. mLg 7.0 : now represented by Mw 6.7
2. parametric epistemic uncertainty increased

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 4: Page __ of __

Expert: Somerville / Saikia 7/29/94

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		mLg 5.5 (Mw 5.2)	mLg 7.0 (Mw 6.7)
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			0.9
	epistemic uncertainty	parametric (ln)	0.2	0.2
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: Changes:
1. MLg 7.0 now represented by Mw 6.7
2. parametric epistemic uncertainty increased

Expert: Somerville / Saikia 7/29/94

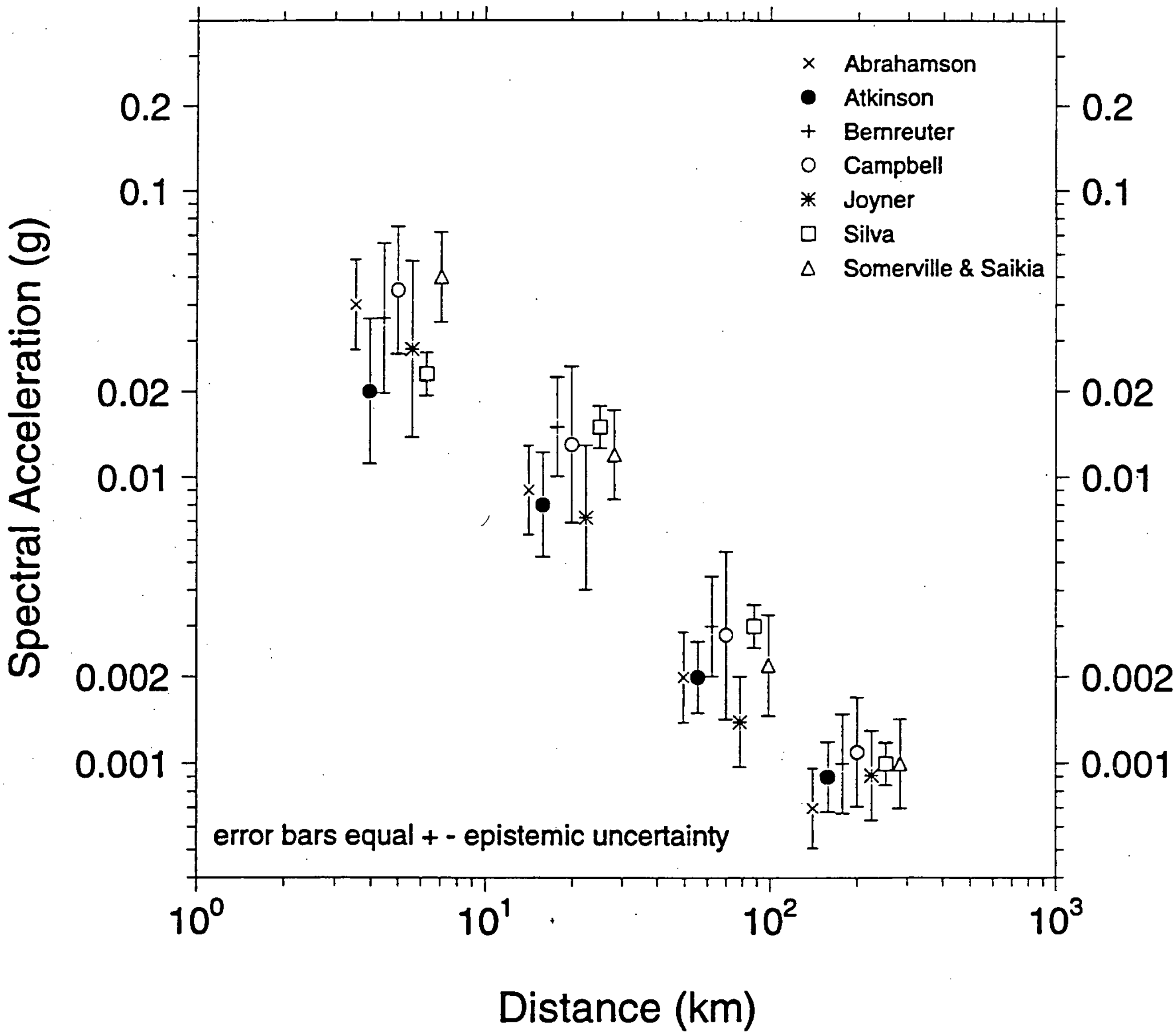
Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5 (Mw 5.2)	m_{Lg} 7.0 (Mw 6.7)
5 km	median amplitude			1.1
	epistemic uncertainty	parametric (ln)	0.2	0.2
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			0.11
	epistemic uncertainty	parametric (ln)	0.25	0.25
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

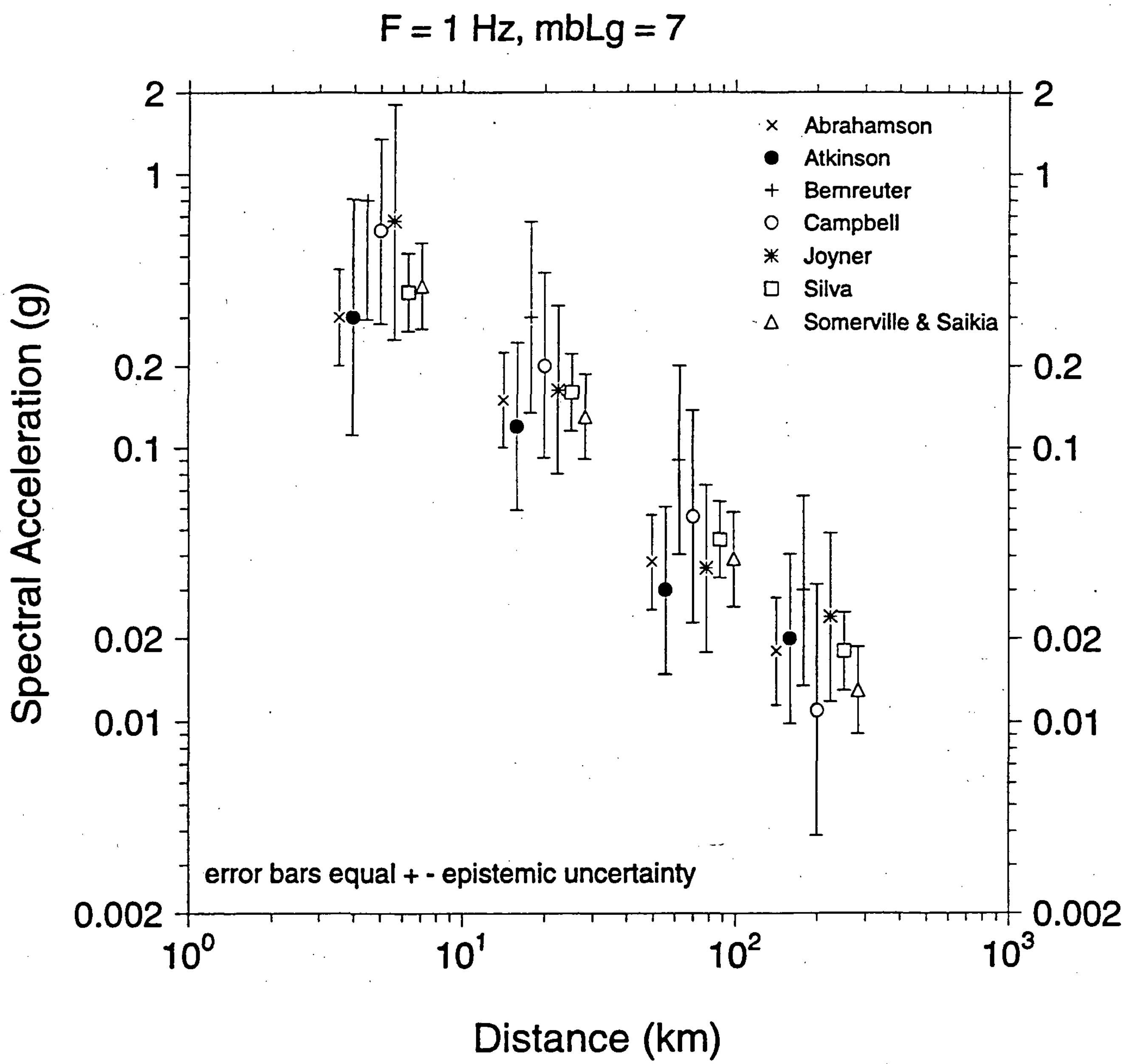
Comments/footnotes: Changes

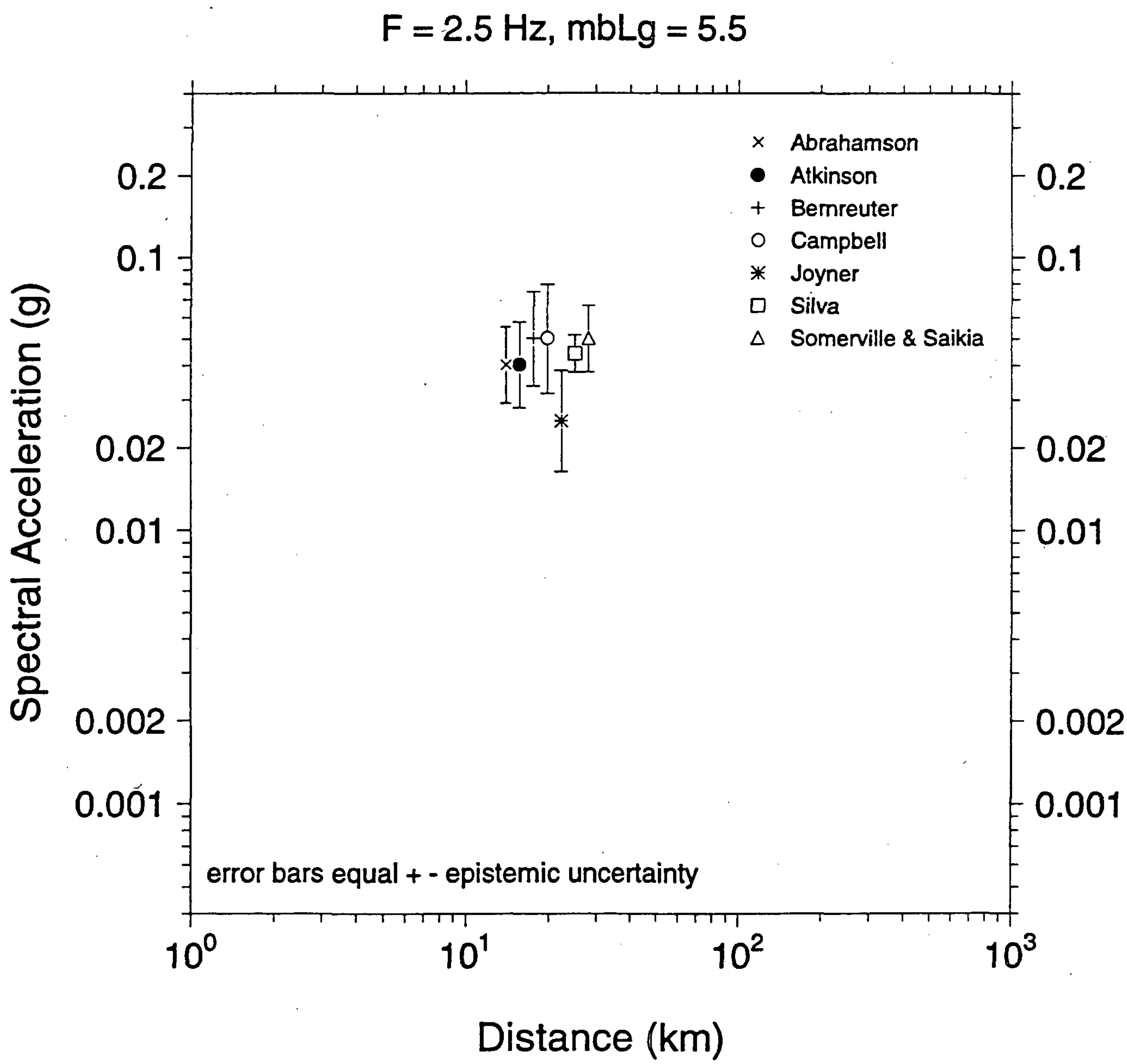
1. mLg is now represented by Mw 6.7
2. parametric epistemic uncertainty increased.

F = 1 Hz, mbLg = 5.5

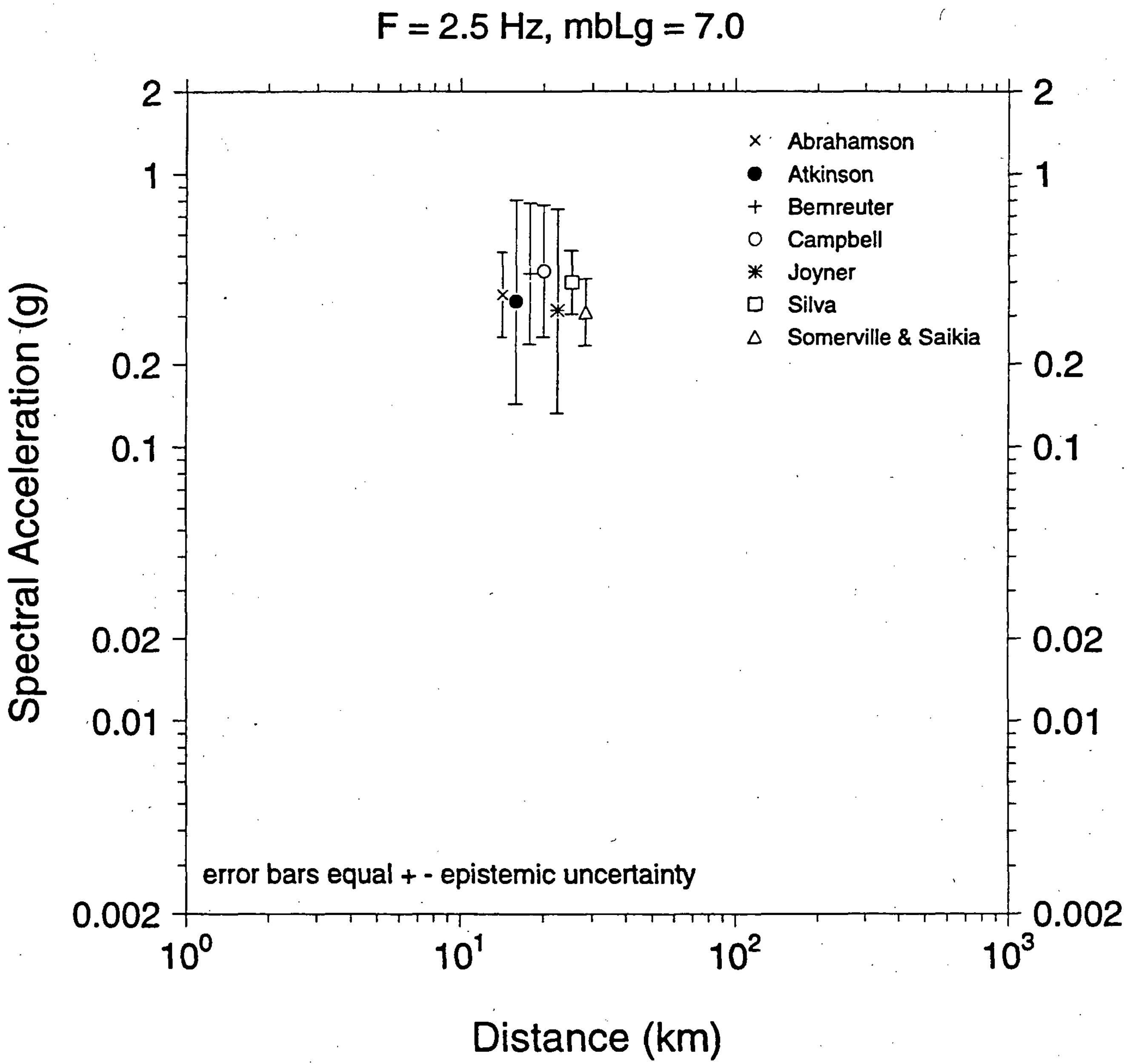


Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
0.2
0.1
0.02
0.01
0.002
0.001
10^0
10^1
10^2
10^3
Distance (km)

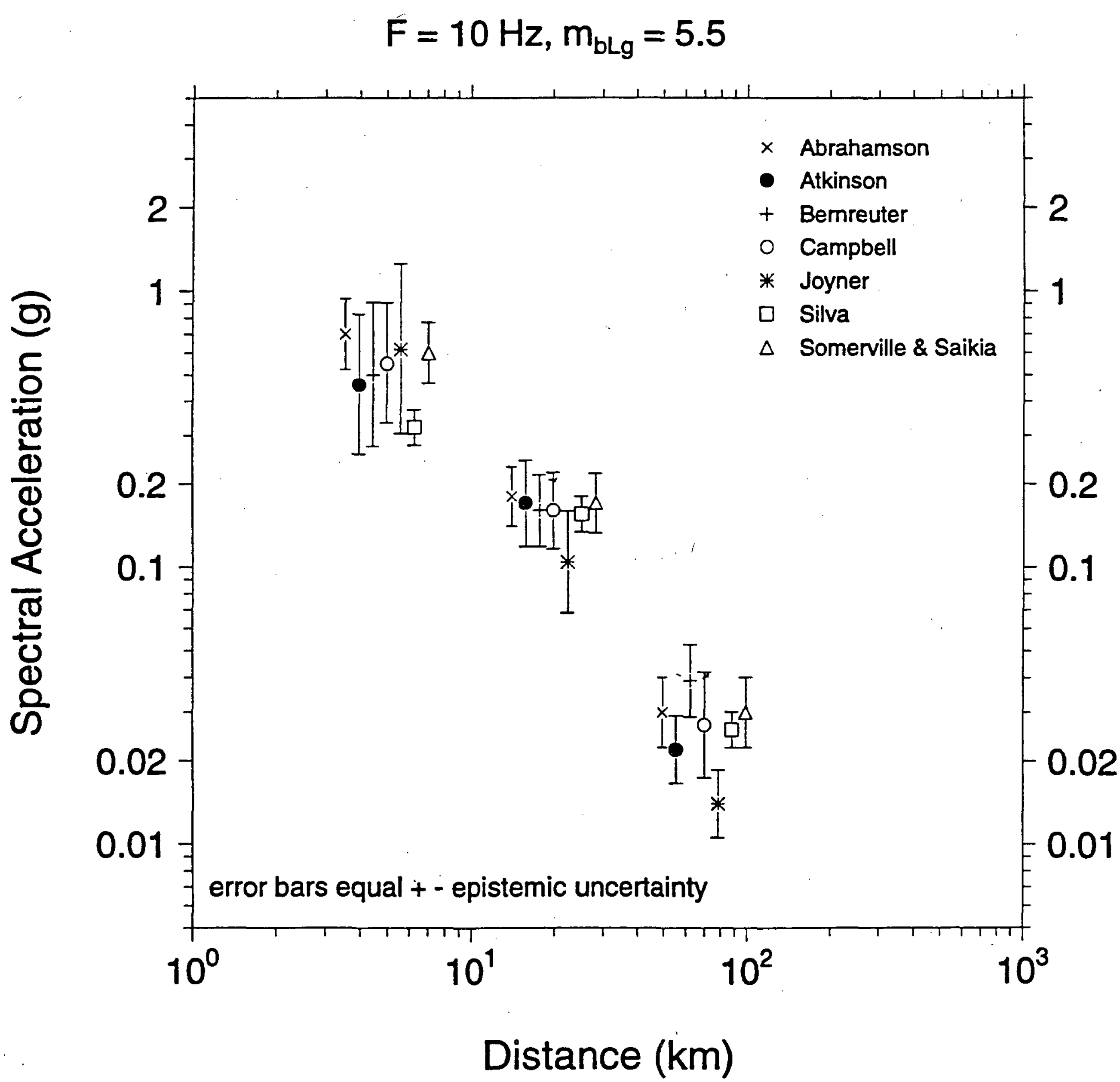

F = 1 Hz, mbLg = 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
Distance (km)
2
1
0.2
0.1
0.02
0.01
0.002
10^0
10^1
10^2
10^3



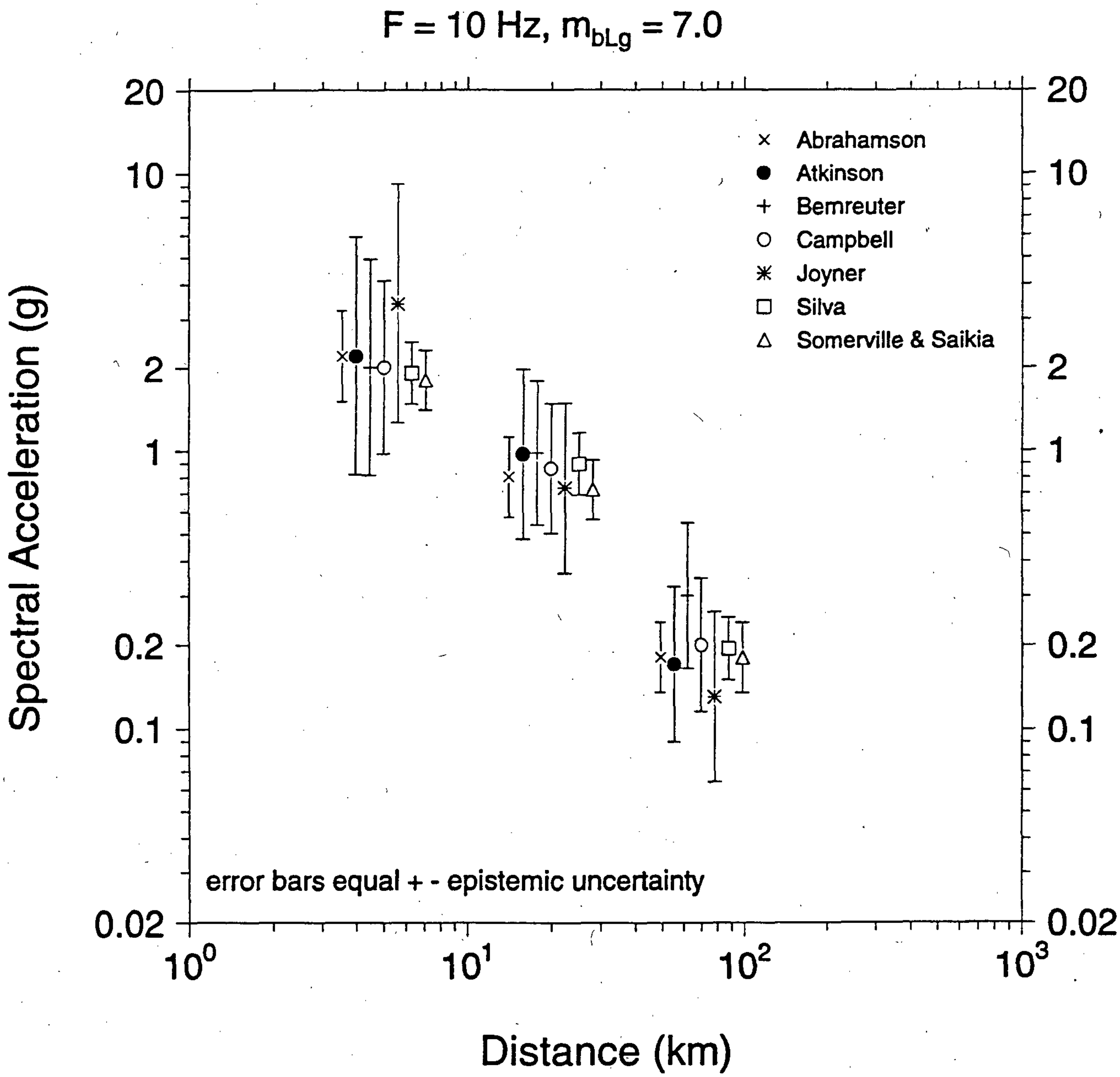
F = 2.5 Hz, mbLg = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Spectral Acceleration (g)
0.2
0.1
0.02
0.01
0.002
0.001
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)



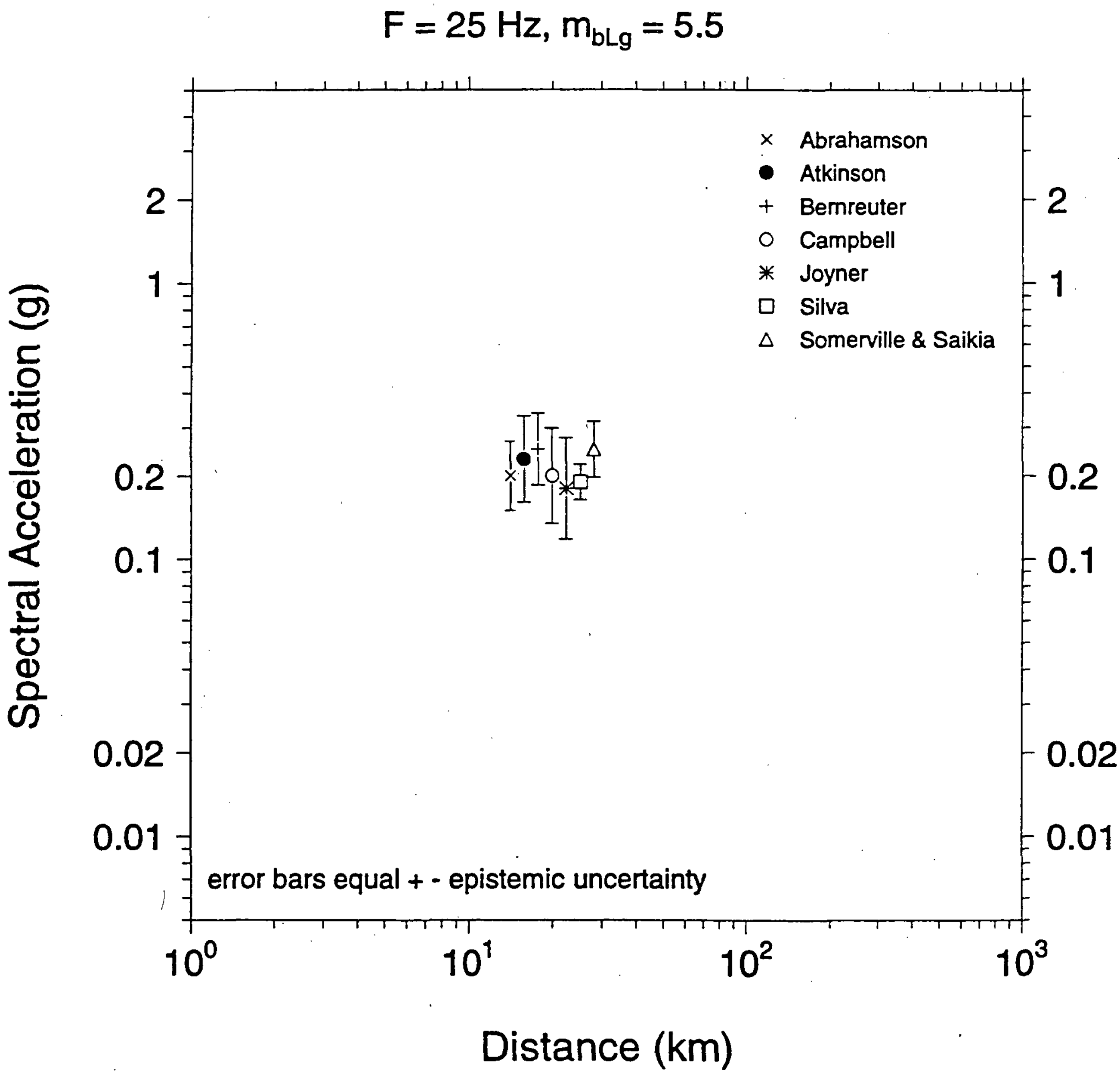
F = 2.5 Hz, mbLg = 7.0
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
0.002
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)



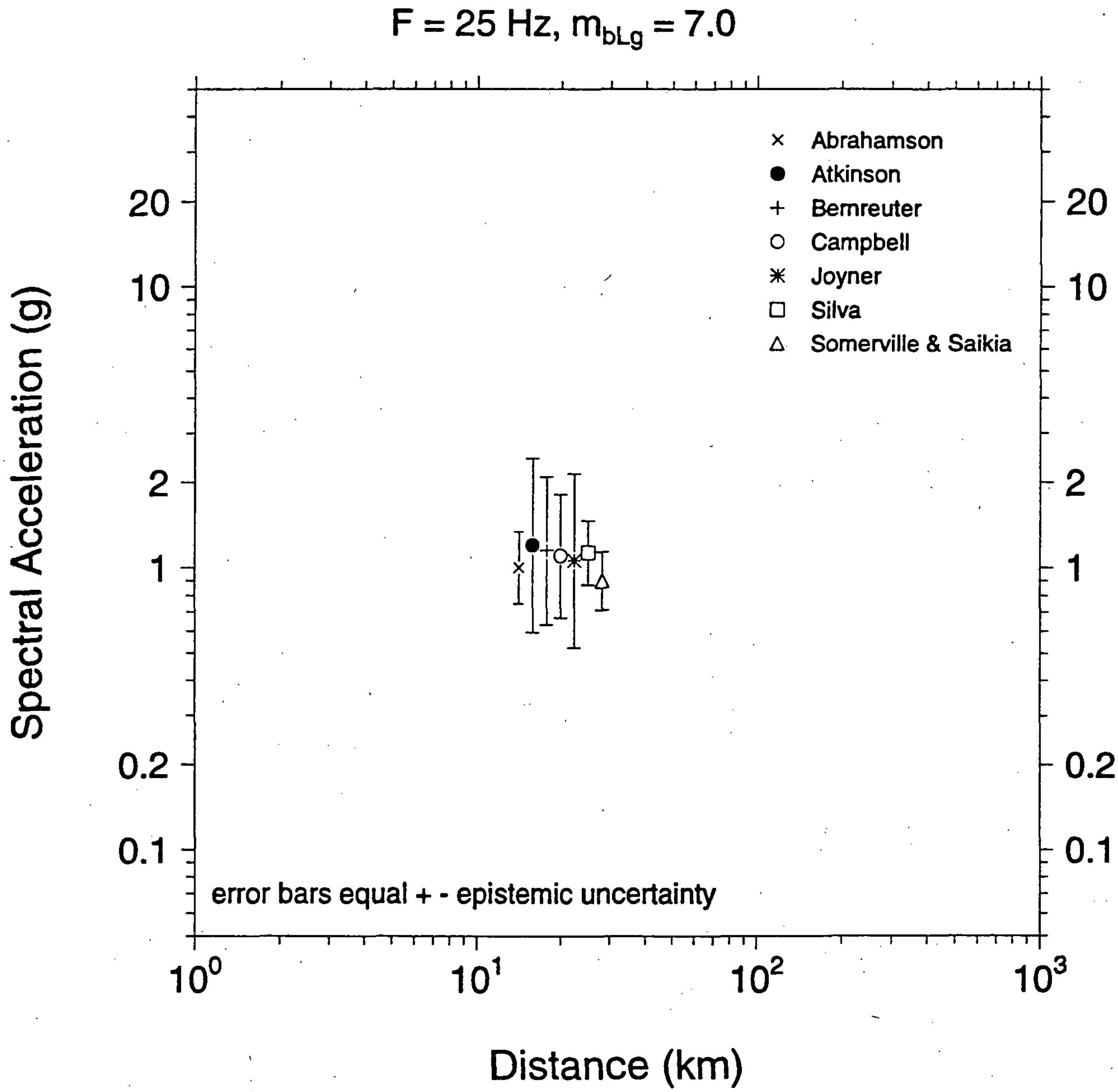
F = 10 Hz, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)



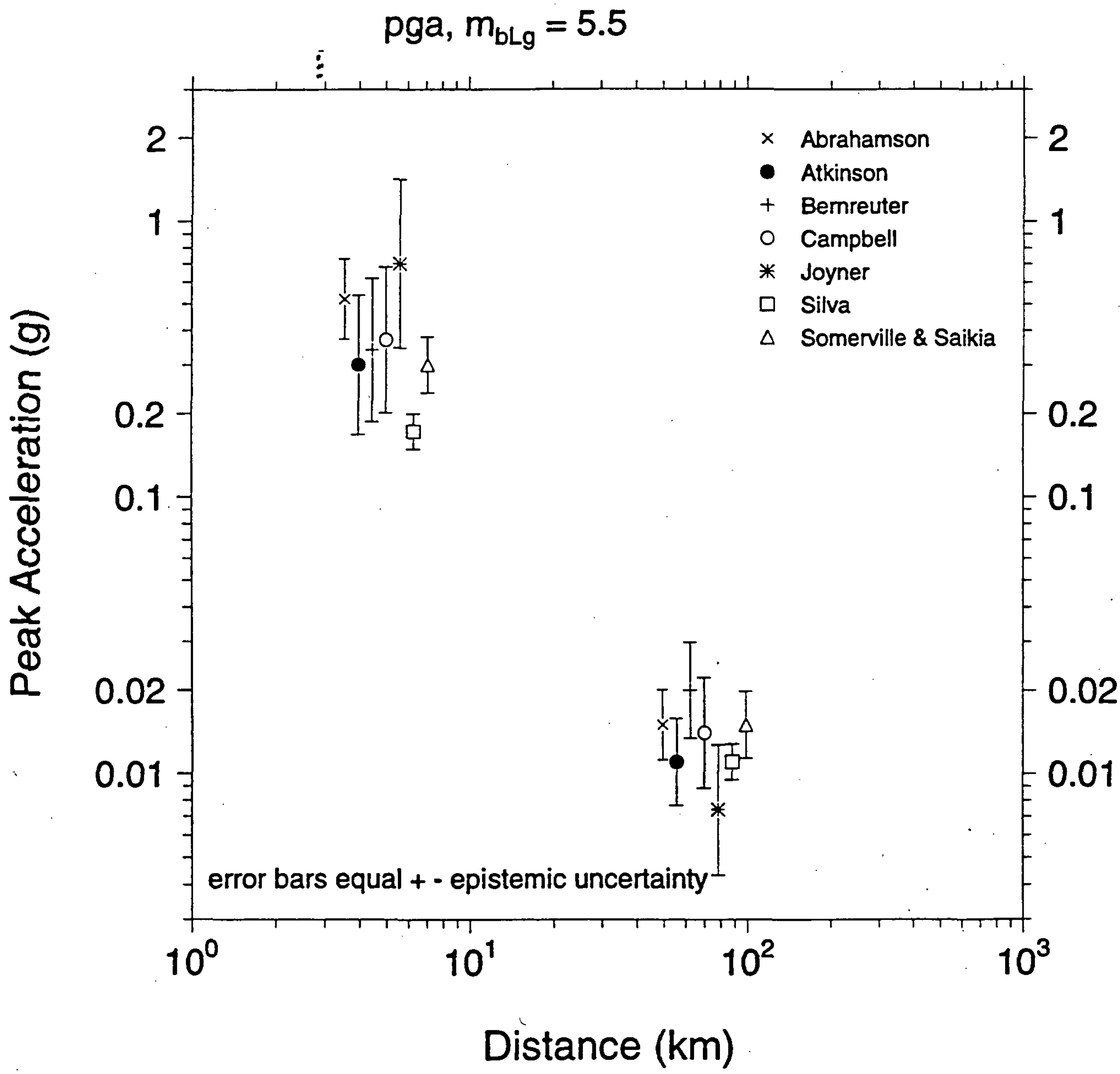
F = 10 Hz, m_{bLg} = 7.0
Spectral Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty

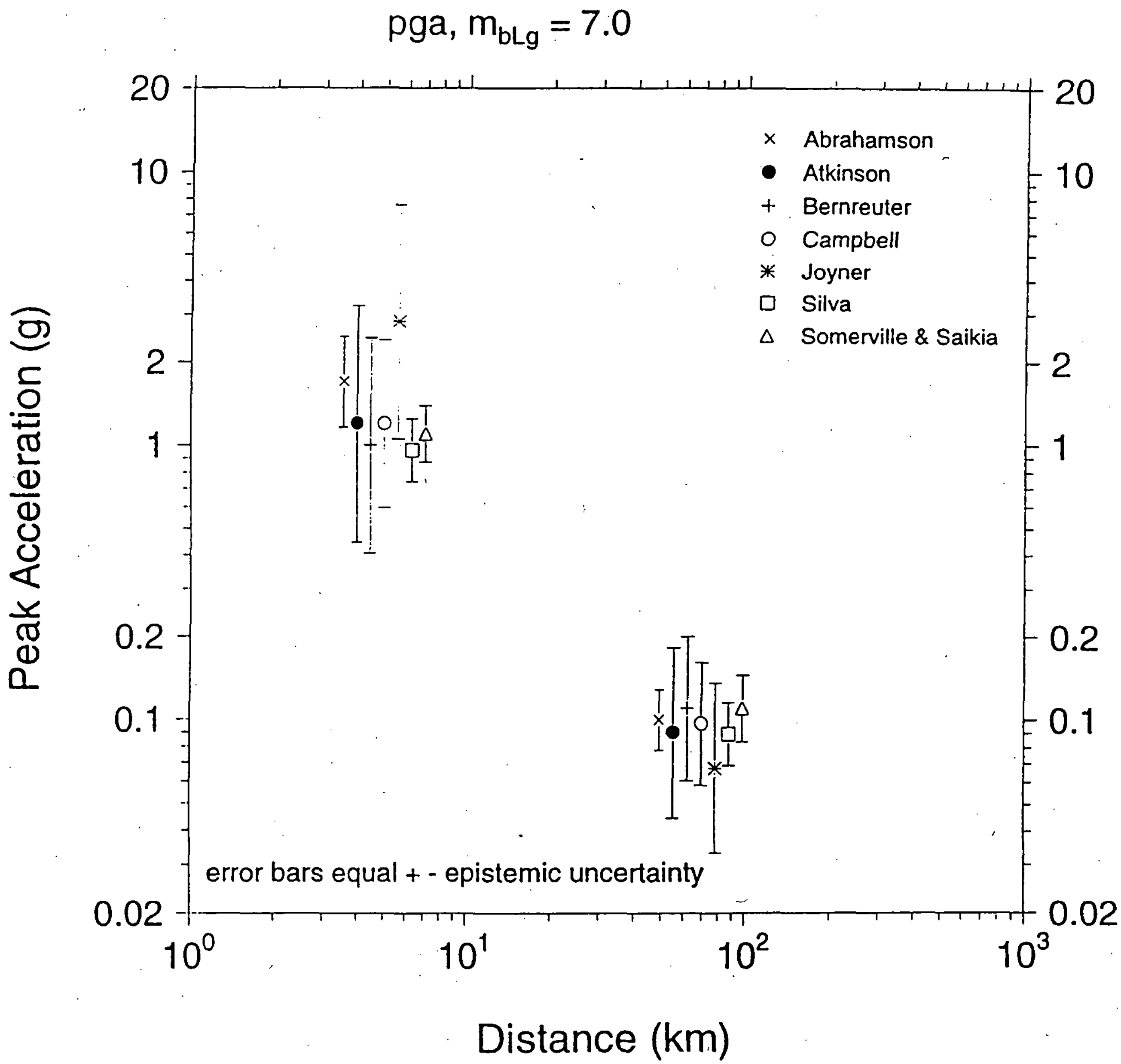


F = 25 Hz, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)



F = 25 Hz, m_{bLg} = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Spectral Acceleration (g)
20
10
2
1
0.2
0.1
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)


pga, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Peak Acceleration (g)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3
Distance (km)


pga, m_{bLg} = 7.0
Peak Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty

ATTACHMENT B-6

INTEGRATORS' SURVEY

GROUND MOTION WORKSHOP II

INTEGRATORS SURVEY

____
NAME

'URPOSE OF SURVEY

- GUIDANCE FOR INTEGATORS
- FOR COMPARING APPROACHES, NOT EXPERTS

CONTEXT OF SURVEY

ALL QUESTIONS SHOULD BE ADDRESSED FOR:

- CENTRAL AND EASTERN UNITED STATES ONLY
- HARD ROCK SITE ONLY

RELATIVE ACCURACY OF FORECASTS

ı this exercise, we would like you to judge the *relative* ability of each model to produce accurate ground ..ıotion estimates. Relative accuracy will be quantified here as your estimate of the relative forecasting error inherent in each model forecast of median ground motion.

Definition of Forecasting Error: We define forecasting error as the expected standard deviation between the model forecast of median ground motion and the true median ground motion in a large number of applications. Thus, the probability of actual median ground motion falling within the error range should be roughly 68%. The error band should embody ***all reasons*** for forecasting error, including uncertainty in model parameters and model structure.

Relative Forecasting Error: To estimate relative forecasting error, for each application (i.e., each column in the table below) give the model you judge most accurate a rating of 100. Then, estimate the forecasting errors of the other models as percentages of the most accurate (for example, a rating of 150 would indicate an expected error band 50% larger than that of the most accurate model).

RELATIVE EXPECTED FORECASTING ERROR

There should be at least one 100 in each column and each number should be greater than or equal to 100:

	1 Hz	1Hz	1Hz	1Hz	2.5Hz	2.5Hz
Frequency:	1 Hz	1Hz	1Hz	1Hz	2.5Hz	2.5Hz
Magnitude:	m_{Lg} 5.5	m_{Lg} 7.0	m_{Lg} 7.0	m_{Lg} 7.0	m_{Lg} 5.5	m_{Lg} 7.0
Distance:	20 km	5 km	20 km	200 km	20 km	20 km
Stoch. Empirical Atten.						
Stoch. Ray Theory Atten.						
Hybrid Empirical						
Advanced Numerical						
Intensity-based						

Frequency:	10 Hz	10 Hz	10 Hz	25 Hz	25 Hz
Magnitude:	m_{Lg} 5.5	m_{Lg} 7.0	m_{Lg} 7.0	m_{Lg} 5.5	m_{Lg} 7.0
Distance:	20 km	5 km	20 km	20 km	20 km
Stoch. Empirical Atten.					
Stoch. Ray Theory Atten.					
Hybrid Empirical					
Advanced Numerical					
Intensity-based					

-ıease summarize any key reasons for the judgments (use back of page if necessary):

CORRELATION AMONG MODEL FORECASTS

Rate each pair of models on their similarity using a scale from 0 (least similar) to 100 (most similar) taking into account *both*:

- Similar interpretations, logic and/or variable settings used to develop forecasts
- Overlapping data sets used to develop forecasts

This similarity judgment can be thought of in terms of correlation in forecasting. Suppose some new data or interpretation becomes available that causes Model 1's forecast to change by X units. By how much would you expect Model 2's forecast to change (i.e., by what percentage of X)?

To make the task easier, use the following conventions:

+++	=	extremely similar	(75-100%	forecast correlation)
++	=	highly similar	(50-75%	forecast correlation)
+	=	somewhat similar	(25-50%	forecast correlation)
0	=	not similar	(0-25%	forecast correlation)

	Stochastic Ray Theory Attenuation	**Hybrid Empirical Attenuation**	**Advanced Numerical**	**Intensity Based**
Stochastic Empirical Attenuation	____	____	____	____
Stochastic Ray Theory Attenuation		____	____	____
Hybrid Empirical			____	____
Advanced Numerical				____

Please summarize your reasons for the judgments (use back of page if necessary):

USING THE APPROACHES FOR FORECASTING

Was your final median estimate based on a weighted average of model forecasts?

_____ My final estimate was based on an explicit set of numerical weights
_____ My final estimate was based informally on a set of weights
_____ I did not think about weights in producing my final estimate

Regardless of how you actually formed your final median estimate, please assign a weight (0 to 100) to each approach if you had to weight the results for each specific application. The weights should sum to 100.

Frequency:	1 Hz	1Hz	1Hz	1Hz	2.5Hz	2.5Hz
Magnitude:	m_{Lg} 5.5	m_{Lg} 7.0	m_{Lg} 7.0	m_{Lg} 7.0	m_{Lg} 5.5	m_{Lg} 7.0
Distance:	20 km	5 km	20 km	200 km	20 km	20 km
Stoch. Empirical Atten.	_____	_____	_____	_____	_____	_____
Stoch. Ray Theory Atten.	_____	_____	_____	_____	_____	_____
Hybrid Empirical	_____	_____	_____	_____	_____	_____
Advanced Numerical	_____	_____	_____	_____	_____	_____
Intensity-based	_____	_____	_____	_____	_____	_____
Total	100	100	100	100	100	100

Frequency:	10 Hz	10 Hz	10 Hz	25 Hz	25 Hz
Magnitude:	m_{Lg} 5.5	m_{Lg} 7.0	m_{Lg} 7.0	m_{Lg} 5.5	m_{Lg} 7.0
Distance:	20 km	5 km	20 km	20 km	20 km
Stoch. Empirical Atten.	_____	_____	_____	_____	_____
Stoch. Ray Theory Atten.	_____	_____	_____	_____	_____
Hybrid Empirical	_____	_____	_____	_____	_____
Advanced Numerical	_____	_____	_____	_____	_____
Intensity-based	_____	_____	_____	_____	_____
Total	100	100	100	100	100

Please summarize your reasons for the judgments. In particular, please explain if the weights seem inconsistent with your assessments of model accuracies and correlations (use back of page if necessary):

Attachment 2

EXPERTS' WRITTEN COMMENTS

RELATIVE FORECASTING UNCERTAINTY:

Abrahamson:

Key reasons for the judgments:
I don't believe the numerical values of the error bands (epistemic line given by the authors (epistemic line given by authors in parentheses in above [table])
Sigma from Gail scaled by 1.6 to get τ from 90% confidence limits.

Atkinson:

Key reasons for the judgments:
As applied up to today (with modifications)

Bernreuter:

Relative Forecasting Uncertainty — Note: My views have changed somewhat as a result of the meeting, hence my estimates are not totally consistent with my original estimates.

Key reasons for the judgments:
Generically: Very crude relative difference.
As applied: I think the Advanced Numerical Model is the best approach for large earthquakes but I have problems with Paul's M_{eq}-M_W and some other factors of his model. Or at least I'm not sure I understand the sensitivities to elements of his model — e.g., source function rupture velocity, step distribution, etc. For 1 Hz m_{Lg}=7 I liked the hybrid approach because it's data-based. However I see a lot of uncertainty in making the corrections.

I'm not sure yet where I stand relative to Gail's model. Right now I'm giving it equal weight with Walt's application. More generally there is considerable difference between them at both 1 and 10Hz. Thus someday I might give significantly different weights between the two. At 10Hz for 1 Hz m_{Lg}=5.5 I downweight the advanced numerical model a bit due to the complexity of putting a few sources over the small rupture area ... I'm not sure I fully understand all of the elements of Paul's model.

Campbell:

Key reasons for the judgments:
[no comments]

Joyner:

Key reasons for the judgments:
I don't have a basis for a quantitative estimate.

Silva: *Key reasons for the judgments*:
re: pga m_{Lg}5.5 20 km: Not in original request and not enough data (comparisons to answer)
re: pga m_{Lg}7.0 20 km: Bias corrected
Sigma from Gail scaled by 1.6 to get τ from 90% confidence limits.

Somerville/Saikia: *Key reasons for the judgments*:
Note: This will vary for varying distance.

CORRELATION AMONG MODEL FORECASTS:

Abrahamson: *If the numbers would change significantly for different cases, please indicate the cases and how the numbers would change* — less correlation for stochastic empirical and stochastic ray for 1 Hz.

Atkinson: *If the numbers would change significantly for different cases, please indicate the cases and how the numbers would change* — [no comments]

Bernreuter: Generically: Maybe the connections are stronger than I think ... then the correlation is stronger. I would defer to Ken's estimate for correlation.

[Stochastic Empirical Attenuation/Stochastic Ray Theory Attenuation] depends upon source model. E.g., if we assume the Stochastic Empirical always includes Gail's model then only ++ but if they are both Burne Models then +++.

Campbell: *If the numbers would change significantly for different cases, please indicate the cases and how the numbers would change* — [no comments]

Joyner: *If the numbers would change significantly for different cases, please indicate the cases and how the numbers would change* — I would expect all of the models to give highly (?) similar results. My choice of 100% as a weighting factor for Stochastic Empirical does not imply that I think the other models are worthless.

Silva: *If the numbers would change significantly for different cases, please indicate the cases and how the numbers would change* — [no comments]

Somerville/Saikia: *If the numbers would change significantly for different cases, please indicate the cases and how the numbers would change* — [no comments]

USING THE APPROACHES FOR FORECASTING:

Abrahamson:

Please summarize any key reasons for the judgments:
Re pga weights, I would have to see the predictions before assigning weights.

Atkinson:

Please summarize any key reasons for the judgments:
I gave the stochastic with empirical inputs half the weight since I think the inputs and results have the best empirical validation, and agree fairly well with independent estimates. I lined up the other 50% based on relative merits and overlaps between them.

Bernreuter:

Please summarize any key reasons for the judgments:
Generically: Depended upon the case — I also used other models e.g., the LLNL composite model. ..... Because of magnitude translation problem I did not tend to give Advanced Numerical Model much weight at m_{Lg}=7.
As applied: Didn't use formal weights. Composite Gail's gave same result. Balanced Silva off Campbell.

Campbell:

Please summarize any key reasons for the judgments:
Note: Experts were not asked to give results based on 20 km for PGA. These values are what I would have given, had I been asked.

See my discussion in my write-up for reasons for assigning weights. I have increased the weight of the Advanced Numerical based on Paul's increase of his M_W for m_{Lg} = 7 to 6.7.

Joyner:

Please summarize any key reasons for the judgments:
My weighting represents my judgment that the first model is clearly superior not that the others are grossly defective. If I were genuinely uncertain as to which was superior and if they gave different results I might depart from 100% weighting.

Silva:

Key reasons for the judgments:
re: pga m_{Lg}5.5 20 km and pga m_{Lg}7.0 20 km: Not in original request; assumed weights apply

Somerville/Saikia:

Key reasons for the judgments:
Note: These weights apply after making the following magnitude adjustments:
m_{Lg}5.5: treat as m_W 5.2
M_{Lg}7.0: treat as M_W 6.7

Stochastic with empirical attenuation: high weight for m_{Lg}5.5 due to source model based on data from region and use of an empirical attenuation function.

Both Stochastic models: low weight for m_{Lg}7.0 due to point source (or adjusted point source) model.

Hybrid empirical — relatively large weight for m_{Lg}7.0 due to constraints from WNA data.

Attachment 3

DETAILED EXPERT INPUTS ON WEIGHTING THE FORECASTS

GROUND MOTION WORKSHOP II

INTEGRATOR SURVEY: EXPERT INPUTS

WEIGHTING THE FORECASTS

Freq.	1
Mag.	5.5
Dist.	20

Exp	SE	SR	HE	AN	TOT
NA	33	25	17	25	100
GA	50	20	10	20	100
DB	34	0	33	33	100
KC	25	25	25	25	100
WJ	100	0	0	0	100
WS	30	50	0	20	100
PS	50	10	10	30	100
Avg	**46**	**19**	**14**	**22**	**100**

Freq.	1
Mag.	7.0
Dist.	20

Exp	SE	SR	HE	AN	TOT
NA	35	18	12	35	100
GA	50	10	10	30	100
DB	x	x	x	x	x
KC	28	28	28	16	100
WJ	100	0	0	0	100
WS	30	50	0	20	100
PS	10	10	30	50	100
Avg	**42**	**19**	**13**	**25**	**100**

Freq.	10
Mag.	5.5
Dist.	20

Exp	SE	SR	HE	AN	TOT
NA	31	23	15	31	100
GA	50	20	10	20	100
DB	25	25	25	25	100
KC	25	25	25	25	100
WJ	100	0	0	0	100
WS	30	50	0	20	100
PS	30	20	20	30	100
Avg	**42**	**23**	**14**	**22**	**100**

Freq.	10
Mag.	7.0
Dist.	20

Exp	SE	SR	HE	AN	TOT
NA	25	25	25	25	100
GA	50	20	10	20	100
DB	x	x	x	x	x
KC	28	28	28	16	100
WJ	100	0	0	0	100
WS	30	50	0	20	100
PS	10	10	30	50	100
Avg	**41**	**22**	**16**	**22**	**100**

Freq.	10
Mag.	5.5
Dist.	20

Exp	SE	SR	HE	AN	TOT
NA	31	23	15	31	100
GA	50	20	10	20	100
DB	25	25	25	25	100
KC	25	25	25	25	100
WJ	100	0	0	0	100
WS	30	50	0	20	100
PS	30	20	20	30	100
Avg	**42**	**23**	**14**	**22**	**100**

Freq.	10
Mag.	7.0
Dist.	20

Exp	SE	SR	HE	AN	TOT
NA	25	25	25	25	100
GA	50	20	10	20	100
DB	x	x	x	x	x
KC	28	28	28	16	100
WJ	100	0	0	0	100
WS	30	50	0	20	100
PS	10	10	30	50	100
Avg	**41**	**22**	**16**	**22**	**100**

*Note: Some experts gave weights to other models. For this table, the weights for the four proponent models were renormalized.

Attachment 4

DETAILED EXPERT INPUTS ON RELATIVE FORECASTING UNCERTAINTY

GROUND MOTION WORKSHOP II

INTEGRATOR SURVEY: EXPERT INPUTS

RELATIVE FORECASTING UNCERTAINTY

Freq. 1, Mag. 5.5, Dist. 20

Exp	SE	SR	HE	AN	AVG
NA	100	100	200	100	125
GA	100	130	150	120	125
DB	100	100	200	125	131
KC	100	120	120	130	118
WJ	x	x	x	x	x
WS	100	125	125	150	125
PS	100	125	125	150	125
Avg	100	117	153	129	125

Freq. 1, Mag. 7.0, Dist. 20

Exp	SE	SR	HE	AN	AVG
NA	100	100	100	100	100
GA	110	120	120	100	113
DB	150	150	100	200	150
KC	100	100	100	140	110
WJ	x	x	x	x	x
WS	125	100	125	150	125
PS	125	100	125	150	125
Avg	118	112	112	140	120

Freq. 10, Mag. 5.5, Dist. 20

Exp	SE	SR	HE	AN	AVG
NA	100	100	200	100	125
GA	100	100	180	100	120
DB	100	100	200	110	128
KC	100	110	110	120	110
WJ	x	x	x	x	x
WS	100	125	125	150	125
PS	100	125	125	150	125
Avg	100	110	157	122	122

Freq. 1, Mag. 5.5, Dist. 5

Exp	SE	SR	HE	AN	AVG
NA	100	100	100	100	100
GA	100	100	120	100	105
DB	100	100	200	200	150
KC	100	100	100	120	105
WJ	x	x	x	x	x
WS	125	100	125	150	125
PS	150	150	120	100	130
Avg	113	108	128	128	119

Freq. 1, Mag. 5.5, Dist. 70

Exp	SE	SR	HE	AN	AVG
NA	x	x	x	x	x
GA	100	110	180	130	130
DB	100	100	200	110	128
KC	100	110	110	120	110
WJ	x	x	x	x	x
WS	x	x	x	x	x
PS	120	140	140	100	125
Avg	105	115	158	115	123

Freq. 1, Mag. 5.5, Dist. 200

Exp	SE	SR	HE	AN	AVG
NA	x	x	x	x	x
GA	100	110	120	110	110
DB	100	100	200	200	150
KC	100	100	100	120	105
WJ	x	x	x	x	x
WS	x	x	x	x	x
PS	150	150	120	100	130
Avg	113	115	135	133	124

ATTACHMENT B-7

EXPERTS 3 (POST-WORKSHOP) RESULTS

FOLLOW UP TO SECOND SSHAC GROUND MOTION WORKSHOP

by

Gabriel R. Toro
Risk Engineering, Inc.

As part of the follow-up and documentation effort following the second ground-motion workshop, we are giving you the opportunity to make first-order revisions to your expert's estimates of ground motion amplitude, epistemic uncertainty, and aleatory uncertainty. We are also seeking additional funding from the project sponsors in order to have you address these issues in more detail and provide predictions over a more dense magnitude-distance grid.

We ask you to consider the following issues, which came up at the Workshop of July 28 and 29.

- Distance. You may ignore the estimates for 5 km. Alternatively, you may provide estimates for 5 km horizontal distance, with due consideration for the effect of focal depth on aleatory uncertainty.

- Aleatory Uncertainty. Recall that your estimates of the aleatory uncertainty are to be applicable to hard-rock conditions. It was mentioned at the Workshop that some estimates of aleatory uncertainty (in particular, EPRI, 1993) contain aleatory uncertainty associated with recordings obtained at sites other than rock sites. If this is the case for your estimates, please make first-order, judgmental corrections to your estimates of aleatory uncertainty so that they represent hard-rock conditions.

- Epistemic Uncertainty. The quantity that we wanted to obtain from the experts is the logarithmic standard deviation that quantifies epistemic uncertainty. One way to think of this quantity, under the assumption of a lognormal distribution, is that the probability of the true median falling outside the [estimated median]$\times\exp[\pm\sigma_{epistemic}]$ range is approximately 30%. Some experts stated that their estimates of epistemic uncertainty in the median represent two logarithmic standard deviations (i.e., the expert estimates that the probability of the true median falling outside the [estimated median]$\times\exp[\pm$uncertainty] range is approximately 5%). Please revise your estimates of epistemic uncertainty, if necessary, so that your estimate represents one logarithmic standard deviation.

  If you think another type of distribution (i.e., triangular) is more appropriate or more intuitive for the representation of epistemic uncertainty, you may use that distribution. If so, please provide adequate information to completely specify the distribution (e.g., provide the 5th and 95th fractiles, as well as the most likely value).

  We also noticed that the epistemic-uncertainty provided by an expert did not include the median estimate of some of the other experts (see the graphs enclosed with these instructions). Please consider this when reviewing your epistemic-uncertainty values. In particular, if one expert's estimate of median amplitude does not fall within your uncertainty range, and you attach some significant credibility to that expert's methods and arguments, you may (or may not) wish to increase your estimates of epistemic uncertainty. If your uncertainty range does not include other experts' median estimates, or is much wider than the scatter among the experts' median estimates, please explain.

The same issues may also apply to your estimates of the uncertainty in the value of the aleatory sigma.

- <u>Data.</u> The issue of what is ENA data was raised during the workshop. Please comment on which ENA data should be used for comparison to your predictions and those of other experts. In particular address issues of: (1) magnitude and distance range to consider, (2) inclusion of vertical data (if so, how to convert to horizontal?), and inclusion of data from soil or soft rock sites (if so, how to convert to hard rock?).

- <u>Documentation</u>: Please describe briefly the rationale for any revisions you make.

Documentation from N. Abrahamson (9/12/94)

Epistemic Uncertainty
I have based my epistemic uncertainties on the range of the medians from the proponent models (excluding Joyner) as well as the empirical data presented in EPRI (1993). One standard deviation is approximated by the range of the proponent medians and empirical data, excluding the largest outlier of the proponent medians. I have excluded the largest outlier because the epistemic uncertainty is a standard deviation and not a bound.

In addition, a minimum value of the epistemic uncertainty is used if the proponent medians all happen to be very similar (lower bound = 0.25). This lower bound is based on the EPRI (1993) epistemic uncertainties rather than the proponent epistemic uncertainties because it is an approximation of the standard error and not a subjective judgment of uncertainty.

With the approach that I have used, there are some cases in which my estimate of the epistemic uncertainty will not cover all of the medians from the different proponents.

Ideally, the epistemic uncertainty should be computed formally using the median and epistemic uncertainty for each proponent model. The expert estimate of the epistemic uncertainty should be the uncertainty of medians of the models, not the uncertainty of a single sample from any of the models. However, we need to account for the correlations between the proponent models.

Data
My comparisons to "data" are based on the EPRI (1993) data set plots. I only considered the horizontal component rock data. I think that the EUS data set is useful for m_{LG} magnitudes 4 to 5.5 and for the distances of 5 to 400 km. The ground motions are not all well constrained over this entire magnitude and distance range, but they do give useful checks against the models.

Since the data set is limited, I think that it is important to check the models using the specific source parameter values (e.g. stress-drop) for the events in the data. The models should not just be checked against the data using comparing the data to the median model predictions for future earthquakes.

I am not in favor of using vertical component data, but since vertical data makes up a large part of the data set, it may be necessary to include it. If verticals are used, the uncertainty of estimating horizontal motion from vertical motion should be included as error bars on the converted data.

The use of data from soil sites can be useful as a guide for some cases, taking into account the expected site effects. For example, at low frequencies, we expect the ground motion on soil to be larger than on rock. If the models significantly overpredict the soil data, then the model will probably overpredict rock data by a larger amount.

Notes:
I assumed an increase in Paul's proponent values for m_{LG}=7.0 to account for his increase of the moment magnitude from 6.4 to 6.7 as discussed at the workshop.

I reduced the aleatory uncertainty to correct for variable site condition. The variable site condition manifests itself in the modeling uncertainty. It may also impact the variability of the stress parameter but I didn't correct for this. I assumed that half of the modeling uncertainty was due to site variability. I then reduced the aleatory standard error appropriately. Since the modeling uncertainty is largest for low frequencies, the largest correction was at 1 Hz.

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Form 2: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.009 ✓	0.15 ✓
	epistemic uncertainty	parametric (ln)	0.30 ✓	0.35 ✓
		median bias	0	0
		uncert. in bias (ln)	0.26	0.30 ✓
	aleatory uncertainty	median σ	0.75 ✓	0.65 ✓
		uncertainty in σ	0.10 ✓	0.15 ✓
70 km	median amplitude		0.0020 ✓	0.038 ✓
	epistemic uncertainty	parametric (ln)	0.30 ✓	0.35
		median bias	0	0
		uncert. in bias (ln)	0.44 ✓	0.54
	aleatory uncertainty	median σ	0.75 ✓	0.65
		uncertainty in σ	0.10	0.15 ✓
200 km	median amplitude		0.00070	0.018 ✓
	epistemic uncertainty	parametric (ln)	0.25 ✓	0.40 ✓
		median bias	0	0 ✓
		uncert. in bias (ln)	0.25 ✓	0.40 ✓
	aleatory uncertainty	median σ	0.75 ✓	0.70 ✓
		uncertainty in σ	0.10 ✓	0.18 ✓

Comments/footnotes:

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Form 2: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.040 ✓	0.36 ✓
	epistemic uncertainty	parametric (ln)	0.25 ✓	0.30 ✓
		median bias	0 ✓	0 ✓
		uncert. in bias (ln)	0.20 ✓	0.25 ✓
	aleatory uncertainty	median σ	0.70 ✓	0.60 ✓
		uncertainty in σ	0.10	0.15 ✓
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Form 3: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.18 ✓	0.80 ✓
	epistemic uncertainty	parametric (ln)	.20 ✓	0.25 ✓
		median bias	0 ✓	0 ✓
		uncert. in bias (ln)	.15 ✓	.16 ✓
	aleatory uncertainty	median σ	0.70 ✓	0.62 ✓
		uncertainty in σ	0.10 ✓	0.15 ✓
70 km	median amplitude		0.030 ✓	0.18 ✓
	epistemic uncertainty	parametric (ln)	0.25 ✓	0.25 ✓
		median bias	0 ✓	0 ✓
		uncert. in bias (ln)	0.16 ✓	0.20 ✓
	aleatory uncertainty	median σ	0.70 ✓	0.62 ✓
		uncertainty in σ	0.10 ✓	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Form 4: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity			m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude				
	epistemic uncertainty	parametric (ln)			
		median bias			
		uncert. in bias (ln)			
	aleatory uncertainty	median σ			
		uncertainty in σ			
20 km	median amplitude			0.20 ✓	1.0 ✓
	epistemic uncertainty	parametric (ln)		0.25 ✓	0.25 ✓
		median bias		0 ✓	0 ✓
		uncert. in bias (ln)		0.15 ✓	0.15 ✓
	aleatory uncertainty	median σ		0.70 ✓	0.57 ✓
		uncertainty in σ		0.10 ✓	0.15 ✓
70 km	median amplitude				
	epistemic uncertainty	parametric (ln)			
		median bias			
		uncert. in bias (ln)			
	aleatory uncertainty	median σ			
		uncertainty in σ			
200 km	median amplitude				
	epistemic uncertainty	parametric (ln)			
		median bias			
		uncert. in bias (ln)			
	aleatory uncertainty	median σ			
		uncertainty in σ			

Comments/footnotes:

Follow-up to SSHAC SECOND GROUND MOTION WORKSHOP

Form 5: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.015 ✓	0.10 ✓
	epistemic uncertainty	parametric (ln)	0.25 ✓	0.20 ✓
		median bias	0 ✓	0 ✓
		uncert. in bias (ln)	0.24 ✓	0.15 ✓
	aleatory uncertainty	median σ	0.75 ✓	0.60 ✓
		uncertainty in σ	0.10 ✓	0.15 ✓
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Expert: Gail Atkinson Aug 20 1994

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.4 ✓
		median bias		
		uncert. in bias (ln)		0.5 ✓
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: These pages show revisions to uncertainty (no entry = no revision).

DATA: Data for comparisons should include all ENA mainshock records on hard-rock, $M \geq 4$. Soil included only if soil response can be reliably estimated. Vert. should be included due to abundance of these data. See Atkinson 1995 for H/V conversion for ENA.

All distances $R \lesssim 1000$ km can be included since atten. is well-determined both empirically + theoretically.

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Form 3: Page 2 of 4

Expert: Gail Atkinson

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.5 ✓
		median bias		
		uncert. in bias (ln)		0.5 ✓
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.4 ✓
		median bias		
		uncert. in bias (ln)		0.4 ✓
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.4 ✓
		median bias		
		uncert. in bias (ln)		0.4 ✓
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Expert: Gail Atkinson

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.4
		median bias		
		uncert. in bias (ln)		0.4
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Follow-up to SSHAC SECOND GROUND MOTION WORKSHOP

Form 5: Page 4 of 4

Expert: Gail Atkinson

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.5 ✓
		median bias		
		uncert. in bias (ln)		0.5 ✓
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.4 ✓
		median bias		
		uncert. in bias (ln)		0.4 ✓
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

EQE

ENGINEERING AND DESIGN

A Division of EQE International

MEMORANDUM

To: Gab Toro
Risk Engineering, Inc.

From: Ken Campbell KWC
EQE International, Inc.

Date: August 27, 1994

Subject: ***Follow-up to Second SSHAC Ground Motion Workshop***

Ideally, I would like to make some changes to both my proponent and expert ground-motion estimates. However, due to my current work load, I am unable to make these changes by your August 31 deadline. I would not, however, expect these anticipated revisions to give significantly different results than those I have already given to you.

The additional effort would account for a revision in my proponent model, a revision in the other proponent models, and a corresponding change in the weights and estimates provided in my expert model. These modifications will have to wait for the additional SSHAC funds, should they be approved.

6555 Olympus Drive ▪ Evergreen, CO 80439 ▪ Telephone/FAX (303) 674-2990

REVISIONS TO GROUND-MOTION ESTIMATES FOR THE NORTHEASTERN U.S. OR SOUTHEASTERN CANADA

W. B. Joyner
August 17, 1994

The ground-motion estimates for 5 km were revised to correspond to 5 km horizontal distance. In my view point-source stochastic models can provide good ground-motion estimates for small horizontal distances if the proper pseudo-depth is used. The pseudo-depth is region-dependent and should scale as the depth distribution of slip in an earthquake. The parameter h of Joyner and Boore (1982) is such a pseudo-depth, and it is largely controlled by data from the 1979 Imperial Valley, California earthquake. For periods of 1 s and longer h has a value about half the depth of the maximum strike-slip offsets in Archuleta's (1984) model of the 1979 earthquake. The small value of pseudo-depth can be explained (Boore and Joyner, 1989) as a consequence of the preferentially greater effect of directivity at sites near the source. For peak acceleration and for response spectra at periods shorter than 0.4 s the values of h are greater, suggesting reduced effects of directivity at shorter periods. The work of Boatwright and Boore (1982), however, has shown that, for some earthquakes at least, there is a large directivity effect at short periods. So, I assume for Eastern North America that the proper pseudo-depth is half the depth of maximum slip. The depth of maximum slip is assumed to be the median hypocentral depth. From the hypocentral data given by EPRI (1993) the pseudo-depth is found to be 7 km with 16 and 84th percentile values of 4 and 13 km. The ground-motion estimates for 5 km horizontal distance were revised using the 7 km pseudo-depth, and the aleatory uncertainty was recomputed to reflect the uncertainty in that parameter. With the 7 km value for pseudo-depth, the estimates previously made for 20, 70, and 200 km correspond to horizontal distances of 18.7, 69.6, and 199.9 km.

I reviewed Gail Atkinson's estimates (as proponent) for aleatory sigma and the uncertainty of aleatory sigma, which I had adopted previously for lack of time to make my own estimates, and agreed with them. I do not have time to make an estimate of epistemic uncertainty.

References

Archuleta, R. J. (1984). A faulting model for the 1979 Imperial Valley earthquake, *J. Geophys. Res.* 89, 4559–4485.

Boatwright, J. and D. M. Boore (1982). Analysis of the ground accelerations radiated by the 1980 Livermore Valley earthquakes for directivity and dynamic source characteristics, *Bull. Seism. Soc. Am.* 72, 1843–1865.

Boore, D. M. and W. B. Joyner (1989). The effect of directivity on the stress parameter determined from ground motion observations, *Bull. Seism. Soc. Am.* 79, 1984–1988.

EPRI (1993).Guidelines for determining design basis ground motions, Volume 1: Method and guidelines for estimating earthquake ground motion in eastern North America, EPRI TR-102293, Electric Power Research Institute.

Joyner, W. B. and D. M. Boore (1982). Prediction of earthquake response spectra, *U.S. Geol. Surv. Open-File Rept. 82-977*, 16 p.

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Expert: W. B. Joyner 8-17-94

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km Horiz.	median amplitude		0.0175 ✓	0.202 ✓
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ	0.9 ✓	0.9 ✓
		uncertainty in σ	0.2 ✓	0.2 ✓
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ	0.8 ✓	0.8 ✓
		uncertainty in σ	0.2 ✓	0.2 ✓
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: m_{Lg} 5.5 ≃ M 5.0

m_{Lg} 7.0 ≃ M 7.0

Aleatory uncertainty based on use of m_{Lg}. If M had been used the Aleatory Uncertainty would have been 0.55 for all frequencies (at distances of 20 km or greater) with a σ of 0.1.

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Form 3: Page 2 **of** 3

Expert: W. B. Joyner 8-17-94

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.392 ✓	.1.62 ✓
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ	0.7 ✓	0.7 ✓
		uncertainty in σ	0.2. ✓	0.2 ✓
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Form 5: Page __ of __

Expert: W. B. Joyner 8-17-94

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.429	1.32
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ	0.9	0.9
		uncertainty in σ	0.2	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Woodward-Clyde

Engineering & sciences applied to the earth & its environment

August 31, 1994

Dr Gabriel Toro
Risk Engineering, Inc.
4155 Darley Ave, Suite 1
Boulder, Co 80303

Dear Gabriel,

The following is our response to your request for follow up to the second SSHAC ground motion workshop.

We have decided to make no changes in the numerical values that we provided at the second day of the second SSHAC workshop. Our responses to the issues that you raised are as follows.

1. Distance. We do not provide estimates for 5 km horizontal distance. Our estimates for 5 km should be ignored.

2. Aleatory Uncertainty. We think that it is important to reevaluate our estimates of aleatory uncertainty to make them applicable to hard rock conditions. Lack of time makes this impractical for now, but we would like to do this as part of further work.

3. Epistemic Uncertainty. Our epistemic uncertainty estimates are for one logarithmic standard deviation. In most cases, our epistemic uncertainty estimates span the median estimates of the three other proponents. In some cases, our epistemic uncertainty estimates do not span the median estimates of other experts. We have not had the opportunity to evaluate the approaches of the other experts in detail, and so for now we have made no adjustments to our epistemic uncertainty estimates, but we are prepared to consider doing so in future work.

4. Data.

Magnitude range: mblg 5.0 and above.

Distance range: 0 to 500 km, with the main focus on 0 to 200 km.

Inclusion of vertical data: The spectral characteristics of vertical data are usually very different from those of horizontal data, and the ratio of vertical to horizontal ground motion amplitudes is also highly variable. We have not used vertical data in deriving our proponents' estimates, and would place low weight on estimates obtained by other proponents and experts using vertical data.

Inclusion of data from soil or soft rock sites: we think that it is possible to adjust these data to hard rock conditions, but have not done so and propose no method here.

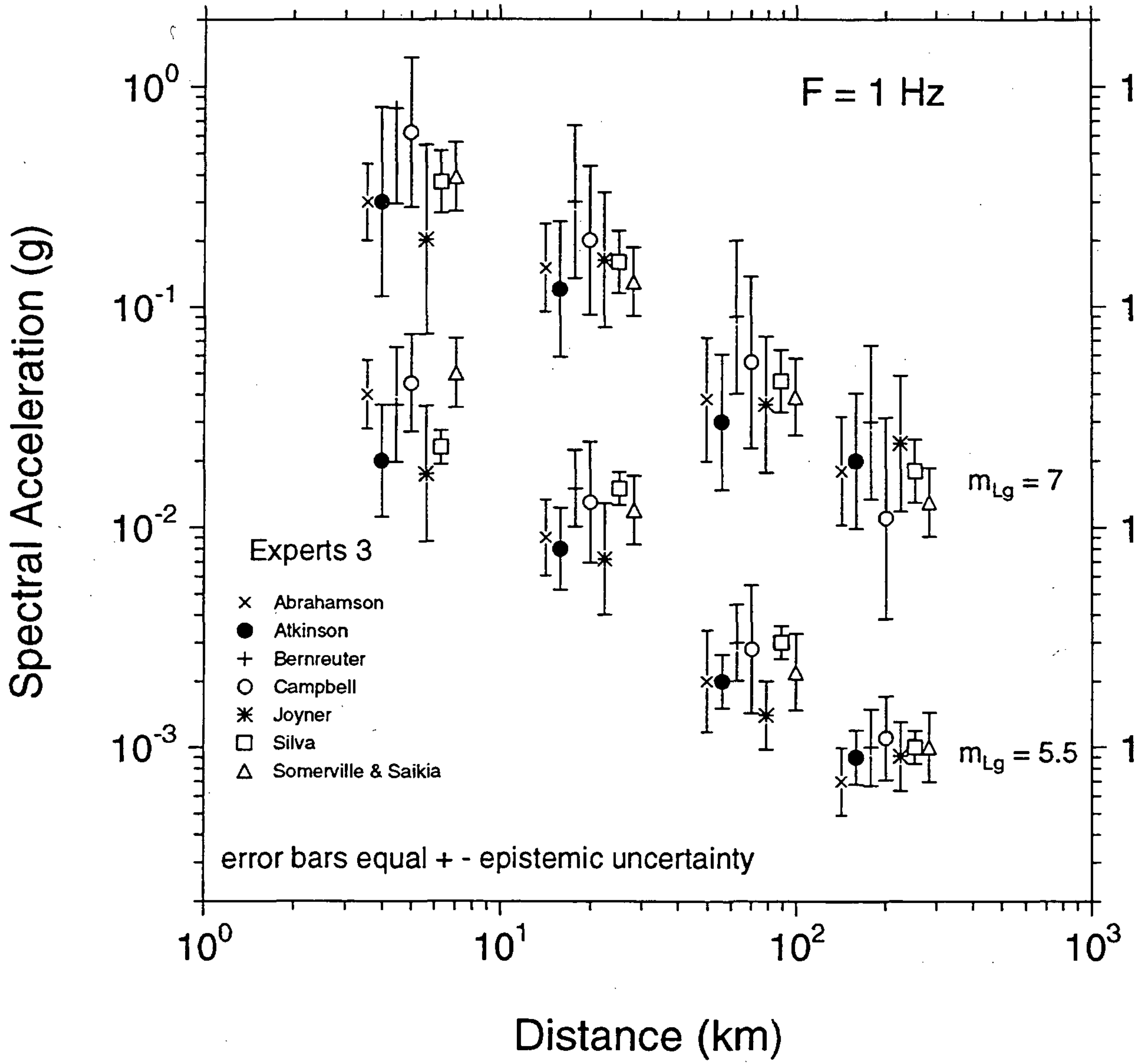
Woodward-Clyde Federal Services • A subsidiary of Woodward-Clyde Group, Inc.
566 El Dorado Street, Suite 100 • Pasadena, California 91101
818-449-7650 • Fax 818-449-3536

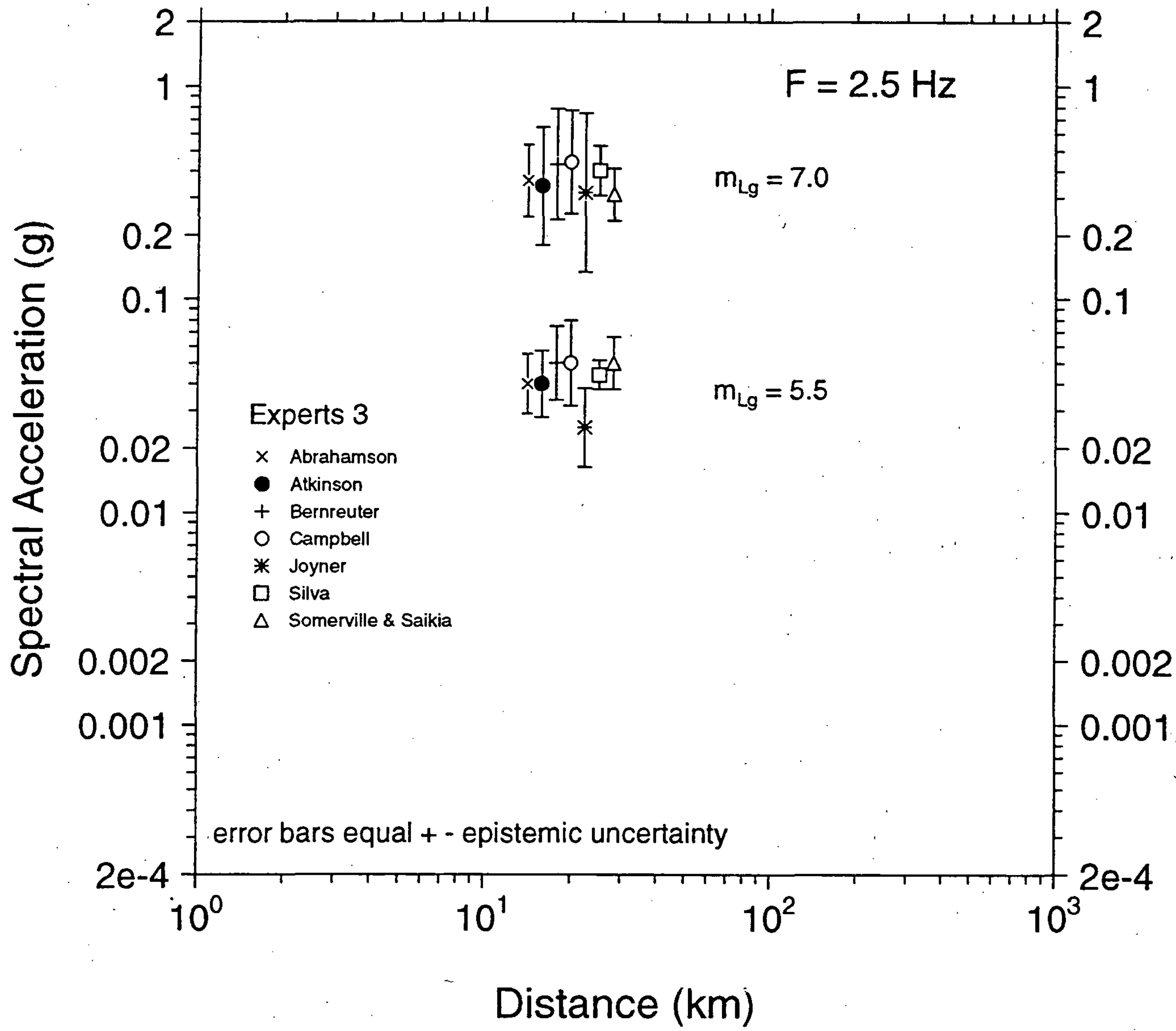
Sincerely,

Paul Somerville

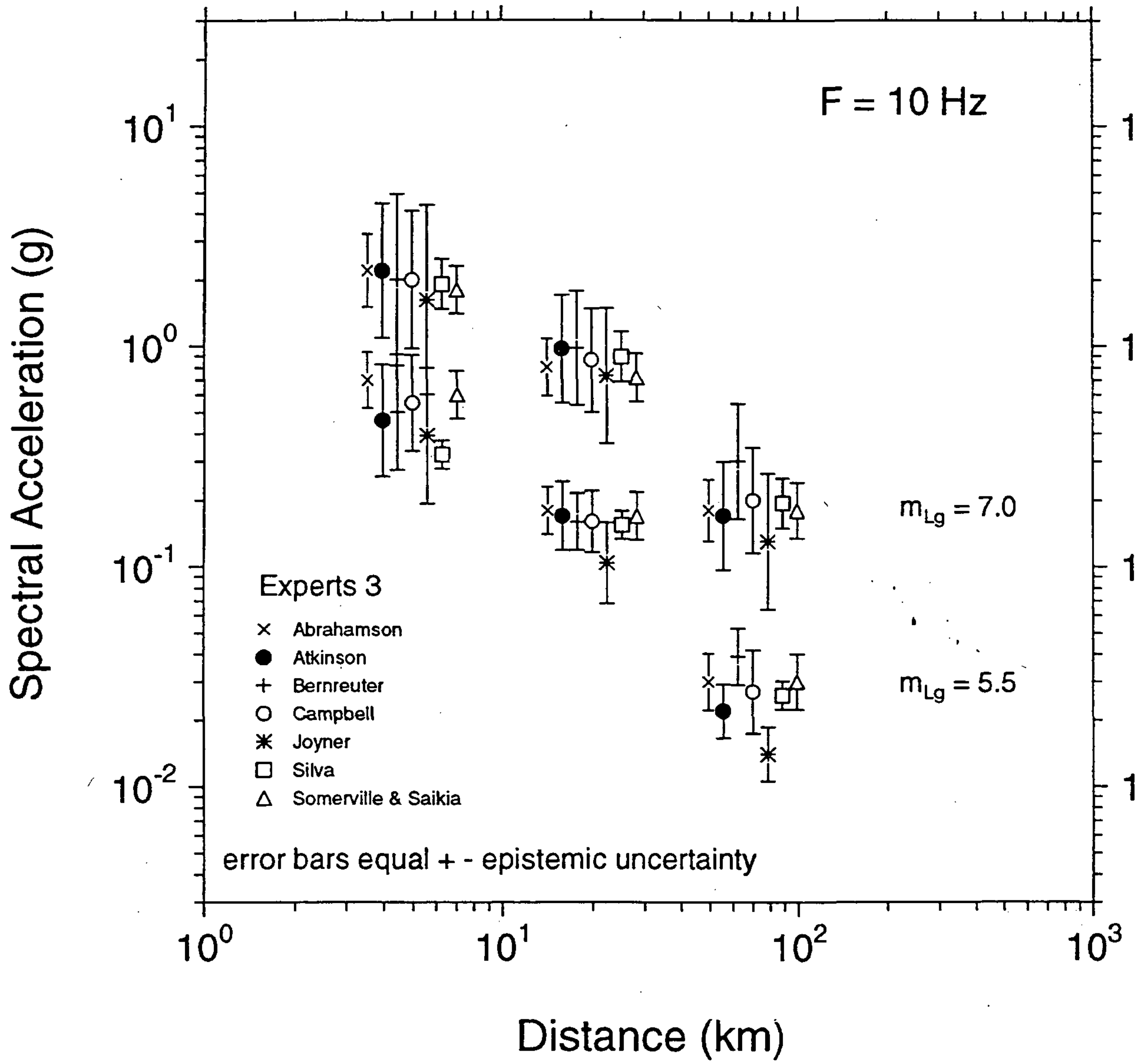
Paul Somerville

Chandan Saikia

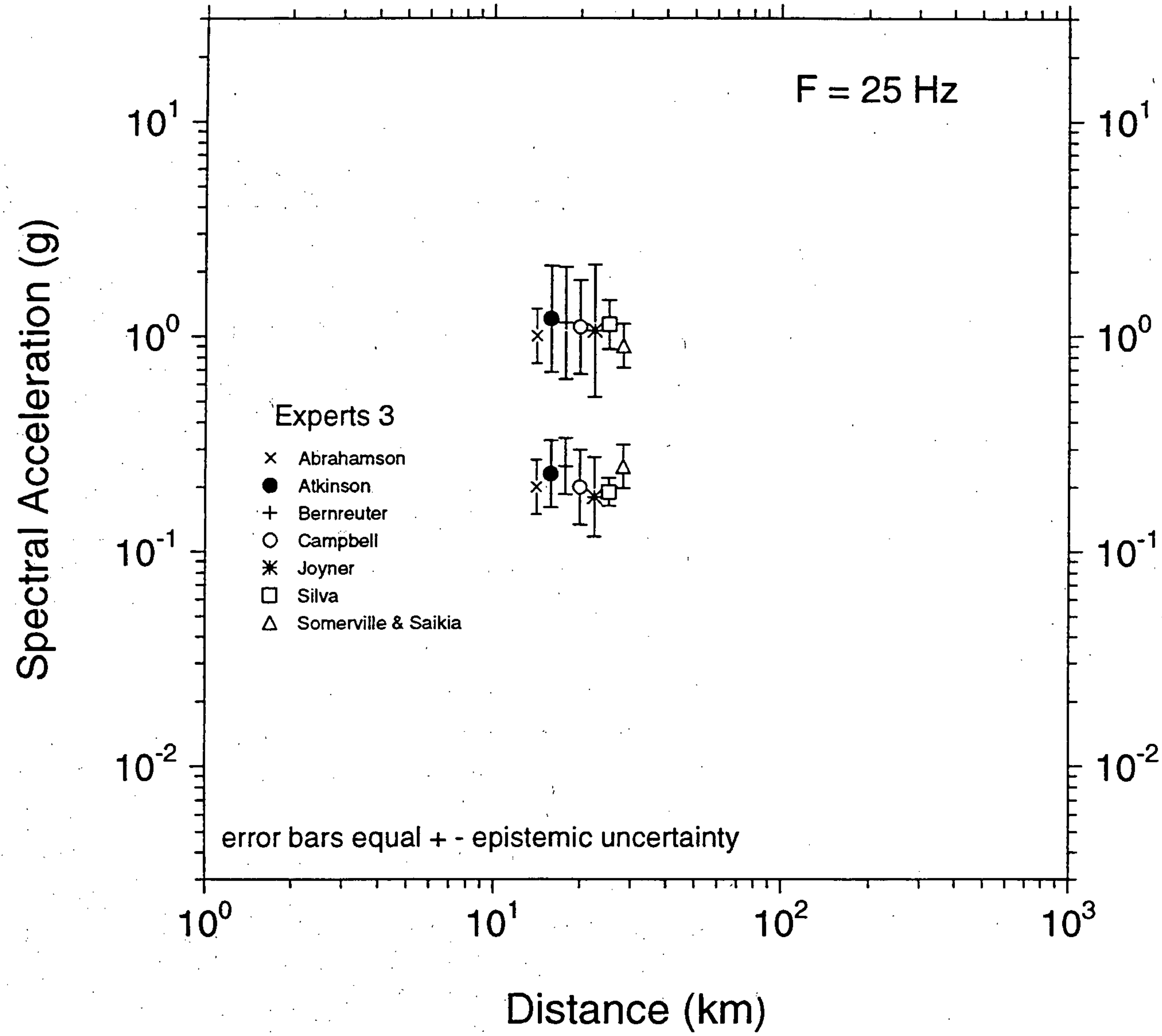

F = 1 Hz
Spectral Acceleration (g)
Distance (km)
10^0
10^{-1}
10^{-2}
10^{-3}
10^0
10^1
10^2
10^3
m_{Lg} = 7
m_{Lg} = 5.5
Experts 3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty

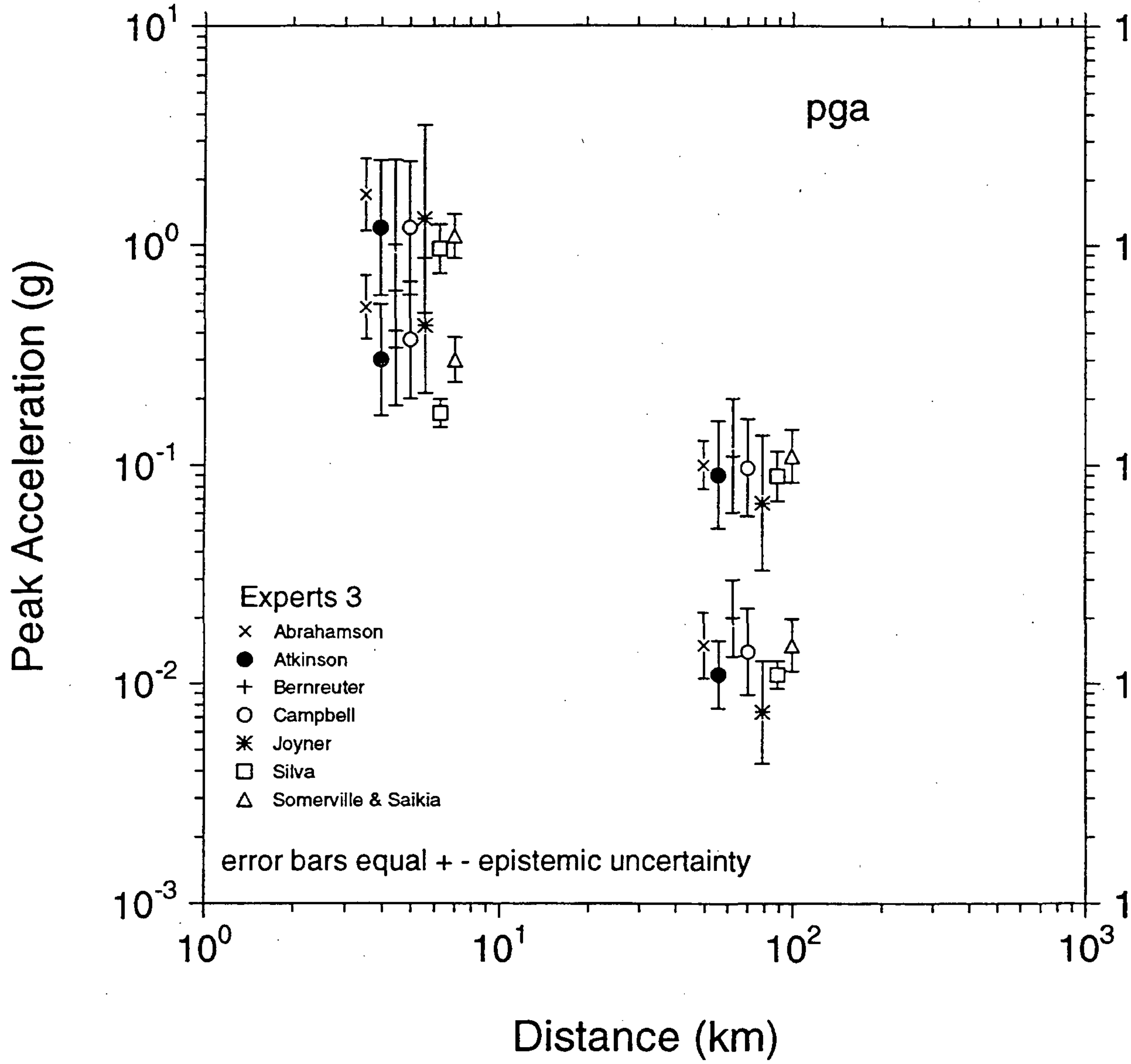


F = 2.5 Hz
m_{Lg} = 7.0
m_{Lg} = 5.5
Experts 3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
Distance (km)
2
1
0.2
0.1
0.02
0.01
0.002
0.001
2e-4
10^0
10^1
10^2
10^3



F = 10 Hz
Spectral Acceleration (g)
10^{1}
10^{0}
10^{-1}
10^{-2}
m_{Lg} = 7.0
m_{Lg} = 5.5
Experts 3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
10^{0}
10^{1}
10^{2}
10^{3}
Distance (km)


F = 25 Hz
Spectral Acceleration (g)
10^{1}
10^{0}
10^{-1}
10^{-2}
Experts 3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
10^{0}
10^{1}
10^{2}
10^{3}
Distance (km)


pga
Peak Acceleration (g)
Distance (km)
Experts 3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty

ATTACHMENT B-8

PREPARATION OF DATA

Attachment 8 - Preparation of Data Set for Comparison with Expert Estimates (by D. Boore)

The source of the data was the EPRI catalog, as described in volume 2 of "Guidelines for Determining Design Basis Ground Motions" (EPRI TR-102293). A subset of data was extracted from the catalog according to the following criteria:

- No aftershocks, whose stress parameters may not be representative of those from mainshocks (e.g., Boore and Atkinson, 1989).
- No recordings from large structures
- Rock recordings (as indicated by "A" in the Cl 3 classification code).
- One subset with m_{bLg} between 4.5 and 6.5, and another with **M** between 4.02 and 6.28 (the reasons for these limits will be discussed shortly).
- Data from vertical and horizontal components of motion extracted separately.

In the course of the work, an error was discovered in the EPRI database response spectral values for the 1990 Mount Laurier, Quebec earthquakes. Upon inquiry, Robert Youngs of Geomatrix Consultants discovered the source of the erroneous values and provided a diskette with the corrected values.

The extracted data are given in Tables 8-1 and 8-2 for the vertical and horizontal components of motion, respectively. After extracting a subset of data, the data were scaled to a fixed magnitude of m_{bLg} 5.5. This was done by using the lookup tables of Atkinson and Boore (1995) to provide the appropriate magnitude scaling (the limits on magnitudes given above were imposed to restrict the magnitude range over which the scaling would be done to plus and minus one unit of m_{bLg} around 5.5). The scaling was done using both magnitude measures if available, and if not available, by using the published magnitude measure. The vertical component data were converted to horizontal component data by multiplying by the frequency-dependent relation given in equation (7) of Atkinson (1993). The scaled data are given in Tables 8-3 and 8-4. For the horizontal component the geometric average of the two horizontal components of motion was used.

Plots of the data using the moment magnitude as the measure of the earthquake size are given in Figures 19 through 29 of Appendix B. The corrected-vertical and horizontal component motions are indicated by different symbols in those figures. There seems to be no systematic difference in the two components of data, giving support to the use of the more numerous vertical-component data. Separation according to the measure of earthquake size, not included here, showed little overall difference.

It should be noted that a disproportionate number of the data come from two well-recorded earthquakes with unusually high stress parameters-- 1988 Saguenay and 1990 Mt. Laurier earthquakes, both having a stress parameter of 517 bars (Atkinson and Boore, 1995). In other words, the dataset may not be representative of the median ground motions expected for the whole population of earthquakes. This must be considered when comparing the ground-motion estimates to the data.

References:

Atkinson, G.M. (1993). Notes on ground motion parameters for eastern North America: duration and H/V ratio, *Bull. Seism. Soc. Am.* **83**, 587--596.

Atkinson, G.M. and D.M. Boore (1995). Ground-motion relations for eastern North America, *Bull. Seism. Soc. Am.* **85**, 17--30.

Boore, D.M. and G.M. Atkinson (1989). Spectral scaling of the 1985 to 1988 Nahanni, Northwest Territories, earthquakes, *Bull. Seism. Soc. Am.* **79**, 1736--1761.

Table 8-1: Vertical component data

Eqid	Eqname	St_no	Desp	Mblg	Mw	Hyp	Epd	Lp	Comp	Amax	F1	F2_5	F10	F25
CG900900	CAPE GIRARDEAU	OLAP	OLD APPLETON, MISSOU	5.00	0.00	47.7	46.2	0.0	VRT	.03414	.00035	.00152	.03130	.16245
FK820100	FRANKLIN FALLS, NH	GNT	ECTN :GNT	4.80	4.35	322.2	322.2	12.0	Z	.00007	.00002	.00009	.00016	.00007
FK820100	FRANKLIN FALLS, NH	LPQ	ECTN :LPQ	4.80	4.35	443.8	443.8	12.0	Z	.00015	.00001	.00008	.00019	.00028
FK820100	FRANKLIN FALLS, NH	MNT	ECTN :MNT	4.80	4.35	272.2	272.1	12.0	Z	.00024	.00001	.00011	.00079	.00029
FK820100	FRANKLIN FALLS, NH	OTT	ECTN :OTT	4.80	4.35	386.6	386.6	12.0	Z	.00015	.00001	.00013	.00042	.00016
FK820100	FRANKLIN FALLS, NH	SBQ	ECTN :SBQ	4.80	4.35	209.4	209.3	12.0	Z	.00033	.00002	.00030	.00075	.00039
FK820100	FRANKLIN FALLS, NH	WBO	ECTN :WBO	4.80	4.35	335.2	335.1	12.0	Z	.00011	.00002	.00011	.00040	.00017
FK820100	FRANKLIN FALLS, NH	2629A	NORTH HARTLAND DAM,	4.80	4.35	62.7	62.6	50.0	VRT	.00382	.00139	.00230	.00745	.01239
FK820100	FRANKLIN FALLS, NH	2630B	NORTH SPRINGFIELD DA	4.80	4.35	76.1	76.0	50.0	VRT	.01392	.00111	.00179	.03526	.03181
GN831000	GOODNOW, NY	CKO	ECTN :CKO	5.60	5.00	339.4	339.4	12.0	Z	.00052	.00015	.00165	.00148	.00056
GN831000	GOODNOW, NY	GNT	ECTN :GNT	5.60	5.00	306.7	306.7	12.0	Z	.00046	.00037	.00105	.00082	.00049
GN831000	GOODNOW, NY	GRQ	ECTN :GRQ	5.60	5.00	322.3	322.3	12.0	Z	.00054	.00014	.00065	.00139	.00062
GN831000	GOODNOW, NY	LPQ	ECTN :LPQ	5.60	5.00	501.3	501.3	12.0	Z	.00024	.00014	.00061	.00047	.00025
GN831000	GOODNOW, NY	MNT	ECTN :MNT	5.60	5.00	180.4	180.4	12.0	Z	.00151	.00040	.00142	.00607	.00212
GN831000	GOODNOW, NY	OTT	ECTN :OTT	5.60	5.00	198.7	198.7	12.0	Z	.00130	.00024	.00166	.00545	.00182
GN831000	GOODNOW, NY	SBQ	ECTN :SBQ	5.60	5.00	243.4	243.4	12.0	Z	.00120	.00045	.00175	.00267	.00132
GN831000	GOODNOW, NY	TRQ	ECTN :TRQ	5.60	5.00	254.6	254.5	12.0	Z	.00135	.00023	.00214	.00393	.00162
GN831000	GOODNOW, NY	WBO	ECTN :WBO	5.60	5.00	143.4	143.4	12.0	Z	.00236	.00017	.00152	.00462	.00352
ML901000	MOUNT-LAURIER QUEBEC	A11	ECTN :A11	5.10	4.70	418.6	418.4	12.0	Z	.00026	.00012	.00064	.00045	.00027
ML901000	MOUNT-LAURIER QUEBEC	A16	ECTN :A16	5.10	4.70	437.4	437.2	12.0	Z	.00028	.00011	.00035	.00061	.00031
ML901000	MOUNT-LAURIER QUEBEC	A21	ECTN :A21	5.10	4.70	466.7	466.5	12.0	Z	.00024	.00008	.00052	.00052	.00026
ML901000	MOUNT-LAURIER QUEBEC	A54	ECTN :A54	5.10	4.70	407.9	407.7	12.0	Z	.00040	.00010	.00081	.00101	.00043
ML901000	MOUNT-LAURIER QUEBEC	A61	ECTN :A61	5.10	4.70	437.5	437.3	12.0	Z	.00015	.00005	.00036	.00036	.00016
ML901000	MOUNT-LAURIER QUEBEC	A64	ECTN :A64	5.10	4.70	456.2	456.0	12.0	Z	.00016	.00007	.00032	.00034	.00017
ML901000	MOUNT-LAURIER QUEBEC	CKO	ECTN :CKO	5.10	4.70	153.6	153.1	12.0	Z	.01101	.00309	.00591	.02254	.01179
ML901000	MOUNT-LAURIER QUEBEC	DPQ	ECTN :DPQ	5.10	4.70	216.7	216.3	12.0	Z	.00206	.00020	.00147	.00541	.00222
ML901000	MOUNT-LAURIER QUEBEC	EEO	ECTN :EEO	5.10	4.70	265.9	265.5	12.0	Z	.00042	.00013	.00034	.00136	.00047
ML901000	MOUNT-LAURIER QUEBEC	GRQ	ECTN :GRQ	5.10	4.70	26.7	23.3	12.0	Z	.09164	.00741	.04047	.23522	.10869
ML901000	MOUNT-LAURIER QUEBEC	MNT	ECTN :MNT	5.10	4.70	189.4	189.0	12.0	Z	.00105	.00009	.00062	.00439	.00113
ML901000	MOUNT-LAURIER QUEBEC	OTT	ECTN :OTT	5.10	4.70	124.4	123.7	12.0	Z	.00140	.00026	.00230	.00493	.00149
ML901000	MOUNT-LAURIER QUEBEC	SBQ	ECTN :SBQ	5.10	4.70	310.0	309.7	12.0	Z	.00044	.00015	.00069	.00113	.00045
ML901000	MOUNT-LAURIER QUEBEC	SUO	ECTN :SUO	5.10	4.70	414.6	414.4	12.0	Z	.00011	.00006	.00011	.00031	.00012
ML901000	MOUNT-LAURIER QUEBEC	SWO	ECTN :SWO	5.10	4.70	413.2	413.0	12.0	Z	.00015	.00008	.00014	.00037	.00016
ML901000	MOUNT-LAURIER QUEBEC	SZO	ECTN :SZO	5.10	4.70	451.8	451.6	12.0	Z	.00011	.00007	.00016	.00041	.00012
ML901000	MOUNT-LAURIER QUEBEC	TRQ	ECTN :TRQ	5.10	4.70	86.6	85.6	12.0	Z	.02936	.00184	.02007	.07323	.03285
ML901000	MOUNT-LAURIER QUEBEC	WBO	ECTN :WBO	5.10	4.70	169.0	168.5	12.0	Z	.01004	.00151	.01182	.02155	.01059
NH851200	NAHANNI, CAN	6097	NW TERR, CANADA: MAC	6.10	6.80	9.7	7.6	50.0	VRT	2.36736	.40354	.63091	5.41788	4.06184
NH851200	NAHANNI, CAN	6099	NW TERR, CANADA: MAC	6.10	6.80	23.4	22.6	50.0	VRT	.18149	.03872	.06846	.26202	.57841
NM760300	NEW MADRID, MO	2415B	WAPPAPELLO DAM, MO,	0.00	4.60	150.5	150.0	25.0	VRT	.00547	.00091	.00172	.01548	.01382
NM910501	NEW MADRID, MO	OLAP	OLD APPLETON, MISSOU	4.60	4.25	114.2	114.0	0.0	VRT	.00880	.00025	.00086	.00843	.02368
NM890400	NEW MADRID, MO	OLAP	OLD APPLETON, MISSOU	4.70	4.70	174.2	173.9	0.0	VRT	.00347	.00023	.00039	.00543	.00909
SG881101	SAGUENAY, CAN	DCKY	DICKEY, MAINE	6.50	5.80	197.0	194.8	50.0	VRT	.03297	.01623	.08274	.06292	.03412
SG881101	SAGUENAY, CAN	EMME	EAST MACHIAS, MAINE	6.50	5.80	472.3	471.4	50.0	VRT	.00178	.00207	.00325	.00280	.00191
SG881101	SAGUENAY, CAN	GGN	ECTN :GGN	6.50	5.80	471.9	471.0	12.0	Z	.00197	.00301	.00389	.00255	.00200
SG881101	SAGUENAY, CAN	GRQ	ECTN :GRQ	6.50	5.80	391.2	390.2	12.0	Z	.00299	.00147	.00534	.00594	.00328
SG881101	SAGUENAY, CAN	GSQ	ECTN :GSQ	6.50	5.80	313.5	312.2	12.0	Z	.00326	.00267	.01492	.00570	.00349
SG881101	SAGUENAY, CAN	KLN	ECTN :KLN	6.50	5.80	389.3	388.2	12.0	Z	.00161	.00162	.00391	.00354	.00164
SG881101	SAGUENAY, CAN	SBQ	ECTN :SBQ	6.50	5.80	311.1	309.8	12.0	Z	.00546	.00472	.00826	.01179	.00615
SG881101	SAGUENAY, CAN	TRQ	ECTN :TRQ	6.50	5.80	332.6	331.3	12.0	Z	.00438	.00266	.00654	.00957	.00498
SG881101	SAGUENAY, CAN	WBO	ECTN :WBO	6.50	5.80	468.2	467.3	12.0	Z	.00283	.00118	.01184	.00562	.00291
SG881101	SAGUENAY, CAN	GSC10	GSC SITE 10 - RIVIER	6.50	5.80	118.1	114.5	50.0	VRT	.02329	.00930	.04130	.05314	.04261
SG881101	SAGUENAY, CAN	GSC14	GSC SITE 14 - Ste-LU	6.50	5.80	101.3	97.1	50.0	VRT	.02101	.01081	.03047	.03555	.03104
SG881101	SAGUENAY, CAN	GSC17	GSC SITE 17 - St-AND	6.50	5.80	70.4	64.1	50.0	VRT	.04522	.00278	.01632	.13527	.11008
SG881101	SAGUENAY, CAN	GSC20	GSC SITE 20 - LES EB	6.50	5.80	95.0	90.4	50.0	VRT	.23434	.01378	.15177	.25816	1.00455
SG881101	SAGUENAY, CAN	GSC5	GSC SITE 5 - TADOUSS	6.50	5.80	113.1	109.3	50.0	VRT	.05328	.01149	.03384	.09346	.11867
SG881101	SAGUENAY, CAN	GSC8	GSC SITE 8 - LA MALB	6.50	5.80	97.5	93.1	50.0	VRT	.06780	.00832	.04335	.15015	.08215
SG881101	SAGUENAY, CAN	GSC9	GSC SITE 9 - St-PASC	6.50	5.80	132.5	129.3	50.0	VRT	.03661	.00965	.07354	.05084	.03750
SG881101	SAGUENAY, CAN	ISFL	ISLAND FALLS, MAINE	6.50	5.80	325.8	324.5	50.0	VRT	.00401	.00253	.00710	.00576	.00490
SG881101	SAGUENAY, CAN	MIME	MILO, MAINE	6.50	5.80	360.8	359.6	50.0	VRT	.00121	.00036	.00092	.00145	.00123
SG881100	SAGUENAY, CAN (F1)	DCKY	DICKEY, MAINE	4.80	4.50	198.6	196.6	50.0	VRT	.00071	.00021	.00081	.00193	.00162
SG881100	SAGUENAY, CAN (F1)	A11	ECTN :A11	4.80	4.50	127.3	124.0	12.0	Z	.00057	.00008	.00035	.00147	.00068

SG881100	SAGUENAY, CAN (F1)	A16	ECTN :A16	4.80	4.50	118.8	115.2	12.0	Z	.00054	.00006	.00013	.00195	.00076
SG881100	SAGUENAY, CAN (F1)	A21	ECTN :A21	4.80	4.50	125.6	122.2	12.0	Z	.00066	.00009	.00018	.00223	.00086
SG881100	SAGUENAY, CAN (F1)	A61	ECTN :A61	4.80	4.50	100.3	96.1	12.0	Z	.00088	.00011	.00030	.00271	.00108
SG881100	SAGUENAY, CAN (F1)	A64	ECTN :A64	4.80	4.50	107.0	103.0	12.0	Z	.00052	.00005	.00028	.00231	.00065
SG881100	SAGUENAY, CAN (F1)	DPQ	ECTN :DPQ	4.80	4.50	202.3	200.2	12.0	Z	.00109	.00006	.00055	.00253	.00123
SG881100	SAGUENAY, CAN (F1)	EBN	ECTN :EBN	4.80	4.50	232.1	230.3	12.0	Z	.00013	.00005	.00011	.00039	.00014
SG881100	SAGUENAY, CAN (F1)	GGN	ECTN :GGN	4.80	4.50	473.8	472.9	12.0	Z	.00003	.00003	.00004	.00006	.00003
SG881100	SAGUENAY, CAN (F1)	GRQ	ECTN :GRQ	4.80	4.50	390.3	389.2	12.0	Z	.00031	.00004	.00036	.00049	.00032
SG881100	SAGUENAY, CAN (F1)	GSQ	ECTN :GSQ	4.80	4.50	314.6	313.2	12.0	Z	.00006	.00005	.00012	.00014	.00007
SG881100	SAGUENAY, CAN (F1)	HTQ	ECTN :HTQ	4.80	4.50	239.3	237.5	12.0	Z	.00020	.00002	.00008	.00052	.00022
SG881100	SAGUENAY, CAN (F1)	KLN	ECTN :KLN	4.80	4.50	391.1	390.0	12.0	Z	.00003	.00002	.00004	.00012	.00004
SG881100	SAGUENAY, CAN (F1)	LPQ	ECTN :LPQ	4.80	4.50	128.3	125.0	12.0	Z	.00066	.00011	.00032	.00238	.00076
SG881100	SAGUENAY, CAN (F1)	MNT	ECTN :MNT	4.80	4.50	346.6	345.4	12.0	Z	.00019	.00003	.00015	.00049	.00020
SG881100	SAGUENAY, CAN (F1)	OTT	ECTN :OTT	4.80	4.50	460.4	459.5	12.0	Z	.00012	.00004	.00026	.00027	.00013
SG881100	SAGUENAY, CAN (F1)	SBQ	ECTN :SBQ	4.80	4.50	311.9	310.6	12.0	Z	.00017	.00011	.00024	.00063	.00019
SG881100	SAGUENAY, CAN (F1)	TRQ	ECTN :TRQ	4.80	4.50	332.1	330.8	12.0	Z	.00032	.00004	.00043	.00074	.00034
SG881100	SAGUENAY, CAN (F1)	WBO	ECTN :WBO	4.80	4.50	468.0	467.1	12.0	Z	.00009	.00003	.00016	.00021	.00009

Table 8-2: Horizontal component data

Eqid	Eqname	St_no	Desp	Mblg	Mw	Hyp	Epd	Lp	Comp	Amax	F1	F2_5	F10	F25
CG900900	CAPE GIRARDEAU	OLAP	OLD APPLETON, MISSOU	5.00	0.00	47.7	46.2	0.0	070	.01899	.00031	.00110	.03366	.05143
CG900900	CAPE GIRARDEAU	OLAP	OLD APPLETON, MISSOU	5.00	0.00	47.7	46.2	0.0	340	.02071	.00038	.00286	.02959	.05788
FK820100	FRANKLIN FALLS, NH	2629A	NORTH HARTLAND DAM,	4.80	4.35	62.7	62.6	50.0	015	.00721	.00117	.00160	.01004	.02240
FK820100	FRANKLIN FALLS, NH	2629A	NORTH HARTLAND DAM,	4.80	4.35	62.7	62.6	50.0	285	.00697	.00087	.00262	.01151	.02284
FK820100	FRANKLIN FALLS, NH	2630B	NORTH SPRINGFIELD DA	4.80	4.35	76.1	76.0	50.0	185	.02303	.00129	.00211	.03414	.10585
FK820100	FRANKLIN FALLS, NH	2630B	NORTH SPRINGFIELD DA	4.80	4.35	76.1	76.0	50.0	275	.02425	.00147	.00262	.05524	.08131
ML901000	MOUNT-LAURIER QUEBEC	A11	ECTN :A11	5.10	4.70	418.6	418.4	12.0	E	.00025	.00012	.00057	.00063	.00026
ML901000	MOUNT-LAURIER QUEBEC	A11	ECTN :A11	5.10	4.70	418.6	418.4	12.0	N	.00018	.00016	.00053	.00037	.00018
ML901000	MOUNT-LAURIER QUEBEC	A16	ECTN :A16	5.10	4.70	437.4	437.2	12.0	E	.00024	.00009	.00042	.00052	.00026
ML901000	MOUNT-LAURIER QUEBEC	A16	ECTN :A16	5.10	4.70	437.4	437.2	12.0	N	.00022	.00010	.00041	.00045	.00023
ML901000	MOUNT-LAURIER QUEBEC	A21	ECTN :A21	5.10	4.70	466.7	466.5	12.0	E	.00040	.00010	.00076	.00079	.00044
ML901000	MOUNT-LAURIER QUEBEC	A21	ECTN :A21	5.10	4.70	466.7	466.5	12.0	N	.00522	.00087	.00382	.00926	.00631
ML901000	MOUNT-LAURIER QUEBEC	A54	ECTN :A54	5.10	4.70	407.9	407.7	12.0	E	.00029	.00006	.00065	.00091	.00033
ML901000	MOUNT-LAURIER QUEBEC	A54	ECTN :A54	5.10	4.70	407.9	407.7	12.0	N	.00065	.00011	.00099	.00102	.00072
ML901000	MOUNT-LAURIER QUEBEC	A61	ECTN :A61	5.10	4.70	437.5	437.3	12.0	E	.00029	.00006	.00047	.00072	.00032
ML901000	MOUNT-LAURIER QUEBEC	A61	ECTN :A61	5.10	4.70	437.5	437.3	12.0	N	.00033	.00014	.00050	.00070	.00035
ML901000	MOUNT-LAURIER QUEBEC	A64	ECTN :A64	5.10	4.70	456.2	456.0	12.0	E	.00023	.00005	.00034	.00056	.00025
ML901000	MOUNT-LAURIER QUEBEC	A64	ECTN :A64	5.10	4.70	456.2	456.0	12.0	N	.00024	.00008	.00054	.00051	.00026
NH851200	NAHANNI, CAN	6097	NW TERR, CANADA: MAC	6.10	6.80	9.7	7.6	50.0	010	1.10133	.43843	.85652	2.49706	2.08663
NH851200	NAHANNI, CAN	6097	NW TERR, CANADA: MAC	6.10	6.80	9.7	7.6	50.0	280	1.34463	.48920	.91542	2.79211	1.39409
NH851200	NAHANNI, CAN	6098	NW TERR, CANADA: MAC	6.10	6.80	9.5	7.4	50.0	240	.54479	.13446	.46777	.65824	1.16859
NH851200	NAHANNI, CAN	6098	NW TERR, CANADA: MAC	6.10	6.80	9.5	7.4	50.0	330	.38978	.28621	.44325	.56768	.68850
NH851200	NAHANNI, CAN	6099	NW TERR, CANADA: MAC	6.10	6.80	23.4	22.6	50.0	270	.18594	.03533	.08840	.29055	.47826
NH851200	NAHANNI, CAN	6099	NW TERR, CANADA: MAC	6.10	6.80	23.4	22.6	50.0	360	.19388	.02325	.05916	.32180	.58918
NH851100	NAHANNI, CAN (F1)	6098	NW TERR, CANADA: MAC	0.00	4.60	18.8	5.5	50.0	240	.45969	.01437	.07207	.48599	.50537
NH851100	NAHANNI, CAN (F1)	6098	NW TERR, CANADA: MAC	0.00	4.60	18.8	5.5	50.0	330	.38152	.01200	.06345	.43404	.47502
NM760300	NEW MADRID, MO	2415B	WAPPAPELLO DAM, MO,	0.00	4.60	150.5	150.0	25.0	128	.01193	.00075	.00241	.01510	.02681
NM760300	NEW MADRID, MO	2415B	WAPPAPELLO DAM, MO,	0.00	4.60	150.5	150.0	25.0	218	.01016	.00042	.00223	.02227	.02000
NM910501	NEW MADRID, MO	OLAP	OLD APPLETON, MISSOU	4.60	4.25	114.2	114.0	0.0	070	.00698	.00029	.00088	.01550	.01596
NM910501	NEW MADRID, MO	OLAP	OLD APPLETON, MISSOU	4.60	4.25	114.2	114.0	0.0	340	.00796	.00043	.00217	.01569	.01693
NM890400	NEW MADRID, MO	OLAP	OLD APPLETON, MISSOU	4.70	4.70	174.2	173.9	0.0	N34	.00278	.00025	.00048	.00594	.00591
NM890400	NEW MADRID, MO	OLAP	OLD APPLETON, MISSOU	4.70	4.70	174.2	173.9	0.0	N70	.00370	.00024	.00044	.00749	.00676
SG881101	SAGUENAY, CAN	DCKY	DICKEY, MAINE	6.50	5.80	197.0	194.8	50.0	N00	.06311	.01633	.08517	.10481	.06511
SG881101	SAGUENAY, CAN	DCKY	DICKEY, MAINE	6.50	5.80	197.0	194.8	50.0	N90	.09152	.02281	.05264	.15159	.09611
SG881101	SAGUENAY, CAN	EMME	EAST MACHIAS, MAINE	6.50	5.80	472.3	471.4	50.0	N33	.00130	.00142	.00252	.00326	.00247
SG881101	SAGUENAY, CAN	EMME	EAST MACHIAS, MAINE	6.50	5.80	472.3	471.4	50.0	N65	.00215	.00275	.00527	.00387	.00282
SG881101	SAGUENAY, CAN	GSC10	GSC SITE 10 - RIVIER	6.50	5.80	118.1	114.5	50.0	000	.04036	.02536	.05401	.10973	.04894
SG881101	SAGUENAY, CAN	GSC10	GSC SITE 10 - RIVIER	6.50	5.80	118.1	114.5	50.0	270	.05700	.02685	.11554	.16052	.06334
SG881101	SAGUENAY, CAN	GSC14	GSC SITE 14 - Ste-LU	6.50	5.80	101.3	97.1	50.0	000	.01384	.00341	.02041	.03198	.02125
SG881101	SAGUENAY, CAN	GSC14	GSC SITE 14 - Ste-LU	6.50	5.80	101.3	97.1	50.0	270	.02328	.00892	.02865	.02867	.02895
SG881101	SAGUENAY, CAN	GSC17	GSC SITE 17 - St-AND	6.50	5.80	70.4	64.1	50.0	000	.15588	.00438	.05348	.15482	.40242
SG881101	SAGUENAY, CAN	GSC17	GSC SITE 17 - St-AND	6.50	5.80	70.4	64.1	50.0	270	.09109	.00411	.02035	.19066	.28120
SG881101	SAGUENAY, CAN	GSC20	GSC SITE 20 - LES EB	6.50	5.80	95.0	90.4	50.0	000	.12545	.01934	.13470	.24654	.20106
SG881101	SAGUENAY, CAN	GSC20	GSC SITE 20 - LES EB	6.50	5.80	95.0	90.4	50.0	270	.10221	.01713	.08726	.19654	.28079
SG881101	SAGUENAY, CAN	GSC5	GSC SITE 5 - TADOUSS	6.50	5.80	113.1	109.3	50.0	007	.00218	.00119	.00145	.00189	.00234
SG881101	SAGUENAY, CAN	GSC5	GSC SITE 5 - TADOUSS	6.50	5.80	113.1	109.3	50.0	097	.02688	.00363	.02400	.06254	.06587
SG881101	SAGUENAY, CAN	GSC8	GSC SITE 8 - LA MALB	6.50	5.80	97.5	93.1	50.0	063	.12418	.03373	.13460	.24726	.15213
SG881101	SAGUENAY, CAN	GSC8	GSC SITE 8 - LA MALB	6.50	5.80	97.5	93.1	50.0	333	.05987	.01207	.04451	.10266	.10569
SG881101	SAGUENAY, CAN	GSC9	GSC SITE 9 - St-PASC	6.50	5.80	132.5	129.3	50.0	000	.04634	.02724	.05870	.08269	.06788
SG881101	SAGUENAY, CAN	GSC9	GSC SITE 9 - St-PASC	6.50	5.80	132.5	129.3	50.0	270	.05576	.01719	.07223	.14121	.07114
SG881101	SAGUENAY, CAN	ISFL	ISLAND FALLS, MAINE	6.50	5.80	325.8	324.5	50.0	N17	.00538	.00552	.01202	.00731	.00678
SG881101	SAGUENAY, CAN	ISFL	ISLAND FALLS, MAINE	6.50	5.80	325.8	324.5	50.0	N26	.00551	.00375	.01128	.00855	.01071
SG881101	SAGUENAY, CAN	MIME	MILO, MAINE	6.50	5.80	360.8	359.6	50.0	N32	.00117	.00039	.00107	.00154	.00155
SG881101	SAGUENAY, CAN	MIME	MILO, MAINE	6.50	5.80	360.8	359.6	50.0	N56	.00118	.00047	.00096	.00169	.00174
SG881100	SAGUENAY, CAN (F1)	DCKY	DICKEY, MAINE	4.80	4.50	198.6	196.6	50.0	000	.00109	.00018	.00073	.00256	.00170
SG881100	SAGUENAY, CAN (F1)	DCKY	DICKEY, MAINE	4.80	4.50	198.6	196.6	50.0	090	.00116	.00019	.00091	.00391	.00195
SG881100	SAGUENAY, CAN (F1)	A11	ECTN :A11	4.80	4.50	127.3	124.0	12.0	E	.00058	.00005	.00062	.00153	.00069
SG881100	SAGUENAY, CAN (F1)	A11	ECTN :A11	4.80	4.50	127.3	124.0	12.0	N	.00060	.00018	.00076	.00219	.00068
SG881100	SAGUENAY, CAN (F1)	A16	ECTN :A16	4.80	4.50	118.8	115.2	12.0	E	.00086	.00005	.00027	.00296	.00106
SG881100	SAGUENAY, CAN (F1)	A16	ECTN :A16	4.80	4.50	118.8	115.2	12.0	N	.00070	.00007	.00037	.00222	.00084
SG881100	SAGUENAY, CAN (F1)	A21	ECTN :A21	4.80	4.50	125.6	122.2	12.0	E	.00113	.00010	.00043	.00428	.00134

