DRAFT

January 18, 2013

Walter Arabasz
PPRP Chairman
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Subject: *EPRI (2004, 2006) Ground-Motion Model (GMM) Review Project: Requested Chapters and Sections to Provide the Updated GMM with Accompanying Text*

Dear Dr. Arabasz:
This letter transmits a CD via overnight mail with the requested chapters and sections that provide a discussion of the preliminary updated EPRI (2004, 2006) GMM. The purpose of transmitting this intermediate document at this time is to facilitate our discussion and decision-making at the PPRP Closure Briefing on February 13, 2013.

Draft text for Sections 6.1, 6.2 and 6.3, Chapter 8 and Chapter 10 are provided. In addition, non-requested, initial drafts of Introductory Materials, Chapters 1, 2, 4, 7, Appendix B, Appendix C and Appendix F are also enclosed to provide additional background and perspective. All transmitted information should be considered a preliminary draft and subject to change based on further review.

We appreciate your taking time to review the enclosed information before the PPRP Closure Briefing on February 13, 2013 to begin the technical and process review by the Participatory Peer Review Panel (PPRP). We will be discussing the enclosed information at a Nuclear Regulatory Commission (NRC) Public Meeting on January 23, 2013. Instructions to access the NRC webinar have been sent in an email dated 1/11/13.

Sincerely,

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EPRI (2004, 2006) Ground-Motion Model (GMM) Review Project

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ABSTRACT

This report describes the Electric Power Research Institute (EPRI) (2004, 2006) Ground-Motion Model (GMM) Review Project, which will provide industry with information necessary to respond to the U.S. Nuclear Regulatory Commission's Request for Information to Title 10 of the Code of Federal Regulations 50.54(f), Recommendation 2.1 of the Near-Term Task Force Review of Insights from the Fukushima Dai-Ichi Accident, dated March 12, 2012.

The purpose of this study was to determine whether the EPRI (2004, 2006) GMM required updating, considering currently available data and seismological understanding of ground motions in the Central and Eastern United States (CEUS); if it did require updating, an update of the model would be developed. The team assembled to conduct the evaluation was composed of distinguished subject-matter experts from industry, government, and academia. The evaluation considered new data, models, and methods. This project solicited and evaluated the center, body, and range of uncertainty based on inputs from acknowledged experts in the larger technical community, used a Senior Seismic Hazard Analysis Committee Level 2 assessment process, and obtained feedback from the Nuclear Regulatory Commission throughout the study. Therefore, the updated model can be used with confidence to calculate ground-motion response spectra at existing nuclear power plant sites with a high level of assurance that the spectra properly represent current technical knowledge.

The study was conducted in two phases. The purpose of Phase 1 was to review the EPRI (2004, 2006) GMM, and the purpose of Phase 2 was to update the EPRI (2004, 2006) GMM, integrating up-to-date data, models, and methods. As part of the project, shear-wave-velocity measurements were obtained at 33 seismic recording stations, with the USGS providing additional measurements obtained at 25 seismic recording stations, to reduce uncertainty by adjusting ground motions to reference conditions. The Project Plan included the establishment of the technical bases for (1) updating the EPRI (2004, 2006) GMM and selecting ground-motion prediction equations (GMPEs) by reviewing the literature and conducting interviews and a workshop with ground motion experts and seismologists, and (2) establishing the analytical approach for adjusting ground motions to reference conditions. Computation of GMPE weights using empirical site class factors was also part of the study, along with an update of the EPRI (2006) aleatory variability model using input from NGA-West 1(2008) and the NGA-West 2 (2012) studies. The seismic hazard for rock conditions at the seven 2012 CEUS demonstration sites were calculated using the updated EPRI (2004, 2006) GMM to compare these seismic hazard results with those in the 2012 CEUS study that used the EPRI (2004, 2006) GMM (Chapter 9).

The decision to proceed with the update of the EPRI (2004, 2006) GMM was based on the following information from Phase 1:

- Seven of the 13 developers of the GMPEs used in the EPRI (2004, 2006) GMM recommended that their GMPEs be replaced.
- Three new GMPEs were developed by ground motion experts during the past 10 years.
- Eighty percent of the earthquake records in a new ground-motion database provided by the NGA-East Project are from earthquakes that occurred after the development of the EPRI (2004) GMM.
- The EPRI (2004, 2006) GMM over predicts ground motions at some magnitude-distance frequency ranges important to nuclear power plant (NPP) probabilistic seismic hazard assessments (PSHAs).

In order to respond to the NRC March 12, 2012, letter, ongoing studies to compute ground-motion response spectra (GMRS) for existing NPPs in the 2012 CEUS study require the most up-to-date, well-founded models of ground motion equations and seismic sources. Phase 2 of the study updated the EPRI (2004, 2006) GMM for calculation of GMRS at existing NPPs in the CEUS with confidence. In Phase 2, the EPRI (2004, 2006) GMM was updated for the Mid-Continent and Gulf regions. Of course, uncertainties in models still exist, but these uncertainties were captured in the EPRI ground motion project with alternative-weighted models. The updated EPRI (2004, 2006) GMM will be suitable for use to address the seismic regulatory issues, pending completion of the NGA-East Project.

Keywords

Ground motion model (GMM)
Ground-motion prediction equations (GMPEs)
Probabilistic seismic hazard analysis (PSHA)

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LIST OF FIGURES AND TABLES
[WILL BE UPDATED LATER]

1
CHAPTER 1 INTRODUCTION

1.1 Background and History

1.1.1 Context of the Study

This chapter describes the process followed and the results of evaluation and integration activities performed for updating the ground motion model (GMM) of the Electric Power Research Institute (EPRI; 2004, 2006).[1] The updated model is intended for use by licensees of nuclear power plants located in the Central and Eastern United States (CEUS) for development of responses to the Title 10 of the Code of Federal Regulations (10 CFR), Section 50.54(f) information request by the U.S. Nuclear Regulatory Commission (NRC) in *Near-Term Task Force (NTTF) Review of Insights for the Fukushima Dai-Ichi Accident, Recommendation 2.1: Seismic*. The recently completed CEUS SSC Model (EPRI/DOE/NRC, 2012) and the updated EPRI (2004, 2006) GMM described in this report provide an up-to-date probabilistic seismic hazard model for use by licensees to compute site-specific probabilistic seismic hazard as required to develop their responses to *NTTF Recommendation 2.1: Seismic*.

The 50.54(f) request for information letter requires that licensees and holders of construction permits under 10 CFR Part 50 reevaluate the seismic hazards at their sites in light of present-day NRC requirements and guidance. Licensees' proposed evaluations and analyses for responding to the information request for *NTTF Recommendation 2.1: Seismic* have been developed by EPRI (2012). The proposed evaluations include the development of performance-based site-specific earthquake ground motion spectra (GMRS) for each currently operating nuclear power plant using current NRC seismic regulatory guidance.

1.1.2 Current Probabilistic Seismic Hazard Analysis Guidance

Current NRC seismic regulatory guidance for nuclear plants requires quantification of uncertainty in proposed seismic design basis ground motions by performance of a probabilistic seismic hazard analyses (PSHA). Methodological guidance for performing a PSHA properly

[1] The EPRI (2004) GMM and updated sigma model (EPRI, 2006) are currently accepted for use in performing probabilistic seismic hazard analyses at nuclear facility sites located in the Central and Eastern United States. For brevity, we refer to the EPRI (2004) GMM updated with the EPRI (2006) sigma model as the EPRI (2004, 2006) GMM, and we refer to the updated model developed in this project as the EPRI (2013) GMM.

represents both scientific and data uncertainty as described in the guidance developed by the Senior Seismic Hazard Analysis Committee, or SSHAC (Budnitz et al., 1997). The SSHAC Guidance drew upon experience from prior studies for development methods and procedures for properly representing uncertainty in PSHAs that had been carried out by the Electric Power Research Institute–Seismicity Owners Group (EPRI-SOG) study (EPRI, 1988) and the Lawrence Livermore National Laboratory (LLNL) study (Bernreuter et al., 1989). These studies had been carried out in parallel over a period of years with the specific goal of developing procedures for properly representing uncertainty in seismic design bases for nuclear facilities as required by the revised seismic and geologic regulation 10 CFR, Part 100.23. Both had undergone extensive review by the NRC and the scientific community.

The SSHAC Guidance describes structured processes for four study levels for developing a PSHA, depending on the intended use of the results (Budnitz et al., 1997). A study Level 2 or 3 is accepted for development of seismic hazard models to be used for evaluating or developing seismic design bases for nuclear plants. A Level 3 process is required for development of seismic hazard models that have regional extent and that will be incorporated into the NRC seismic regulatory guidance and used for PSHAs at many specific sites. A Level 3 process is also required for development of a site-specific PSHA at sites where no regional seismic hazard models exists. For development of a site-specific PSHA using an existing regional seismic hazard model, a Level 2 process is accepted for evaluating whether any enhancements of the existing accepted regional model may be required for the specific site.

Regardless of the study level, the goal of a SSHAC study is to capture uncertainty in both current technical knowledge and currently available data, and to properly represent the uncertainty in the PSHA. The SSHAC Guidance expresses this fundamental goal as follows:

> Regardless of the scale of the PSHA study, the goal remains the same: to represent the center, the body, and the range (CBR) of technical interpretations that the larger informed technical community (ITC) would have if they were to conduct the study [Budnitz et al., 1997, p. 27].

Recently, in NUREG-2117 (*Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies*), the NRC recast the goal in language that more clearly connects the goal to practical implementation based on experience gained since 1997 (NRC, 2012). The fundamental goal expressed in the SSHAC Guidance remains unchanged. In NUREG-2117, the goal is expressed as follows.

> The fundamental goal of a SSHAC process is to carry out properly and document completely the activities of evaluation and integration, defined as:
>
> *Evaluation:* The consideration of the complete set of data, models, and methods proposed by the larger technical community that are relevant to the hazard analysis.
>
> *Integration:* Representing the center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessment of existing data, models, and methods).

Current NRC seismic regulatory guidance for nuclear plants located in the CEUS uses the recently completed CEUS SSC Model 2012 (EPRI/DOE/NRC, 2012), coupled with the EPRI

(2004, 2006) Ground Motion Model. The CEUS SSC Model 2012 was developed in a SSHAC Level 3 study that was conducted over the period from April 2008 through December 2011. This newly developed CEUS SSC model replaced the more-than-20-years-old regional CEUS SSC models that were developed independently by the EPRI-SOG SSC model (EPRI, 1988) and the Lawrence Livermore National Laboratory (LLNL) SSC model (Bernreuter et al., 1989). These CEUS SSC models were developed to support an evaluation of the potential for occurrence of a large-magnitude earthquake at any location in the CEUS, identified as the "Charleston Earthquake Issue" (EPRI, 1989). Subsequently, the models were incorporated into the NRC's seismic and regulatory guidance for satisfying the requirements of the new seismic regulation 10 CFR 100.23 to quantify uncertainty in proposed seismic design basis ground motions (NRC, 1997). A SSHAC Level 3 study, the NGA-East Project, has been initiated with the goal of developing a new ground motion model for the CEUS that will *replace* the EPRI (2004, 2006) model. Implementation of the NGA-East Project has progressed to the stage of compiling a comprehensive updated database of ground motion recordings. However, the evaluation and integration process required for development of the replacement model will not be completed before at least 2015, which is well beyond the date when licensees are required to respond to *NTTF Recommendation 2.1*.

Thus the EPRI (2004, 2006) GMM accepted for use in PSHAs for Combined License Applications (COLAs) is the most current SSHAC Level 3 ground motion model available for use to meet the 18-month deadline established by the NRC for licensees' responses to the information request for *NTTF Recommendation 2.1*. Ten years have passed since the EPRI (2004) SSHAC Level 3 assessment was begun in 2002, and 8 years have passed since the SSHAC Level 2 assessment for updating the sigma component of the model was begun in 2005. Consistent with SSHAC guidelines and the fact that new data, models, and methods have become available, an update of the EPRI (2004, 2006) GMM is required in order to provide up-to-date technical bases for use by licensees in the development of responses to *NTTF Recommendation 2.1*.

1.1.3 EPRI 2004 Ground Motion Model and EPRI 2006 Update of Sigma Model

After the NRC accepted the CEUS seismic source model developed in the EPRI-SOG study (EPRI, 1988), EPRI performed a major CEUS ground motion study targeted on developing an understanding of aleatory variability and epistemic uncertainty in ground motion prediction models (GMPEs). The study resulted in the EPRI (1993) GMM, which included an assessment of epistemic uncertainty in the median motions and an assessment of aleatory variability/sigma model. Essentially, all of the then active ground motion modeling experts participated in the study, which stimulated follow-on individual research by a number of the participants who produced an equal number of proponent ground motion models. The EPRI (1993) model, together with models subsequently developed by individual researchers, formed the body of information for the EPRI (2004) GMM project. The EPRI (2006) sigma model was developed by implementation of a SSHAC Level 3 study and provided a CEUS GMM that represented the center, body, and range of the then available GMPEs.

Results of interviews with experts during this study did not indicate a need to change the conclusions of EPRI (2006) with regard to differences between CENA and WNA aleatory variability. Repeated analysis was performed for this study using final published values of aleatory variability from NGA-West 1 (2008) papers for four models that provided both inter-earthquake variability and intra-earthquake variability. The final aleatory model used for this study considered preliminary results of NGA-West 2 (2012). Additional discussion is provided in Chapter 8.

1.1.4 NRC Guidance for Updating Seismic Hazard Models

Guidance for updating an accepted existing seismic hazard model is contained in NUREG-2117 (NRC, 2012). The guidance addresses the expectation that with the passage of time after a model is completed, new data will become available, and advances in technology will occur that may necessitate updating or modifying the accepted existing model. In particular, NUREG-2117, Chapter 6, provides guidance on evaluations to determine whether updating an accepted existing hazard model is required in order to maintain the fundamental goal of a SSHAC process to capture the center, body, and range of technically defensible interpretations at the particular time. Thus, for a later application of an existing accepted model, it is necessary to perform an evaluation to determine whether the model should be updated or modified. The guidance takes into account the viability of the accepted existing model as well as the intended use of the model for a regulatory application. Depending on the intended use (e.g., update of seismic regulatory guidance that may be used for multiple licensing applications versus a site-specific application, or one-time resolution of a specific regulatory issue), the required update may be to either replace (completely set aside), revise (modify), or refine (incorporate site-specific information into) the existing model.

As stated above, a SSHAC Level 3 process is required for development of a seismic hazard model that is intended to replace an accepted existing model in the NRC's seismic regulatory guidance. The replacement process requires topical review and acceptance of the proposed replacement model for generic application as well as updating of seismic regulatory guidance. A SSHAC Level 2 process may be used for modification or refinement of a viable accepted existing SSHAC Level 3 model in order to address a specific regulatory issue or a site-specific application.

A SSHAC Level 2 study with enhancements has been implemented for updating the EPRI (2004, 2006) GMM model. as described in this report. The study was implemented in two phases. Phase 1 consisted of evaluations of the significantly more extensive strong-motion database that is currently available and the advances in ground motion modeling that have been made during the past 10 years. These evaluations resulted in the conclusion that the model should be modified in order to properly represent current data and advances in ground motion modeling. Phase 2 consisted of evaluations of the updated database and advances in ground motion modeling and integration for modifying the EPRI (2004, 2006) GMM to represent the center, body, and range of current technically defensible interpretations. The detailed description of the implementation process is described in Chapter 4 of this report.

2
CHAPTER 2 DEVELOPMENT OF PROJECT PLAN

2.1 Due Diligence (October 2011 to March 2012)

Licensees of nuclear power plants located in the CEUS are expected to use the CEUS SSC model (EPRI/DOE/NRC, 2012) and the appropriate EPRI (2004, 2006) ground motion model to compute GMRS at existing plant sites. Considering the importance of the GMRS calculation to support the licensees' responses to *NTTF Recommendation 2.1*, EPRI funded this project for the purpose of reviewing, and if necessary, updating the EPRI (2004, 2006) GMM for calculating the earthquake ground motion response spectra (GMRS) at existing nuclear power plant sites. A structured, unbiased process with the involvement of the technical community, regulator, and oversight groups was followed to evaluate whether the EPRI (2004, 2006) GMM is appropriate for developing GMRS for nuclear power plant sites in the CEUS.

For evaluating whether the EPRI (2004, 2006) GMM should be updated, industry sought the insights and perspectives of recognized ground-motion experts, using conference calls, interviews, and a meeting. Table 2.1-1 lists the dates for these contacts and the professionals who participated, some of whom had been involved in the SSHAC studies, which were initiated in 2002 and which developed the EPRI (2004, 2006) GMM. The following situations and recommendations concerning current state of GMM practice for the CEUS came from these discussions.

- It has been 10 years since the EPRI (2004) SSHAC Level 3 process evaluation and integration using then available ground motion prediction equations (GMPEs) was begun in 2002 and about 8 years since the EPRI (2006) SSHAC Level 2 evaluation and integration process for updating sigma component of the model was begun in 2005.
- A new ground-motion database has been assembled by the NGA-East Project, and new experience has been gained from the NGA-West 2 and PEGASOS projects (refs). The updating of the sigma component of the model assessment (EPRI, 2006) was based on experience from the NGA-West Project.
- New ground-motion prediction equations (GMPEs) and new CEUS ground-motion studies have been published since the EPRI (2004) SSHAC Level 3 workshops, including Atkinson (2004a, 2004b, 2008); Atkinson and Boore (2006, 2011); Atkinson and Kaka (2007); Atkinson and Kraeva (2010); Atkinson and Morrison (2009); Atkinson et al. (2011); Boatwright and Seekins (2011); Boore (2012); Boore et al. (2010); Campbell (2004, 2009); Pezeshk et al. (2011); Sonley and Atkinson (2006); Tavakoli and Pezeshk (2005); and Zandieh and Pezeshk (2010). A preliminary comparison of Atkinson et al.

(2011), Atkinson and Boore (2011), and Pezeshk et al. (2011) with the EPRI (2004, 2006) GMM suggests there may be differences with the new models.

- New significant earthquakes have occurred since 2002 (e.g., the magnitude 5.8 Mineral, Virginia, earthquake on August 23, 2011) that should be considered in the review of the EPRI (2004, 2006) GMM. Main-shock data from the Mineral, Virginia, earthquake provides information on source spectrum and some insight and constraint on magnitude-fault-area relations and stress drop. Portable instruments installed after the main shock occurred provide a very large three-component data set, which provides constraint on geometrical spreading near the source, vertical/horizontal component amplitude ratios, and the effect of radiation pattern near the source. Other important earthquakes since 2002 include the 2008 magnitude 5.3 Mt. Carmel, Illinois, earthquake and the 2010 magnitude 5.0 Val des Bois, Quebec, earthquake.
- One hybrid GMPE in the EPRI (2004, 2006) GMM has unphysical behavior at long distances.
- Some GMPEs do better in certain magnitude distance ranges. This should be taken into account when evaluating them and when incorporating them into a GMM.
- Modification of the existing four clusters may be necessary to account for revised magnitude and distance terms.
- Calculation of sigma should take into account the site-condition conversion to reduce scatter. New information may result in different sigma for small- and large-magnitude earthquakes.
- Correlations between ground motion parameters need to be considered: (a) geometrical spreading and stress drop, (b) kappa correction, (c) sigma models, and (d) site correction.

After these insights and perspectives were received from the ground motion experts, it became clear that significant new data, as well as potentially significant advances in ground motion modeling, have become available since the EPRI (2004, 2006) GMM was developed. Given these developments, industry developed a work plan for evaluating the EPRI (2004, 2006) GMM, considering the new data and modeling advances, and, if determined to be needed, updating the model for specific use in the development of licensees' responses to *NTTF Recommendation 2.1.*

2.2 Work Plan (March 2012 to June 2012)

An important component of the Work Plan has been to take full advantage of the updated database and findings from the NGA-East Project available at the time and from the USGS Seismic Hazard Mapping Project. Other data and information developed over the past 10 years were also evaluated.

The Work Plan consists of a series of tasks designed to implement the project in two phases. Phase 1, consisting of Tasks 1 through 4, reviewed the EPRI (2004, 2006) GMM in light of up-to-date data, models, and methods to determine whether this GMM remains appropriate for calculating GMRS at existing nuclear power plant sites. The Phase 1 results were discussed with the PPRP, Senior Technical Advisors, Sponsor, and NRC Observers, and a decision was made to proceed with Phase 2. Phase 2, consisting of Tasks 5 through 12, implemented the SSHAC Level 2 process for updating EPRI (2004, 2006) GMM, integrating new data, models, and methods.

The project drew upon work accomplished to date by the NGA-East Project, which is being performed as a SSHAC Level 3 assessment process. The goal of the NGA-East Project is to develop a new CEUS GMM intended to replace the EPRI (2004, 2006) GMM. The tasks for Phase 1 and Phase 2 are described below. The relationship between the phases, tasks, and decision points is shown on Figure 2.1-1

2.2.1 Task 1—Development of Project Plan and Approval by Participatory Peer Review Panel and NRC Observers

The Project Manager and TI Team developed the Project Plan, which was then reviewed by the PPRP, Senior Technical Advisors, Observers, and NRC representatives. Comments were addressed in the finalization of the plan. Decision Point 1 on Figure 2.1-1 was met with reviewer approval.

2.2.2 Task 2—Obtain Ground-Motion Database and Identify New CEUS GMPEs

The first goal of this task was to obtain a comprehensive ground-motion database for use in reviewing the EPRI (2004, 2006) GMM. The TI Team determined that the NGA-East CENA ground-motion database fulfilled this goal, so this database was obtained. In addition to the compilation of data, this task included (1) the management and documentation of data, (2) the presentation of data for the TI Team to use during working meetings, and (3) communication with the NGA-East Project regarding the status of its quality control of the database and any data it may add to the database. The second goal of this task was to compile a comprehensive bibliography on CEUS ground motions and related themes, consisting mainly of published papers but also including work in progress and the "gray literature." In addition to literature reviews, the TI Team members interviewed researchers working on CEUS ground-motion modeling and related topics and obtained copies of papers under review or in press and an update on the researchers' ongoing work.

2.2.2.1 Literature Reviews

The literature review tables in Appendix B document the results of the reviews by the TI Team and demonstrate the structured and systematic evaluation of the range of diverse interpretations from the larger technical community. Full citations of references are provided in the table in Appendix B and in Chapter 11—References.

2.2.2.2 Interviews

The TI Team interviewed the resource experts and proponents listed in Appendix C who are working on CEUS ground motions and related topics, to obtain an update on their ongoing work, including copies of papers under review or in press. To facilitate the interview process, the TI Team prepared the questions listed in Appendix C to use during the interview. The resource expert and proponent interview tables in Appendix C document the information obtained from the interviews and demonstrate the structured and systematic evaluation of the range of diverse interpretations from the larger technical community.

2.2.3 Task 3—Obtain Shear-Wave-Velocity Measurements at Seismic Recording Stations

The goal of this task was to obtain shear-wave-velocity measurements at strong ground motion sites from which recordings that are in the NGA-East ground-motion database have been obtained. Shear-wave velocities to a minimum depth of 30 m (V_{S30})[1] were obtained. As part of the project, shear-wave-velocity measurements were obtained at 33 seismic recording stations, with the USGS providing additional measurements obtained at 25 seismic recording stations, to reduce uncertainty by adjusting ground motions to reference conditions.

This project started with a list of stations for shear-wave-velocity measurements that were prepared by the NGA-East Geotechnical Working Group. The group's criteria for the selection of the seismic recording stations were proximity to nuclear plant sites (with a preference for rock-over-soil sites) and location within the United States (for ease of access). The TI Team modified this list to include more recordings from earthquakes with magnitudes greater than 5 and 4 to 5, giving preference to recordings at distances less than 500 km. Stations on deep soil were avoided because the removal of site effect is more difficult for these sites. Stations for which the NGA-East database already included V_{S30} values were not included in the list.

2.2.4 Task 4—Test EPRI (2004, 2006) Ground Motion Model (GMM)

The goal of this task was to test the EPRI (2004, 2006) GMM against the consensus state of knowledge and data assembled in Tasks 2 and 3. Two initial steps were performed: reviewing and evaluating new CEUS GMPEs and correcting the ground motion data for site effects for comparison to the EPRI (2004, 2006) GMM. Establishment of the analytical approach for adjusting ground motions to reference conditions and computation of GMPE weights using empirical site class factors were also part of this task. The result of Task 4 was an estimate of the anticipated change in the median amplitude and in the epistemic uncertainty as a result of the new data and models, for various magnitude and distance ranges. Decision Point 2 on Figure 2-1 to proceed with Phase 2 was reached at the end of Task 4.

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[1] V_{S30} is defined as the time-averaged shear-wave velocity to a depth of 30 m. It is calculated as 30 m divided by the one-way vertical travel time of shear waves to a depth of 30 m.

2.2.5 Task 5—Update EPRI (2004, 2006) GMM

The goal of this task, contingent upon the results of Task 4, was to develop an updated EPRI (2004, 2006) GMM. This task consisted of the following major steps:

- Evaluate within-cluster epistemic uncertainty.
- Check consistency of corrected data (and adjust, if necessary).
- Develop parametric GMPEs for PSHA.
- Consider modifying the EPRI (2006) model for sigma following the EPRI (2006) approach.

Chapter 8 provides details about the development of the updated EPRI (2004, 2006) GMM.

Comparison of residuals for EPRI (2004) and new candidate GMPEs was made using an empirical site correction and an analytical site correction for seismic recording stations. Site classes in the empirical approach were assigned based on V_{S30} and geologic descriptions in the NGA-East database. In the analytical approach, measured shear-wave-velocity data were used to correct for site amplification.

The results of interviews with experts indicated that there was no need to change the conclusions of EPRI (2006) with regard to differences between Central and Eastern North America (CENA) and Western North America (WNA) aleatory variability. Analysis was repeated using final published values of aleatory variability from NGA-West 1 (2008) papers for four models, and the final model was reviewed based on preliminary results from NGA-West 2 (2012).

2.2.6 Task 6—Workshop: Interactions with Technical Community

The goal of this task was to present and discuss the preliminary ground-motion model in a public forum, with the opportunity for feedback from resource experts and proponents from the technical community. Table 2.2.6-1 provides a list of resource experts and proponents participating in the workshop. This was accomplished in a one-day ground motion workshop held on October 17, 2012.

The focus of the workshop was a roundtable discussion to achieve the goal of this task. Copies of the Project Overview were sent to the resource experts and proponents prior to the workshop. The TI Team provided the results from Task 5 performed to develop the preliminary updated EPRI (2004, 2006) GMM, and a targeted discussion followed. Feedback from the resource experts and proponents, the PPRP, and Observers (NRC, USGS, Defense Nuclear Facilities Safety Board [DNFSB], and NGA-East Project) was sought immediately afterwards.

The PPRP provided a final report regarding the preliminary updated EPRI (2004, 2006) GMM on October 23, 2012 (Appendix H). TI Team and Project Manager (PM) dialogue with resource experts and proponents continued after the workshop. Documentation for the post-workshop dialogue is provided in Appendix E. The feedback obtained during and after the workshop was used to ensure that the preliminary updated EPRI (2004, 2006) GMM was consistent with current data, models, and methods and then make the decision to proceed to finalize the updated EPRI (2004, 2006) GMM.

2.2.7 Task 7—Calculate Seismic Hazard at Seven Demonstration Sites

The goal of this task was to calculate the seismic hazard for rock conditions at the seven CEUS SSC demonstration sites using the EPRI (2013) GMM, and to compare these seismic hazard results with the results in the CEUS SSC Report (EPRI/DOE/NRC, 2012) that used the EPRI (2004, 2006) GMM. An additional goal was to perform a sensitivity analysis to quantify the hazard implications of the various branches and components of the EPRI (2013) model.

Beyond the scope of the Project Plan, additional sensitivity studies on seismic hazards were performed by specific equations and by an epistemic sigma model at the seven demonstration sites, including seven frequencies to provide further insights on the model at 0.5 Hz, which was a problem frequency in EPRI (2004), and at 25 Hz, which is a critical high frequency for nuclear plant design. Also, sensitivity plots on contributions by source for some critical frequencies and sites were made to compare to sensitivities presented in the CEUS SSC Report (EPRI/DOE/NRC, 2012). An example is the Houston demonstration site, for which comparisons were made between EPRI (2004) hazards using the Mid-Continent equations for New Madrid, with the EPRI (2013) hazards using the Gulf equations for New Madrid.

2.2.8 Task 8—Finalize Updated EPRI (2004, 2006) GMM

In light of the feedback received in the workshop conducted for Task 6, and using the final database and input from the PPRP, Senior Technical Advisors, Observers, and NRC representatives, the TI Team finalized the updated EPRI (2004, 2006) GMM. Uncertainties in currently available data, models, and methods were fully characterized and represented in the updated model. The technical basis for relative weights was developed and documented.

2.2.9 Task 9—Document EPRI (2004, 2006) GMM Review Project in Draft Report

This task includes the documentation of the EPRI (2004, 2006) GMM Review Project in a draft report. The process and technical aspects of the study are described to provide the fundamental basis for the acceptance and subsequent use by other parties.

2.2.10 Task 10—Review Draft Report by PPRP and Other Reviewers

As defined in the SSHAC Guidelines, the PPRP reviewed the draft report from the standpoint of both the technical content and the process followed, and provided written comments. The Senior Technical Advisors and Observers, including the NRC representatives, also provided comments in writing. A closure meeting was held on February 13, 2013, with the PPRP, Senior Technical Advisors, and Observers, including the NRC representatives, to discuss their comments and the resolution of those comments.

2.2.11 Task 11—Finalize EPRI (2004, 2006) GMM Review Report

The Project Team reviewed comments made by the PPRP and other reviewers, incorporated the comments, obtained agreement from the PPRP and NRC that comments were resolved, and completed the final EPRI (2004, 2006) GMM Review Report.

2.2.12 Task 12—Issue EPRI (2004, 2006) GMM Review Report

Editorial and publication issues were resolved, and the EPRI Technical Report was provided to EPRI for publication.

2.2.13 Project Manager (PM) and Technical Integration (TI) Team Evaluation and Integration Working Meetings and Conference Calls

Working meetings and conference calls were held to consider and discuss a variety of topics. Much of the actual SSHAC assessment processes of evaluation and integration occurred at the working meetings that took place before and after the workshop. The PPRP, Senior Technical Advisors, and Observers, including the NRC representatives, were invited to the working meetings. Each working meeting lasted one day and was documented. A summary of highlights and the presentations made during the working meeting were provided to all meeting participants afterwards. Many conference calls were also held throughout the study period to discuss and resolve the numerous technical issues associated with the project assessments and to communicate with the PPRP, Senior Technical Advisors, and Observers, including the NRC representatives. At the invitation of the NRC, the Project Manager and members of the TI Team participated in NRC public meetings to communicate project activities during the study period.

Appendix E provides the highlights for the working meetings. The technical working meetings and conference calls as part of the EPRI (2004, 2006) GMM Review Project are listed in Table 2.2.6-1.

Table 2.1-1. Industry Due Diligence Review—Participant Acknowledgments

Contact Type	Date	Participants
Conference Call	November 8, 2011	G. Atkinson, J. Bailess, J. Hamel, R. Kassawara, K. Keithline, J. Marrone, S. McDuffie, R. McGuire, M. Petersen, L. Salomone, J.C. Stepp, G. Toro, B. Youngs
Interviews	October 26, 2011	N. Abrahamson
	November 2, 2011	M. McCann
	November 3, 2011	W. Silva
Meeting	November 30, 2011	A. Frankel, C. Goulet, R. McGuire, M. Moschetti, C. Mueller, M. Petersen, S. Rezaeian, L. Salomone, J.C. Stepp, G. Toro
Conference Call—Project “Kickoff” Call	March 8, 2012	N. Abrahamson, J. Ake, W. Arabasz, S. Bozkurt, M. Chapman, J. Hamel, R. Kassawara, J. Kimball, R. McGuire, C. Mueller, C. Munson, R. Quittmeyer, L. Salomone, J.C. Stepp

Table 2.2.6-1. Technical Meetings and Conference Calls Conducted as Part of the EPRI (2004, 2006) Ground-Motion Model (GMM) Review Project (as of 1/15/13)

Title	Date	Invited Participants	Observers
Working Meeting #1—“Kickoff” Conference Call	March 8, 2012	TI Team, Project Manager (PM), Senior Technical Advisor(s) (STA), PPRP	NRC, DNFSB
TI Conference Calls (March 2012)	March 13, 20, 2012	TI Team, PM, STA	
NRC Public Meeting	April 2-3, 2012	XXXXXXXXXXX	XXXXXXXXXXX
Working Meeting #2	April 26, 2012	TI Team, PM, STA, PPRP	NRC, DNFSB, USGS, GEOVision, UTA
Working Meeting #3	May 24, 2012	TI Team, PM, STA, PPRP, L. Al-Atik (Resource Expert)	NRC, DNFSB, USGS, NGA-East Project Liaison (N. Abrahamson), J. Hamel (EPRI)
TI Conference Calls (June 2012)	June 6, 13, 20, 2012	TI Team, PM, STA	
Working Meeting #4	June 27, 2012	TI Team, PM, STA, PPRP, G. Atkinson (Resource Expert)	NRC, USGS, NGA-East Project Liaison (N. Abrahamson)
TI Conference Calls (July 2012)	July 2,10, 17, 27, 2012	TI Team, PM, STA	
TI Conference Calls (August 2012)	August 2,6,13, 2012	TI Team, PM, STA	
Project Conference Call	August 3, 2012	TI Team, PM, STA	PPRP, NRC, DNFSB
Working Meeting #5	August 14, 2012	TI Team, PM, STA, PPRP	NRC, DNFSB, K. Keithline (NEI), D. Moore (Southern Nuclear), J. Hamel (EPRI), R. Kassawara (EPRI)
NRC Public Meeting	August 16, 2012	XXXXXXXXXXX	XXXXXXXXXXX
TI Conference Calls (September 2013)	September 3,10, 2012	TI Team, PM, STA	
Project Conf. Call	September 20, 2012	TI Team, PM, STA	PPRP, NRC, DNFSB
NRC Public Meeting	September 21, 2012	XXXXXXXXXXX	XXXXXXXXXXX
TI Conference Calls (October 2012)	October 2, 9,16, 22, 26, 2012	TI Team, PM, STA	
Workshop: Interactions	October 17, 2012	TI Team, PM, STA,	NRC, DNFSB,

Title	Date	Invited Participants	Observers
with Technical Community		PPRP, Resource Experts and Proponents	R. Kassawara (EPRI), S. McDuffie (DOE), D. Moore (Southern Nuclear), R. Kayen (USGS), C. Goulet (NGA-East Project)
NRC Public Meeting	October 18, 2012	XXXXXXXXXXX	XXXXXXXXXXXX
PM Conference Call	November 2, 2012	TI Team, PM, STA, W. Mooney (USGS Resource Expert) W. Silva (Resource Expert	
TI Conference Calls (November 2012)	November 5,7,19,26, 2012	TI Team, PM, STA	
Project Conference Call	November 12, 2012	TI Team, PM, STA	PPRP, NRC, DNFSB
TI Conference Calls (December 2012)	December 3,17, 18, 2012	TI Team, PM, STA	
Project Conference Call	December 19, 2012	TI Team, PM, STA	PPRP, NRC, DNFSB
TI Conference Call (January 2013)	January 2, 8 2013	TI Team, PM, STA	
Sponsor Briefing	January 15, 2013	PM and TI Team Member	
NRC Public Meeting	January 23, 2013	XXXXXXXXXXX	XXXXXXXXXXXX
Project Conference Call	February 1, 2013	TI Team, PM, STA	PPRP, NRC, DNFSB
PPRP Closure Briefing	February 13, 2013	TI Team, PM, STA, PPRP, NRC	DNFSB, NGA-East Project

Table 2.2.13-1. Technical Community Resource Experts and Proponents at Workshop

Participant	Organization
Jon Ake*	NRC
Gail Atkinson	University of Western Ontario
Jack Boatwright	USGS
Dave Boore	USGS
Chris Cramer	University of Memphis
Christine Goulet	University of California at Berkeley
Vladimir Graizer*	NRC
Annie Kammerer*	NRC
Robert Kayen	USGS
Jeffrey Kimball*	DNFSB
Stephen McDuffie*	U.S. Department of Energy
Clifford Munson*	NRC
Shahram Pezeshk	University of Memphis
Walter Silva	Pacific Engineering
Paul Somerville	URS Corpooration

* Resource Expert Observer

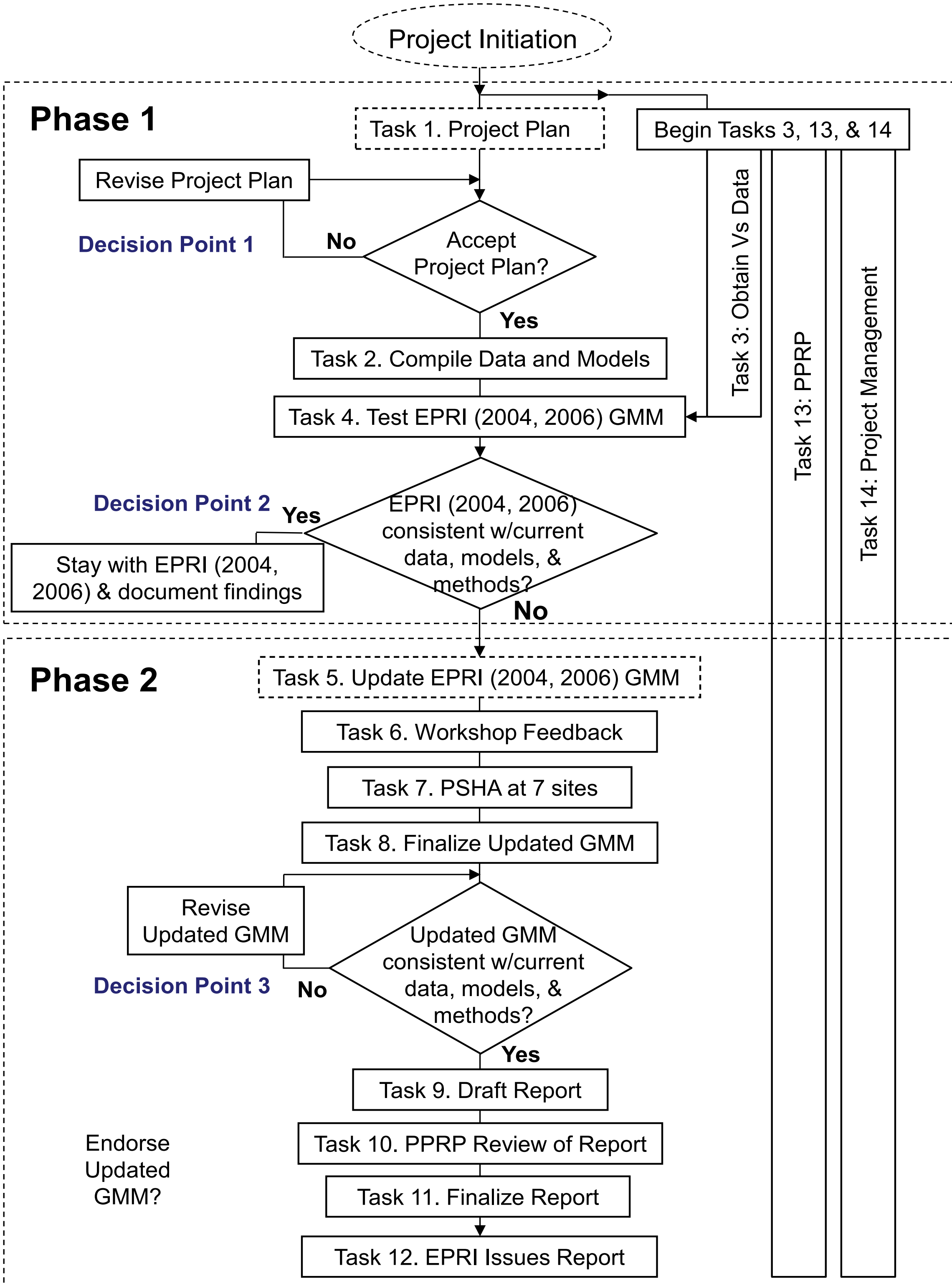

Figure 2.1-1. Project Flow Chart, Including Decision Points

4

CHAPTER 4
SSHAC LEVEL 2 ASSESSMENT PROCESS AND ITS IMPLEMENTATION FOR THIS STUDY

This chapter describes the SSHAC Level 2 assessment process, how it was implemented to perform the EPRI (2004, 2006) Ground-Motion Model (GMM) study, and how that implementation was accomplished in compliance with the SSHAC Guidance. Level 2 studies prescribed in NUREG/CR-6372[1] include communications with members of the technical community to enable the Technical Integrator (TI) to thoroughly understand current technical knowledge and uncertainties in both data and technical interpretations (ref). A project report, which is subject to peer review, documents the technical assessments. Discussion of the SSHAC process in this chapter comes from two sources:

- The SSHAC document, *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts* (Budnitz et al., 1997).
- NUREG-2117, *Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies* (NRC, 2012).

The steps (attributes) of the Level 2 analysis are presented in Section 4.8 and were incorporated into the process implemented for the EPRI (2004, 2006) GMM Review Project. It should be emphasized, however, that the additional steps (attributes) beyond those summarized in Section 4.8 characterize the assessment process used for the EPRI (2004, 2006) GMM Review Project.

4.1 Goals and Activities of a SSHAC Assessment Process

The fundamental goal of a SSHAC study is to capture uncertainties in technical knowledge and in available data. The SSHAC Guidance expresses this fundamental goal in this way:

> Regardless of the scale of the PSHA study, the goal remains the same: to represent the center, the body, and the range (CBR) of technical interpretations that the larger informed technical community (ITC) would have if they were to conduct the study [Budnitz et al., 1997, p. 27].

Recently, in NUREG-2117, *Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies*, the NRC recast the goal in language that more clearly connects it to practical implementation based on experience gained since 1997 (NRC, 2012). The fundamental goal

[1] Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts: Main Report (NUREG/CR-6372, two volumes

expressed in the SSHAC Guidance remains unchanged. In NUREG-2117, this goal is expressed as follows:

> The fundamental goal of a SSHAC process is to carry out properly and document completely the activities of evaluation and integration, defined as:
>
> *Evaluation:* The consideration of the complete set of data, models, and methods proposed by the larger technical community that are relevant to the hazard analysis.
>
> *Integration:* Representing the center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessment of existing data, models and methods).

In NUREG-2117, the term "community distribution," which is used frequently in the SSHAC Guidance to describe the outcome from a SSHAC assessment process, is clarified by substituting the term "integrated distribution." This is to remove any perception that the final assessments and models were arrived at through a mere poll of the community.

4.2 Project Organization

This section explains the organization of the EPRI (2004, 2006) GMM Review Project, including the responsibilities of the project participants. Section 4.3 presents a discussion of the lines of communication between the participants. The roles that various participants play in a SSHAC assessment process are important and are defined specifically in the SSHAC Guidance (Budnitz et al., 1997) and in NUREG-2117 (NRC, 2012). The EPRI (2004, 2006) GMM Review Project was conducted in accordance with the SSHAC Guidance, which explicitly defines the roles of project participants who contribute to a PSHA project. Beginning with the review of the roles prior to the Kick-Off conference call on March 8, 2012, all project participants were informed of their expected roles before their participation, and they were reminded of their roles during the Kick-Off conference call, at working meetings and, as required, at other opportunities throughout the project. Table 2.2.6-1 identifies the technical meetings that were conducted during the course of the project, including the participants and meeting dates.

The project organization is shown in chart form on Figure 4.2-1, and participant roles and responsibilities are summarized below.

4.2.1 Project Sponsor: EPRI Management

The Electric Power Research Institute (EPRI) sponsored the EPRI (2004, 2006) Ground-Motion Model (GMM) Review Project. EPRI Management included an Executive Director and a Senior Project Manager, as shown on Figure 4.2-1. The primary responsibility of the EPRI Management was defining the sponsor expectations, sharing the sponsor expectations with the Project Manager, and, with the support of the Project Manager, keeping EPRI members abreast of project activities and progress. Additional responsibilities included the following:

- Securing funding for the project and awarding a contract to obtain shear-wave-velocity measurements at approximately 33 recording stations.

- Assuming responsibility for contract management and providing the fundamental interface for contracts.
- Monitoring spending and adherence to the Project Plan.
- Working with the Database Manager to resolve copyright issues.
- Defining the level of transparency to use for products developed during the study.
- Providing support for the Participatory Peer Review Panel (PPRP) Closure Briefing at EPRI offices in Palo Alto, California.
- Establishing publication requirements for the Project Plan and report.
- Reviewing and giving approval of the EPRI (2004, 2006) GMM Review Project draft and final report.

4.2.2 Project Manager

The primary responsibilities of the Project Manager were serving as the point of contact between the project and the Sponsor and ensuring adherence to scope, schedule, budgets, and contractual requirements. The Project Manager had the primary responsibility for the delivery of all technical products. Additional responsibilities included the following:

- Interfacing with PPRP, Technical Integration (TI) Team, Senior Technical Advisors, Sponsor, and Observers.
- Serving as the point of contact to keep the Sponsor, PPRP, Senior Technical Advisors, Observers, and the public apprised of project activities and progress.
- Reviewing technical products provided by the TI Team.
- Working with the TI Lead to organize working meetings.
- Working with the EPRI Executive Director and the EPRI Senior Project Manager to communicate information to the project team regarding contractual requirements and the publication requirements established for the Project Plan and report.
- Assisting the Executive Director and the EPRI Senior Project Manager in establishing and maintaining budgets and schedules.
- Working with Norm Abrahamson, Yousef Bozorgnia, Christine Goulet, and Charles Mueller to share information about the project and to obtain inputs from the NGA-East Project and the USGS National Seismic Hazard Mapping Project.
- Leading the TI Team’s efforts to obtain shear-wave-velocity profiles at 33 recording stations, and additional profiles from the USGS obtained at 25 recording stations.
- Serving as the principal spokesperson to the external community, including the NRC, Defense Nuclear Facilities Safety Board (DNFSB), and the public.

4.2.3 Participatory Peer Review Panel

Participatory peer review was considered a key aspect of the project's assessment process. *Participatory peer review* is defined as an ongoing or continuous process that provides the peer reviewers with full and frequent access throughout the entire project, in contrast to a late-stage peer review that occurs when a project has almost been completed, as in a Level 2 study. This was to ensure that the process followed was adequate, uncertainties were properly considered and incorporated into the analysis, and the results provided a reasonable representation of the diversity of views of the technical community. The principal benefit of a participatory peer review is that if problems are discovered, the opportunity exists for a mid-course correction without the need for work to be substantially redone at the end.

The primary responsibility of the project PPRP was reviewing the technical and process aspects of the project. A *technical peer review* is a review of the earth sciences aspects of a study, including a review to ensure that all applicable technical hypotheses have been considered. A *process peer review* is a review of how the study is structured and executed. Additional responsibilities of PPRP members included the following:

- Attending working meetings and the TI Team workshop, plus participating in conference calls to observe the process and monitor progress of the project.
- Interacting occasionally with the Project Manager and TI Team as a resource expert, if requested.
- Providing written review comments, in the form of a single consensus letter report, on the Project Plan, the decision to update the EPRI ground-motion model, and the draft and final versions of the project report.
- Providing oral and written review comments, as required, on interim technical assessments or other products made by the TI Team at key points during the project.
- Participating in the PPRP Closure Briefing in Palo Alto, California.
- Providing a written closure report to the Project Manager for inclusion in the final project report.
- Performing other tasks, as feasible, requested by the Project Manager (e.g., reviewing the list of Resource and Proponent Experts invited to the workshop to interact with the TI Team).

4.2.4 Technical Integration Team

The TI Lead is responsible for ensuring that all TI Team members know their roles as evaluators and that they maintain those roles throughout the course of the project. The TI Team members are responsible for developing and documenting the technical basis for all project evaluations, assessments, and products. Additional responsibilities included the following:

- Implementing the SSHAC Level 2 assessment methodology throughout the project, including all key assessment steps of evaluation and integration.

- Working with the Project Manager to develop the Project Plan.
- Maintaining scope, schedule, and budget.
- Developing the project database.
- Compiling post-2002 ground-motion prediction equations (GMPEs).
- Conducting working meetings and other project meetings, as required.
- Participating in conference calls.
- Facilitating the requisite expert interactions.
- Communicating with the Project Manager and the PPRP and responding to reviews, as required.
- Providing technical products and technical assessments and justification for their bases.
- Documenting all process and technical aspects of the study and decisions in a project report.

4.2.5 Database Manager

The primary responsibility of the Database Manager was retrieving and compiling applicable data for use by the TI Team. Additional responsibilities included the following:

- Retrieving and compiling applicable data, such as data sets from the USGS National Seismic Hazard Mapping Project and the NGA-East Project.
- Providing data sets in appropriate formats for use in the TI Team deliberations.
- Providing an FTP site for the project team to share information.
- Participating in conference calls.
- Providing support for resolving copyright issues, working meetings, and PPRP and Sponsor briefings, as required.
- Providing support and assistance for report preparation, including preparing figures.

4.2.6 Senior Technical Advisors

The primary responsibility of the Senior Technical Advisors was providing their technical knowledge and experience on specific topics of discussion regarding ground motion to the TI Team and Project Manager throughout the study. Additional responsibilities included the following:

- Providing insights, data, and viewpoints at the request of the Project Manager and TI Team.
- Providing current data, models, and methods to keep the TI Team abreast of ground motion developments since the 2002 workshops for EPRI (2004).

- Providing a basis for assessing the technical bases and uncertainties with recent and ongoing ground-motion-related studies in the technical community.
- Attending working meetings, participating in conference calls, and attending the PPRP Closure Briefing at the end of the project.
- Reviewing and providing comments on the draft and final project report.

4.2.7 Observers

Observers from industry and government were invited by the Project Manager to share their technical knowledge and experience on specific topics of discussion regarding ground motion with the TI Team and Project Manager throughout the study. Observers were not considered members of the project team, but they were kept abreast of project activities, decisions, and progress. Observers attended project meetings at their option.

4.2.8 Other Project Participants: Experts and Specialty Contractors

Three types of experts having distinctive roles are identified in a SSHAC assessment process: Resource Experts, Proponent Experts, and Evaluator Experts. Resource Experts and Proponent Experts were responsible for sharing their knowledge and experience on specific topics, as requested by the Project Manager and TI Team.

A Resource Expert is a technical expert with specialized knowledge of a particular data set, model, or method of importance to the hazard analysis. The expertise may be in the form of site-specific experience or knowledge of particular methodologies or procedures. A number of Resource Experts participated in the workshop and in interviews outside the workshop environment (Table 2.2.6-1).

A Proponent Expert is an expert who advocates a particular hypothesis or technical position. At the October 17, 2012, workshop, several Proponent Experts presented their ground motion models and explained the merits of the models' elements and correlation of ground-motion-model parameters. The workshop provided the opportunity for the TI Team to question the Proponent Experts about the technical support and uncertainties associated with their models.

An Evaluator Expert is an expert who can evaluate the relative credibility of multiple alternative hypotheses to explain a given set of observations. Each Evaluator Expert uses professional judgment to quantify uncertainties, based on review and evaluation of all potential hypotheses and available data. An evaluator may challenge a proponent's position and question the technical basis for conclusions as a means of gaining insight into the uncertainties. The members of the Project TI Team were charged with fulfilling the roles of Evaluator Experts.

A Specialty Contractor was responsible for providing specific activities and products to the Project Manager and TI Team.

4.3 Project Lines of Communication and Points of Contact

The lines of communication and points of contact are shown on Figure 4.3-1; this figure is provided to illustrate the flow of information between members of the project team that kept them aware of project developments and communications in a timely manner. The Project Manager was the point of contact for transmitting correspondence and work products to and from the TI Team, PPRP, Senior Technical Advisors, NRC, Observers, and Sponsor. The Project Manager, with the assistance of the TI Team, informed the Chairman of the PPRP and Sponsor of process and technical developments. The Project Manager and TI Team ensured that the Specialty Contractor and the Resource and Proponent Experts had the required information to support the project. The Project Manager was copied on all correspondence and work products.

4.4 Evaluation and Integration Activities

As outlined at the beginning of the project in the Project Plan, the EPRI (2004, 2006) GMM Review Project was structured around a set of tasks and activities that would fulfill the requirements of a SSHAC Level 2 project. The key evaluation and integration activities that define the EPRI (2004, 2006) GMM Review Project are described in detail in Chapter 2 and more generally in this section.

4.4.1 Database Development

A fundamental resource developed as part of the EPRI (2004, 2006) GMM Review Project is the project database. The database mainly provides information for the use of the TI Team in its evaluation and integration processes. Most of the database consists of a new ground-motion database provided by the NGA-East Project, publications from the literature (Appendix B), shear wave velocity profiles at 33 seismic recording stations obtained during this study and shear-wave velocity profiles at an additional 25 seismic recording stations provided by the U.S. Geological Survey (USGS). A summary of the project database is given in Appendix A, and a description of the data is provided in the metadata files.

4.4.2 Identification of Significant issues

The experience by the TI Team as developers and end users of ground motion models was considered in the identification of significant issues. This experience was supplemented using sensitivity analyses performed for this study. In addition, experience gained from the ongoing NGA-East Project was shared by resource experts with the TI Team during working meetings. Appendix E provides highlights from the working meetings. This productive cooperation with the NGA-East Project provided valuable insights and perspective regarding the significant ground-motion parameters.

4.4.3 Final Report Development

The goal of the workshop was to present and discuss the preliminary ground-motion model in a public forum, with the opportunity for feedback from resource experts and proponents from the technical community. The goal of this task was met by participating in a one-day ground-motion workshop on October 17, 2012. The Project Manager and TI Team developed objectives and an agenda for the workshop, which was reviewed by the PPRP, specifically identifying those proponents who were asked to present targeted technical discussions for workshop participants, so as to ensure that the project's feedback goals would be met. The feedback gained at this workshop ensured that no significant issues had been overlooked and allowed the TI Team to gauge the reaction of the community to the proposed EPRI (2013) GMM, uncertainties, and assessments of weights. This information provided a basis for the finalization of the ground motion model.

The focus of the workshop was a roundtable discussion to achieve the goal of the workshop. There was a review of the Project Overview sent to the resource experts and proponents prior to the workshop. The TI Team provided the results from Task 5 performed to develop the preliminary updated EPRI (2004, 2006) GMM and a targeted discussion followed. The TI Team presented the preliminary ground-motion model, with particular emphasis on how alternative viewpoints and uncertainties were captured. The technical bases for the assessments and weights were described to allow for a reasoned discussion of the constraints provided by the available data. Feedback from the resource experts and proponents, the PPRP and Observers (NRC, USGS, DNFSB and NGA-East Project) was obtained during the workshop. The Project Manager invited resource experts and proponents to provide post-workshop comments and continue the dialogue with the TI Team that began with the interviews (Appendix C). The PPRP provided a final report regarding the workshop and the preliminary updated EPRI (2004, 2006) GMM on October 23, 2012 (Appendix H).

4.4.4 Working Meetings

Although the workshop provided an opportunity for the TI Team to consider and discuss a variety of topics, much of the actual SSHAC assessment processes of evaluation and integration occurred at the working meetings that took place before the workshop. The PPRP, Senior Technical Advisors, Observers that included NRC Staff and selected resource experts and proponents participated in working meetings. Except for Working Meeting #1 that was a conference call, the working meetings were held in a conference room environment with the handouts available to all participants during the meeting. Each working meeting was focused on one or more agenda items that required attention by the TI Team. Each working meeting was documented, and Appendix E provides the agenda and highlights for the five working meetings held. The Project Manager distributed highlights for each working meeting to all participants. The working meetings held are summarized in Table 2.2.6-1.

4.4.5 Preliminary Updated Model Development

The TI Team developed the preliminary updated EPRI (2004, 2006) GMM using the results from Task 2. The project plan included the establishment of the technical bases for (1) updating the EPRI (2004, 2006) GMM and selecting GMPEs by reviewing the literature and conducting interviews and holding a workshop with ground-motion experts, and (2) establishing the analytical approach for adjusting ground motions to reference conditions. Computation of GMPE weights using empirical site class factors was also part of the study, along with an update of the EPRI (2006) aleatory variability model.

4.4.6 Completion and Review of Preliminary and Final Updated Ground-Motion Model

The TI Team continued its ongoing refinement of the updated EPRI (2004, 2006) GMM as part of Task 5. Analyses performed to assess the preliminary updated EPRI (2004, 2006) GMM resulted in changes to the ground motion prediction equations assigned to a cluster. Weights were modified based on the continued analyses performed using the preliminary updated EPRI (2004, 2006) GMM. The draft updated EPRI (2004, 2006) GMM was then completed and, as defined in the SSHAC guidelines, it is based on a systematic evaluation of the data, models, and methods proposed by the larger technical community and an integration process that provides the TI Team’s representation of the center, body, and range of technically defensible interpretations. The draft ground-motion model was documented in a Hazard Input Document (HID) and provided to the project hazard analyst for Task 7.

To facilitate the discussion at the PPRP Closure Briefing on February 13, 2013, the draft ground-motion model with accompanying text to explain the model was provided to the PPRP and Observers, which included NRC Staff, on January 21, 2013. A public meeting to discuss the draft ground motion model was held in Washington D.C. on January 23, 2013. This intermediate document provided important background information prior to the Closure Briefing on February 13, 2013, so that any issues could be discussed and resolved, and acceptance of the updated EPRI (2004, 2006) GMM could be obtained during the meeting.

Following the PPRP Closure Briefing, work on the draft report continued, and the Project Manager provided the draft report to the PPRP and Observers, including the NRC Staff, for review on March 13, 2013. The PPRP and the Observers, including the NRC Staff, issued a comprehensive set of comments on the draft ground-motion model on April 10, 2013. The comments were incorporated during the preparation of the final report, and the Project Manager provided the final report to EPRI on April 30, 2013, for publication.

4.5 Documentation

The Final updated EPRI (2004, 2006) GMM is documented in an HID, which was provided to the hazard analyst for performance of Task 7, and it is documented in this final project report. The steps involved in this documentation are summarized below.

4.5.1 Development of the Hazard Input Document

Upon completion of the final updated GMM, the essential elements of the model were documented in the HID for the project (Appendix G). The HID is the key deliverable of the project that can be used for hazard calculations in the future. Specifically, this document is meant for the hazard analyst—providing clarity about the model to be implemented and obviating the need to distill the model from the full report. The HID helps ensure that implementation of the model, which can be challenging due to its size and complexity, is as intended. The technical assessments that constitute the Final updated GMM are not justified nor discussed in the HID. The technical justifications for the assessments in the HID are given in this project report.

4.5.2 Development of Earlier Draft Report

The draft project report documented all the assessments made by the TI Team in 2012 and summarized the methodology that was used to make the assessments. All members of the TI Team including a Senior Technical Advisor and the Project Manager developed the draft report. The report summarized all the key process steps, discussed their consistency with a SSHAC Level 2 assessment process, provided a description of all key project deliverables, and provided a technical discussion and explanation for all elements of the updated GMM. The appendices to the report provided project-specific documentation of key products such as the final HID, literature review and interview summary tables, the project database, summaries of the working meetings and workshop and project written communications. The goal of both the draft and final project reports is to provide a self-contained complete description of all aspects of the project such that future readers of the report understand the methodology, the technical elements of the GMM model and the technical bases for all assessments. The draft report included the following features:

- A description and justification for the methodology followed, including justification for the SSHAC study level used.
- The database used in the analysis.
- A description of the GMM, including the technical basis for all assessments and the data that were relied upon.
- The seismic hazard results at the seven test sites, including a comparison of the hazard using the EPRI (2004, 2006) GMM and the EPRI (2013) GMM developed by this project.

The documentation in the draft and final reports provides the fundamental basis for the acceptance and subsequent use by other parties.

4.5.3 Draft Report Review

Review of the draft report began in January 2013. Drafts of Sections 6.1 and 6.2 and Chapters 8 and 10 were given to the PPRP and Observers, including the NRC Staff, on January 21, 2013, in order to provide the technical elements of the GMM model and the technical bases for all assessments prior to the PPRP Closure Briefing on February 13, 2013. The NRC held a public meeting to discuss the EPRI (2004, 2006) GMM Review Project on January 23, 2013. Preparation and review of the draft report continued after the PPRP Closure Briefing.

Review of the draft report was conducted by the PPRP, the Observers including the NRC, the Sponsor, and other groups, and written review comments were provide to the TI Team for its consideration. In accordance with the SSHAC assessment, the TI Team was instructed to give highest priority to the PPRP comments, but to consider all the reviewer comments in making revisions to the project report. The goal of the report review process was to provide the PPRP and other stakeholders an opportunity to comment on the completeness, clarity, and consistency of the documentation of the GMM. Consistent with its role within a SSHAC assessment process, the PPRP provided its comments pertaining to both the documentation of the process followed in the project as well as the technical assessments included in the GMM. The PPRP review comments are documented in Appendix H. The TI Team considered all reviewer comments.

4.5.4 Final Report Development

A Final report was developed that reflects revisions made in light of reviewer comments. The fundamental bases for revisions to the draft report were the written comments provided by the PPRP and other reviewers. A systematic process was followed for the responding to each of the reviewer comments to ensure that all commented were addressed.

4.6 Participatory Peer Review Panel

4.6.1 Roles and Responsibilities

SSHAC guidance specifies that if a PSHA project is to be successful, the crucial need for a strong peer review process cannot be overemphasized. The members of the PPRP met the SSHAC criteria that peer reviewers "must be 'peers' in the true sense: recognized experts on the subject matter under review" (Budnitz et al., 1997, p. 48). The purpose of peer review is to provide assurance of the following:

- A proper SSHAC Level 2 process with additional steps (attributes) has been followed.
- The diversity of views prevailing within the technical community has been considered.
- Knowledge and uncertainties have been properly quantified and incorporated into the analysis.
- Documentation is clear and complete.

The EPRI (2004, 2006) GMM Review Project used a *participatory* peer review process, which involved continuous review throughout all phases of the project. The use of a participatory peer review process exceeds guidelines for a SSHAC Level 2 assessment process. As recommended by the SSHAC guidelines, the PPRP was responsible for reviewing both the technical and process aspects of the project. The peer reviewers interacted frequently with the TI Team, provided written comments at prescribed intervals, and reviewed and approved the project report.

4.6.2 Reviews and Feedback

The purpose of a participatory peer review process, as opposed to a "late-stage" process in the guidelines for a SSHAC Level 2 assessment process, is to provide advice and recommendations during the course of the study and not just near the end of the study. Such feedback is valuable to the TI Team and improves the focus and quality of the evaluation and integration processes. For example, early in the project, the PPRP reviewed the Project Plan and provided its views on the planned work activities. PPRP review comments were instrumental in the TI Team's developing documentations that included literature review and interview summary tables (Appendix B and Appendix C) and will benefit future users of the study. The PPRP technical reviews also greatly assisted the team in focusing on key technical issues and ensuring a complete evaluation of all applicable data, models and methods.

To assist in the PPRP's monitoring and review of the project, the PPRP was invited to all working meetings and the workshop and to participate in project conference calls (Table 2.2.6-1). These technical meetings and conference calls served as opportunities for the PPRP to ask questions and gain clarification about the bases for updating the EPRI (2004, 2006) GMM and the technical elements of the draft and final updated EPRI (2004, 2006) GMM. Representatives from the PPRP were present as observers at all five working meetings of the TI Team. These technical meetings and conference calls provided the PPRP with additional perspective on the technical assessments being made by the TI Team.

In terms of written review of the project report, the PPRP provided a set of comments on the draft report that addressed both technical issues and process issues. The PPRP comments on the draft report were defined as either "mandatory," meaning the review comments must be addressed by the TI Team in its final documentation of the project report or "non-mandatory," meaning that the comments are intended solely to help improve the final report. The TI Team considered all comments. After revision of the draft report in light of comments from the PPRP, as well as comments from the sponsor and observers (NRC and DNFSB), a final report, that included the PPRP final report, was issued to EPRI for publication.

4.6.3 Fulfillment of SSHAC-Prescribed Scope of Review of Both Technical and Process Issues

The SSHAC guidelines highly recommend that a participatory peer review process be followed and that the peer review process be directed at both the technical and process aspects of the study (Budnitz et al., 1997, p. 50). Because most of the prescribed Level 2 process (NUREG/CR-6372) is not conducted in an environment that is amenable to ongoing peer review as in Level 3 and 4 studies, use of a participatory peer review process in the EPRI (2004, 2006) GMM Review Project exceeded the guidelines for a SSHAC Level 2 assessment process. The technical aspects include the TI Team's evaluation process for considering the applicable data, models, and methods that exist within the larger technical community, and the integration process that represents the center, body, and range of technically defensible interpretations. The technical aspects require technical expertise in the areas of ground-motion modeling and development of ground motion response spectra on the part of the PPRP, while the process aspects require a knowledge and experience in the application of SSHAC assessment processes. Process aspects include carrying out all methodological steps for a SSHAC Level 2 assessment process. The PPRP and the EPRI (2004, 2006) GMM Review Project Team included the requisite expertise and experience to fulfill both aspects of its charge. Individual members of the panel and the project team have experience in the technical fields related to GMM, as well as considerable project experience related to SSHAC studies or studies using similar methodologies (see Appendix F).

The final product of the SSHAC peer review process is a final closure letter from the PPRP providing its views on whether the TI Team has successfully implemented a SSHAC Level 2 assessment process, and whether, as a result, the technical assessments included in the GMM are technically defensible and adequately documented. The final activity conducted by the PPRP was the development of this closure letter, which is included in this report.

4.7 Consistency of EPRI (2004, 2006) GMM Review Project with SSHAC Guidelines

In this section, the steps (attributes) for implementing a SSHAC Level 2 study are presented together with additional actions that were taken for implementation of this project. Working meetings and working telephone conference calls held for implementing the EPRI (2004, 2006) GMM Review Project are listed in Table 2.2.6-1, and working meeting summaries are contained in Appendix E.

Step 1. Identify and engage peer reviewers.

The Project Leader (also referred to as the Project Manager), perhaps in conjunction with the Project Sponsor, is responsible for identifying and selecting peer reviewers.

Step 2. Identify available information and design analyses and information retrieval methods.

The TI is responsible for assembling all relevant technical data and other relevant information. This includes identification of technical researchers and proponents that the TI intends to contact during the course of the study to gain insight into their positions and interpretations. In addition, the TI defines the procedures and methods that will be followed in conducting the hazard analysis.

Step 3. Perform analyses, accumulate information relevant to issue, and develop representation of community distribution.

This step is the heart of a SSHAC Level 2 study. Specifically, the TI is responsible for understanding the entire spectrum of technical information that is relevant to performing the required evaluation and integration activities of the study. This includes the written literature, recent work by other experts, and other technical sources.

Step 4. Perform data diagnostics and respond to peer reviews.

Interactive peer review during the project implementation is an essential activity of a SSHAC Level 2 study. The TI can use the peer review team as a sounding board to learn whether the full range of technical views has been identified and evaluated and assessed in the integration of the hazard model. Generally, in a Level 2 study, on-going peer review would occur after Steps 2, 3 and 4. A variety of sensitivity analyses should be carried out and shared with the peer reviewers to understand the most significant issues, sources of uncertainty, and data sets used to address the issues.

Step 5. Document process and results.

This step is vital in order to assure clarity for an understanding of the study by third parties.

The process used for the EPRI (2004, 2006) GMM Review Project incorporated the steps (attributes) listed above. In addition, the following enhancements were implemented in the assessment process used for the EPRI (2004, 2006) GMM Review Project:

1. The Project Manager identified four professionals to serve as the TI Team in rather than one professional serving as a Technical Integrator. The following selection criteria were used:
    a. Ground-motion experts and engineers who have an excellent professional reputation and possess widely recognized competence based on academic training and relevant experience.
    b. Understanding of the general problem area through experience.
    c. Availability and willingness to participate in the project.
    d. Personal attributes that include strong communication and interpersonal skills, flexibility and impartiality and the ability to evaluate scope of available data and weight it in the integrated study results.
2. The Project Manager, TI Team, and Sponsor identified four professionals to serve as a Participatory Peer Review Panel (PPRP), which was carried out from project inception to assess process and technical findings in contrast to the Level 2 guidance that requires more limited peer review during the project and review of the project documentation at the end of the project. The criteria used to select the PPRP were similar to the criteria used for the TI Team.
3. Participatory peer review of the entire process that included periodic written reviews, review of draft report and final written review of technical evaluations and process used.
4. A Closure PPRP briefing on February 13, 2013, was added to identify any outstanding issues and a path forward, if necessary, to resolve issues in contrast to Level 2 guidance.

5. A workshop to enhance interaction with the technical community was added on October 17, 2012, in contrast to the prescribed Level 2 guidance.
6. A preliminary ground-motion model was developed prior to the Feedback workshop in contrast to Level 2 guidance.
7. An HID provided input to hazard calculations. Seismic hazard calculations were added to compare the seismic hazard results with results in the CEUS SSC Report (EPRI/DOE/NRC, 2012), a SSHAC Level 3 study that used the EPRI (2004, 2006) GMM, and to identify any technical issues with respect to the updated EPRI (2004, 2006) GMM.
8. Development of a draft and final project report that included documentation of the SSHAC process, technical bases, and results.

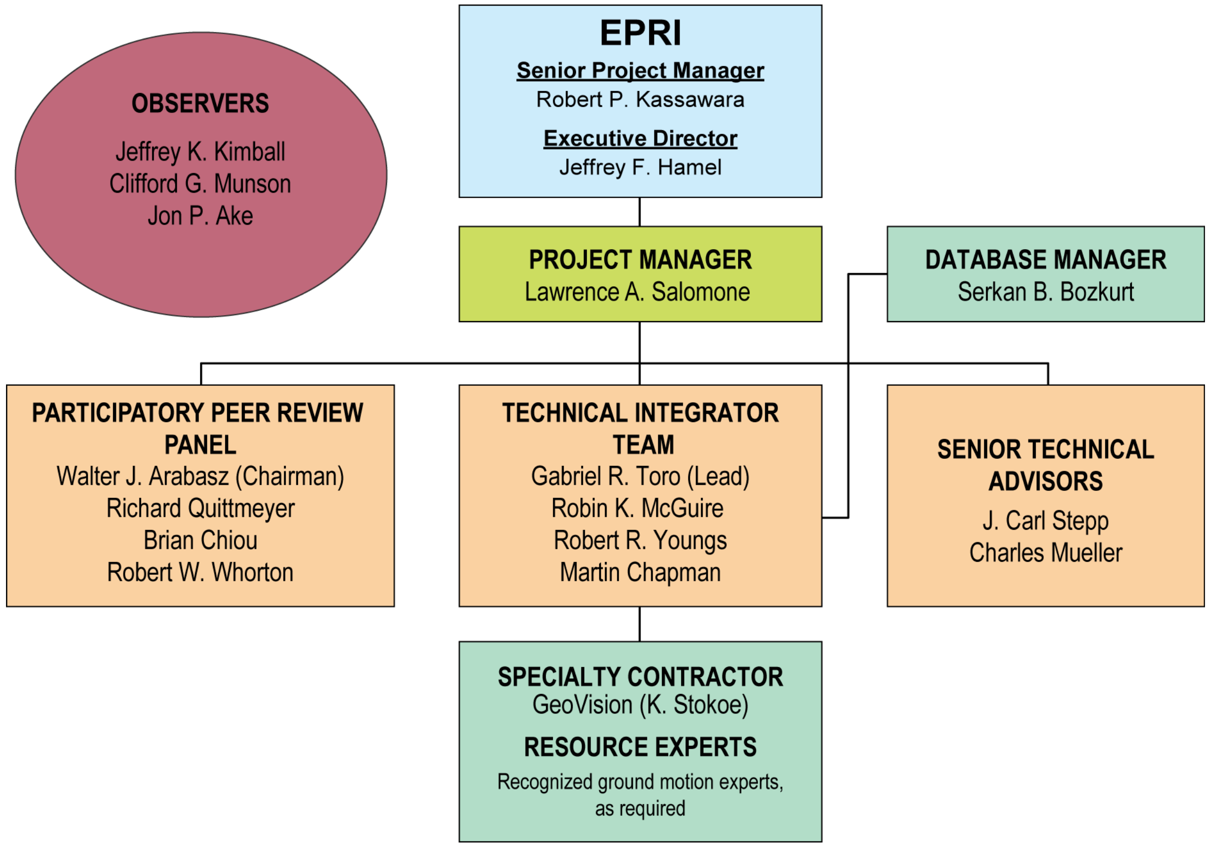

Figure 4.2-1.EPRI (2004, 2006) GMM Review Project organization chart

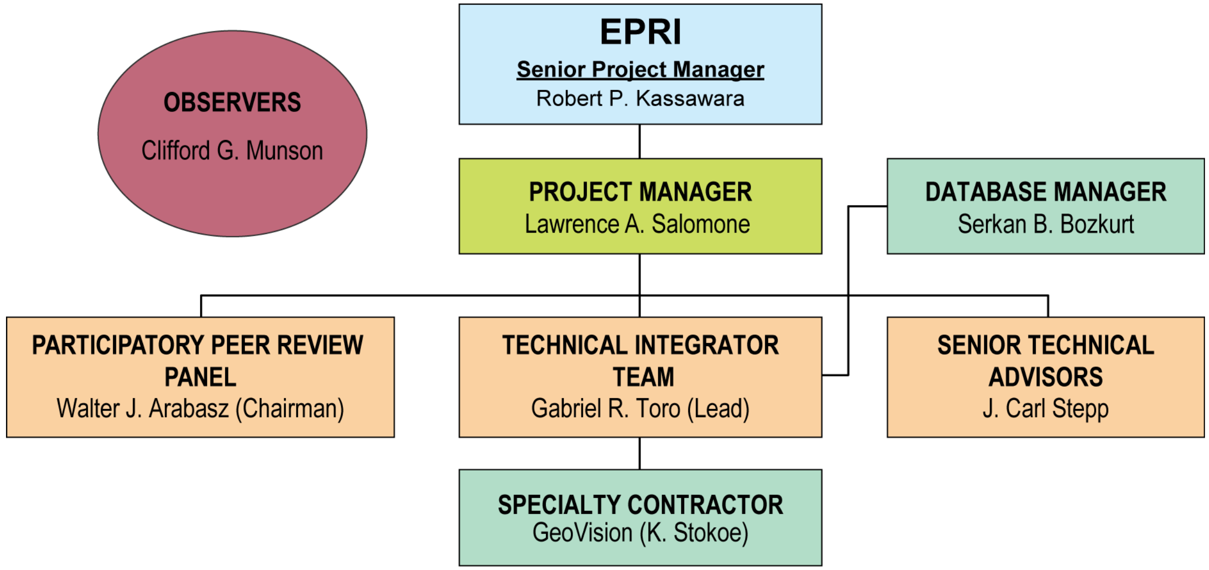

Figure 4.3-1. Chart showing lines of communication and points of contact

6

CHAPTER 6 RESULTS: GROUND MOTION DATABASE, IDENTIFICATION OF NEW CEUS GMPES, ADJUSTMENT OF RECORDED MOTIONS, AND COMPARISONS OF OBSERVATIONS TO EPRI (2004) GMM

6.1 Compilation of Updated Database

6.1.1 Updated Ground-Motion Database

A database of ground motion recordings was prepared for use in testing the available CENA GMPEs. The starting point was the ground motion database assembled by the PEER NGA-East Project (reference). The PEER NGA-East database was obtained in the form of an Excel file containing 27,800 records of individual ground motion components. The earthquake information consists of magnitude and location for 91 events. The recording information consists of station, location, and in many cases a brief description of the site geology. The ground motion data consists of peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), and 5 percent damped pseudospectral acceleration (PSA) at 105 structural periods from 0.01 to 10 seconds (structural frequencies from 100 Hz to 0.1 Hz). The file also includes the values of the high pass and low pass filters used in processing the records. The PSA values outside the range of the filter corners are entered as –12345.

The database processing consists of the following steps:

- Developing geometric mean ground motions for horizontal components.
- Review and refinement of the moment magnitude estimates for each earthquake.
- Estimation of the rupture and Joyner-Boore distance for each recording.
- Incorporation of available estimates of V_{S30} for recording stations.
- Development of general site classifications for recording sites.

Geometric Mean

Boore et al. (2006) and Boore (2010) introduced improved measures of the amplitude of horizontal ground motions that have come to replace the traditional geometric mean of the as recorded components. However, as discussed by Boore (2010), the differences between these measures and the geometric mean are relatively small (at most about 7 percent). These small differences are not considered large enough to affect relative comparisons of the CENA GMPEs with ground motion data. Therefore, the geometric mean is used in this study. The geometric means of the ground motions for the recordings with two horizontal components were computed. Only these recordings were retained for use in the analysis. The result was 9,191 individual horizontal components.

Review of Moment Magnitudes

Table 6.1.1-1 lists information on moment magnitude for the 91 events contained in the PEER NGA-East database. This information was used to assign the moment magnitudes listed in the right-hand column of Table 6.1.1-1. For a majority of the earthquakes of **M** 3.5 and larger, the moment magnitudes were computed from values of seismic moment using the relationship of (Hanks and Kanamori, 1979). For a number of smaller earthquakes, the values of **M** were based on conversions from other magnitude scales, such as those developed in NUREG-2115 (EPRI, DOE, NRC, 2012).

Estimation of Rupture and Joyner-Boore Distances

The PEER NGA-East database provides epicentral and hypocentral distances for the recordings. However, most of the GMPE's under consideration use either the rupture or Joyner-Boore distance measure. Values of rupture distance and Joyner-Boore distance were estimated for the recordings using the simulation process developed in Appendix B of Chiou and Youngs (2008). The process involves simulating ruptures using the the relationship between magnitude and rupture area defined by Somerville et al. (2001). The ruptures are placed on the hypocentral location using the focal mechanism information in the PEER NGA-East database for orientation. The location of the hypocenter within the rupture plane is simulated using the distributions described by Chiou and Youngs (2008). For each simulated rupture, the distances are computed to all the stations with recordings. The process is repeated over 101 simulations and the median distance to each site obtained. Then the simulated ruptures are searched to identify the one that produces the minmum squared difference from the median distances for all stations.

Figure 6.1.1-1 compares the simulated Joyner-Boore distances with the epicentral distances for the recordings in the database. Because of the small size of most of the earthquakes, the differences between epicentral distance and Joyner-Boore distance are generally small.

Incorporation of V_{S30} Data and Estimates

The PEER NGA-East database contains V_{S30} values for a limited number of stations. Additional data gathered during the duration of this project have been added, as described in Section 6.1.3. The measured shear wave velocities were augmented by estimated V_{S30} values for a large number of stations from the study by Silva et al. (2011).

Development of Rock Site Categories for CENA Data

The focus of this study is on the development of representative ground motion models for hard rock site conditions in CENA. Following the approach of EPRI (2004), comparisons of candidate GMPEs with ground motion data will be used as part of the process of model development. Because of the limited amout of CENA ground motion data available at the time, the EPRI (2004) study used all data from sites classified as rock. For this study, an attempt was made to account for differences in rock site conditions in the comparisons with GMPEs.

The first step was to group the recording sites into three classes, as defined in Table 6.1.1-2, based on the general geologic descriptions given in the PEER NGA-East database. Class A represents rocks typically of Mesozoic age or older, Class B represents rocks of Cenozoic age or younger that are typically sedimentary rocks, and Class C represents soil sites. These general classifications, along with the available V_{S30} information, were used to group the sites into three general rock site categories (hard rock, intermediate rock, and soft rock) using the criteria shown below.

Initial Rock Site Category Criteria

Rock Site Category	Criteria
Hard Rock	Class A or B $V_{S30} \geq 2{,}000$ m/s
Intermediate Rock	Class A or B with $1{,}000 \leq V_{S30} < 2{,}000$ m/s or Class A with unknown V_{S30}
Soft Rock	Class A or B with $500 \leq V_{S30} < 1{,}000$ m/s or Class B with unknown V_{S30}

The boundary between hard and intermediate rock was set at 2,000 m/s.

Figure 6.1.1-2 shows the magnitude-distance distribution for the recordings in the assembled ground motion database. The plot on the left shows the available data for 10 Hz PSA, and the plot on the right shows the available data for 1 Hz PSA. Table 6.1.1-2 lists the numbers of recordings of each rock category in the magnitude and distance ranges used in performing the assessments of the candidate GMPEs.

6.1.2 Identification of New CEUS GMPEs

This effort had as its objective the identification of CEUS GMPEs that were developed after the EPRI (2004) technical work was completed (in late 2003). This effort began in the fall of 2011 (prior to formal initiation of this project) during a series of meetings and conference calls organized by the Project Manager, was informed by the interviews and literature reviews performed by the TI Team and documented in Appendices A and B, and was completed by internal TI Team discussions.

The following six models were identified as part of this process. They are listed in alphabetical order, together with the abbreviations that will be used to refer to these models in the sections that follow.

- A08—Atkinson (2008) with Atkinson-Boore (2011) modifications. This GMPE is in essence the Boore-Atkinson (2008) NGA-West model, where the anelastic-attenuation term has been modified so it shows a long-distance decay similar to that of CEUS motions. Atkinson (2008) calls this approach "Referenced Empirical." This approach is similar in spirit to the Hybrid Empirical Approach developed by Campbell (2003), although it does not go through the formal steps of using host and target stochastic models to adjust the GMPE. The published A08 GMPE was altered slightly to remove the non-monotonic dependence on distance. Dr. Atkinson agreed with the alteration.
- AB06—Atkinson-Boore (2006) with Atkinson-Boore (2011) modifications. This is a GMPE derived from motions calculated with an extended-source stochastic model, with source characteristics calibrated for California and then modified so they conform to CEUS source scaling of Somerville (19XX). The geometric and anelastic attenuation are based on Atkinson (2004). Atkinson and Boore (2011) modified the model by making the stress parameters magnitude-dependent.
- PZT11—Pezeshk, Zandieh, and Tavakoli (2011). This is a GMPE developed using the hybrid-empirical approach proposed by Campbell (2003). The authors use several 2008 NGA-West GMPEs to define the host empirical models. The host and target stochastic models use constant stress and single-corner spectra. The geometric and anelastic attenuation model of Atkinson (2004) is used for the target region. The functional form of the GMPE is the same used by Atkinson and Boore (2006).
- SSCCSS, SSCVS, and SDCS—Silva et al. (2003). These three GMPEs, developed by Silva and coworkers using point-source stochastic models (with the alternative assumptions of Single Corner Constant Stress with Saturation, Single Corner Variable Stress, and Double Corner with Saturation, respectively). These GMPEs are similar to the GMPEs developed by the same authors in 2002 and used in EPRI (2004).

6.1.3 Shear-Wave-Velocity Measurements at Seismic Recording Stations

This project utilized shear-wave velocity (V_S) profiles at recording sites from the following sources:

- Measurements obtained by Geovision and the University of Texas as part of this project.
- Measurements obtained by the USGS and made available to this project in draft form.
- Measurements from the literature, as compiled by the NGA-East database and Geotechnical Working Groups, and made available to this project.

For recording sites with no measured profiles, V_{S30} estimates were obtained from other sources, in the following order of priority:

- V_{S30} estimates compiled by the NGA-East Project from the literature.
- Estimates in Atkinson's Engineering Seismology Toolbox (20xx).
- Indirect estimates obtained by Silva et al. (20xx).
- Estimates based on the NGA-East geological description.

Chapter 7 provides more details on the profile data obtained by this project and by the USGS. Section 6.2 describes how these data were used to estimate ground-motion amplitudes at reference site conditions from the recorded amplitudes.

6.2 Adjustment for Recording-Site Conditions

The purpose of this effort is to develop procedure to adjust the recorded ground motions to the reference conditions for which the hard-rock GMPEs have been defined. The reference profile adopted for this project is the same one used in the EPRI (1993) and EPRI (2004) projects, namely a profile with shear-wave velocity of 2,830 m/s over the top 1.3 km and with kappa equal to 0.006 s. Further details on this reference profile are provided in Section 6.2.1.1 below.

This adjustment is performed using two approaches, namely, an analytical approach and an empirical approach. Both approaches are used in this chapter to test the applicability of the EPRI (2004) GMM in light of new data, and in Chapter 8 to develop an updated GMM.

6.2.1 Analytical Adjustment for Recording-Site Condition

6.2.1.1 Characterization of the Profiles

The characterization of the profile at each recording station (and of the reference profile) consists of the following quantities:

- The depth-wise variation of the shear-wave velocity V_S and the density ρ.

- The anelastic attenuation through the soil and near-surface rock, characterized by parameter kappa.[1]

In defining these parameters, an effort was made to maintain consistency with the NEI procedure developed by Silva (2012).

At the time this work was performed, a total of 54 recording-station profiles were available, from this project, from the USGS, and from NGA-East[2] (see Table 6.2.1.1-1). For recording stations that had repeated measurements, the measurement that was received first was used. If estimates were available for the emplacement depth of the sensor, the portion of the profile above that depth was removed for the purposes of calculating amplification factors or V_{S30}.

The velocity profiles documented in Chapter 7 extend only to 30 or 50 meters depth and it becomes necessary to extend them to depths of one kilometer or more in order to quantify amplification factors at frequencies as low as 0.1 Hz. To this effect, the templates developed by Silva (2012; shown on Figure 6.2.1.1-1 and provided by Silva in tabular form) were utilized. This was the approach followed:

1. Determine the two template profiles that bound the measured V_S at the bottom of the profile (denote them template high and template low) and calculate the interpolation factor in ln[V_S] space using the V_S values at that depth, i.e.,

$$\theta = \frac{\ln[V_S(\text{measured})] - \ln[V_S(\text{template low})]}{\ln[V_S(\text{template high})] - \ln[V_S(\text{template low})]} \qquad (6.2.1.1\text{-}1)$$

2. For each depth z below the bottom of the measured profile, interpolate, calculate the interpolated V_S as

$$V_S(z) = \exp\{\theta \ln[V_S(z)(\text{template high})] + (1-\theta)\ln[V_S(z)(\text{template low})]\} \qquad (6.2.2.1\text{-}2)$$

3. Splice the interpolated profile to the measured profile.

Figures 6.2.1.1-2 and 6.2.1.1-3 illustrate this process for site ET.SWET in Tennessee. Figure 6.2.1.1-2 depicts the profile measured by the University of Texas. Figure 6.2.1.1-3 depicts the top 1,000 m of the extended profile that is used for the calculation of amplification factors.

The density ρ(z) is less variable than V_S. For depths at which no density information is available, the approach recommended by Boore (2007) for the estimation of density as a function of V_S is used.

For parameter kappa, this project followed the approach recommended by Silva (2012), i.e.:

[1] In terms of the original definition of kappa by Anderson and Hough (19??), the kappa used here corresponds to the value of kappa at zero epicentral distance, which is written sometimes as κ(0) or κ_0. For the sake of brevity, this report will omit the 0.

[2] Some USGS and NGA-East profiles, which had low Vs30 or for which there were no interesting horizontal recordings in the NGA-East flat file were not considered.