SG881100	SAGUENAY, CAN (F1)	A21	ECTN :A21	4.80	4.50	125.6	122.2	12.0	N	.00162	.00006	.00044	.00499	.00181
SG881100	SAGUENAY, CAN (F1)	A61	ECTN :A61	4.80	4.50	100.3	96.1	12.0	E	.00172	.00010	.00045	.00441	.00221
SG881100	SAGUENAY, CAN (F1)	A61	ECTN :A61	4.80	4.50	100.3	96.1	12.0	N	.00159	.00010	.00031	.00401	.00203
SG881100	SAGUENAY, CAN (F1)	A64	ECTN :A64	4.80	4.50	107.0	103.0	12.0	E	.00069	.00009	.00018	.00282	.00090
SG881100	SAGUENAY, CAN (F1)	A64	ECTN :A64	4.80	4.50	107.0	103.0	12.0	N	.00121	.00006	.00021	.00353	.00149

Table 8-3: Scaled vertical component data

eqid	staid	Lp	hypd	epd	mbLg	pgambLg	f1mbLg	f2p5mLg	f10mbLg	f25mbLg	mw	pgamw	f1mw	f2p5mw	f10mw	f25mw
CG900900	OLAP	0.0	47.7	46.2	5.00	0.06142	0.00107	0.00436	0.08228	0.47927	0.00	0.00000	0.00000	0.00000	0.00000	0.00000
FK820100	GNT	12.0	322.2	322.2	4.80	0.00018	0.00011	0.00037	0.00060	0.00000	4.35	0.00017	0.00010	0.00035	0.00057	0.00000
FK820100	LPQ	12.0	443.8	443.8	4.80	0.00042	0.00006	0.00034	0.00070	0.00000	4.35	0.00039	0.00005	0.00032	0.00067	0.00000
FK820100	MNT	12.0	272.2	272.1	4.80	0.00062	0.00005	0.00046	0.00288	0.00000	4.35	0.00059	0.00005	0.00043	0.00273	0.00000
FK820100	OTT	12.0	386.6	386.6	4.80	0.00041	0.00006	0.00055	0.00156	0.00000	4.35	0.00039	0.00005	0.00051	0.00149	0.00000
FK820100	SBQ	12.0	209.4	209.3	4.80	0.00083	0.00011	0.00128	0.00271	0.00000	4.35	0.00079	0.00010	0.00119	0.00258	0.00000
FK820100	WBO	12.0	335.2	335.1	4.80	0.00029	0.00011	0.00046	0.00149	0.00000	4.35	0.00027	0.00010	0.00043	0.00141	0.00000
FK820100	2629A	50.0	62.7	62.6	4.80	0.00869	0.00667	0.00931	0.02601	0.04572	4.35	0.00833	0.00612	0.00877	0.02483	0.04351
FK820100	2630B	50.0	76.1	76.0	4.80	0.03209	0.00555	0.00746	0.12630	0.11361	4.35	0.03066	0.00507	0.00699	0.11976	0.10839
GN831000	CKO	12.0	339.4	339.4	5.60	0.00043	0.00013	0.00162	0.00182	0.00000	5.00	0.00052	0.00017	0.00207	0.00218	0.00000
GN831000	GNT	12.0	306.7	306.7	5.60	0.00038	0.00032	0.00103	0.00101	0.00000	5.00	0.00046	0.00042	0.00132	0.00121	0.00000
GN831000	GRQ	12.0	322.3	322.3	5.60	0.00045	0.00012	0.00064	0.00171	0.00000	5.00	0.00054	0.00016	0.00082	0.00205	0.00000
GN831000	LPQ	12.0	501.3	501.3	5.60	0.00019	0.00012	0.00061	0.00057	0.00000	5.00	0.00024	0.00016	0.00077	0.00069	0.00000
GN831000	MNT	12.0	180.4	180.4	5.60	0.00128	0.00034	0.00143	0.00754	0.00000	5.00	0.00151	0.00045	0.00178	0.00896	0.00000
GN831000	OTT	12.0	198.7	198.7	5.60	0.00111	0.00021	0.00168	0.00679	0.00000	5.00	0.00130	0.00027	0.00208	0.00804	0.00000
GN831000	SBQ	12.0	243.4	243.4	5.60	0.00099	0.00039	0.00176	0.00331	0.00000	5.00	0.00120	0.00051	0.00220	0.00394	0.00000
GN831000	TRQ	12.0	254.6	254.5	5.60	0.00110	0.00020	0.00214	0.00486	0.00000	5.00	0.00135	0.00026	0.00268	0.00580	0.00000
GN831000	WBO	12.0	143.4	143.4	5.60	0.00198	0.00015	0.00153	0.00572	0.00000	5.00	0.00236	0.00019	0.00191	0.00682	0.00000
ML901000	A11	12.0	418.6	418.4	5.10	0.00046	0.00032	0.00156	0.00111	0.00000	4.70	0.00040	0.00026	0.00133	0.00098	0.00000
ML901000	A16	12.0	437.4	437.2	5.10	0.00050	0.00029	0.00086	0.00150	0.00000	4.70	0.00043	0.00024	0.00073	0.00133	0.00000
ML901000	A21	12.0	466.7	466.5	5.10	0.00043	0.00021	0.00128	0.00128	0.00000	4.70	0.00037	0.00017	0.00110	0.00114	0.00000
ML901000	A54	12.0	407.9	407.7	5.10	0.00070	0.00027	0.00197	0.00249	0.00000	4.70	0.00062	0.00022	0.00167	0.00219	0.00000
ML901000	A61	12.0	437.5	437.3	5.10	0.00027	0.00013	0.00088	0.00089	0.00000	4.70	0.00023	0.00011	0.00075	0.00078	0.00000
ML901000	A64	12.0	456.2	456.0	5.10	0.00028	0.00019	0.00079	0.00084	0.00000	4.70	0.00025	0.00015	0.00067	0.00074	0.00000
ML901000	CKO	12.0	153.6	153.1	5.10	0.01814	0.00787	0.01458	0.05593	0.00000	4.70	0.01611	0.00642	0.01245	0.05022	0.00000
ML901000	DPQ	12.0	216.7	216.3	5.10	0.00346	0.00052	0.00356	0.01321	0.00000	4.70	0.00305	0.00042	0.00304	0.01183	0.00000
ML901000	EEO	12.0	265.9	265.5	5.10	0.00071	0.00033	0.00080	0.00333	0.00000	4.70	0.00062	0.00028	0.00067	0.00298	0.00000
ML901000	GRQ	12.0	26.7	23.3	5.10	0.14220	0.01818	0.09500	0.54413	0.00000	4.70	0.12845	0.01491	0.08041	0.47931	0.00000
ML901000	MNT	12.0	189.4	189.0	5.10	0.00176	0.00023	0.00153	0.01076	0.00000	4.70	0.00155	0.00019	0.00131	0.00965	0.00000
ML901000	OTT	12.0	124.4	123.7	5.10	0.00222	0.00069	0.00572	0.01217	0.00000	4.70	0.00197	0.00056	0.00498	0.01082	0.00000
ML901000	SBQ	12.0	310.0	309.7	5.10	0.00074	0.00039	0.00164	0.00278	0.00000	4.70	0.00065	0.00032	0.00138	0.00248	0.00000
ML901000	SUO	12.0	414.6	414.4	5.10	0.00019	0.00016	0.00027	0.00076	0.00000	4.70	0.00017	0.00013	0.00023	0.00067	0.00000
ML901000	SWO	12.0	413.2	413.0	5.10	0.00026	0.00021	0.00034	0.00091	0.00000	4.70	0.00023	0.00018	0.00029	0.00080	0.00000
ML901000	SZO	12.0	451.8	451.6	5.10	0.00019	0.00019	0.00039	0.00101	0.00000	4.70	0.00017	0.00015	0.00034	0.00089	0.00000
ML901000	TRQ	12.0	86.6	85.6	5.10	0.04688	0.00475	0.05057	0.17596	0.00000	4.70	0.04164	0.00386	0.04307	0.15912	0.00000
ML901000	WBO	12.0	169.0	168.5	5.10	0.01670	0.00385	0.02918	0.05325	0.00000	4.70	0.01480	0.00314	0.02486	0.04785	0.00000
NH851200	6097	50.0	9.7	7.6	6.10	1.45879	0.15210	0.30660	4.09583	3.74862	6.80	0.74176	0.03906	0.09745	1.91306	1.89750
NH851200	6099	50.0	23.4	22.6	6.10	0.08866	0.01376	0.03125	0.17827	0.46160	6.80	0.03893	0.00350	0.00932	0.07387	0.20088
NM760300	2415B	25.0	150.5	150.0	0.00	0.00000	0.00000	0.00000	0.00000	0.00000	4.60	0.00907	0.00237	0.00430	0.03877	0.03528
NM910501	OLAP	0.0	114.2	114.0	4.60	0.02702	0.00216	0.00549	0.04012	0.11601	4.25	0.02240	0.00152	0.00407	0.03331	0.09803
NM890400	OLAP	0.0	174.2	173.9	4.70	0.00978	0.00157	0.00205	0.02306	0.03839	4.70	0.00512	0.00048	0.00082	0.01202	0.02101
SG881101	DCKY	50.0	197.0	194.8	6.50	0.00771	0.00247	0.01724	0.02291	0.01430	5.80	0.01332	0.00494	0.03324	0.03714	0.02262
SG881101	EMME	50.0	472.3	471.4	6.50	0.00034	0.00029	0.00065	0.00089	0.00063	5.80	0.00061	0.00059	0.00124	0.00153	0.00113
SG881101	GGN	12.0	471.9	471.0	6.50	0.00037	0.00042	0.00078	0.00081	0.00000	5.80	0.00067	0.00086	0.00148	0.00139	0.00000
SG881101	GRQ	12.0	391.2	390.2	6.50	0.00059	0.00022	0.00108	0.00200	0.00000	5.80	0.00106	0.00045	0.00202	0.00334	0.00000
SG881101	GSQ	12.0	313.5	312.2	6.50	0.00067	0.00039	0.00301	0.00199	0.00000	5.80	0.00117	0.00079	0.00566	0.00322	0.00000
SG881101	KLN	12.0	389.3	388.2	6.50	0.00032	0.00024	0.00079	0.00119	0.00000	5.80	0.00057	0.00049	0.00148	0.00199	0.00000
SG881101	SBQ	12.0	311.1	309.8	6.50	0.00113	0.00069	0.00167	0.00413	0.00000	5.80	0.00196	0.00140	0.00314	0.00666	0.00000
SG881101	TRQ	12.0	332.6	331.3	6.50	0.00090	0.00039	0.00132	0.00332	0.00000	5.80	0.00157	0.00080	0.00248	0.00540	0.00000
SG881101	WBO	12.0	468.2	467.3	6.50	0.00054	0.00017	0.00237	0.00179	0.00000	5.80	0.00097	0.00034	0.00451	0.00307	0.00000
SG881101	GSC10	50.0	118.1	114.5	6.50	0.00573	0.00148	0.00908	0.01921	0.01874	5.80	0.00944	0.00299	0.01612	0.03213	0.02992
SG881101	GSC14	50.0	101.3	97.1	6.50	0.00525	0.00172	0.00671	0.01255	0.01309	5.80	0.00852	0.00332	0.01231	0.02097	0.02120
SG881101	GSC17	50.0	70.4	64.1	6.50	0.01164	0.00042	0.00351	0.04955	0.04628	5.80	0.01830	0.00086	0.00658	0.08119	0.07438
SG881101	GSC20	50.0	95.0	90.4	6.50	0.05881	0.00216	0.03348	0.09154	0.42038	5.80	0.09493	0.00428	0.06174	0.15284	0.68109
SG881101	GSC5	50.0	113.1	109.3	6.50	0.01316	0.00183	0.00745	0.03356	0.05158	5.80	0.02161	0.00365	0.01334	0.05612	0.08268
SG881101	GSC8	50.0	97.5	93.1	6.50	0.01698	0.00131	0.00956	0.05306	0.03445	5.80	0.02748	0.00257	0.01760	0.08864	0.05584
SG881101	GSC9	50.0	132.5	129.3	6.50	0.00894	0.00153	0.01605	0.01865	0.01638	5.80	0.01489	0.00310	0.02851	0.03112	0.02626
SG881101	ISFL	50.0	325.8	324.5	6.50	0.00082	0.00037	0.00143	0.00200	0.00182	5.80	0.00143	0.00076	0.00269	0.00325	0.00321
SG881101	MIME	50.0	360.8	359.6	6.50	0.00024	0.00005	0.00019	0.00049	0.00045	5.80	0.00043	0.00011	0.00035	0.00082	0.00079
SG881100	DCKY	50.0	198.6	196.6	4.80	0.00179	0.00112	0.00346	0.00700	0.00608	4.50	0.00138	0.00069	0.00241	0.00536	0.00495
SG881100	A11	12.0	127.3	124.0	4.80	0.00134	0.00041	0.00145	0.00537	0.00000	4.50	0.00104	0.00027	0.00102	0.00418	0.00000
SG881100	A16	12.0	118.8	115.2	4.80	0.00127	0.00031	0.00054	0.00707	0.00000	4.50	0.00099	0.00020	0.00039	0.00547	0.00000

SG881100	A21	12.0	125.6	122.2	4.80	0.00155	0.00046	0.00075	0.00813	0.00000	4.50	0.00120	0.00030	0.00052	0.00634	0.00000
SG881100	A61	12.0	100.3	96.1	4.80	0.00205	0.00060	0.00130	0.00966	0.00000	4.50	0.00164	0.00038	0.00094	0.00728	0.00000
SG881100	A64	12.0	107.0	103.0	4.80	0.00121	0.00027	0.00120	0.00828	0.00000	4.50	0.00096	0.00017	0.00086	0.00631	0.00000
SG881100	DPQ	12.0	202.3	200.2	4.80	0.00275	0.00032	0.00235	0.00916	0.00000	4.50	0.00213	0.00020	0.00163	0.00703	0.00000
SG881100	EBN	12.0	232.1	230.3	4.80	0.00033	0.00026	0.00047	0.00141	0.00000	4.50	0.00025	0.00016	0.00032	0.00108	0.00000
SG881100	GGN	12.0	473.8	472.9	4.80	0.00008	0.00017	0.00017	0.00022	0.00000	4.50	0.00006	0.00010	0.00012	0.00017	0.00000
SG881100	GRQ	12.0	390.3	389.2	4.80	0.00084	0.00023	0.00153	0.00182	0.00000	4.50	0.00063	0.00014	0.00106	0.00141	0.00000
SG881100	GSQ	12.0	314.6	313.2	4.80	0.00016	0.00027	0.00049	0.00052	0.00000	4.50	0.00012	0.00016	0.00035	0.00039	0.00000
SG881100	HTQ	12.0	239.3	237.5	4.80	0.00051	0.00010	0.00034	0.00187	0.00000	4.50	0.00039	0.00006	0.00023	0.00145	0.00000
SG881100	KLN	12.0	391.1	390.0	4.80	0.00008	0.00011	0.00017	0.00045	0.00000	4.50	0.00006	0.00007	0.00012	0.00034	0.00000
SG881100	LPQ	12.0	128.3	125.0	4.80	0.00156	0.00056	0.00133	0.00869	0.00000	4.50	0.00121	0.00037	0.00093	0.00676	0.00000
SG881100	MNT	12.0	346.6	345.4	4.80	0.00050	0.00016	0.00063	0.00183	0.00000	4.50	0.00038	0.00010	0.00044	0.00139	0.00000
SG881100	OTT	12.0	460.4	459.5	4.80	0.00034	0.00022	0.00111	0.00100	0.00000	4.50	0.00025	0.00014	0.00077	0.00077	0.00000
SG881100	SBQ	12.0	311.9	310.6	4.80	0.00044	0.00058	0.00099	0.00234	0.00000	4.50	0.00033	0.00036	0.00070	0.00177	0.00000
SG881100	TRQ	12.0	332.1	330.8	4.80	0.00084	0.00022	0.00178	0.00276	0.00000	4.50	0.00063	0.00013	0.00127	0.00209	0.00000
SG881100	WBO	12.0	468.0	467.1	4.80	0.00025	0.00017	0.00069	0.00078	0.00000	4.50	0.00019	0.00010	0.00047	0.00059	0.00000

Tabel 8-4: Scaled horizontal component data

eqid	staid	Lp	hypd	epd	mbLg	pgambLg	f1mbLg	f2p5mLg	f10mbLg	f25mbLg	mw	pgamw	f1mw	f2p5mw	f10mw	f25mw
CG900900	OLAP	0.0	47.7	46.2	5.00	0.03568	0.00093	0.00405	0.05623	0.09801	0.00	0.00000	0.00000	0.00000	0.00000	0.00000
FK820100	2629A	50.0	62.7	62.6	4.80	0.01613	0.00430	0.00661	0.02544	0.05082	4.35	0.01545	0.00394	0.00622	0.02428	0.04836
FK820100	2630B	50.0	76.1	76.0	4.80	0.05449	0.00610	0.00781	0.10544	0.20175	4.35	0.05205	0.00559	0.00732	0.09998	0.19248
ML901000	A11	12.0	418.6	418.4	5.10	0.00037	0.00033	0.00107	0.00081	0.00000	4.70	0.00033	0.00027	0.00091	0.00071	0.00000
ML901000	A16	12.0	437.4	437.2	5.10	0.00041	0.00022	0.00081	0.00081	0.00000	4.70	0.00036	0.00018	0.00069	0.00071	0.00000
ML901000	A21	12.0	466.7	466.5	5.10	0.00256	0.00069	0.00335	0.00451	0.00000	4.70	0.00225	0.00056	0.00287	0.00400	0.00000
ML901000	A54	12.0	407.9	407.7	5.10	0.00076	0.00019	0.00155	0.00161	0.00000	4.70	0.00067	0.00016	0.00132	0.00141	0.00000
ML901000	A61	12.0	437.5	437.3	5.10	0.00055	0.00022	0.00095	0.00118	0.00000	4.70	0.00048	0.00018	0.00081	0.00105	0.00000
ML901000	A64	12.0	456.2	456.0	5.10	0.00042	0.00015	0.00084	0.00089	0.00000	4.70	0.00036	0.00012	0.00072	0.00079	0.00000
NH851200	6097	50.0	9.7	7.6	6.10	0.74987	0.15489	0.34302	1.35298	0.95842	6.80	0.38129	0.03978	0.10903	0.63195	0.48514
NH851200	6098	50.0	9.5	7.4	6.10	0.28396	0.06561	0.17639	0.31322	0.50405	6.80	0.14439	0.01685	0.05607	0.14630	0.25514
NH851200	6099	50.0	23.4	22.6	6.10	0.09275	0.00903	0.02631	0.14101	0.25795	6.80	0.04072	0.00230	0.00785	0.05843	0.11225
NH851100	6098	50.0	18.8	5.5	0.00	0.00000	0.00000	0.00000	0.00000	0.00000	4.60	0.63856	0.02631	0.12093	0.70304	0.73327
NM760300	2415B	25.0	150.5	150.0	0.00	0.00000	0.00000	0.00000	0.00000	0.00000	4.60	0.01825	0.00130	0.00462	0.03113	0.03600
NM910501	OLAP	0.0	114.2	114.0	4.60	0.02289	0.00271	0.00703	0.05030	0.04903	4.25	0.01897	0.00191	0.00522	0.04177	0.04144
NM890400	OLAP	0.0	174.2	173.9	4.70	0.00904	0.00149	0.00193	0.01920	0.01625	4.70	0.00473	0.00045	0.00077	0.01001	0.00889
SG881101	DCKY	50.0	197.0	194.8	6.50	0.01777	0.00261	0.01112	0.03111	0.02018	5.80	0.03071	0.00521	0.02145	0.05042	0.03194
SG881101	EMME	50.0	472.3	471.4	6.50	0.00032	0.00025	0.00058	0.00077	0.00053	5.80	0.00057	0.00050	0.00111	0.00131	0.00095
SG881101	GSC10	50.0	118.1	114.5	6.50	0.01179	0.00369	0.01385	0.03252	0.01491	5.80	0.01945	0.00745	0.02458	0.05439	0.02381
SG881101	GSC14	50.0	101.3	97.1	6.50	0.00448	0.00078	0.00425	0.00724	0.00637	5.80	0.00728	0.00150	0.00779	0.01211	0.01032
SG881101	GSC17	50.0	70.4	64.1	6.50	0.03068	0.00056	0.00566	0.04266	0.08612	5.80	0.04821	0.00117	0.01060	0.06989	0.13840
SG881101	GSC20	50.0	95.0	90.4	6.50	0.02842	0.00253	0.01907	0.05291	0.06054	5.80	0.04587	0.00502	0.03516	0.08833	0.09809
SG881101	GSC5	50.0	113.1	109.3	6.50	0.00189	0.00029	0.00103	0.00265	0.00329	5.80	0.00310	0.00059	0.00185	0.00442	0.00527
SG881101	GSC8	50.0	97.5	93.1	6.50	0.02160	0.00282	0.01360	0.03816	0.03237	5.80	0.03495	0.00552	0.02505	0.06375	0.05248
SG881101	GSC9	50.0	132.5	129.3	6.50	0.01241	0.00305	0.01133	0.02687	0.01849	5.80	0.02068	0.00618	0.02013	0.04483	0.02963
SG881101	ISFL	50.0	325.8	324.5	6.50	0.00112	0.00059	0.00187	0.00186	0.00193	5.80	0.00195	0.00121	0.00352	0.00302	0.00340
SG881101	MIME	50.0	360.8	359.6	6.50	0.00024	0.00006	0.00016	0.00037	0.00037	5.80	0.00042	0.00011	0.00031	0.00062	0.00064
SG881100	DCKY	50.0	198.6	196.6	4.80	0.00283	0.00088	0.00277	0.00778	0.00416	4.50	0.00219	0.00054	0.00194	0.00596	0.00339
SG881100	A11	12.0	127.3	124.0	4.80	0.00139	0.00043	0.00227	0.00453	0.00000	4.50	0.00108	0.00028	0.00159	0.00353	0.00000
SG881100	A16	12.0	118.8	115.2	4.80	0.00182	0.00027	0.00105	0.00630	0.00000	4.50	0.00142	0.00018	0.00075	0.00487	0.00000
SG881100	A21	12.0	125.6	122.2	4.80	0.00318	0.00035	0.00144	0.01142	0.00000	4.50	0.00246	0.00023	0.00101	0.00890	0.00000
SG881100	A61	12.0	100.3	96.1	4.80	0.00385	0.00048	0.00129	0.01016	0.00000	4.50	0.00308	0.00031	0.00094	0.00766	0.00000
SG881100	A64	12.0	107.0	103.0	4.80	0.00213	0.00035	0.00066	0.00767	0.00000	4.50	0.00169	0.00022	0.00048	0.00584	0.00000

APPENDIX C

MAGNITUDE WORKSHOP

JUNE 14, 1994

BOULDER, COLORADO

C.1 PURPOSE OF WORKSHOP

The magnitude measures used in PSHA are different in the tectonically active western United States and in the more stable parts of the country. In the west, the moment magnitude is the most commonly used magnitude, whereas in the rest of the country the shorter-period magnitude m_{bLg} is used. To some extent this difference in usage stems from historical reasons. The chairmen of the SSHAC subcommittees on Seismicity and Source Characterization (Kevin J. Coppersmith) and Ground Motion (David M. Boore) organized a workshop to discuss whether the existing usage of magnitudes should continue, or whether the SSHAC recommendation should be that one magnitude measure be used for PSHA throughout the country and if so, which one.

C.2 BACKGROUND DISCUSSION

Decisions regarding which magnitude to use should be guided by this fundamental question: what magnitude will lead to the smallest uncertainty in the PSHA results? The answer to this question depends on many factors, and may depend on the period of ground motion for which PSHA results are being computed. The interplay between SSC and ground motion needs is crucial and can be complex. An ideal magnitude from the point of view of those predicting ground motion is useless if that magnitude cannot be predicted for future events in the region for which a PSHA is being computed. A few background comments are given here for those readers not familiar with the various magnitudes, how they influence ground motion predictions, and how they are typically determined for use in a PSHA.

Moment magnitude (**M**) is simply related to the seismic moment of an earthquake through the equation $\mathbf{M} = (2/3) \log M_0 - 10.7$ (Hanks and Kanamori, 1979, equation 7). The seismic moment is determined from the area and amount of slip across the rupture surface or from waves at periods great enough that the wavelengths exceed the dimensions of the rupture surface. m_{bLg}, on the other hand, is measured from the peak amplitudes of seismographs with natural periods between about 0.2 and 10 seconds.

A critical question is how the magnitudes are determined for previous events. In the tectonically active parts of the United States earthquakes occur frequently enough that the seismicity catalogs required for PSHA can rely almost entirely on instrumentally-recorded earthquakes. This is in distinct contrast to the other parts of the country, where historical descriptions of damage (intensity) must be used. In the latter case, correlations between intensity measures and the magnitudes, developed from instrumental data from the region under consideration or by combining data from similar regions throughout the world, are used to assign magnitudes.

In the tectonically-active regions, seismic moment is, without question, the preferred magnitude. There is not only a large body of instrumental data, but also paleoseismological studies of slip rates and recurrence on faults can be used in PSHA. Because of this, the main focus in the rest of this Appendix will be on what magnitudes to use for PSHA in other parts of the country. In other parts of the country m_{bLg} is the commonly-used magnitude. This is to some extent due to its invention by Otto Nuttli, who had a great interest in earthquakes in central and eastern United States; Prof. Nuttli not only invented the magnitude, but he also derived ways to relate it to intensity. It is also true that recurrence statistics must often by computed from the statistics of events with magnitudes less than about 3.5, and the catalog of instrumentally recorded events for such small earthquakes is almost exclusively in terms of m_{bLg}. In the last few years, however, a major project has been completed that has made significant progress on using seismic intensities to determine moment magnitudes for historical earthquakes (Johnston et al, 1993, Johnston, 1995a, 1995b, 1995c).

How are magnitudes used in predicting ground motions? A basic understanding of this can be obtained by considering a simple, and commonly used, spectral scaling model. Figure C1 shows the source acceleration spectra for **M** = 6.5 and 7.5 earthquakes, for two values of the stress parameter. Note that by definition, the curves differ by a factor of $10^{1.5}$ at low frequencies (the levels of this part of the spectra are directly proportional to seismic moment). The stress parameter is introduced to allow for variable amounts of high-frequency radiation for a fixed seismic moment. This parameterization has been used to analyze many earthquakes in the United States, and therefore some statistics are available on the stress parameters. Returning to Fig. C1, note that predictions of ground shaking will be most sensitive to stress parameter variations at the higher frequencies of most interest to earthquake hazard reduction (the stress dependence of the ground motion for different oscillator frequencies is shown in Fig. C2 for a fixed moment magnitude). On the other hand, if the spectra had been plotted for two magnitudes defined at 1 Hz, for example, then by definition the spectra at high frequency would be independent of the stress parameter (the high frequency spectral level goes as $M_0{}^{1/3}\Delta\sigma^{2/3}$, and earthquakes with different stress parameters can lead to the same high frequency levels if their seismic moments differ so that the level stays the same); in this case, the variation in the spectral levels shifts from high frequency to low frequency. Ground motions are often computed using spectral scaling models such as these, particularly in the central and eastern United States. It is clear that predictions of ground motions at the higher frequencies in terms of **M** will be subject to aleatory uncertainty due to variable stress parameters. It would seem to make sense, then, to use a higher-frequency measure of magnitude, such as m_{bLg}. As we will shortly discuss, there are practical difficulties in determining m_{bLg} that can introduce considerable epistemic uncertainty in that measure. Recently, Atkinson and Hanks (1995) have proposed a magnitude (**m**) that is proportional to the high-frequency level of the acceleration source spectra. This would be the ideal measure if seismic recurrence can be derived in terms of **m**. Atkinson and Hanks demonstrate that **m** can be determined from intensity observations with equal or less uncertainty than **M**. Discussion at the workshop involved all three magnitudes.

It is not necessarily a straightforward matter to shift between magnitude measures. Most methods for predicting ground motions in the central and eastern United States use the moment magnitude as a fundamental parameter, and the seismicity and earthquake recurrence is usually given in terms of m_{bLg}. According to the previous discussion, the ground-motion predictions should be done for a range of stress parameters and seismic moments that all give the specified short-period magnitude. This is seldom done, and requires additional assumptions about instrument type, attenuation of waves with distance, and so on. Empirical relations have been used, but these are not well-determined from data. This is shown in Fig. C3. The data in Figure C3 can be fit with a straight line, but all theoretical calculations find that the relation should be curved. Unfortunately, the curvature is most pronounced for the magnitudes for which there is little data. As shown in the figure, uncertainty in correlation of magnitudes can lead to ground-motion uncertainties of a factor of 2 at large magnitudes.

C.3 ORGANIZATION OF THE WORKSHOP

The workshop was held on the afternoon of June 14, 1994, at the Boulderado Hotel in Boulder, Colorado, immediately following the SSC workshop described in Appendix H. Many of the attendees at the SSC workshop were encouraged to stay for the Magnitude Workshop. The list of attendees is given in Table C1. The agenda for the workshop was very simple. After a welcome and introduction by the organizers, Dr. Gail Atkinson presented a review of the new magnitude **m** and her views and studies related to the fundamental question of the workshop (her presentation has been published as Atkinson, 1995). The rest of the workshop consisted of a group discussion first of Dr. Atkinson's presentation and then directed toward the questions of whether **M** or **m** should be used for all PSHA.

C.4 SUMMARY OF PRESENTATION

Dr. Atkinson studied the residuals between observed ground motions and predictions made in terms of the three magnitudes **M**, **m**, and m_{bLg} (which she calls m_N). Her conclusions from the residuals are best summarized in the following quote from her paper (Atkinson, 1995):

> "The optimal choice of magnitude scale for seismic hazard evaluation is that which reduces random uncertainty in ground motion predictions to the lowest possible levels. For moderate earthquakes, **M** is optimal for frequencies of 2Hz or less, while **m** is optimal for greater frequencies. m_N is not an optimal choice in any frequency band. If a single magnitude scale is to be used, then **m** will be the best choice in most cases, for two reasons: (i) for large (**M**>6) events, it will yield the lowest uncertainty in predicted ground motions over the primary frequency and of engineering interest (1 to 10 Hz); and (ii) it is the only magnitude that can be reliably determined for both modern and pre-instrumental earthquakes."

As discussed in the previous section, the high-frequency spectral level of ground motion is controlled by seismic moment and the stress parameter (which is also commonly referred to as the "stress drop"). Dr. Atkinson considered using the stress parameter as an additional parameter in ground motion predictions, with these conclusions (also taken from Atkinson, 1995):

> "An alternative to using a high-frequency magnitude scale in hazard analysis would be to include stress drop as a predictive variable in ground motion relations (M. Chapman, personal communication, 1994). We could estimate ground motion amplitudes at all frequencies, with minimal scatter, from **M**, stress drop, and distance, and then integrate over these variables in the hazard analysis. However this would require explicit specification of the stress drop distribution for each source zone (since high-frequency amplitudes depend on both **M** and stress drop). The advantage of using **m** is that it obviates this need, because it implicitly carries the required high-frequency information that is provided by moment and stress drop."

C.5 DISCUSSIONS AND CONCLUSIONS

After Dr. Atkinson's presentation of these results and conclusions, there was considerable discussion among the attendees. The discussion was initially focused on the idea of using **m** as the sole magnitude. In view of the work of Johnston and colleagues (Johnston et al, 1993; Johnston, 1995a, 1995b, 1995c), it was not generally agreed that "it is the only magnitude that can be reliably determined for both modern and pre-instrumental earthquakes". On the other hand, there was considerable interest in **m**. Noting, however, that it has not been sufficiently tested (for example, in western North America), the general consensus was that **m** should not be used for PSHA during the short-term. There was strong agreement, however, that **m** shows much promise and that a vigorous evaluation of **m** should be made for possible future use as the magnitude of choice in PSHA.

The discussion then turned to a consideration of moment magnitude, **M**; should it replace m_{bLg}? It was noted that any magnitude measure has pros and cons: for m_{bLg}, the pros are that it is the magnitude used for seismicity catalogs, and that ground motions for a specified m_{bLg} should be less variable at periods of interest than for those for a given **M**; the cons are that the catalog values are not particularly well determined, both instrumentally (because of differences in response of the seismographs and in analysis procedures) and from pre-instrumental earthquakes (which are usually based on an epicentral intensity, I_0), and is not a natural parameter in the usual methods for predicting ground motions. For **M** the pros are that it is a natural variable for ground-motion models and that it is can be determined from paleoseismological information; its cons are that it is a measure of motion at long periods and therefore ground motions computed using it are subject to variability due to variability in the stress parameter.

One of the apparent advantages of m_{bLg} is that the seismicity catalog uses it as the magnitude measure. There was considerable discussion about whether **M** could be determined for the earthquakes in the catalog. It is clear that this can be done for larger events, for which the area enclosed within intensities of various levels are available. The main problem would be with the smaller events, for which the only data are either I_0 or difficult-to-digitize instrumental recordings from seismographs of limited bandwidth. There was general optimism, however, that the seismicity catalog could be restructured in terms of **M**.

The following conclusions were reached by the participants:

1. Keep the status quo for the time being (**M** for PSHA in the west, m_{bLg} for PSHA in the rest of the country).

2. Initiate a project to redo the seismicity catalog in terms of **M**. It was felt that this project could be completed within a few years, and the consensus was that **M** would then become the standard analysis for PSHA (for a length of time depending on the outcome of the next recommendation). It is essential that SSC experts be involved in the effort to do the magnitude conversions.

3. Encourage in-depth evaluation of the newly proposed magnitude **m**.

TABLE C1
PARTICIPANTS IN MAGNITUDE WORKSHOP
JUNE 14, 1994

Gail Atkinson
Don L. Bernreuter
David M. Boore
Kevin Coppersmith
Arch C. Johnston
Jeffrey K. Kimball
Carl Kisslinger
Joe J. Litehiser, Jr.
Jean B. Savy
John F. Schneider
J. Carl Stepp
Gabriel R. Toro

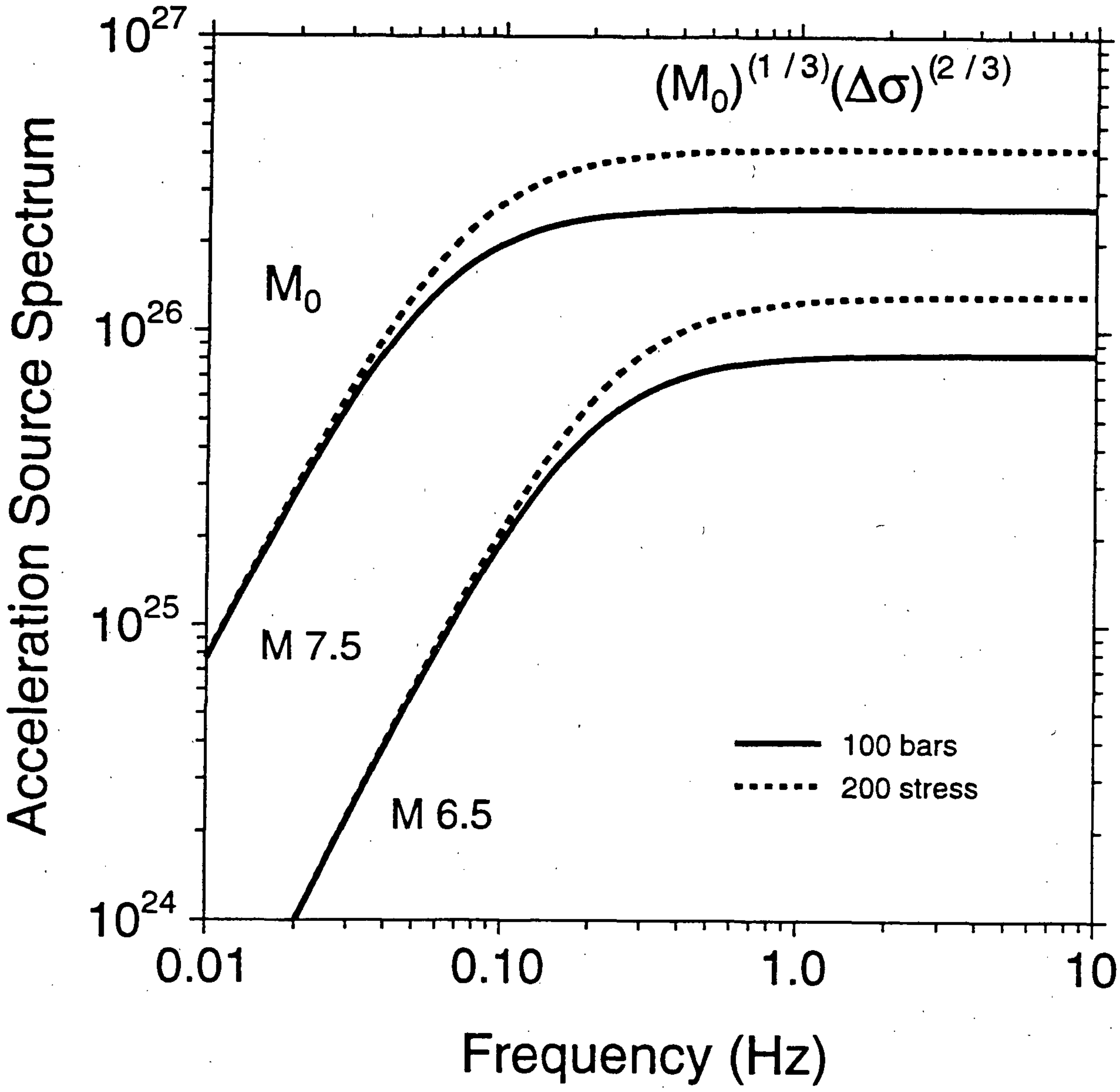


Figure C-1 Source acceleration spectra for moment magnitudes 6.5 and 7.5 and stress parameters of 100 and 200 bars. The low-frequency and high-frequency spectral levels scales as seismic moment (M_0) and seismic moment to the 1/3 power times stress parameter ($\Delta\sigma$) to the 2/3 power, respectively.

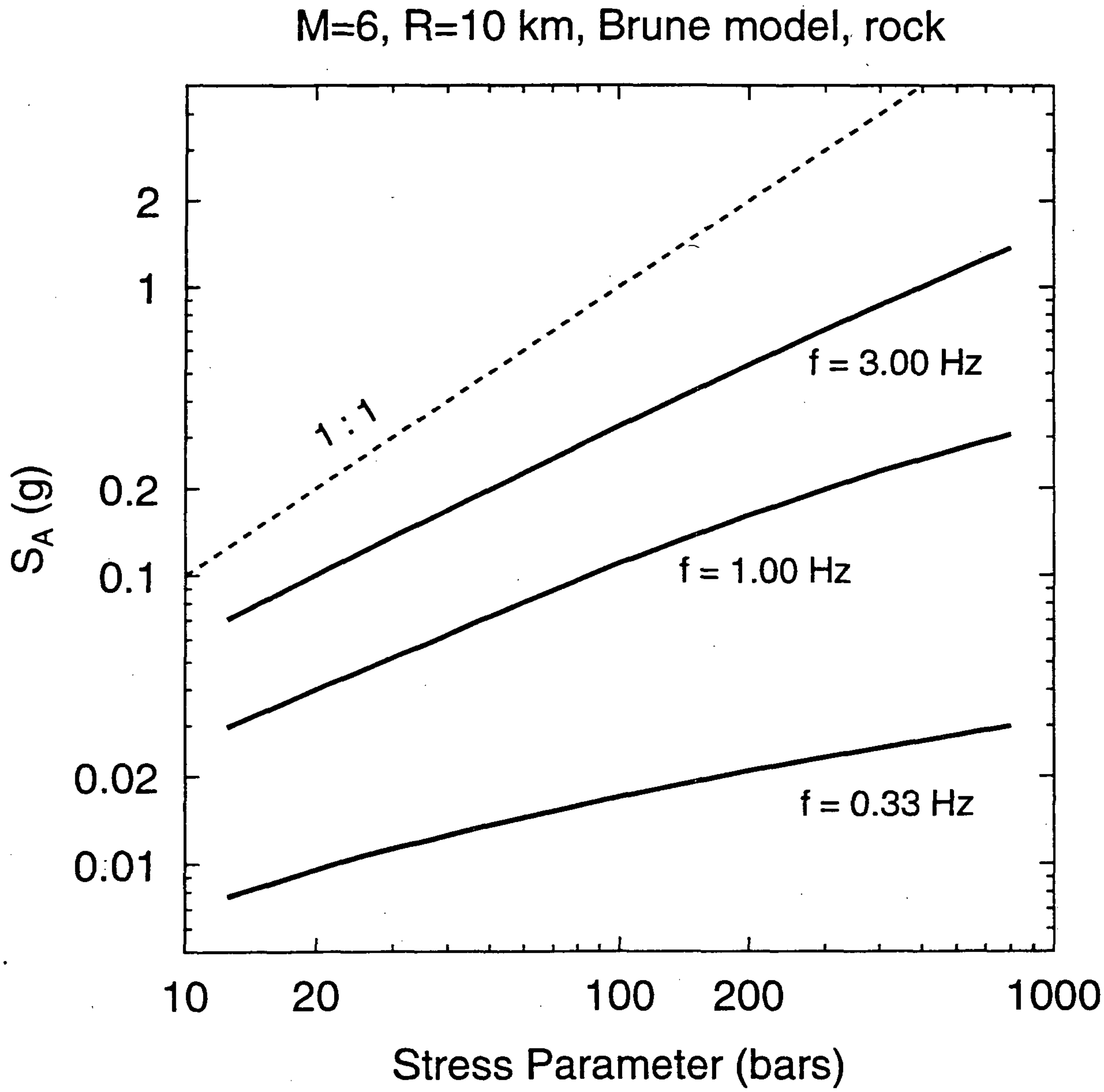
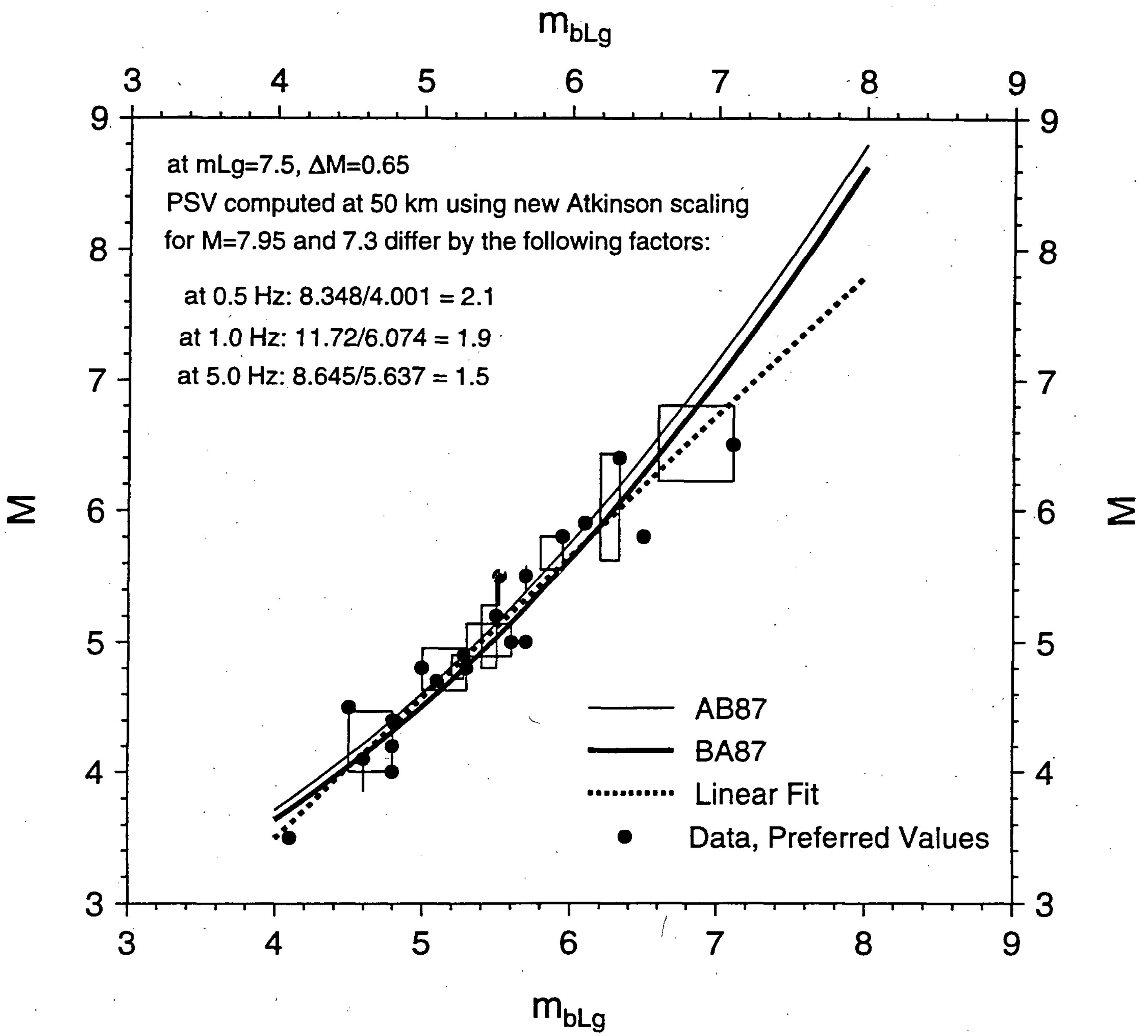


Figure C-2 The dependence of acceleration response spectra on stress parameter, for a fixed distance of 10 km and a seismic moment of 6.0. The dependence is shown for oscillator frequencies of 0.33, 1.0, and 3.0 Hz. The dashed line shows a 1:1 ratio, for reference. Note that the dependence on stress parameter is greater for higher frequencies.



mmnsshac.grg mmndata1.gra Dec 5, 1994 2:37:07 pm mmndata2.gra Dec 5, 1994 2:37:07 pm

m4sshac.gra Dec 5, 1994 2:37:07 pm D. M. Boore

Figure C-3 M versus M_{blg}, adapted from Boore and Atkinson (1987). The curves labeled "AB87" and BA87" are from Atkinson and Boore (1987) and Boore and Atkinson (1987), respectively. The boxes indicate the range of values, with the preferred values given by the solid dots. The difference in ground-motion predictions for two possible moment magnitudes estimated for a short period magnitude of 7.5 is summarized in the notes in the upper left-hand corner of the figure.

APPENDIX D

LESSONS LEARNED FROM LLNL ELICITATION OF GROUND MOTION

by

Richard W. Mensing

The basic seismic hazard calculation involves evaluating the sum:

$$\sum_k \lambda_{ok} \int_r \int_m P\left(GM > a_o \mid m, r\right) dH_k\ (m)\ dG_k(r) \tag{1}$$

where λ_{ok} is the expected number of earthquakes, per time period and unit area, in the kth area of homogeneous seismicity; H_k (m and G_k (r) are the magnitude and distance (from the site) distributions applicable to the kth area and P (·) is the conditional complementary distribution function of the ground motion measure, e.g., peak ground acceleration.

The important point to be recognized, from the perspective of eliciting ground motion, is that the ground motion information needed for a seismic hazard (SH) assessment is the conditional frequency distribution of ground motion at a site, conditional on earthquakes of magnitude m occurring at distance r from the site, for all m, r. Recognition and acceptance of this fact influences the elicitation of ground motion information. A second important point is the need to have a clear understanding of what the distribution represents. In principle, given a site, the distribution represents the potential variation in the ground motion measure at the site among all earthquakes of magnitude m occurring at locations which are r distance units from the site. There are many causes for this variation. One cause is the variation in the source characteristics at the different locations which are the same distance from the site. Similarly, differences in the earth's structure between the site and these different locations will cause the characteristics of the seismic waves travel paths to be variable and contribute to the variation in the ground motion measure at the site. Identification and representation of the variation in the ground motion attributable to them is an important issue relevant to elicitation of ground motion. This issue will be discussed further in the succeeding sections.

The purpose of this paper is to identify some of the lessons learned by EPRI and LLNL during their past experiences developing ground motion information. Hopefully, describing these experiences will be helpful in developing a sound credible methodology for eliciting ground motion information needed for SH assessments. Section 2 outlines LLNL's experiences eliciting ground motion information using panels of experts. Several lessons learned are highlighted. The EPRI experiences, lessons learned and a discussion of their current approach and position regarding ground motion models are the topics of Section 3.

LLNL's Experiences Eliciting Ground Motion Information (R. Mensing, LLNL)

LLNL's efforts at deriving ground motion information has been based on eliciting the judgments of experts. The initial efforts were based primarily on having experts make judgments about ground motion models and the level of random variation as quantified by the standard deviation of the natural logarithm of the ground motion measure. The primary lessons learned from the initial elicitations were:

Lesson 1: Asking experts to weigh ground motion models is NOT a good way to elicit the needed ground motion information

Lesson 2: Experts have difficulty quantifying the standard deviation of the natural logarithm of a ground motion measure

Having experts weigh ground motion models is based on the assumption that the variation in ground motion, conditional on m, r, is best described by a lognormal distribution. In this case, ground motion models are descriptions of the expected value (mean) of the natural logarithm of a ground motion measure as a function of m, r, and, perhaps, other variables. Having experts weigh ground motion models was an attempt to quantify their uncertainty in specifying the expected value as a function of m, r. This was not successful because:

- It is asking the wrong question; to ask experts to weight models directs their attention to the models instead of the parameter of interest—the expected value or mean of the logarithm of the ground motion measure.

- Weighing models is a very restrictive way of asking experts to quantify the level of evidence of their state of knowledge regarding the parameter of interest—the expected value

Quantifying the standard deviation is difficult because:

- It is a mathematical concept and does not have any physical meaning; this forces the experts to rely on statistical calculations to provide values; these calculations are data and model dependent; thus, the experts provide a WIDE range of estimates

- There is a lot of uncertainty, lack of understanding, and lack of knowledge regarding what sources of variation should be included in the standard deviation and what, if any, variation is accounted for in the variation between different ground motion models

Overall, the lessons learned were that asking experts to weigh models and estimate the standard deviation were <u>not</u> the appropriate way to elicit ground motion information.

Prior to LLNL's most recent attempt to elicit ground motion information, a workshop on eliciting ground motion information was held (Ref. 1*). The workshop involved discussion and interaction with a panel of experts on eliciting and aggregating expert opinions. Based on the panels deliberations, it was clear that any approach to eliciting ground motion information must concentrate on the ground motion distribution. Based on the recommendations of the panel, LLNL's most recent elicitation was based on eliciting

1) The distributional model for the conditional ground motion distribution

2) The experts' probability distributions for the parameters of the conditional ground motion distribution as a function of m, r

With regard to the distributional model, the lesson learned was:

Lesson 3: The lognormal model is the accepted distribution model for the conditional ground motion frequency distribution, given m, r.

Based on the experts' 100 percent selection of the lognormal model, elicitation of the parameters was based on eliciting the experts' probability (uncertainty) distribution of the expected value and standard deviation of the logarithm of the ground motion measure at several pairs of values of m, r spanning the ranges of m and r. LLNL's experience in this elicitation was much more positive, at least with regard to the expected value. the lesson learned was:

Lesson 4: Experts are able to quantify their judgments about the expected value of the lognormal conditional ground motion frequency distributions as a function of m, r, the experts concentrated on specifying their judgments about the value of the expected value and their uncertainty/level of evidence about that value, rather than on the "quality" of ground motion models, i.e. they focused on the parameter of interest.

The experts' probability distributions were elicited in terms of bounds and a most likely value. Although one or two gave values as a function of m, r directly, most expressed their state of knowledge by providing a recipe for assessing the bounds and most likely value as a function on m, r in terms of:

- Weighted combinations of ground motion models for the bounds and most likely value as a function of m, r

- A weighted combination of ground motion models for the most likely value and multiplying factors, as a function of m, r, for the bounds

Overall, the quality of information about the expected value accumulated in the latest elicitation was considered quite satisfactory and certainly much better than the earlier elicitations. On the other hand, even wit considerable concentrated efforts at improving the information about the standard deviations, the results are not encouraging. The latest LLNL approach included trying to have experts assess fractiles of the ground motion frequency distributions as a function of m, r. This was not successful; most experts are strongly committed to assessing the standard deviation. Thus, the lesson learned was:

Lesson 5: There is a need to derive information about the random variation in ground motion, given m, r, in some other way than direct elicitation from experts.

One hypotheses for the possible difficulties in eliciting consistent assessments of the standard deviation between experts is a lack of clear understanding of the sources of variation represented by the random variation in ground motion. Conceptually, a ground motion measure can be modeled as

$$\ln GM = a_o + f_1(m,r) + f_2(u_1, u_2 ......) + E$$

where f_1 (m, r) represents the dependence on m, r, f_2 (u_1 , u_2 ......) introduces the influence of the source and attenuation variables, e.g. stress drop, fault parameters, travel path parameters; and E represents stochastic and unmodeled variation. [Note: site effects are generally modeled separately, hence, are not included in the discussion.] An important issue is the inclusion of the source and attenuation variables, i.e., f_2 (u_1 , u_2......). The inclusion of these variables affects the ground motion models in two ways:

1) It affects the values of the coefficients associated with m and r in f_1 (m, r)

2) It affects the statistical estimate of the standard deviation associated with the stochastic variation term E

Inclusion or non-inclusion of f_2 (u_1, u_2......) varies between models. In addition, the extent to which the source and attenuation variables vary between data sets used to develop ground motion models and estimates of the standard deviation are likely to vary considerably. Also, LLNL's experience is that some experts are basing their bounds for the expected value on the ranges of these source and attenuation variables. That is, the variation in ground motion due to the variation in f_2 (u_1, u_2......) is included in uncertainty. Is this the correct representation? If so, how can it be assured it is not included in the stochastic variation?

For example, consider stress drop, a source parameter. Three potential representations of variation in stress drop are:

1) Stress drop is a constant over location but its value is unknown

2) Stress drop is a physical variable which varies between locations, hence is a stochastic variable; its distribution is known

3) Stress drop is a physical variable, hence is stochastic; its distribution is unknown

In Model 1, the level of stress drop affects the level of ground motion, hence its expected value. Since its contribution to the ground motion is unknown, it can only be estimated with uncertainty. Hence, under the model, stress drop uncertainty contributes to uncertainty in the expected value of the ground motion measure. In Model 2, since stress drop is a stochastic variable, it contributes to the stochastic variation in the ground motion measure, i.e., it contributes to the standard deviation of the logarithm of the ground motion measure. In Model 3, stress drop contributes to both stochastic variation and uncertainty. The uncertainty in the expected value of the distribution of the stress drop contributes to the uncertainty in the expected value of the logarithm of the ground motion measure variability stress drop, identified by standard deviation, contributes to the stochastic variation of the ground motion measure; and its uncertainty contributes to the uncertainty in the standard deviation of the logarithm of the ground motion measure.

Overall, another lesson learned was:

Lesson 6: There is a definite need to identify and clearly understand the various sources of variation in ground motion and to partition these sources into those that contribute to uncertainty in the expected value and those that contribute to stochastic variation and, hence, the standard deviation.

This suggests that a meaningful exercise would be to have a small select group interact on the problems of ground motion variation. Perhaps, such a discussion could lead to a clearer understanding and a consensus assessment of the standard deviation representing stochastic variation.

On additional lesson came out of the workshop with the panel on expert elicitations. It was their recommendations that the ground motion information derived from experts be aggregated prior to combining it with seismicity information in the seismic hazard calculations. Thus, assuming the lognormal distribution and basing the elicitation on the expected value and standard deviation as a function of m, r, the lesson learned was:

Lesson 7: Individual joint probability distributions for the expected value and standard deviation, as a function of m, r should be combined to create an aggregate joint probability distribution as a function of m, r.

This recommendation leaves an open issue-how to create the aggregated joint probability distribution as a function of m, r.

APPENDIX E

EMPIRICAL SOURCE/THEORETICAL PATH MODELING METHOD

by
Dr. Norman Abrahamson

E.1 INTRODUCTION

The empirical source/theoretical modeling method for predicting strong ground motions (Somerville and Saikia proponents) has been described in several papers (Wald et al., 1988; Somerville et al., 1991; and Cohee et al., 1991) but these papers do not provide a full description of the method as it is now used. This write-up provides a more complete description of the current state of the method.

This method has also been called the semi-empirical source function method. The terminology for this method has been a source of confusion in the past. In this write-up, I've used a terminology that differs from Somerville, but I think it is easier to follow.

In general terms, the semi-empirical source method computes the ground motion from finite faults. The basic methodology for estimating mainshock ground motions by summing ground motions from small events is similar to other finite-fault methods. The fault is divided into discrete sub-fault elements. The ground motion for each sub-fault element is estimated by summing the ground motions from a number of subevents with appropriate time lags. Large scale asperities are introduced by varying the slip distribution over the fault surface (sub-fault elements). The mainshock motion is then computed by scaling and lagging the motions from these sub-fault elements to simulate the propagation of the rupture over the fault surface.

The details of computing the subevent motions and the sub-fault element motions is the main difference between this method and other finite-fault methods. Conceptually, the method is a generalization of the empirical Greens function (EGF) method.

In the EGF method, recordings from small earthquakes distributed over the source zone and recorded at the site of interest are used to represent the Green's functions including the sub-event source, wave propagation, and site-specific response effects. The ground motion for a larger earthquake is computed by summing the EGFs with the appropriate time delays and scaling to represent the mainshock source rupture process. The strength of this method is that the site specific path and site effects are included directly.

In the ideal case, the hypocenters of the small earthquakes used as EGF are distributed such that they cover all of the sub-fault elements. Also, the EGF should have the same focal mechanism as the mainshock. The main drawback to this method is that most sites for which we want to estimate ground motion have few if any recordings of small earthquakes and the earthquakes do not cover the entire fault rupture surface.

The empirical source function/theoretical path (ESF/TF) method addresses this short coming of the EGF method by providing a procedure for transporting EGFs from a well recorded earthquake to different sites and source mechanisms. The method provides a means of transporting the stochastic information in the EGF to other sites and sources while accounting for the deterministic effects of differences in the site, crust (path), and source mechanisms. A key assumption of the method is that the unmodeled effects in the 0-15 km distance range apply equally to all phases at all distances. This assumption is discussed in more detail in the summary.

E.2 STEPS IN THE EMPIRICAL SOURCE FUNCTION METHOD

As an outline, the steps involved in the empirical source function method are described below.

1. Develop a set of empirical source functions.
   - 1a. Select a well recorded small earthquake for use as EGFs.
   - 1b. Remove the first order effects of the wave propagation from the EGFs. This gives a set of "reduced" EGFs.
   - 1c. Decompose the reduced EGFs into SH, SV, and P waves on the vertical, radial, and transverse components and classify each wavelet by its theoretical radiation pattern amplitude. This gives a set of empirical source functions.

2. Compute the motions for a subevent for the new source and site. (This step is repeated for each sub-fault element and for each wave type).

   2a. Compute the theoretical GF for the new site.

   2b. Compute the theoretical radiation pattern

   2c. Select an empirical source function with a radiation pattern amplitude that is similar to the theoretical valued computed in step 2b.

   2d. Convolve the selected empirical source function with the theoretical GF from step 2a.

   2e. Apply a receiver correction to account for the effect of the incidence angles and velocity structure on the partitioning of the waves onto the vertical, transverse and radial components.

3. Compute the sub-fault element ground motions

   3a. Estimate the mainshock and subevent rise-times.

   3b. Compute the number of subevent "firings" for each sub-fault elements from the ratio of the mainshock rise-time over the subevent rise-time.

   3c. Lag the subevent ground motions by the subevent rise-time (with some randomness in the lag times) and sum the lagged ground motions.

4. Compute the mainshock ground motions

   4a. Develop a slip distribution for the finite fault and select a hypocenter location.

   4b. Scale the sub-fault ground motions by the slip amplitude for the given sub-fault element (scaling is normalized such that the total moment is equal to the mainshock moment).

4c. Lag the subevent ground motions to account for the rupture velocity (with some randomness in the lag times).

4d. Sum the lagged and scaled ground motions from the sub-fault elements.

These steps are described in more detail below.

E.2.1 Develop the Set of Empirical Source Functions

Before the method can be used, the set of empirical source functions need to be developed. This is the major overhead involved in this procedure and makes the procedure more difficult to use, however, it only needs to be done once for each set of EGF.

Select a small earthquake that is well recorded in the near source region. A requirement is that this small earthquake must have a reliable estimate of the moment and the focal mechanism. (To have confidence is using the method, the recorded ground motions should be able to be modeled. If the waveforms cannot be modeled accurately, then the concept of breaking the ground motion down into its basic components and the recombining them in a different way based on understanding the source is not appropriate.)

The EGFs are then modified to remove the first order effects of the wave propagation. The theoretical Green's function is computed for each site that recorded the small earthquake. The theoretical Green's function could be deconvolved from the recorded empirical Green's function (e.g. Jacob and Horton method), however, due to zeros in the theoretical spectrum, this deconvolution is often unstable. Since the EGF are recorded at close distances (within about 1-2 source depths), the direct waves will dominate the GF. To capture the first order effects of the wave propagation, only the direct wave is used in the theoretical GF calculation. These theoretical Green's functions are quite simple; they are typically close to a step function. The deconvolution can be approximated by dividing the EGF by the amplitude of the step function, G_o. This amplitude is computed from the ratio of the maximum amplitude of the EGF convolved with the theoretical Green's function to the maximum amplitude of the EGF. That is

$$G_o = \frac{\max[S(t) * G(t)]}{\max[S(t)]}$$

where S(t) is the EGF and G(t) is the theoretical GF for the desired wave type (P, SV, or SV waves). At this point, we have a set of reduced empirical Green's functions.

The reduced EGFs at each recording site are separated into P-wave and S-wave time windows and then decomposed into SH, SV, and P wavelets on the transverse, radial, and vertical components. The three components from the EGF lead to 5 wavelets: SH_t, SV_z, SV_r, P_z, P_r.

Each wavelet is then classified by its <u>expected</u> radiation pattern amplitude (see Figure 1). The expected radiation pattern amplitude is the theoretical value for the double couple source. The classification is done using the absolute value of the amplitude of the expected radiation pattern (e.g. between 0 and 1). The sign of the radiation pattern is noted as well for later use (to allow the correct polarity to be included). This gives a set of empirical source functions (ESF).

From this point on, the ESFs from a single site are no longer kept together. That is, each ESF is treated independently and is just classified by the expected radiation pattern amplitude. This is a key difference from the EGF method which keeps the three components together. By separating the components, the procedure can be used to estimate ground motions for focal mechanisms other than the mechanism of the small earthquake used for the EGF. This allows the method to transport the EGFs to other source mechanisms.

The term empirical source function is used here because the dominate features in the wavelets should be due to the source; however, the ESF do contain other effects than just the source. For example, since only the direct wave amplitude is used to remove the wave propagation effects, any complexities, such as scattering will still be present in the ESF.

<u>Receiver Correction</u>

The partitioning of the waves into the horizontal and vertical components depends on the angle of incidence of the waves. In general, this angle may be different for the desired site than for the site that recorded the EGF due to differences in the velocity structure at the sites. To account for this difference, a receiver correction is applied to the ESF. This correction is approximated by the ratio of the theoretical whole-space receiver functions which results in the following relations:

$$P_z' = \frac{1}{2}\left(\frac{\alpha_1 \cos i_2}{\alpha_2 \cos i_1}\right)P_z + \frac{1}{2}\left(\frac{\alpha_1 \cos i_2}{\alpha_2 \cos i_1}\right)P_R$$

$$P_R' = \frac{1}{2}\left(\frac{\alpha_1 \sin i_2}{\alpha_2 \cos i_1}\right)P_z + \frac{1}{2}\left(\frac{\alpha_1 \sin i_2}{\alpha_2 \sin i_1}\right)P_R$$

$$SV_Z' = \frac{1}{2}\left(\frac{\beta_1 \sin i_2}{\beta_2 \sin i_1}\right)SV_z + \frac{1}{2}\left(\frac{\beta_1 \sin i_2}{\beta_2 \cos i_1}\right)SV_R$$

$$SV_R' = \frac{1}{2}\left(\frac{\beta_1 \cos i_2}{\beta_2 \sin i_1}\right)SV_z + \frac{1}{2}\left(\frac{\beta_1 \cos i_2}{\beta_2 \cos i_1}\right)SV_R$$

$$SH'_T = \left(\frac{\beta_1 \sin i_2}{\beta_2 \sin i_1}\right)SH_T,$$

where a_1, b_1, and i_1 are the P and S velocities and incidence angle at the site at which the empirical GF was recorded and a_2, b_2, and i_2 are similar parameters at the site of interest.

E.2.2 Subevent Ground Motions

To compute the ground motions from a subevent, the theoretical radiation patterns for the P, SH, and SV components are computed for each sub-fault element. Using the set of ESF as a library, the ESF whose radiation pattern amplitude is similar to the desired radiation pattern amplitude is selected (Figure 2). Specifically, a weighting function, given by a normal distribution centered at the desired radiation pattern amplitude is used to assign a weight to each ESF. The standard deviation of the weighting function is about 0.1 radiation pattern amplitude units. The weights are normalized such that they sum to unity, then the distribution of ESF is then sampled using these weights.

In initial applications of this model, the ESF with the radiation pattern amplitude closest to the desired amplitude was selected (e.g. it was given weight of 1 and all others were given a weight of zero). A drawback of this simpler approach is that if there were several ESF with similar radiation pattern amplitudes then one may be sampled much more often then the others. Consider, for example if three ESF had similar radiation pattern values, then the one in the middle would almost never be selected. Using a weighting function makes the resulting ground motion simulations less sensitive to the set of ESF used. Using a weighting function also allows different ESF to be selected for a given sub-fault element which provides an additional source of randomness.

The ESF are then convolved with theoretical GF computed for the new site using the generalized rays method (Helmberger and Harkrider, 1978). Only the direct P and S waves and the primary reflections from each layer below the source are included in most applications of the model, however, more complete GF could be computed if desired. (For example, in the EUS, more rays are needed to build up LG waves.)

After applying the receiver function correction discussed earlier, we have the ground motions at the site from the subevent. We then need to combine the subevent ground motions to estimate the sub-fault element ground motions and then combine the sub-fault element ground motions to estimate the mainshock ground motions.

E.2.3 Estimation of Sub-Fault Ground Motions

The sub-fault element ground motion is computed by lagging and summing a number of subevent ground motions.

The number of subevents summed in each sub-fault element is given by the ratio of the mainshock and subevent rise-times. The subevent rise time is estimated as part of the modeling of the subevent that was needed to determine its moment and mechanism. The mainshock rise-time is estimated from empirical relations developed by Somerville (1991):

$$\log_{10} \text{Rise} - \text{Time(sec)} = -8.76 + \frac{1}{3} \log_{10} M_o$$

The number of subevents per sub-fault element, N_{sub}, is given by

$$N_{sub} = RT \frac{RT_{MS}}{RT_{sub}}$$

The sub-fault element ground motions are computed by summing the lagged The delay time for the i^{th} subevent is given by

$$LagTime_i = (i-1)RT_{sub} + \varepsilon$$

where e is a random variable from a normal distribution with mean 0 and standard deviation of $RT_{sub}/6$. The stochastic component to the time lags is included to avoid building up periodicities in the ground motion. The amount of variability was determined by trial and error during initial calibration of the method.

For each of the N_{sub} ESF required to be summed, a separate sampling of the ESF library is made. Therefore, the N_{sub} ESF used to estimate the sub-fault element ground motion are not necessarily the same.

E.2.4 Estimation of Mainshock Ground Motions

A stochastic component is included in the slip velocity at a point and in the rupture velocity to simulate the complexities in the rupture dynamics.

Large scale asperities are introduced by varying the slip distribution over the fault surface. The slip distribution is developed in the wavenumber domain. The Fourier amplitude of the slip distribution is modeled by two Butterworth filters (along strike and down dip). The corner wavenumbers of the filters were estimated from 12 events (Somerville, 1991) with estimated slip models and are give by:

$$\ln kcx = 6.08 - 1.6M$$

$$\ln kcy = 6.69 - 1.6M$$

where kcx is the corner wavenumber along strike and kcy is the corner wavenumber downdip. The number of poles for both filters is 1.4. The phase angles are computed from tapered noise that is uncorrelated at high wavenumbers and but are partially correlated at low wavenumbers. The tapers along the edges and down-dip were also developed from the analysis of the 12 events (Somerville, 1991).

The hypocenter is randomly located in the bottom half of the rupture plane, excluding 10% of the rupture length at each end.

The rupture velocity is taken as 80% of the shear-wave velocity at the hypocenter. The rupture time for each fault element is determined from the average of the time at which the rupture first reaches and last exists the element: $(t_a + t_b)/2$ in Figure 3. A stochastic component is also included in the rupture time for each element to simulate the complexities in the rupture dynamics. The stochastic component is a random sample from a normal distribution with mean 0 and standard deviation of $(t_b - t_a)/6$.

Scale factor for each sub-fault element are computed based on the ratio of the mainshock and subevent moments and the slip distribution. The scale factor the sub-fault element ij is given by

$$\mathrm{Scale}_{ij} = \frac{M_o^{MS}}{N_{sub} M_o^{sub}} \frac{\mathrm{Slip}_{ij}}{\sum_{i=1}^{nx} \sum_{j=1}^{ny} \mathrm{Slip}_{ij}}$$

where N_{sub} is the number of subevents per sub-fault element; nx and ny are the number of sub-fault elements along strike and along dip, respectively; slip_{ij} is the slip distribution; M_o^{MS} and M_o^{sub} are the seismic moments for the mainshock and subevent, respectively.

Using these scale factors and lag times, the sub-fault element ground motions are summed to give the mainshock ground motion.

E.3 SUMMARY

The empirical source function method is a generalization of the EGF method that allows it to be applied to regions and source mechanism for which there are insufficient data to use the EGF method. A consequence of this generalization, is that the method is much more complex than the EGF method.

The strengths and weaknesses of the method are outlined below.

Strengths

- Ability to transfer EGF to other regions and sources

  The ability to transfer EGF to other regions and sources is the main strength of the method. This feature makes the method practical to use for most engineering problems.

- Empirical representation of the radiation pattern

  There is still disagreement about the degree to which the theoretical radiation pattern should be included in ground motion simulations at moderate frequencies. Some procedures include the theoretical radiation pattern at all frequencies, others use a "water level" approach, and others use a fixed constant. The empirical source function method avoids this issue by incorporating an empirical representation of the radiation pattern.

- Tested against EUS and WUS data

  The model has been tested against recorded earthquake ground motions in both the EUS and the WUS. As part of these tests, the model bias and modeling uncertainty (aleatory uncertainty) have been estimated. The model generally shows unbiased predictions of the data over the frequency band of 2-30 Hz.

Weaknesses

- Difficult to Use

  This model is much more difficult to use than other methods. The development of the ESF takes a substantial effort.

- Large number of source parameters required

  There are many more source parameters required compared to a simple model such as the stochastic model. Properly treating the variability and correlations between theses source parameters is difficult.

- Some site effects are folded into the ESF

  The detailed site response is not removed from the EGF. Therefore, some of the site response effects remain in the ESF and are incorporated in the predicted ground motions for a new site.

- Sensitive to the selection of the event and recordings to use as EGF

  The selection of the event used for the EGF can have a significant effect on the ground motions. The source parameters of the selected event (e.g. stress-drop) are assumed to apply to the new region and/or new source.

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APPENDIX F

CHARACTERIZATION OF UNCERTAINTY IN GROUND-MOTION PREDICTIONS

by

Gabriel R. Toro

F.1 INTRODUCTION

This appendix expands on the characterization of uncertainty in ground-motion that was presented in Section 5.5. The presentation begins with an illustration of the various types of uncertainty, by considering a simplified setting and then moving to a more realistic setting. This is followed by an illustration of the characterization of uncertainty in the context of various physical and empirical ground-motion models, and how the quantification of parametric uncertainty depends on the application. This is followed by an example showing the steps in the quantification of uncertainty for a stochastic ground-motion model. Finally, this appendix provides examples showing the effect of aleatory and epistemic ground-motion uncertainties on the calculated hazard.

F.2 UNCERTAINTY CHARACTERIZATION: SIMPLIFIED SETTING

Consider first the hypothetical situation in which there are thousands of records from earthquakes in the region of interest, all having the magnitude (m_x), same distance (r_x), and same site category (s_x) for the prediction at hand. Given these data, we can compute the true value of the mean ln[ground-motion amplitude] at a certain frequency as

$$\ln[Amplitude]_{\text{true mean}} = \frac{1}{N}\sum_{i=1}^{N} \ln[Amplitude]_{\text{observed}, i} \tag{F-1}$$

where N is the number of records. One can also compute the true standard deviation associated with aleatory uncertainty (which is due to aleatory variations in all source, path, and site factors other than region, magnitude, distance, and site category) from the observed scatter as

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(\ln[Amplitude]_{\text{observed}, i} - \ln[Amplitude]_{\text{true mean}}\right)^2} \tag{F-2}$$

Assume also that we have a deterministic predictive model (e.g., a physical model, a stochastic model[1], or an empirical attenuation function) of the form:

$$\ln[Amplitude]_{\text{pred}} = f(m, r, \text{ site category; } \boldsymbol{P}) \tag{F-3}$$

where $\boldsymbol{P}$ is a vector of explicit model parameters (e.g., stress drop, focal depth, slip distribution, etc.) and that we know the parameter values $\boldsymbol{P}_i$ for each record. Because the predictive model does not include all physical processes and parameters affecting ground motions, the predicted amplitude for a given record will likely differ from the observed amplitude, even if we have perfect knowledge of the parameters $\boldsymbol{P}_i$ for that event. Moreover, the predictive model may have a bias (i.e., a tendency to over- or under-predict observations), so that the mean of the predictions from all events may differ from the true mean value given by Equation F-1. The bias in the predictive model can be evaluated by comparing observations and predictions for the available recordings for the same magnitude, distance, and site category of interest; i.e.,

[1]We consider "stochastic" ground-motion models (e.g., Hanks and McGuire, 1981; Boore, 1983) as deterministic models, because they are typically used to predict only the mean value of ln[amplitude].

$$\mu = \frac{1}{N}\sum_{i=1}^{N}\left(\ln[Amplitude]_{\text{observed, } i} - f(m_x, r_x, s_x;\ \boldsymbol{P}_i)\right) \tag{F-4}$$

or

$$\mu = \ln[Amplitude]_{\text{true mean}} - \frac{1}{N}\sum_{i=1}^{N} f(m_x, r_x, s_x;\ \boldsymbol{P}_i) \tag{F-5}$$

Knowing the model bias, we can construct a bias-corrected model[2]

$$\bar{f}(m_x, r_x, s_x;\ \boldsymbol{P}_i) = f(m_x, r_x, s_x;\ \boldsymbol{P}_i) + \mu \tag{F-6}$$

By considering the unbiased model, it is possible to decompose the aleatory uncertainty given by Equation F-2 into two parts, as follows:

a) A **parametric** portion, representing scatter that can be explained in terms of the model parameters in vector ***P*** (e.g., some events have high stress drop, some have low stress drop).

b) A **modeling** portion, representing those physical processes not explicitly included in the deterministic model (e.g., crustal heterogeneity, P waves).

In terms of this decomposition, Equation F-2 is re-written as[3],

[2]Here, we assume that the bias is the same for all magnitudes, distances, site conditions, and values of ***P***. We will return to this issue later.

[3]We assume that the predictive model's dependence on the parameters in vector ***P*** is correct.

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\begin{array}{l} \frac{1}{N}\sum_{i=1}^{N}\left(\bar{f}(m_x, r_x, s_x; \boldsymbol{P}_i) - \ln[Amplitude]_{\text{true mean}}\right)^2 + \\ \frac{1}{N}\sum_{i=1}^{N}\left(\ln[Amplitude]_{\text{observed},\, i} - \bar{f}(m_x, r_x, s_x; \boldsymbol{P}_i)\right)^2 \end{array}} \quad \textbf{(F-7)}$$

where the first summation represents aleatory parametric uncertainty and the second summation represents aleatory modeling uncertainty. Assuming that we know the distribution of $\boldsymbol{P}$ in our data set, the parametric term may be computed analytically as an expectation over the parameter values, obtaining

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\begin{array}{l} E_{\boldsymbol{P}}\left[\left(\bar{f}(m_x, r_x, s_x; \boldsymbol{P}) - \ln[Amplitude]_{\text{true mean}}\right)^2\right] + \\ \frac{1}{N}\sum_{i=1}^{N}\left(\ln[Amplitude]_{\text{observed},\, i} - \bar{f}(m_x, r_x, s_x; \boldsymbol{P}_i)\right)^2 \end{array}} \quad \textbf{(F-8)}$$

At this point, we can make several observations about aleatory uncertainty and its partition into parametric and aleatory uncertainty.

1. The value of the aleatory uncertainty given in equations F-2 and F-8 is determined by the physics of seismic sources and wave propagation and by our choice of ground-motion measure and explanatory variables. Given a choice of ground-motion measure and explanatory variables, there is nothing arbitrary about the aleatory uncertainty. There are only three ways to change the value of the aleatory uncertainty, as follows: (1) by changing the ground-motion measure (e.g., switching from spectral acceleration to average spectral acceleration over a frequency band), (2) by changing the explanatory variables (e.g., using a different magnitude scale, adding source depth as an explanatory variable), or (2) by re-defining the distribution of the parameters in $\boldsymbol{P}$ (e.g., deciding that we are only going to consider ground motions coming from thrust earthquakes). In practice, one may obtain different estimates of aleatory uncertainty

(as we will see later), due to limitations in the data or deficiencies in the model. In principle, however, the aleatory uncertainty for given m_x, r_x, and s_x is fixed.

2. The partition between aleatory-parametric and aleatory-modeling uncertainty is model-dependent. If one reduces the scatter between observations and predictions by making the model more complete, one introduces new parameters in the model. Unless these parameters are known a priori for future earthquakes, there will be an increase in parametric uncertainty and the total aleatory uncertainty will be maintained. A reduction in modeling uncertainty may be beneficial, nonetheless, if it allows the incorporation of site-specific information through an updated (typically narrower) site- or region-specific distributions of ***P***.

3. The above discussion assumes that the predictive model's dependence on the parameters in vector ***P*** is correct. If the model exaggerates the effect of a parameter, both terms in Equation F-8 become inflated, and the quantity in Equation F-8 is larger than that in Equation F-2.

In reality, the available ground-motion data are limited. The number of available records for the magnitude, distance, and site category of interest (i.e., m_x, r_x, s_x) is small at best. Assume, for the moment, that we have a small number n of records for (m_x, r_x, s_x) . We can apply an equation analogous to Equation F-4 (but with the smaller sample size) to estimate the model bias; i.e.,

$$\hat{\mu}=\frac{1}{n}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed, } i}-f(m_x,r_x,s_x;\ \boldsymbol{P}_i)\right) \quad \textbf{(F-9)}$$

but this estimate of the bias has statistical uncertainty because n is small. The resulting uncertainty in

$$\tilde{f}(m_x,r_x,s_x;\ \boldsymbol{P}_i)=f(m_x,r_x,s_x;\ \boldsymbol{P}_i)+\hat{\mu} \quad \textbf{(F-10)}$$

is epistemic modeling uncertainty.

Limitations in the data also introduce a parametric component of epistemic uncertainty in physical ground-motion models: we do not know the true distributions of model parameters $\boldsymbol{P}$, particularly their central tendencies. (e.g., we do not know the median stress drop for the region of interest). Thus, epistemic parametric uncertainty arises when we compute the mean ln-amplitude as

$$\ln[Amplitude]_{pred.\ mean} = E_P\left[\tilde{f}(m_x, r_x, s_x;\ \boldsymbol{P}_i)\right] \qquad \textbf{(F-11)}$$

using uncertain distribution parameters for $\boldsymbol{P}$. Returning to the example of stress drop, the extent of this uncertainty depends on the uncertainty in the median stress drop and on the sensitivity of $f(m_x, r_x, s_x;\ \boldsymbol{P})$ to stress drop.

There is also epistemic uncertainty associated with the estimated $\sigma_{\ln[\mathrm{Ampl.}],\mathrm{aleatory}}$ because the modeling uncertainty is estimated using a small number of records and because there is statistical uncertainty about the distribution of $\boldsymbol{P}$ (particularly their standard deviations).

In practice, the data are so limited that one is required to pool data from multiple magnitudes, distances, and site categories, in order to estimate the bias and the aleatory modeling uncertainty. In doing this, there is the implicit assumption that the predictive model $f(m,r,\text{site category};\ \boldsymbol{P})$ is equally good, and has the same bias, for the magnitudes, distances, and site categories represented in the data as for (m_x ,r_x ,s_x). This assumption introduces additional epistemic uncertainty, especially when there are few data near (m_x ,r_x ,s_x). This epistemic uncertainty can be incorporated in two ways, as follows: (1) by considering alternative models, and (2) by allowing the bias and aleatory modeling uncertainty to be magnitude-,distance-, or site-dependent.

This partitioning of aleatory uncertainty into its parametric and modeling components is not necessary, but some investigators consider it useful when working with physically based models. One advantage of physical models and the parametric/modeling partition presented here is that one can use a variety of data sets, possibly from different regions, thus alleviating the problems caused by the absence of data at (m_x, r_x, s_x). If one is developing a ground-motion model for a region with limited data, one can use strong-motion data (coming mostly from California) to estimate the bias and aleatory modeling uncertainty. One can also use regional or teleseismic seismograph data to estimate the distribution of model parameters such as stress drop and anelastic attenuation, and then use the model to calculate the associated parametric uncertainties. The example application to be illustrated in Section F.4 will illustrate this process in more detail. If, on the other hand, data at or near (m_x ,r_x ,s_x) are abundant in the region of interest, empirical methods provide a more direct method for the characterization of ground motion and its uncertainty. Another advantage of physical models and the parametric/modeling partition is that it allows the incorporation of site-specific information in the form of site- or region-specific distributions for the parameters in ***P***.

F.3 ILLUSTRATIONS OF PARAMETRIC AND MODELING UNCERTAINTY

The examples that follow illustrate the definition of parametric and modeling uncertainties for various ground-motion models. These models are used to predict ground-motion in the usual manner required for seismic-hazard analysis (i.e., using magnitude, distance, and possibly site conditions as the only explanatory variables). The models are presented in decreasing order of physical detail. For the sake of simplicity, site effects are not considered in this discussion.

F.3.1. Extended-Source Models.

Extended-source models contain a kinematic representation of the generation of seismic energy along the rupture surface and a model of wave propagation through the crust (typically assuming a flat-layered crustal structure). A description of these models is given in Appendix E. Examples of this kind of models are given by Wald et al. (1988) and Herrmann and Jost (1988). Here, unlike the above two references, we consider the case in which the model is used to predict ground-motions as a function of moment magnitude and distance, rather than the situation where the location of the site relative to the rupture (or at least to the fault) is fixed.

The following are parameters that are explicitly included in the physical ground-motion model:

1. <u>Source Parameters</u>: rupture dimensions*, slip distribution, hypocentral location, rupture velocity*, rise time*, slip time-function*, rake angle;
2. <u>Geometry</u>: rupture location, azimuth of site relative to rupture;
3. <u>Wave Propagation</u>: Crustal S-wave velocity structure (typically 1-D), anelastic attenuation (Q)*;

Those parameters that are treated as varying randomly from event to event or from site to site contribute to parametric uncertainty. In order to quantify the contribution of a parameter to the aleatory uncertainty in the predicted ground motions, one must first specify the parameter's probability distribution (aleatory). More precisely, one must specify the <u>joint</u> probability distributions of all such parameters, given magnitude and distance. Uncertainty in the specification of these parameters, due to incomplete data or alternative interpretations of the data, contributes to epistemic parametric uncertainty.

Those parameters that are present in the model but are assumed constant or are assumed to be <u>deterministic</u> functions of the explanatory variables and of other parameters, do not contribute to parametric uncertainty. Any deficiencies in these assumptions will contribute to modeling uncertainty and are captured by comparing predictions to observations (to the extent that the data used to quantify modeling uncertainty covers a wide enough range of conditions). The asterisks in the above list indicate those parameters that were treated as constant or deterministic by Wald et al. (1988).

Physical phenomena that are not included in the model (e.g, site effects, complexity of energy release at the source, non-uniform rupture velocity, deviation from a flat-layered crust, wave scattering due to small-scale crustal heterogeneity) also contribute to modeling uncertainty and are captured by comparing predictions to observations.

F.3.2. Point-Source Stochastic Models.

Point-source stochastic models use a simple frequency-domain representation of seismic energy release at the source. The representation of wave propagation may explicitly include the effect of crustal velocity structure (e.g., Ou and Herrmann, 1990), or it may consist of a more simplified representation (Herrmann, 1985). An example of this model is the EPRI (1993) ground-motion model, which forms the basis for this example. As in the above example, we consider the case in which the model is used to predict ground-motions as a function of magnitude (moment magnitude or m_{Lg}) and horizontal distance.

The following parameters are specifically included in the point-source stochastic ground-motion model:

1. Source Parameters: seismic moment, stress drop, asperity depth (i.e., depth at which the point source is located);

2. Geometry: horizontal distance to asperity;

3. Wave Propagation: Crustal S-wave velocity structure (typically 1-D), anelastic attenuation (Q), site kappa;

In the EPRI study, all parameters in the above list (except crustal velocity structure) were treated as uncertain. The effect of crustal velocity structure is captured as modeling uncertainty (to the extent that the data used to quantify modeling uncertainty samples the variations in crustal structure within the study region).

The effects of those parameters that appear in the extended-source model but do not appear in the stochastic point-source model (e.g., slip distribution, rake angle, rupture velocity, rupture location, site azimuth, etc.) are captured as modeling uncertainty.

Physical phenomena that are not included in this model or the extended-source model (e.g, complexity of energy release at the source, non-uniform rupture velocity, deviation from a flat-layered crust, wave scattering due to small-scale crustal heterogeneity) are also captured as modeling uncertainty.

F.3.2. Empirical Attenuation Equations.

In most cases, the functional form of the attenuation equation is based on physical considerations. Thus, the difference between empirically derived attenuation equations and the physical models described earlier may not be as large as it first appears (the main difference relates to how parameters are interpreted and estimated; i.e., which data are used and how they are used).

In an empirical attenuation equation, the empirically derived coefficients of the attenuation equation take the role of parameters. They have no aleatory uncertainty, however, because they are assumed to be the same for all events.

The empirically derived coefficients have epistemic uncertainty, representing statistical uncertainty associated with sample size. The statistical uncertainty in the coefficients is routinely calculated as part of the regression calculations. The calculated statistical uncertainty is typically very small, however, and is not representative of the true epistemic uncertainty. This is likely the result of ignoring correlations in the data and of under-parameterization. In practice, additional epistemic uncertainty is introduced by considering attenuation equations developed by various investigators, who use somewhat different data sets (which may differ in their data-selection criteria or in their interpretations of the data), functional forms, and fitting procedures.

If the attenuation equation contains explanatory variables other than magnitude and distance (e.g., depth to basement, average shear-wave velocity in the upper 30 m, soil category, style of faulting), which are not known with certainty for the seismic sources and site of interest, one must consider parametric uncertainty. To the extent that a parameter is constant (though, perhaps, unknown) for the site and seismic sources of interest, uncertainty in that parameter is epistemic. To the extent that a parameter is expected to vary from event to event, uncertainty in that parameter is aleatory. As in physical models, there is a trade-off between modeling and parametric uncertainty: if a physical parameter is added, modeling uncertainty is reduced but parametric uncertainty is increased. The total uncertainty is reduced only when the parameter's distribution is narrowed.

Modeling uncertainty is characterized by the residual standard deviation obtained from the regression analysis. This modeling uncertainty contains both aleatory and epistemic components (though one may, at first thought, think it is all aleatory). Some of this uncertainty is associated with local site conditions (beyond the site characterization used in the attenuation equation) and with regional variations in crustal structure and in Q, and could be resolved with additional data. For instance, if one has ten or more strong-motion recordings at the site of interest, one should be able to obtain refined predictions for that particular site (with lower modeling uncertainty and with somewhat higher or lower median predictions), by combining the regional predictions from the attenuation equation and the site-specific observations. Also, one would not treat data from that site in the same way as data from other sites in the same region. In practice, however, this distinction between the aleatory and epistemic components of the residual standard deviation is difficult to make and the standard deviation is considered all aleatory.

F.3.3 Application-Dependent Nature of Parametric Uncertainty.

So far, we have seen how the probability distributions representing parametric uncertainty depend on the model being used (e.g., physical vs. stochastic vs. empirical). In addition, these distributions may also depend on the type of application being performed and on how the integration tasks are divided between the ground-motion analyst and the seismic-hazard analyst. All these issues affect the calculated uncertainty. These issues are best explained by means of several examples.

Consider, as a first example, the application of an extended-source model to develop fault-specific attenuation equations for a site in which the fault-site geometry is fairly well known (e.g., the San Andreas fault and a site in the San Francisco peninsula). The ground-motion analyst will know the fault dip (to within 10 to 20 degrees), style of faulting, on which side of the fault the site is located, and many other parameters. Thus, many of the parameters related to the site-fault geometry will be fixed or will have narrow distributions. The ground-motion analyst will still have to consider multiple locations of the rupture (as the independent variable) and multiple nucleation-point locations within that rupture[4] (as parameters to integrate over) and report amplitude and uncertainty as a function of magnitude and rupture location. The seismic-hazard analyst would integrate over magnitude and rupture location to obtain the hazard.

Consider now the application of the same extended-source model to the development of a generic attenuation equation (using distance to the rupture as the distance metric) for the same region where the site is located. The model parameters are the same as in the previous application, but the ground-motion analyst will have to integrate over more parameters or over wider distributions of these parameters. For instance, the ground-motion analyst will have to consider much wider distributions of dip angle and style of faulting, he will have to consider sites on either side of a dipping fault, etc. Because the seismic-hazard analyst wants results as a function of magnitude and rupture distance, he will have to integrate over all these parameters, and also over rupture location given rupture distance, to obtain a mean prediction and the associated epistemic and aleatory parametric uncertainties. Even though the modeling uncertainty is the same, the total uncertainty will be higher in the second example because the parametric uncertainty is higher.

Consider now the application of the same extended-source model to develop generic attenuation equations for CEUS (using m_{Lg} and hypocentral distance as explanatory variables). Now, because the ground-motion model does not use m_{Lg} or hypocentral distance directly as parameters), the ground-motion analyst must integrate over two more uncertain

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[4]If there were two faults that contribute significantly to seismic hazard at the site, one strike-slip and the other thrust, it would be natural to use different distributions for a number of their parametric uncertainties. Thus, the traditional division of labor between ground-motion modeling (amplitude given M and R, irrespective of seismic source) and characterization of the seismic sources (joint distribution of M and R) may not be appropriate.

quantities: moment magnitude (for given m_{Lg}) and hypocentral distance (for given rupture location).

Finally, consider the EPRI (1993) study described below, where integration over depth was performed as part of the ground-motion modeling (depth is usually taken as fixed or integrated over in the seismic-hazard analysis). The result of this integration is increased parametric uncertainty at distances of 20 km or less (this will be seen in Figure F-9).

In all these cases, the uncertainty (particularly the aleatory uncertainty) will be different because the ground-motion analyst is having to integrate over different distributions of model parameters.

F.4. ESTIMATION OF UNCERTAINTY IN GROUND-MOTION MODELS

This section provides more details on how the various components of uncertainty are calculated in the context of physical models. The EPRI work on the stochastic model will be the basis for this presentation, with more general comments where appropriate.

F.4.1. Modeling Uncertainty.

Modeling uncertainty is quantified by comparing model predictions to actual observations. For each event and record modeled, one finds the values of the free model parameters (i.e., those model parameters without asterisks or obvious physical constraints in the above section) that minimize the sum of squared differences between predicted and observed amplitudes[5],

[5]It is typical to consider Fourier amplitudes, rather than spectral accelerations, in the minimization (inversion) process to determine the optimal parameter values, even though the engineering predictions are made for (pseudo) spectral acceleration. One reason for this is that the spectral acceleration at frequency f may be driven by energy at much lower frequencies.

summed over the frequency range of engineering interest. The sampling on frequency may be arithmetic or logarithmic, thereby giving more or less weight, respectively, to high frequencies. The optimal parameter values should, of course, be physically reasonable. Sometimes, independently derived parameter values are used. The amplitudes considered are log spectral accelerations over the frequency range of engineering interest.

Using the residuals $\varepsilon_{ij}(f)$ (observed–predicted amplitude at frequency f), one then obtains the model bias

$$\mu(f)=\frac{1}{n}\sum_{i\ (\text{events})}\sum_{j\ (\text{sites})}\varepsilon_{ij}(f) \tag{F-12}$$

and the bias-corrected variance

$$\sigma_{\varepsilon}^{2}(f)=\frac{1}{n-1}\sum_{i\ (\text{events})}\sum_{j\ (\text{sites})}\left(\varepsilon_{ij}(f)-\mu(f)\right)^{2} \tag{F-13}$$

where n is the number of records used in the process.

The EPRI (1993) characterization of modeling uncertainty used data in the magnitude-distance range of engineering interest, coming from a mixture of ENA and California earthquakes (i.e, Saguenay, Nahanni, Loma Prieta and Whittier Narrows). Figure F-1 shows the bias as a function of frequency for the EPRI stochastic model. It shows that the bias is essentially zero for frequencies above 3 Hz and negative (i.e., conservative) for lower frequencies. Because the bias was negligible or negative, the model predictions were not corrected for bias. Figure F-2 shows the aleatory modeling uncertainty (dashed line; labeled "Modeling Randomness"), which is estimated as $\sigma_{\varepsilon}(f)$.

The epistemic uncertainty of the EPRI model was computed from the bias and the site-to-site variance of the "D terms," which represent frequency-independent site terms obtained during the inversion process (further details and motivation for the D terms are provided in Section 3 of EPRI, 1993). Figure F-2 also shows the total modeling uncertainty (i.e., $[\text{aleatory}^2+\text{epistemic}^2]^{1/2}$, solid line; labeled "Modeling Randomness and uncertainty").

The computation of the modeling epistemic uncertainty merits discussion. Setting aside the D terms, one can say that the modeling epistemic uncertainty may be computed from the model bias, the statistical uncertainty in the bias, or both. An intuitive justification for using the bias as an indication of modeling epistemic uncertainty is that a large bias (whether positive or negative) detracts from the model's credibility (one may interpret this as a prior belief or expectation that the model bias would turn out to be zero or small). A problem with this argument is that it suggests that if the model over-predicts the data using one data set, it is not unlikely that it will under-predict the data by roughly the same amount if we use another data set. This approach suggests that one should not correct the model for bias.

Alternatively, one can take an empirical position and view the bias as a calibration constant to be determined from the data (with no meaning assigned to its actual value). Then, it follows that the modeling epistemic uncertainty should be calculated as the statistical uncertainty in the bias. Care should be taken, however, to account for correlation in the data when calculating the statistical uncertainty, because this correlation reduces the number of effective degrees of freedom[6]. This is the approach implied in Section F-2 and is perhaps the most widely accepted approach; it suggests that one should correct the model for bias.

F.4.1. Parametric Uncertainty

The quantification of parametric uncertainty in ground motions consists of two steps, as follows:

1. Quantification of the uncertainty (both aleatory and epistemic) in the model parameters.

[6]For instance, considering the residual ϵ_{ij} as the sum of an inter-event and an intra-event component, all recordings from the same event will be correlated because they share the same value of the inter-event term. A similar situation arises with recordings at the same site from several earthquakes.

2. Propagation of uncertainties in model parameters into uncertainty in ground-motion amplitude. Again, this must be done for both aleatory and epistemic uncertainty.

The uncertainty in free model parameters is obtained from the "observed" values of these parameters in the events and recordings investigated. As with the calculation of modeling uncertainty, the process involves finding optimal values of the free model parameters, so that the best fit between model and observations is obtained (this is what seismologists call inverting for the parameters). Then, instead of focusing on the misfit between model and observations, one focuses on the event-to-event and site-to-site variation of the parameters.

The observed variation in the parameters (e.g., event-to-event variation in stress drop) is used to characterize the aleatory parametric uncertainty. The associated statistical uncertainty (e.g., uncertainty about the median stress drop in ENA) represents epistemic uncertainty. One should also characterize probabilistic dependencies, if indicated by the parameter observations. Because the parameters are not directly observed, but are inferred from an inversion, it may be necessary to consider the uncertainty associated with each "observation," and the correlations that arise when the inversion procedure has trouble resolving between two parameters.

Ideally, these calculations should be performed with the same data set used in the calculation of modeling uncertainty; this would guarantee that there is no double-counting of uncertainties. In practice, this is not always possible due to limitations in the availability of data, particularly for the magnitude-distance combinations that dominate seismic hazard. One often has to use different data sets to estimate different parameters, use independently determined parameter values, use subjective probability assessments, or a combination of these.

The EPRI (1993) study considered the following free model parameters: stress drop, asperity depth, anelastic attenuation (Q), and near-site anelastic attenuation (κ) (recall Section F.3.2). Different data sets were used to characterize uncertainty in stress drop, and κ. The characterization of Q used results from inversions, together with published results for the region, and subjective weights.

The characterization of stress drop and its uncertainty considered the following two data sets:

1. Atkinson's (1993) data set of estimated high-frequency stress-parameter[7] values for 21 ENA main events (See Figure F-3). Estimates for events since 1982 were obtained by fitting model predictions of Fourier amplitude to the observed Fourier amplitudes from regional recordings. Estimates for earlier events used intensity data. The calculated logarithmic-mean stress drop is 120 bars (with a statistical uncertainty of $\times e^{\pm 0.16}$); the logarithmic standard deviation is 0.71.

2. Estimates of Brune stress drop[7] obtained by inverting near-source recordings from 12 earthquakes in ENA (Figure F-4). The calculated logarithmic-mean stress drop is 145 bars ($\times e^{\pm 0.16}$); the logarithmic standard deviation is 0.86. Neither data set shows a tendency towards stress drops increasing with moment magnitude.

The Atkinson (1993) data set is used to formulate the model predictions because the high-frequency stress parameter is more directly related to high-frequency ground motions and because this data set contains a better sampling of larger events. Recognizing that there are few events above magnitude 6 (these events have, in fact a lower median and lower scatter than the other events), the epistemic uncertainty in stress drop is taken to be higher for **M**>6, while keeping the total parametric uncertainty constant (see Figure F-5)[8].

The distribution of focal depth was constructed from several compilations of focal depth for

[7]The high-frequency stress-parameter and the Brune stress drop represent two ways of calculating the stress drop $\Delta\sigma$ that appears in the stochastic model. The former is calculated by fitting only the flat high-frequency portion of the source spectrum above the "corner frequency"; the latter is calculated by fitting the Fourier spectrum over a wider range (this range is limited by noise and by instrument-response characteristics).

[8]This may be viewed as partially relaxing the assumption of magnitude-independent stress drop for the higher magnitudes. The reduction in aleatory uncertainty with increasing magnitude is consistent with the experience in California.

earthquakes in CEUS and in similar tectonic environments. Statistically significant differences were found between plate margins (portions of the crust near the continental/oceanic transition zone) and other areas of the stable-continental crust. The distribution used in the ground-motion simulations is based on the pooled data from both regions (Figure F-6).

Uncertainty in Q was specified by means of three alternative Q models for each geographic region (see Figure F-7), with equal weights. These models nearly cover the range of Q models in the literature.

The median value of κ for CEUS hard rock was estimated as 0.006 sec, obtained by fitting the observed shape of the normalized response spectrum at high frequencies. The associated uncertainty in $\ln(\kappa)$ was estimated as 0.4, based on 20 rock recordings from the Loma Prieta earthquake. Uncertainty in κ is conservatively represented by three equally likely values of 0.003, 0.006, and 0.012 (this discrete distribution has 50% higher uncertainty than estimated).

In the EPRI study, all uncertainty in depth, Q, and kappa is taken as aleatory[9]. This inconsistency does not introduce a large error because these parameters (with the exception of depth at short distances) have only a modest effect on the uncertainty in ground-motion amplitude at frequencies below 10 Hz (as we will show below).

The EPRI example shows how one can use a variety of data sources to characterize uncertainty in the parameters of a physical ground-motion model.

The propagation of parameter uncertainties into uncertainties in ground-motion amplitudes is

[9]This assumption is equivalent to assuming that the ground-motions will be predicted for an ENA hard-rock site chosen at random; hence; site-to-site variability (within the same "hard-rock" classification), and regional variation in depth and Q are treated as aleatory. Within a strict perspective on epistemic and aleatory uncertainty, this would not be appropriate for a site-specific application. This is recognized in Section 9 of EPRI (1993). Section F-5 contains guidance for site-specific applications.

one of derived distributions. Because of the partition of uncertainty into its epistemic and aleatory components, the problem is actually one of two nested derived-distribution problems. If we represent the epistemic and aleatory portions by logarithmic means and a standard deviation, the problem is greatly simplified, as shown in Section 5.5.2.

It is useful to display the various contributions to aleatory and epistemic uncertainty. Figure F-8 shows the various contributions to aleatory uncertainty as a function of distance and magnitude, for spectral acceleration at 1 and 10 Hz. Depth is an important contributor to aleatory uncertainty at distances of 5 km or less. Stress drop and modeling uncertainty are equally important at small distances. Modeling uncertainty is more important for 1 Hz than for 10 Hz; stress drop is more important for 10 Hz than for 1 Hz. Q is of little importance at distances less than 100 km; κ is unimportant at all distances. Q and κ become more important at 25 Hz (not shown).

Similarly, Figure F-9 shown the contributions to epistemic uncertainty, as well as the total uncertainty, as a function of magnitude. The epistemic uncertainty is higher for higher magnitudes, due to the higher epistemic uncertainty in the median stress drop.

F.5. PARAMETRIC UNCERTAINTIES: SITE-SPECIFIC PERSPECTIVE

The characterization of parametric uncertainty adopted in the EPRI (1993) work described above, and in most other ground-motion studies, treats systematic intra-region geographic variation[10] in a parameter as aleatory uncertainty. This is done because the available data make it difficult to differentiate intra-region geographic variation from other, less predictable, forms of uncertainty. If one takes the perspective of a given site (which is the appropriate

[10]One example of this systematic intra-region variability would be a difference in geometric and anelastic attenuation between northern and southern California, which would cause an increase in the residual standard deviation obtained in regression studies. A similar situation arises for intra-category variation in relation to site response (e.g., variations in kappa among hard rock sites).

perspective in nearly all situations), the intra-region geographic variation becomes epistemic uncertainty because it can be reduced with the collection and analysis of data at a more local scale. These new data would be anticipated to yield parameter distributions that are tighter than the generic distributions used in the EPRI study and to have median values within the one-sigma ranges of the generic medians. These site-specific distributions would result in lower aleatory uncertainty and in median attenuation equations that are somewhat different from the generic EPRI results.

This section illustrates how site-specific data could be incorporated and used to derive new attenuation functions that reflect these site-specific data.

The availability of site-specific data (or, more generally, data collected at a smaller geographic scale) about a parameter will resolve some or all the epistemic uncertainty in the parameter. This will typically translate into smaller epistemic standard deviation and a median value that is different from the original median. In practice, the amount of site-specific data may not be large, so it may be best to combine the site-specific data and the generic distribution[11].

Focal Depth. Site-specific investigations of hypocentral depth would focus on the tectonic province where the site is located. Because the distribution of depth depends on the location of the site (margins vs. others), site-specific information on depth is always available (as long as one knows the coordinates of the site and its surrounding seismic sources). If the nearby seismic sources affecting the site are located in the coastal margin, one should use the depth distribution for margins. If they are located elsewhere in CEUS, one should use the depth

[11] If only the site-specific data are used, the associated statistical uncertainty may be very large because of the small sample size. On the other hand, one does not want to simply pool the generic and site-specific data, because the site-specific data are more relevant to the site. What one needs is a procedure that properly weights the site-specific and generic data. For instance, the site-specific data set should receive more weight if it shows less scatter or if its sample size is increased by gathering additional site-specific data. Appendix 6A of EPRI (1993) provides an example of combining site-specific and generic information, using a procedure that is loosely based on empirical Bayes methods.

distribution for "others" (see Figure F-10). If the site is near the boundary between the two regions, one should use the pooled distribution in Figure F-6. Statistical (epistemic) uncertainty arises at sites located in a margin because the data set is small.

Q. Site-specific investigations of Q would focus on a radius of 100 to 500 km around the site, with the choice of radius being dictated by the distances to the seismic source zones that contribute to seismic hazard at the site. The regionalizations by Singh and Herrmann (1983) and Gupta et al. (1989) provide a starting point for the development of site-specific values of Q. The following example uses results from these two studies to obtain site-specific estimates of Q for a site in south-eastern Wyoming. Figure F-11 shows the estimates of Q from these two studies (heavy line: Singh and Herrmann; error bars: Gupta et al). Also shown are the three Q models considered in the EPRI (1993) generic calculations (thin lines; given equal weights in the EPRI calculations). Based on these two results, which show values of Q above the median EPRI value, the weights for the three EPRI models are changed to [0.4 (higher Q model), 0.5 (middle), 0.1 (lower)]. The remaining uncertainty (i.e., the uncertainty represented by means of the updated weights) could be treated as aleatory.

Kappa. Site-specific investigations of κ would focus on the local geology of the site and should include any significant variations among locations (buildings) within the site. Information on κ might be obtained from local recordings obtained with a temporary seismograph network, from local measurements of near-surface shear-wave velocity (using, for example, the correlations between velocity and κ developed by Silva, 1991), from local measurements of anelastic attenuation, or from analogies with other sites with similar geology. Changes in κ as a result of site-specific information would affect the predicted amplitudes for high-frequency (> 10 Hz) ground motions and peak ground acceleration. Site-specific parameter information of this type would be incorporated by using the site-specific parameter distributions, instead of the generic distributions, in the propagation of parametric uncertainties. The result would be a new value of the median ground motions, and a likely decrease in the total parametric uncertainty ($[\text{aleatory}^2+\text{epistemic}^2]^{1/2}$). This decrease in parametric uncertainty would be due to a reduction in epistemic parametric uncertainty, but may be labeled as due to a decrease in aleatory parametric uncertainty because of the difficulty in separating geographical variations (which are epistemic) from aleatory uncertainty.

F.6. EFFECT OF GROUND-MOTION UNCERTAINTY ON HAZARD RESULTS

In most modern seismic hazard studies, aleatory and epistemic uncertainties (in magnitudes, locations, and ground-motion amplitude) are treated separately in the calculations and displayed separately in the results. Aleatory uncertainty is displayed by the shape of the hazard curves. Epistemic uncertainty is displayed by the spread among the fractile hazard curves. (If the epistemic uncertainty is zero, all fractile hazard curves, and the mean curve, coincide.)

This section shows typical hazard results and how these are affected by the epistemic and aleatory uncertainties in ground motions. We present results obtained using the EPRI/SOG (EPRI, 1986, 1988) methodology and inputs, but the observed trends are valid in general. We show results for both PGA and 1-Hz PSV for a New England site (we observed the same general trends for a midwestern site located in a low-seismicity region approximately 500 km away from the New Madrid source zone).

Figures F-12 and F-13 show the effect of the aleatory uncertainty (σ) on the mean and fractile results (without changing the epistemic uncertainty). The thick lines represent results obtained using an aleatory σ of 0.5 (natural log units) for both PGA and 1 Hz. The thin lines represent results obtained using an aleatory σ of 0.6 for PGA (this used to be the rule-of-thumb value) and 0.76 for 1-Hz (Boore and Joyner, 1988).

Results for PGA indicate little difference for hazards of 10^{-4} or greater (the region used for setting design spectra). Differences become important (though not dominant) for the lower hazards that are important in seismic PRA studies. Results for 1 Hz indicate important differences, even near 10^{-4}. This is a result of the higher aleatory σ (other results, not shown here, indicate that we would have obtained the same effect if we had used 0.76 for PGA).

Another related issue is the trade-off between epistemic and aleatory uncertainties (i.e., what happens to the calculated hazard if some contributor to uncertainty is mis-labeled and put in the wrong bin?). One can prove that the mean hazard is unchanged and that the median hazard increases[12], if the aleatory σ is increased while keeping the total (aleatory+epistemic) uncertainty in ground-motions constant.

These results show the importance of proper quantification of aleatory and epistemic uncertainty in ground-motion predictions. Differences greater than 0.1 lead to significant differences in calculated hazard, even for the amplitudes considered in setting design levels. Because epistemic and aleatory uncertainties are treated differently in making design and retrofit decisions, and because the median hazard is sometimes the preferred central measure of hazard due to its stability, it is also important to allocate uncertainties in the proper category.

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[12]The latter results requires (or is easily obtained with) the additional assumption that the total epistemic uncertainty in hazard is lognormal.

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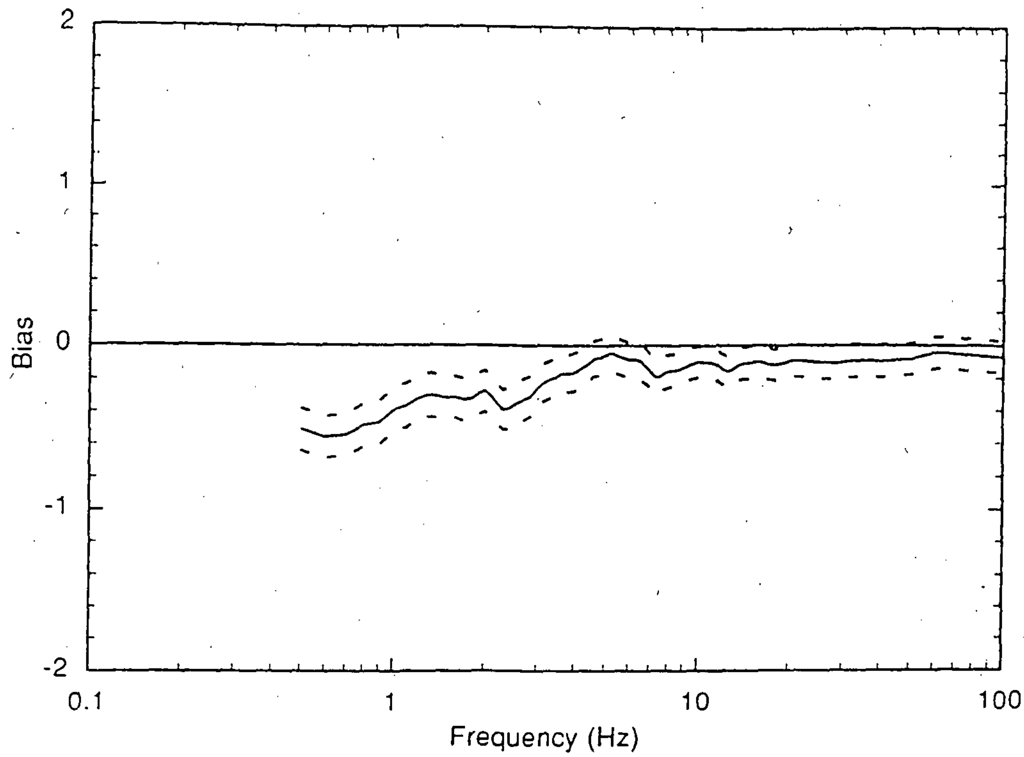


Figure F-1. Modeling bias for the EPRI (1993) stochastic model, obtained using 61 recordings from four events. Dashed lines indicate 90% confidence limits.

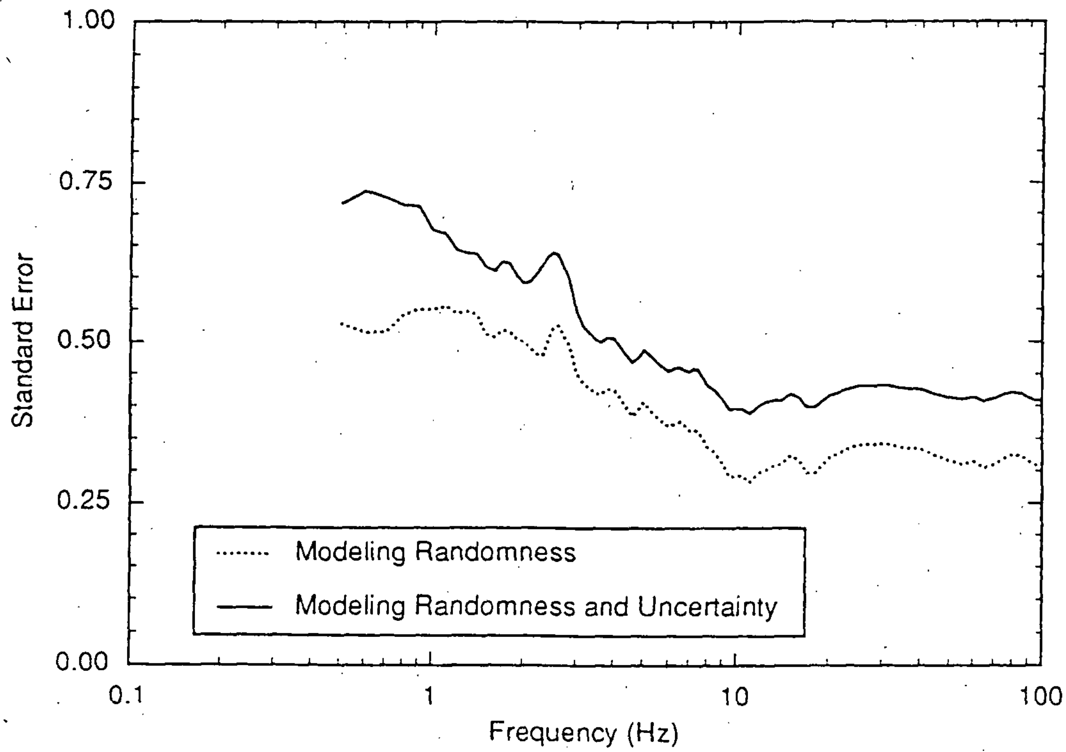


Figure F-2. Modeling uncertainty for the EPRI (1993) stochastic model, obtained using 61 recordings from four events. Dashed line: indicates the modeling aleatory uncertainty; solid line: total modeling uncertainty (aleatory+epistemic).

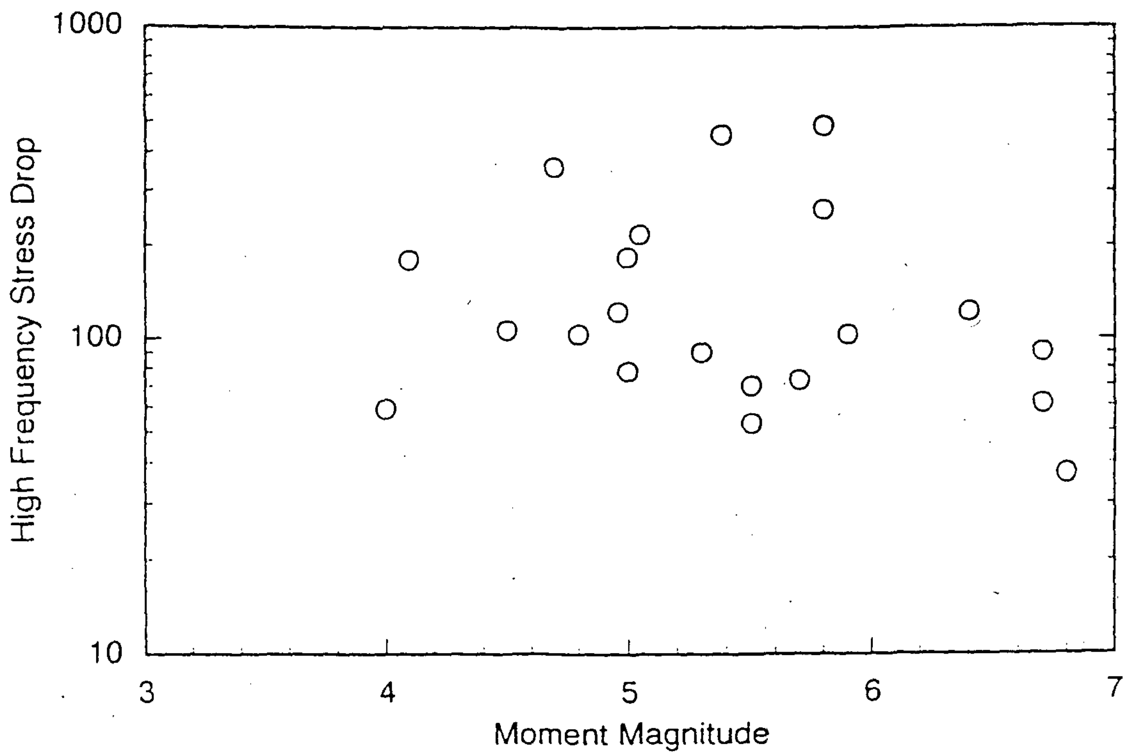


Figure F-3. High-frequency stress parameters (values are modified from Atkinson, 1993). Source: EPRI (1993, vol. 5).

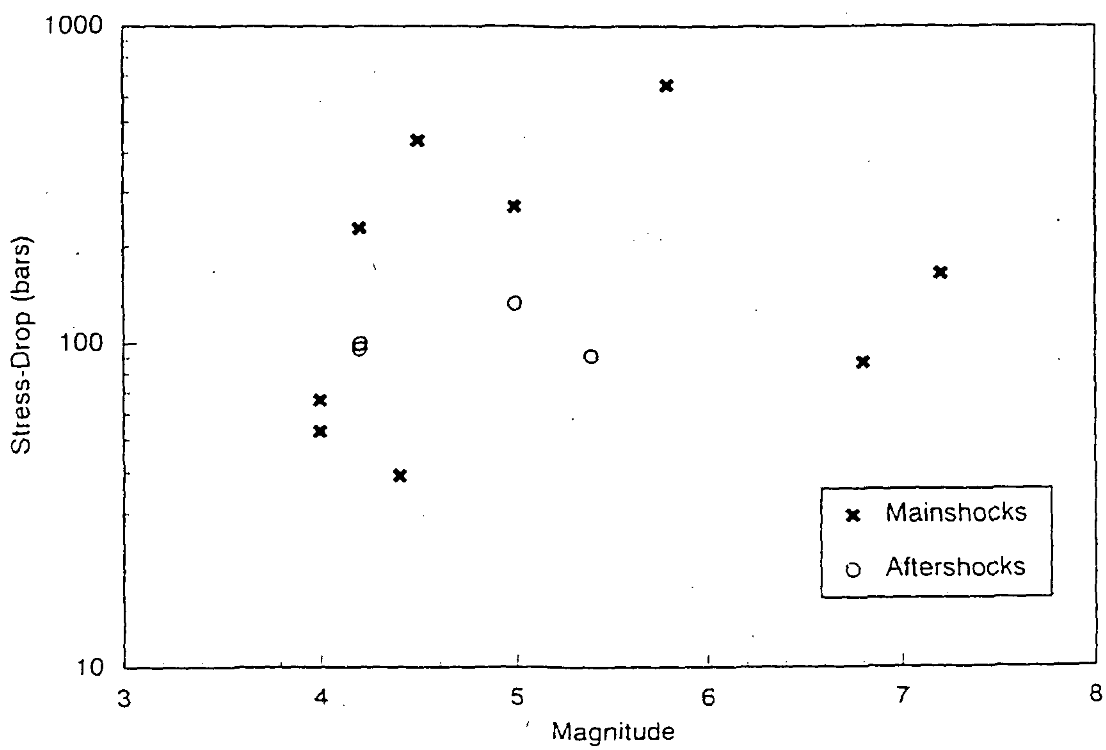


Figure F-4. Brune stress drops for stable continental regions estimated by inversion of the Fourier amplitude spectrum.

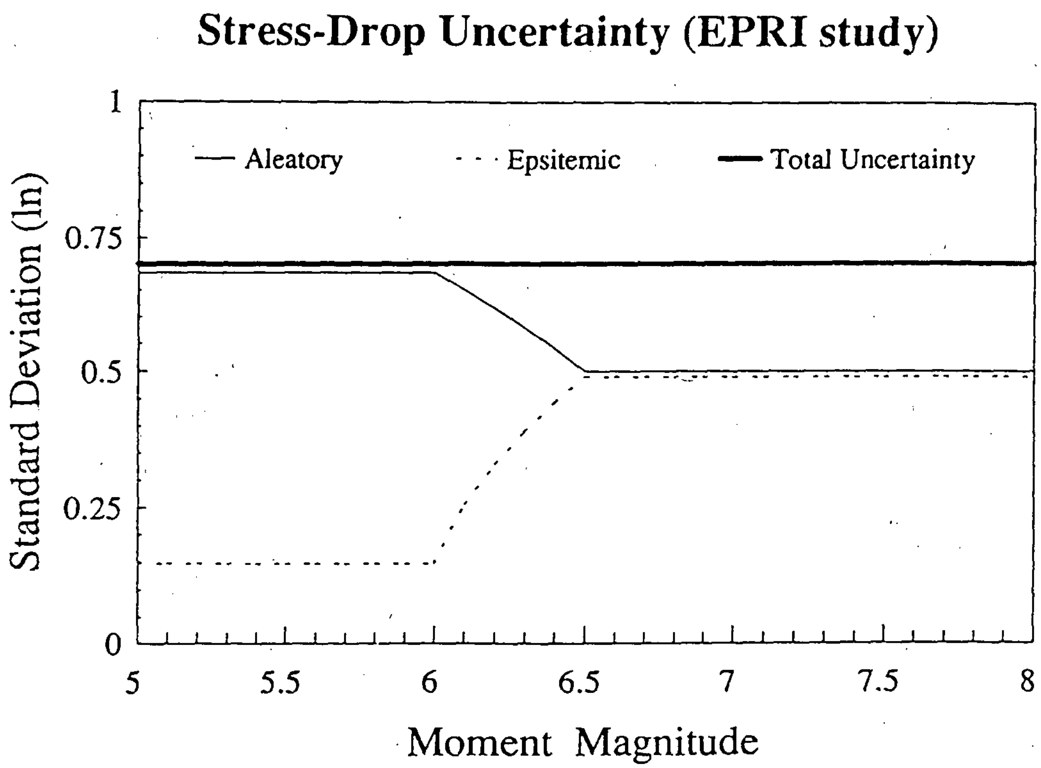


Figure F-5. Aleatory and epistemic uncertainty in stress drop in the EPRI (1993) study. Modified from Toro et al. (1995).

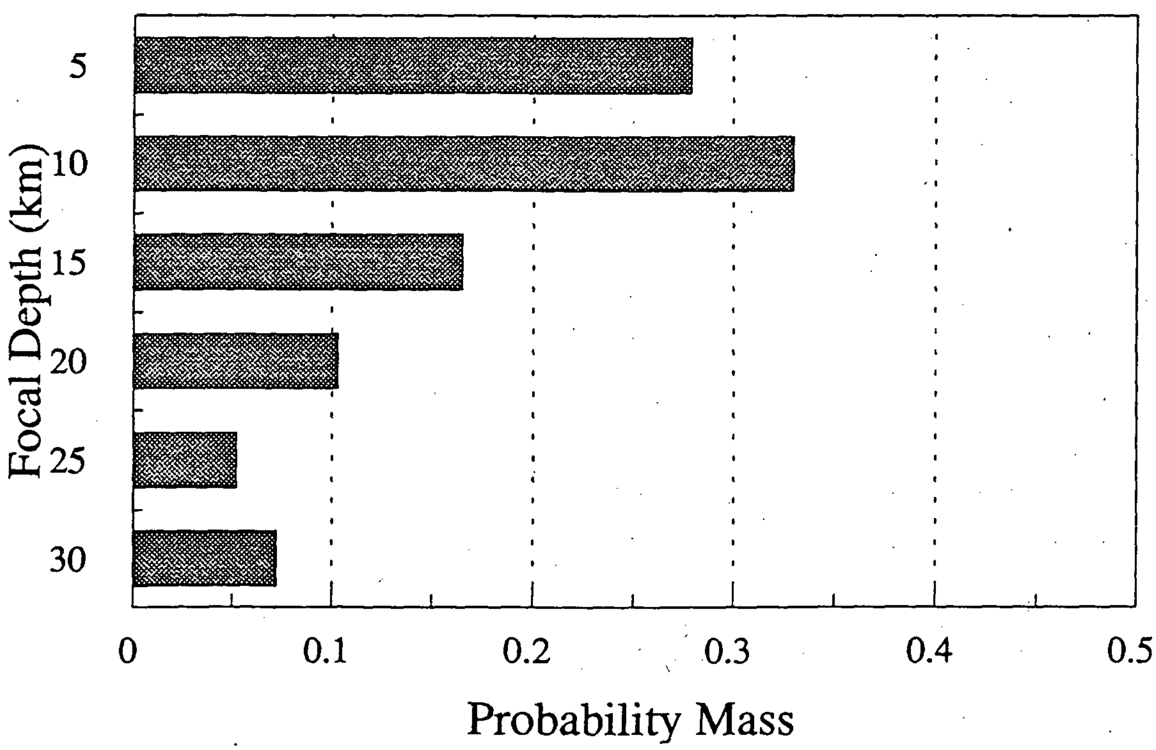


Figure F-6. Distribution of focal depth (aleatory) in the EPRI (1993) study. Source: Toro et al. (1994).

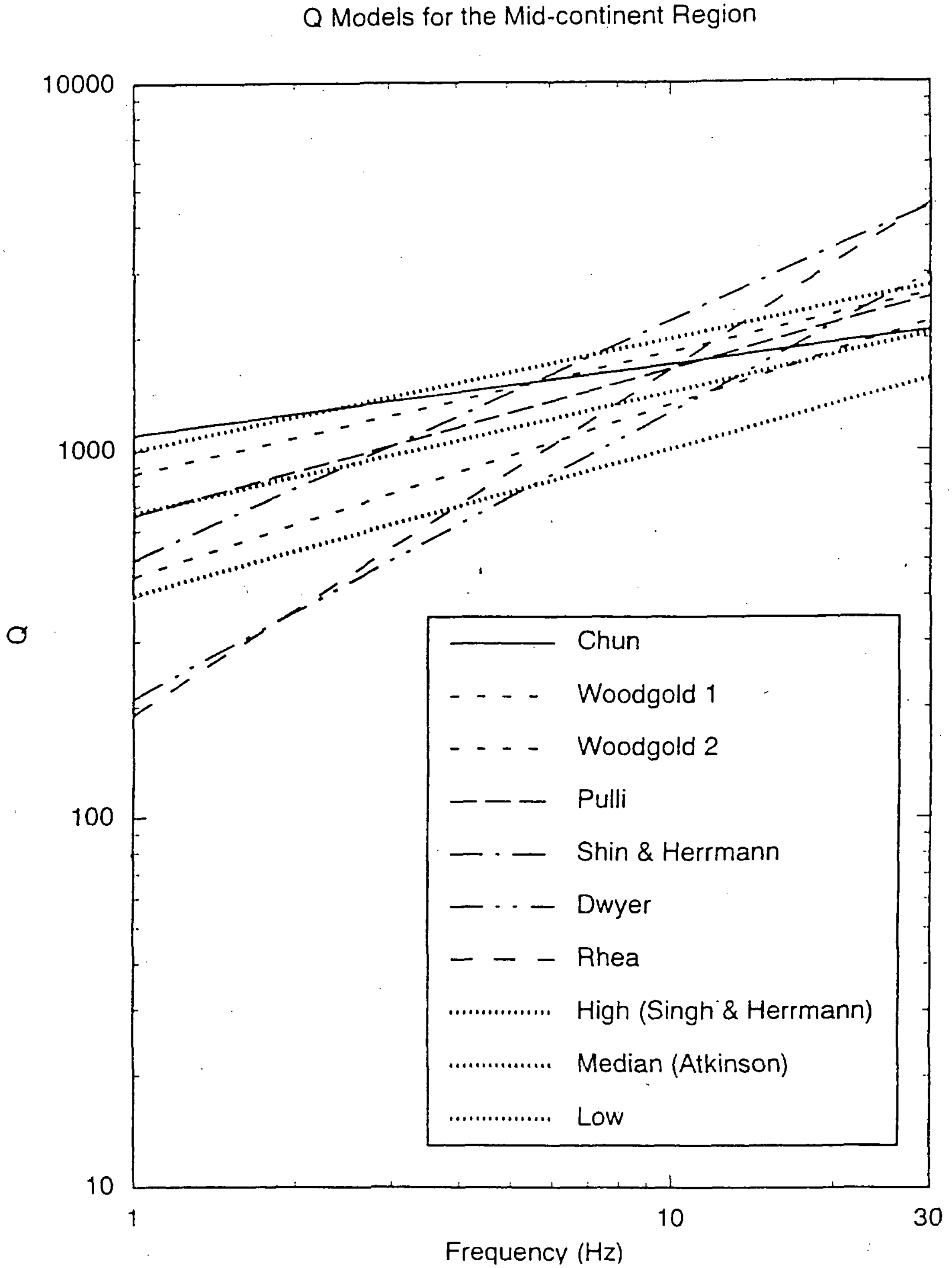


Figure F-7. Representation of Q in the mid-continent region and its aleatory uncertainty in the EPRI (1993) study. The Q models shown as dashed lines are given equal weights.

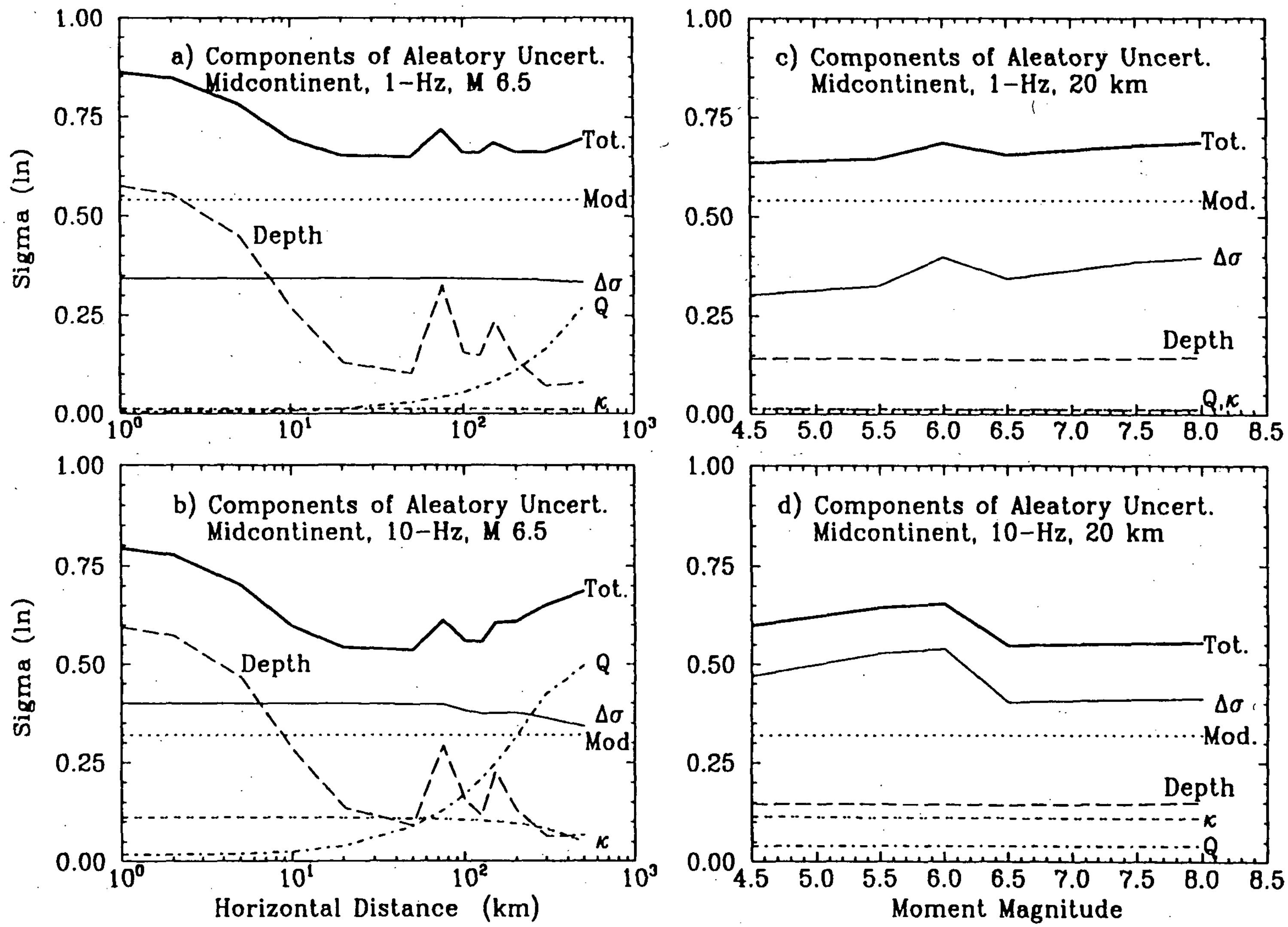


Figure F-8. Contributions to aleatory uncertainty in ground motion predictions from the EPRI (1993) study. Modified from Toro et al. (1995).

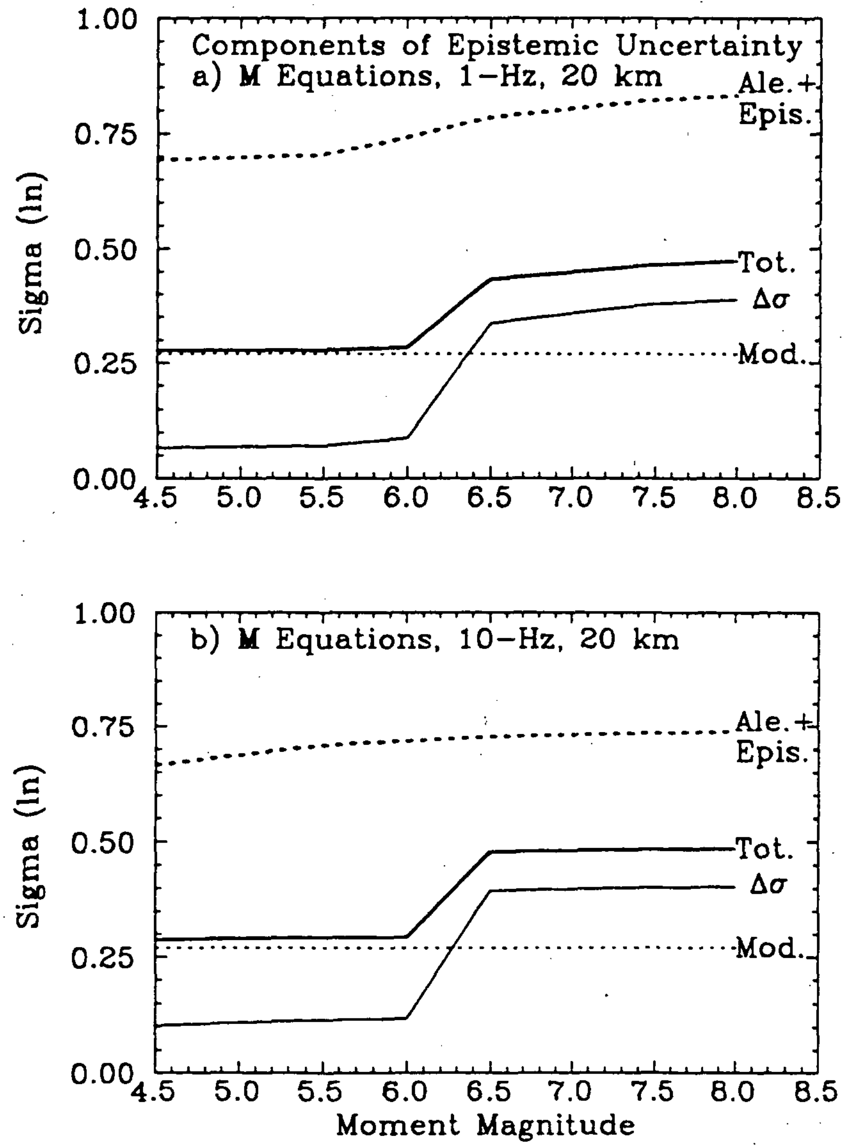


Figure F-9. Contributions to epistemic uncertainty in ground-motion predictions from the EPRI (1993) study. Modified from Toro et al. (1995).

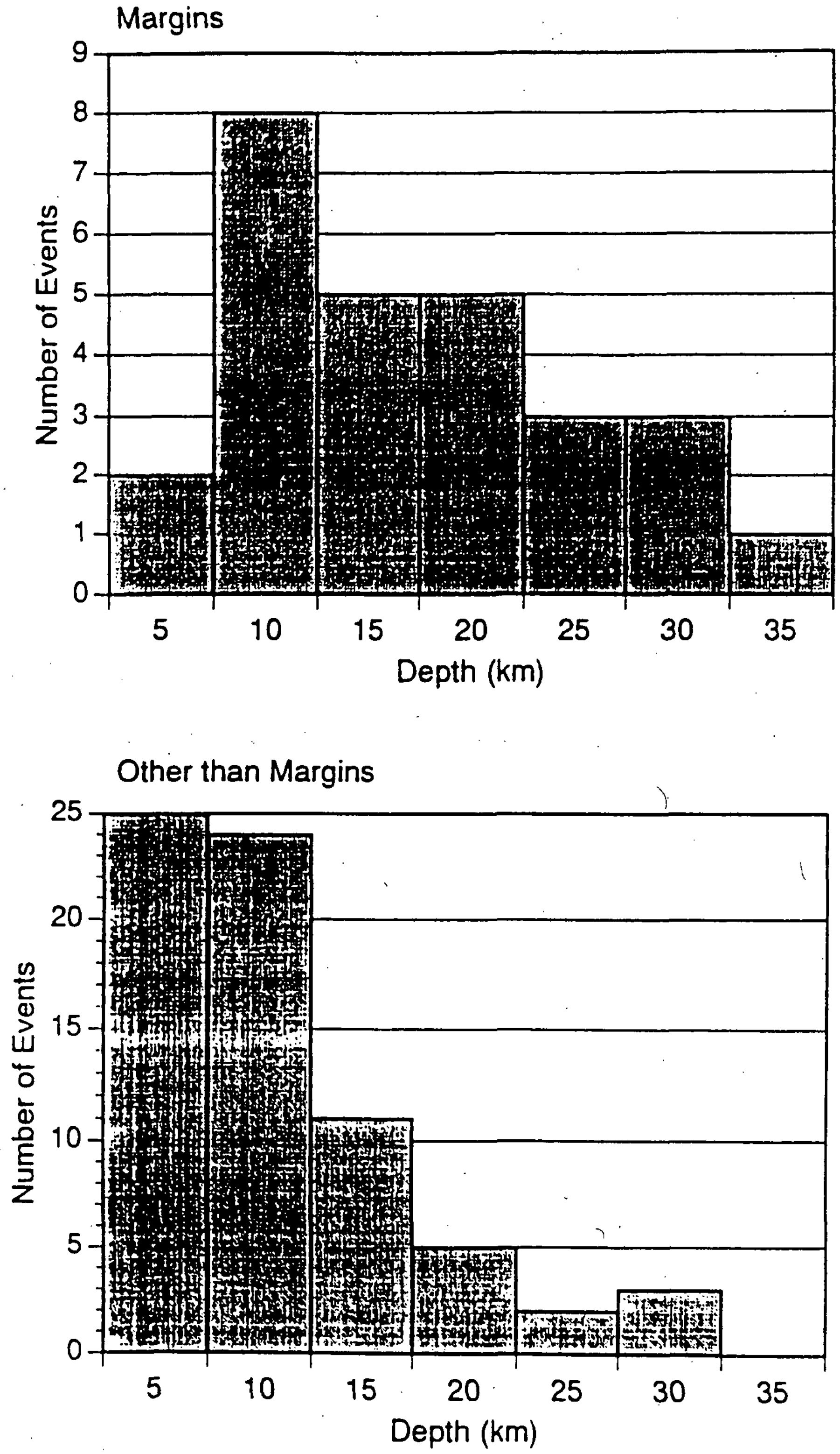


Figure F-10. Depth distribution model for margins and non-margins based on the combined eastern North America, Africa, and Australia data set. This depth distribution model is considered in the regression analysis in Section 9. Source: EPRI (1993).

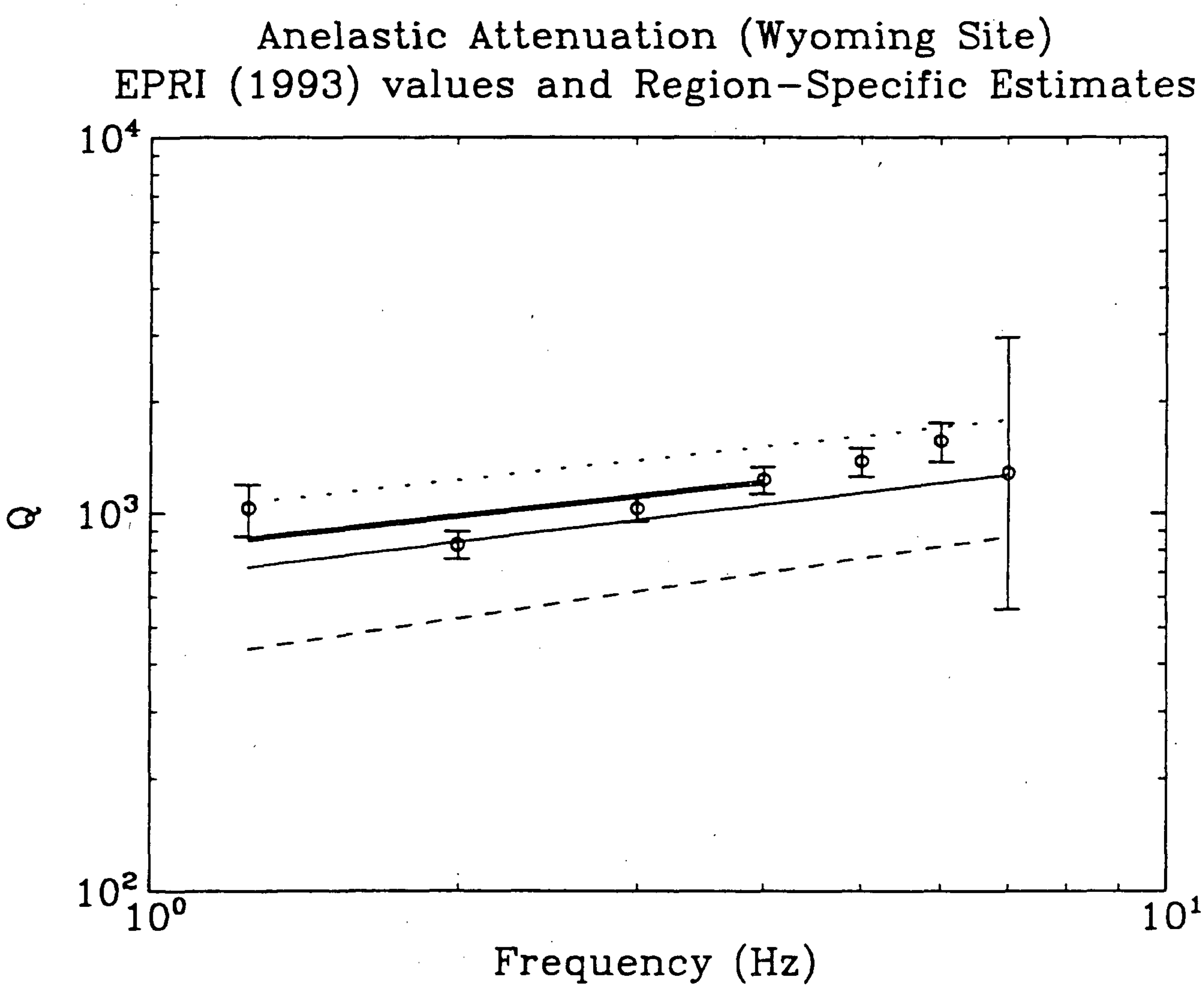


Figure F-11. Example on the use of site-specific (in this case region-specific) information on Q. The site specific data comes from Gupta et al. (1989, error bars) and Singh and Herrmann (1983, heavy solid line). Also shown are the three Q models considered in the EPRI (1993) generic calculations (thin lines; given equal weights in the EPRI calculations). Based on the site-specific data, the weights are changed to 0.4 (dots), 0.5 (solid), and 0.1 (dashed).

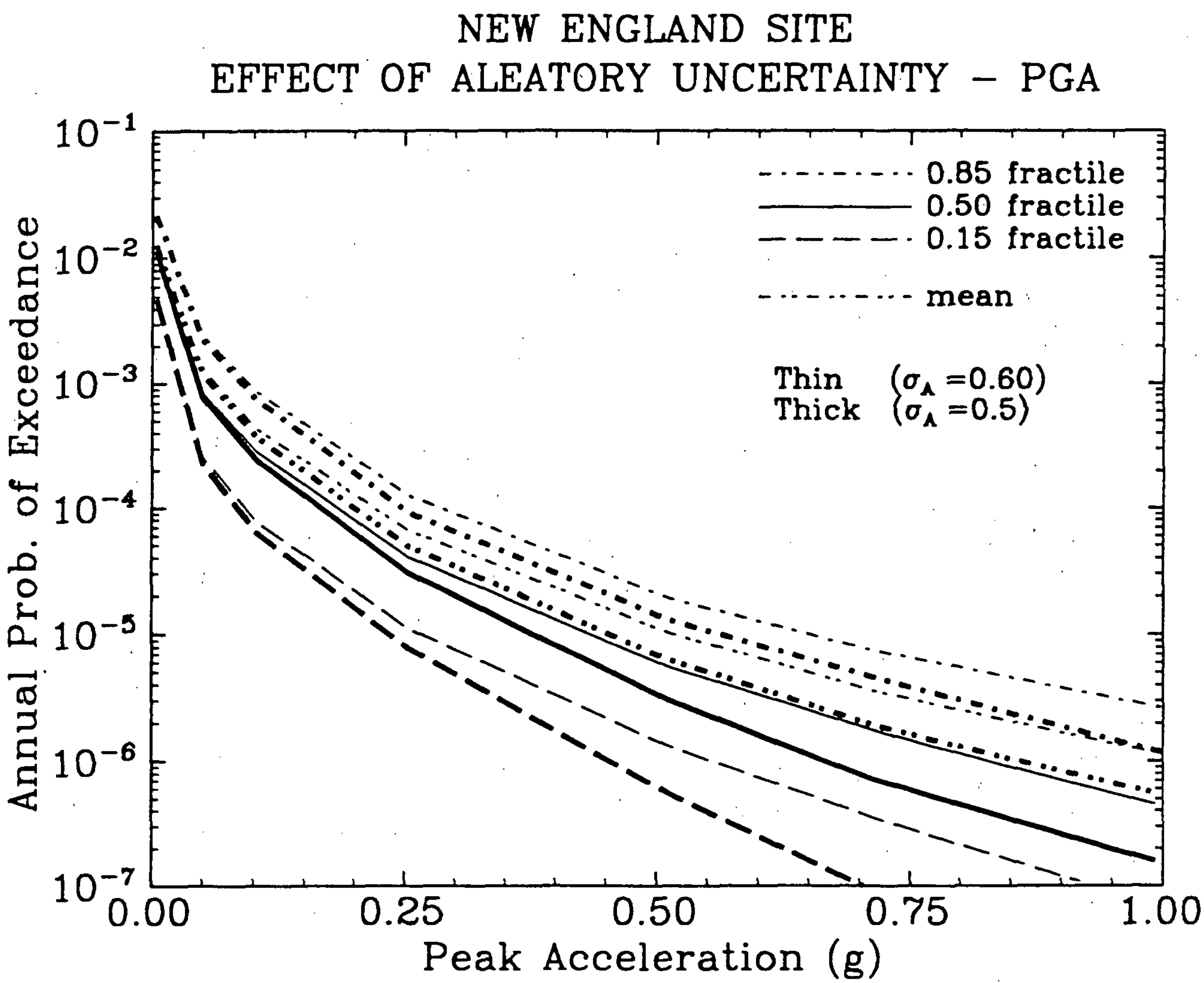


Figure F-12. Sensitivity of calculated seismic hazard to aleatory uncertainty in ground motions; results for PGA. The epistemic uncertainty is kept constant.

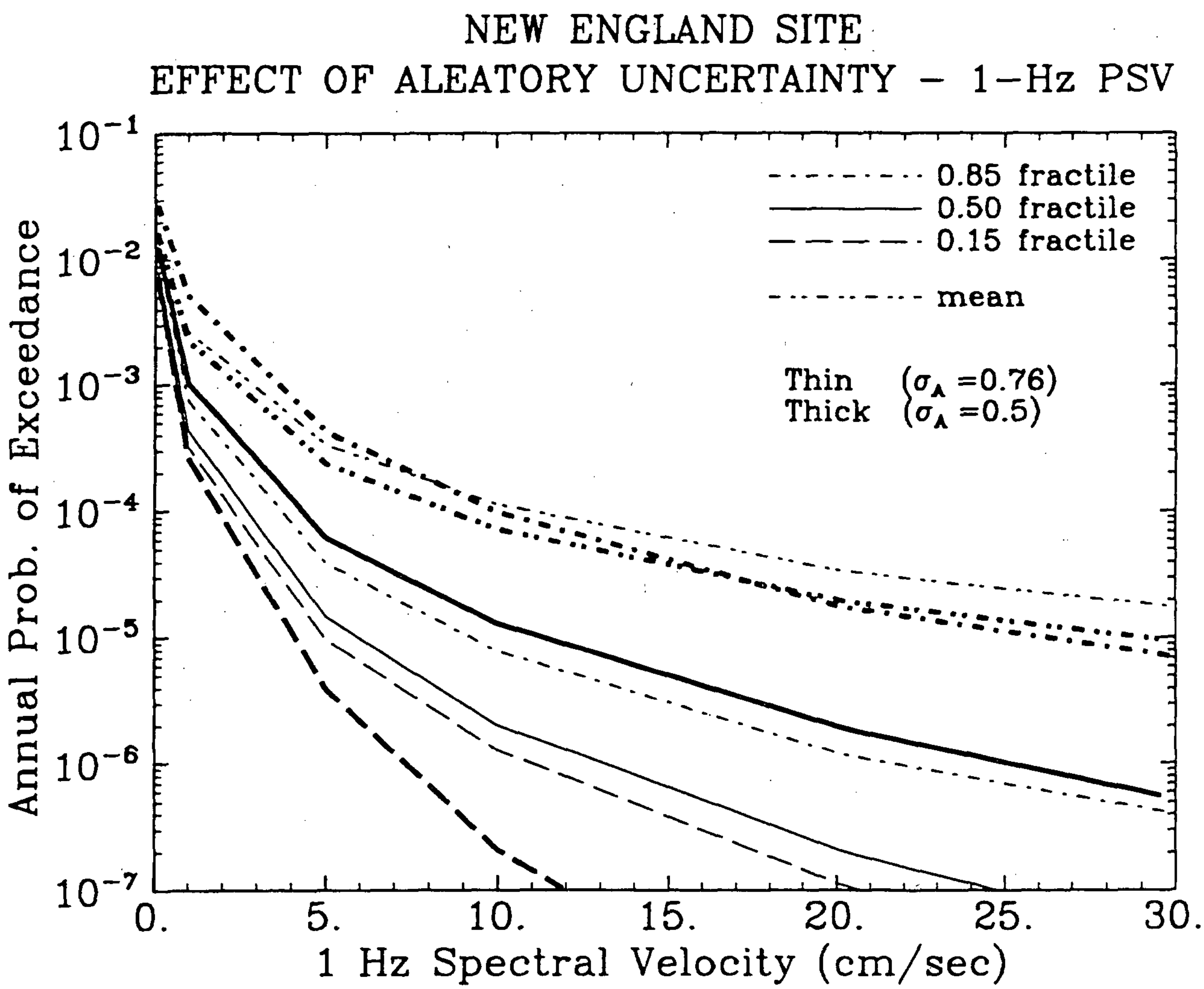


Figure F-13. Sensitivity of calculated seismic hazard to aleatory uncertainty in ground motions; results for 1-Hz spectral velocity. The epistemic uncertainty is kept constant.

APPENDIX G

SIGNIFICANT PARAMETERS IN SEISMIC HAZARD CALCULATIONS

by

Robin K. McGuire

G.1 INTRODUCTION

A significant amount of effort must go into seismic hazard analysis to obtain meaningful results, and this effort should be used in the most efficient way possible. To this end, it is important to examine what parameters contribute significantly to seismic hazard, and to determine when changes in those parameters make significant differences to the imputed hazard. The identification of important parameters can then be made on an informed basis so that maximum effort can be guided toward evaluating those parameters that make the most difference to the hazard.

The evaluation of which parameters lead to significant changes in the hazard is ultimately the responsibility of the analyst. However, guidelines can be drawn based on generic analyses so that the initial allocation of resources and effort can be made in a reasonable way. Without this guidance, a full seismic hazard analysis would have to be made at each site, including quantification of parameter uncertainties, to evaluate which parameters are most significant. If this is done, all of the effort to quantify parameter uncertainties has already been completed.

The real benefit in considering which parameters contribute to significant changes in hazard comes from being able to concentrate on the evaluation (both in the sense of the best estimate and of the uncertainty) of important parameters while neglecting, or treating in a crude fashion, other parameters that are not significant or are only marginally significant. Thus consideration of significant parameters involves both an evaluation of what drives the seismic hazard in the sense of the best-estimate hazard, and what contributes significantly to uncertainties in hazard. To these ends we formulate a procedure to guide the evaluation of which parameters deserve the most scrutiny. We also present generic results that document the changes in hazard that result from varying certain parameters, so that initial concentrations of effort can be decided upon in an informed way.

These results will be useful to guide the efforts of earth scientists providing inputs to seismic hazard analyses. Such scientists may have little experience with probabilistic seismic hazard calculations, and without guidance may expend significant effort making interpretations and estimating parameters that matter little. Using the guidelines developed here will allow concentration on the inputs that matter most, resulting both in more efficiency and in a better estimate of seismic hazard.

G.2 DEFINITION OF SIGNIFICANT CHANGE

What is of most concern is the relative influence that one model or parameter has on the hazard, compared to other models and parameters. Given the finite limits of resources, scope, and time that all seismic hazard projects have, concentration should be placed on those interpretations that have the most influence. However, it also is useful to think in terms of absolute changes in hazard, for example to make decisions on whether to include or exclude certain models. Even though the contribution of these models might be low on a relative scale, if they would influence the hazard at an absolute level greater than some threshold, a case can be made that they should be studied and included in the seismic hazard computations.

Decisions regarding seismic hazard inputs can be divided into two types:

1. Should certain models and parameters be included in the calculations? In other words, should the underlying concepts be modeled at all, or should they be ignored? An example is the modeling of seismic sources that are successively farther and farther away from the site of interest. At some point a distant source will not contribute significantly to the hazard and should be ignored.
2. Should certain models and parameters have their uncertainty quantified? In this context a model or parameter may be required to evaluate the seismic hazard, but uncertainty in that model or parameter may or may not contribute to the uncertainty in seismic hazard.

For example, the host source for a site might dominate the seismic hazard, but (particularly for high frequency measures of ground motion) the maximum magnitude might not be a critical parameter in the calculations. Thus, while a maximum magnitude is needed, quantifying its uncertainty does not change the best estimate of seismic hazard nor the uncertainty in hazard. This does not relieve the analyst of the responsibility of making an accurate, defendable estimate of the maximum magnitude; indeed, the assessment that parameter uncertainty would not contribute to seismic hazard uncertainty depends on an accurate assessment of the parameter to start with.

Given the above two types of applications, guidelines can be offered on the levels of change in seismic hazard that would be significant. These guidelines are stated in terms of hazard calculations (annual frequencies of exceedence), which can be examined as a direct output of the seismic hazard analysis, but have their basis in the ground motion associated with a chosen annual frequency level. The two are related through the following:

$$\Delta \text{ Ground Motion} \simeq (\Delta \text{ Seismic Hazard})^{-1/S}$$

where Δ is the multiplicative factor by which the ground motion or seismic hazard changes, and S is the slope of the hazard curve in a log-log plot at the ground motion level of interest. For example, if the slope of the seismic hazard curve is -3 (a typical value), a parameter change that causes the hazard to change by a factor of 1.3 will cause the ground motion at the initial annual frequency of exceedence to change by a factor of 1.09. The relationship is approximate because the slope of the hazard curve changes as a function of ground motion amplitude.

Guidelines for decisions regarding models and parameters in the seismic hazard analysis are as follows. These are based on a slope of -3 for the hazard curve, and should be adjusted for the site-specific slope once it is determined from preliminary analyses.

Guideline A. To determine models and parameters to include, contributions to hazard must be included so that not more than 3% of the hazard (annual frequency of exceedence) is missing. As a practical matter, of course, what we are trying to find is the total hazard, so we can only take 3% of the total calculated hazard and compare it to the remainder that might not be modeled. For example, if five sources together indicate a hazard of X at a site for a given ground motion amplitude, we are justified in neglecting other sources if together they contribute less than 3% of X at that amplitude. The rationale here is that we want the ground motion for a chosen annual frequency of exceedence to be accurate to at least 1%; with a slope of -3 in the hazard curve, this translates to the above criterion.

Guideline B. To determine models and parameters whose uncertainty should be quantified, the squared variation in hazard of the models and parameters whose uncertainty is being neglected must not exceed 10% of the total squared variation in hazard. For example, if the squared variation in hazard from models and parameters whose hazard is quantified is Y, the estimated squared variation from other models and parameters must not exceed 10% of Y. The rationale is that, if the squared variation in hazard is accurate to 10%, the standard deviation will be accurate to 5%, and the associated change in ground motion will be accurate to better than 2% (assuming a slope of -3 in the hazard curves). This means that the 85th percentile ground motion for a given annual frequency of exceedence should be accurate to 2%.

An example of the application of these guidelines is given in the next subsection.

G.3 FORMAT FOR EVALUATING SIGNIFICANT CHANGES IN HAZARD

A format is presented here wherein decisions regarding the important models, parameters, and uncertainties can be determined for a seismic hazard analysis, in order to ensure that the most critical elements are included. It should be emphasized that a proper seismic hazard analysis involves some iteration between models, earth scientists providing inputs, and results, so that assurance of the validity of results is reached based on the site-specific calculations. The format and guidelines offered here should be used as a tool in that evaluation process, not as a substitute for it.

Table G-1 lists models and parameters that should be considered when evaluating which to include and which uncertainties to model. In most cases for each primary parameter there is a second critical parameter that is important in governing the importance of the first. For example the depth distribution of earthquakes may be important for the host source for a site, where earthquakes can occur directly under the site. The depth distribution is not important if the source lies several hundred km from the site.

A format for evaluating the importance of models and parameters in the hazard calculations is presented in Table G-2. Column (1) indicates the source (fault or area) being considered, and Column (2) lists the models or parameters considered for that source. All of the models and parameters identified in Table G-1 should in general be considered, unless they are not relevant to a specific application.

A preliminary seismic hazard calculation should be performed using first estimates of each model and parameter, and using first estimates of uncertainties. At the preliminary stage this calculation can use single estimates of each model and parameter, as long as uncertainties have been quantified in a preliminary fashion so that a reasonable estimate of the mean value can be derived. The hazard level (annual frequency of exceedence) for each source is listed in Column (3); it is repeated for each parameter being evaluated for each source. Thus for example Column (3) in Table G-2 lists "H_1" after each parameter for source 1.

Column (4) indicates the partial derivative of the hazard with respect to each parameter for each source. In a preliminary evaluation this can be obtained from the results presented in the next subsection; in a final seismic hazard calculation sensitivity studies should be used to determine these partial derivatives. Again this illustrates the iterative nature of the analysis: the evaluation of model and parameter importance should be made at several different levels of detail and accuracy during the analysis, to guide later analyses.

Column (5) of Table G-2 lists the uncertainty of each parameter, as provided by earth scientists or other analysts providing input to the application. These should be represented as standard deviations of each parameter's uncertainty, in the units of that parameter. For example, the standard deviation of M_{max} should be listed in magnitude units. (Exceptions are discussed in Section G.5 below.)

The uncertainty in hazard caused by each parameter is calculated in Column (6) as the product of Columns (3), (4), and (5). This gives, for each entry, the amount that the hazard is expected to vary as a result of the absolute level of hazard, the sensitivity of hazard to that parameter, and the level of uncertainty in that parameter. Large contribution to the uncertainty in hazard requires three things: (a) that the source be a major contributor to hazard, (b) that the calculated hazard be sensitivity to a particular parameter, and (c) that that parameter be uncertain to a significant degree. Column (6) is an approximation to the standard deviation in hazard caused by uncertainties in that parameter. Column (7) of Table G-2 transforms the values of Column (6) into contributions to the variance in hazard by squaring the entries.

The guidelines offered above for determining significant contributions to hazard can be followed by deriving the sums shown in the last row of Table G-2. The first sum, in Column (3), shows the total hazard for the chosen ground motion amplitude. Guideline A can be applied by comparing the hazard contributed by each source (H_i) to the summation of the H_i's. The second sum, at the bottom of Column (7), shows the sum of the variances for the individual entries in Column (7). The individual contributions for each source and parameter can be compared to this sum to determine their level of significance, using Guideline B.

Column (8) in Table G-2 is included to indicate whether that source and parameter will be included in the uncertainty modeling. When a source is disregarded because it contributes little to the hazard, of course none of its parameters need be specified (except to the extent needed for documentation. When a model or parameter of a source is treated without uncertainty (because its contribution to uncertainty is small), a best estimate value of that parameter still needs to be specified so that hazard calculations can be made.

The format described here allows objective decisions to be made on which models and parameters to include in a seismic hazard calculation and for which models and parameters uncertainty is important to include. The format can be applied at several levels in the analysis, for example:

- at the screening stage, when preliminary decisions must be made on the sources to include in the analysis. Here first estimates of models and parameters would be used, with partial derivatives obtained from general results such as presented in the next subsection, and general estimates of parameter uncertainties (e.g. taken by analogy from other regions) can be used.

- at the draft calculation stage, when assurance is sought that the predominant contributors to seismic hazard and its uncertainty have been included. Here site-specific sensitivities of hazard should be used to obtain the partial derivatives, along with draft assessments of parameter uncertainties.

- at the project documentation stage, when final interpretations are available and it is necessary to document the decisions regarding including and excluding various models and parameters. Here again, site-specific studies of seismic hazard should be used to obtain the partial derivatives needed for the format.

Adopting a format such as that illustrated here will provide assurance that the significant contributions to seismic hazard have been included in the analysis.

G.4 EXAMPLES OF SEISMIC HAZARD SENSITIVITIES

Examples of the sensitivity of seismic hazard calculations to various seismic source models and parameter values are presented in this subsection. The objective of these calculations is to create a data set of sensitivity calculations that can be used for preliminary screening and to develop first-cut partial derivatives as required by the guidelines described in the previous subsection. Sites are selected that are subject to seismic hazard from realistic representations of seismic sources in the eastern U.S. and California. While we believe the sensitivity calculations to be valid and useful, they are not a substitute for site-specific calculations.

Three groups of sites are studied here. Group A sites lie to the east of the New Madrid fault system in the central Mississippi embayment (see Figure G-1). This source has a large maximum magnitude ($M_{max} = 7.5$). Group B sites lie within and to the west of a large area source in eastern Massachusetts (see Figure G-16); this source has a moderate maximum magnitude ($M_{max} = 6.3$). Group C sites are a set of sites that lie to the east of the Hayward fault in California (see Figure G-27). This fault has a moderate-to-high maximum magnitude ($M_{max} = 7.0$). The representations of the sources for groups A and B are taken from the EPRI (1989) study of seismic hazard in the central and eastern U.S. The parameters of the Hayward fault are taken from recent studies of California faults, their activity rates and maximum magnitudes.

The attenuation equations used for the sensitivity studies in the eastern Column (groups A and B) are those of the recent EPRI-sponsored study of ground motions in the eastern Column (EPRI, 1993). For the California example (Group C) the attenuation equations of Joyner and Boore (1993) and Campbell (1993). In this application only the median rock ground motion equations were used, as all that is required is a reasonable attenuation equation that shows the effects of source geometries and source parameters.

The seismic hazard was calculated at each site in the group, both for base-case estimates of parameters and for variations of those parameters. Results are presented graphically, showing the original calculated hazard and the change in hazard as the parameters are varied from the base case. Figure G-2a is an example of the sensitivity of hazard to changes in beta, the parameter of the exponential magnitude distribution that is equal to the Richter b-value times ln(10). The top figure shows the calculated hazard at the string of sites, and the bottom figure shows the percentage change in hazard, for distances of 0 to 500 km from the New Madrid fault. In these calculations all other parameters have been fixed at their best-estimate values. The density of site locations is higher closer to the fault where more precision is required because the seismic hazard and its sensitivity may change more quickly with distance.

Figure "a" in each group shows the sensitivities for a spectral level corresponding to a PGA of 0.1g, and Figure "b" in each group is similar but for a spectral level corresponding to a PGA of 0.3g. (For Group C sites in California the PGA levels used are 0.3g and 0.6g, respectively, recognizing the generally higher level of seismic design that applies in California.) The order of the figures is as follows:

Figures G-2 through G-8: Group A sites, 10 Hz.
Figures G-9 through G-15: Group A sites, 1 Hz.
Figures G-17 through G-21: Group B sites, 10 Hz.
Figures G-22 through G-26: Group B sites, 1 Hz.
Figures G-28 through G-34: Group C sites, 10 Hz.
Figures G-35 through G-41: Group C sites, 1 Hz.

Individual interpretations are warranted for each of the figures in an actual application where decisions must be made on retaining or disregarding certain models and parameters. The following general conclusions regarding the sensitivities can be stated:

1. Sensitivity to beta is moderate, and it decreases at small source-to-site distances (less than 25 km).
2. Sensitivity to the depth distribution is negligible except at small source-to-site distances (less than 50 km).
3. Sensitivity to whether an exponential or characteristic magnitude distribution is used depends on whether a slip rate constraint or a seismicity constraint is used to fix the rate of activity. If a slip rate constraint is used, the maximum sensitivity occurs for very close or very distant sites. If a seismicity constraint is used, calculations at all distances are sensitive to the choice of model.
4. Sensitivity to maximum magnitude is largest at large source-to-site distances. It increases with ground motion amplitude, and is largest when the mean M_{max} value is lower. (The sensitivity is greater when the mean M_{max} is 6.0 or 6.5 than when the mean M_{max} is 7.5 or

7.8. Note when comparing Figures G-6a and G-7a [and other figures] that the range of M_{max} values in Figure G-7a is 1.2 units whereas it is 0.6 units in Figure G-6a.)

5. Uncertainty in fault location causes a moderate sensitivity for most sites for high frequencies, and less sensitivity at low frequencies. For source areas this applies to sites located outside the source, but especially sites near the source border.

Note that on Figures G-17 through G-26, sites located at distances less than 80 km are inside the source boundaries, so the hazard is more-or-less constant (particularly for sites at distances indicated as less than 50 km, which are well within the source borders).

The lower curve on each plot can be used to calculate partial derivatives of hazard to use in the format recommended above. An example of this application is given in the next section. For a particular site, determine the distance to the relevant source and pick a change in the parameter value that represents one sigma in the uncertainty distribution. For example, for M_{max} this might be 0.2 magnitude units, and for a site located 65 km from an area source boundary Figure 19b indicates a sensitivity of +50% for a decrease of 0.2 units in M_{max} from 6.0 to 5.8. (A site located 65 km from the source boundary is plotted at 150 km on Figure 19b.) In general the larger of an increase or a decrease in the subject parameter should be used. With a sensitivity of +50%, the partial derivative is calculated as ln(1.50)/0.2 = 2.03. This partial derivative can be used in Table G-2.

G.5 EXAMPLE APPLICATION

An example is presented next to show how the sensitivity plots of the previous section can be used in conjunction with Table G-2 to check Guidelines A and B. A hypothetical mid-continent site is chosen that is 200 km from a major fault (called Fault F), is located 50 km inside one source (called Source H, the host source) with a low maximum magnitude, and is located 100 km from the border of another source (called Source Z) with a moderate maximum magnitude. For this example the plots for Group A and Group B sites, presented in the previous section, are used to determine the sensitivities.

Table G-3 lists the critical parameters for each of the three hypothetical sources. These parameters have been chosen for illustration and are not meant to represent any particular source, including the New Madrid fault. For Fault F we use Figures G-2 through G-15 at a distance of 200 km (the distance of the fault from the site) to determine sensitivities. For Source H we use Figures G-17 through G-26 at a distance of 30 km (the point marked "*" on Figure G-16, which is 50 km inside the source) to determine sensitivities. For Source Z we also use Figures G-17 through G-26 but at a distance of 190 km (the point marked "+" on Figure G-16, which is 100 km outside the source). Also, we assume that the hazard from Source Z is twice that shown on Figures G-17 through G-26, because of the assumed activity rate of Source Z (Table G-3).

The parameter evaluation is carried out using the relevant figures as described above. For this example we describe the calculations of entries in Table G-2 for Source H, but the other sources are evaluated in a similar way. The calculated values for all sources are summarized in Table G-4 for 10 Hz spectral acceleration corresponding to a ground motion of 0.3g.

Hazard levels H_i. The hazard level is read from the top of Figure G-17b as 1.4×10^{-4} at 35 km. This goes in Column (3) of Table G-4.

Activity rate. A figure is not used for activity rate because hazard is directly proportional to this parameter. Therefore we can calculate Column (4) in Table G-4 using a factor of 2 (the standard deviation) as

$$\partial(\ln[\text{Hazard}])/\partial p = 0.69/2 = 0.35$$

β. The bottom of Figure G-17b indicates that changing β by 0.5 changes hazard by 20%. Thus

$$\partial(\ln[\text{Hazard}])/\partial p = 0.18/{-0.5} = -0.36$$

Here the negative sign means that the hazard increases as β decreases, and vice versa.

Depth. The bottom of Figure G-18b is used for assessment of the effects of depth. Here the sensitivity may not be symmetrical, so we compute the two alternative depth changes separately:

3 km depth, sensitivity is a factor of +7%:

$$\partial(\ln[\text{Hazard}])/\partial p = 0.068/{-2} = -0.034$$

10 km depth, sensitivity is a factor of -22%:

$$\partial(\ln[\text{Hazard}])/\partial p = -0.248/5 = -0.050$$

The negative sign here again means that the hazard increases as the depth decreases, and vice versa. The average of these sensitivities, -0.042, is used in Table G-4.

<u>M_{max}</u>. Figure G-19b (bottom) is used for this sensitivity. This plot shows that changing M_{max} by 0.3 units changes the hazard by 25%. Thus

$$\partial(\ln[\text{Hazard}])/\partial p = 0.223/0.3 = 0.744$$

<u>Distance to source border</u>. Figures G-21a and G-21b show very low sensitivity to changes in the border location for a site well inside the source, as would be expected. Thus

$$\partial(\ln[\text{Hazard}])/\partial p = 0$$

These values are shown in Column (4) of Table G-4. Column (5) lists the uncertainties in parameters, which are in most cases the standard deviations. Where discrete alternatives exist among choices, such as for the magnitude distribution on the fault, it is acceptable (and conservative) to indicate "alt." under Column (5) and treat this with a value of unity. Column (6) shows the product of Columns (3), (4), and (5), and Column (7) shows the square of Column (6).

Totals are shown for Columns (3) and (7). Under Column (3), the total hazard is indicated as 1.45E-4. Checking the values for individual sources, we see that Source H (hazard of 1.4E-4) contributes 96.6% of the total. Thus Source H alone does not meet Guideline A (inclusion of 97% of the hazard), so we should include the next highest contributor to hazard, Source Z. Fault F contributes less than 0.5% to the total hazard, so it is excluded ("N" is inserted in the Column (8) of Table G-4).

Checking the contribution to variance, the total of the contributions in Column (7) is 1.15E-8, and two parameters contribute 92% of that total. These are the rate and M_{max} uncertainties for Source H. The β uncertainty for Source H contributes another 5.5% to the total variance. Following Guideline B, we select rate and M_{max} for Source H to have the uncertainty quantified, and indicate for the remaining parameters in both Sources H and Z that only best estimates need be modeled. (As a practical matter, if the rate uncertainty is being quantified for a source, it would usually be little additional work to quantify the β uncertainty. Since this would result in 97% of the total uncertainty being included, it would ordinarily be done.)

Several points are worth mentioning for this example. First, examining lower structural frequencies (e.g. 1 Hz) or lower amplitudes of ground motion usually results in more sources and parameters being included than 10 Hz. Second, for discrete alternatives (e.g. the characteristic vs. exponential magnitude distribution for Fault F), it is usually acceptable to show the change in ln[hazard] as the change in hazard when changing from one parameter assumption to the other, and to treat the parameter change as unity. This will work as long as the base case choice is more conservative than the alternative. Finally, the standard deviation of activity rate in Table G-3, and the sensitivity to activity rate in Table G-4 (Column (4)), are treated as factors on the mean rate. This leads to the same result as treating the standard deviation and sensitivity in units of events per year.

G.6 SUMMARY

Appendix G has presented typical sensitivity studies that show the relationship between calculated hazard and parameter changes. These studies are for common values of parameters and for a range of site locations with respect to seismic sources. They can be used as guidance to determine the most critical sources and parameters to concentrate on in a seismic hazard assessment, both for inclusion in the calculations and for uncertainty quantification.

References

EPRI (1989). Probabilistic seismic hazard evaluations at nuclear plant sites in the central and eastern United States: resolution of the Charleston earthquake issue. Electric Power Research Inst. Rept NP-6395, Palo Alto, April.

EPRI (1993). Guidelines for determining design basis ground motions. Electric Power Research Inst. Rept. 102293, Palo Alto, November.

TABLE G-1

MODELS AND PARAMETERS FOR CONSIDERATION

Primary Model or Parameter	Other Critical Parameter
Source or fault location	Distance to source boundary or fault.
Depth distribution	Distance to source boundary or fault.
Maximum magnitude	Best estimate of m_{max} (8 is different from 6).
Magnitude distribution (exponential vs. characteristic)	Contribution of that source/fault: designation of slip rates or activity rates.
Activity rate	(none)
b-value	Best estimate of m_{max}.
Homogenous vs. spatially-varying seismicity	Location of site relative to average rate.
Correlation of source parameter uncertainty	Specific parameter and correlation model.
Correlation of source activity	Range of activities and correlation.

TABLE 2

FORMAT FOR SOURCE AND PARAMETER EVALUATION

(1) Source	(2) Parameter (p)	(3) Hazard*	(4) ∂{ln[Hazard]}/∂p**	(5) Unc. in p***	(6) Uncert. due to p (6)=(3)·(4)·(5)	(7) Contribution to variance $(6)^2$	(8) Include (y/n)
1	Mmax	H_1					
1	depth	H_1					
"	.	H_1					
"	.	H_1					
2	Mmax	H_2					
2	depth	H_2					
		H_2					
		H_2					
Total		$\sum_i H_i$				$\sum_i (4)_i^2$	

* From preliminary hazard calculations
** From task 3 sensitivity results
*** From seismicity expert

TABLE G-3

EXAMPLE PARAMETERS FOR HYPOTHETICAL SOURCES

Parameter	Fault F	Source Q	Source Z
Mean activity rate	10^{-3}/yr*	10^{-3}/yr^{+}	2x10^{-3}/yr**
S.D. of activity rate	factor of 1.2	factor of 2	factor of 2
Mean β	2.0	2.7	2.7
S.D. of β	0.2	0.5	0.5
Base Case Depth Dist.	2-20 km	5 km	5 km
Alternative Depth Dist.	8-30 km	3 or 10 km	3 or 10 km
Base Case Mag. Dist.	char.	exp.	exp.
Alternative Mag. Dist.	exp.	--	--
Mean m_{max}	7.5	6.0	6.0
S.D. of m_{max}	0.4	0.3	0.3
Mean dist. to source/border	200 km	50 km (inside)	100 km (outside)
S.D. of dist. to source/border	5 km	10 km	10 km

* Equivalent to the rate used to calculate sensitivities for Group A sites.
\+ Equivalent to the rate used to calculate sensitivities for Group B sites.
** Equivalent to two times the rate used to calculate sensitivities for Group B sites.

TABLE G-4

SOURCE AND PARAMETER EVALUATION FOR EXAMPLE PROBLEM

(1) Source	(2) Parameter P	(3) Hazard	(4) $\partial/\ln[\text{Hazard}]/\partial p$	(5) unc. in p	(6) unc. due to p	(7) cont. to var.	(8) include* (Y/B.E./N)
F	act. rate	5E-7	0.35	1.2	2.1E-7	4.4E-14	N
	β	5E-7	1.11	0.2	1.1E-7	1.2E-14	N
	depth	5E-7	0.01	alt.	5.0E-9	2.5E-17	N
	mag. dist.	5E-7	7.7	alt.	3.8E-6	1.5E-11	N
	m_{max}	5E-7	0.97	0.4	1.9E-7	3.8E-14	N
	distance	5E-7	0.045	5	1.1E-7	1.3E-14	N
H	act. rate	1.4E-4	0.35	2	9.8E-5	9.6E-9	Y
	β	1.4E-4	-0.36	0.5	-2.5E-5	6.3E-10	B.E.
	depth	1.4E-4	-0.042	2.9	-1.7E-5	2.9E-10	B.E.
	m_{max}	1.4E-4	0.744	0.3	3.1E-5	9.6E-10	Y
	distance	1.4E-4	0	10	0	0	B.E.
Z	act. rate	5E-6	0.35	2	1.7E-6	2.9E-12	B.E.
	β	5E-6	1.00	0.5	-1.2E-6	1.4E-12	B.E.
	depth	5E-6	~0	2.9	0	0	B.E.
	m_{max}	5E-6	2	0.3	1.5E-6	2.3E-12	B.E.
	distance	5E-6	-.049	10	-1.2E-6	1.4E-12	B.E.
		$\sum H_i =$ 1.45E-4				$\sum =$ 1.15E-8	

* Y = include parameter uncertainty, B.E. = include parameter best estimate, N = exclude source

Line Source (EUS)

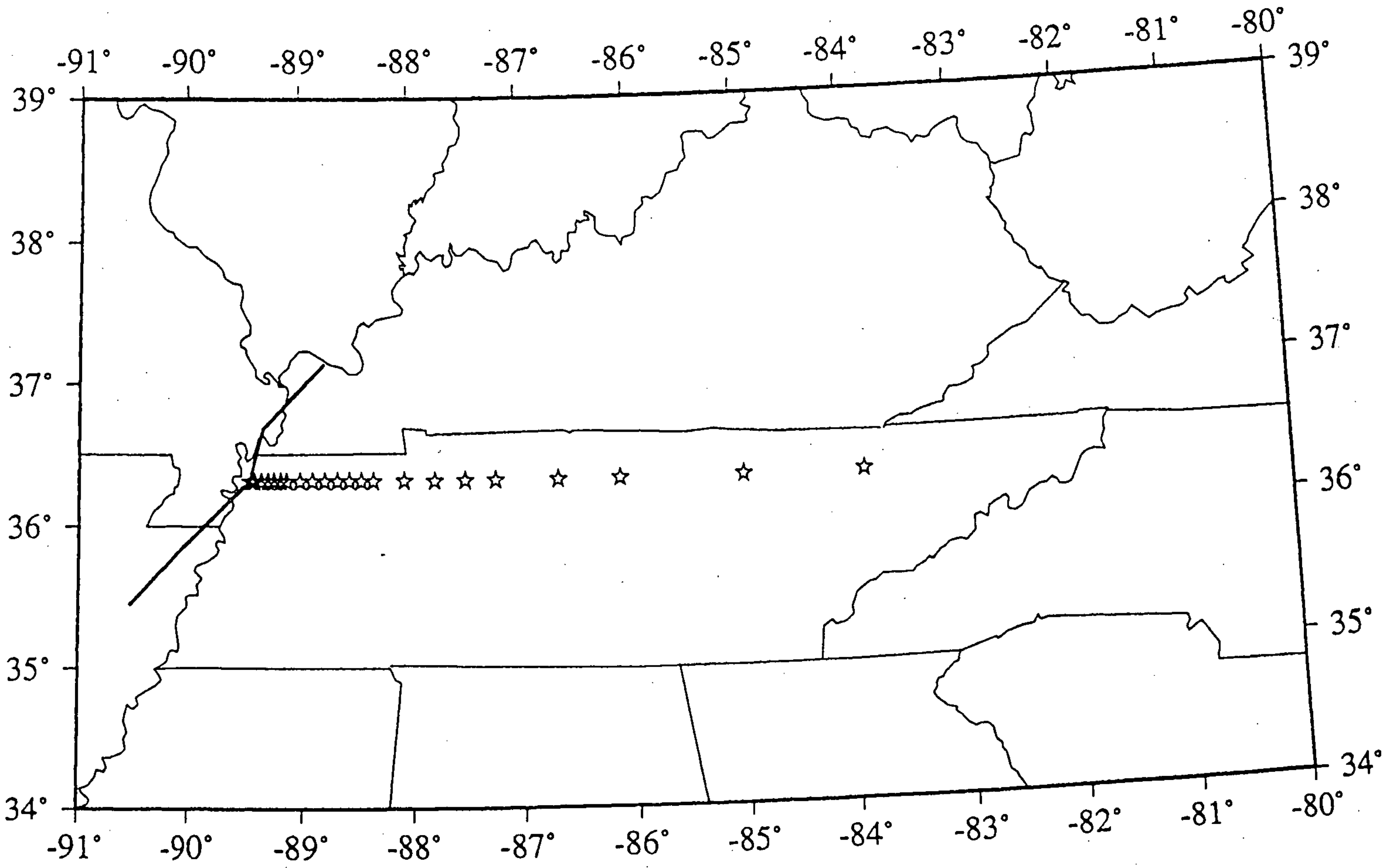
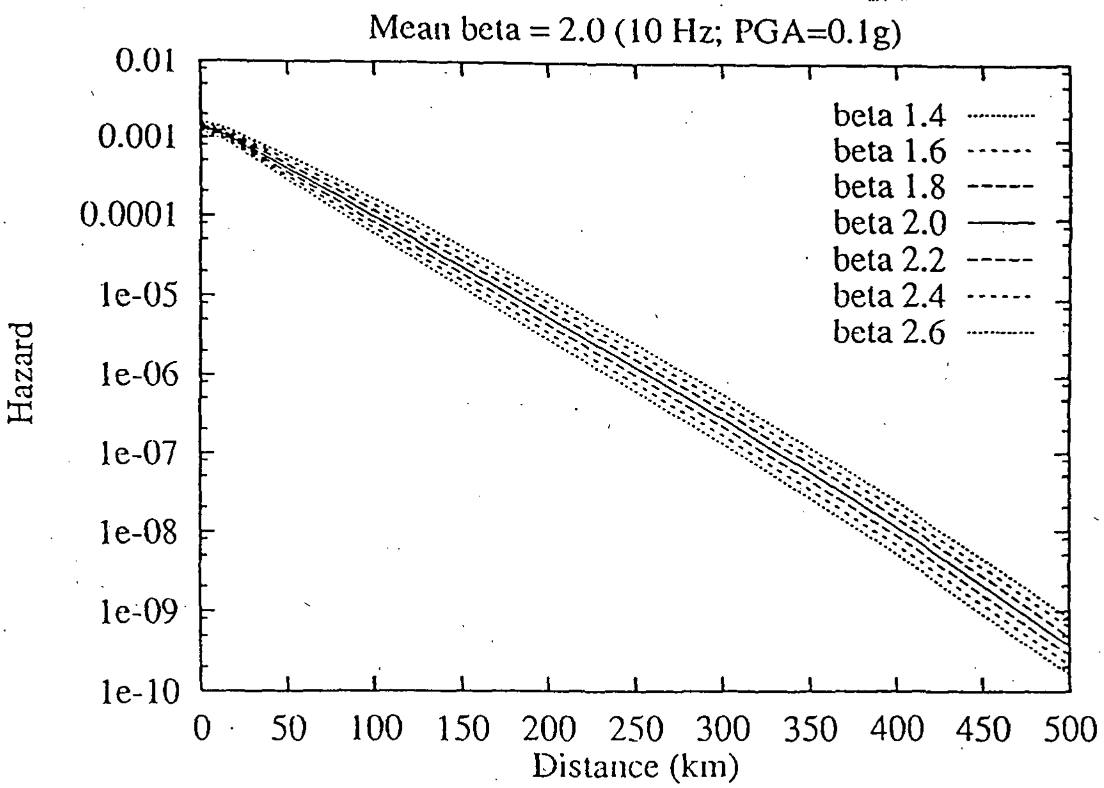


Figure G-1. Configuration of Group A sites with line source.



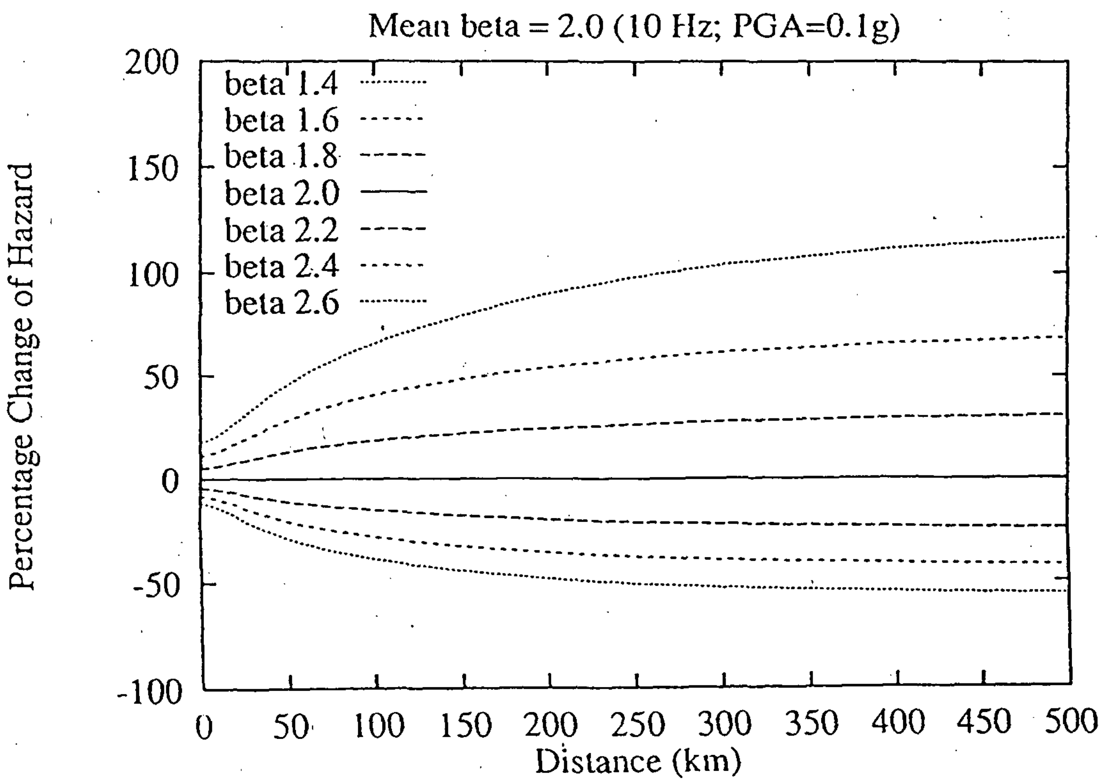
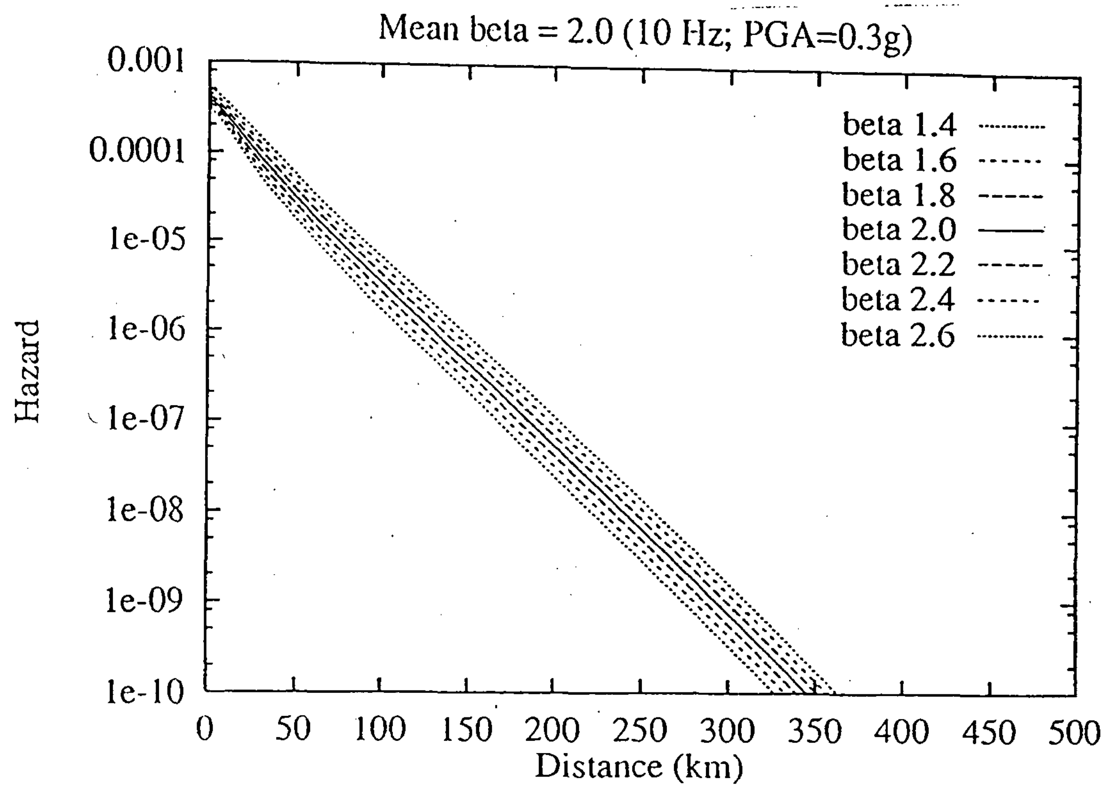


Figure G-2a. Sensitivity of 10 Hz hazard to beta for PGA = 0.1g, Group A sites.



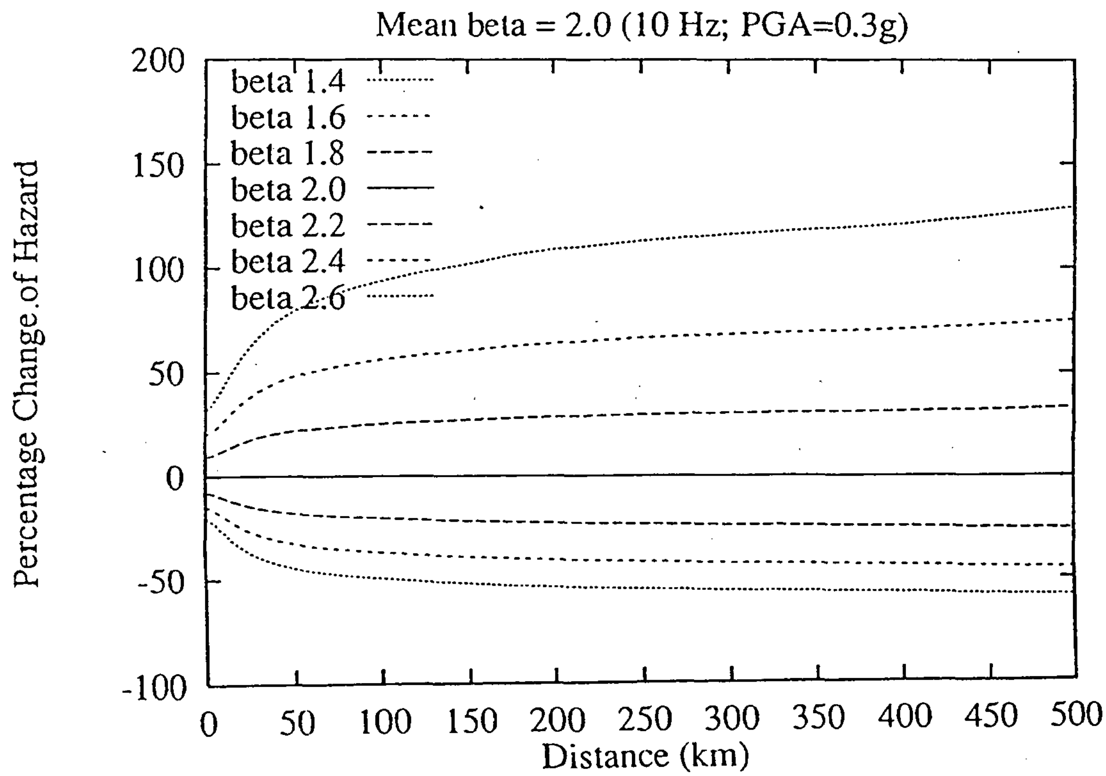
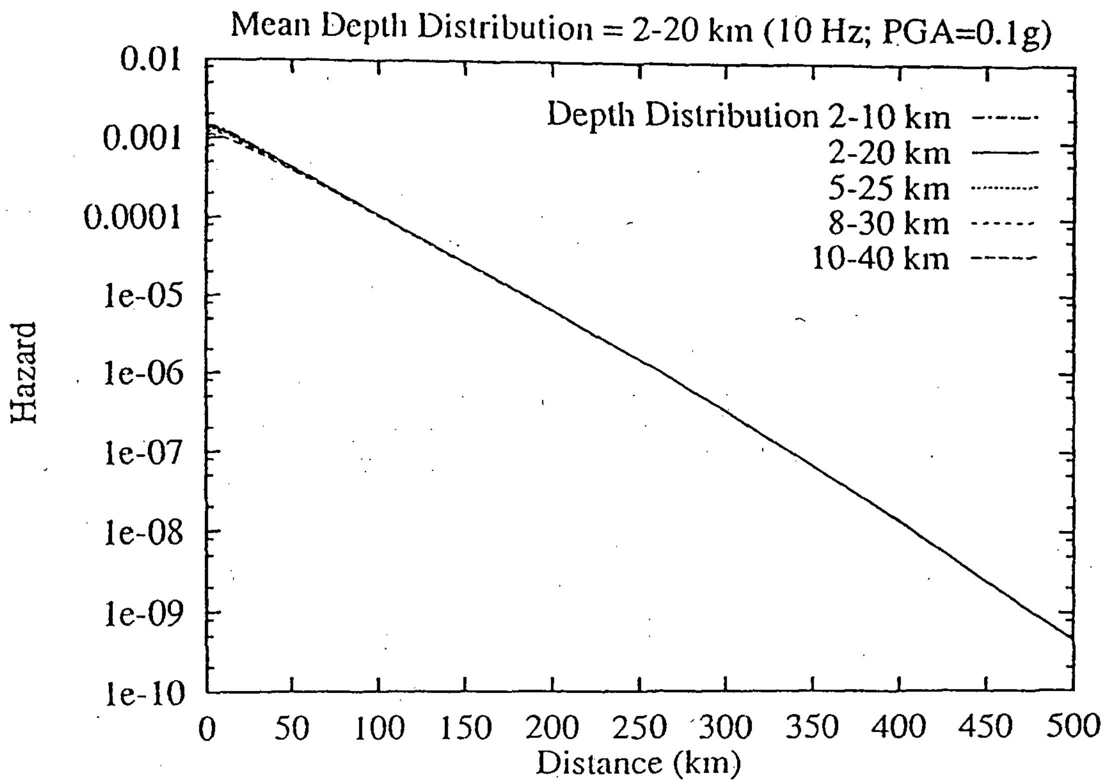


Figure G-2b. Sensitivity of 10 Hz hazard to beta for PGA = 0.3g, Group A sites.



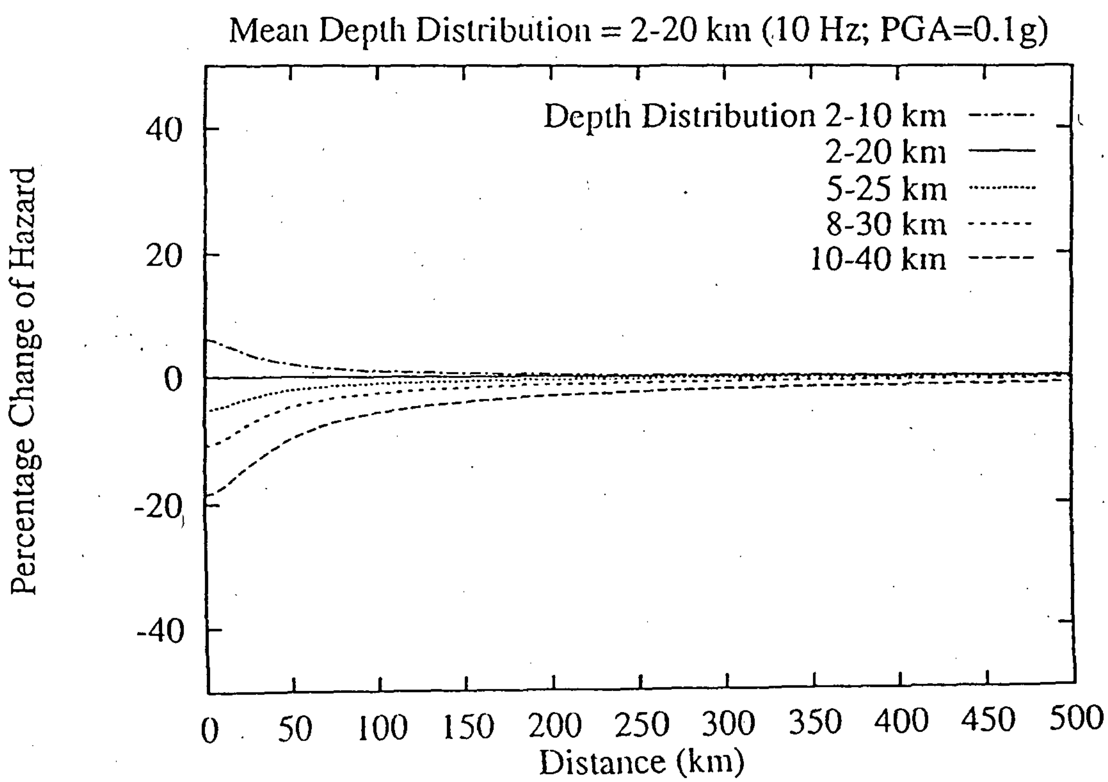
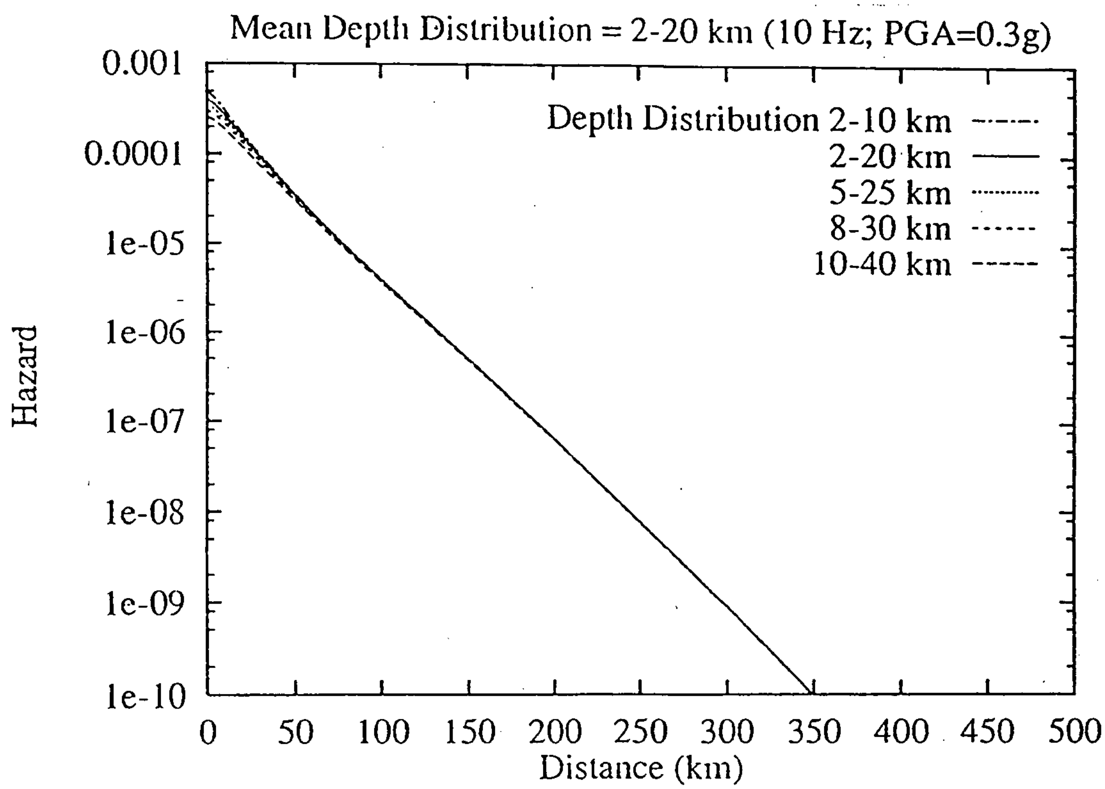


Figure G-3a. Sensitivity of 10 Hz hazard to depth distribution for PGA = 0.1g, Group A sites.



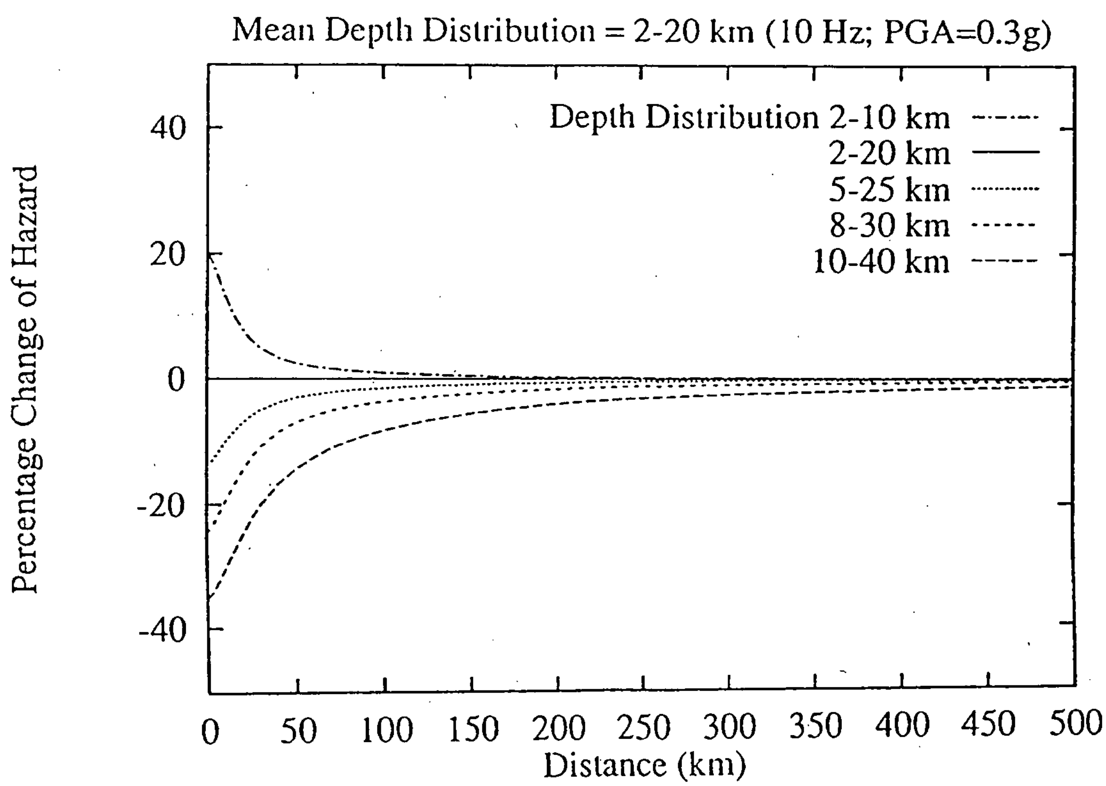


Figure G-3b. Sensitivity of 10 Hz hazard to depth distribution for PGA = 0.3g, Group A sites.

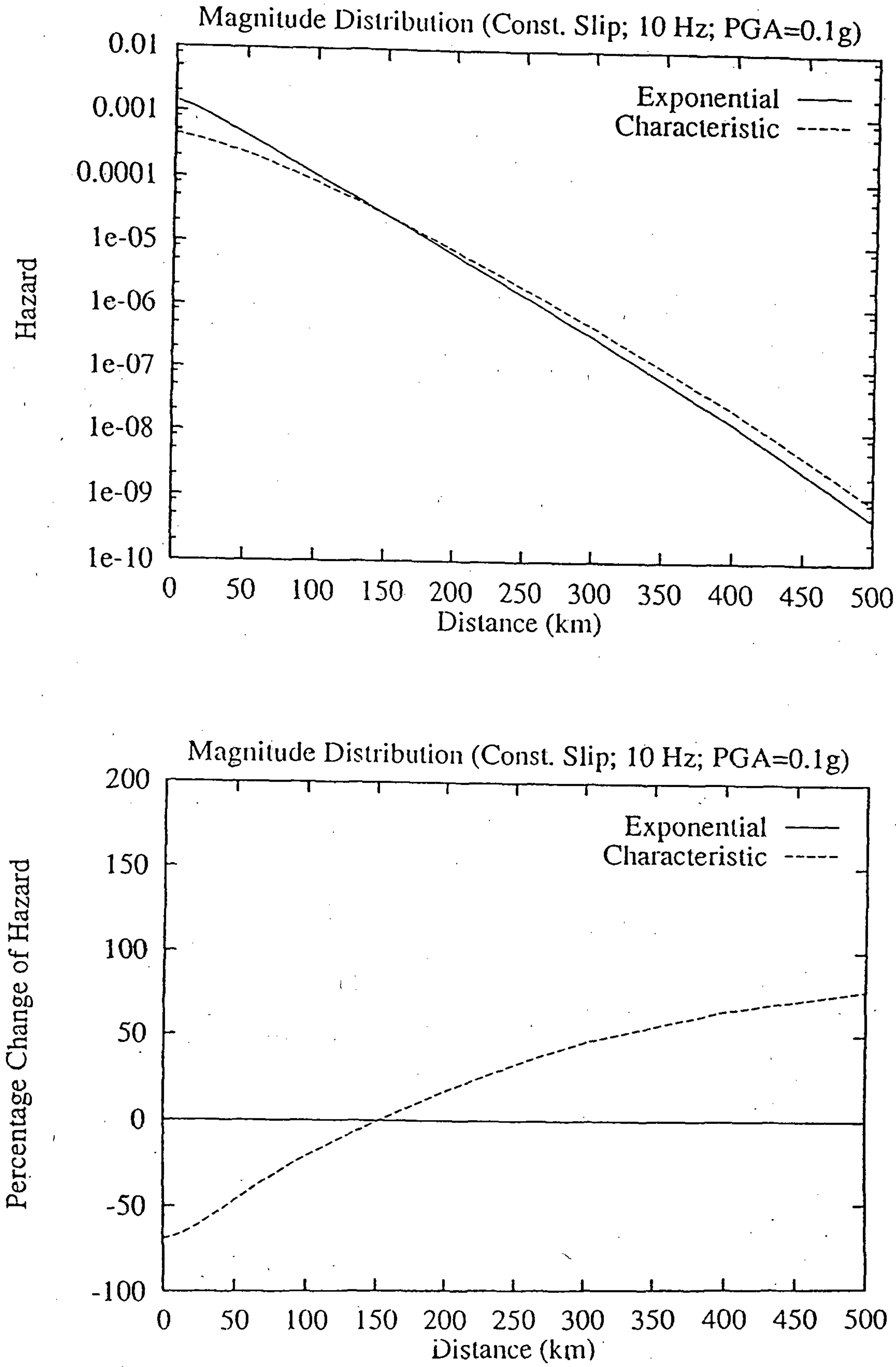
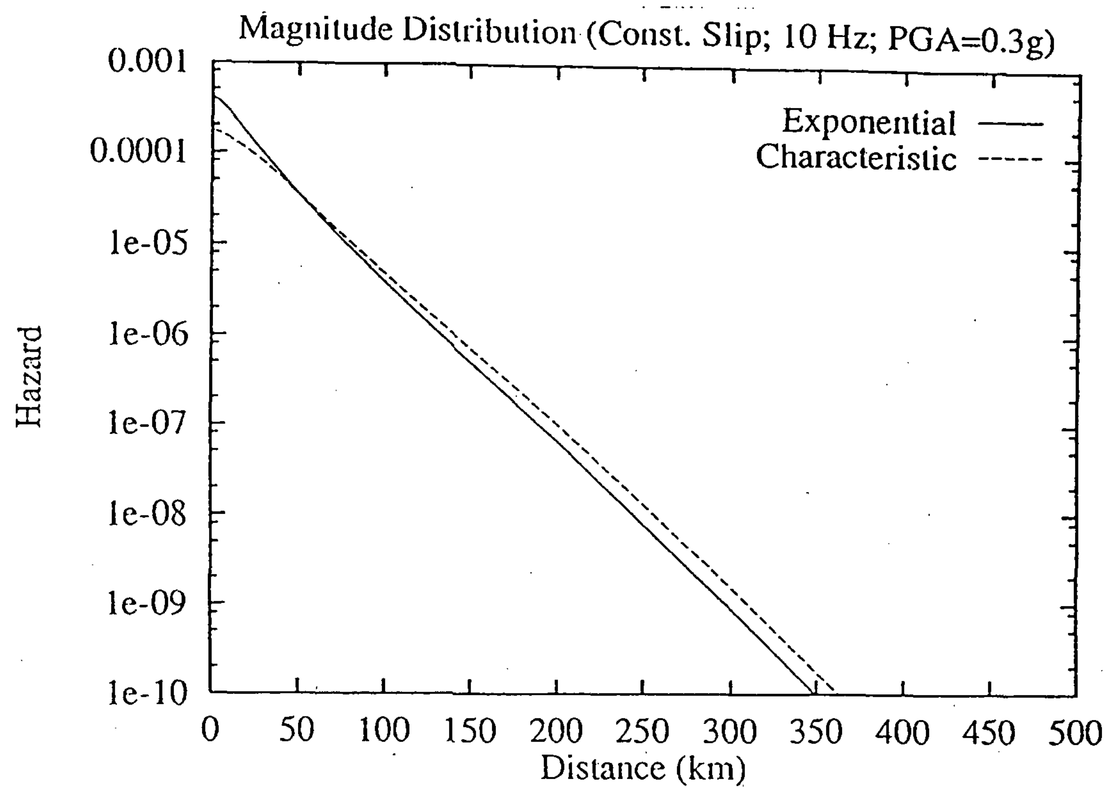


Figure G-4a. Sensitivity of 10 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.1g, Group A sites.



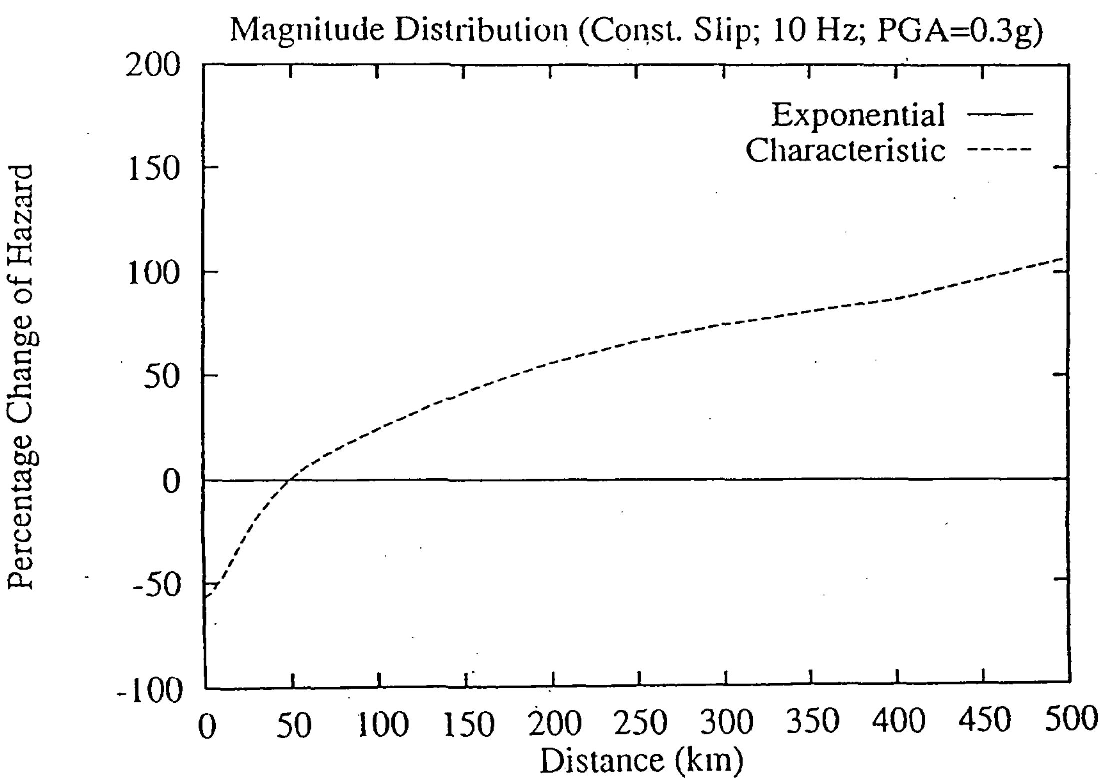
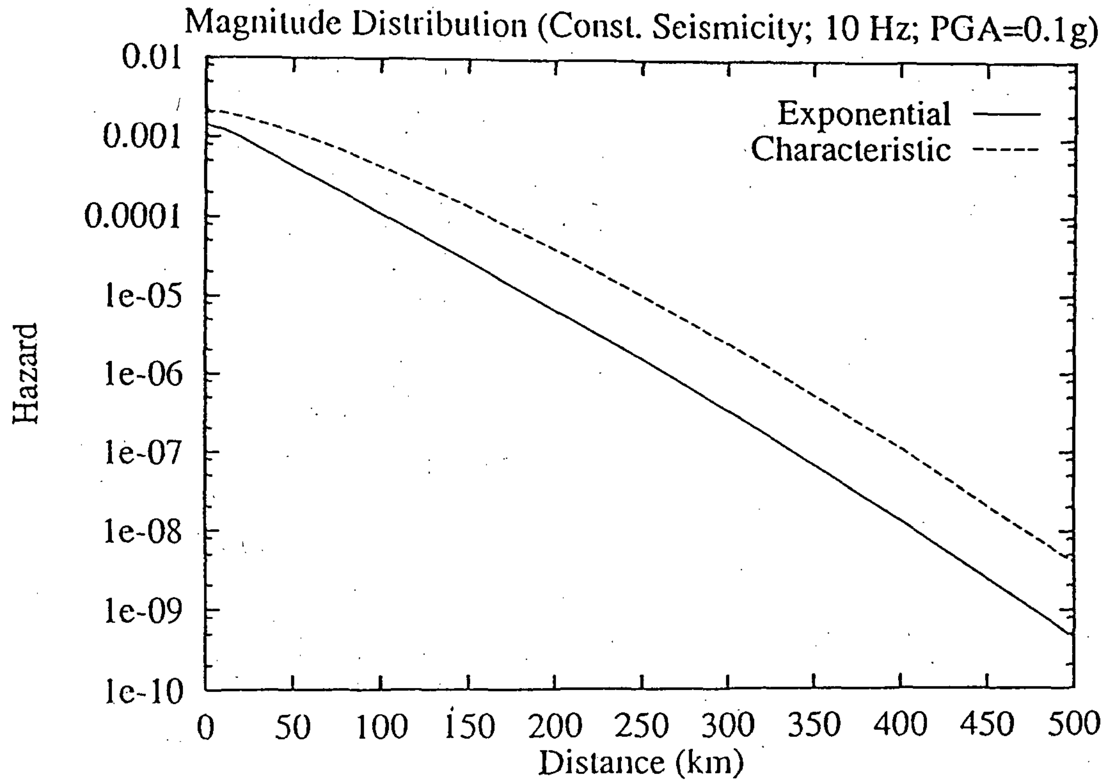


Figure G-4b. Sensitivity of 10 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.3g, Group A sites.



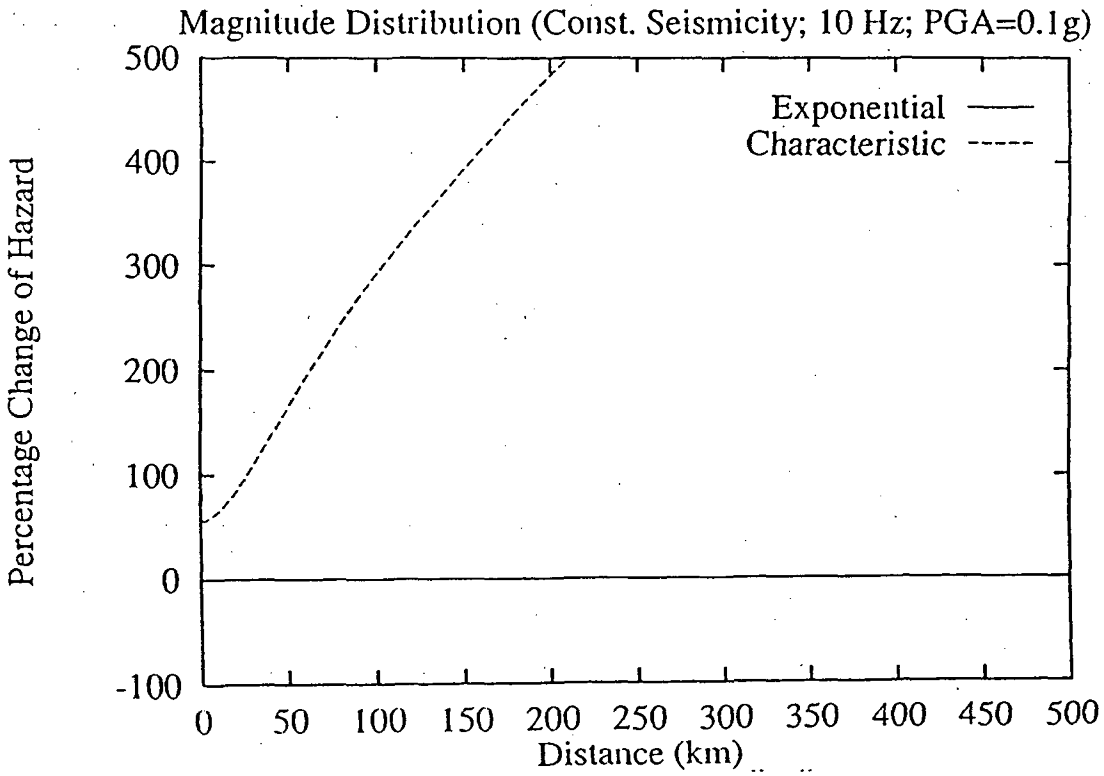
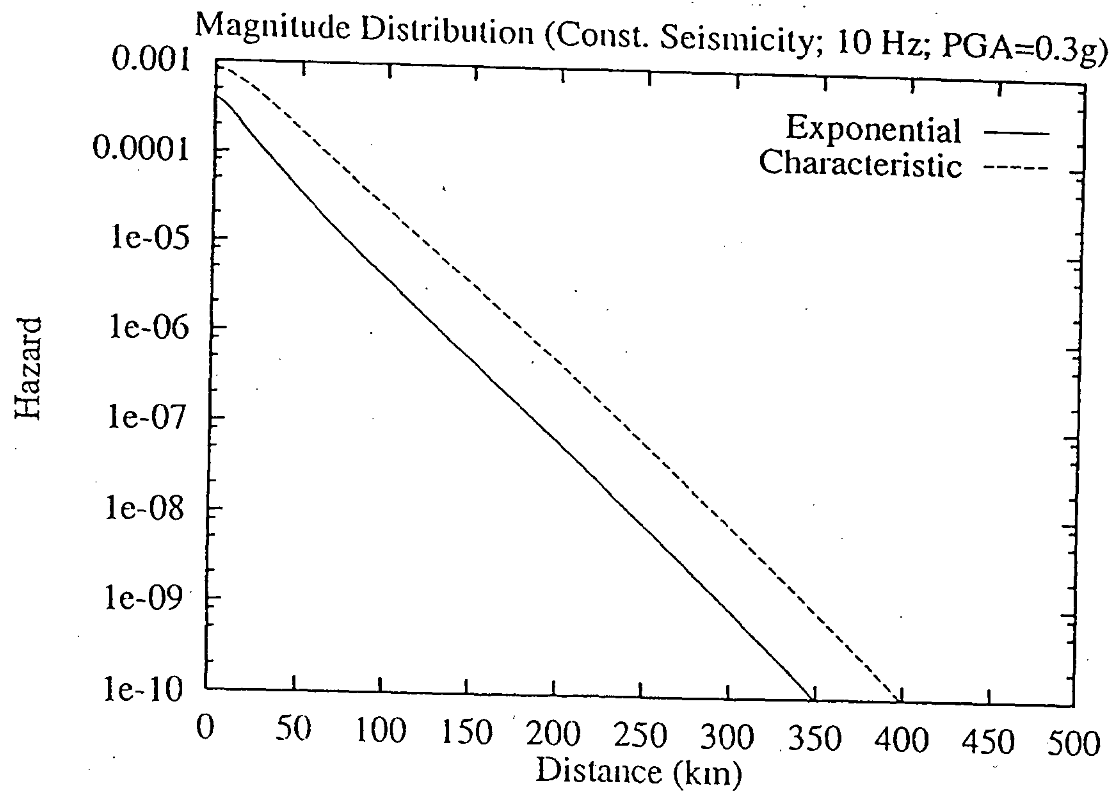


Figure G-5a. Sensitivity of 10 Hz hazard to magnitude distribution (with constant seismicity assumption), PGA = 0.1g, Group A sites.



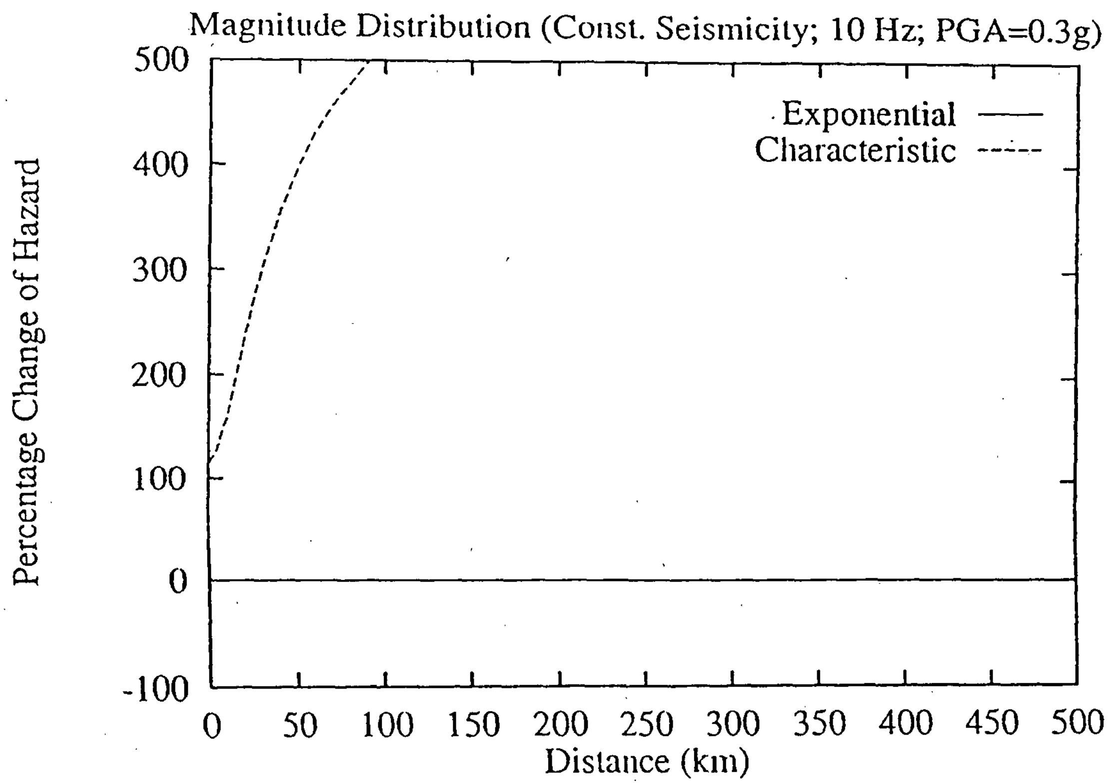
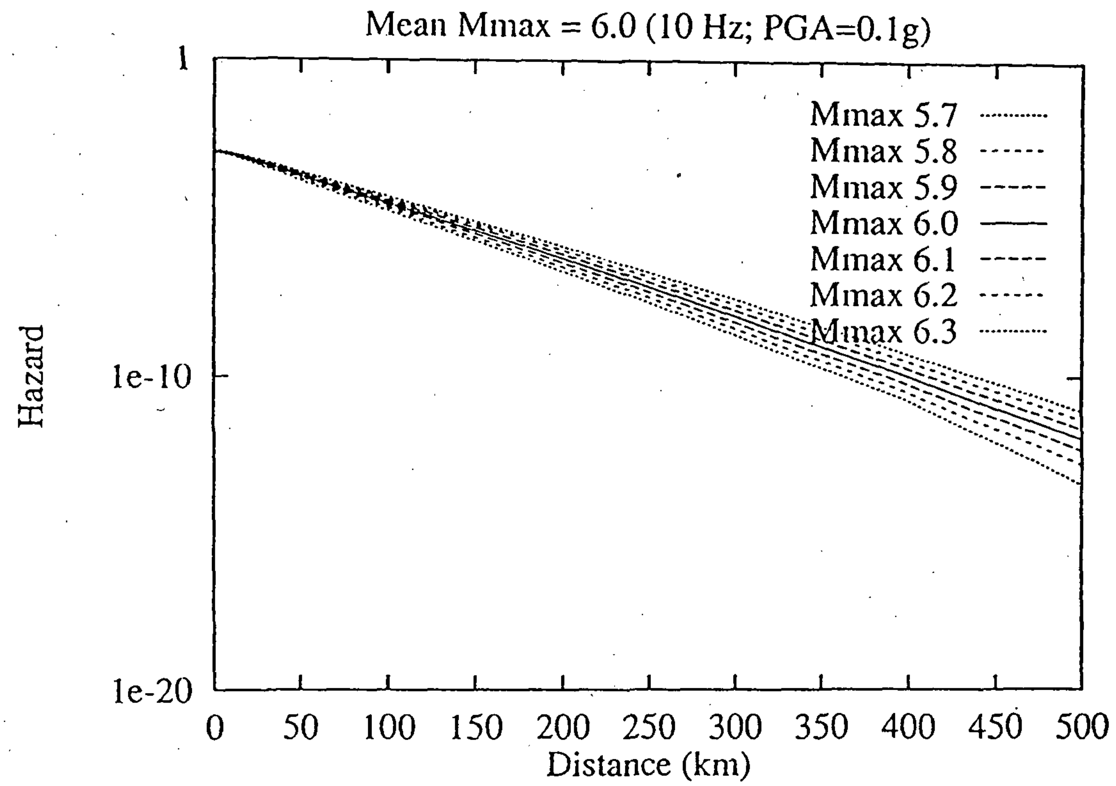


Figure G-5b. Sensitivity of 10 Hz hazard to magnitude distribution, (with constant seismicity assumption), PGA = 0.3g, Group A sites.



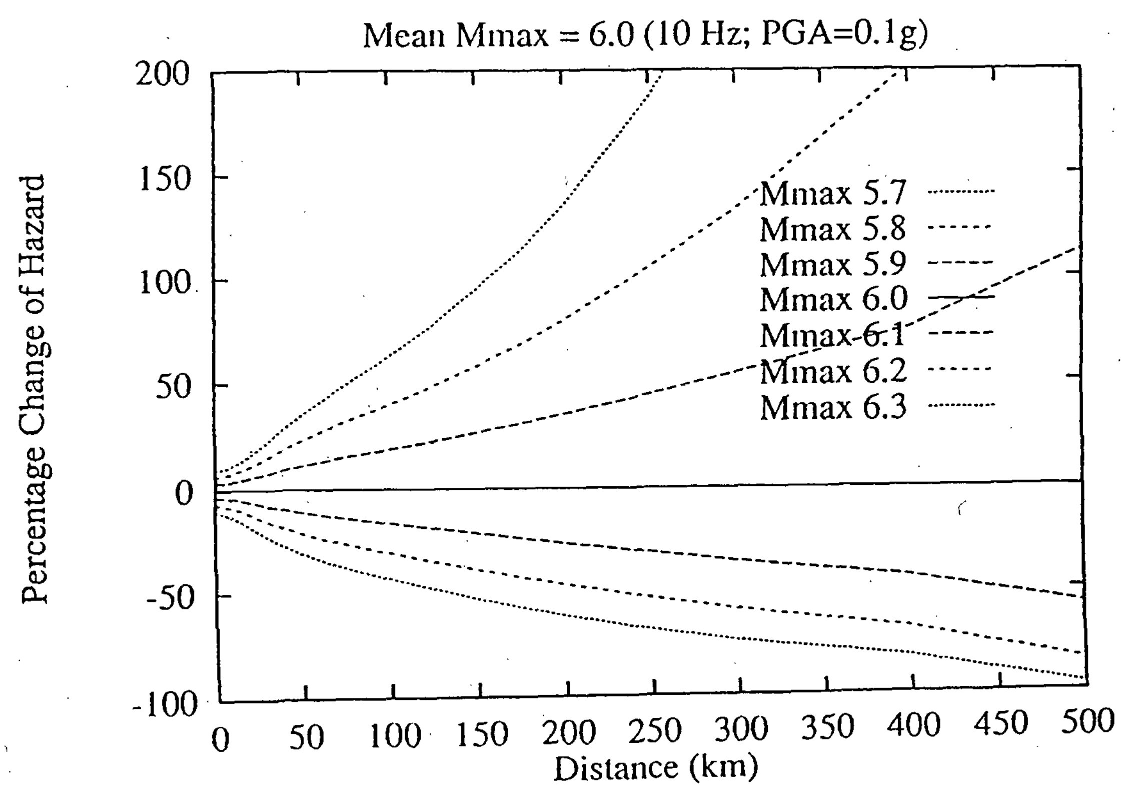


Figure G-6a. Sensitivity of 10 Hz hazard to m_{max} = 6.0, PGA = 0.1g, Group A sites.