- For rock with at least 1,000 m of firm sedimentary rock (i.e., material between 500 and 2,000 m/s), use Silva et al. (1998) equation for kappa as a function of V_{S30}, which (after conversion to natural logarithms and m/s) takes the form $\ln[\kappa(\mathrm{s})] = 3.9575 - 1.093 \ln[V_{S30}(\mathrm{m/s})]$. This equation is close to the equation obtained by Van Houtte et al. (2011) using a much larger data set.
- For thinner rock, use 0.006 s plus the kappa associated with Q=40 (calculated over the thickness of deposits with $V_S < 3{,}000$ m/s).
- For soils with a depth to hard rock of 1,000 m or greater, use $k = 0.04\mathrm{s}$ (which is also the maximum kappa for all cases).[3]
- For thinner soils, use $\kappa(\mathrm{s}) = 0.0000605 \times H(\mathrm{m}) + 0.006$, where $H(\mathrm{m})$ is the thickness of the sedimentary column ($V_S < 3{,}000$ m/s) in meters.

Uncertainty in these parameters is specified as follows (also based on the recommendations of Silva, 2012):

- Uncertainty in V_S is characterized by a logarithmic standard deviation of 0.35. This factor accounts both for uncertainty in velocity and uncertainty in the approach for the calculation of amplification factors. V_S is randomized using a two-point distribution and full depth-wise correlation, resulting in two profiles with V_S (z) equal to exp(–0.35) and exp(+0.35) times the base-case V_S (z) (the base-case profile is also run in the calculations, but is given no weight).
- Uncertainty in ρ is characterized by a logarithmic standard deviation of $0.35 \times 0.25 = 0.0875$ (derived from the value for V_S using the approximation $\rho \propto V_S^{0.25}$ discussed by Boore, 2007). ln[ρ] is assumed to be perfectly correlated with V_S, so that a high V_S profile is associated with a high density.
- Uncertainty in kappa is characterized by a logarithmic standard deviation of 0.4 and is taken as independent of V_S. Kappa is randomized using a two-point distribution, resulting in two profiles with kappa equal to exp(–0.4) and exp(+0.4) times the base-case kappa (the base-case kappa is also run in the calculations, but is given no weight).

The reference profile adopted for this project is the same one used in the EPRI (1993) and EPRI (2004) projects. This profile corresponds to hard rock, with a shear-wave velocity of 2,830 m/s over the top 1.3 km (see Table 6.2.1.1-2 for the entire profile). The associated kappa is 0.006 s.

6.2.1.2 Details of the Analytical Approach

The purpose of the analytical approach is to adjust the recorded horizontal spectral amplitudes to the reference site conditions, using information about the station's V_S profile. This project uses

[3] The analysis of Gulf Coast recordings at deep-soil sites presented in Section 8.9.1.1 indicates values of kappa greater than 0.04 s. There is no inconsistency between those results and the value of 0.04 s because all the stations considered in this Chapter are outside the Gulf Coast.

the Boore and Joyner (1997) Quarter Wavelength (or QWL) approach to quantify the amplification ratio between the recording station and the reference profile. The adjustment process consists of four steps, as follows:

1. Calculation of amplification factors in terms of Fourier amplitude.
2. Calculation of Fourier amplitudes from the recorded horizontal spectra.
3. Adjustment of the Fourier spectra to the reference conditions by dividing them by the (recording site)/reference Fourier-amplitude ratio.
4. Calculation of the adjusted reference-site spectral amplitudes.

Calculation of Amplification Factors

Following Joyner and Boore (1997), the ratio of spectral amplitudes between a real site and a hypothetical site with shear-wave velocity and density equal to those at the source is given by

$$A(f) = \sqrt{\frac{\rho_S \beta_S}{\bar{\rho}[z(f)]\bar{\beta}[z(f)]}} \exp(-\pi\kappa f) \qquad (6.2.1.2\text{-}1)$$

where β denotes shear-wave velocity, subscript S denotes properties at the source, and the quantities in the denominator represent time-weighted averages of the density and V_S, as defined below.

The S-wave travel time to a depth z is calculated as

$$t(z) = \int_0^z \frac{du}{\beta(u)} \qquad (6.2.1.2\text{-}2)$$

where u represents depth.

For a particular frequency f, the associated averaging depth z(f) is the depth z such that $f = [4t(z)]^{-1}$. The associated time-averaged shear-wave velocity is calculated as

$$\bar{\beta}[z(f)] = \frac{z(f)}{t[z(f)]} \qquad (6.2.1.2\text{-}3)$$

Similarly, the associated time-averaged density is calculated as

$$\bar{\rho}[z(f)] = \frac{\int_0^{z(f)} \frac{\rho(u)du}{\beta(u)}}{t[z(f)]} \tag{6.2.1.2-4}$$

Applying Equation 6.2.1.2-1 to both the recording-site profile and the reference profile, one can obtain the amplification factor (recording site/reference), as follows:

$$A_{site/ref}(f) = \sqrt{\frac{\overline{\rho_{ref}}(f)\overline{\beta_{ref}}(f)}{\overline{\rho_{site}}(f)\overline{\beta_{site}}(f)}} \exp\left[-\pi(\kappa_{site} - \kappa_{ref})f\right] \tag{6.2.1.2-5}$$

where *ref* refers to the reference conditions and *site* refers to the recording-site conditions.[4] The dependence on z is not shown explicitly in the above equation for the sake of clarity, but it is understood that the calculations involve the frequency-dependent averaging depth *z(f)* and that the two averaging depths are different (i.e., $z_{ref}(f) \neq z_{site}(f)$).

The calculation of this amplification factor was performed for the five alternative profiles generated in Section 6.2.1.1 at each recording site (i.e., best-estimate profile and 4 profiles associated with randomized V_S and kappa), resulting in 5 sets of amplification factors as a function of frequency.

Note that this Fourier amplification factor is independent of the record (provided that soil linearity is maintained, which is the case for all the records considered). The amplification factor in terms of response spectra is different for different records because the motions have different frequency content as a result of differences in magnitude and distance.

Calculation of Recording-Site Fourier Spectrum

The Fourier amplitude spectrum of the recorded motion is calculated using the Inverse Random Vibration Theory (IRVT; see Gasparini and Vanmarcke, 1976, or Rathje et al., 2005), as implemented by Kottke (2012).[5] Inputs to this calculation are the recording-site response-spectral ordinates from the horizontal flat file (see Section 6.1.1), and the ground-motion duration, which is calculated using the expression

[4] During the preparation of the draft report, an error was detected in the implementation of the amplification factor in Eq. 6.2.1.2-5. Test calculations indicate that this factor was underestimated by 30% or less (the largest error occurs for soft-rock sites), resulting in overestimation of the adjusted amplitudes (for reference conditions), and a moderate increase in the error bars shown in Section 6.3.1. This error does not affect the empirical adjustment. The results in Chapter 6 have already been corrected, but the upated GMM in Chapter 8 has not. Because the analytical adjustment gets 50% weight in the Chapter 8 calculations, the anticipated effect of this error is to bring down the Chapter 8 GMM amplitudes by a factor of less than 15%.
[5] In the Kottke (2012) scripts, the maximum number of IRVT iterations was increased from 30 to 300.

$$T = 0.1R + 1/f_C \tag{6.2.1.2-6}$$

where R is distance and f_c is the corner frequency, which is calculated using a Brune model with 120 bar stress drop.[6] The coefficient of the distance-dependent term is double the value typically used (e.g., Herrmann, 1985) but agrees better with the durations computed from the available NGA-East time histories.

The IRVT approach may not always resolve the high-frequency portion of the Fourier spectrum (i.e., in the region where spectral acceleration is approaching PGA). To overcome this limitation, Fourier spectra were also calculated from the NGA-East time histories and were used to determine the shape of the Fourier spectrum at high frequencies.

This calculation is performed for all recordings obtained at sites with profile information, for magnitudes greater than 3.75 and distances less than 1,000 km. The resulting number of records is 489.

Adjustment of Recording-Site Fourier Spectrum to Obtain Reference-Site Fourier Spectrum

At each recording site, the Recording-Site Fourier spectrum for each record is divided by the (recording site)/reference amplification factor $A_{site/ref}(f)$ calculated with Equation 6.2.1.2-5, to obtain the Fourier spectra adjusted for site conditions. This calculation is performed for the 489 records selected above and for the five alternative amplification factors.

Calculation of Adjusted Response Spectra

Finally, the adjusted Fourier spectra are converted to adjusted spectral accelerations using RVT (again, using the implementation of RVT by Kottke, 2012). The duration given by Equation 6.2.1.2-6 is also used in this calculation. For each record, this calculation is performed separately for the five alternative amplification factors. The four results associated with the ±σ branches on V_S and kappa are then used to calculate the logarithmic mean and standard deviation of the adjusted spectral acceleration.

Although the IRVT and RVT approaches are typically used with smooth spectra, the also work well with the jagged spectra from individual records. The accuracy of this procedure is also commensurate with the accuracy of the Quarter-Wavelength approach.

[6] The sensitivity of the IRVT and RVT calculations to duration is small. In particular, the sensitivity to stress drop is very weak for the magnitudes and distances of interest.

Typical Results

Figure 6.2.1.2-1 illustrates the calculation of the (recording site)/reference Fourier amplification factor for the ET.SWET station for which the profiles are shown on Figures 6.2.1.1-1 and 6.2.1.1-2. The thin lines on the top portion of the figures indicate the amplification factors calculated using the five alternative combinations of V_S s and kappa. The corresponding thick lines show the calculated logarithmic mean ±σ amplification factors. The red line on the bottom portion shows the logarithmic standard deviation of the amplification factor (referenced to the right vertical axis). This standard deviation has moderate values for frequencies lower than 25 Hz, but becomes much larger at higher frequencies as a result of the 40 percent uncertainty in the recording-site kappa.

Figure 6.2.1.2-2 illustrates the calculation of the adjusted spectra for an **M** 4.6 earthquake recorded at 85 km. The figure shows the five adjusted spectra, as well as the original spectrum. Figures 6.2.1.1-1 and 6.2.1.1-2 show that the adjustment compensates for gross impedance and kappa effects, as one would expect, but it does not compensate for the resonance effect at 10 Hz. Similar figures for the same stations and other earthquakes also show a peak at 10 Hz, which one may be able to remove with an approach that takes resonances into account.

6.2.2 Empirical Adjustment for Recording Site Conditions

The EPRI (2004) median models for the four clusters were used to compute residuals with respect to the ground motion database developed in Section 6.1.1. The residuals are defined as the natural log of the ratio observed PSA divided by predicted PSA. Figures 6.2.2-1 through 6.2.2-4 show the residuals for the four cluster median models developed in EPRI (2004) for data from earthquakes of magnitude **M** 4.75 and larger. The residual plots show variable results from frequency to frequency among the four clusters, with Cluster 3 tending to overpredict the data and Cluster 1 tending to underpredict at low frequencies. Many of the residual plots show some trend at distances beyond 300 to 500 km.

The residuals for each of the EPRI (2004) cluster median models were analysed to identify the significance of site classification in the assessment of the average residual. Several models were tested. Model 1 did not include the effect of site classification and estimated only C_0, the mean residual.

$$\ln(\text{Residual})_{\text{Model1}} = C_0 + \varepsilon_{i,j} \tag{6.2.2-1}$$

In Equation 6.2.2-1, the error term is designated $\varepsilon_{i,j}$ to indicate the j^{th} recording for the i^{th} earthquake. Because of the within earthquake correlation of the residuals linear mixed effects regression was performed using the statistical package **R** (**R** Development Core Team, 2012). The second model included factors to account for differences between ground motions on the three rock catagories. The residuals were analyzed using the model:

$$\ln(\text{Residual})_{\text{Model 2}} = C_0 + C_{IR}F_{IR} + C_{SR}F_{SR} + \varepsilon_{i,j} \tag{6.2.2-2}$$

In Equation 6.2.2-2, F_{IR} and F_{SR} are indicator (dummy) variables that take on the value 1 for intermediate rock sites or soft rock sites, respectively, and are 0 otherwise.

Figures 6.2.2-5 through 6.2.2-8 show the results of the analyses of the residuals applying Equations 6.2.2-1 and 6.2.2-2 for residuals for the four EPRI (2004) median cluster models. The top left-hand plot shows the values of the coefficient C_0 obtained using Model 1 and the top right-hand plot shows the values of the coefficient C_0 obtained using Model 2. The vertical bars represent 90 percent conficence intervals on the fitted parameters. The results are shown for the analysis of data restricted to four magnitude-distance ranges. The results again are mixed across models and frequencies. In many cases, the 90 percent confidence intervals for the mean residual encompass 0, although the results for Cluster 3 show consistent overprediction. It should be noted that the EPRI (2004) Cluster 4 model was intended to apply only to earthquakes of **M** 6 and larger, for which there are only a few recordings in the database assembled for the project.

The bottom plots on Figures 6.2.2-5 through 6.2.2-8 show the values of the site category scaling coefficients C_{IR} and C_{SR}. As can be seen, the 90 percent confidence intervals for these coefficients typically encompass 0. Results of appling the Akaike Information Criteria (AIC) test (Akaike, 1974) or the related Schwartz Bayesian Information Criteria (BIC) test (Schwartz, 1978) typically show that the use of Model 2 does not produce a statistically better fit to the residuals compared to Model 1. A third model was tested using only scaling for soft rock.

$$\ln(\text{Residual})_{\text{Model 3}} = C_0 + C_{SR}F_{SR} + \varepsilon_{i,j} \tag{6.2.2-3}$$

Model 3 was found to be an improvement over Model 2, but in general, not an improvement over Model 1 in terms of fitting the residuals.

6.3 Test EPRI (2004, 2006) Ground-Motion Model: Comparisons of Observations toGMM Predictions

6.3.1 Comparisons Using Analytical Adjustment for Recording-Site Conditions

This section compares the adjusted motions calculated in Section 6.2.1 to the median EPRI (2004) GMPEs. Comparisons are made using logarithmic residuals (natural logarithm of the ratio of the observed/predicted motions).[7]

Residuals are shown for sites with $V_{S30} \geq 500$ m/s and earthquakes with **M** ≥ 3.75, for both the adjusted and unadjusted spectral amplitudes. For the adjusted amplitudes, the error bars show the $\pm 1\sigma$ uncertainty in the adjustment factor. Residuals outside the usable frequency range of the

[7] For the sake of illustration, a residual of -1 indicates overprediction by a factor of exp(1) or approximately 2.7. Similarly, a residual of +1 indicates underprediction by a factor of approximately 2.7.

original record, as determined by the NGA-East Project, are not shown. Although these comparisons show distances to 1,000 km, the focus of this project is distances less than 500 km, with particular emphasis on distances less than 100 km.

Figures 6.3.1-1 through 6.3.1-12 show the comparisons for Clusters 1, 2, and 3 and for frequencies of 1, 5, 10, and 25 Hz. Cluster 4 is not considered because this cluster is not used for earthquakes in the magnitude range spanned by the data. In general, these comparisons indicate that the EPRI (2004) cluster medians GMPEs tend to overpredict the observations for distances less than 100 km. In this distance range, most observations come from **M** 3.75–4.75, but the larger-magnitude data tend to support this conclusion. The conclusion is generally the same for the adjusted and unadjusted recordings, but is stronger for the former. At distances of 100 to 500 km, there is rough agreement between the cluster medians and the recordings. At longer distances, there may be over- or underprediction, depending on cluster and frequencies.

Comparing the adjusted and unadjusted observations, one can observe that the former cause a small reduction in scatter, with the possible exception of 25 Hz. The 25 Hz results also show large error bars, indicating that uncertainty in the recording-site kappas makes it difficult to draw conclusions about the high-frequency amplitudes.

6.3.2 Comparisons Using Empirical Adjustment for Recording-Site Conditions

The results presented in Section 6.2.2 indicate that the empirical scaling coefficients for the three rock site catagories do not provide an improvement in the fitting of the residuals to the entire rock site database developed in Section 6.1.1. This may be due in part the the limited data available with which to classify many of the recording sites. Nevertheless, it is useful to plot the data versus the range of ground motions predicted by the EPRI (2004) GMM.

Figures 6.3.2-1 through 6.3.2-6 show the ground motion data for PSA of 0.5, 1, 2.5, 5, 10, and 25 Hz, respectively. Each figure contains plots for three magnitude ranges, 4.75 ≤ **M** < 5.25, 5.25 ≤ **M** < 5.75, and 5.75 ≤ **M** < 6.25. The points show the values of rock site PSA from the database color coded by the site categories. The data are unscaled. The curves show the range of ground motions predicted by the EPRI (2004) model. The dashed curves show the range for Clusters 1, 2, and 3 models (lowest 5th percentile model to highest 95th percentile model). These predictions are for the central magnitude of each magnitude bin, **M** 5, 5.5, and 6 from left to right. For the largest magnitude interval, the dashed-dot curve shows the range including Cluster 4.

Figures 6.3.2-7 through 6.3.2-12 show the same ground motion data, but now scaled by the site category scale factors shown in Section 6.2.2. For the data in magnitude ranges 4.75 ≤ **M** < 5.25 and 5.25 ≤ **M** < 5.75, the scale factor is equal to 1 over the average values of C_{IR} and C_{SR} obtained for Clusters 1, 2, and 3, and for the magnitude range 5.75 ≤ **M** < 6.25, the scale factors include the results for Cluster 4. Comparison of these figures with Figures 6.3.2-1 through 6.3.2-6 show only small differences as the scale factors are generally small.

The comparisons on Figures 6.3.2-1 through 6.3.2-12 indicate that, in general, the ground motion data fall for the most part within the range of the ground motions predicted by the EPRI (2004) median models. The 5th percentile and 95th percentile models developed by EPRI (2004) were indended to represent the epistemic uncertainty in the median ground motions. However, the results shown in this section indicate that the range in median models is also capturing a large portion of the aleatory variablity in ground motions. This might be expected for the cases of limited data, such as that for 25 Hz PSA, but not necessarily for cases where there is a large amount of data.

6.4 Conclusions from Comparisons

Text

6.4.1 Bias

Text

6.4.2 Epistemic Uncertainty

6.5 Decision Point 2—Basis for Proceeding with Updating EPRI (2004, 2006) GMM

Text

6.5.1 PPRP Feedback

Text

6.5.2 EPRI Communication to Nuclear Regulatory Commission

Table 6.1.1-1
Moment Magnitudes for Earthquake in Ground Motion Database

PEER NGA-East Event Number	Earthquake	Date	Information Used To Assign Magnitude	Assigned Moment Magnitude (M)
1	Charlevoix QC	1925/03/01	Bent (1992)	6.36
2	Grand Banks NL	1929/11/18	Johnston (1996)	7.18
3	Timiskaming QC	1935/11/01	Johnston (1996)	6.15
4	CornwallMassena ON	1944/09/05	Johnston (1996)	5.79
5	Saguenay QC	1988/11/25	Johnston (1996)	5.85
6	La Malbaie QC	1997/08/20	NUREG-2115	3.3
7	La Malbaie QC	1997/10/28	Du et al. (2003)	4.29
8	Cap-Rouge QC	1997/11/06	Du et al. (2003)	4.44
9	Cote-Nord QC	1999/03/16	Du et al. (2003)	4.47
10	Kipawa QC	2000/01/01	Du et al. (2003)	4.63
11	La Malbaie QC	2000/06/15	Atkinson (2004)	3.1
12	Laurentide QC	2000/07/12	Atkinson (2004)	3.5
13	Laurentide QC aftershock	2000/07/12	Atkinson (2004)	2.9
14	Ashtabula NY	2001/01/26	Du et al. (2003)	3.88
15	Enola AR	2001/05/04	SLU	4.37
16	Au Sable Forks NY	2002/04/20	SLU	5
17	LacLaratelle QC	2002/06/05	SLU	3.67
18	Caborn IN	2002/06/18	SLU	4.6
19	Boyd NE	2002/11/03	SLU	4.18
20	Charleston SC	2002/11/11	SLU	4.03
21	Ft Payne AL	2003/04/29	SLU	4.7
22	Blytheville AR	2003/04/30	NGA-East	3.67
23	Bardwell KY	2003/06/06	SLU	4.02
24	La Malbaie QC	2003/06/13	SLU	3.37
25	Bark Lake QC	2003/10/12	NEDB	4

PEER NGA-East Event Number	Earthquake	Date	Information Used To Assign Magnitude	Assigned Moment Magnitude (M)
26	Jefferson VA	2003/12/09	Kim and Chapman	4.25
27	St Teresa MX	2004/04/06	NGA-East	4.31
28	La Baie QC	2004/05/04	NEDB	3
29	Prairie Center IL	2004/06/28	SLU	4.19
30	Port Hope ON	2004/08/04	SLU	3.15
31	Milligan Ridge AR	2005/02/10	SLU	4.14
32	RiviereDuLoup QC	2005/03/06	SLU	4.65
33	Shady Grove AR	2005/05/01	SLU	4.25
34	Miston TN	2005/06/02	SLU	4.01
35	Thurso ON	2006/02/25	SLU	3.67
36	Hawkesbury ON	2006/02/26	NEDB	2.6
37	BaieSaintPaul QC	2006/04/07	SLU	3.8
38	Ridgely TN	2006/09/07	NUREG-2115	3.35
39	Gulf of Mexico	2006/09/10	USGS	5.85
40	Acadia ME	2006/10/03	SLU	3.9
41	Marston MO	2006/10/18	NUREG-2115	3.47
42	Marvin VA mine collapse	2006/11/02		
43	Skeggs VA mine collapse	2006/11/23		
44	Cobourg ON	2007/07/19	NEDB	2.8
45	BaieSaintPaul QC	2008/01/03	NEDB	2.9
46	Mt Carmel IL	2008/04/18	SLU	5.26
47	Mt Carmel IL aftershock	2008/04/18	SLU	4.64
48	Mt Carmel IL aftershock	2008/04/21	SLU	4.03
49	Mt Carmel IL aftershock	2008/04/25	SLU	3.75
50	Buckingham QC	2008/06/11	NEDB	3.0
51	RiviereDuLoup QC	2008/11/15	SLU	3.6
52	Pine Forest SC	2008/12/16	NUREG-2115	3.16

PEER NGA-East Event Number	Earthquake	Date	Information Used To Assign Magnitude	Assigned Moment Magnitude (M)
53	Rosehill SC	2009/01/29	NUREG-2115 conversions	2.8
54	Palmetto SC	2009/05/06	NUREG-2115 conversions	2.2
55	Constance Bay ON	2009/05/08	NUREG-2115 conversions	2.7
56	Jones OK	2010/01/15	SLU	3.84
57	Lincoln OK	2010/02/27	SLU	4.18
58	Whiting MO	2010/03/02	SLU	3.4
59	Lebanon IL	2010/05/21	NUREG-2115 conversions	2.6
60	Val-des-Bois QC	2010/06/23	SLU	5.07
61	St. Flavien QC	2010/07/23	NEDB	3.6
62	Bhuj India	2001/01/26	NGA-East	7.6
63	Mont Laurier QC	1990/10/19	Johnston (1996)	4.56
64	Montgomery MD	2010/07/16	SLU	3.42
65	Gazli USSR	1976/05/17	NGA-West	6.8
66	Slaughterville OK	2010/10/13	SLU	4.36
67	Guy AR	2010/10/15	SLU	3.86
68	Concord NH	2010 /09/26	NGA-East	2.8
69	Nahanni NWT foreshock	1985/11/09	NGA-East	4.4
70	Nahanni NWT	1985/12/23	NGA-West	6.76
71	Nahanni NWT aftershock	1985/12/23	NGA-East	5.1
72	Nahanni NWT aftershock	1985/12/25	NGA-East	5.2
73	Arcadia OK	2010/11/24	SLU	3.96
74	Bethel Acres OK	2010/12/12	SLU	3.23
75	Greentown IN	2010/12/30	SLU	3.85
76	Guy AR	2010/11/20	SLU	3.9

PEER NGA-East Event Number	Earthquake	Date	Information Used To Assign Magnitude	Assigned Moment Magnitude (M)
77	Greenbrier AR	2011/02/17	NGA-East	4.0
78	Greenbrier AR	2011/02/18	NGA-East	4.0
79	Greenbrier AR	2011/02/18	NGA-East	4.0
80	Greenbrier AR	2011/02/28	SLU	4.67
81	Sullivan MO	2011/06/07	SLU	3.89
82	Eagle Lake ME	2006/07/14	SLU	3.51
83	Val-des-Bois QC aftershock	2010/06/24	NUREG-2115 conversions	2.7
84	Val-des-Bois QC aftershock?	2010/07/22	NUREG-2115 conversions	2.5
85	Hawkesbury ON	2011/03/16	SLU	3.48
86	CharlevoixSZ QC	2001/05/22	Atkinson (2004)	3.43
87	BaieSaintPaul QC	2002/08/17	Atkinson (2004)	3.04
88	Mineral VA	2011/08/23	SLU	5.74
89	Mineral VA aftershock	2011/08/25	SLU	3.97
90	Sparks OK	2011/11/05	SLU	4.73
91	Sparks OK	2011/11/06	SLU	5.62

NEDB—http://www.earthquakescanada.nrcan.gc.ca/index-eng.php

NUREG-2115—Central *and Eastern United States Seismic Source Characterization for Nuclear Facilities* (EPRI/DOE/NRC, 2012)

SLU—http://www.eas.slu.edu/eqc/eqc_mt/MECH.NA/

Table 6.1.1-2
Number of Rock Site Recordings In Assembled Strong Motion Data

Magnitude Range	Distance Range	Rock Category	Number of Recordings for PSA at Frequency of:					
			0.5 Hz	**1 Hz**	**2.5 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
3.75 ≤ M < 4.75	R_{JB} ≤ 500 km	Soft	1392	1685	1686	1524	835	143
		Intermediate	416	505	504	466	277	58
		Hard	13	22	22	22	14	2
M ≥ 4.75	R_{JB} ≤ 500 km	Soft	321	316	306	298	238	84
		Intermediate	144	158	157	154	130	30
		Hard	11	11	11	11	9	3

Table 6.2.1.1-1.
Recording Stations Where the Analytical Update Was Applied

Station	Data Source	Depth of Instrument Emplacement (m; if known and non-zero)	Comments
AG.WHAR	Geovision		
CN.ACTO	NGA-East		
CN.ALGO	NGA-East		
CN.OTT	NGA-East	13.00	
CN.PEMO	NGA-East		
CN.WLVO	NGA-East		
ET.SWET	Univ. of Texas	2.44	
GS.OK001	Geovision		Modified top layer as done by Geovision
GS.OK002	Geovision		
GS.OK005	Geovision		used average of 2 arrays
GS.OK008	Geovision		top layer made equal to 2nd as per Geovision
GS.OK009	Geovision		used average of array 2 Love+Rayleigh; layers 1 and 2--> layer 3 (stiffer below bldg)
GS.OK010	Geovision		average of Love & Rayleigh; replaced 1st layer with 2nd
IU.SSPA	Univ. of Texas		
LD.MVL	USGS		prelim from USGS
MN.CVVA	Univ. of Texas	0.61	
NM.BLO	USGS	3.50	prelim from USGS
NM.CBHT	NGA-East		
NM.HAIL	NGA-East		
NM.JCMO	USGS	1.00	prelim from USGS
NM.SEAR	Geovision	1.00	
NM.SIUC	Geovision	5.50	
NM.UALR	Geovision		
NM.USIN	NGA-East		

Station	Data Source	Depth of Instrument Emplacement (m; if known and non-zero)	Comments
NM.WVIL	NGA-East		
NP.2549	USGS		prelim from USGS
NP.2555	USGS		prelim from USGS
NP.2648	USGS		prelim from USGS
NQ.Q793	Geovision		chgd 1st layer as per GV,
PE.PAGS	USGS		prelim from USGS; may want to exclude (very strong Vs inversion)
PE.PSUB	USGS		prelim from USGS
PE.PSWB	Geovision	4.00	
PN.PPBLN	Geovision	2.50	
PN.PPCWF	Geovision	4.50	
PN.PPMOO	Geovision	4.00	use Rayleigh
PN.PPPCH	Geovision		use array 2 Rayleigh (~average value of Vs30)
PN.PPPHS	Geovision	2.50	
SE.RCRC	Univ. of Texas	0.61	
SE.URVA	Univ. of Texas	0.61	depth from Martin Chapman
SE.VWCC	Univ. of Texas	5.88	sensor depth taken as 19.3 ft (M.Chapman: "The sensor on a concrete pad poured directly on Paleozoic shale")
US.ACSO	USGS	1.00	USGS preliminary; model 1AM
US.BLA	Univ. of Texas	30.48	sensor depth is taken as depth to 5000 fps as per M. Chapman's email
US.CBN	Univ. of Texas	4.57	
US.CNNC	USGS		prelim from USGS
US.GOGA	Univ. of Texas	0.10	
US.LBNH	Geovision	1.00	
US.LONY	Geovision	1.00	
US.LRAL	Univ. of Texas	0.10	

Station	Data Source	Depth of Instrument Emplacement (m; if known and non-zero)	Comments
US.MCWV	USGS		prelim from USGS
US.MIAR	Geovision	1.00	
US.MYNC	Univ. of Texas	0.30	
US.NCB	Geovision	1.00	
US.TZTN	USGS		prelim from USGS
US.WMOK	Geovision	0.50	

Table 6.2.1.1-2.
Reference Shear-Wave-Velocity Profile

Thickness (m)	V_S (m/s)	Density (gr/cc)
1,300	2,830	2.52
11,000	3,520	2.71
28,000	3,750	2.78
—	4,620	3.34

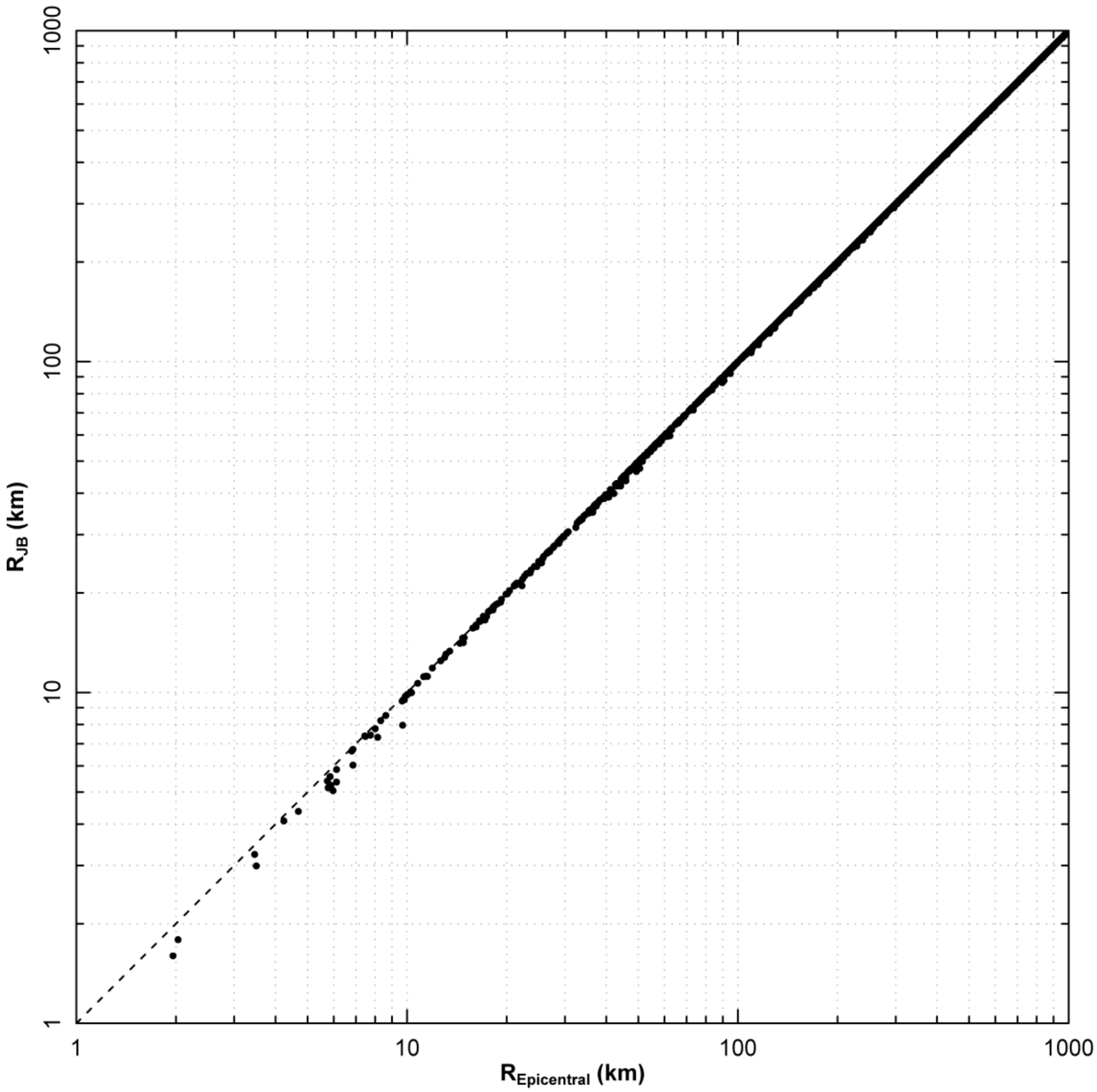

Figure 6.1.1-1. Comparison of epicentral and simulated Joyner-Boore distances for the ground motion database

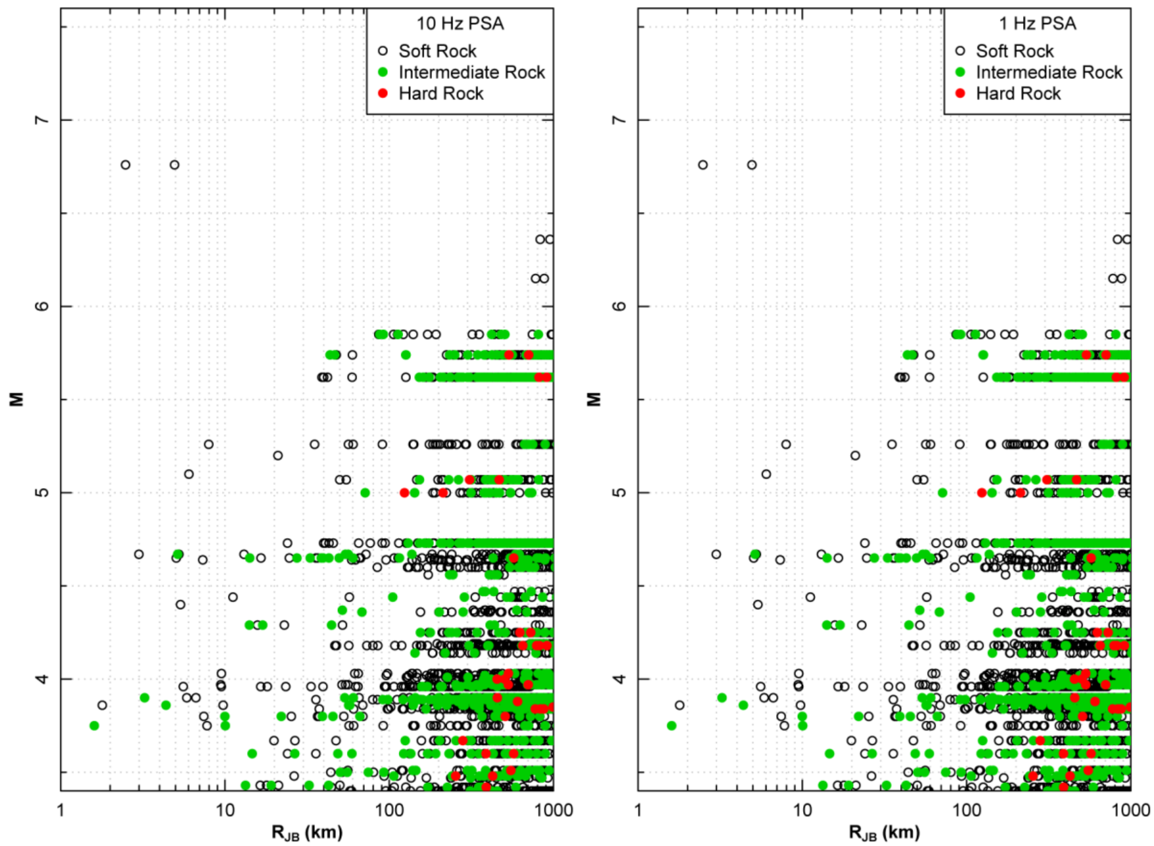

Figure 6.1.1-2. Magnitude-distance distribution of the rock site database developed for the project

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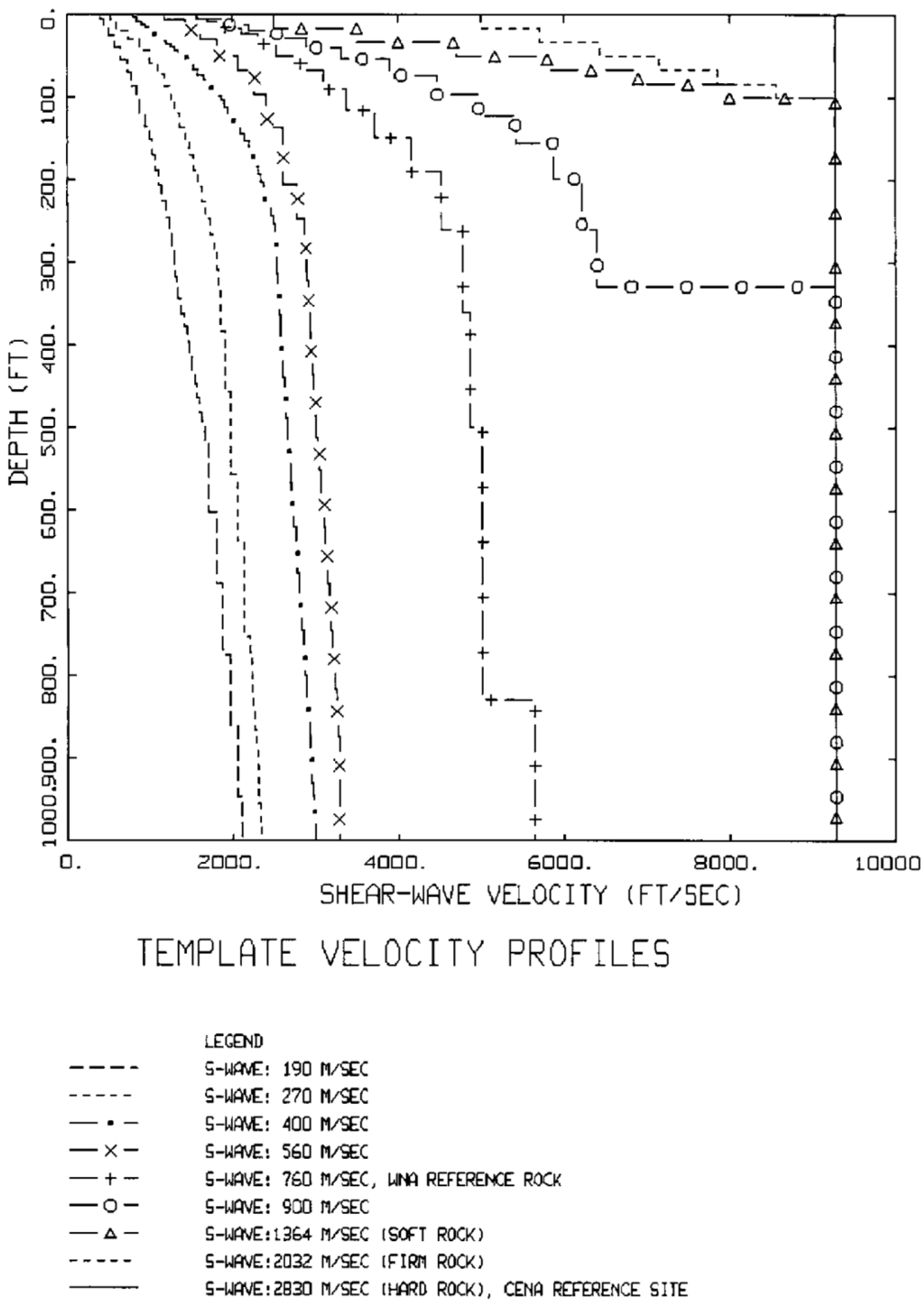

Figure 6.2.1.1-1. Template shear-wave velocity profiles used for extending the measured profiles. Source: Silva (2012)

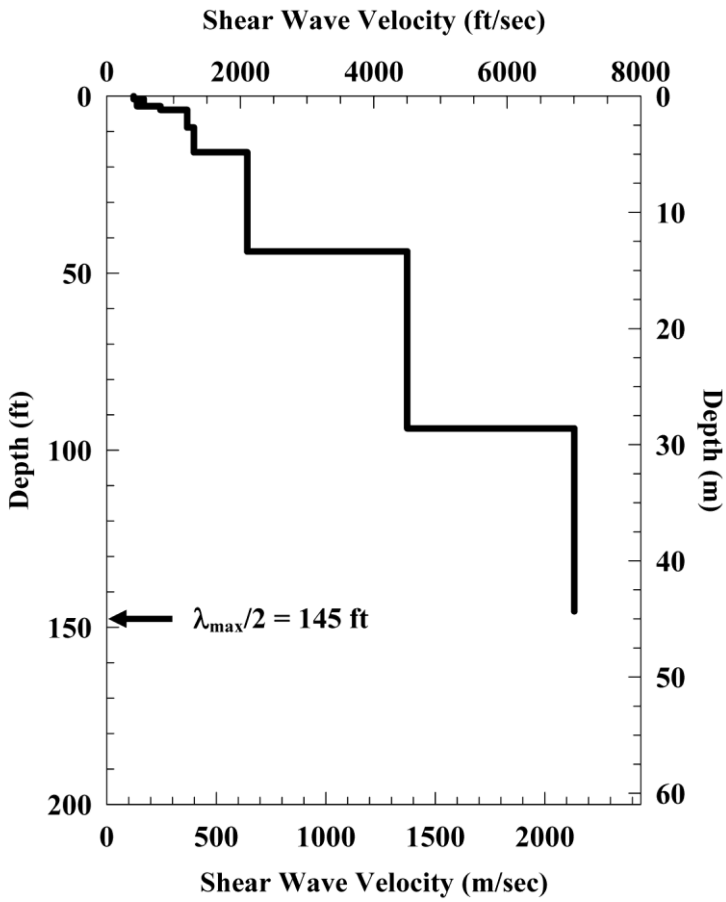

Figure 6.2.1.1-2. Example of measured shear-wave velocity profile: profile for station ET.SWET as measured by the University of Texas

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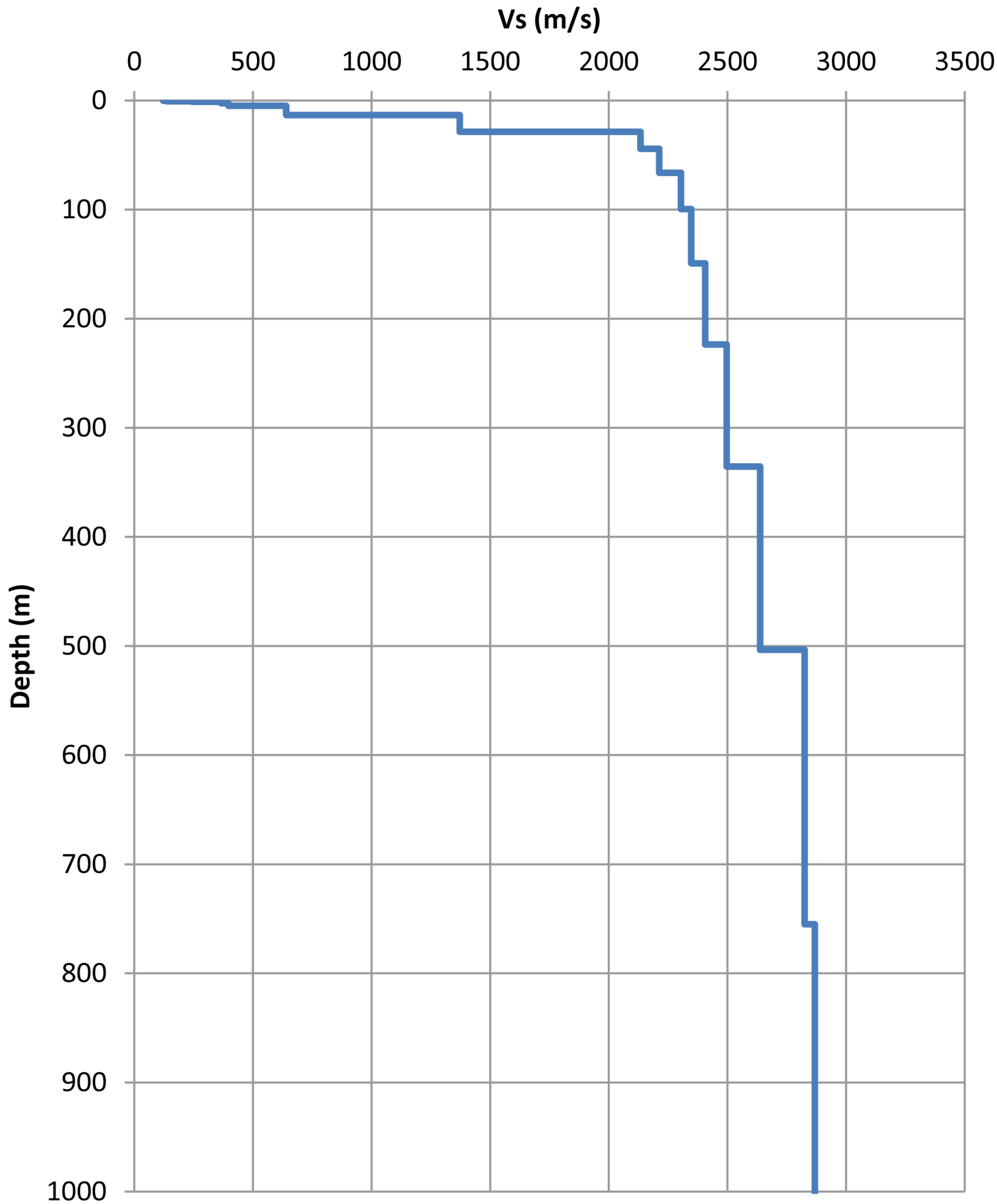

Figure 6.2.1.1-3. Example of extended shear-wave velocity profile: profile for station ET.SWET

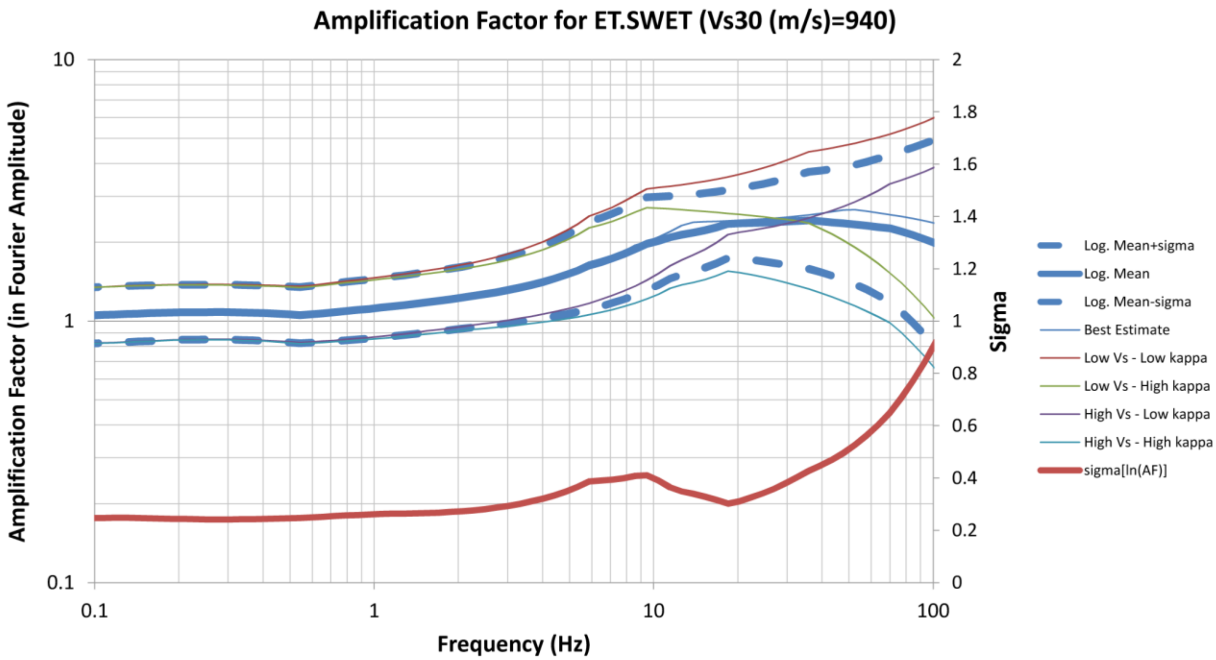

Figure 6.2.1.2-1. Calculation of the (recording site)/reference Fourier amplification factor for rock station ET.SWET

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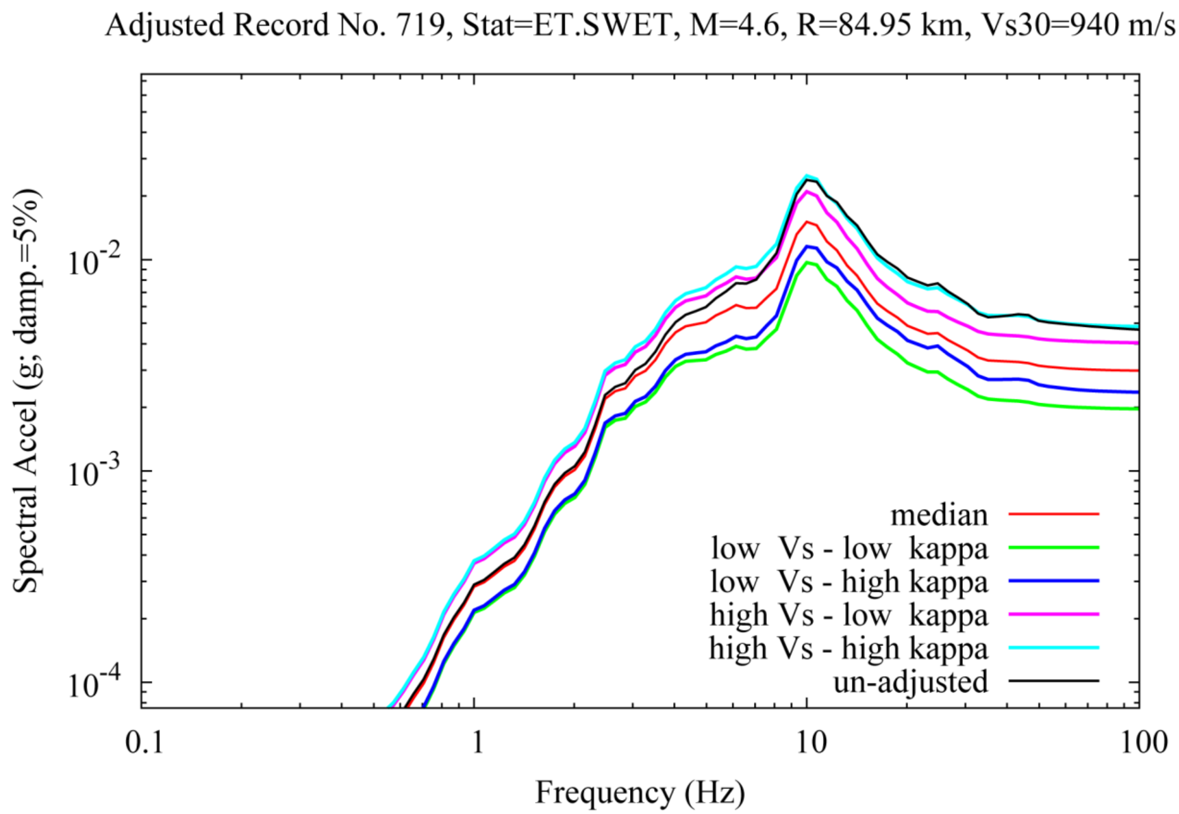

Figure 6.2.1.2-2. Adjusted and original response spectra for an M 4.6 earthquake recorder at rock station ET.SWET at a distance of 85 km. (Note: figure will be redrawn in a format similar to that of Figure 6.2.1.2-1)

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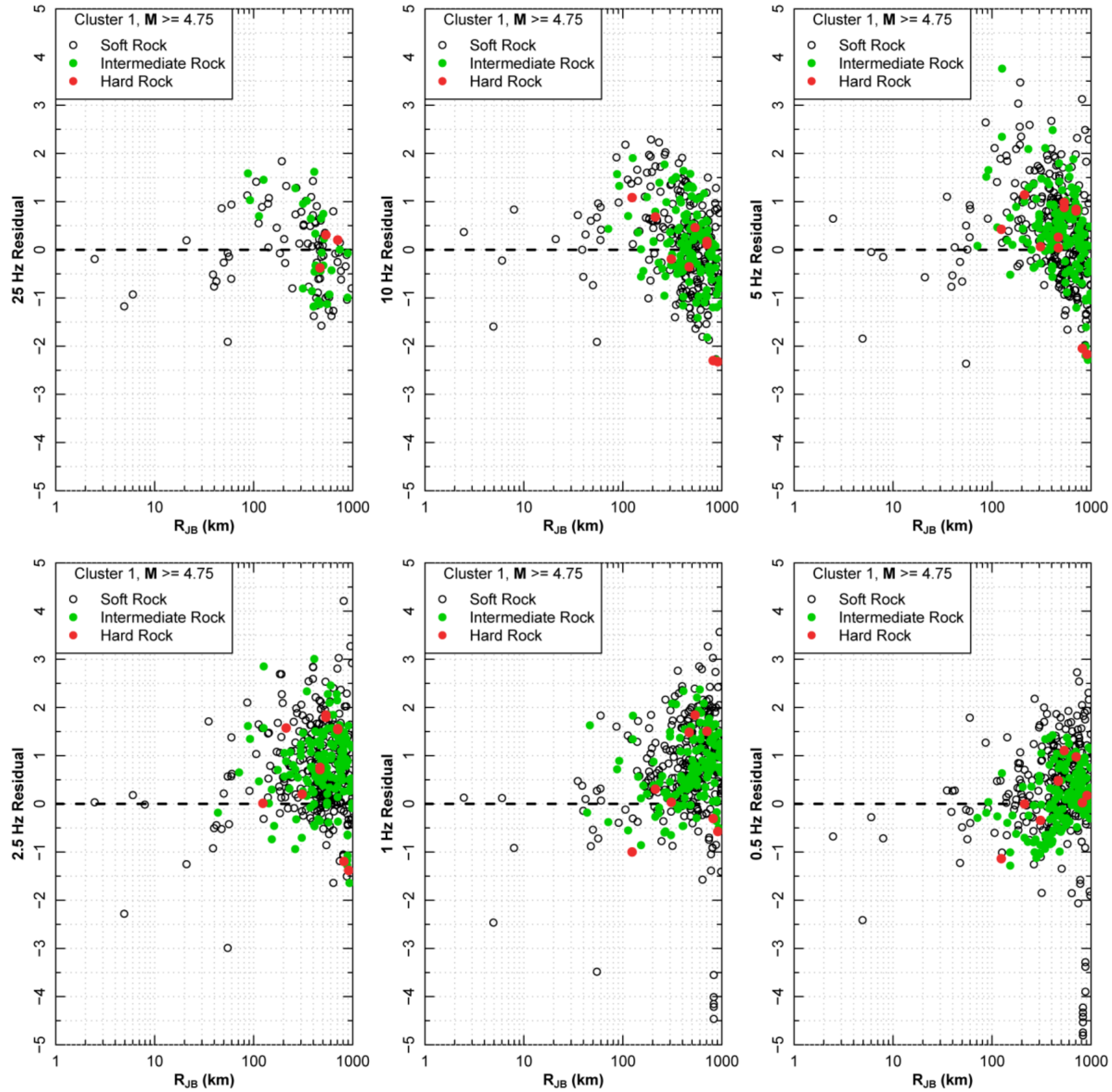

Figure 6.2.2-1. Rock site data PSA residuals computed using the EPRI (2004) Cluster 1 median GMPE

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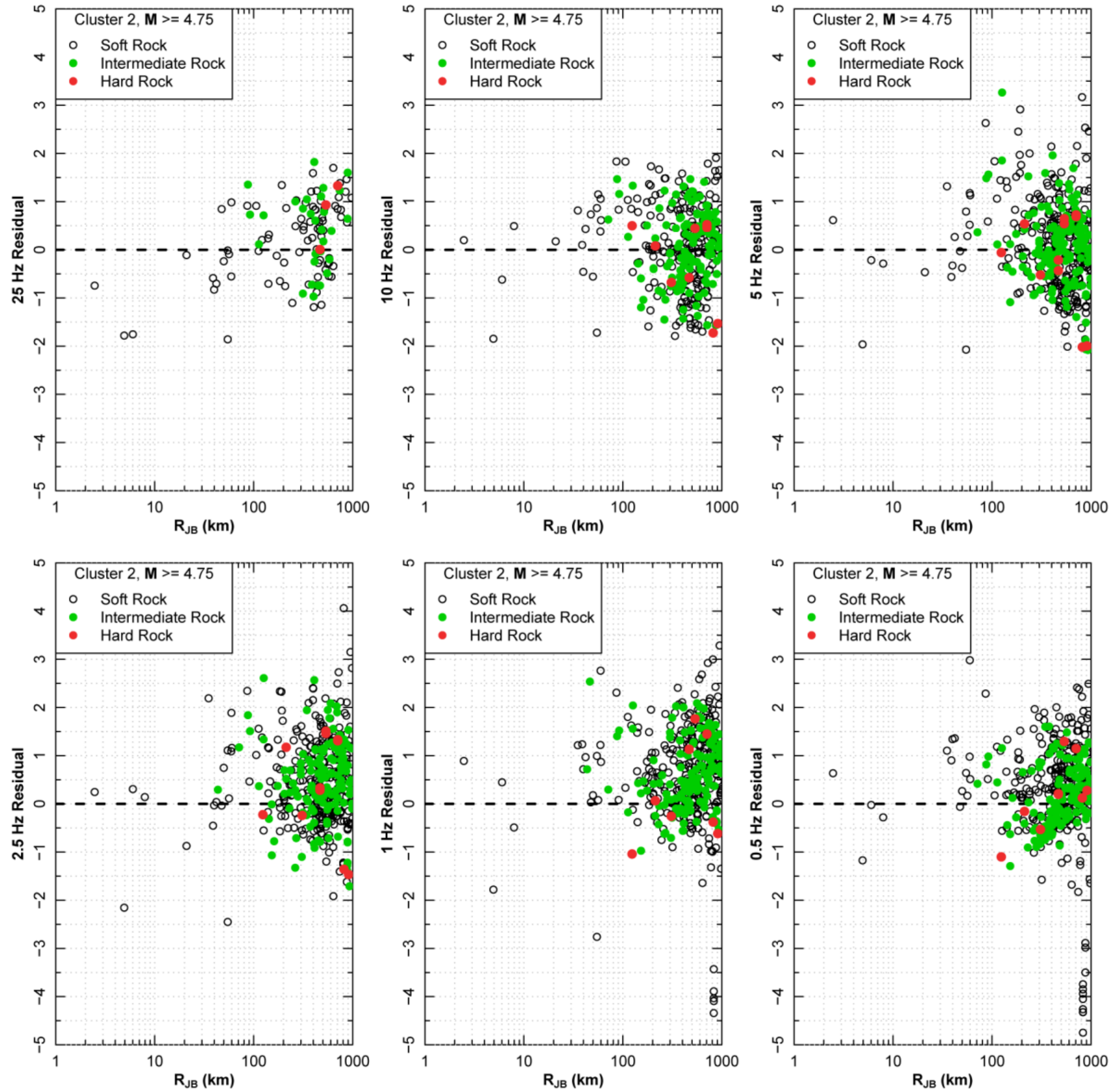

Figure 6.2.2-2. Rock site data PSA residuals computed using the EPRI (2004) Cluster 2 median GMPE

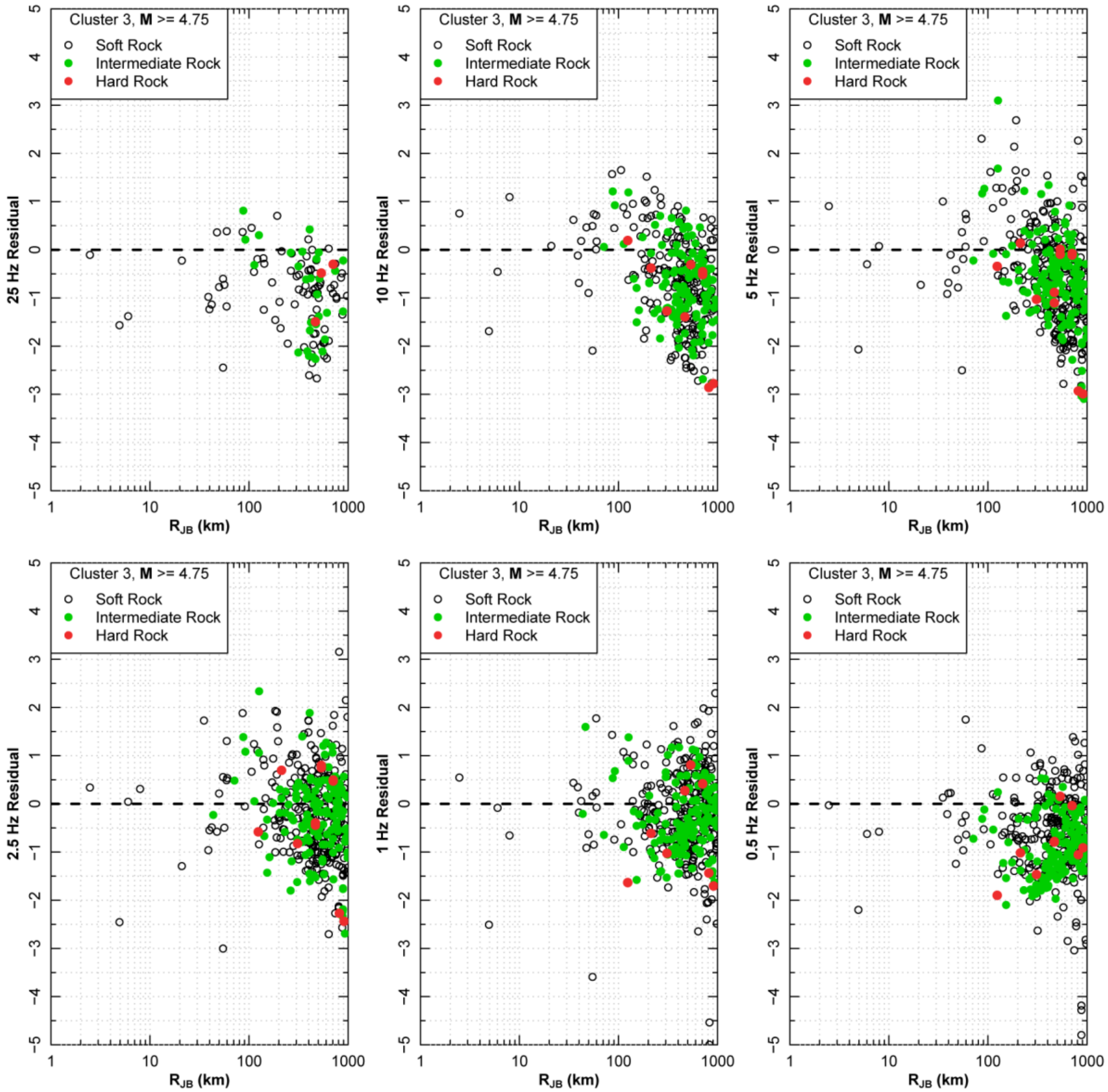

Figure 6.2.2-3. Rock site data PSA residuals computed using the EPRI (2004) Cluster 3 median GMPE

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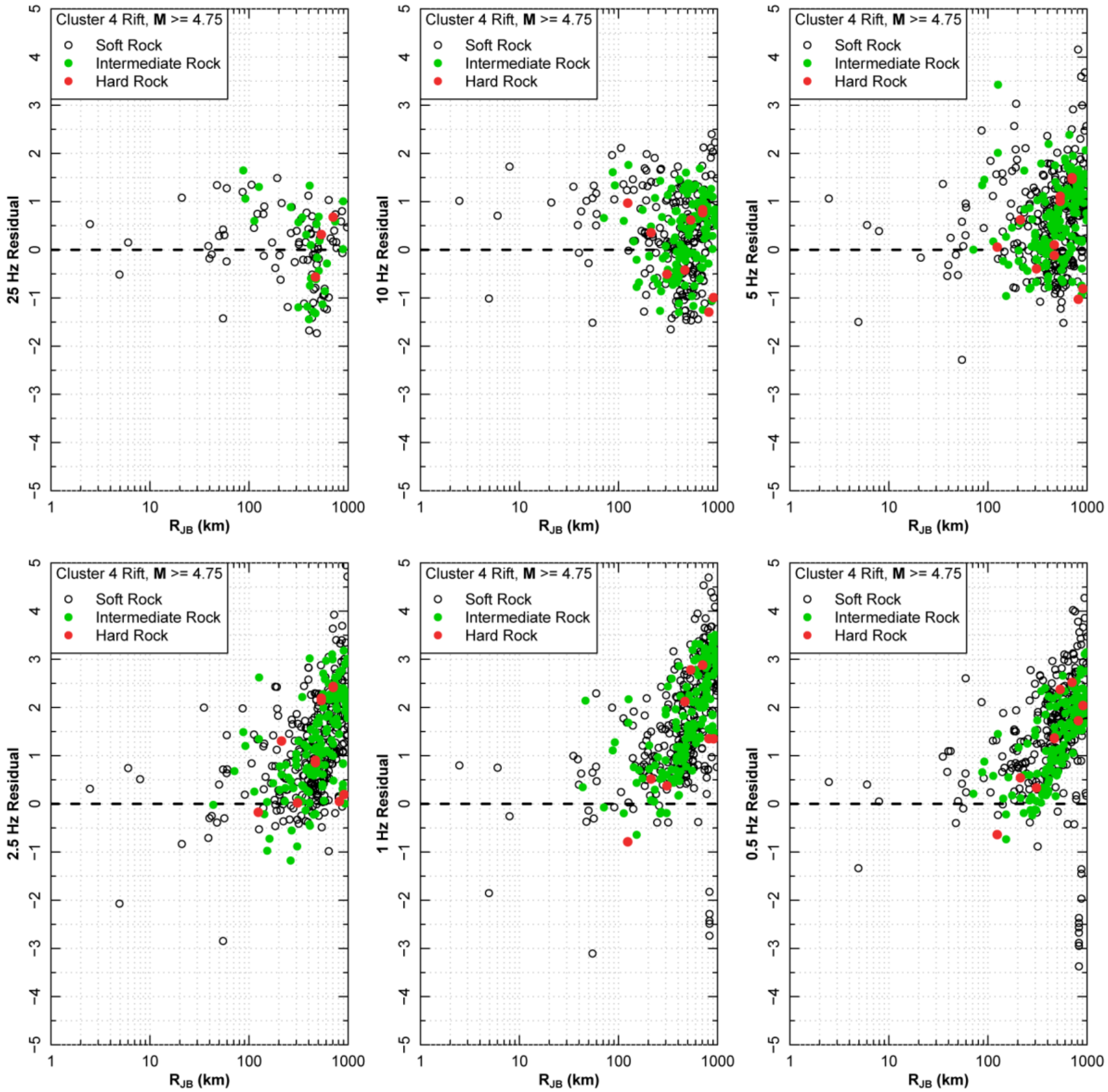

Figure 6.2.2-4. Rock site data PSA residuals computed using the EPRI (2004) Cluster 4 (Rift) median GMPE

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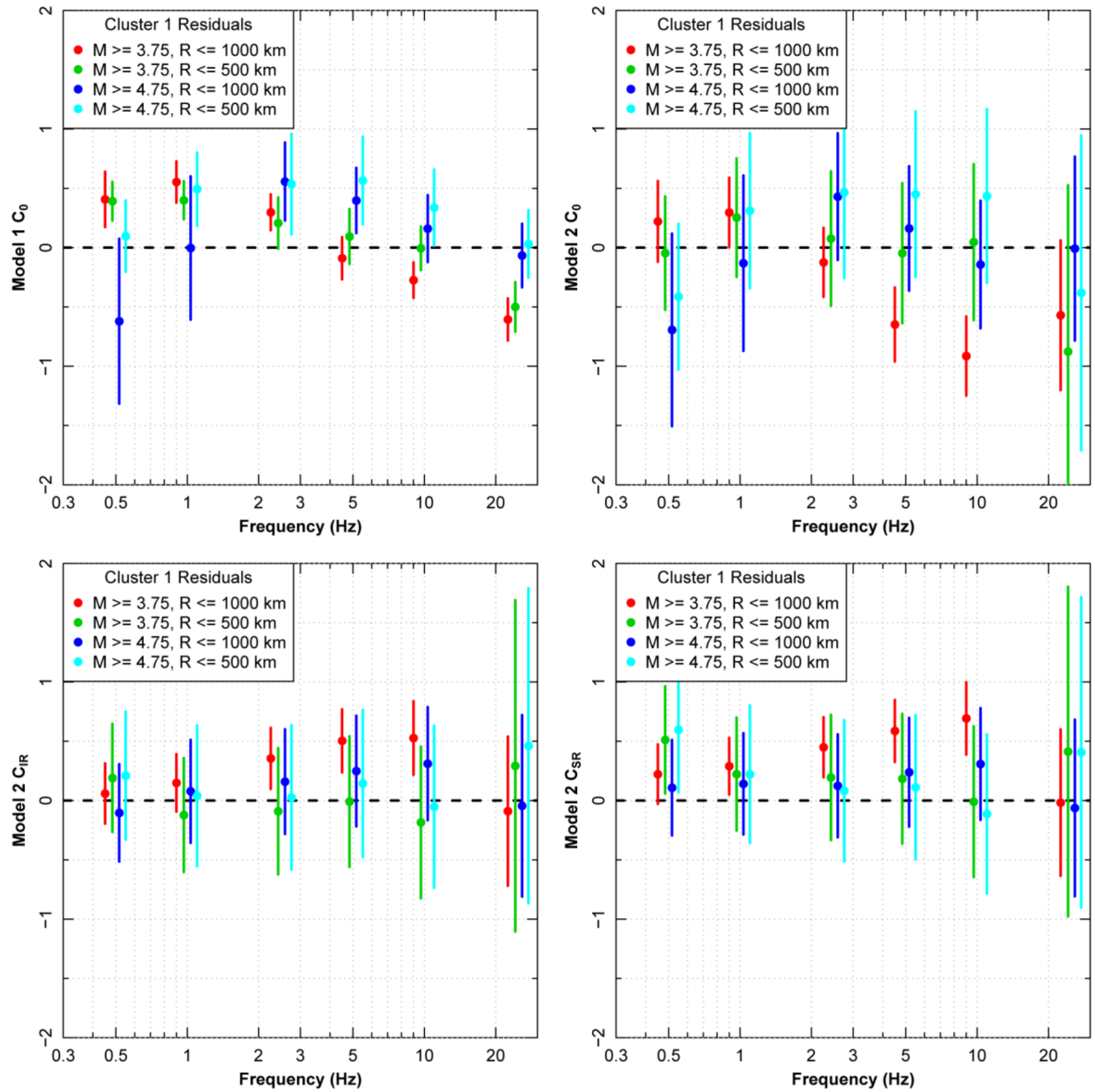

Figure 6.2.2-5. Coefficients of Model 1 (Equations 6.2.2-1) and Model 2 (Equation 6.2.2-2) fit to the EPRI (2004) Cluster 1 residuals shown on Figure 6.2.2-1

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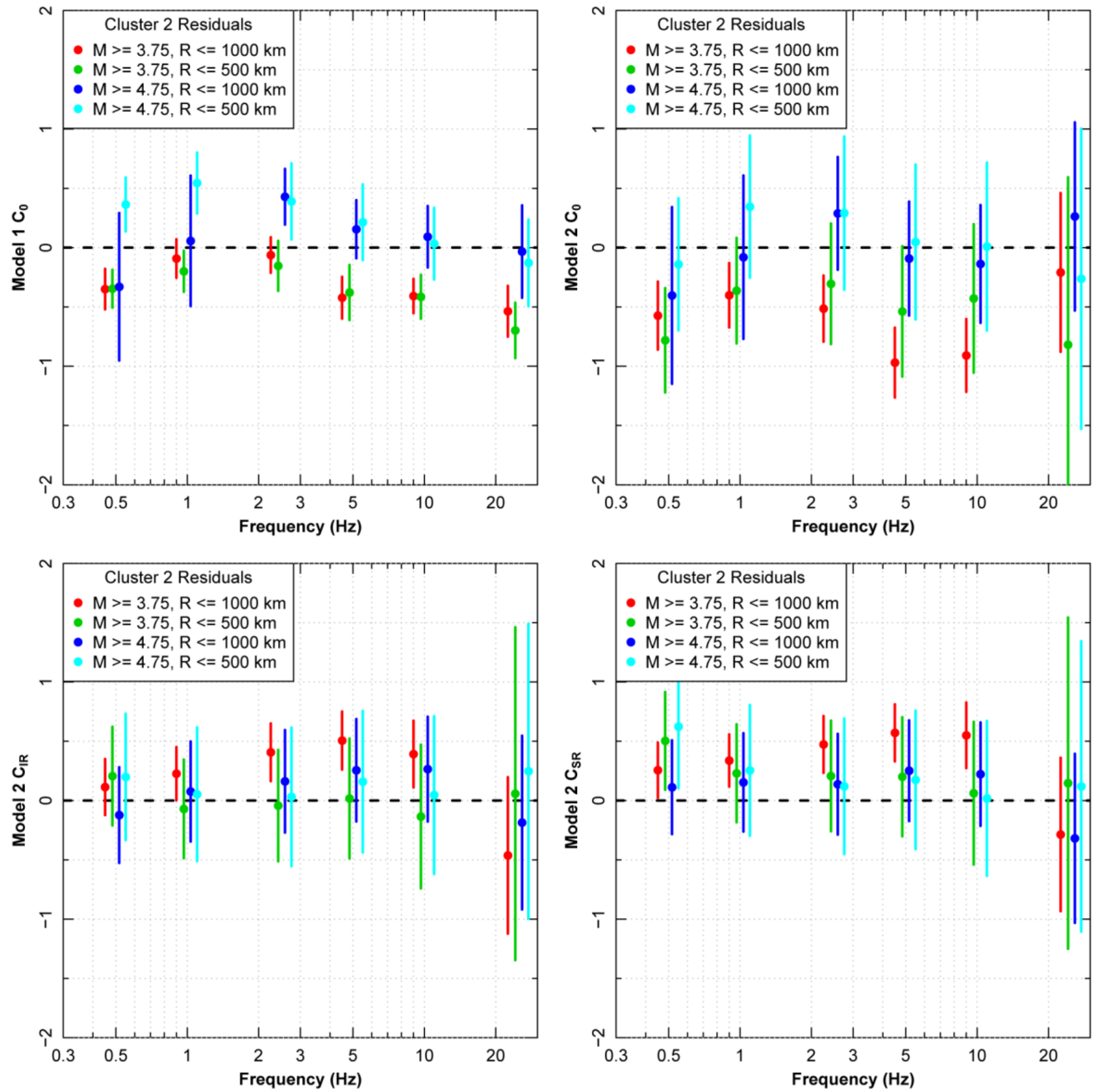

Figure 6.2.2-6. Coefficients of Model 1 (Equations 6.2.2-1) and Model 2 (Equation 6.2.2-2) fit to the EPRI (2004) Cluster 2 residuals shown on Figure 6.2.2-2

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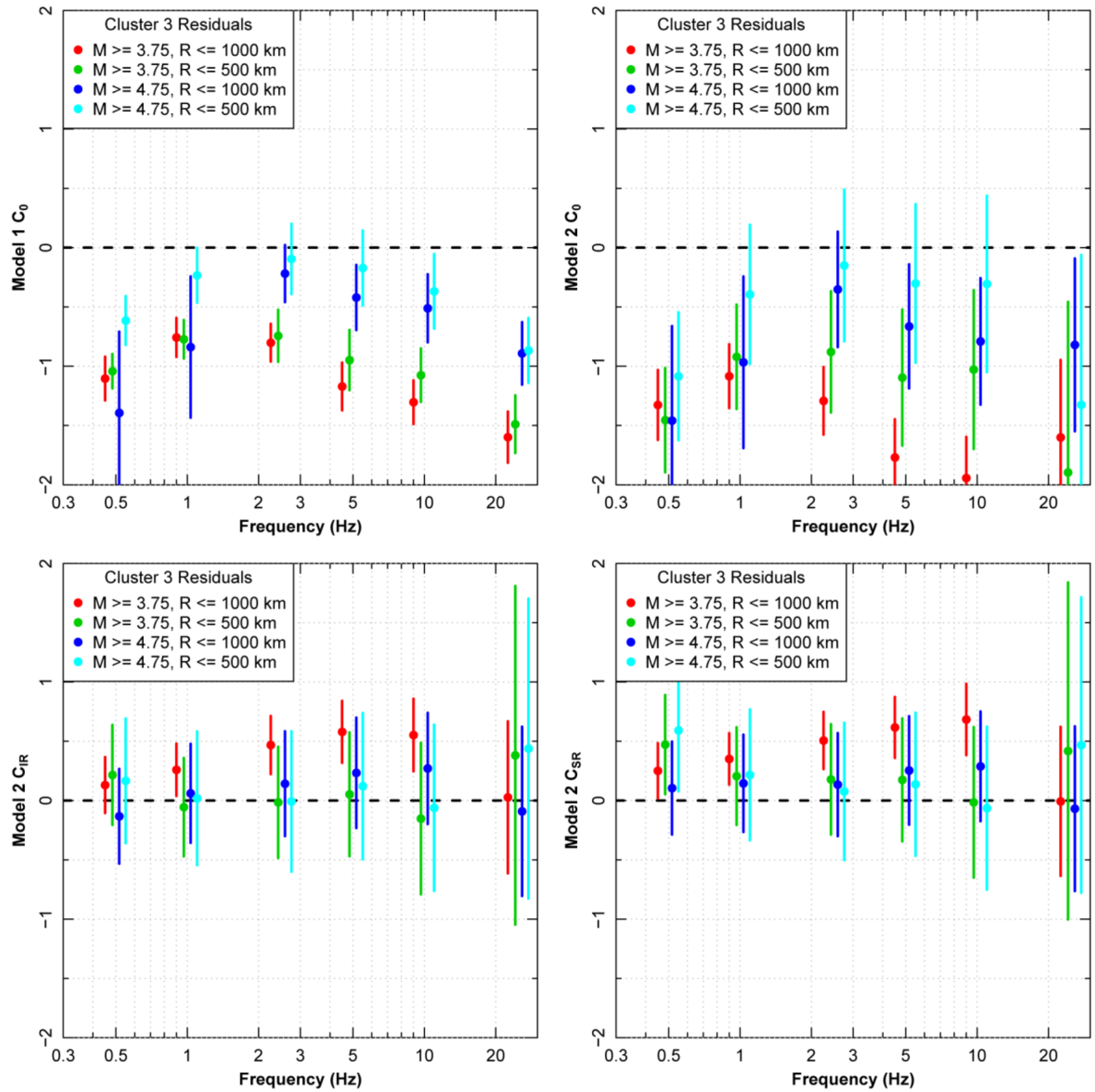

Figure 6.2.2-7. Coefficients of Model 1 (Equations 6.2.2-1) and Model 2 (Equation 6.2.2-2) fit to the EPRI (2004) Cluster 3 residuals shown on Figure 6.2.2-3

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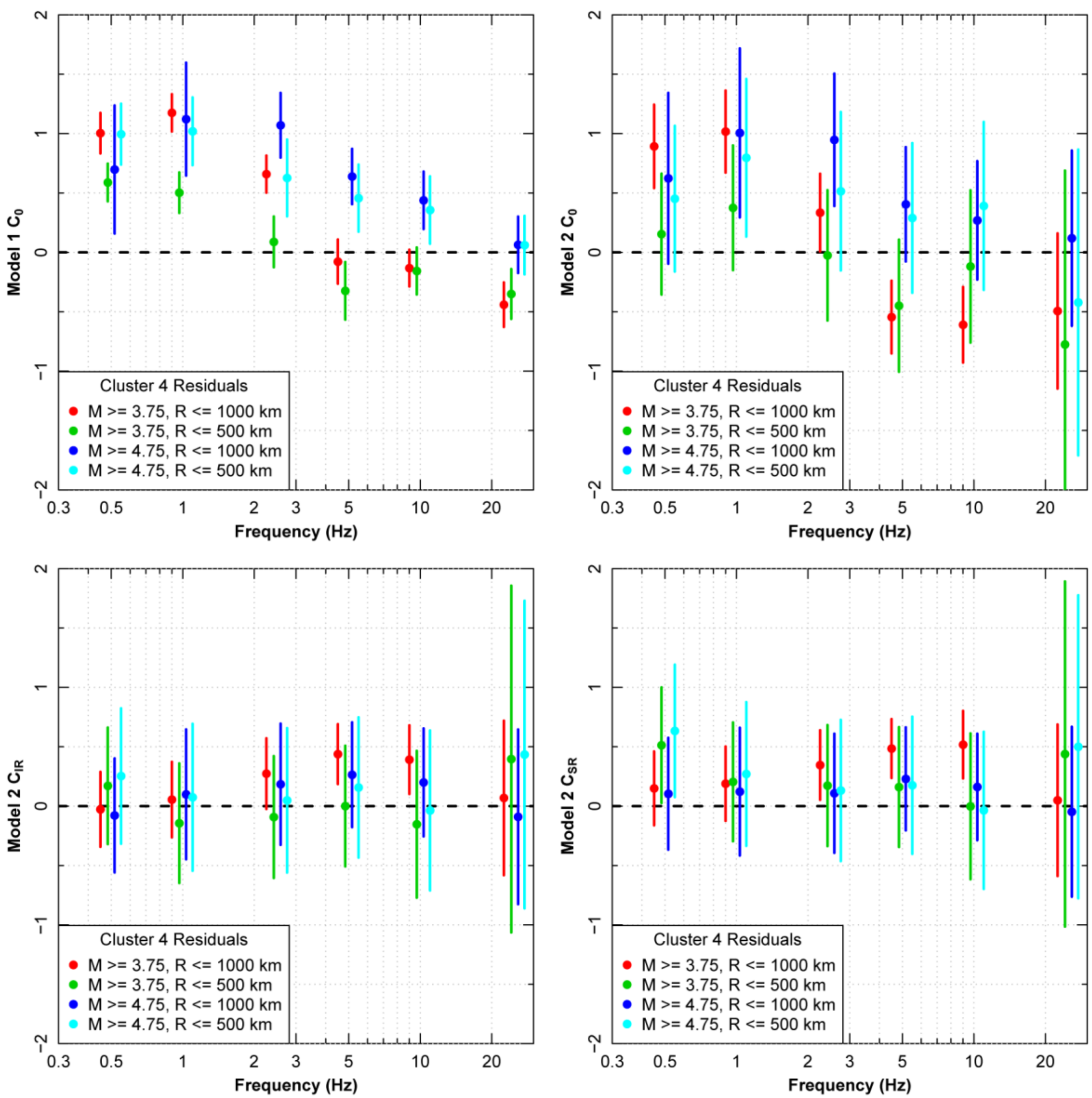

Figure 6.2.2-8. Coefficients of Model 1 (Equations 6.2.2-1) and Model 2 (Equation 6.2.2-2) fit to the EPRI (2004) Cluster 4 (Rift) residuals shown on Figure 6.2.2-4

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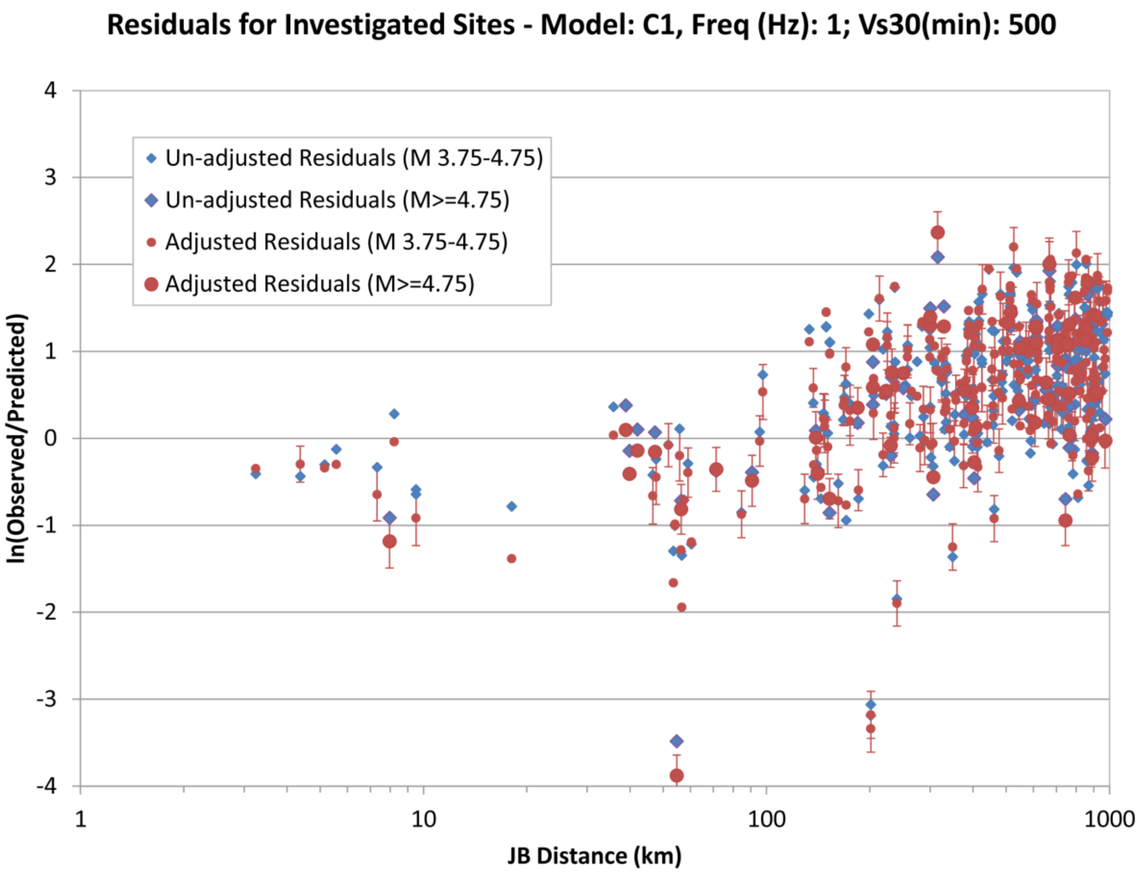

Figure 6.3.1-1. Residuals between the adjusted and unadjusted spectral accelerations and the EPRI (2004) median GMPE for Cluster 1 and frequency 1 Hz