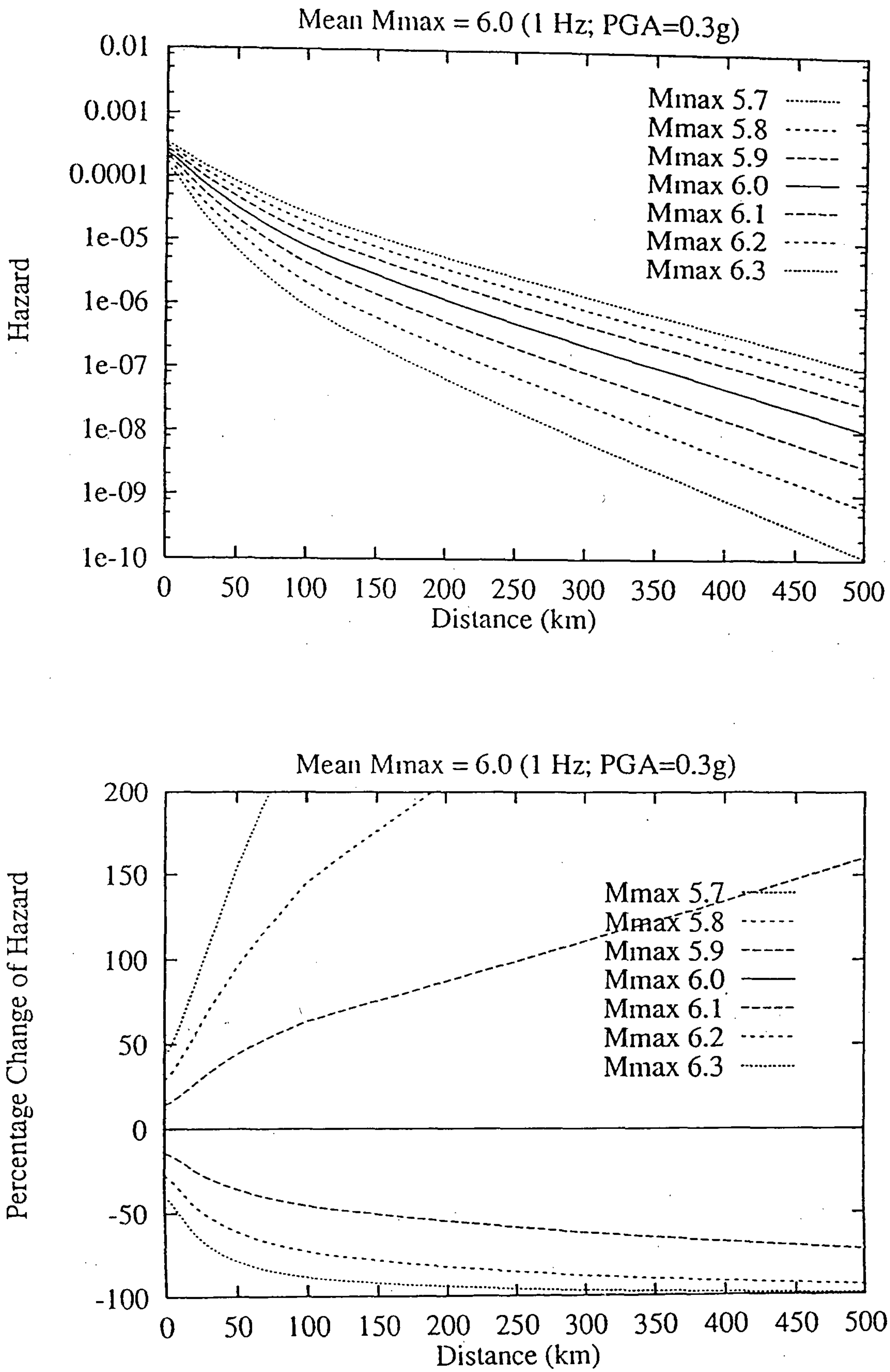


Figure G-6b. Sensitivity of 10 Hz hazard to m_{max} = 6.0, PGA = 0.3g, Group A sites.

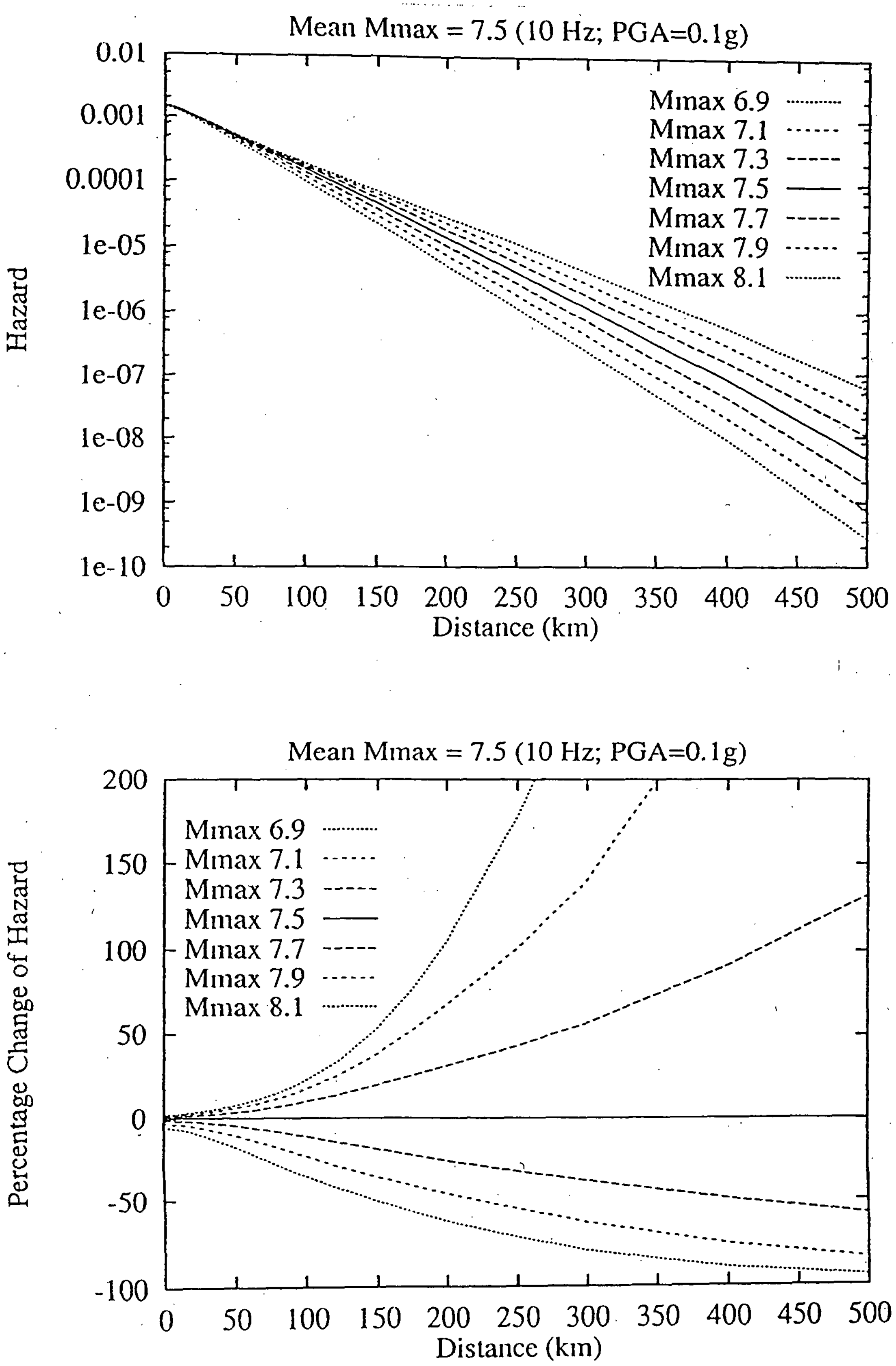
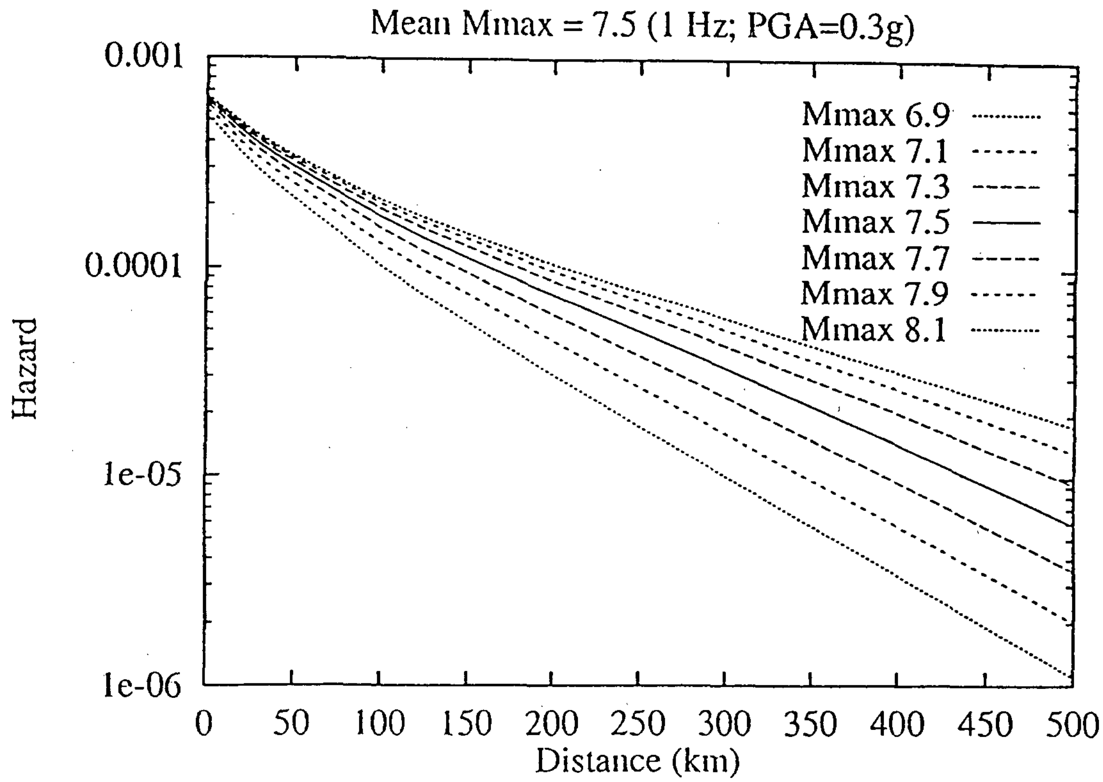


Figure G-7a. Sensitivity of 10 Hz hazard to $m_{max} = 7.5$, PGA = 0.1g, Group A sites.



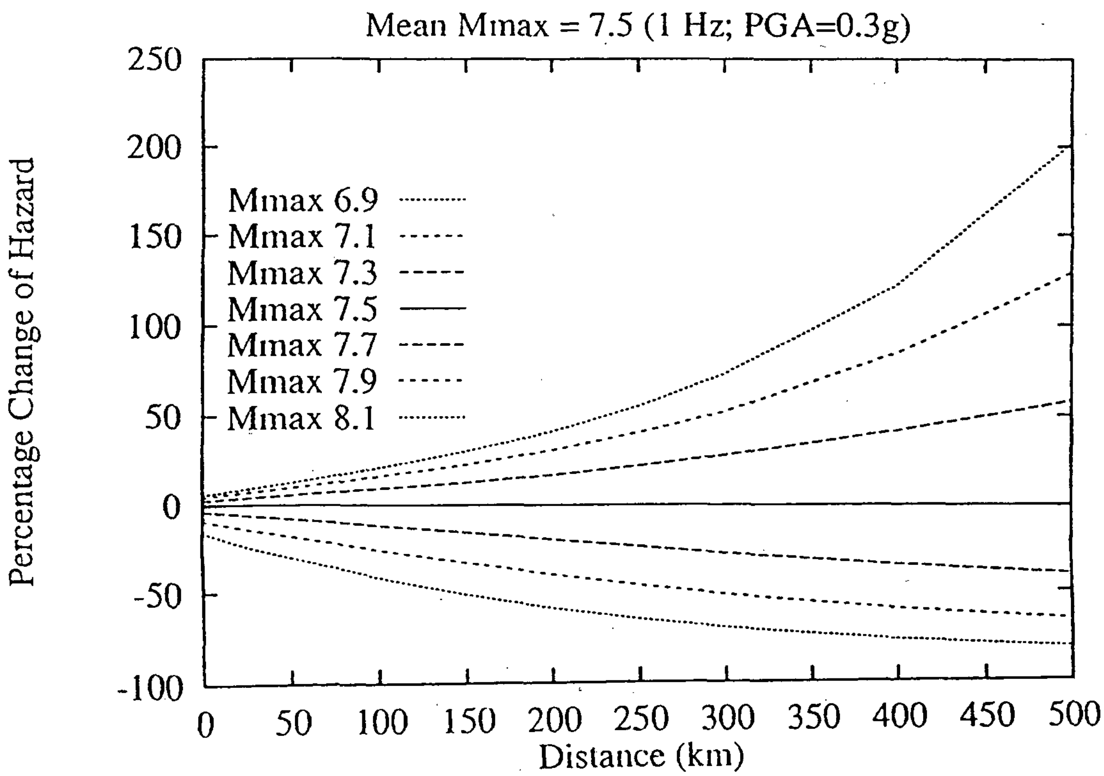


Figure G-7b. Sensitivity of 10 Hz hazard to m_{max} = 7.5, PGA = 0.3g, Group A sites.

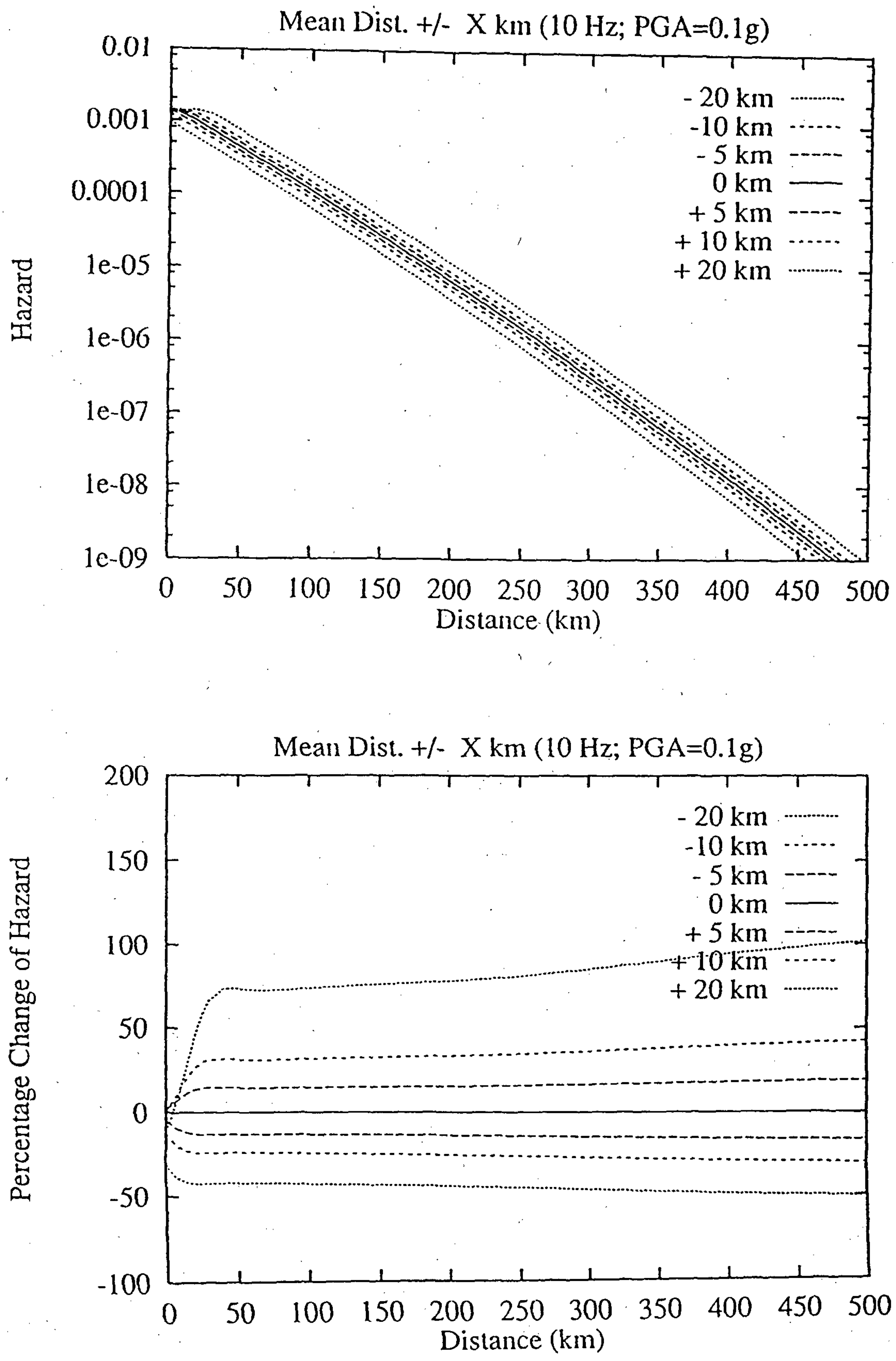
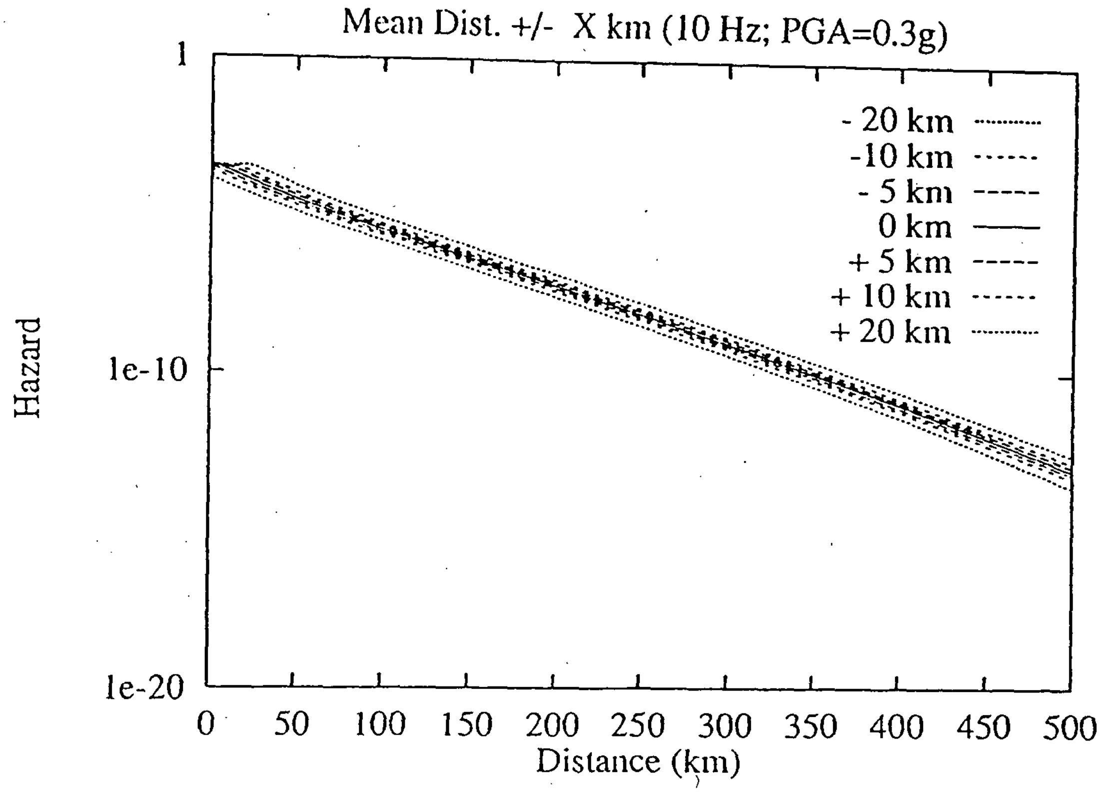


Figure G-8a. Sensitivity of 10 Hz hazard to distance from fault, PGA = 0.1g, Group A sites.



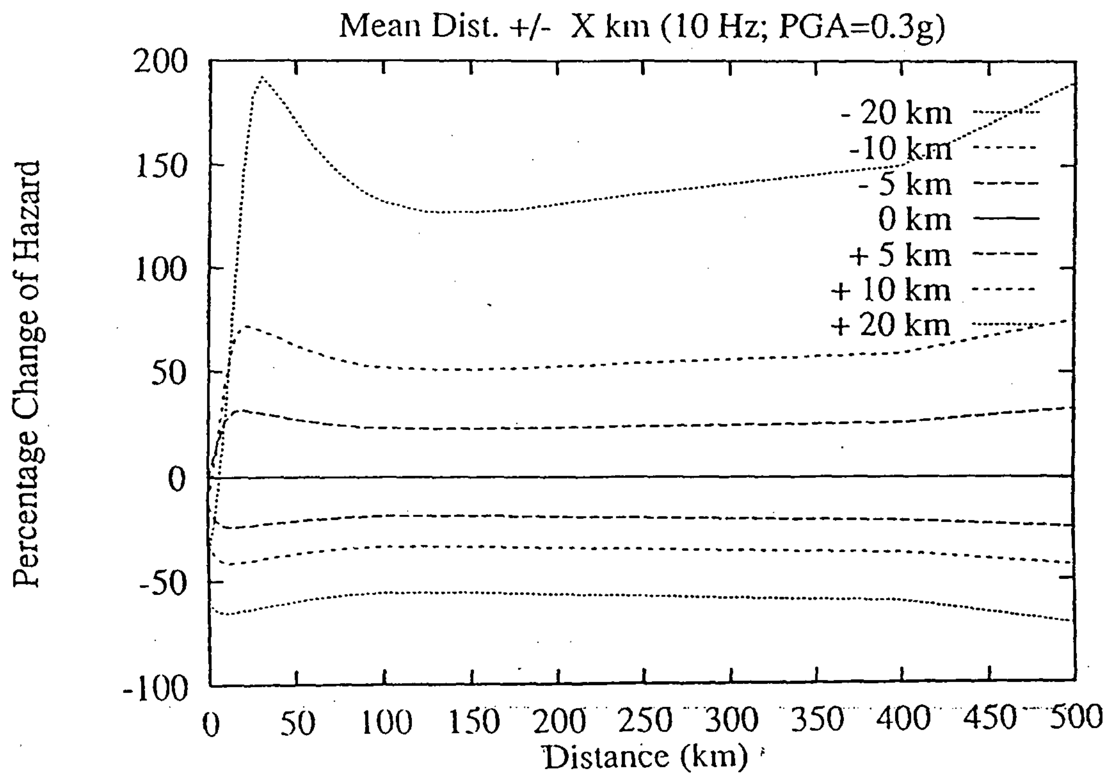
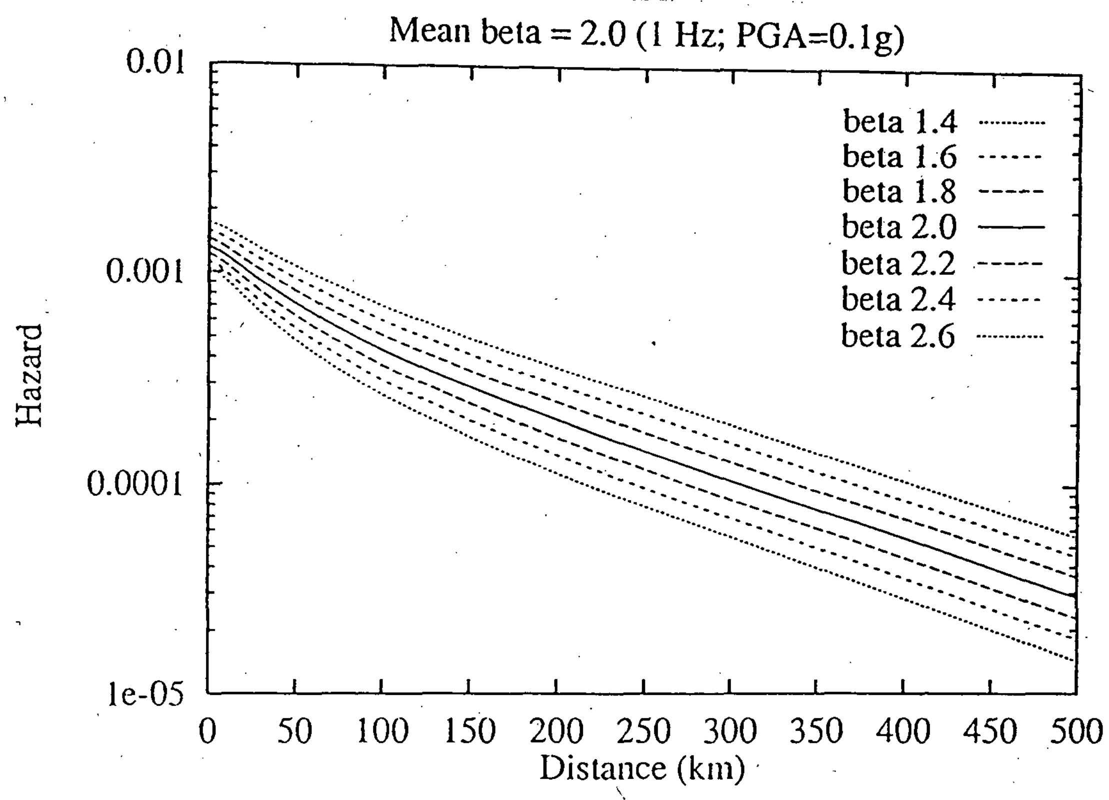


Figure G-8b. Sensitivity of 10 Hz hazard to distance from fault, PGA = 0.3g, Group A sites.



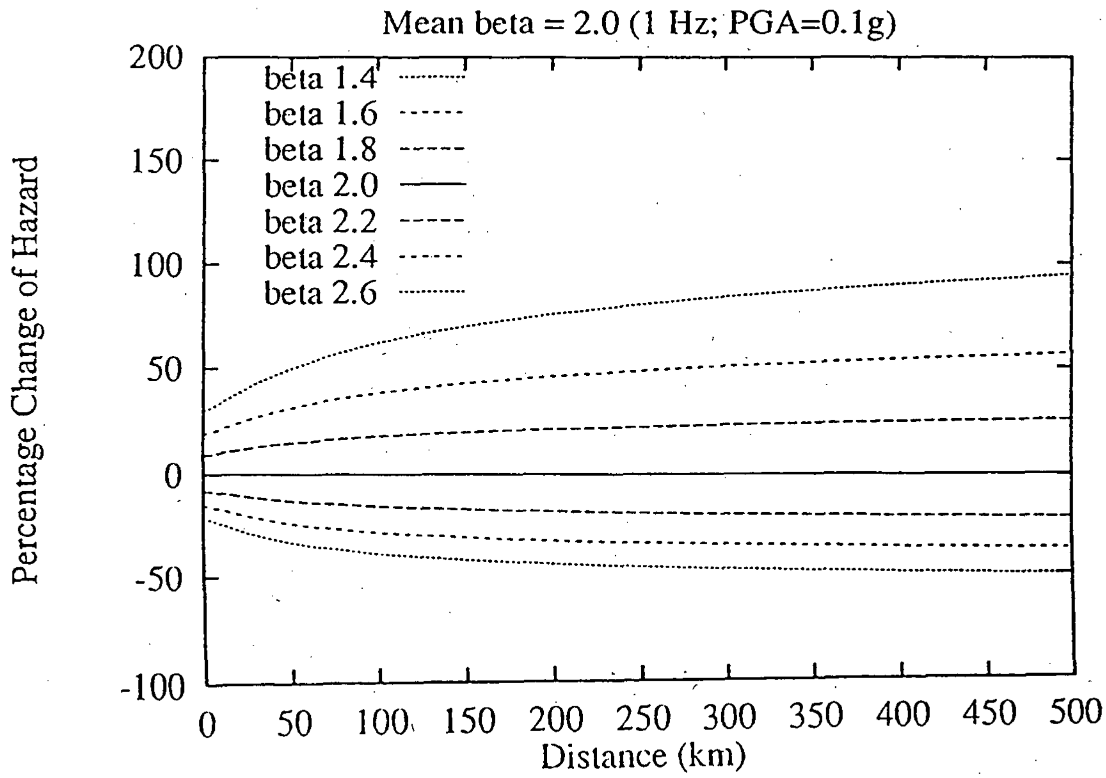


Figure G-9a. Sensitivity of 1 Hz hazard to beta for PGA = 0.1g, Group A sites.

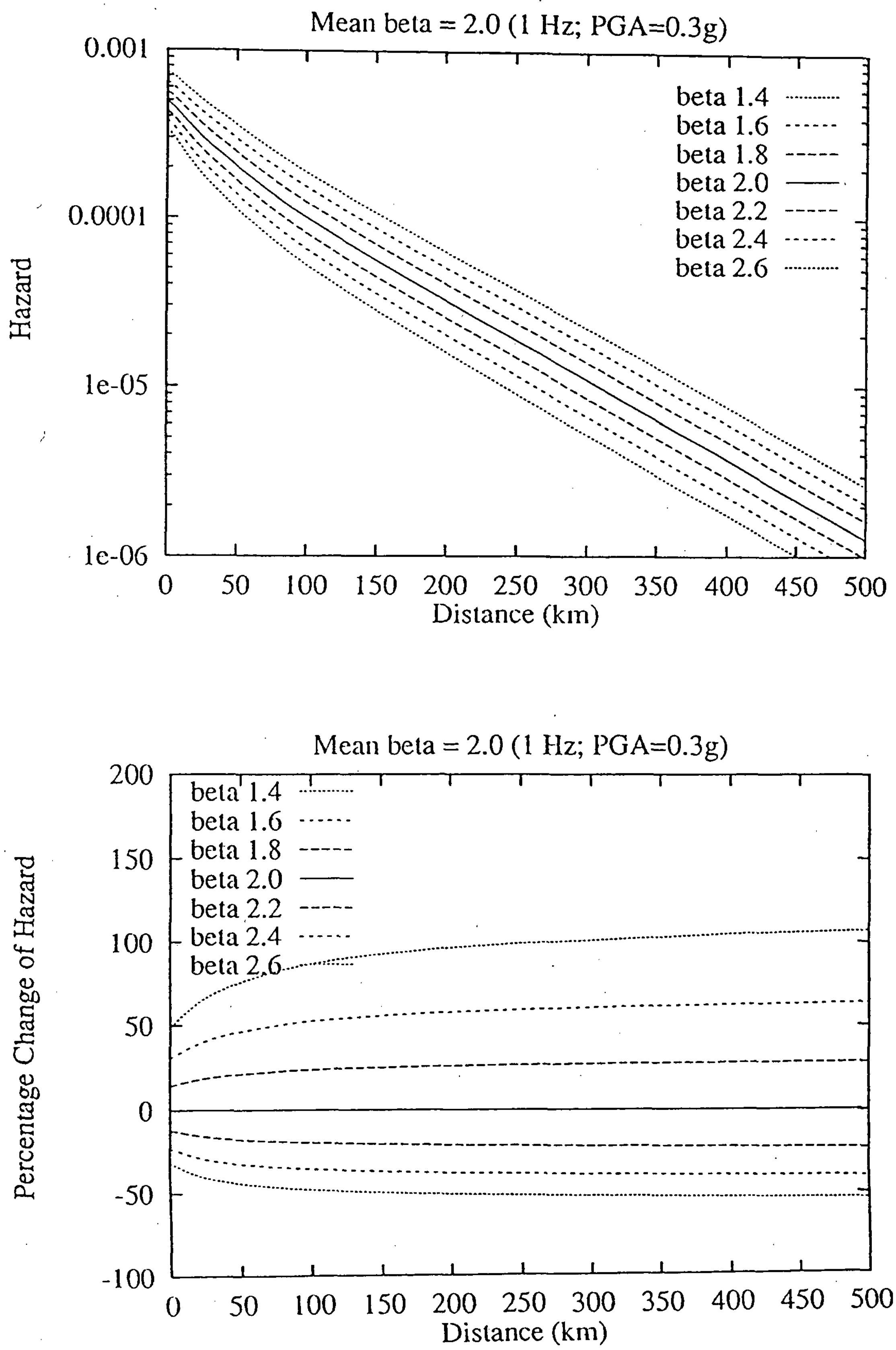
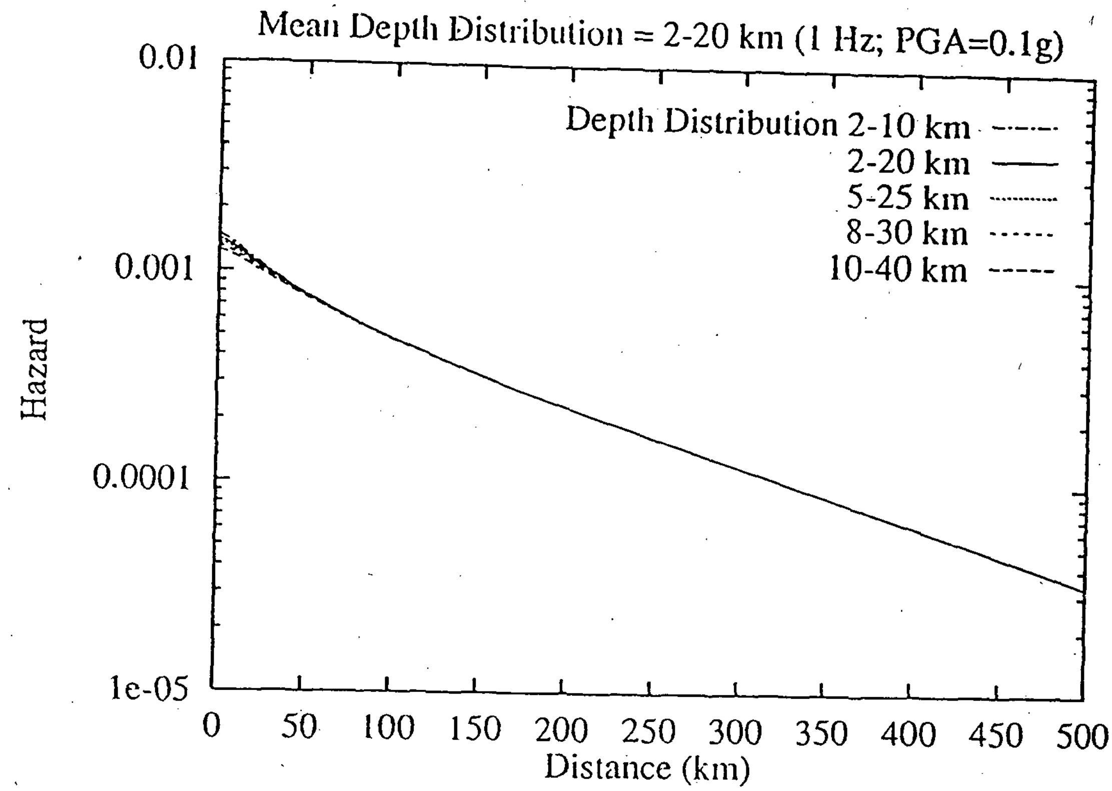


Figure G-9b. Sensitivity of 1 Hz hazard to beta for PGA = 0.3g, Group A sites.



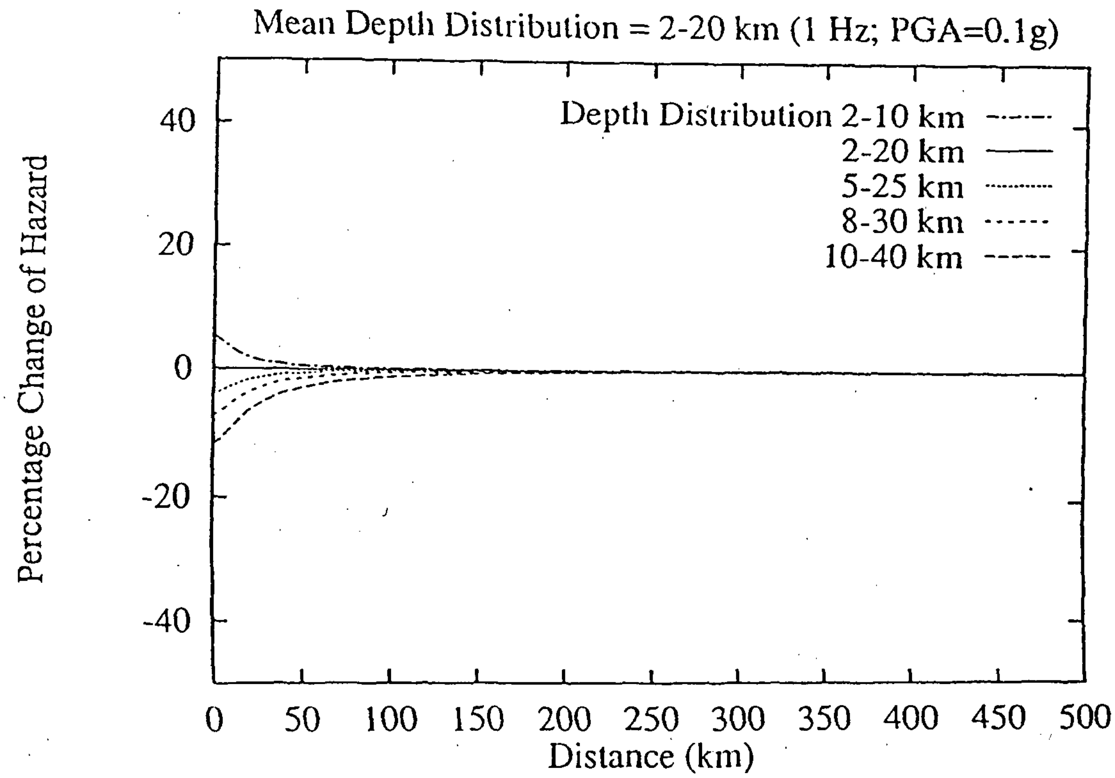
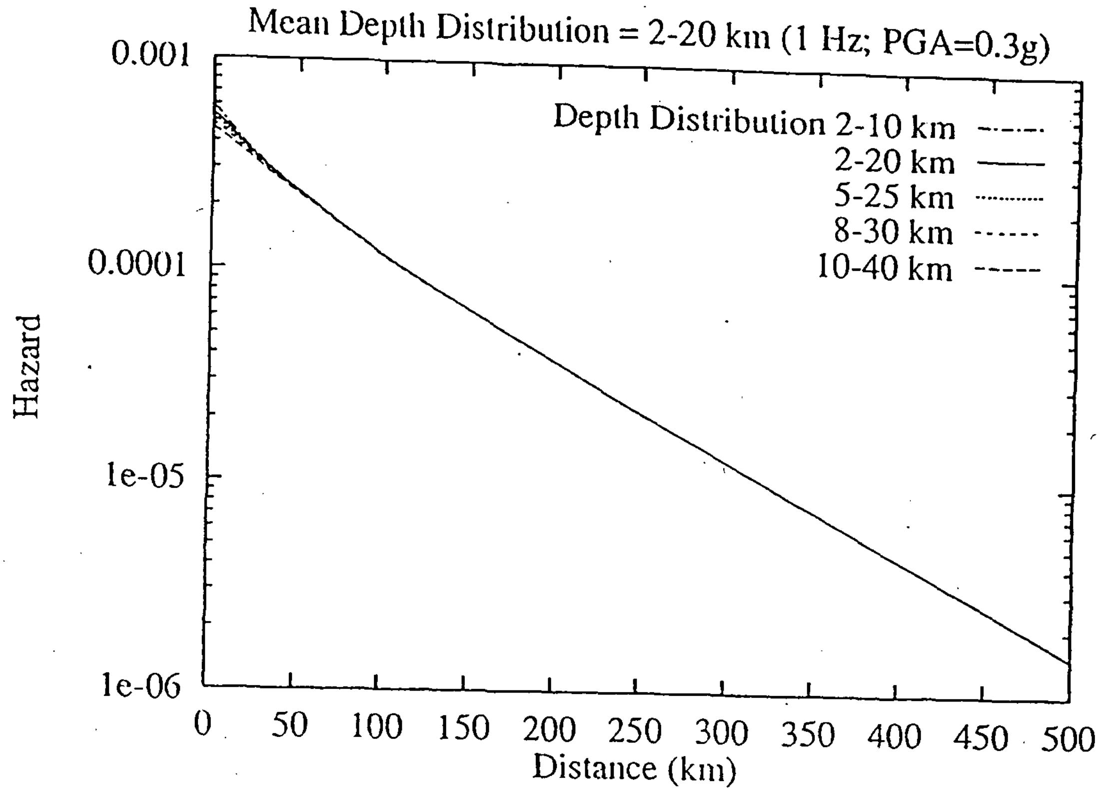


Figure G-10a. Sensitivity of 1 Hz hazard to depth distribution for PGA = 0.1g, Group A sites.



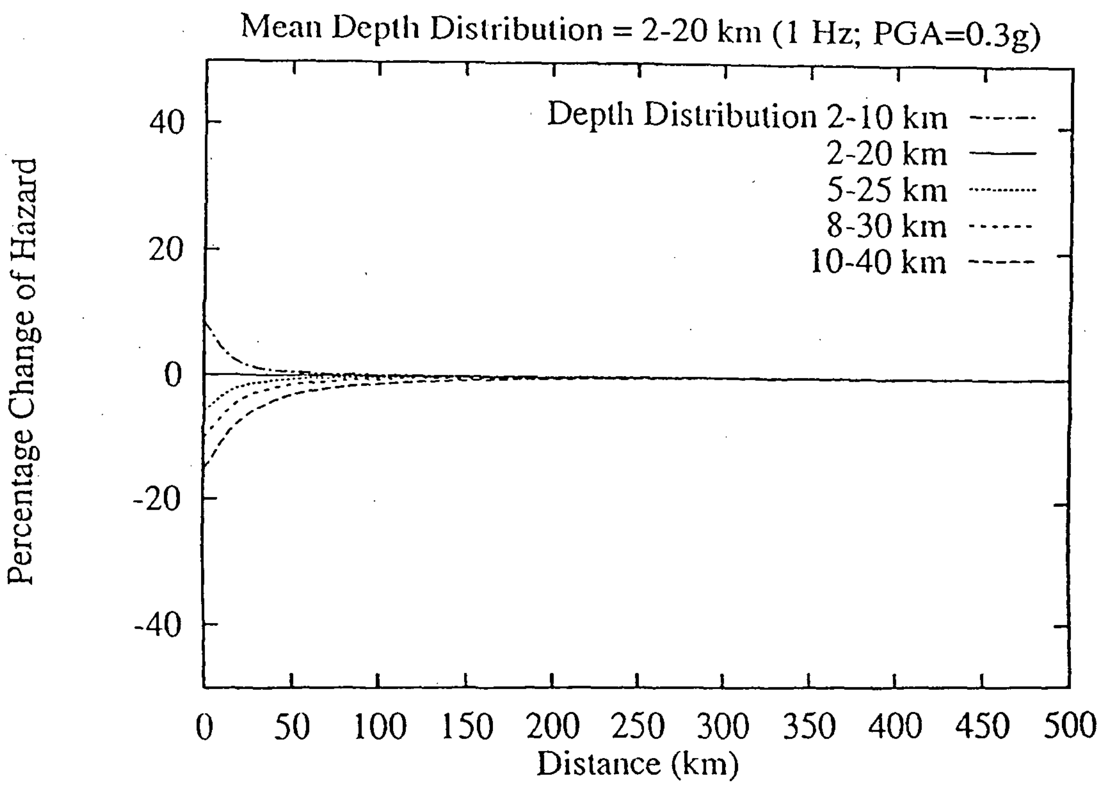
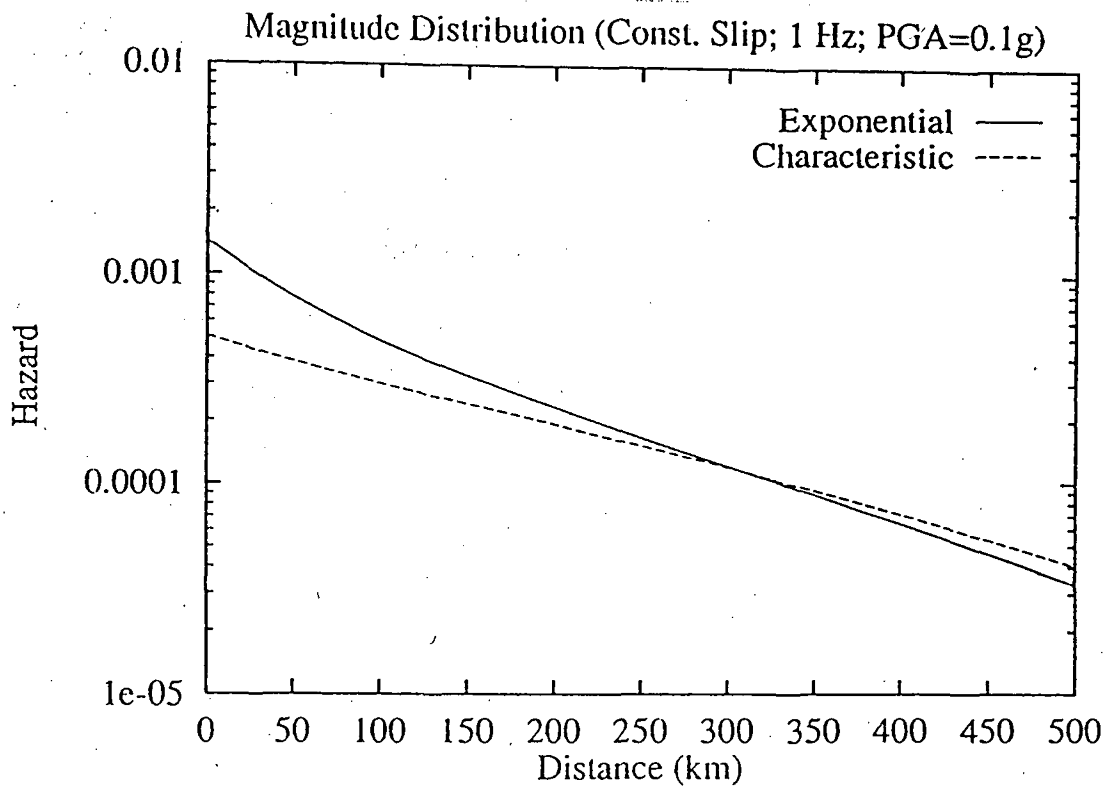


Figure G-10b. Sensitivity of 1 Hz hazard to depth distribution for PGA = 0.3g, Group A sites.



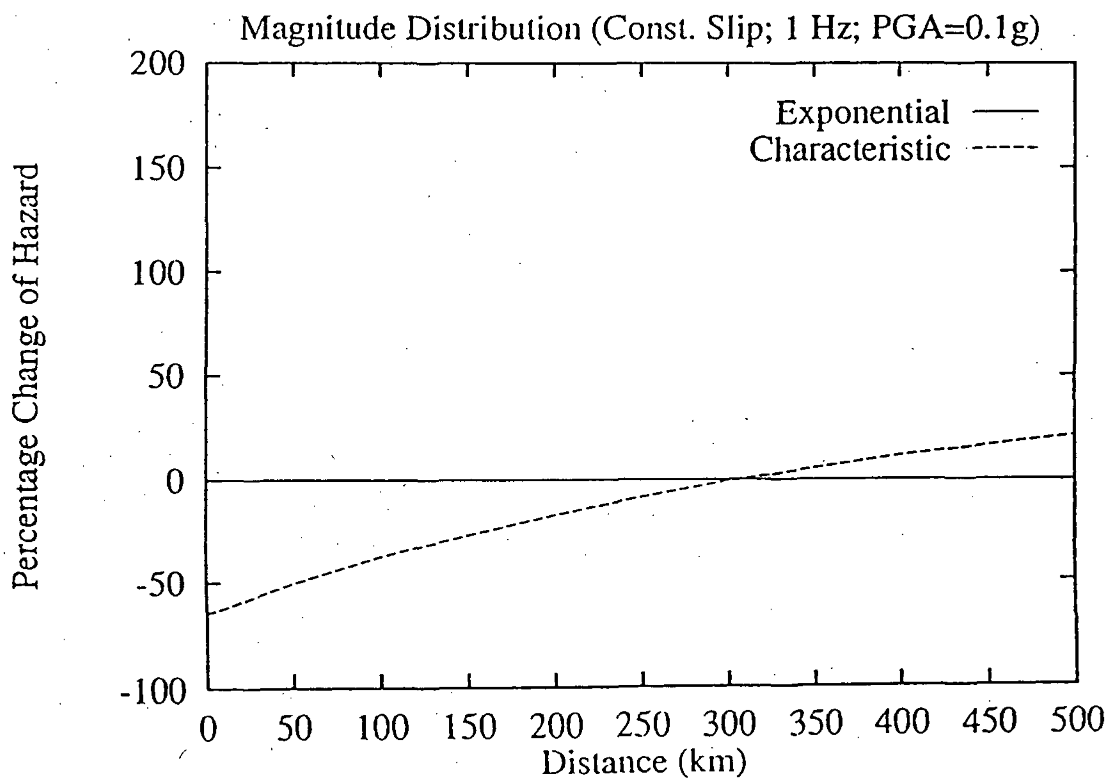
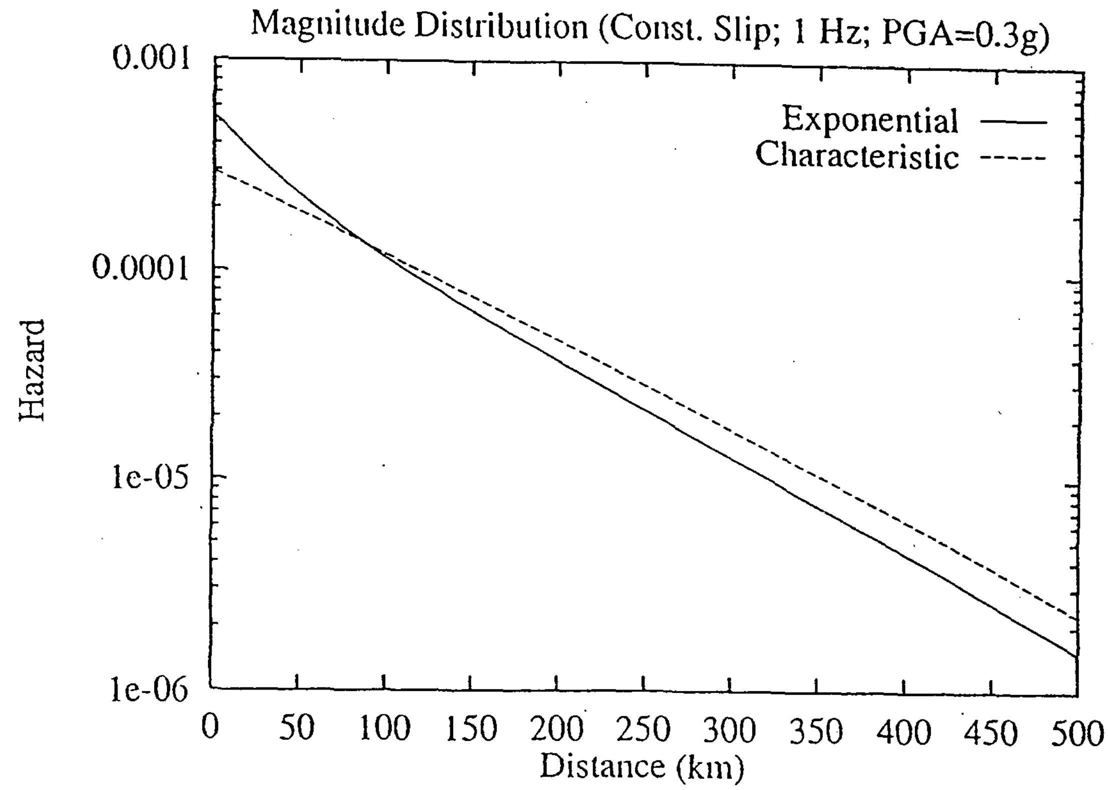


Figure G-11a. Sensitivity of 1 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.1g, Group A sites.



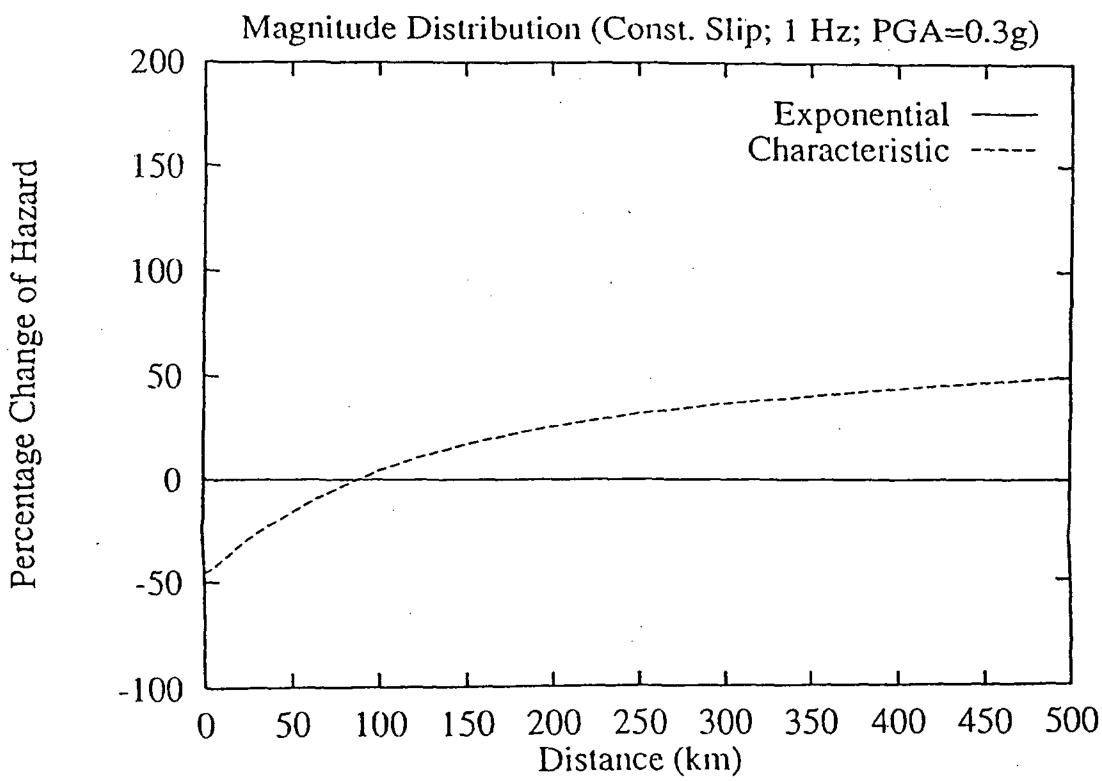
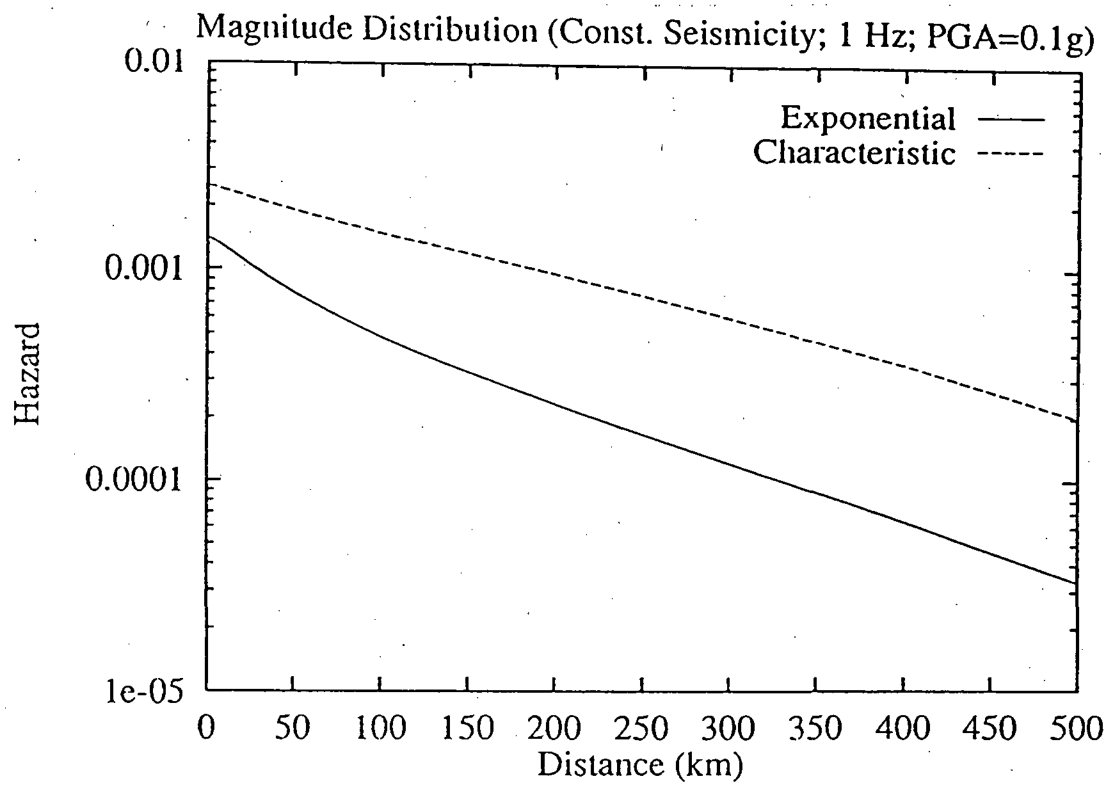


Figure G-11b. Sensitivity of 1 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.3g, Group A sites.



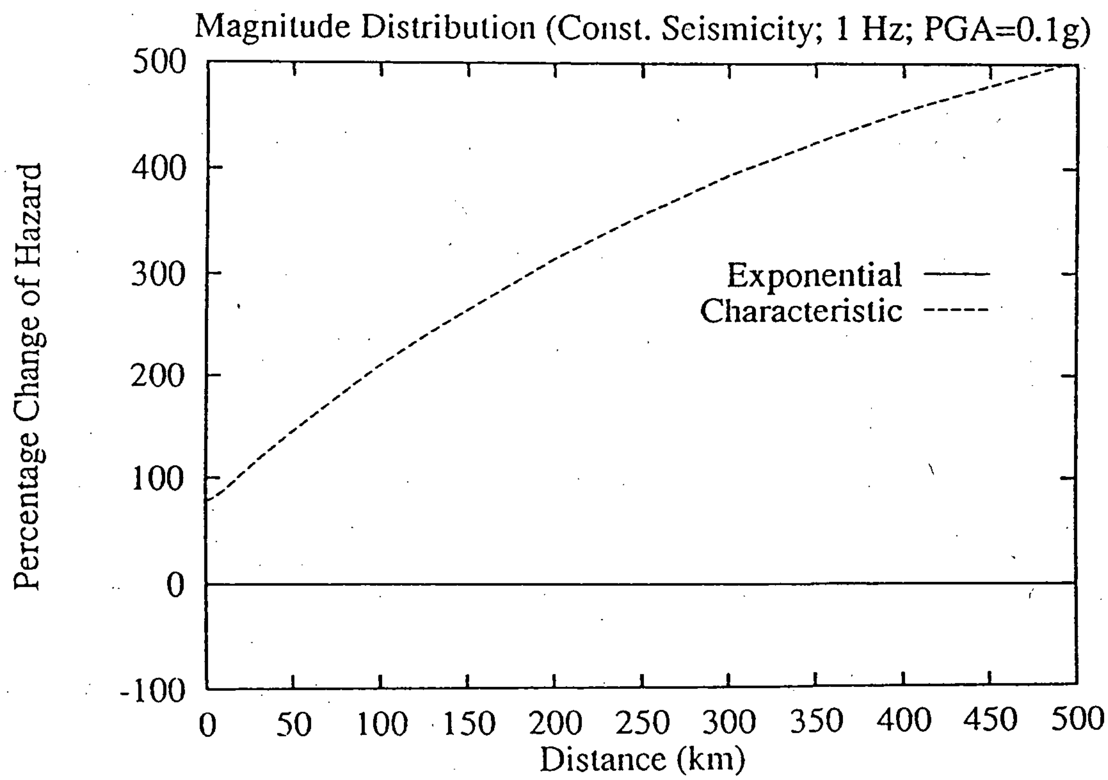
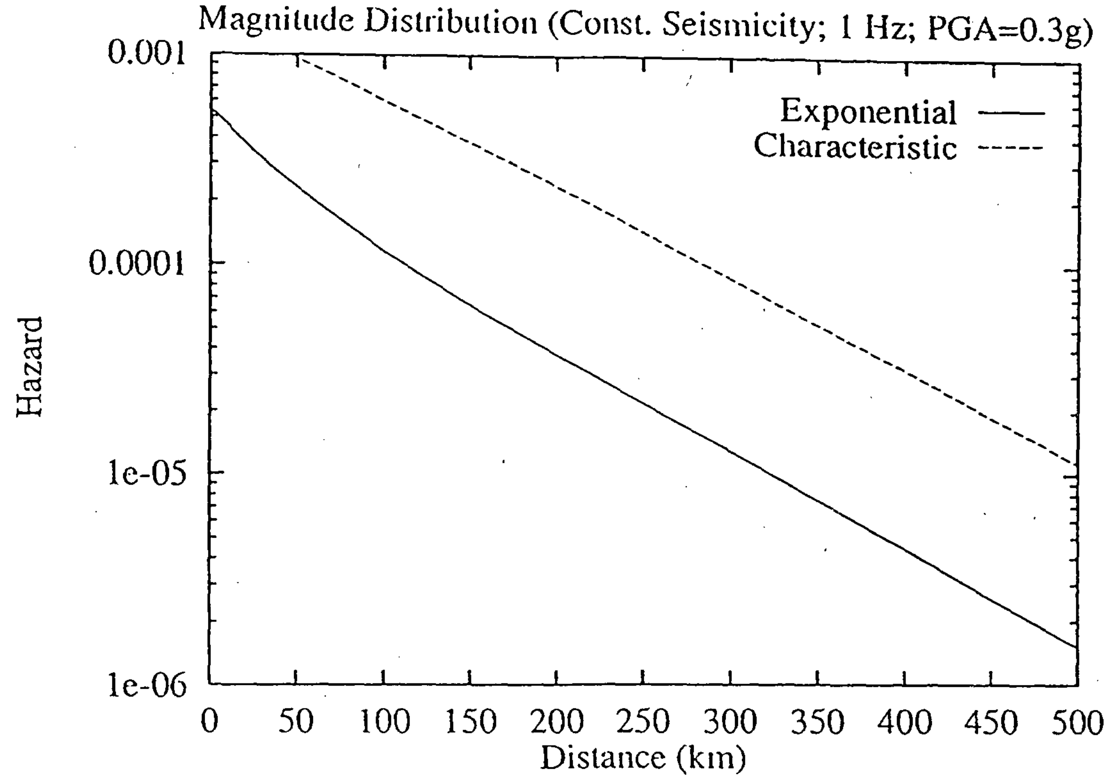


Figure G-12a. Sensitivity of 1 Hz hazard to magnitude distribution (with constant seismicity assumption), PGA = 0.1g, Group A sites.



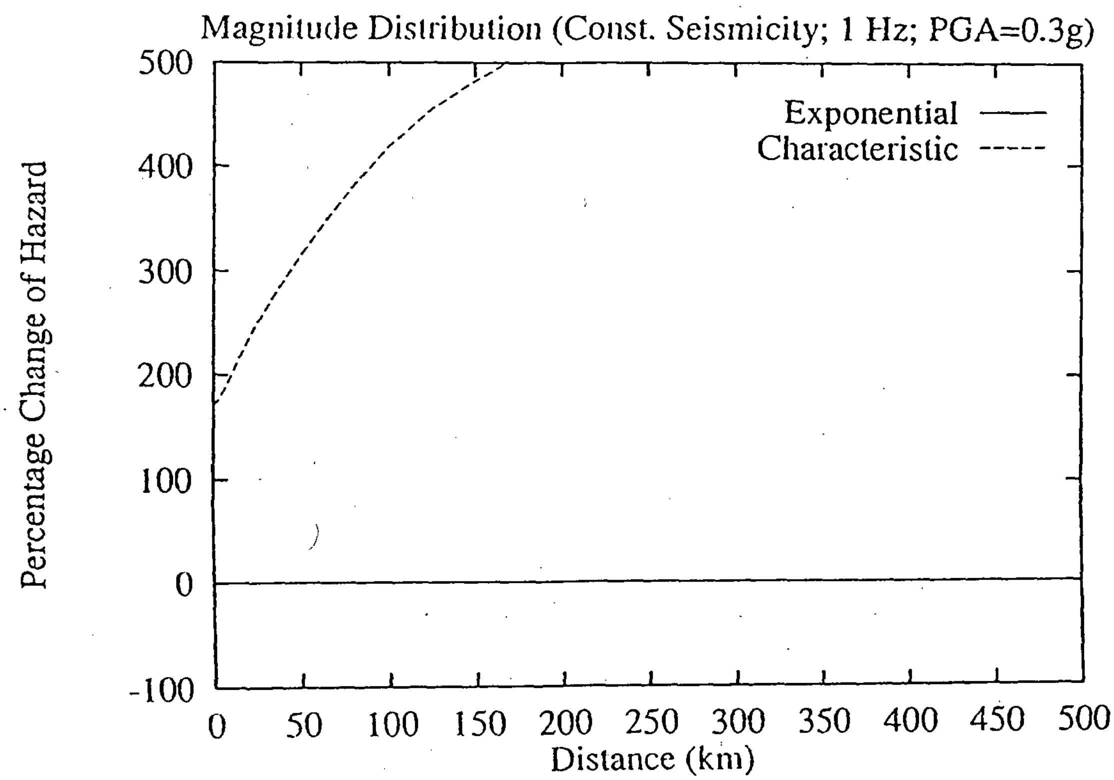
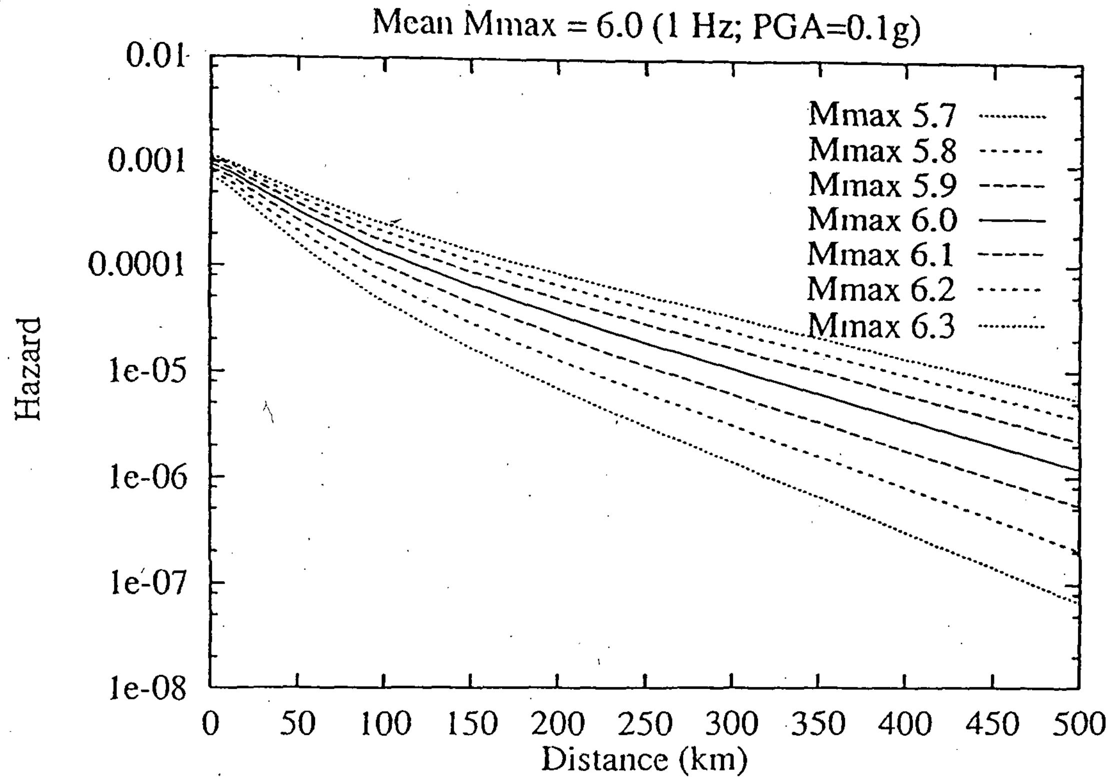


Figure G-12b. Sensitivity of 1 Hz hazard to magnitude distribution (with constant seismicity assumption), PGA = 0.3g, Group A sites.



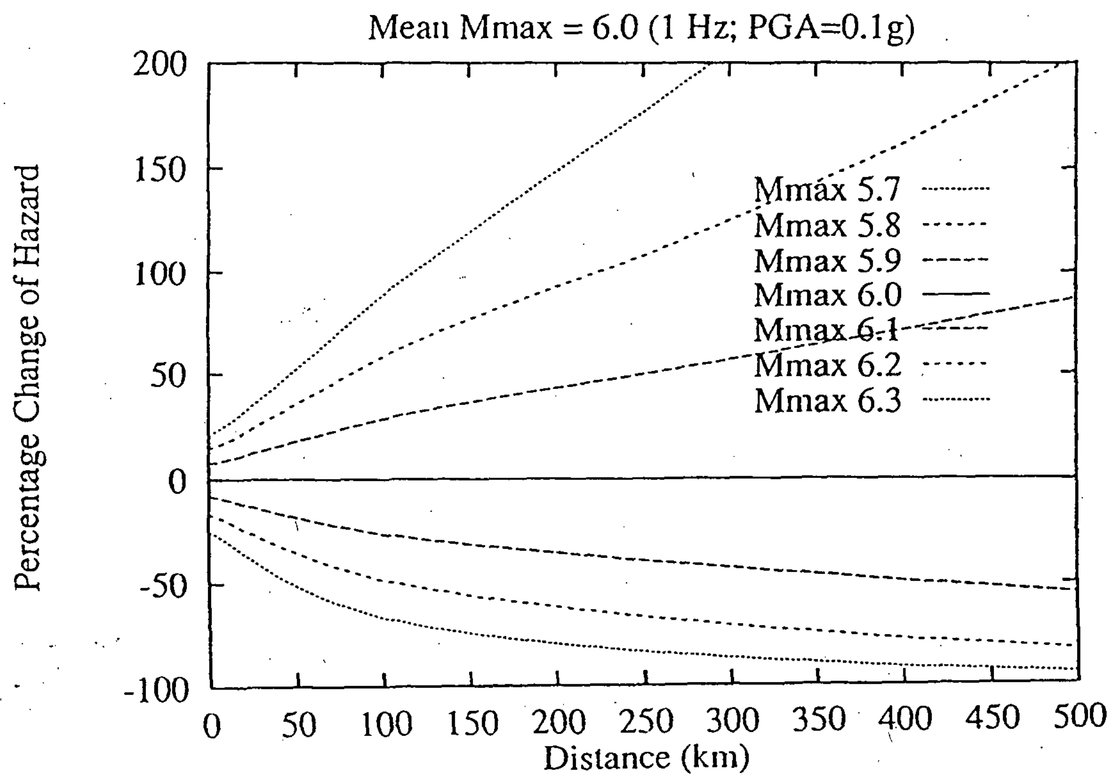
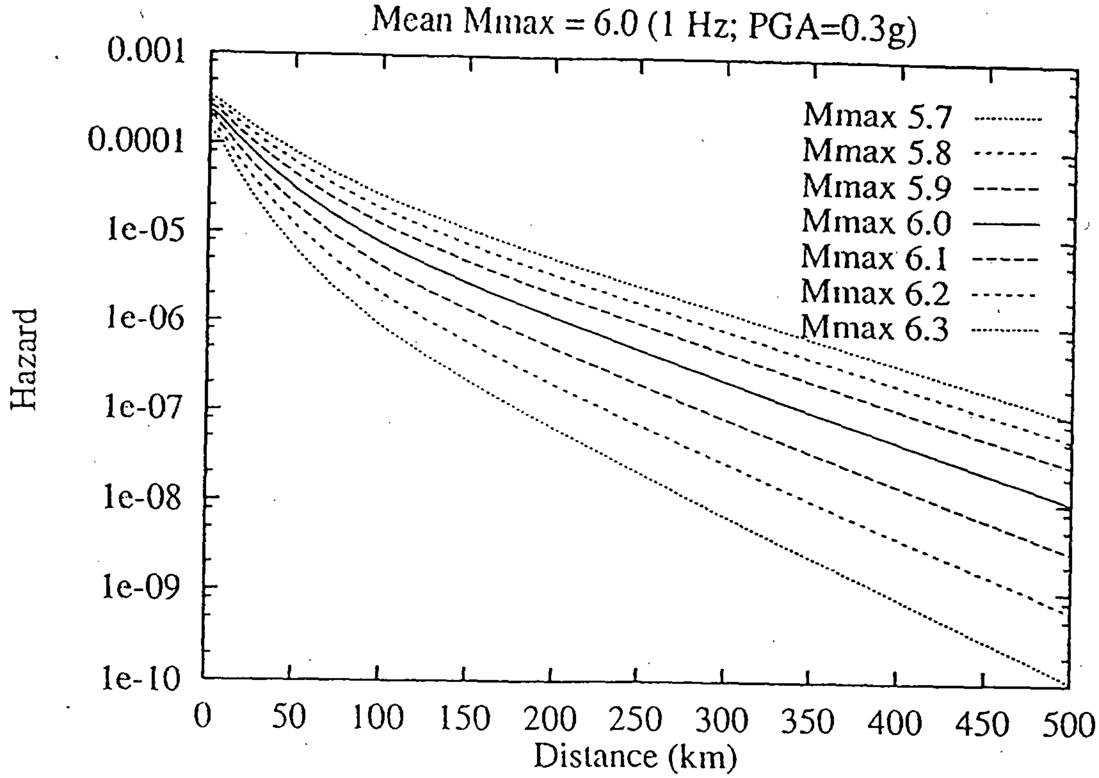


Figure G-13a. Sensitivity of 1 Hz hazard to m_{max} = 6.0, PGA = 0.1g, Group A sites.



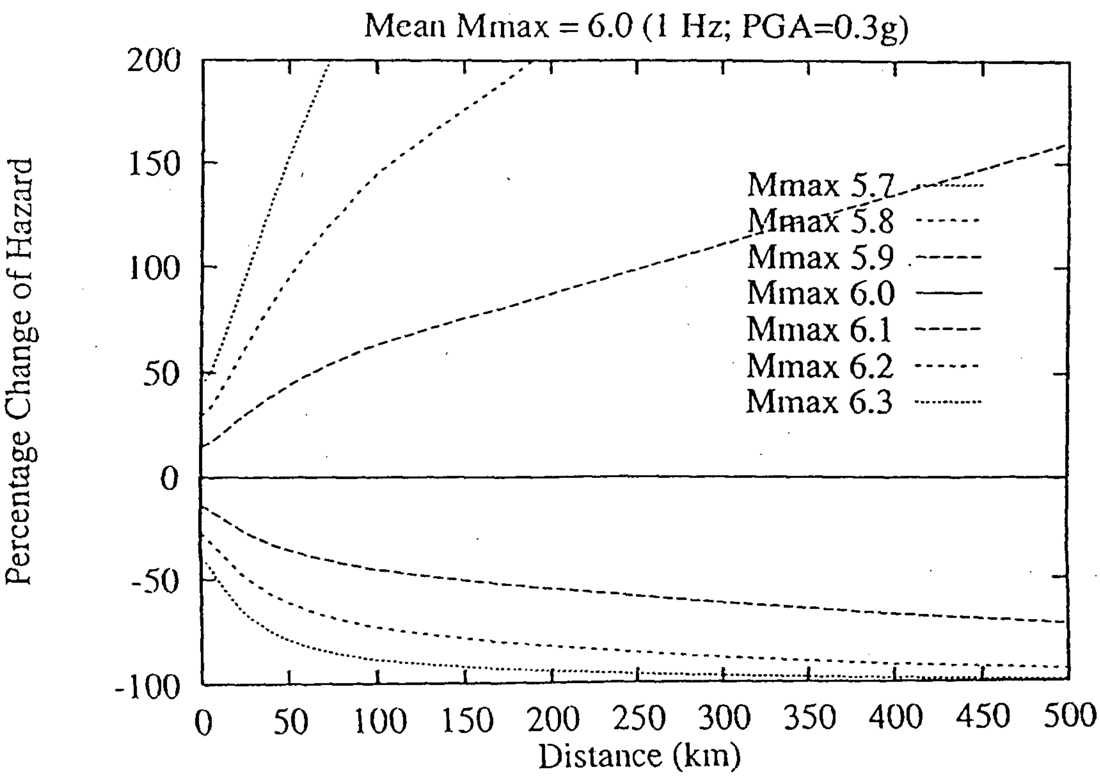
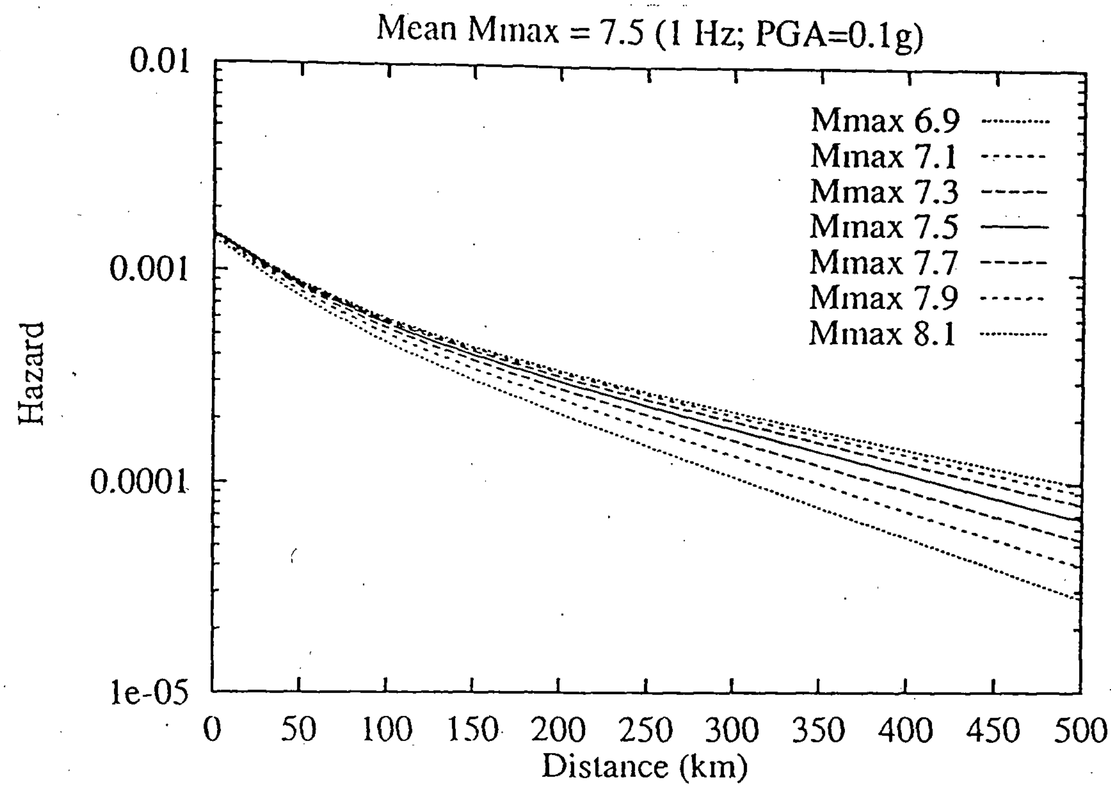


Figure G-13b. Sensitivity of 1 Hz hazard to m_{max} = 6.0, PGA = 0.3g, Group A sites.



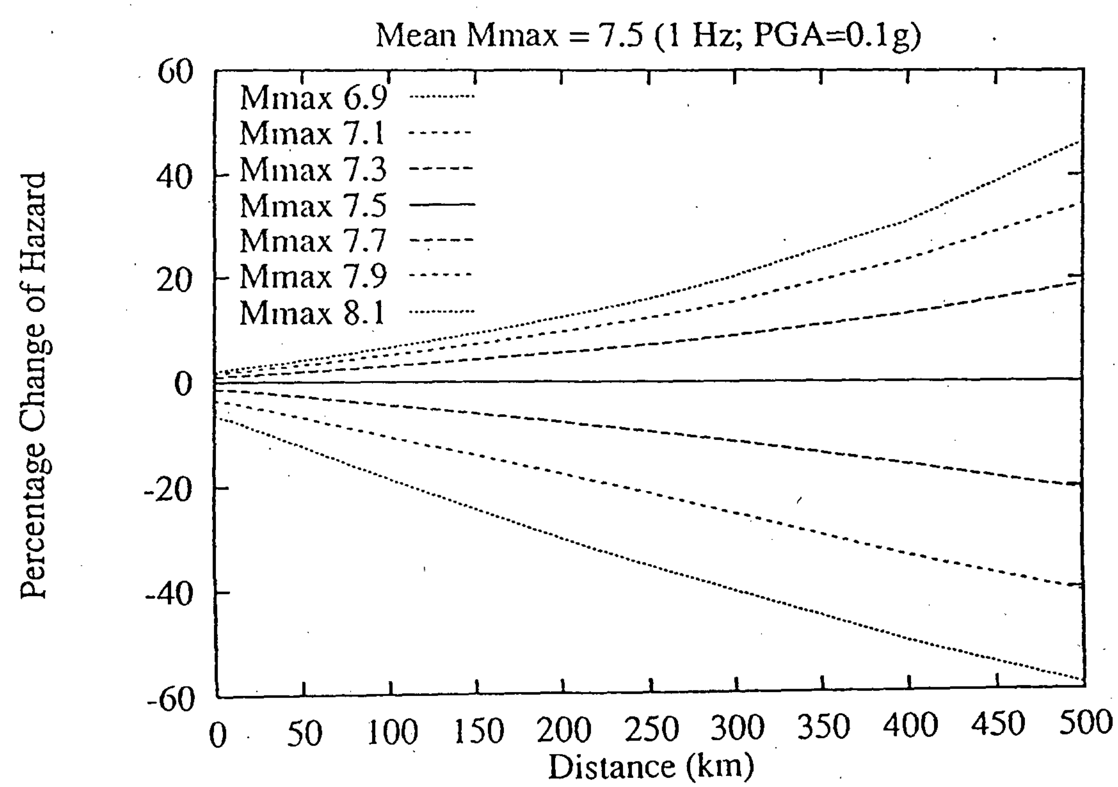
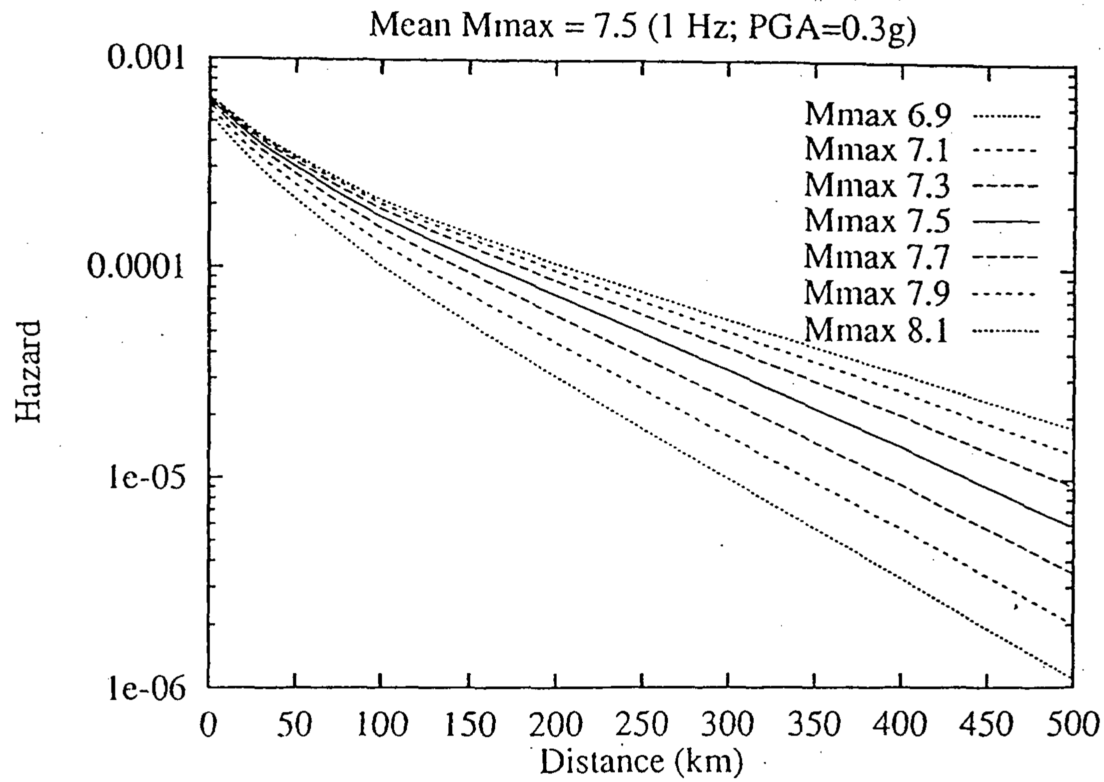


Figure G-14a. Sensitivity of 1 Hz hazard to m_{max} = 7.5, PGA = 0.1g, Group A sites.



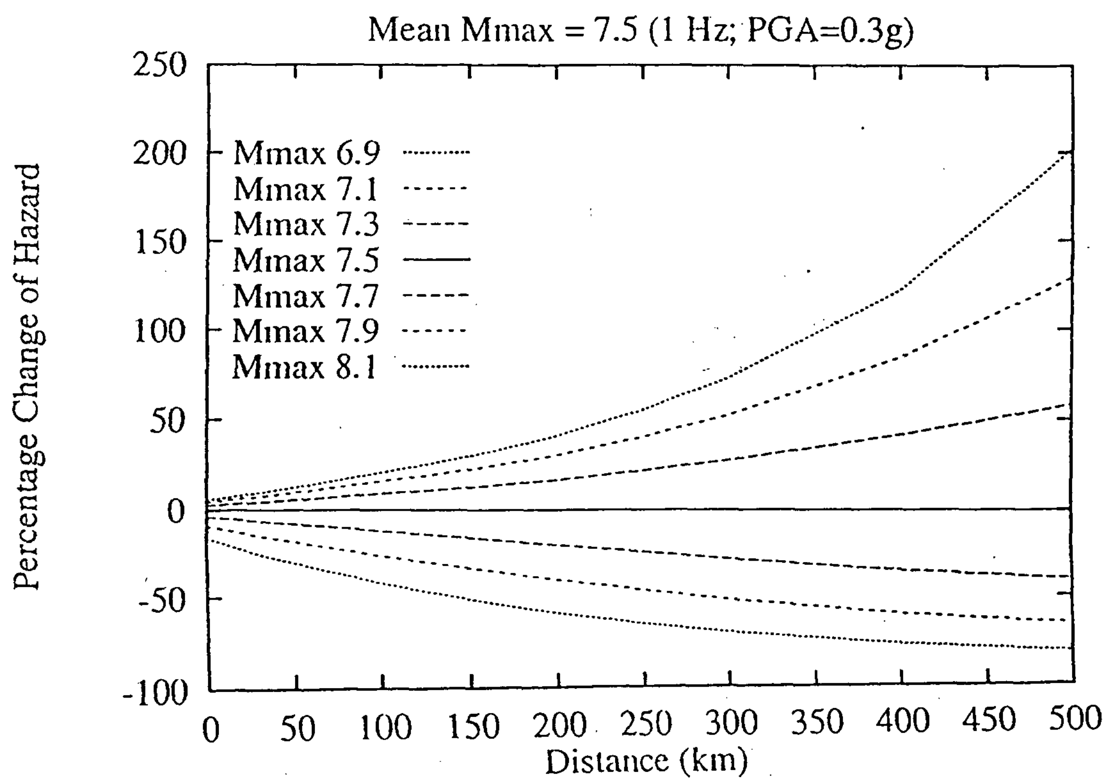
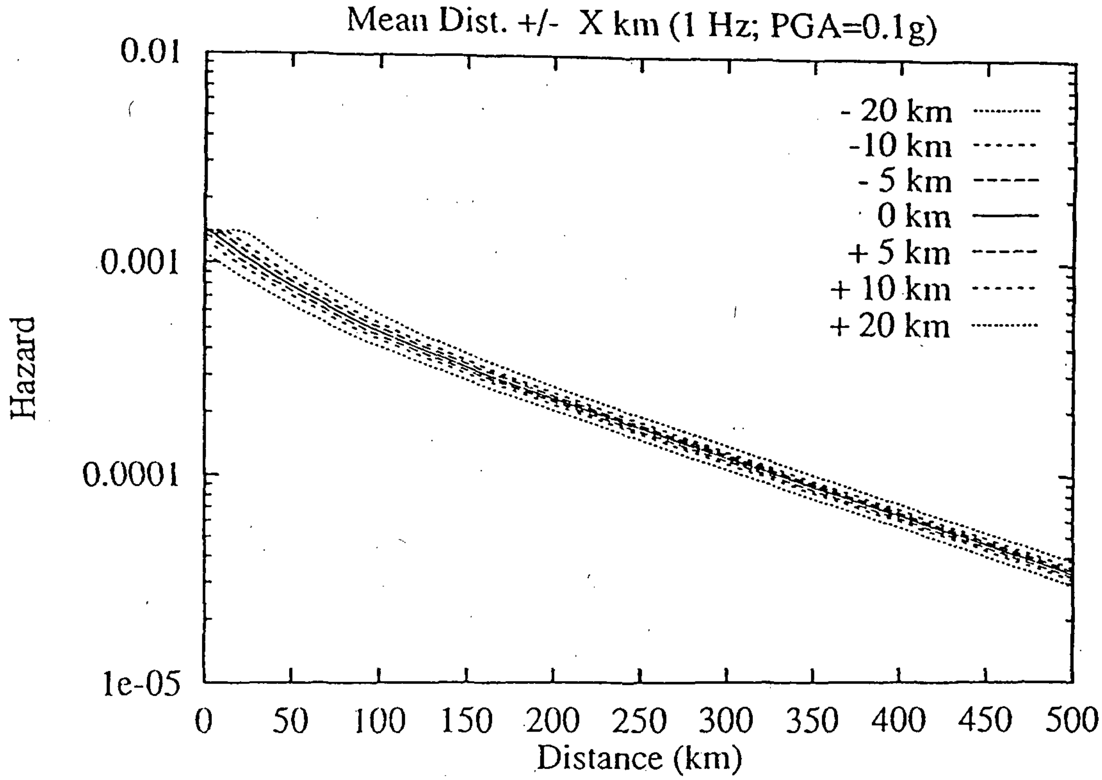


Figure G-14b. Sensitivity of 1 Hz hazard to m_{max} = 7.5, PGA = 0.3g, Group A sites.



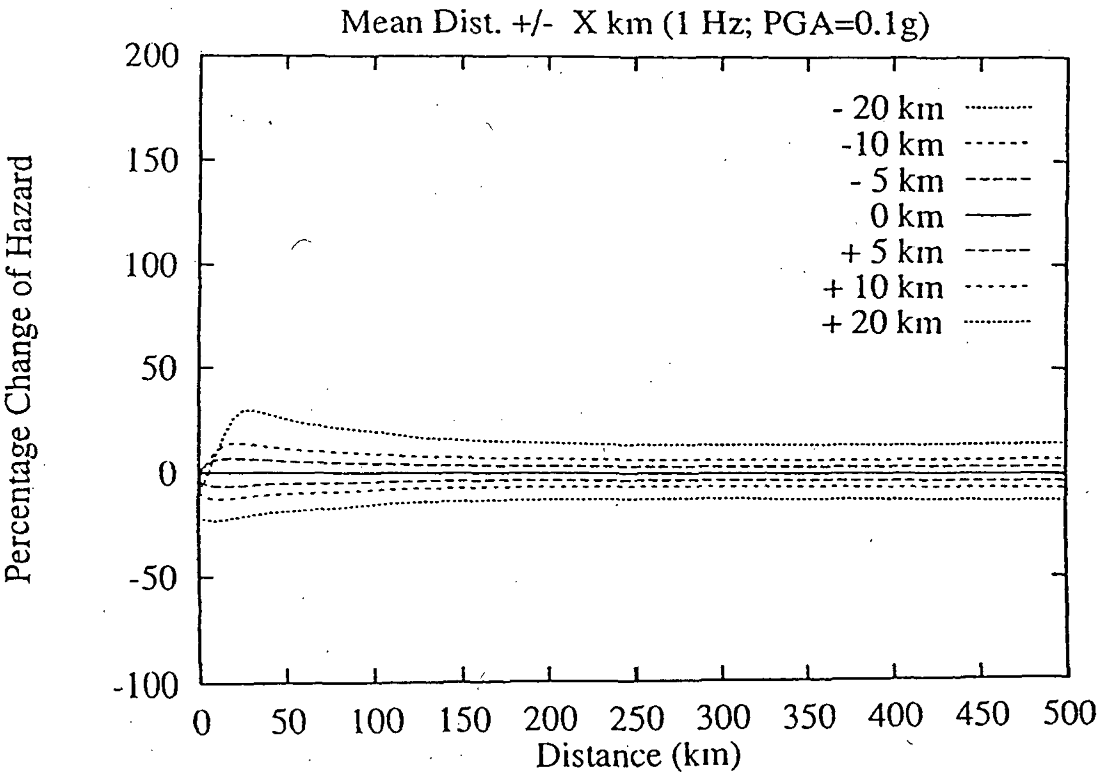
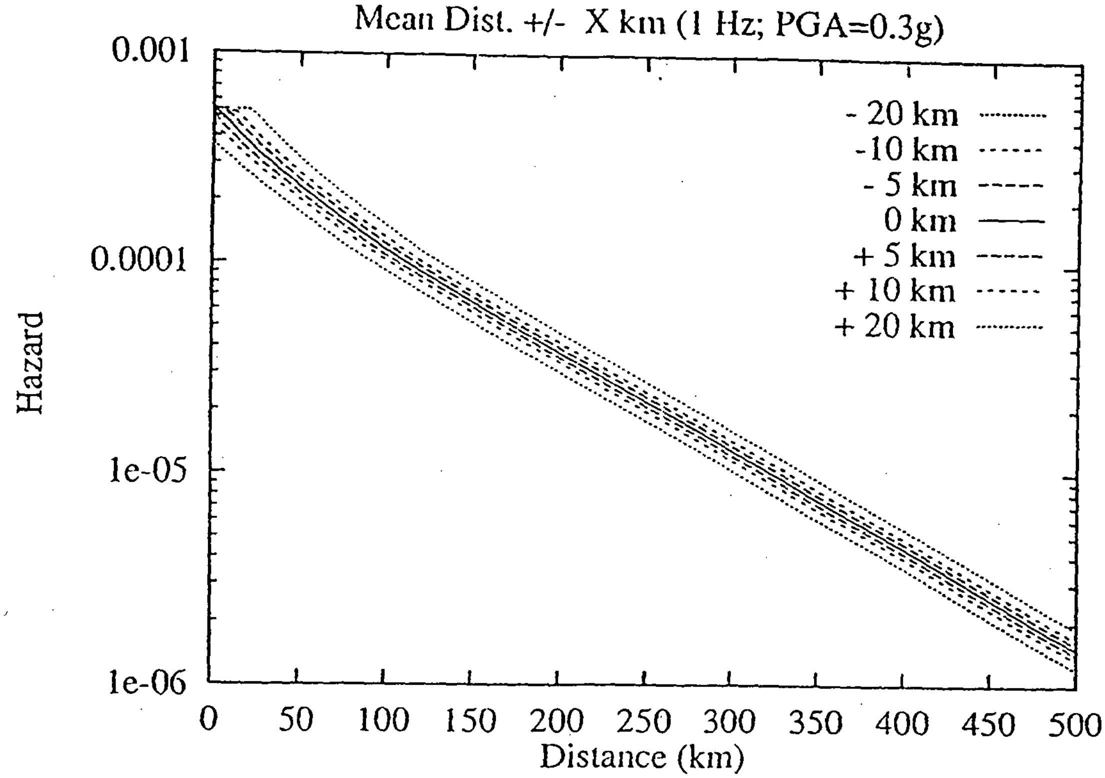


Figure G-15a. Sensitivity of 1 Hz hazard to distance from fault, PGA = 0.1g, Group A sites.



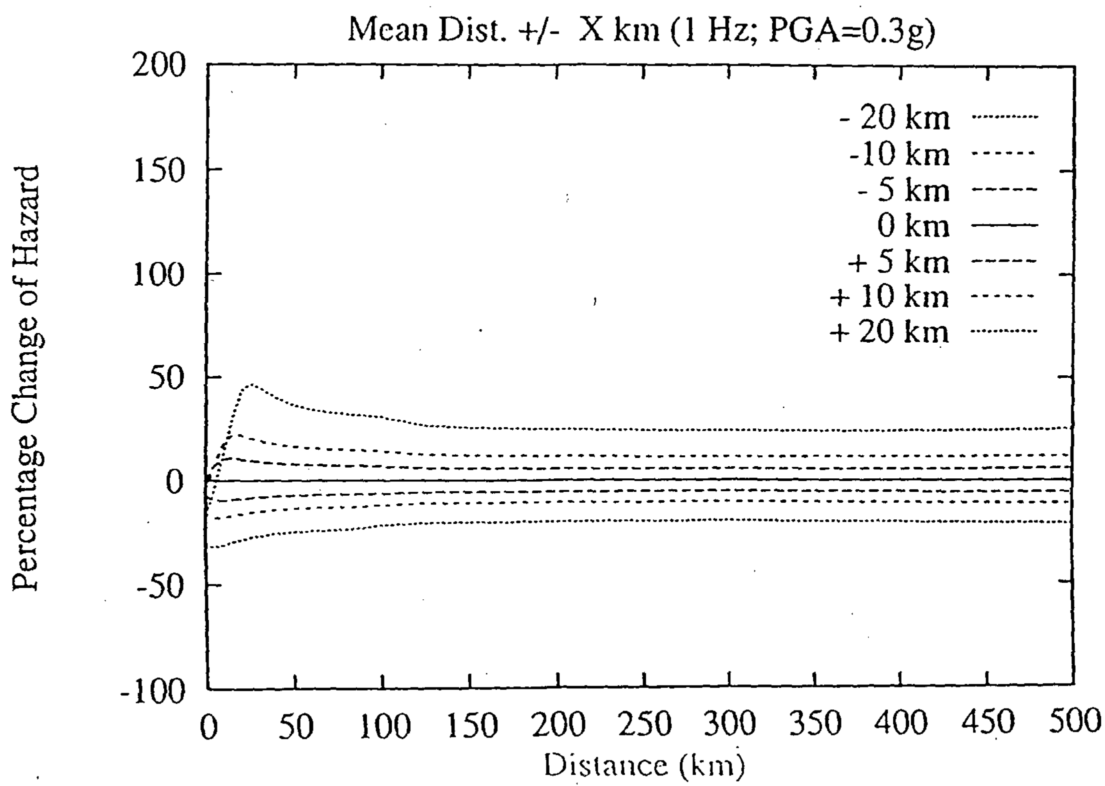


Figure G-15b. Sensitivity of 1 Hz hazard to distance from fault, PGA = 0.3g, Group A sites.

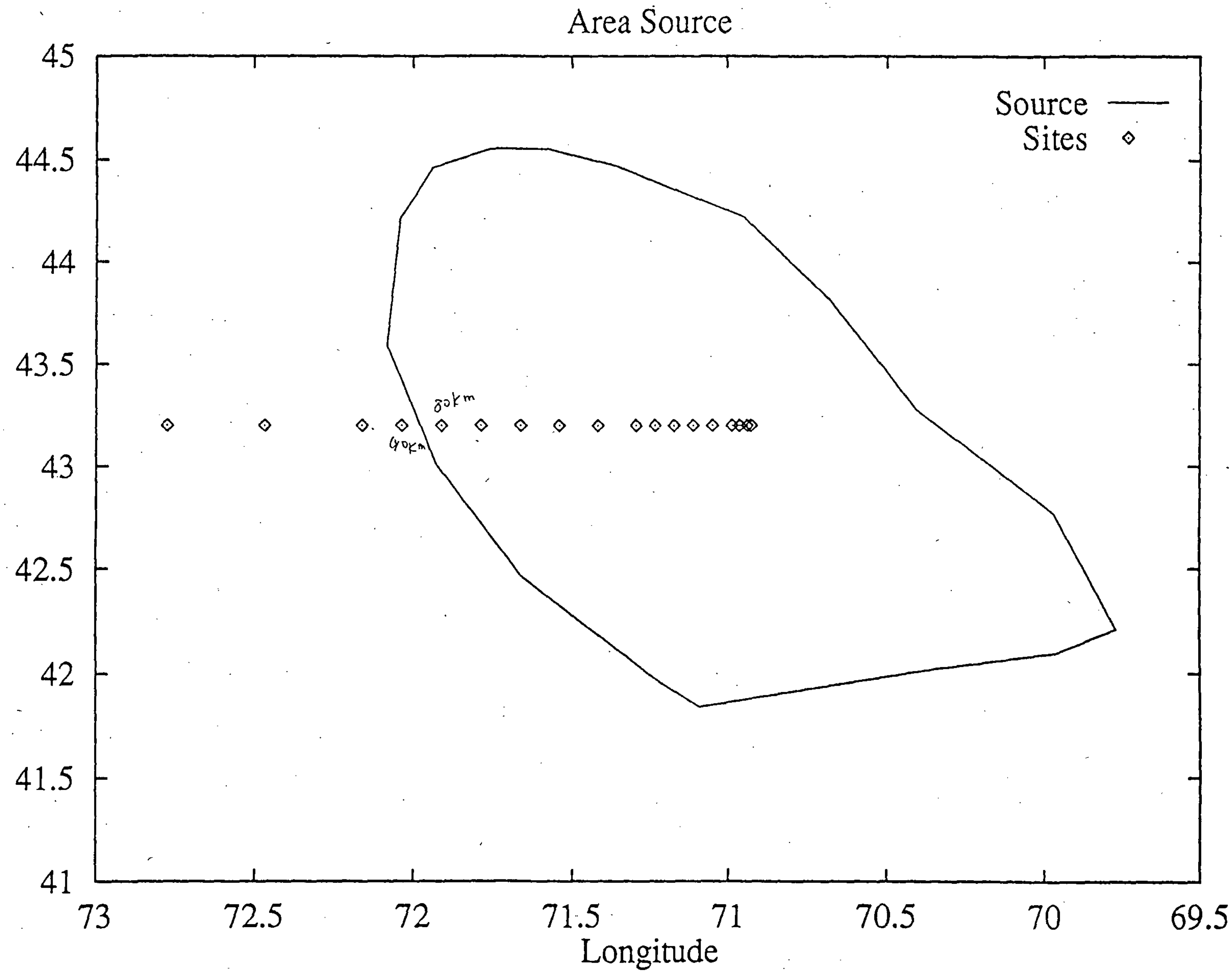


Figure 16. Configuration of Group B sites with line source.

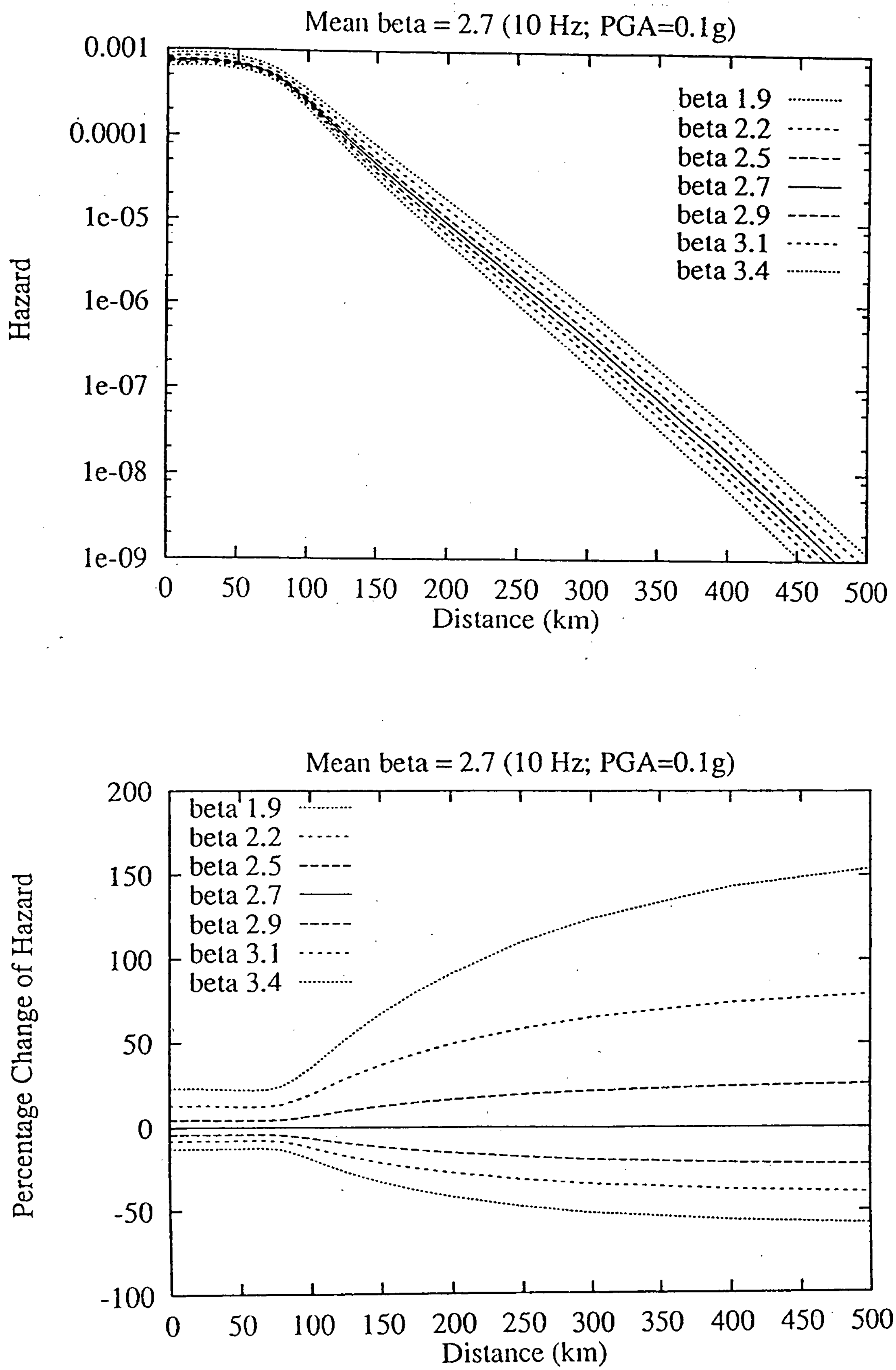
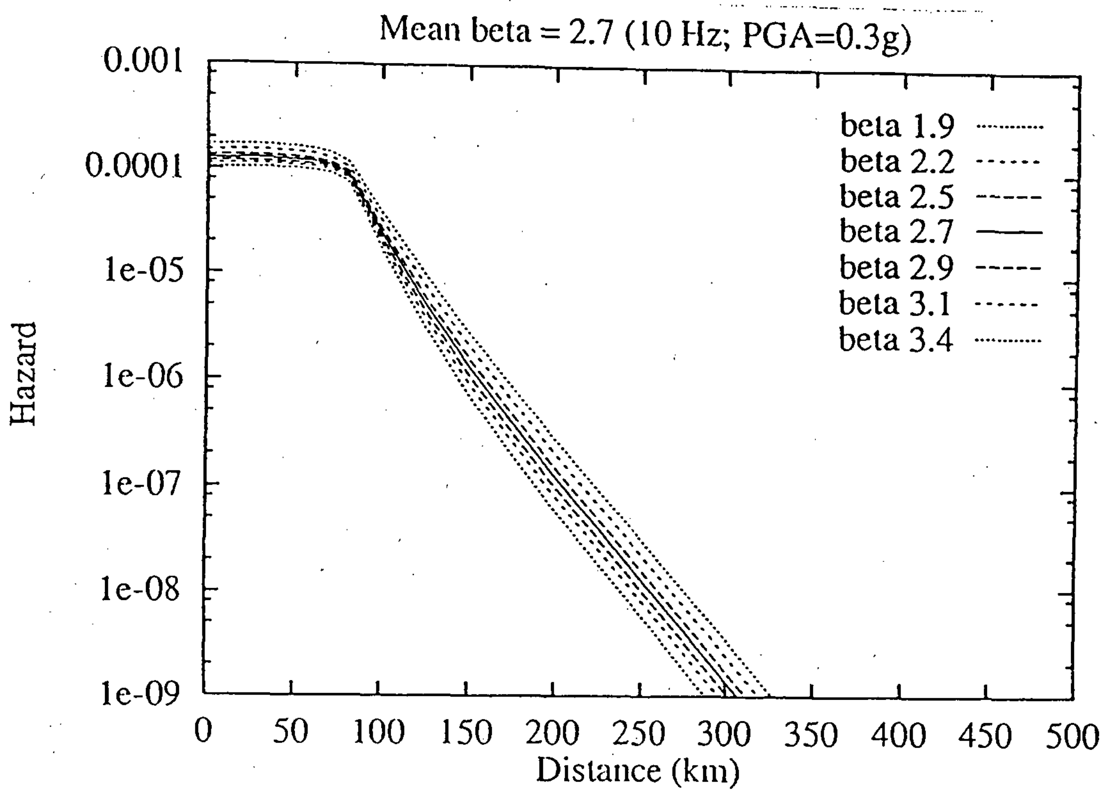


Figure G-17a. Sensitivity of 10 Hz hazard to beta for PGA = 0.1g, Group B sites.



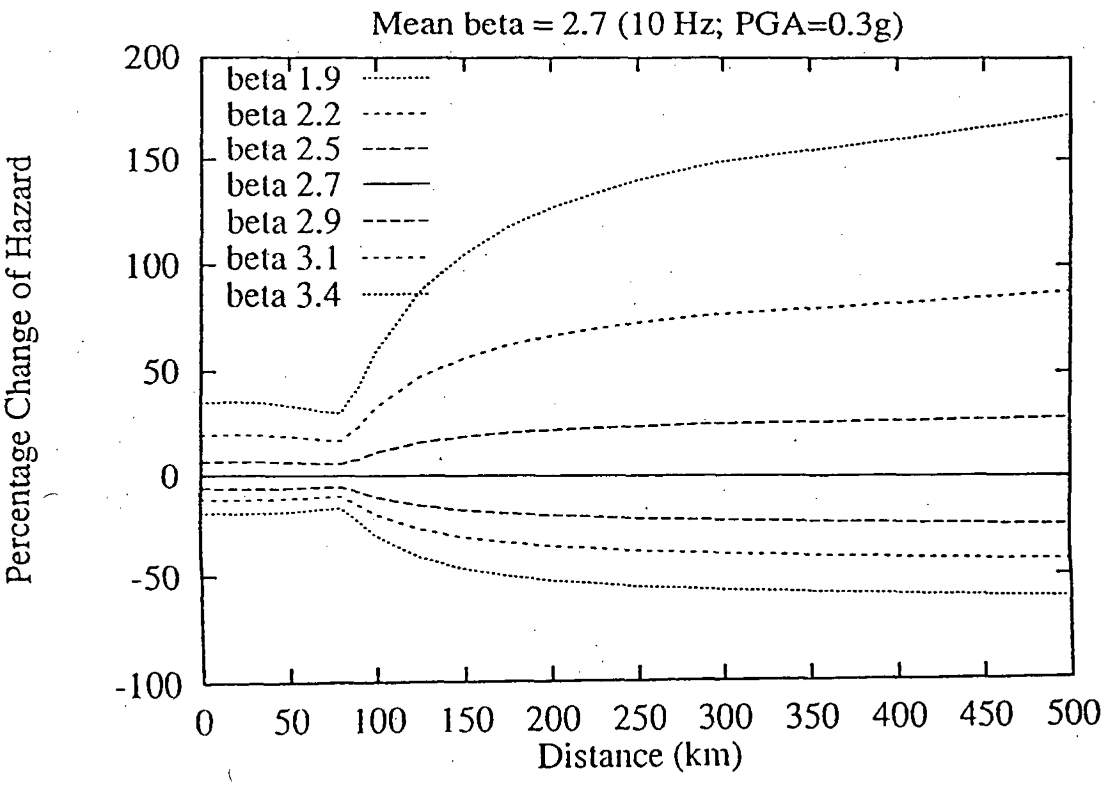
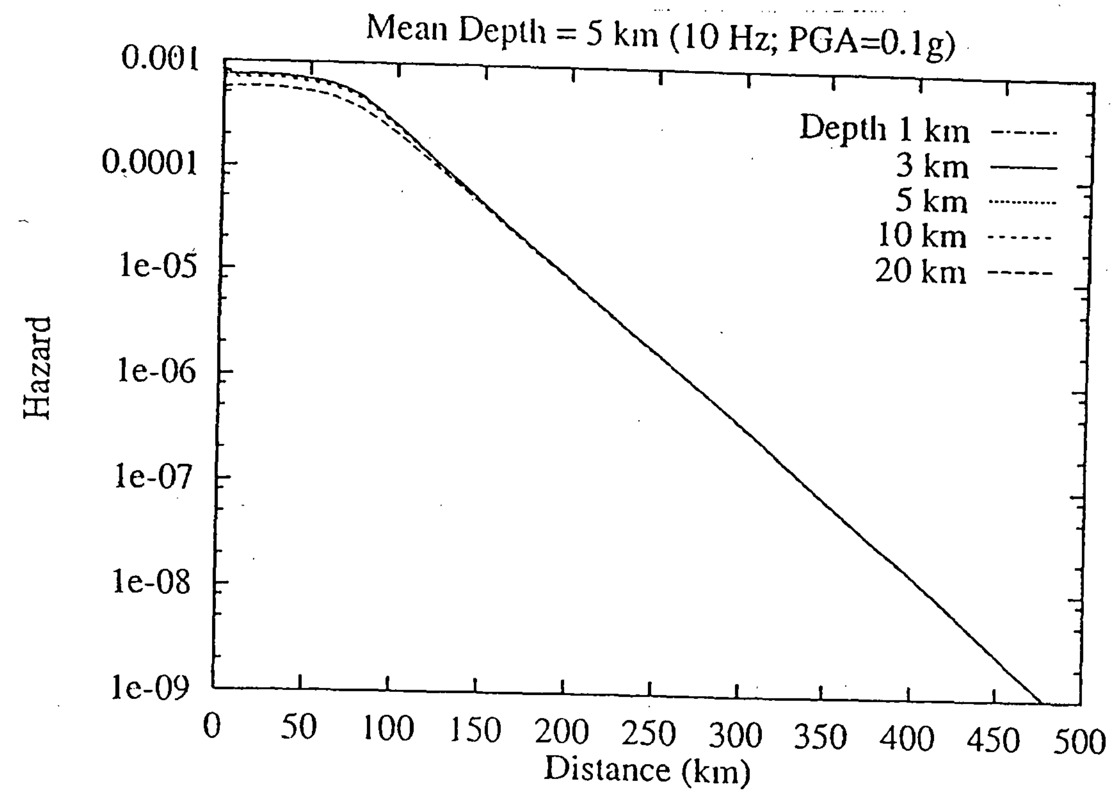


Figure G-17b. Sensitivity of 10 Hz hazard to beta for PGA = 0.3g, Group B sites.



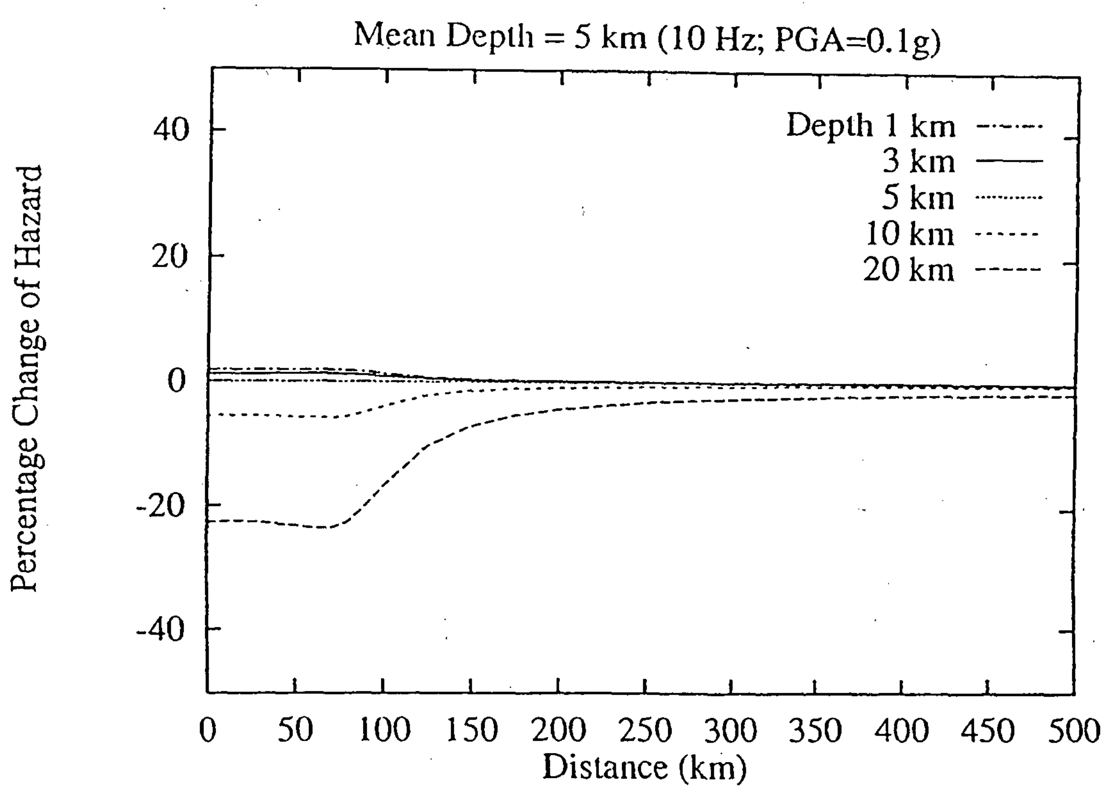


Figure G-18a. Sensitivity of 10 Hz hazard to depth distribution for PGA = 0.1g, Group B sites.

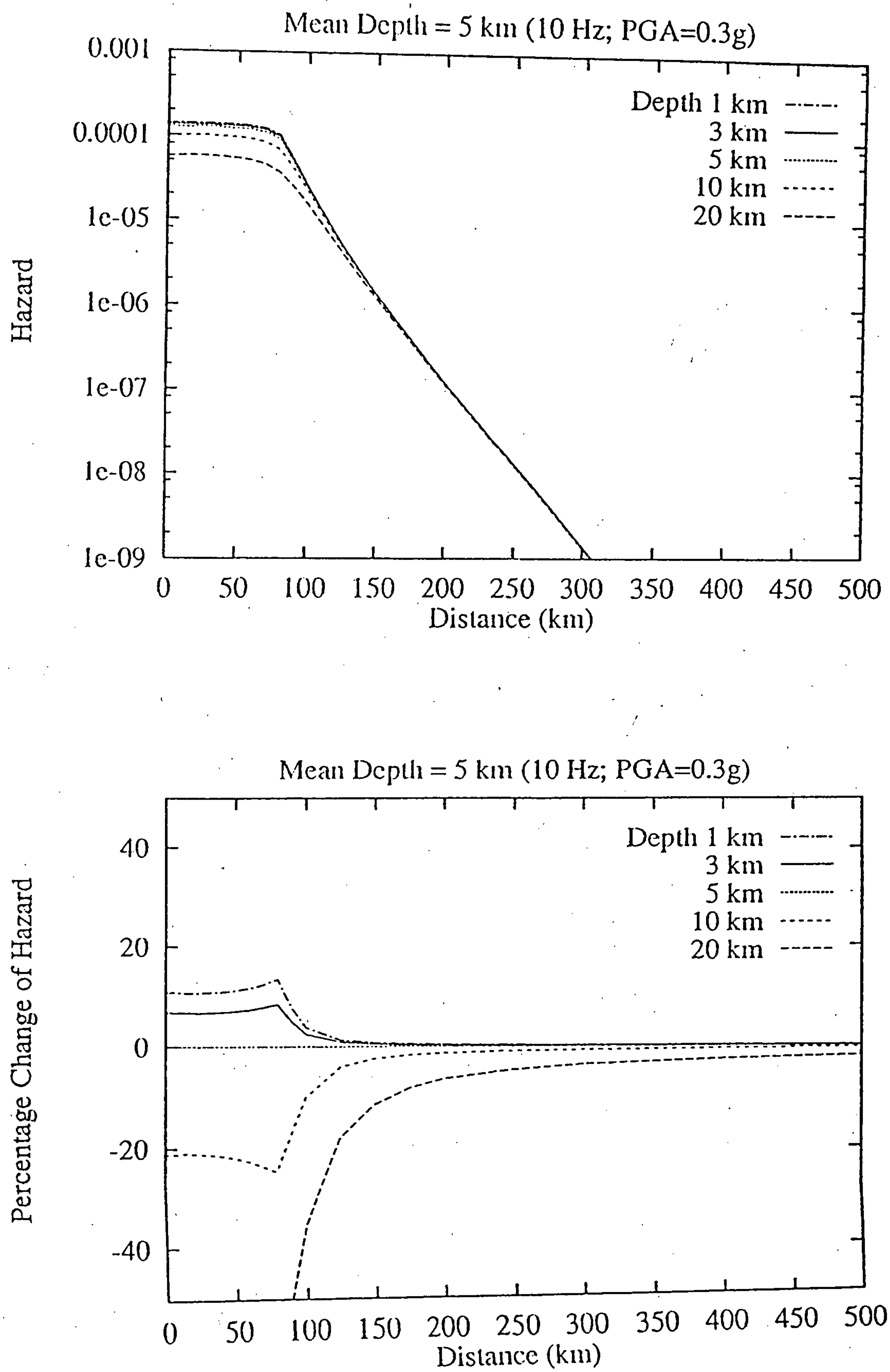
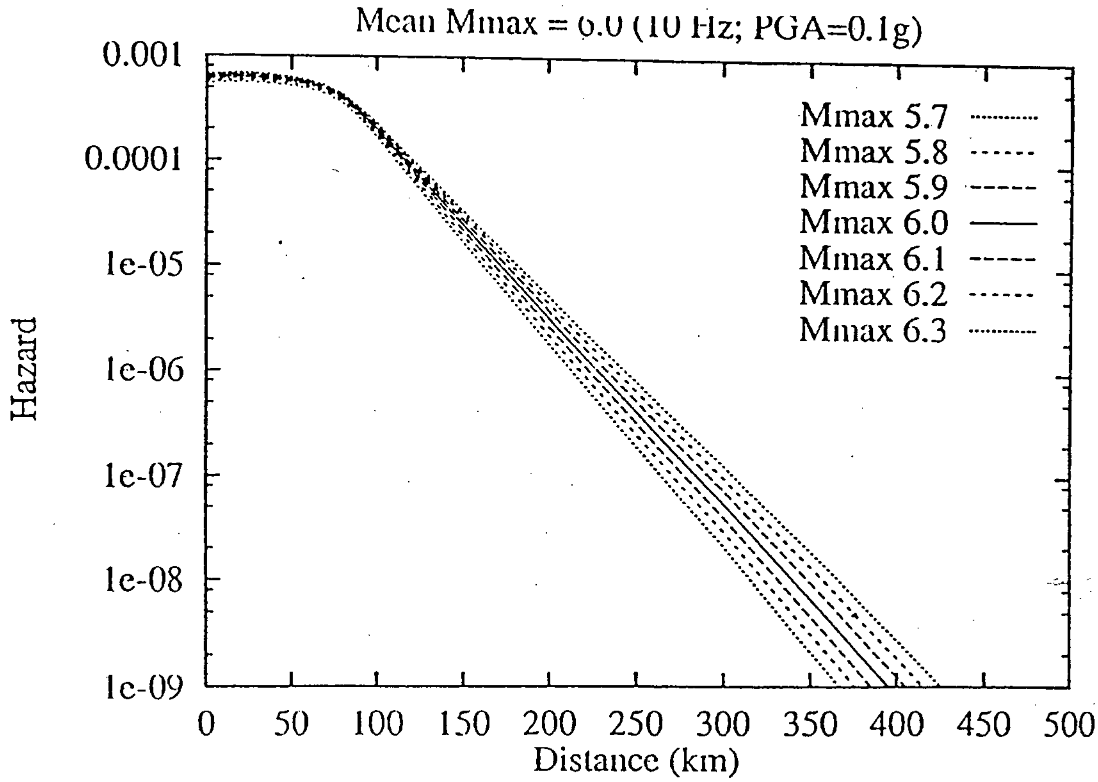


Figure G-18b. Sensitivity of 10 Hz hazard to depth distribution for PGA = 0.3g, Group B sites.



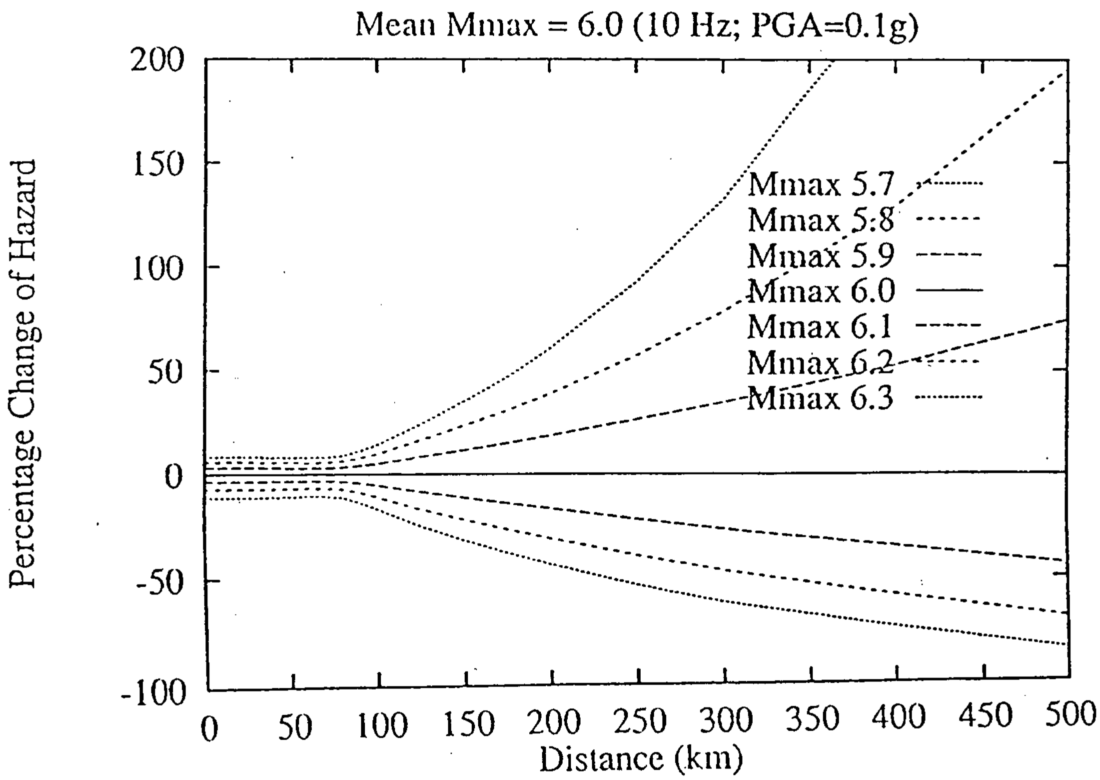
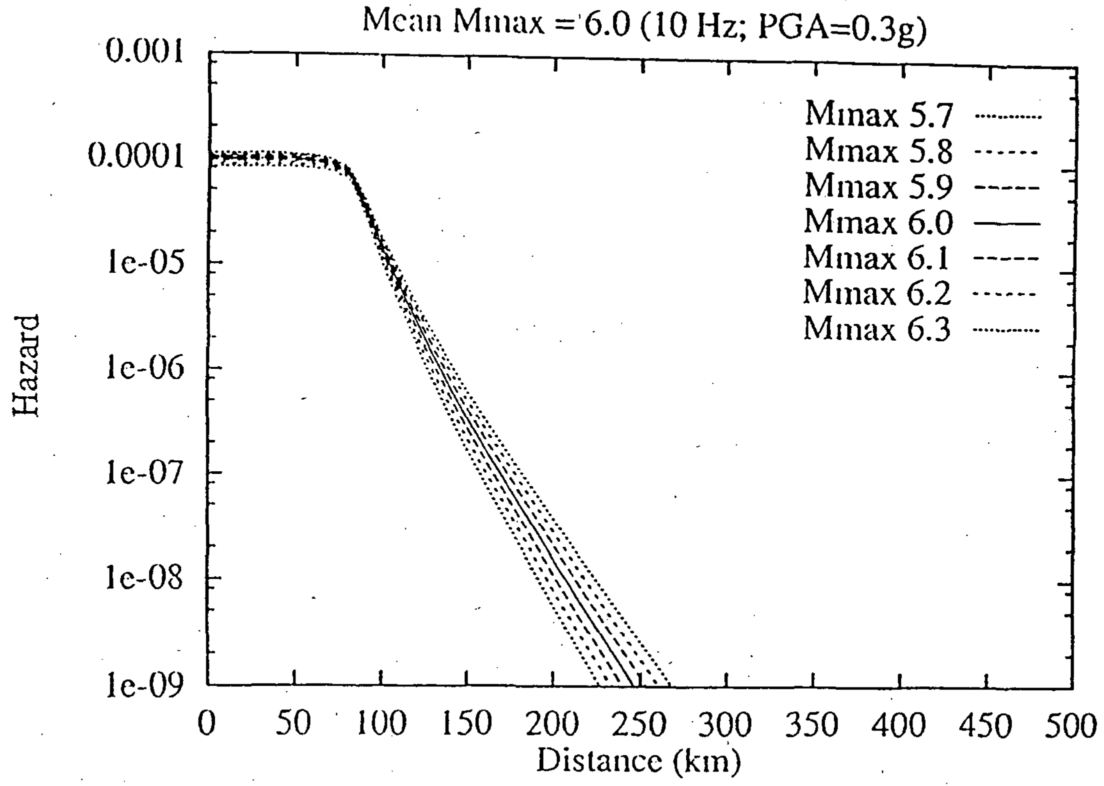


Figure G-19a. Sensitivity of 10 Hz hazard to m_{max} = 6.0, PGA = 0.1g, Group B sites.



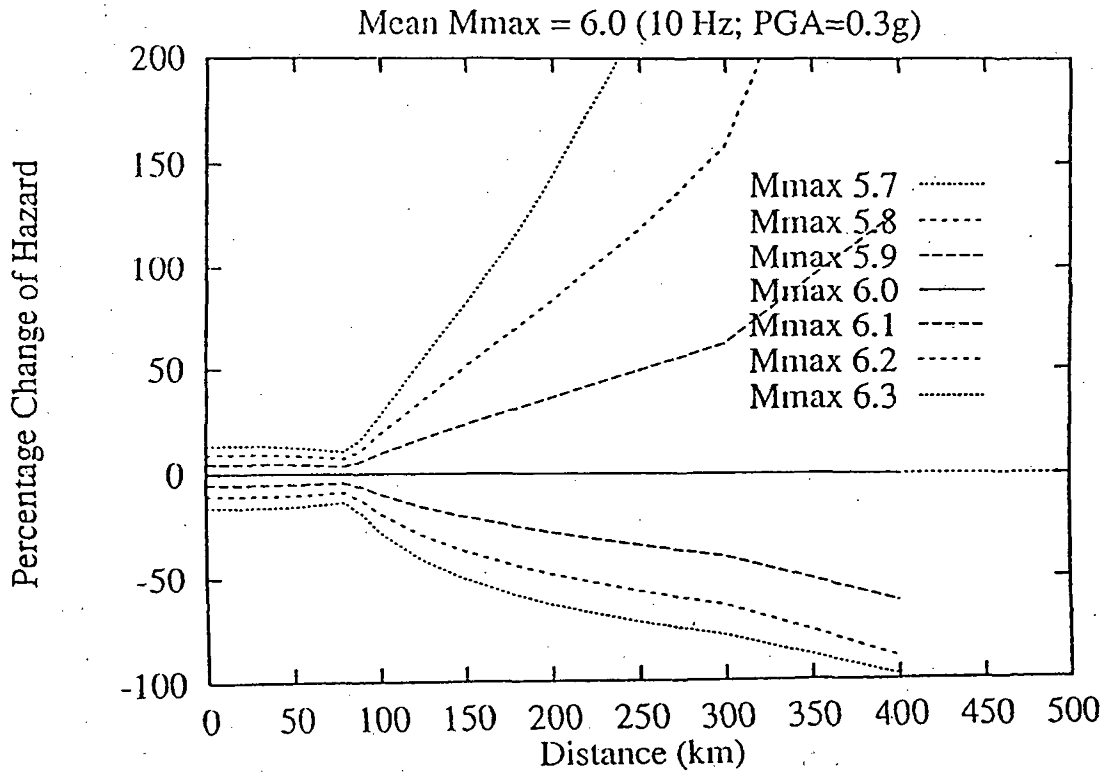


Figure G-19b. Sensitivity of 10 Hz hazard to m_{max} = 6.0, PGA = 0.3g, Group B sites.

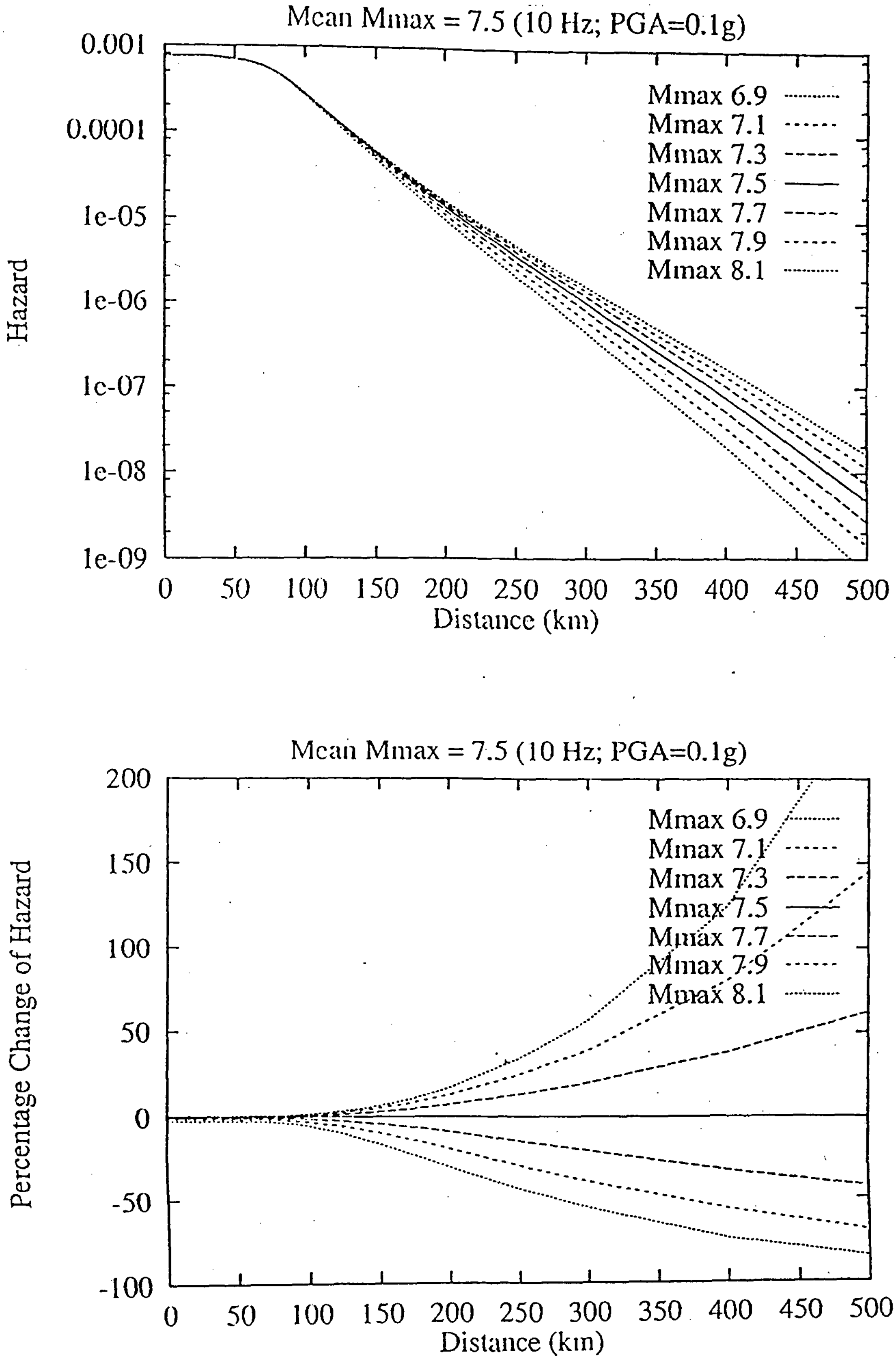
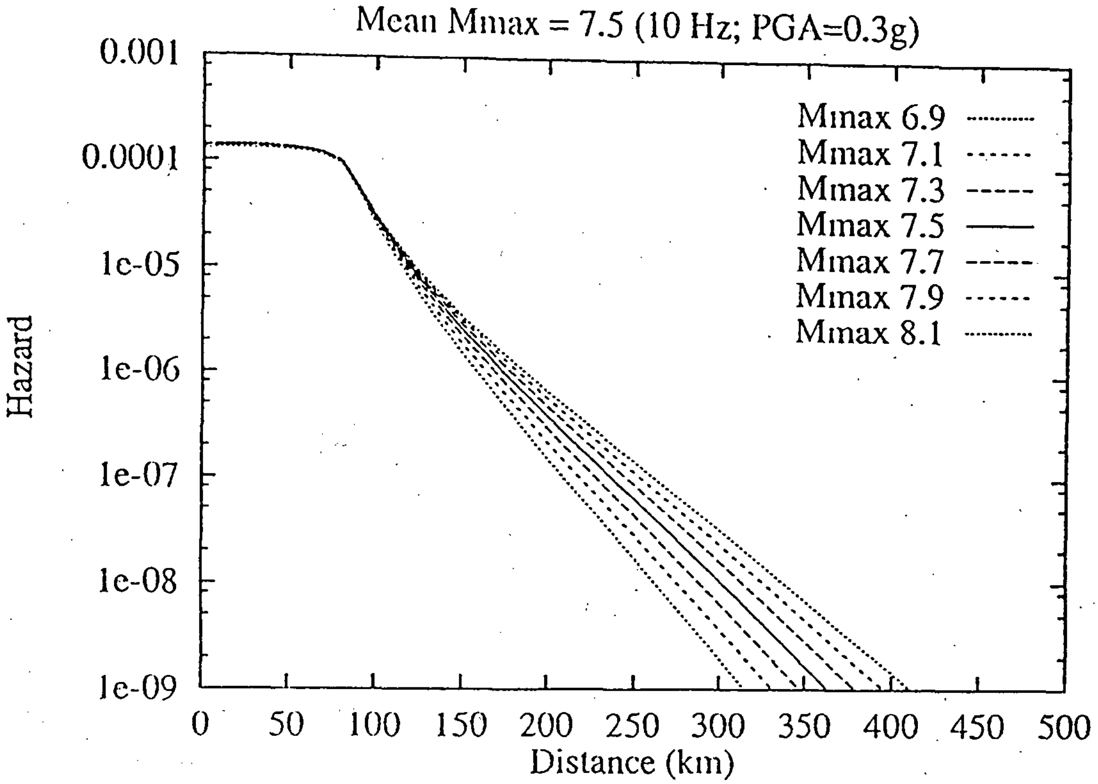


Figure G-20a. Sensitivity of 10 Hz hazard to m_{max} = 7.5, PGA = 0.1g, Group B sites.



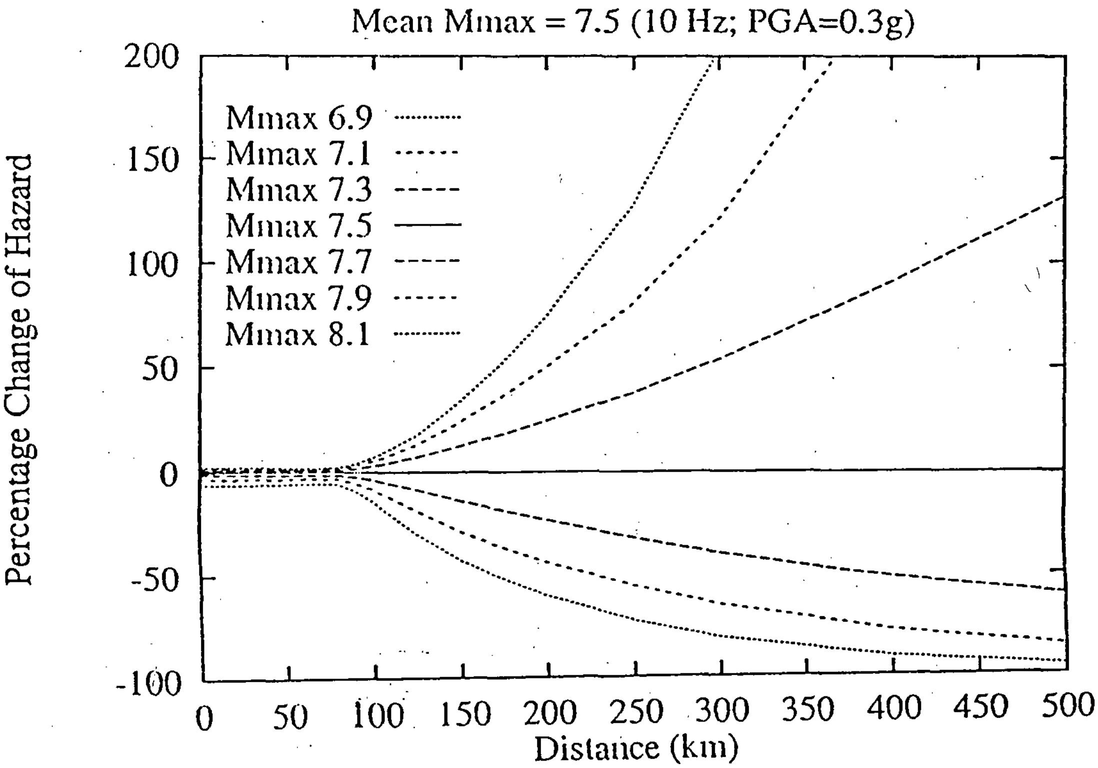
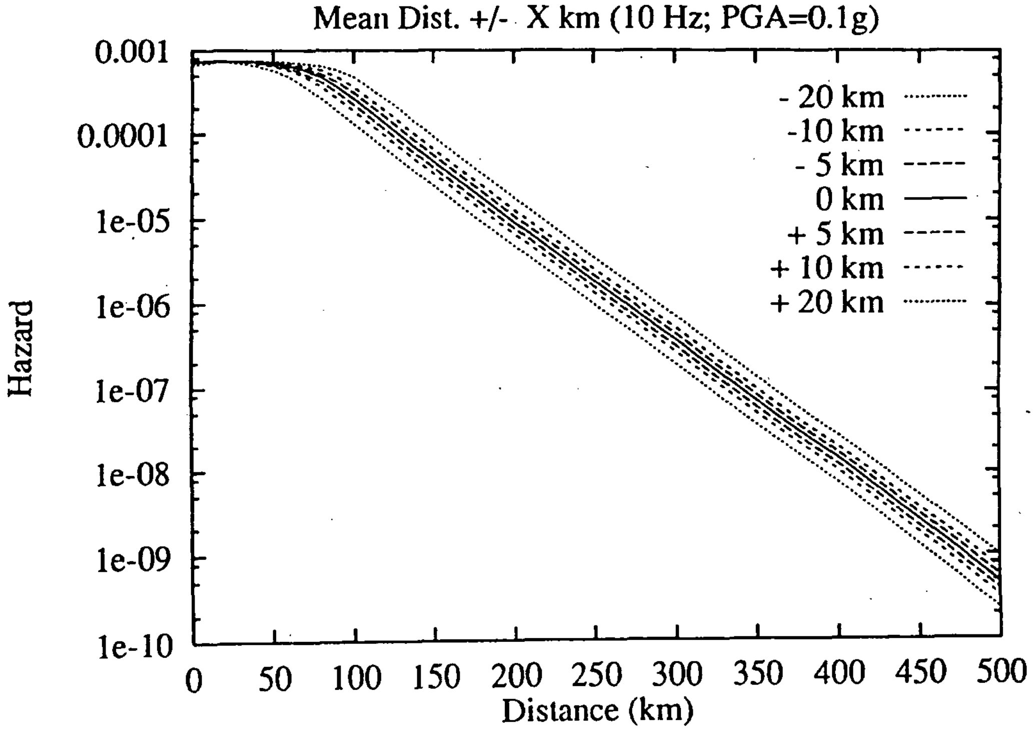


Figure G-20b. Sensitivity of 10 Hz hazard to m_{max} = 7.5, PGA = 0.3g, Group B sites.



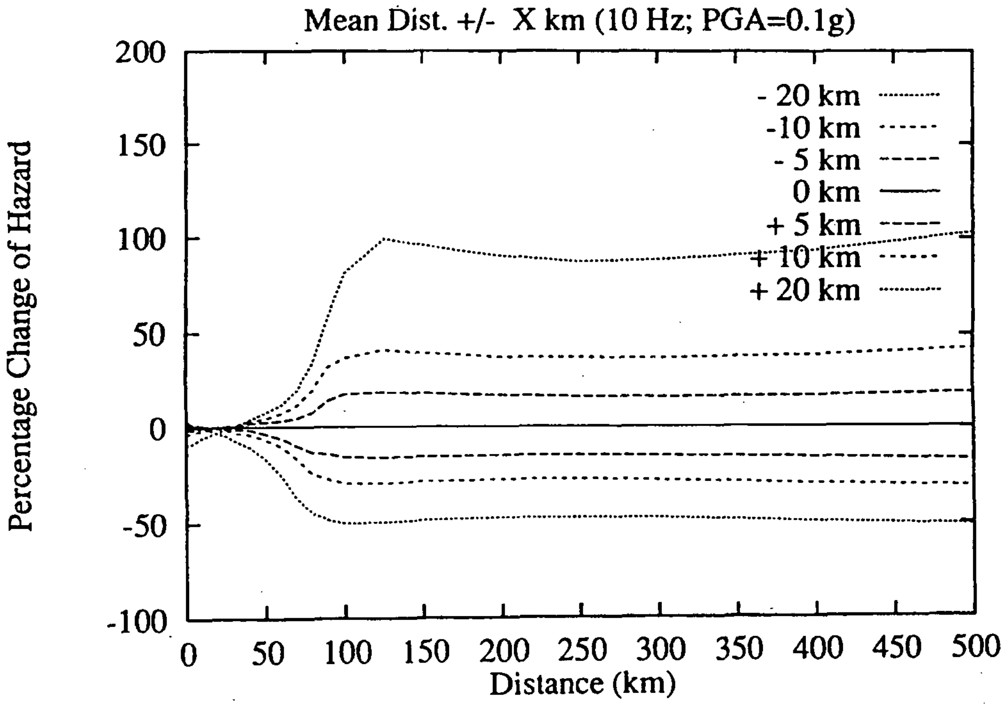


Figure G-21a. Sensitivity of 10 Hz hazard to distance from fault, PGA=0.1g, Group B sites.

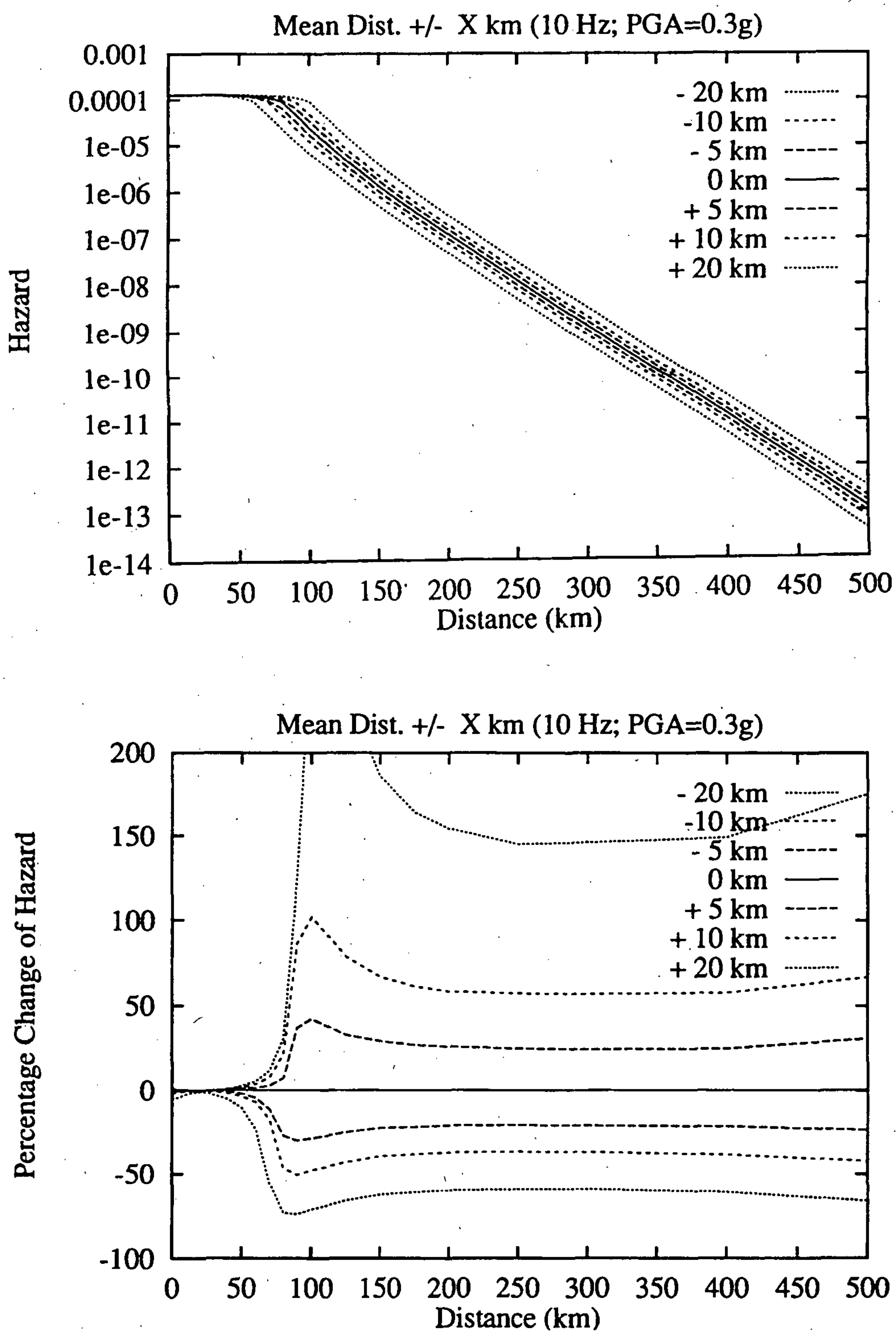


Figure G-21b. Sensitivity of 10 Hz hazard to distance from fault, PGA=0.3g, Group B sites.

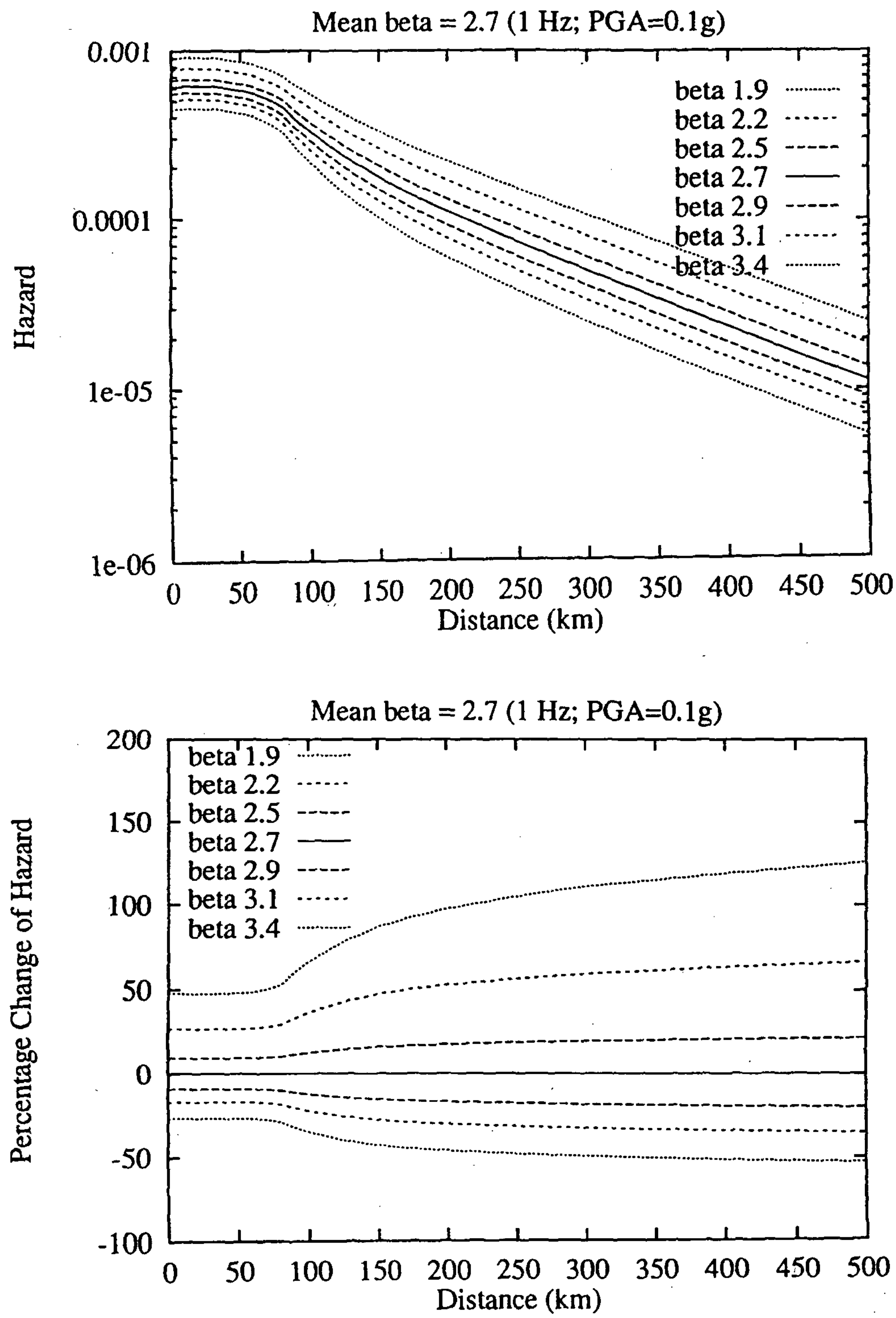
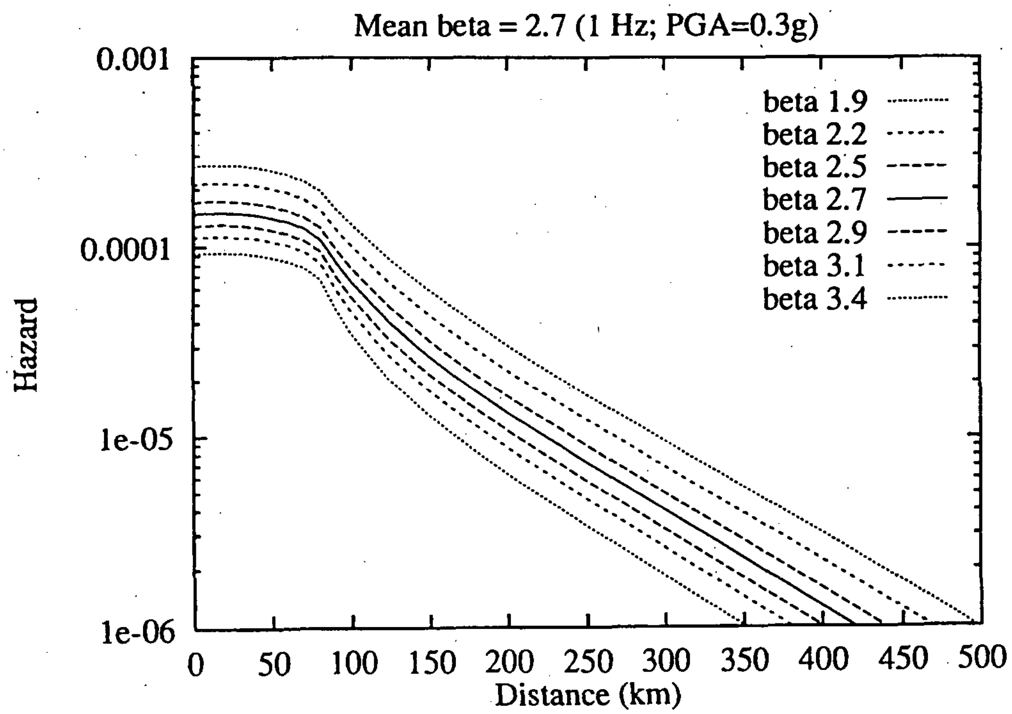


Figure G-22a. Sensitivity of 1 Hz hazard to beta for PGA=0.1g, Group B sites.



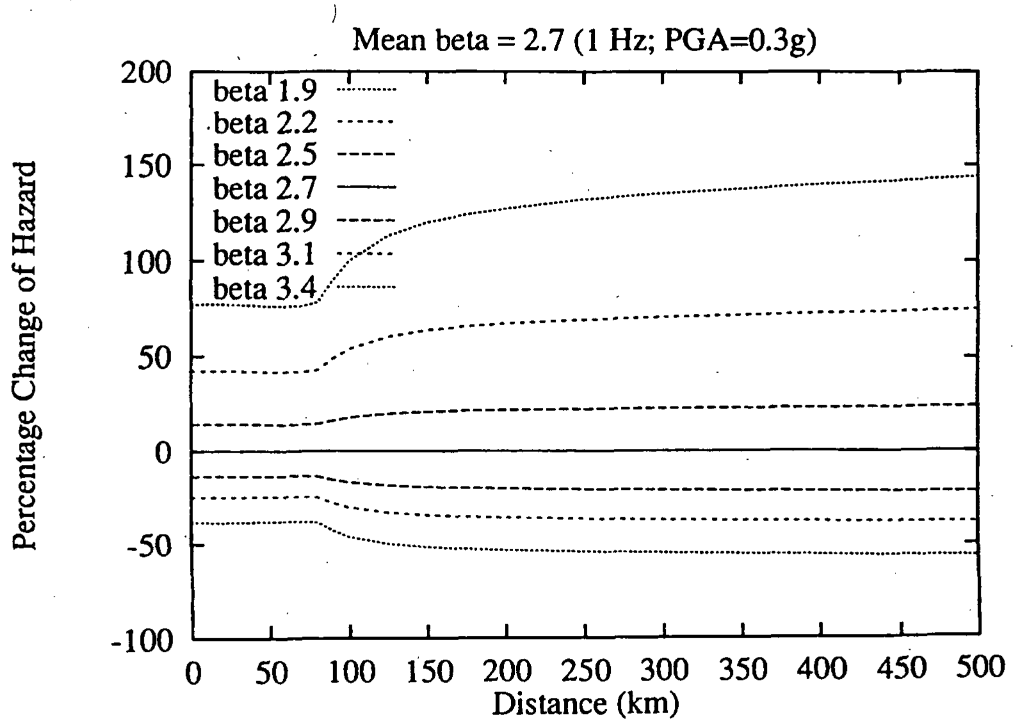


Figure G-22b. Sensitivity of 1 Hz hazard to beta for PGA=0.3g, Group B sites.

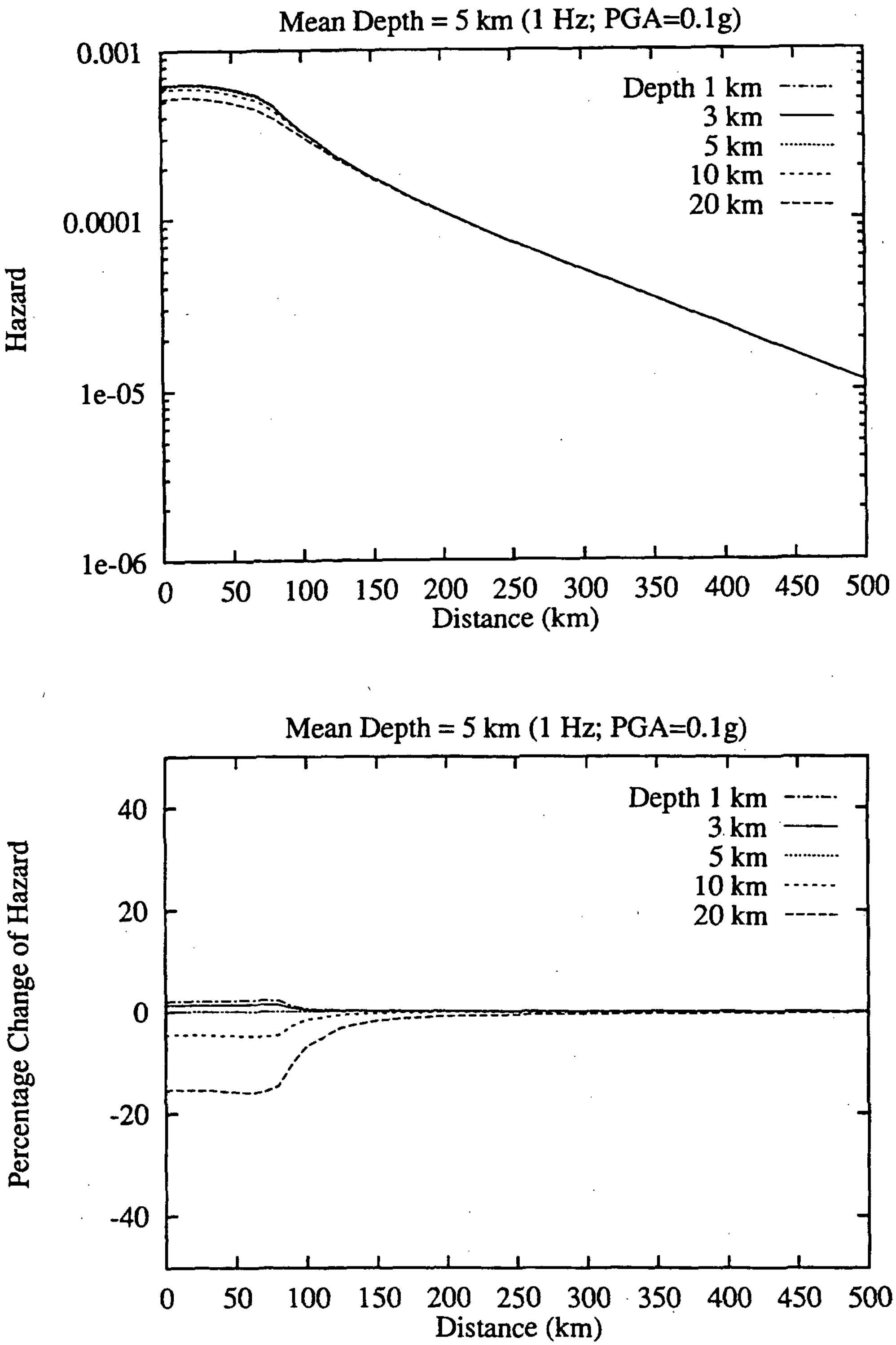
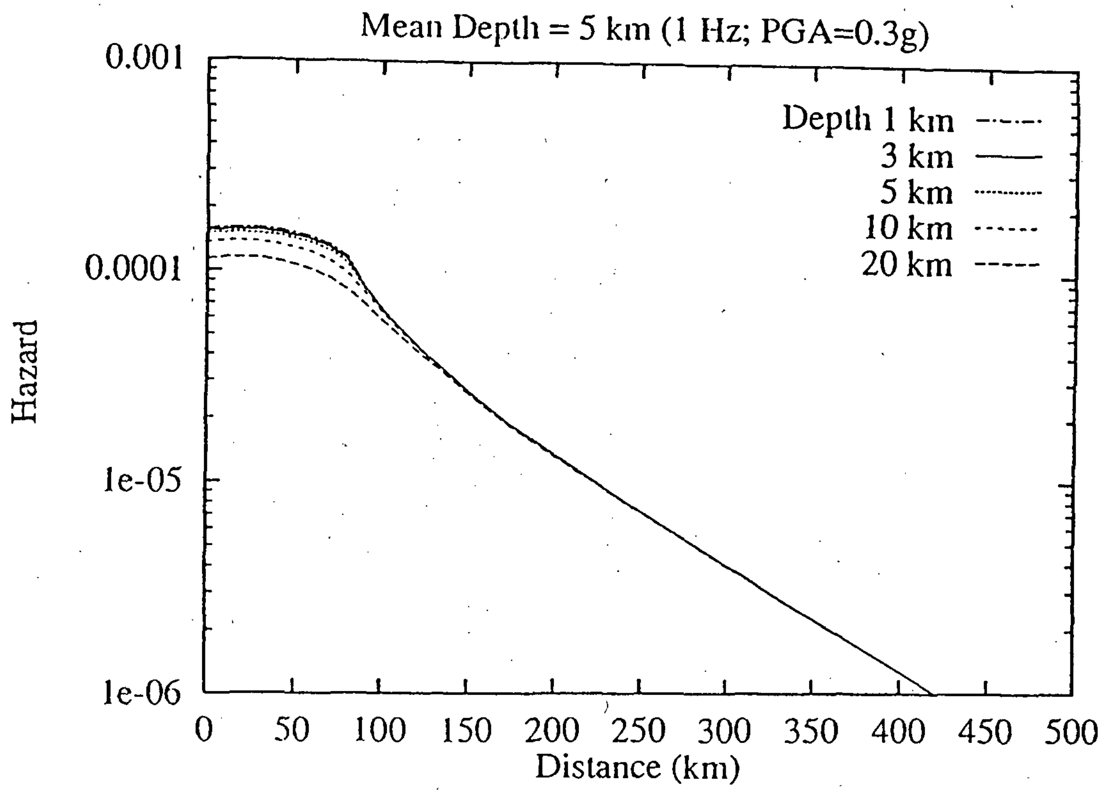


Figure G-23a. Sensitivity of 1 Hz hazard to depth distribution for PGA=0.1g, Group B sites.



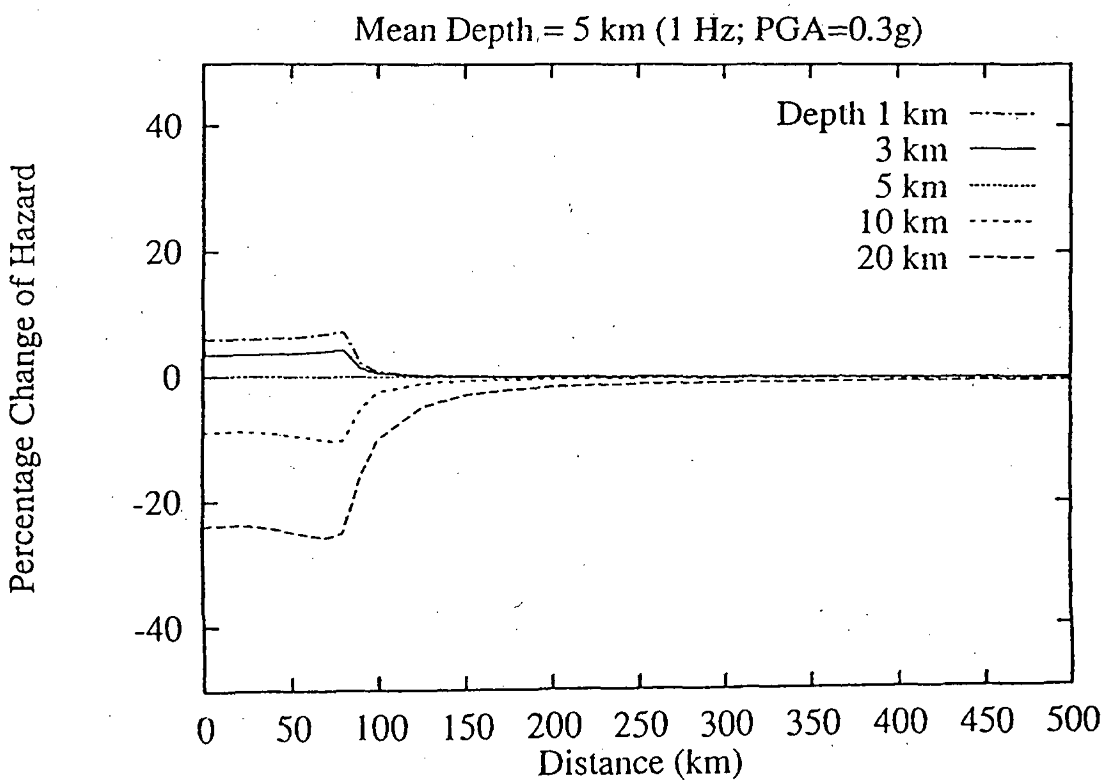
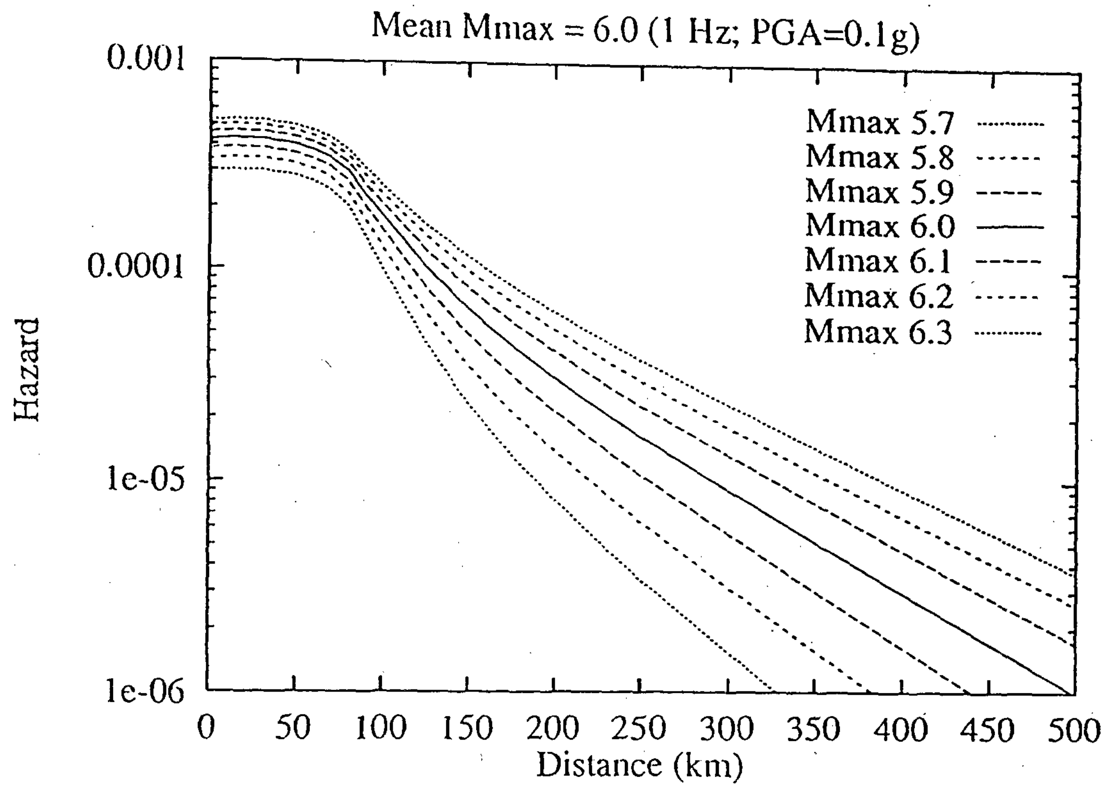


Figure G-23b. Sensitivity of 1 Hz hazard to depth distribution for PGA = 0.3g, Group B sites.



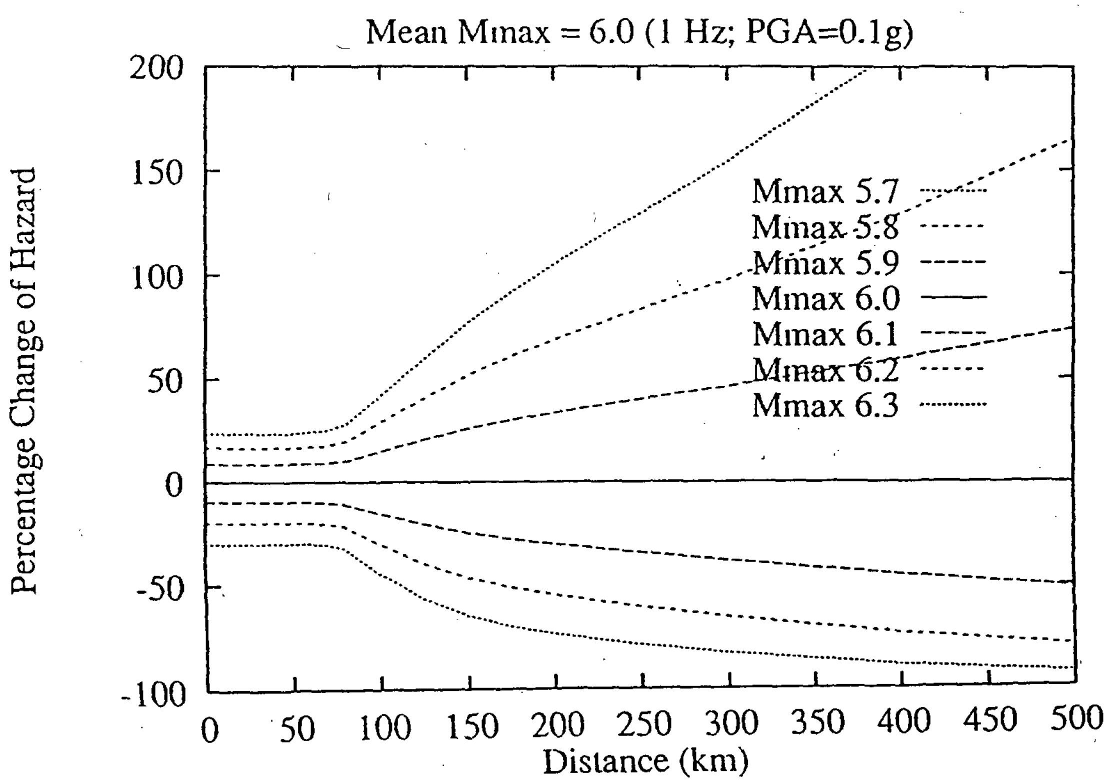
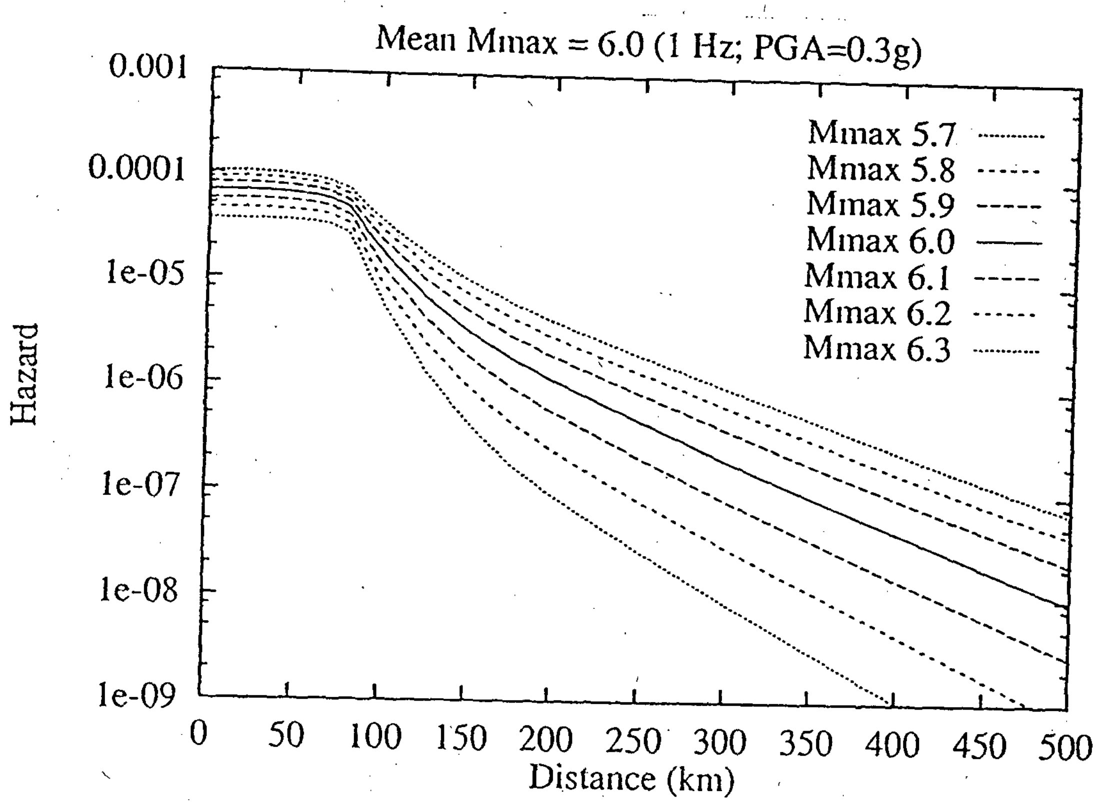


Figure G-24a. Sensitivity of 1 Hz hazard to m_{max} = 6.0, PGA = 0.1g, Group B sites.



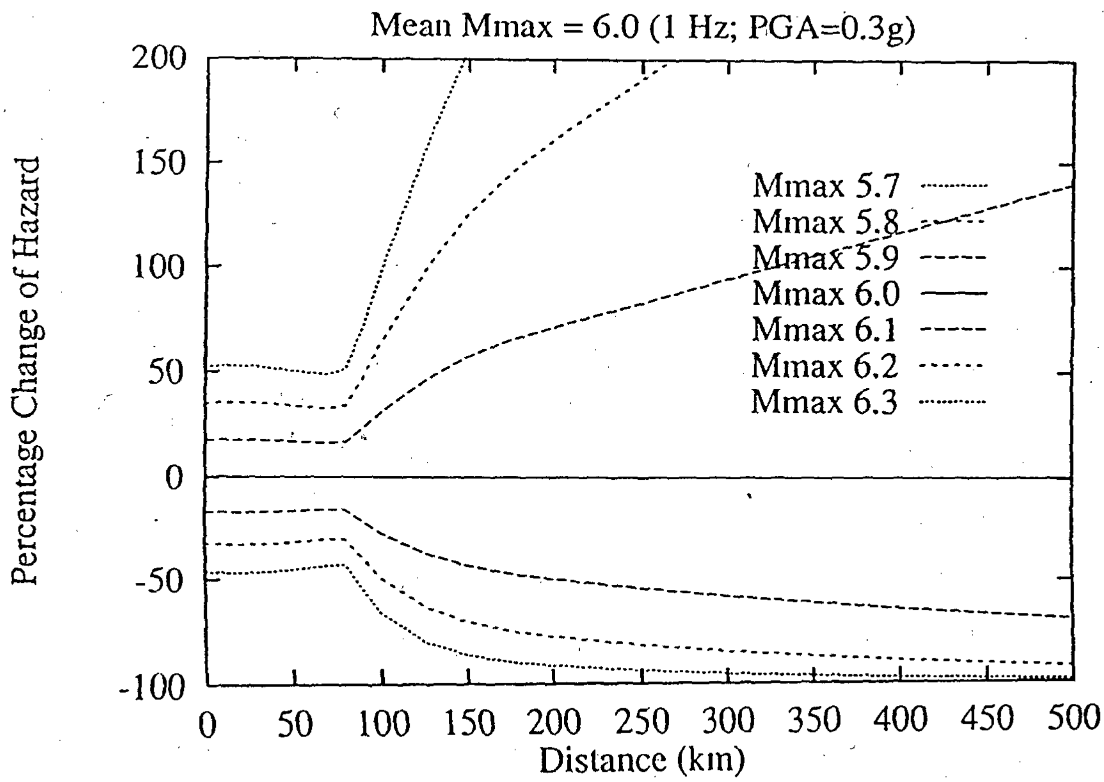
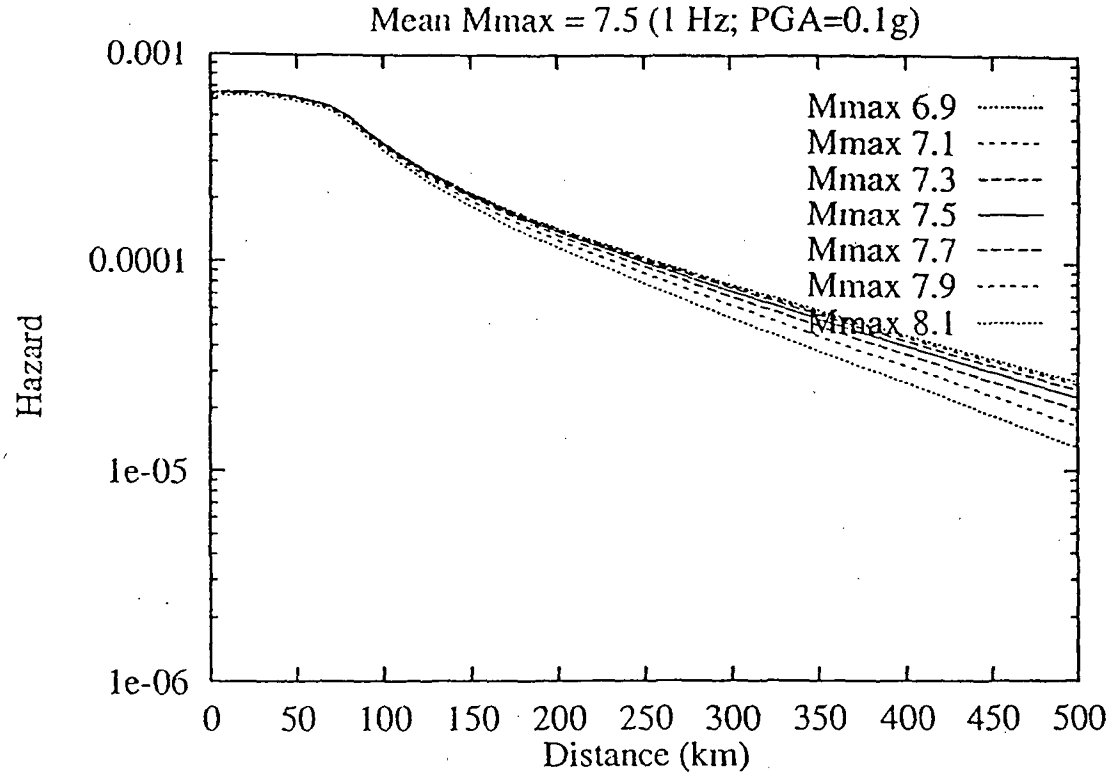


Figure G-24b. Sensitivity of 1 Hz hazard to m_{max} = 6.0, PGA = 0.3g, Group B sites.



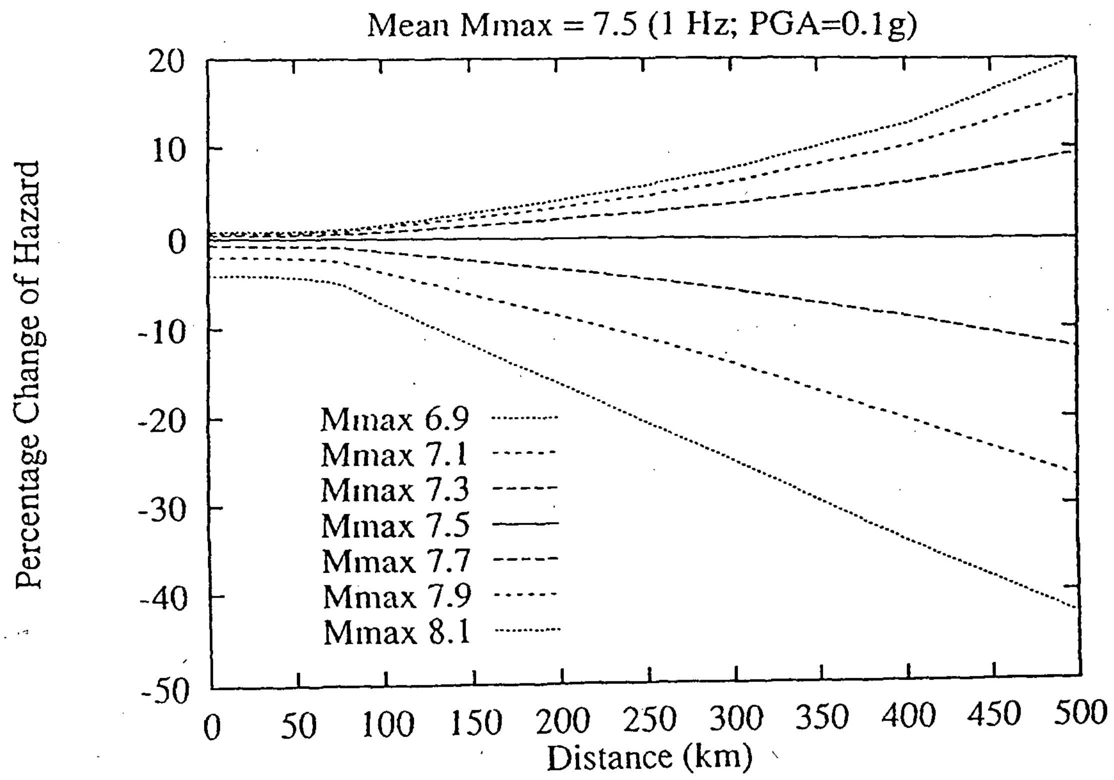


Figure G-25a. Sensitivity of 1 Hz hazard to m_{max} = 7.5, PGA = 0.1g, Group B sites.

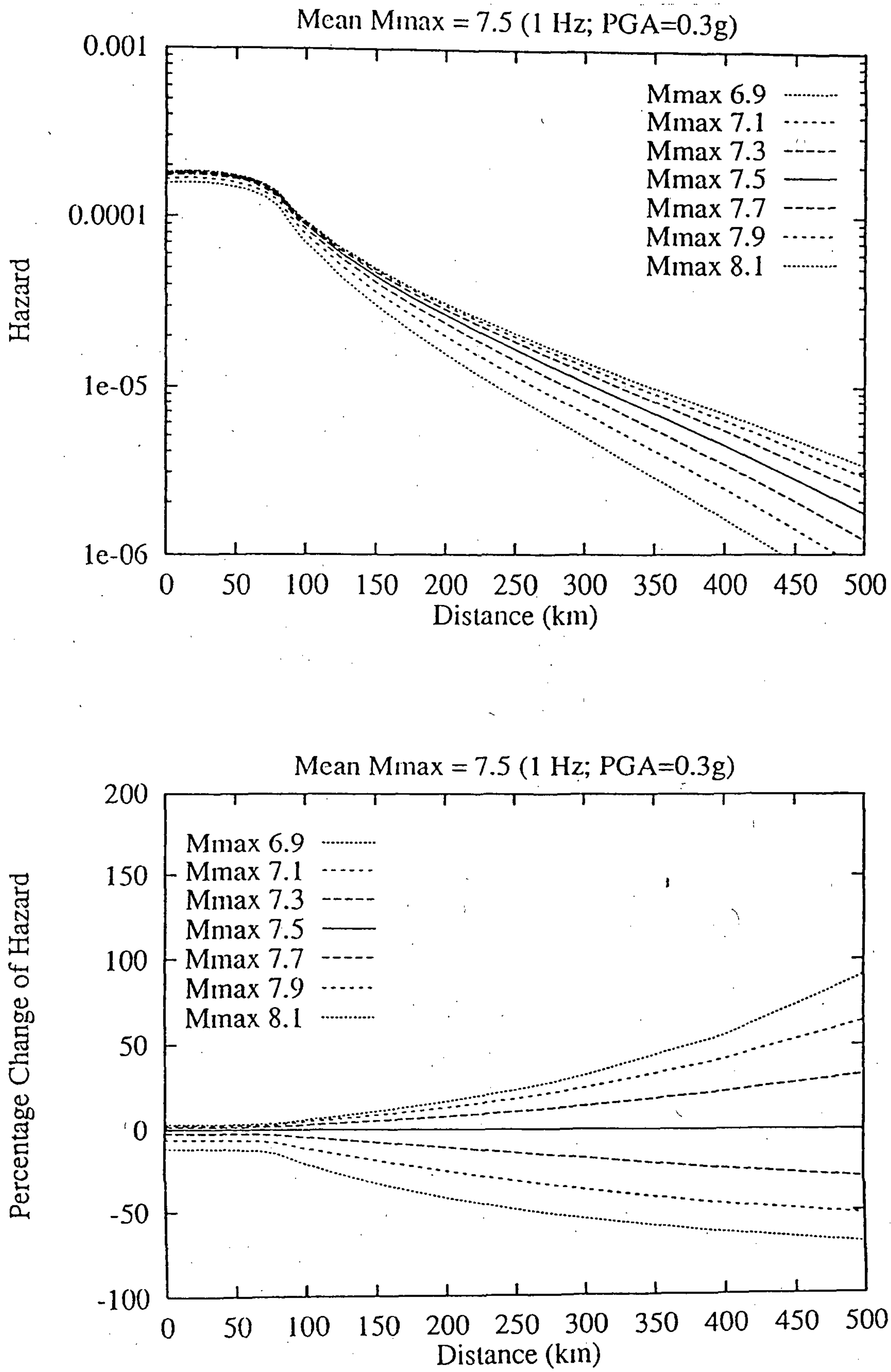


Figure G-25b. Sensitivity of 1 Hz hazard to m_{max} = 7.5, PGA = 0.3g, Group B sites.

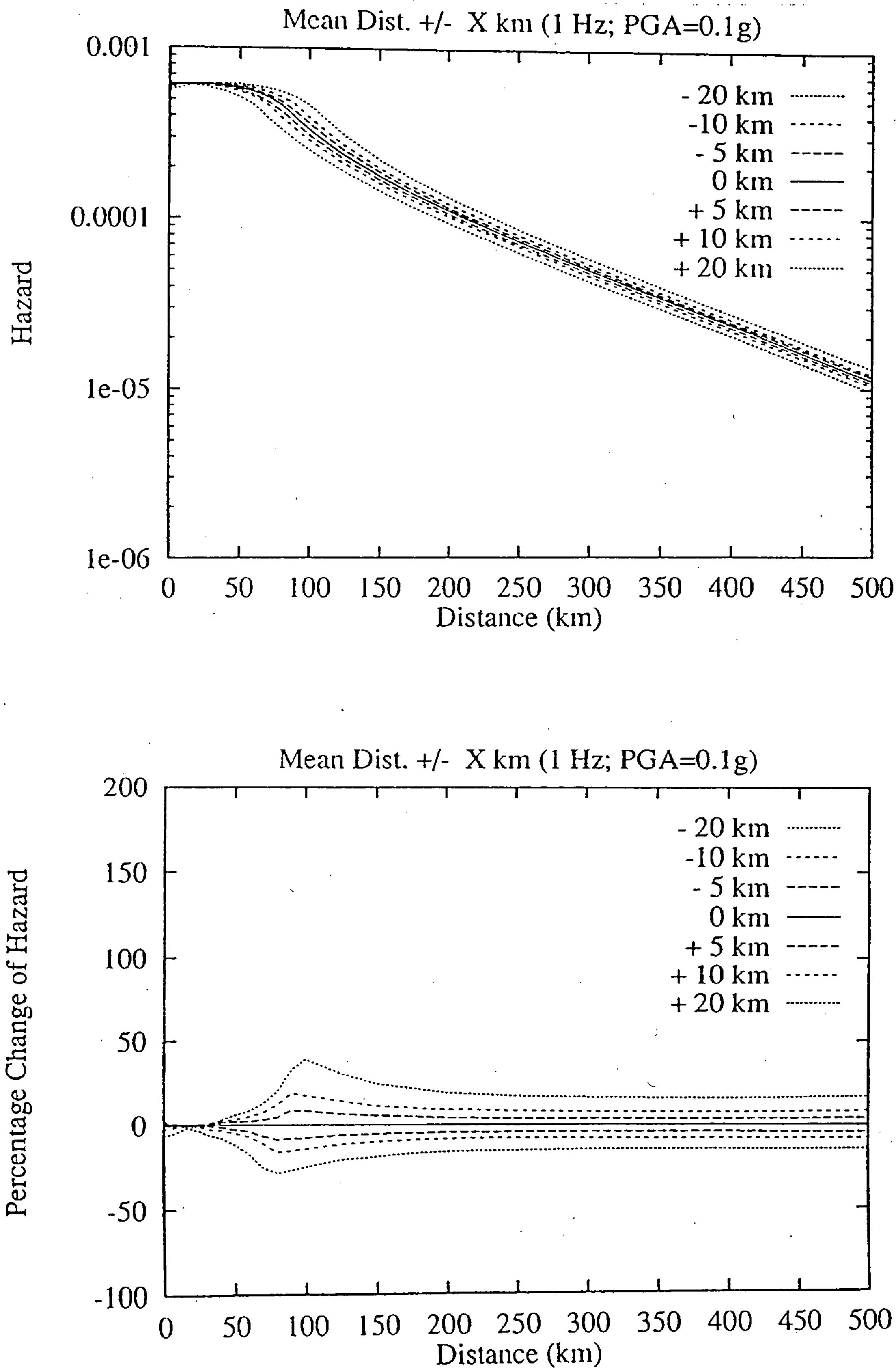


Figure G-26a. Sensitivity of 1 Hz hazard to distance from fault, PGA = 0.1g, Group B sites.

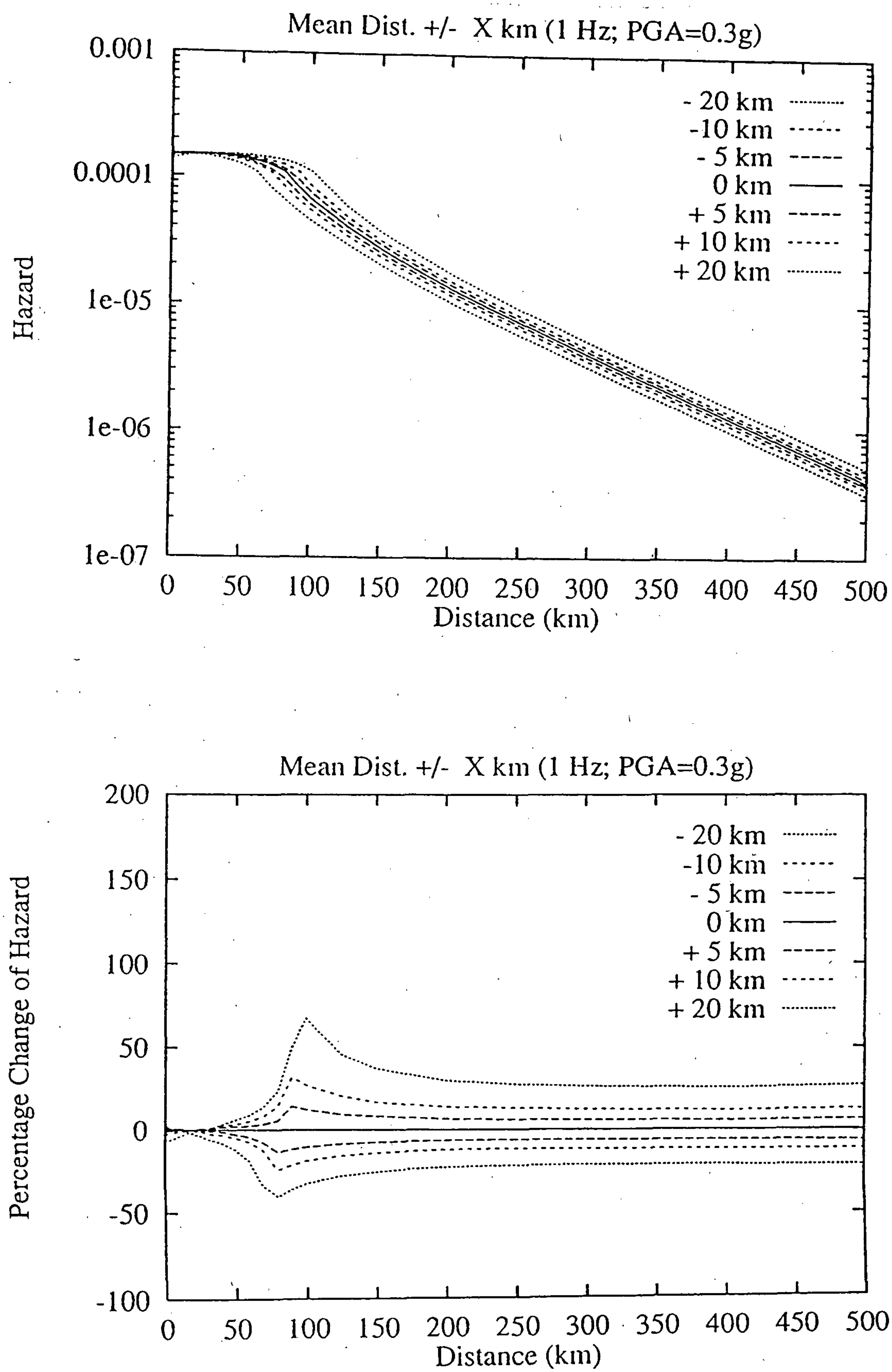


Figure G-26b. Sensitivity of 1 Hz hazard to distance from fault, PGA = 0.3g, Group B sites.

Line Source (WUS)

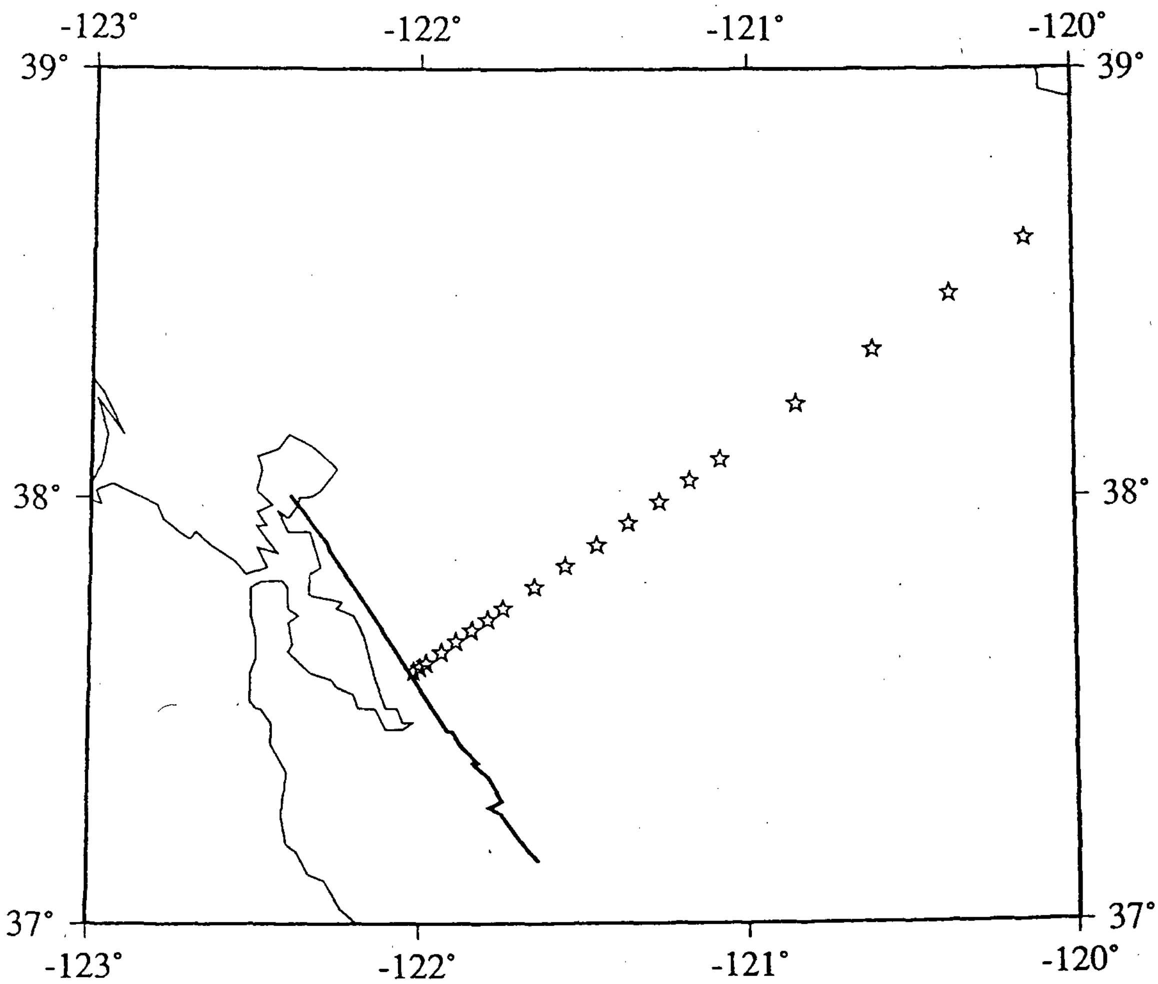
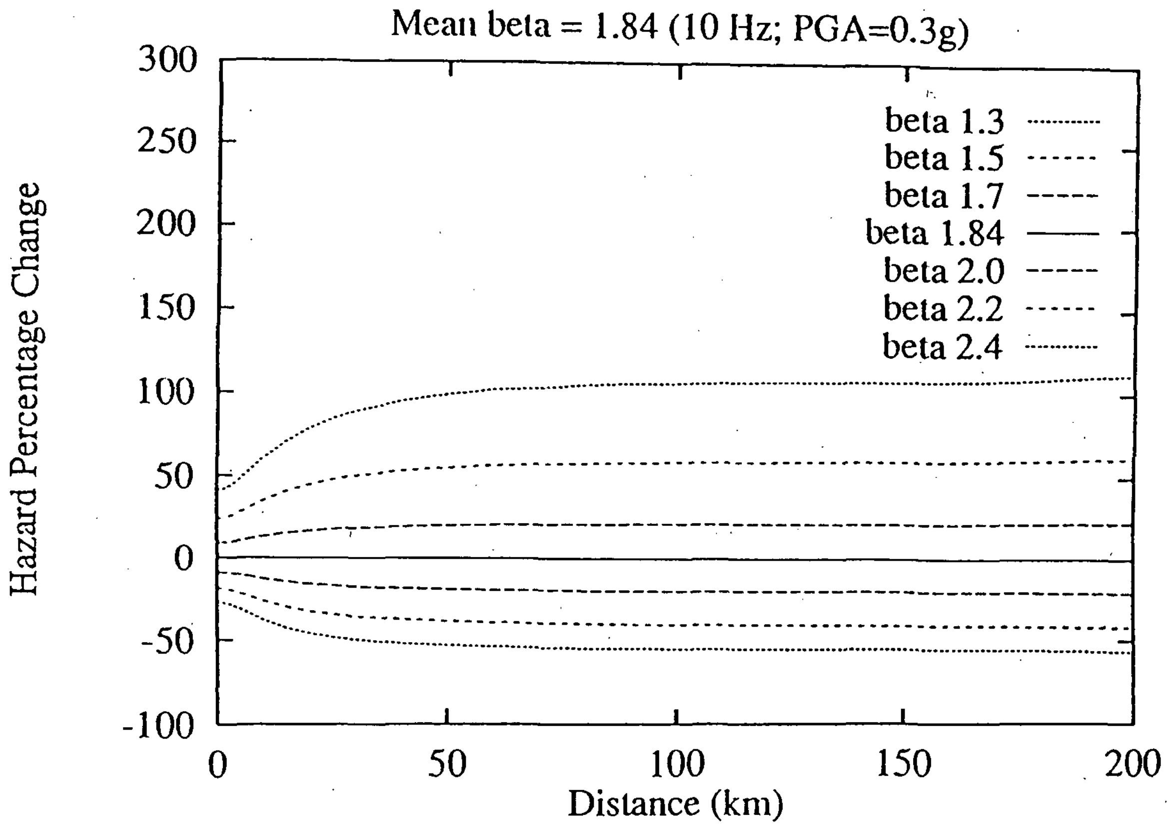


Figure G-27: Location of Group C sites with respect to Hayward fault.



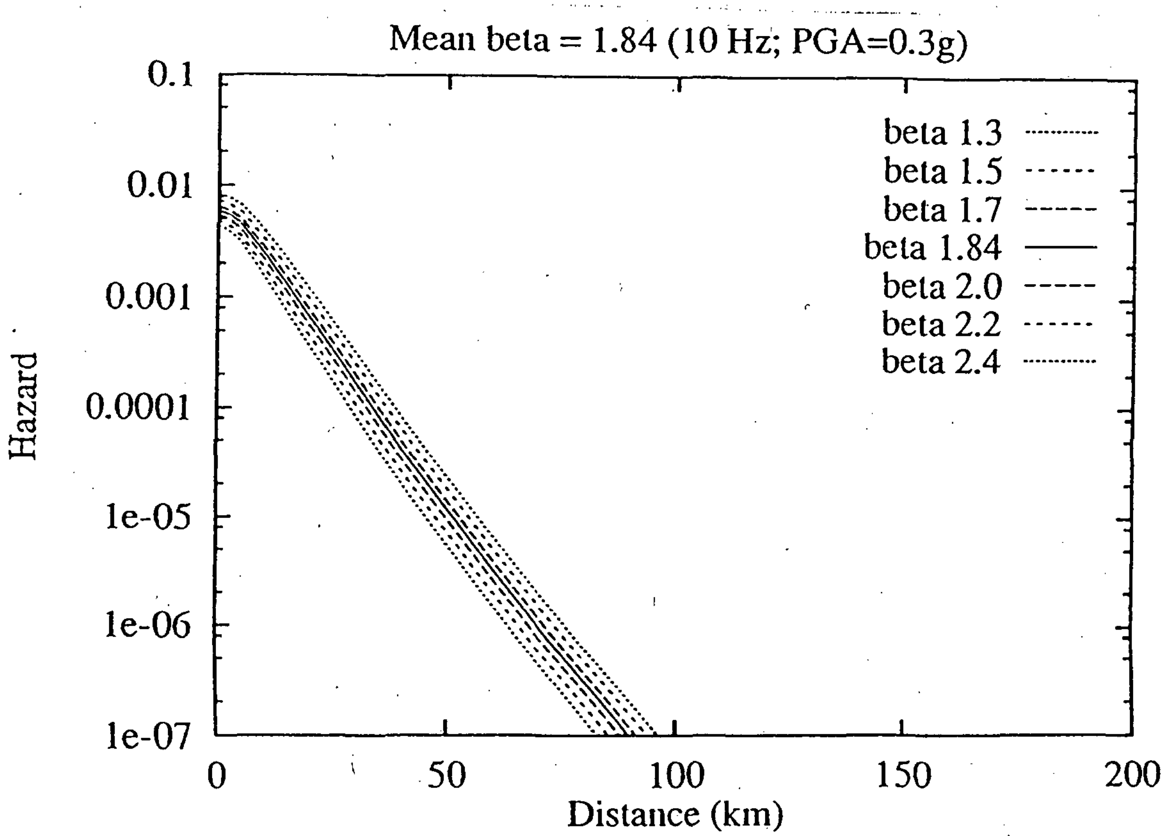
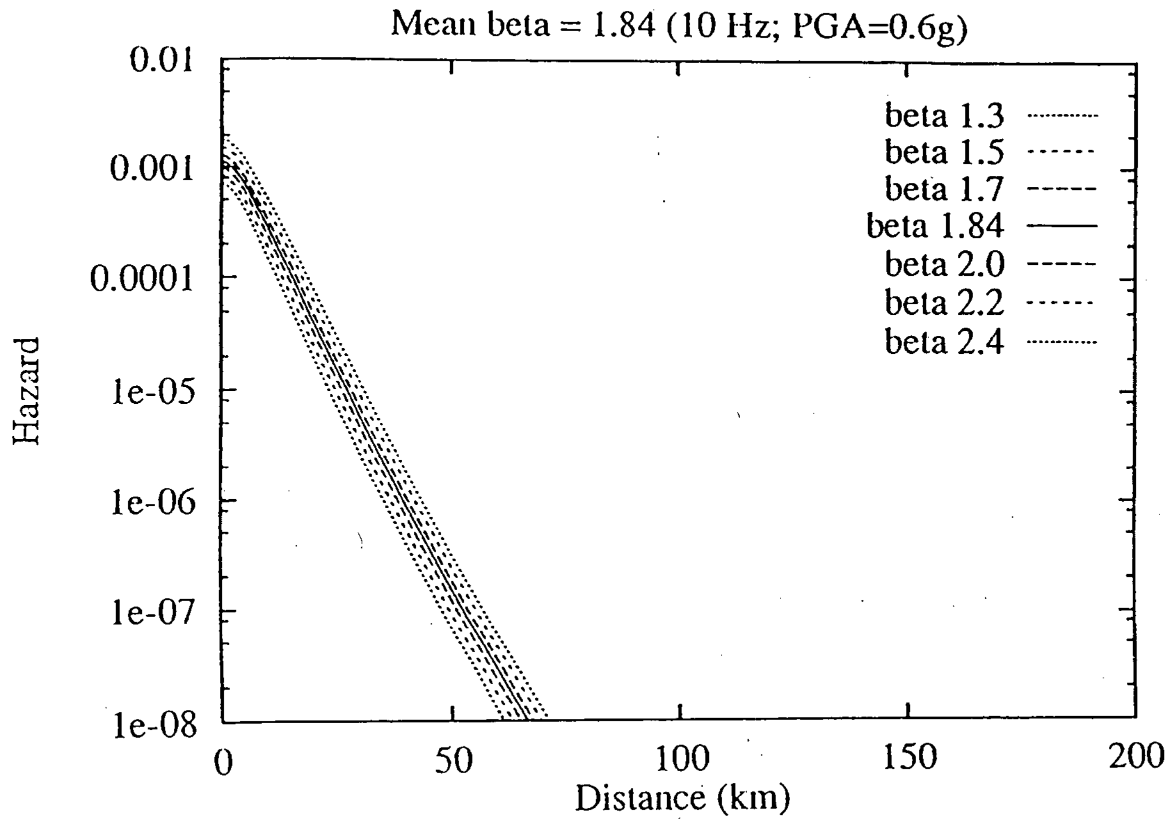


Figure G-28a. Sensitivity of 10 Hz hazard to beta for PGA = 0.3g, Group C sites.



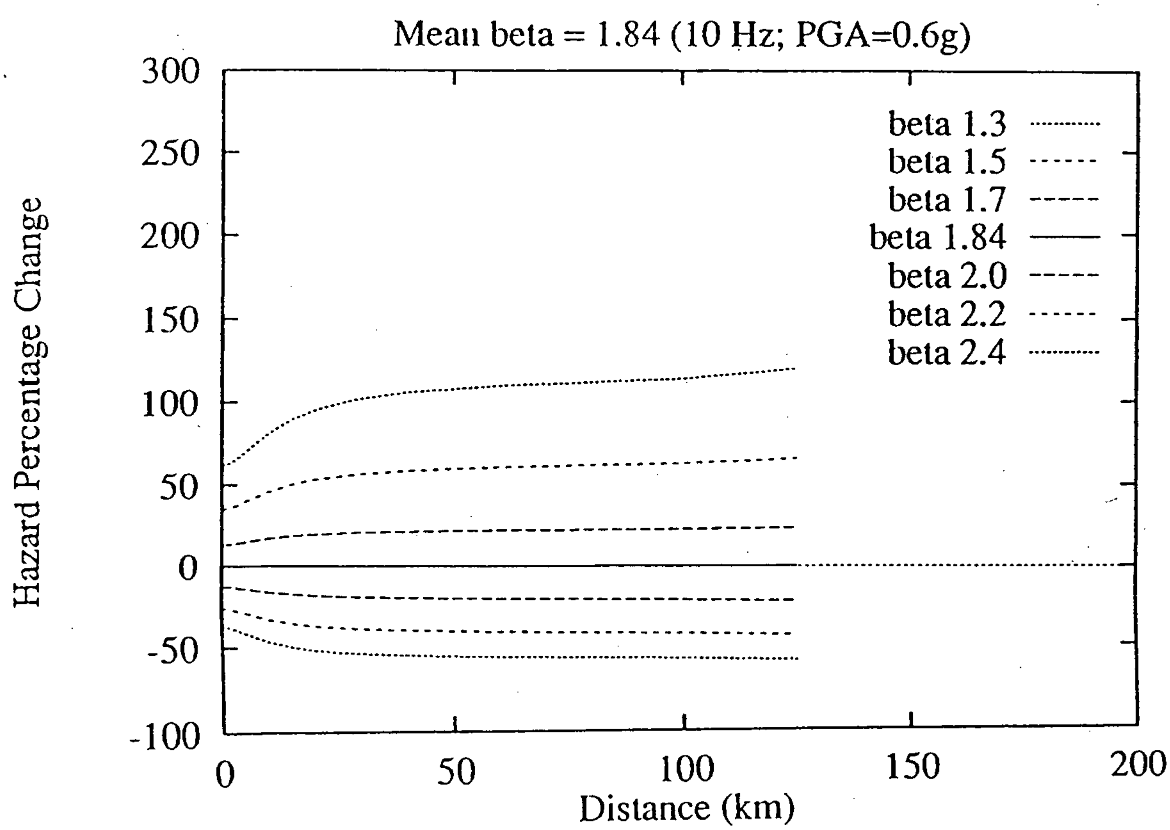


Figure G-28b. Sensitivity of 10 Hz hazard to beta for PGA = 0.6g, Group C sites.

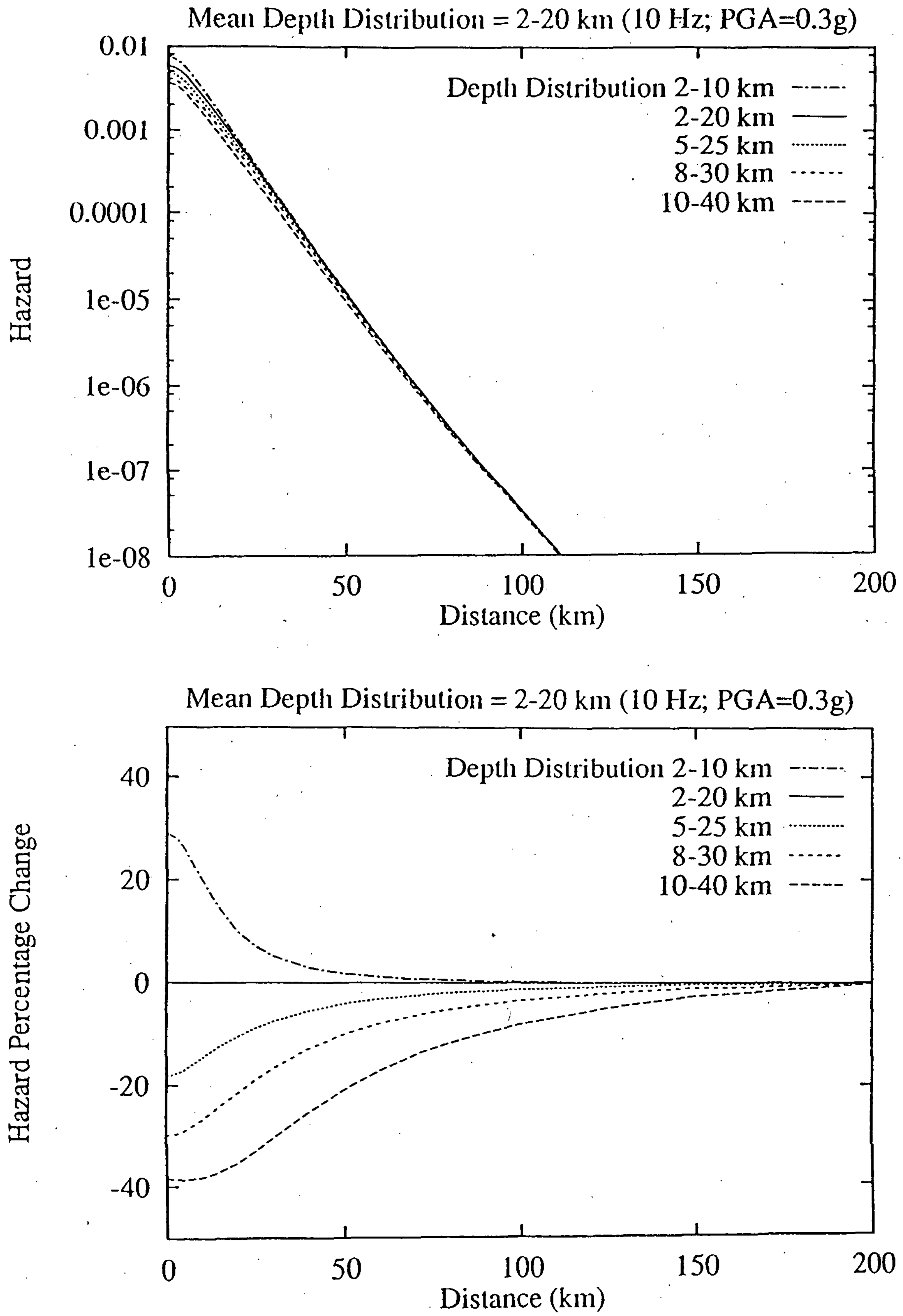
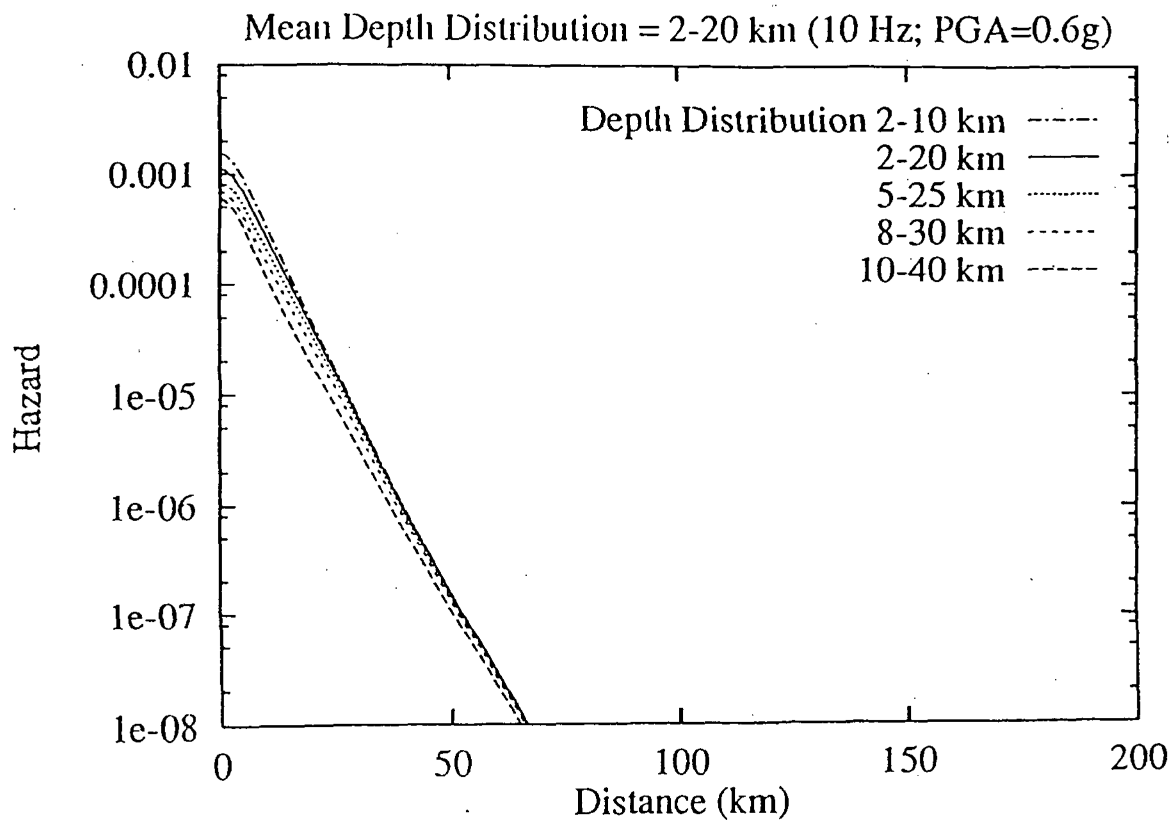


Figure G-29a. Sensitivity of 10 Hz hazard to depth distribution for PGA = 0.3g, Group C sites.



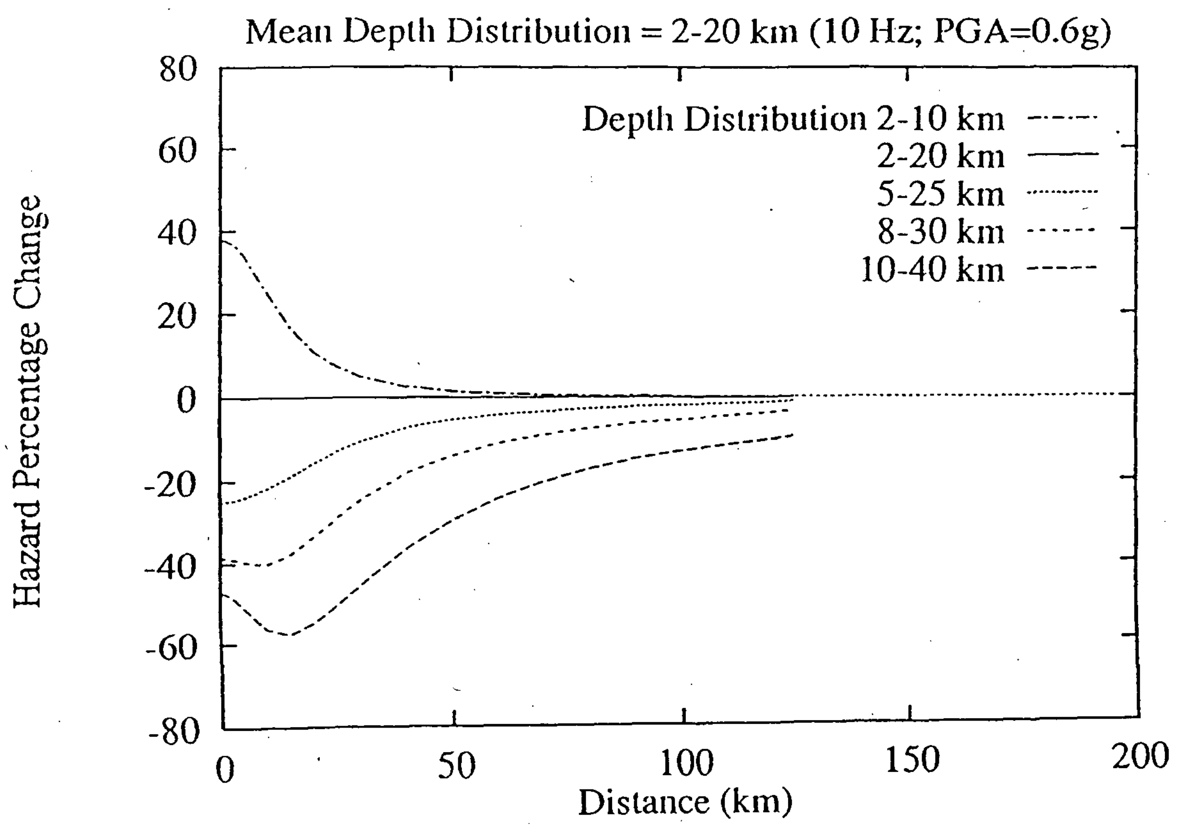
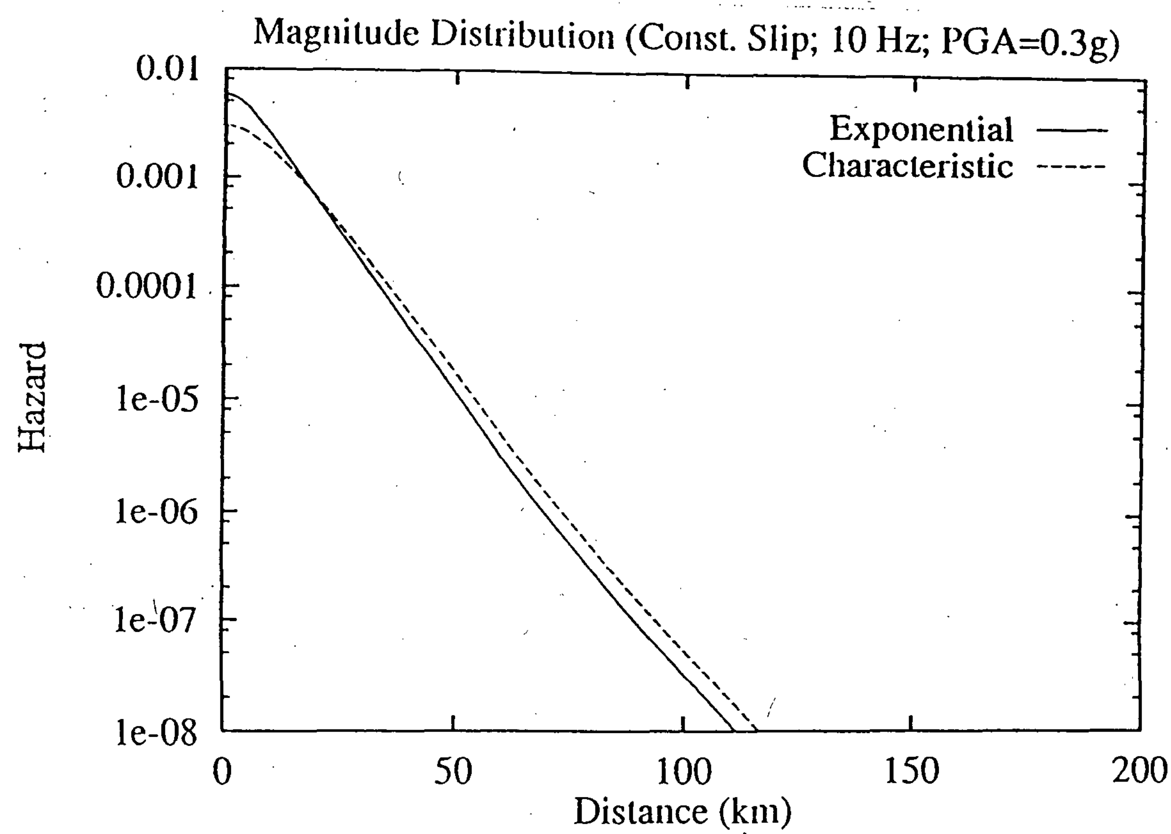


Figure G-29b. Sensitivity of 10 Hz hazard to depth distribution for PGA = 0.6g, Group C sites.



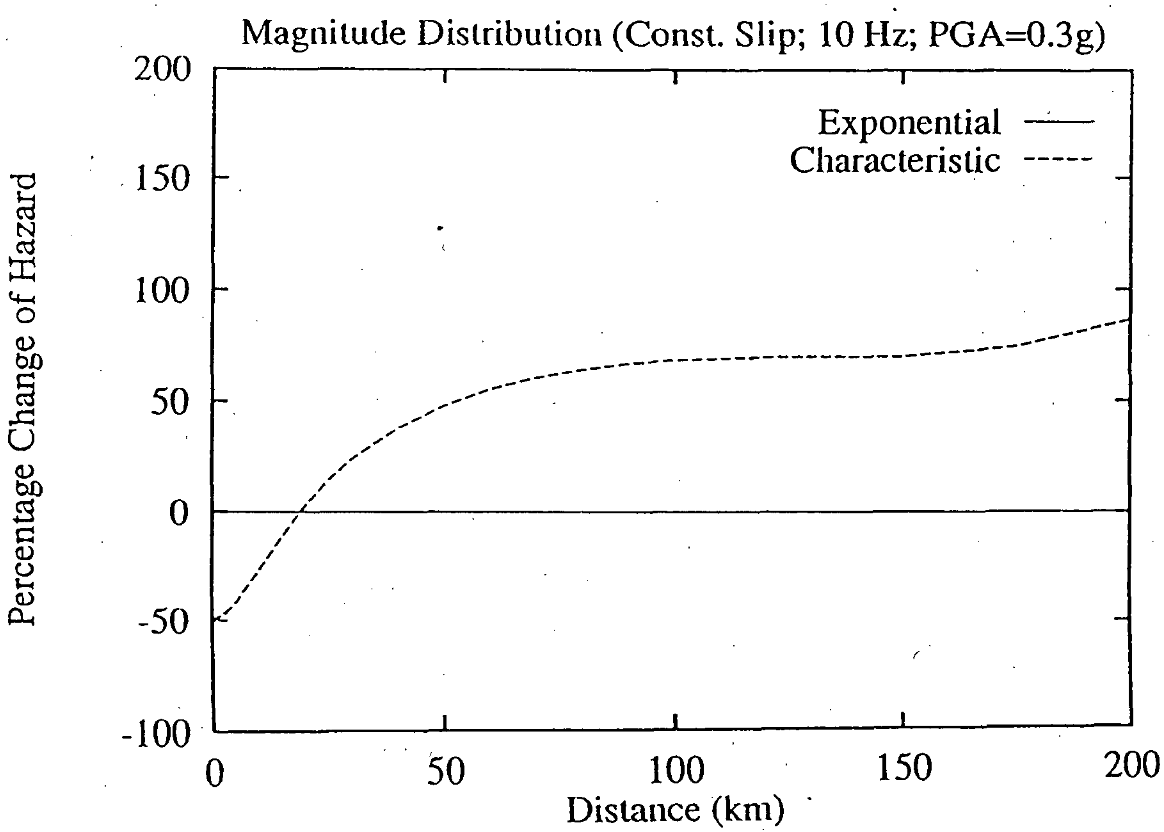
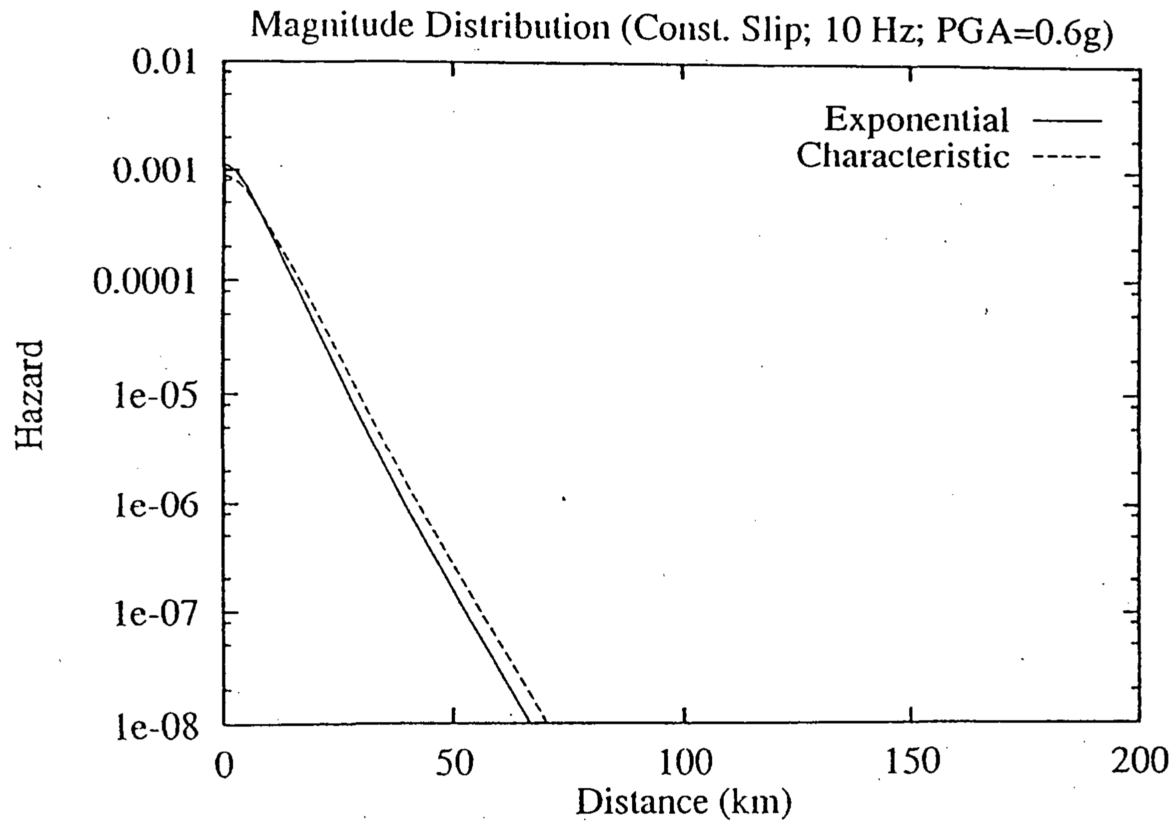


Figure G-30a. Sensitivity of 10 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.3g, Group C sites.