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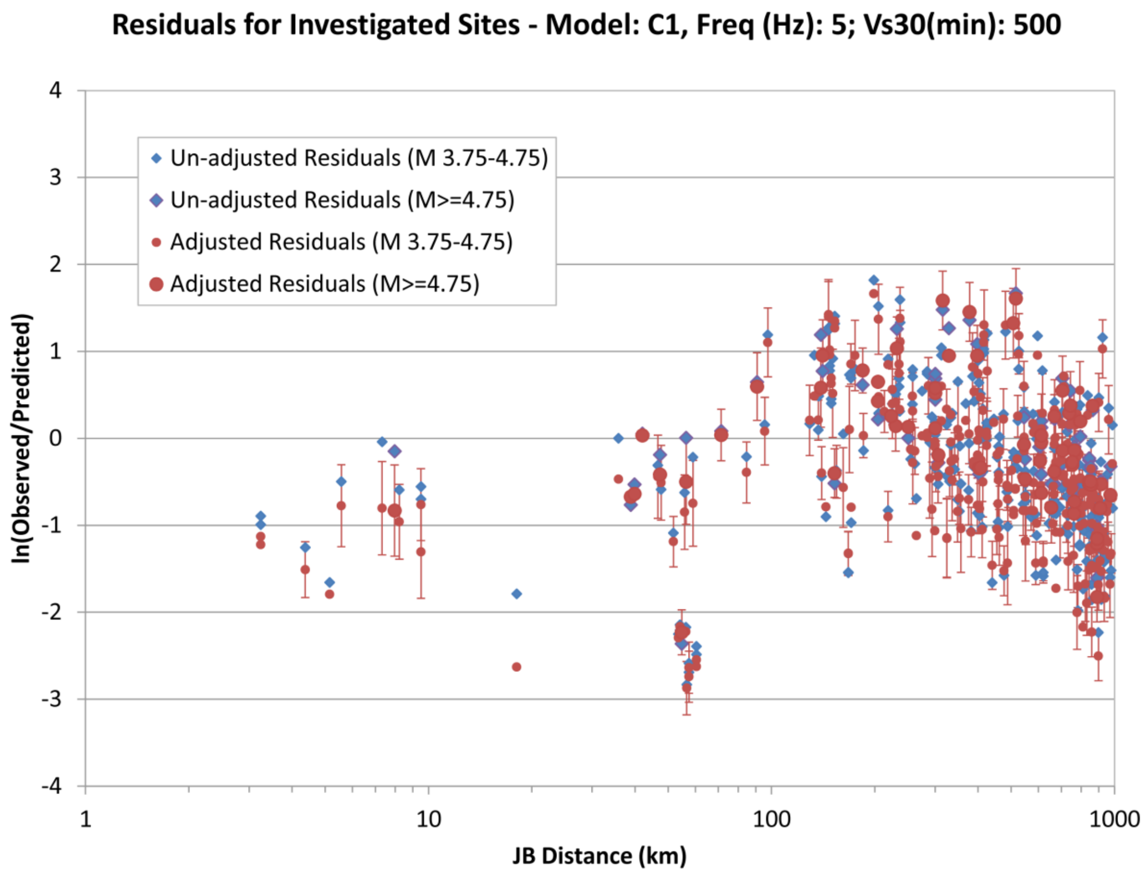

Figure 6.3.1-2. Residuals between the adjusted and unadjusted spectral accelerations and the EPRI (2004) median GMPE for Cluster 1 and frequency 5 Hz

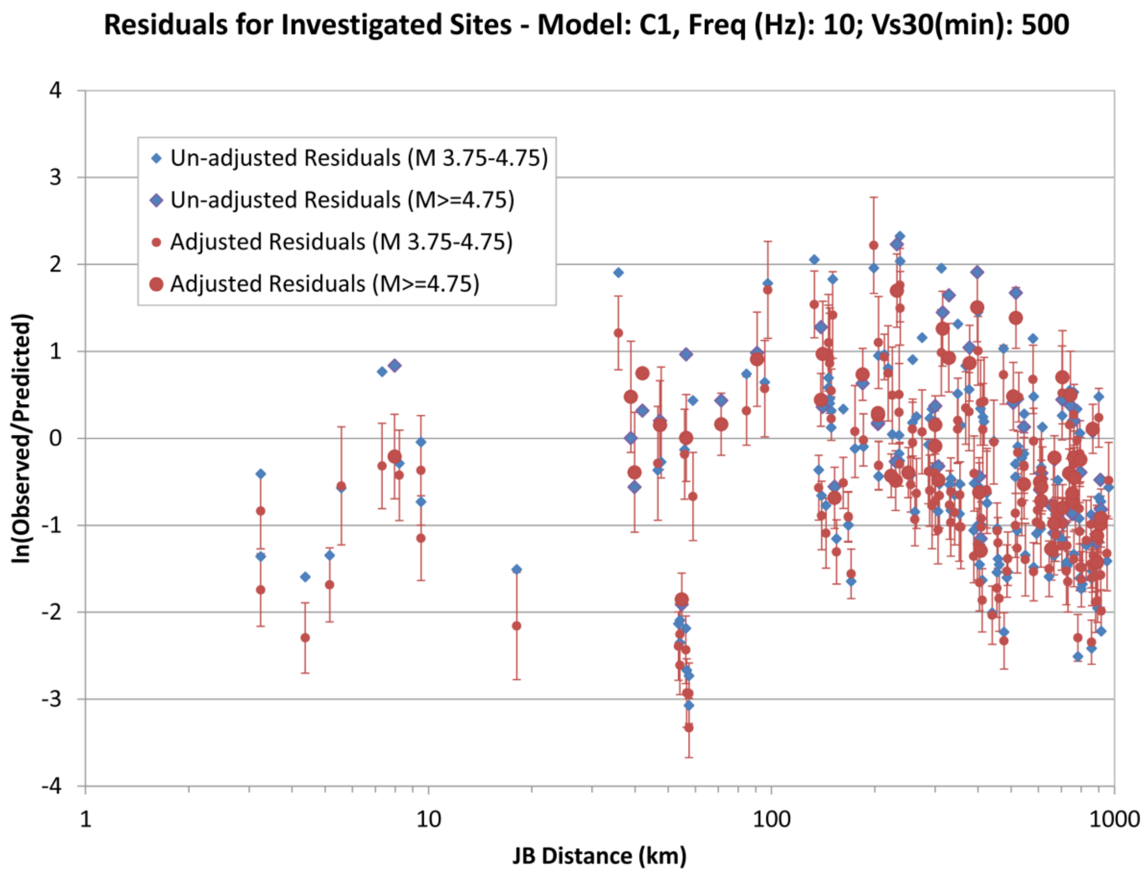

Figure 6.3.1-3. Residuals between the adjusted and unadjusted spectral accelerations and the EPRI (2004) median GMPE for Cluster 1 and frequency 10 Hz

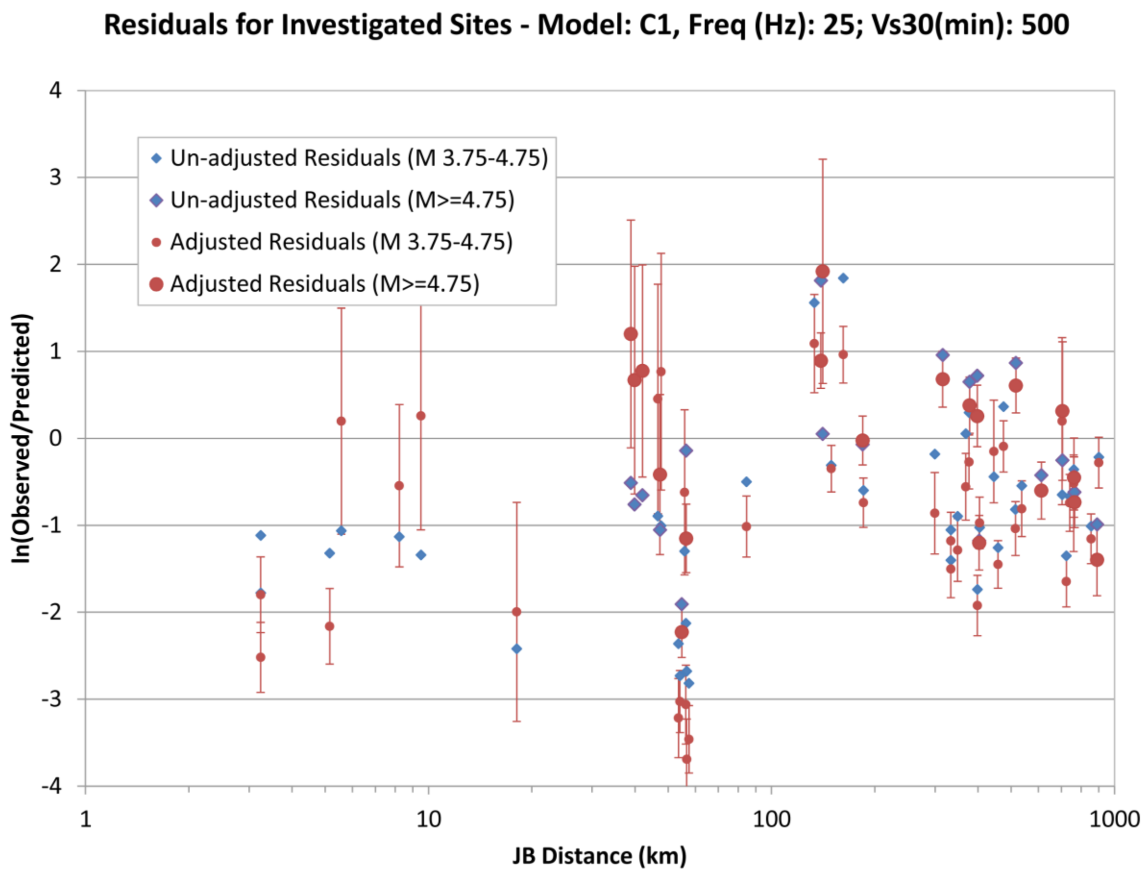

Figure 6.3.1-4. Residuals between the adjusted and unadjusted spectral accelerations and the EPRI (2004) median GMPE for Cluster 1 and frequency 25 Hz

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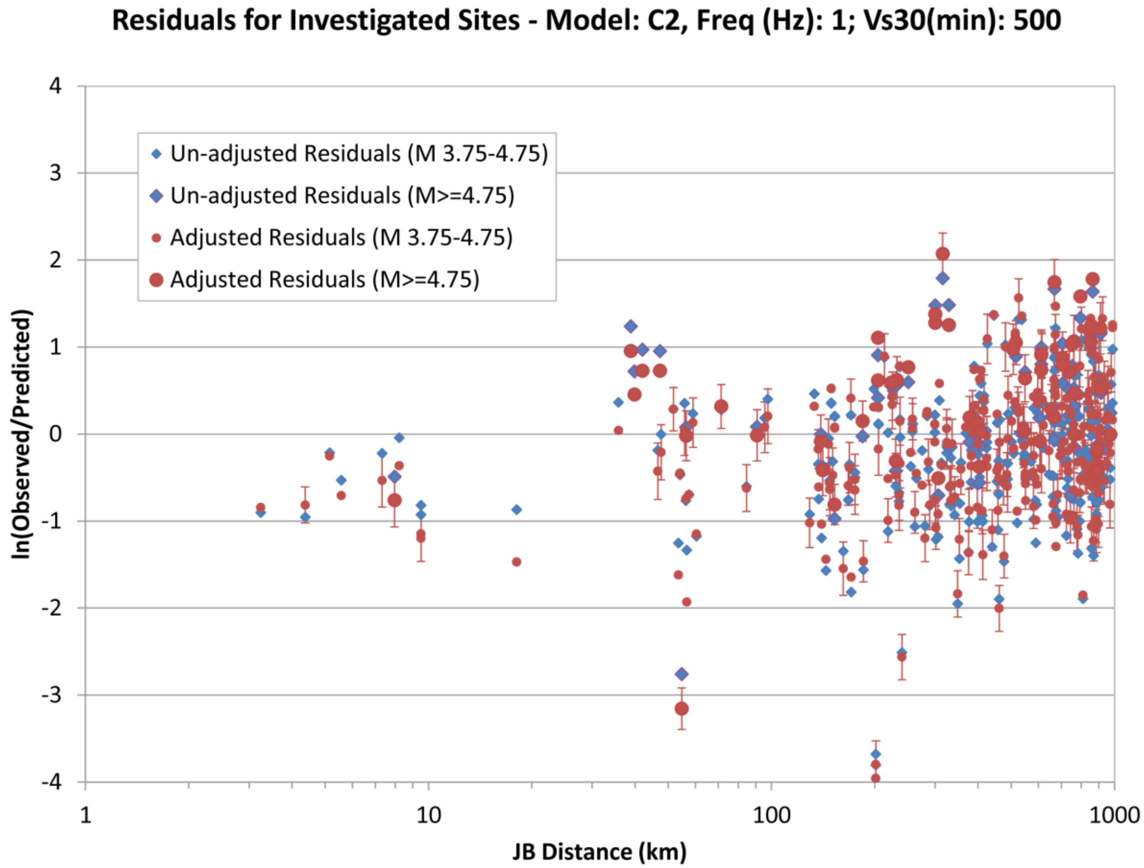

Figure 6.3.1-5. Residuals between the adjusted and unadjusted spectral accelerations and the EPRI (2004) median GMPE for Cluster 2 and frequency 1 Hz

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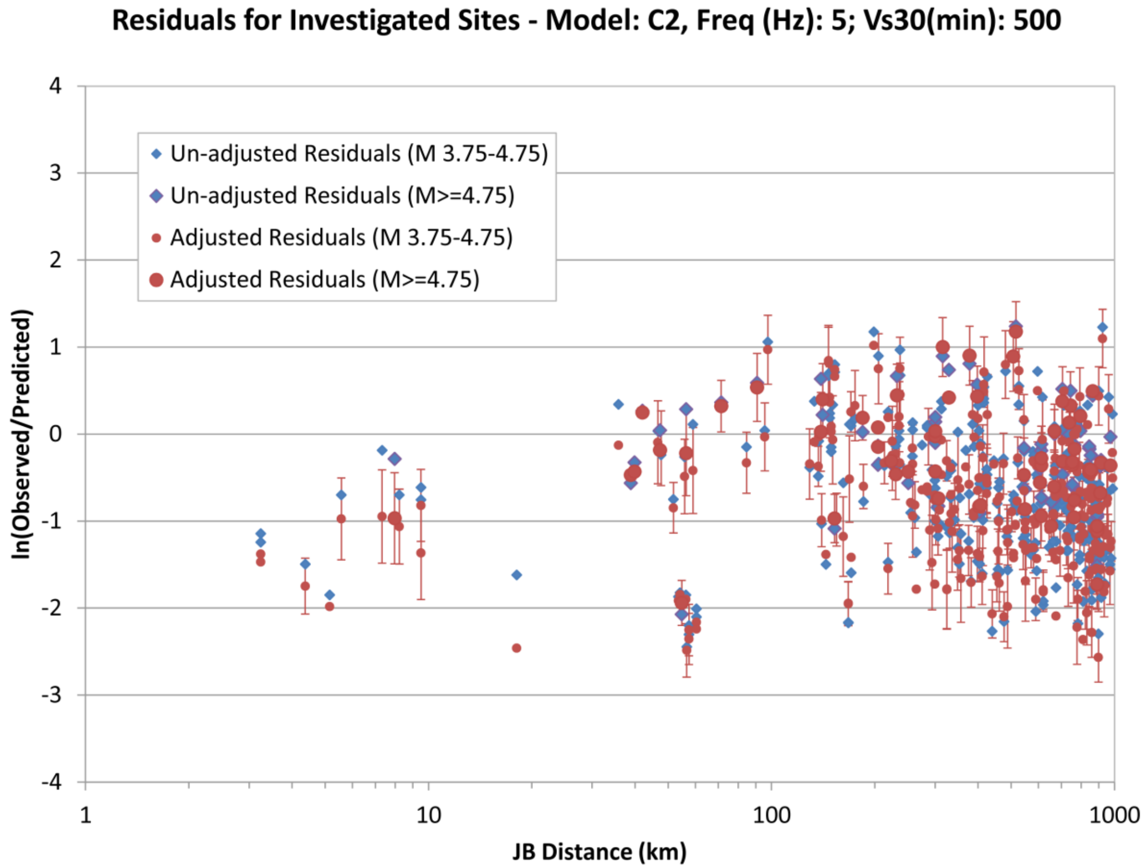

Figure 6.3.1-6. Residuals between the adjusted and unadjusted spectral accelerations and the EPRI (2004) median GMPE for Cluster 2 and frequency 5 Hz

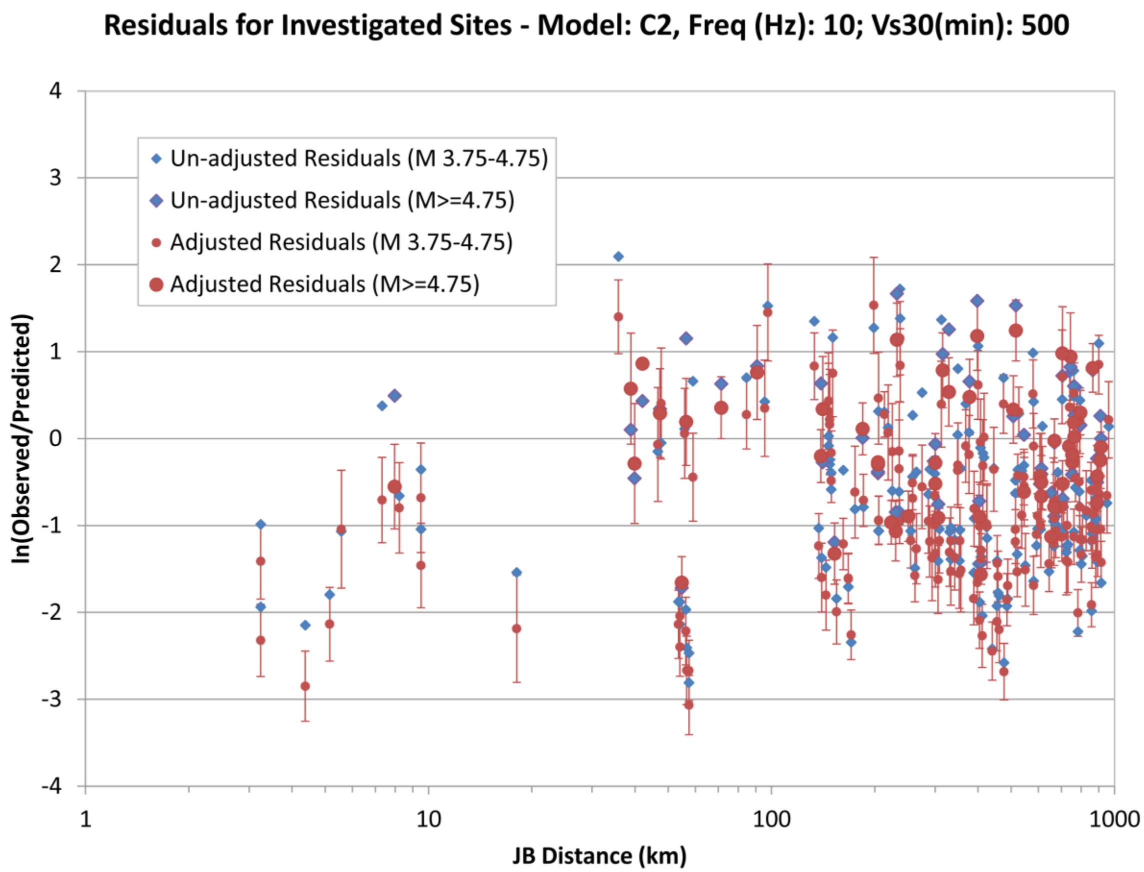

Figure 6.3.1-7. Residuals between the adjusted and unadjusted spectral accelerations and the EPRI (2004) median GMPE for Cluster 2 and frequency 10 Hz

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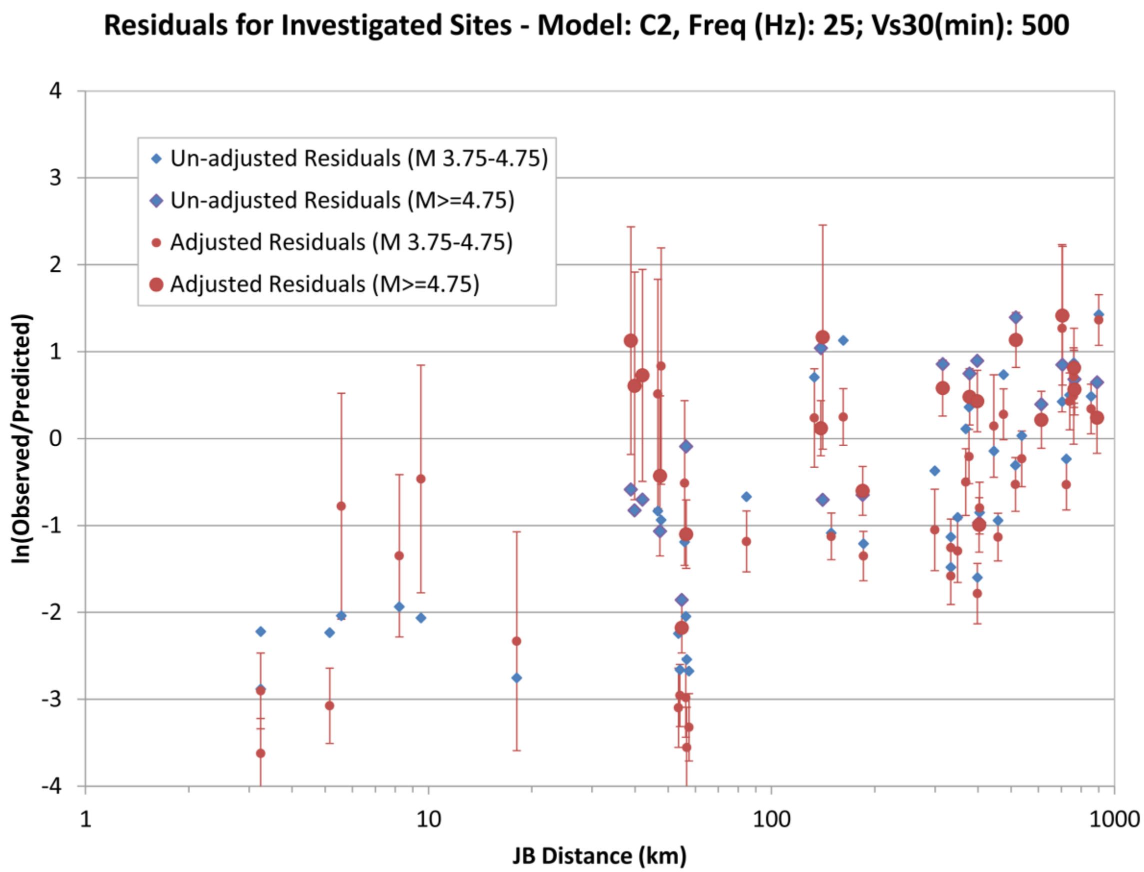

Figure 6.3.1-8. Residuals between the adjusted and unadjusted spectral accelerations and the EPRI (2004) median GMPE for Cluster 2 and frequency 25 Hz

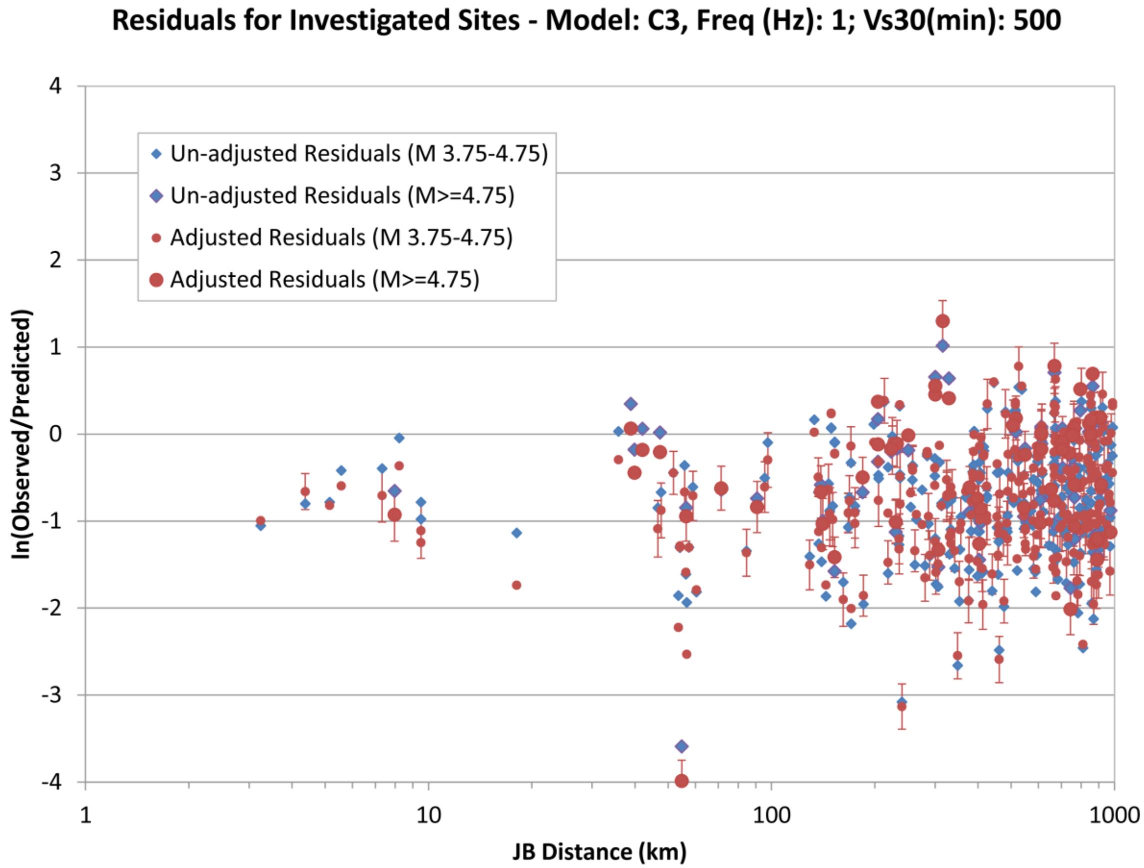

Figure 6.3.1-9. Residuals between the adjusted and unadjusted spectral accelerations and the EPRI (2004) median GMPE for Cluster 3 and frequency 1 Hz

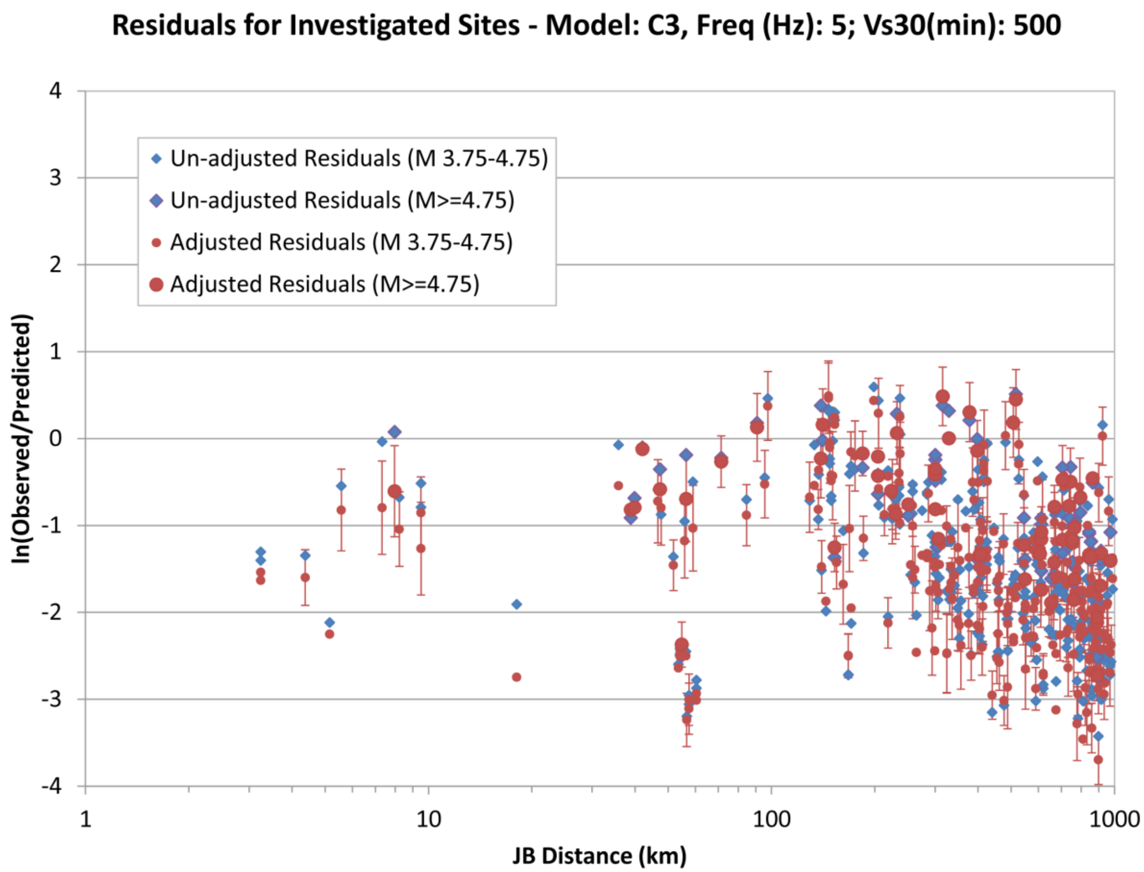

Figure 6.3.1-10. Residuals between the adjusted and unadjusted spectral accelerations and the EPRI (2004) median GMPE for Cluster 3 and frequency 5 Hz

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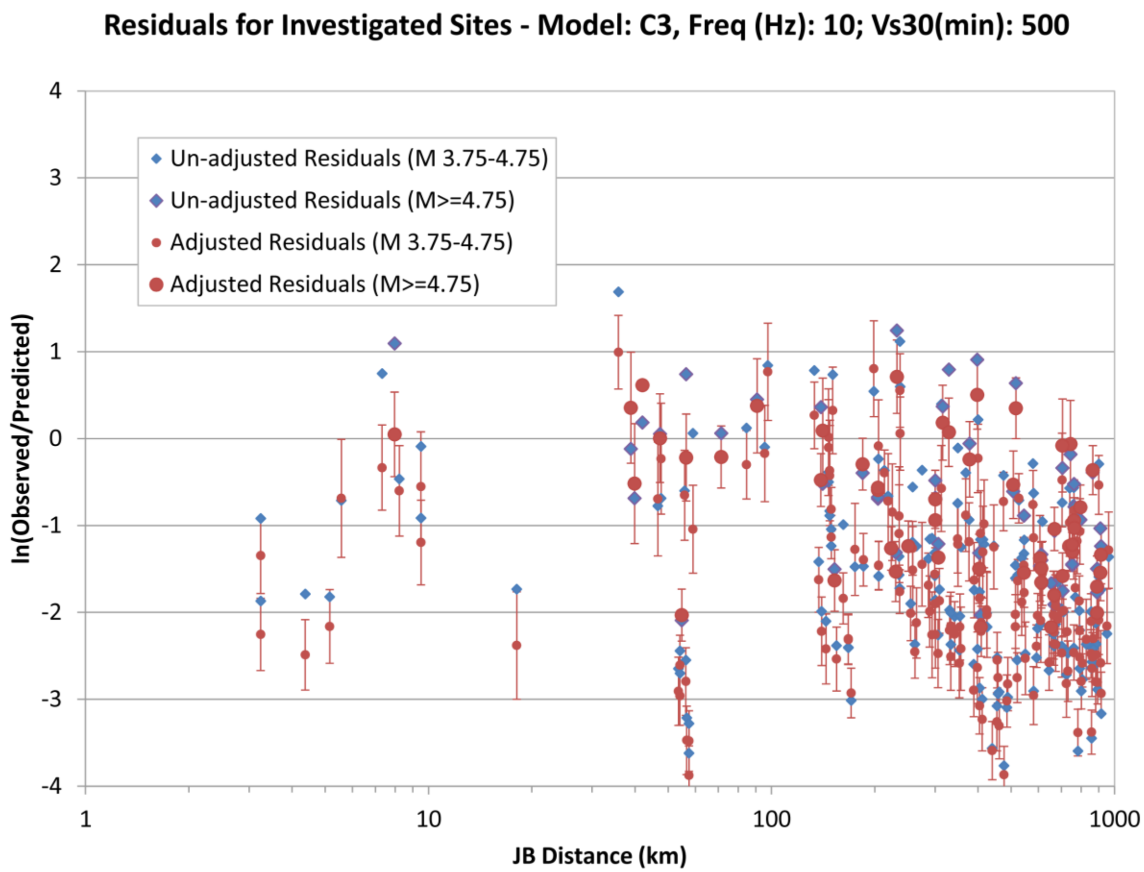

Figure 6.3.1-11. Residuals between the adjusted and unadjusted spectral accelerations and the EPRI (2004) median GMPE for Cluster 3 and frequency 10 Hz

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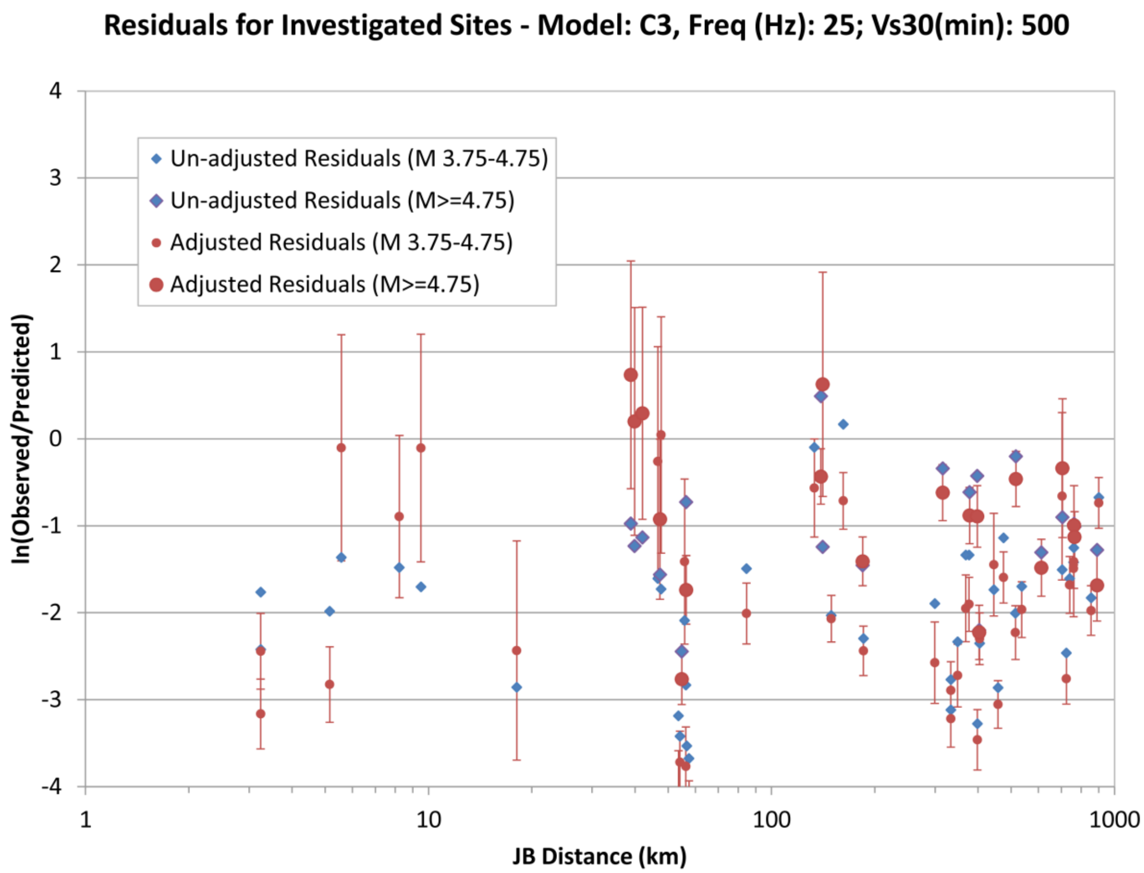

Figure 6.3.1-12. Residuals between the adjusted and unadjusted spectral accelerations and the EPRI (2004) median GMPE for Cluster 3 and frequency 25 Hz

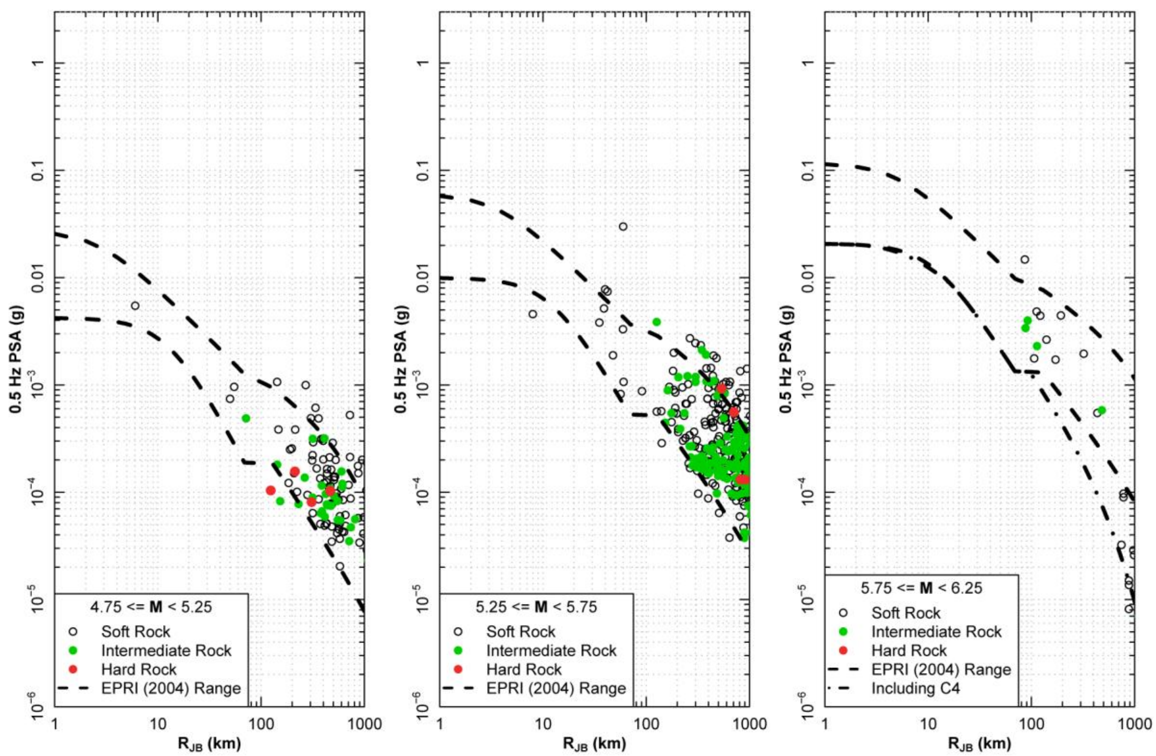

Figure 6.3.2-1 Comparison of unadjusted CENA rock site 0.5 Hz PSA data with range in ground motions predicted by the EPRI (2004) ground motion model

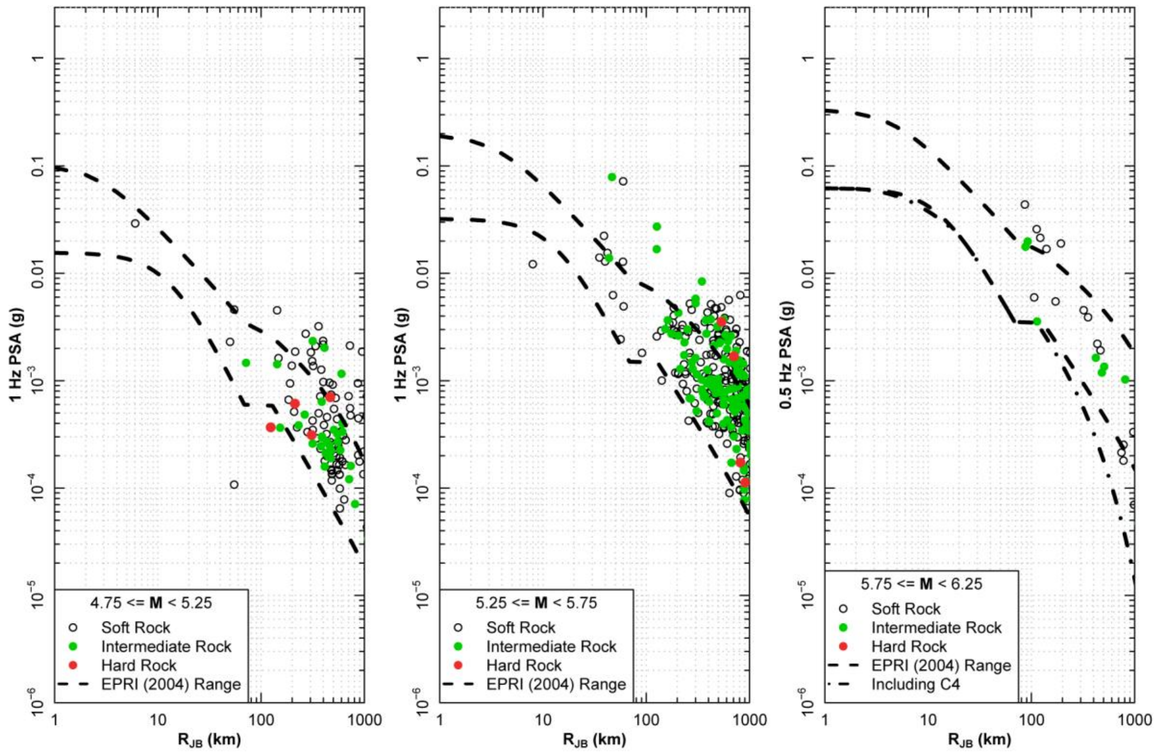

Figure 6.3.2-2 Comparison of unadjusted CENA rock site 1 Hz PSA data with range in ground motions predicted by the EPRI (2004) ground motion model

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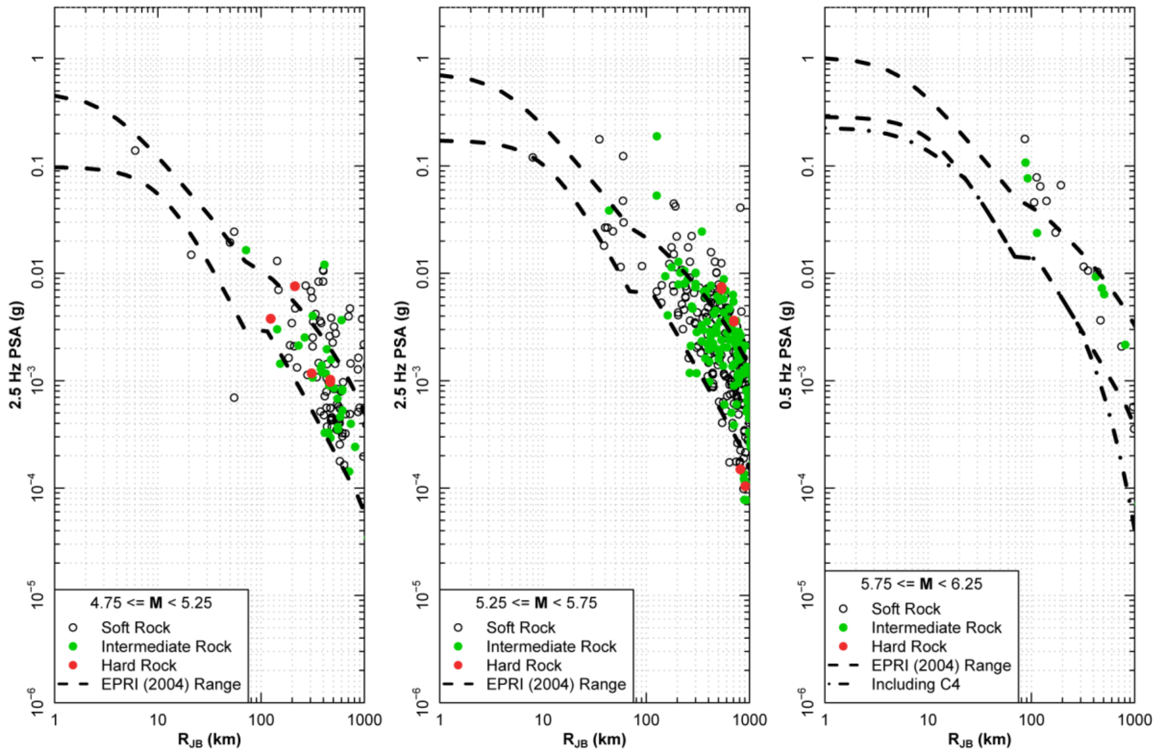

Figure 6.3.2-3 Comparison of unadjusted CENA rock site 2.5 Hz PSA data with range in ground motions predicted by the EPRI (2004) ground motion model

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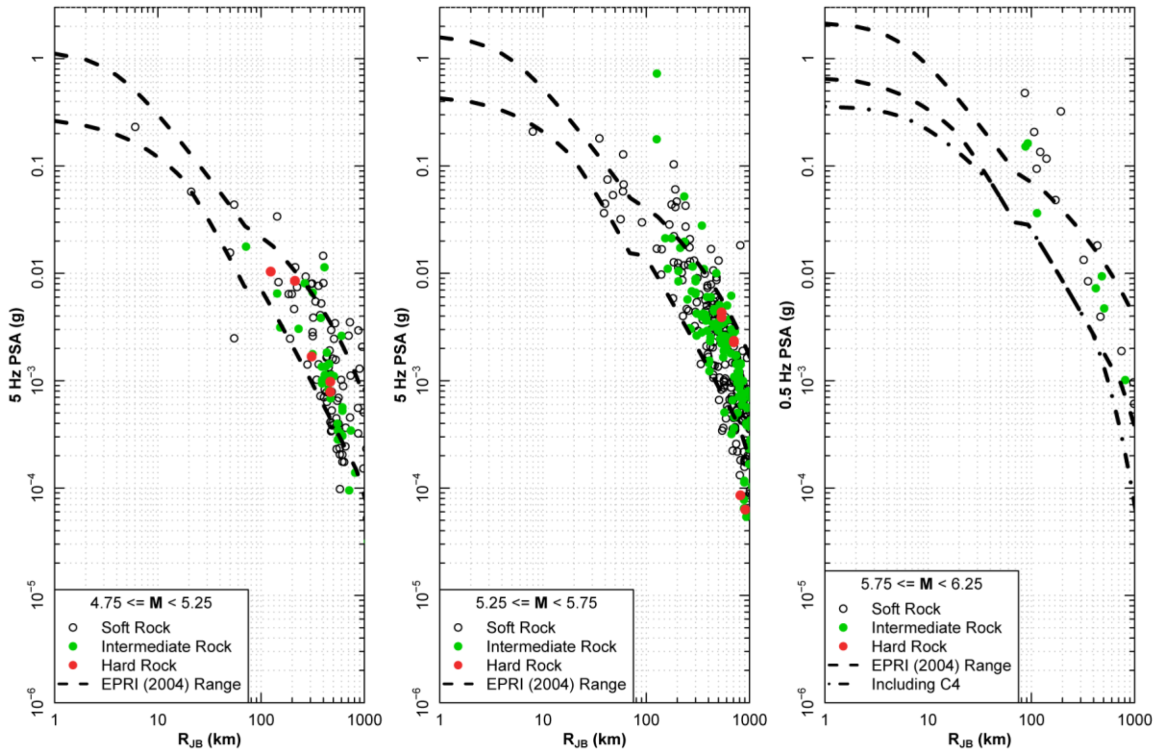

Figure 6.3.2-4 Comparison of unadjusted CENA rock site 5 Hz PSA data with range in ground motions predicted by the EPRI (2004) ground motion model

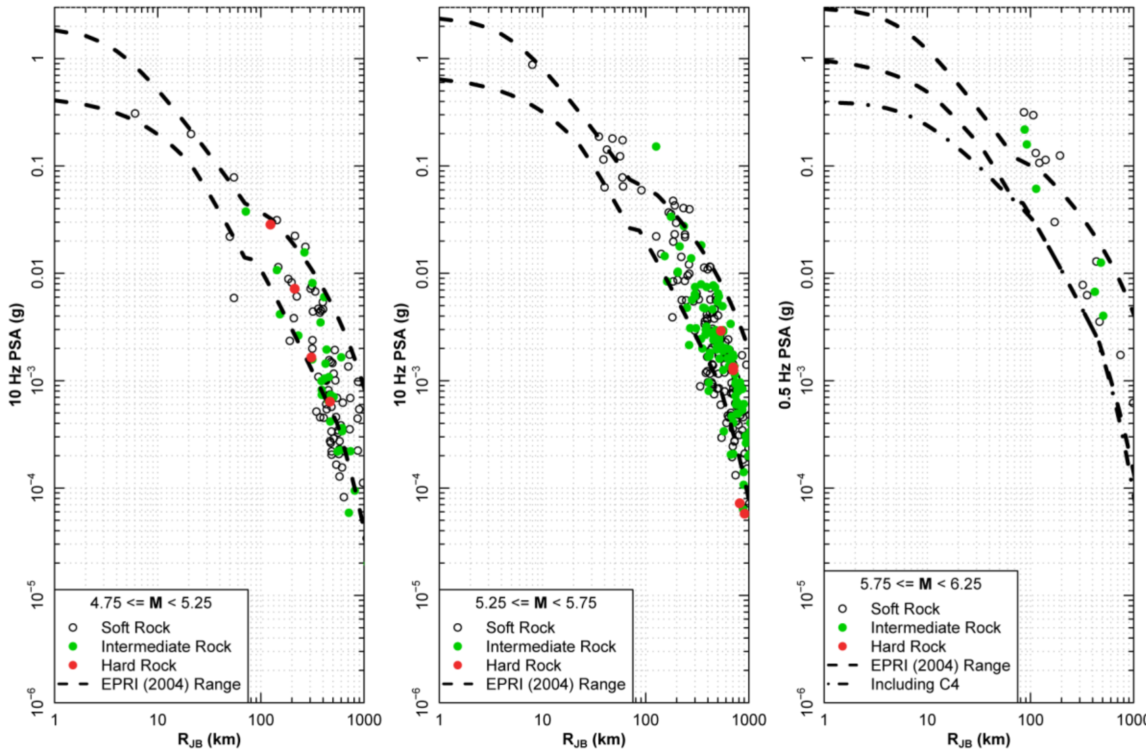

Figure 6.3.2-5 Comparison of unadjusted CENA rock site 10 Hz PSA data with range in ground motions predicted by the EPRI (2004) ground motion model

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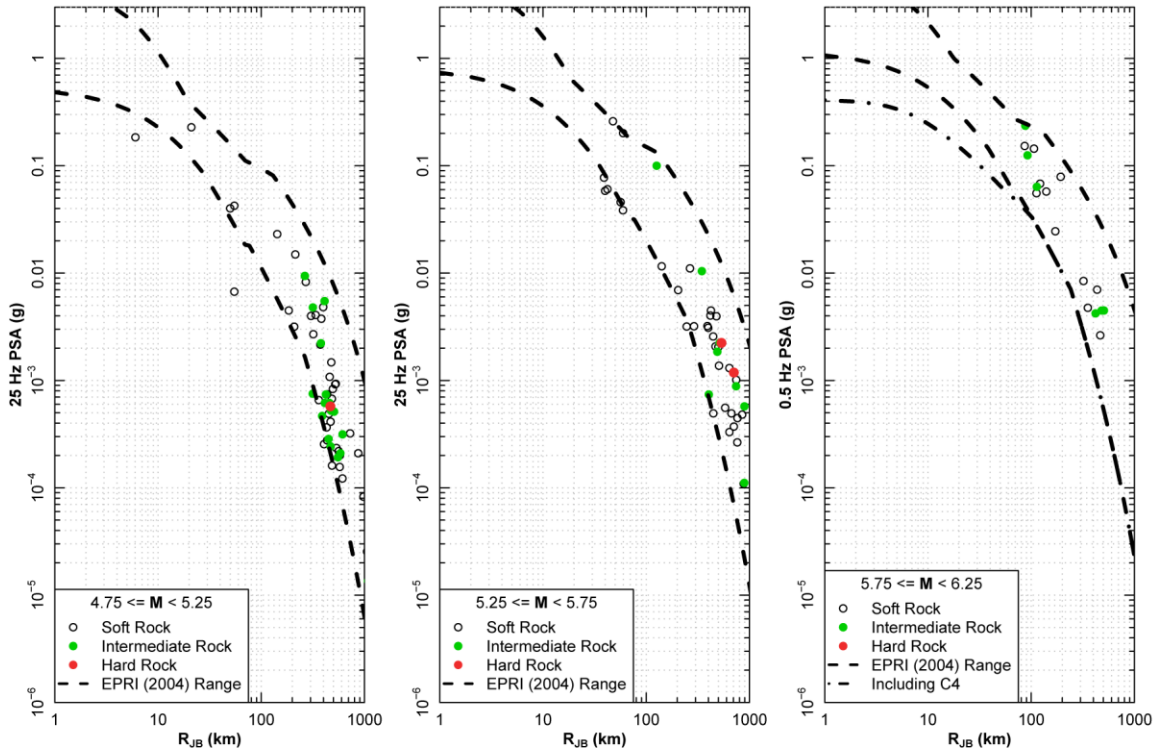

Figure 6.3.2-6 Comparison of unadjusted CENA rock site 25 Hz PSA data with range in ground motions predicted by the EPRI (2004) ground motion model

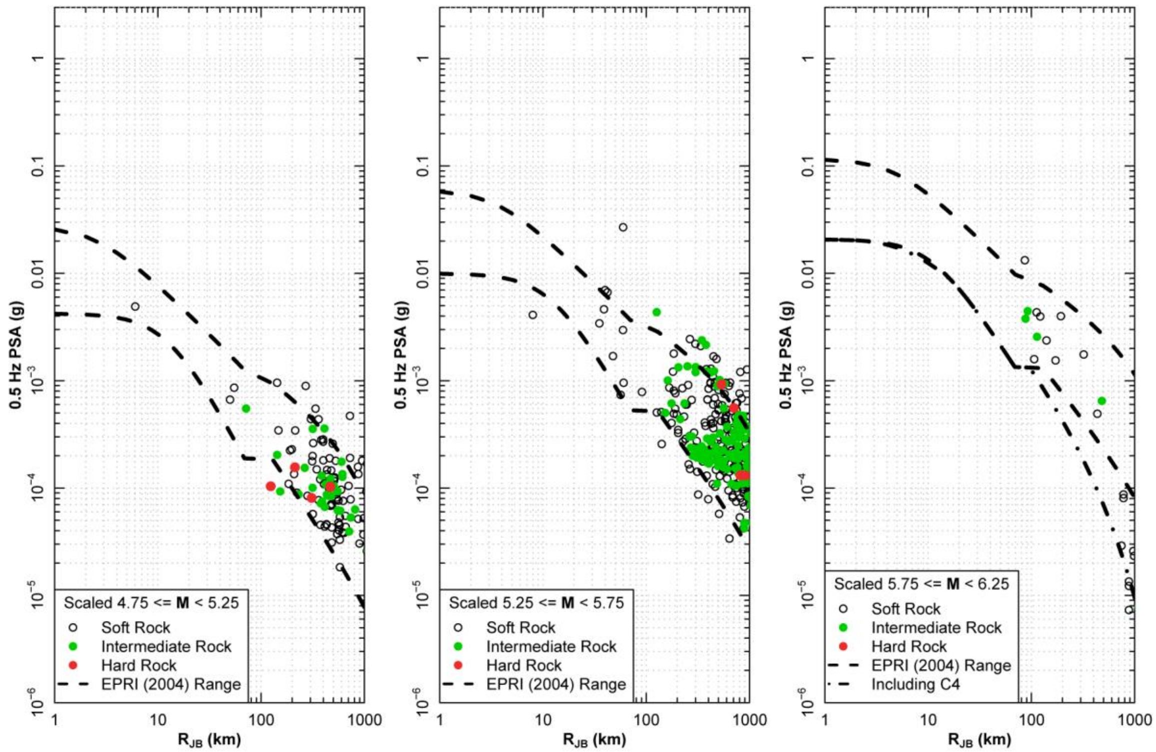

Figure 6.3.2-7 Comparison of scaled CENA rock site 0.5 Hz PSA data with range in ground motions predicted by the EPRI (2004) ground motion model

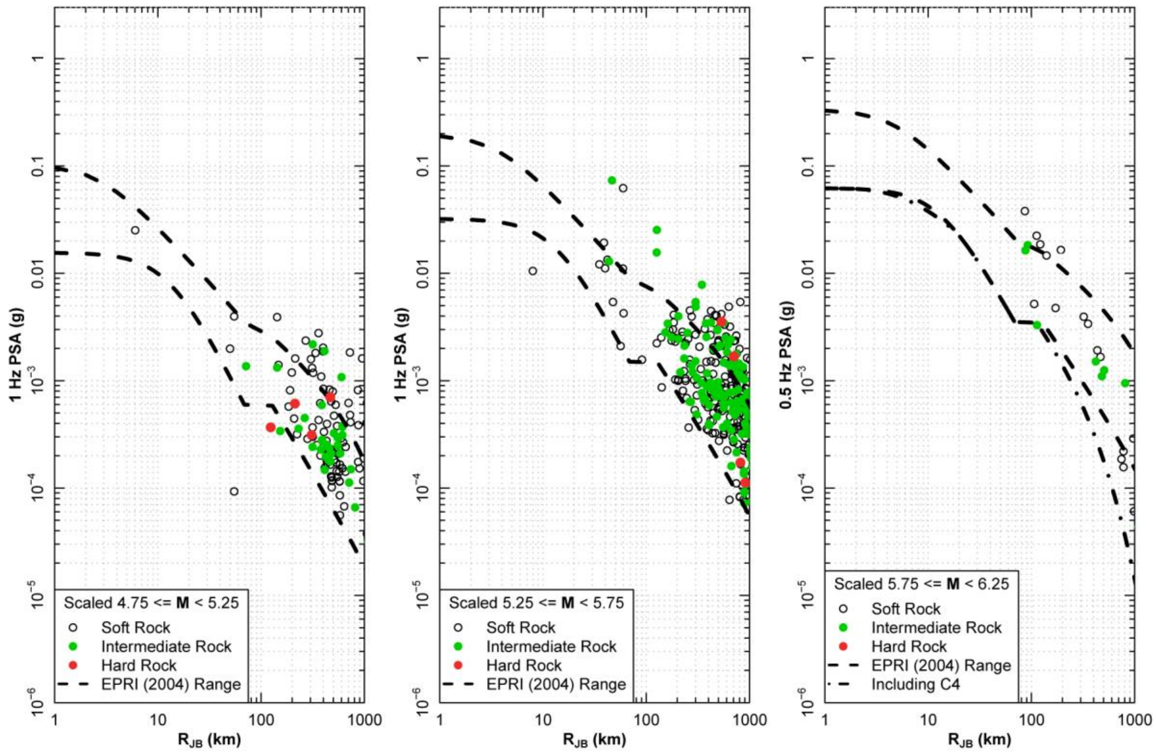

Figure 6.3.2-8 Comparison of scaled CENA rock site 1 Hz PSA data with range in ground motions predicted by the EPRI (2004) ground motion model

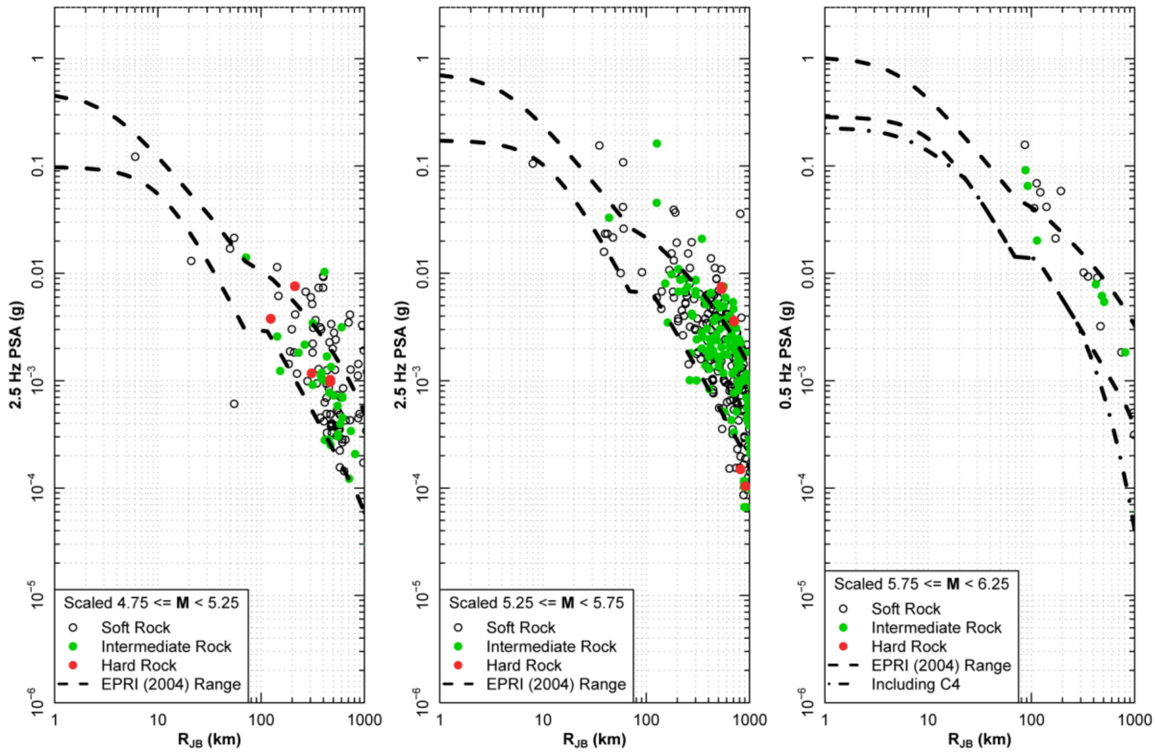

Figure 6.3.2-9 Comparison of scaled CENA rock site 25 Hz PSA data with range in ground motions predicted by the EPRI (2004) ground motion model

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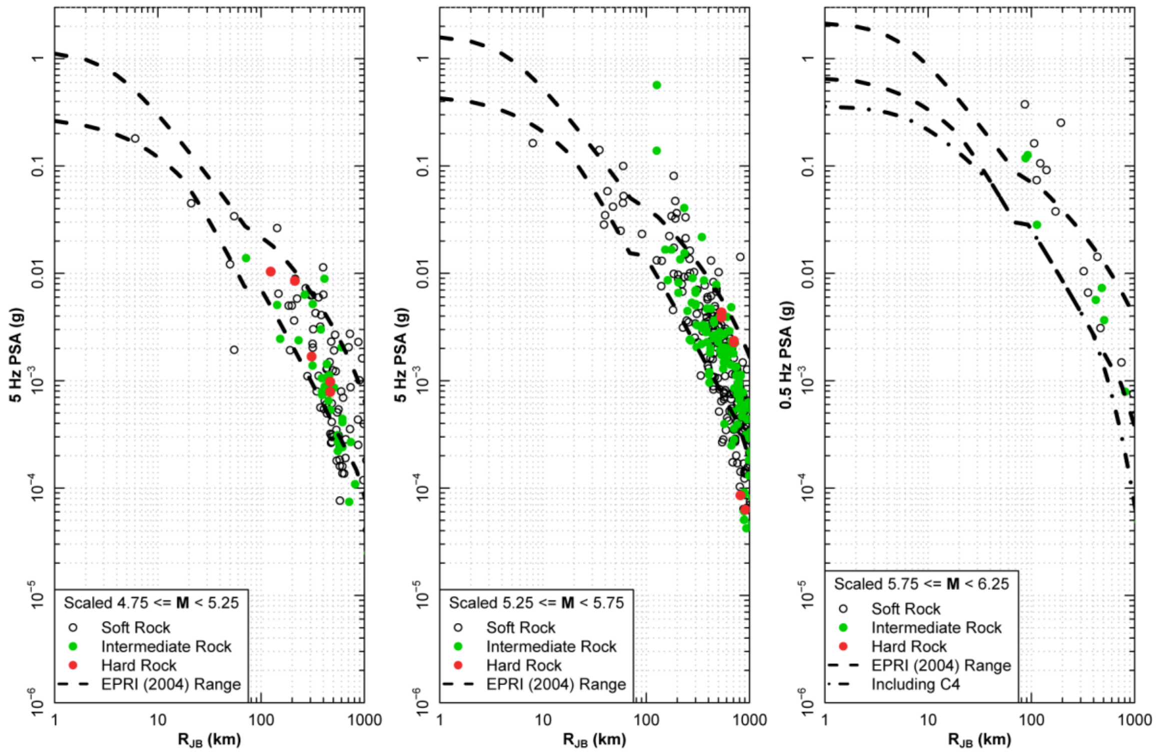

Figure 6.3.2-10 Comparison of scaled CENA rock site 5 Hz PSA data with range in ground motions predicted by the EPRI (2004) ground motion model

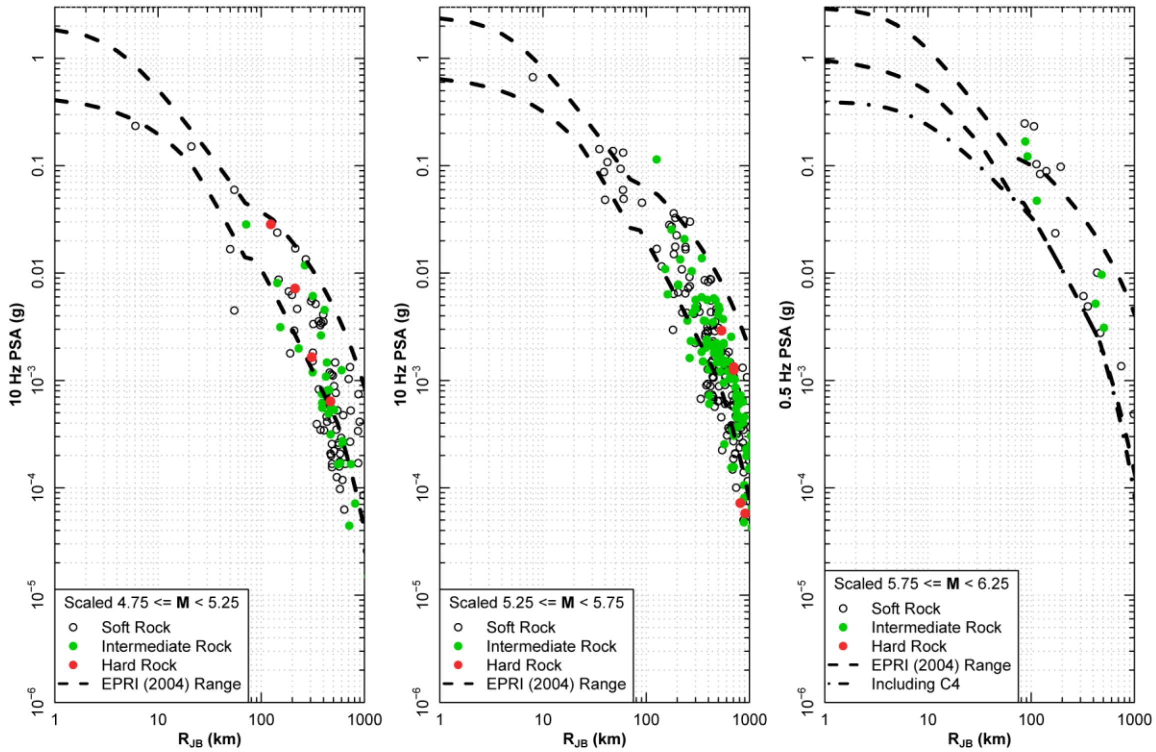

Figure 6.3.2-11 Comparison of scaled CENA rock site 10 Hz PSA data with range in ground motions predicted by the EPRI (2004) ground motion model

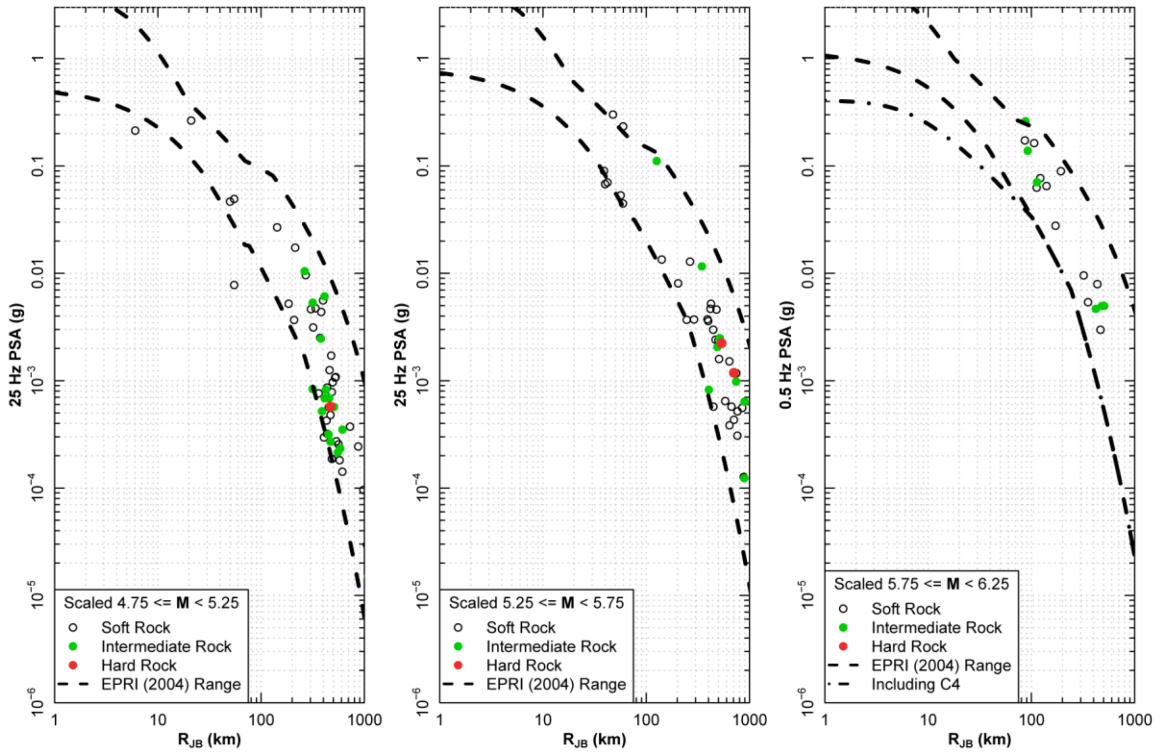

Figure 6.3.2-12 Comparison of scaled CENA rock site 25 Hz PSA data with range in ground motions predicted by the EPRI (2004) ground motion model

7

CHAPTER 7
RESULTS: SHEAR WAVE VELOCITY MEASUREMENTS AT SEISMIC RECORDING STATIONS

This chapter describes the investigation to develop S-wave velocity (Vs) models to a depth of 30 m, or more, and to estimate the average shear wave velocity of the upper 30 m (Vs_{30}) at 33 earthquake recording stations located in the Central and Eastern United States (CEUS) (Figure 7-1 and Table 7-1).

Geophysical techniques utilized during this investigation consisted primarily of active surface wave techniques consisting of spectral analysis of surface waves (SASW) and multichannel analysis of surface waves (MASW-Rayleigh wave, MALW-Love wave). At many locations it also included P-and S-wave seismic refraction to assist in characterizing hard rock sites. None of the sites had sufficient background noise to warrant the use of passive surface wave techniques.

GEOVision managed the investigation using input from the Project Manager, Technical Integration (TI) Team and the NGA-East Project Geotechnical Working Group regarding the seismic recording stations chosen for shear wave velocity measurement. To improve quality and ensure schedule requirements were met, two groups of sites were characterized using two separate surface wave geophysical approaches conducted by GEOVision (GV) and the University of Texas at Austin (UT) independently. The southern-most eleven (11) sites in Alabama, Georgia, Virginia and West Virginia were characterized by UT under subcontract to GV and the remaining twenty-two (22) sites by GV. There were two overlapping sites also characterized by GEOVision. Generally, the UT approach utilized the SASW method; whereas the GV approach included MASW, MALW, and seismic refraction (both P-and S-wave), as necessary and applicable, depending on site conditions. The field investigation was conducted between May 15, 2012 and July 19, 2012.

7.1 Technical Approach

Characterization of S-wave velocity structure at the seismic stations in the CEUS was expected to be quite difficult because many sites have a thin layer of low velocity sediments overlying high velocity rock. In such cases, dominant higher modes are often a significant issue when applying surface wave techniques utilizing Rayleigh waves. To overcome these difficulties, two different strategies were utilized. UT utilized the SASW technique with a vibratory energy source for large receiver spacings and modeling software capable of incorporating the effects of higher mode Rayleigh waves. GeoVision utilized a strategy that incorporated the MASW (Rayleigh wave), MALW (Love wave) and P- and S-wave seismic refraction techniques. The P- and S-wave refraction techniques were expected to be of limited use at sedimentary rock sites, as the seismic refraction technique cannot image velocity inversions that are often present to varying degrees in such environments. However, the seismic refraction surveys were expected to be useful for identifying the depth of the saturated zone and bedrock, maximum seismic velocities in the upper 30 m and to quantify lateral velocity variation. The MASW technique was expected to be effective at sites with a thick sequence of sediments overlying rock and sites with rock at the surface. The MALW technique was expected to be effective at shallow rock sites and sites with steep velocity gradients. Previous investigations have revealed several geologic conditions where the MALW technique can be more effective than the MASW technique at characterizing subsurface velocity structure. These include sites with a thin low velocity sediment layer over much stiffer sediments/rock, shallow rock sites and sites with a steep velocity gradient in rock. At such sites, dominant higher modes and/or superposition of modes are often problematic in Rayleigh wave data, but the fundamental mode is dominant in Love wave data. Multi-mode or effective mode solutions can often adequately model the Rayleigh wave dispersion curve at these types of sites, but fundamental mode inversion of Love wave data is less complicated.

7.2 Discussion and Results

A total of 33 seismic station sites were characterized during this investigation. Eleven (11) of these sites were characterized by UT using the SASW technique and modeling software capable of accounting for the higher mode Rayleigh wave energy often prevalent in the types of geologic environments encountered. The other twenty-two (22) sites were characterized by GV using a combination of techniques including MASW, MALW and P- and S-wave seismic refraction. Two (2) of the sites characterized by UT were also characterized using the procedures deployed by GV (ET.SWET and US.CBN), although the testing arrays were not exactly coincident. Of the twenty-four (24) sites characterized by GV, 16 were characterized by the MALW technique, 4 by the MASW technique and 4 with both the MASW and MALW techniques. The MALW technique was used more extensively than typically applied because geologic conditions at many of the sites consist of a thin, low velocity sediment layer over much higher velocity rock. In such geologic environments, higher mode Rayleigh waves can be dominant over a wide frequency range; whereas, the fundamental mode Love wave is typically dominant. Although multi-mode or effective mode inversion of Rayleigh wave dispersion data can often be effective in these conditions, inversion of the fundamental mode Love wave dispersion data likely has less uncertainty. Velocity models developed by modeling of P-wave and S-wave refraction data were not typically considered to accurately represent subsurface velocity structure at sites consisting of sedimentary rock because the seismic refraction technique cannot detect velocity inversions that are often present in such environments. However, P- and S-wave refraction models were very useful to quantify approximate lateral velocity variation beneath the surface wave arrays; identify the depth and P-wave velocity of the saturated zone, which is preferably constrained during modeling of Rayleigh wave data; determine depth to bedrock and estimate the maximum seismic velocities in the near surface.

The technical approaches used by UT and GV are both considered viable for characterizing sites with the types of velocity structure encountered during this investigation.

The results of this investigation are presented in the individual site reports contained in EPRI Report XXXXXX. Each report generally included the following information:

1. Coordinates (latitude and longitude in WGS84 coordinate system) for:
   1.1. The station (if different from the published data and accessible to a GPS unit).
   1.2. The ends of surface wave and seismic refraction arrays.
2. Photos of field setup, showing instruments and methods, as well as the seismic station.
3. Geophysical methods utilized.
4. Written description of site conditions.
5. Georeferenced site map and geologic map showing testing location(s).
6. Velocity structure plots and tables.
7. Calculated V_{S30} and estimated V_{S30} adjusted for seismic station conditions.
8. Depth of sensors
9. Miscellaneous observations and discussion.

Table 7-2 summarizes the results of the investigation to measure shear wave velocity at seismic recording stations.

7.3 Observations

Based on the investigation conducted including evaluating the results from the shear wave velocity measurements at the overlapping stations (ET.SWET and US.CBN), the following observations are warranted:

- Shear wave velocity for hard rock sites are, in general, below the reference rock velocity of 2800 m/s; Some recording stations had shear wave velocities at about the reference rock velocity at depths greater than 30 m (e.g. PN.PPBLN - Indiana and US.WMOK - Oklahoma).

- Velocity inversions occurred at some sites; Shear Wave Velocity of Layer 1 in the profile can be higher than Layer 2.

- Information on the depth of seismograph emplacement was obtained for the recording stations.

- The geology at the recording stations can be highly variable; Lateral velocity variation is an important issue at many sites; Future investigations may require more testing arrays.

- Different array locations, anisotropy and depth of water table assumed can cause differences when making shear wave velocity measurements.

7.4 USGS Shear Wave Velocity Data

The USGS measured shear wave velocity at seismic recording stations during 2011 and 2012 (Ref XXX). The measurements are based on surface wave dispersion, so the sensor depth in all cases is 0 meters. Figure 7.3-1 shows the location of the USGS Virginia SASW Analysis Stations. Table 7.3-1 provides a summary of the USGS Shear Wave Velocity Results, and Table 7.3-2 provides the USGS site locations.

7.5 Use of Shear Wave Velocity Data

Shear wave velocity data were used for the empirical approach and analytical approaches described in Chapter 6, and then used in Chapters 6 and 8 to evaluate the EPRI (2004) GMM and to develop weights for the GMPEs in the updated GMM.

In the analytical approach, shear-wave velocity profiles at 54 recording sites were considered (33 from this project, supplemented by profiles compiled by the NGA-East project and draft USGS profiles). Because these profiles extend to 30-50 m in depth, they were extended to greater depths using template profiles developed by Silva (2012). Further details on the use of these data are provided in Section 6.2.2.1.

In the empirical approach, recording sites were grouped into four categories based on V_{S30}. For sites with no measured profiles, other data were used, in the following order of priority: V_{S30} estimates compiled by the NGA-East project from the literature, estimates in Atkinson's Engineering Seismology Toolbox (20xx), indirect estimates obtained by Silva et al. (20xx), and estimates based on the NGA-East geological description. Further details on the use of these data are provided in Section 6.2.2.2.

Table 7-1. Locations of Seismic Recording Stations in the Central and Eastern U.S.

SITE LOCATIONS				
Source	**Site**	**Latitude**	**Longitude**	**State**
GV	AG.WHAR	35.29016	-92.28849	Arkansas
GV	ET.SWET (GV)	35.21631	-85.93191	Tennessee
U of T	ET.SWET (UTA)	35.21625	-85.93184	Tennessee
GV-Visual	GS.OK001	35.56117	-97.28998	Oklahoma
USGS	GS.OK002	35.54930	-97.19660	Oklahoma
GV-Visual	GS.OK005	35.65492	-97.19142	Oklahoma
USGS	GS.OK008	35.50710	-97.38380	Oklahoma
USGS	GS.OK009	35.58131	-97.42290	Oklahoma
USGS	GS.OK010	35.62482	-97.22410	Oklahoma
U of T	IU.SSPA	40.63574	-77.88758	Pennsylvania
U of T	NM.CVVA	38.02180	-78.53216	Virginia
USGS	NM.SEAR	35.25469	-91.71469	Arkansas
GV-Visual	NM.SIUC	37.71500	-89.21782	Illinois
GV	NM.UALR	34.77502	-92.34314	Arkansas
USGS	NQ.Q793	37.85470	-77.91680	Virginia
GV-Visual	PE.PSWB	41.30532	-76.01521	Pennsylvania
GV	PN.PPBLN	39.19866	-86.54972	Indiana
GV	PN.PPCWF	40.02212	-86.90712	Indiana
USGS	PN.PPMOO	39.61960	-86.37670	Indiana
USGS	PN.PPPCH	38.36700	-87.58100	Indiana
GV	PN.PPPHS	40.86087	-86.49458	Indiana
U of T	SE.RCRC	37.43205	-79.27186	Virginia
U of T	SE.URVA	37.57093	-77.53572	Virginia
U of T	SE.VWCC	37.24595	-79.97757	Virginia
U of T	US.BLA	37.21148	-80.42044	Virginia
U of T	US.CBN (GV)	38.20369	-77.37487	Virginia
U of T	US.CBN (UTA)	38.20369	-77.37487	Virginia
U of T	US.GOGA	33.41476	-83.47324	Georgia
GV	US.LBNH	44.24028	-71.92612	New Hampshire
USGS	US.LONY	44.61969	-74.58289	New York
U of T	US.LRAL	33.03997	-86.99776	Alabama
GV	US.MIAR	34.54573	-93.57683	Arkansas
U of T	US.MYNC	35.07451	-84.12640	North Carolina
GV	US.NCB	43.97344	-74.22309	New York
GV	US.WMOK	34.73783	-98.78070	Oklahoma

Table 7-2. Shear Wave Velocity Investigation Results

STATION	CREW	STATE	DEPTH OF SENSOR (M)	METHOD	DEPTH OF INVESTIGATION (M)	V_S MAX (M/S)	V_S30 (M/S)	Site Class (NEHRP)	ADJUSTED V_S30 (M/S)
AG.WHAR	GEOVision	Arkansas	1	MALW	30+	2443	1190	B	1403
ET.SWET	UTA- Stokoe	Tennessee	2.5	SASW	44+	2134	715	B	926
ET.SWET	GEOVision	Tennessee	2.5	MALW	40+	2133	840	B	1097
GS.OK001	GEOVision	Oklahoma	Grnd. Floor of School	MALW	30+	1134	595	C	615 [1]
GS.OK002	GEOVision	Oklahoma	Conc. slab in house garage	MALW	30+	964	694	C	725 [1]
GS.OK005	GEOVision	Oklahoma	Ground Floor of School	MALW	30+	1041	596	C	613 [1]
GS.OK008	GEOVision	Oklahoma	Grnd. Floor Spencer City Hall; location has changed	MALW	30+	908	583	C	610 [1]
GS.OK009	GEOVision	Oklahoma	School Bldg.	MASW, MALW	35+	815	306	D	322 [2]
GS.OK010	GEOVision	Oklahoma	Grnd. Floor of Garage	MASW, MALW	40+	1121	576	C	605 [1]
IU.SSPA	UTA-Stokoe	Pennsylvania	Sensor 1 - 0	SASW	41+	1219	939	B	Sensor 1- 939
NM.CVVA	UTA-Stokoe	Virginia	0.6	SASW	46+	1158	581	C	627
NM.SEAR	GEOVision	Arkansas	1	MALW	30+	2128	984	B	1254
NM.SIUC	GEOVision	Illinois	5.5	MALW	35+	1097	491	B/C[6]	762
NM.UALR	GEOVision	Arkansas	Ground Level	MALW	30+	1985	1288	B	1288
NQ.Q793	GEOVision	Virginia	Floor of garage in nearby structure	MALW	35+	1671	367	C	380 [1]
PE.PSWB	GEOVision	Pennsylvania	4	MASW	40+	1220	551	C	649
PN.PPBLN	GEOVision	Indiana	2.5	MALW	30+	2834	1077	A[6]	1982
PN.PPCWF	GEOVision	Indiana	4.5	MALW	30+	1327	466	C	647
PN.PPMOO	GEOVision	Indiana	4	MASW, MALW	35+	957	503	C	587
PN.PPPCH	GEOVision	Indiana	Ground Floor of School	MASW, MALW	30+	1201	428	C	460 [3]
PN.PPPHS	GEOVision	Indiana	2.5	MASW	40+	711	325	D/C	365
SE.RCRC	UTA-Stokoe	Virginia	0.6	SASW	45+	1524	519	C	549
SE.URVA	UTA-Stokoe	Virginia	0.6	SASW	44+	2134	528	C	563
SE.VWCC	UTA-Stokoe	Virginia	Ground Level	SASW	45+	1219	357	D	357
US.BLA	UTA-Stokoe	Virginia	0.6	SASW	45+	1524	700	B	789
US.CBN	UTA-Stokoe	Virginia	6	SASW	59+	488	251	D	274
US.CBN	GEOVision	Virginia	6	MASW	40+	412	249	D	269
US.GOGA	UTA-Stokoe	Georgia	0.1	SASW	45+	671	296	D	299
US.LBNH	GEOVision	New Hampshire	1	MALW	30+	1891	850	B	1043
US.LONY	GEOVision	New York	1.1	MALW	30+	2488	1100	B	1425 [4]
US.LRAL	UTA-Stokoe	Alabama	0.1	SASW	43+	914	568	C	573
US.MIAR	GEOVision	Arkansas	1	MALW	35+	2662	1090	B	1295
US.MYNC	UTA-Stokoe	North Carolina	0.3	SASW	33+	1219	495	C	522
US.NCB	GEOVision	New York	1	MALW	30+	2064	1002	B/A	1503 [4]
US.WMOK	GEOVision	Oklahoma	0.5	MASW	35+	2755	1642	A	1859

1. Vs30 estimated after replacing the velocity of the upper layer with that of the underlying layer to account for the sensor being located in a structure on engineered fill
2. Vs30 estimated after replacing the velocity of the upper two layers with that of the underlying layer to account for the sensor being located in a structure on engineered fill
3. Vs30 assuming that the minimum VS beneath the building housing the seismic station is 200 m/s
4. Vs30 between 1 and 31 m to account for the sensor being about 1m deep and on rock)
5. Maximum Vs of recommended model
6. Based on adjusted Vs30

Table 7.3-1. Shear Wave Velocity Results – USGS Stations

STATION	DEPTH OF INVESTIGATION FORWARD (m)	DEPTH OF INVESTIGATION MANUAL (m)	Vs MAX (m/s) FORWARD	Vs MAX (m/s) MANUAL	Vs30 (m/s) FORWARD	Vs30 (m/s) MANUAL	Site Class (NEHRP)	AVERAGE Vs (m/s) for ENTIRE PROFILE FORWARD	AVERAGE Vs (m/s) for ENTIRE PROFILE MANUAL	DATE
935RES	38.406	41.680	821.335	634.000	340.80	364.00	D	381.80	413.10	12/08/2012
936CBN	63.767	65.280	364.283	389.000	269.00	279.50	D	312.00	320.10	12/08/2012
938MAR	41.809	49.420	828.478	1133.000	371.60	388.90	C	436.70	481.80	04/24/2012
939PAG	35.653	42.960	324.681	242.000	430.80	525.30	C	352.80	361.80	04/25/2012
940MVL	68.502	46.840	2735.121	2107.000	720.10	671.50	C	1181.80	873.10	04/25/2012
941PSB	45.881	49.750	1336.407	1243.000	352.90	391.20	C	452.40	515.10	04/26/2012
942DXL	59.344	50.490	1855.529	1588.000	617.10	609.10	C	870.60	781.00	04/27/2012
943WNC	44.053	49.750	690.059	664.000	353.40	357.30	C	403.00	425.90	04/28/2012
944MIN	71.309	80.590	1099.316	959.000	525.90	606.80	C	713.00	738.00	04/28/2012
945JSR	33.660	35.480	786.416	916.000	480.60	476.60	C	501.80	514.80	04/28/2012
946CMB	64.733	65.270	864.810	959.000	371.40	362.00	C	499.90	488.40	04/29/2012
947UVR	49.980	49.970	748.604	758.000	351.30	358.90	D	429.40	449.70	04/29/2012
948LWR	65.822	66.300	964.436	1096.000	328.50	325.40	D	498.50	498.10	04/30/2012
949NQ1	48.784	50.510	2099.811	2043.000	648.00	655.40	C	855.60	881.90	04/30/2012
950PRB	30.000	30.000	882.967	824.000	522.90	497.90	C	522.90	497.90	06/11/2012
951ETU	30.000	30.000	1810.456	1171.000	710.90	633.20	C	710.90	633.20	06/13/2012
952ASH	42.200	49.370	720.520	788.000	359.10	357.50	D	418.30	443.50	06/13/2012
953TZN	31.000	31.200	1168.270	1376.200	708.50	713.50	C	717.60	726.90	06/13/2012
954SAL	30.000	30.540	1491.585	1340.000	396.20	431.20	C	396.20	436.50	06/14/2012
955WM	64.169	69.980	1010.687	1095.000	346.10	341.50	D	483.60	501.60	06/15/2012
956PRZ	64.169	68.690	1020.507	1052.000	342.30	334.30	D	479.90	486.60	06/15/2012
957SI	79.949	82.390	609.440	628.000	274.70	271.80	D	392.50	396.80	06/25/2012
958NNC	65.121	68.100	424.874	417.000	296.10	285.90	D	334.90	332.00	06/26/2012
959MWV	37.523	39.730	2992.381	2379.000	1465.30	1483.40	B	1632.40	1645.10	06/27/2012

Table 7.3-2. USGS Station Locations

STATION	LATITUDE	LONGITUDE	LOCATION	CITY, STATE	OPERATOR
935RES	38.950500	-77.336140	935RES-Reston Fire Station	Reston, VA	NSMP, 2555
936CBN	38.203610	-77.372810	USGS CORBIN Observatory, USGS	Fredericksburg, VA	ANSS Backbone, USCBN
938MAR	39.416410	-77.907072	Martinsburg VA Hospital, WV Martinsburg; VA Medical Center	Martinsburg, WV	NSMP, 2511
939PAG	40.227100	-76.723200	939 Penn. Geological Survey	Harrisburg, PA	GSPA, PAGS
940MVL	39.999200	-76.350600	Millersville Univ.	Millersville, PA	Lamont-Doherty, MVL
941PSB	39.926960	-75.451200	Penn State Univ.	Brandywine, PA	GSPA, PSUB
942DXL	39.957100	-75.189600	Drexel University Lancaster Ave; Hess Engineering Bldg	Philadelphia, PA	NSMP, 2648
943WNC	38.930095	-77.070600	Washington National Cathedral	Washington, DC	NetQuakes, WNC WNC_NQ_01
944MIN	38.028310	-77.840450	Mineral; B&B Contractors	Mineral, VA	NSMP, 2560
945JSR	37.695200	-77.879800	J. Sargent Reynolds C.C.	Richmond, VA	Virginia Tech, JSRW
946CMB	37.488100	-78.256300	Cumberland Fire station, Volunteer Rescue Squad	Cumberland, VA	NSMP, 2558
947UVR	37.570900	-77.534000	University of Richmond, VA	Richmond, VA	Virginia Tech, URVA
948LWR	38.077120	-77.750080	Mineral Area - Lake Anne, VA	Lake Anne, VA	NetQuakes, GS.LWRD
949NQ1	38.936000	-77.332000	USGS National Headquarters	Reston, VA	NetQuakes, RestonUSGS NQ1
950PRB	37.327500	-80.734500	Pearisburg; Giles County Courthouse	Pearisburg, VA	NSMP, 2549
951ETU	36.307000	-82.379510	Eastern Tennessee State Univ. Mountain Home VA Center	Johnson City, TN	NSMP, 2405
952ASH	35.591200	-82.484400	Charles George Va Hospital, Oteen; Va Medical Center	Ashville, NC	NSMP, 2510
953TZN	36.543300	-83.550400	Tazwell, TN TZTN	Tazwell, TN	USGS, USTZTN
954SAL	35.685100	-80.488800	Salisbury, NC Hefner VA Hospital Site	Salisbury, NC	NSMP, 2506
955WM	38.888500	-77.034600	Washington Monument, Sylvan Stage, East Ellipse	Washington, DC	Washington Monument NAMA ,
956PRZ	38.895200	-77.039400	Presidents Park, Ellipse, White House-Ellipse Park	Washington, DC	NetQuakes, CAPTL
957SI	38.841975	-76.940730	Smithsonian Institution, Museum Support Facilities	Suitland, Maryland	Mineral, Virginia Site Response,
958NNC	35.239800	-77.890600	Cliffs of Neuse Park, 958NNC USCNNC seismometer	Goldsboro, NC	ANSS Backbone, USCNNC
959MWV	39.658000	-79.846000	Geological Survey of West Virginia	Morgantown, WV	ANSS Backbone, USMCWV

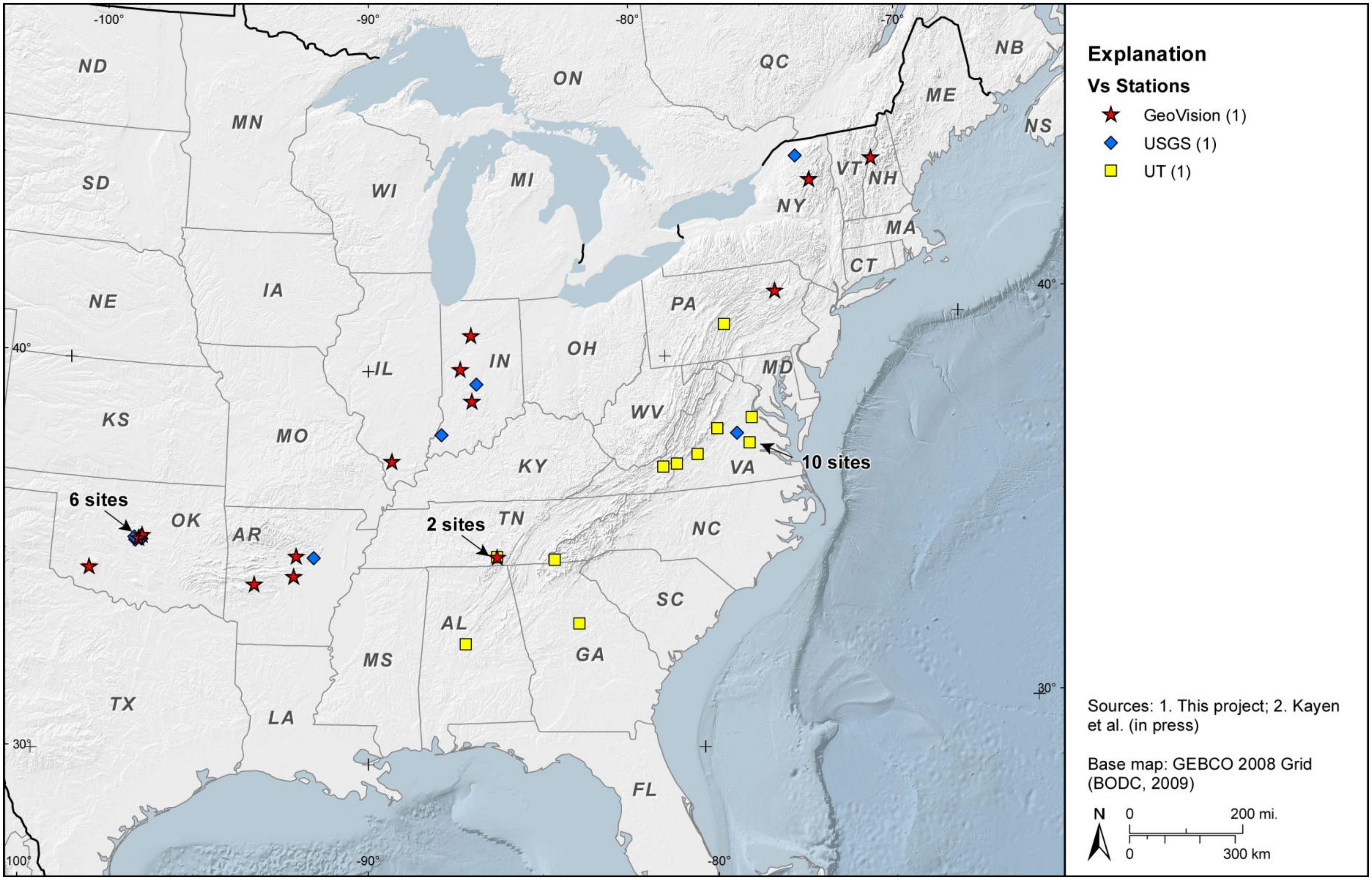

Figure 7-1. Locations of Seismic Recording Stations in the Central and Eastern U.S.