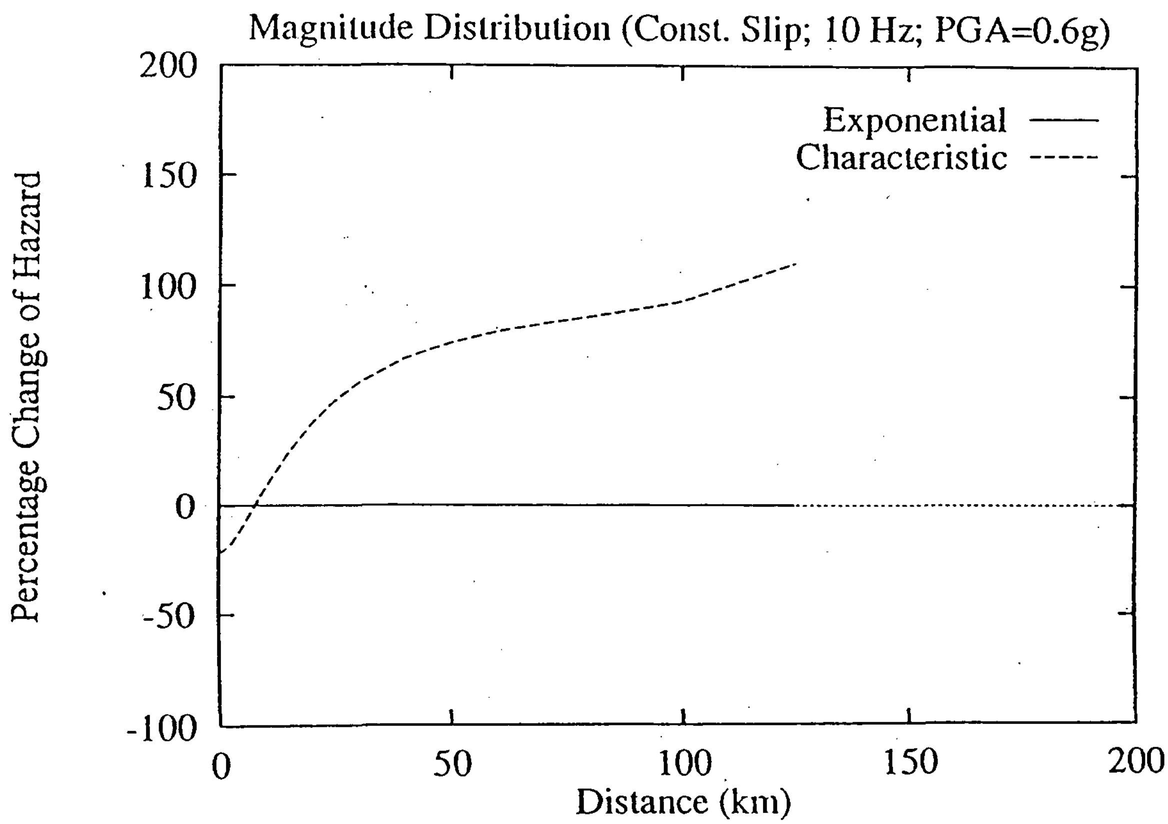
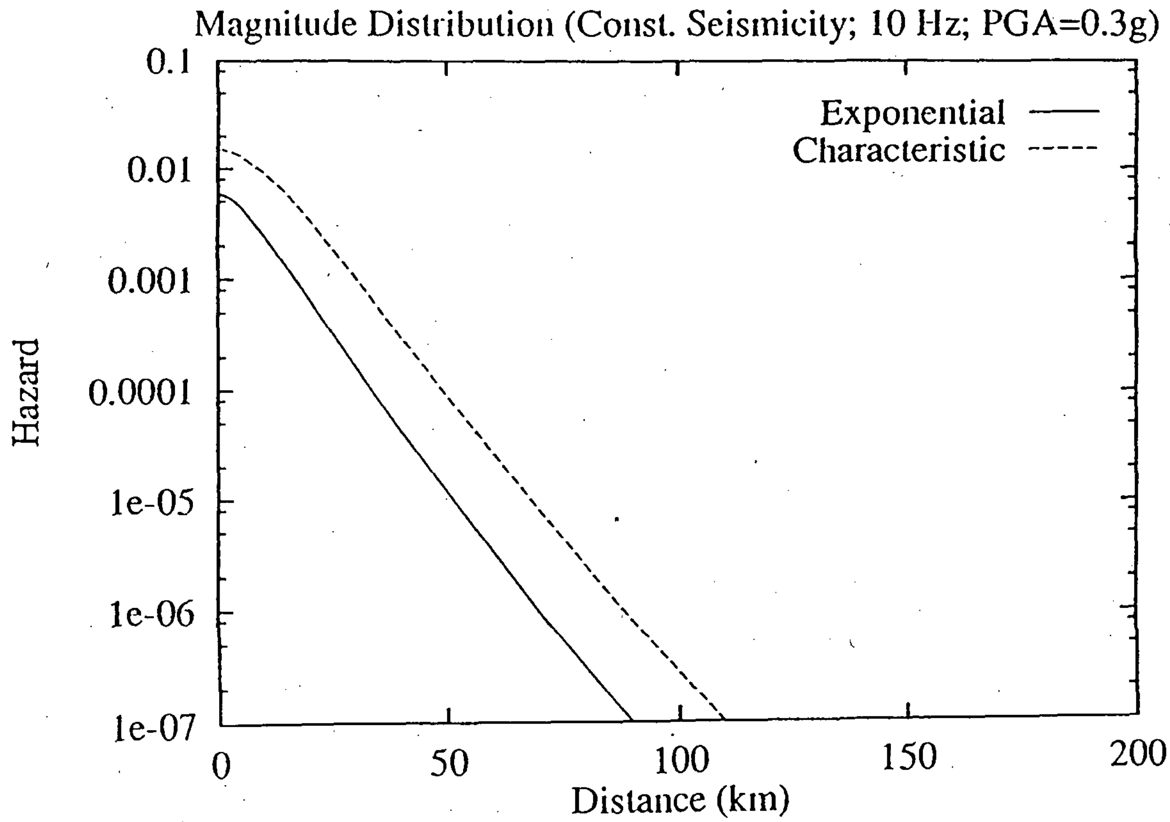


Figure G-30b. Sensitivity of 10 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.6g, Group C sites.



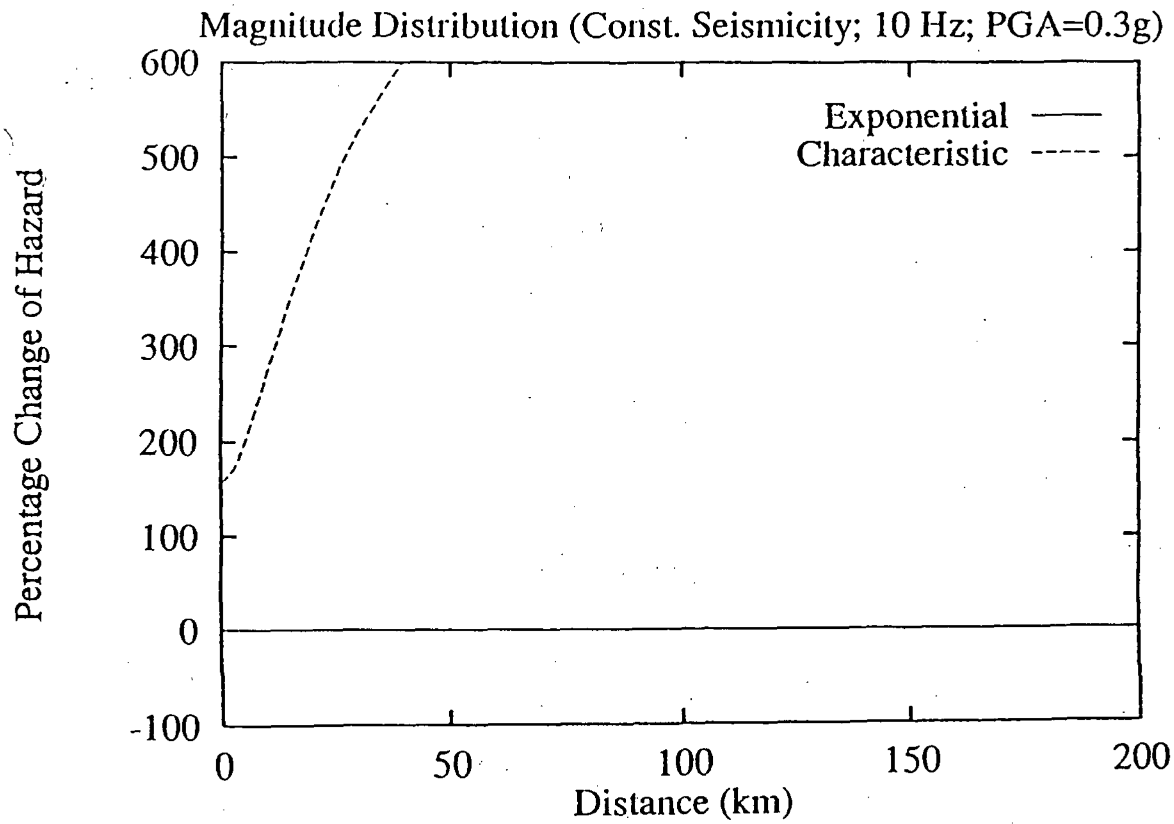
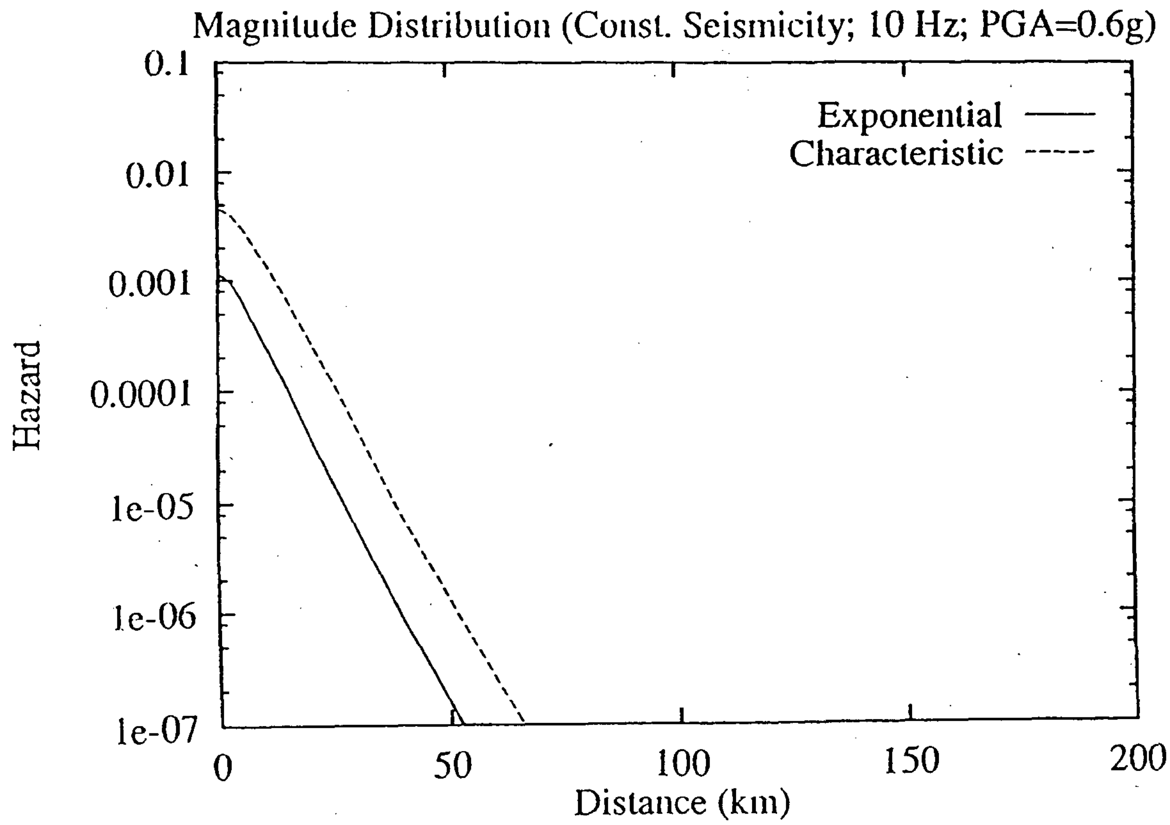


Figure G-31a. Sensitivity of 10 Hz hazard to magnitude distribution (with constant seismicity assumption), PGA = 0.3g, Group C sites.



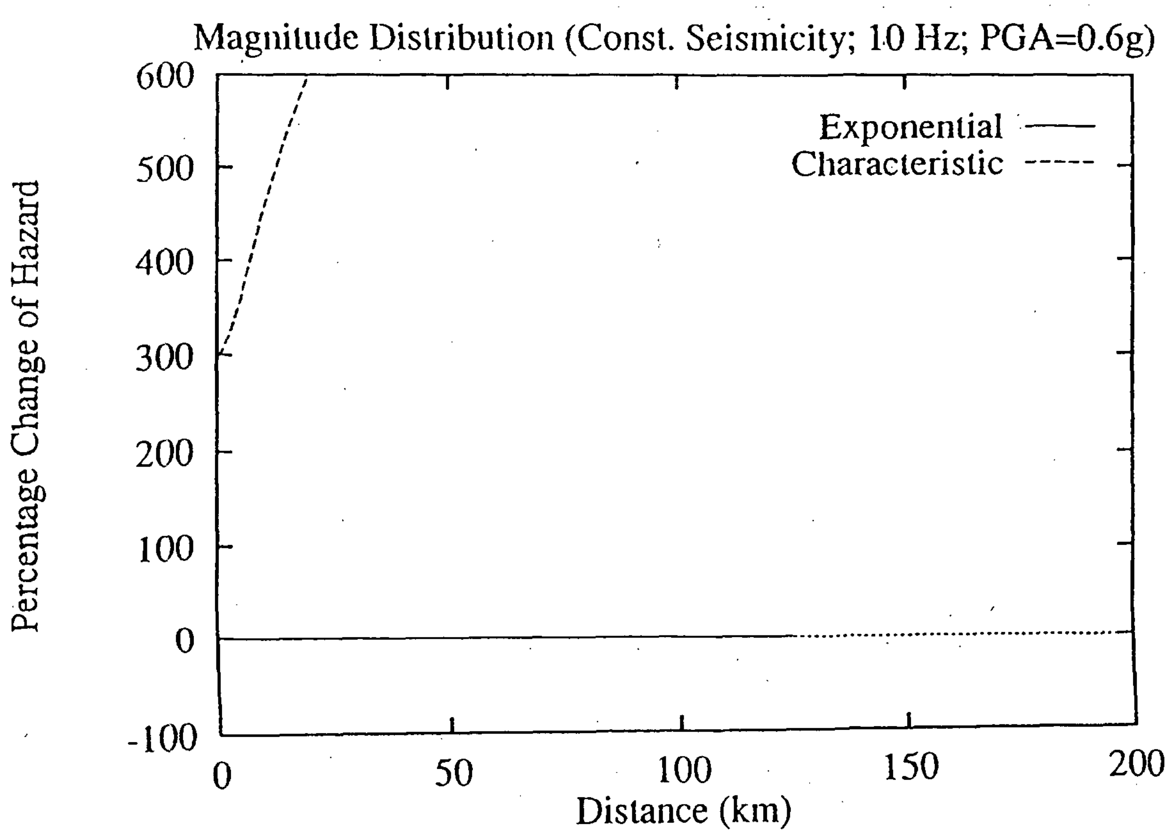
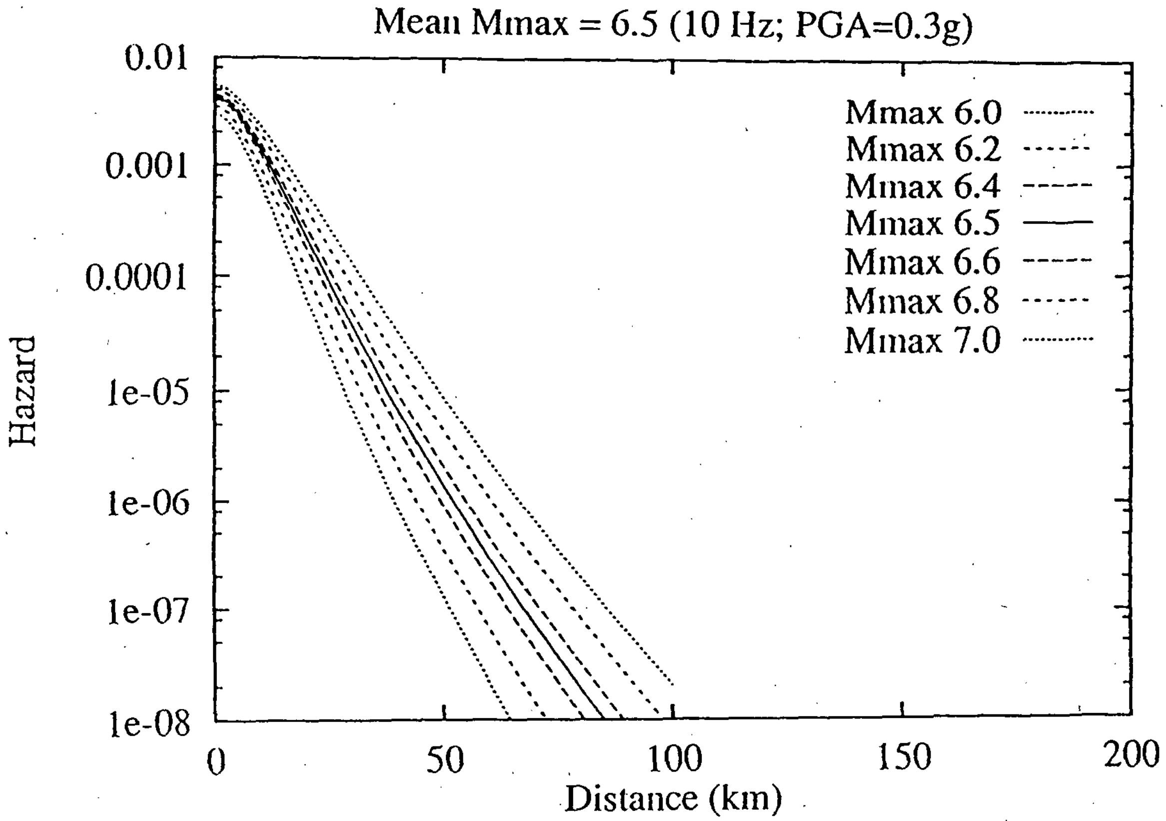


Figure G-31b. Sensitivity of 10 Hz hazard to magnitude distribution, (with constant seismicity assumption), PGA = 0.6g, Group C sites.



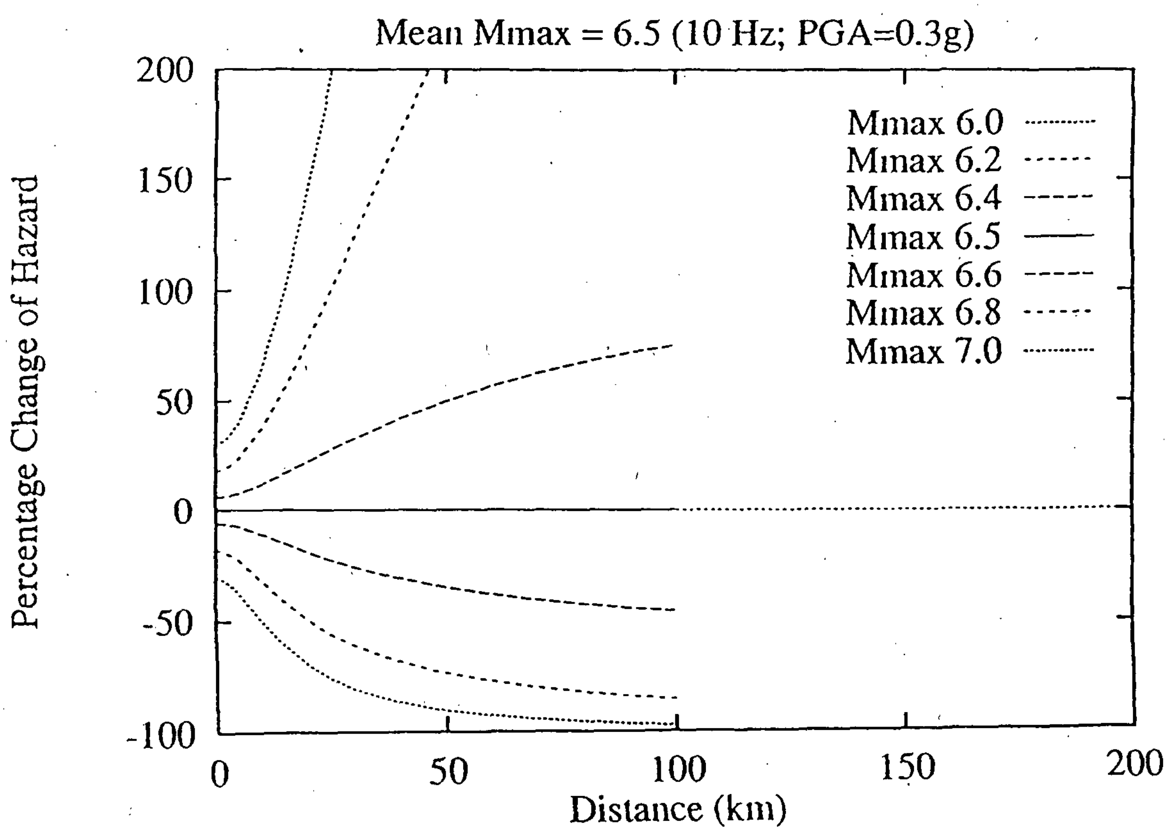


Figure G-32a. Sensitivity of 10 Hz hazard to m_{max} = 6.0, PGA = 0.3g, Group C sites.

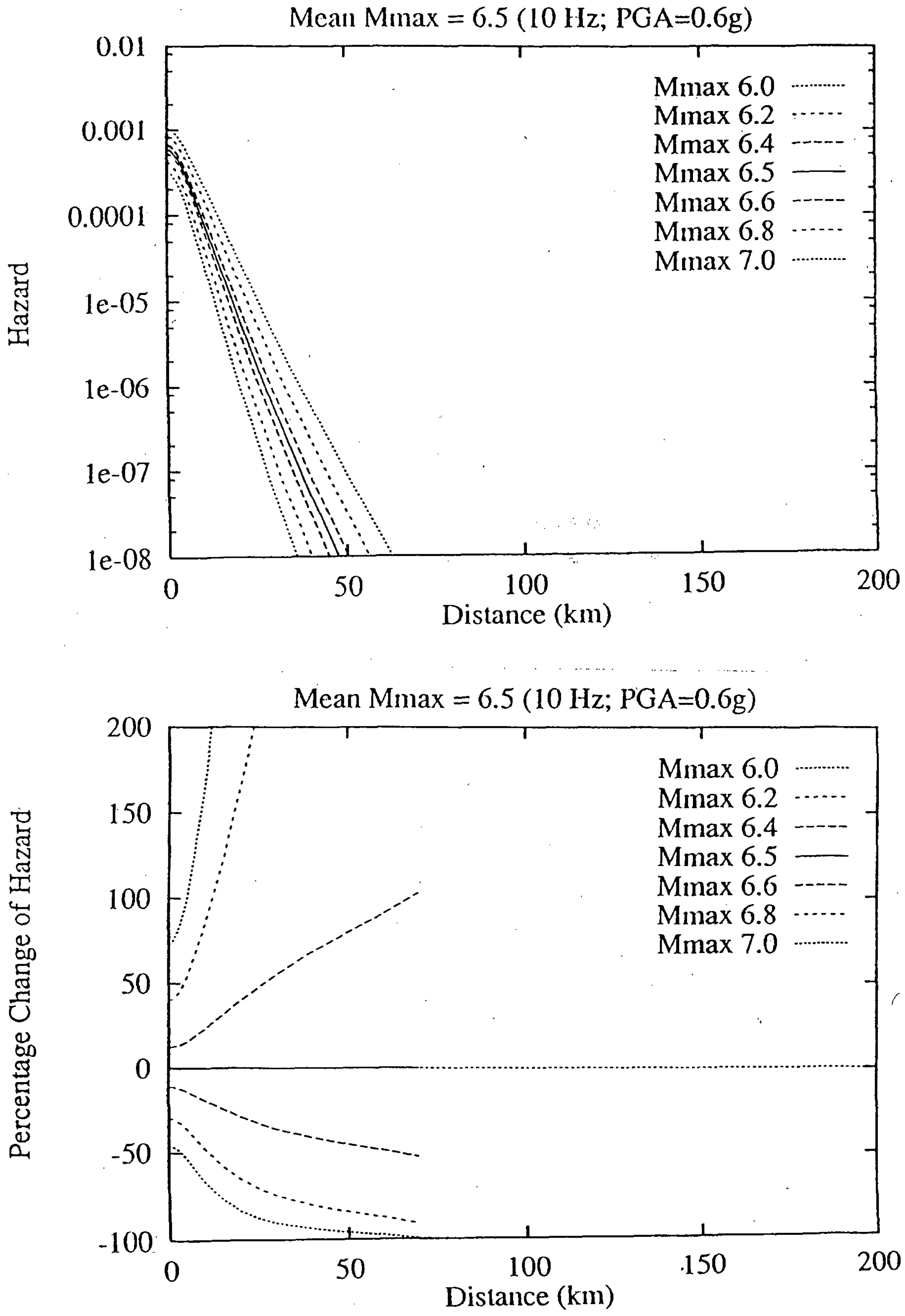
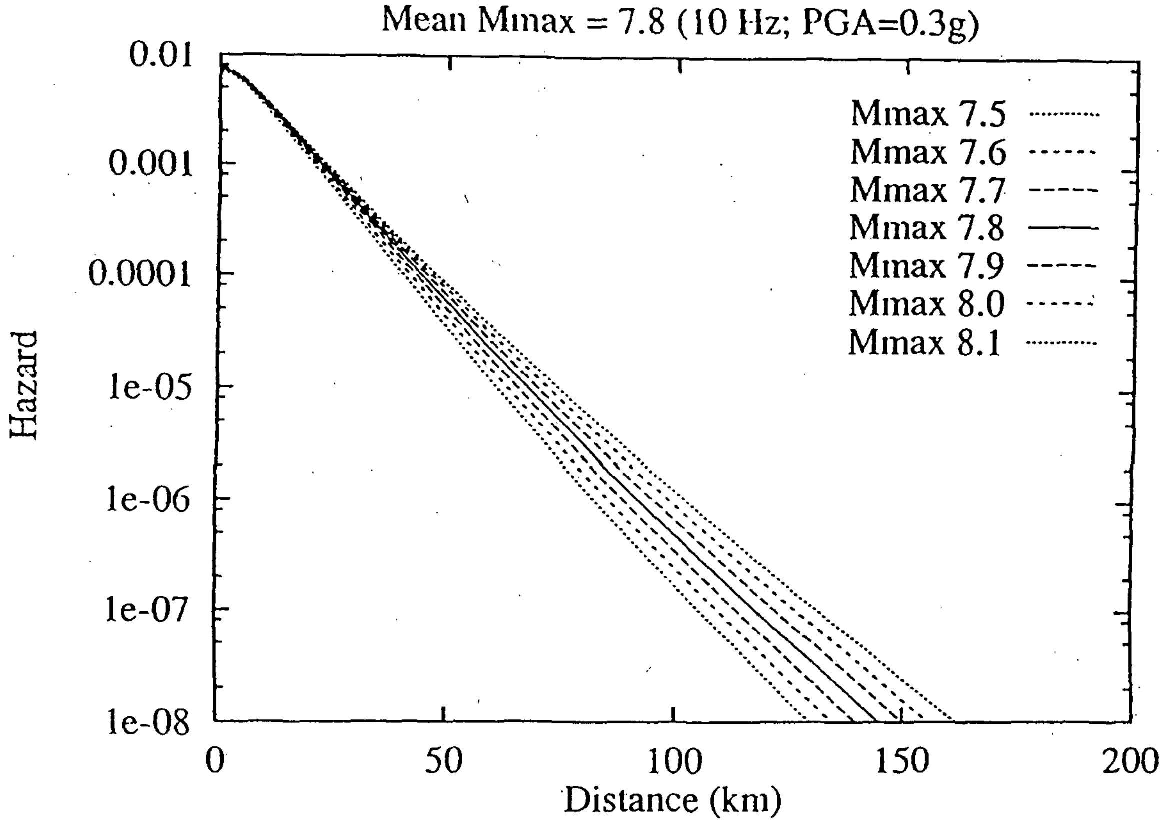


Figure G-32b. Sensitivity of 10 Hz hazard to m_{max} = 6.0, PGA = 0.6g, Group C sites.



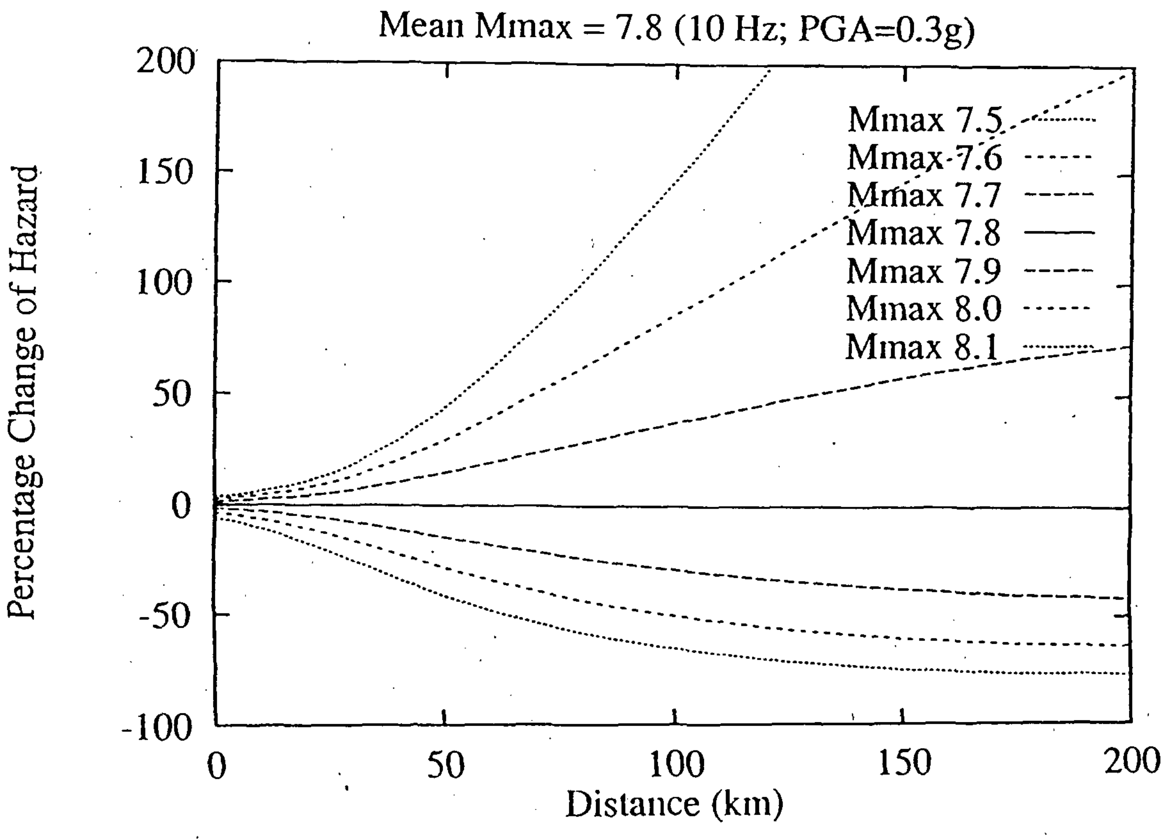
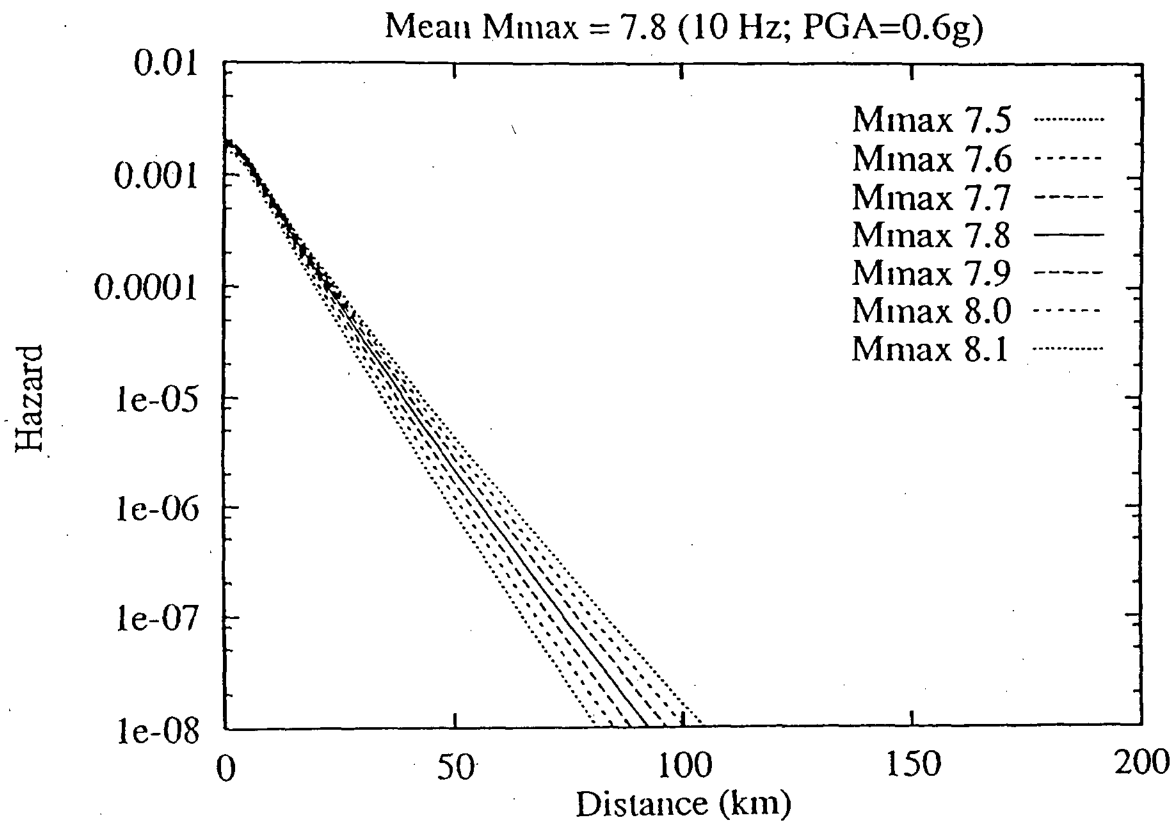


Figure G-33a. Sensitivity of 10 Hz hazard to m_{max} = 7.5, PGA = 0.3g, Group C sites.



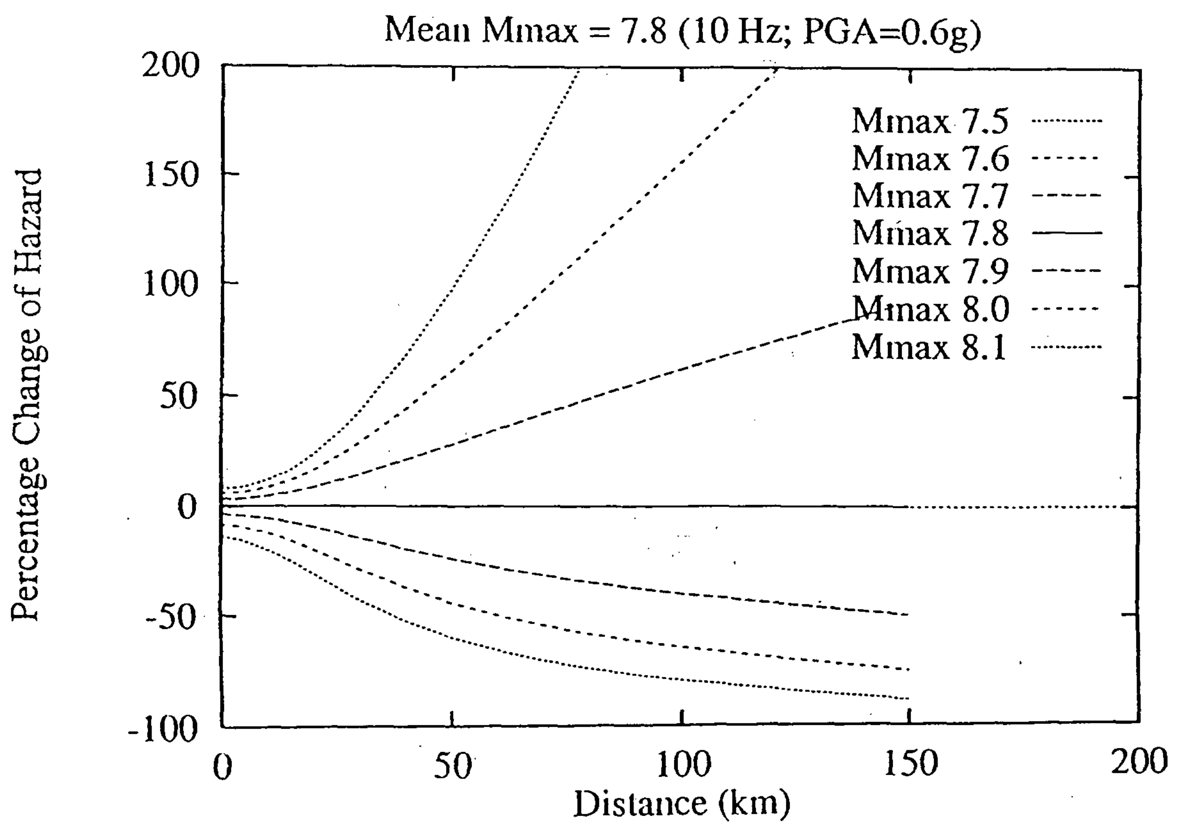


Figure G-33b. Sensitivity of 10 Hz hazard to m_{max} = 7.5, PGA = 0.6g, Group C sites.

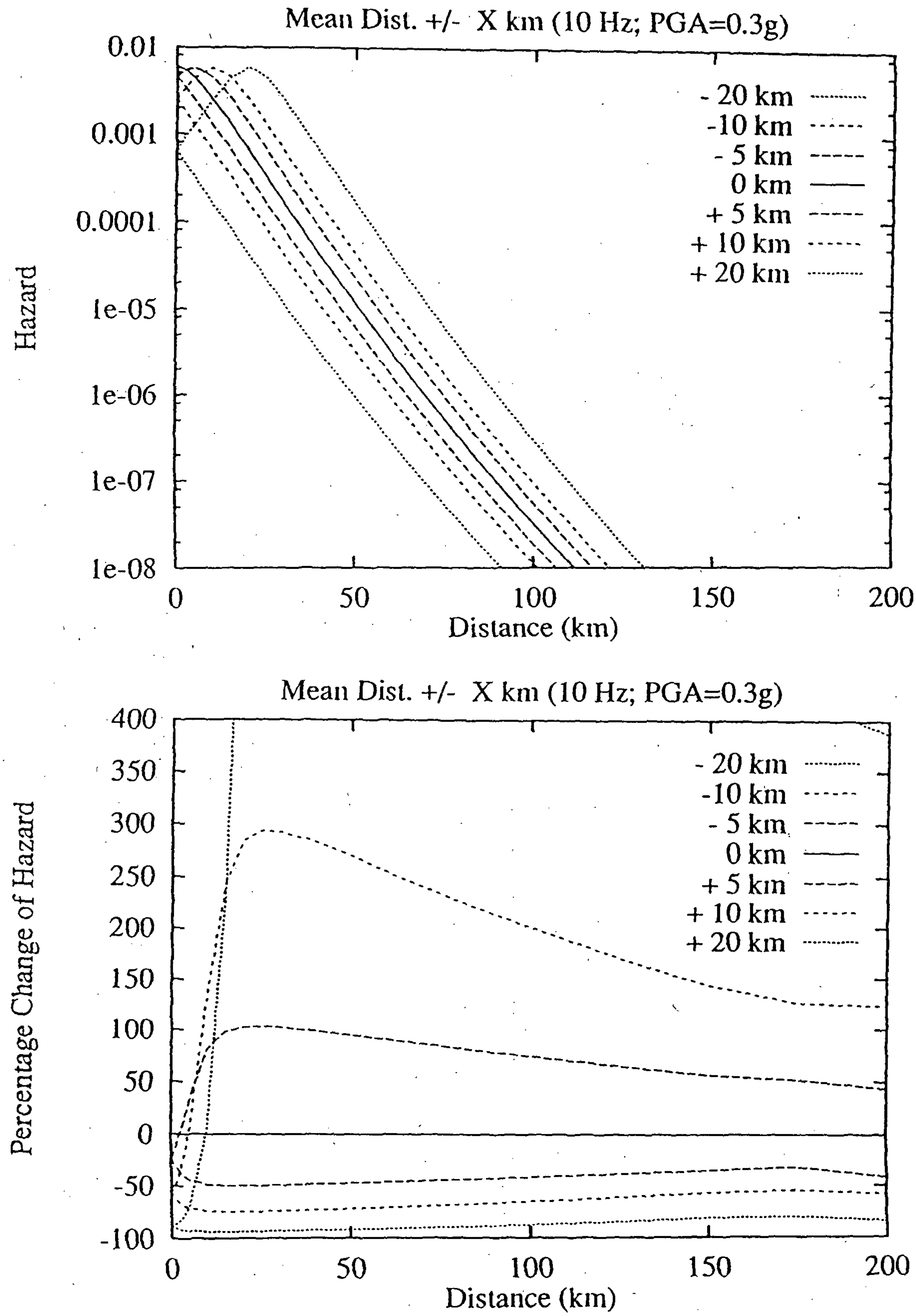
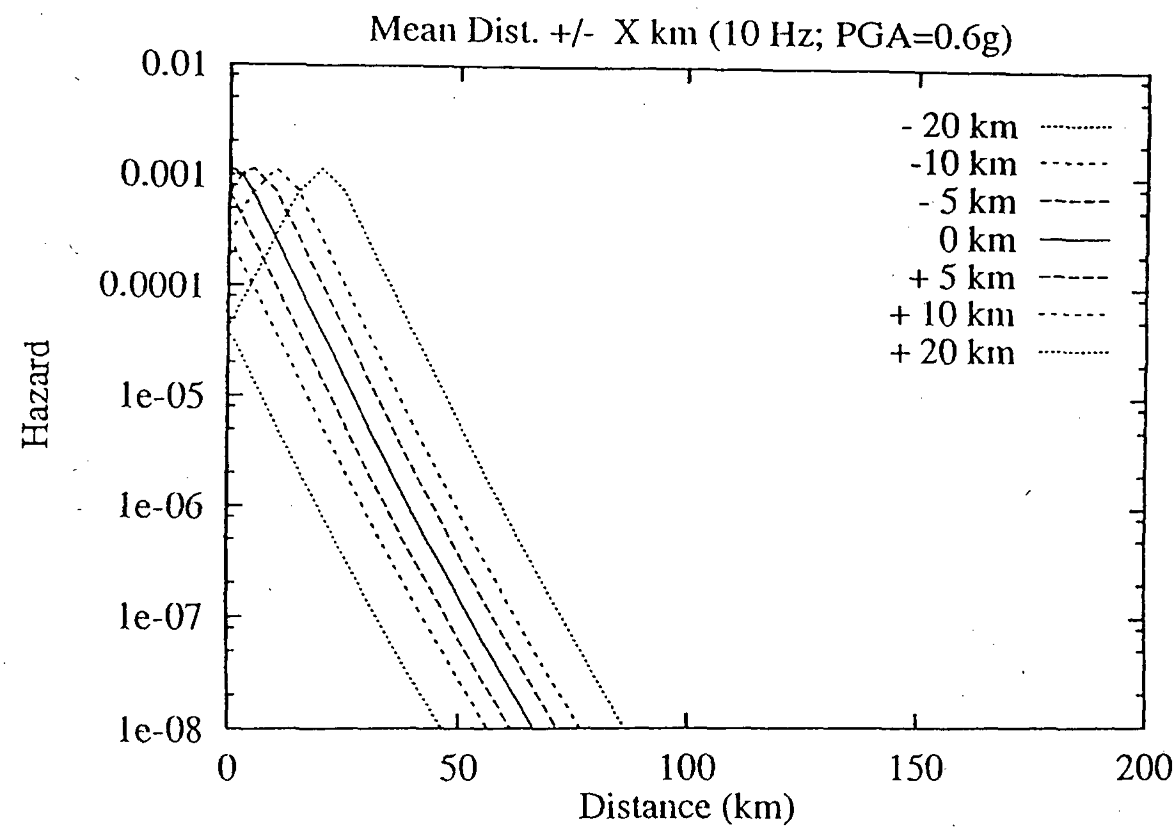


Figure G-34a. Sensitivity of 10 Hz hazard to distance from fault, PGA = 0.3g, Group C sites.



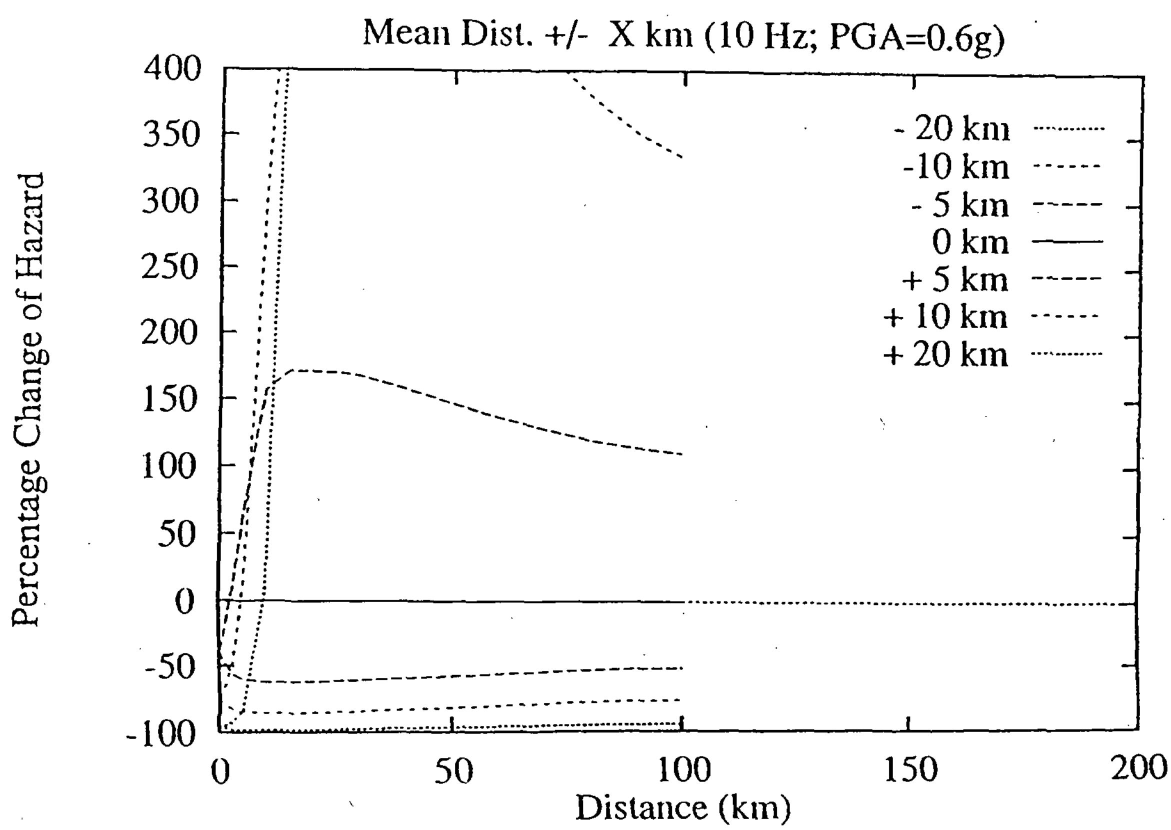


Figure G-34b. Sensitivity of 10 Hz hazard to distance from fault, PGA = 0.6g, Group C sites.

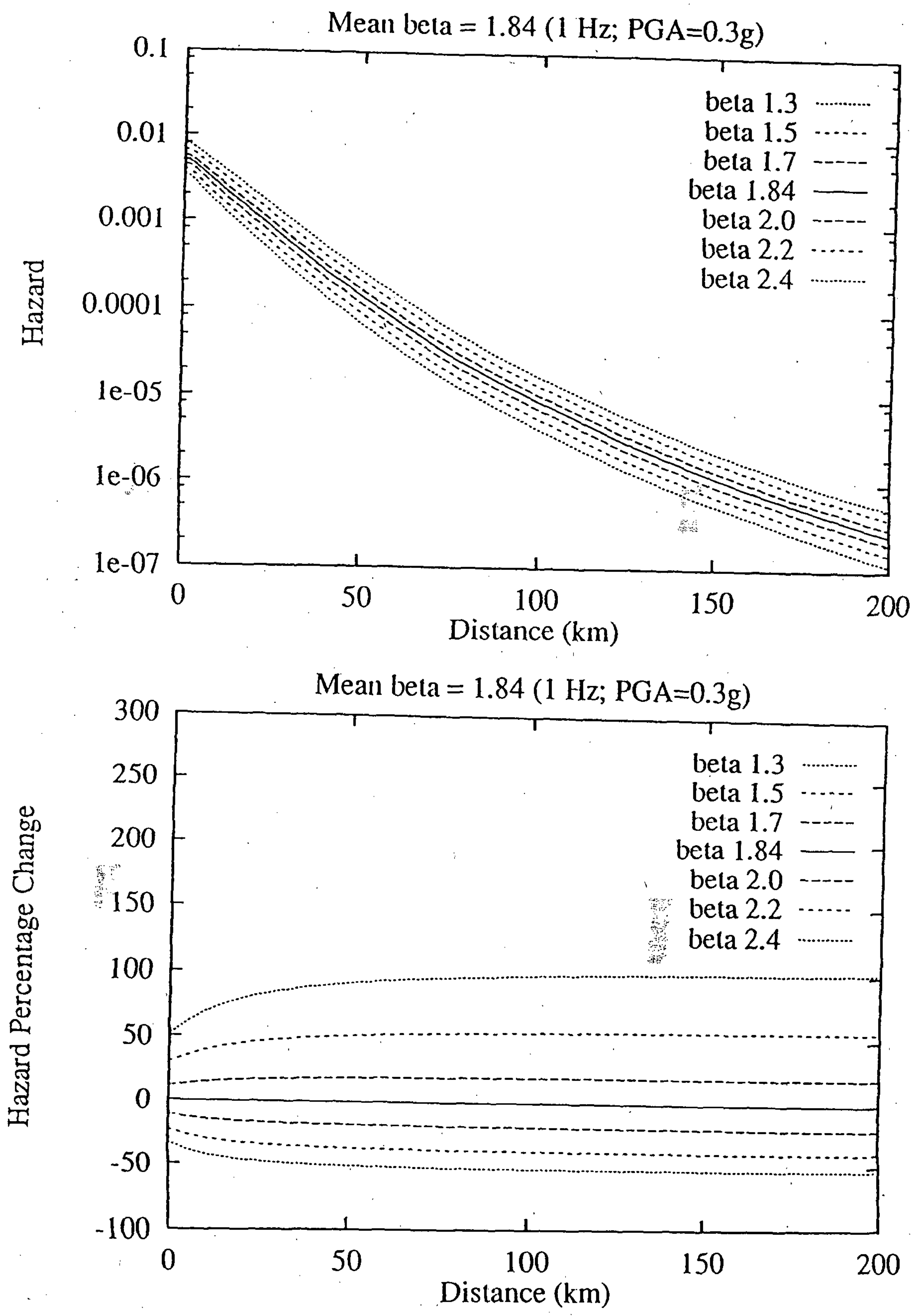


Figure G-35a. Sensitivity of 1 Hz hazard to beta for PGA = 0.3g, Group C sites.

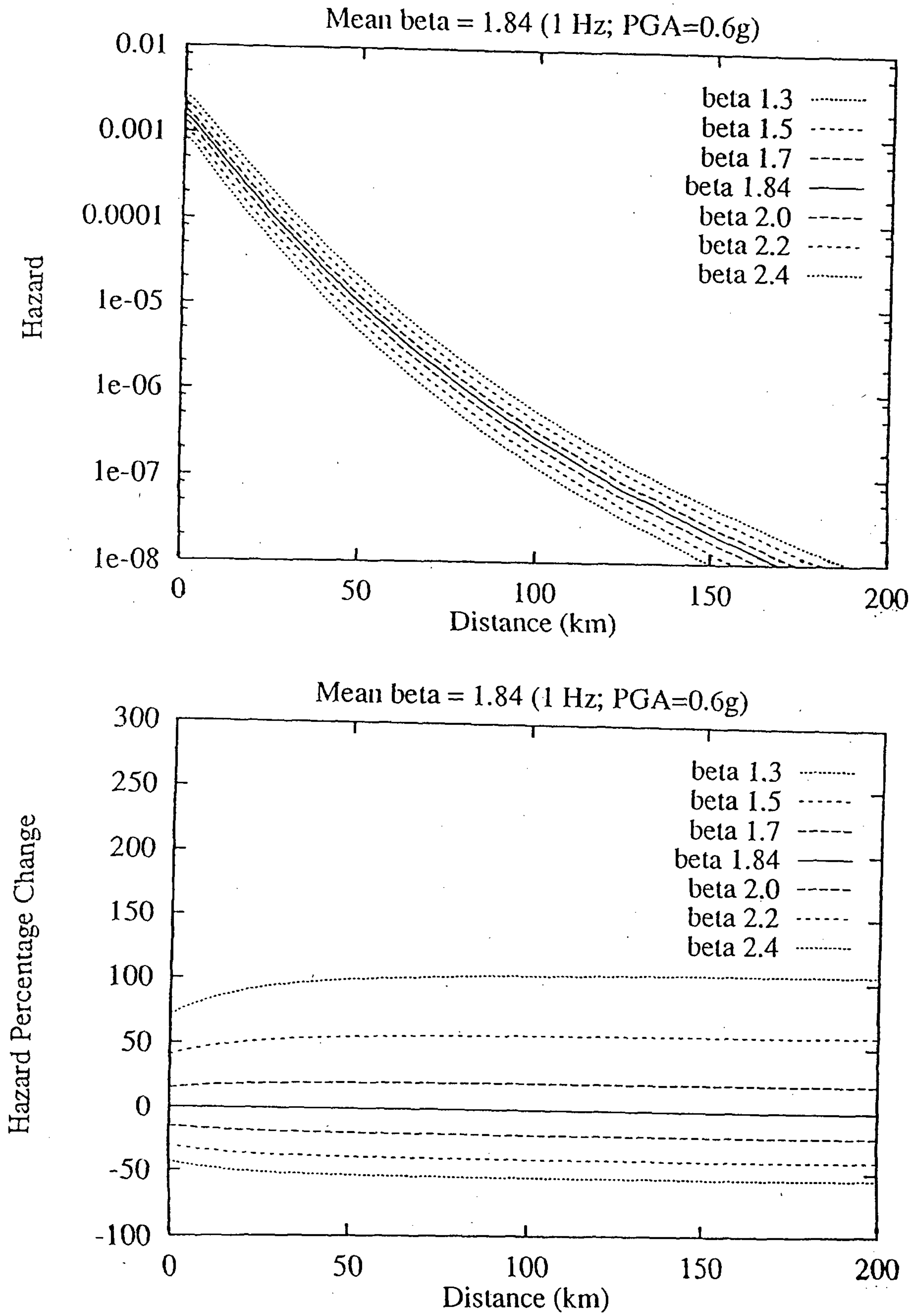
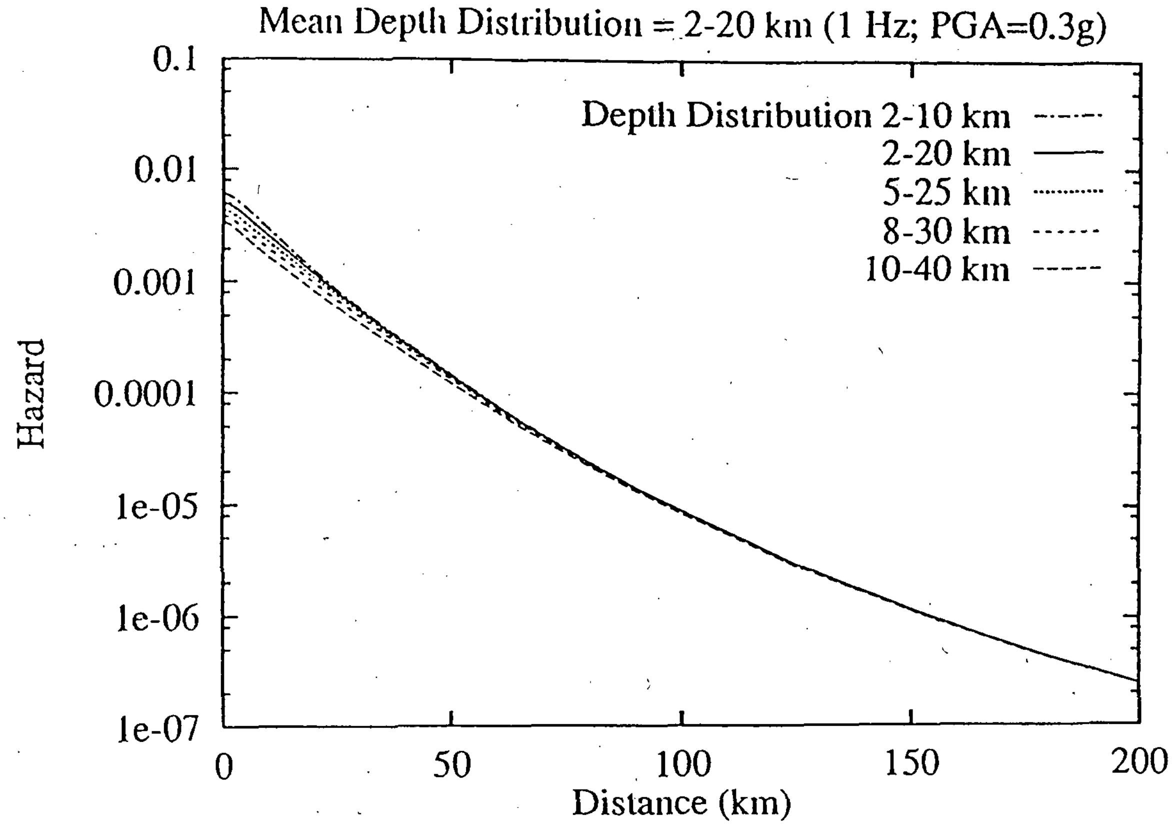


Figure G-35b. Sensitivity of 1 Hz hazard to beta for PGA = 0.6g, Group C sites.



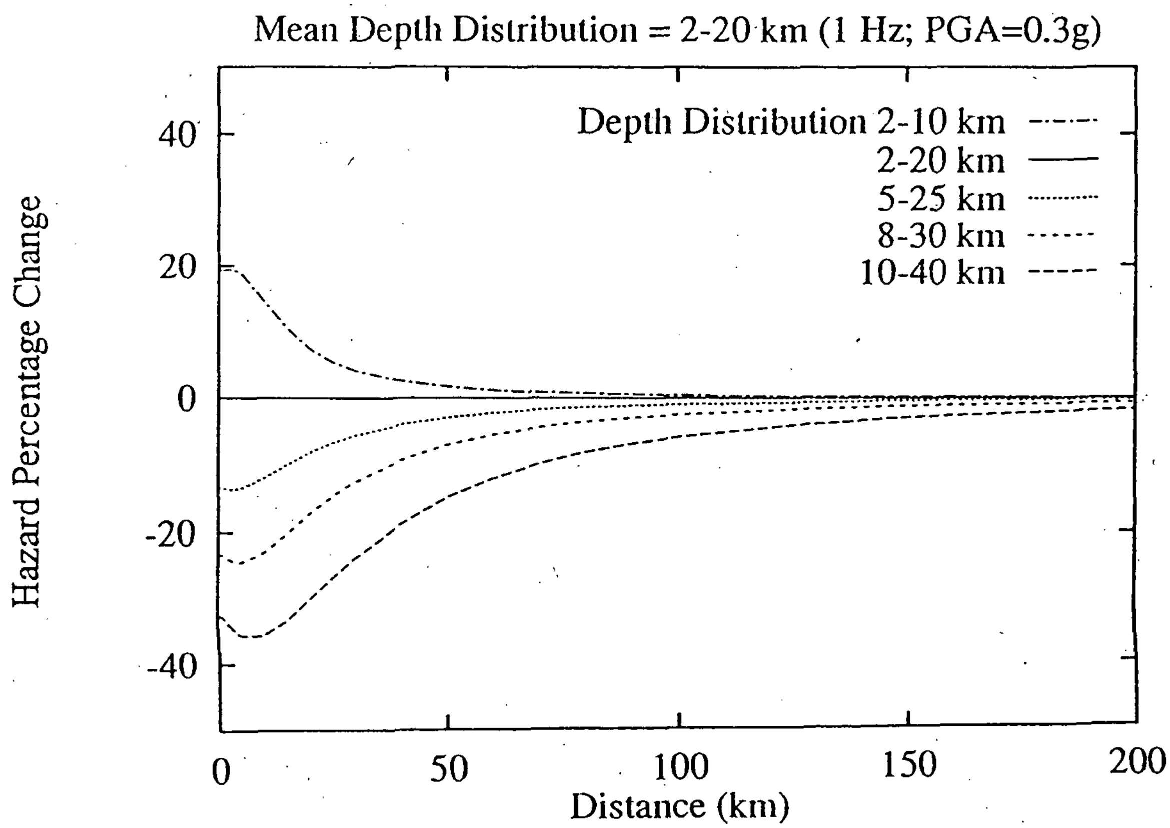


Figure G-36a. Sensitivity of 1 Hz hazard to depth distribution for PGA = 0.3g, Group C sites.

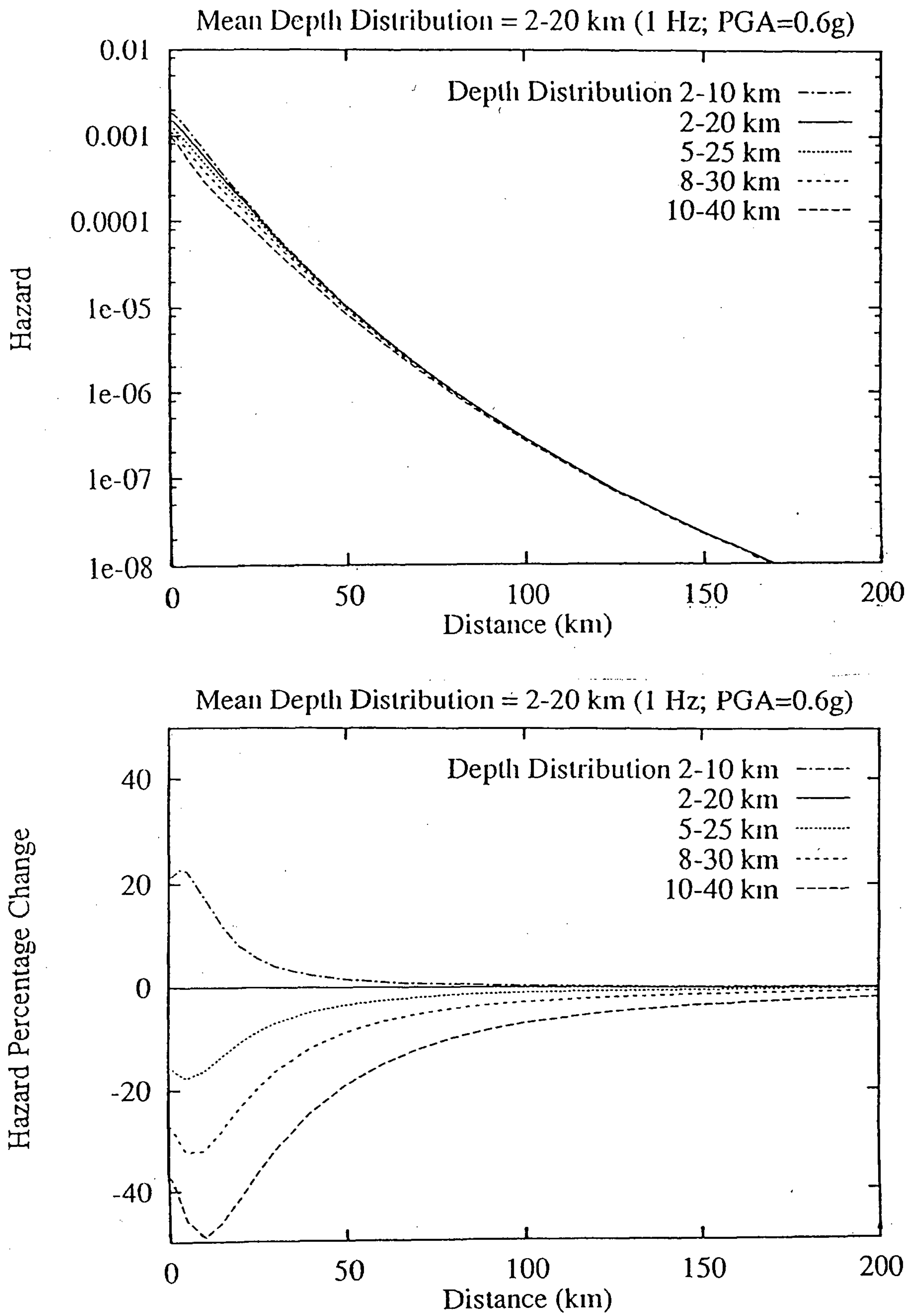
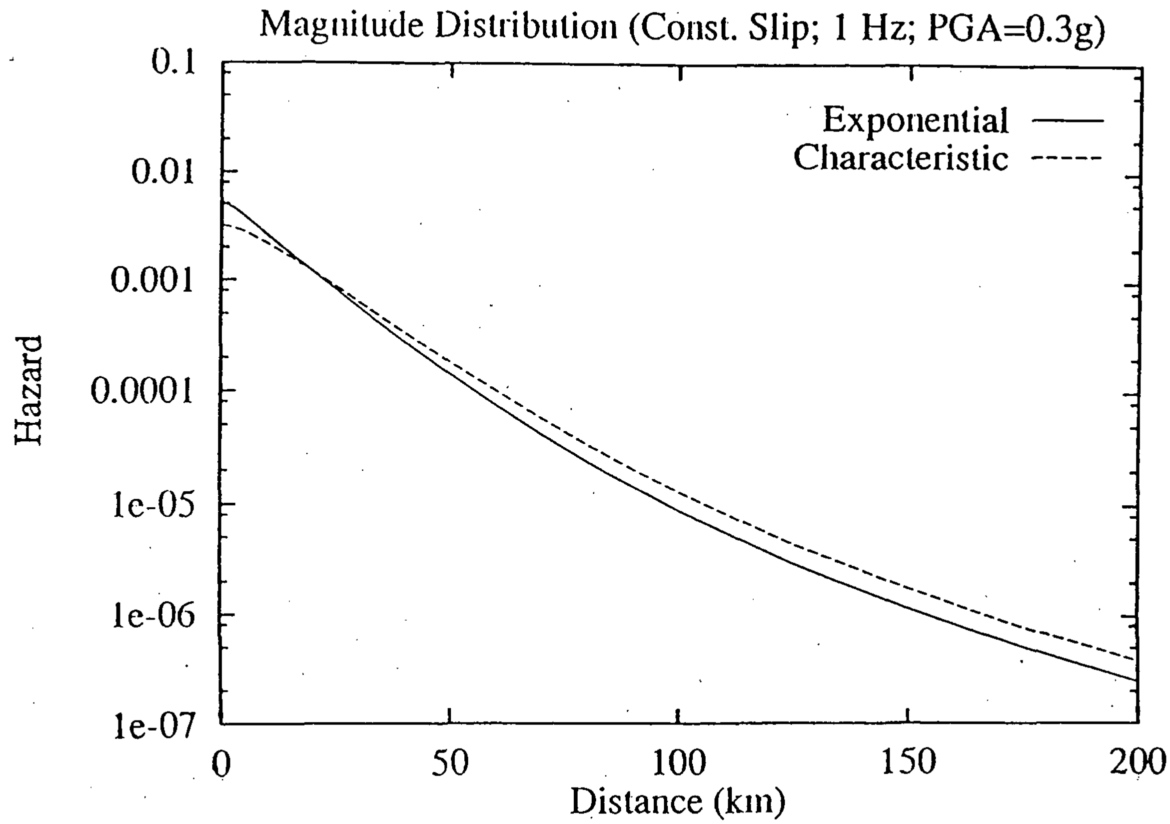


Figure G-36b. Sensitivity of 1 Hz hazard to depth distribution for PGA = 0.6g, Group C sites.



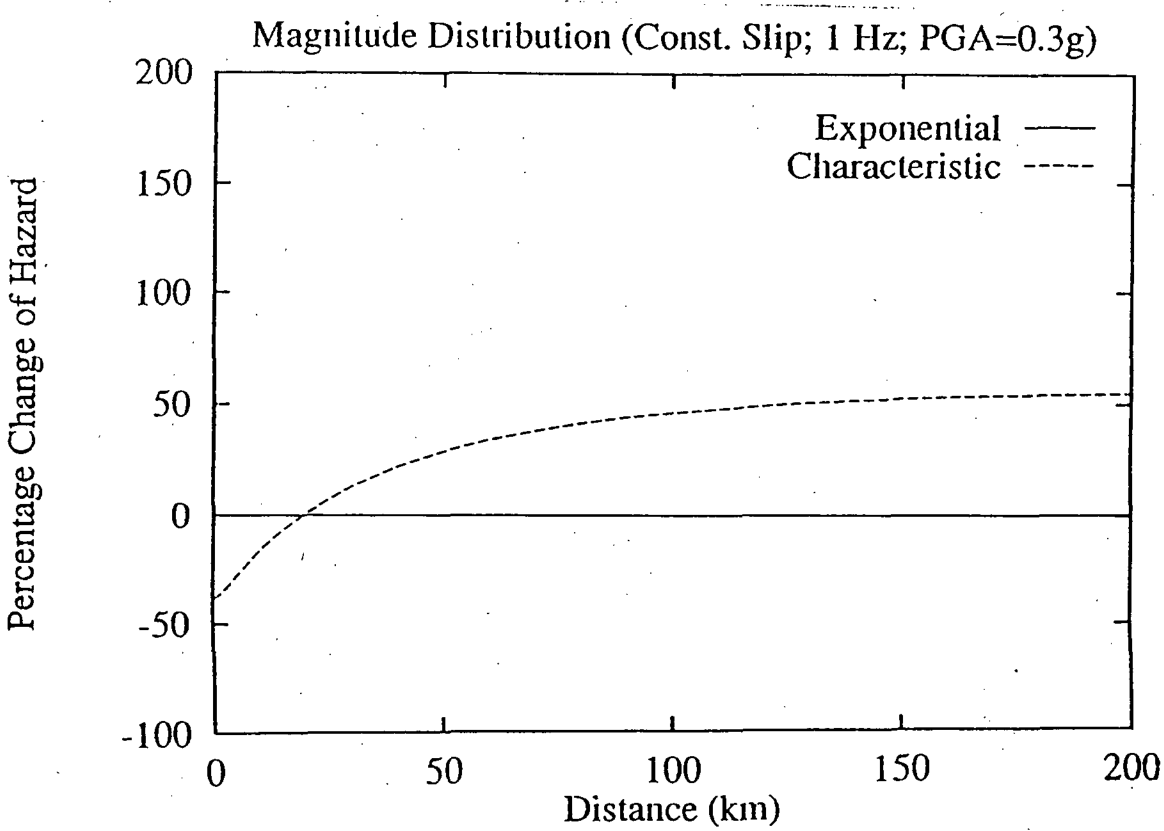
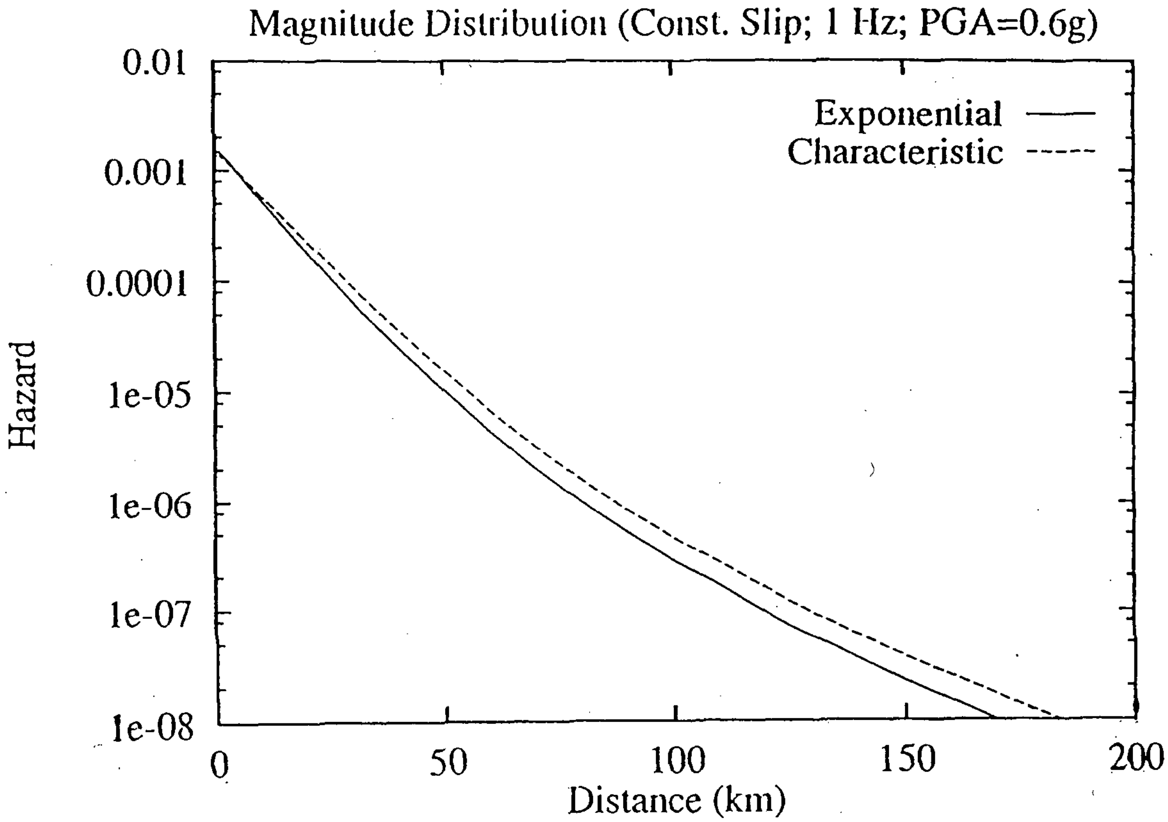


Figure G-37a. Sensitivity of 1 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.3g, Group C sites.



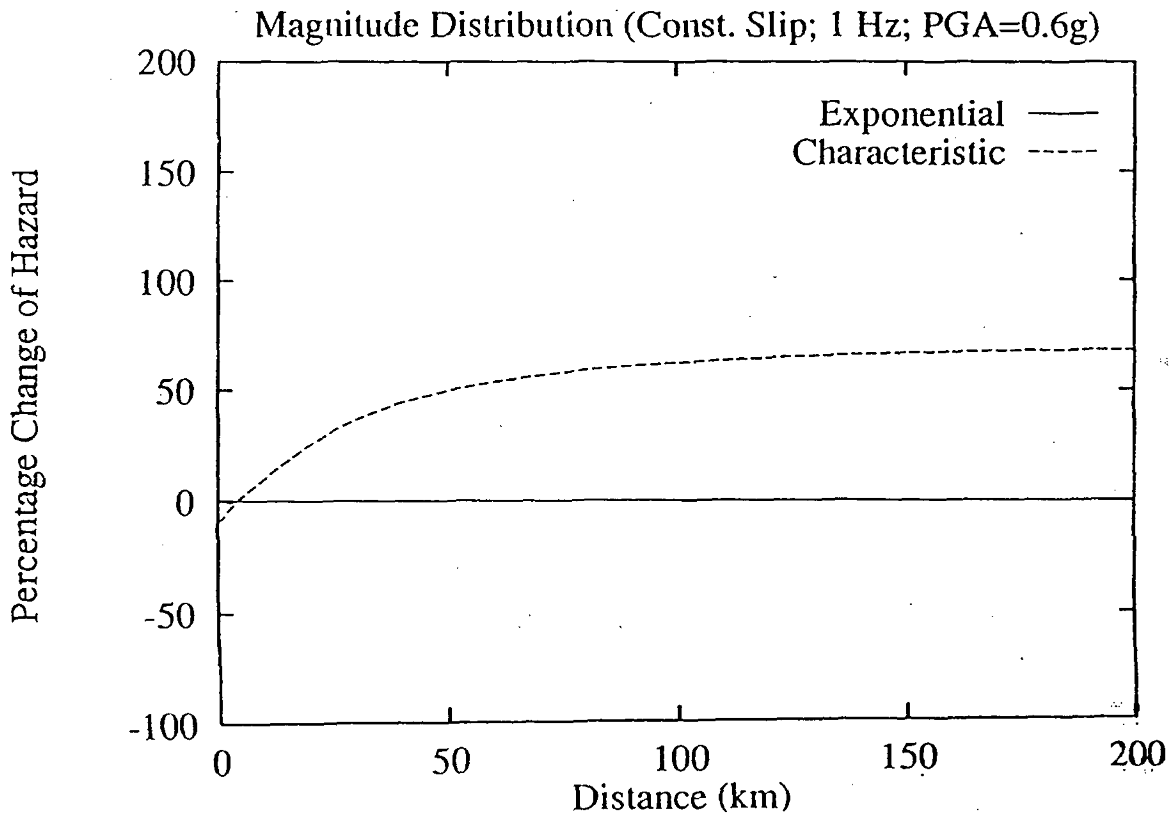
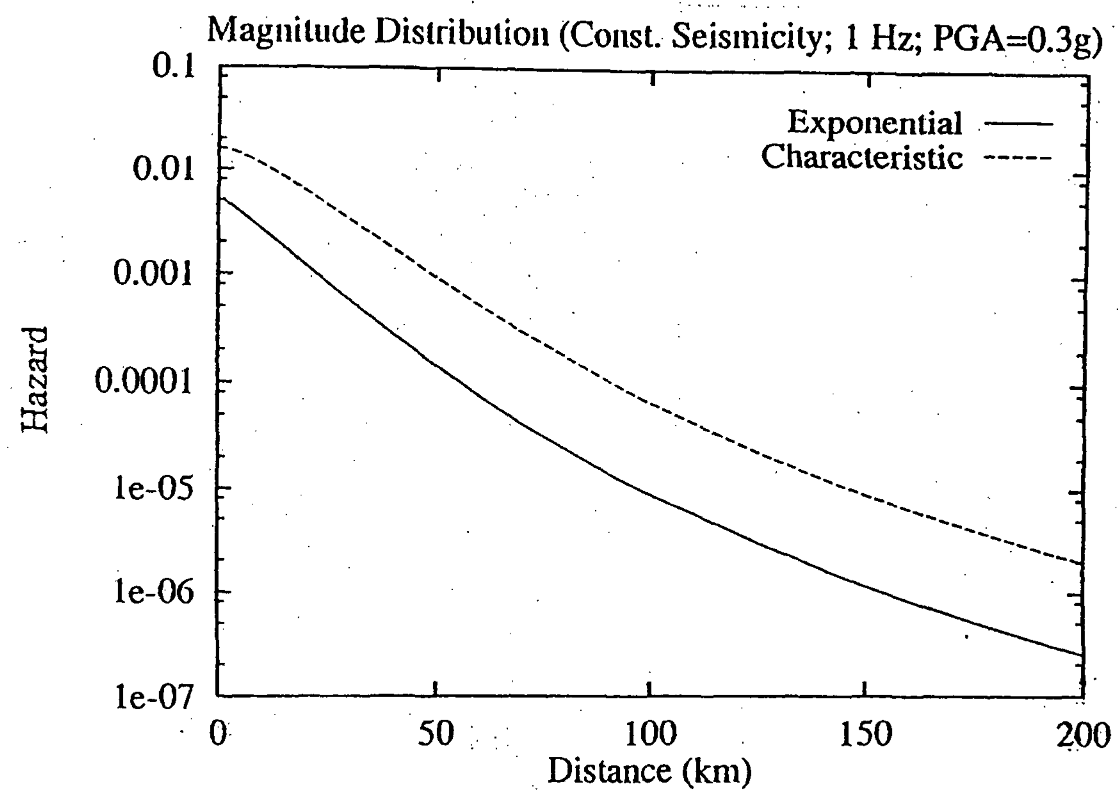


Figure G-37b. Sensitivity of 1 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.6g, Group C sites.



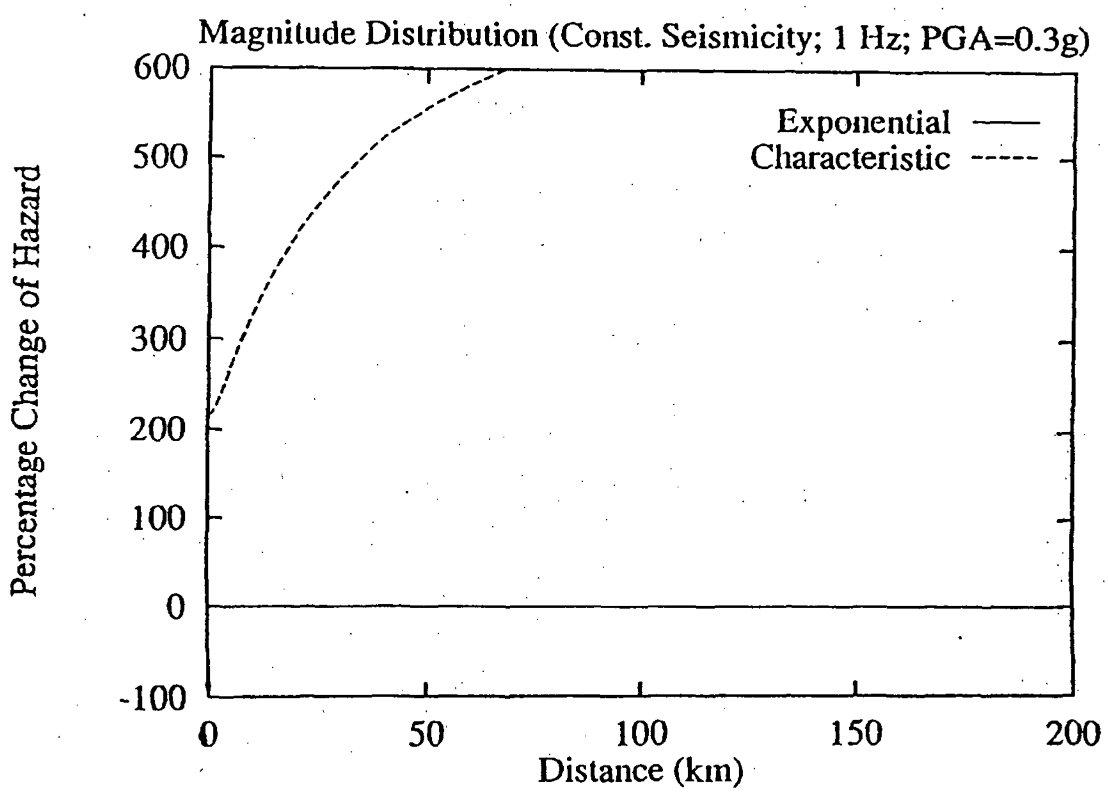


Figure G-38a. Sensitivity of 1 Hz hazard to magnitude distribution (with constant seismicity assumption), PGA = 0.3g, Group C sites.

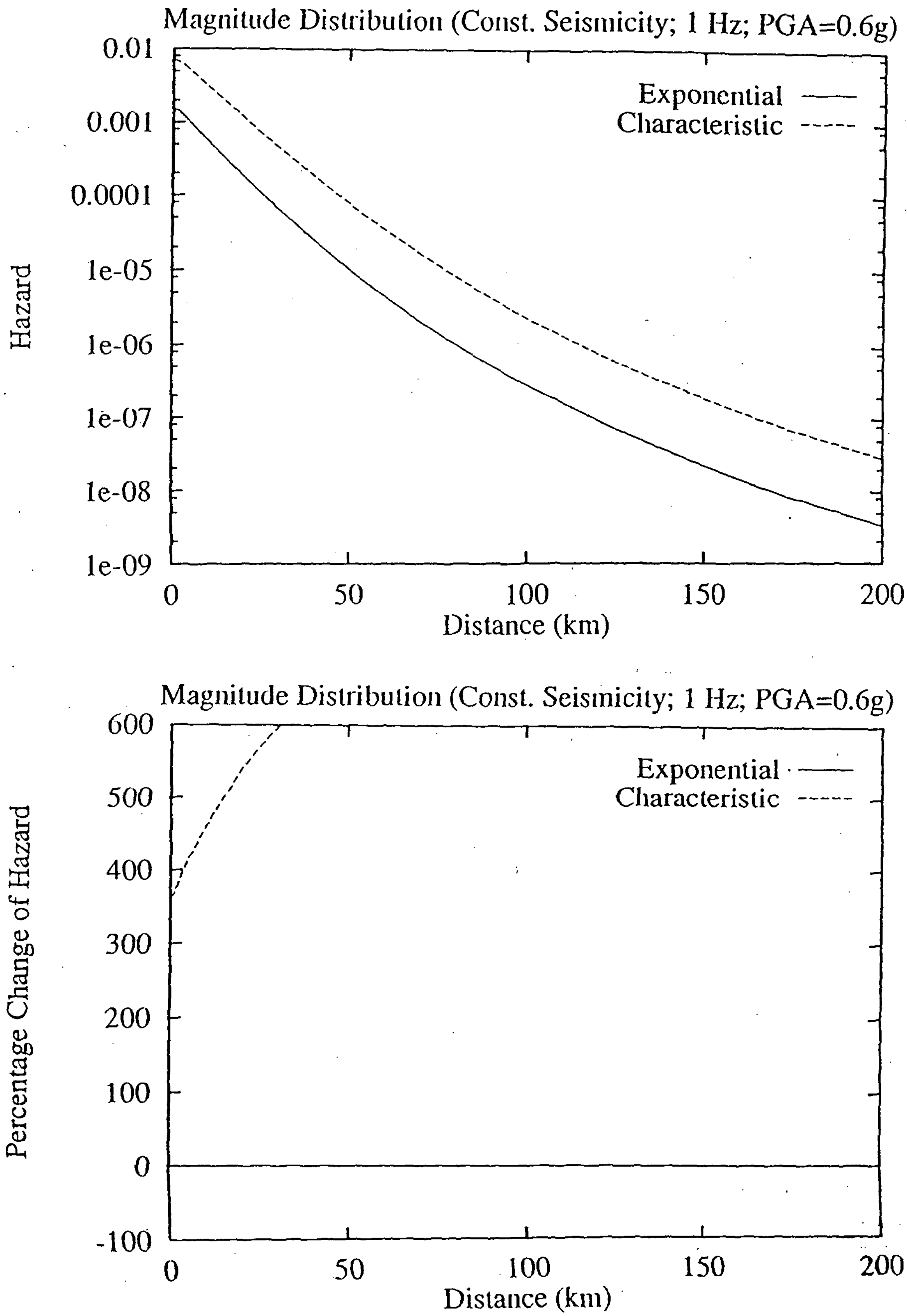
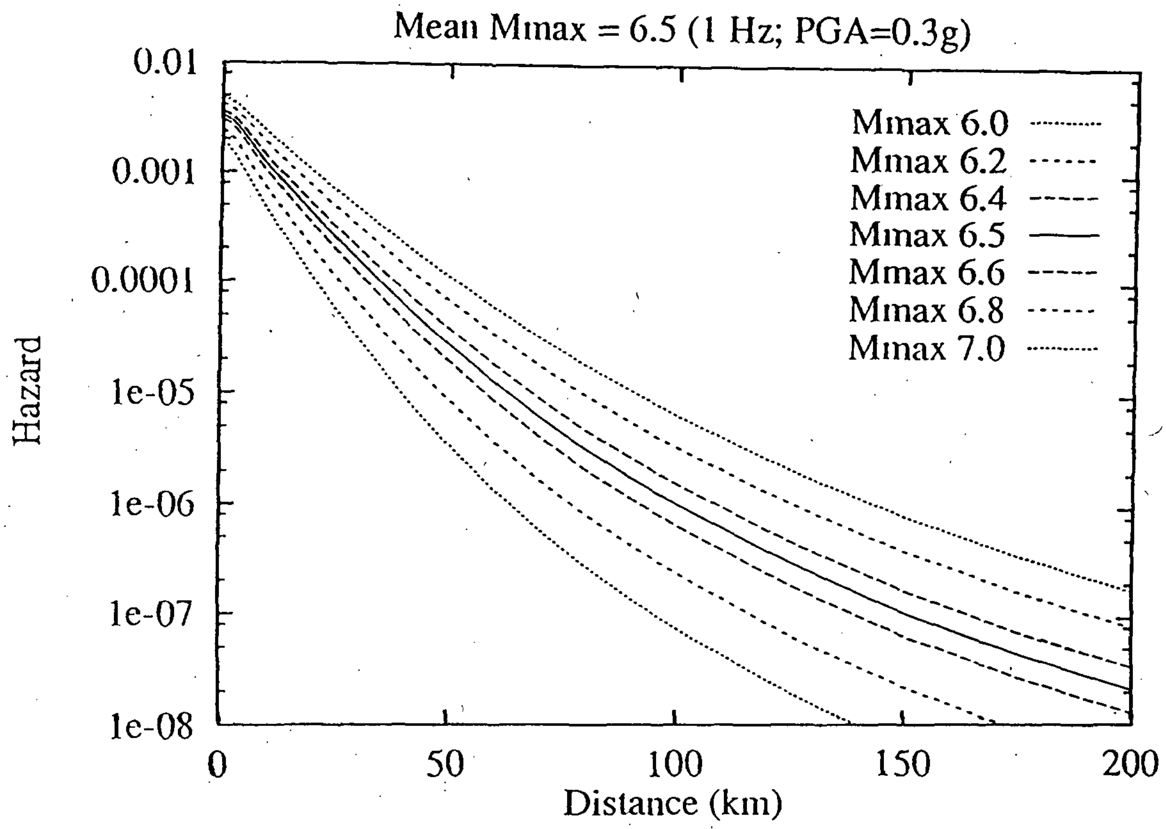


Figure G-38b. Sensitivity of 1 Hz hazard to magnitude distribution (with constant seismicity assumption), PGA = 0.6g, Group C sites.



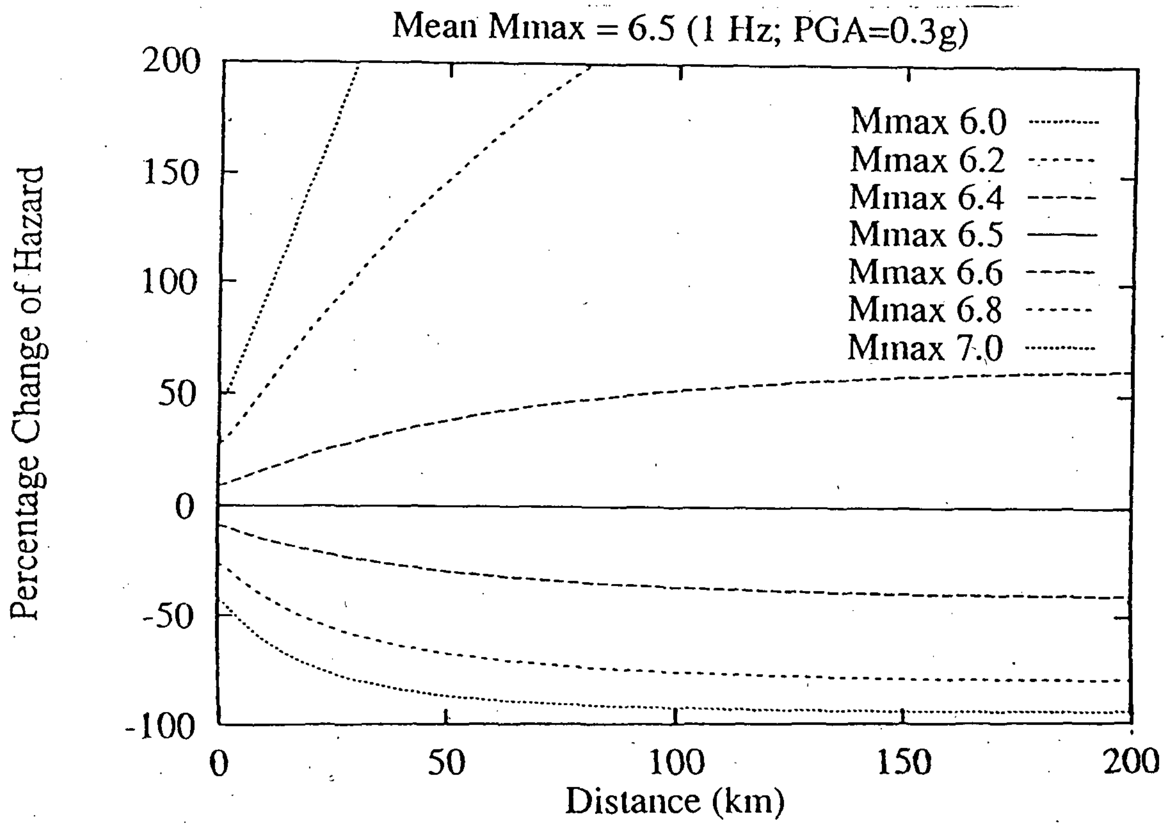


Figure G-39a. Sensitivity of 1 Hz hazard to m_{max} = 6.0, PGA = 0.3g, Group C sites.

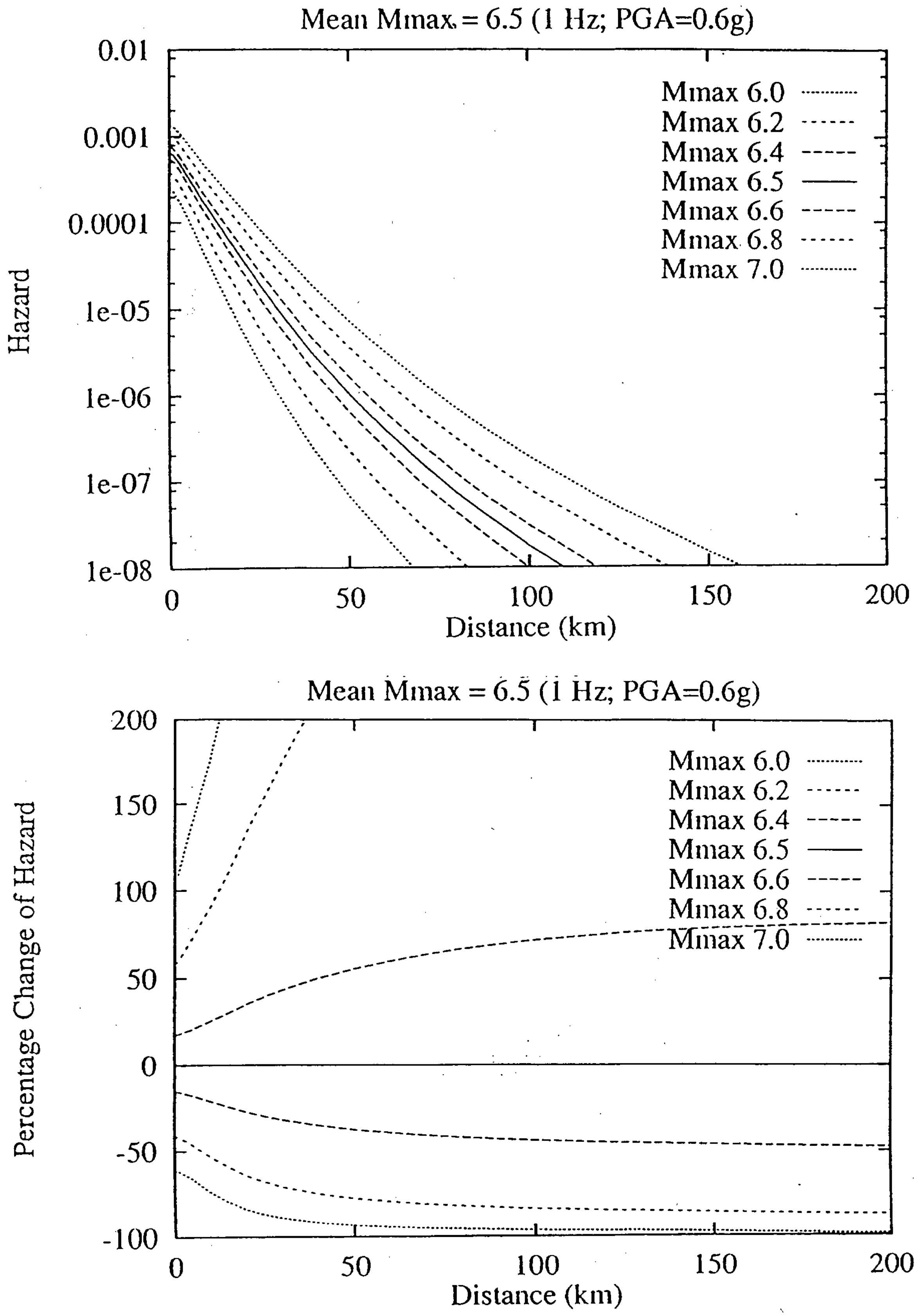
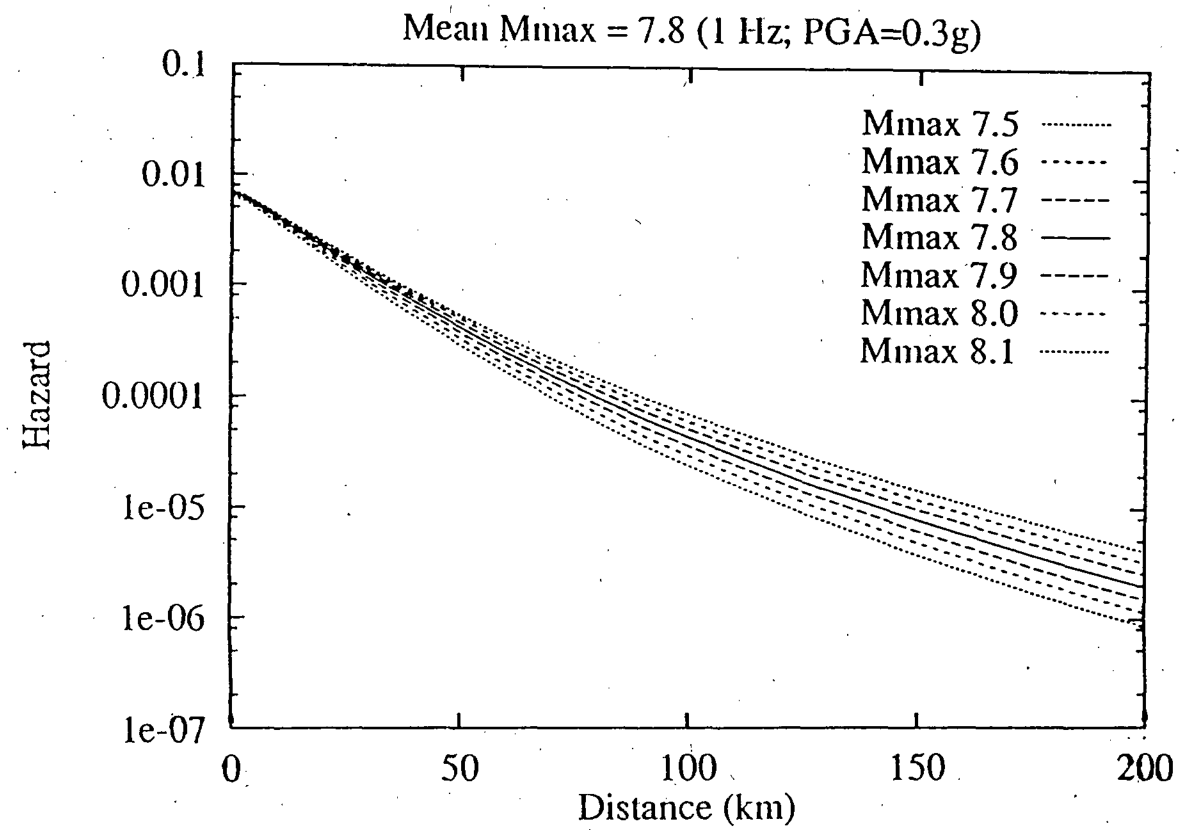


Figure G-39b. Sensitivity of 1 Hz hazard to m_{max} = 6.0, PGA = 0.6g, Group C sites.



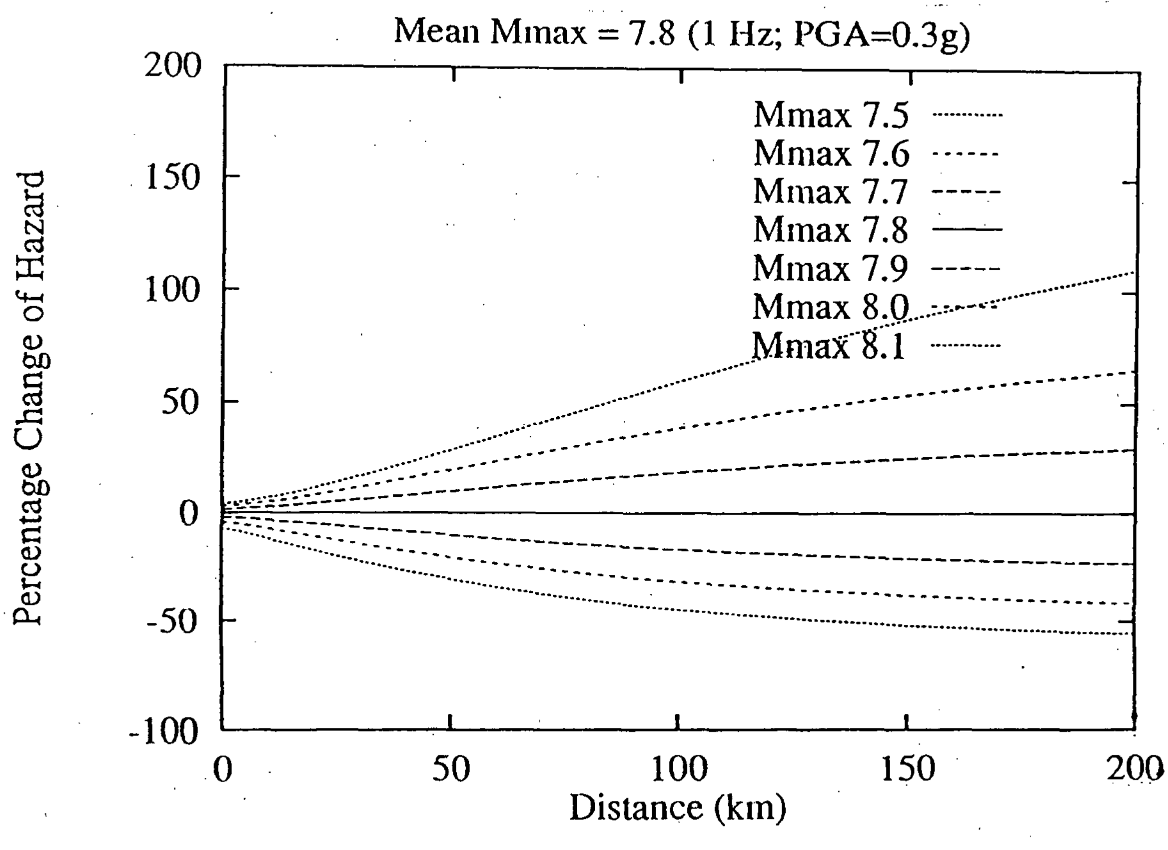
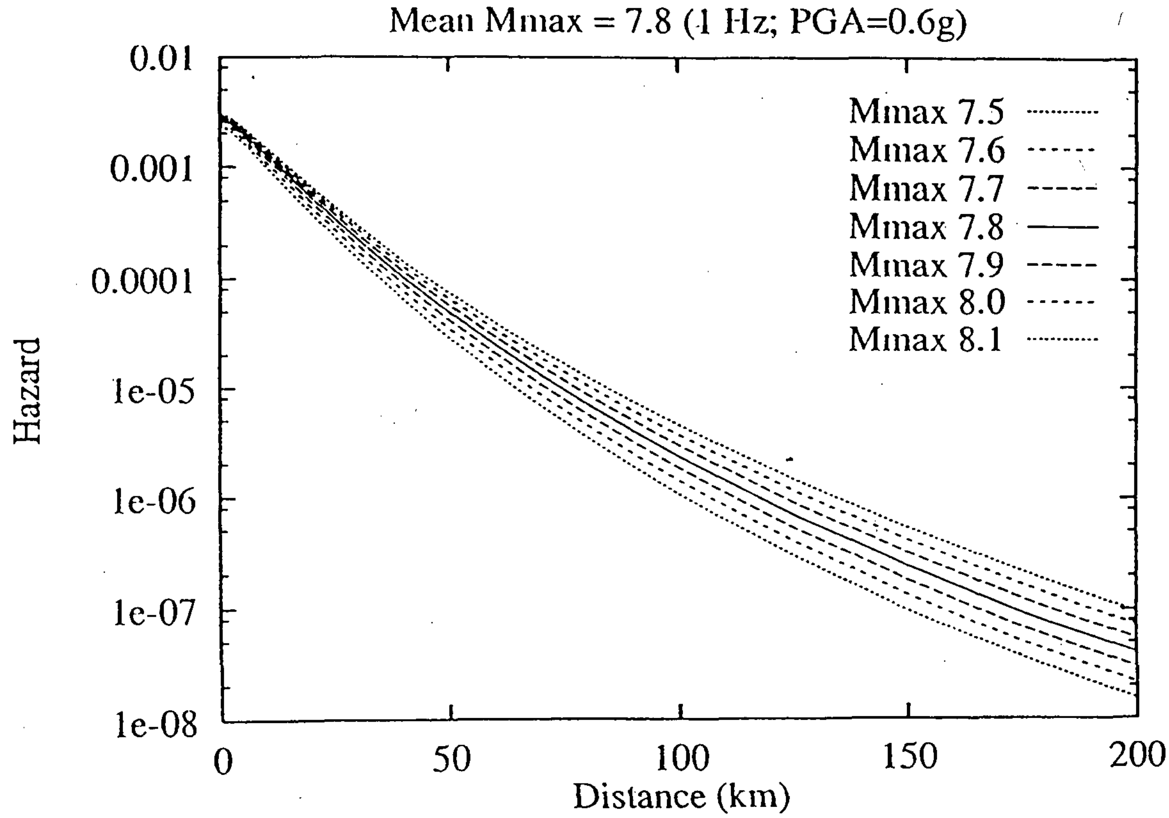


Figure G-40a. Sensitivity of 1 Hz hazard to m_{max} = 7.5, PGA = 0.3g, Group C sites.



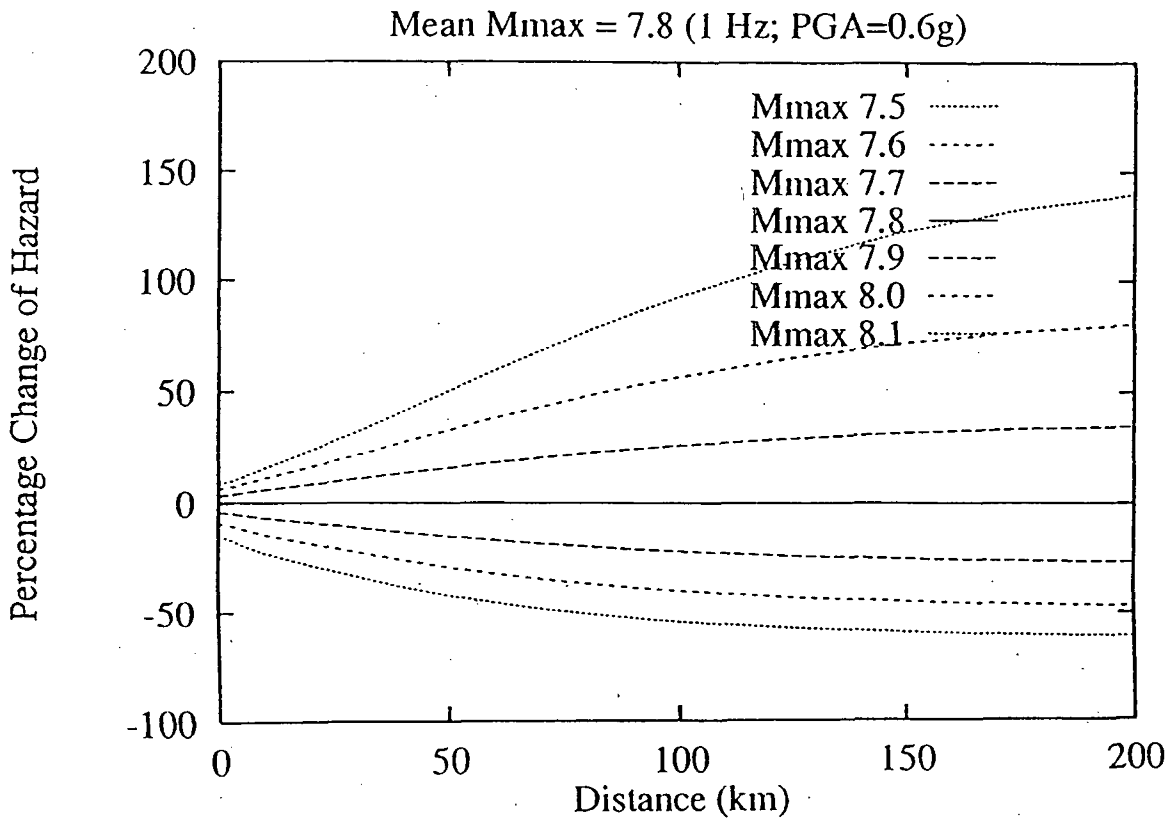
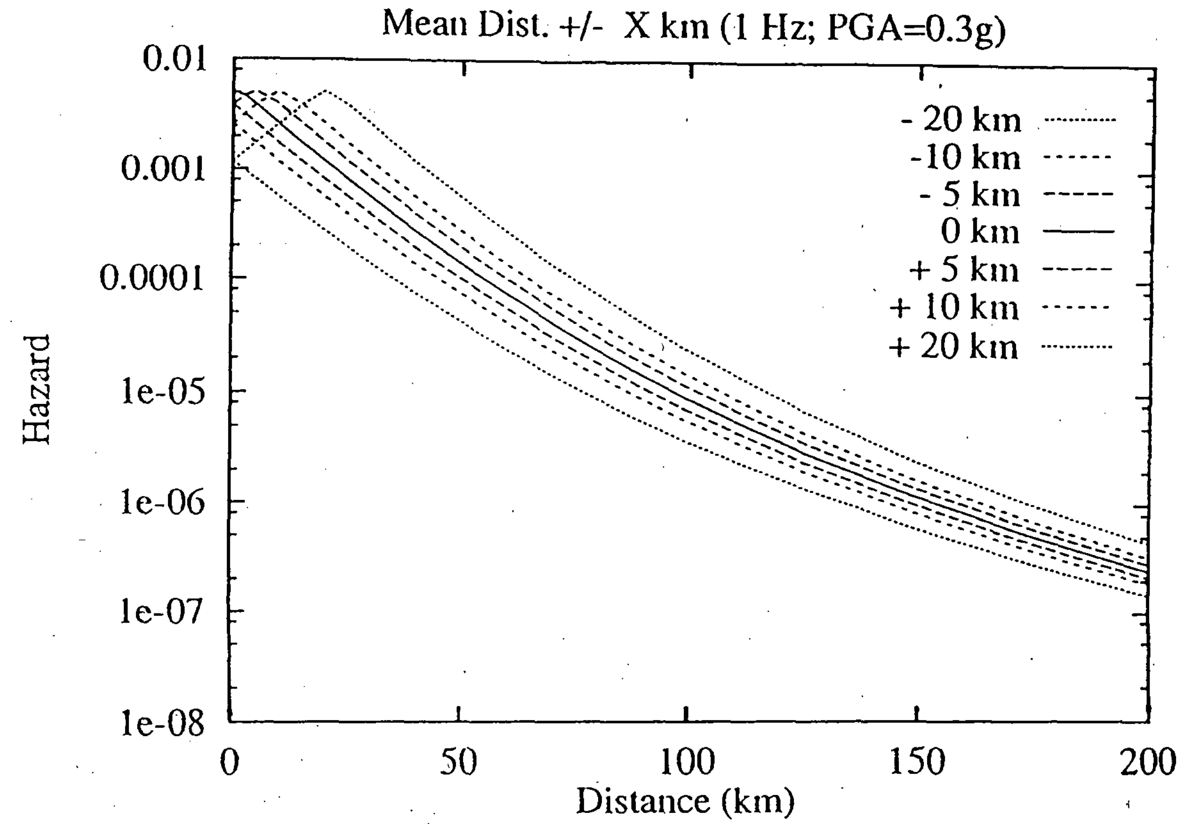


Figure G-40b. Sensitivity of 1 Hz hazard to m_{max} = 7.5, PGA = 0.6g, Group C sites.



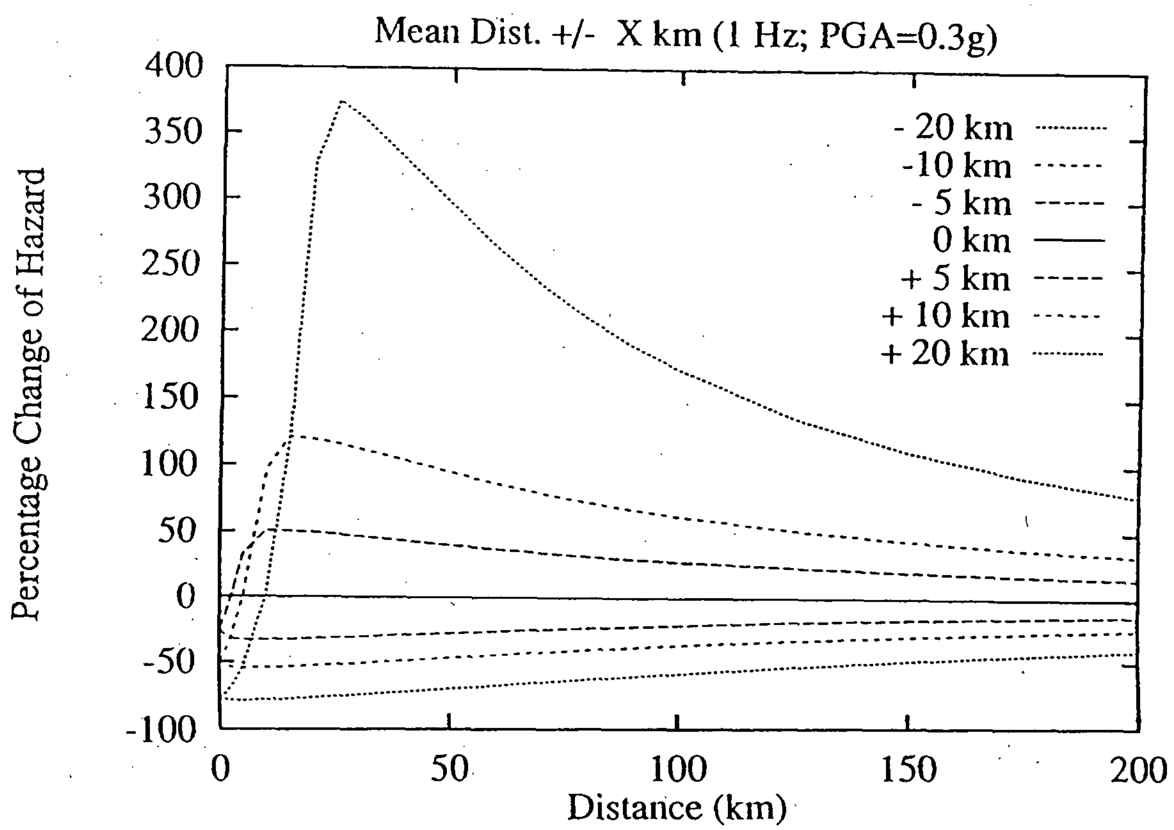


Figure G-41a. Sensitivity of 1 Hz hazard to distance from fault, PGA = 0.3g, Group C sites.