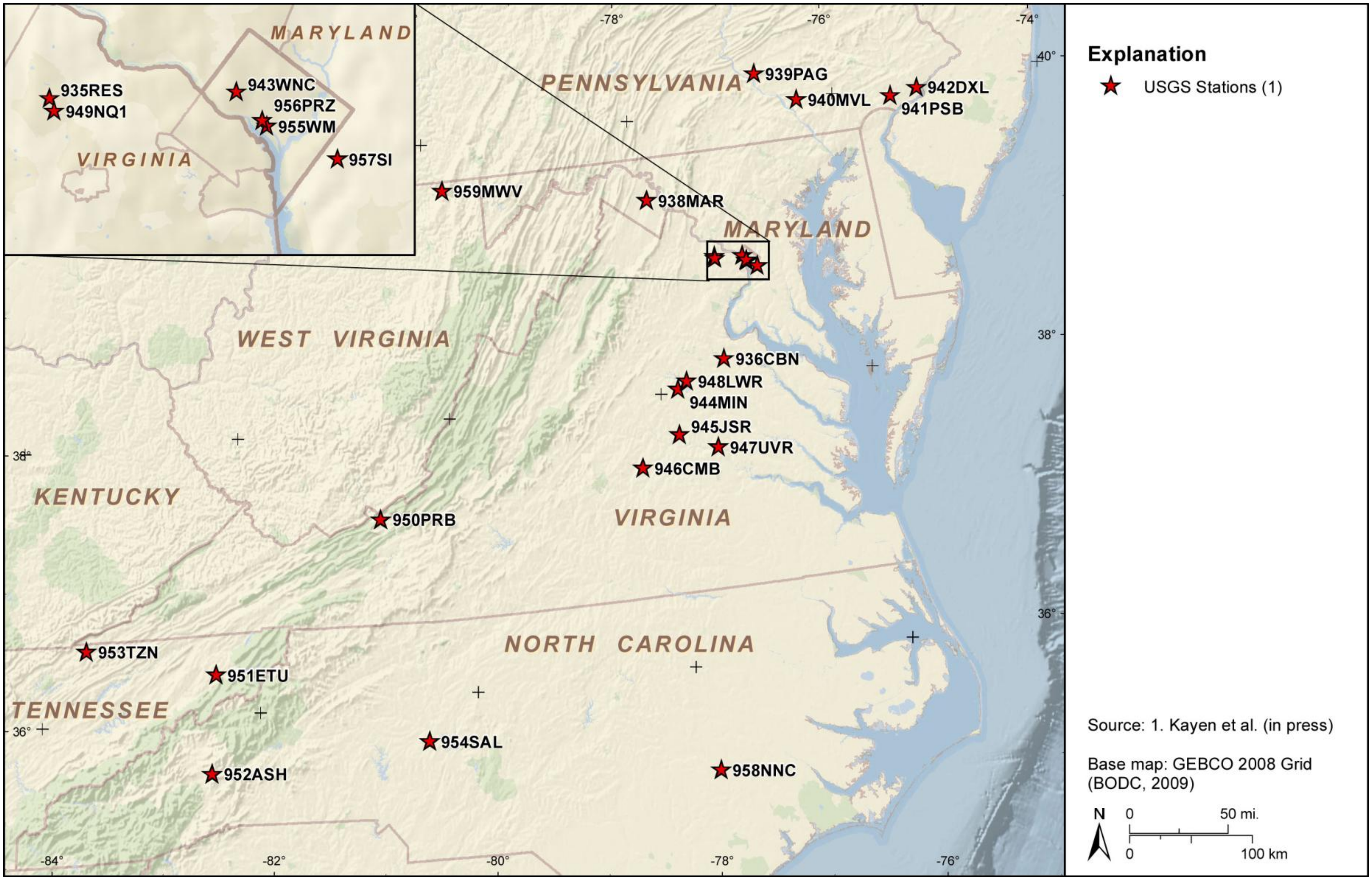

Figure 7.3-1. Locations of USGS Virginia SASW Stations

8
CHAPTER 8
RESULTS: UPDATED EPRI (2004, 2006) GROUND-MOTION MODEL

8.1 Development of Final Ground-Motion Database

The ground motion database presented in Section 6.1.1 was updated for us in formulating the updated ground motion model. The updates included the addition of the final set of shear wave velocity measurements obtained during the project and the use of V_{S30} values for additional sites from the Engineering Seismology Toolbox (www.seismotoolbox.ca) developed by Dr. Gail Atkinson and her co-workers. Review of the distribution of estimated and measured V_{S30} values suggested that a more logical break point between the hard rock and intermediate rock categories would be at a V_{S30} value of 1,890 m/s as there were a number of sites with V_{S30} values just below 2,000 m/s. The site classification data were also reviewed and the final site categories assigned using the following updated criteria.

Final Rock Site Category Criteria

Rock Site Category	Criteria
Hard Rock	Class A or B $V_{S30} \geq 1{,}890$ m/s
Intermediate Rock	Class A or B with $1{,}000 \leq V_{S30} < 1{,}890$ m/s or Class A with unknown V_{S30}
Soft Rock	Class A or B with $500 \leq V_{S30} < 1{,}000$ m/s or Class B with unknown V_{S30}

Figure 8.1-1 shows the magnitude-distance distribution for the recordings in the assembled ground motion database. The plot on the left shows the available data for 10 Hz PSA and the plot on the right shows the available data for 1 Hz PSA. Table 8.1-1 lists the numbers of recordings of each rock category in the magnitude and distances ranges used in performing the assessments of the candidate GMPEs. Comparison of these results with those shown presented in Section 6.1.1 indicates that there has been a large increase in data assigned to hard rock sites.

The updated ground motion database was tested using the approach described in Section 6.2.2 to see if there was an improvement of the correlation between ground motion amplitude and the site catagories. The residuals for the four EPRI (2004) cluster median GMPEs were refit using

Model 1 (Equation 6.2.2-1) and Model 2 (Equation 6.2.2-2) using the updated database site classifications. Figures 8.1-2 through 8.1-5 show the resulting fitted coefficients. Comparison of these results with those shown in Figures 6.2.2-5 through 6.2.2-8 indicate that the rock site category scaling coefficients C_{IR} and C_{SR} are better determined (narrower conficence intervals). The soft rock scaling coefficient C_{SR} is statistically significant for many cases while the 90 percent condifence interval for the intermediate rock coefficient C_{IR} often spans zero. Results of appling the AIC and BIC tests again showed the use of Model 2 does not produce a statistically better fit to the residuals compared to Model 1 for many cases. However, the use of Model 3 (Equation 6.2.2-3) with only scaling for soft rock did result in an improvement in fitting the residuals (lower AIC and BIC scores) compared to Model 1 without scaling for site category. It may be that the lack of significance of the intermediate rock scaling coefficient is due to the difficulty in correctly categorizing the recording sites given the available information.

Based on the result that significant correlation of the residuals with the soft rock category was found, Model 3 (Equation 6.2.2-3) was used for the empirical site corrections in the analyses of the candidate GMPEs.

8.2 Technical Bases for Ground-Motion Predictions Equations and Development of Final Clusters

8.2.1 Selection of Candidate GMPEs and Specification of Cluster Groupings

Candidate GMPEs

Section 6.1.2 described the process for identification and selection of well-supported CEUS GMPEs that were developed since completion of the technical work that led to EPRI (2004), and summarizes the main features of these GMPEs. In addition, the Resource Experts that were contacted (see Appendix C) were asked to indicate which of the EPRI (2004) GMPEs have not been superseded, retain technical validity, and should be be considered in conjunction with the new GMPEs. The following GMPEs in each EPRI (2004) Cluster were identified as valid by the Resource Experts:

- EPRI (2004) Cluster 1: Single-corner Stochastic Models. Two versions of the Silva et al. (2002) single-corner GMPE, namely the Single-Corner Constant Stress with Saturation (SSCCSS), and the Single-Corner Variable Stress (SSCVS) were identified as retaining technical validity. Furthermore, it was felt that it was important to retain these two alternative models for scaling at higher magnitudes as a way to represent epistemic uncertainty. The corresponding GMPEs in Silva et al. (2003), which are nearly identical to these 2002 versions, were considered instead of these two. In addition, the Frankel et al. (1996) and Toro et al. (1997) single-corner stochastic models were also considered to retain technical validity.
- EPRI (2004) Cluster 2: Double-corner Stochastic Models. One version of the Silva et al. (2002) double-corner GMPE, namely the Double-Corner Variable Stress (SDCVS) was identified as retaining technical validity. As was the case for the Silva et al. (2002) single-corner models, the nearly identical 2003 version was used instead

- EPRI (2004) Cluster 3: Hybrid Empirical Models. The three hybrid-empirical models in EPRI (2004) are considered to be superseded.
- EPRI (2004) Cluster 4: Finite Source/Green's Function Models. The one model in this cluster, namely the Somerville et al. (2001) is still considered to be valid. In particular, this model has unique seismological features and no similar model has been developed that would supersed it. This model produces two slightly different GMPEs for rifted and non-rifted sources (the difference arises as a result if differences in the depth distributions). Both GMPEs will be used.

Definition of GMPE Clusters

The project TI Team concluded that maintaining the EPRI (2004) strategy of grouping the alternative GMPEs into clusters of similar GMPEs, and then assigning weights using a two-stage approach, provides a convenient mechanism for quantifying the central tendency and epistemic uncertainty in ground-motion amplitude. The rationale for defining these clusters is provided below.

The decision to maintain the structure of Clusters 1 and 4 is a natural one, although the updated Cluster 1 contains a subset of the EPRI (2004) GMPEs. The definition of the other clusters is less obvious. After comparing the behavior of the various GMPEs not in Clusters 1 and 4, it was decided to define two additional clusters (which we call Clusters 2 and 3, but are un-related to Clusters 2 and 3 of EPRI, 2004) and to make geometrical spreading within the first 100 km the defining characteristic for the un-assigned GMPEs. The resulting updated clusters and the assignment of GMPEs to these clusters are given in Table 8.2.1-1. This table also shows the abbreviated names for these GMPEs, which will be used throughout this chapter.

8.2.2 Consideration of Arkansas and Oklahoma Earthquakes

A question was raised during project review about the possibility that the earthquakes that have occurred in central Arkansas and Oklahoma have lower stress drops that other earthquakes occurring within the Mid-Continent region of CENA. This question was investigated by computing event terms for individual earthquakes using the residuals for three of the candidate CENA GMPEs fit using the empirical site scaling Model 3 (Equation 6.2.2-3). Figures 8.2.2-1, 8.2.2-2, and 8.2.2-3 show the results of the analyses using the Atkinson (2008) referenced empirical GMPE as updated by Atkinson and Boore (2011), designated A08', the Atkinson and Boore (2008) GMPE as updated by Atkinson and Boore (2011), designated AB06', and the Pezeshk et al. (2011) GMPE, designated "PZT". Each figure shows the results for the six structrural frequencies analyzed: 0.5, 1, 2.5, 5, 10, and 25 Hz. The solid circles show the calculated event term for the individual earthquakes computed using linear mixed effects. The vertical lines denote approximate 90 percent confidence intervals for the event terms. The event terms for the central Arkansas and Oklahoma earthquakes are denoted by light and dark blue, respectively, and those for the remaining CENA earthquakes by red.

Consistent results were obtained for all three models. For 25 Hz PSA residuals, the event terms for the central Arkansas and Oklahoma earthquakes are lower on average than for the remaining earthquakes. However, as the structural frequency decreases, the difference between the central Arkansas and Oklahoma earthquakes and the other CENA earthquakes disappears.

The statistical significance of the difference seen for 25 Hz was tested by adding an indicator variable for the central Arkansas and Oklahoma earthquakes that allows for an average difference from the remaining CENA earthquakes. For 25 Hz, this augmented model produce a better fit to the residuals (lower AIC and BIC scores). However, for 10 Hz, the augment model produced only a marginally better fit (lower AIC score, but higer BIC score). At lower frequencies, the augmented model did not produce a better fite (both AIC and BIC scores were higher).

The central Arkansas and Oklahoma earthquakes occurred at shallower depths than the majority of the other CENA earthquakes. Some recent empirical GMPEs for active tectonic regions have included an effect of increasing ground motion with increasing depth (e.g. Abrahamson and Silva, 2008; Chiou and Youngs, 2008). Figure 8.2.2-4 plots the 25 Hz event terms for the three GMPEs versus hypocentral depth. The 25 Hz residuals were then fit with Model 3 augmented by a term linear in depth. The results of applying this model were mixed. No improvement was found for he A08' model (higher AIC and BIC scores), an improvement was found for the AB06' model (lower AIC and BIC scores), and mixed results were found for the PZT model (lower AIC, higher BIC).

Besides a depth effect, the lower high frequency motions for the central Arkansas and Oklahoma earthquakes could be the result of two factors, lower earthquake stress drop or higher site kappa in that region. Lower stress drop may correlate with shallower depth or it may be systematic in the region. It is also expected that the effect of lower stress drop might affect a broader frequency range than the effect of higher kappa.

The results of these analyses did not produce a conclusive answer. Therefore, the analyses of the candidate GMPEs using the CENA ground motion database considered two alternatives, one in which all earthquake data were used to GMPE weighting and one in which the data from the central Arkansas and Oklahoma earthquakes were excluded.

8.2.3 Approach for the Calculation of Within-Cluster Weights

Rationale and Mathematics of the Weighting Approach

This approach assigns weights to the GMPEs in a cluster based on each GMPE's consistency with the data. The approach is similar in spirit to that used in EPRI (2004), but more refined mathematically. It accounts for the following factors:

- Intra-event correlation. Records from the same earthquake are correlated because they share the same source characteristics. The presence of this positive correlation makes the data less informative than they would be if they were independent.
- Uncertainty in the soil correction. Records obtained at the same site are correlated in the sense that each particular site has a tendency to consistently over- or under-predict

amplitudes, relative to a typical site. The presence of this positive correlation makes the data less informative than they would be if they were independent.

- Weights that depend on magnitude and distance, to account for the engineering importance and diagnostic power of data in the various M-R ranges.
- Sensitivity to sample size. Weights should be sharp if data are abundant and should be less definitive (i.e., closer to uniform) if data are scarce.
- Incorporation of subjective weight to GMPEs within a cluster, in order to down-weight GMPEs that may be almost identical and do not represent independently developed models.
- The ability to combine weights calculated for difference frequencies, as well as weights obtained using different modeling approaches or assumptions, in a consistent manner.

The calculation of weights for a particular frequency, cluster, and approach for adjusting to site conditions works with the ground-motion residuals for each GMPE. The residual associated with the *i*-th GMPE, the *j*-th earthquake, and the *k*-th station is represented as ε_{ijk} and is calculated as

$$\varepsilon_{ijk} = \ln[\mathrm{Ampl}_{ijk}]_{\mathrm{observed}} - \ln[\mu_{ijk}] \tag{8.2.3-1}$$

where $\mu_{ijk} = \mu_i(M_j, R_{jk})$ is the amplitude predicted by the i-th GMPE for event with magnitude M_j and distance R_{jk}.

The approach used in this project works with the likelihood of the observed residuals given model i, which is closely related to the inverse sum of squared residuals used the EPRI (2004) approach, but provides more flexibility to include effects such as the uncertainty in site correction, and has a stronger basis in theory (as discussed by Scherbaum et al., 2009). The development of this approach is provided below.

Assume first (for the sake of explanation) that the recordings are all obtained at sites with properties identical to the reference site, so that no site adjustment is necessary and there is no uncertainty in the value of the adjustment factor. In this hypothetical case, one can write

$$\varepsilon_{ijk} = \ln[\mathrm{Ampl}_{ijk}]_{\mathrm{observed}} - \ln[\mu_{ijk}] = \delta B_j + \delta W_{jk} \tag{8.2.3-2}$$

where δB_j represents between-event variation (with standard deviation τ) and δW_{jk} represents within-event station-to-station variation (with standard deviation ϕ). Because all recordings are obtained at real sites, with characteristics different from those at the reference site, the uncertainty in the site adjustment must be considered, obtaining

$$\varepsilon_{ijk} = \ln[\mathrm{Ampl}_{ijk}]_{\mathrm{adjusted\ observation}} - \ln[\mu_{ijk}] = \delta B_j + \delta W_{jk} + \delta C_{jk} \tag{8.2.3-3}$$

where δC_{jk} represents uncertainty in the value of the ln[Adjustment Factor] to reference rock for earthquake j and station k (with standard deviation $\sigma_{C,jk}$, which was computed as described in Section 6.2)[1].

To calculate the standard deviation of each epsilon term, one can use the values of τ and ϕ adopted by this project, which are documented in Section 8.8, as the site-adjustment standard deviation $\sigma_{C,jk}$, which was computed for each recording in Section 6.2. Furthermore, epsilon values from the same earthquake are correlated because they share a common δB_j term. Using the information in Eq. 8.2.3-3, one can calculate the equation for the covariance between any two residuals as follows:

$$Cov\left[\varepsilon_{ijk}, \varepsilon_{irs}\right] = \tau^2 \delta_{jr} + \phi^2 \delta_{jr} \delta_{ks} + \sigma_{C,jk} \sigma_{C,rs} \delta_{ks} \tag{8.2.3-4}$$

where δ_{xy} is the Kronecker delta (equal to 1 if the two indices are equal, equal to 0 if they are different).

In words, the covariance matrix between two epsilons is the sum of three terms. The first term is equal to τ^2 if both residuals are associated with the same earthquake and zero otherwise, the second term is equal to □^{2} between a residual and itself (same earthquake, same station) and zero otherwise, and the third term is equal to $\sigma_{C,jk}\sigma_{C,rs}$ if both residuals are associated with recordings at the same station and zero otherwise.

For brevity in notation, all the residuals associated with one GMPE are arranged into a column vector $\boldsymbol{\varepsilon}_i$ and all the associated covariances are arranged into a square covariance matrix $\boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}$.

Using the epsilon vector for the i-th GMPE, and using the standard assumption of joint normality of the residuals, the likelihood function of the observations given the GMPE takes the form

$$L(\boldsymbol{\varepsilon}_i) = \exp\left(-\frac{1}{2}\boldsymbol{\varepsilon}_i{}^T \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}{}^{-1} \boldsymbol{\varepsilon}_i\right) \tag{8.2.3-5}$$

where constant terms that do not depend on the data or on the specific GMPE have been omitted. Using the likelihood functions for all GMPEs in the cluster, one can compute the weight for each GMPE as

[1] Note that the standard deviation of δC_{jk} for a given station is, in general, different for different earthquakes. Consider, for instance a frequency of 25 Hz and recordings from a nearby earthquake and a very distant one. The 25-Hz spectral acceleration is more sensitive to kappa for the nearby earthquake than for the distance one, resulting in a higher standard deviation for the nearby earthquake. A related issue is whether the δC_{jk}'s for two recordings at the same station should be treated as fully correlated. This project assumes full correlation.

$$w_i = \frac{L(\boldsymbol{\varepsilon}_i)}{\sum_i L(\boldsymbol{\varepsilon}_i)} \tag{8.2.3-6}$$

This exponential form in the likelihood has a similar behavior to the EPRI (2004) approach, in the sense that larger squared residuals lead to lower weights. They differ in the sense that the likelihood-based approach uses a negative-exponential functional form rather than reciprocals of sums of squares, in the sense that the covariance matrix contains scale information (i.e., residuals smaller than the corresponding standard deviation incur a low penalty, regardless of the size of other residuals), in the sense that within-event correlation is handled in a manner that is more efficient statistically (similar to the random-effect formulation of Abrahamson and Youngs (1992), and in the sense that the record-specific values of σ_C are easily handled. In Cluster 1, the weights obtained for the two Silva et al. (2003) GMPEs are halved and then all the weights are re-normalized. Effectively, these two GMPEs are counted as one GMPE because they have many elements in common.

In practice, some magnitude-distance combinations are more important than others, because they differ in engineering significance and diagnostic power. To adjust the importance of the data as a function of magnitude and distance, the data for each frequency are partitioned into six magnitude-distance bins, the calculation of weights (eqs. 8.2.3-5 and 8.2.3-6) is performed separately for each bin, and then the results are combined according to the bins' importance and sample size, as described below.

The first step in adjusting for each bin's importance is to assign an importance factor *t* to each bin (using different importance factors for high and low frequencies, the factors for low frequencies are given in parentheses), as follows:

	M 3.75 to 4.75	**M** 4.75 and greater
Rjb 0 to 70 km	1/ 4 (1/4)	**1 (1)**
Rjb 70 to 150 km	1/12 (1/4)	1/3 (1)
Rjb 150 to 500 km	1/24 (1/4)	1/6 (1)

A further adjustment is necessary because the low-magnitude and large-distance bins may contain much more data than the more interesting bins, which may have the undesirable effect of a less important bin controlling the calculation of weights (despite having a lower importance factor).[2] This adjustment is made by multiplying each bin's importance factor t_{MR} by the quantity $\max(n'_{>4.75,0-70}/n'_{MR}, 1)$, resulting in $t'_{MR} = t_{MR} \times \max(n'_{>4.75,0-70}/n'_{MR}, 1)$, where n'_{MR} is the equivalent sample size in an arbitrary magnitude-distance (MR) bin and $n'_{>4.75,0-70}$ is the

[2] As a sensitivity test, the TI Team considered the effect of giving zero weight to the M < 4.75 data. The effect of this change was found to be small.

equivalent sample size in the most important bin. The equivalent sample size is the numer of residuals in the bin, reduced by the effect of correlation, and is given by the equation

$$n'_{MR} = n_{MR} \frac{\mathrm{Tr}(\Sigma_{MR})}{\mathbf{1}^T \Sigma_{MR} \mathbf{1}} \qquad (8.2.3\text{-}7)$$

where Σ_{MR} is the covariance matrix of the residuals contained in an arbitrary MR bin, Tr( ) denotes the trace of this matrix, n_{MR} is the number if residuals in the bin, and **1** is a unit column vector of size n_{MR}.

To combine the weights for all bins, the weights for each bin are raised to the power t'_{MR} and then multiplied over all the bins, and finally normalized so the weights for all GMPEs add to unity. So, the combined weight for the *i*-th GMPE is give by

$$w_i = \alpha \prod_{MR} w_{i,MR}{}^{t'_{MR}} \qquad (8.2.3\text{-}8)$$

where α is a normalizing constant so that the weights for all GMPEs in the cluster add to unity.

In the above calculation, raising weights to a power smaller than unity is equivalent to reducing the sample size in the bin, effectively making the residuals in the bin less influential for the purposes of calculating weights. Similarly, the multiplication of weights from different bins is consistent with the way likelihoods from independent data are combined[3].

Weights are calculated separately for different frequencies using the approach described below. Then, the weights for all high frequencies (5, 10, and 25 Hz) are combined into one weight and the weights for all low frequencies (0.5, 1, and 2.5 Hz) are combined into another. The steps for the combining the high-frequency weights are as follows: (1) multiply the 25 Hz, 10 Hz, and 5 Hz weights for each GMPE; (2) raise each weight to a power of 0.446; and (3) normalize the weights. The steps for combining the low-frequency weights are identical. The power of 0.446 accounts for the correlation between spectral accelerations at these three frequencies, and is calculated using the correlation coefficients of Baker and and Jayaram (2008)[4] and similar arguments of equivalent sample size.

All the manipulations of weights described so far use multiplication, together with exponentiation to adjust for importance or correlation. As indicated earlier, this is consistent with the way likelihoods from different data sets are combined. The remaining two steps are done

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[3] By simply multiplying bin weights, one is effectively ignoring that there is some correlation between the residuals in separate bins. Consideration of this correlation would be difficult and its effect is likely small.

[4] The correlation coefficients by Baker and Jayaram are modified to account for WUS-CEUS differences in frequency content by assuming that the contours in their Figure 4b remain parallel to each other between 10 and 25 Hz.

arithmetically because these steps involve alternative interpretations or adjustments of the same data set.

The next combination step consists of averaging (using equal weights) the GMPE weights obtained with the analytical and empirical adjustments for site conditions. The TI Team gives equal weights to the two approaches. On the one hand, the analytical approach has the advantage that it uses more information. On the other hand, this information is available for only a fraction of the recording sites and the empirical approach can make use of many more recordings. By using both approaches, the final results are more robust.

The final combination step consists of averaging (using equal weights) the GMPE weights obtained with and without the data from earthquakes in Oklahoma and Arkansas that were discussed in Section 8.2.2. The TI Team gives equal weights to the hypotheses that these earthquakes have source characteristics that are (or are not) representative of CEUS seismic sources.

8.2.4 Development of Within-Cluster Epistemic Uncertainty

The EPRI (2004) study developed a representation of the within-cluster epistmic uncertainty by combining three sources of uncertainty. The first factor was model-model variability of the weighted models within a cluster. The model to model standard error, $\sigma_{\text{model-to-model}}$, is computed using Equation 8.2.4-1.

$$\sigma(m,r,f)_{\text{model-to-model}} = \left\{ \sum_i w_i \times \left(\ln\left[z_i(m,r,f) / \hat{z}(m,r,f) \right] \right)^2 \Big/ \sum_i w_i \right\}^{1/2} \qquad (8.2.4\text{-}1)$$

In Equation 8.2.4, $z_i(m.r.f)$ is the median ground motion prediction for the i^{th} GMPE amd $\hat{z}(m,r,f)$ is the weighted mean log ground motion prediction for the models in the cluster obtained by:

$$\hat{z}(m,r,f) = \sum_i w_i \times \ln\left[z_i(m,r,f) \right] \Big/ \sum_i w_i \qquad (8.2.4\text{-}2)$$

The second source was as assessment of the parametric uncertainty in the parameters used in the development of the individual models. This uncertainty was separated in a source part and a path part and separate parametric uncertainty analyses were used to assess σ_{source} and σ_{path}. Examples of the parametric source uncertainty are uncertainty in the median stress drop (stress parameter) used in the single-corner stochastic models and examples of the path uncertainty are uncertainty in the Q model used in assessing distance attenuation.

The third source of uncertainty was the standard error from fitting the cluster median ground motions with an algebraic function form. The composite epistemic uncertainty for the cluster median model was then obtained by summing the variances assuming all of the sources of uncertainty are independent.

$$\sigma(m,r,f)_{\text{clustermedian-2004}} = \begin{Bmatrix} \sigma^2(m,r,f)_{\text{model-to-model}} + \sigma^2(m,r,f)_{\text{source}} + \\ \sigma^2(m,r,f)_{\text{path}} + \sigma^2(m,r,f)_{\text{median fit}} \end{Bmatrix}^{1/2} \qquad (8.2.4\text{-}3)$$

For this study, the above approach was modified for the following reasons.

First, the concept of independent source and path parameteric uncertainties was not used. One issue with this approach is that the assessment of source and path terms are often dependent upon each other, requiring that a joint distribution for the variability be defined that properly accounts for correlations. Secondly, some of the candidate models do not lend themselves readily to assessment of parametric uncertainties. For example, the Atkinson (2008) referenced empirical model uses fits of residuals for CENA ground motion data from the Boore and Atkinson (2008) active tectonic region GMPE to produce to a CENA GMPE. Representing the epistemic uncertainty in this model should be based on the uncertainty in the Boore and Atkinson (2008) GMPE and the statistical uncertainty in the fitting of the residuals. Defining parameteric uncertainty for finite fault simulation models is also difficult. EPRI (2004) applied the single corner stochastic model source uncertainty to more complicated models as a surrogate estimate, but that becomes more problematic as the complexity of the underlying ground motion prediction approach expands.

Secondly, the greatly expanded CENA ground motion database available for use provides the ability to make an assessment of how well medain ground motion estimates are constrained by data. This uncertainty was assessed by calculating the standard error in the distance-dependent mean model residual, using the analytically adjusted residuals for **M**>3.75, and taking correlation into account by means of the covariance matrix introduced in Section 8.2.3. The mean residual is taken as constant for distances less than 10 km, piece-wise linear (in log-distance – log-amplitude space) with hinges at 10, 70, and 150 km, and linear (in distance – log-amplitude space) between 150 and 500 km. The third minor change was to ignore the contribution of the standard error in fitting the cluster medians. As will be shown below in Section 8.4, the cluster median ground motions are well fit by the chosen algebraic forms such that the standard error of the fit has a neglible contribution to the overall uncertainty.

The model-to-model variability was retained as it remains an important source of epistemic uncertainty. The overall cluster median epistemic uncertainty was taken to be the envelope of the model-to-model standard deviation, $\sigma_{\text{model-to-model}}$, and the data-based estimate of the standard deviation of the median, $\sigma_{\text{data constraint}}$:

$$\sigma(m,r,f)_{\text{clustermedian-2013}} = \max\left\{\sigma^2(m,r,f)_{\text{model-to-model}}, \sigma^2(m,r,f)_{\text{data constraint}}\right\} \qquad (8.2.4\text{-}4)$$

The reason for taking the envelope (instead of the sum) of these two variances is that they represent different manifestations of the same epistemic uncertainty.

8.2.5 Development of Cluster Weights

Following EPRI (2004), the approach for the calculation of cluster weights takes into account consistency with the data, as well other more subjective factors. The portion of the weights that measure consistency with the data are calculated using the residuals between the adjusted recordings and the median GMPEs from the various clusters, following the same approach described in Section 8.2.3 for within-cluster weights.

The subjective portion of the weight takes into account the TI Team's judgment regarding the Cluster's robustness and ability to extrapolate properly from the available recordings to the magnitude-distance combinations of engineering interest. The purpose is to assign more weight to the Clusters that are judged to be more robust, rather than rewarding scientific merit or elegance. Section 8.7 provides details on this process.

8.3 Calculation of Within-Cluster Weights

8.3.1 Weights Obtained with Analytically Adjusted Recordings

(Text to be added later.)

8.3.2 Calculation of Within-Cluster Weights Based on Empirical Site Adjustments

The calculation of within-cluster weights based on empirical site adjustments followed the general procedure descrined in Section 8.3 using analytical site corrections. The first step was to compute the residuals for the rock site database described in Section 8.1 using each of the candidate GMPEs. Figures 8.3.2-1a through 8.3.2-9b show the resulting residuals for 9 candidate models. The residuals are plotted against Joyner-Boore distance, but the specified distance metric used by each model (i.e., either rupture distance or Joyner-Boore distance) was used to compute the residuals. For the Somervill et al. (2001) models, earthquakes were catorized as occurring inside of or outside of rifted zones and the appropriate Rift or Nonrift version of the model was used to compute the residuals. Part a of each figure shows the residuals for the magnitude range $3.75 \leq \mathbf{M} < 4.75$ and part b shows the residuals for $\mathbf{M} \geq 4.75$.

The residuals for the magnitude range $3.75 \leq \mathbf{M} < 4.75$ typically show more of a trend with distance and greater offset from 0 than those for $\mathbf{M} \geq 4.75$. This is not suprising given that many of the GMPEs were not developed to predict ground motions for earthquakes less than about **M** 5 and the Somerville et al. (2001) GMPE (SEL) was based on simulations for earthquakes of **M** 6 and greater.

As discussed in Section 8.1, the empirical site correction that was found to generally produce an improved fit to residuals was Model 3 (Equation 6.2.2-3) in which a scale factor is found for only the soft rock site category and the intermediate and hard rock sites are considered one group. Figures 8.3.2-10a, 8.3.2-10b, and 8.3.2-10c show the resulting values of C_0 and C_{SR} obtained for each of the candidate GMPEs. Values are shown for four different magnitude-distance ranges of the data. The results show considerable variability in the mean residual, $C_{0,}$ for the combined hard rock and intermediate rock category across frequencies and among the different candidate GMPEs, but all of the GMPEs produce consistant estimates of the soft rock category scaling factor C_{SR}.

Using the formulation developed in Section 8.2.3, the likelihood value for each GMPE was computed for the six magnitude-distance bins. The empirically adjusted residual for the j^{th} recording of the i^{th} earthquake was computed using the expression:

$$\varepsilon_{ij}^{\text{empirically adjusted}} = \varepsilon_{ij} - C_{SR} F_{jk}^{SR} \tag{8.3.2-1}$$

The parameter F_{jk}^{SR} takes on the value 1 if the k^{th} site is in the soft rock category and 0 otherwise. The values of C_{SR} for data in the range of $\mathbf{M} \geq 4..75$ and $R \leq 500$ km were used as this is the magnitude range given the greatest weight, although the values for other magnitude-distance ranges are similar.

The variance matrix is constructed in a similar manner to that described in Section 8.3 using the assigned values of τ and φ for CENA earthquake ground motion data developed in Section 8.8. The variance estimate for the site adjustment factor was set equal to the standard error of estimation for C_{SR} for the k^{th} site if it is in the soft rock category, and 0 otherwise.

Likelihood values were computed for the nine candidate GMPEs for the six structural frequencies and the six magnitude-distance bins. These values were computed with and without the central Arkansas and Oklahoma earthquake data. The relative likelihoods were then normalized to produce relative weights for the models within the clusters defined in Section 8.2.1 and using the approach introduced in Section 8.2.3. Results from the calculation of within-cluster weights are given in Section 8.3.3

8.3.3 Results for Within-Cluster Weights

As indicated in Section 8.2.3, the calculation of weights for the GMPEs in each cluster involves the following steps:

1. Calculation of GMPE weights for each Magnitude-distance (MR) bin. This is done separately for each MR bin, each frequency, and each adjustment approach, with and without the Oklahoma and Arkansas earthquakes.
2. Multiplicative combination of weights for the various MR bins, taking into account their importance factors and effective sample sizes, obtaining GMPE weights for each frequency. This is done separately for each frequency, each adjustment approach, with and without the Oklahoma and Arkansas earthquakes.
3. Multiplicative combination of weights for the various high and low frequencies, taking their correlation into account, obtaining GMPE weights for high frequency and low frequency. This is done separately for high and low frequencies, each each adjustment approach, with and without the Oklahoma and Arkansas earthquakes.

4. Arithmetic combination of weights for the two adjustment approaches, obtaining GMPE weights for high frequency and low frequency. This is done separately for high and low frequencies, with and without the Oklahoma and Arkansas earthquakes.
5. Arithmetic combination of weights obtained with and without the Oklahoma and Arkansas data, obtaining final GMPE weights for high frequency and low frequency. This is done separately separately for high and low frequencies.

Tables 8.3.3-1 through 8.3.3-4 show the calculation of the weights by bin and the combination of bin weights for 10 Hz (i.e., the first two steps), for both adjustment approaches and for Clusters 1 and 3. Tables 8.3.3-5, 8.3.3-7, and 8.3.3-9 show the combination of weights for high and low frequencies (i.e., the third and fourth steps) and for the two adjustment approaches, for Clusters 1, 2, and 3. Tables 8.3.3-6, 8.3.3-8, and 8.3.3-10 show the combination of weights calculated with and without the Oklahoma and Arkansas earthquakes (i.e., the fifth step), for both high and low frequencies, for Clusters 1, 2, and 3. Finally, Table 8.3.3-11 lists the calculated weights for Clusters 1, 2, and 3.

Because Cluster 4 contains only the Somerville et al. (2001), albeit in two different versions, this GMPE gets unit weight.

8.4 Cluster Median GM Models for the Mid-Continent

Following the approach of EPRI (2004), the weights assigned to the individual candidate GMPEs within each cluster were used to calculate weighed mean values of ln(PSA) for a range of magnitudes and distances. These median values were then fit with an algebraic form to produce the median GMPE for each cluster. Cluster median values of PSA were computed for **M** 5, 5.5, 6, 6.5, 7, 7.5, and 8 earthquakes at distances from 1 to 1,000 km.

The AB08' and PZT models use rupture distance as the distance metric, while the rest use Joyner-Boore distance. To simplify application, all of the cluster median GMPEs were developed in terms of Joyner-Boore distance. In order to produce estimates for a given Joyner-Boore distance using the AB08' and PZT models, ruptures were simulated for a distribution of fault depths and the weighted average of the ln(PSA) values based on the resulting rupture distances was used as the GMPE estimate. This is the process used in EPRI (2004) to produce the Joyner-Boore distance version of the hard rock Frankel et al. (1996) GMPE used in this study. The simulations used an equally weighted mixture of vertical and 40 degree dipping ruptures. The rupture area as a function of magnitude was defined using the relationship log(RA) = **M** - 4.35 based on the area-seismic moment relationship for CENA earthquakes developed by Somerville (2001). The rupture depth was specified by simulating a hypocenter focal depth from a focal depth distribution and then placing the hypocenter at a point 2/3 from the top of the rupture. The resulting magnitude-dependent rupture depth distributions were trimmed to remove ruptures that extended outside of the depth range 0 to 30 km, and renormalized.

The focal depth distribution was developed using the well located earthquake dataset from the NUREG-2115 earthquake catalog. Figure 8.4-1 shows the distributions of focal depth for four magnitude intervals: $3 \le \mathbf{M} < 4$, $4 \le \mathbf{M} < 5$, $\mathbf{M} \ge 5$, and $\mathbf{M} \ge 4$. The distributions have similar shapes and the distribution for $\mathbf{M} \ge 4$ was used in the simulations.

Figures 8.4-2, 8.4-3, and 8.4-4 show the results of developing the median ground motions for Clusters 1, 2, and 3, respectively. Each figure has parts a through g for the six structural frequencies (0.5, 1, 2.5, 5, 10, and 25 Hz) and PGA. Shown on each plot are the motions predicted by the component GMPEs and the resulting weighted median motion. Plots are provided for magnitudes **M** 5, 6, 7, and 8.

The mean values of ln(PSA) and ln (PGA) for Clusters 1, 2, and 3 were then fit with algebraic forms. The GMPE for Cluster 4 was left unchanged from EPRI (2004). Two forms were used. The values of ln(PSA) and ln(PGA) for Clusters 1 and 3 were fit with the form:

$$
\begin{aligned}
\ln(PSA) = {} & C_1 + C_2\mathbf{M} + C_3\mathbf{M}^2 + (C_4 + C_5\mathbf{M}) \times R_1 + \\
& (C_6 + C_7\mathbf{M}) \times R_2 \; + \; (C_8 + C_9\mathbf{M}) \times R_3 \; + (C_{10} + C_{11}\mathbf{M}) \times R' \\
R' = {} & \sqrt{R_{JB}^2 + \{\exp(C_{12} + C_{13}\mathbf{M})\}^2} \\
R_1 = {} & \min[\ln(R'), \ln(C_{14})] \\
R_2 = {} & \max\{\min[\ln(R'/C_{14}), \ln(C_{15}/C_{14})], 0\} \\
R_2 = {} & \max\{\ln(R'/C_{15}), 0\}
\end{aligned}
\tag{8.4-1}
$$

This form has the flexibility to represet the tri-linear distance attenuation shapes with distance break points at C_{14} and C_{15}.

The values of ln(PSA) and ln (PGA) for Cluster 2 were fit with the form:

$$
\begin{aligned}
\ln(PSA) = {} & C_1 + C_2\mathbf{M} + C_3\mathbf{M}^2 + C_4\mathbf{M}^3 + \\
& [C_5 + C_6 \times \min(\mathbf{M}, C_{14}) \; + C_7 \times \max(\mathbf{M} - C_{14}, 0)] \times \ln(R') + \\
& [C_8 + C_9 \times \min(\mathbf{M}, C_{14}) \; + C_{10} \times \max(\mathbf{M} - C_{14}, 0)] \times R' \\
R' = {} & R_{JB} + \exp\{C_{11} + C_{12}\mathbf{M} + C_{13}\mathbf{M}^2\}
\end{aligned}
\tag{8.4-2}
$$

This form was needed to capture a break in scaling that occurs at magnitude C_{14}.

Figures 8.4-5, 8.4-6, and 8.4.7 show the fits of the above forms to the values of ln(PSA) and ln(PGA) for Clusters 1, 2, and 3, respectively. As can be seen, the functional forms provide a close match to the median ground motion values.

8.5 Overall Epistemic Uncertainty for Each Cluster and Calculation of High and Low GM Models for the Mid-Continent

As part of the development of the new median models for Clusters 1, 2, and 3, the values of $\sigma_{\text{model-to-model}}$ were computed using Equations 8.2.4-1 and 8.2.4-2. Figures 8.5-1, 8.5-2, and 8.5-3 show the resulting values for Clusters 1, 2, and 3, respectively. Each figure shows the values of $\sigma_{\text{model-to-model}}$ for magnitude **M** 5, 6, 7, and 8 earthquakes for the six structural frequencies and PGA. The "Raw" values shown by the dashed line indicate the values computed at each specific distance. As indicated, these values have abrupt changes reflecting details of the relative behavior of the GMPEs as a function of distance. Following the approach used in EPRI (2004), these values were smoothed over distance using a Gaussian smoothing operator on $\ln(R_{JB})$ with a smoothing parameter of $h = 1$. The resulting smoothed values of $\sigma_{\text{model-to-model}}$ are shown by the solid curves color coded by magnitude.

Also shown on Figures 8.5-1, 8.5-2, and 8.5-3 by the black dash-dot lines are the assessed data constraints on the epistemic uncertainty of median ground motions. As discussed in Section 8.2.4, the epistemic uncertainty in the median model for each cluster is taken as the envelope of the model-to-model standard deviation, $\sigma_{\text{model-to-model}}$, and the data-based estimate of the standard deviation of the median, $\sigma_{\text{data constraint}}$. Figures 8.5-4, 8.5-5, and 8.5-6 show the envelope of the smoothed values of $\sigma_{\text{model-to-model}}$ and $\sigma_{\text{data constraint}}$ as a function of magnitude and R_{JB} for PGA and PSA at the six structural frequencies. These values are used to represent the epistemic uncertainty in the median ground motions for the new Clusters 1, 2, and 3.

Following the procedure used in EPRI (2004), the epistemic uncertainy in median CENA ground motions is represented by the three point discrete distribution proposed by Keefer and Bodily (1983). The three values are a value at the median with a weight of 0.63 and values at the 5^{th} percentile and 95^{th} percentiles of the uncertainty distribution, each weighted 0.185. For a normal distribution, the 5^{th} and 95^{th} percentiles occur at -1.645 and +1.645 standard deviations respectively. The envelop values of the standard deviation of the median shown on Figures 8.5-3, 8.5-4, and 8.5-5 were then used to compute 5^{th} percentile and 95^{th} percentile ground motions relative to the median ground motion models developed in Section 8.4. Figures 8.5-7a, 8.5-8a, and 8.5-9a show the resulting 5^{th} percentile ground motions for the new Clusters 1, 2, and 3, respectively, and Figures Figures 8.5-7b, 8.5-8b, and 8.5-9b show the resulting 95^{th} percentile ground motions. These ground motion values were then fit with the functional forms used in Section 8.4 to fir the corresponding median models. The fitted algebraic forms are shown by the black dashed lines. As was the case for the median models, the selected functional forms given by Equations 8.4-1 and 8.4-2 provide a close match to the ground motion values.

8.6 Adjustments from Epicenteral toJoyner-Boore Distance

For computation efficiency in hazard calculations for distributed seismicity sources, EPRI (2004) provides relationships that allow the use of an epicentral distance measure in PSHA calcululations. The process used in EPRI (2004) was repeated for the updated cluster models. (Details will be provided later.)

8.7 Cluster Weights

As indicated in Section 8.2.5, the cluster weights are calculated on the basis of consistency of the cluster medians with the data (after adjusting the data to reference site conditions) and on the TI Team's judgment regarding the each Cluster's GMPSs robustness as extrapolators for magnitude and distance ranges of engineering interest for which data are not available.

The calculation of weights based on consistency follows the same general approach for within-cluster weights that was introduced in Section 8.2.3 and applied in Section 8.2.3. For Cluster 4, it was necessary to identify each recording as rifted or non-rifted depending on its hypocentral coordinates, in order to use the appropriate variant of the Somerville et al. 2001) GMPE for each recording.

One difference with the approach followed for within-cluster weights is that the data-consistency weights for high frequency and low frequency are combined. There are two reasons for this additional step, as follows: (1) using the same weights for all frequencies makes the PSHA calculations simpler because there is only one ground-motion logic tree for all frequencies, and (2) using the same weights avoids the possibility of uniform-hazard spectra with unrealistic shape discontinuities between 2.5 and 5 Hz.

Tables 8.7-1 through 8.7-4 show the calculation of weights by MR bin, and the combination of these weights, for frequencies of 1 and 10 Hz, for both approaches for adjustment, using the Oklahoma and Arkansas data. Tables 8.7-5 and 8.7-6 show the combination of these results across frequency and across both approaches for site adjustment, with and without the Oklahoma and Arkansas data. Table 8.7-7 shows the combination of cluster weights with and without the Oklahoma and Arkansas data.

Table 8.7-8 shows the combination of the data-consistency and Confidence weights. Both criteria are given equal weight, in contrast to EPRI (2004) where data consistency was given only 25% weight. In the judgment of the TI Team, it is appropriate to give more weight to data consistency because much more data are available to this project than were available to EPRI (2004). On the other hand, these data are not yet definitive enough to justify using them as the only criterion, because the numbe of data for **M**>5 at distances less than 100 km is still limited.

Evening out the weights somewhat by means of the Confidence weights achieves the following two related objectives: (1) it tends to produce more reliable results because Clusters 1 and 4 are judged to have some degree of credibility by the TI Team and by the technical community; and (2) it gives weight to GMPSs that make different assumptions regarding magnitude scaling, thereby causing a realistic increase in the epistemic uncertainty.

The assignment of slightly higher confidence weights to Clusters 2 and 3 was based on the following considerations: (1) Clusters 2 and 3 include more recent GMPEs, which have had the benefit of more CEUS data and more technical insights drawn from recent work and from larger-magnitude data in active crustal regions; and (2) this weighting scheme yields roughly equal weights to GMPEs with 1/R and $1/R^{1.3}$ geometrical spreading, which is a desirable outcome given the current state of uncertainty regarding geometrical spreading[5].

8.8 Updated EPRI 2006 Aleatory Variability Model

EPRI (2006) performed an extensive analysis of the basis for assessing the proper aleatory variability (sigma) to assign to CENA ground-motion models. It concluded that empirically based estimates from active tectonic regions are appropriate with some minor adjustments. Recently, Atkinson (2013) also concluded that aleatory variability in CENA ground motions should be similar to that for earthquake motions in active tectonic resgions.

The approach used in EPRI (2006) has been followed in developing the updated aleatory variability models for use with median model. EPRI (2006) used the results of the preliminary PEER NGA model development to assess the alteatory variability for active tectonic regions. Those preliminary results indicated magnitude-independent aleatory variability and this form was incorportated into the ERPI (2006) aleatory variability model. Since that time, the completed NGA West GMPEs were published in 2008. The GMPEs of Abrahamson and Silva (2008), Chiou and Youngs (2008), and Idriss (2008) incorporated magnitiude-dependent aleatory variability, and the models of Boore and Atkinson (2008) and Campbell and Bozorgnia (2008) did not.

The intent of this update to the EPRI (2006) aleatory was to utilize the final NGA West results as a basis. However, the PEER NGA Project is conducting an update to the NGA West project, NGA West 2. Preliminary results of these analyses are available in draft form and they suggest some changes to the ground motion estimates published in the 2008 NGA West papers. Table 8.8-1 lists the average of the aleatory variability values for the four preliminary NGA West 2 (2012) empirical models that incorporate the breakdown into inter-event and intra-event components (Abrahamson and Silva, 2012; Boore et al., 2012; Campbell and Bozorgnia, 2012; and Chiou and Youngs, 2012). Using the current convention, the inter-event component of aleatory variability is labeled tau (τ) and the intra-event component is labeled phi (φ) such that the total aleatory variability sigma (σ) is given by:

$$\sigma = \sqrt{\tau^2 + \phi^2} \quad (8.8\text{-}1)$$

The aleatory variability for the Idriss (2008) and preliminary (2012) models was not included because the estimates were not derived using this separation of inter-event and intra-event components.

The values listed in the left hand columns of the table under the heading “Average of NGA West 2” were computed by averaging the variances τ^2 and φ^2 of the individual models. The Boore et al. (2012) and Campbell and Bozorgnia (2012) preliminary GMPEs provided values for only a

[5] Upon further study and with the benefit of additional data not available at present, this issue of 1/R versus $1/R^{1.3}$ geometrical-spreading may turn out to be an issue of regional differences in wave propagation. With the current knowledge, it can only be treated as epistemic uncertainty.

limited number of structural frequencies. The ratios of the 2012/2008 values at these frequencies were used to produce estimates at the other structural frequencies. The table lists values for **M** 5, **M** 6, and **M** 7 earthquakes as two of the relationships include magnitude-dependent aleatory variability with break points at **M** 5, **M** 6, and **M** 7.

The prelimary NGA West 12 total aleatory variability results for the four models considered fell approximately into two groups separated by about 0.1 units (natural log of ground motion amplitude). A test was performed to evaluate the need for including these two as alternative epistemic uncertainty estimates, rather than using the composite average value. The test involved computed seismic hazard for site in a unform source zone with a radius of 200 km in which earthquakes occur with a rate of 1 event per year of **M** 3 and larger, with a *b*-value of 1 and a maximum magnitude of **M** 7.5. Hazard analyses were performed using values of 0.55 and 0.65, and the results averaged to produce a mean hazard (assuming equal weights on the two estimates, which is consistent with the groupings of the NGA West 2 estimates). The resulting hazard curve is shown by the red solid curve on Figure 8.8-1. The hazard analysis was repeated using the variance averaged value of 0.602 and the result is shown by the black dashed curve. The results are very close, with the hazard computed using the variance average sigma of 0.602 being slightly lower by less than 1 percent for frequencies of exceedance > 10^{-6}, and by about 5 percent at 10^{-7}. Therefore, it was concluded that the difference in the grouping of the aleatory variability models could be adequately represented by an average value for the purpose of computing mean hazard.

Following the approach used in EPRI (2006), the values derived from active tectonic regions are adjusted for application to CENA by slightly increasing the earthquake-to-earthquake variability τ by 0.03 units. In addition, the values of τ and φ at high frequency (40 and 25 Hz) are increased to equal to the value at 10 Hz to account for the increased high-frequency content of CENA ground motions. The EPRI (2006) model included a lower weighted alternative for a reduction to the intra-event variability φ of 0.03 units. The effect of this alternative on the total standard devation is small and it was not included in the updated model.

The right hand columns of Table 8.8-1 list the resulting updated aleatory variability model for CENA earthquake ground motions. Figure 8.8-2 shows the resulting total aleatory variability computed from these values using Equation 8.8-1. These are compared to those computed using the EPRI (2006) aleatory model on the figure.

8.9 Development of Alternate Set of Median GMPEs for the Gulf Coast

8.9.1 Basis for Defining Gulf Coast Region

Salvador (1991a) describes the Gulf of Mexico basin as a roughly circular structural basin, filled in the central part with approximately 15 km of Triassic to Holocene sedimentary rocks. The central part of the basin is occupied by the Gulf of Mexico with maximum water depths of 3,750 meters. The floor of the Gulf rises steeply to the east and south, along the Florida and Campeche Escarpments: to the west and north, it rises more gradually to the coast, forming a well-defined continental rise, slope and shelf. A broad coastal plain forms the northern part of the basin in

Texas, Arkansas, Louisiana, Mississippi, Alabama, Georgia and Florida, and the basement rocks in those regions were involved in the structural development of Gulf of Mexico. Geophysical surveys indicate that the deep central part of the basin is underlain by oceanic crust, whereas the U.S. Gulf Coastal Plain and the Florida Platform are underlain by either thick continental crust or thinned "transitional" crust. The transitional (rifted or extended) crust occurs beneath the coastal areas of the Gulf Coast states. The landward margins of the Gulf of Mexico basin in the United States are marked by the Marathon and Llano Precambrian uplifts in southern Texas, the Paleozoic Ouachita orogenic belt in north-central Texas, Oklahoma and Arkansas, the Mississippi Embayment, and the southern reaches of the Paleozoic Appalachian orogenic belt.

Very few permanent seismographic stations exist in the Gulf Coastal Plain. However, on the basis of several early deployments of temporary seismic arrays, the region was known to differ, in terms of regional Lg phase attenuation, from large regions of cratonic North America. In a previous study for EPRI, Gupta et al. (1989) developed a regionalization of Q models for North America. Their data set consisted of short-period, three-component recordings from the Long Range Seismic Measurements (LRSM) and Regional Seismic Test Network (RSTN) seismic stations. Gupta et al. (1989) separated the Q values into 8 distinct geophysical regions, based on Bouguer gravity contours interpreted to delineate regions with differing crustal structure/compositional characteristics. EPRI (1993) defined 16 velocity structure regions in the central and eastern United States and correlated them with five of the Q regions defined by Gupta et al. (1989). Four of the five Q models were quite similar, with the exception being region 8 that consisted of the coastal areas of Texas, Louisiana, Mississippi, Alabama, southern Georgia and the entire state of Florida. That region exhibited much lower Q than the other four models. Recently, new data have become available that can shed more light on these earlier findings.

The observation of strong attenuation in the Gulf coastal region is linked to major differences in the structure and lithology of the region, compared to the cratonic platform and Ouachita orogenic belt to the north. The southern part of the Gulf Coastal Plain is underlain by thinned continental crust that was affected by early Mesozoic extensional tectonics associated with the formation of the Gulf of Mexico (Salvador, 1991a; EPRI, 2012). This crustal thinning can be expected to have some impact on the propagation of the Lg phase. Lg is a crust-guided phase that is sensitive to lateral changes in crustal structure and is typically the largest amplitude phase observed on seismograms at regional distances in regions underlain by thick continental crust (Kennett, 1986). The transition between thick North American continental crust and thin oceanic crust of the Gulf of Mexico occurs in the southern Gulf Coastal Plain area. An additional factor affecting attenuation in this region is the presence of an extremely thick Mesozoic and Cenozoic sedimentary section in the region affected by crustal extension. Near the coastline in Texas, Louisiana and Mississippi, the sedimentary section reaches a thickness in excess of 10 km (Salvador 1991b). Shear wave velocities in the upper crust in this region are much lower than in regions of the mid-continent, due to the thick section of sedimentary rock (Mooney, 2012).

The geographic extent of the Gulf coastal region of interest here includes the northern and eastern margin of the Gulf of Mexico structural basin in the United States that is underlain by basement that experienced thinning by extension during the early Mesozoic. The analysis involved seismic stations located in three structural/seismotectonic regions recognized by EPRI (2012): ECC-GC (extended continental crust- Gulf coastal region); GHEX (Gulf coast highly extended continental crust) and RR (Reelfoot Rift). These classifications refer to the structure of the basement rock beneath the thick Mesozoic-Cenozoic Gulf coastal plain sedimentary sequence.

8.9.1.1 Evaluation of Regional Path/Source Effects from Recent Earthquake Recordings

The Earthscope Transportable Array (TA) was located in central United States in 2010 and 2011, as shown in Figure 8.9-1. The array was comprised of over 200 broadband stations spaced on a 70 km grid extending from the Gulf coast to the Canadian border. To advance eastward, the western-most column of stations along a north-south line was moved eastward to form a new column of stations on the eastern edge of the array. Each station remained at a given location for approximately 2 years. Several felt earthquakes occurred in Arkansas, Oklahoma and Texas during the time the TA was in these regions. The seismicity and high seismic station density provided an opportunity to examine Lg wave propagation in the Gulf coastal area using a new, high-quality data set.

The objective of the analysis of the TA data was to quantify Q in the basement rocks of the upper crust in the Gulf coastal region, taking into account the large thickness of Cretaceous-Cenozoic sediments in the coastal areas. Figure 8.9-2 shows the epicenters of the 16 earthquakes that provided data for analysis, and the boundary of the Gulf coast region in the vicinity of the epicenters. Table 8.9-1 lists the dates, hypocenters and moment magnitudes of the 16 earthquakes, derived by Herrmann (2013).

Data Processing

The raw broadband data from the 16 earthquakes in Table 8.9-1 recorded at TA stations within 1000 km of the earthquake epicenters were downloaded from the IRIS Data Management Center website (http://www.iris.edu/hq/) along with the files containing instrument displacement response represented as Laplace transform poles and zeros in SAC format. The data segments for each station were 600 seconds in length, beginning 20 seconds prior to the earthquake origin time. The three-component recordings for each station were corrected to ground acceleration.

The focus of the analysis was the attenuation of the Lg phase on the horizontal components. The analysis involved computation of the Fourier transform of a windowed time segment containing the maximum amplitude of the Lg phase and required development of models for the prediction of the Lg phase arrival time and signal duration at a given epicentral distance.

The Lg phase arrival times from the February 28, 2011 Arkansas earthquake were picked at approximately 250 stations within 600 km of the source, and the travel times were regressed on epicentral distance using a linear model (Figure 8.9-3). The model for the prediction of Lg phase onset time is

$$T_{Lg} = T_0 + {}^{r}/_{3.53}, \qquad (8.9\text{-}1)$$

Where T_{Lg} is the arrival time of the initial onset of the Lg phase, T_0 is the earthquake origin time and r is epicentral distance in kilometers.

The duration of the window for Fourier analysis of the Lg phase was defined by examination of the integral of the squared acceleration time series. The duration of the Lg window, t_d, was defined according to the following:

$$\int_{T_{Lg}}^{T_{Lg}+t_d} a^2\,dt = 0.7 \int_{T_{Lg}}^{T_{Lg}+100} a^2\,dt, \qquad 8.9\text{-}2)$$

where a is the ground acceleration. The Lg signal duration is defined as the time at which the integral of the squared acceleration time series (starting at timeT_{Lg}) reaches 70% of its value at T_{Lg}+100 seconds. A duration versus distance relationship was determined using the data from the February 28, 2011 Arkansas earthquake. Figure 8.9-4 shows the estimates of t_d according to Equation 8.9-2, plotted versus epicentral distance. A straight line was fitted to those data by linear regression, with the result

$$t_d = 8.71 + 0.026\,r. \qquad (8.9\text{-}3)$$

The standard errors for the slope and intercept are 0.0018 and 1.126, respectively. Equations 8.9-1 and 8.9-3 define the Lg window used for Fourier analysis of the Lg wave at all the stations involved in this study.

The mean value of the Fourier acceleration amplitudes were calculated for each of 12 frequency intervals, or bins: (0.2-0.3, 0.3-0.4, 0.4-0.6, 0.6-0.8, 0.8-1.2, 1.2-1.6, 1.6-2.4, 2.4-3.2, 3.2-4.8, 4.8-6.4, 6.4-9.6, and 9.6-12.8 Hz). The center frequencies of each bin were: 0.25, 0.35, 0.5, 0.7, 1.0, 1.4, 2.0, 2.8, 4.0, 5.6, 8.0, and 11.2 Hz. The geometric mean of the amplitudes of the two horizontal components at each station was calculated for each frequency bin and used for analysis.

Figure 8.9-5 shows an example of the data recorded at two stations approximately 500 km from the epicenter of the February 28, 2011 earthquake in central Arkansas. Station P37A is in northern Missouri and station 441A is in southern Louisiana. Note the difference in amplitude, with the station near the Gulf coast exhibiting extreme attenuation of high frequency energy, compared to the station to the North in the cratonic platform.

Regression Model

The objective was to quantify the Lg quality factor for the basement beneath the Gulf coastal region. Several different regression models were examined, which led to the conclusion that the attenuation observed at the various stations in the Gulf coastal region is highly correlated with the thickness of the Cretaceous and younger sedimentary section beneath the stations. Stations near the coastline, where the depth to the basement is approximately 12 km (Salvador, 1991b) exhibit extremely strong attenuation, in comparison to stations near the margin of the Gulf coastal plain where the sedimentary section is thin. To a useful first approximation, the total attenuation observed in the Gulf coast region can be considered to involve two components. The first component is dependent on the travel time of the wave energy through the basement. This time is proportional to the source-receiver distance. The second component is proportional to the time the wave energy spends in the sedimentary section, and is proportional to the thickness of the sediments in the vicinity of the station. This behavior suggested the following form for a regression model to estimate Q, the Lg quality factor for the basement beneath the Gulf coastal region:

$$Ln\left[\frac{A_{ij}(f)}{S_i(f)G(r_{ij})}\right] = R_j(f) - \frac{\pi r_{ij} f}{QV}, \tag{8.9-4}$$

where
$A_{ij}(f)$ = Fourier acceleration amplitude (geometric mean of the two horizontal components),
$S_i(f)$ = Earthquake source amplitude spectrum,
$G(r_{ij})$= Geometrical spreading (independent of frequency f),
$R_j(f)$ = Receiver (Site) amplitude term,
r_{ij} = epicentral distance, from ith earthquake to the jth receiver station.
V = Lg velocity (3.53 km/s).

In Equation 8.9-4, the source spectrum for each earthquake and the geometrical spreading is assumed to be known. The unknowns to be determined are Q in the basement and R_j, a receiver (site response) term for each of the j stations. This formulation separates, to a large degree, the two components of attenuation and concentrates the attenuation due to the sedimentary sequence beneath the receiver station in the first term on the right-hand-side of Equation 8.9-4 (the R_j terms), whereas attenuation in the basement between the source and the receiver is represented by the second term on the right, that involves Q and distance. The source spectra were modeled according to Brune (1970) with unit radiation pattern, crustal density of 2700 kg/m^3, shear wave velocity at the source of 3.53 km/s and two alternative values for stress drop: 10 MPa and 5 MPa. The estimates of Q are quite insensitive to the two choices of stress drop. The seismic moments assumed for the earthquakes are those determined by Herrmann (2013), with corresponding moment magnitudes listed in Table 8.9-1.

Two geometrical spreading models were examined to assess sensitivity of the estimates of Q to uncertainty concerning geometrical spreading at near-source distances. Because the great majority of the data are at distances exceeding 120 km, uncertainty concerning geometrical spreading to a distance of 120 km has virtually no impact on estimates of Q, but instead impacts the estimates of the receiver (site response) terms (Rj).

Geometrical Spreading Model 1:

$$G(r) = r^{-1.3},\ r \leq 60\ km,$$

$$G(r) = 60^{-1.3}, 60 \leq r \leq 120\ km,$$

$$G(r) = 60^{-1.3}\left(\frac{r}{120}\right)^{-0.5}, r > 120\ km.$$

Geometrical Spreading Model 2:
$G(r) = r^{-1.0}$, $r \le 60\ km$,

$G(r) = 60^{-1.0}$, $60 \le r \le 120\ km$,

$G(r) = 60^{-1.0}\left(\frac{r}{120}\right)^{-0.8}$, $r > 120\ km$.

Results

Table 8.9-2 lists the estimates of Q for the 12 frequency bands examined, along with the regression standard errors of estimate, for both geometrical spreading models, and an assumed stress drop of 10 MPa. Note that the estimates of Q are not sensitive to the choice of geometrical spreading model. Figure 8.9-6 shows Q versus frequency (geometrical spreading model 1). The filled circles show the values in Table 8.9-2, computed assuming a stress drop of 10 MPa. The open circles show values assuming a stress drop of 5 MPa. Note that results are insensitive to the assumed stress drop. The solid line is a least squares fit to the data in Table 8.9-2 (geometrical spreading model 1), stress drop 10 MPa. The result is

$\log Q = (2.562 \pm 0.014) + (0.624 \pm 0.025) \log f$,
or
$Q = 365 f^{0.624}$.

The corresponding result for a stress drop of 5 Mpa is
$\log Q = (2.575 \pm 0.015) + (0.615 \pm 0.026) \log f$,
or
$Q = 376 f^{0.615}$.

Figure 8.9-7 shows the mean site response for stations in the Gulf Coast region south of latitude 33N, using geometrical spreading model 1. The mean values plotted in Figure 8.9-7 were computed according to

$$mean\ site\ response = exp\left(\frac{1}{n}\sum_{i=1}^{n} R_i\right), \qquad (8.9\text{-}5)$$

where n is the total number of receivers south of latitude 33N, for a given frequency. The dashed and dotted lines in Figure 8.9-7 show the mean +/- standard error estimates of the site terms. Figure 8.9-8 shows the mean receiver (site) terms for stations in the Gulf Coast region south of latitude 33N, using geometrical spreading model 1, plotted to illustrate the linear relationship between the receiver (site) terms and frequency. The values plotted in Figure 8.9-8 were computed according to

$$mean\ receiver\ (site) term = \frac{1}{n}\sum_{i=1}^{n} R_i, \qquad (8.9\text{-}6)$$

where, again, n is the total number of receivers south of latitude 33N, for a given frequency. The dotted line shows a linear regression fit to mean receiver (site) terms, implying a K_o value of 0.096 +/- 0.010 seconds.

Figures 8.9-9 and 8.9-10 are analogous to Figures 8.9-7 and 8.9-8, but are based on geometrical spreading model 2. The Q estimates are insensitive to the choice of spreading model, but the amplitudes of the receiver (site) term spectra are sensitive to the choice of spreading model. Note, however, that the slope of the mean receiver (site) terms versus frequency are independent of the assumed geometrical spreading, implying K_o = 0.096 seconds for the average condition in the Gulf coast region south of Latitude 33N.

Figures 8.9-11, 8.9-12, 8.9-13 and 8.9-14 show the regression residuals and the site terms for the 12 frequency bands plotted in map view. The geographic extent of the Gulf coast region is indicated by a solid line. Note that as frequency increases, the receiver (site) terms become smaller (less positive), particularly near the coast with the thickness of the sedimentary section is greatest. The negative receiver terms at 4 Hz occur in a region where the depth to the base of the marine sedimentary sequence exceeds 6 km (Salvador, 1991b). At frequencies greater than 4 Hz, recordings from many of the stations near the coast could not be used in the regression, because of low signal-to-noise ratios due to extreme attenuation. Consequently, those stations do not appear in Figure 8.9-14, for 5.6 Hz and higher.

8.9.1.2 Evauation of USGS Crustal Database for Gulf Region

8.9.2 Modification of Midcontinent GMM for Application to Gulf Coast Crustal Region

This section documents the process of modifying the Midcontinent GMM developed in Sections 8.1 through 8.7 so that one can be compute ground-motion amplitudes for earthquake paths that travel primarily through Gulf-Coast crust. This modification is done by accounting for differences in anelastic attenuation between the Midcontinent and the Gulf, using the Gulf Q model developed in Section 8.9.1 and following an approach analogous to the approach followed in EPRI (2004).

Ideally, one should develop the GMM for the Gulf Coast region by following an approach parallel to the approach followed in Sections 8.1 through 8.7. Unfortunately, the data and models available at present do not permit this.

The results in Section 8.9.1 contain other useful insights regarding ground motions in the Gulf region, particularly insights about the effects of the thick sedimentary column beneath sites in the region, which may lead to values of kappa much greater than those considered in Chapter 6. These effects are not considered as part of the modifications introduced in this Section, because it is understood that those effects are to be introduced on a site-specific basis as part of the site-response analysis. Therefore, the bottom of the site column used in the site-response analysis should correspond to a horizon with a shear-wave velocity of approximately 2,830 m/s [6].

[6] This interface between the rock GMM and the site response is somewhat different from what was done in EPRI (1993) and EPRI (2004), where some differences in impedance were included in the derivation of the Gulf model. The approach followed here is preferable because it is less likely to lead to double counting of impedance effects.

Q Models for the Midcontinent and Gulf

There are two widely used Q models for the CEUS Midcontinent, namely the models by Silva et al. (2002) and by Atkinson (2004). The Silva et al model is used by the Silva et al GMPEs in Clusters 1 and 2 and was used in EPRI (2004) as the "host" Q model for the Midcontinent in the EPRI (2004) Midcontinent-to-Gulf conversion. The Atkinson model is used by the AB06' and PZT11 GMPEs in Cluster 3. The FEL and TOL GMPEs use earlier Q models. The A08' and SEL GMPEs do not explicitly use Q models of this kind.

The Silva et al. (2002) and Atkinson (2004) Q models are shown in Figure 8.9.2-1. These two models differ substantially in their values at low and high frequencies and in the spectral shapes that they generate if used with the same source spectrum. Also shown is the harmonic average of these two Q models[7].

Also shown Figure 8.9.2-1 is the Q model for the Gulf region developed in Section 8.9.1 using Transportable Array data, which will be used as the "target"[8] Q model for the Gulf in the Midcontinent-to-Gulf conversion. Also shown is the Gulf Q model of EPRI (1993), which was the target Q model for the Gulf in the EPRI (2004) conversion.

The harmonic-average of the two Midcontinent models will be used as the "host" Q model for the Midcontinent in the Midcontinent-to-Gulf conversion performed below. This model represents a compromise between the Silva and Atkinson models and shows a modest dependence on frequency. One immediate advantage if it is that it predicts more anelastic attenuation in the Gulf than in the Midcontinent for nearly all frequencies, as one would expect.

It is worth noting that, although Q models are usually derived mainly on the basis of data between 1 and 10 or 20 Hz, they are plotted here (and in calculations) for much higher frequencies. In addition, Q often has a minimum near 1 Hz (see, for example, Atkisnon, 2004). Thus, it may be inappropriate to extrapolate relations of the form $Q(f) = Q_0 f^{\eta}$ below 1 Hz. To alleviate this issue, the Midcontinent and Gulf Q models will be trated as flat for frequencies below 1 Hz.

It is also worth noting that the difference between the host and target Q models was much greater in EPRI (2004) (i.e., the difference between the dotted lines in Figure 8.9.2-1) than it is in this project (i.e., the difference between the solid lines). Therefore, the difference between Midcontinent and Gulf GMPEs at long distances is expected to be smaller.

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[7] Using the harmonic-average Q is equivalent to computing the Fourier amplitude using both Midcontinent Q models on and then calculating their logarithmic average.

[8] The terms host and target are used in the contect of Campbell's (20??) hybrid empirical method.

Details of the Midcontinent to Gulf Conversion

EPRI (2004) used Campbell's (20XX) Hybrid Empirical Method (HEM) to perform the Midcontinent to Gulf conversion. This project will utilize the IRVT approach introduced by Al-Atik et al. (2012), which represents a modern variant of the HEM method. Although the IRVT approach was introduced to make kappa adjustments, it can also be used for Q adjustments. IRVT has the advantage that there is no need for the definition of complete target and host RVT models, because the IRVT approach back-figures the implicit host model and then applies the prescribed differences between host and target.

The calculations for one Midcontinent GMPE (e.g., the Cluster 1 median curve) and one magnitude-distance combination proceed as follows:

1. Calculate the Midcontinent response spectrum at 0.5, 1, 2.5, 5, 10, 25, and 100 Hz (PGA) using the corresponding GMPEs for these frequencies. Interpolate linealy in log-log space between frequencies and extrapolate between 0.5 Hz and 0.1 Hz assuming that spectral acceleration in this range is proportional to 1/period.
2. Convert the Midcontinent response spectrum to Midcontinent Fourier spectrum using IRVT, as implemented by Kottke (2012[9]).
3. Convert the Midcontinent Fourier spectrum to a Gulf Fourier spectrum. This is done by multiplying the Fourier expectrum by the frequency-dependent Q adjustment

$$\exp\left\{-\frac{\pi f R}{\beta}\left[\frac{1}{Q_{Gulf}}-\frac{1}{Q_{Midcontinent}}\right]\right\} \qquad (8.9.2\text{-}1)$$

   where β is the crustal shear-wave velocity (taken as 3.7 km/s).
4. Convert the Gulf Fourier spectrum to the Gulf response spectrum using RVT and read the spectral accelerations at 0.5, 1, 2.5, 5, 10, 25, and 100 Hz for further processing. Again, Kottke's (2012) implementation of RVT is used.
5. If necessary, make the following two consistency adjustments to the Gulf spectral accelerations at 25 and 100 Hz: (1) reduce Sa(100) in the Gulf, if necessary, so that Sa(25)/Sa(100) in the Gulf is greater than or equal than its value in the Midcontinent; and (2) make Sa(25) and Sa(100) the same in the Gulf and the Midcontinent if Sa(25) is greater in the Gulf than in the Midcontinent. The first adjustment is performed for all points, but the magnitude of the adjustment is very small at distances less than 100 km. The second adjustment is necessary at

For each Midcontinent GMPE, these calculations are performed for **M** between 5 and 8, with an increment of 0.25 **M** units, and for 68 distances between 1 and 1,000 km. The 871 "data" points for each frequency are then fit using the same functional forms used in Sections 8.4 and 8.5. These calculations are performed for all four Clusters. For Cluster 4, they are done separately for rifted and non-rifted conditions.

[9] In the Kottke (2012) scripts, the maximum number of IRVT iterations was increased from 30 to 300.

Results

Figures 8.9.2-2 through 8.9.2-36 compare the Gulf and Midcontinent GMPEs for all clusters and branches. As anticipated, the amplitudes are similar at short distances but the Gulf amplitudes are lower at longer distances.

8.10 Comparison with EPRI (2004, 2006)

Figures 8.10-1 through 8.10-7 compare the updated GMM developed in this chapter for the Midcontinent to the corresponding EPRI (2004) GMM. These comparisons consider all curves in all clusters, and use line thickness to convey each curve's weight by making thickness proportional to weight[10]. For **M**<6 (i.e., the left panel), Cluster 4 is not shown and the weights have been normalized, in accordance with the recommended use of Cluster 4 in both the updated and EPRI GMMs.

These figures indicate that the updated GMM is somewhat lower than EPRI (2004), when the two models are taken as a whole. The greater differences occur at low frequencies and high magnitudes.

Both GMMs encompass broad uncertainty ranges, which is consistent with the present state of knowledge regarding ground motions in the CEUS. In addition, there is a substantial overlap between these ranges, indicating that the updated GMM does not represent a radical departure from the EPRI (2004) GMM. The observed differences are the result of possessing and using substantially more data and having acquired additional insights from other regions over a period of nearly ten years.

[10] Because very thin lines are difficult to reproduce and see clearly, it was not possible to maintain proportionality between thickness and weight for the curves that have very low weights, while avoiding the use of very thick lines for the curves with the highest weights. To this effect, some low-weighted curves are shown as dashed lines to indicate that their thickness has been doubled.

Table 8.1.1-1 Number of Rock Site Recordings In Assembled Strong Motion Data

Magnitude Range	Distance Range	Rock Category	Number of Recordings for PSA at Frequency of:					
			0.5 Hz	1 Hz	2.5 Hz	5 Hz	10 Hz	25 Hz
$3.75 \le \mathbf{M} < 4.75$	$R_{JB} \le 500$ km	Soft	612	738	736	689	340	62
		Intermediate	348	431	430	402	250	46
		Hard	152	235	241	233	181	93
$\mathbf{M} \ge 4.75$	$R_{JB} \le 500$ km	Soft	174	182	183	180	140	51
		Intermediate	120	134	135	132	116	33
		Hard	67	68	68	68	65	37

Table 8.2.1-1. Updated GMPE Clusters.

Cluster	Model Type	Models
1	Single Corner Brune Source	Silva et al (2003) Single Corner, Constant Stress with Saturation - SSCCSS Silva et al (2003) Single Corner, Variable Stress - SSCVS Toro et al (1997) - TEL Frankel et al (1996) – FEL
2	Complex/Empirical ~R^{-1} Geometrical spreading to 100 km	Silva et al (2003) Double Corner with Saturation - SDCS Atkinson (2008) with Atkinson-Boore (2011) revision - A08'
3	Complex/Empirical ~$R^{-1.3}$ Geometrical spreading to 70 km	Atkinson-Boore (2008) with Atkinson-Boore (2011) revision - AB06' Pezesck, Zandieh, and Tavakoli (2011) - PZT11
4	Finite Source /Green's Function	Somerville et al. (2001); slightly different models for rifted and non-rifted sources - SEL

Table 8.3.3-1 .Calculation of GMPE weights for Cluster 1, 10 Hz Spectral Acceleration, analytical adjustment for site conditions, and including Oklahoma-Arkansas data.

Mmin	Mmax	Rmin	Rmax	Equiv. Sample Size	Importance Factor	Exponent	SSCCSS	SSCVS	TEL	FEL
3.75	4.75	0.1	70	11.92	0.2500	0.1010	0.9936	0.7549	0.2663	0.4091
3.75	4.75	70	150	7.437	0.0833	0.0540	0.8672	0.9450	0.9218	0.9460
3.75	4.75	150	500	31.04	0.0417	0.0065	1.0000	0.9611	0.7296	0.8919
4.75	-	0.1	70	4.815	1.0000	1.0000	0.3332	0.2945	0.1665	0.2058
4.75	-	70	150	3.554	0.3333	0.3333	0.3957	0.4910	0.6802	0.7963
4.75	-	150	500	8.936	0.1667	0.0898	0.7466	0.8430	0.9516	0.8785
						Raw	0.0424	0.0418	0.0193	0.0497
						Normalized	**0.2769**	**0.2727**	**0.1260**	**0.3244**

Table 8.3.3-2. Calculation of GMPE weights for Cluster 1, 10 Hz Spectral Acceleration, empirical adjustment for site conditions, and including Oklahoma-Arkansas data.

Mmin	Mmax	Rmin	Rmax	Equiv. Sample Size	Importance Factor	exponent	SSCCSS	SSCVS	Tel	Fel
3.75	4.75	0	70	20.16	0.2500	0.1203	0.9985	0.5883	0.0439	0.1674
3.75	4.75	70	150	23.61	0.0833	0.0343	0.9453	0.9927	0.5647	0.6137
3.75	4.75	150	500	40.60	0.0417	0.0100	1.0000	0.8990	0.4523	0.8184
4.75	-	0	70	9.71	1.0000	1.0000	0.1244	0.2085	0.3660	0.3011
4.75	-	70	150	6.65	0.3333	0.3333	0.1798	0.2822	0.4811	0.9511
4.75	-	150	500	12.17	0.1667	0.1329	0.1485	0.1543	0.7369	0.9860
						Raw	0.0016	0.0024	0.0015	0.0237
						Normalized	**0.0538**	**0.0818**	**0.0499**	**0.8145**

Table 8.3.3-3. Calculation of GMPE weights for Cluster 3, 10 Hz Spectral Acceleration, analytical adjustment for site conditions, and including Oklahoma-Arkansas data.

Mmin	Mmax	Rmin	Rmax	Equiv. Sample Size	Importance Factor	exponent	AB06'	PZT
3.75	4.75	0	70	11.92	0.25	0.1010	0.9998	0.5246
3.75	4.75	70	150	7.44	0.08	0.0540	0.9768	0.9454
3.75	4.75	150	500	31.04	0.04	0.0065	1.0000	0.8375
4.75	-	0	70	4.81	1.00	1.0000	0.5071	0.4929
4.75	-	70	150	3.55	0.33	0.3333	0.7870	0.8003
4.75	-	150	500	8.94	0.17	0.0898	0.9494	0.9288
						Raw	0.1850	0.0761
						Normalized	**0.7086**	**0.2914**

Table 8.3.3-4. Calculation of GMPE weights for Cluster 3, 10 Hz Spectral Acceleration, empirical adjustment for site conditions, and including Oklahoma-Arkansas data.