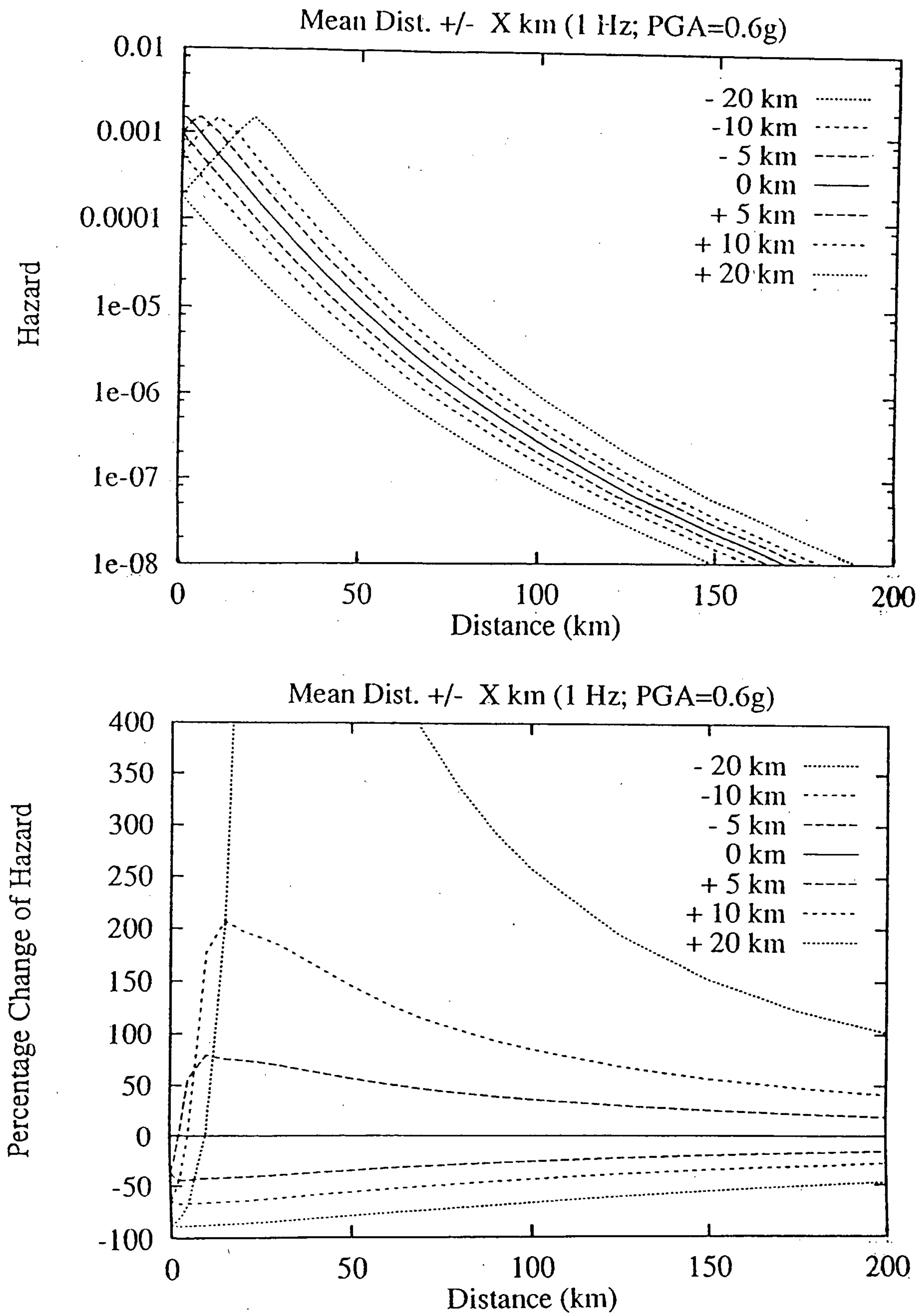


Figure G-41b. Sensitivity of 1 Hz hazard to distance from fault, PGA = 0.6g, Group C sites.

APPENDIX H

SEISMIC SOURCE CHARACTERIZATION WORKSHOP
JUNE 13-14, 1994
BOULDER, COLORADO

Purpose of the Workshop

SSHAC sponsored a two-day workshop with the following primary purpose: to gain first-hand information on what methods were successful and unsuccessful in eliciting seismic source characterization (SSC) information, from the perspectives of those SSC experts who were elicited. In addition, the experts were asked to give their personal reactions and recommendations to the approaches being contemplated by the SSHAC for eliciting SSC information (e.g., the role of the technical facilitator/integrator). Six experts with considerable experience in providing SSC information, primarily for eastern U.S. (EUS) sites but with some WUS experience as well, were selected for attendance at the workshop. Also in attendance were members of SSHAC's SSC Subcommittee and contractors for SSHAC (Apostolakis, Budnitz, Cluff, Cornell, McGuire, Bernreuter, Savy, and Mensing) and representatives of the sponsors (Bieniawski, Stepp, Schneider, and Zurflueh).

Although several workshops on the *technical (or substantive) issues* related to SSC have been conducted, this SSC workshop was the first time that specific focus has been given to *elicitation (or normative) issues* in the SSC domain. As such, the focus of the workshop was unique to the participants and, based on feedback from the experts, provided an incentive to examine methodology issues that they had not considered previously. For example, all of the experts have participated in technical workshops and, as active participants, have provided their scientific interpretations of the mechanisms for earthquakes in the EUS. In the SSC workshop they had an opportunity to discuss the value of such technical workshops and interactions in exchanging information prior to formal SSC elicitations. Further, they were asked to consider the scope of such interactions (i.e., should elicitations be conducted in a workshop setting), the focus and number of such interactions (e.g., identifying data needs, outlining alternative approaches, etc.), and the pros and cons of encouraging expert interaction prior to and following elicitations. Several topics were considered in the SSC workshop, such as the criteria and methods that should be used to select the experts, that many of the experts had not considered at all in the past.

The primary focus was on SSC assessments for the EUS, reflecting the make-up of the workshop participants. Further, the discussion centered around methodologies most appropriate for large, regional seismic hazard assessments, with lesser emphasis on site-specific studies or more modest studies.

Prior to the workshop, each expert was asked (via telephone) a series of questions about his experience and opinions regarding methodologies for eliciting SSC information. Based on these interviews, several key issues were identified for which there appeared to be either strong opinions or significant differences of opinion. These key issues provided the basis for the agenda for the meeting. The findings related to each of these issues is summarized below.

Use of Expert Teams vs. Individuals

The issue is the relative pros and cons of eliciting the judgments of experts as individuals or as multi-disciplinary teams. The experts were able to identify several advantages and disadvantages to either approach. For example:

Team Approach: Pros

- Can use multiple disciplines to deal with the range of technical SSC issues
- Provides for more interaction and sharing of knowledge among experts
- Ensures a higher energy level; less time commitment for individual members of the team
- Allows for individual lack of expertise in some areas

- Provides for challenge of ideas and lessens variance due to misunderstandings of evidence and misunderstandings of the issues

Team Approach: Cons

- Team may be subject to dominance by a single (outspoken) individual
- Can be expensive because it involves several people
- May lead to a more `homogenized' product (i.e., less total uncertainty) if there is a requirement for team consensus
- Result may be less defendable because there is no individual ownership

Individual Approach: Pros

- Less expensive and more straightforward
- Individual ownership/responsibility of the result (assuming waive anonymity)
- Not subject to the problems of group consensus and thereby may capture a wider diversity of interpretation

Individual Approach: Cons

- Most individuals are limited in their expertise and may run out of endurance
- Must ensure that all individuals have data available
- Must be coupled with workshops or other interactions to provide for exchange and challenge of ideas

The general conclusion in light of these pros and cons seems to be that either approach is acceptable. All of the experts emphasized that SSC is multidisciplinary and requires the infusion of a wide range of technical expertise. By their nature, teams can span the needed range of expertise, but have some disadvantages as noted above. The individual approach can work provided that there is a concerted effort to provide each expert with the means of spanning the range of disciplines himself. It was suggested by some experts that future hazard studies should attempt to capture the advantages of both approaches by, for example, allowing the experts to work as small teams during the project (e.g., identifying data needs, forming interpretations, etc.) and then eliciting each individual separately. Another alternative might be to have a team of technical experts that serves as a resource to each individual expert to provide data, discuss interpretations, etc.

Interactions Among Experts

This issue is the amount and frequency of interactions among SSC experts in forums such as workshops or smaller working meetings. All of the experts strongly endorsed having multiple interactions during the SSC process: early on to identify data needs, during the process to discuss data interpretations and models, and following the elicitations to discuss the interpretations prior to hazard calculations. The workshops and meetings serve several purposes such as educating the experts on the available data and tectonic interpretations, deciding on what are the important technical issues and which issues are addressable, identifying methods and procedures for evaluating SSC characteristics, and reviewing and challenging alternative interpretations. Many of the experts felt that a workshop *following* the elicitations would provide a valuable opportunity to review each expert's interpretations and uncertainties, and would provide a final opportunity for the expert to make changes prior to the hazard calculations. Another valuable purpose of workshops is to train the experts in the methods that would be used to elicit their judgments and subjective probabilities. It was also noted that workshops can provide an opportunity for observers (e.g., regulatory representatives or sponsors) to witness and understand the process.

Each expert cited experience with both beneficial and worthless workshops and provided the following advice:

- Provide for plenty of time to plan and set the agenda for the workshop

- Assign responsibilities to participants well in advance of the meeting and ensure that participants are prepared and aware of their position within the overall agenda

- Strike a balance between tight control of the progress of the meeting and allowing for a free exchange of ideas by all participants

- Provide written material to participants in advance of the meeting.

It was suggested that, because it is often difficult to schedule workshops such that active participation in ensured, perhaps an SSC "camp" at a remote location lasting several days would be an effective way to promote mutual education (both seismotectonic and probability training) and exchange of ideas.

Most experts felt that a workshop setting was not appropriate for conducting elicitations, but could be an opportunity to provide a demonstration of elicitation procedures through some example assessments using a "model team".

Role of the Technical Facilitator/Integrator (TFI) Team

The issue is the "strength" of the TFI relative to the experts, ranging from a strong role (TFI runs the project, integrates the results, and takes responsibility for the results) to a weak role (TFI organizes logistics, combines expert assessments, but the experts take responsibility for the results). Because the TFI issue is complex and multi-faceted (e.g., management of the project, aggregation, ownership for the product, etc.), the responses from the experts were varied. Here we consider the role of the TFI in organizing and leading the project and in conducting the expert elicitations. The role of the TFI relative to integration or aggregation is considered separately below.

The TFI should be a team of 2-3 individuals knowledgeable in SSC as well as elicitation issues. It was generally agreed that the TFI team should have a strong technical background and standing in the SSC community. This would provide for the proper focus in group interactions and in the elicitations. At workshops and other meetings, the

TFI should be proactive and keep the discussions on track, but should not impose its own technical interpretations on the group. The TFI should attempt to draw out all participants' views to ensure that a balanced spectrum of technical interpretations is discussed. Another important responsibility of the TFI is to focus the free discussion of technical issues toward those issues of greatest significance to the hazard results. These issues may not be intuitively obvious to many of the experts at a workshop. For example, considerable discussion could ensue regarding recent paleoseismic evidence for the occurrence of large-magnitude earthquakes at a location at a large distance from a site of interest. The TFI should remind the experts that the importance of the new findings would revolve around their possible implications to the characteristics of seismic sources closer to the site.

The experts felt that the role of the TFI in the elicitations was crucial. (In the discussion, it was assumed that the elicitations would occur as individual interviews, perhaps followed by additional work by the expert to complete the assessment). In this format it was felt that the SSC expert within the TFI team should take the lead in asking the questions and documenting the responses. The normative expert on the TFI team should also be present in the elicitation to help with the quantification of uncertainty using subjective probabilities.

Elicitation Approaches

The issue is the means by which experts are elicited and their judgments documented. Issues discussed relate to the basic format to the elicitations, the nature of the information elicited (e.g., specify parameters or methods for calculating parameters), and the pitfalls to avoid in making the elicitations.

The elicitation should be viewed as only one step in a larger process that prepares and educates the expert for the assessment. Basic elements of the SSC elicitation process are the following:

- Identify technical issues and data bases
- Provide all data to experts
- Conduct multiple workshops/meetings for exchange of data, interpretations, probability training, etc.

- Conduct elicitations
- Discuss results, uncertainties, implications, feedback
- Finalize interpretations

In this context, the actual elicitation occurs late in the process, thus taking advantage of the information exchange that has occurred. The preferred approach to eliciting SSC information is through "one-on-one" interviews with each expert and the TFI team present. Written questionnaires, without extensive follow-up and discussion, were not viewed as appropriate. It was suggested that written questionnaires might be provided prior to interviews to help focus the elicitation. Further, the exact questions to be asked could be formulated by the experts and TFI jointly at a workshop, thus limiting the possibilities for misunderstandings. In the elicitations, every effort should be made to avoid bias in the questioning, to probe for the technical basis for the interpretations, and to maintain flexibility such that a variety of approaches could be used by experts to arrive at their interpretations.

Documentation of the elicitations is essential to the credibility of the assessment and should include the expert's assessments of SSC characteristics, the uncertainties associated with the characteristics, and the technical basis for the assessment. Documentation can be accomplished in different ways. The TFI can prepare a written record of the elicitation during the interview and provide it to the expert for his review and approval following the elicitation. The experts can themselves prepare a written summary of their assessment prior to or following the elicitation session. Experience has shown that the former approach, which places the logistical burden on the TFI and the technical burden on the expert, is most effective in maintaining the pace of a seismic hazard analysis.

More specifically, the experts also were asked to give their opinions regarding the manner in which SSC information should be elicited from them and their level of comfort for different techniques. For example, the experts were asked whether they felt more comfortable providing their own *parameter values* or specifying a *methodology* for calculating parameter values (and allowing the TFI to calculate the values). The answers to this question were mixed; some experts prefer to do the calculations themselves, while others feel comfortable selecting methodologies and examining the calculated results. It was noted that their preference could be related to the amount of time and resources provided to the experts to do their own calculations. Another question was asked regarding a preference for expressing parameter uncertainties as continuous probability distributions or as discrete values with weights. Again, the response was mixed and expressed personal preferences. In cases where continuous distributions are provided, there was strong sentiment to provide very simple representations (e.g., triangular distributions) and not to be forced to quantify the extreme tails of the distribution. It was felt that the present level of knowledge about SSC parameters is not sufficient to provide a reasonable `level of comfort' in expressing these tails.

Number of Experts and Technical Support

The issues here are the optimal number of SSC experts that might be required for a seismic hazard analysis and the level of technical support that should be provided. As discussed below in the context of aggregation, the criteria and process for selecting the experts were considered to be very important as well. In general, the experts felt that the number of experts cannot be rigidly defined but should, in any case, be sufficient to span the full range and diversity of interpretations. This can vary by whether the seismic hazard analysis is being conducted for a large region (whereby the range of geographic expertise may require more experts) versus a site-specific evaluation (whereby few experts may actually exist). A related issue is the amount and quality of data that have been gathered for the SSC assessment (e.g., a site-specific analysis for which there exists a site-specific data base may require fewer experts to interpret the data for SSC purposes).

In addition to the experts whose judgments are elicited, it is also desirable to involve technical specialists as resources. The specialists can make technical presentations at workshops and participate in interactions regarding new data, interpretations, etc. The experts recognized that the involvement of these specialists can be expensive, but they also expressed a comfort level that is reached when scientific researchers summarize their most recent findings to the experts prior to their formulating their SSC interpretations. As an example, a geologist conducting paleoseismic investigations at a particular location in the EUS could summarize his findings at a workshop devoted to methods for assessing earthquake recurrence. Through discussions with the specialist, the SSC experts would be brought up to date with the latest findings and could ask specific questions that relate to the uncertainties and degree of confidence that the researcher places in the results.

Availability of Data Bases

The issue is the degree to which SSC-related data bases should be made available to the experts and, if so, the format of those data. All of the experts concluded that any seismic hazard analysis should strive to make data available to the SSC experts. It is recognized that for more modest studies, it may only be possible to compile existing data (e.g., reprints of published articles). Nevertheless, every effort should be made to get a uniform data base to all of the experts so that differences in SSC interpretations are due to true differences in interpretation and not due to differences in available data. It is also recognized that regional studies may require different data sets (e.g., regional earthquake catalogs) than site-specific studies (e.g., regional seismic network data). In all cases, the project should attempt to provide the data in a format that the experts are most comfortable with. An example was given that reams of computer output listing historical earthquakes is often not a useful way of providing catalog data. Early in the project, preferably at a workshop devoted to data needs, the experts can identify the key data bases that will be needed to address important SSC issues. This is also an opportunity to specify data formats and any data processing that the experts may request to have carried out for them.

Most of the experts agreed that the earth sciences are entering a new era of data and information exchange that can radically improve the problem of dissemination and formatting of multiple SSC-related databases. For example, many data sets such as earthquake catalogs and geophysical data are amenable to compilation on Geographic Information Systems (GIS). Because GIS-type formats allow for variable representations of the data (e.g., map scales can be specified by each user), they can be very useful for the experts. An additional need is the ability to have the data bases in a form that is interactive, such that they can be searched, processed, or otherwise interpreted. Electronic mail systems such as the Internet and data provided on CD-ROM are becoming highly efficient vehicles for transferring large databases at reasonable cost and should be considered for future SSC studies.

Some experts expressed a desire that, because of improved efficiencies in the compilation and transfer of data, *both* unprocessed and, where appropriate, processed data should be provided to the experts. The procedures used in data processing should be explained fully to the experts. Examples given were geophysical data where various types of frequency filtering may be accomplished, and earthquake catalogs where corrections to earthquake magnitudes may be carried out.

Seismic Source Maps

The issue is the technical basis for defining seismic sources, the usefulness of allowing seismicity parameters to vary within a zone, and the possibility that `consensus' seismic source maps might be developed. It was agreed by all of the experts that the process of identifying the geometry of seismic sources (particularly in the EUS) is highly interpretive and subject to the criteria each expert feels are most appropriate. The experts cited a wide range of data that they use to interpret seismic sources, including: historical seismicity data, paleoseismic data, geophysical anomalies, tectonic maps showing faults and other evidence for deformation, presence of inferred or observed geologic features that serve as stress concentrators such as fault intersections and rifts, geomorphic anomalies, GPS (global positioning system) and geodetic measurements of crustal strain, plate tectonic models, etc.

It was emphasized that a clear definition should be provided (presumably by the expert defining his/her sources) as to what criteria are being used. For many experts, the principal criterion for deciding whether or not a seismic source boundary is required is the assessment of whether there is a change in the maximum earthquake magnitude (Mmax) from one region to another. Inasmuch as changes in, say, the tectonics from one region to another might lead to a change in Mmax, the tectonics can then be used to help define seismic source boundaries. Some experts would use a criterion of significant changes in any of the seismicity parameters (i.e., a, b, or Mmax). In these cases it would be useful to provide to the experts a map of the a and b-values across a region, say for one-degree cells, as a help in defining source boundaries. Most experts felt that the SSC methodology should have the flexibility to allow for variation of a and b-values within a given seismic source, with variable degrees of smoothing of the parameters.

Some recent reviews of probabilistic seismic hazard analysis have criticized the procedure as poorly constrained, citing the wide variation in seismic source geometries in the EUS as symptomatic of the lack of any clear understanding of earthquake processes in this region. A possible mechanism for dealing with the issue might be to develop a single `consensus' map (or a small number of maps) that either represents a single interpretation that all experts can agree upon or that represents an integration of individual maps developed by experts. This concept was explored at the workshop. The general conclusion was that, at the present time, our understanding of earthquake sources in the EUS is not sufficient to allow for the development of such a map. It was noted that in more active tectonic environments, such as coastal California, single seismic source maps were feasible. But even here uncertainties in the locations of buried or blind faults, and sources having uncertain activity such as the Cascadia subduction zone, would lead to different interpretations.

Likewise, it was concluded that there is no efficient way to "mechanically integrate" alternative seismic source maps to arrive at a single map (noting, of course, that the seismic hazard analysis in fact integrates the maps at the ground motion level). The reason for the different source configurations is, in fact, different scientific interpretations of what controls the spatial distribution of future seismicity. In most cases, the pattern of observed seismicity has a strong influence on the shape of seismic sources. However, tectonic information is also believed to be important and subject to variable interpretations. The method used in the EPRI study whereby individual tectonic features were evaluated for their probability of activity was cited as an effective procedure for encouraging experts to make explicit their consideration of tectonic information. It was concluded that each expert should attempt to document the technical basis for each seismic source and the criteria and data that were used, and that flexibility in the methodology should be maintained such that variations in seismicity parameters within a given seismic source can be allowed.

The experts expressed variable preference for quantifying their uncertainties in seismic source interpretations by either: specifying alternative source boundaries each with an associated weight, or specifying global alternative maps for a region each with an associated weight. Both approaches appear to be effective at quantifying the uncertainties in source geometries for regional seismic hazard studies.

Seismicity Parameter Assessments and Feedback

The issue is the procedure for eliciting seismicity parameters (a,b, Mmax) and the types of feedback and sensitivity analyses that should be provided to the experts to assist in their assessments.

When asked about the methods for assessing earthquake recurrence, the experts noted that the primary data base for the assessment is the historical earthquake record. Because of its importance, the need to process the catalog for recurrence evaluation carefully was discussed, including uniform identification of earthquake magnitudes, catalog completeness, removal of dependent events, etc. It was noted that paleoseismicity data, although only available at a few localities in the EUS, can be extremely important in establishing the recurrence rate of large, damaging earthquakes. Likewise, fault slip rate data, if available, provide a possible constraint. Many of the experts felt that the installation of a wide-scale geodetic network (GPS) system in the U.S. will eventually allow the use of crustal strain data to characterize recurrence rates within the more active portions of the EUS.

In terms of recurrence parameter assessments, the experts expressed different preferences for assessments of a-values and b-values (and their correlation) or assessments of recurrence intervals for particular earthquake magnitudes. It was concluded that both procedures should be made available to the experts and, after application of one approach by the expert, the alternative approach might be applied to provide a `check.' For example, the expert might specify his ranges of a-values and b-values and their correlation for a particular seismic source; the implied mean recurrence intervals for, say, moderate and large-magnitude earthquakes could then be calculated and provided to the expert as a check for consistency. In terms of recurrence parameters, some experts expressed a desire to do the calculations of the parameters themselves from the earthquake catalog; others would rather specify a methodology for calculation and allow the TFI to calculate the parameters, which they would then review. As noted previously, the experts felt that allowing for variations in a-values and b-values within a seismic source was an attractive option. No one felt that it was necessary to allow for variations in Mmax within a seismic source, and some felt that this would violate their basic definition of a seismic source.

Methods for assessing Mmax in the EUS are variable and rely heavily on expert judgment. Cited factors to consider when assessing Mmax for a seismic source include: historical seismicity, paleoseismicity including geomorphic evidence, dimensions of the source or tectonic feature, the 1,000-year earthquake magnitude, the type of tectonic feature or crust (e.g., rifts versus craton), and analogies to similar tectonic environments. An inherent difficulty in the assessment of Mmax is that it is intended in the hazard analysis to be the maximum *possible* earthquake (i.e., the upper-bound truncation of the recurrence curve) and not an earthquake having a particular recurrence interval. It was noted that extensive research on the EUS maximum magnitude problem will be published by EPRI in the near future and should help in the assessments.

There was discussion of the types of feedback and sensitivity analyses that could be provided to the experts to help in their assessments. Most of these relate to providing a comparison of the assessed or `predicted' recurrence rates for a seismic source with the observed or historical seismicity. Although none of the experts felt that the predicted rates *must* match the observed rates, particularly given the usually inadequate number of observed events, any significant deviations from the observed rates should be fully understood and explained by the expert. Typical feedbacks might include a comparison of the predicted rates (including uncertainties) with the observed rates calculated over different subsets of the total seismicity catalog (e.g., the instrumental period, the historical period, different completeness periods, etc.). One expert suggested that perhaps a `predicted seismicity map' might be constructed for a region based on the assessed recurrence parameters; this map could then be compared with the observed seismicity map. In addition, it could be useful to see how different assumptions about recurrence parameters (say, variations in b-values) might affect the implied recurrence intervals for large-magnitude events in a region. This result might then be compared with paleoseismic recurrence intervals in the same region or with observed strain rates or seismic moment rates. Finally, it was suggested that it would also be helpful to see, for particular sites where seismic hazard is calculated, the degree of sensitivity that the calculated hazard has to variations in recurrence parameters.

Aggregation of SSC Assessments

The issue is the manner in which the individual assessments provided by multiple experts should be combined in order to calculate the seismic hazard. The active discussions covered such issues as applying weights and who does so, dealing with uneven expertise, component-level aggregation, and the role of expert interaction in achieving aggregation. Strong opinions were voiced on this subject and the salient conclusions are summarized below.

By their very nature, individual SSC assessments are difficult to combine. This is because the process begins with seismic source maps, which for the EUS are likely to be different. Then, because all of the subsequent parameters relate to the seismic sources identified initially, there is no easy way to compare or combine the interpretations expert to expert. As discussed above, consideration was given at the workshop to the prospect for developing consensus source maps or mechanically integrating alternative source maps, with the conclusion that such was not possible with some limited exceptions. Exceptions might include active portions of the WUS, very active sources in the EUS (e.g., the configuration of the New Madrid seismic source may be similar among multiple experts), and local site-specific hazard analyses where a very limited number of sources are being considered. Consequently, the potential for component-level aggregation at the seismic source level or recurrence parameters for particular sources is generally not possible. We are therefore left with the need to aggregate the SSC interpretations at the final level of the seismic hazard calculations. What rule, then, should be used to integrate the `entire' SSC assessments for each expert at the hazard level?

Most of the experts expressed the need (or requirement) to combine the SSC assessments using equal weights from expert to expert. Those expressing a desire or allowance for differential weights provided alternative mechanisms for doing so. One possibility is to allow for the experts to give themselves a relative weight that, in particular, might provide for a downweighting in a geographical area or discipline that is outside of the expertise of the expert. Importantly, this would not be a weight relative to the other experts but would be on a rating scale (of, say, 0 to 5) expressing the degree of expertise that the individual possesses in that area or discipline. Another alternative for differential weights might be to allow an independent panel to evaluate the experts on the basis of their `total performance' on the SSC assessment. This evaluation would not be of the experts' reputations or standing in the community, but of their input to the particular project in question. Finally, a provision could be made to allow for the TFI, an independent panel, or perhaps the expert himself/herself to assign zero weight to the assessment in those cases where the expert simply was not able to perform satisfactorily on the project (this could be due to a lack of motivation, unforeseen time constraints that prevented proper preparation, or expertise wholly outside of the realm of SSC).

Although variable degrees of adamancy existed, there was general consensus that the *goal* of the integration process, from the very start of the project, should be to assign equal weights to SSC expert assessments and to be in a strong, defensible position to do so at the end of the project. Several mechanisms were discussed that would provide for this outcome, including:

- Selection of the experts: explicit selection criteria should be established at the beginning of the project that ensure the proper depth of SSC expertise, reputation in the scientific community, balance of technical views, and representation from alternative groups. Further, the project must be discussed in detail with the expert to ensure familiarity with the types of assessments that will be required for the SSC.

- Motivation and commitment: Each potential expert must be contacted to ensure that he/she is able and willing to make the appropriate commitment of time and effort to carry out the assessment. Potential expert should also be willing to discuss their technical views openly with their peers on the project.

- Dissemination of data: A key part of the SSC assessment should be the identification, compilation, and dissemination of all data bases that the experts will need to make their assessments. The data bases must be made available to all of the experts in uniform fashion. If specialized processing is requested by an individual expert, the results should be made available to the other experts as they desire.

- Education and training: Throughout the project, in the workshops and other meetings, effort should be devoted to reviewing data sets, scientific findings, and SSC-related methodologies and procedures. As appropriate, technical specialists should be invited to discuss their recent findings. In addition, training should be given to the SSC experts in methods for eliciting expert judgment. The goal should be to allow for each expert to supplement his prior training and to fill gaps in knowledge.

- Expert interactions: The interactions of experts in workshops, small working meetings, and in informal settings should be encouraged. The technical exchange of ideas and hypotheses, and the challenge of these ideas by peers, is a natural process familiar to scientists. The goal is not to suppress unorthodox ideas but to ferret out misunderstandings, gaps in knowledge, reliance on outdated data, etc. This process will result in a `behavioral' aggregation of SSC interpretations.

- Allow to defer: SSC is a multi-disciplinary problem and, despite efforts to educate the experts in fields beyond their own experience, an expert may wish to decline addressing certain aspects of the SSC assessment. Provision should be made to allow him to do so in the elicitation. Gaps would have to be filled using `default' assessments, which must be explained to the expert.

- Post-elicitation interaction: Following the elicitations, the experts should be presented with the assessments made by the other experts, perhaps in a workshop setting. This will allow the experts to review the technical basis for the other assessments, review and discuss their own interpretations with their peers, and to review sensitivity analyses conducted for the assessments. Provision must be made to allow for a final modification of the SSC assessments prior to calculation of the final seismic hazard results.

APPENDIX I

SPATIALLY VARYING SEISMICITY AND ITS EFFECT ON SEISMIC HAZARD

I.1 INTRODUCTION

This Appendix illustrates the treatment of spatially varying seismicity parameters within a seismic source. We use examples from three sites to illustrate the seismicity parameters obtained under various smoothing assumptions, the corresponding epistemic uncertainty in seismicity parameters, and the resulting epistemic uncertainty in the computed seismic hazard. These results support the recommendations provided in Section 4.3.5.

Spatial variability in seismicity is important for large background sources, especially in sources with large contrasts in seismic activity or very low activity rates. We use the EPRI (1986) model of spatially varying seismicity because this model represents the most thorough treatment of this issue, including the calculation of epistemic uncertainty, and because this model was available to this study.

I.2 METHODOLOGY AND ILLUSTRATIVE EXAMPLES

I.2.1 Seismicity Parameters and Smoothing Assumptions

The EPRI methodology for the calculation of spatially varying seismicity parameters estimates separate values of parameters a[1] and b for each 1-degree sub-source contained in the source. The

[1]Parameter a is defined in the EPRI methodology as the decimal logarithm of the rate of earthquakes with $3.3<m_b\leq3.9$ per square degree. This definition (i.e., anchored at the lowest magnitude in the EPRI catalog) is preferable to the standard definition (anchored at magnitude 0), because there is little or no correlation between a and b when these parameters are estimated using maximum likelihood or regression.

resulting seismicity parameters may be viewed as maps of a and b within the source. The a and b values for the sub-sources are estimated using a penalized maximum-likelihood formulation. The likelihood function for all a and b values in the source is the product of the likelihood functions for the individual sub-sources, with each sub-source likelihood function calculated in the standard manner (e.g., Weichert, 1980). The likelihood function for the a and b values of a sub-source depend only on the earthquakes in that sub-source.

Spatial smoothness between adjacent sub-sources is introduced by multiplying the likelihood function by penalty functions of the form:

$$Q_a = \prod_i \exp\left\{ -\frac{W_a}{2} (a_i - \hat{a}_i)^2 \right\} \tag{I-1}$$

$$Q_b = \prod_i \exp\left\{ -\frac{W_b}{2} (b_i - \hat{b}_i)^2 \right\} \tag{I-2}$$

where the subscript i indicates sub-source and the quantities $\hat{a}_i$ and $\hat{b}_i$ indicate the average values of a and b in all sub-sources adjacent to sub-source i. Parameters W_a and W_b are the smoothing parameters for a and b; they control the amount of spatial roughness that is tolerated in the {a,b} maps. The penalty terms may be interpreted as prior distributions on the spatial roughness of a and b, with W_a and W_b being the reciprocals of the prior deviations from adjacent sub-sources. Large values of W_a and W_b indicate a strong belief that seismic activity is uniform throughout the source[2]. Lower values of W_a and W_b indicate a belief that not all portions of the

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[2]The assumption of uniform seismicity implies that no portions of the source are more active than others. If this assumption were valid, a seismicity plot from a very long catalog would show a roughly uniform pattern of events. The assumption of uniform seismicity is <u>different</u> from the situation where the expert believes that seismicity may or may not be uniform, but does not have sufficient information to characterize the spatial variability of seismicity at a scale finer than the source's dimensions. The former assumption implies no epistemic uncertainty in the

earth's crust contained in the source are identical in their seismogenic characteristics, that some degree of spatial variation in seismic activity within the source is possible, and that the spatial distribution of historical seismicity provides information about that spatial variability. Multiple alternative values of W_a and W_b (referred to as multiple "smoothing assumptions") may be specified, in order to represent the expert's uncertainty about the proper amount of smoothing for a given source. Statistical tests of the type discussed in Section 4.3.5 aid the expert in the specification of smoothing parameters. Typically, more smoothness is specified for b than for a, because b is believed to be regionally stable.

The estimated {a,b} maps are obtained by finding the maps that maximize the penalized likelihood function. If both W_a and W_b are very large (say, 1000), one obtains the conventional homogeneous solution (i.e., constant a and b within the source). If both W_a and W_b are 0, the a and b values for each sub-source depend only on the seismicity within the sub-source and one obtains the same parameters that one would obtain by treating each sub-source as a separate source. Intermediate values of W_a and W_b yield solutions where the value of a and b within a source depend on both the seismicity within those sources and the seismicity in adjacent sources. The spatial roughness in the resulting maps of a and b depends on both the values of the smoothing parameters and the statistical significance of activity contrasts in the catalog.

The first example to be considered here is Bechtel's southern Appalachians background source from the EPRI (1986) study (the same source shown in Section 4.3.5). The geometry of this source and its seismicity are shown in Figure I.1; the three smoothing assumptions specified by the Bechtel team are shown in Table I.1

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within-source spatial distribution of the activity rate, the latter implies epistemic uncertainty. Because we wish to characterize both the epistemic and aleatory uncertainty in the hazard (See Section 2.2), it is important to consider this difference between uniform seismicity and the inability to specify a within-source spatial distribution of the activity rate.

Table I-1. Smoothing Parameters for Bechtel Background Sources

Assumption	Weight	Smoothing on a	W_a	Smoothing on b	W_b
1	1/3	Full	999	Full	999
2	1/3	Low	5	High	100
3	1/3	Low	5	Low	25

Figures I-2 through I-4 show the spatial distributions of the activity rate (m_b>3.3) and b value for the southern Appalachians source, under the three smoothing assumptions. For the last two smoothing assumptions, the ratio between the highest activity rate (near New York City) and the lowest activity rate (central Alabama) is approximately 30. For the last smoothing assumption, the values of b range from 0.8 to 1.1.

I.2.2. Effect of Spatial Variability on Seismic Hazard and its Epistemic uncertainty

The spatial variability of seismicity parameters within a seismic source affects the calculated seismic hazard, particularly for sites located within that source. Under the assumption of homogeneous seismicity (i.e., full smoothing), the hazard from a seismic source is the same for all sites located within that source and sufficiently far from the source boundaries, regardless of the actual distribution of historical seismicity within that source. Under partial or no smoothing, the hazard from a seismic source is not necessarily the same for all sites within that source (although the PSHA calculation in Eq. 2.2 involves some spatial weighting of activity rates). The effect of spatial variability in seismicity is incorporated in the hazard calculations by integrating separately the contributions from each sub-source within a source. These calculations are performed separately for the different smoothing assumptions, in order to quantify the sensitivity of seismic hazard to smoothing assumptions and the resulting epistemic uncertainty in the hazard due to uncertainty about the proper smoothing assumption.

The assumptions about smoothing also have an effect on the statistical uncertainty in the estimates of the seismicity parameters a and b (another contributor to epistemic uncertainty). If one makes the conventional assumption of homogeneous seismicity (i.e., full smoothing), all the seismicity data within the source are used to estimate only two parameters; namely a and b for the entire source. One potential problem with assuming homogeneous seismicity is that any statistically significant deviations between the data and the homogeneous-seismicity model (i.e., lack of fit), such as the deviations shown in Figure 4.6, are not captured as epistemic uncertainty anywhere in the process. If spatial variability is introduced, and values of a and b are calculated for each sub-source, the number of independent parameters being estimated is greater than two, resulting in higher statistical uncertainty in these parameter estimates. Thus, the smoothing assumptions have an effect on the calculated statistical uncertainty in seismicity parameters[3].

Analytical quantification of statistical uncertainty in the seismicity parameters (for a given smoothing assumptions) and propagation of this uncertainty through the hazard calculation is not practical because of the complex correlation between the seismicity parameters of the sub-sources. We use a powerful, but computationally intensive, way to characterize this statistical uncertainty is by using a technique known as bootstrapping (Efron, 1982). The calculation of statistical uncertainty in the seismicity parameters, and the associated epistemic uncertainty in hazard, is performed in the following steps.

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[3]This paragraph would seem to suggest that one should assume homogeneous seismicity, whether this assumption is justified or not, because it leads to a lower epistemic uncertainty in the calculated hazard. The difficulty is that the conventional treatment of seismic sources in PSHA does not provide for a way to express uncertainty in whether or not a seismic source has truly homogeneous seismicity. The assumption of spatially varying seismicity thus appears to be penalized because it leads to higher uncertainty in the estimated parameters. If the data do not suggest homogeneity in seismicity, and the expert has no other reasons for assuming homogeneity (possible reasons might be based on the geological or geophysical homogeneity of a well-studied source, analogous regions, etc.), the uncertainties that arise when one allows for spatial variability are real and should be considered.

1. Generate artificial earthquake catalogs. Two approaches may be followed: empirical or parametric bootstrapping. In empirical bootstrapping, each artificial catalog is formed by selecting events at random (with replacement) from the historical catalog. In parametric bootstrapping, a map of a and b is first calculated using the actual catalog and penalized maximum likelihood. Then, artificial catalogs are generated from the stochastic recurrence model defined by the calculated {a,b} map, using a Monte Carlo approach. Empirical bootstrapping has the advantage that it does not rely on parametric assumptions (e.g., stationary Poisson occurrences), but has the disadvantage that no artificial events will ever occur in a sub-source with no historical events.

2. Calculate one map of a and b within the source for each artificial catalog, using the maximum penalized likelihood procedure described earlier.

3. Calculate seismic hazard for each {a,b} map obtained in step 2.

4. Calculate summary statistics to display the effect of statistical uncertainty on the estimated seismicity parameters and on the hazard.

These calculations were performed for the southern Appalachians background source. Fifty artificial catalogs were generated using parametric bootstrapping, for the three smoothing assumptions in Table I-1. Figures I-5 through I-7 show the standard deviations in a and b obtained for the three smoothing assumptions. Because the activity rate (m_b>3) is proportional to 10^a, the coefficient of variation of the rate is approximately equal to the standard deviation of a times ln(10)=2.3. Comparing Figures I-5 to I-6 and I-7, we see that statistical uncertainty in a is much higher under low smoothing than under full smoothing, especially for the sub-sources with very low activity rates. Comparing Figures I-6 and I-7, we see similar results for statistical uncertainty in b.

Seismic hazard calculations were performed for two sites located in this background source (step 2 above). For the sake of computational efficiency, only the hazard contributed by this background source is considered. The first site considered is Washington, D.C. (38.9°N, 77.04 °W), which is located in an area of low seismicity, but is not far from areas of higher activity (particularly the Central Virginia seismic zone). Figure I-8a through c show the calculated hazard under the three alternative smoothing assumptions given in Table I-1. The spread between the fractile curves represent the effect of statistical uncertainty in a and b[4]. Figure I-8d shows the sensitivity of the median hazard to the various smoothing assumptions; this sensitivity introduces epistemic uncertainty because the team was uncertain about the proper smoothing assumption. Figure I-8e shows the total epistemic uncertainty in the hazard due to seismicity parameters (including both statistical uncertainty in a and b and epistemic uncertainty in the smoothing parameters). This figure may be compared to Figure I-8f, which shows the total epistemic uncertainty in the hazard[5] (due to epistemic uncertainty in seismicity parameters, maximum magnitude, and attenuation equations). This comparison shows that, in this case at least, epistemic uncertainty in seismicity parameters is a small contributor to the total epistemic uncertainty in hazard for this site. Even if an expert had specified low smoothing on a and b as the only smoothing assumption, the contribution of epistemic uncertainty in seismicity parameters to the total epistemic uncertainty in hazard would be small.

Washington, D.C., is located near a sub-source corner. Thus, four sub-sources contribute significantly to the hazard. Calculations were also performed for a nearby hypothetical site in the middle of the same sub-source (38.5°N, 77.5 °W) to investigate the sensitivity of the above results to location within a sub-source. Differences between the two locations were small.

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[4]The uncertainties due to maximum magnitude and attenuation equations were removed from the hazard results by averaging all hazard curves obtained using the same smoothing assumption and artificial catalog, but with different maximum magnitudes and attenuation equations. The scatter that remains (among average hazard curves) represents uncertainty due to smoothing assumptions and/or seismicity parameters. This averaging procedure preserves the mean hazard curve, but distorts the median.

[5]These calculations used the maximum-magnitude distribution specified by Bechtel for this source (5.7[0.1], 6.0[0.4], 6.3[0.4], 6.6[0.1]) and the ground-motion epistemic uncertainty in the EPRI(1993) ground-motion model.

The second site considered is located in central Alabama (32.5°N, 86.5 °W), in an area of very low seismicity (only two events in the host sub-source and adjacent sub-sources) near the SW corner of the same background source. Results are presented in Figure I-9a through f. Unlike the Washington, D.C. case, the epistemic uncertainty due to seismicity parameters is a large contributor to epistemic uncertainty in the hazard.

The third site considered is located in central Minnesota (44.5°N, 89.5 °W), in a low-seismicity portion of Bechtel's Northern Great Plains background source (Figure I-10). Hazard results are shown in Figures I-11a through f[6]. Comparison of Figures I-11e and f shows that epistemic uncertainty in seismicity parameters is a moderate contributor to the total epistemic uncertainty in hazard for this site. Rough calculations suggest that ignoring epistemic uncertainty in seismicity parameters (both statistical uncertainty and epistemic uncertainty in smoothing parameters) would result in approximately a moderate reduction in the epistemic uncertainty in hazard (in the form of a 25% reduction in the distance between the median and 85-percentile hazard curves in Figure I-11f).

I.3 DISCUSSION AND SUMMARY OF RESULTS

The results shown here illustrate one approach for the treatment of spatially varying seismicity within a seismic source, and the implications of that treatment on seismic hazard and its epistemic uncertainty. These results support the recommendations in Section 4.3.5. A number of additional insights can be drawn from these results. These insights are useful for deciding how to treat seismicity in a large background source.

Results indicate that the smoothing assumptions may have a significant effect on the hazard from

[6]These calculations used the maximum-magnitude distribution specified by Bechtel for this source (5.4[0.1], 5.7[0.4], 6.0[0.4], 6.6[0.1]) and the ground-motion epistemic uncertainty in the EPRI(1993) ground-motion model.

large background sources that contain the site and have non-uniform spatial patterns of seismicity. These effects are most important when the site is located on a large patch of very low or no seismicity (e.g., the Alabama and Minnesota sites).

If the assumption of homogeneous seismicity is relaxed, allowing for some spatial variation of seismicity parameters within the source, the statistical uncertainty in the seismicity parameters is increased. This increase is moderate if high smoothing on b is specified, but becomes large if low smoothing on b is specified. The latter effect is generally ameliorated in practice by the tendency to specify more smoothing for b than for a (or by giving a low weight to the assumption of low smoothing on b, as done in the examples considered here), because it is believed that b is more spatially uniform. On the other hand, b may not be stable at the scale of individual faults within the seismic source, if those faults have characteristic magnitudes (as postulated by Schwartz and Coppersmith, 1984, and Wesnousky, 1995, among others).

For the three sites and smoothing assumptions considered here, the sensitivity of the hazard to smoothing assumptions provides an indication of the epistemic uncertainty in hazard due to statistical uncertainty in seismicity parameters. Moreover, the epistemic uncertainty due to smoothing assumptions is roughly half the total epistemic uncertainty due to seismicity (i.e., the epistemic uncertainty due to both smoothing assumptions and statistical uncertainty in parameters).

The three examples considered here did not include a site in a high-seismicity portion of the background source (e.g., New York city). One can anticipate, however, that the effect of smoothing assumptions will be comparable to that at the lower-seismicity sites, but the effect of statistical uncertainty will be lower.

All calculations shown here considered PGA. Calculations for 1-Hz spectral velocity were also performed at one of the sites. Results indicate that the epistemic uncertainty in hazard due to seismicity parameters is slightly smaller for 1 Hz than for PGA. This suggests that the reduction in epistemic uncertainty associated with more spatial averaging (due to the slower attenuation of

1-Hz energy with distance) compensates for the increase associated with more sensitivity to larger magnitudes (whose recurrence rates are more uncertain).

The hazard results presented here relate to one background source. At many sites, sources other than the background source make significant contributions to seismic hazard. Thus, epistemic uncertainty in the seismicity parameters for a background source may not be an important contributor to the total epistemic uncertainty in the hazard at a site, even if it is an important contributor when only the background source is considered. On the other hand, there are sites (like the Minnesota site and many other sites in the upper Midwest) where the background source is the dominant contributor to hazard for PGA and for other high-frequency measures of ground motion. The recommendations in Section 4.3.5 provide conservative guidance regarding the need to consider spatial variability for a background source depending on that source's contribution to the total hazard. Additionally, one may apply the procedure in Tables G-2 through G-4 (see Appendix G) to decide whether to consider spatial variability for a background source.

These insights are based on calculations for one expert team and a limited number of sites, but are believed to be typical. Also, the calculated epistemic uncertainties are based on certain modeling assumptions (particularly the assumption of Poisson, independent, exponential [PIE] earthquake occurrences). The uncertainties would be higher, for example, if earthquake occurrences followed an on-off process (e.g., Bender, 1984; Coppersmith, 1988).

I.4 ALTERNATIVE MODELS

An alternative approach for the treatment of spatially varying seismicity has been developed by the USGS for national seismic-hazard mapping (Frankel, 1995; Frankel et al., 1995). This approach simply assigns to each sub-source an activity rate computed as a weighted average of rates in that sub-source and nearby sub-sources, using a weighting function (or kernel) with a correlation distance of 50 km. An important difference between the USGS approach and the EPRI approach used here is that the USGS approach introduces smoothness without regard for the statistical significance of seismicity contrasts. The following example clarifies this distinction. Suppose there is a group of nearby sub-sources 1, 2, 3, 4, ... m, with earthquake counts n_1, n_2, n_3, n_4, ... n_m , where the n_i's are of the order of 0 to 5. Suppose that the USGS smoothing procedure assigns to these sources the smoothed activity rates s_1, s_2, s_3, s_4, ... s_m. Consider another group of sub-sources with earthquake counts $10n_1$, $10n_2$, $10n_3$, $10n_4$, ... $10n_m$. The USGS smoothing procedure would apply the same smoothing weights to both sets of earthquake counts and would assign the smoothed activity rates $10s_1$, $10s_2$, $10s_3$,$10s_4$, ... $10s_m$ to the second set of sources. The EPRI procedure (with partial smoothing) would, on the other hand, perform more smoothing on the first set of sub-sources because seismicity contrasts in the first set of sub-sources have less statistical significance than contrasts in the second set of sub-sources. In terms of the penalized likelihood formulation, the sub-source likelihood functions for the second set are more peaked (because more data are available) and the optimal solution is therefore influenced more by the sub-source likelihood functions and less by the (smoothing) penalty functions.

Another important difference in the way the EPRI and USGS approaches to spatial variability have been used relates to the treatment of seismic source zones and source boundaries. The EPRI approach has been used mainly to characterize seismicity within a seismic source zone. In contrast, the USGS approach has been applied over the entire central and eastern U.S., without considering any seismic source zones. This fundamental methodological difference about the validity of seismic source zones is not, however, inherent to the smoothing approaches. The penalized-likelihood-based EPRI model of spatial variability can be applied without source boundaries (treating the whole CEUS as one large source), and the kernel-based USGS smoothing approach can be used within a seismic source (after straightforward correction for edge effects).

The EPRI approach presented above considers spatial variations in seismicity over distances of 50 to 100 km. A model that considers variations in seismicity over a smaller spatial scale has been proposed by Wu and Cornell (1993). In this model, the activity rate within a background source is itself presumed to be a stochastic point process (i.e., the spatial distribution of activity rate within a background source is made up of scattered spikes reflecting active features). Future earthquakes will only occur where past earthquakes have occurred and in other, still undetected, discrete locations. According to this model, if the seismicity catalog were infinitely long and all earthquake locations were sufficiently accurate, one would observe all events clustering into a relatively small number of active points on the background source, without ever filling up the entire source. This model constitutes an interesting limiting case, corresponding to zero spatial correlation in seismicity. The physical and empirical validity of models of this type, and their implications on the calculated hazard and its epistemic uncertainty, should be explored further. These issues may be important at sites where the seismic hazard is controlled by background sources.

I.5 REFERENCES

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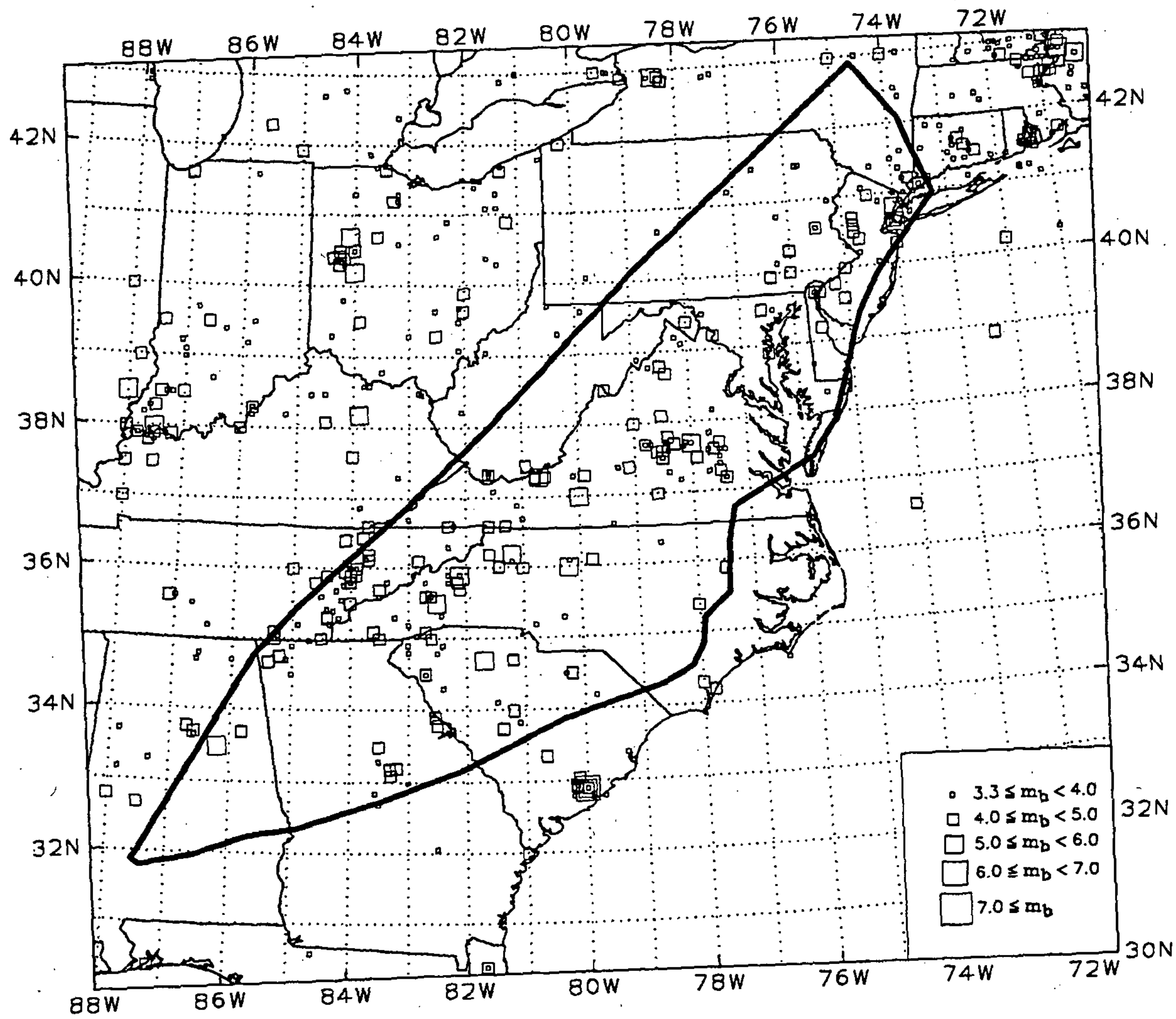


Figure I-1. Map showing the Bechtel background source for the southern Appalachians and the historical seismicity in the EPRI catalog.

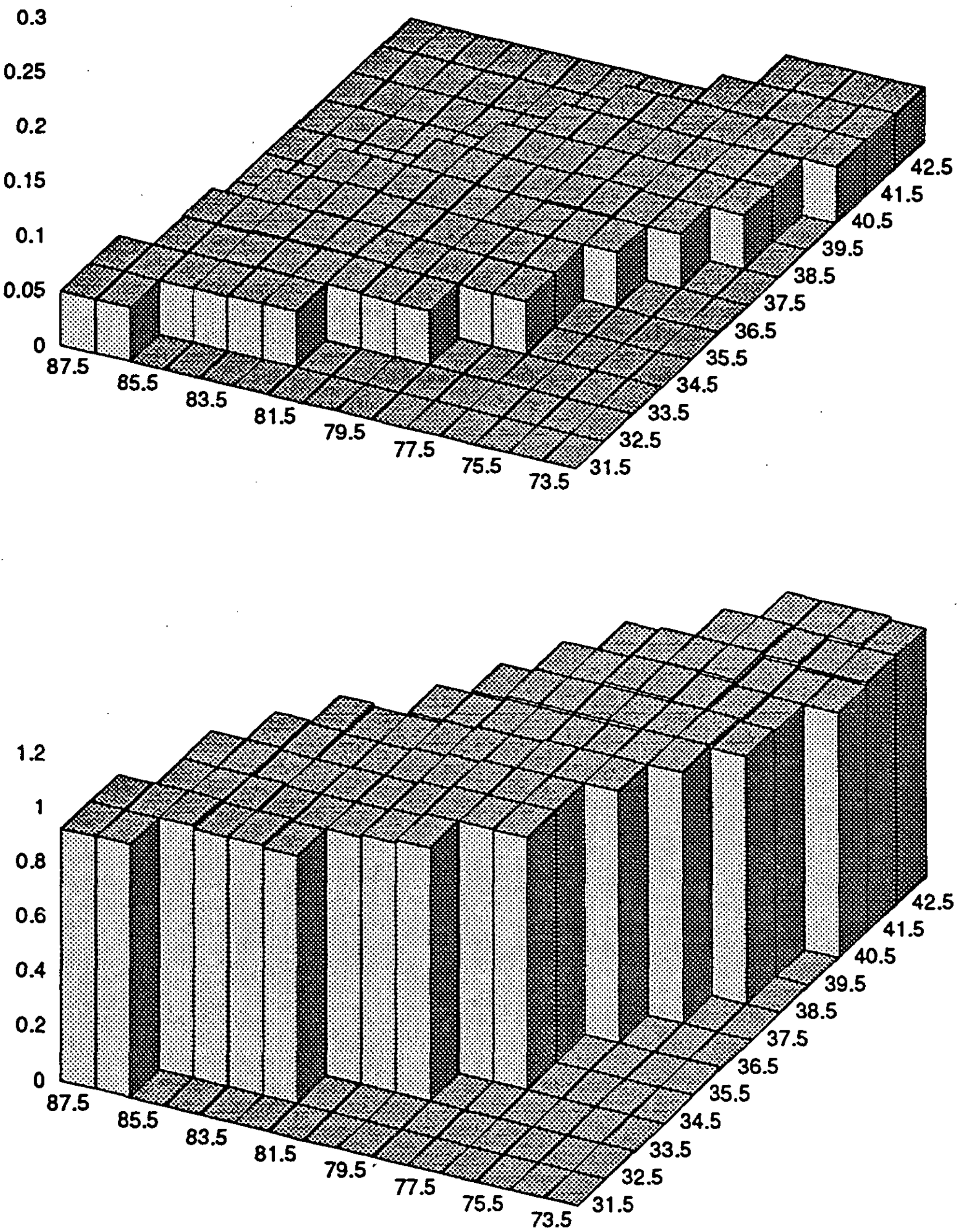


Figure I-2. Spatial distributions of rate (m_b>3.3) per unit area (events/yr/deg^2; top) and *b* value (bottom) for the background source in Figure I-1. First smoothing assumption.

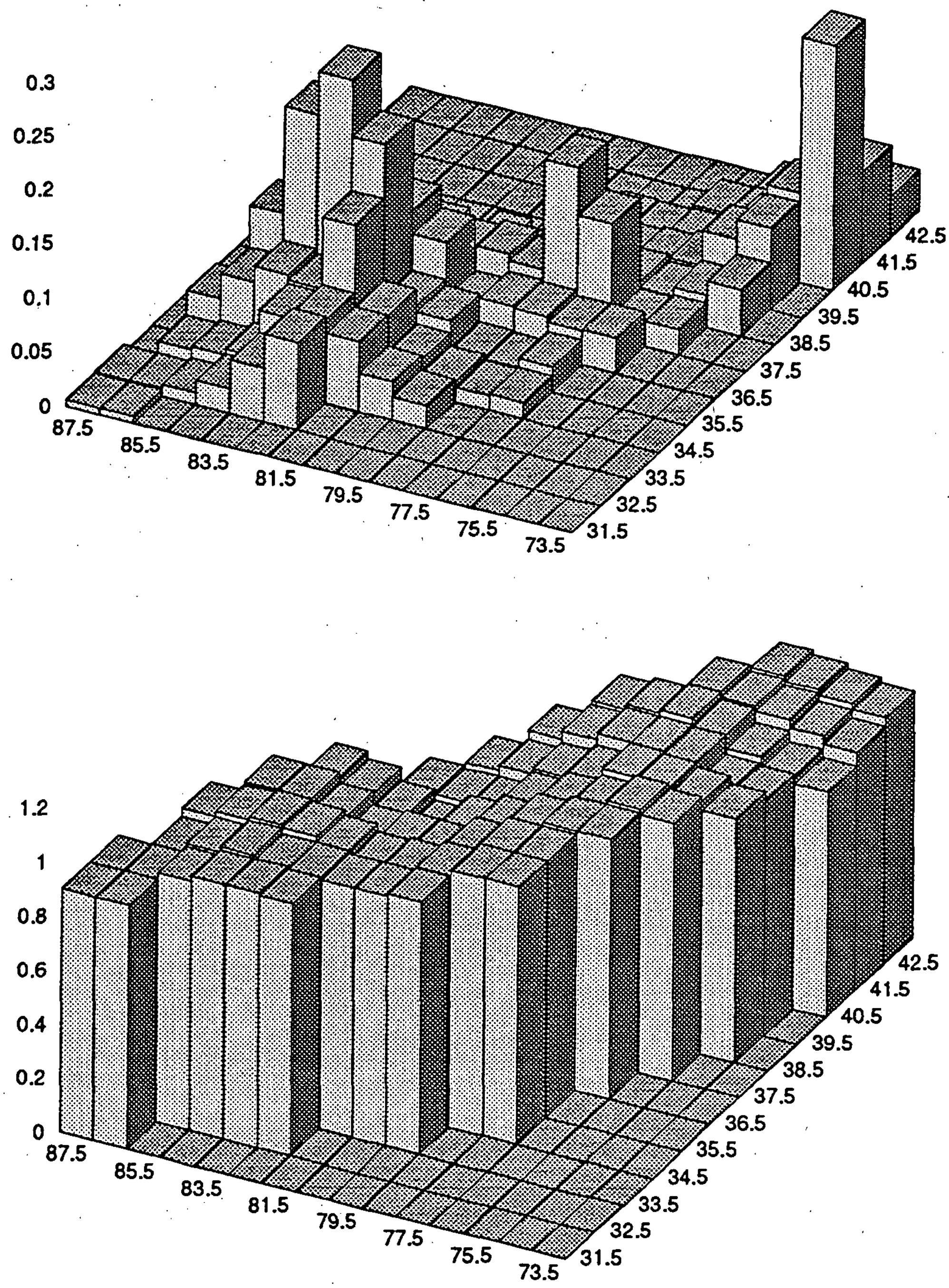


Figure I-3. Spatial distributions of rate (m_b>3.3) per unit area (events/yr/deg^2; top) and *b* value (bottom) for the background source in Figure I-1. Second smoothing assumption.

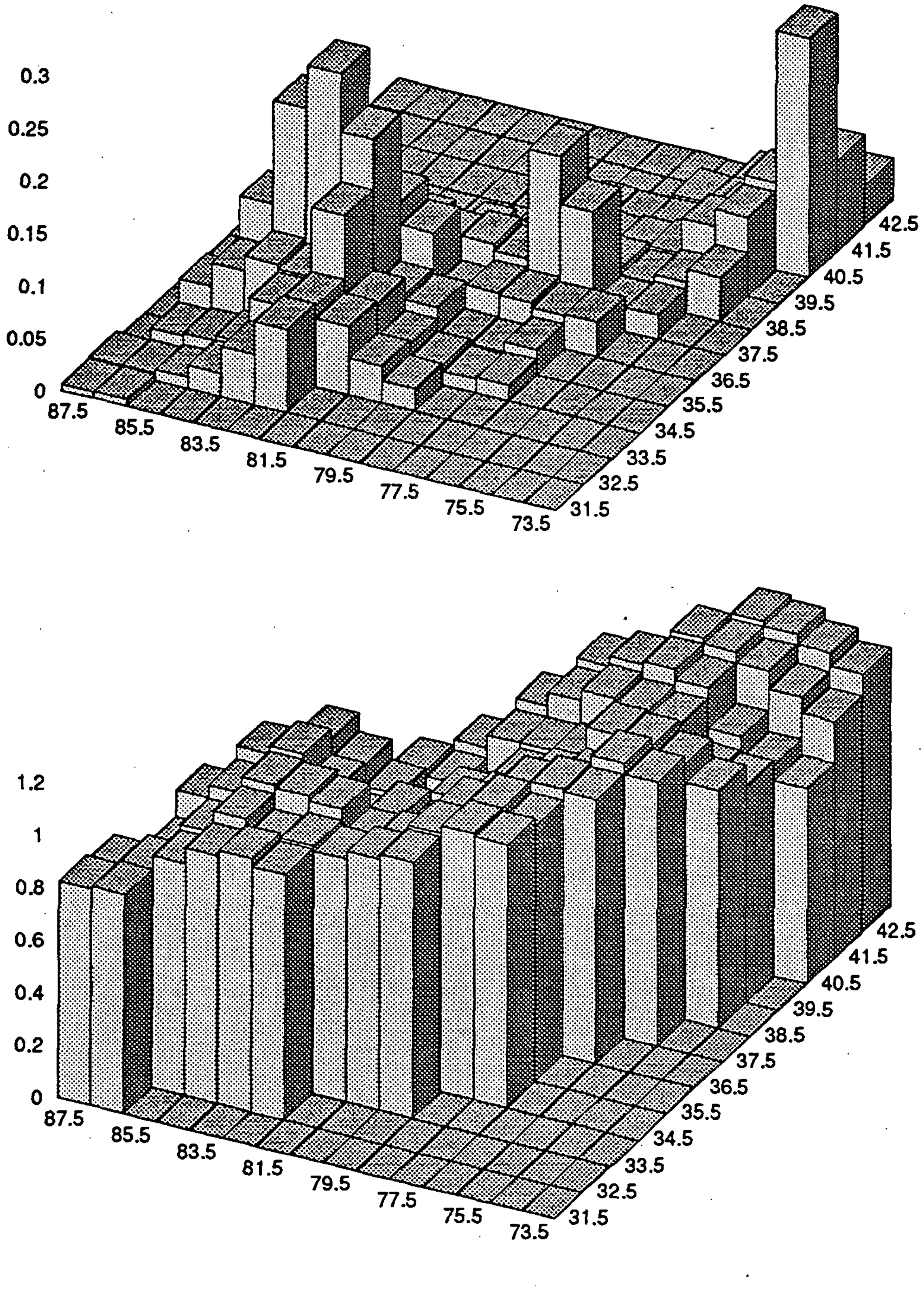
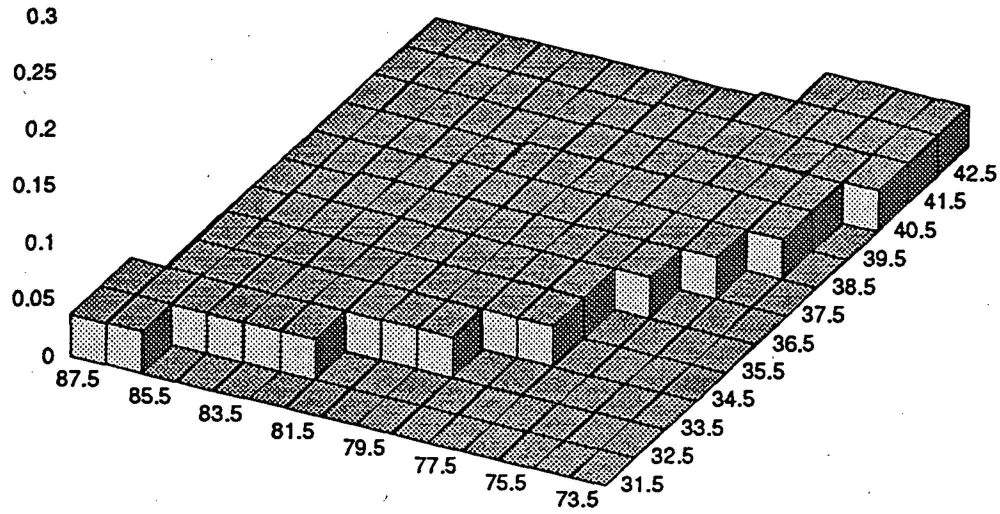


Figure I-4. Spatial distributions of rate (m_b>3.3) per unit area (events/yr/deg^2; top) and *b* value (bottom) for the background source in Figure I-1. Third smoothing assumption.



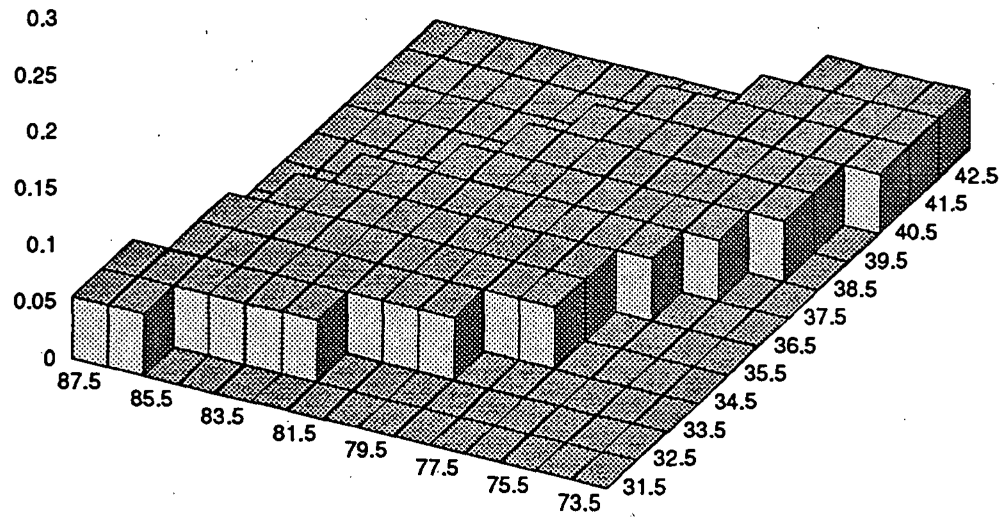
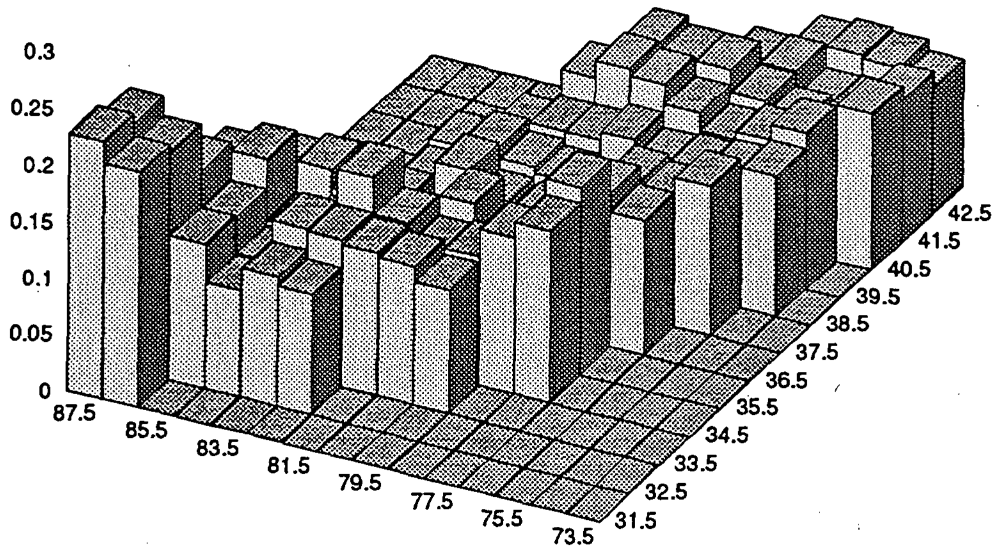


Figure I-5. Spatial distributions of the standard deviations of the *a* (top) and *b* (bottom) values for the background source in Figure I-1. First smoothing assumption.



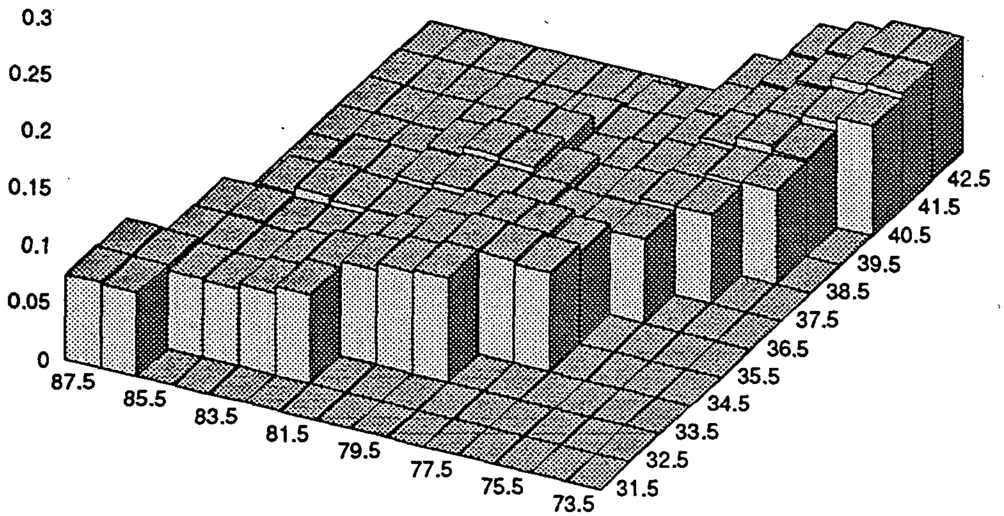
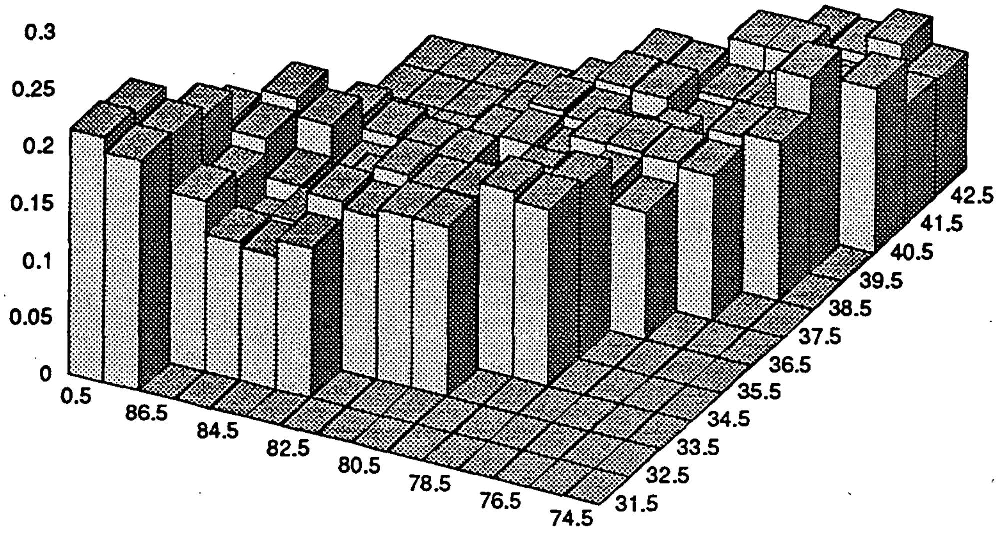


Figure I-6. Spatial distributions of the standard deviations of the *a* (top) and *b* (bottom) values for the background source in Figure I-1. Second smoothing assumption.



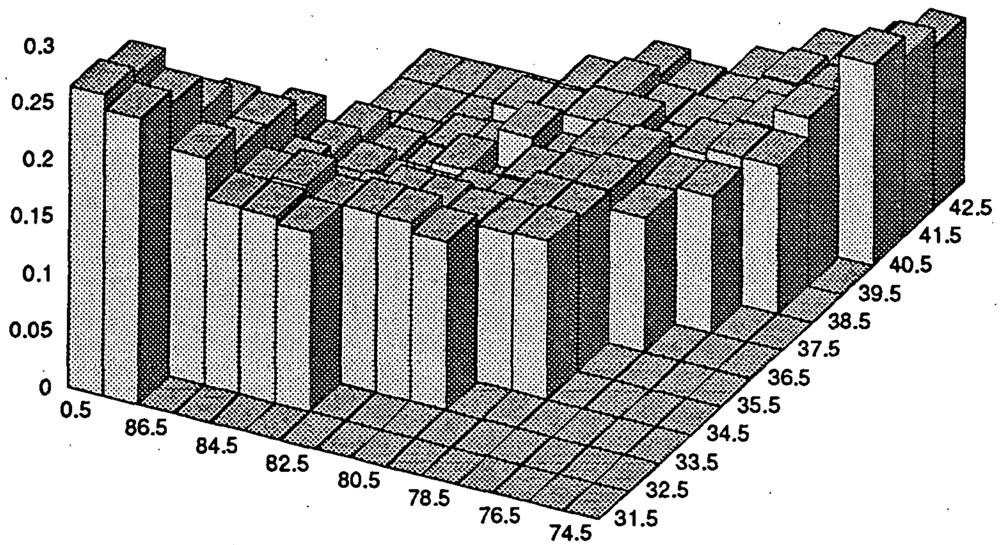
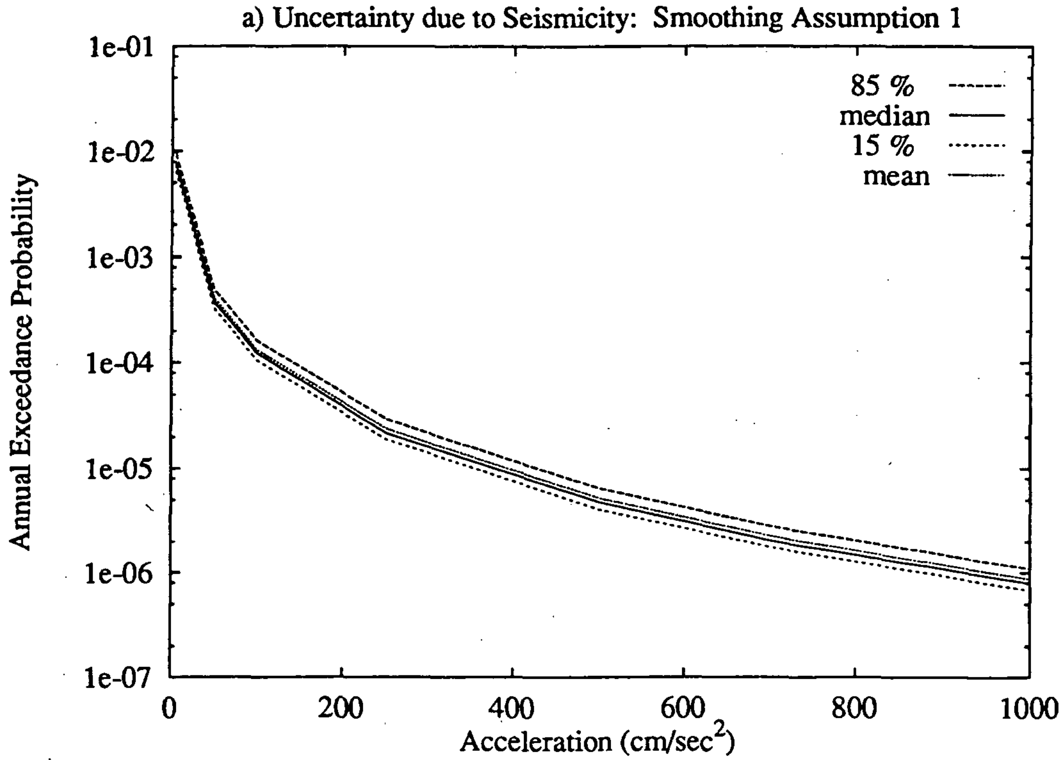


Figure I-7. Spatial distributions of the standard deviations of the *a* (top) and *b* (bottom) values for the background source in Figure I-1. Third smoothing assumption.



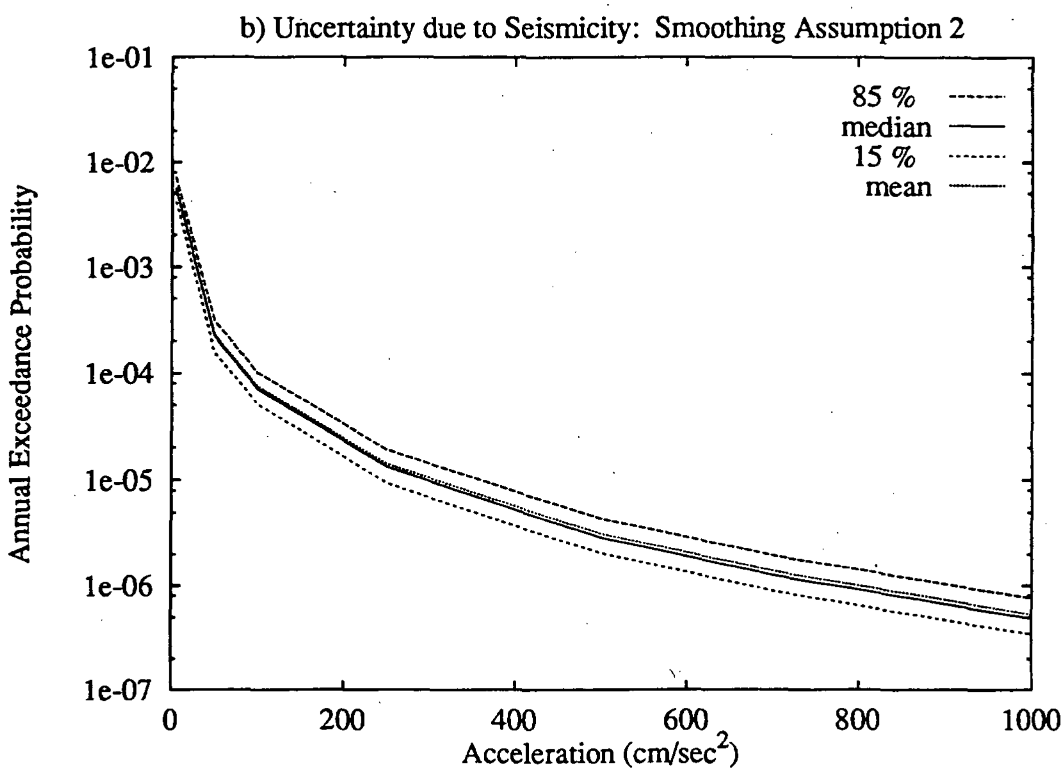
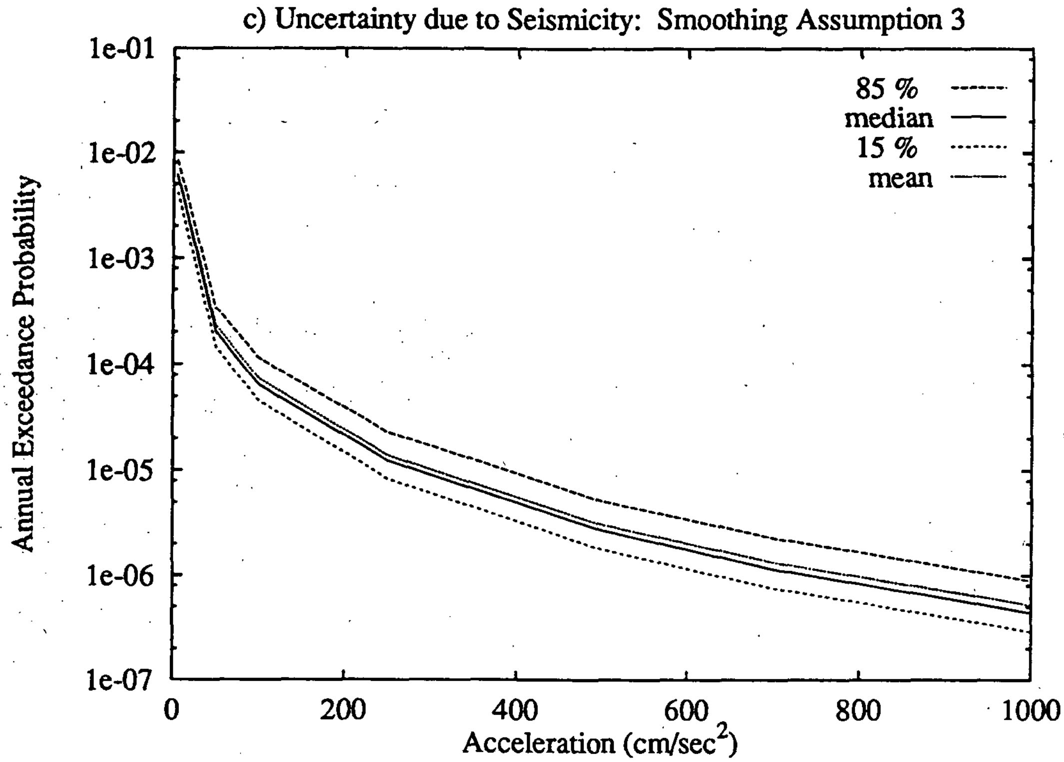


Figure I-8. Seismic hazard results for Washington, D.C. site. (a) Hazard under smoothing assumption 1. (b) Hazard under smoothing assumption 2. Fractiles indicate effect of statistical uncertainty in seismicity parameters.



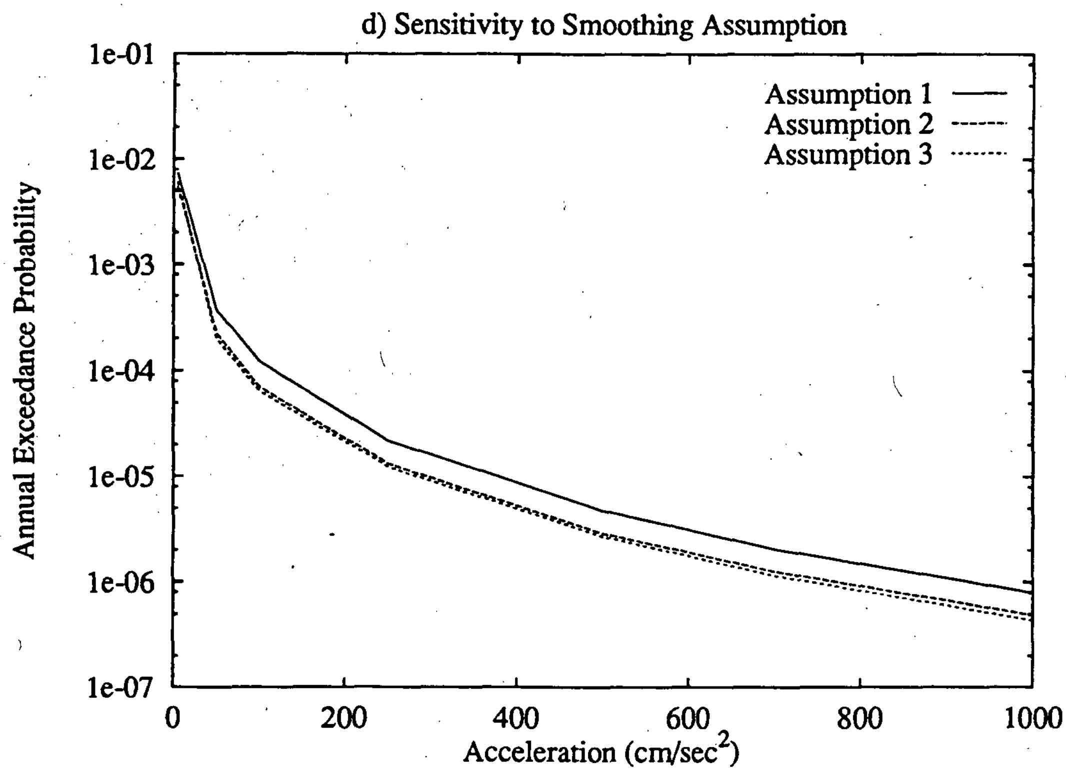
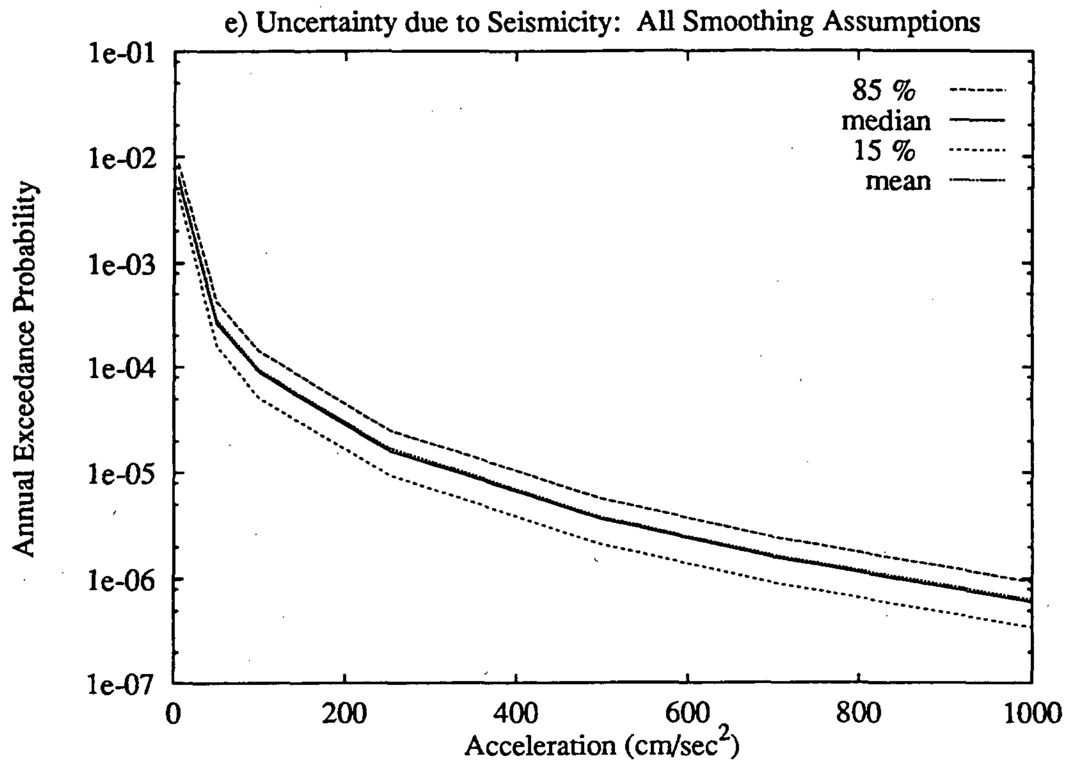


Figure I-8 (continued). Seismic hazard results for Washington, D.C. site. (c) Hazard undersmoothing assumption 3. (d) Sensitivity of the hazard to smoothing assumptions.



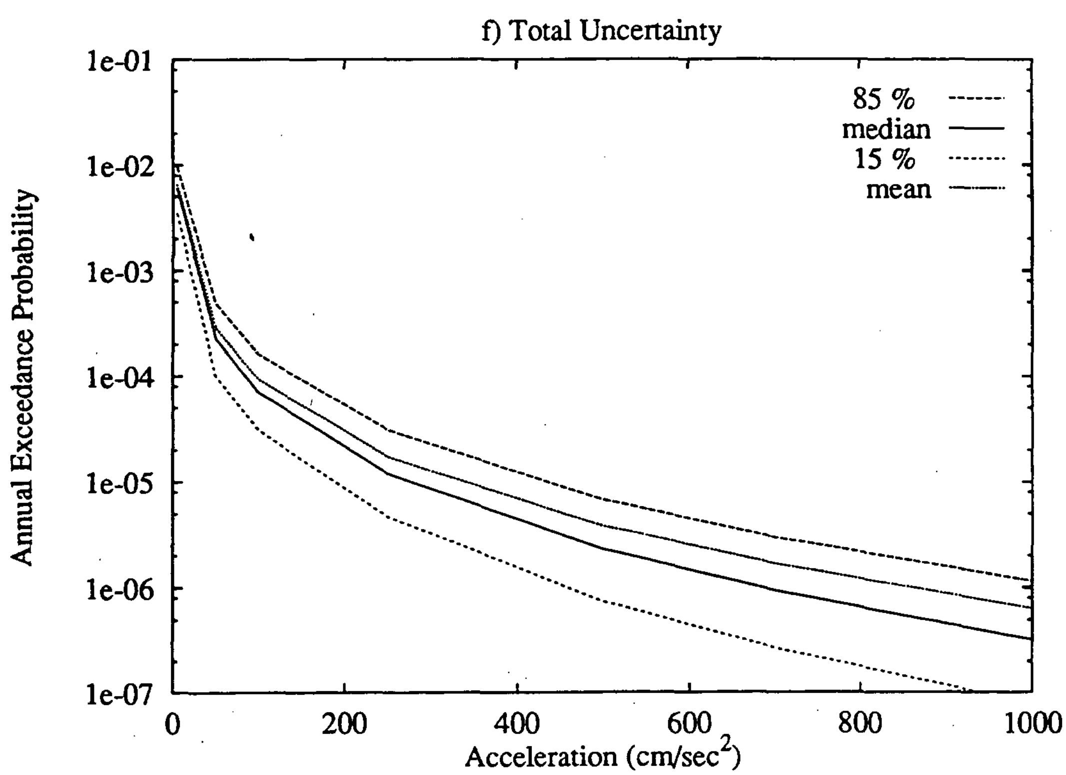


Figure I-8 (continued). Seismic hazard results for Washington, D.C. site. (e) Uncertainty due to smoothing options and statistical uncertainty in seismicity parameters. (f) Total uncertainty in hazard.

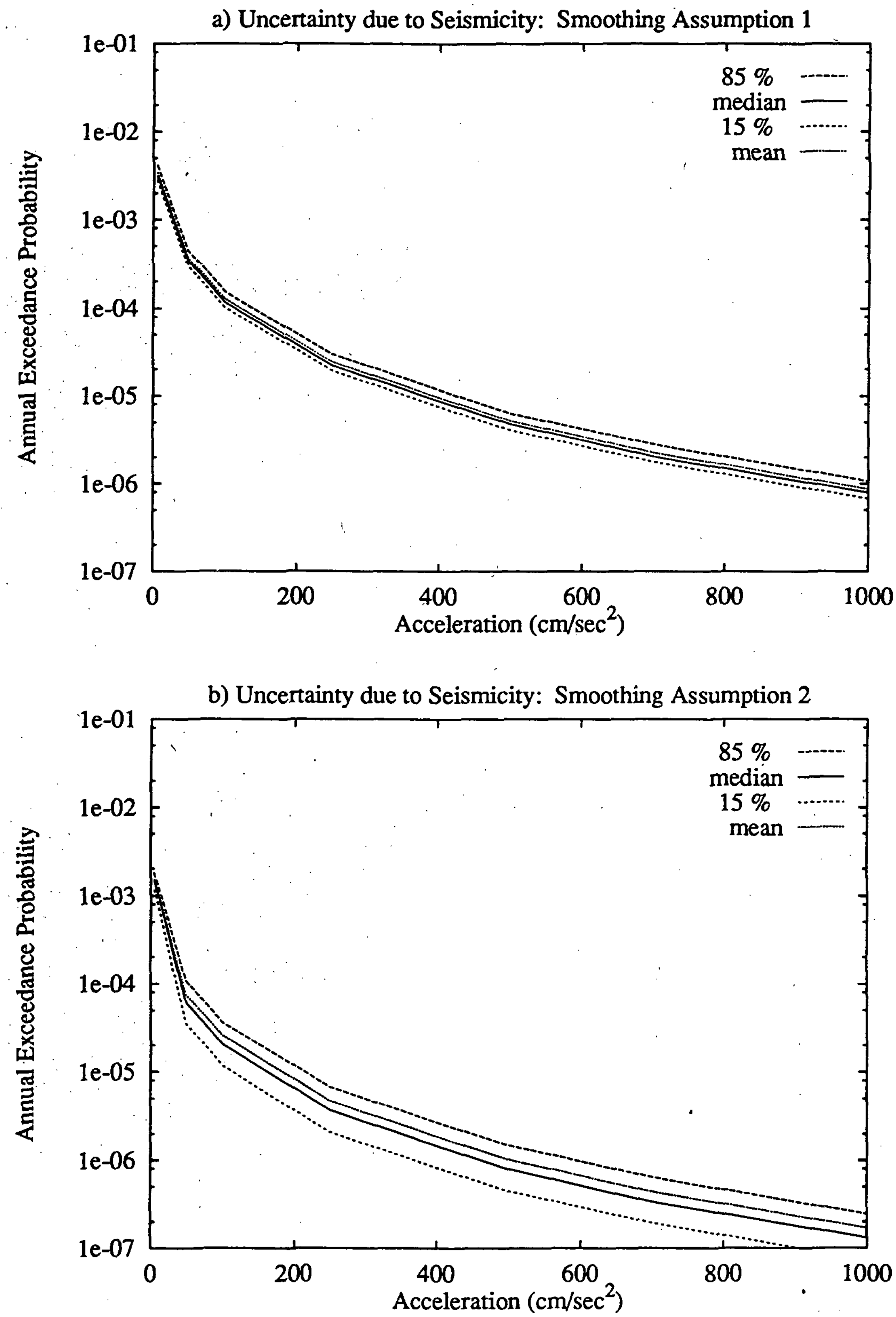
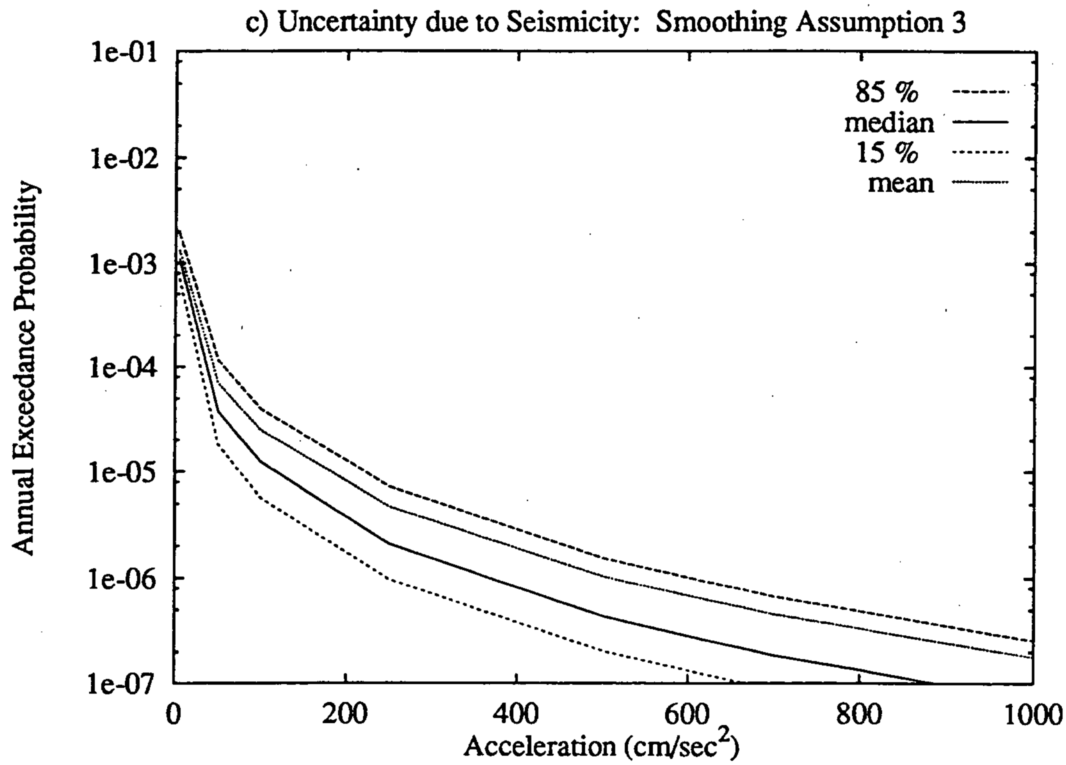


Figure I-9. Seismic hazard results for central Alabama site. (a) Hazard under smoothing assumption 1. (b) Hazard under smoothing assumption 2. Fractiles indicate effect of statistical uncertainty in seismicity parameters.



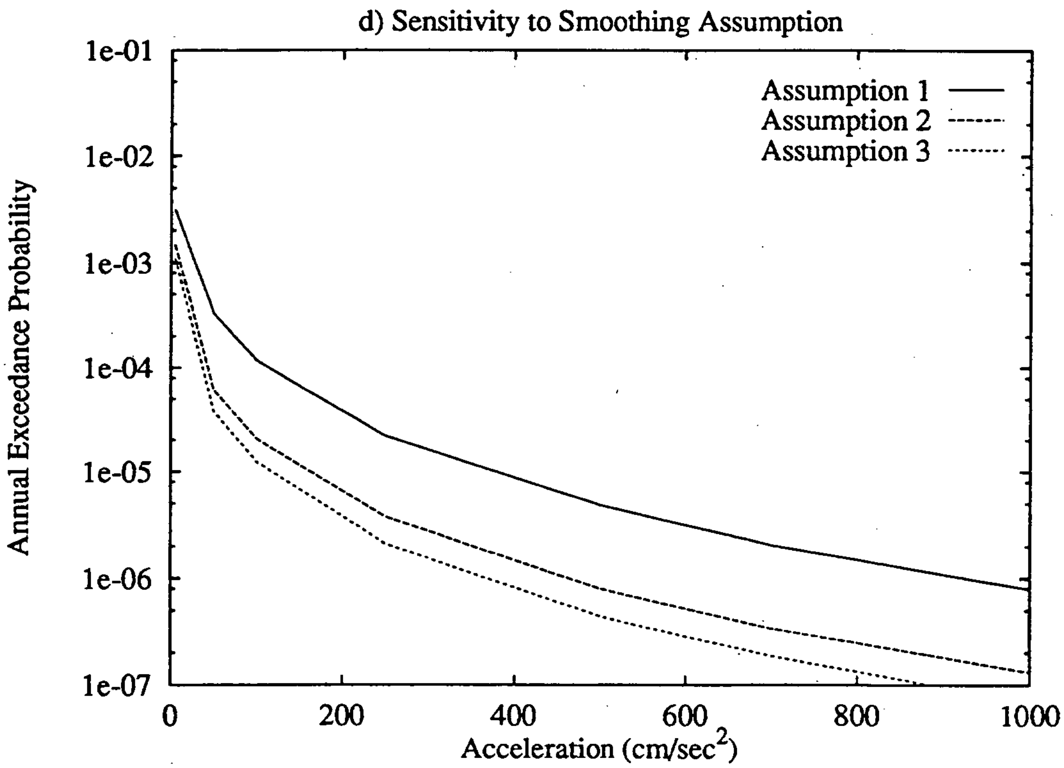
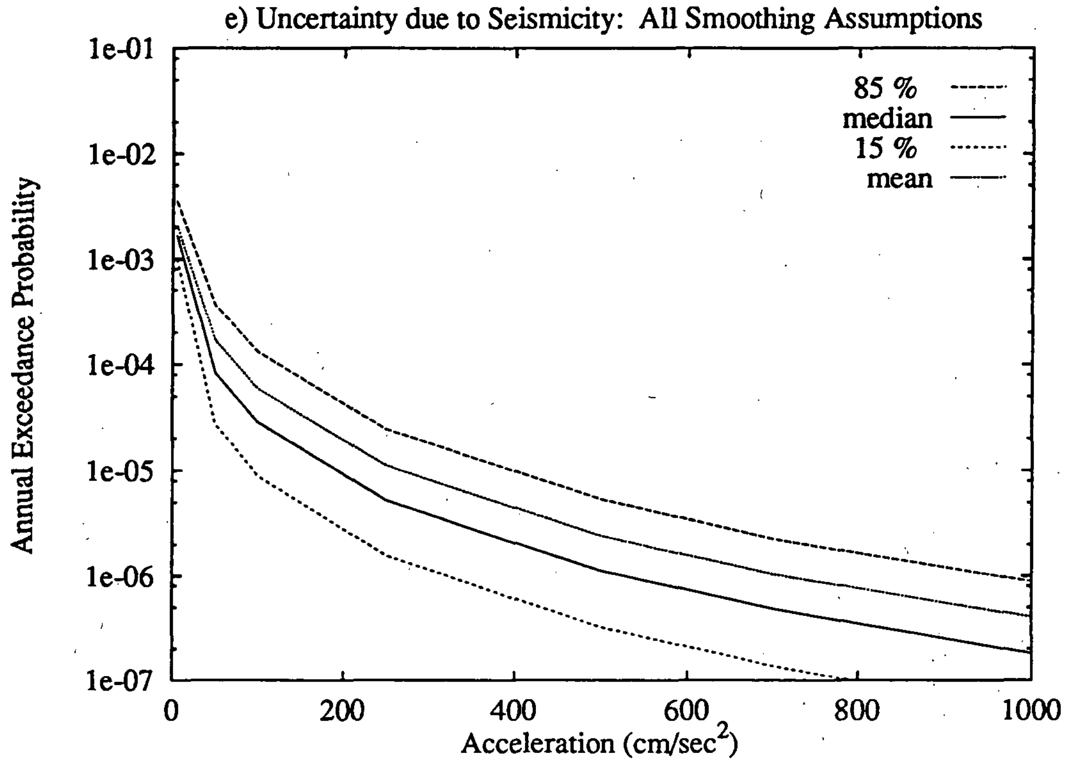


Figure I-9 (continued). Seismic hazard results for central Alabama site. (c) Hazard undersmoothing assumption 3. (d) Sensitivity of the hazard to smoothing assumptions.



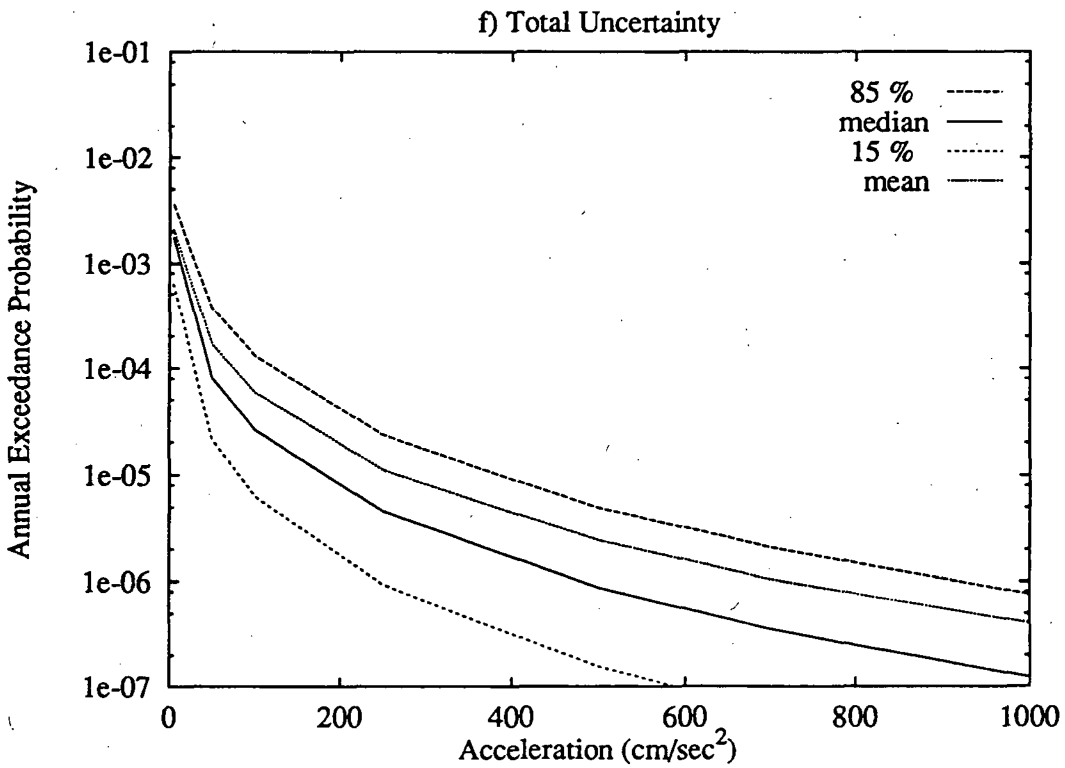


Figure I-9 (continued). Seismic hazard results for central Alabama site. (e) Uncertainty due to smoothing options and statistical uncertainty in seismicity parameters. (f) Total uncertainty in hazard.

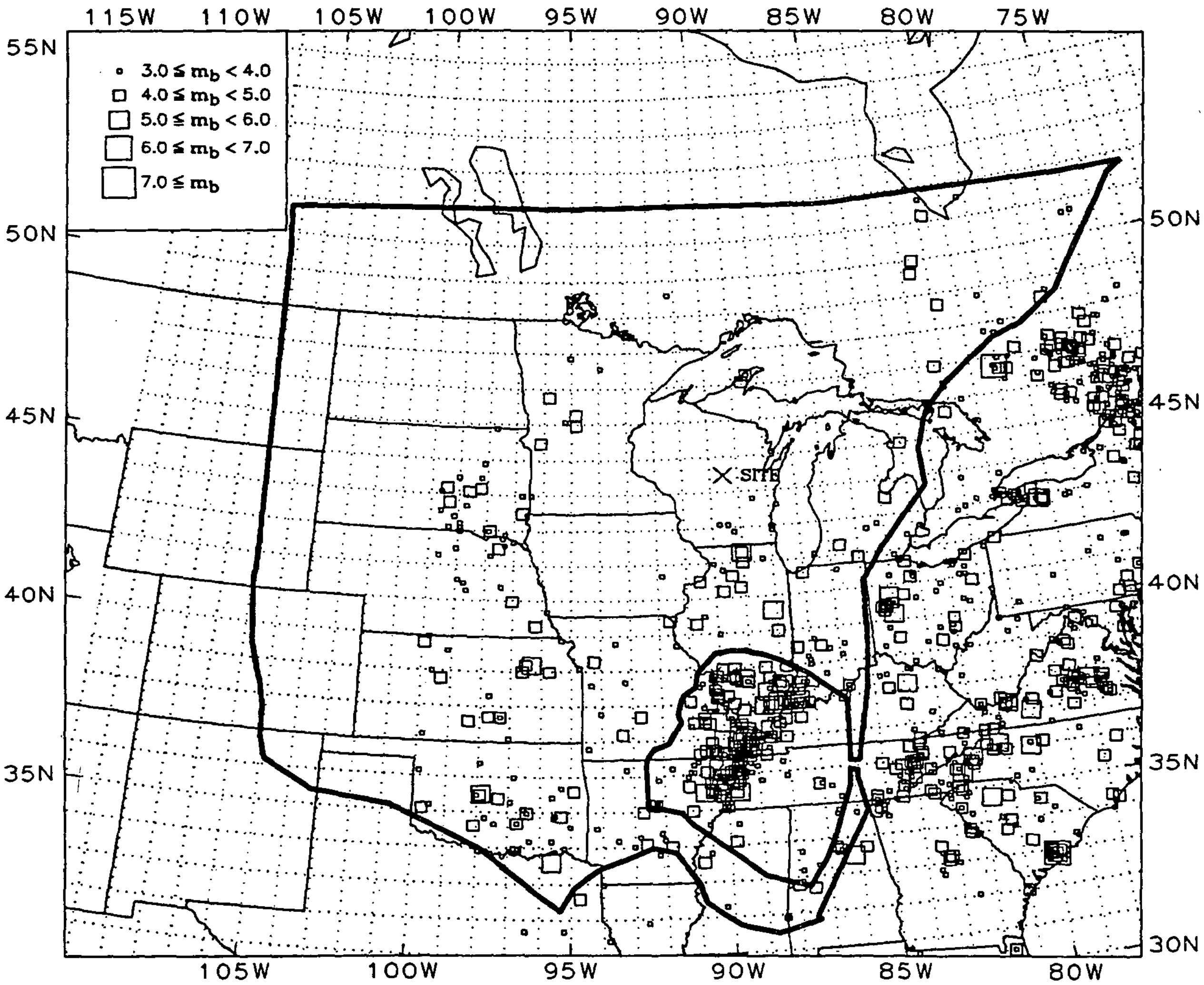


Figure I-10. Map showing the Bechtel background source for the central Minnesota site and the historical seismicity in the EPRI catalog.

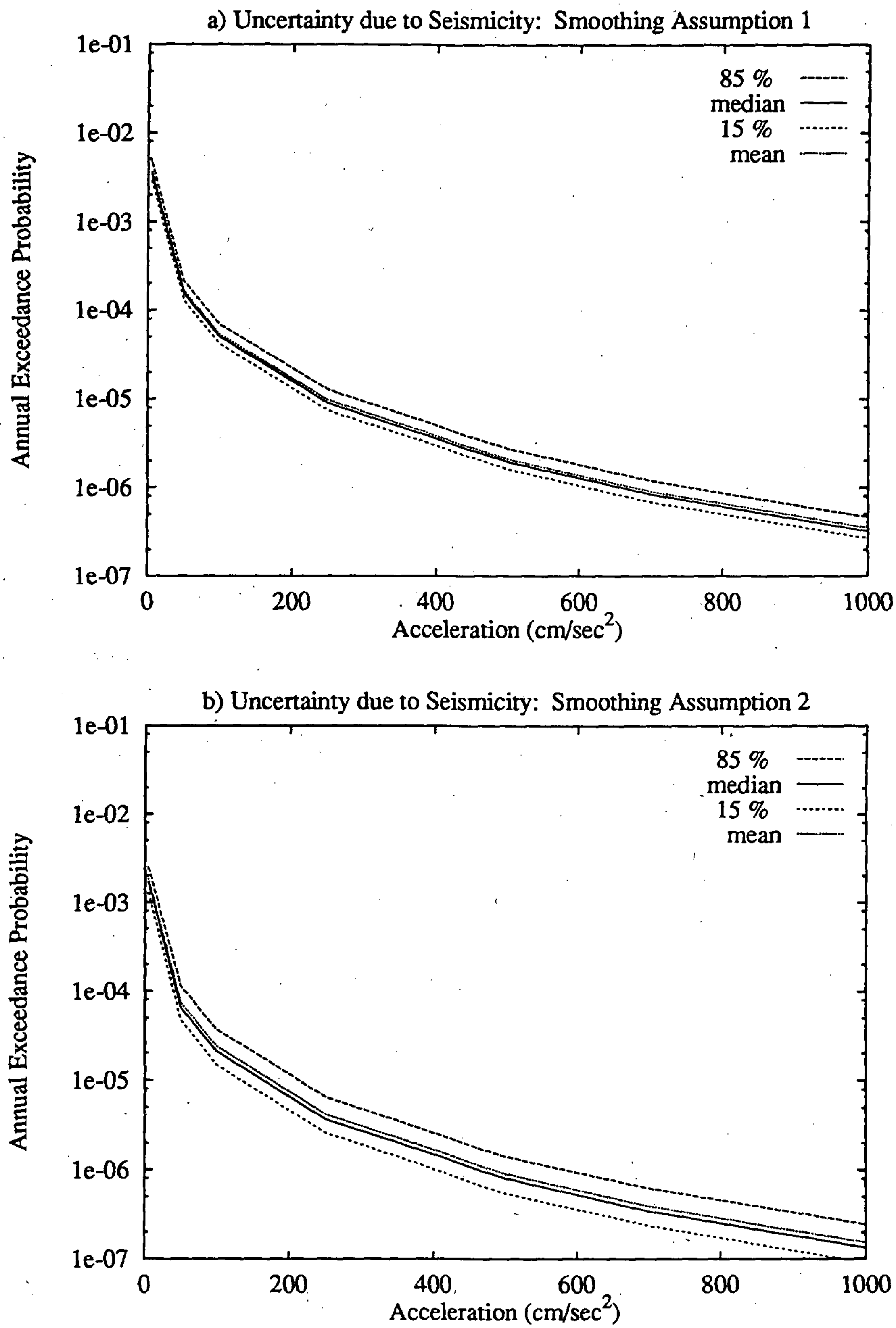
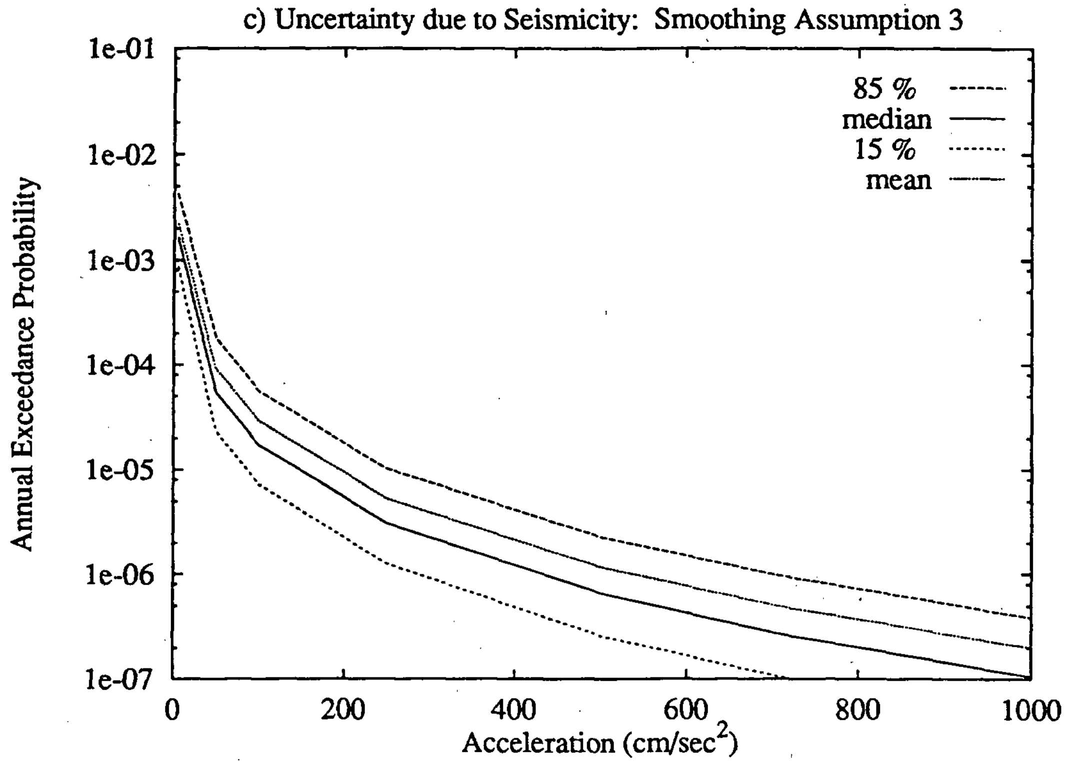


Figure I-11. Seismic hazard results for central Minnesota site. (a) Hazard under smoothing assumption 1. (b) Hazard under smoothing assumption 2. Fractiles indicate effect of statistical uncertainty in seismicity parameters.



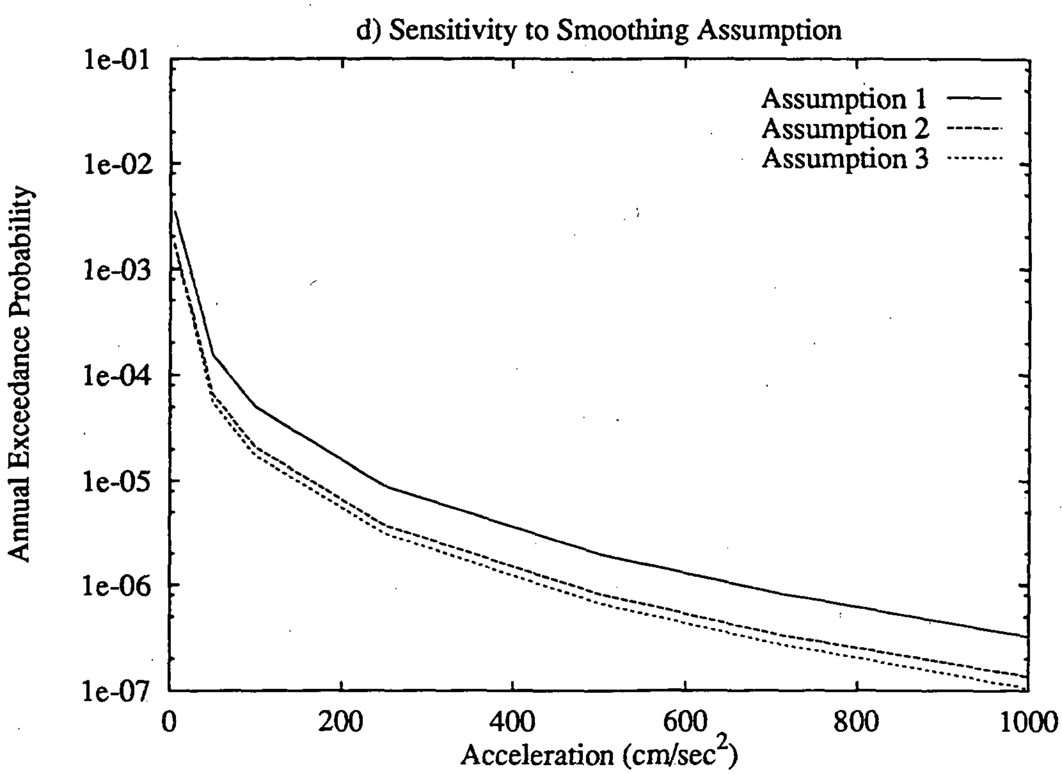
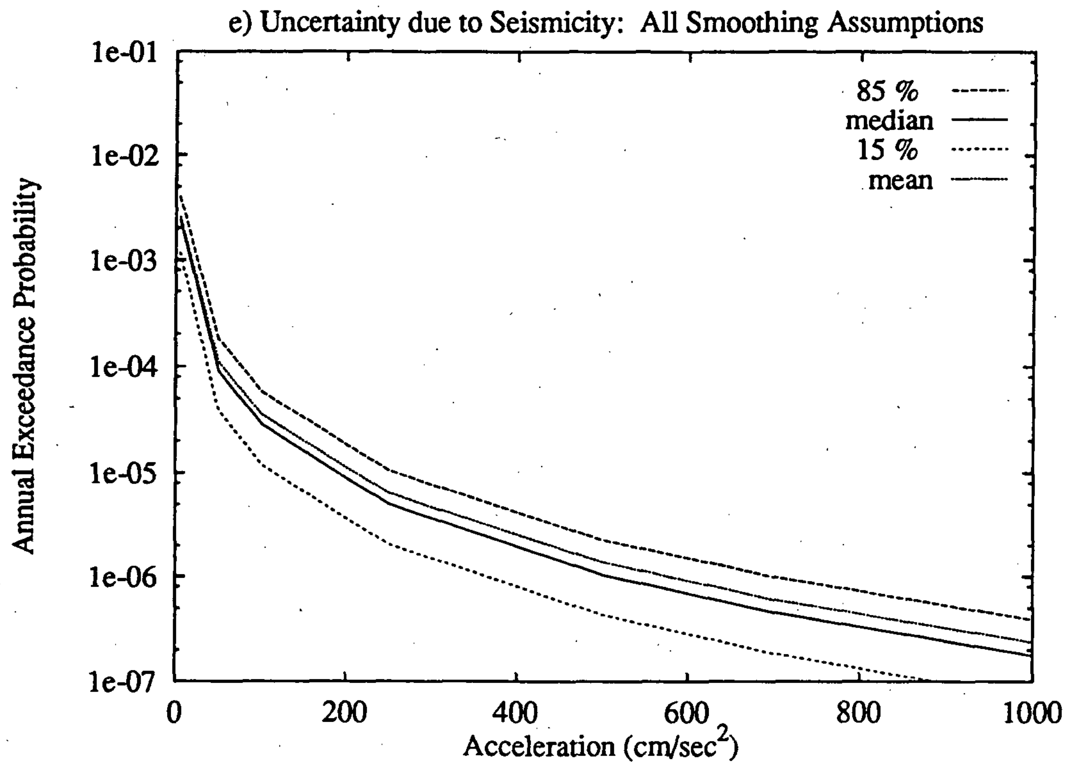


Figure I-11 (continued). Seismic hazard results for central Minnesota site. (c) Hazard undersmoothing assumption 3. (d) Sensitivity of the hazard to smoothing assumptions.



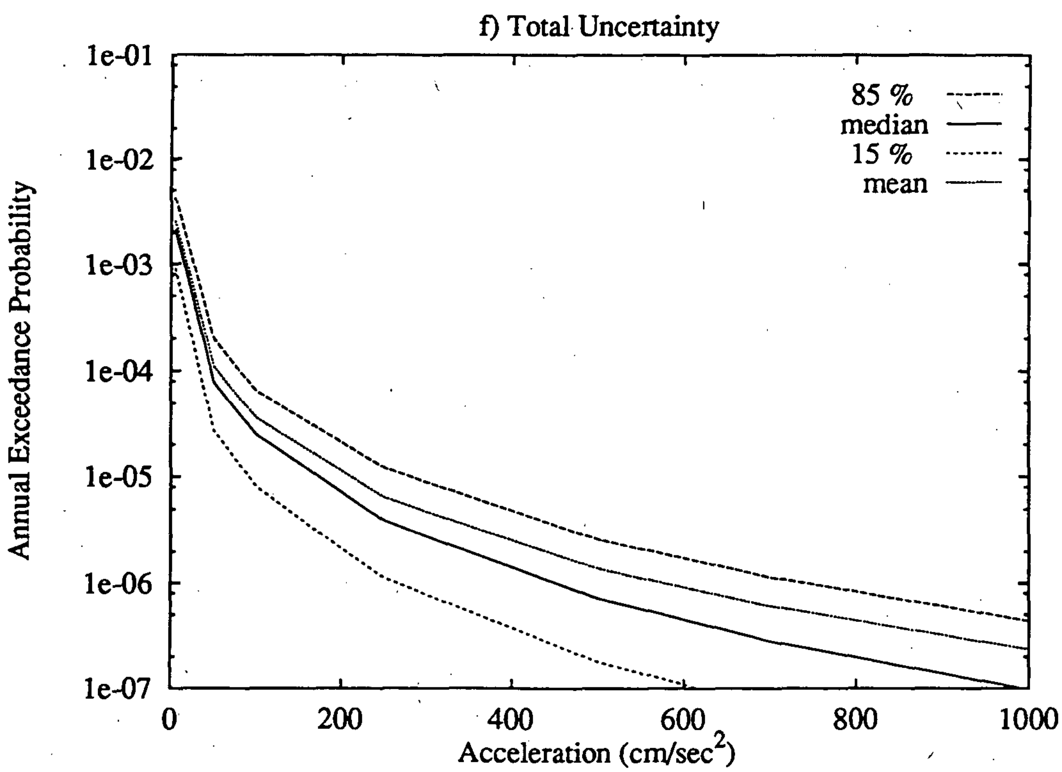


Figure I-11 (continued). Seismic hazard results for central Minnesota site. (e) Uncertainty due to smoothing options and statistical uncertainty in seismicity parameters. (f) Total uncertainty in hazard.

APPENDIX J

GUIDANCE ON TFI PRINCIPLES AND PROCEDURES

This appendix contains guidance to supplement Chapter 3 in four areas. Section 1 describes a more detailed perspective on historical approaches to the multiple expert problem, Section 2 provides additional facilitation guidance and Section 3 provides additional integration guidance. Section 4 presents details of the two stage elicitation process and Section 5 a simplified model of the TFI process. Some of the discussion in this section has been sprinkled throughout Chapter 3 of the main body of the report, but much of the appendix contains new details for the practicing TFI and TI. The partial redundancy in this appendix is recognized; it is necessary to make the report a more useful reference document for various types of users.

Section 1. Guidance on Historical Approaches to the Expert-Use Problem

This section provides additional detail on the literature on expert-use schemes. One of the principal reasons for introducing the TFI concept lies with the step that deals with the aggregation of the elicited information. To place the TFI approach in perspective, it is useful to review existing aggregation approaches.

Historical Aggregation Schemes

Historically, two basic types of aggregation processes have been used:

- Mathematical Schemes, in which expert inputs are combined using a mathematical formula, and
- Behavioral Schemes, in which aggregation is accomplished through consensus or some type of qualitative argument.

A great variety of mathematical schemes have been proposed and reviewed in the literature, e.g., in (Cooke, 1991; Genest and Zidek, 1986; Clemen, 1989; and Lindley, 1988). They include linear and logarithmic opinion pools, weights on the parameter values of underlying probability distributions, and Bayesian models.

Most behavioral schemes are centered around some type of consensus process in which the group through either structured or unstructured interaction is given the task of reaching a consensus. A number of such schemes have been discussed in the literature, e.g., in (Meyer and Booker, 1991). They include Delphi methods (Linstone and Turoff, 1975) and expert "information" (rather than "opinion") focused group interaction (Kaplan, 1992).

In seismic hazard analysis, both mathematical and behavioral schemes have been used. The analysts typically decide at which level aggregation will take place (e.g., at the ground-motion level or at the overall seismic-hazard level) and they employ mathematical combination formulas either explicitly (e.g., equal or unequal weights on expert probability distributions) or implicitly (e.g., throwing out outliers, implying zero weights, or Monte Carlo sampling implying equal weights).

Mathematical aggregation has several advantages. The logic is transparent and completely checkable. Combination formulas can isolate and separate specific assessments of dependence, expertise, and overlap, so that sensitivity studies are straightforward. Unfortunately, given the current state of the art, there are several substantial disadvantages to mathematical aggregation, at least if applied in a cookbook fashion. Mathematical models are not advanced enough to include all the factors that are important. A survey of the literature on this subject reveals that each model makes assumptions that may be only partially relevant to the problem at hand; worse, important considerations, such as the degree of interdependence of the expert inputs, are either not handled at all by most models or are addressed in a very limited way. This view is consistent with Winkler's statement (Statistical Science, 1986): "My own feeling is that different combining rules are suitable for different situations, and any search for a single, all-purpose, "objective" combining procedure is futile." Similarly, Kaplan (1992) states: "Needless to say, the expert opinion "problem", so called, is never going to be 'solved' by any single mechanical or cookbook-type procedure. The expert information approach should be viewed as one more tool in the toolbox. A skillful user will create the right mix to fit each situation and his or her own style."

Consensus processes are designed to encourage a group to reach consensus. The major advantage of this scheme is that, if the information exchange is full and unbiased, and if the result truly reflects each expert's state of information, then the consensus result is credible and non-controversial. Unfortunately, there are several problems with such methods. The overriding concern is whether the result is a true consensus that accurately reflects the diversity of education, experience and reasoning within a group, or whether it is more the result of negotiation. The result may also depend strongly on personalities, with the more forceful experts overwhelming the less forceful ones. There is also the risk of suppressing uncertainty; it is easy for a group to fall into the trap of suppressing discussion of differences and focusing on points of agreement, because it is a more comfortable process.

Should consensus be an objective? Recall the discussion in Chapter 3 of the four types of consensus. In theory, where there are unsettled technical issues, consensus of type 1 or 2 ("technical consensus"} should rarely occur. In practice, technical consensus is better viewed as a convenient result, not as an objective. Moreover, to get a high-quality and non-controversial representation of the state of information of an expert community, it is important to include a wide range of expert opinion, which tends to inhibit technical consensus but does not necessarily inhibit consensus of types 3 and 4. SSHAC believes that is very important, whatever process is used, not to force unwarranted consensus of any kind that appears to be agreement but that does not reflect the state of information of any reasonable individual or group.

Section 2. Guidance on Facilitation

This section lists a number of useful facilitation tips and traps designed to help the TFI accomplish the thorough interaction required by the SSHAC process. It is must reading for would-be TFIs.

<u>Emphasis on Interaction</u>

The TFI must conduct structured, facilitated discussions in which the focus is on underlying models and hypotheses, rather than on individual experts. Viewing the individuals as experts who provide evaluations of data and models for the TFI is an attractive alternative compared to the view of experts as advocates of their own models or assessments.

Basic elements of the TFI elicitation process were developed and tested in the two SSHAC ground motion workshops (documented in Appendices A and B). The workshops generated much useful information exchange and provided information directly useful for the TFI. Feedback from the experts who participated in those two workshops suggests that the process is viewed as a very useful one from the point of view of the experts themselves. In the course of isolating sources of disagreement, many common points of agreement were established and a number of points of unintended disagreement were revealed. The workshop seemed to generate a great deal of clarity and new understanding on matters ranging from data to models to methodology to philosophy.

Types of disagreements

The "disagreement onion" in Figure J-1 (adapted from (Bonduelle, 1987)), illustrates the different types of disagreement that may occur among a group of experts. Experts may disagree about underlying scientific hypotheses and principles; these would be reflected in different model structures. Even for the same model structure, different experts have very different interpretations of the relevance and implications of different available data sets; this is termed data disagreement. Also, two experts who agree on the basic model structure and on the appropriate data may still disagree about the correct value of model parameters. Finally, even with agreement on models, data and parameter values, we have observed that ground motion experts may disagree substantially about the ranges of uncertainties that affect seismic hazard.

Figure J-1 also illustrates what we observed in the SSHAC workshops, namely that much disagreement at each level may be unintended due to incomplete communication among experts, and sometimes just due to simple misunderstandings (as discussed in Chapter 3, similar conclusions were reached by the organizers of the Ispra Benchmark Exercises). The TFI Team must be chosen carefully to be capable of understanding, exposing and analyzing each of the various sources of disagreement.

In addressing the potential types of expert disagreement, the elicitation and group interaction processes must be designed carefully to:

- Identify sources and kinds of disagreement;
- Eliminate unintended disagreement; and
- Promote full understanding among the experts and the TFI of all substantive disagreements.

In order to achieve these goals, the process is highly interactive and necessarily time consuming.

Thus, it is clear that the TFI must act as a scientist, as an information elicitor and as a facilitator for group interactions. The substantive expert in the TFI team is essential in clarifying and facilitating scientific interchange and in summarizing points of agreement and disagreement. It is preferable to have the TFI substantive expert lead most of the technical discussions, with the TFI normative expert taking a supporting role in the face-to-face group discussions. The substantive expert has the credibility and ability to play devil's advocate, to help the group focus on what affects PSHA and to play back key scientific points to the group.

<u>Interactive Process</u>

Chapters 4 and 5 provide step-by-step guidance for the TFI facilitation process for seismic source characterization and ground motion, respectively. Here, to illustrate the highly interactive nature of the facilitation process, Figure J-2 provides a road map of the ground motion elicitation process used in the SSHAC workshops. Note that in most stages there are group interactions and each group interaction is preceded and succeeded by TFI interaction with individual experts (these individual interactions range from informal interchanges to formal elicitations).

In the ground motion application, the group interactions are naturally organized into two group workshops (illustrated by the dotted line boxes in the figure) but the number of workshops is not as important as ensuring that every type of interaction occurs.

Asking the experts to wear different "hats" in which they view themselves at different times in the interaction as (i) proponents or defenders of a particular position, (ii) as expert evaluators of the range of different positions and as (iii) integrators who are representing the overall expert community can be very effective.

Focus on Logic before Numbers

The focus in initial interactions should be on the logic of different basic approaches, rather than on different "flavors" of the same basic approach. There should be much more dialogue at the level of structure than at the level of numbers. Over-focusing on numbers can get the group quickly fixated on too fine a level of detail; however, as the interaction evolves, numbers become increasingly useful to the extent that they show how different modeling approaches work over ranges of applications and how well they fit data.

SSHAC believes that it is important to have a large and diverse group of experts who can act as multiple evaluators to make sure that all credible points of view are represented, including all fundamental interpretations and modeling approaches. The set of experts as a group should have a comprehensive understanding of existing data and its limitations and should be capable of representing the overall expert community as a whole.

In initial group interactions, the agenda should be organized around a discussion of modeling approaches. The TFI should isolate and then focus on areas of strong agreement and disagreement. The purpose is not to achieve consensus on technical points (although that is a good outcome if it is a true consensus) but rather a detailed understanding of the rationale for underlying differences. The discussion should illuminate and eliminate any unintended disagreements. Typically, the experts will want to reconsider their estimates after the group discussion. This can be done informally (say over-night) at the workshop, but then needs to be done more carefully immediately after the workshop. Similarly, the TFI may need a round of individual interactions after the group meeting to make sure that the basis for the expert estimates is fully understood.

Active Listening

SSHAC believes that it is extremely important for the TFI to summarize points of agreement and disagreement. This is accomplished by playing back a clear summary of the conversation frequently during the meeting. A useful facilitation model is the concept of "active listening", in which a person's reasoning is not fully understood unless each listener can explain the point back to the person who made it. A useful facilitation device is for the TFI to ask experts who are having difficulty communicating to try to state each other's positions clearly. Sometimes, this is not possible, in which case the TFI needs to assist.

Experts are far more comfortable with a process in which they are not only allowed, but encouraged, to provide a full accounting of their expertise, including the data and models they rely on and details of their interpretations. Until the TFI can state each expert's position in a form agreeable to that expert, complete communication has not been achieved.

All group meetings in which experts interact require careful facilitation. It is critical for the TFI to set the right tone for the meeting. In doing so, two elements are critical:

- The purpose is not to choose the best model or answer. The experts should be made to understand that the TFI concept is founded on the premise that there is no one correct model or answer, and that the meeting will not be focused on trying to identify a single "winner" or "loser." It is very important psychologically to have the participants feel that they are not there to win or lose, but to get the important scientific and application issues out on the table for everyone to understand.

- The purpose is not to achieve technical consensus. Technical consensus may occur as a serendipitous outcome, but it is important to state explicitly that the meeting will not be a failure if consensus is not achieved. It is also important psychologically for the participants not to feel that they are contributing to a failed meeting, if everyone does not agree. Rather, it should be communicated that all the experts are credible experienced evaluators or they would not be there in the first place, and that disagreement is not only expected, but perfectly acceptable.

SSHAC strongly suggests that the TFI meet with at least several of the experts individually in preparation for group meetings. This greatly aids the TFI in anticipating potential confusions and problems, in understanding the subsequent discussion at the group level, and in helping pre-structure discussion topics and define key agenda items.

Time must be allocated for enough iteration so that the TFI can come to a full understanding of the basis for the model estimates. Roughly a month should be allocated afterwards for individual interactions among the TFI and the proponents and experts, and for final model and expert estimates.

Data

A key lesson in the SSHAC workshops was that it is crucial to dig into the details of data issues in order to understand the model results and expert positions. The goal is to see if consensus can be reached on what data should be used against which to check expert and model estimates. If, as is likely, no consensus is reached, then a clear understanding of the reasons for differences must be reached. For example, in the ground motion arena, issues that may work against a consensus include differing ideas on whether to include recordings from abutments of dams and basements of tall buildings, whether or not to include aftershock data, whether to include data that may have been affected by local geologic conditions, whether to include data collected at distances beyond the distance to the first operational non-triggered instrument, whether to include data from other geographic regions, and so on.

Resource Experts

Another essential attribute of the TFI concept is a person or small group called "resource experts." Resource experts are needed for processing expert information, technical note-taking at group meetings, providing detailed instructions to experts, disseminating results of model or PSHA runs and expert assessments, handling logistics, etc. At least one resource expert must be a substantive expert in his or her own right, who is knowledgeable on the subject matter and familiar with the data and models.

The heavy focus on intensive interaction in the TFI process implies the need for ongoing technical and administrative interaction with a large group of people. Thus, the choice of resource experts can make or break the process. It is also essential that the resource experts report directly to the TFI because the team must respond quickly to expert logistical and technical needs in order for the process to work.

Expert Buy-in

An important psychological aspect of the TFI process is that in Stage II it puts the experts in the role of integrators in which they are expected to integrate the diverse interpretations of the whole technical community. One way of viewing the process is that the experts are essentially being asked to provide the TFI with their best advice on how to integrate. Evidence from the SSHAC workshops indicates that experts are highly willing to use information from different points of view and are quite willing to learn and change their opinions, so long as they do not feel that they are being attacked personally or feel pressured to do so.

Another lesson learned from previous elicitation exercises in the seismic hazard arena, and from a large number of discussions with seismicity and ground motion experts as the SSHAC project unfolded, is that experts are very suspicious about any process that appears to be a "black box". A common concern is that mechanical schemes that are applied without much expert interaction, even equal weighting schemes, tend to look and feel to the participant like they are "reductionist". Experts are unhappy and wary if they feel as if they have been asked to summarize their entire body of professional expertise in the form of a few numbers which have unclear impacts on the final answer.

An important aspect of the TFI process is that the panel experts, as independent evaluators, must provide input to the TFI as to how they would evaluate all models, data and information. Then, as integrators, they must provide input as to how to represent the overall informed expert community. It is important that the experts understand these high-responsibility roles; if the experts feel involved, they will tend to be constructive, and rather than resisting the process, will assist it.

Another important element of the group interaction is for the experts to write down explicitly their judgment about the relative forecasting abilities of the various models and how much overlap or similarity there is between different classes of models. Verbal interaction provides a great deal of information on the rationale for why different experts place different weights on different models, but it is important to quantify these judgments both to ensure that the TFI understands the various positions and to make sure that the experts themselves are thinking consistently about the issues. Such information can be processed by the simple expert aggregation formulas described below. The survey for the second SSHAC ground motion workshop provides a starting point for such a quantification (the survey and its results are discussed in Appendix B).

When the TFI is comfortable that the bases for each model's and expert's inputs are completely understood, the TFI team should develop composite estimates and distributions. In the seismic-source-characterization arena, this may only be possible at the final-hazard-curve stage, because different expert maps preclude further disaggregation. The TFI should carefully document the rationale for the TFI estimate and present it to the experts. If resources and time are available, it is best to do this in face-to-face meetings (individually or group); if not, written feedback from the experts can be adequate.

After interacting with the experts, the TFI forms a final position/representation and then obtains feedback from each expert on whether the TFI's representation is a "fair" picture of the expert community as a whole. An effective interaction process should result in most, if not all, experts agreeing that the TFI position is a reasonable composite representation. However, each expert should be given the opportunity to document his or her own specific position as an independent evaluator. The TFI is responsible for presenting all individual positions in the project report and for defending the ultimate representation.

Expert Aggregation Checklist

The TFI must carefully consider each expert aggregation issue discussed in Section 3 below. It is especially important to evaluate the relative forecasting power of the key models and approaches, as well as the degree of dependence or correlation among the approaches (discussed below). It is also useful to apply the simplified aggregation models, described below, but these should be viewed as providing guidelines only. The value of applying these simple models, especially for TFI members who are less familiar with probability elicitation principles, is to see how each basic issue can affect the final aggregated probability distribution.

Section 3. Guidance on Integration: Issues and Models

As stated earlier, SSHAC expects that the TFI will aggregate the expert input behaviorally using mathematical models in a supporting role to gain insights into the implications of various plausible assumptions. Before addressing different models for aggregating expert judgments, we need to consider the various forms that such judgments may take in PSHA studies:

- *The experts may provide point estimates or probability distributions for a scalar quantity.* An example is an epistemic distribution on the maximum earthquake magnitude for a seismic source.

- *The experts may provide probability distributions for correlated parameters.* An example is the a and b pairs in seismicity assessment.

- *The experts may use different models to estimate a scalar.* An example is the estimation of the median value of the ground motion parameter for a specified magnitude, distance and spectral frequency.

- *The experts may provide alternative seismic source maps and their relative weights.*

- *Finally, in the TFI context, the experts may provide evaluations (possibly including weights) for a range of models and proponent positions.*

Many variations in these cases can be visualized. For example, the experts may not provide a full distribution function for a scalar, but only a point estimate with or without a statement on how confident they are in that estimate (e.g., a standard deviation or a 5-95 probability range).

These distinctions are critical to understanding which aggregation concepts or tools are applicable. For example, most of the mathematical combination formulas in the literature apply to the problem of aggregating several experts' probability distributions on a single scalar variable. However, for seismic source maps, it would be meaningless to compare one expert's "a" value defined over one source zone with another expert's "a" value defined over a differently configured source zone.

The issues below are intentionally discussed in a general context. They can be applied at different levels in the TFI process. For example, the section on equal weights is probably most useful for the TFI in attempting to create conditions for equally weighting the experts-as-integrators' (Stage II) composite representations. In contrast, the material on dependence and unequal weights is probably more useful for individual panelists acting as evaluators (Stage I), or to the TFI in educating the panelists, who will almost certainly want to weight different models and scientific hypotheses unequally (the surveys for the two Ground Motion workshops were based on the expert-use concepts described below).

The remainder of this section provides background and guidance to the TFI or TI regarding a set of important aggregation issues that are commonly encountered in practice. The issues are not intended to be a comprehensive list of all issues involved in expert aggregation. Rather, it is a minimal checklist of fundamental issues that should be addressed.

For each aggregation issue, we include a description of a simplified mathematical aggregation model that addresses it. The model is included only to provide insights; the final result should always be the result of a behavioral process (which, of course, may be a TFI decision to use a specific mathematical scheme). There is no "right" model; thus, SSHAC recommends that the TFI examine the results of application of two or more models for each issue to develop insights as to how that issue affects the aggregation process.

Important Caveat

The issue discussions are intentionally oriented towards the classical context of aggregating experts-as-proponents, not the TFI context of aggregating experts-as-integrators. The distinction is critical, but to save needless repetition, since the set of issues special to the TFI context are dealt with extensively in main report, they will be mentioned here only occasionally.

In the experts-as-proponents context, it is important to note that, in concept, the issues apply equally well to either expert interpretations or models and/or their parameter values. At a conceptual level, models or experts may be viewed as entities that provide forecasts (deterministic or probabilistic) that are, in essence, noisy observations of the real world. For simplicity, much of the text below addresses multiple-expert issues, but the very same issues underlie the use of multiple models.

Different Degrees of Expertise

Simply put, all experts are not created equal. Common sense says that different experts will have different degrees of information, experience, competence and forecasting ability, particularly when considering a specific site or geographical region. For example, two equally capable experts may have very different degrees of expertise about a particular region of the United States if one of the experts has specialized in that region and the other has not. Any meaningful attempt to represent the composite state of information of a community of experts must deal explicitly with potential differences in expertise, either by behaviorally creating conditions under which equal weighting is appropriate or in some manner unequally weighting the different expert assessments. Equal weighting schemes are dealt with separately below; here we discuss the case in which equal weighting is not appropriate.

Consider the simple case in which two proponent experts provide point estimates of some uncertain scalar quantity. Suppose, hypothetically, that the experts have been observed making similar estimates or forecasts over a long period of time (e.g., Dow-Jones levels one week in the future) and we were able to observe the difference between the actual outcome and the forecast in each case. One simple measure of expertise in this case is the standard deviation of the forecasting error. Consider the example shown in Figure J-3 in which two experts provide the point forecasts labeled E1 and E2, each with a different observed forecasting error distribution. On the right we contrast the answers that would be attained by equal weights versus weighting based on expertise. The simple model described below will show one possible way to aggregate based on expertise; however, the main point here is that common sense demands that the most reasonable aggregate forecast be shaded more towards Expert 2's forecast than Expert 1's.

In PSHA practice, of course, such empirical error distributions are rarely, if ever, available. Ground motion and seismological models change over time, and data sometimes are extremely scarce. Thus, the analysis above must be based on judgmental error distributions rather than empirical ones, but the same basic logic applies.

Outliers

An important special case of unequal expertise is experts who provide opinions that are "outliers," that is, estimates or judgments that are extreme relative to the other interpretations. Outlier opinions may be viewed as just a special case of the weighting problem in the sense that throwing out an outlier opinion has the same mathematical effect as attaching a negligible weight to that opinion. However, treatment of outlier opinions can affect the success of an integration process.

If the issue is dealt with directly, outlier interpretations can be dealt with explicitly by forming judgments about their value conditional on the logic and empirical support that is supplied. For example, if an proponent supplies an outlier estimate, and supplies a credible rationale and provides explicit supporting data and interpretations, then that estimate ought to be given significant weight. However, if the proponent cannot technically support an outlier position, then the position should be given less, if any, weight. Recall from Section 3.3.3 that in the case of a outlier panelist acting as an integrator (Stage II), the outlier issue has a special twist, i.e., whether the expert's representation is an unbiased estimate of the composite distribution of the overall expert community. In this case, as discussed earlier, the panelist may be violating the conditions for retention on the panel.

The alternative to addressing the outlier issue directly is very unattractive. Suppose that for some reason (political expediency, simplicity, etc.) an outlier proponent expert whose position leads to especially high seismic hazard is given equal weight with the other proponents. The problem here is that the outlier estimate, being by definition extreme, can greatly affect the final aggregate result. This is especially dangerous in the seismic hazard arena in which small probabilities abound: for example, if three experts assess the probability of an event to be 0.1% and one outlier expert assesses the probability to be 10%, the equal-weighted aggregate estimate is close to 2.5%, twenty-five times more than the three similar assessments!

Fortunately, there are rigorous methods for dealing explicitly with differing levels of expertise, especially among panel members; moreover, it is often possible to do this without insulting the experts or creating heated debate. One approach is to facilitate enough structured panel interaction so that experts wind up with roughly the same degree of expertise regarding the specific issue of interest. A very useful approach, which was followed in the SSHAC ground-motion workshops (Appendices A and B) is to go one stage deeper and determine the scientific hypotheses and models on which experts base their judgments and then conduct a dialogue so that aggregation can be considered at the level of models. This is good practice in general and it avoids the stigma of assigning differential weights to different individuals. (Note that in seismic source characterization, the problem is more difficult because different expert maps make direct comparisons impossible. This makes it even more critical to focus on intensive expert interaction at the level of more basic hypotheses and models.)

A Simple Mathematical Aggregation Model for Independent Experts

This subsection will describe the well known Bayesian Normal model for independent experts who provide a point of a scalar quantity. This model and others presented here are based on variants of the multivariate Normal model developed by Winkler (Winkler, 1981) and the Conditional Likelihood model developed by Clemen and Winkler (Clemen and Winkler, 1992). Later, we will discuss the implications of experts providing full probability distributions. A model specially tailored to the TFI process in which expert judgments are viewed as samples of the overall expert community is also treated separately below.

This independent-experts model and the following simplified aggregation models are presented, not as mechanical methods for calculating the final composite distribution, but rather as sensitivity analysis tools for the TFI to use to develop insights for a given application into the relative importance of the different basic aggregation issues. The TFI should perform extensive sensitivity analyses by exercising a set of alternative aggregation models over a wide range of assumptions. Examples of expert-aggregation sensitivity analyses are found in [Chhibber, et. al., 1994].

The Bayesian model treats an expert's estimate as a noisy observation of the real world and the aggregation formula is derived as a simple linear-weighting formula where the weights are equal to the precision (the reciprocal of the variance) of the experts' forecasting error distributions. The variance is judgmentally assigned by an informed evaluator (TI or TFI).

For convenience, consider the case of three independent experts (the formulas are easily generalizable) who provide estimates of some uncertain quantity, μ:

$\mu_1 = \mu + \varepsilon_1$	Expert 1's estimate
$\mu_2 = \mu + \varepsilon_2$	Expert 2's estimate
$\mu_3 = \mu + \varepsilon_3$	Expert 3's estimate

Here, the ε_i's denote forecasting errors equal to the difference between the estimates and the true value; for this simple model the forecasting errors are assumed to be independently normally distributed with zero mean and variance σ_i^2. The result of a Bayesian analysis is that the TFI's aggregated distribution is Normal as well, with mean,

$$\mu_* = \lambda_1\mu_1 + \lambda_2\mu_2 + \lambda_3\mu_3$$

and variance,

$$\sigma_*^2 = 1/(h_1 + h_2 + h_3)$$

where h_i is equal to the precision (reciprocal of the variance) of the forecast error of Expert i,

Forecast precision: $h_i = 1/\sigma_i^2$

The result assumes a "non-informative" prior distribution, i.e., that the TFI does not introduce any of his own prior judgment into the estimates. The weights (λ_i's), which sum to unity, are computed as the relative precisions in each forecast:

Weight for Expert i: $\lambda_i = h_i/(h_1 + h_2 + h_3)$

Note that the weights have a specific meaning: they reflect each Expert's judged (by the TFI) precision as a forecaster. They are not *ad hoc* probabilities of "correctness," but well defined judgments. In this simplest model, the TFI must form one judgment per weight. If, as in many applications, the experts provided an entire distribution (in the Normal context, a mean and variance), the TFI could interpret the width (e.g., standard deviation) of the distribution as an indication of the expert's confidence in his or her own forecasting ability. The TFI could, of course, adjust this number based on an assessment of whether the expert was a biased estimator of his own forecasting precision.

The three tables below provide numerical examples of how the model works. The first table assumes that two experts provide mean estimates of 60 for some uncertain quantity, while a third expert estimates the quantity at 120. The experts are judged *a priori* to be equally accurate -- each expert's forecasting accuracy, measured here by the standard deviation of his forecast error, is assumed to be equal to 30.

Independent Experts: Case 1 -- Equal Forecasting Accuracies

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	80
Accuracy (std. dev.)	30	30	30	17
Calculated Weights	0.33	0.33	0.33	1.00

Note that the aggregated estimate is equal to the weighted average of the three expert estimates and that equal accuracies results in equal weights. The next table shows an example in which Expert 3 is judged to be more accurate than Experts 1 and 2:

Independent Experts: Case 2 -- Unequal Forecasting Accuracy

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	92
Accuracy (std. dev.)	30	30	20	15
Calculated Weights	0.24	0.24	0.52	1.00

For comparison, here is an example in which Expert 3's accuracy is even higher relative to the other two experts:

Independent Experts: Case 3 -- Larger Difference in Forecasting Accuracy

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	109
Accuracy (std. dev.)	30	30	10	9
Calculated Weights	0.09	0.09	0.82	1.00

The tables show that the weights are *not* simply proportional to the experts' judged accuracies. Although the independent-expert model is simplified, it illustrates the danger of having experts assign weights without instruction. It is preferable to have the TFI and/or the experts to first form explicit judgments about forecasting accuracy, and then use these judgments to determine the appropriate weights.

One consequence of the independent-additive error model is that as the number of experts goes up, the posterior standard deviation of the estimate goes to zero. If the experts were truly independent estimators of a single parameter, this would not be counter-intuitive, but it is difficult to think of real multiple-expert cases in which this would-be satisfactory result: simply adding experts to a panel typically does not ensure elimination of all uncertainty. The non-independent-expert model presented in the next section provides a partial resolution of this issue. Later, we will introduce a model in which the posterior standard deviation does not go to zero as the number of experts is increased, but rather converges (in the simplest case) to the average variance of the expert distributions.

Further, it is clear that the aggregated standard deviation is <u>independent</u> of the diversity of the experts' point estimates (the μ_i's). Whether these values are equal or widely separated, the aggregate accuracy or precision is calculated to be the same. This conclusion, which also seems contrary to the natural reaction to such observations, created the motivation for the TFI model presented at the end of this appendix.

Non-Independent Experts

The issue of non-independence among experts is critically important because it significantly affects both the aggregated estimate and the amount of uncertainty that one associates with the estimate. It has been the single most difficult practical issue in applications (Morris, 1977; Winkler, 1981; Chhibber and Apostolakis, 1994), which have traditionally placed experts in a proponent role.

The discussion below has two very different purposes: First, to provide the underlying analytical basis for the TFI process, which aims at achieving strong, but roughly equal, interdependence among panel members. Second, to provide a discussion of issues that must be dealt with in aggregating judgments of *proponent* experts who have not been exposed to a carefully structured TFI-like interactive process. To avoid repetition, and for clarity, the discussion below assumes that the experts are proponents (*not* evaluators or integrators); we assume that the interested reader will see the relevance to the design of the TFI process.

Explicitly dealing with dependence among proponent experts is in many ways the toughest expert integration issue of all. Stated simply, the degree of overlap in expert data bases and/or models and reasoning processes can significantly affect the ability to integrate the knowledge of a group of experts. Here is a simple example: two expert weather forecasters use different methods and data to come up with two forecasts of rain of 20% and 80%. If the experts are equally credible, you might conclude that you should average the two estimates to obtain a "best estimate" of 50%. Suppose then that a third forecaster says 80%. How does this affect your state of information? Common sense says that it matters a great deal whether the third forecaster provided an independent forecast or simply used the same data and reasoning as the other 80% expert.

The generally accepted decision analysis definition of expert dependence (Morris, 1974) is based on a conditional probability statement: two experts E1 and E2 are considered to be dependent when the probability distribution on E2's estimate (before he or she provides it), *given the true value of the variable of interest*, depends also on E1's estimate. In other words, E2's estimate is correlated, not only with the true value, but also with E1's estimate.

Researchers on expert use have proposed a large number of models of expert dependence consistent with the general definition, ranging from very simple to extremely sophisticated (one of the simplest models is described below). However, while the details of the models vary, they all strongly support the assertion that understanding the degree of dependence among the group of experts is essential to determining how to integrate their judgments. Yet, dependence is often ignored in many expert combination formulas, probably because it is difficult to think about, much less quantify.

Non-independence results from at least four sources: overlapping data, overlapping methodology, direct observation, and exchange of viewpoints. These relationships between expert judgments (or models) that result in non-independence are illustrated in Figure J-4.

Overlapping data result from the fact that in most situations most experts have access to the same basic information and are basing their opinions on roughly the same body of data. Overlapping methodology exists, if experts in the field have similar academic and professional training or read the same literature. In this case, even if experts observe different data, they may be expected to employ many of the same modeling methods or modes of thinking. The peer review process in the scientific community also causes dependence among experts. The direct observation of other expert opinions, the presentation of public reports to the scientific community, and the open discussion of viewpoints and hypotheses will add to the overlap among expert judgments.

It is important to distinguish between two cases: 1.) two experts who, acting as informed evaluators, happen to choose the same model, estimate or data set, and 2.) two experts, one of whom simply "parrots" the other's estimate without independent thinking. In the first case, the experts performed independent evaluations, and are not (necessarily) probabilistically dependent in the sense defined above, since *a priori* they were not constrained to use the same model. In the second case, the two experts are clearly completely dependent, since *a priori*, knowing the first expert's estimate also specifies the second expert's estimate, regardless of the true state of the world. Robin McGuire provides an example of five experts, four of whom believe that F=MA, and one of whom believes that $F=M^2A^2$. Can the last expert make the case that his method deserves 0.5 weight because the first four experts are dependent (they employ many of the same modes of thinking, etc.)? The answer is "no" because the four experts independently arrived at their common choice of modeling methods. Ultimately, the presumption of dependence or independence among experts must be a judgment call that the TFI must make and defend.

In the case that a subset of experts happen to choose the same model, the credibility of that model becomes especially important. Instead of assessing the degree of dependence among the expert estimates, [Bonano and Apostolakis, 1991], and [Chhibber, Apostolakis, and Okrent, 1994] propose that the model itself be considered as the "expert," with the estimates of the experts being treated as independent evaluations of the credibility of that model. A decision to use this type of approach will have to be made by the TFI based on the evidence that is available regarding the source of dependence of the expert estimates. It also demonstrates, once again, that no mechanistic mathematical aggregation schemes can be chosen *a priori* and that the TFI must evaluate the totality of the available evidence.

A simple example of the potentially large impact of dependence is shown in Figure J-5. Consider three experts who, for the sake of argument we shall assume are believed to have equal expertise, so that other than issues of dependence, equal weighting would be appropriate. Suppose E1 provides a probability of 0.1 for an event and E2 and E3 say that the probability is 0.9. If the experts were completely independent, then a simple average would imply an aggregated probability of 0.63. However, suppose that the latter two experts are completely dependent (e.g., imagine that the three experts are weather forecasters, and that expert 3 simply listens to expert 2's weather forecast and adopts it as his own). Then, clearly, expert 3 is redundant and the best estimate would be a simple average of expert 1 and expert 2's probabilities, or 0.5. The redundancy of additional experts when there is strong dependence is discussed more generally in [Clemen and Winkler, 1985].

In simple terms, failing to take into account dependence or correlation among experts results in double counting. In the seismic hazard field in which seismologists and ground motion experts are generally intimately aware of others' models and databases, there is likely to be a large amount of non-independence among proponents, so that this issue is not merely theoretical. For example, in the second SSHAC ground motion workshop, seven ground motion experts were asked to judge the amount of correlation among estimates that they provided and the correlation was significant (see Appendix B).

A Simple Mathematical Dependent - Expert Model

Here we present one of the simplest expert-aggregation models that explicitly addresses the issue of dependence among the experts -- the Normal-linear-dependence model. The basic result is that the impact on the composite distribution of an additional expert is a function of how correlated that expert is with other experts. Basic references include [(Clemen, 1987); (Winkler, 1981); (Clemen and Winkler, 1992); (Morris, 1977); and (Apostolakis and Mosleh, 1986)].

Once again, the model treats an expert's estimate as a noisy observation of the real world; in this model, however, the errors inherent in the experts' estimates are probabilistically interdependent in a simple linear way, as follows

$\mu_1 = \mu + \varepsilon_1$

$\mu_2 = \beta_2 \mu + \alpha_{21} \mu_1 + \varepsilon_2$ where $\beta_2 = 1 - \alpha_{21}$

$\mu_3 = \beta_3 \mu + \alpha_{31} \mu_1 + \alpha_{32} \mu_2 + \varepsilon_3$ where $\beta_3 = 1 - \alpha_{31} - \alpha_{32}$

Once again, the epsilons denote forecasting error, normally distributed with zero mean and variance σ_i^2. However, now, the forecasting error is conditional on knowledge of, not only the true value μ, but also on knowledge of the preceding experts' estimates. The α_{ij}'s and the σ_i^2's capture the degree of dependence or "overlap" with each of the preceding experts, and the β_i's may be thought of as the degree of independence or non-overlap with the preceding experts. For example, setting α_{21} equal to 0.5 would indicate that the TFI believes that Expert 2's estimate is equally dependent on the true value and on Expert 1's estimate -- alternatively, Expert 2 has a 50% overlap with Expert 1. Setting α_{21} equal to 1.0 would indicate the belief that Expert 2 simply repeats (without independent thinking) Expert 1.

The result (not derived here) of the Normal-linear dependence model is that the TFI's aggregated distribution is also Normal with mean:

Aggregated mean: $\mu_* = \lambda_1\mu_1 + \lambda_2\mu_2 + \lambda_3\mu_3$

and precision/variance:

Aggregated precision: $h_* = h_1 + \beta_2^2 h_2 + \beta_3^2 h_3$
Aggregated variance: $\sigma_*^2 = 1/h_*$

where, as in the independent case, the weights sum to unity (a *result*, not an assumption). But, now the weights depend on the specific assessments of dependence (the α_{ij}'s) as well as the assessed precision of the forecasts (the h_i's):

$\lambda_1 = (h_1 - \beta_2\alpha_{31}h_2 - \beta_3\alpha_{31}h_3)/h_*$
$\lambda_2 = (\beta_2 h_2 - \beta_3\alpha_{32}h_3)/h_*$
$\lambda_3 = (\beta_3 h_3)/h_*$

The above model was developed by Clemen and Winkler (1992). We propose a simple variant in order to simplify the assessment task. A difficulty with using the model directly is that the forecast error distribution for each expert is, by definition, conditional on knowledge of the predecessor expert estimates. Unfortunately, the variance or precision of these conditional densities do not reflect particularly intuitive quantities. Logically, by the rules of probability, the conditional variance must be less than the unconditional variance; however, it is unlikely for someone to have relevant experience on which to base this judgment (it depends, not only on an expert's individual forecasting ability, but also on his interdependence with the specific experts in the group). A more natural quantity to think about would seem to be the unconditional variance, which is a measure of each expert's individual forecasting accuracy, independent of the other experts. Assessment of the unconditional variance could be related to relevant experience gained by comparing past expert forecasts and actual outcomes. It turns out that the conditional variances can be calculated from assessments of the unconditional variances and the α_{ij}'s. Thus, in the remainder of this appendix, including the examples below, the assessments are assumed to be judgments of *unconditional* forecasting accuracy (which are translated to conditional variances for use in the above formulas -- we omit the details for brevity).

The example below is identical to "Independent Experts: Case 1," except that Expert 2 is assumed to be 50% dependent on Expert 1 ($\alpha_{21} = 0.5$, $\alpha_{31} = \alpha_{32} = 0.0$):

Dependent Experts: Case 1 -- Experts 1 and 2 Dependent

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	86
Accuracy (std. dev.)	30	30	30	20
Dependence on Expert 1		0.5	0.0	
Dependence on Expert 2			0.0	
Dependence on true value	1.0	0.5	1.0	
Calculated Weights	0.29	0.24	0.52	1.00

In comparison with the independent-expert case, the effect of dependence between Experts 1 and 2 is to shade the result more towards Expert 3, reflecting the model's implicit elimination of "double counting" the redundant information shared by Experts 1 and 2. Next, we consider the effect of increased dependence between the first two experts.

Dependent Experts: Case 2 -- Increased Dependence Between Experts 1 and 2

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	89
Accuracy (std. dev.)	30	30	30	21
Dependence on Expert 1		0.90	0.0	
Dependence on Expert 2			0.0	
Dependence on true value	1.0	0.10	1.0	
Calculated Weights	0.26	0.26	0.49	1.00

Increasing the dependence between Experts 1 and 2 results in an aggregated estimate even closer to that of Expert 3. Dependence of 0.9 is close to complete informational overlap; in fact, the aggregated estimate of 89 is close to the estimate of 90 that would be obtained by ignoring the one of the two dependent experts. Thus, the dependent-expert model effectively avoids double counting two overlapping information sources. Note also the effect on aggregate accuracy.

The next example illustrates a case in which all three experts are correlated, with Expert 3 having a 25% and 50% interdependence with the first two experts.

Dependent Experts: Case 3 -- Dependence Among All Three Experts

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	74
Accuracy (std. dev.)	30	30	30	23
Dependence on Expert 1		0.25	0.25	
Dependence on Expert 2			0.5	
Dependence on true value	1.0	0.75	0.25	
Calculated Weights	0.41	0.35	0.24	1.00

Notice that, not only is Expert 3 downweighted due to the dependence, but that the aggregated variance is increased relative to the cases with less expert interdependence. In general, as experts are added to a group, we would expect them, after a point, to have less and less independent knowledge (lower α_{ij}'s). In the limit, as the dependence on the true value goes to zero, the incremental reduction in the final variance diminishes to zero. Thus, explicitly modeling expert dependence offers a partial solution to the problem of artificially low variances. However, it does not address the intuitive observation that if n experts agree on an estimate and on a range (i.e., they concur on the forecast and on the forecast uncertainty), the aggregated estimate ought to have the same range. Moreover, the aggregated accuracy is insensitive to the diversity among estimates. We will return to this issue in the final section.

In summary, even with dependence, the aggregated estimate is always a weighted average of the individual-expert estimates. Just as in the independent-expert case, the weights have specific underlying interpretations. They depend on two types of parameters: 1.) a parameter that reflects each expert's judged precision as an individual forecaster, and 2.) parameters that reflect each expert's degree of knowledge overlap with the other experts.

An alternate, and equivalent, formulation of this model is in terms of multivariate normal distributions. In the simple case of two experts, the likelihood function in Bayes' theorem is the bivariate normal distribution with three parameters, i.e., σ_2 (the standard deviation for expert 1, which is the same as that for ε_1 of the preceding model: σ_2, the standard deviation for expert 2, which is the same as that for ε_2; and ρ, which is the correlation coefficient. It is easy to show that α_{21}, the measure of dependence in the preceding model, is equal to $(\rho\sigma_2)/\sigma_1$. The expressions for the posterior variance and precision are just as before, with the appropriate change in β_2. The weights are now:

$$\lambda_1 = (h_1/h_*) \{(1 - \rho\sigma_1/\sigma_2)/(1 - \rho^2)\}$$
$$\lambda_2 = (h_2/h_*) \{(1 - \rho\sigma_2/\sigma_1)/(1 - \rho^2)\}.$$

Once again, we see that equal weights require that the precisions of the two experts be equal (i.e., σ_1 and σ_2 must be equal). For more than two experts, these results can be generalized using matrices.

A criticism of these simple models is the requirement of assessing the numerical values of the parameters. Some guidance is available, e.g., the correlation coefficient can be assessed using expressions for the concordance probability given in the literature [Gokhale and Press, 1982]. In fact, given the large uncertainties in risk assessments, [Chhibber and Apostolakis, 1993] utilize concordance probabilities to show that high accuracy in assessing ρ is not required. For the TFI, high accuracy is not critical, because the TFI team is using these models only to conduct sensitivity analyses and, thus, to gain insights into the impact of various sets of assumptions (the preceding tables are examples of such analyses; for further examples, see[Chhibber, Apostolakis, and Okrent, 1994]).

Equal Weights

The issue of whether to aggregate expert judgments or model results using equal weights is really just a special case of the unequal weights implied by explicitly taking into account differing degrees of expertise. However, because the practice of equally weighting expert judgments has been so prevalent in past seismic hazard and other public policy studies, it deserves special attention.

The attraction of equal weights is that it avoids at least two extremely difficult issues:

- No one is forced to make what can be a very politically charged judgment (who is the best expert?)

- No one is forced to make what can be very difficult assessments (if not equal weights, what?)

The equal weights approach is simple to apply. Basically, it involves taking a simple average of expert estimates, probabilities or probability distributions. But, the simplicity can be deceptive. Figure J-6 illustrates that there are at least three types of averages that may be taken. The second two, equally weighting fractiles of distributions and equally weighting moments or other statistics (e.g., means and variances) of distributions are two common mistakes that should be avoided. As indicated in the figure, they both can grossly underestimate the appropriate amount of uncertainty in the aggregate distribution. If equal weights are to be applied, they should be applied to distributions. But the figure shows one immediate problem which we will discuss in detail below, namely that the resulting shape of the aggregate distribution may be an artifact of the equal weighting scheme and may have no intuitive or physical basis.

It is worth repeating that a desirable outcome of the TFI facilitation process with its emphasis on shared information and heavy interaction is the situation under which equal weights are appropriate. However, it is essential to understand and detect the presence of such a condition.

In the traditional context of weighting proponent experts or models, there are two fundamental issues to address in considering equal weights (a third issue particular to the TFI process, whether the expert-as-integrator evaluations are representative of the overall expert community was discussed in Chapter 3). As discussed in the dependence section above, if proponent experts are correlated, then applying equal weights implicitly double counts the data and models they have used. However, this is not a problem if all the correlations are roughly equal in magnitude (see mathematical model below). Second, application of equal weights assumes that there are no substantive differences in the relative expertise among the different experts -- they may have differences in specialized knowledge for the application at hand, but they should be equally credible as scientists.

Assigning equal weights to proponent positions is not a benign assumption, especially if one position is an outlier. Equal weights on probabilities or probability distributions is not equivalent to equal weights on the underlying scientific hypotheses (which is generally unrealistic in itself!). Actually, equal weights can be quite biased towards the composition of the set of experts being evaluated. If two experts out of ten form estimates based on similar scientific hypotheses (ways of thinking, modeling approaches, etc.) and eight experts condition on another hypothesis, then equal weights is essentially giving 20% weight to the first hypothesis and 80% weight to the second hypotheses. In other words, the answer would depend on the specific composition of the group. Thus, deciding a priori on an equal-weighting-type scheme makes the decision as to whom to weight especially important (indeed, absolutely critical if there is not intensive expert interaction).

The bottom line with equal weight methods is that they are legitimate if they are the result of a more sophisticated analysis, but they should never be assumed without close scrutiny. If after detailed analysis and interaction, it is believed that a set of experts is roughly equally credible and roughly equally interdependent, then equal weights may be appropriate. But equal weights should not be preordained.

The above observations indicate why the TFI process is designed to provide an explicit mechanism for ensuring comprehensive and detailed information exchange that moves the panelists towards equal expertise and high, but equal interdependence for the application at hand. Without this information exchange, using equal weights on the positions of an expert panel can introduce systematic errors into the final hazard curve.

A Simple Mathematical Model for Evaluating Equal Weights

This section illustrates how the simple expert-aggregation models described above can be used to estimate, for different degrees of correlation and forecasting uncertainty, how much error results from assuming equal weights. A variant of the dependent-experts model represents the dependence among the experts with a multivariate Normal distribution, parameterized by a mean vector and a covariance matrix (Clemen and Winkler, 1985; Clemen and Winkler, 1992). The covariance matrix can be specified with a vector of variances (individual forecasting accuracies) plus a correlation matrix in which each entry is the correlation between a pair of experts' estimates. For brevity, we state without proof the intuitive notion that equal weights will result *if and only if all the correlations between different pairs of experts are equal and all experts are judged to be equally accurate estimators.* In other words, the degree of interdependence among any pair of experts must be exactly the same as that between any other pair. The correlations can be calculated from the assessments of accuracy and dependence described in the dependent expert combination models above. Case 1 below illustrates one example of equal weights resulting from equal assessed accuracies and equal assessed correlations. The top table lays out an example set of assessed inputs; the lower table gives the calculated (equal-correlation) correlation matrix.

Equal Weights: Case 1 -- Equal Correlation Among All Expert Pairs

	Expert 1	**Expert 2**	**Expert 3**	**Aggregated**
Estimate (mean)	60	60	120	80
Accuracy (std. dev.)	30	30	30	24
Dependence on Expert 1		0.5	0.33	
Dependence on Expert 2			0.33	
Dependence on true value	1.0	0.5	0.33	
Calculated Weights	0.33	0.33	0.33	1.00

Equal Weights: Case 1 -- Calculated Matrix of Correlations

	Expert 1	Expert 2	Expert 3
Expert 1	1.0	0.5	0.5
Expert 2	0.5	1.0	0.5
Expert 3	0.5	0.5	1.0

A common mistake is to assume that equal forecasting accuracy is the only necessary condition for equal weights. The table below shows for equal forecast accuracies (standard deviation of 20) how the calculated weights vary as a function of differences in expert correlations. The table was constructed by assuming that Expert 3 is uncorrelated with Experts 1 and 2 and then calculating the weights resulting from varying the correlation (ρ) between Experts 1 and 2.

Equal Weights: Case 2 -- Error Introduced by Assuming Equal Weights When Experts are Not Equally Correlated

	Expert 1	Expert 2	Expert 3	Aggregated
Equal Weights	0.33	0.33	0.33	80
ρ = 0.25	0.31	0.31	0.38	83
ρ = 0.50	0.29	0.29	0.43	86
ρ = 0.75	0.27	0.27	0.47	89
ρ = 1.00	0.25	0.25	0.50	90

For example, if equal weights were applied in a case where Experts 1 and 2 were actually 75% correlated, the resulting estimate would be over 10% too low (80 rather than 89). This case is intentionally extreme; in most real applications the error would be much smaller.

Non-Equal Weights

In practice, the weights assigned to expert judgments often appear in one of two forms: the linear opinion pool and the logarithmic opinion pool [Genest and Zidek, 1986; Cooke, 1991]. To make the discussion concrete, let $p_1,\ldots,p_n$ be the set of probabilities that n experts supply for an uncertain event (these are analogous to the point forecasts discussed above), and let $w_1\ldots,w_n$ be the weights that are assigned to these experts by the TFI (their sum is equal to unity). Then, the linear opinion pool (see the simple mathematical model above) gives the aggregated probability P of this event as:

$$P = \sum_{i=l}^{n} w_i \, p_i$$

while, the logarithmic opinion pool calculates it as:

$$P = [\prod_{i=1}^{n} (p_i)^{w_i}] / \{[\prod_{i=1}^{n} (p_i)^{w_i}] + [\prod_{i=1}^{n} (1-p_i)^{w_i}]\}$$

The NUREG-1150 method [Hora and Iman, 1989] is the arithmetic pool with equal weights, i.e., $w_i = n^{-1}$. It is interesting to note that, in practice, the choice of the aggregation method is primarily dictated by the numerical values of the p_i's, i.e., when they differ significantly, analysts tend to use the logarithmic pool. Unfortunately, this decision is arbitrary, and its impact on the results can be at least as significant as the choice of the expert weights.

There is no universally accepted approach to the determination of these weights. However, some ideas have been proposed in the literature that may be helpful.

One idea is to ask experts to self-rate themselves or, better yet, to self-weight the set of different basic approaches. Such an exercise is susceptible to the same kinds of biases that may distort probability judgments, although such self-ratings were found useful in early Delphi exercises [Linstone and Turoff, 1975] and were used by LLNL in the 1980's EUS study. A variation that may be more meaningful in PSHA is to ask the experts to quantify their relative forecasting or estimating ability. This means that, for example, they could declare themselves more competent to develop seismic source maps for certain regions of the country, while they would feel less confident in their assessments for other regions. This way, the expert is not judging his or her overall expertise, but, rather, the relative value of his or her judgments. This approach worked well in the SSHAC ground motion workshops.

An extension of the expert-supplied ratings idea is to ask the experts to rate each other's forecasting ability. There are several formal methods for using such information, but they are based on very strong assumptions [De Groot, 1974; Cooke, 1991]. Nevertheless, this type of information may be very useful to the TFI for behavioral aggregation.

An interesting approach to the determination of weights is proposed in what Cooke calls the "classical" model [Cooke, 1991]. The weights are derived by comparing the expert estimates of some unknown (to them) quantities with their actual values which are already known to the decision maker. The assumption is that the performance of the experts with regard to these "seed" or "calibration" variables would be comparable to their performance in answering questions about the unknown quantities of interest. Unfortunately, finding these seed variables for the difficult issues that are encountered in PSHA would be far from straightforward, although, in fairness, it should be stated that such an exercise has not been attempted.

It is worth repeating here that these approaches to weight estimation should be utilized by the TFI only indirectly (although the TFI may need to be more direct for seismic source characterization). The reason is that no method can capture fully the salient characteristics of every problem. In the example discussed in Chapter 3 (Figure 3.3), the TFI was required to form an opinion regarding the applicability of the disputed evidence, and did so as a function of one of the variables, something that any formal weighting scheme would have a very hard time modeling.

Level of Aggregation

A basic issue in seismic hazard analysis is at what level in the analysis to aggregate the multiple expert and model inputs. This is one issue that has a clear answer: aggregation should be performed at the most detailed level possible (for example, aggregate first at the ground motion characterization level and seismic source characterization level separately before the final hazard calculation, rather than aggregate at the hazard calculation level). The primary reason for this is that disaggregation allows focused application of expertise and engenders more debate and interaction on specific points. However, there are some important aggregation issues as well. The remainder of this section raises issues primarily of interest to the normative elicitation expert in the TFI team who needs to consider them in designing both the elicitation and integration process.

Sometimes, such as in the case of seismic maps or ground motion models with different functional forms, it is simply impossible to aggregate at a detailed level because the components are incomparable. One expert's seismic source zone map may be different than another expert's map, so that basic variables, such as activity rates, cannot be compared because they are defined over different regions. However, when experts are supplying judgments about variables that are comparable or that can be manipulated so as to be comparable (e.g., have experts compare their implied activity rate estimates for artificial zones defined by two or three concentric circles around a site), it is beneficial to address and aggregate variables at the component level.

The benefits of disaggregation make it important for the TFI to be active in seeking ways to structure the analysis so that the experts may interact to debate and compare interpretations at as detailed a level as possible. There are at least three basic reasons for aggregating at a detailed level:

- Aggregation at a high level can obscure distinctions that experts make and inhibit useful debate about more fundamental parts of the problem.
- Aggregation at a low level allows different experts to focus their specialized expertise on the parts of the problem they know best and the TFI to spend resources on the issues that are most critical.
- Aggregation at a high level can sometimes filter out important structural information and can produce a result that is logically inconsistent with information at a more detailed level.

Thus, there are both logical and process-related reasons to aggregate at a low level based on the basic principle:

> Basic principle - *The final composite distribution should be consistent with the best composite assessment on each underlying variable.*

This seemingly innocuous principle can lead to serious contradictions if it is not followed. For example, consider two uncertain variables, x and y, that everyone agrees are probabilistically independent: they have no physical relationship whatsoever to each other and there is unanimity in the expert community that the conditional distribution on y given x is equal to the marginal distribution on y. If a higher-level variable z is a function of both x and y, and if individual experts each assess both x and y, then aggregating across experts at the z level can produce a probability distribution on z that contains implicit dependence between x and y ... a relationship that *every* expert agrees is not appropriate. If the expert discussion and aggregation is performed at the x and y level, this problem is automatically avoided. Figure J-7 displays this principle graphically.

Potential issues for the TFI related to this principle are most easily described with a simple example illustrated in Figure J-8. Suppose that two experts assess the probability that a fault is active. Using the type of tectonic framework developed by EPRI, they each assess the probability of 'favorable geometry,' that is, geometry that tends to be associated with earthquakes. They also assess the conditional probability of the fault being active, conditional on whether or not there is favorable geometry (this might be thought of as scientific uncertainty). Notice that the two experts give very different marginal and conditional probabilities (the first two columns of the figure), but in both cases, the calculated probability that the fault is active is 0.2. For illustrative purposes only, suppose we agree to weight equally the judgments of the two experts. If we equally weight at the result level (i.e., the probability-of-activity level), the aggregate probability is 0.2. However, if we equally weight the three component probability assessments that the experts provide, and then calculate the probability of activity from the component probabilities, the result is a probability of activity of 0.31, which is significantly different! Also note that the composite uncertainty is different.

If the aggregation were performed at the high level, it would appear that the experts completely agreed. But this would be only because important structural information has been filtered out in performing the aggregation. In fact, Expert 2 makes a very significant distinction based on the geometry of the fault, whereas Expert 1 does not.

Aggregating at the component level helps create the highly desirable situation in which the component definitions are identical across experts. Each expert should understand his or her component probabilities in relation to the range of component probabilities. The experts should not have to worry about comparing the composite aggregate result with the aggregate of composite results.

An important practical reason for disaggregation is that without it, the experts may be forced to make assessments that mix in information about factors on which they do not have specialized expertise. One could imagine that Expert 1 as a geologist who is more familiar with the region in question and its geometry, whereas Expert 2 is a geophysicist who is more familiar with the probability of activity conditional on the underlying geometry. Common sense would be to use the geologist's probability to describe the informational uncertainty and the geophysicist's conditional probabilities to describe the scientific uncertainty. The result is shown in the fifth column of the figure, where the resulting calculated probability of activity is 0.65. This illustrates that the analysis at the component level not only provides logical consistency, but also provides a useful focus for specialized expertise. (In fact, the inconsistency discussed above does not even occur if different specialized sets of multiple experts address the two different uncertainties!)

The same observations can be made even in a deterministic analysis in which multiple experts provide different deterministic models of a phenomenon. Here, inconsistencies can arise in dealing with non-linear relationships among multiple factors. Consider, in Table 5.3 below, the estimates of mean ground motion as a function of distance provided by four experts (playing the role of proponents) in the second SSHAC ground motion workshop (see Figure J-9). For the sake of illustration, two dotted lines were drawn through the Atkinson and Somerville/Saikia estimates (the experts' reasoning was, in fact, not based on simple linear models, but the result is close enough to be useful for illustrative purposes). The dotted lines in the figure indicate that over the regions of distance given, the relationships on a log scale are roughly linear of the form:

$$\log g = a \log d + b,$$

where g is mean spectral acceleration and d is distance to the rupture. The table contrasts what the answer would be if we aggregate at the component level, i.e., aggregate the a values and b values, then estimate the ground motion, contrasted with aggregating at a high level, i.e., averaging the two experts' estimated ground motion. (We note for statisticians that at least two deeper issues are masked by the deterministic nature of this example: first, a and b are not generally considered to be probabilistically independent, and second, in the probabilistic case, it will be true that the mean of the aggregate is equal to the weighted individual means.)

This example is based on equal weights for simplicity, but that is not important to the conclusion. If the TFI believes that the best value of a is -1.12 and the best value of b is 1.32, then the ground motion of 3.7 estimated by high level aggregation is inconsistent with the TFI's state of knowledge about a and b. (Mathematically, this inconsistency stems from the well-known fact that the mean of a non-linear function is not equal to the function evaluated at the mean.)

Again, independent of the mathematics, an important process observation is that it is more fruitful to have the experts focus on the values of a and b than to debate estimates of the overall ground motion. For example, it may be that the experts agree on the slope, but not on the intercept, which would lead the TFI to prompt them to explore this cause of the systematic difference between their two curves.

Implications of Issues

The bottom line concerning these and other expert aggregation issues is that there are no recipes for how to deal with all of them. The good news, however, is that analysis of the issues has resulted in a set of concepts and methods that can provide guidelines for aggregating expert judgments. The TFI process is designed to ensure that these issues are addressed in the most explicit way possible, and to utilize the various expert elicitation tools that have been developed to address these issues.

Section 4. Guidance on the Two Stage Elicitation Process

Here we describe in more detail the types of assessments required of the experts in the two-stage elicitation process introduced in Section 3.3.4. This section builds on the previous description. At the end of the section we present a simplified mathematical model that provides insights into the two-stage procedure and its implications.

Before presenting the details, note that the first stage is more traditional, and will consume the bulk of time and expense. Much of the time and expense are due to the fact that the Stage I elicitation requires the full range of separate group interactions defined in Section 2's detailed facilitation guidance. The second stage, while novel, should be relatively brief and inexpensive (probably less than one additional day of group interaction), as the experts are building on the knowledge they have already acquired in Stage I.

Recall that the genesis of the two-stage approach is the goal of forming a composite representation of the scientific community.

Stage I Each Panelist as an Independent, Informed Evaluator

For a given variable or model parameter value, this stage requires two traditional (for PSHA) assessments:

a) Each expert gives his best (mean) estimate, based on an evaluation of the full range of models, evidence, data and proponent positions in the community. The assessments are performed only after thorough facilitated interaction (including sharing of all relevant local or site-specific information) as described in Step 6 (Analysis, aggregation, and resolution of disagreements) below.

Result: The average of the mean estimates provides an initial estimate of the panel's composite mean. The variance of the mean estimates provides one component of an initial estimate of the panel's composite variance.

b) Each expert assesses his epistemic uncertainty in the mean estimate. This is also based on thorough interaction; in particular, each expert is exposed to the full range of other panel member estimates (which should generally lead to appropriately wide distributions if there is substantial disagreement).

Result: The mean of the expert-supplied variances provides the other component of an initial estimate of the panel's composite variance.

Note that the TFI need not be limited to assessments of means and variances; indeed, it is often preferable to encode non-parametric distributions without being limited to a set of summary statistics, or even a particular functional form. It is possible to estimate the composite distribution in these cases as well; we address only means and variances here for simplicity of exposition.

If the TFI's goal was to represent the panel's knowledge, the elicitation would stop here (after sufficient interaction, iteration, etc.). However, a second stage is necessary to represent the overall scientific community state of knowledge.

Stage II Panelists as Integrators, Representing the Overall Expert Community

In this stage, the panelists would provide two types of assessments, based partially on what they each observed from other panel members in the first stage:

a) Each expert provides an estimate of what the composite mean of the entire community would be, assuming that the community were provided the same information base and opportunity for interaction that the panel has had.

Result: The difference, if any, between an expert's personal estimate and his population estimate is a measure of his own intended bias relative to the community. Moreover, the average of the biases is an estimate of the panel's overall bias relative to the overall community.

b) Each expert assesses the composite uncertainty in the community through two assessments: (1.) an estimate of the variance in the distribution of mean estimates throughout the community, and (2) an estimate of the expected variance in the individual experts' distributions.

Result: These assessments provide an indication of whether the panel believes its estimated uncertainty range is representative of the expert community at large.

A pertinent special case is when one expert (i.e., the "incognito" proponent) assumes that the panel of n experts represents the community and the other n-1 experts do not agree -- they see him instead as a singular point (1 out of N, not 1 out of n). In this case, the TFI need not automatically downweight that expert's assessment of the community mean; rather, the TFI should attempt to gather more specific data by asking the apparent proponent to provide names and references of others in the expert community who he believes share his view or position. This provides the TFI and the panel with a more explicit basis for evaluating the expert's assumption.

Chapter 5 on Ground Motion explains how results of the two stage process were used to develop a final TFI position in the context of the two SSHAC Ground Motion workshops.

Section 5. A Mathematical Model For The TFI Process

This section presents a mathematical aggregation model developed in the SSHAC project. This model, called the "TFI model," provides a conceptual framework for elements of the TFI elicitation and expert aggregation processes. It can be used for conducting sensitivity analyses and developing intuition. This model has not been published or externally reviewed. It is presented here solely for the insights it might generate -- the TFI process does not depend upon the model.

This section goes into more mathematical detail than the other sections on aggregation models. Readers uninterested in the mathematics may wish to skip directly to the *Example Results* subsection, which is presented last.

Background

The TFI model was developed in an attempt to extend existing mathematical aggregation models to address some issues in seismic hazard estimation that classical mathematical models ignore or address only partially. The TFI model differs from the simple Bayesian models discussed above in that it results in a wider aggregate distribution that explicitly reflects the observed variation among expert estimates (this component of uncertainty is ignored in the simple Bayesian models). It also provides an underlying conceptual structure for ad hoc methods that involve simple weighted averages of distributions, but, in contrast to these methods, the TFI model explicitly adds the uncertainty introduced by sampling only a small number of experts from the overall expert community. Moreover, the TFI model provides a logical structure for determining when and if equal weights are appropriate. Finally, and perhaps most importantly, the Stage II analysis in which the experts act as integrators is unique to the TFI model.

We use the term "classical models" for convenience to describe formal Bayesian aggregation models, but we do not wish to imply that there is a small set of well-accepted Bayesian models. In fact, skilled modelers invariably mix and match several models from a large set of existing models to address any given problem [Clemen and Winkler, 1992] or apply ad hoc methods (e.g., equal weights on distributions) that produce results similar to those of the TFI model

Classical formal aggregation models present several issues. First, it is extremely difficult to quantify dependence among experts, especially after dependence-inducing, intensive interaction, although some promising work has recently been published [Clemen and Jouini, 1994]. And, as demonstrated above, misestimating interdependence not only skews the composite mean, but also the composite variance. But, even with a perfect model of dependence, another deeper problem is not addressed by most aggregation models. Consider, for example, the case in which the experts are completely independent (in the formal sense defined above) and in which they have achieved (intentional) consensus on the estimated value of some uncertain quantity. Many Bayesian models would produce a posterior distribution reflecting far less uncertainty than that of any individual expert. A simple example is that if five independent experts agree that the probability of rain is 60%, direct Bayesian updating results in an aggregated probability of over 99%. Allowing for probabilistic dependence reduces this effect, but does not eliminate it. In fact, short of complete dependence among the experts, classical aggregation results in a posterior probability higher than the experts unanimous 60%.

The TFI model avoids this problem. It has the desirable property that if all experts agree on a probability distribution, the aggregated or composite distribution is precisely the consensus distribution.

The TFI model is not entirely inconsistent with ad hoc aggregation practices used in certain previous risk analyses; indeed, it may be viewed as providing conceptual Bayesian underpinnings to certain simple intuitive methods that have been used for years. For example, in NUREG 1150, an aggregated distribution was formed based on an equally-weighted mixture of expert distributions. As we shall see, this ad hoc procedure is consistent with the TFI-model result, but only conditional on a set of important conditions, which include a large and representative panel as well as a formal process for conducting intensive expert interaction and interchange leading to equal problem expertise and interdependence among all experts.

Approach

For clarity, we will address one of the simplest cases, that of estimating a fixed but uncertain (epistemically) scalar quantity of interest, such as the height of the Eiffel Tower or the long term slip rate on a fault. The model may be extended to other more complex cases, such as estimating a set of moments or fractiles of the distribution of ground motion in the Eastern U.S. at a given distance and magnitude, but these cases extend beyond the scope of this appendix.

Our development will proceed in two steps corresponding to elicitation Stages I and II. Recall that in Stage I, the experts assess the uncertain quantity of interest. By viewing the panel of experts as a sample of the overall community of such experts, we shall infer an initial "best" or composite estimate of the community distribution. However, this is not the final composite distribution, but rather a useful intermediate input for both the TFI and the panel in the Stage II assessment. In Stage II, the experts estimate the (unknown) community distribution directly.

For both Stage I and Stage II we will also derive a "predictive distribution" reflecting the updated state of information of a single individual beginning with an "uninformative" prior distribution. As we shall demonstrate, the predictive distribution is a higher-variance version of the best estimate of the community distribution, adjusted to reflect the sampling uncertainty inherent in a limited panel size.

Stage I -- Experts as Evaluators

We begin by addressing Stage I of the elicitation process. Suppose that an individual expert provides a subjective probability distribution on a continuous unknown quantity, x. A non-informed layman would do well to adopt the distribution of the informed expert as his own, so long as the layman believes that the expert has a much stronger capability and training in the appropriate field to make objective, unbiased evaluations of all available information, including data, contending scientific theories and interpretations, models, and hypotheses.

Similarly, suppose hypothetically that a decision maker were able to assemble a large set of experts believed to be objective evaluators, and then to inform them through a process of disseminating information, providing for interaction with proponents of relevant scientific hypotheses, and then promoting and facilitating interaction and debate among the evaluators. Such a decision maker would be well advised to use as his distribution the mixture of the distributions of the individual experts if he believed that the experts (as a consequence of the interaction) in this "perfect community" were effectively equally informed on the issue of interest and equally interdependent (see equal-weights discussion above).

We define this mixture or "community distribution" as the target of our inference. In the discussion below we will assume a mixture calculated with equal weights based on an idealized "perfect community" of unbiased, equally informed experts. We then estimate this hypothetical distribution by sampling "real" experts and putting them through a less-than-perfect process of information exchange and interaction. Finally, at the end of Stage I, we leave open the possibility of the integrators (Stage II experts and the TFI) using unequal weights or even qualitative weighing if appropriate because the sample is "faulty" (e.g., the TFI perceives a bias in an expert, but for some reason doesn't remove him from the panel). In any case, we needn't be too concerned about equal weights in the Stage I model since the Stage I distributions are not the final recommended distributions.

To begin the analysis, let x be the uncertain quantity of interest, and assume that each of N informed experts has an elicited distribution,

f_i (x) = Expert *i*'s distribution

with mean or "best estimate,"

$$E_i(x) = \mu_i$$

and variance,

$$V_i(x) = v_i$$

The community of N experts as a population can be characterized by a frequency histogram of $\mu_i's$, with expected value, or average,

$$E_C(\mu) = \frac{1}{N}\sum_{i=1}^{N}\mu_i$$

and variance,

$$V_C(\mu) = \frac{1}{N}\sum_{i=1}^{N}\left[\mu_i - E_C(\mu)\right]^2$$

Similarly, the population is characterized by a frequency histogram of v_i's, with expected value and variance,

$$E_C(v) = \frac{1}{N}\sum_{i=1}^{N}v_i$$

and

$$V_C(v) = \frac{1}{N}\sum_{i=i}^{N}\left[v_i - E_C(v)\right]^2$$

Next, consider the composite community distribution defined by the mixture,

$$f_C(x) = \frac{1}{N}\sum_{i=1}^{N}f_i(x) \qquad \textit{composite community distribution}$$

which is our estimation goal. Probability theory implies that the mean and variance of this composite community distribution are,

$$\begin{aligned} E_C(x) &= \frac{1}{N}\sum_{i=1}^{N}\mu_i \\ &= E_C(\mu) \end{aligned}$$

and

$$\begin{aligned} V_C(x) &= E_C\left(\left[x - E_C(x)\right]^2\right) = \frac{1}{N}\sum_{i=1}^{N}v_i + \frac{1}{N}\sum_{i=1}^{N}\left[\mu_i - E_C(\mu)\right]^2 \\ &= E_C(v) + V_C(\mu) \end{aligned}$$

This simple but significant result indicates that the variance of the composite distribution reflects both the ("typical" or average) individual expert uncertainty, $E_C(v)$, and, in addition, the expert-to-expert diversity, $V_C(\mu)$. These two components of variation are equivalent to Martz's "within-expert" and "between-expert" variations [Martz, 1984], but the TFI model is based on a very different conceptual framework.

The implication of the above results is that a first-order representation of the community, i.e., the mean and variance, $E_C(x)$ and $V_C(x)$, are dependent upon three quantities: 1.) the community's average best estimate, $E_C(\mu)$, 2.) the community's average epistemic variance, $E_C(v)$, and 3.) the variance of best estimates within the community, $V_C(v)$. Unfortunately, these quantities are unknown because the entire expert community is too large to engage in the intensive interaction necessary for the TFI process. Thus, we treat the three quantities as uncertain and as the primary targets of estimation.

Inference about the Community Distribution

Suppose now that we "sample" the expert community by eliciting a subset of n (n<<N) "evaluator" experts. The logical estimate of the community mean is the sample average of the Panel experts' means,

$$\hat{E}_C(x) = \hat{E}_C(\mu) = \frac{1}{n}\sum_{i=1}^{n} \mu_i \equiv E_P(\mu) \qquad \textit{estimate of community mean}$$

where we have adopted the conventions that a "hat" indicates a "best" estimate and a "P" subscript indicates an observable sample quantity from the Panel elicitation. Similarly, we can estimate the average individual variance within the community with the sample average of the Panel variances,

$$\hat{E}_C(v) = \frac{1}{n}\sum_{i=1}^{n} v_i \equiv E_P(v) \qquad \textit{estimate of community average individual variance}$$

Finally, using analogous reasoning, we can estimate the variance of the community estimates as,

$$\hat{V}_C(v) = \frac{1}{n}\sum_{i=1}^{n}\left[v_i - E_P(v)\right]^2 \equiv V_P(v) \quad \textit{est. of community variance in individual variances}$$

and estimate the community expert-to-expert diversity as,

$$\hat{V}_C(\mu) = \frac{1}{n}\sum_{i-1}^{n}\left[\mu_i - E_P(\mu)\right]^2 \equiv V_P(\mu) \qquad \textit{estimate of community diversity}$$

We are now prepared to express the estimate of the composite community variance as the sum of two sample quantities,

$$\begin{aligned}\hat{V}_C(x) &= \hat{E}_C(v) + \hat{V}_C(\mu)\\ &= E_P(v) + V_P(\mu)\end{aligned}$$

and the estimate of the entire community distribution as the mixture of the individual panelists' elicited distributions,

$$\hat{f}_C(x) = \frac{1}{n}\sum_{i=1}^{n} f_i(x) = f_P(x) \qquad \textit{estimate of community distribution}$$

An interesting result is that the magnitude of $\hat{V}_C(v)$ does not influence the final composite distribution.

<u>Sampling Uncertainty</u>

Basic mathematical statistical analysis says that, based on n draws from a large population of N μ_i values, the variance of the estimator $\hat{E}_C(\mu)$ of the community mean is approximately (the approximation gets better as n increases),

$$\text{Variance of mean estimator } = \frac{1}{n}V_C(\mu) \cong \frac{1}{n}\hat{V}_C(\mu) = \frac{1}{n}V_P(\mu)$$

Therefore, an approximate 84% confidence limit on the community's best estimate is,

$$E_P(\mu) \pm \left(V_P(\mu)/n\right)^{1/2}$$

In other words, the larger the sample or panel size, the higher the confidence that the estimate of the community mean is accurate. The same reasoning applies to determining the variance of the estimator of the average individual variance, i.e., the estimator of $E_C(v)$,

Variance of average individual variance estimator $= \frac{1}{n}V_C(v) \cong \frac{1}{n}\hat{V}_C(v) = \frac{1}{n}V_P(v)$

It is more difficult to get an estimate of the variance of estimators of other variances of interest such as $V_C(\mu)$ and $V_C(v)$, or $V_C(x)$, without distributional assumptions, but suffice it to say that they decrease roughly like 1/n.

The implication is that increasing the panel size reduces our uncertainty in estimating the community's composite distribution and its parameters. To develop insight as to how quickly the sampling uncertainty shrinks even for small n, it is possible to develop non-approximate models based on specific named distributions, but this is beyond the scope of this appendix.

Stage I Predictive Distribution

After sampling the n experts it is possible to develop a "predictive" distribution that reflects not only the estimate of the community distribution but also the additional uncertainty caused by the fact that only a subset of the population were elicited. This distribution is sometimes called the "posterior" distribution because it represents the updated probability distribution of an individual who begins with a "diffuse" or "uninformative" prior. Determination of the predictive distribution follows a straightforward but cumbersome Bayesian statistical analysis. Let us for first order simplicity assume that the sampling uncertainty is adequately captured by determining the effects on the mean and variance of the predictive distribution. It is easy to show that the mean of the predictive distribution remains the best estimate or panel average,

$E_I(x|f_i,\ldots,f_n) = \hat{E}_C(x) = E_P(\mu)$ *expected value of Stage I predictive distribution* where we have adopted the Bayesian notational convention of making the conditioning on the expert distributions explicit. The subscript indicates that this distribution is based only on Stage I information. The variance of the predictive distribution is increased above that of the estimated community distribution by a term that decreases as 1/n (again we omit the details of the derivation for brevity),

$$\begin{aligned} V_I(x|f_i,\ldots,f_n) &\cong \hat{V}_C(x) + \frac{1}{n}V_P(\mu) \\ &= E_P(v) + V_P(\mu)\left(1+\frac{1}{n}\right) \end{aligned} \qquad \textit{Stage I predictive variance}$$

This important result says that the total uncertainty in the variable x after the Stage I elicitation is the sum of three terms: 1.) the average panel (epistemic) variance, 2.) the diversity of the panel's best estimates, plus 3.) a contribution that diminishes as 1/n associated with eliciting opinions from only a subset of n experts.

Most importantly, in contrast to most other Bayesian approaches to expert aggregation, in this approach only a portion of the posterior uncertainty reduces with increasing panel size. More experts help provide better (i.e., more confident) estimates of the average community variance and expert-to-expert diversity, but additional experts cannot be expected to reduce these underlying components of the uncertainty about x in the scientific community.

Stage II -- Experts as Integrators

Traditional processes stop at the end of Stage I, but it is extremely useful to have the experts themselves estimate the community distribution directly. In Stage II, the TFI asks each panelist both whether he believes he, as an individual, is representative of the community as a whole, and whether the overall panel (i.e., both the location and width of the panel's composite distribution) is representative of the community.

Thus, the estimated community distribution and its moments from Stage I are viewed as intermediate information for the TFI and the experts in their integrator roles to use to form their own estimates of the community distribution. They are not constrained to use equal weights, and, indeed, it is very useful to perform sensitivity analyses that show how the Stage I results change with different weighting schemes.

The basic issue each integrator-expert must consider is how representative the results of the panel interaction would be if it were possible to extend the interaction to the overall community. For example, if an integrator feels that the panel experts after interaction would tend to have higher estimates than the community as a whole, he would estimate the community mean as being higher than the panel mean. Similarly, each integrator can judge whether the panel's range of estimates is likely to be tighter or wider than that of the community. Each integrator observes in the TFI-led interaction, how each panelist influenced others on the panel. As part of the Stage II exercise, each integrator expert must consider whether the same degree of influence would apply to the overall community.

We could ask each expert for detailed information, such as full probability distributions on the mean and variance of the community distribution, but for simplicity here we assume that each expert simply provides a best estimate of the community distribution,

c_i (x) = Expert *i*'s best estimate of community distribution

Expert i's best estimates of the mean and variance of this community distribution are denoted, $E_i(\mu_C)$ and $E_i(v_C)$, respectively, where in terms of our earlier notation,

$$\mu_C = E_C(x)$$

and

$$v_C = V_C(x)$$

Following exactly parallel logic as for Stage I, the Stage II best estimate of the composite distribution is,

$$\hat{c}_C(x) = \frac{1}{n}\sum_{i=1}^{n} c_i(x)$$ *Stage II composite distribution*

We use the same notational conventions as in Stage I but with double "hats" indicating Stage II estimates. The mean of the Stage II composite distribution is,

$$\hat{\hat{E}}(x) = \hat{\hat{E}}_C(\mu_C) \equiv \frac{1}{n}\sum_{i=1}^{n} E_i(\mu_C) \equiv E_P(\mu_C) \qquad \textit{Stage II composite mean}$$

and its variance is,

$$\begin{aligned}\hat{\hat{V}}_C(x) &= \frac{1}{n}\sum_{i=1}^{n} E_i(v_C) + \frac{1}{n}\sum_{i=1}^{n}\left[E_i(\mu_C) - E_P(\mu_C)\right]^2 \\ &\equiv E_P(v_C) + V_P(\mu_C) \qquad \textit{Stage II composite variance}\end{aligned}$$

Also, paralleling Stage I, the predictive distribution for Stage II has mean,

$$E_{\text{II}}(x|c_i,\ldots,c_n) = \hat{\hat{E}}_C(x) = E_P(\mu_C) \qquad \textit{mean of Stage II predictive distribution}$$

and variance,

$$\begin{aligned}V_{\text{II}}(x|c_i,\ldots,c_n) &\equiv \hat{\hat{V}}_C(x) + \frac{1}{n}V_P(\mu_C) \\ &= E_P(v) + V_P(\mu_C)\left(1+\frac{1}{n}\right) \qquad \textit{variance of Stage II predictive distribution}\end{aligned}$$

The Stage II predictive distribution is the final distribution. Of course the TFI is not constrained to form it based on equal weights, but equal weights are even more likely to be appropriate for the Stage II distribution than Stage I for the reasons discussed in Chapter 3.

Bayesian Interpretation of the TFI Model

We note to the reader familiar with Bayesian techniques that, while the TFI model may appear to be based on a non-Bayesian way of viewing the problem, it is not inconsistent with Bayesian tenets. The Bayesian approach attempts to characterize the appropriate posterior state of information of a single decision maker. In the public policy context, this number of individual decision makers at different levels, and a number of participants in the decision-making process, all of whom need to use the results of the expert interaction, and 2.) even if there were one clearly identified decision maker, representing his or her state of information places them uncomfortably in a role like that of a "super-expert." The TFI model leaves any individual the freedom to interpret or modify the results in any way they choose. But, it seems unlikely that any layman integrator would want to choose a different predictive distribution than that based on the estimated hypothetical "perfect-community" distribution, unless he had reason to suspect technical or motivational bias (which is exactly what the TFI expert selection and interaction processes are designed to eliminate). In any case, one can show that the predictive distribution is equivalent to Bayesian updating for an individual with a non-informative prior who believes the experts are exchangeable(as defined by Clemen and Jouini, 1994).

Example Results: Comparison of the TFI and Classical Models

We conclude with some examples that contrast the results of the TFI model with the simple classical models presented earlier in this appendix that do not incorporate the diversity of expert estimates in the final aggregated result. Of course, the experienced decision analyst would never use these models to estimate posterior variances, but would customize models for the application at hand. For example, classical Bayesian models typically provide an intuitive answer for the mean estimate (indeed, often the same answer as the Community model), and they are often used just for mean estimation, not for variance estimation.

For ease of exposition, some simplifying assumptions have been made in the examples. First, we assume for comparison a Stage I analysis only since classical models do not address Stage II. Also, the cases all ignore sampling uncertainty and each case assumes that all experts are independent (if the experts were assumed to be equally interdependent, the TFI model results would be unchanged and the classical model would result in the same composite mean with a higher composite standard deviation).

The classical model used to determine the results below was the simple Normal-additive estimation error model presented earlier in this appendix. The TFI model assumes equal weights, but the results are generalizable. Each case is described by a table of expert estimates and composite results, followed by a simple graphical display of the results.

CASE 1: Complete Agreement

Consider first the case of complete consensus:

	INPUTS					COMPOSITE	
	Expert 1	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Classical Model**	**TFI Model**
Mean	10	10	10	10	10	10	10
Std. Dev.	5	5	5	5	5	2.2	5

```
Expert Elicited Ranges       |-------------|
                             |-------------|
                             |-------------|
                             |-------------|
                             |-------------|

Classical Composite              |---|

TFI Composite                |-------------|
```

When all the experts agree on the mean and the standard deviation of an uncertain quantity, the TFI model reflects this consensus. The classical model reflects the consensus mean but estimates significantly less posterior uncertainty than any individual expert. Consider now a case where the experts agree on the spread but disagree on the best estimate:

CASE 2: Variation in Mean Estimates

	INPUTS					COMPOSITE	
	Expert 1	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Classical Model**	**TFI Model**
Mean	10	10	30	50	50	30	30
Std. Dev.	5	5	5	5	5	2.2	21

```
Expert Ranges          |-------------|
                       |-------------|
                                           |-------------|
                                                                 |-------------|
                                                                 |-------------|

Classical Composite                            |---|

TFI Composite                        |-------------------------|
```

The models agree on the posterior estimate but differ by an order of magnitude on the posterior standard deviation. The standard deviation of the TFI model is predominantly driven by the variation among the experts' mean estimates. The classical model is insensitive to this variation. Consider the same case with more elicited uncertainty:

CASE 3: Experts Assess High Uncertainty Range

	INPUTS					COMPOSITE	
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Classical Model	TFI Model
Mean	10	10	30	50	50	30	30
Std. Dev.	40	40	40	40	40	18	45

```
Expert Ranges            |----------------------------------------|
                         |----------------------------------------|
                                             |----------------------------------------|
                                                                 |----------------------------------------|
                                                                 |----------------------------------------|

Classical Composite                                |-----------------|

TFI Composite                             |----------------------------------------------|
```

This case shows that both models are sensitive to the experts' assessed standard deviations. Now suppose highly confident experts disagree:

CASE 4: Highly Confident Experts with Substantial Disagreement

	INPUTS					COMPOSITE	
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Classical Model	TFI Model
Mean	10	10	30	50	50	30	30
Std. Dev.	0.1	0.1	0.1	0.1	0.1	0.05	20

```
Expert Ranges                                       ||
                                                    ||
                                                                ||
                                                                          ||
                                                                          ||

Classical Composite                                             |

TFI Composite                                         |----------------|
```

If the experts estimates are widely different, even if each expert assigns high confidence to his estimate (hopefully unrealistic after intensive interaction!), the TFI model estimates high uncertainty due to the implied diversity in the expert community, whereas the classical model estimates virtual certainty. Finally, consider the most general case in which the experts disagree about best estimates and ranges.

CASE 5: Diversity in Means and Ranges

	INPUTS					COMPOSITE	
	Expert 1	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Classical Model**	**TFI Model**
Mean	10	10	30	50	50	14	30
Std. Dev.	8	5	40	15	25	4	20

```
Expert Ranges           |---------|
                             |------|
                             |-------------------------------------|
                                                                     |--------------|
                                                                |-------------------------|

Classical Composite                   |--|

TFI Composite                   |-----------------------------|
```

When experts provide disparate mean and uncertainty estimates, the two types of models can differ dramatically.

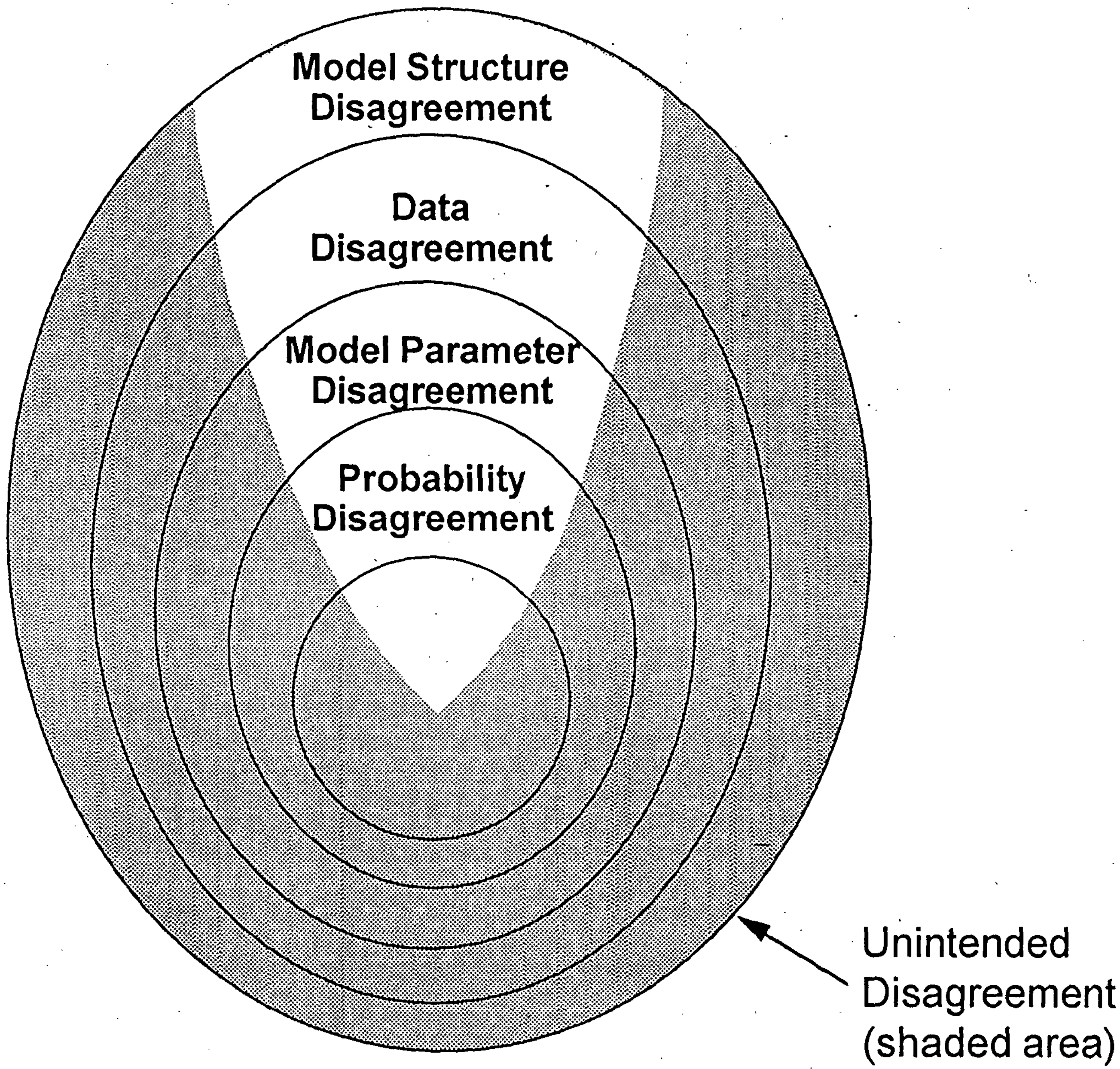


Figure J-1. Peeling the Disagreement Onion

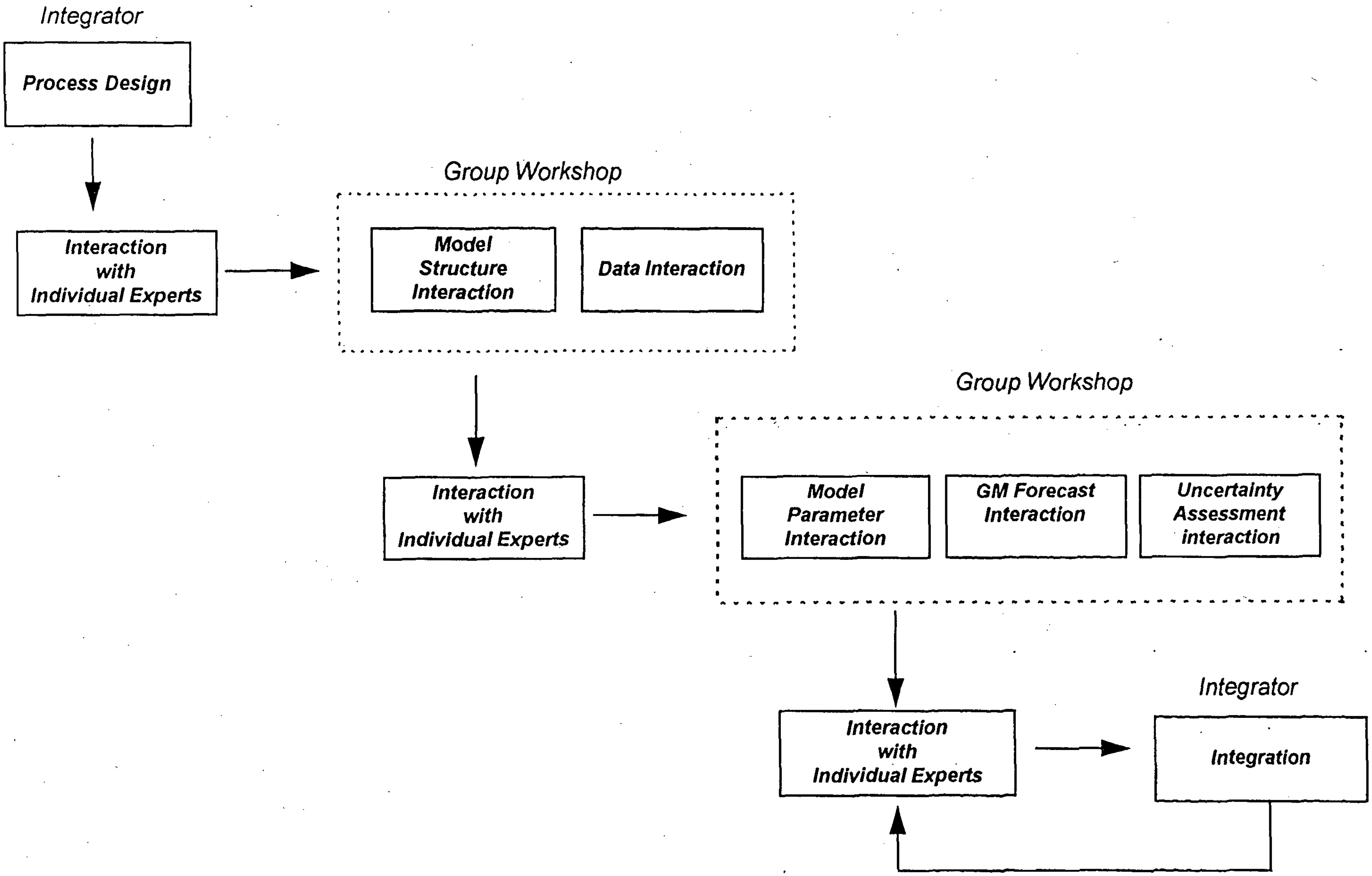


Figure J-2. Roadmap of GM Elicitation Process

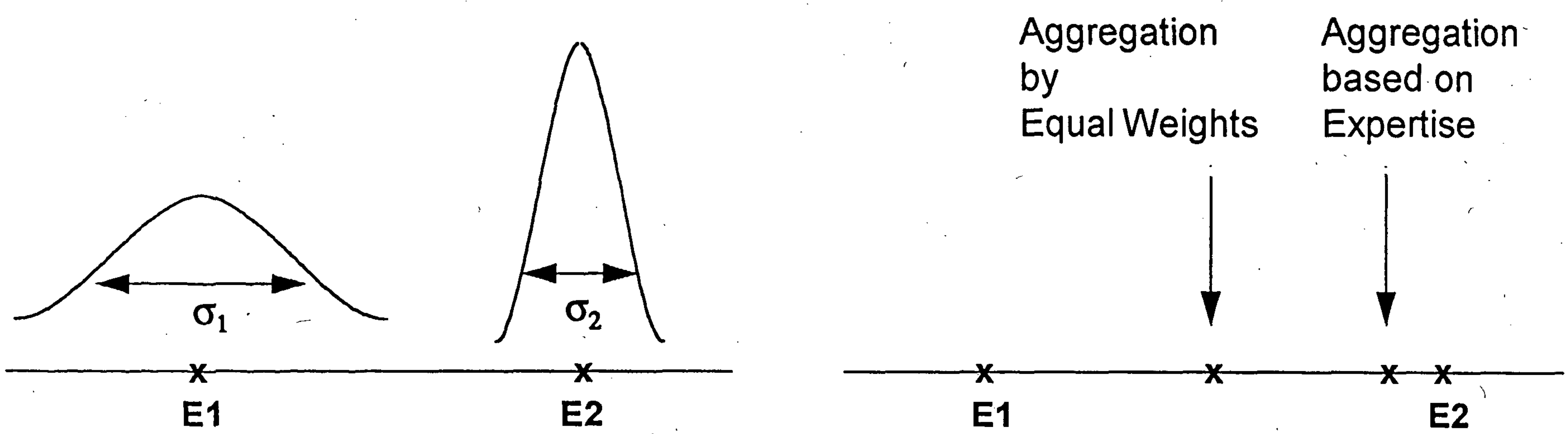


Figure J-3. Expert 2's Forecast Is Less Uncertain Than Expert 1's

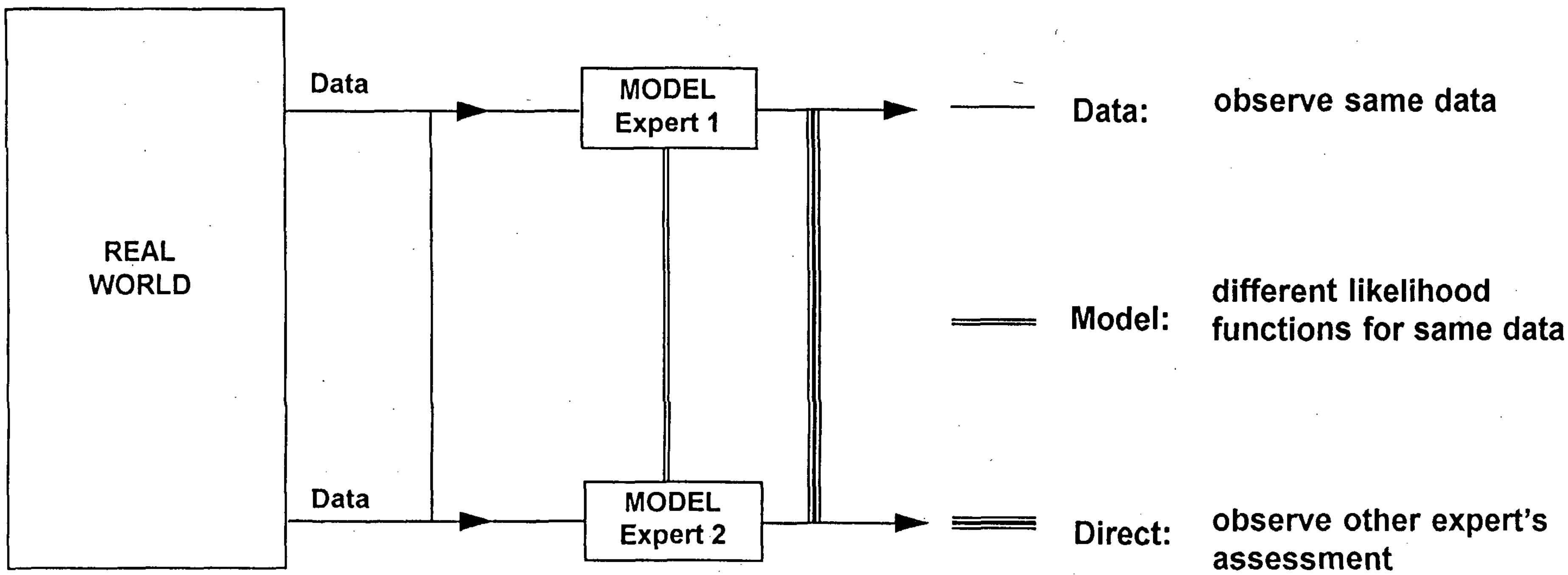


Figure J-4. Nonindependent experts

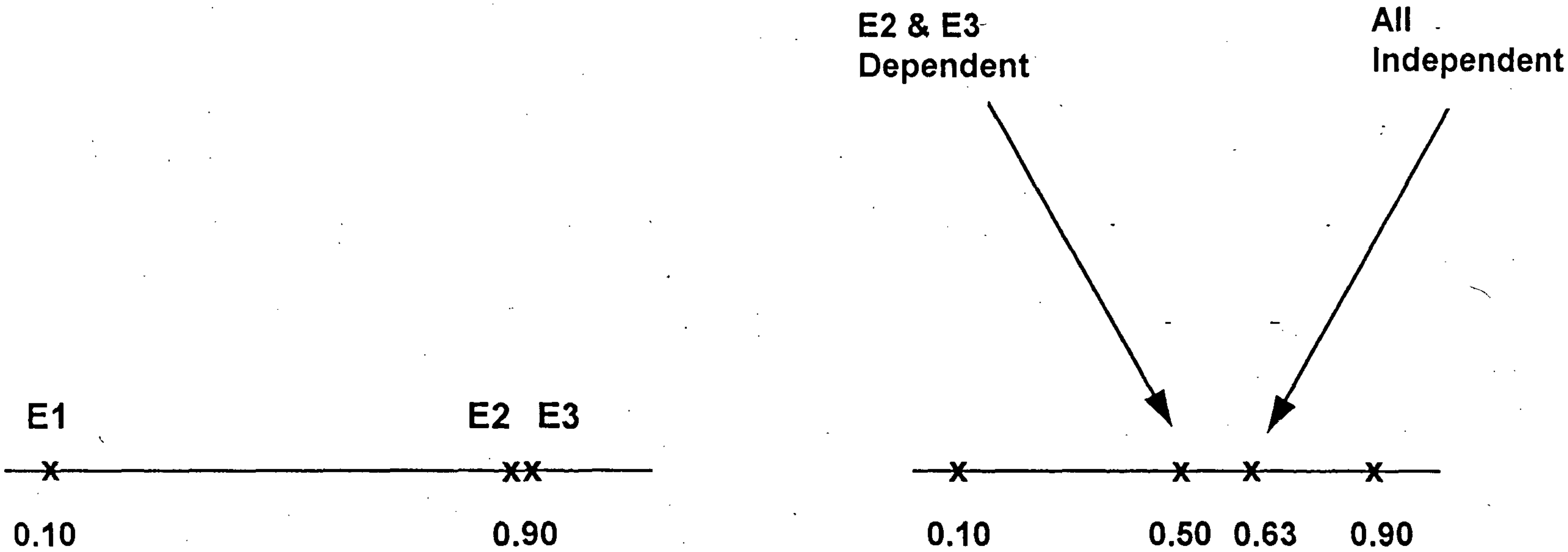


Figure J-5. The Impact of Expert Dependence on Aggregation

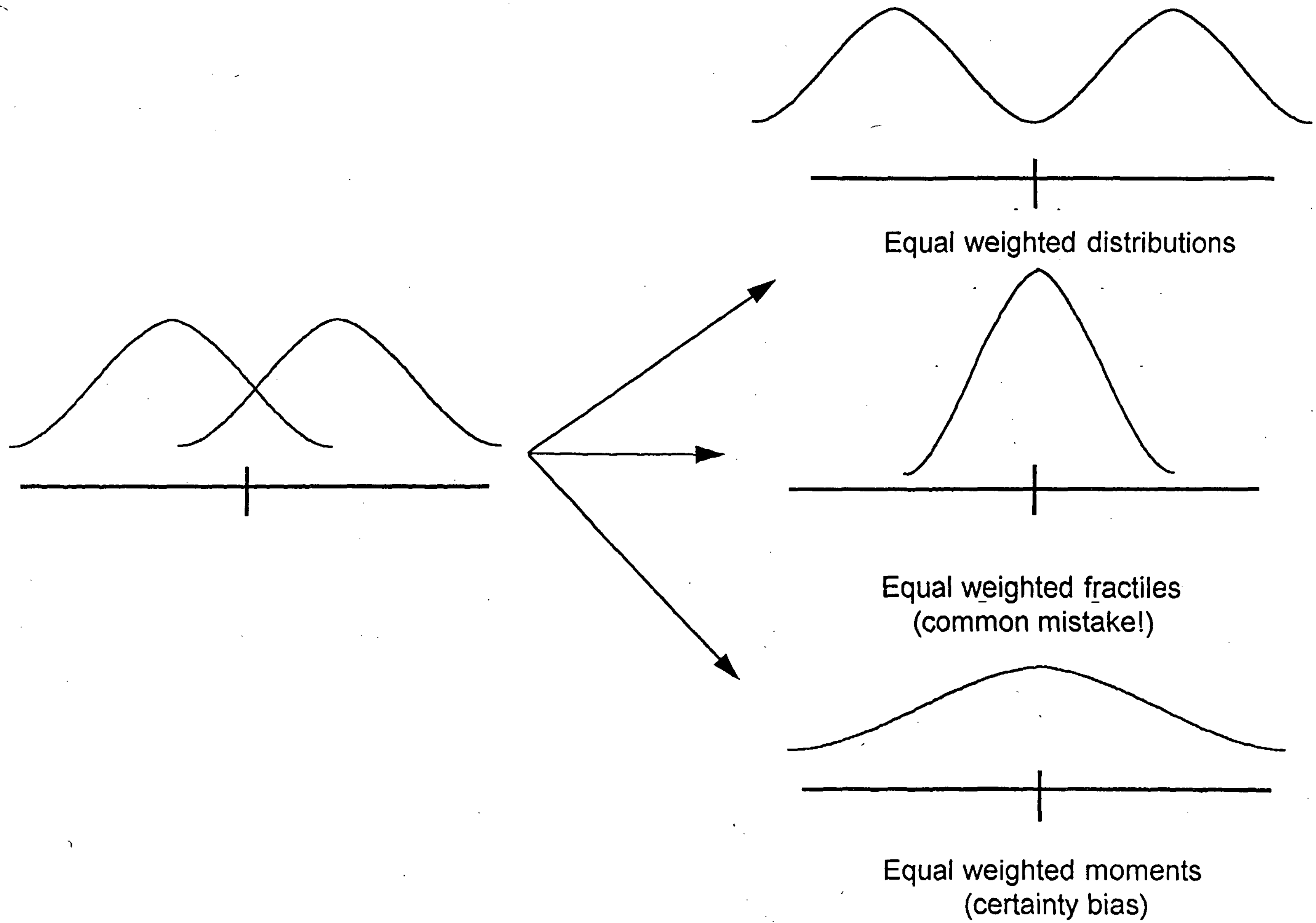


Figure J-6. Averages of What?

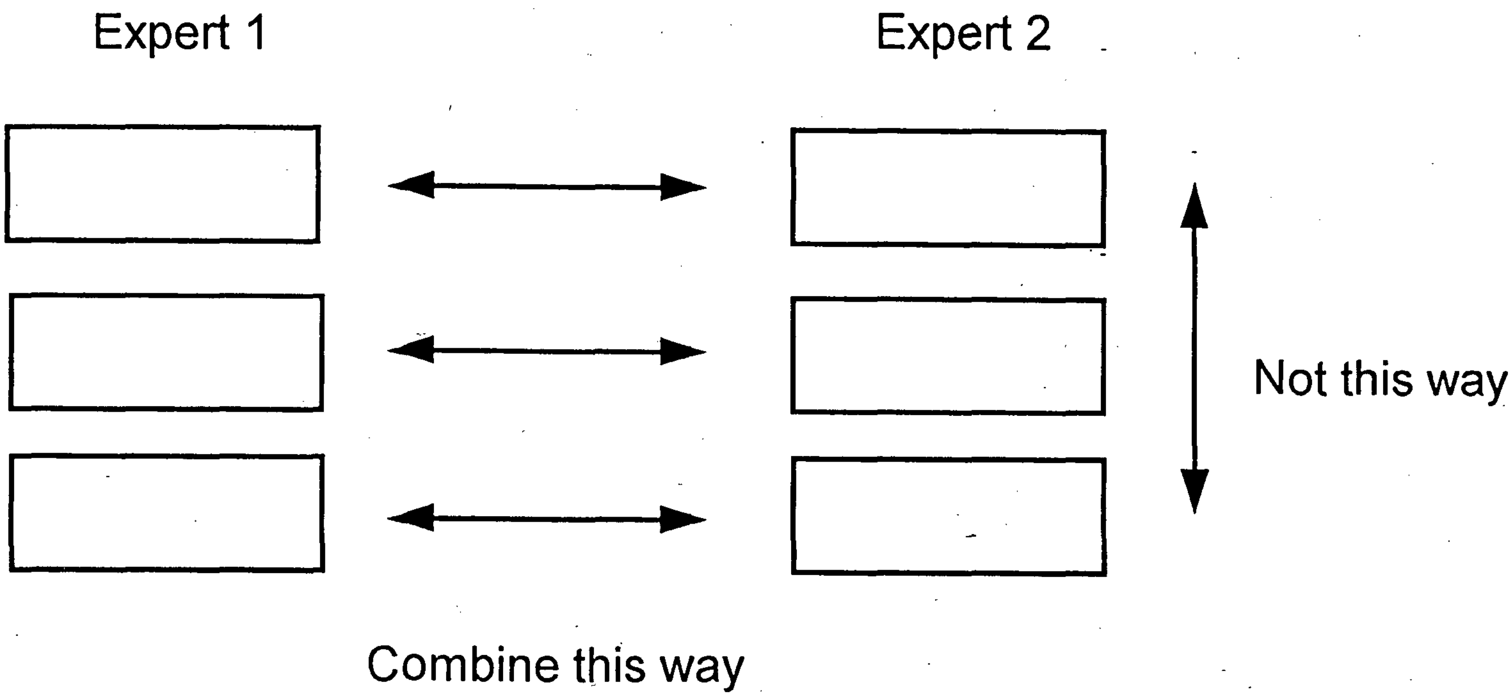


Figure J-7. Basic Issue: Level of Aggregation

		Expert 1	Expert 2	Direct Aggregation	Multi-stage Aggregation	Unequal Weights E1: Geologist E2: Geophysicist
Geological Uncertainty	p(Favorable)	.8	.2	--	.5	.8
Seismic Uncertainty	p(Active/Favorable	.2	.8	--	.5	.8
	p(Active/Unfavorable	.2	.05	--	.125	.05
Calculated	p(Active)	.2	.2	.2	.31	.65

Figure J-8. Example of Two Levels of Aggregation

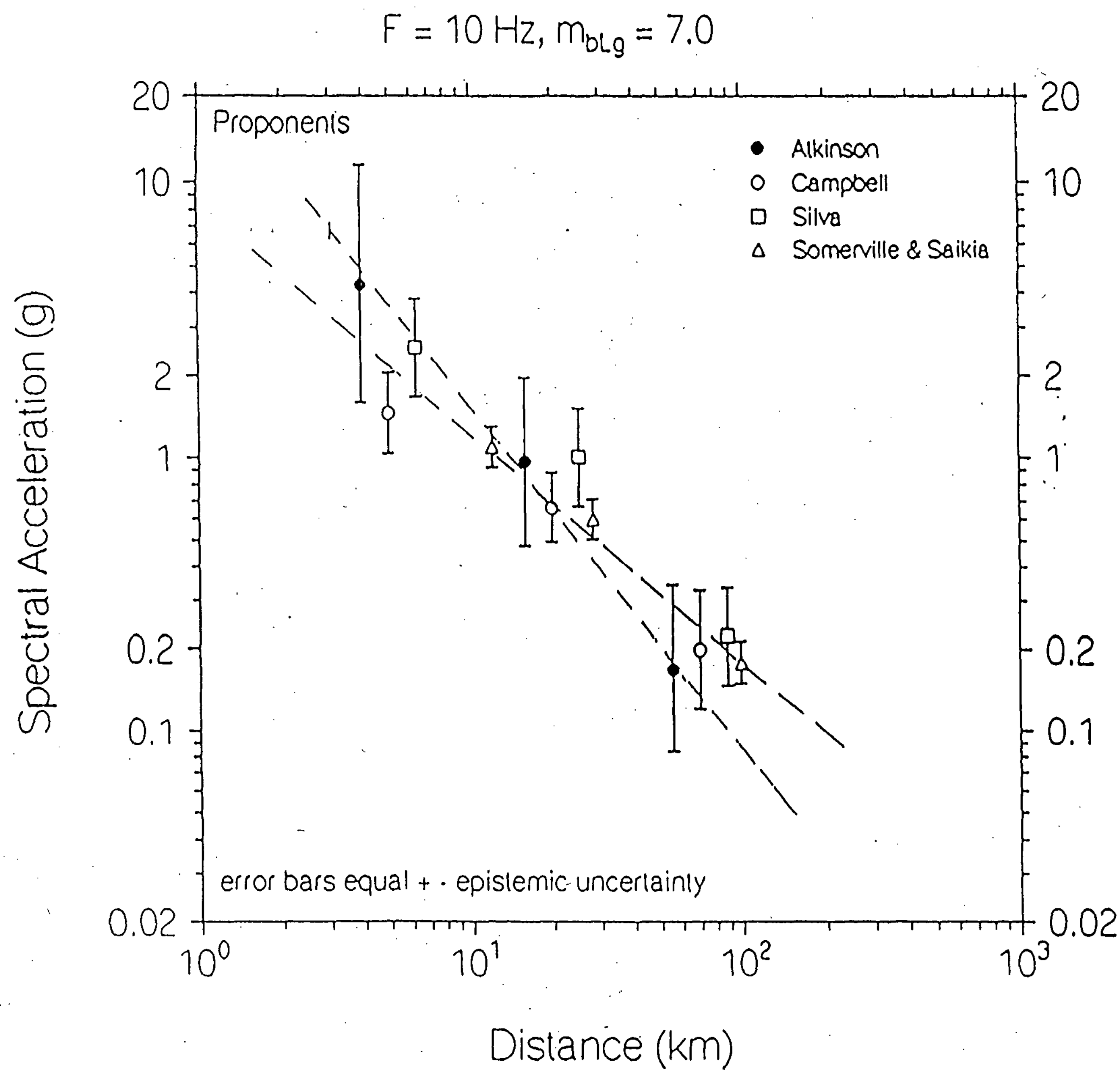


Figure J-9. Ground Motion Estimates from Workshop II

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11. ABSTRACT *(200 words or less)*

Probabilistic Seismic Hazard Analysis (PSHA) is a methodology that estimates the likelihood that various levels of earthquake-caused ground motion will be exceeded at a given location in a given future time period. Due to large uncertainties in all the geosciences data and in their modeling, multiple model interpretations are often possible. This leads to disagreement among experts, which in the past has led to disagreement on the selection of ground motion for design at a given site. The Senior Seismic Hazards Analysis Committee (SSHAC) reviewed past studies, including the Lawrence Livermore National Laboratory and the EPRI landmark PSHA studies of the 1980's and examined ways to improve on the present state-of-the-art. The Committee's most important conclusion is that differences in PSHA results are due to procedural rather than technical differences. Thus, in addition to providing a detailed documentation on state-of-the-art elements of a PSHA, this report provides a series of procedural recommendations. The role of experts is analyzed in detail Two entities are formally defined – the Technical Integrator (TI) and the Technical Facilitator Integrator (FI) – to account for the various levels of complexity in the technical issues and different levels of efforts needed in a given study.

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