Mmin	Mmax	Rmin	Rmax	Equiv. Sample Size	Importance Factor	exponent	AB06’	PZT
3.75	4.75	0	70	20.16	0.2500	0.1203	1.0000	0.3217
3.75	4.75	70	150	23.61	0.0833	0.0343	1.0000	0.6950
3.75	4.75	150	500	40.60	0.0417	0.0100	1.0000	0.6118
4.75	-	0	70	9.71	1.0000	1.0000	0.3145	0.6855
4.75	-	70	150	6.65	0.3333	0.3333	0.7901	0.7973
4.75	-	150	500	12.17	0.1667	0.1329	0.8978	0.9249
						Raw	0.1116	0.0346
						Normalized	**0.7634**	**0.2366**

Table 8.3.3-5. Combination of weights for Cluster 1, with Oklahoma and Arkansas earthquakes

	Analytical Site Adjustments				Empirical Site Adjustments			
	SSCCSS	**SSCVS**	**TEL**	**FEL**	**SSCCSS**	**SSCVS**	**TEL**	**FEL**
25 Hz	0.60	0.27	0.11	0.02	0.89	0.10	0.01	0.00
10 Hz	0.28	0.27	0.13	0.32	0.05	0.08	0.05	0.81
5 Hz	0.61	0.34	0.00	0.04	0.38	0.41	0.00	0.21
Combined HF	**0.61**	**0.33**	**0.02**	**0.04**	**0.66**	**0.32**	**0.00**	**0.01**
Comb. HF Analytical + Empirical	**0.64**	**0.32**	**0.01**	**0.03**				
2.5 Hz	0.30	0.68	0.01	0.00	0.04	0.96	0.00	0.00
1 Hz	0.43	0.57	0.00	0.00	0.09	0.91	0.00	0.00
0.5 Hz	0.43	0.51	0.01	0.05	0.41	0.59	0.00	0.00
Combined LF	**0.36**	**0.64**	**0.00**	**0.00**	**0.07**	**0.93**	**0.00**	**0.00**
Comb. LF Analytical + Empirical	**0.22**	**0.78**	**0.00**	**0.00**				

Table 8.3.3-6. Final Combination of weights for Cluster 1
(considering with and without Oklahoma and Arkansas earthquakes)

	SSCCSS	**SSCVS**	**TEL**	**FEL**
HF with	0.64	0.32	0.01	0.03
HF without	0.26	0.24	0.20	0.31
HF Combined	0.45	0.28	0.11	0.17
LF with	0.22	0.78	0.00	0.00
LF without	0.27	0.73	0.00	0.00
LF Combined	0.24	0.76	0.00	0.00

Table 8.3.3-7. Combination of weights for Cluster 2, with Oklahoma and Arkansas earthquakes

	Analytical Site Adjustments		Empirical Site Adjustments	
	A08'	**SDCS**	**A08'**	**SDCS**
25 Hz	0.05	0.95	0.02	0.98
10 Hz	0.42	0.58	0.99	0.01
5 Hz	0.63	0.37	1.00	0.00
Combined HF	**0.23**	**0.77**	**0.98**	**0.02**
Comb. HF Analytical + Empirical	**0.60**	**0.40**		
2.5 Hz	0.99	0.01	1.00	0.00
1 Hz	0.99	0.01	1.00	0.00
0.5 Hz	0.35	0.65	0.51	0.49
Combined LF	**0.99**	**0.01**	**1.00**	**0.00**
Comb. LF Analytical + Empirical	**0.99**	**0.01**		

Table 8.3.3-8. Final Combination of weights for Cluster 2 (considering with and without Oklahoma and Arkansas earthquakes)

	A08'	SDCS
HF with	0.60	0.40
HF without	0.58	0.42
HF Combined	0.59	0.41
LF with	0.99	0.01
LF without	0.98	0.02
LF Combined	0.99	0.01

Table 8.3.3-9. Combination of weights for Cluster 3, with Oklahoma and Arkansas earthquakes

	Analytical Site Adjustments		Empirical Site Adjustments	
	AB06p	**PZT**	**AB06p**	**PZT**
25 Hz	0.91	0.09	0.91	0.09
10 Hz	0.71	0.29	0.76	0.24
5 Hz	0.83	0.17	0.85	0.15
Combined HF	**0.89**	**0.11**	**0.91**	**0.09**
Comb. HF Analytical + Empirical	**0.90**	**0.10**		
2.5 Hz	0.79	0.21	1.00	0.00
1 Hz	0.49	0.51	0.38	0.62
0.5 Hz	0.60	0.40	0.53	0.47
Combined LF	**0.68**	**0.32**	**0.90**	**0.10**
Comb. LF Analytical + Empirical	**0.79**	**0.21**		

Table 8.3.3-10. Final Combination of weights for Cluster 3 (considering with and without Oklahoma and Arkansas earthquakes)

	AB06p	**PZT**
HF with	0.90	0.10
HF without	0.37	0.63
HF Combined	0.63	0.37
LF with	0.79	0.21
LF without	0.70	0.30
LF Combined	0.75	0.25

Table 8.3.3-11. Final within-cluster weights.

Cluster	1				2		3	
GMPE	SSCCSS	SSCVS	TEL	FEL	A08'	SDCS	AB06p	PZT
HF Weight	0.45	0.28	0.11	0.17	0.59	0.41	0.63	0.37
LF Weight	0.24	0.76	0.00	0.00	0.99	0.01	0.75	0.25

Table 8.7-1. Calculation of cluster weights by bin for 10 Hz, analytical approach, and using Oklahoma and Arkansas data.

Mmin	Mmax	Rmin	Rmax	Equiv. Sample Size	Importance Factor	exponent	Cluster 1	Cluster 2	Cluster 3	Cluster 4
3.75	4.75	0	70	11.92	0.2500	0.1010	0.5066	0.6187	0.9950	0.7207
3.75	4.75	70	150	7.44	0.0833	0.0540	0.9546	0.8300	0.9019	0.9515
3.75	4.75	150	500	31.04	0.0417	0.0065	0.9337	1.0000	0.7928	0.8403
4.75	-	0	70	4.81	1.0000	1.0000	0.2803	0.2952	0.2595	0.1650
4.75	-	70	150	3.55	0.3333	0.3333	0.5800	0.7231	0.6079	0.5870
4.75	-	150	500	8.94	0.1667	0.0898	0.8215	0.7873	0.9070	0.9364
						Raw	0.0603	0.0863	0.1018	0.0523
						Normalized	**0.2005**	**0.2871**	**0.3386**	**0.1738**

Table 8.7-2. Calculation of cluster weights by bin for 10 Hz, empirical approach, and using Oklahoma and Arkansas data.

Mmin	Mmax	Rmin	Rmax	Equiv. Sample Size	Importance Factor	exponent	Cluster 1	Cluster 2	Cluster 3	Cluster 4
3.75	4.75	0	70	20.16	0.2500	0.1203	0.2917	0.3473	0.9999	0.3840
3.75	4.75	70	150	23.61	0.0833	0.0343	0.9798	0.9723	0.7607	0.8513
3.75	4.75	150	500	40.60	0.0417	0.0100	0.8198	1.0000	0.5310	0.6146
4.75	-	0	70	9.71	1.0000	1.0000	0.1775	0.7974	0.0178	0.0073
4.75	-	70	150	6.65	0.3333	0.3333	0.3461	0.9646	0.2845	0.3365
4.75	-	150	500	12.17	0.1667	0.1329	0.3148	0.9381	0.6503	0.8673
						Raw	0.0023	0.1218	0.0013	0.0004
						Normalized	**0.0180**	**0.9680**	**0.0106**	**0.0034**

Table 8.7-3. Calculation of cluster weights by bin for 1 Hz, empirical approach, and using Oklahoma and Arkansas data.

Mmin	Mmax	Rmin	Rmax	Equiv. Sample Size	Importance Factor	exponent	Cluster 1	Cluster 2	Cluster 3	Cluster 4
3.75	4.75	0	70	14.12	0.2500	0.0784	0.4670	0.9750	0.9041	0.2951
3.75	4.75	70	150	9.83	0.2500	0.1126	0.7481	0.1634	0.6603	0.9881
3.75	4.75	150	500	39.38	0.2500	0.0281	0.5378	0.0421	1.0000	0.6185
4.75	-	0	70	4.43	1.0000	1.0000	0.0068	0.2503	0.6562	0.0867
4.75	-	70	150	3.49	1.0000	1.0000	0.2462	0.2631	0.2174	0.2733
4.75	-	150	500	8.96	1.0000	0.4940	0.1305	0.3523	0.9293	0.0274
						Raw	0.0000	0.0002	0.0791	0.0001
						Normalized	**0.0005**	**0.0020**	**0.9961**	**0.0015**

Table 8.7-4. Calculation of cluster weights by bin for 1 Hz, empirical approach, and using Oklahoma and Arkansas data.

Mmin	Mmax	Rmin	Rmax	Equiv. Sample Size	Importance Factor	exponent	Cluster 1	Cluster 2	Cluster 3	Cluster 4
3.75	4.75	0	70	18.46	0.2500	0.1485	0.1279	0.7550	0.9760	0.0341
3.75	4.75	70	150	24.83	0.2500	0.1104	0.8240	0.1029	0.9787	0.5444
3.75	4.75	150	500	47.56	0.2500	0.0577	0.1525	0.0000	1.0000	0.0535
4.75	-	0	70	10.97	1.0000	1.0000	0.0157	0.6138	0.1000	0.2706
4.75	-	70	150	8.04	1.0000	1.0000	0.2255	0.4926	0.2362	0.0457
4.75	-	150	500	13.33	1.0000	0.8231	0.0230	0.4958	0.6236	0.0000
						Raw	0.0000	0.0000	0.0141	0.0000
						Normalized	**0.0000**	**0.0000**	**0.9999**	**0.0000**

Table 8.7-5. Combination of Cluster weights for multiple frequencies and for analytical and empirical approaches for site adjustment, including Oklahoma and Arkansas data.

	Analytical Site Adjustments				Empirical Site Adjustments			
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**
25 Hz	0.04	0.01	0.60	0.35	0.03	0.03	0.24	0.69
10 Hz	0.20	0.29	0.34	0.17	0.02	0.97	0.01	0.00
5 Hz	0.03	0.16	0.75	0.06	0.00	0.91	0.06	0.03
Combined HF	**0.04**	**0.07**	**0.75**	**0.14**	**0.01**	**0.85**	**0.08**	**0.06**
Comb. HF Analytical + Empirical	**0.03**	**0.46**	**0.42**	**0.10**				
2.5 Hz	0.00	0.00	0.99	0.01	0.00	0.01	0.99	0.00
1 Hz	0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00
0.5 Hz	0.56	0.01	0.08	0.34	0.03	0.00	0.97	0.00
Combined LF	**0.00**	**0.00**	**0.99**	**0.01**	**0.00**	**0.00**	**1.00**	**0.00**
Comb. LF Analytical + Empirical	**0.00**	**0.00**	**0.99**	**0.01**				

Table 8.7-6. Combination of Cluster weights for multiple frequencies and for analytical and empirical approaches for site adjustment, not including Oklahoma and Arkansas data.

	Analytical Site Adjustments				Empirical Site Adjustments			
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**
25 Hz	0.05	0.01	0.49	0.45	0.13	0.78	0.03	0.06
10 Hz	0.17	0.13	0.42	0.28	0.03	0.96	0.00	0.01
5 Hz	0.06	0.10	0.65	0.19	0.01	0.46	0.02	0.51
Combined HF	**0.05**	**0.03**	**0.63**	**0.29**	**0.02**	**0.94**	**0.00**	**0.04**
Comb. HF Analytical + Empirical	**0.03**	**0.49**	**0.32**	**0.16**				
2.5 Hz	0.00	0.01	0.98	0.01	0.00	0.02	0.98	0.00
1 Hz	0.00	0.01	0.99	0.00	0.00	0.00	1.00	0.00
0.5 Hz	0.18	0.13	0.51	0.18	0.00	0.00	1.00	0.00
Combined LF	**0.00**	**0.01**	**0.99**	**0.00**	**0.00**	**0.00**	**1.00**	**0.00**
Comb. LF Analytical + Empirical	**0.00**	**0.00**	**0.99**	**0.00**				

Table 8.7-7. Combination of Cluster weights with and without including the Oklahoma and Arkansas earthquakes.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4
HF with	0.03	0.46	0.42	0.10
HF without	0.03	0.49	0.32	0.16
HF Combined	0.03	0.47	0.37	0.13
LF with	0.00	0.00	0.99	0.01
LF without	0.00	0.00	0.99	0.00
LF Combined	0.00	0.00	0.99	0.00

Table 8.7-8. Combination of Cluster data-consistency and confidence weights

	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Weight Based on Consistency with Data (avg. HF and LF) 50%	0.02	0.24	0.68	0.07
Weight Based on Confidence in GMPEs 50%	0.20	0.30	0.30	0.20
Combined Weight	0.11	0.27	0.49	0.13

Table 8.8-1. Aleatory variability for the 4 NGA models and the selected values for CENA.

Spectral Period (sec)	Average of NGA West 2						Adjusted for CENA					
	M 5		M 6		M ≥ 7		M 5		M 6		M ≥ 7	
	τ	φ	τ	φ	τ	φ	τ	φ	τ	φ	τ	φ
0.01 (PGA)	0.35	0.55	0.33	0.51	0.31	0.50	0.38	0.55	0.36	0.51	0.34	0.50
0.025	0.35	0.56	0.33	0.52	0.31	0.50	0.42	0.60	0.40	0.56	0.38	0.54
0.04	0.37	0.58	0.34	0.53	0.32	0.52	0.42	0.60	0.40	0.56	0.38	0.54
0.1	0.39	0.60	0.37	0.56	0.35	0.54	0.42	0.60	0.40	0.56	0.38	0.54
0.2	0.36	0.60	0.34	0.57	0.32	0.55	0.39	0.60	0.37	0.57	0.35	0.55
0.4	0.35	0.61	0.33	0.59	0.31	0.57	0.38	0.61	0.36	0.59	0.34	0.57
1.0	0.39	0.62	0.38	0.62	0.36	0.61	0.42	0.62	0.41	0.62	0.39	0.61
2.0	0.45	0.61	0.44	0.61	0.42	0.61	0.48	0.61	0.47	0.61	0.45	0.61
4.0	0.47	0.61	0.45	0.62	0.44	0.61	0.50	0.61	0.48	0.62	0.47	0.61

Table 8.9-1. Earthquakes Used for Analysis.

State	Date	Magnitude	Latitude	Longitude	Depth
Arkansas	10/15/2010	3.83	35.28	-92.32	5.0
Arkansas	11/20/2010	3.87	35.32	-92.32	5.0
Arkansas	2/17/2011	3.80	35.28	-92.36	6.0
Arkansas	2/18/2011	3.88	35.26	-92.37	8.0
Arkansas	2/18/2011	4.07	35.27	-92.38	8.0
Arkansas	2/28/2011	4.65	35.26	-92.34	4.0
Arkansas	4/7/2011	3.73	35.25	-92.37	3.0
Arkansas	4/8/2011	3.86	35.26	-92.36	4.0
Oklahoma	2/27/2010	4.15	35.54	-96.75	4.0
Oklahoma	10/13/2010	4.30	35.20	-97.31	14.0
Oklahoma	11/24/2010	3.93	35.63	-97.25	3.0
Oklahoma	12/12/2010	3.20	35.39	-97.00	4.0
Oklahoma	11/6/2011	5.59	35.54	-96.75	8.0
Texas	9/11/2011	4.40	32.87	-100.8	5.0
Texas	10/20/2011	4.59	28.81	-98.15	3.0
Texas	5/17/2012	4.83	31.90	-94.33	4.0

Table 8.9-2. Estimates of Q for Gulf Coast Region.

Frequency (Hz)	Geo. Spreading Model 1		Geo. Spreading Model 2	
	Q	σ	Q	σ
0.25	182	38	179	37
0.35	180	17	179	16
0.50	254	22	252	23
0.70	265	17	265	16
1.00	352	21	350	22
1.40	451	25	449	25
2.00	537	25	535	25
2.80	620	25	617	25
4.00	806	32	805	32
5.60	1013	40	1013	40
8.00	1377	62	1374	61
11.2	2009	141	2012	142

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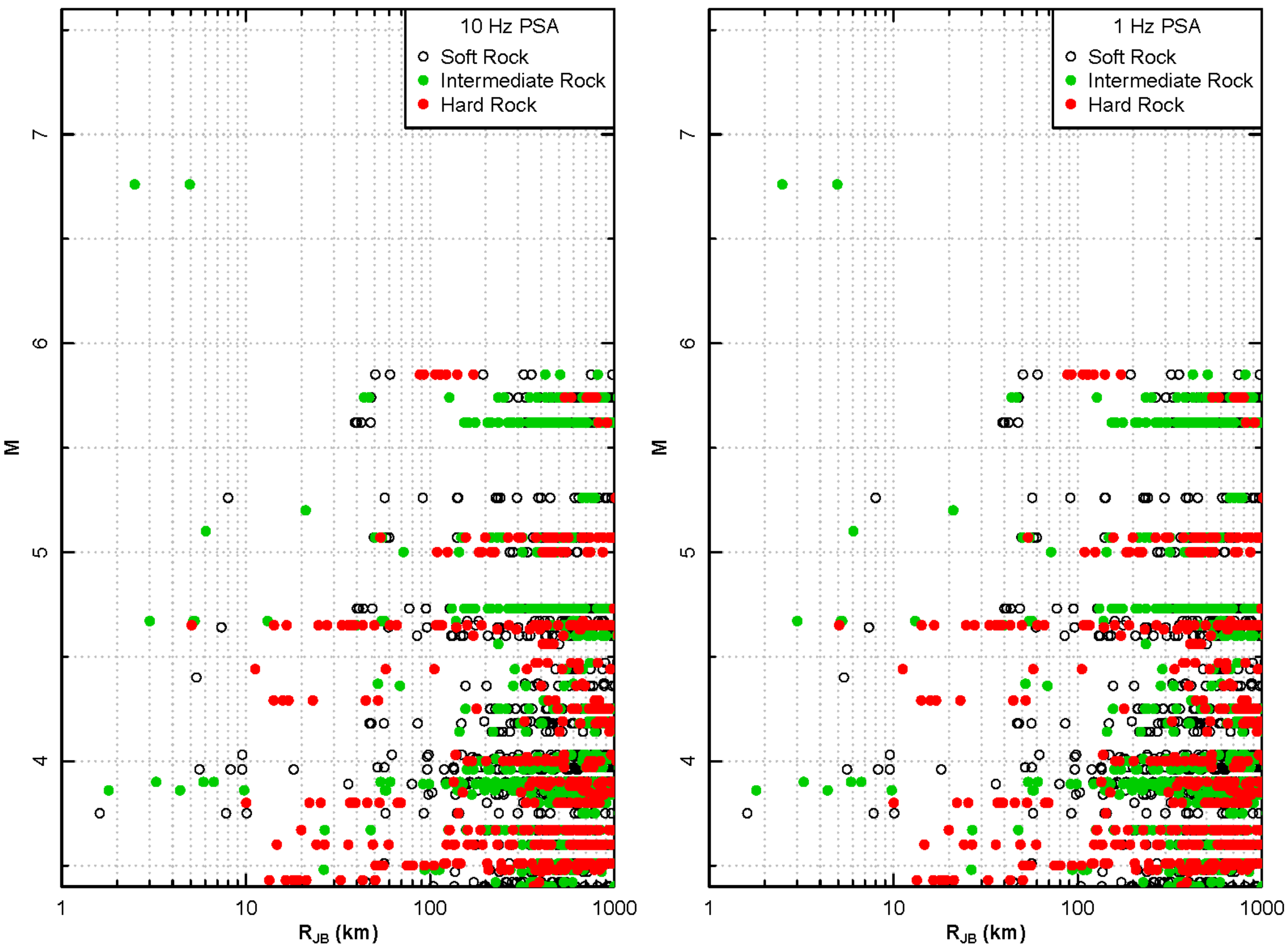

Figure 8.1-1. Magnitude-distance distribution of the updated rock site database developed for the project

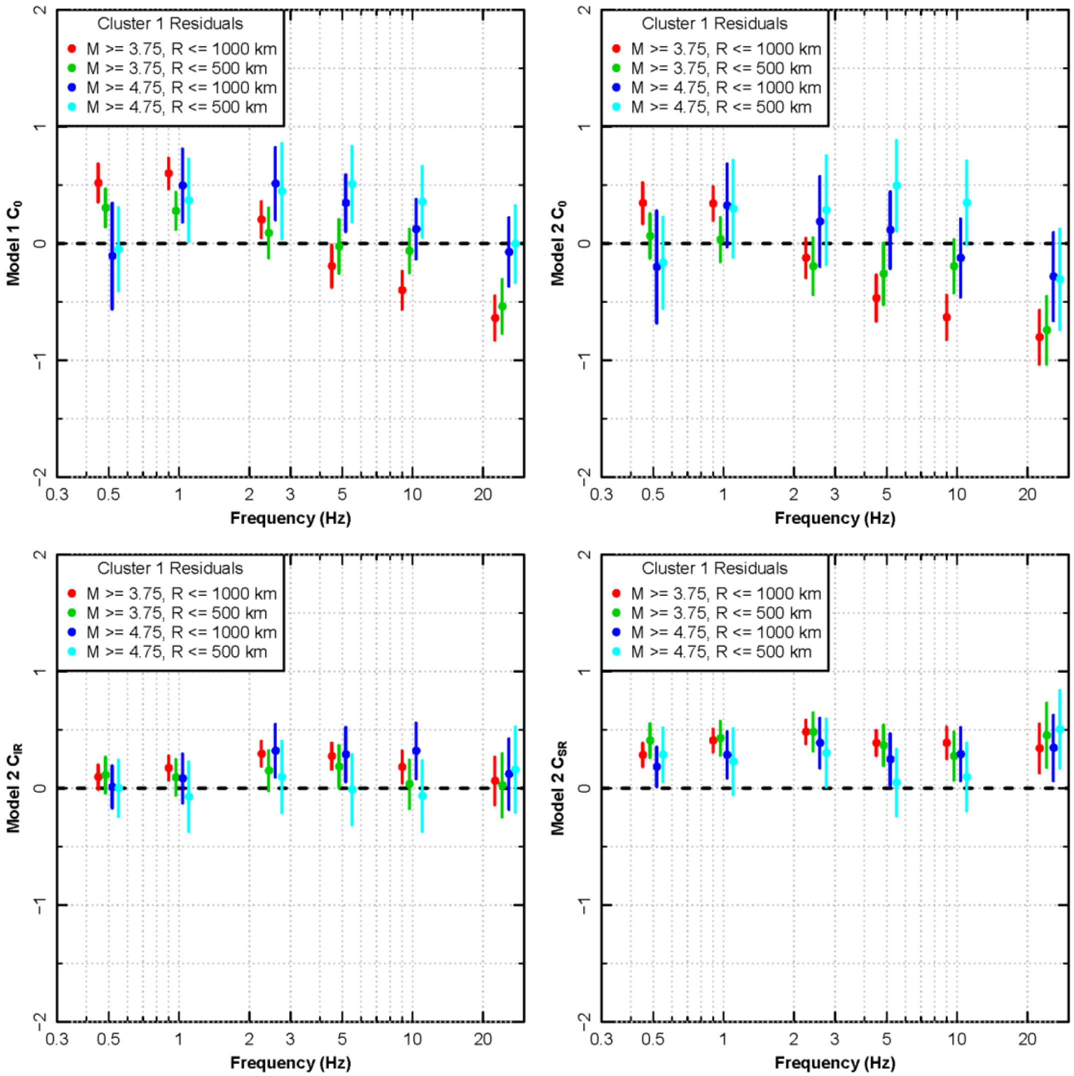

Figure 8.1-2. Coefficients of Model 1 (Equations 6.2.2-1) and Model 2 (Equation 6.2.2-2) fit to residual for the updated ground motion data base using the EPRI (2004) Cluster 1 median GMPE

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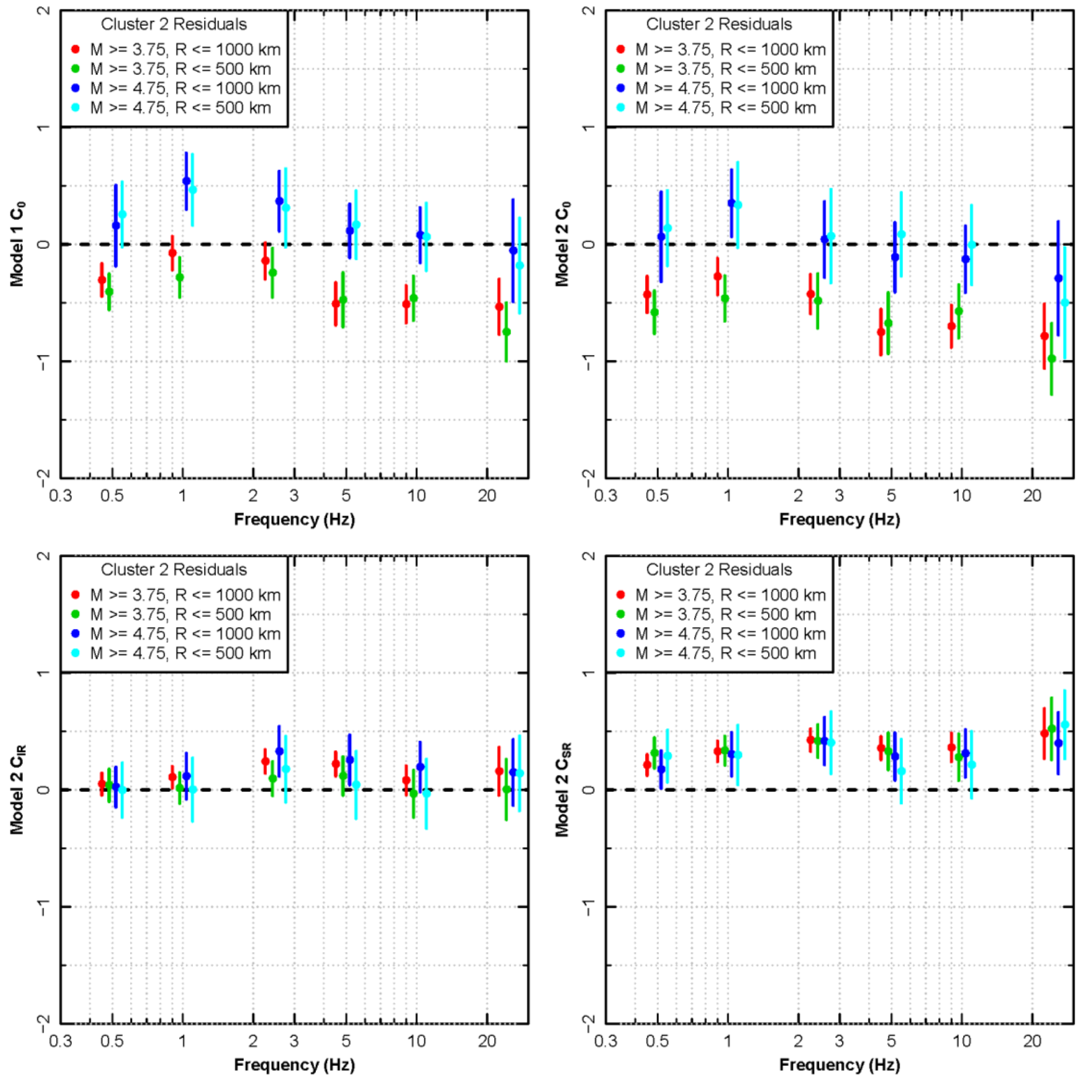

Figure 8.1-3. Coefficients of Model 1 (Equations 6.2.2-1) and Model 2 (Equation 6.2.2-2) fit to residual for the updated ground motion data base using the EPRI (2004) Cluster 2 median GMPE

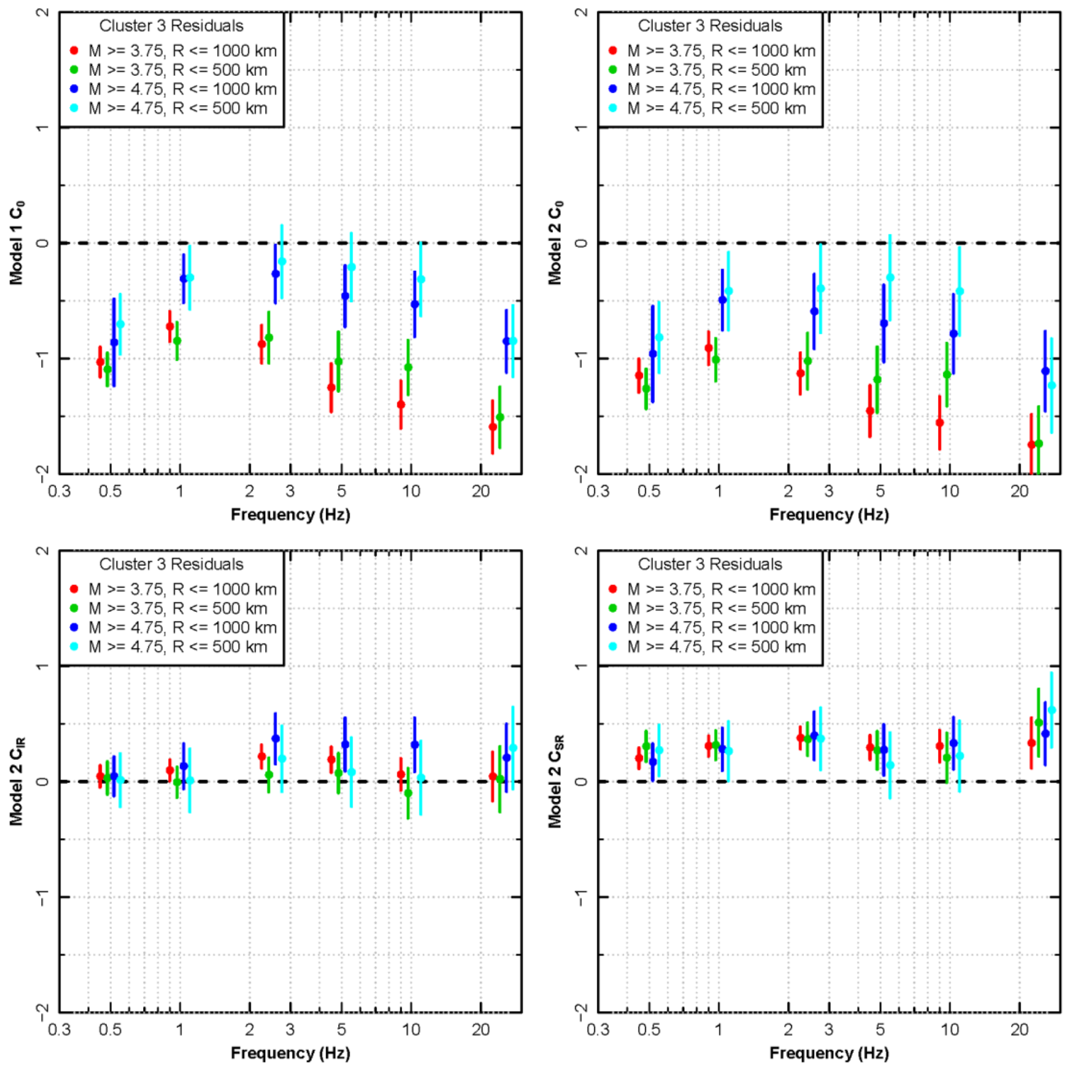

Figure 8.1-4. Coefficients of Model 1 (Equations 6.2.2-1) and Model 2 (Equation 6.2.2-2) fit to residual for the updated ground motion data base using the EPRI (2004) Cluster 3 median GMPE

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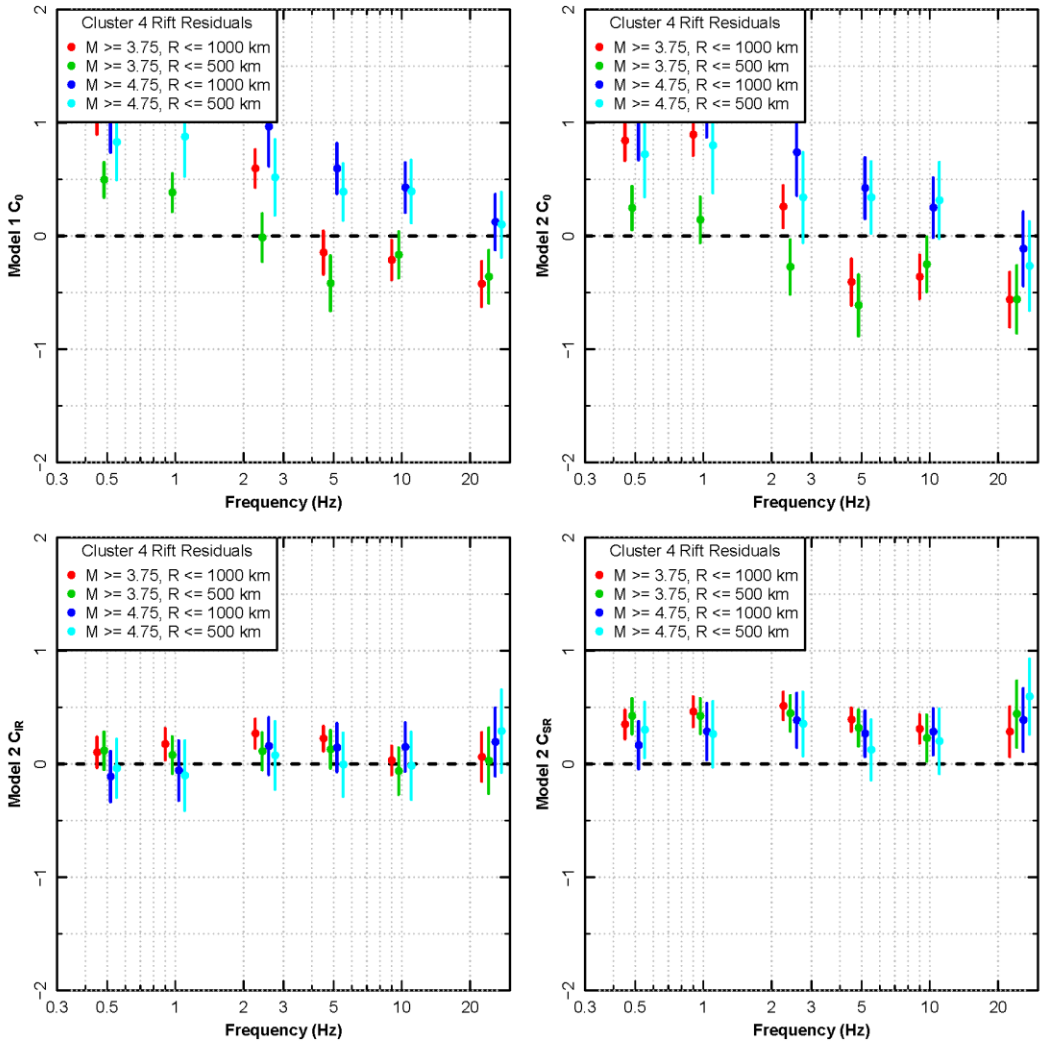

Figure 8.1-5. Coefficients of Model 1 (Equations 6.2.2-1) and Model 2 (Equation 6.2.2-2) fit to residual for the updated ground motion data base using the EPRI (2004) Cluster 4 (Rift) median GMPE

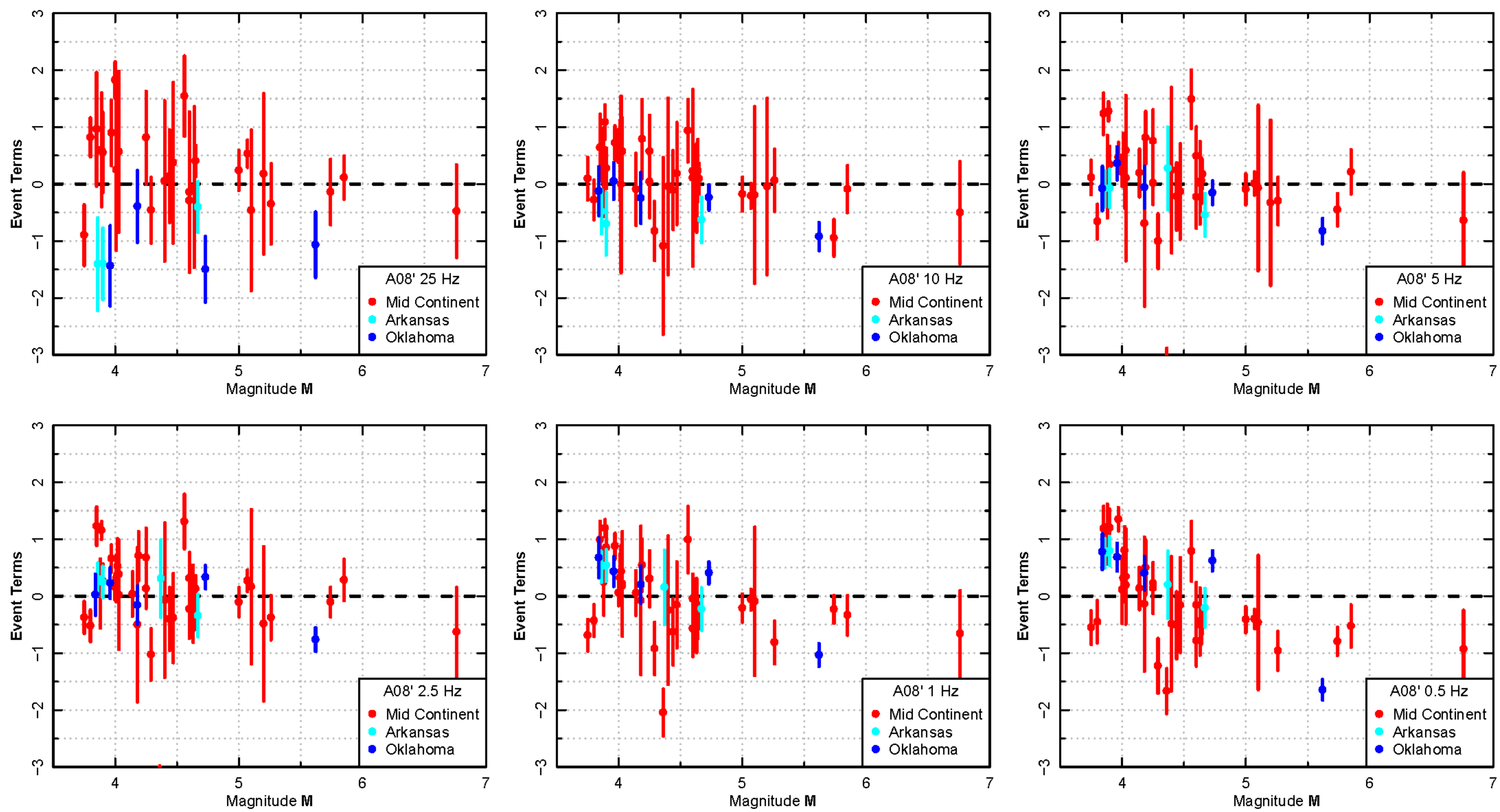

Figure 8.2.2-1. Individual earthquake event terms for rock site residuals obtained using the A08prime GMPE fit using Model 1 (Equation 6.2.2-1) plotted versus **M**

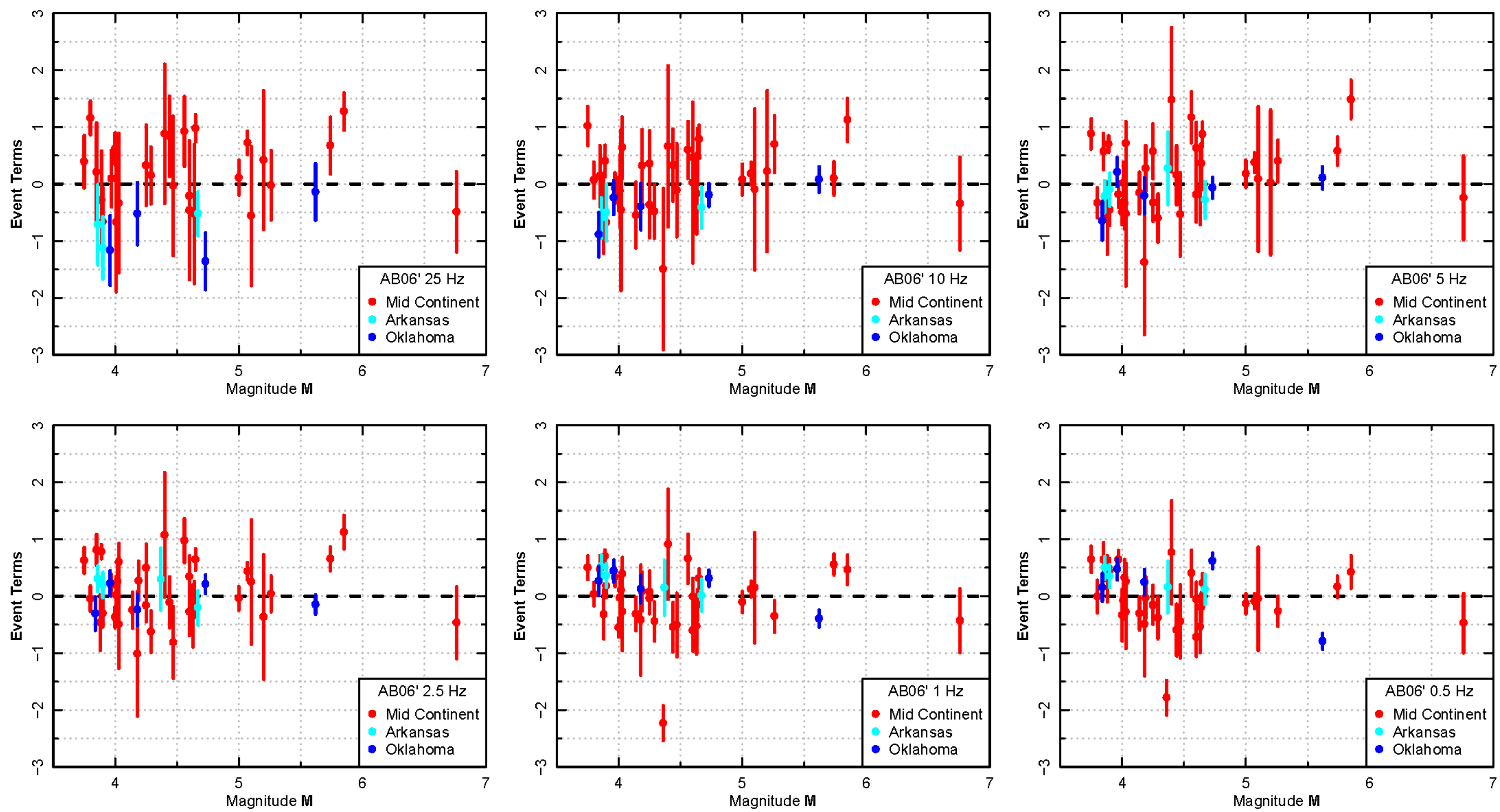

Figure 8.2.2-2. Individual earthquake event terms for rock site residuals obtained using the AB06prime GMPE fit using Model 1 (Equation 6.2.2-1) plotted versus **M**

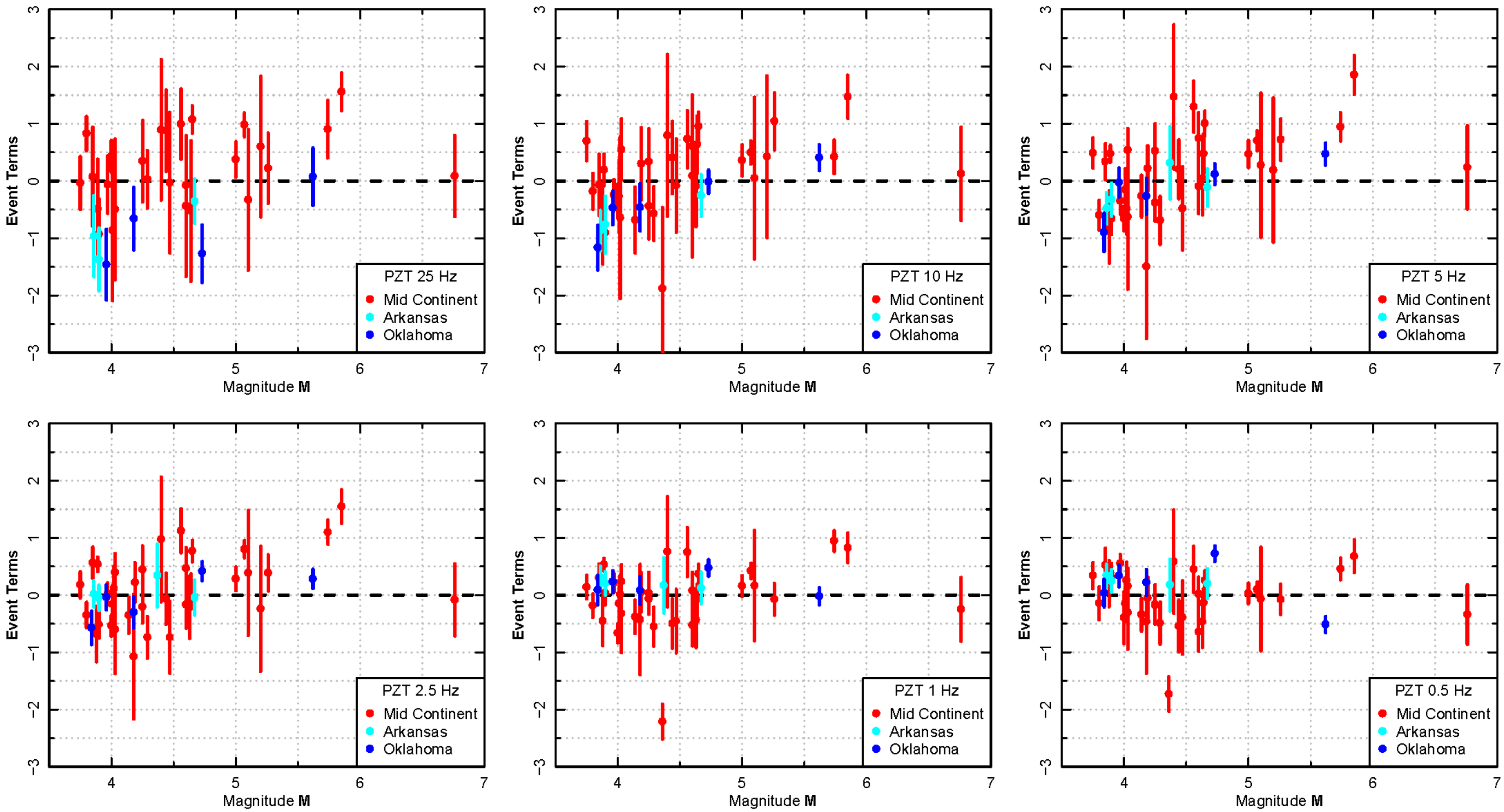

Figure 8.2.2-3. Individual earthquake event terms for rock site residuals obtained using the PZT GMPE fit using Model 1 (Equation 6.2.2-1) plotted versus **M**

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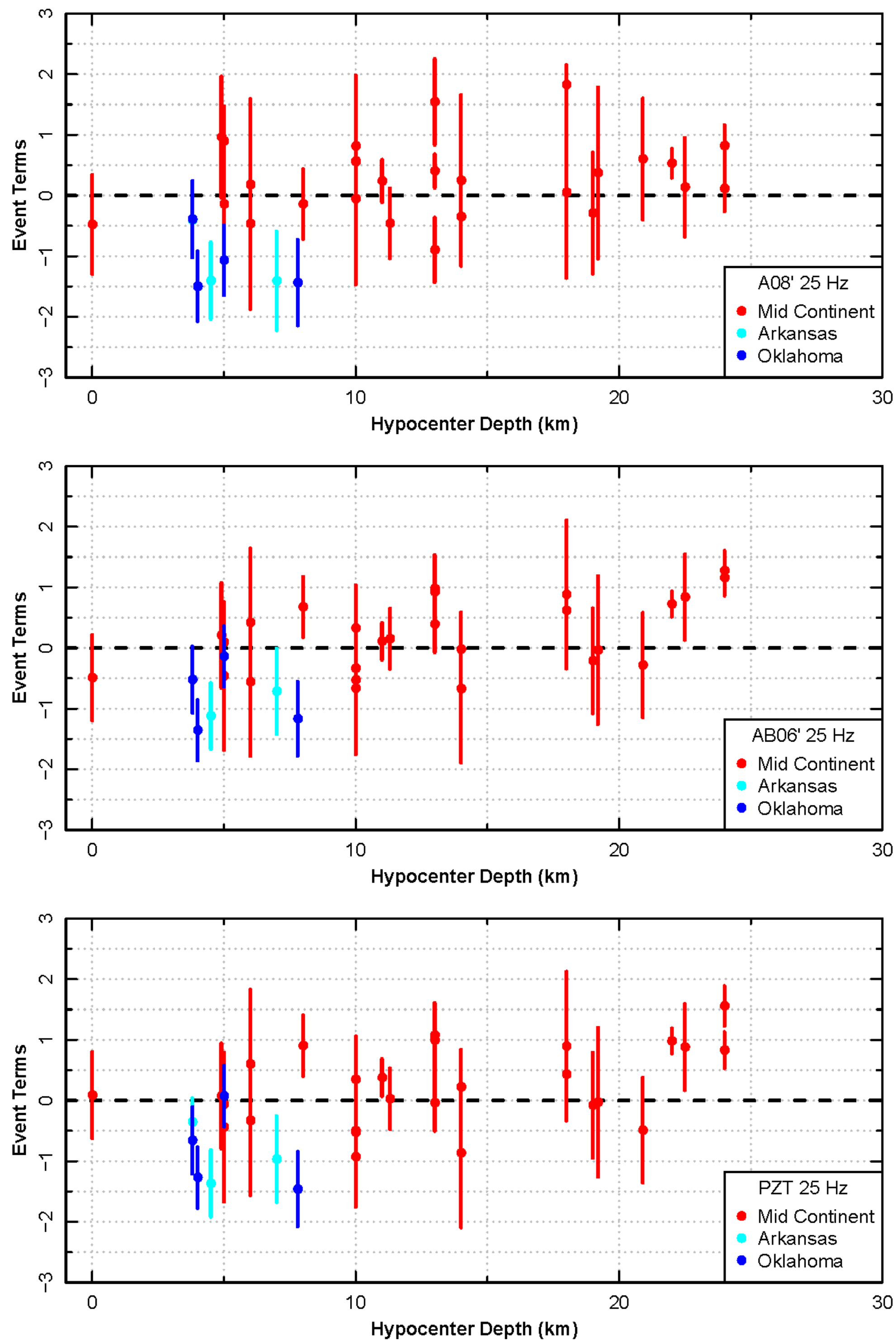

Figure 8.2.2-4. Individual earthquake event terms for rock site 25 Hz residuals plotted versus hypocenter depth

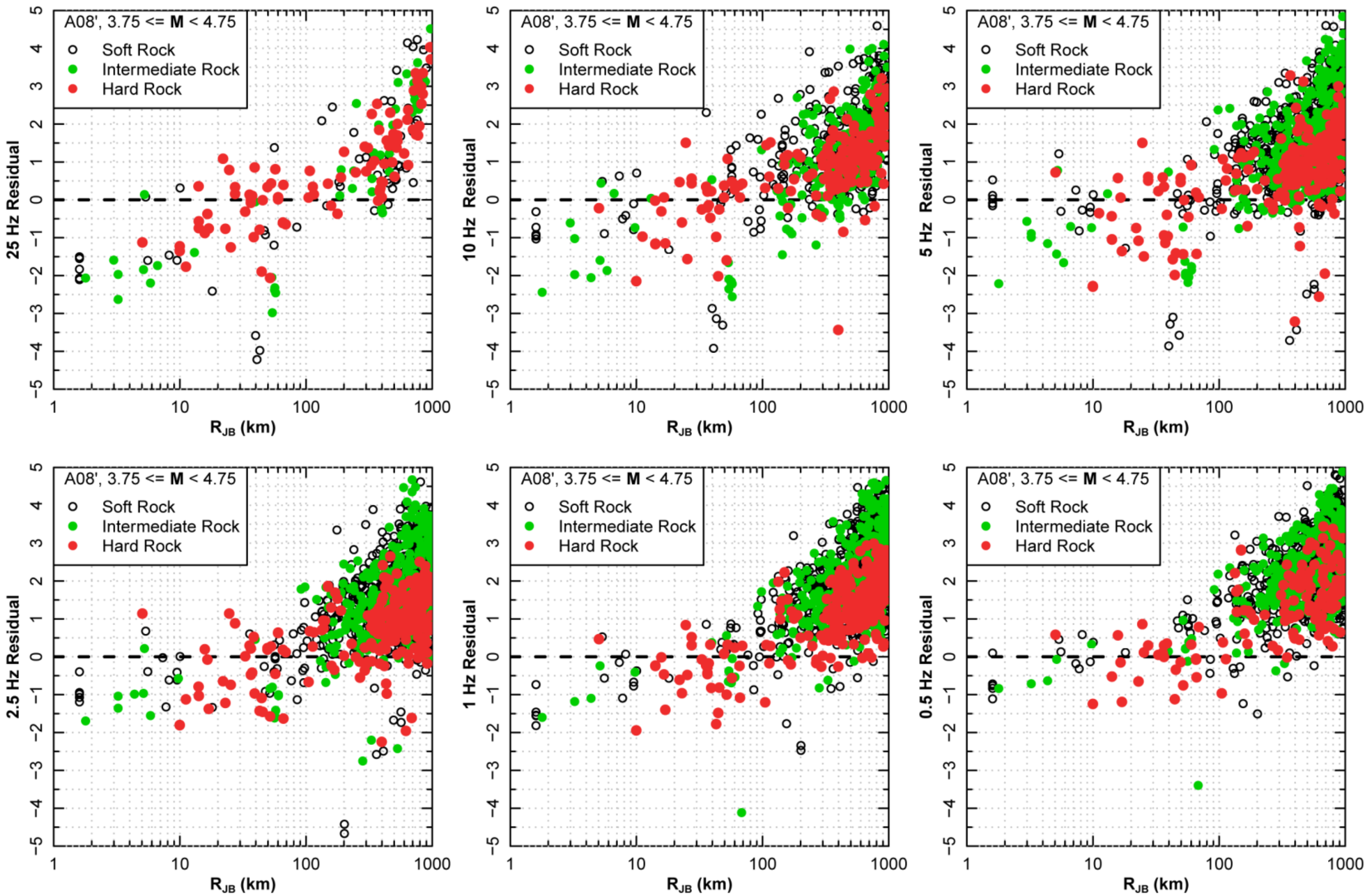

Figure 8.3.2-1a. Rock site residuals for data from 3.75 ≤ **M** < 4.75 earthquakes computed using the A08' GMPE

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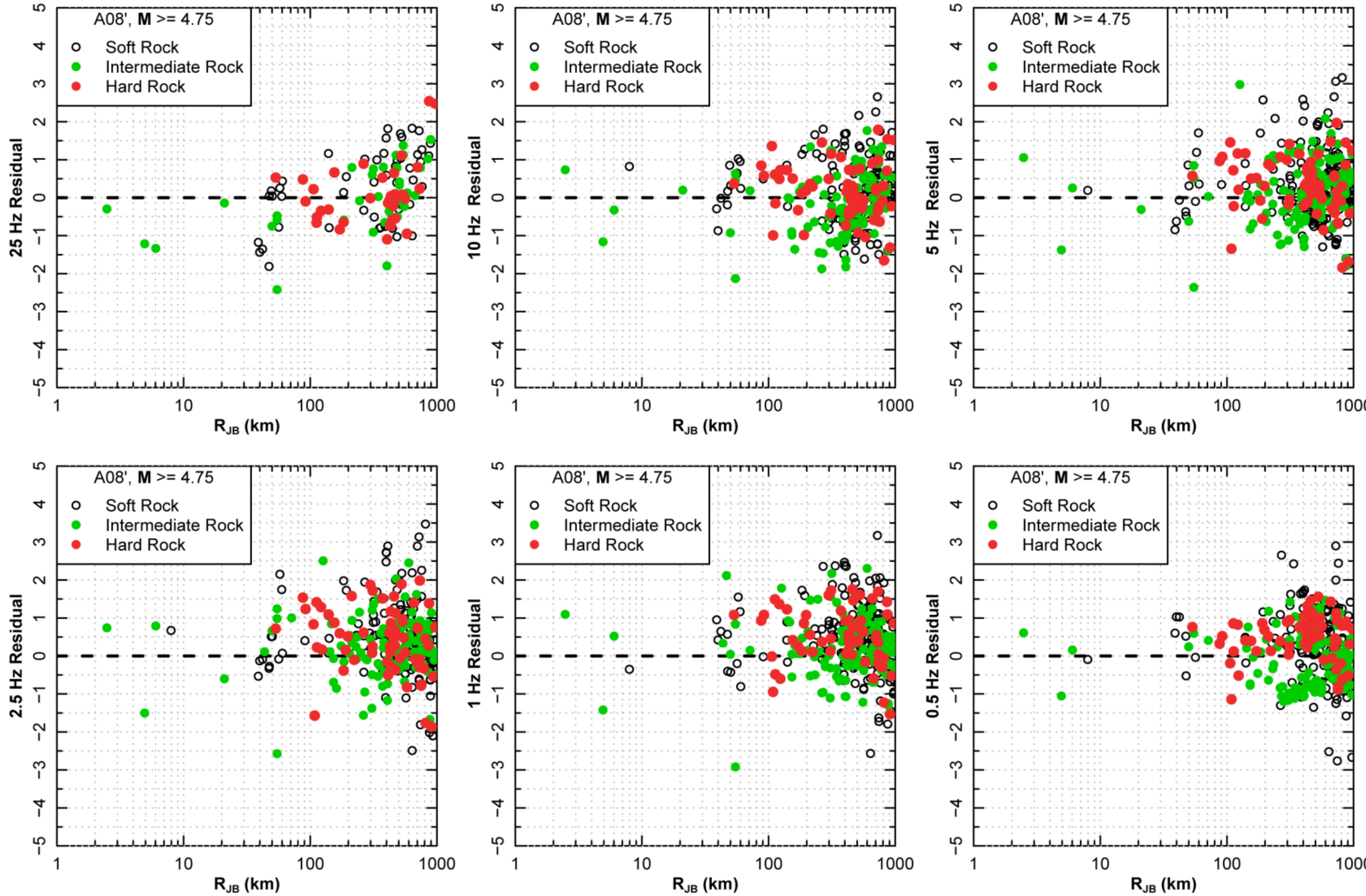

Figure 8.3.2-1b. Rock site residuals for data from **M** ≥ 4.75 earthquakes computed using the A08' GMPE

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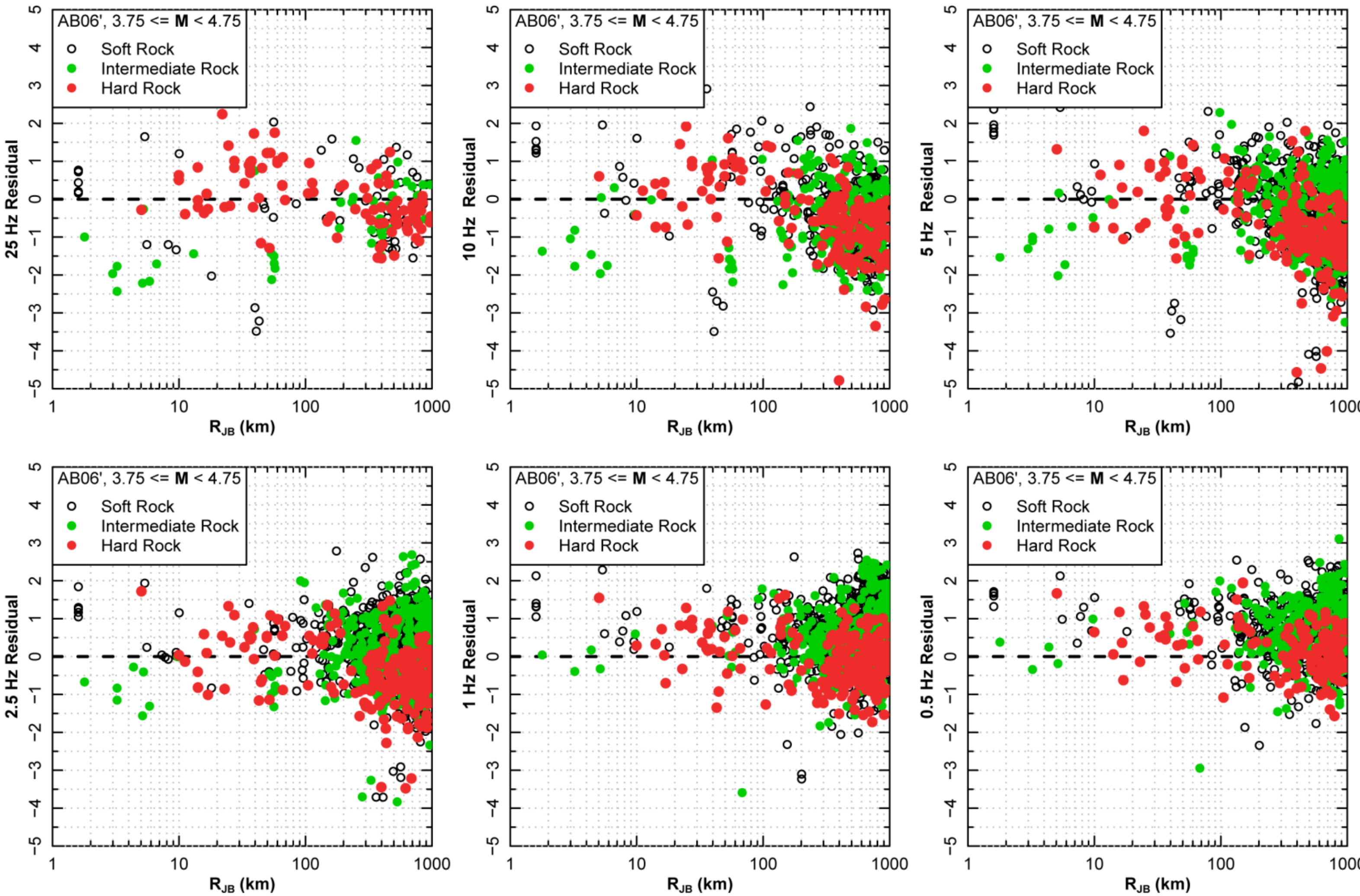

Figure 8.3.2-2a. Rock site residuals for data from 3.75 ≤ **M** < 4.75 earthquakes computed using the AB06' GMPE

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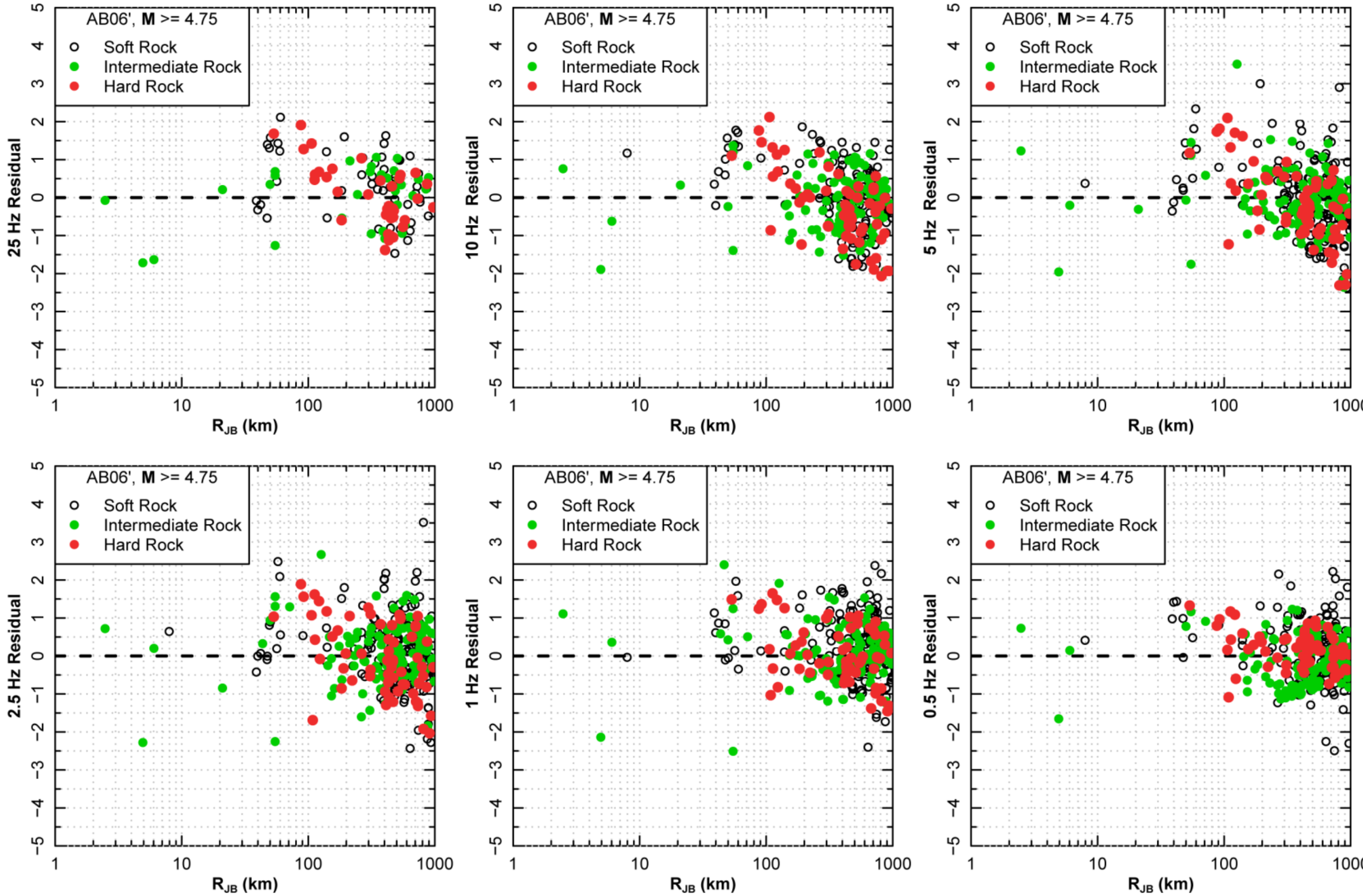

Figure 8.3.2-2b. Rock site residuals for data from **M** ≥ 4.75 earthquakes computed using the AB06’ GMPE

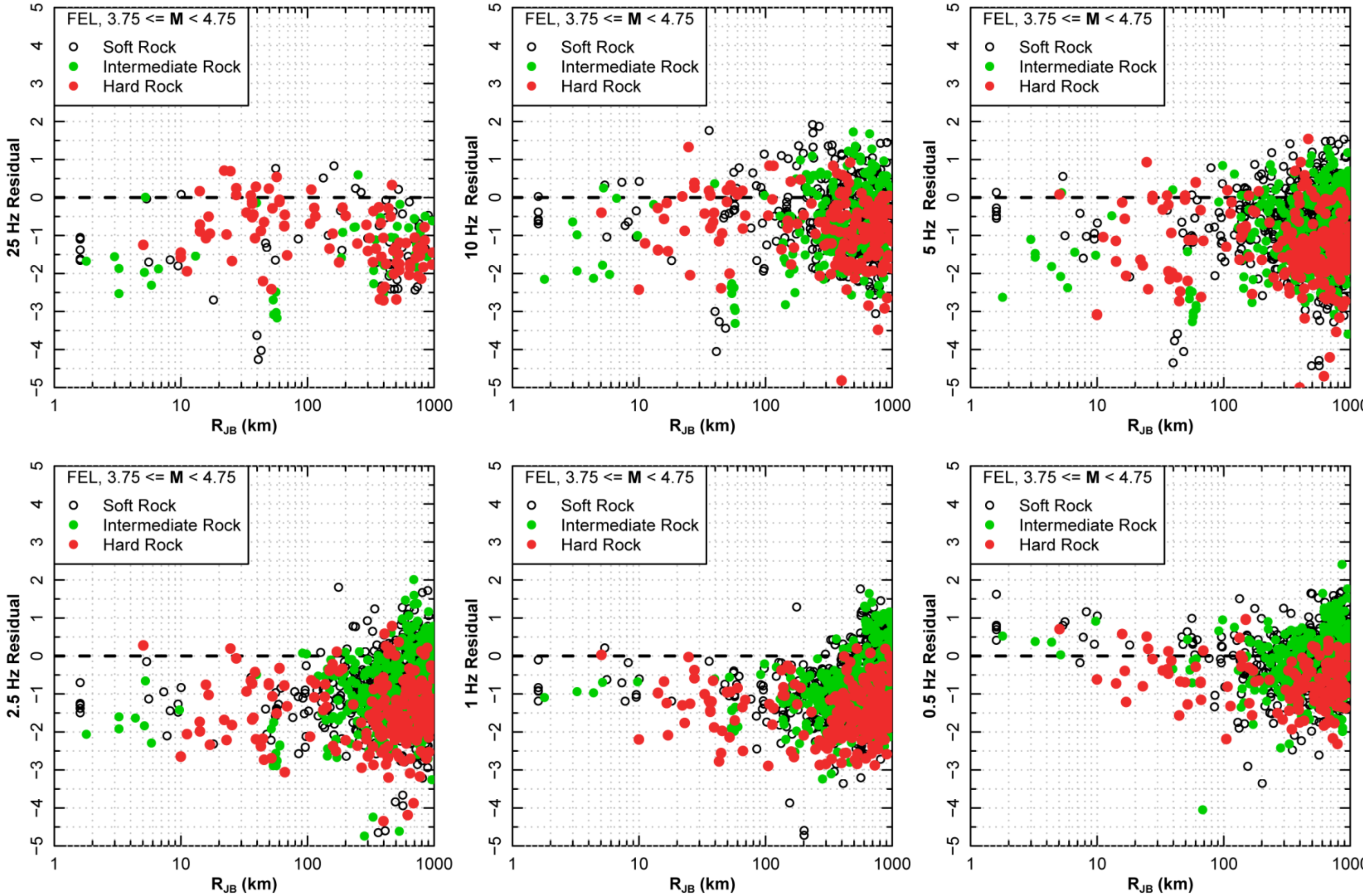

Figure 8.3.2-3a. Rock site residuals for data from 3.75 ≤ **M** < 4.75 earthquakes computed using the FEL GMPE

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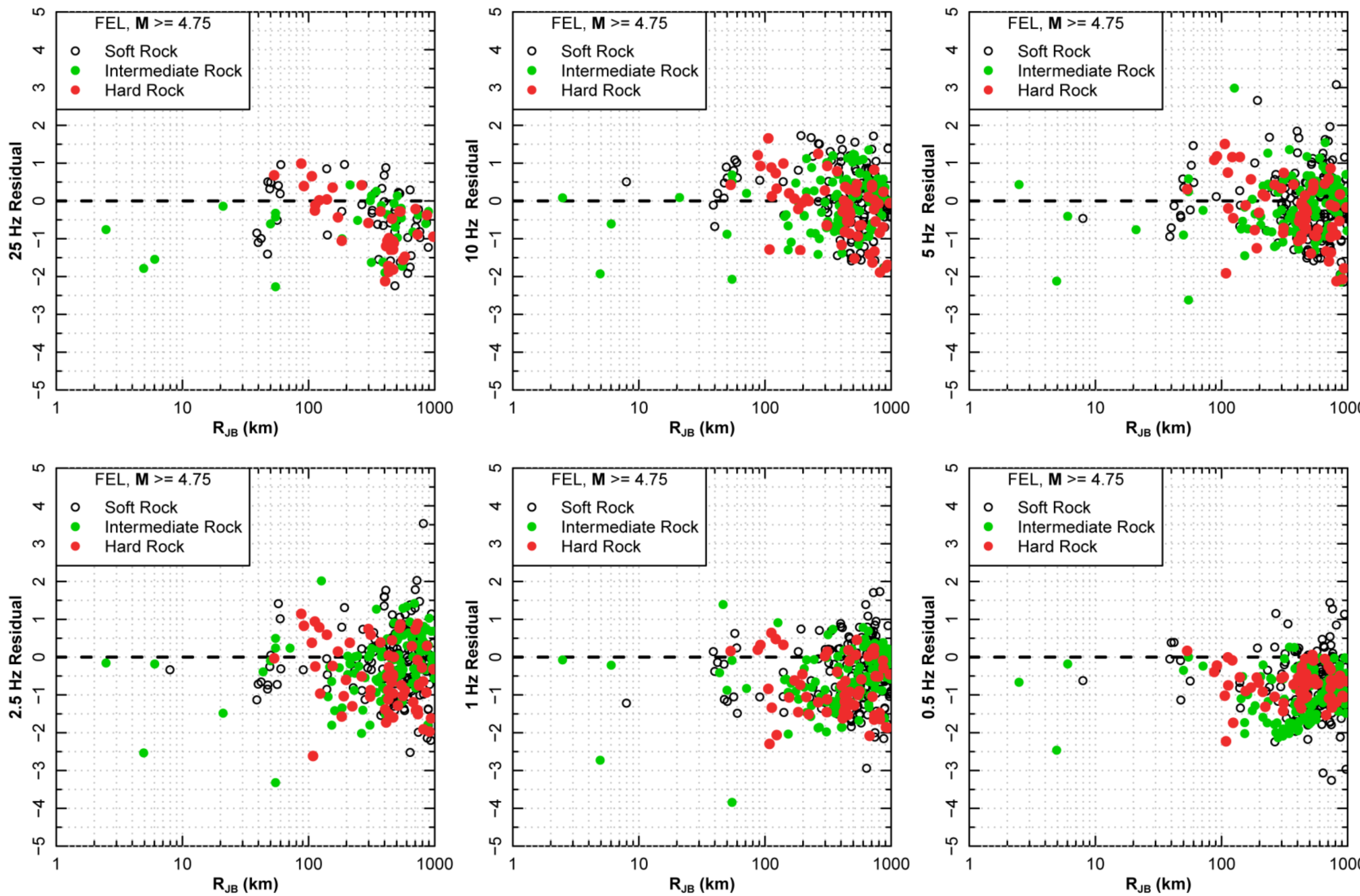

Figure 8.3.2-3b. Rock site residuals for data from **M** ≥ 4.75 earthquakes computed using the FEL GMPE

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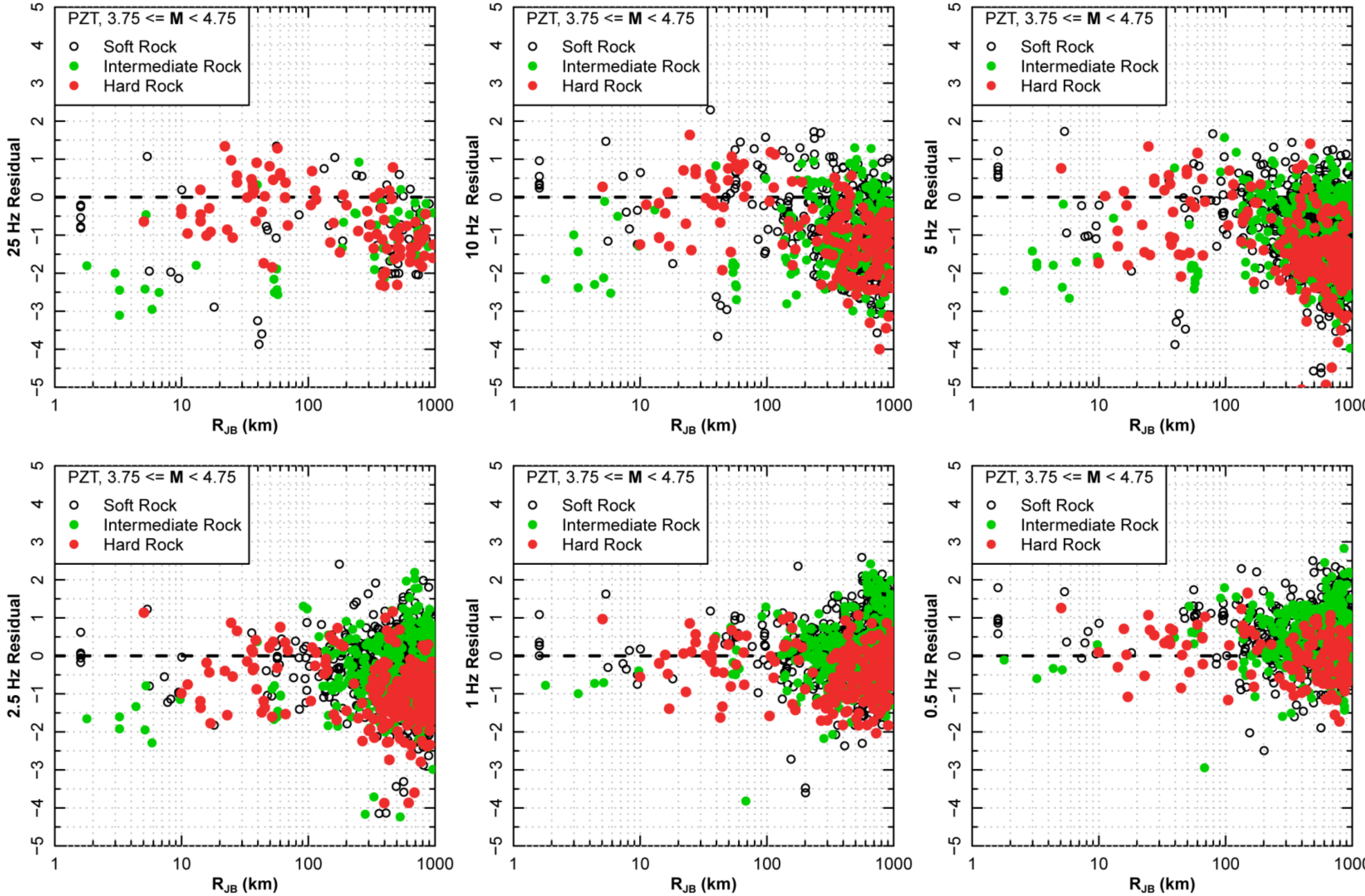

Figure 8.3.2-4a. Rock site residuals for data from 3.75 ≤ **M** < 4.75 earthquakes computed using the PZT GMPE

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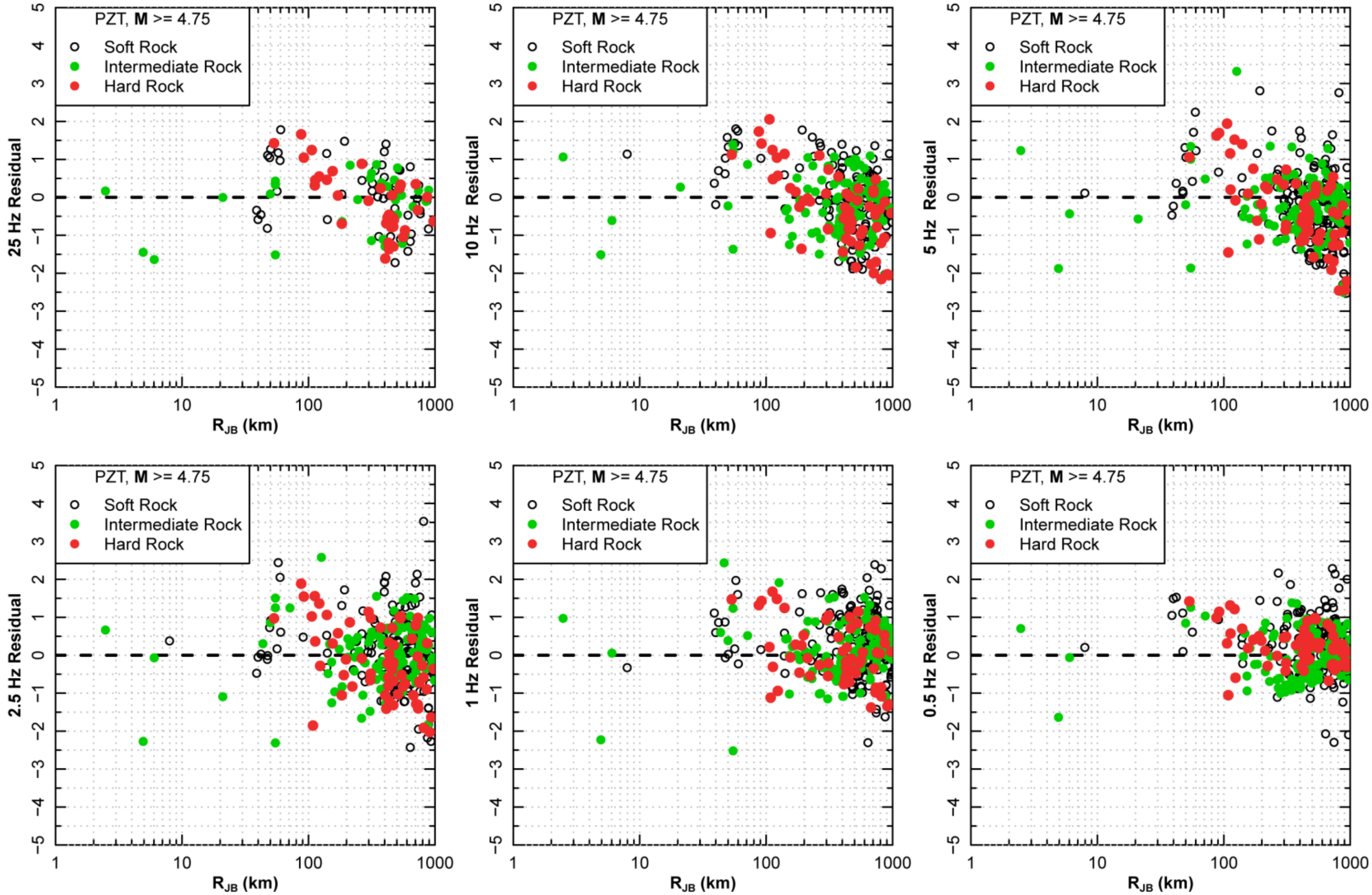

Figure 8.3.2-4b. Rock site residuals for data from **M** ≥ 4.75 earthquakes computed using the PZT GMPE

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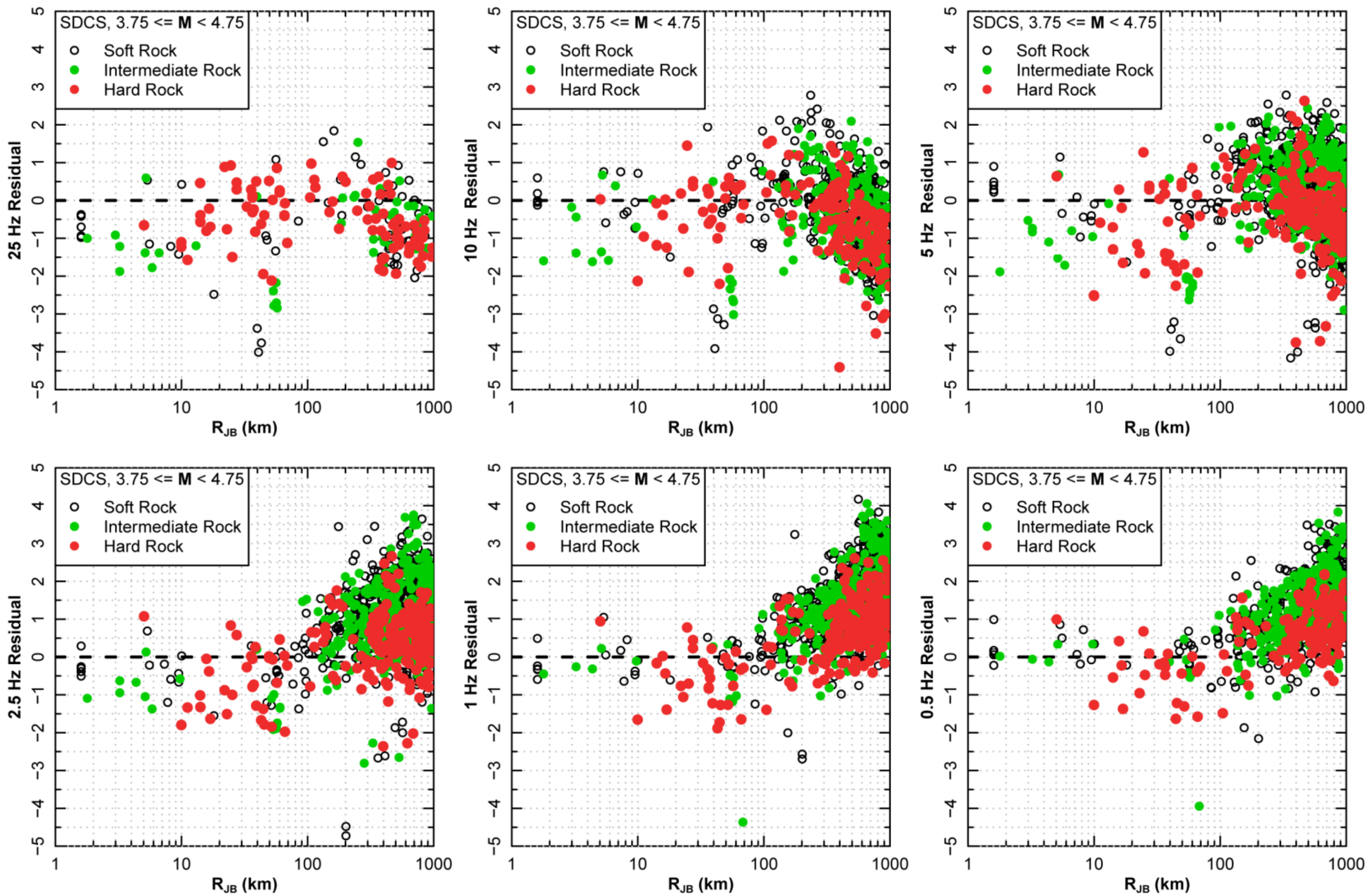

Figure 8.3.2-5a. Rock site residuals for data from 3.75 ≤ **M** < 4.75 earthquakes computed using the SDCS GMPE

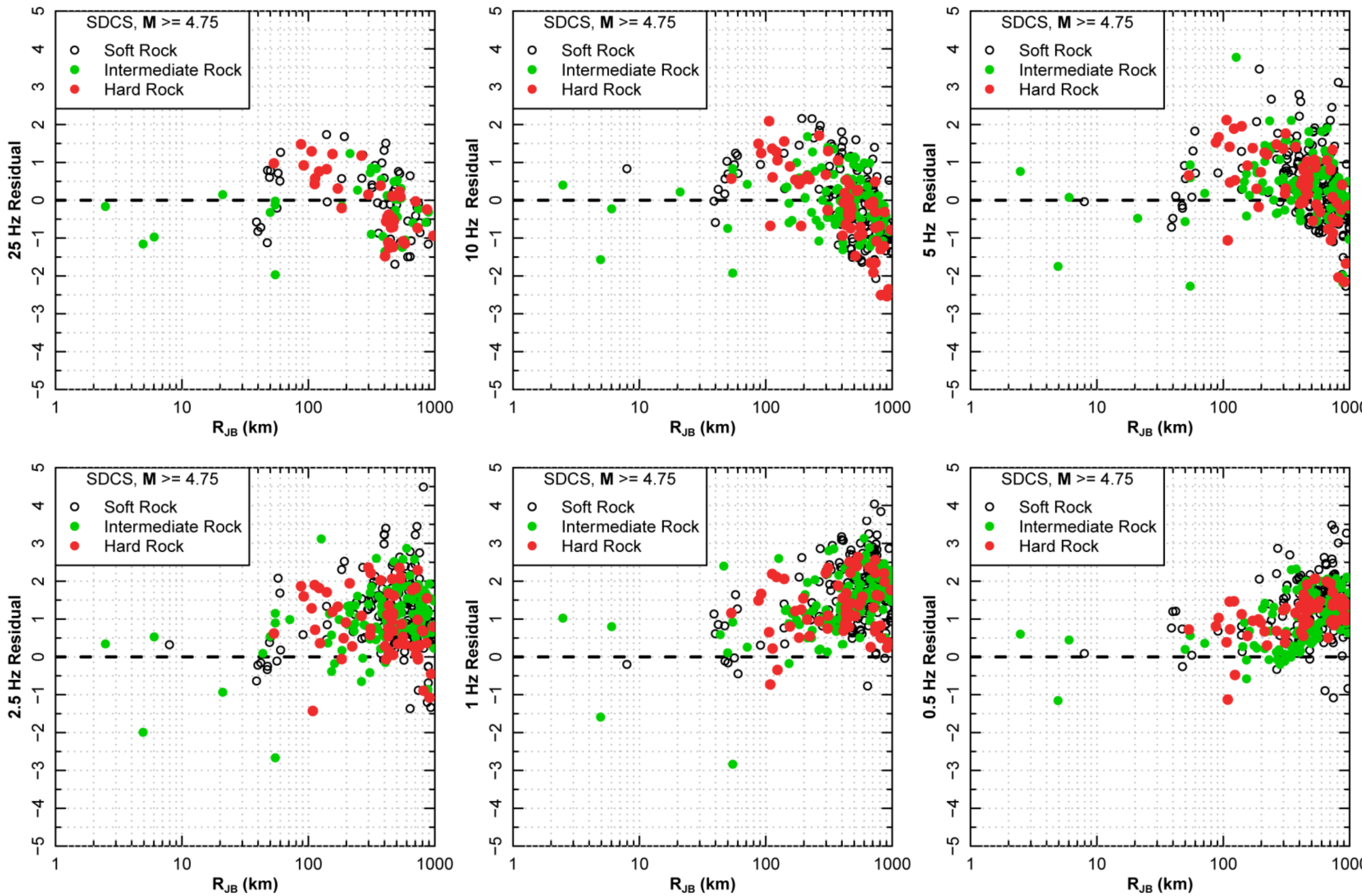

Figure 8.3.2-5b. Rock site residuals for data from **M** ≥ 4.75 earthquakes computed using the SDCS GMPE

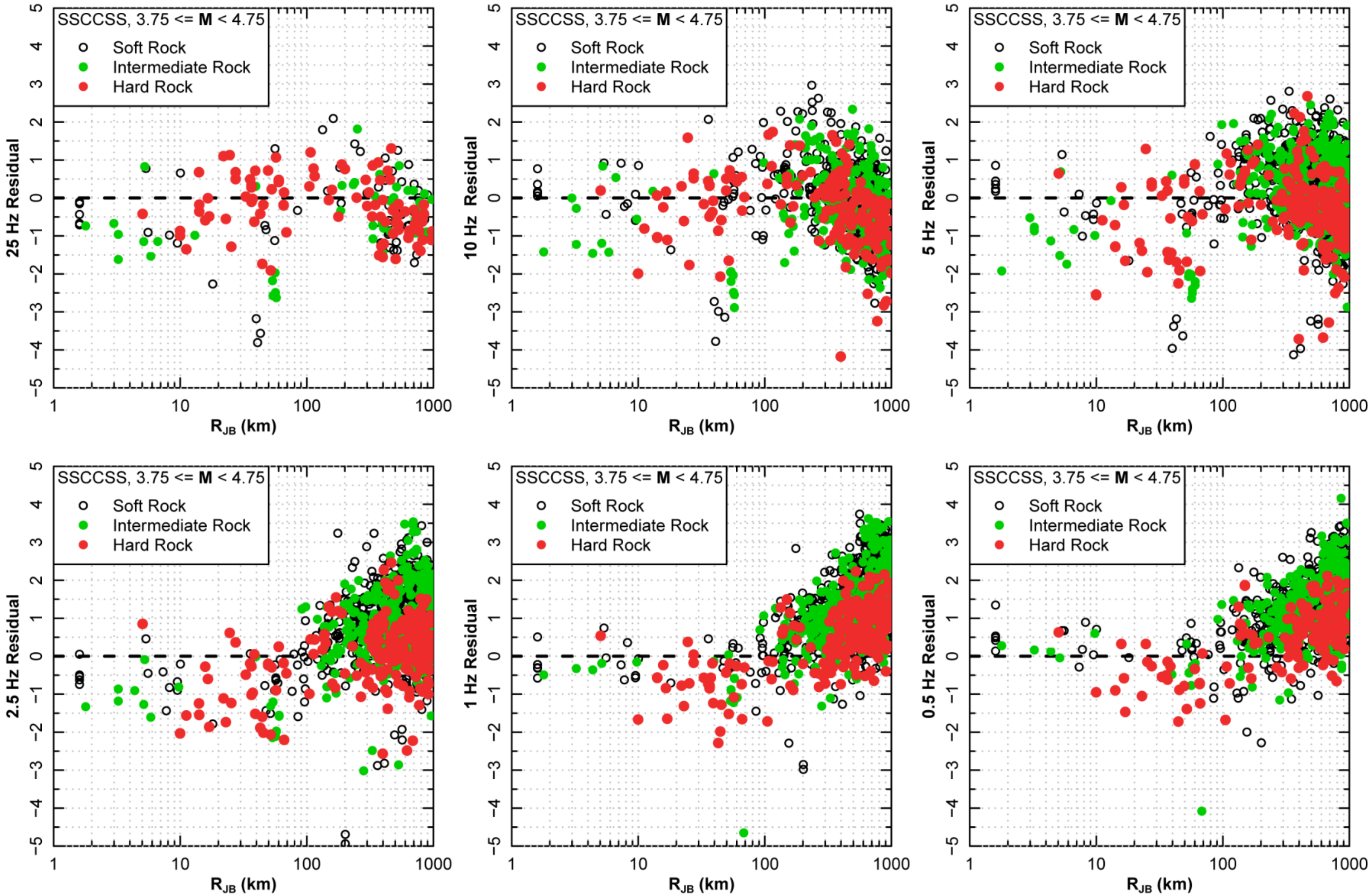

Figure 8.3.2-6a. Rock site residuals for data from 3.75 ≤ **M** < 4.75 earthquakes computed using the SSCCSS GMPE

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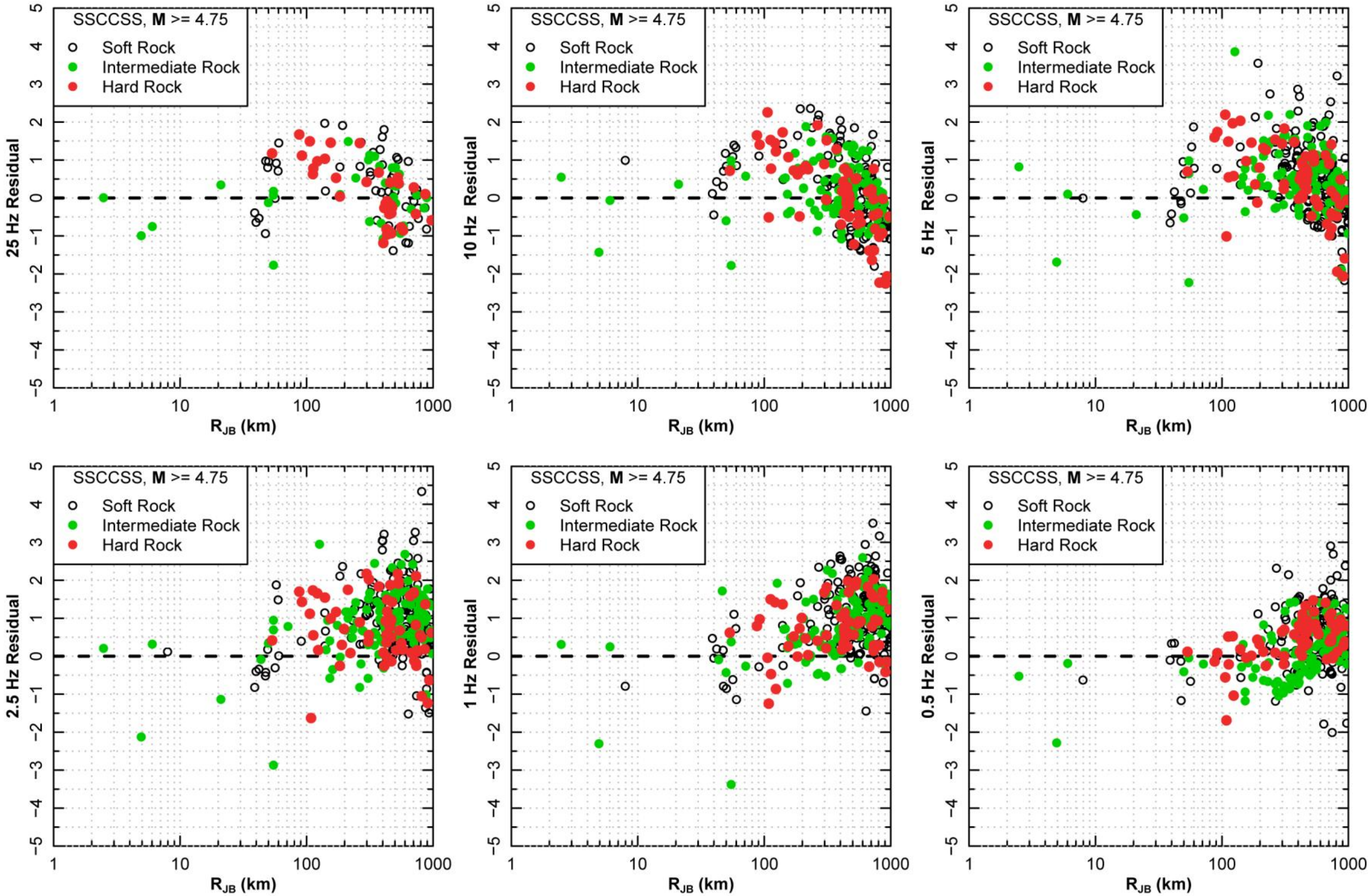

Figure 8.3.2-6b. Rock site residuals for data from **M** ≥ 4.75 earthquakes computed using the SSCCS GMPE

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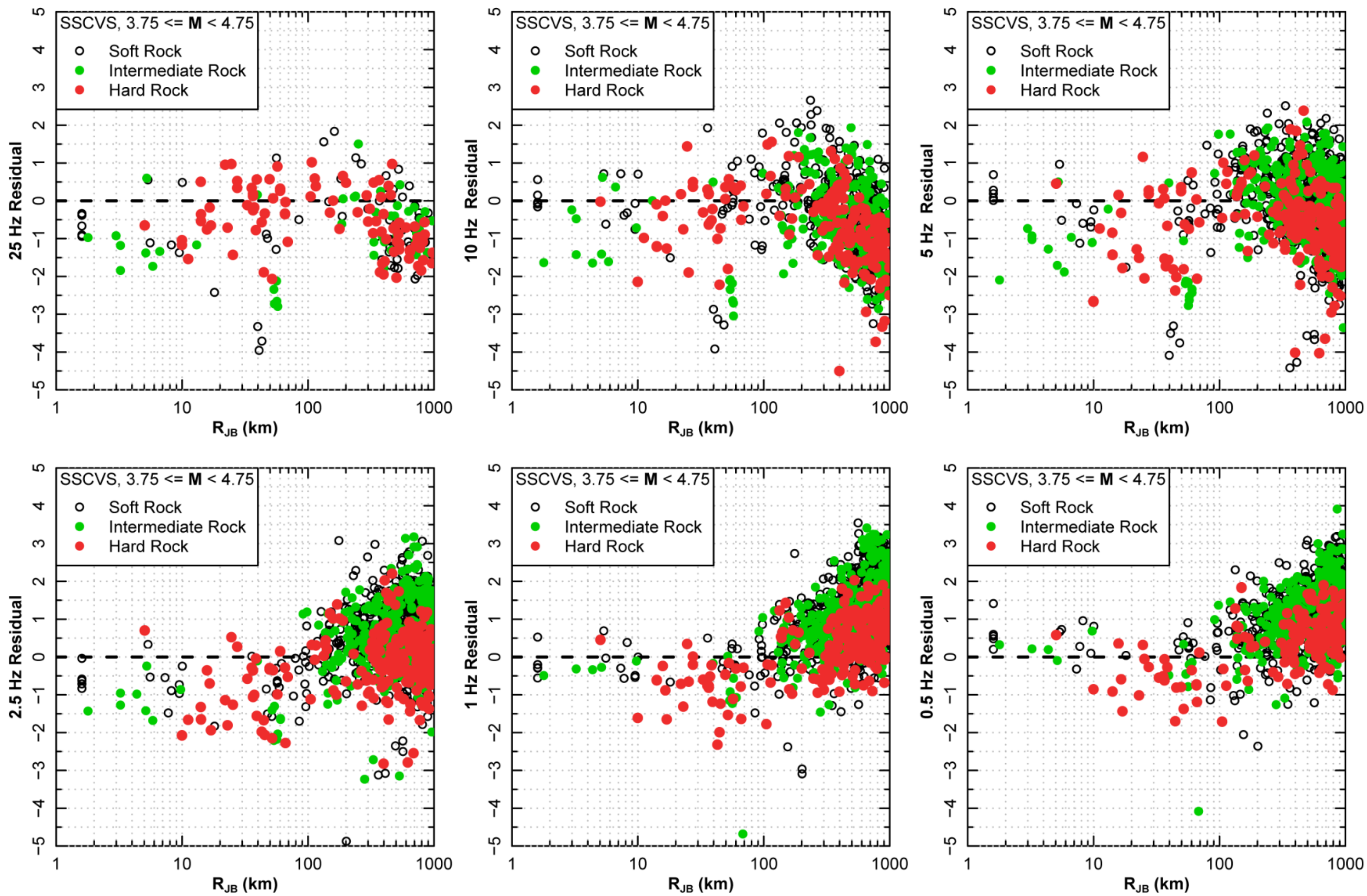

Figure 8.3.2-7a. Rock site residuals for data from 3.75 ≤ **M** < 4.75 earthquakes computed using the SSCVS GMPE

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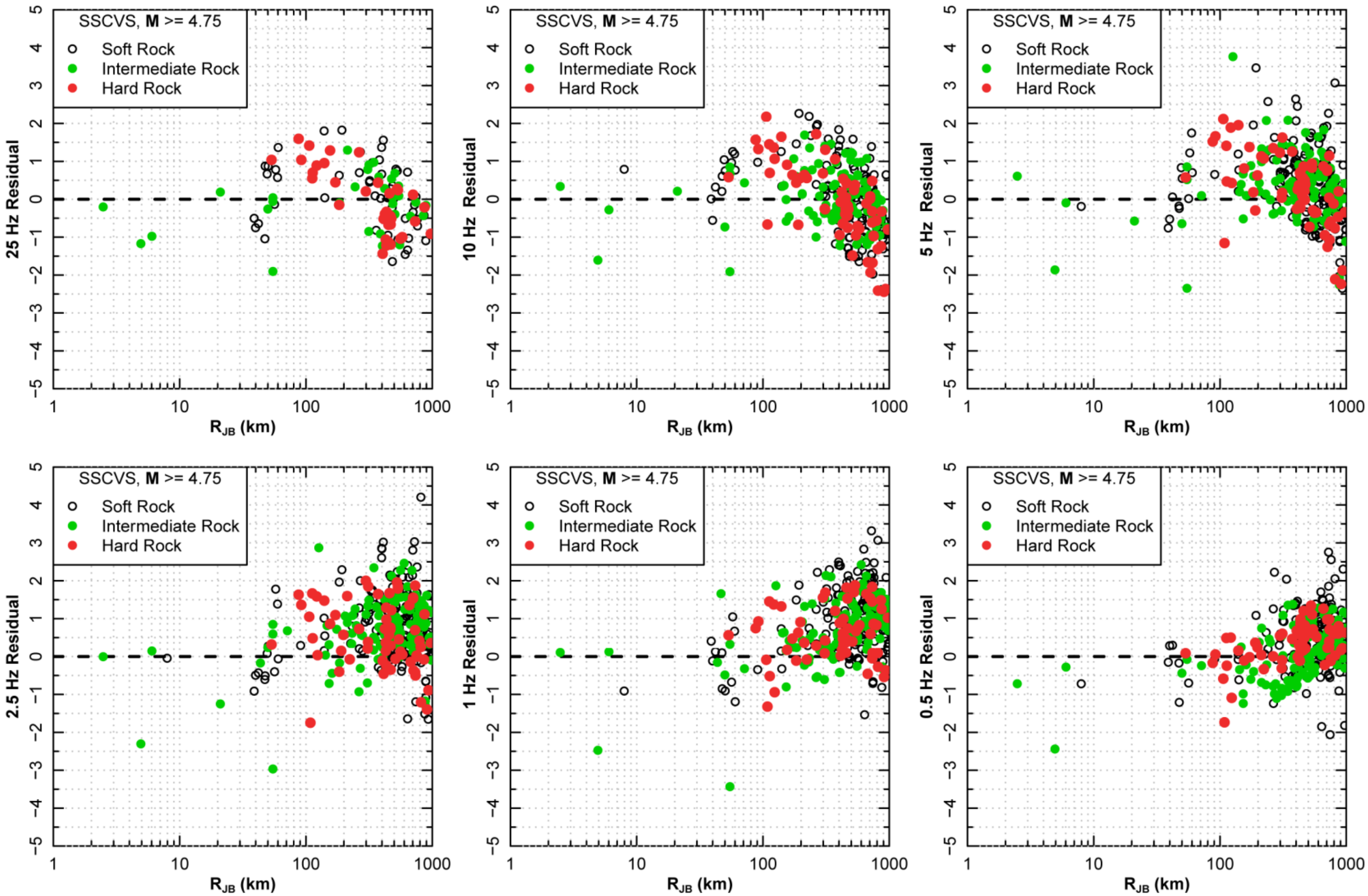

Figure 8.3.2-7b. Rock site residuals for data from **M** ≥ 4.75 earthquakes computed using the SSCVS GMPE

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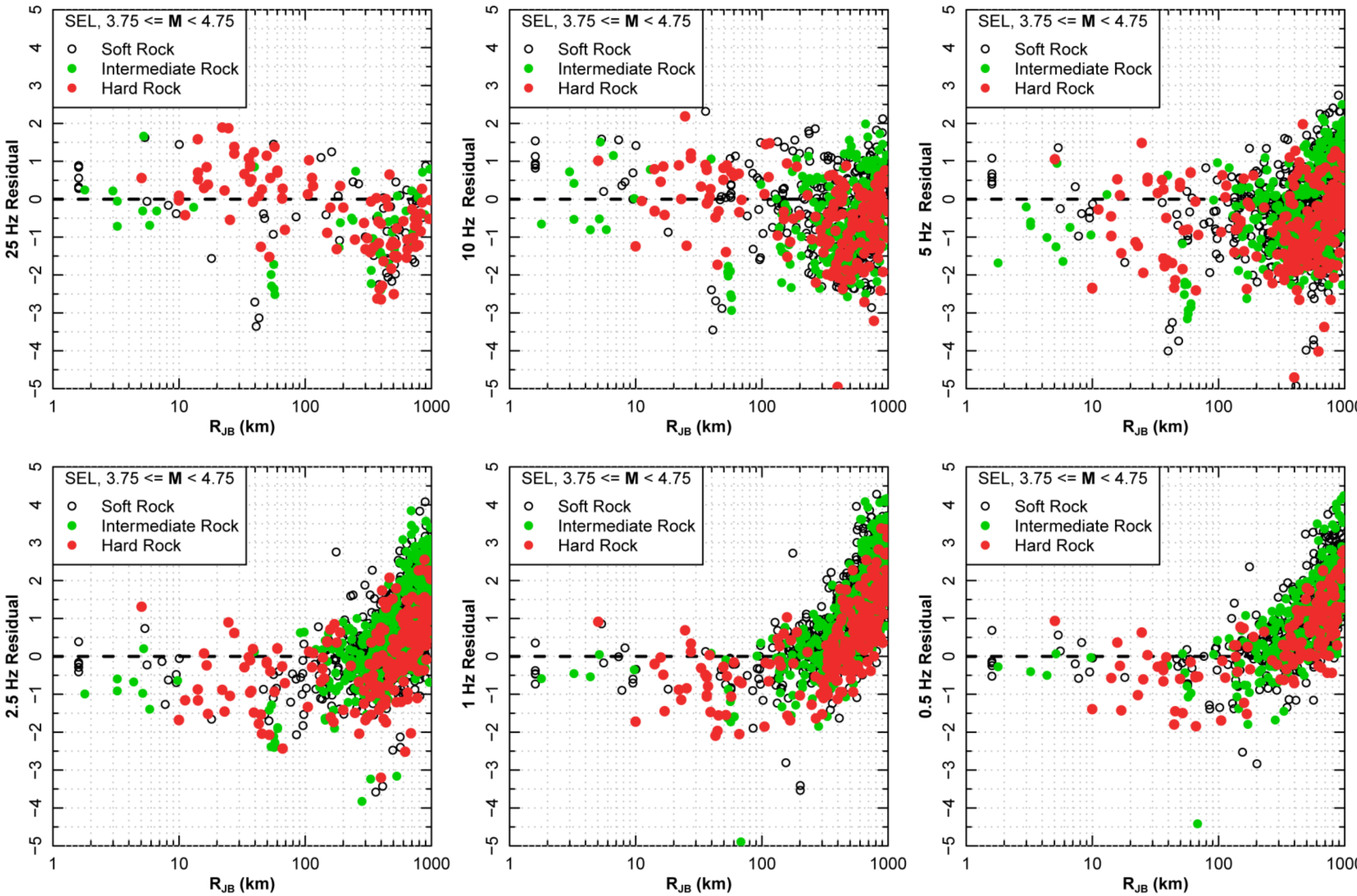

Figure 8.3.2-8a. Rock site residuals for data from 3.75 ≤ **M** < 4.75 earthquakes computed using the SEL GMPE

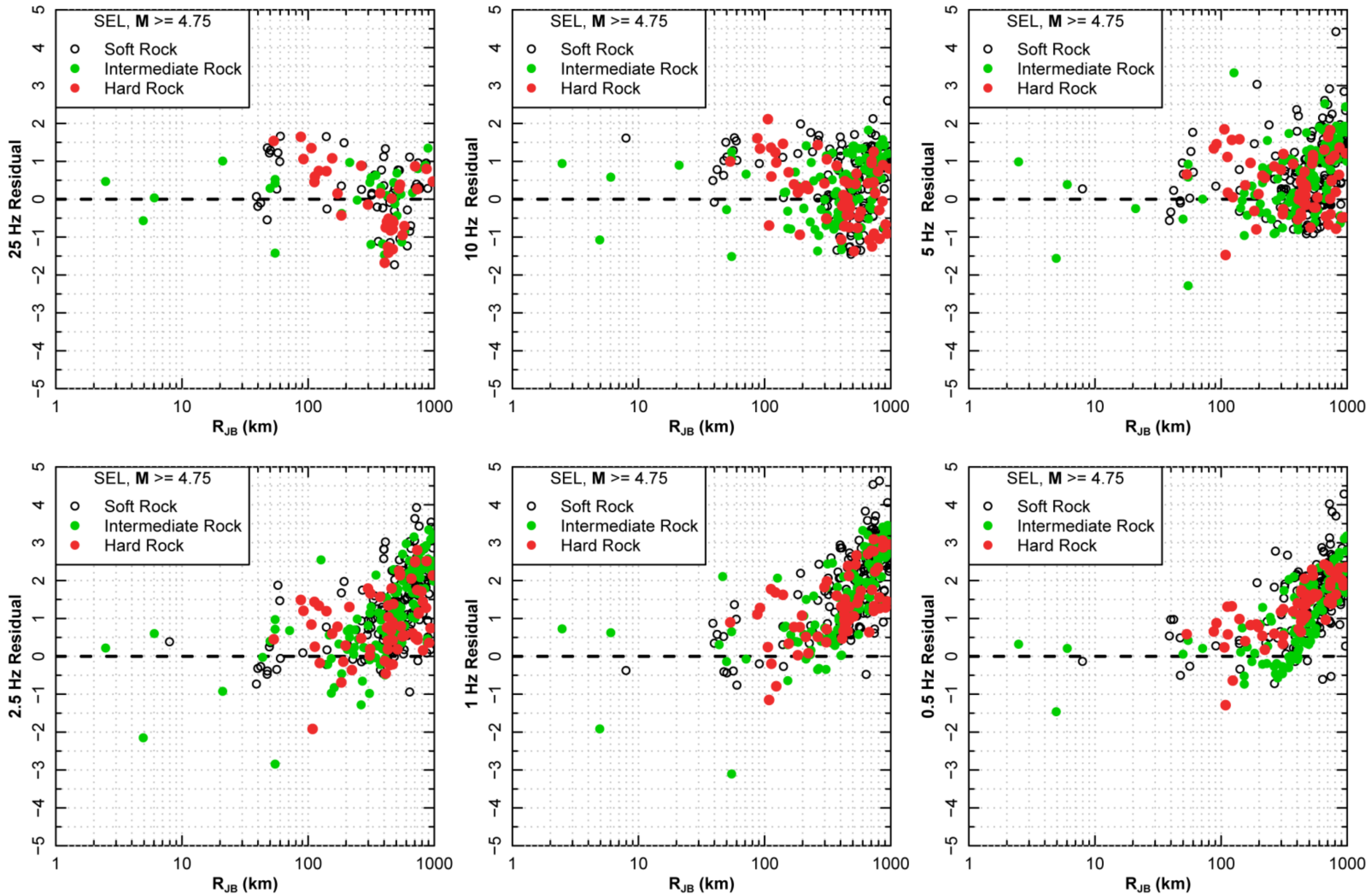

Figure 8.3.2-8b. Rock site residuals for data from **M** ≥ 4.75 earthquakes computed using the SEL GMPE

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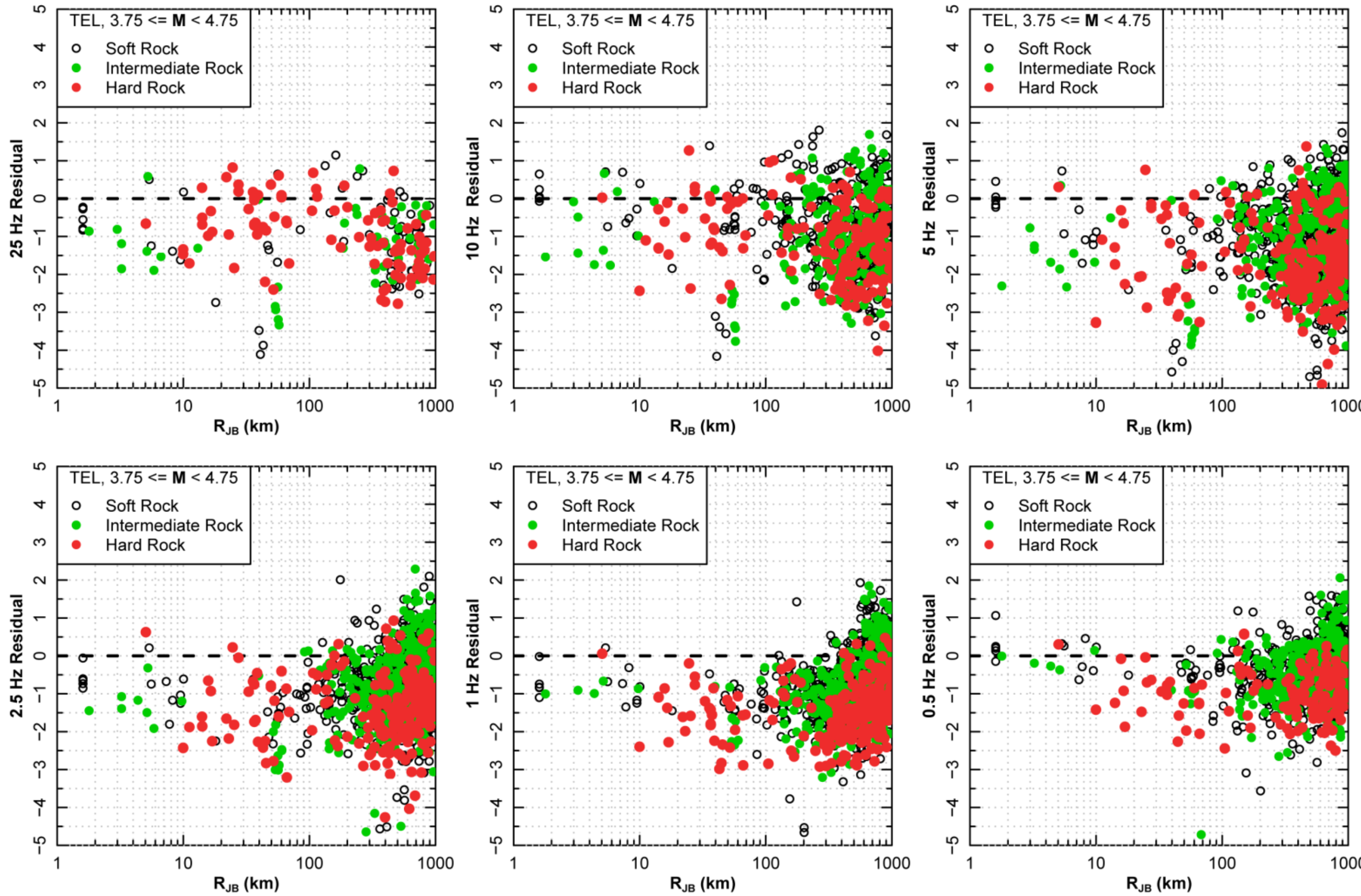

Figure 8.3.2-9a. Rock site residuals for data from 3.75 ≤ **M** < 4.75 earthquakes computed using the TEL GMPE

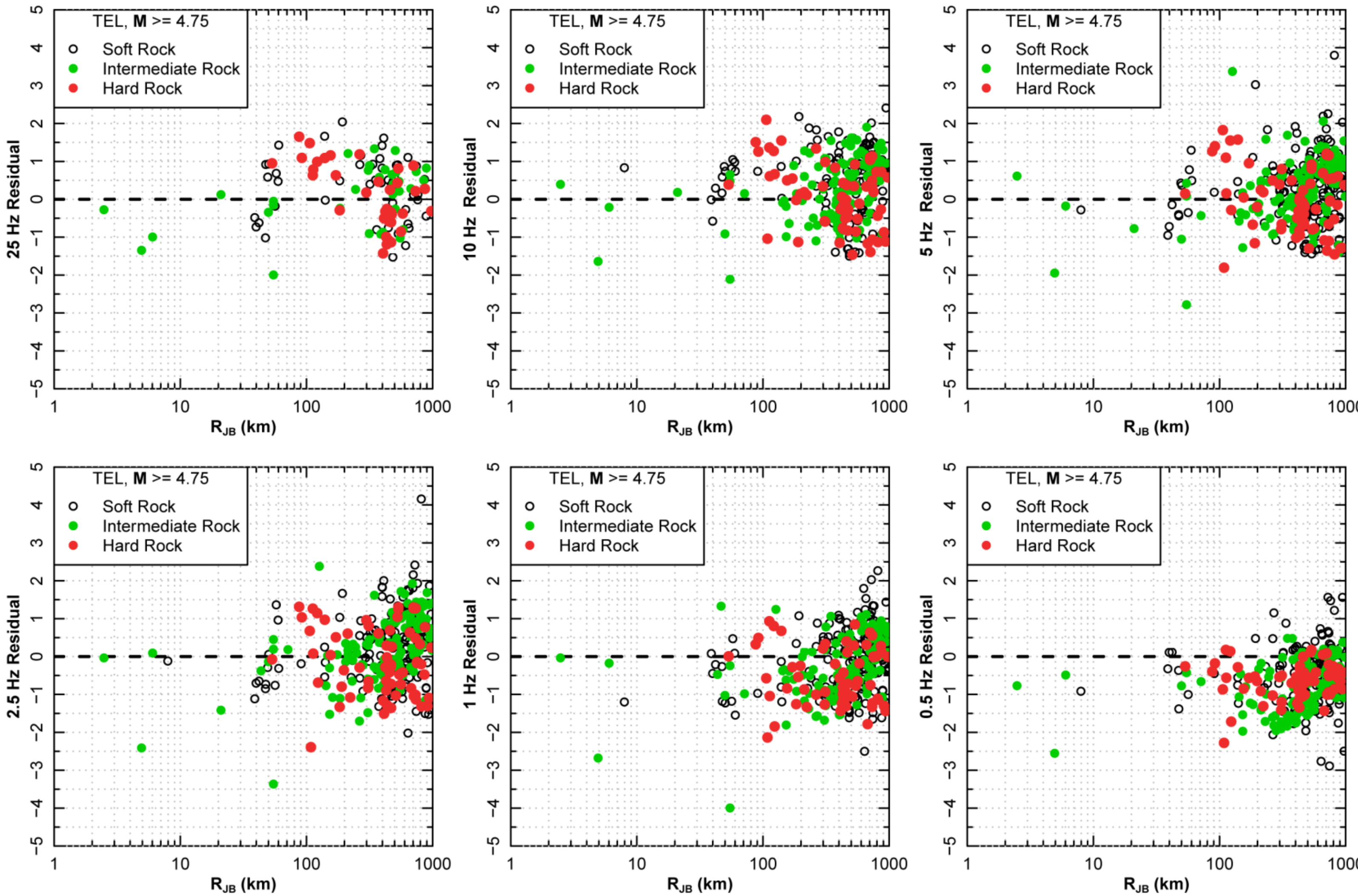

Figure 8.3.2-9b. Rock site residuals for data from **M** ≥ 4.75 earthquakes computed using the TEL GMPE

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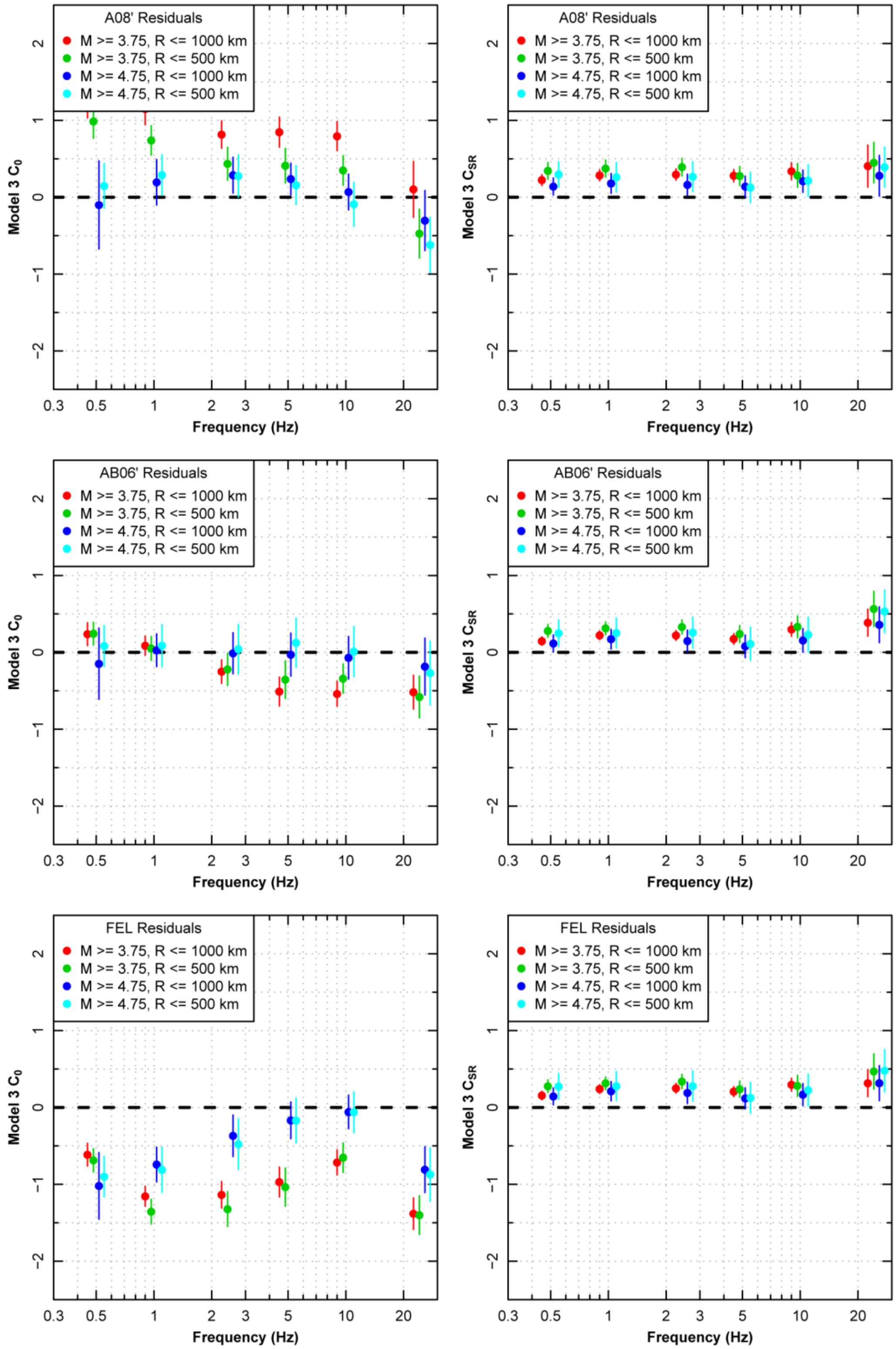

Figure 8.3.2-10a. Coefficients C_0 and C_{SR} obtained from fitting the rock site residuals for the A08', AB06', and FEL GMPEs using Model 3 (Equation 6.2.2-3)

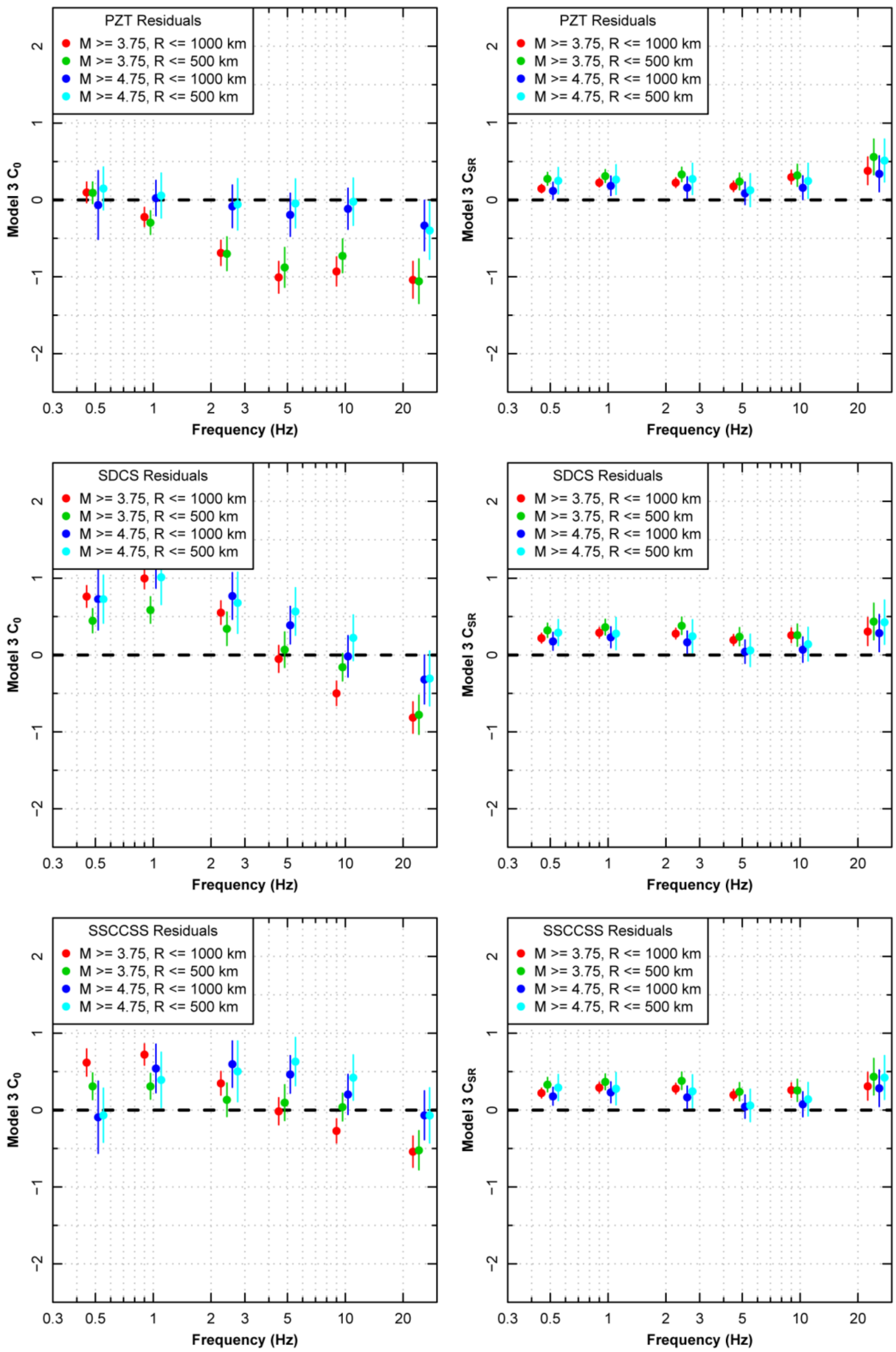

Figure 8.3.2-10b. Coefficients C_0 and C_{SR} obtained from fitting the rock site residuals for the PZT, SDCS, and SSCCS GMPEs using Model 3 (Equation 6.2.2-3)

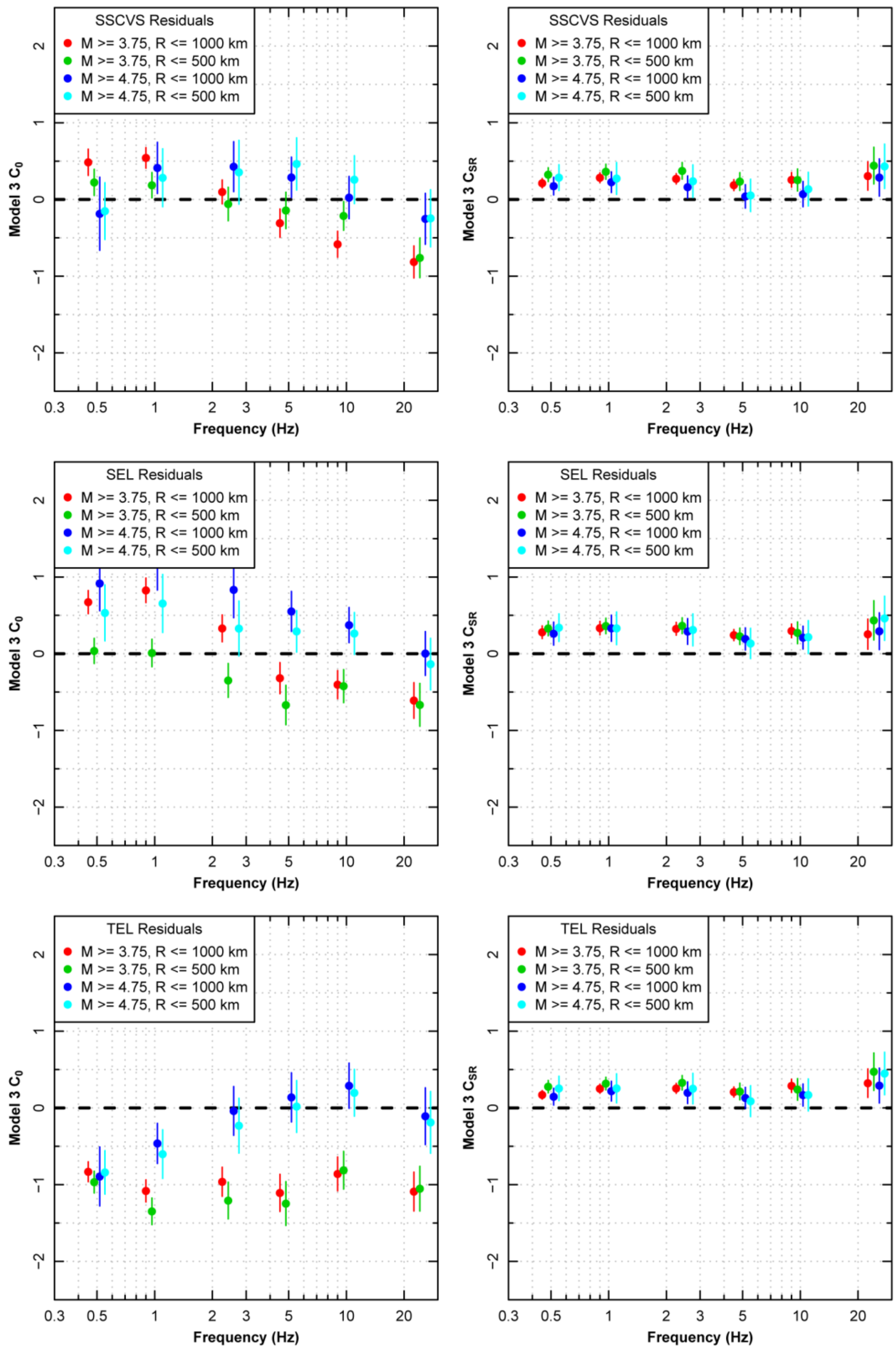

Figure 8.3.2-10c. Coefficients C_0 and C_{SR} obtained from fitting the rock site residuals for the SSCVS, SEL, and TFEL GMPEs using Model 3 (Equation 6.2.2-3)

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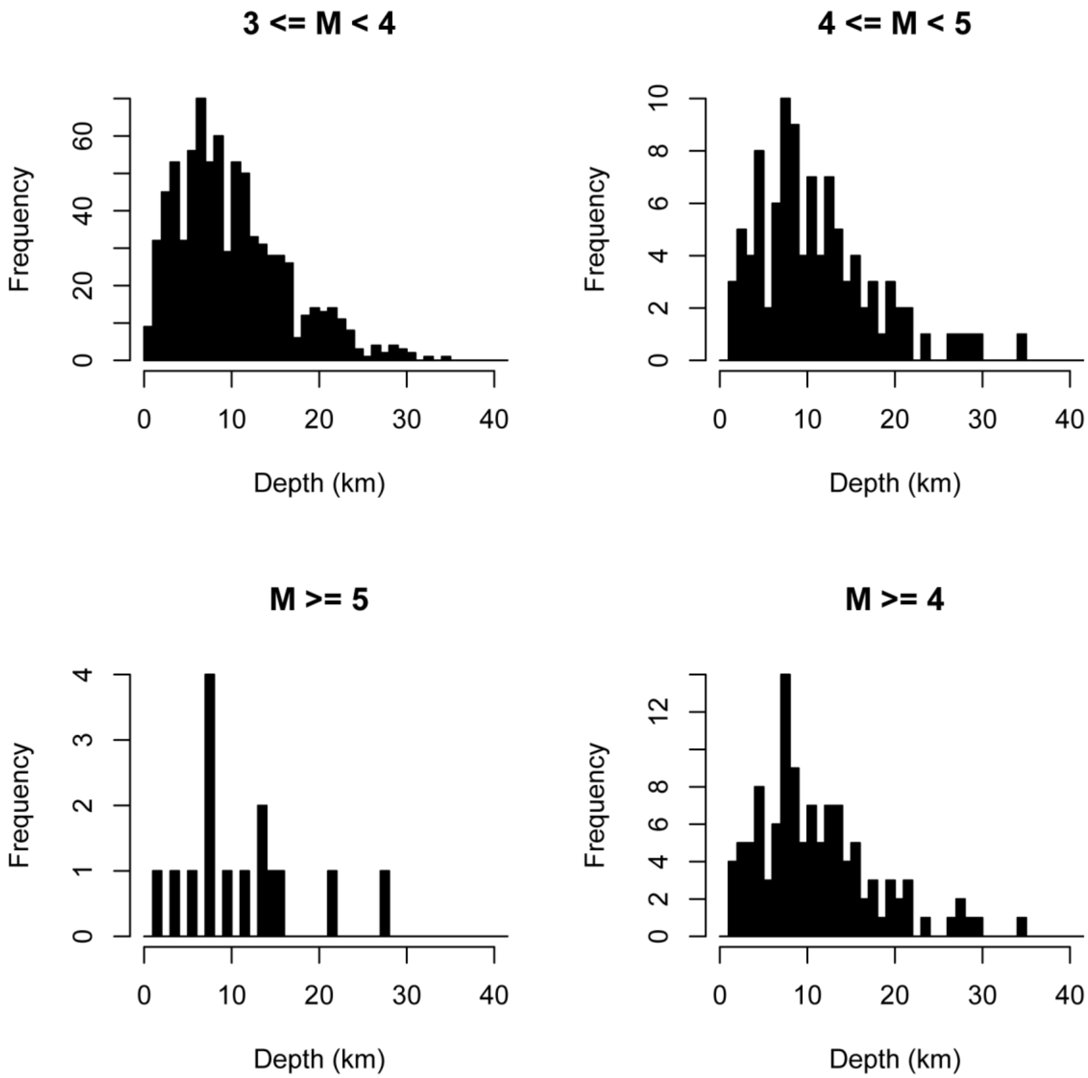

Figure 8.4-1. Focal depth distributions for well located earthquakes in the CENA catalog from NUREG-2115

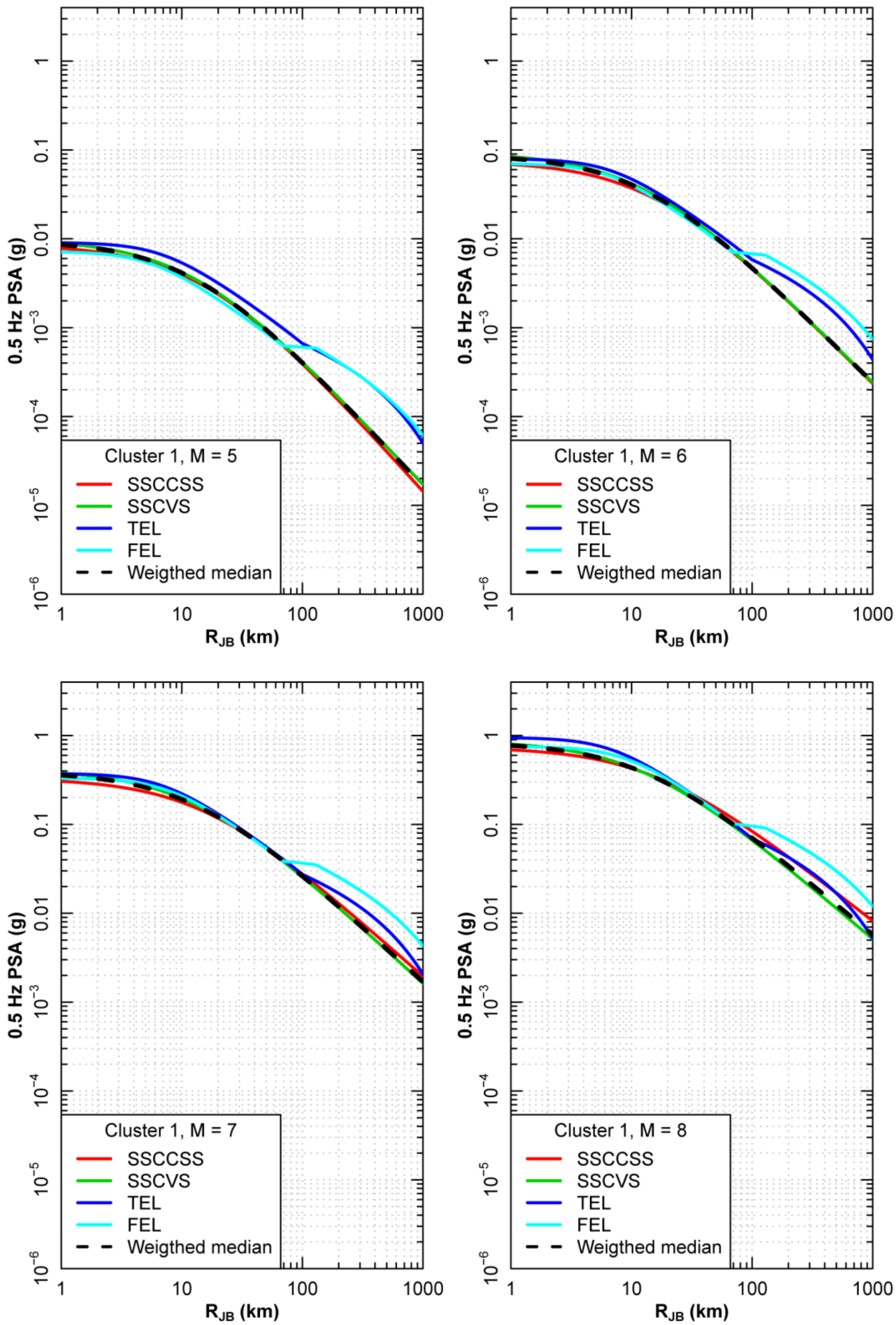

Figure 8.4-2a. Component GMPE predictions and median ground motions for 0.5 Hz PSA for Cluster 1

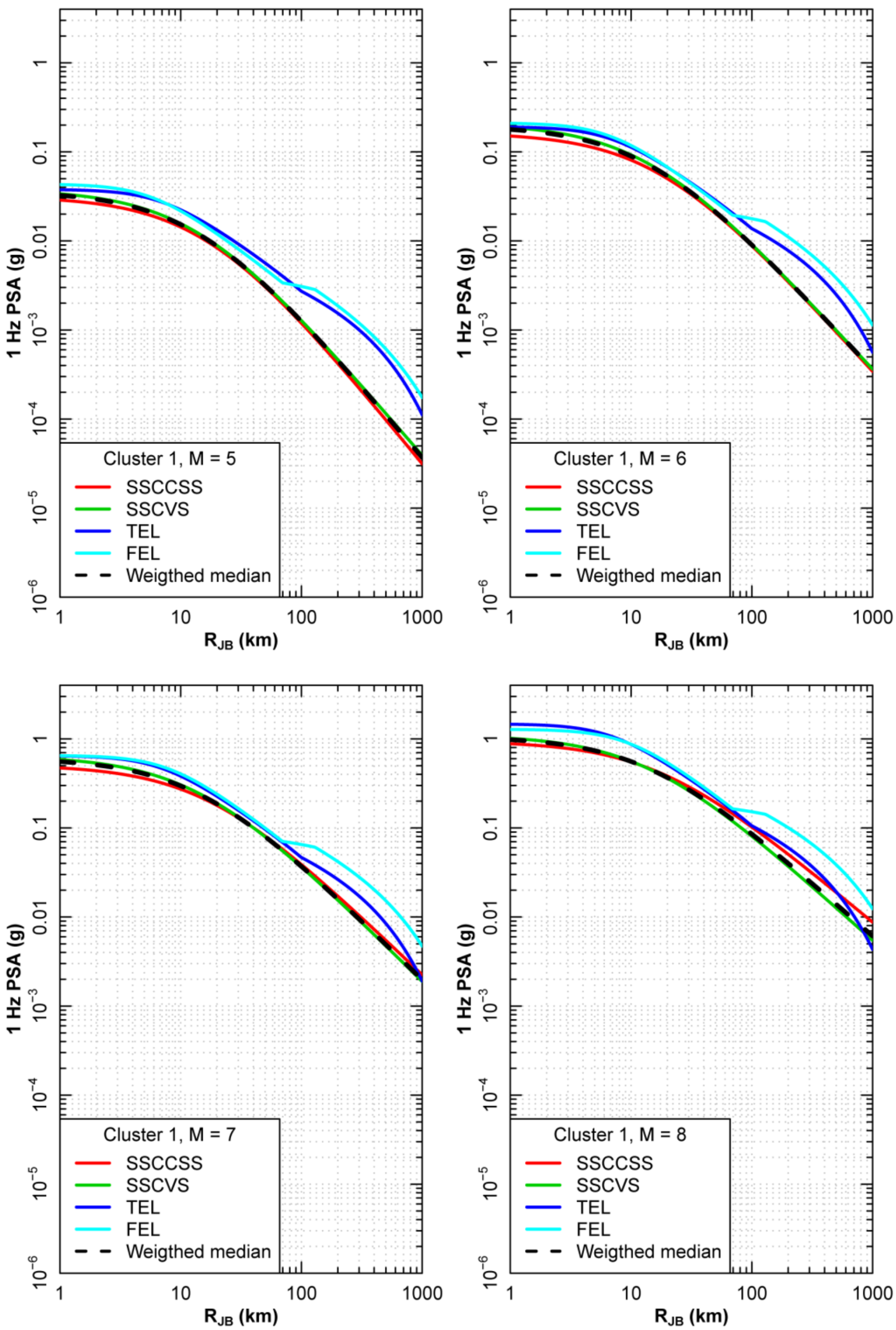

Figure 8.4-2b. Component GMPE predictions and median ground motions
for 1 Hz PSA for Cluster 1

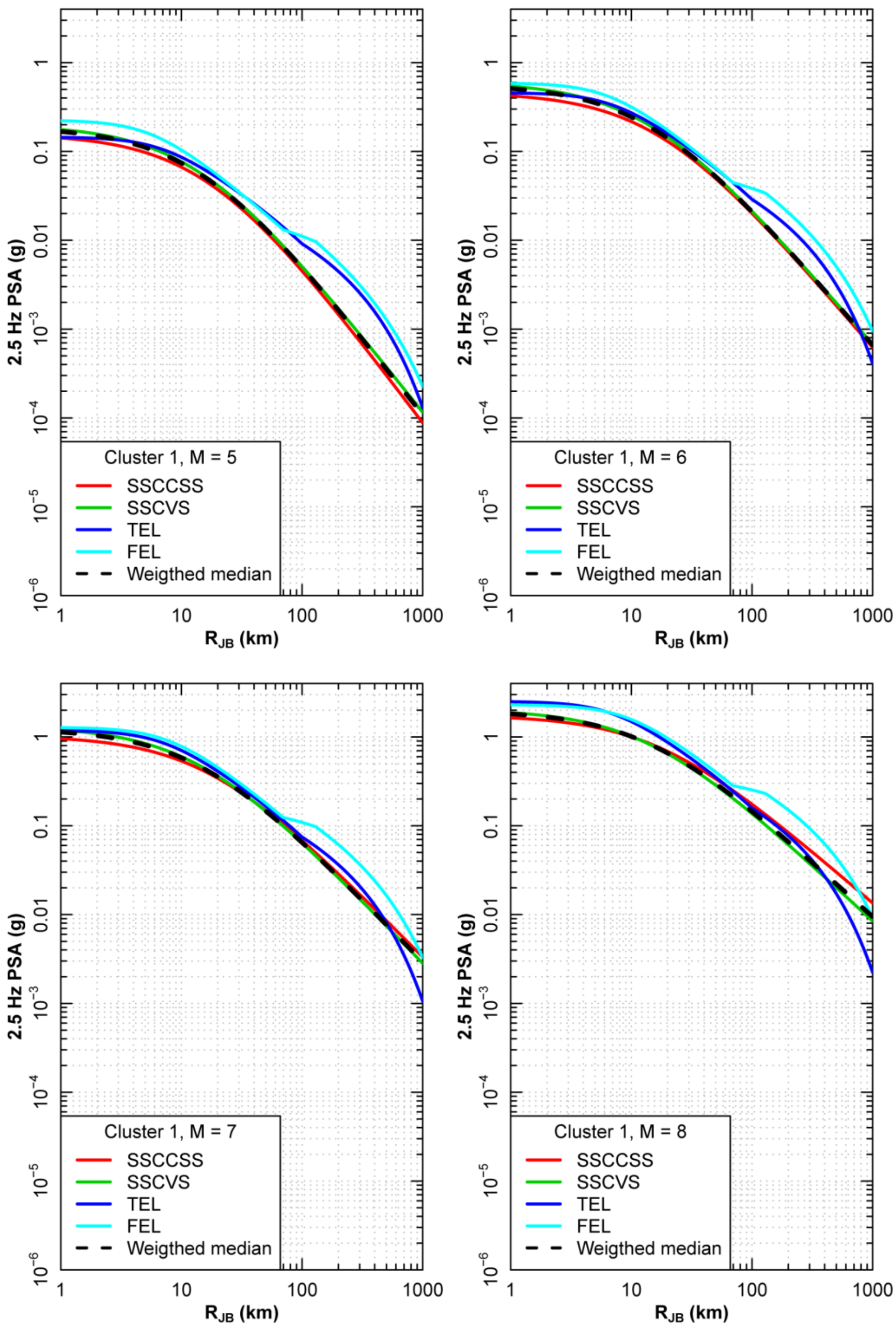

Figure 8.4-2c. Component GMPE predictions and median ground motions for 2.5 Hz PSA for Cluster 1

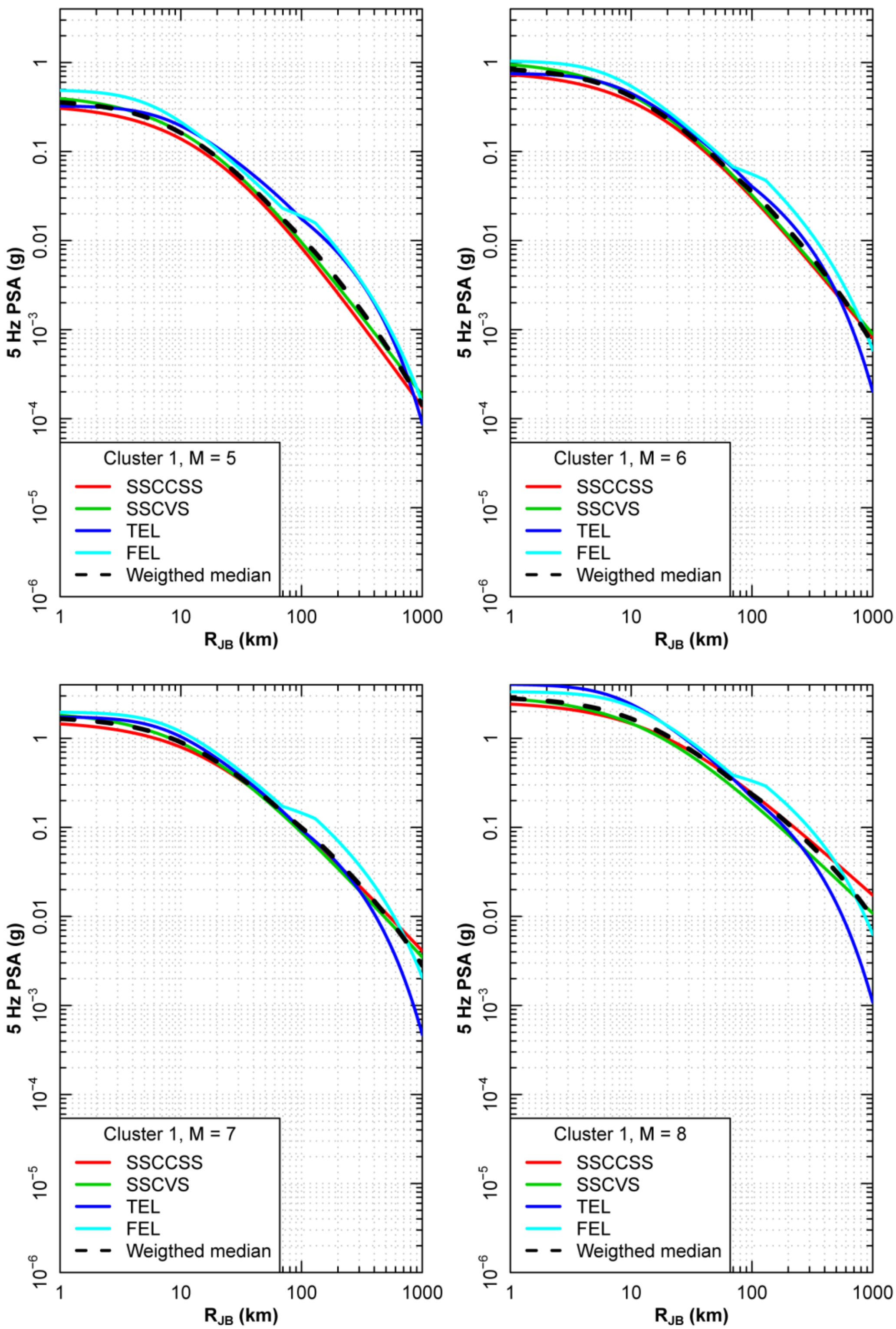

Figure 8.4-2d. Component GMPE predictions and median ground motions for 5 Hz PSA for Cluster 1

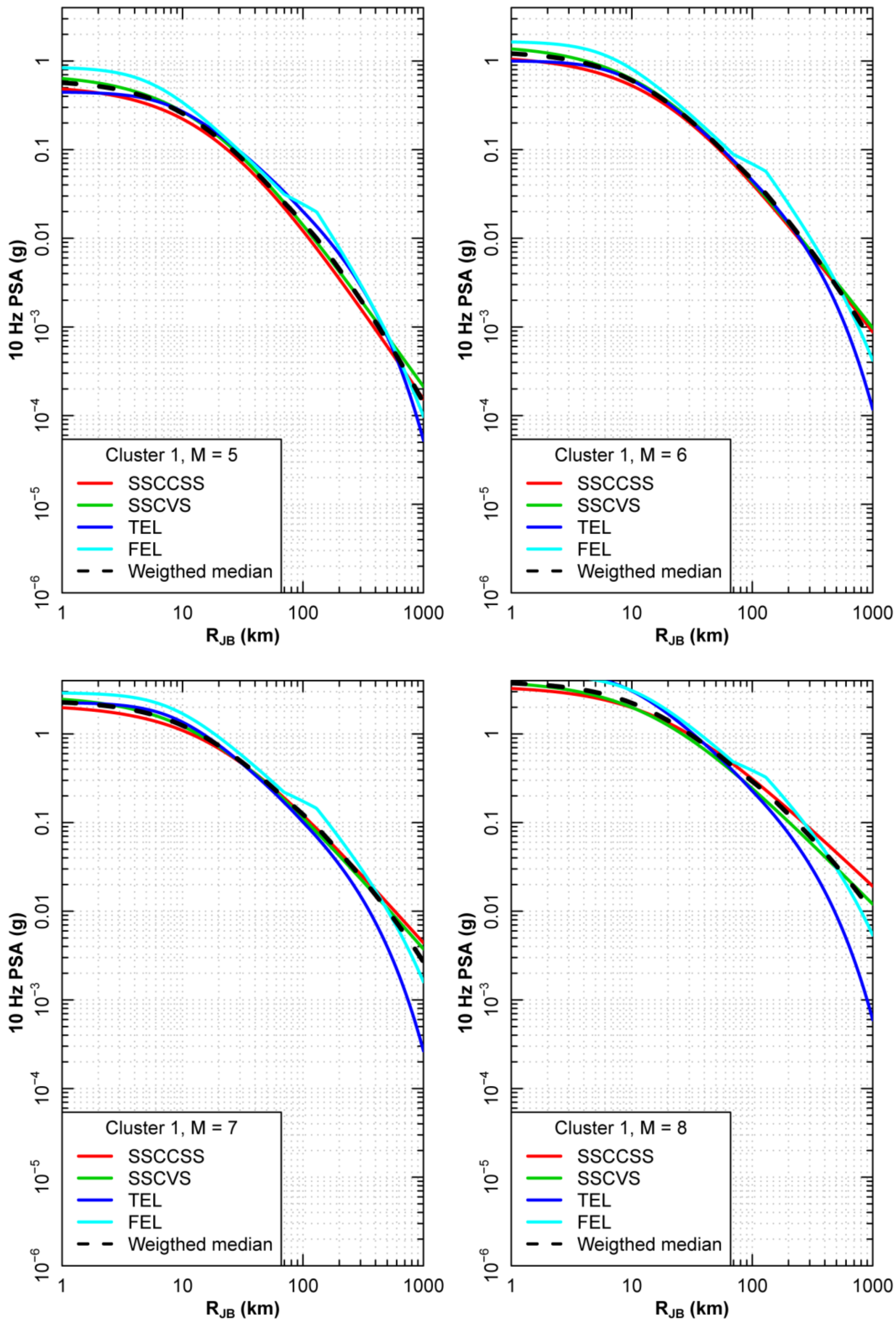

Figure 8.4-2e. Component GMPE predictions and median ground motions or 10 Hz PSA for Cluster 1

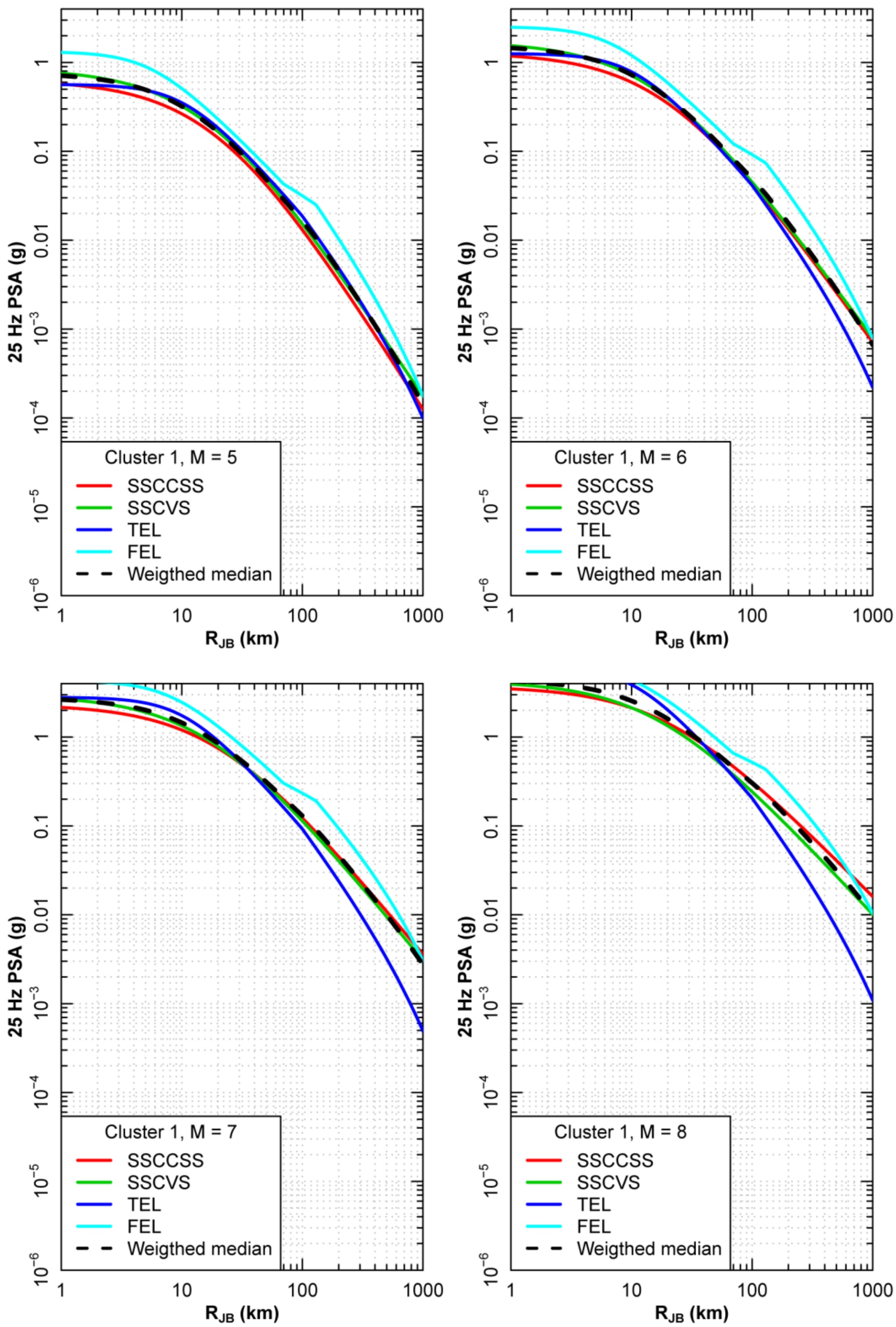

Figure 8.4-2f. Component GMPE predictions and median ground motions for 25 Hz PSA for Cluster 1

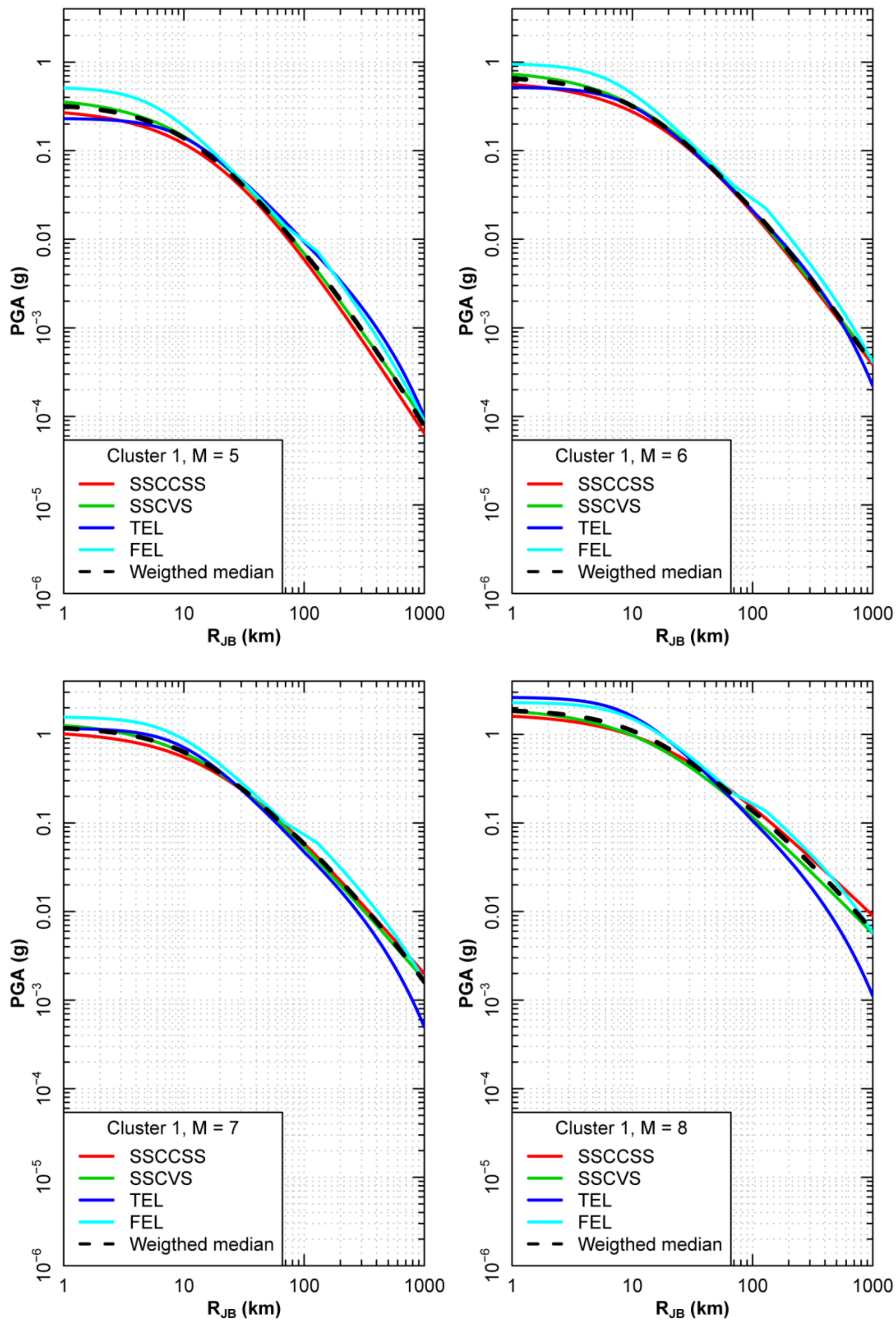

Figure 8.4-2g. Component GMPE predictions and median ground motions for PGA for Cluster 1

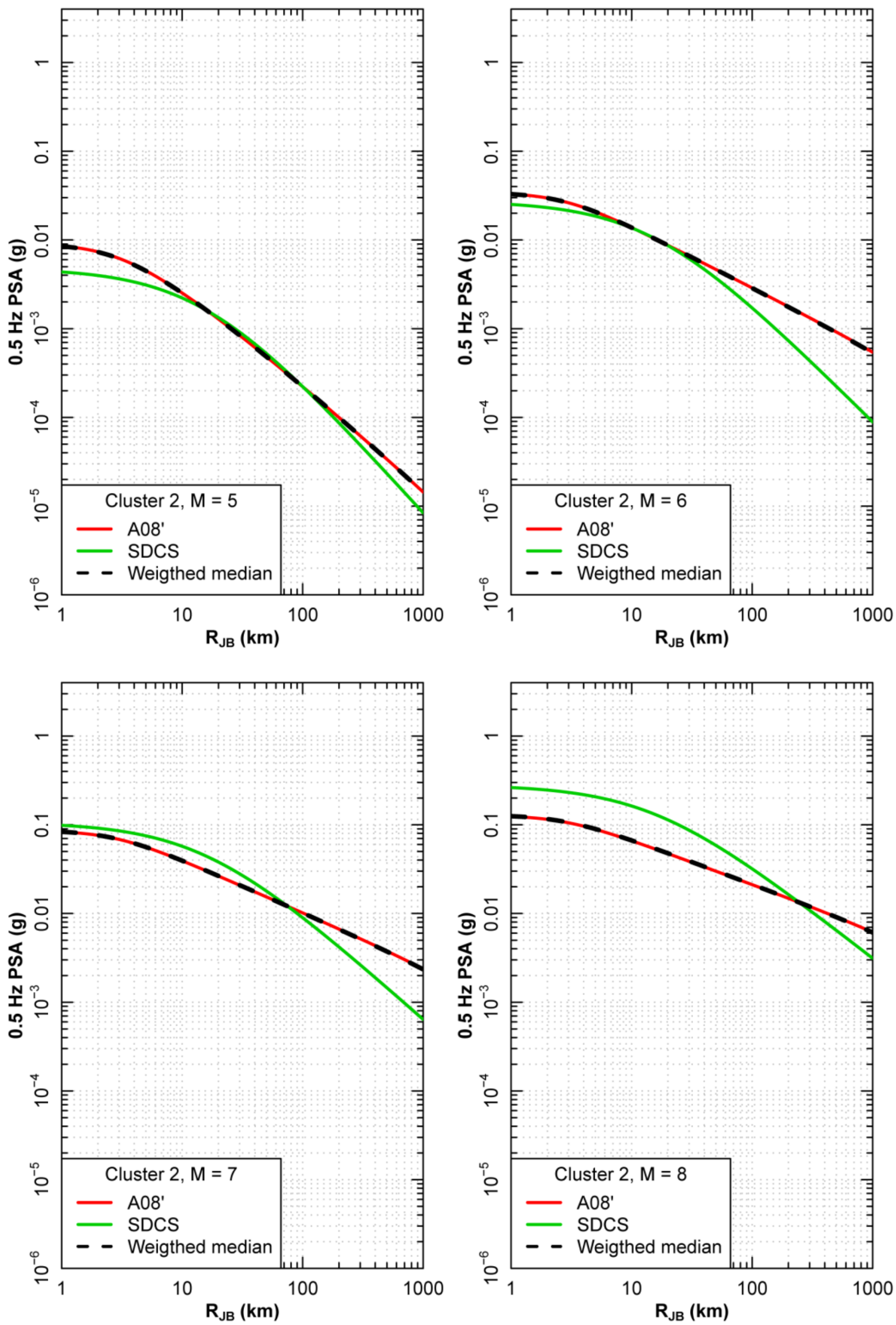

Figure 8.4-3a. Component GMPE predictions and median ground motions for 0.5 Hz PSA for Cluster 2

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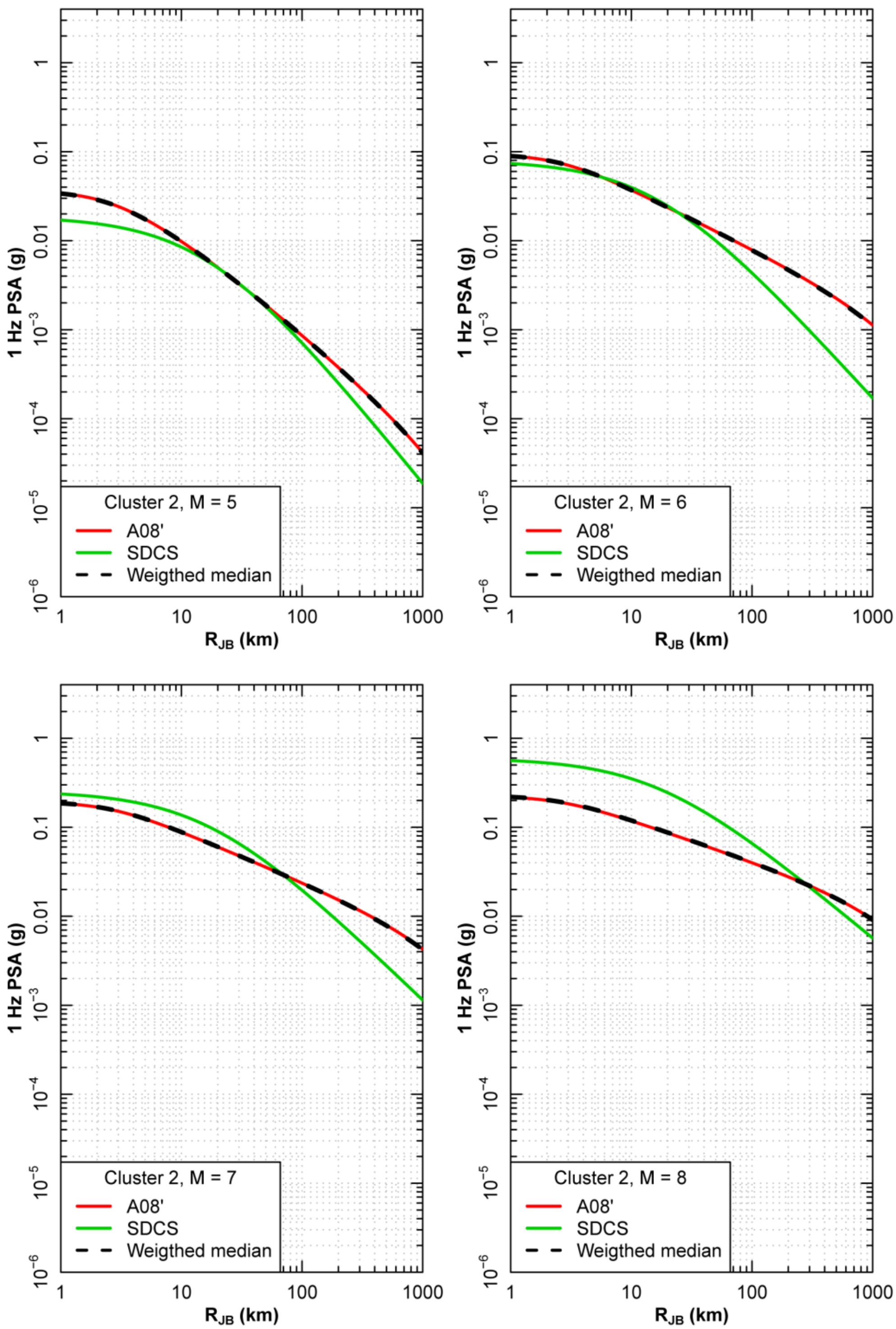

Figure 8.4-3b. Component GMPE predictions and median ground motions for 1 Hz PSA for Cluster 2

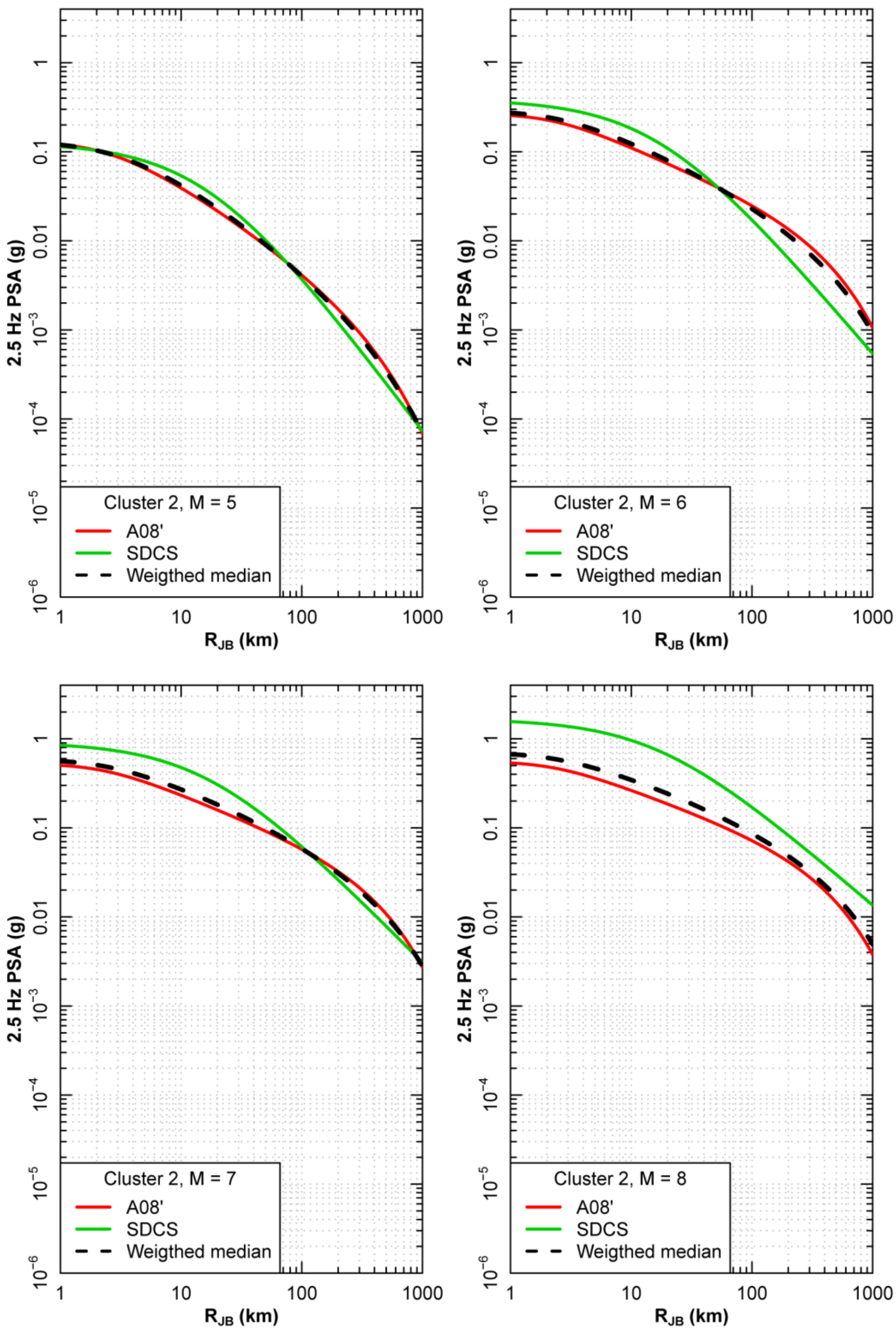

Figure 8.4-3c. Component GMPE predictions and median ground motions for 2.5 Hz PSA for Cluster 2

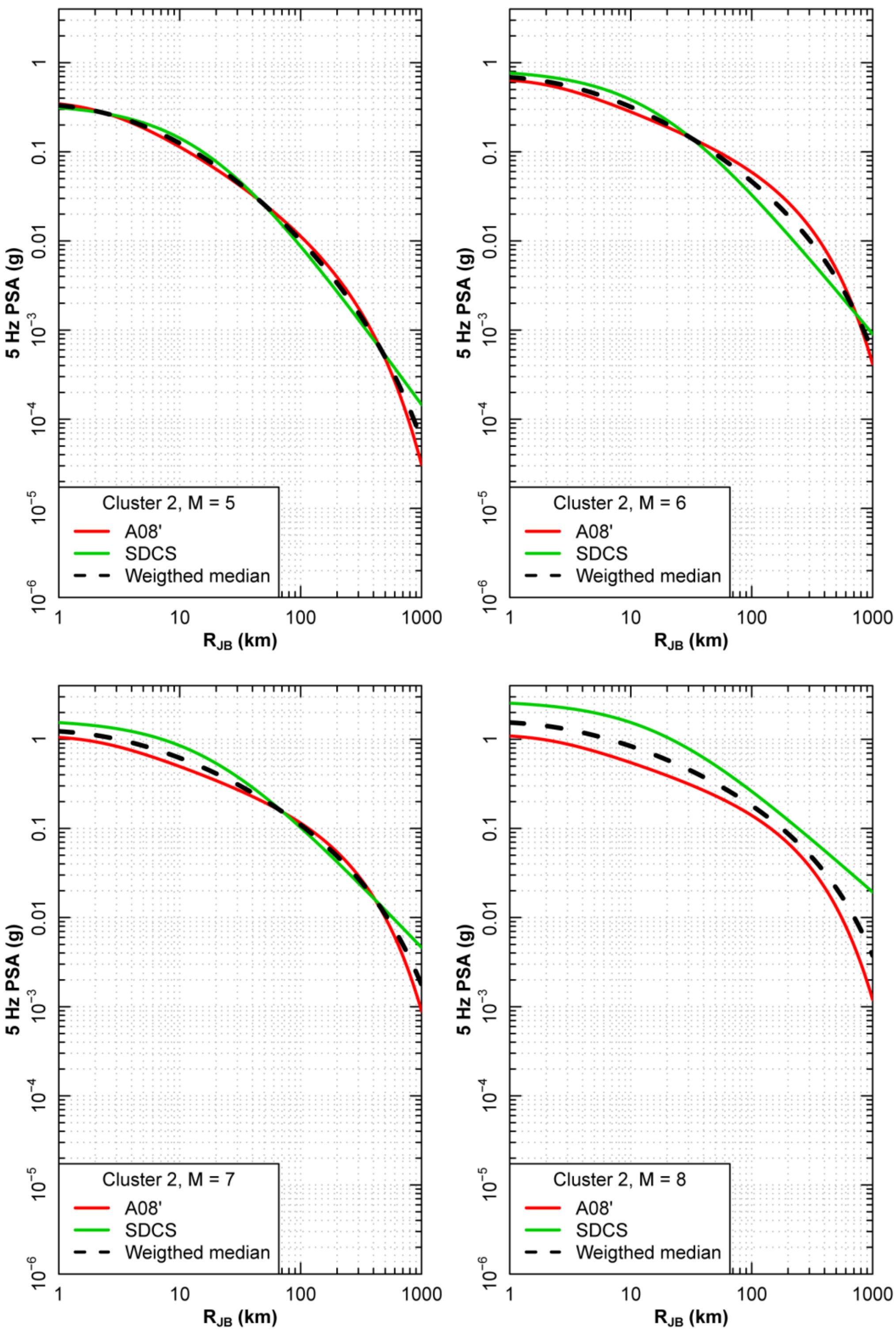

Figure 8.4-3d. Component GMPE predictions and median ground motions for 5 Hz PSA for Cluster 2

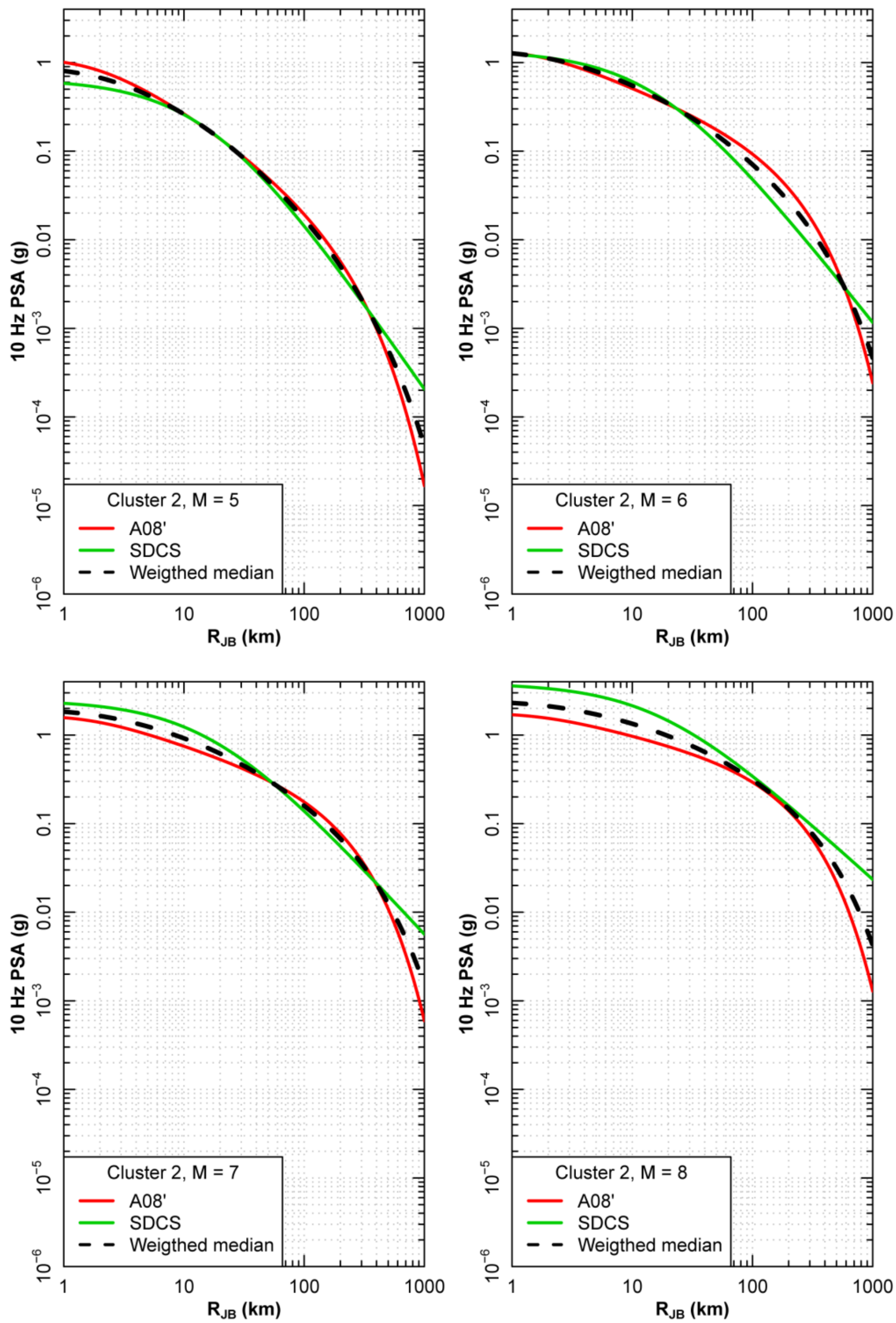

Figure 8.4-3e. Component GMPE predictions and median ground motions for 10 Hz PSA for Cluster 2

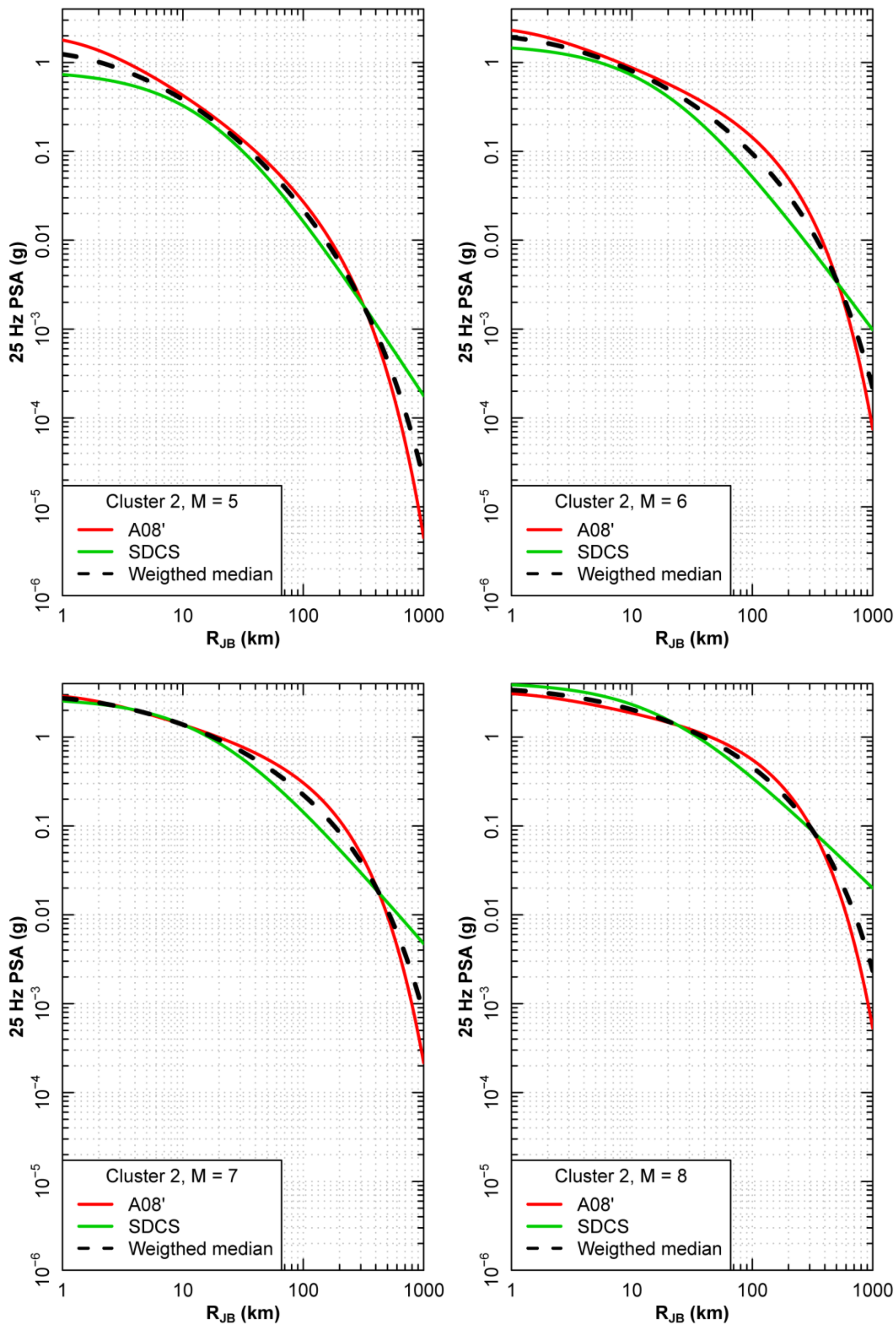

Figure 8.4-3f. Component GMPE predictions and median ground motions for 25 Hz PSA for Cluster 2

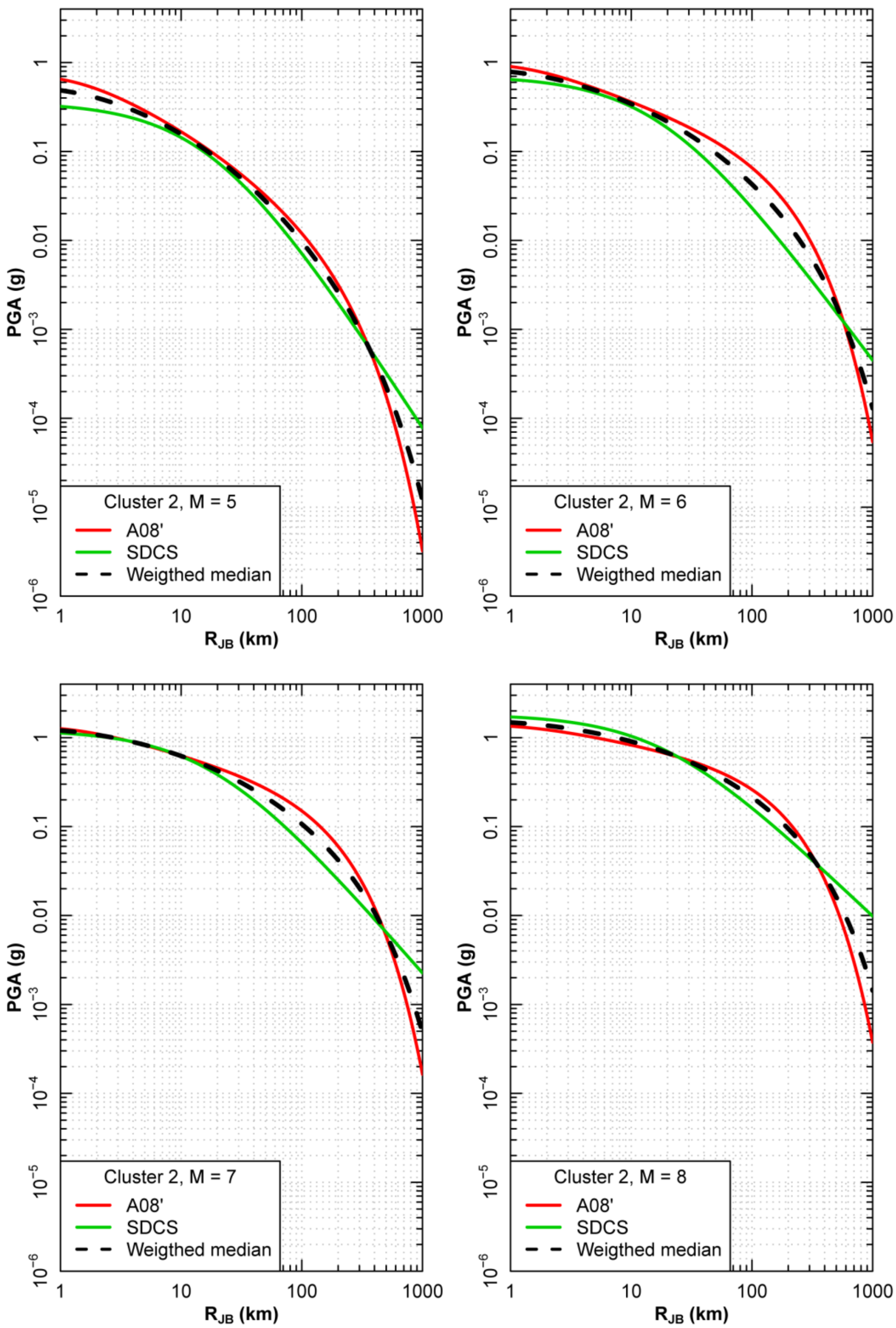

Figure 8.4-3g. Component GMPE predictions and median ground motions for PGA for Cluster 2

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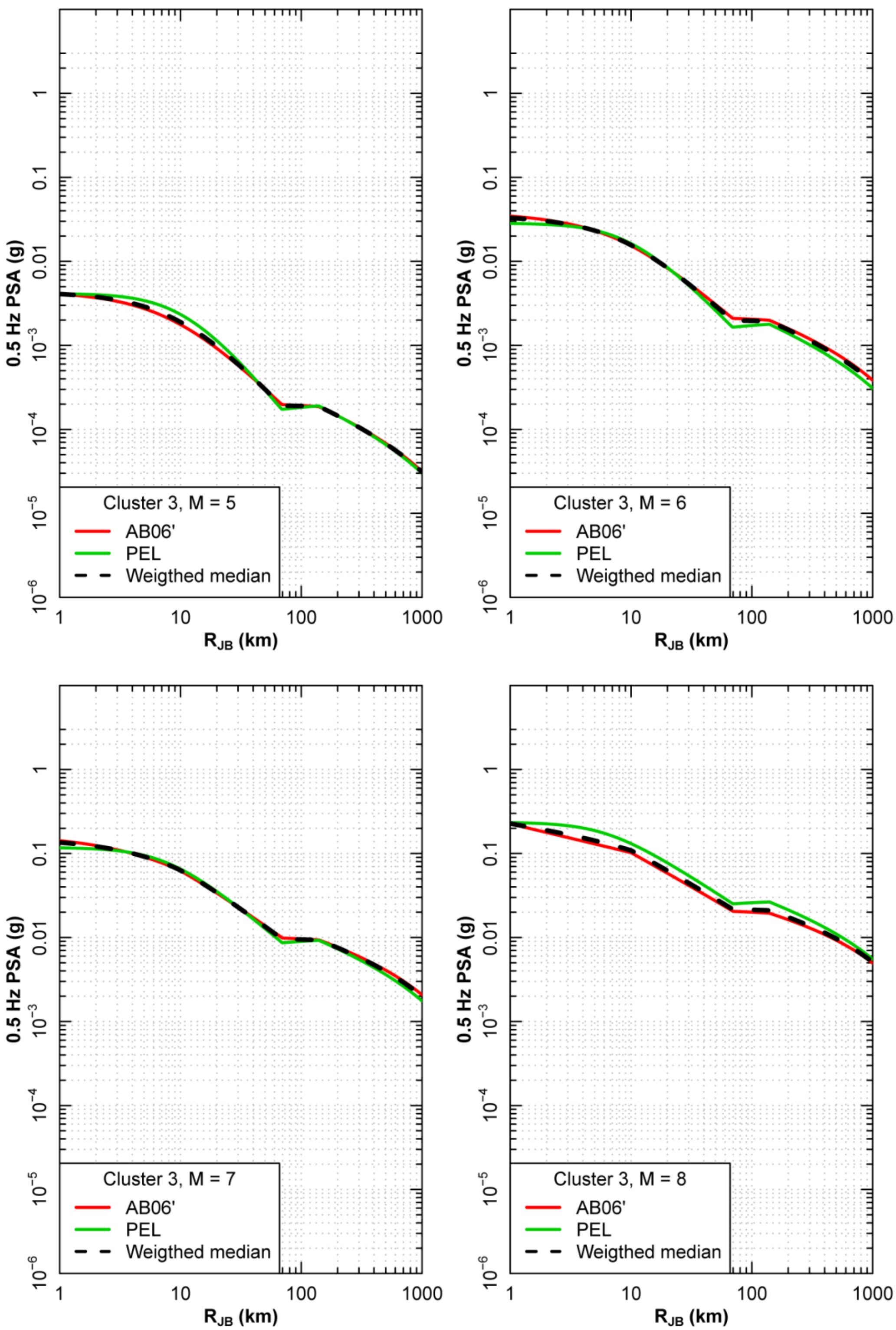

Figure 8.4-4a. Component GMPE predictions and median ground motions for 0.5 Hz PSA for Cluster 3

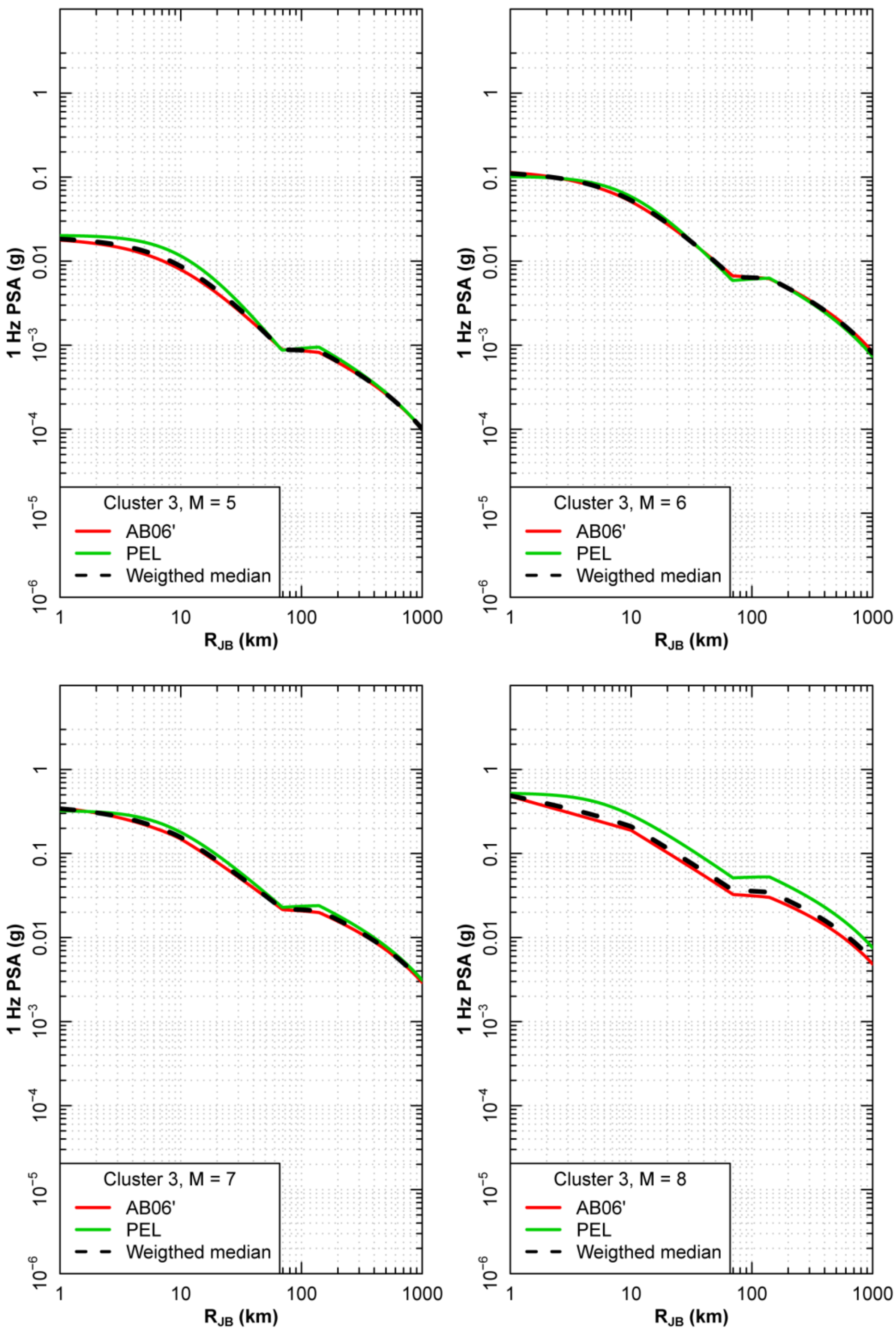

Figure 8.4-4b. Component GMPE predictions and median ground motions for 1 Hz PSA for Cluster 3

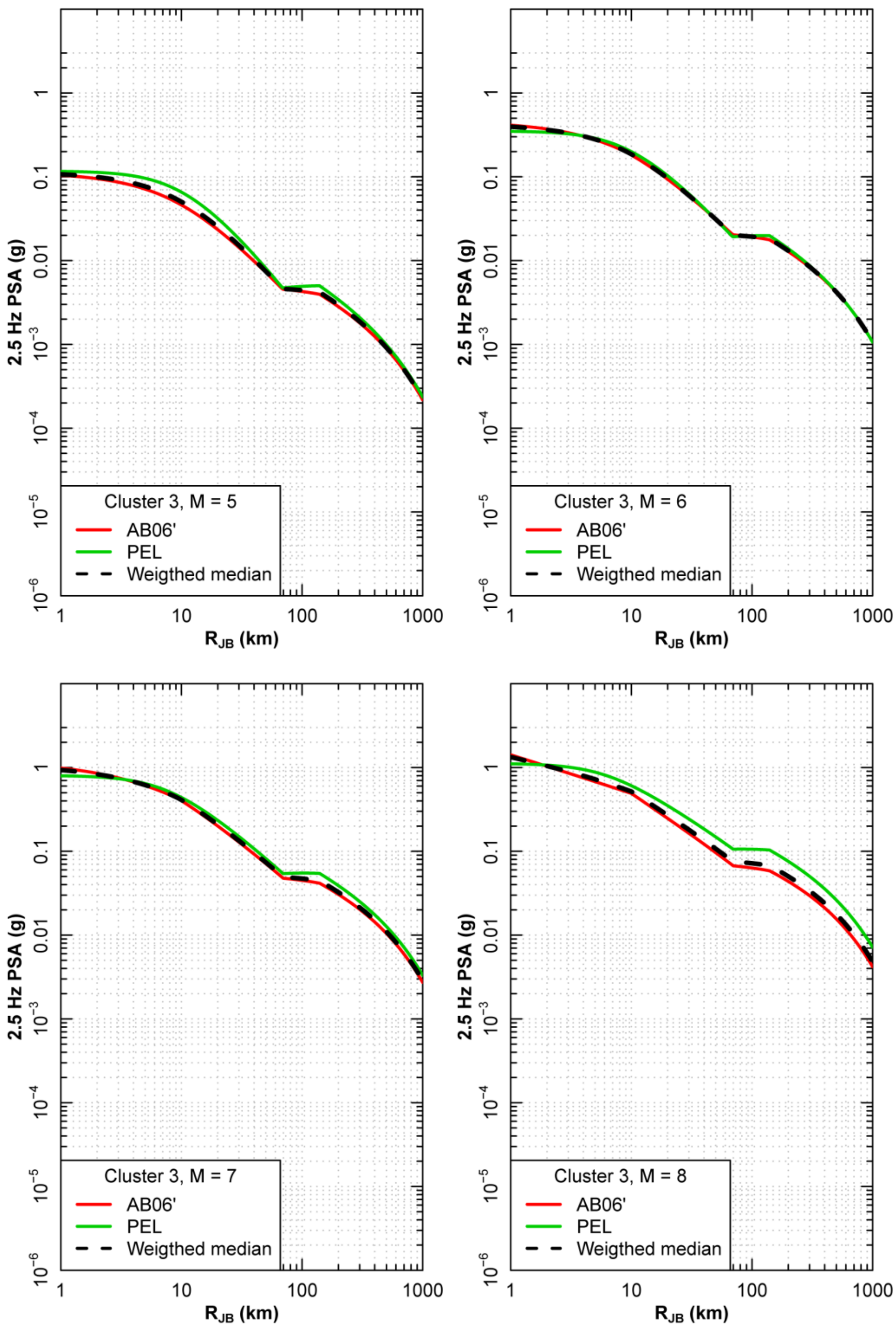

Figure 8.4-4c. Component GMPE predictions and median ground motions for 2.5 Hz PSA for Cluster 3

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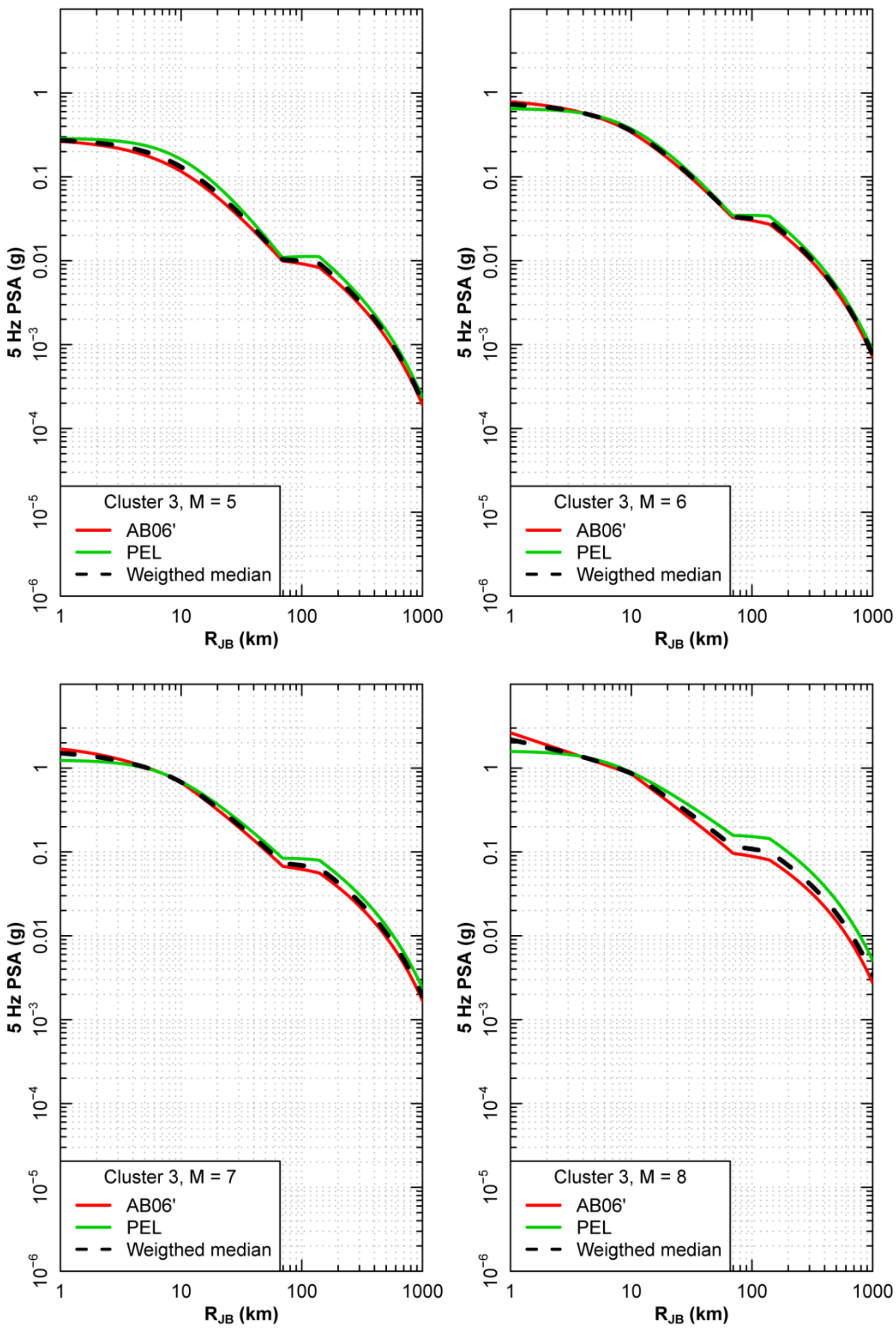

Figure 8.4-4d. Component GMPE predictions and median ground motions for 5 Hz PSA for Cluster 3

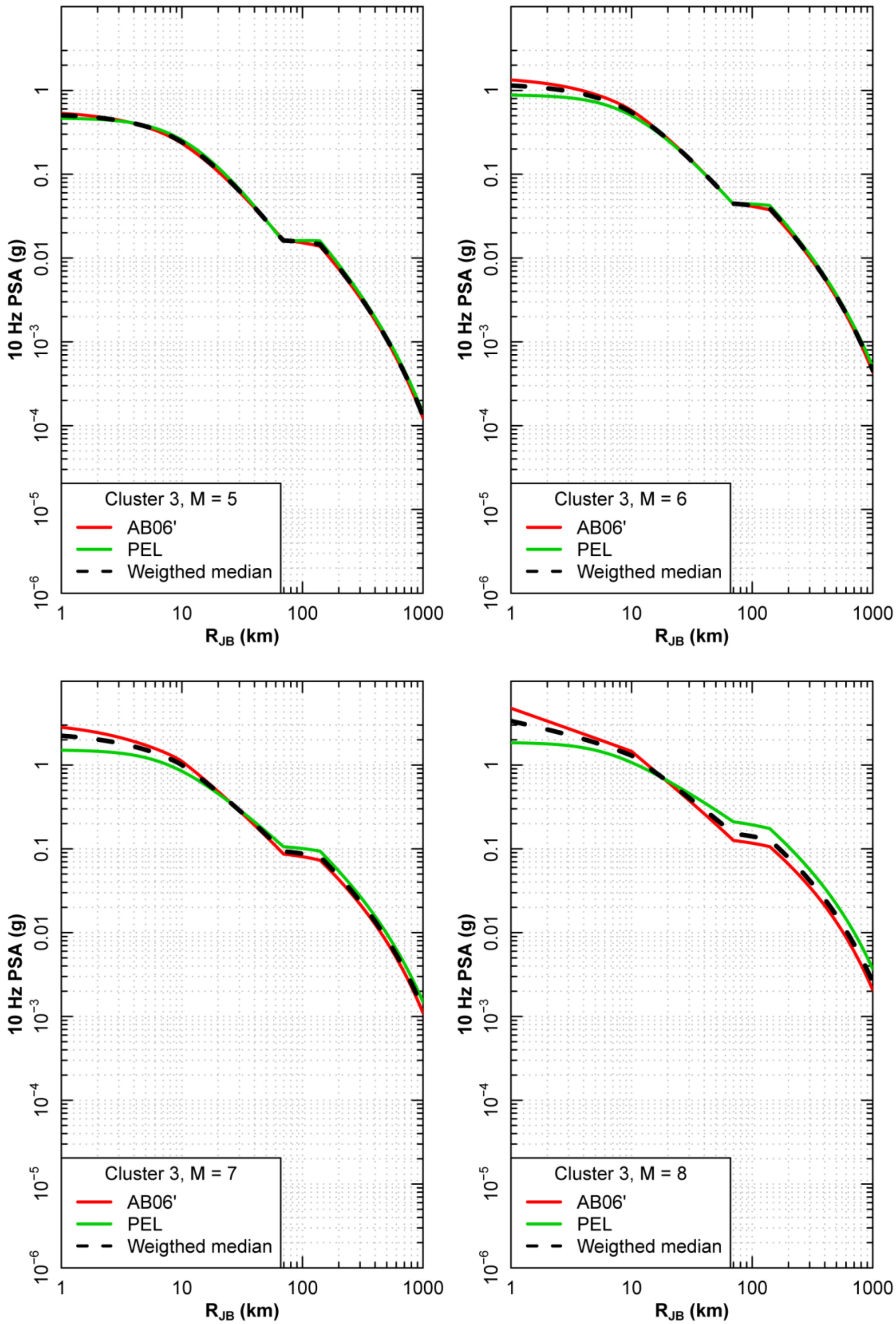

Figure 8.4-4e. Component GMPE predictions and median ground motions for 10 Hz PSA for Cluster 3

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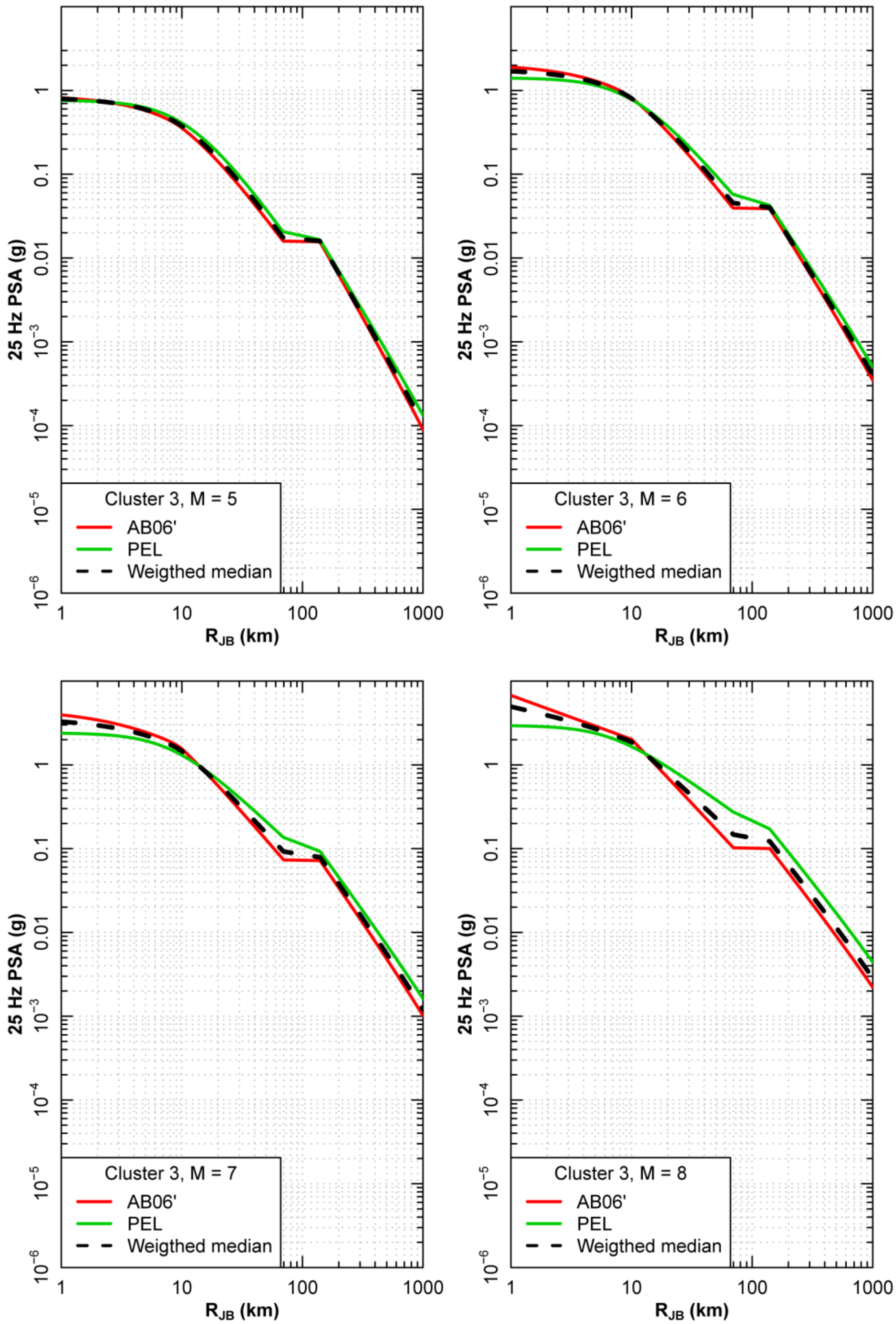

Figure 8.4-4f. Component GMPE predictions and median ground motions for 25 Hz PSA for Cluster 3

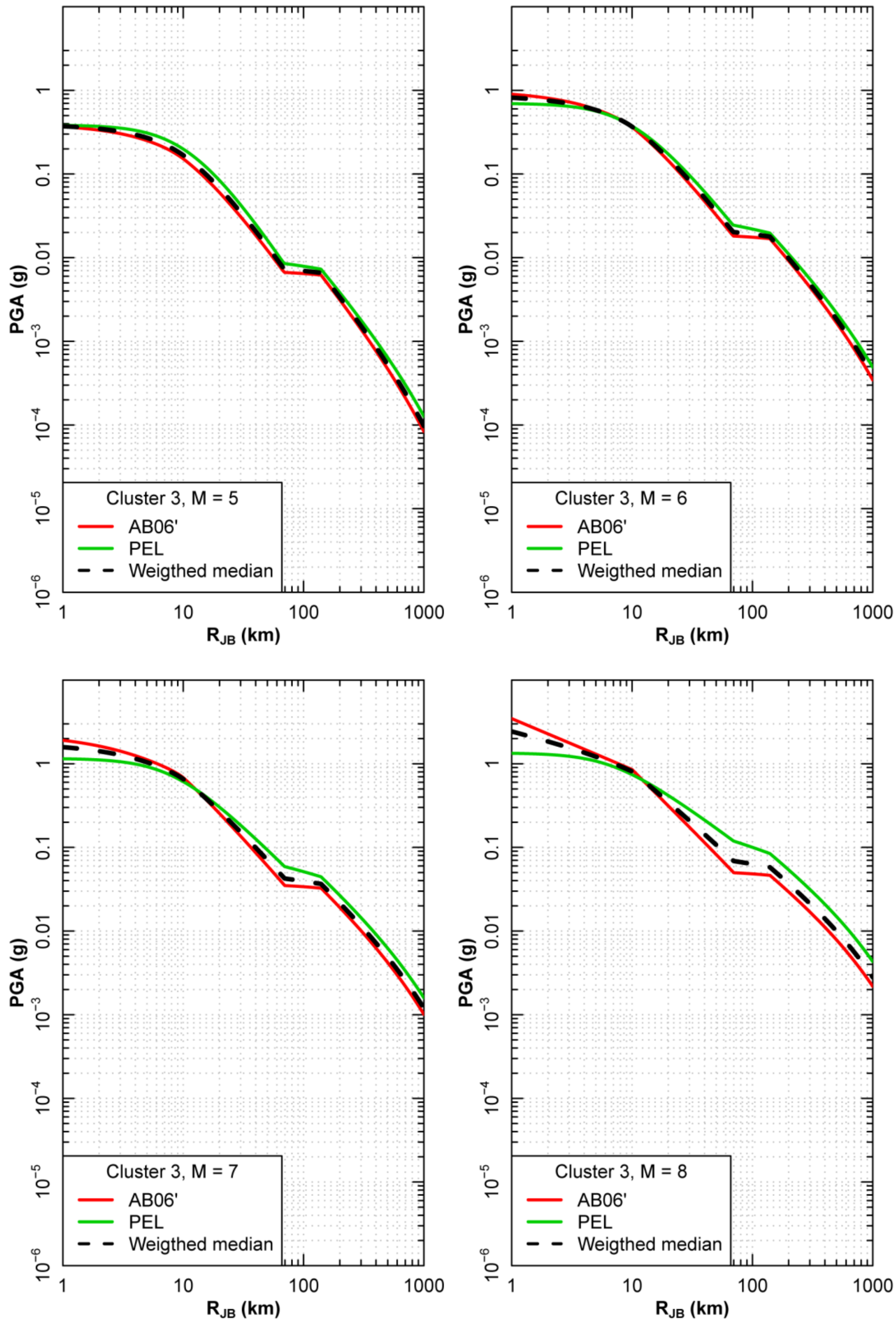

Figure 8.4-4g. Component GMPE predictions and median ground motions for PGA for Cluster 3

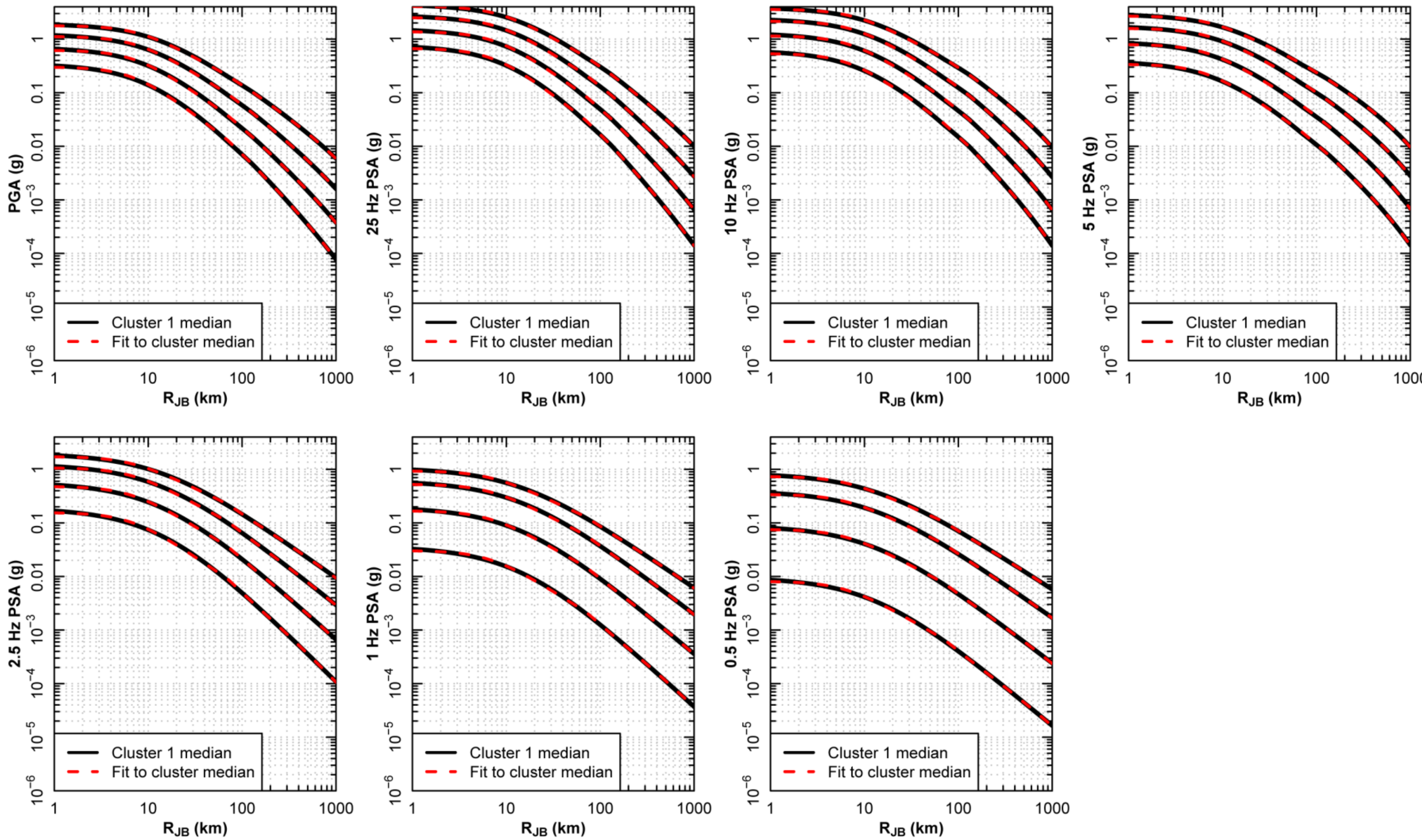

Figure 8.4-5. Fit of Equation 8.4-1 to mean ln(PSA) and ln(PGA) for Cluster 1 for **M** 5, 6, 7, and 8

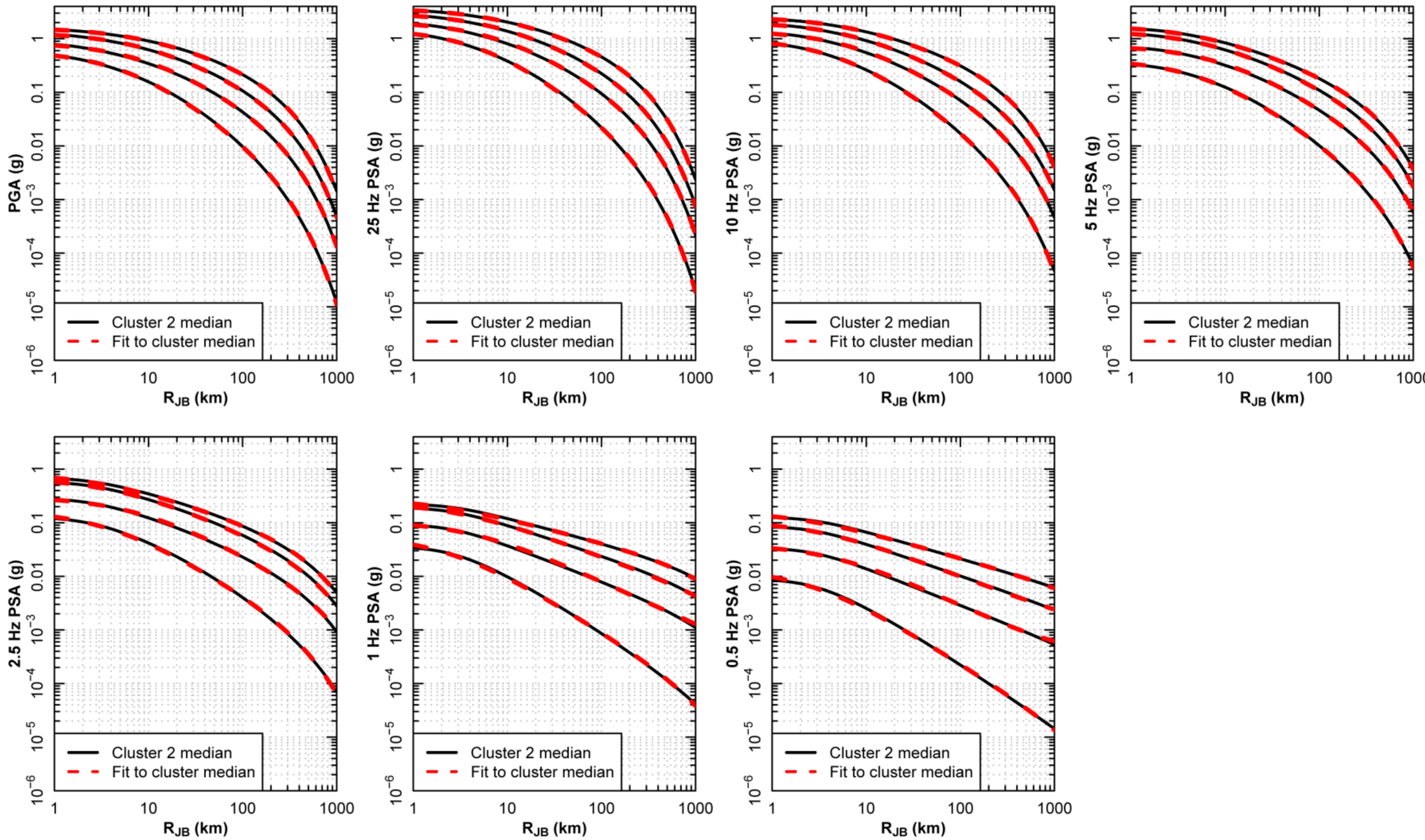

Figure 8.4-6. Fit of Equation 8.4-2 to mean ln(PSA) and ln(PGA) for Cluster 2 for **M** 5, 6, 7, and 8

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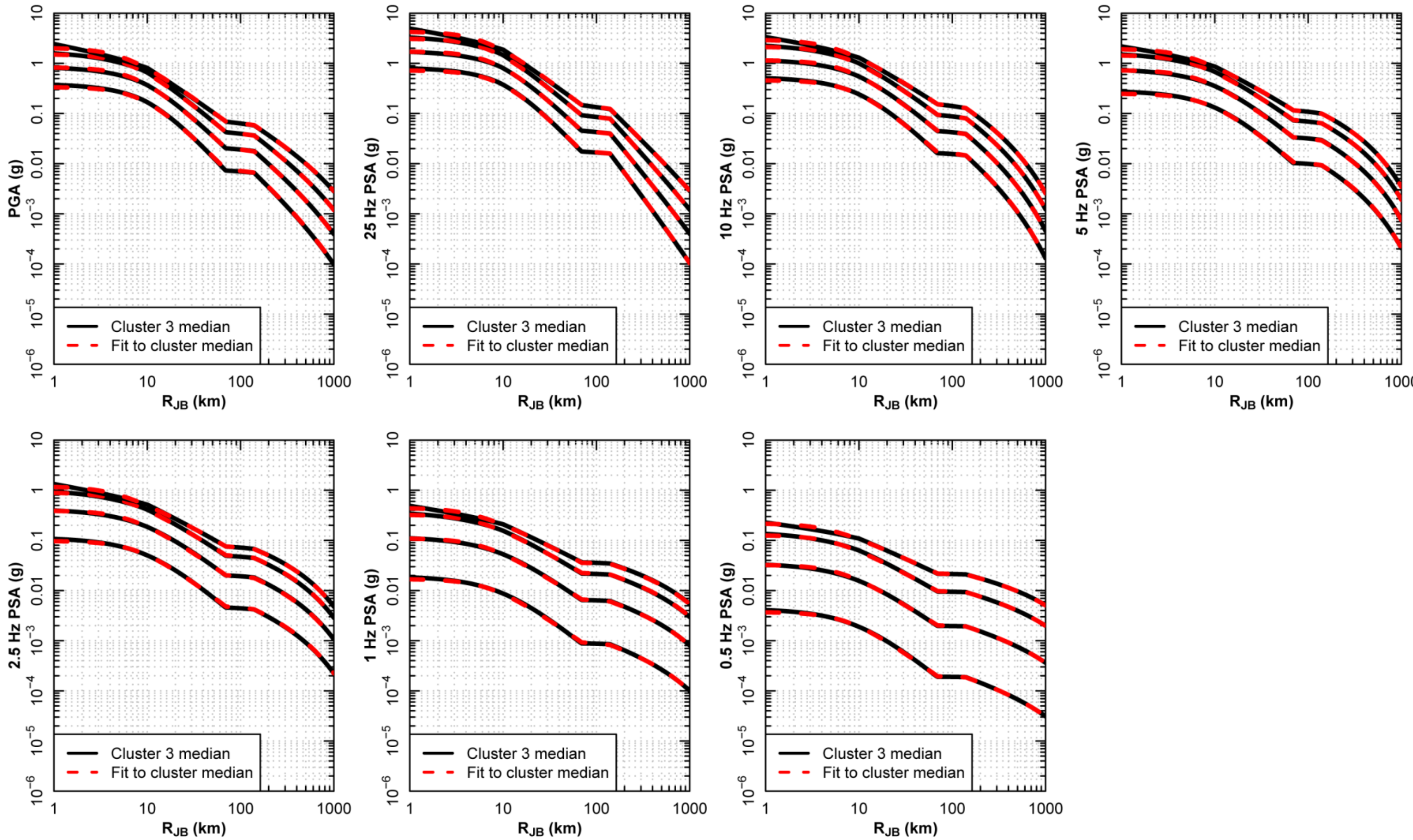

Figure 8.4-7. Fit of Equation 8.4-1 to mean ln(PSA) and ln(PGA) for Cluster 3 for **M** 5, 6, 7, and 8

DRAFT

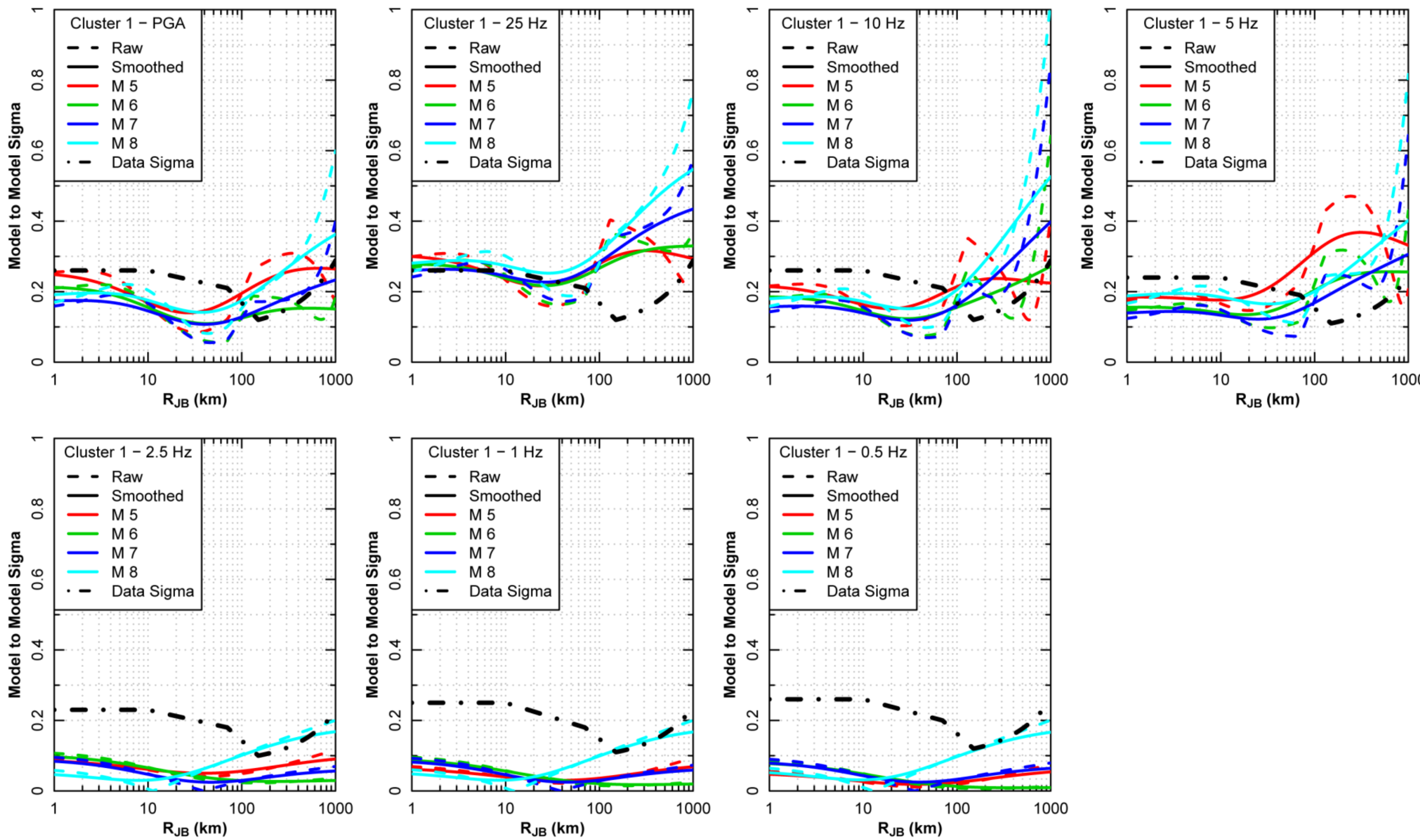

Figure 8.5-1 Epistemic uncertainties for Cluster 1

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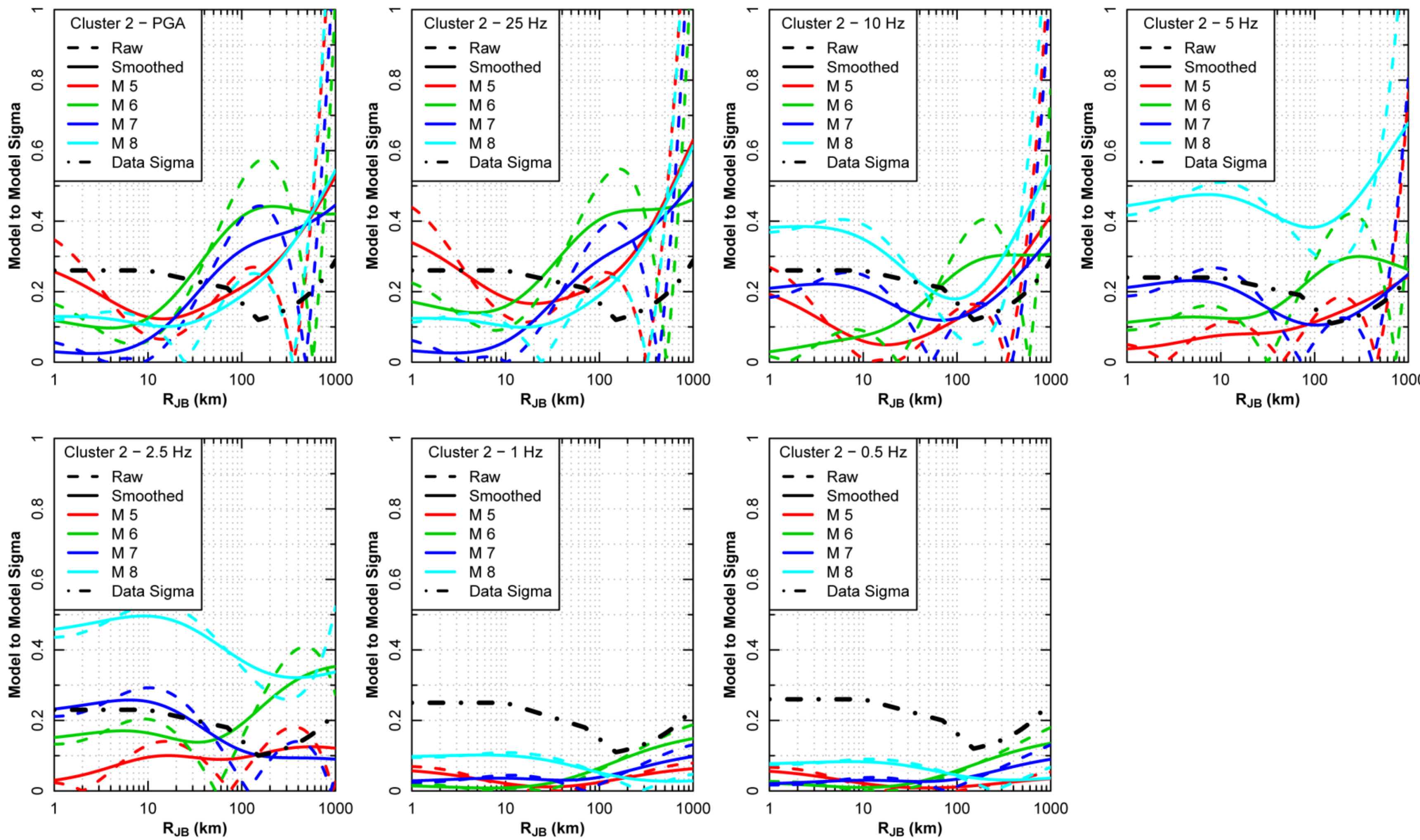

Figure 8.5-2 Epistemic uncertainties for Cluster 2

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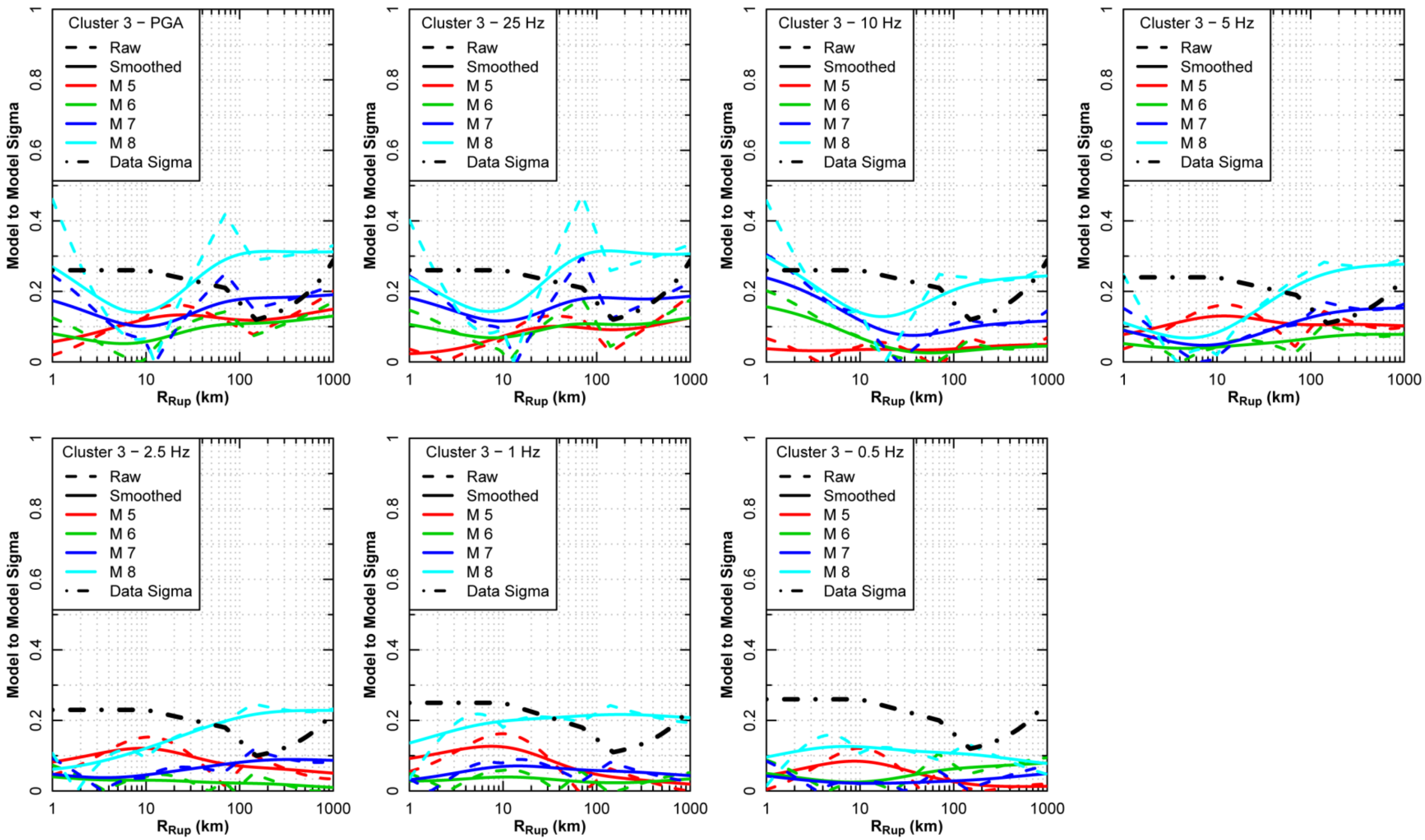

Figure 8.5-3 Epistemic uncertainties for Cluster 3

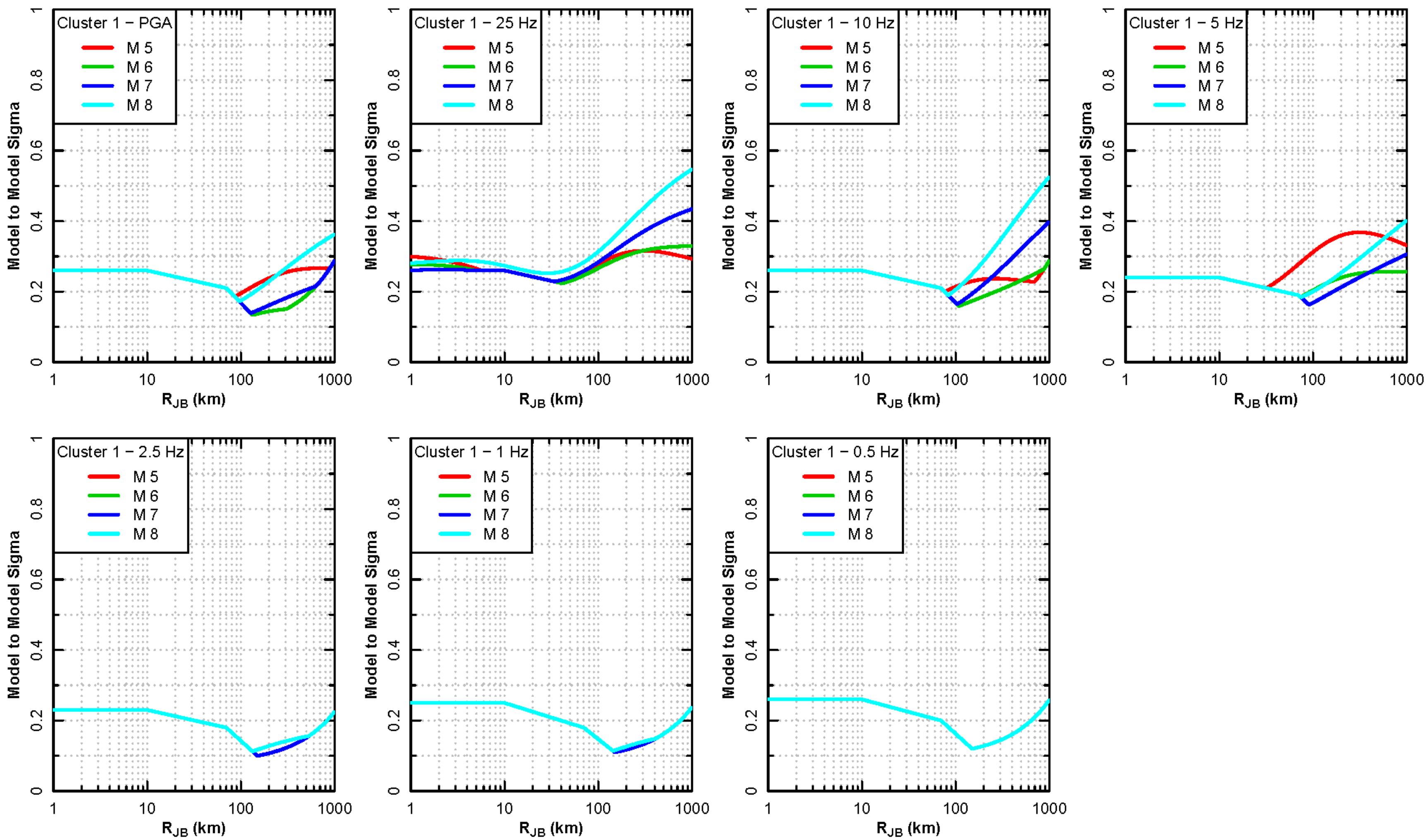

Figure 8.5-4 Smoothed enveloping epistemic uncertainties for Cluster 1

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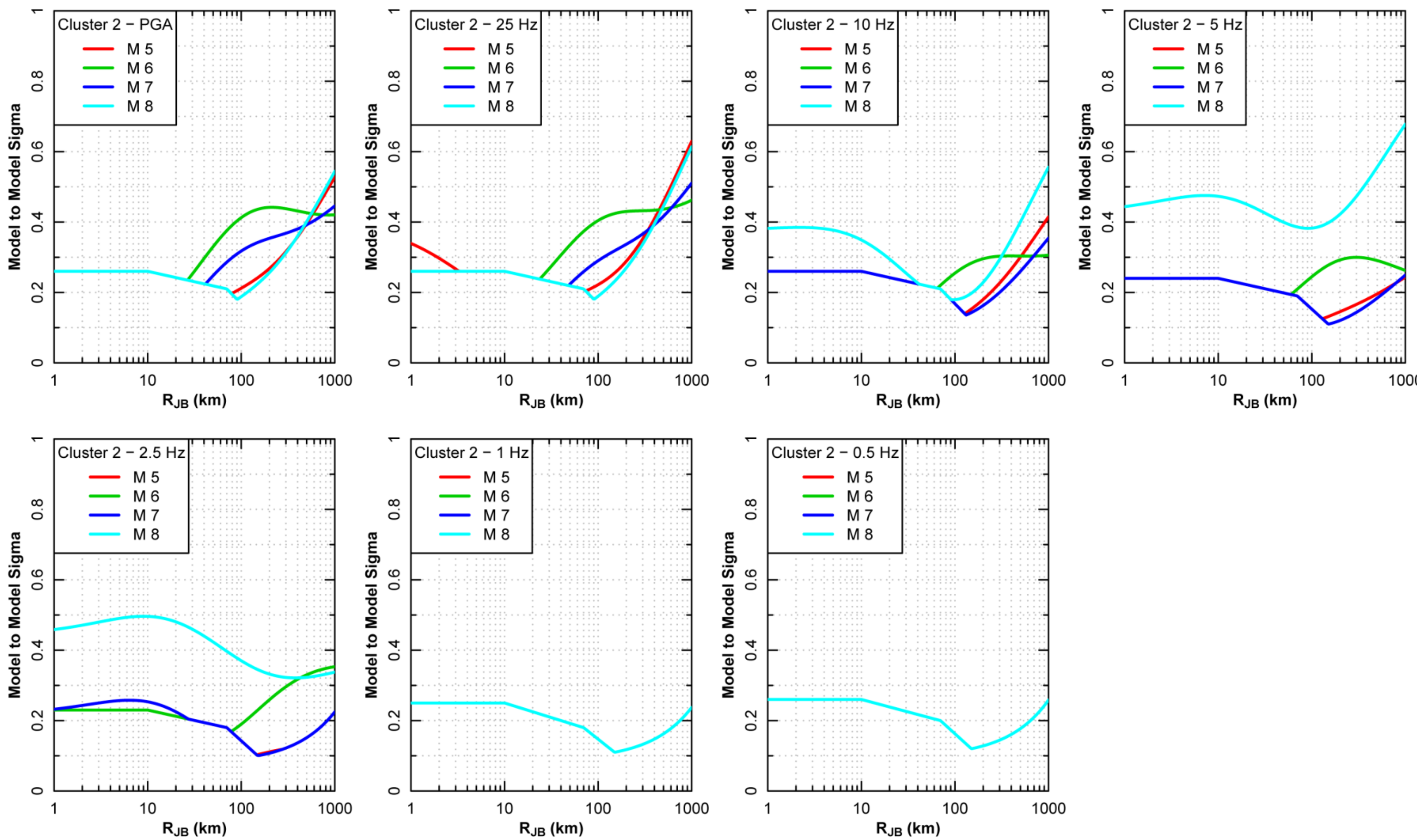

Figure 8.5-5 Smoothed enveloping epistemic uncertainties for Cluster 2

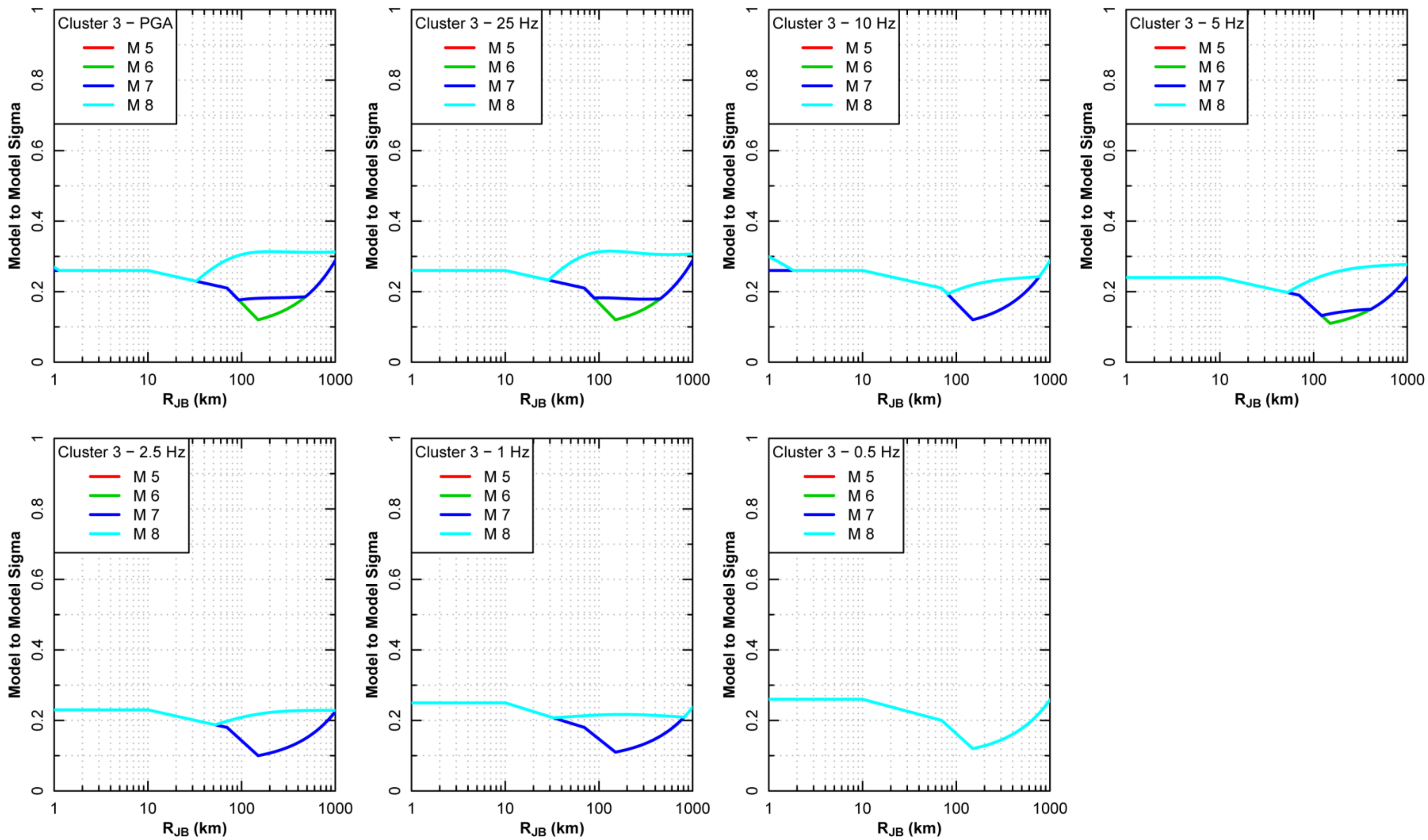

Figure 8.5-6 Smoothed enveloping epistemic uncertainties for Cluster 3

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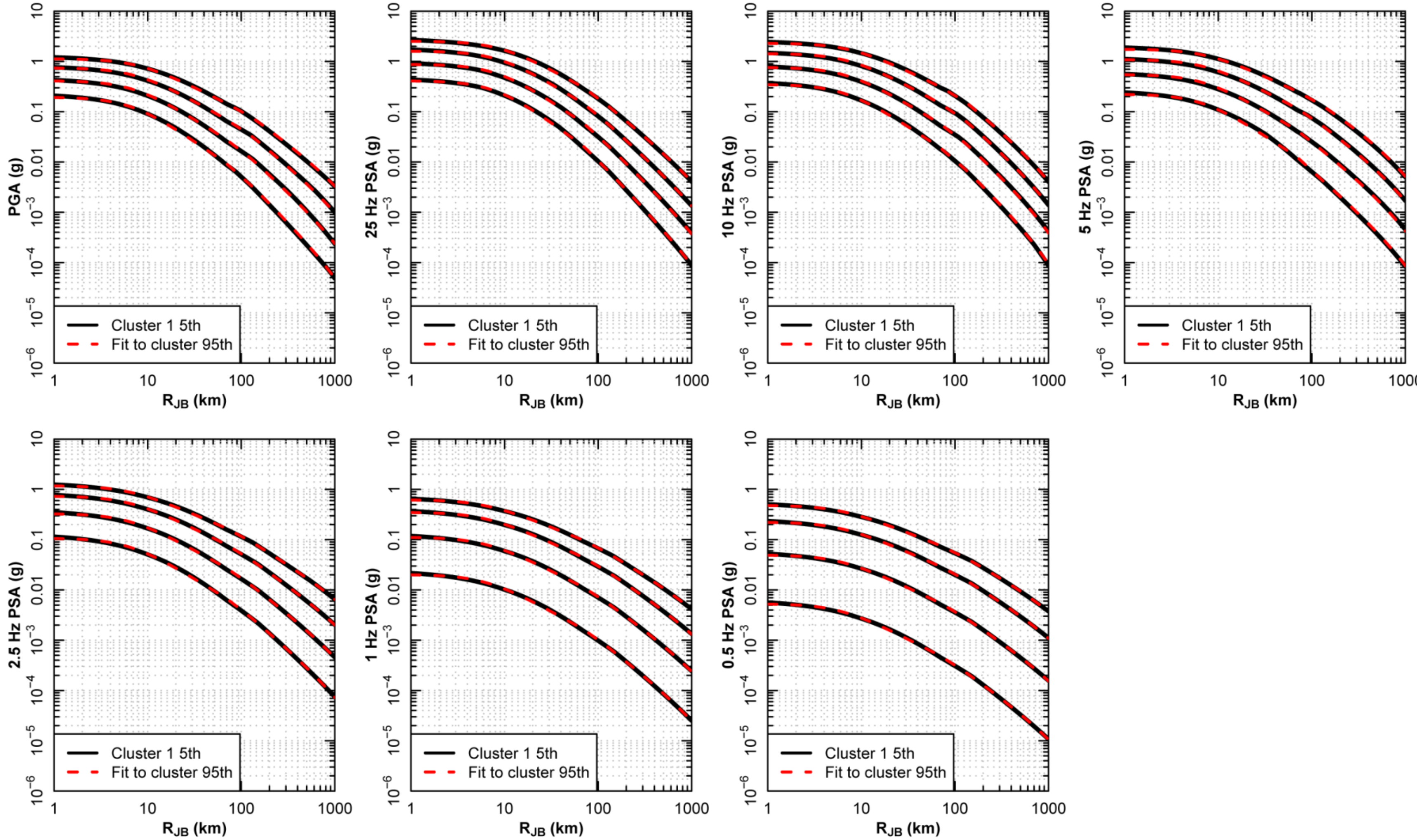

Figure 8.5-7a. Fit of Equation 8.4-1 to 5th percentile ln(PSA) and ln(PGA) for Cluster 1 for **M** 5, 6, 7, and 8

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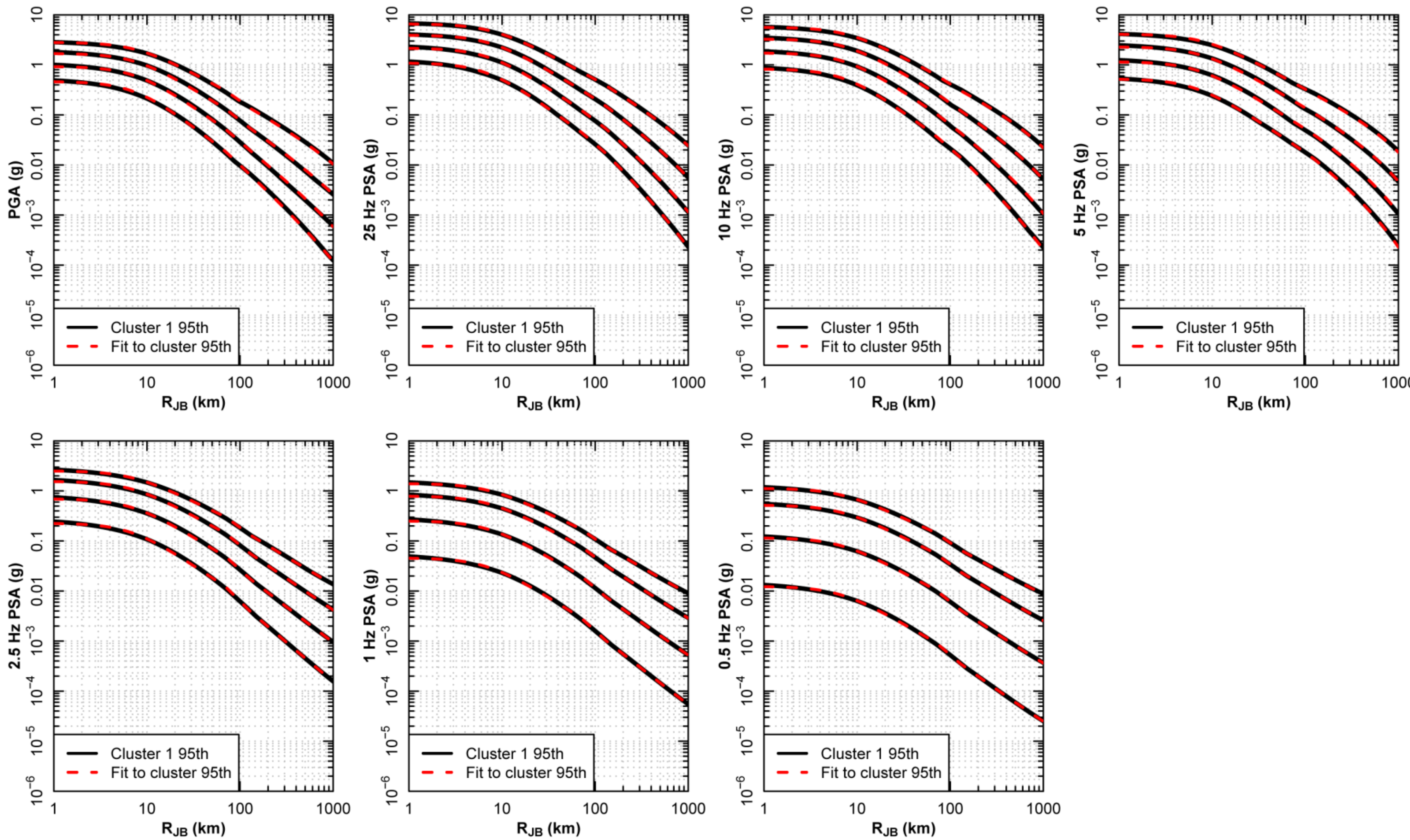

Figure 8.5-7b. Fit of Equation 8.4-1 to 95th percentile ln(PSA) and ln(PGA) for Cluster 1 for **M** 5, 6, 7, and 8

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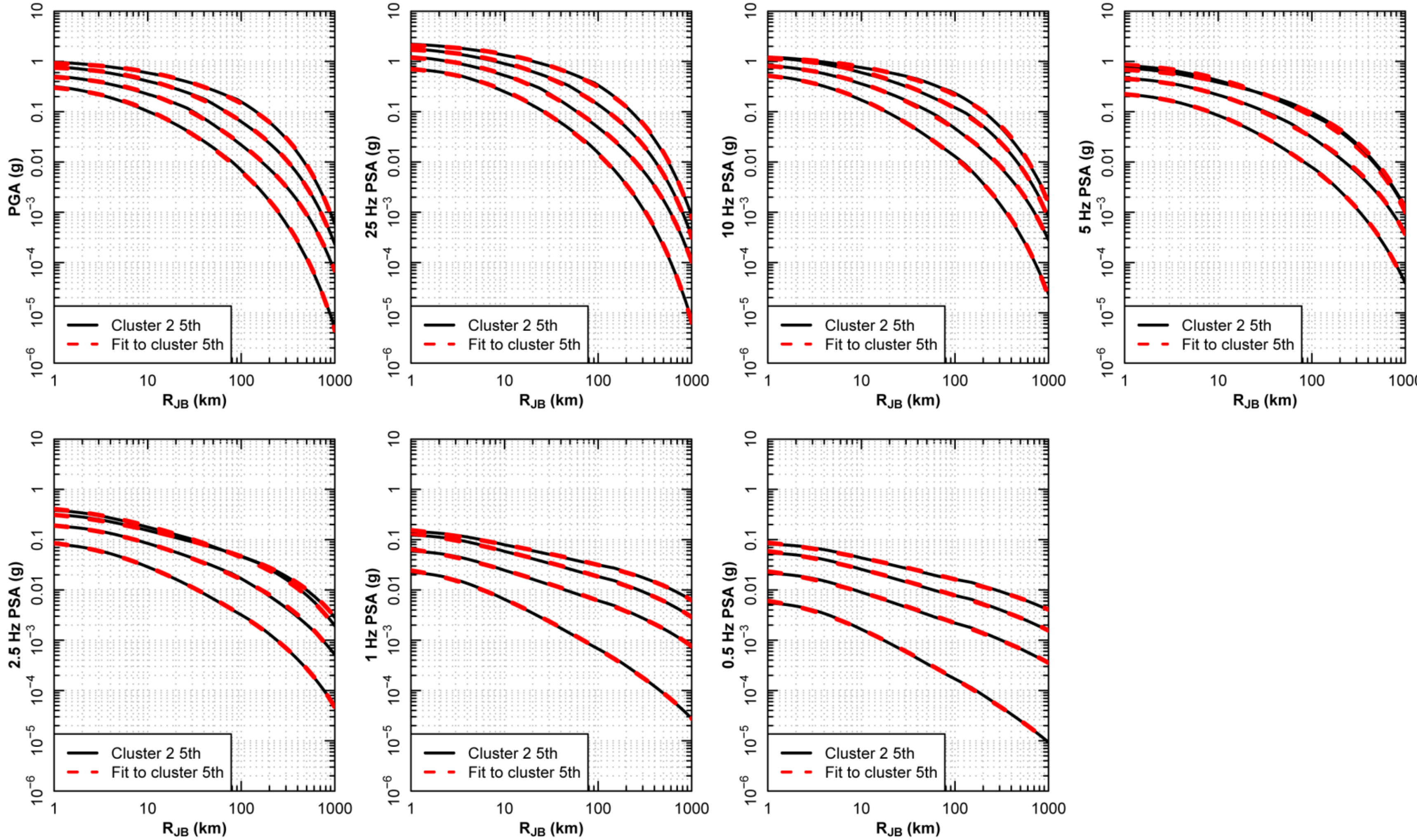

Figure 8.5-8a. Fit of Equation 8.4-1 to 5th percentile ln(PSA) and ln(PGA) for Cluster 2 for **M** 5, 6, 7, and 8

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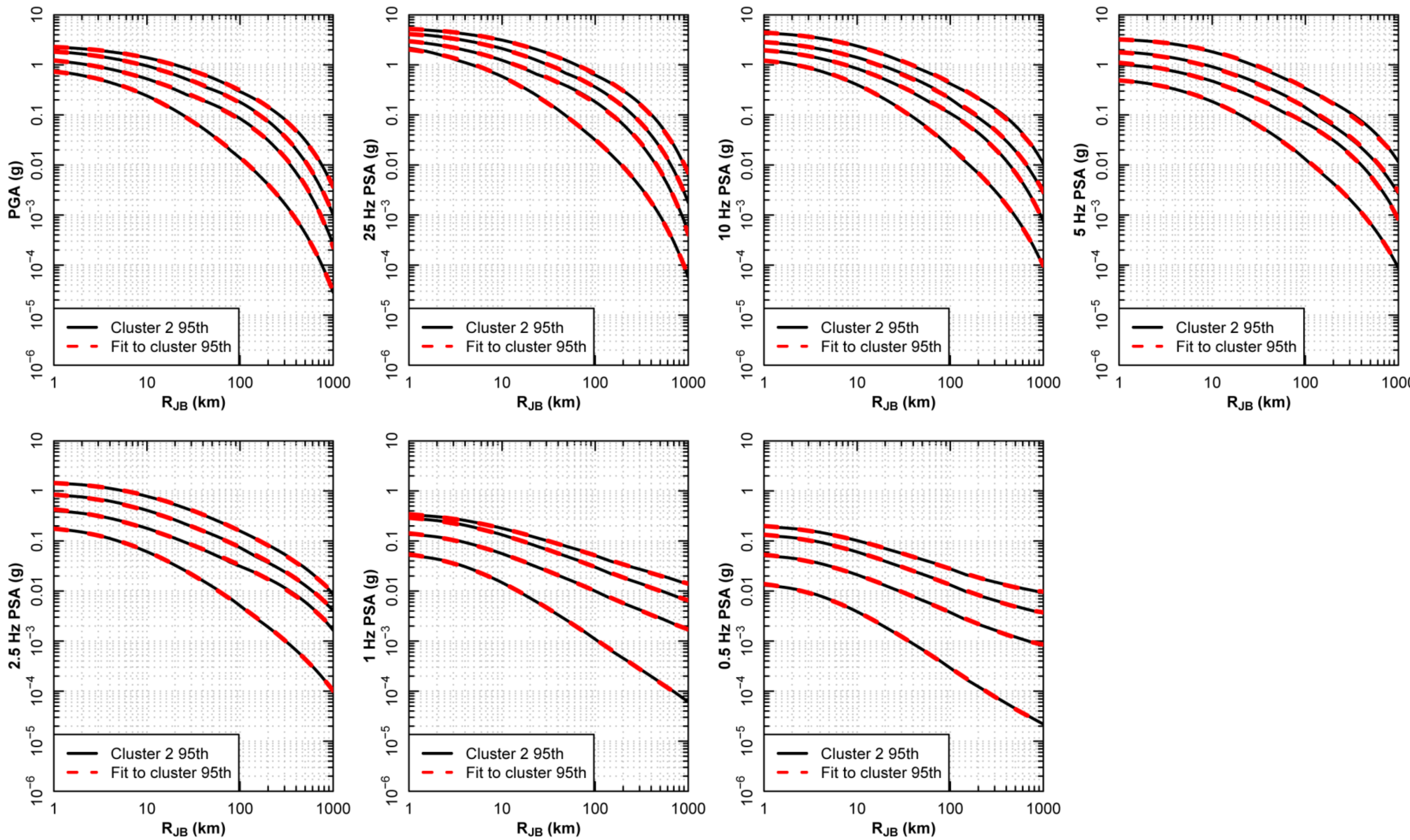

Figure 8.5-8b. Fit of Equation 8.4-1 to 95th percentile ln(PSA) and ln(PGA) for Cluster 2 for **M** 5, 6, 7, and 8

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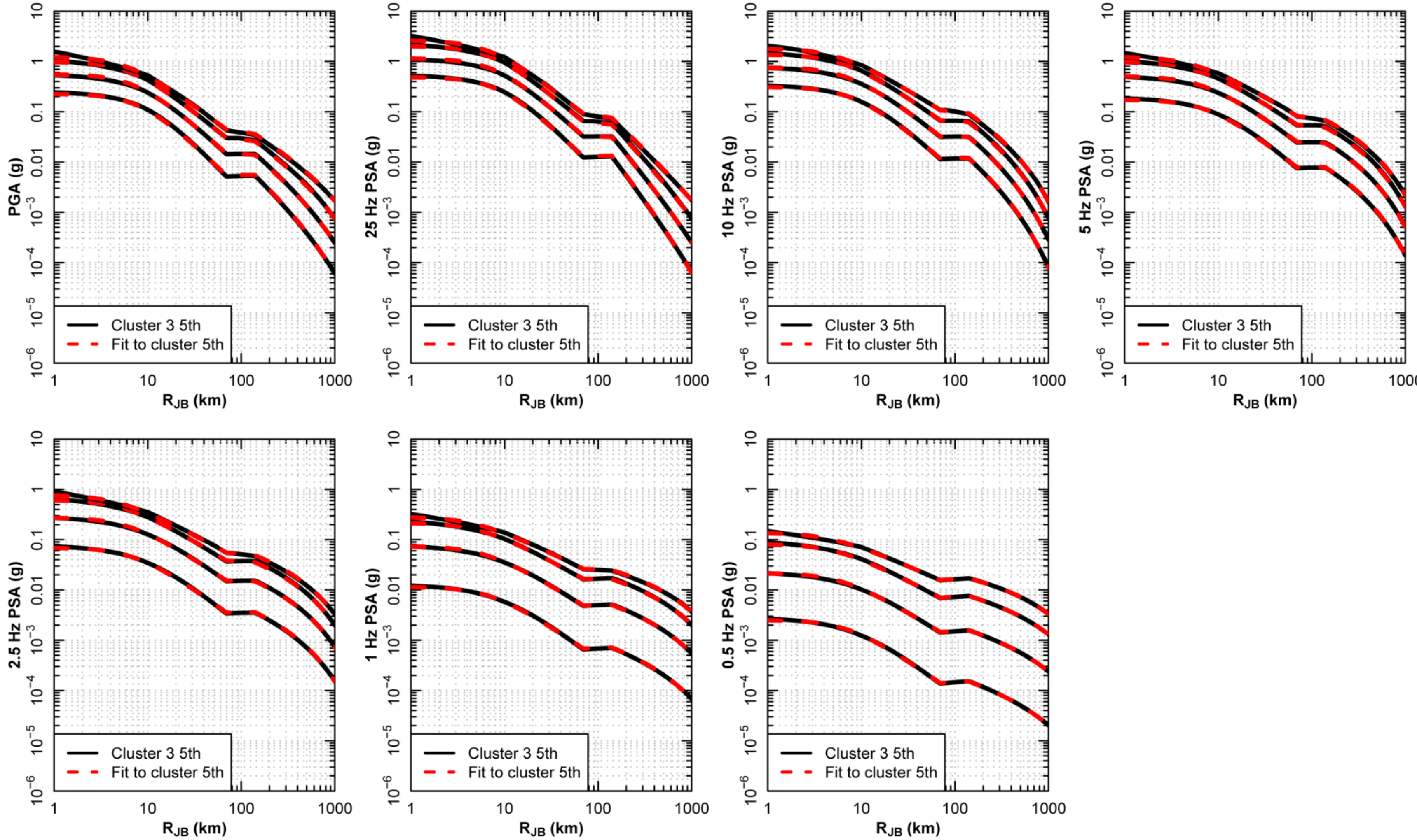

Figure 8.5-9a. Fit of Equation 8.4-1 to 5th percentile ln(PSA) and ln(PGA) for Cluster 3 for **M** 5, 6, 7, and 8

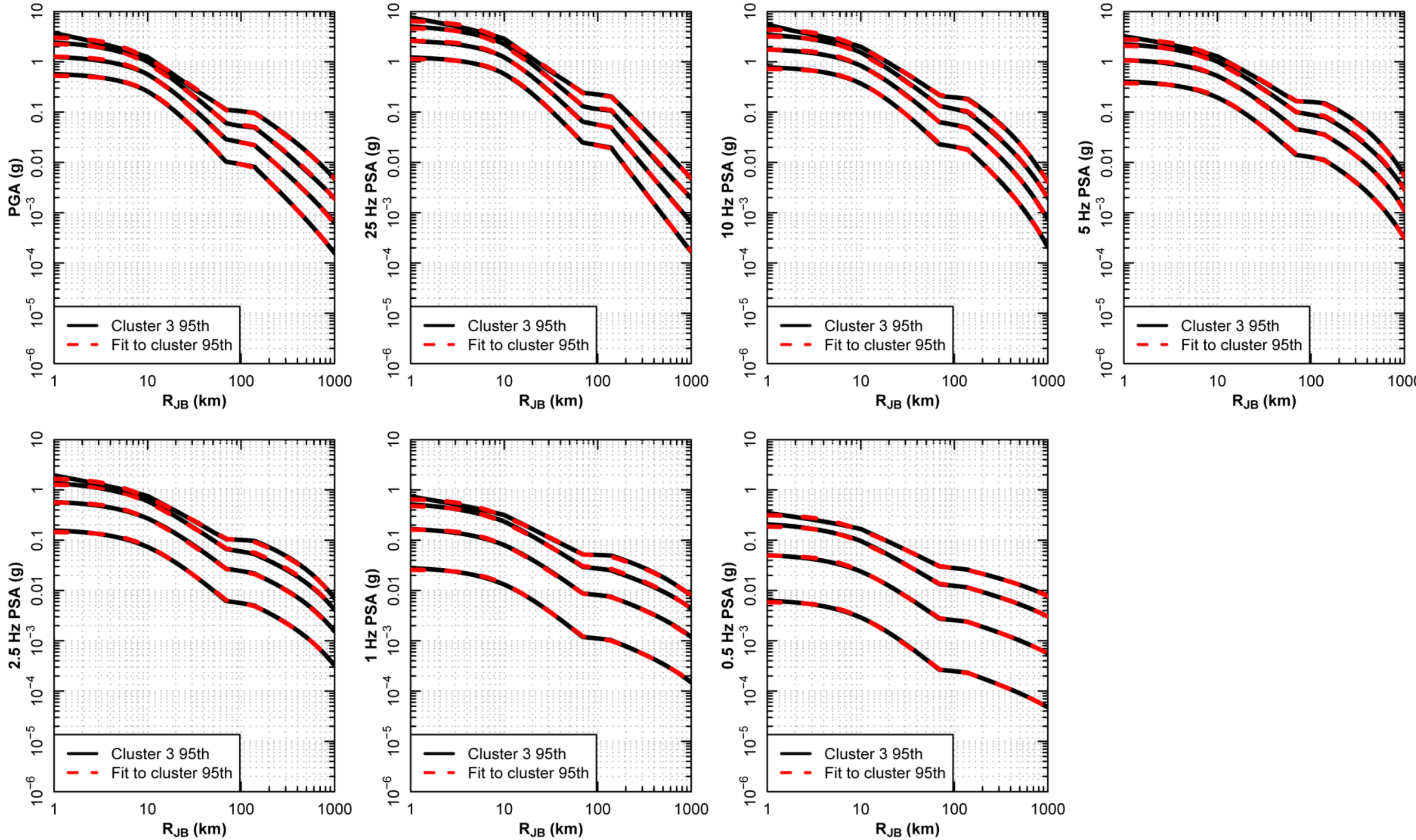

Figure 8.5-9b. Fit of Equation 8.4-1 to 95th percentile ln(PSA) and ln(PGA) for Cluster 3 for **M** 5, 6, 7, and 8

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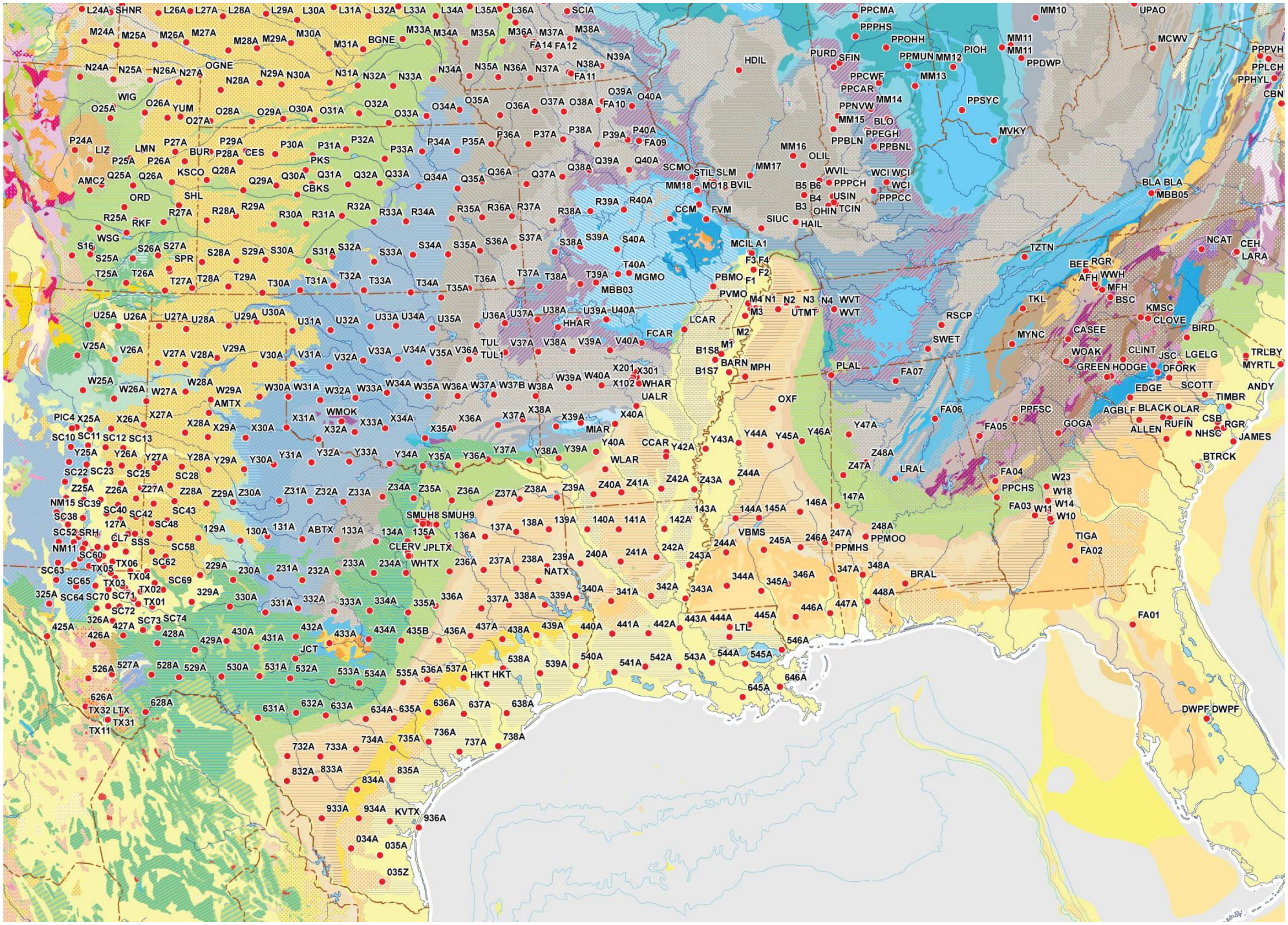

Figure 8.9-1. Geologic Map of the southern U.S. showing the locations of Earthscope Transportable Array Stations, and permanent broadband stations during 2011. From Garrity, C.P. and D.R. Soller (2009).

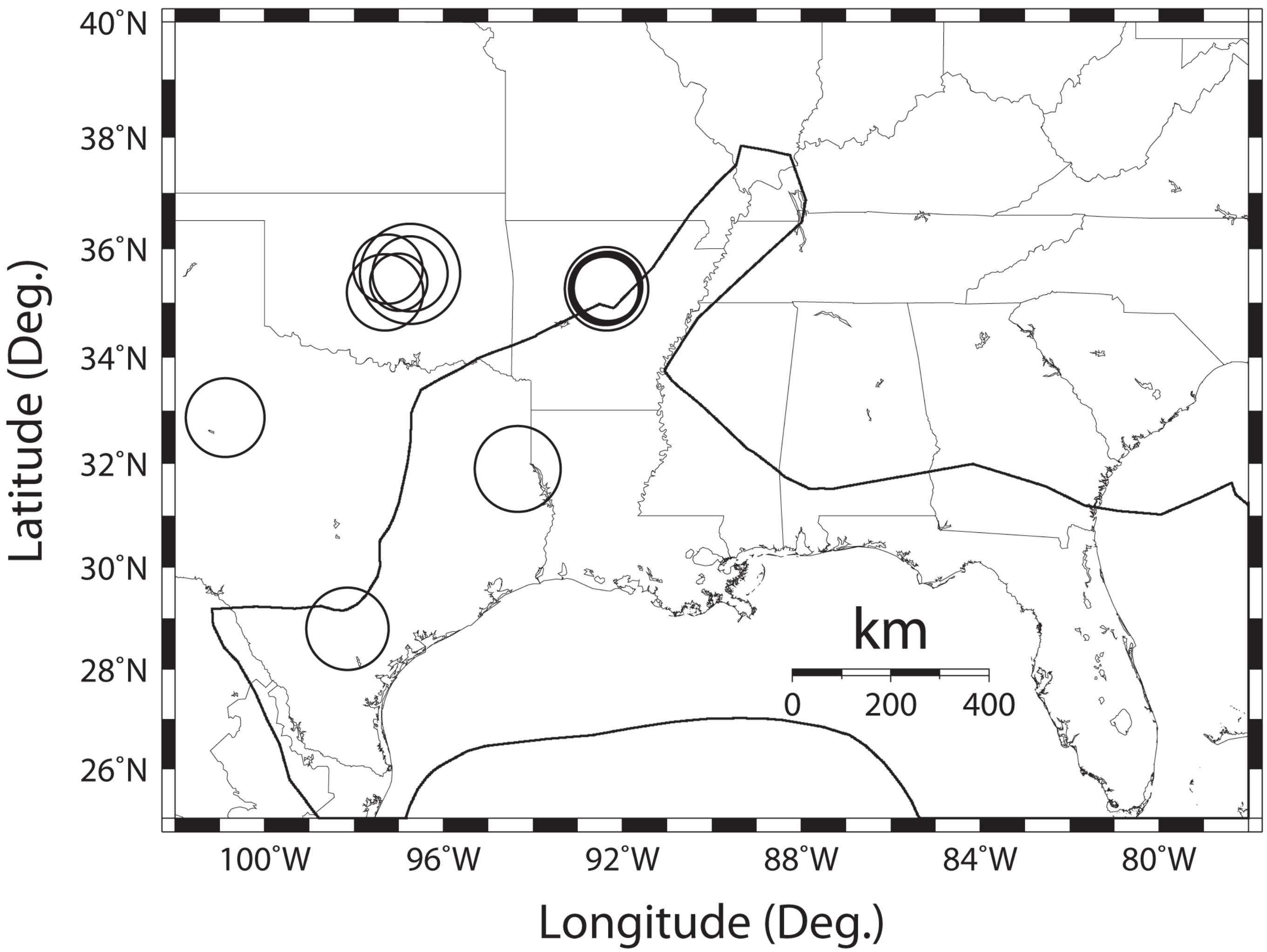

Figure 8.9-2. Epicenters of earthquakes providing data from analysis (Table 8.9-1).
The thick solid line show the boundary of the Gulf coastal region defined on the basis of extended crust (EPRI, 2012).

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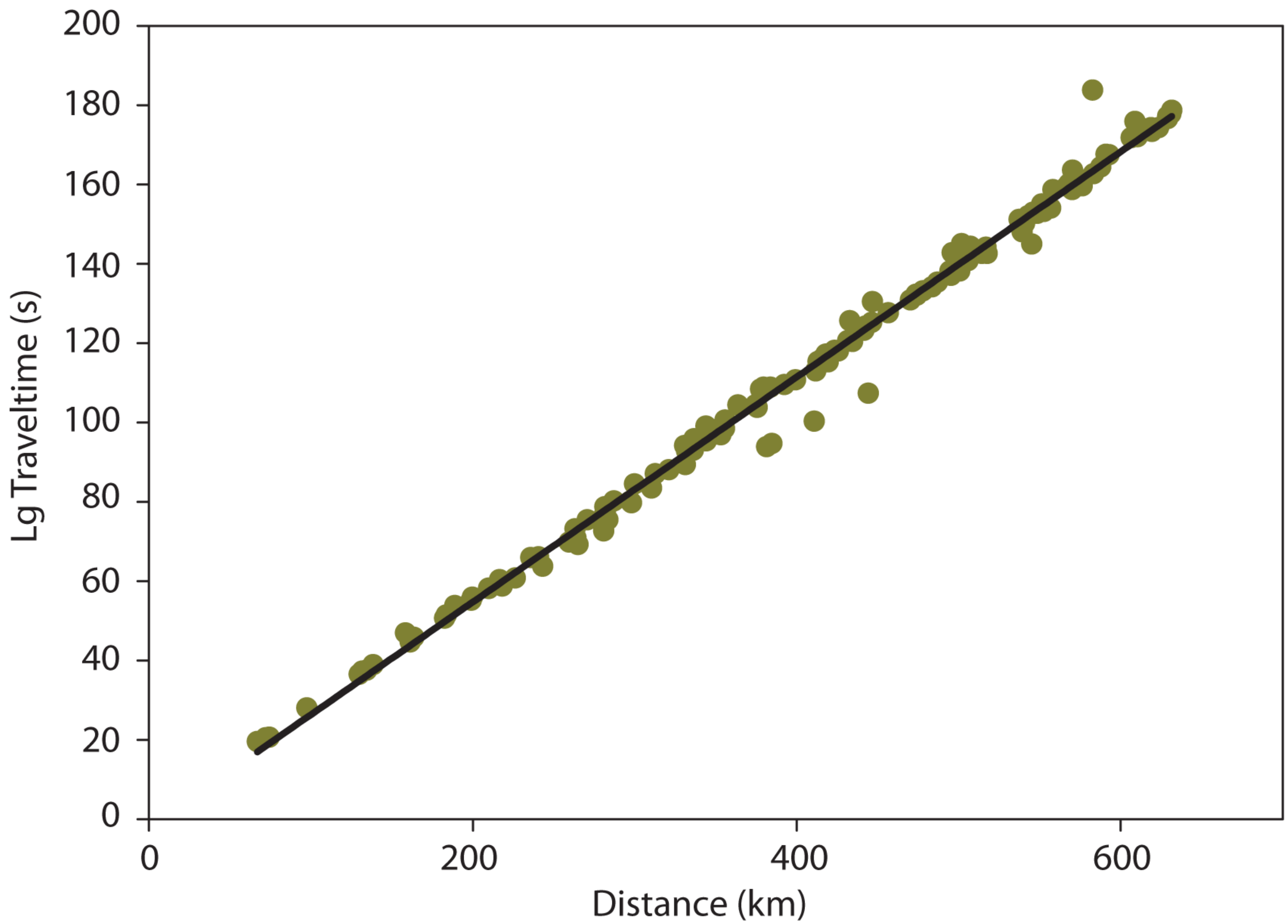

Figure 8.9-3. Lg travel time versus epicentral distance observed from the February 28, 2011 Arkansas earthquake. The line shows a least-squares fit to the data.

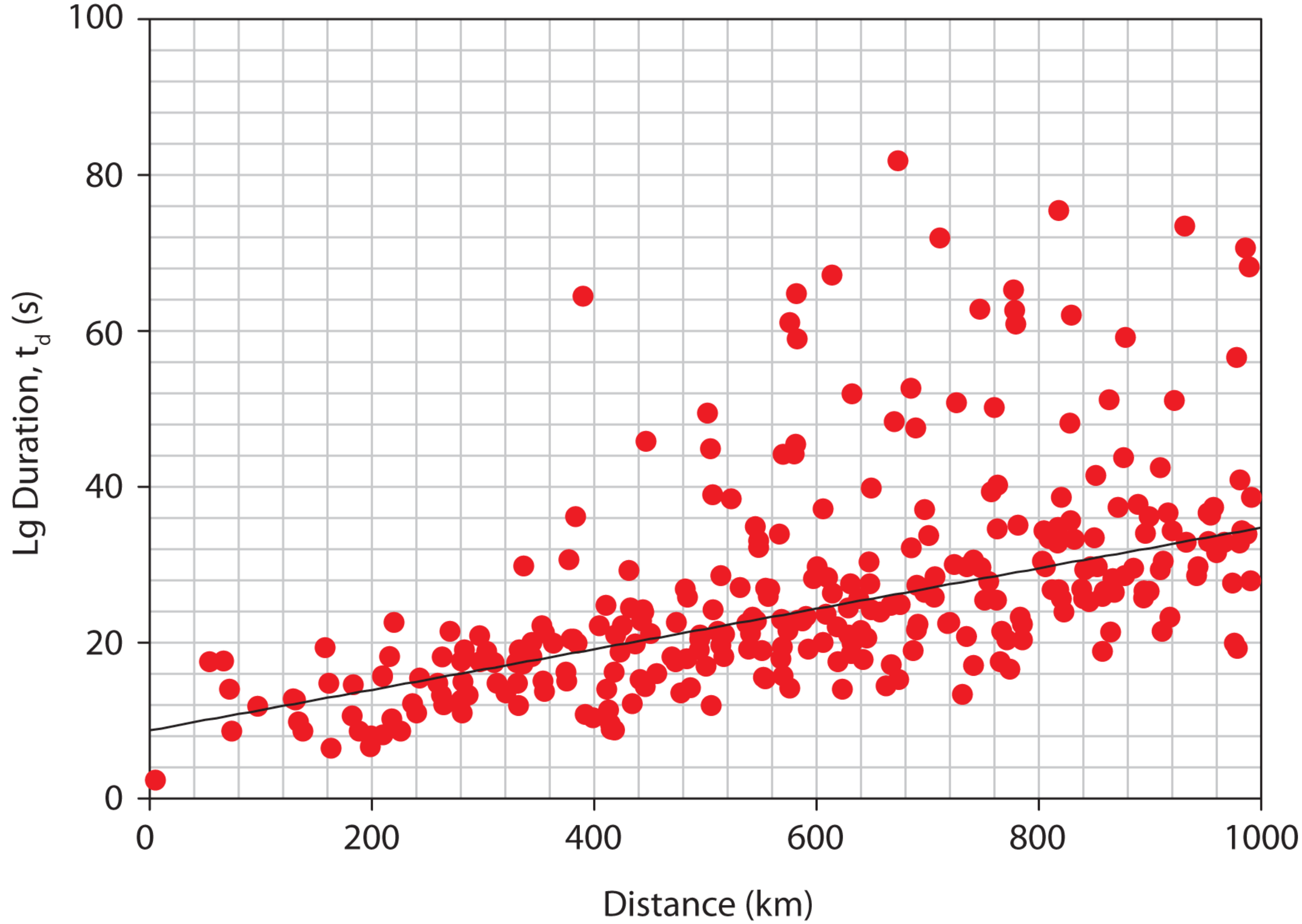

Figure 8.9-4. Lg duration versus epicentral distance observed from the February 28, 2011 Arkansas earthquake. The line shows a least-squares fit to the data.

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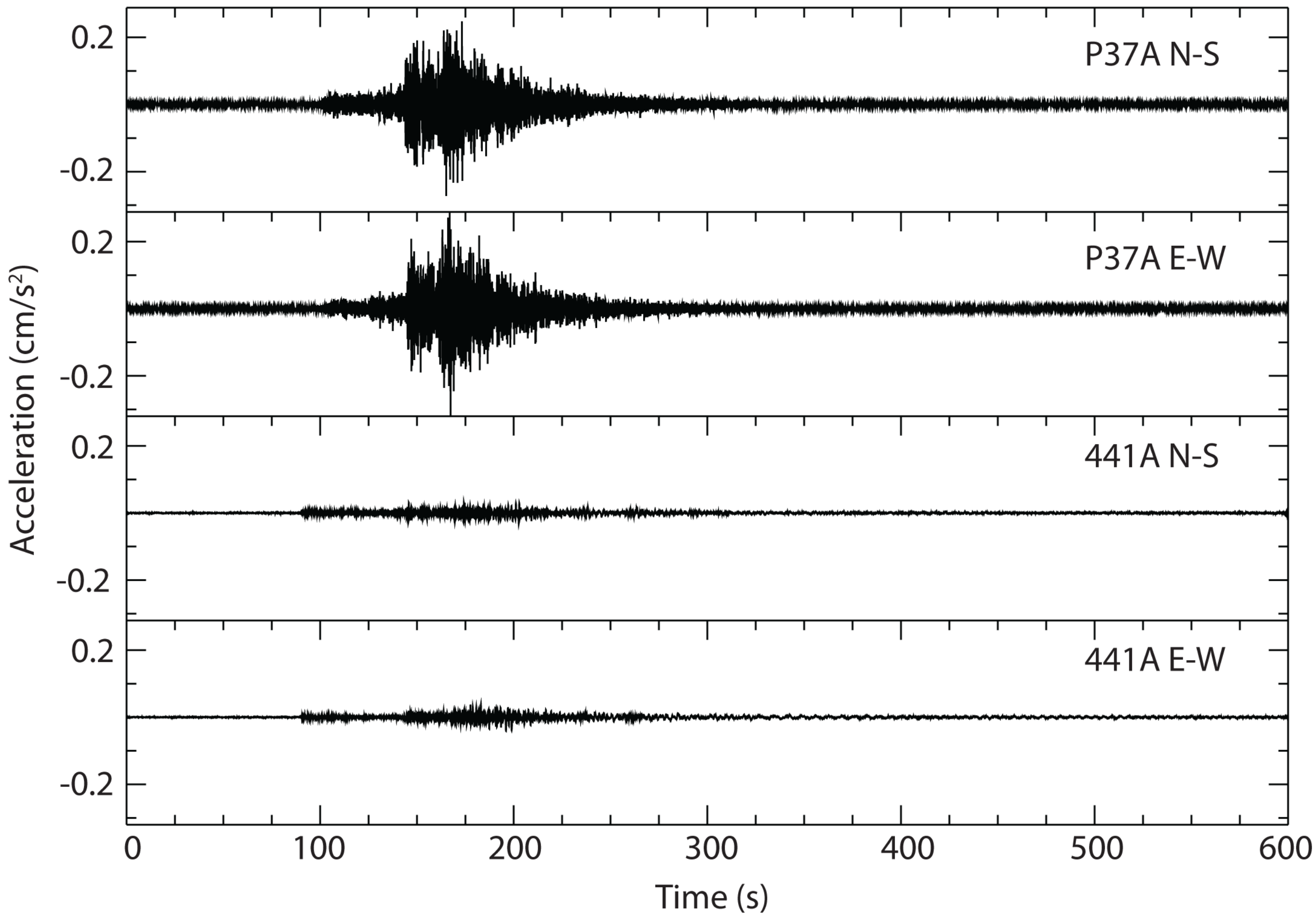

Figure 8.9-5. Horizontal component acceleration recordings at station P37A in northern Missouri and station 441A in southern Louisiana, from the February 28, 2011 earthquake in central Arkansas. The epicenter distance is approximately 500 km for both stations.

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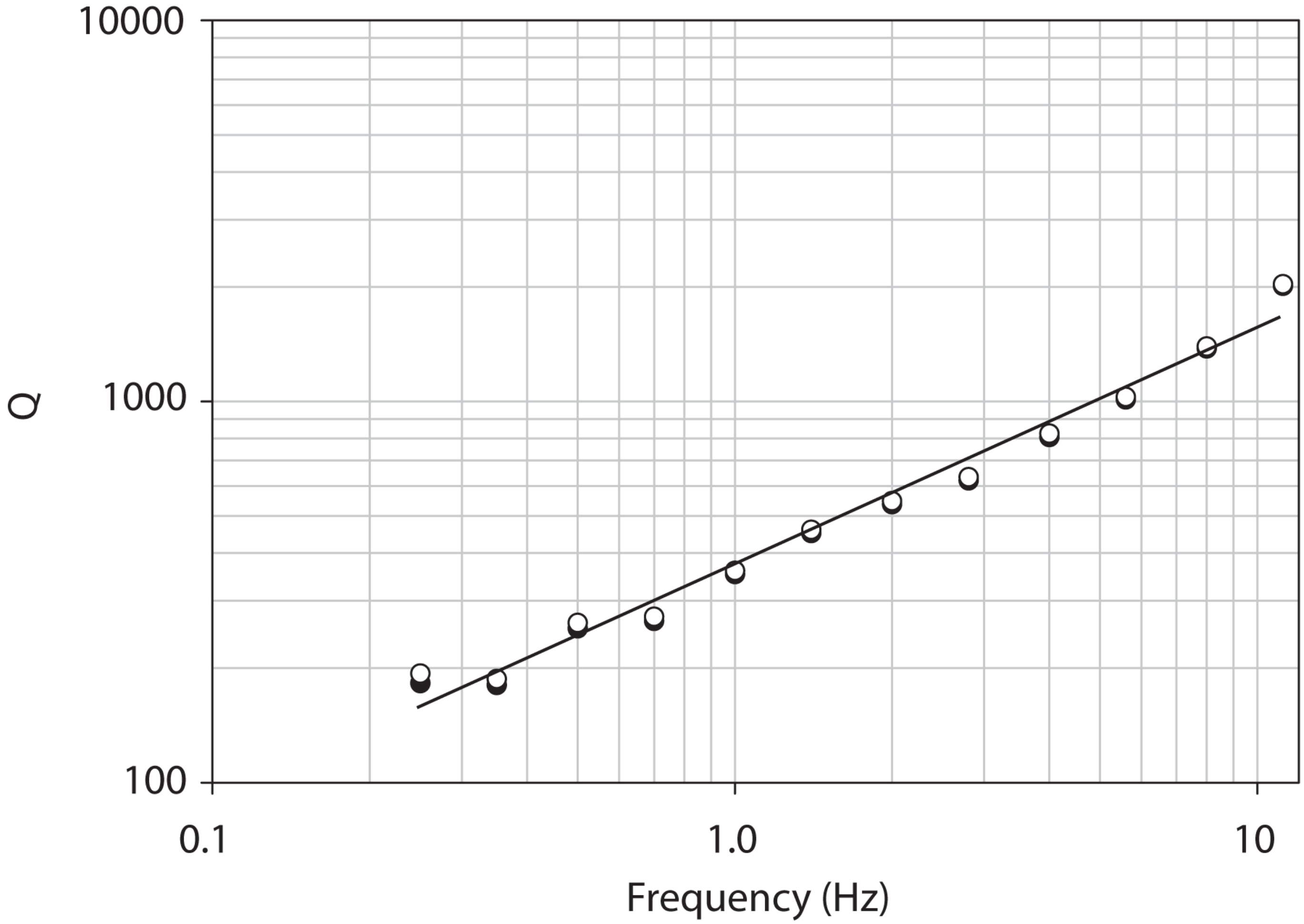

Figure 8.9-6. Filled circles show the mean estimates of Q at 12 frequencies between 0.25 and 11.2 Hz using data recorded at stations in the Gulf Coast Region and assuming geometrical spreading model 1. Open circles show estimates of Q assuming a stress drop of 5 MPa: filled circles assume a stress drop of 10 MPa.

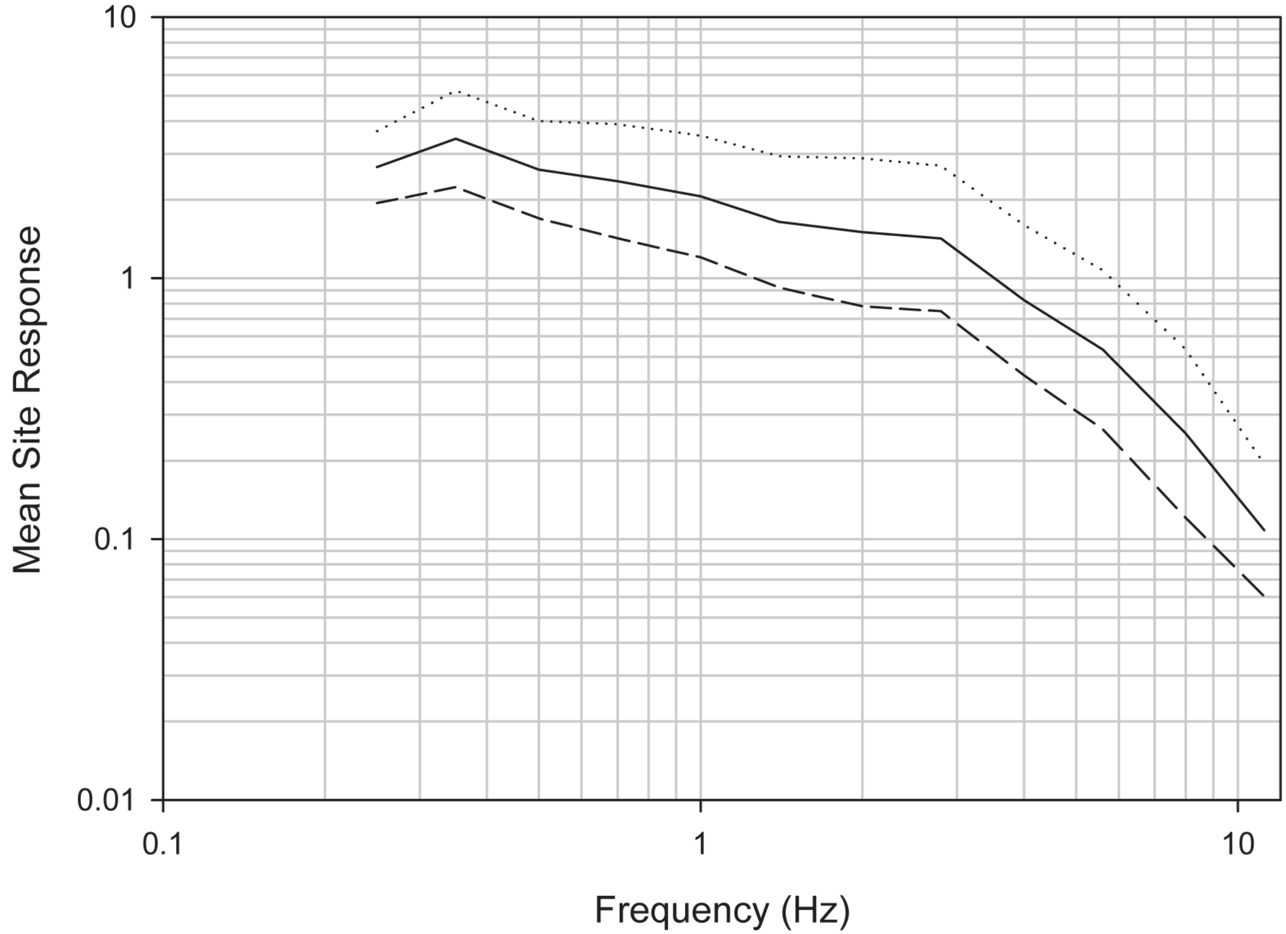

Figure 8.9-7. The solid line shows mean site response for stations in the Gulf coast region south of latitude 33N, using geometrical spreading model 1. The dashed and dotted lines show the mean +/- standard error estimates of the site terms.

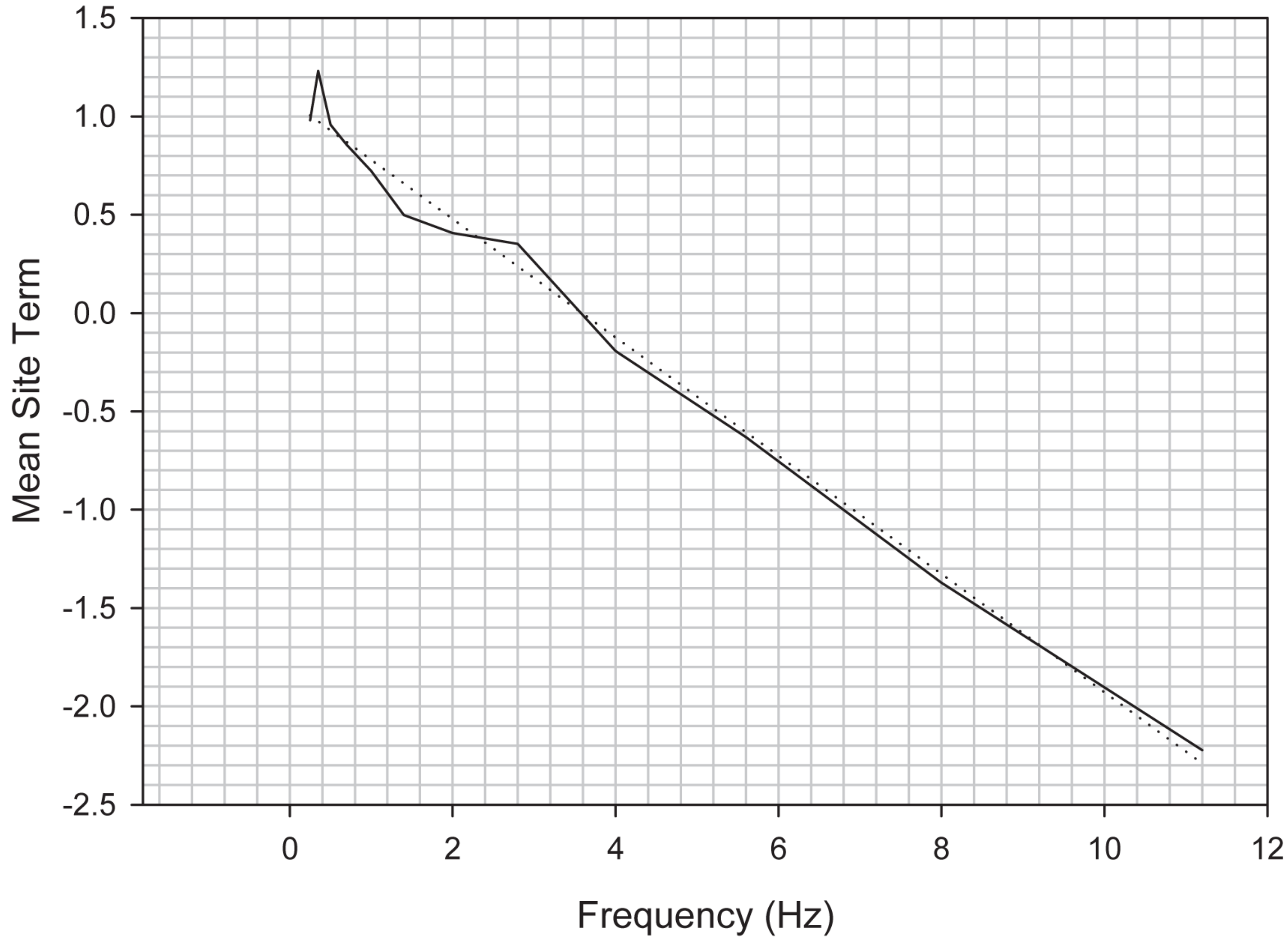

Figure 8.9-8. The solid line shows mean receiver (site) terms for stations in the Gulf coast region south of latitude 33N, using geometrical spreading model 1. The dotted line shows a linear regression fit to the site terms, implying a K_o value of 0.096 +/- 0.010.

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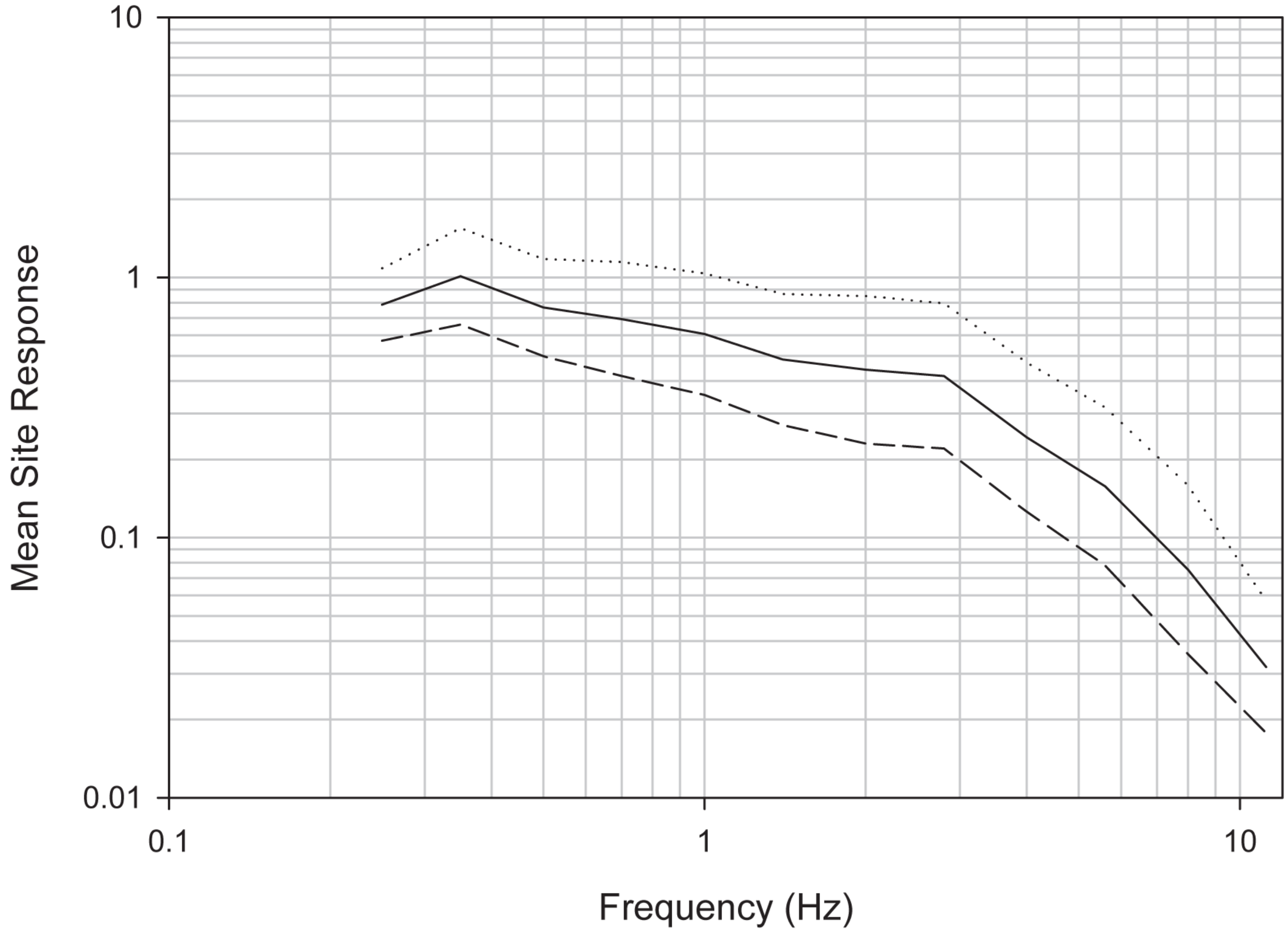

Figure 8.9-9. The solid line shows mean site response for stations in the Gulf coast region south of latitude 33N, using geometrical spreading model 2. The dashed and dotted lines show the mean +/- standard error estimates of the site terms.

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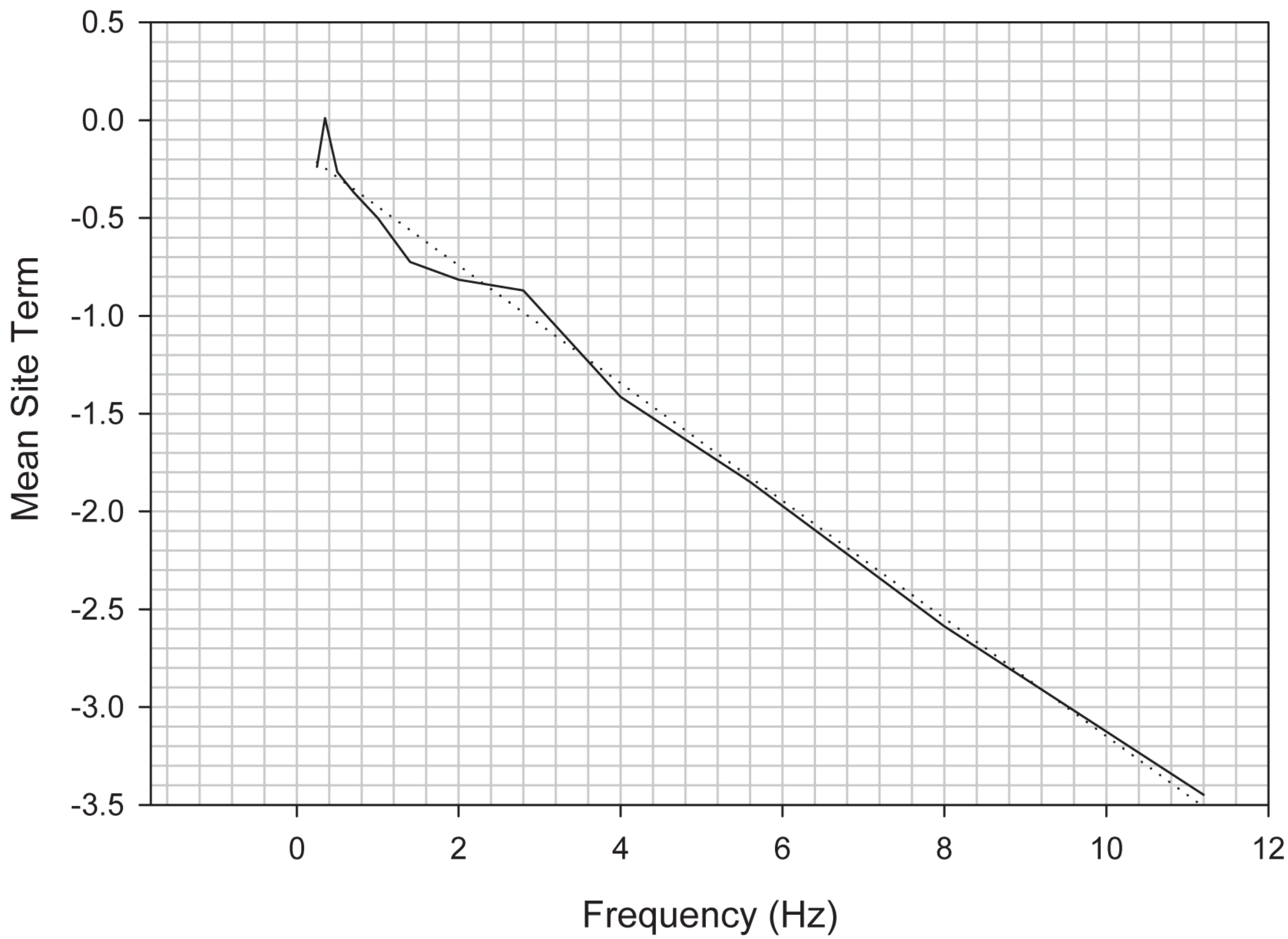

Figure 8.9-10. The solid line shows mean receiver (site) terms for stations in the Gulf coast region south of latitude 33N, using geometrical spreading model 2. The dotted line shows a linear regression fit to the site terms, implying a K_o value of 0.096 +/- 0.010.

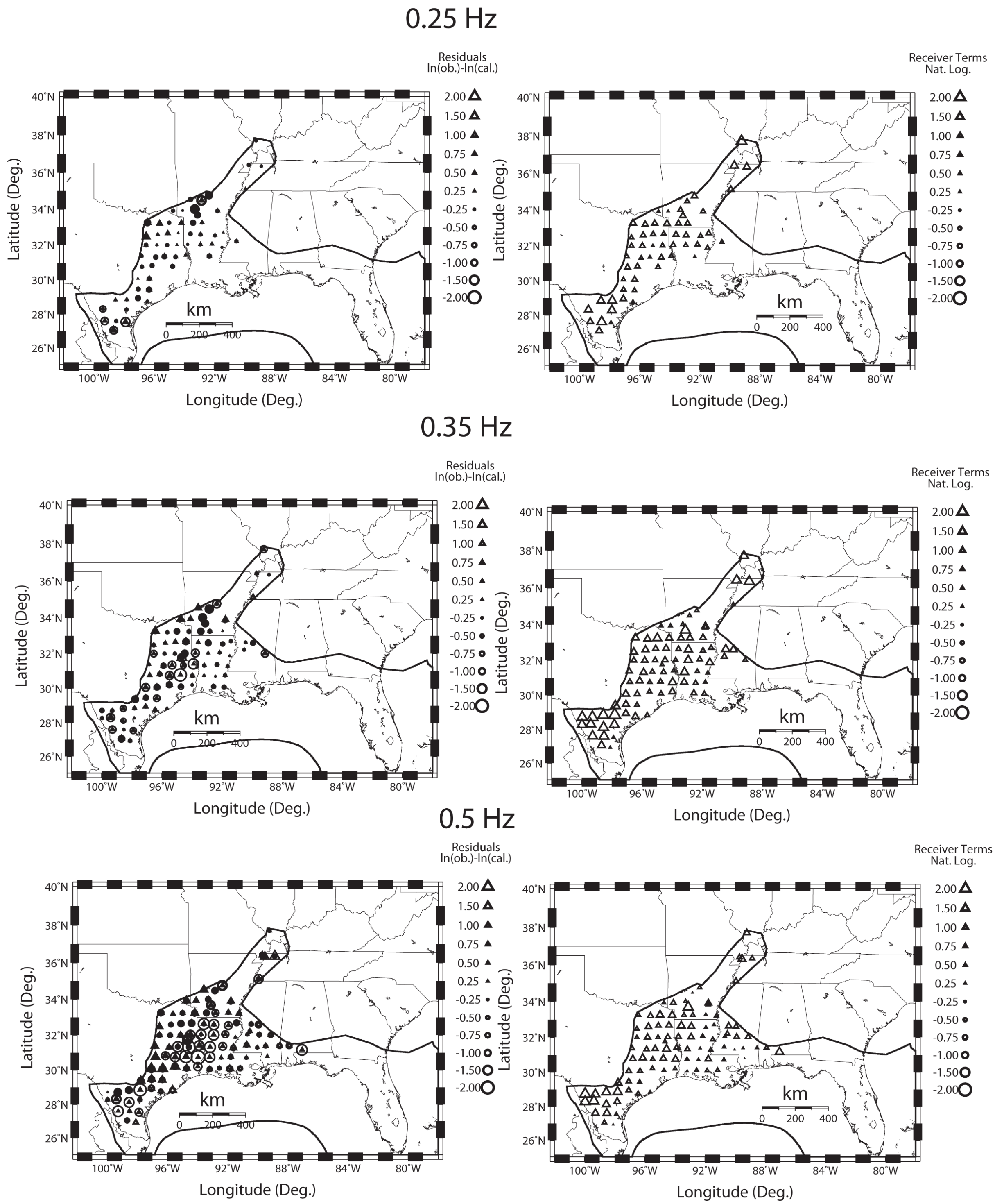

Figure 8.9-11. Residuals (left) and Receiver Terms (Site Terms) for 0.25Hz (top), 0.35 Hz (middle) and 0.5 Hz (bottom). Regression assuming geometrical spreading model 1.

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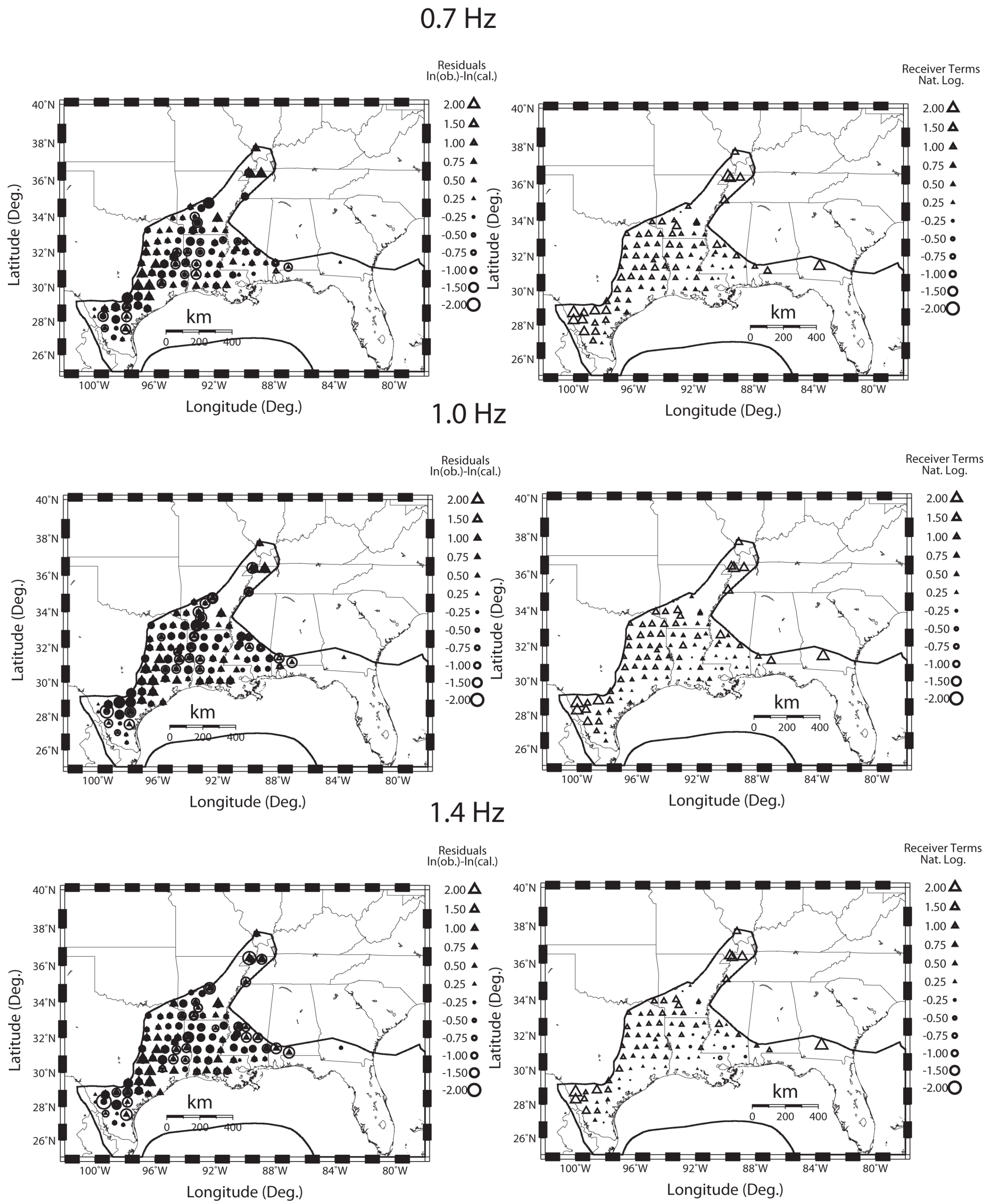

Figure 8.9-12. Residuals (left) and Receiver Terms (Site Terms) for 0.7Hz (top), 1.0 Hz (middle) and 1.4 Hz (bottom). Regression assuming geometrical spreading model 1.

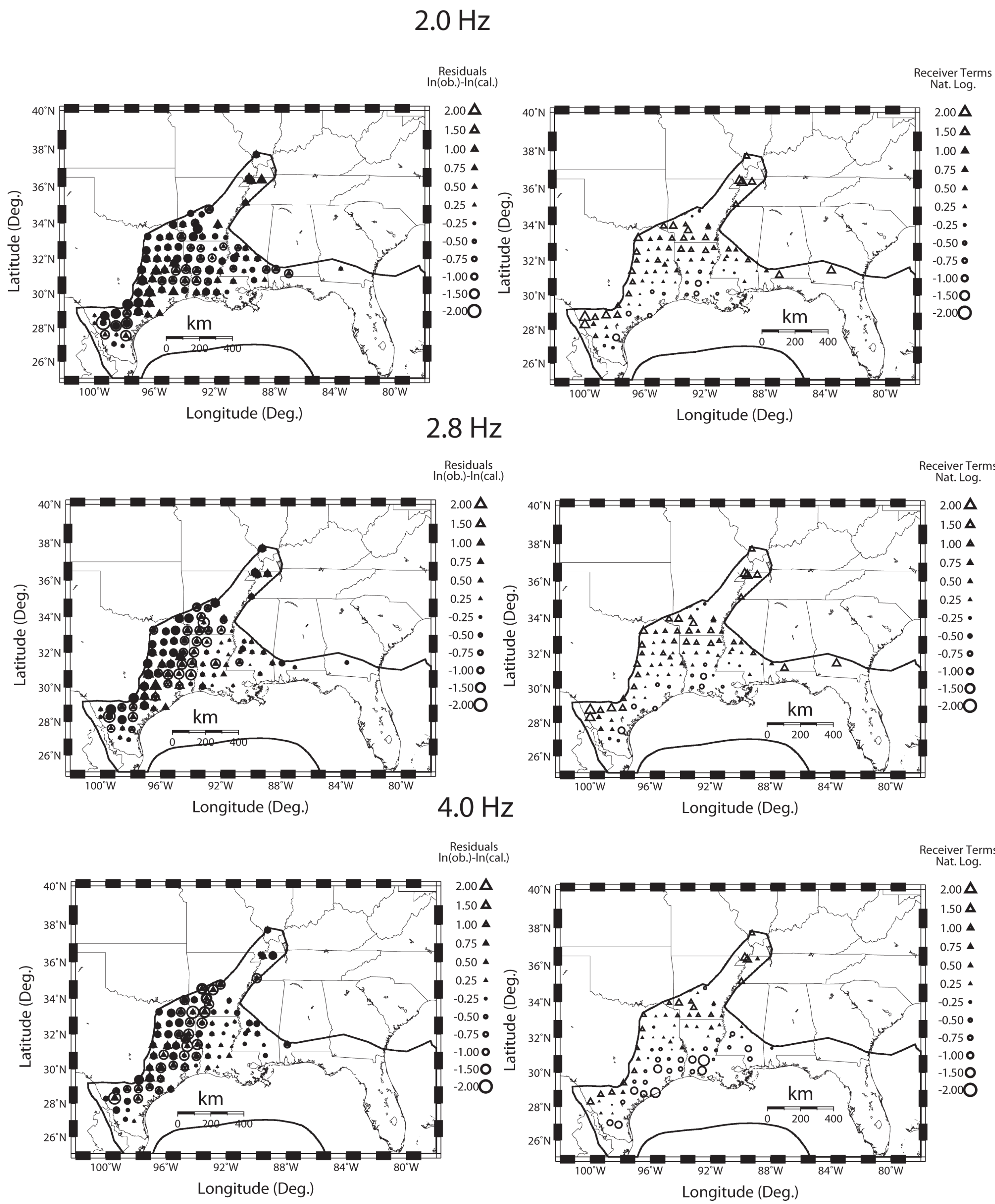

Figure 8.9-13. Residuals (left) and Receiver Terms (Site Terms) for 2.0 Hz (top), 2.8 Hz (middle) and 4.0 Hz (bottom). Regression assuming geometrical spreading model 1.

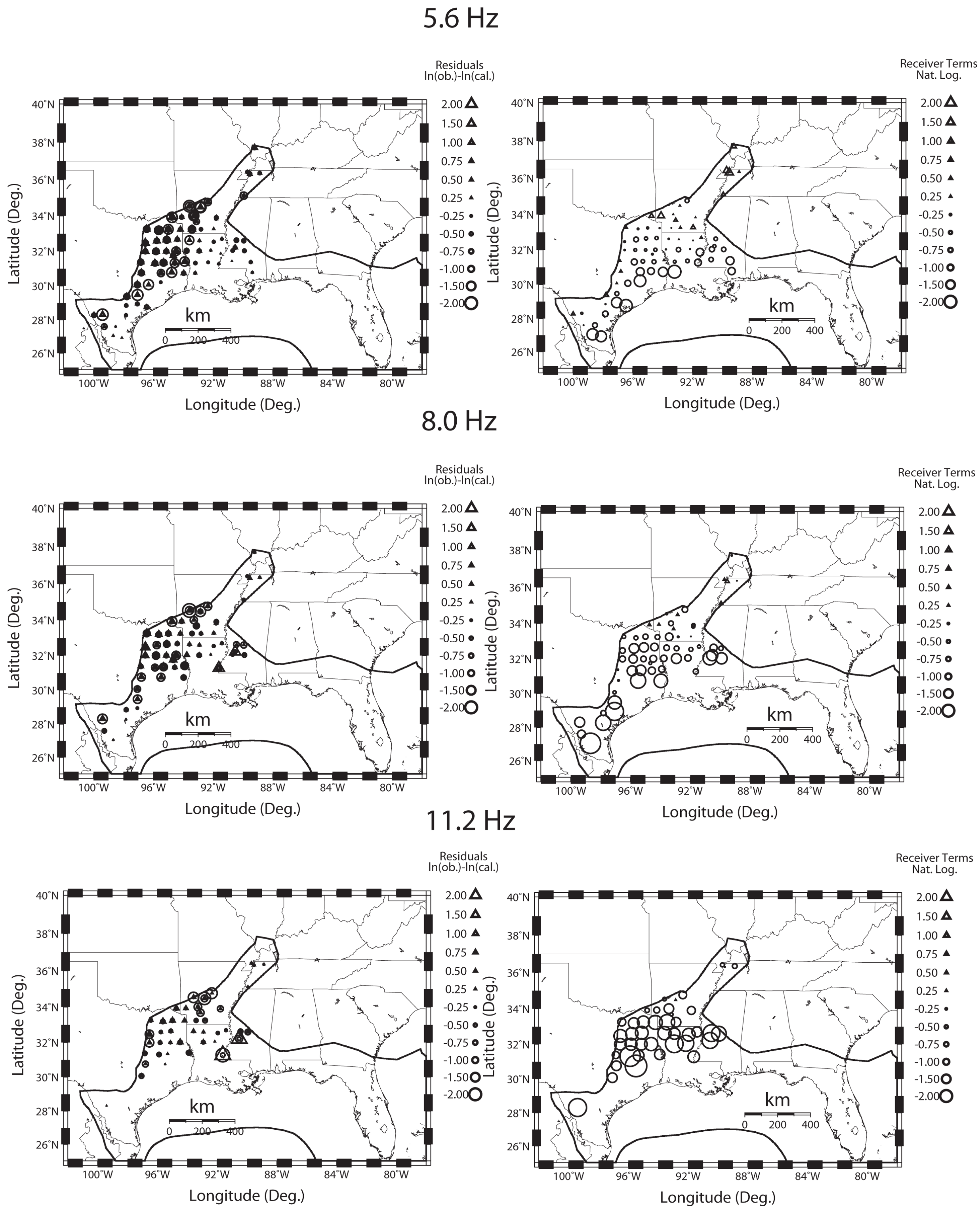

Figure 8.9-14. Residuals (left) and Receiver Terms (Site Terms) for 5.6 Hz (top), 8.0 Hz (middle) and 11.2 Hz (bottom). Regression assuming geometrical spreading model 1.

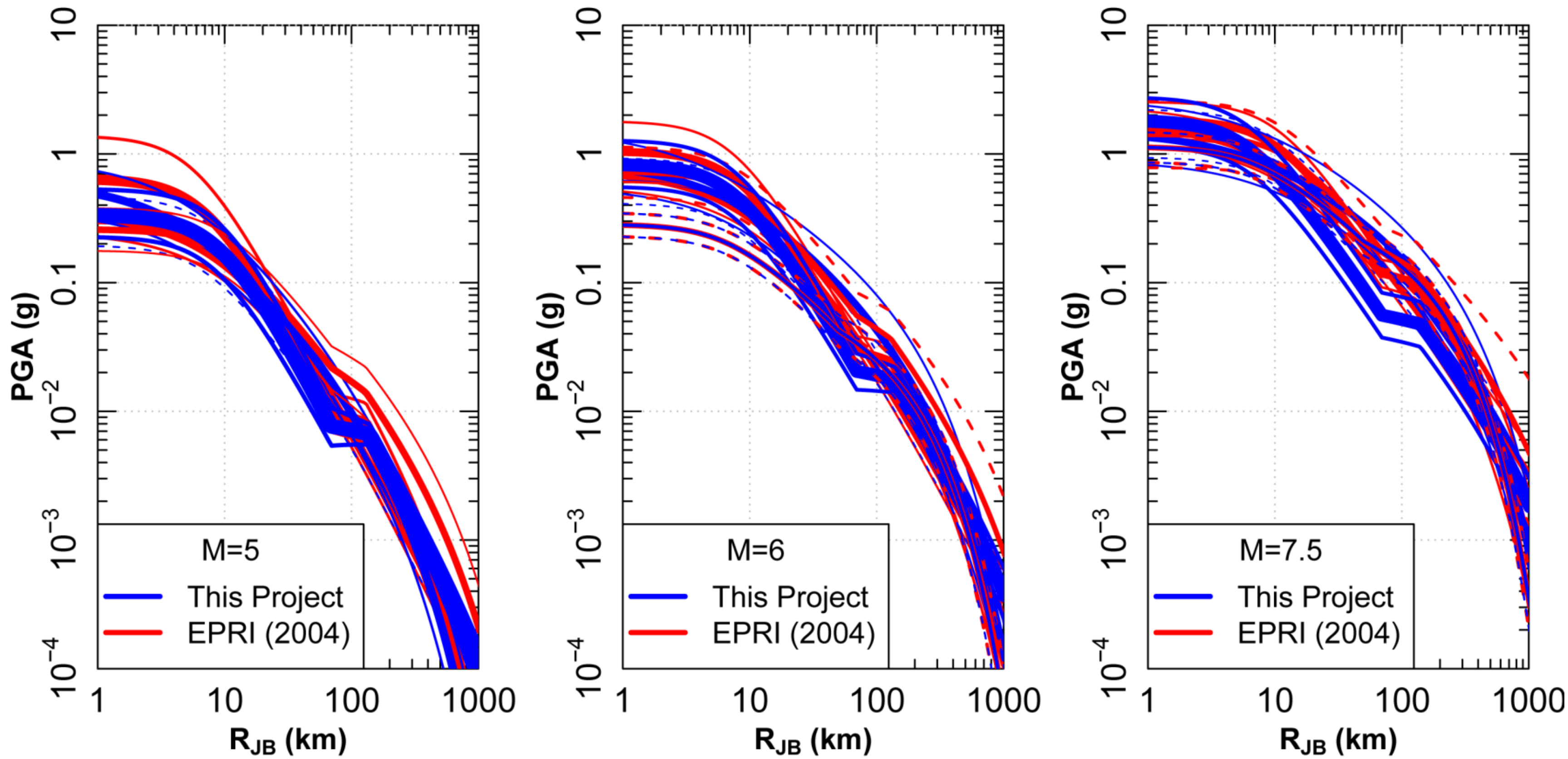

Figure 8.10-1. Comparison of updated and EPRI (2004) GMMs for 100 Hz spectral acceleration (PGA)

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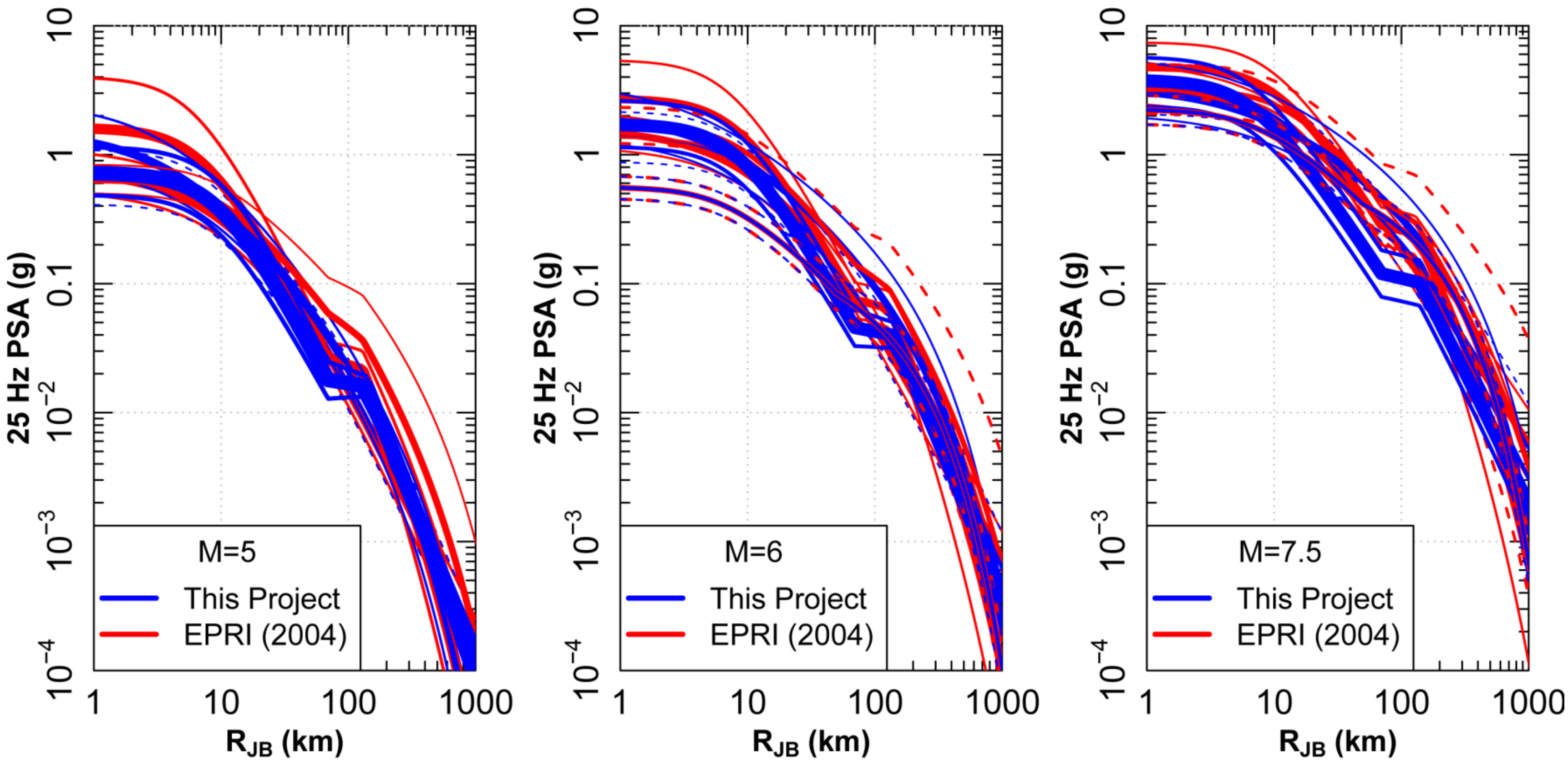

Figure 8.10-2. Comparison of updated and EPRI (2004) GMMs for 25 Hz spectral acceleration

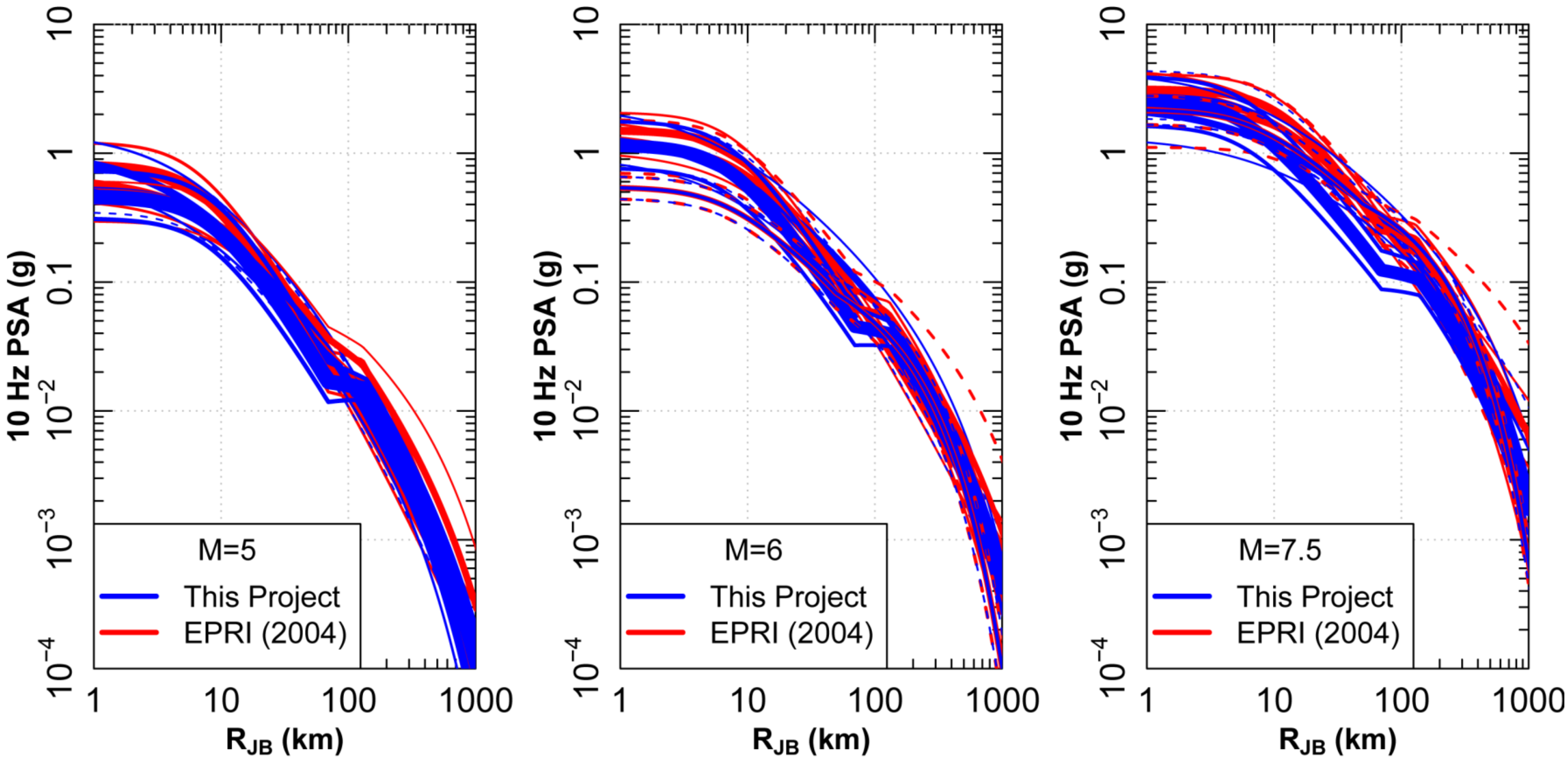

Figure 8.10-3. Comparison of updated and EPRI (2004) GMMs for 10 Hz spectral acceleration

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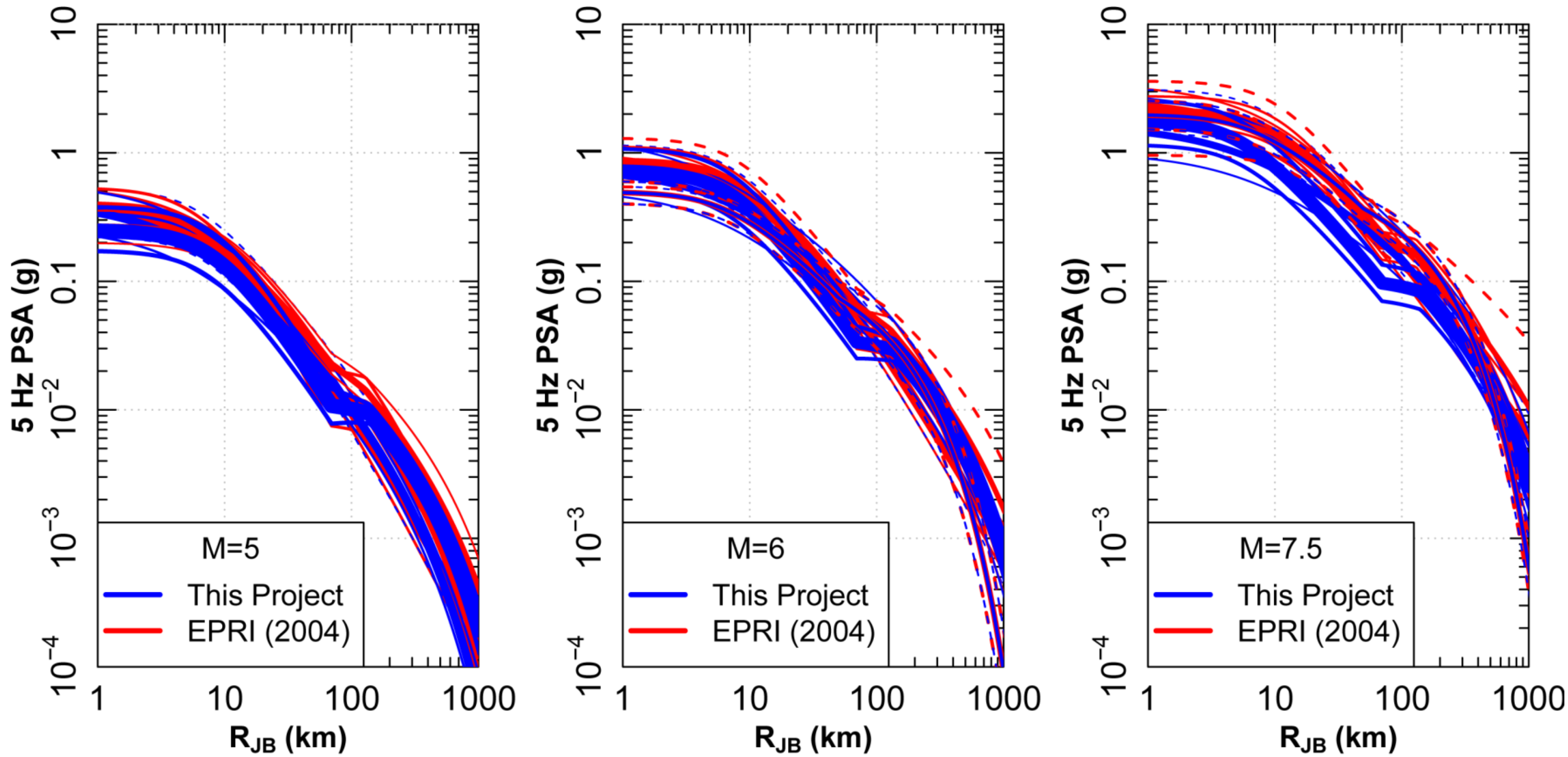

Figure 8.10-4. Comparison of updated and EPRI (2004) GMMs for 5 Hz spectral acceleration

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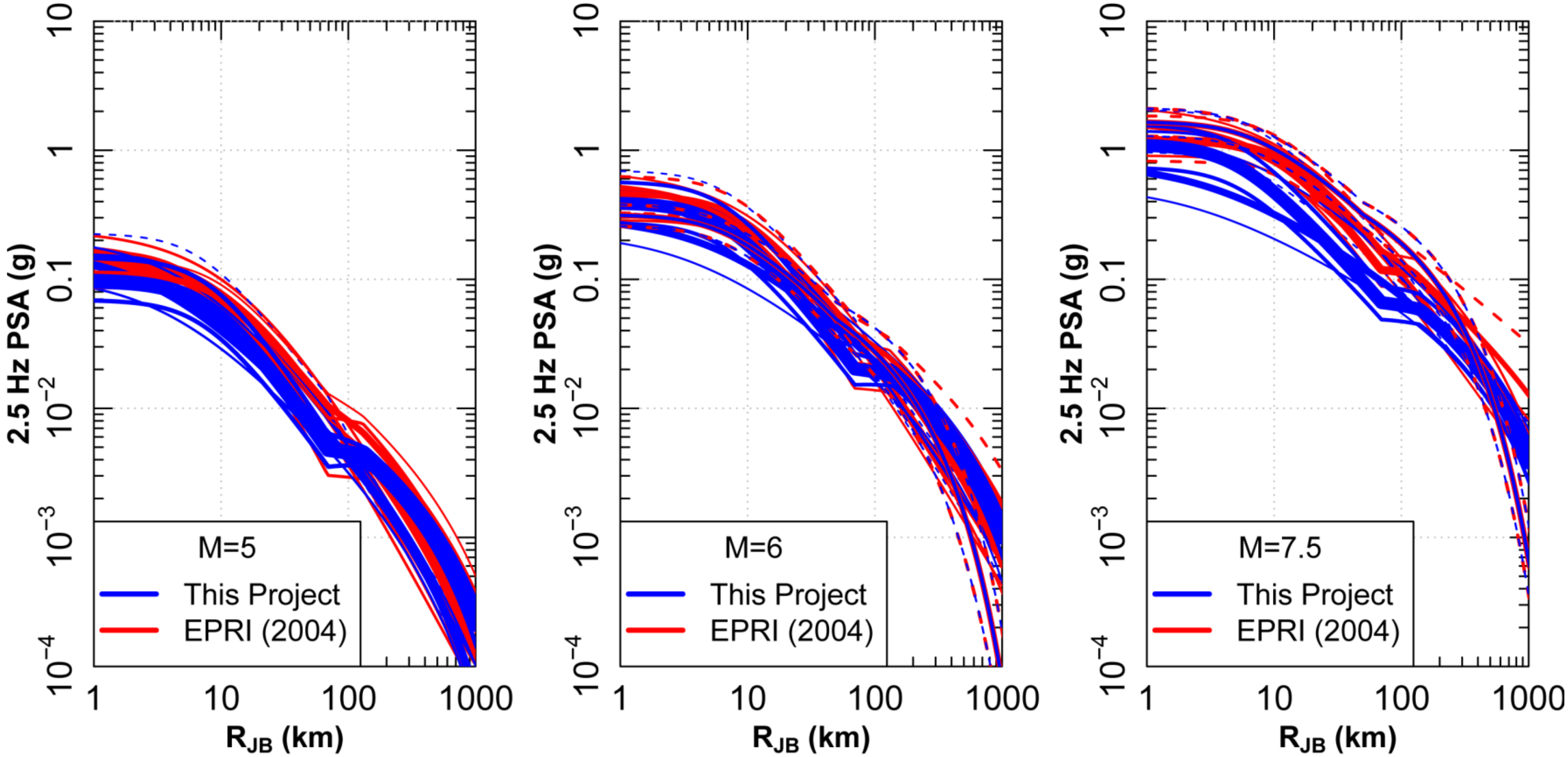

Figure 8.10-5. Comparison of updated and EPRI (2004) GMMs for 2.5 Hz spectral acceleration

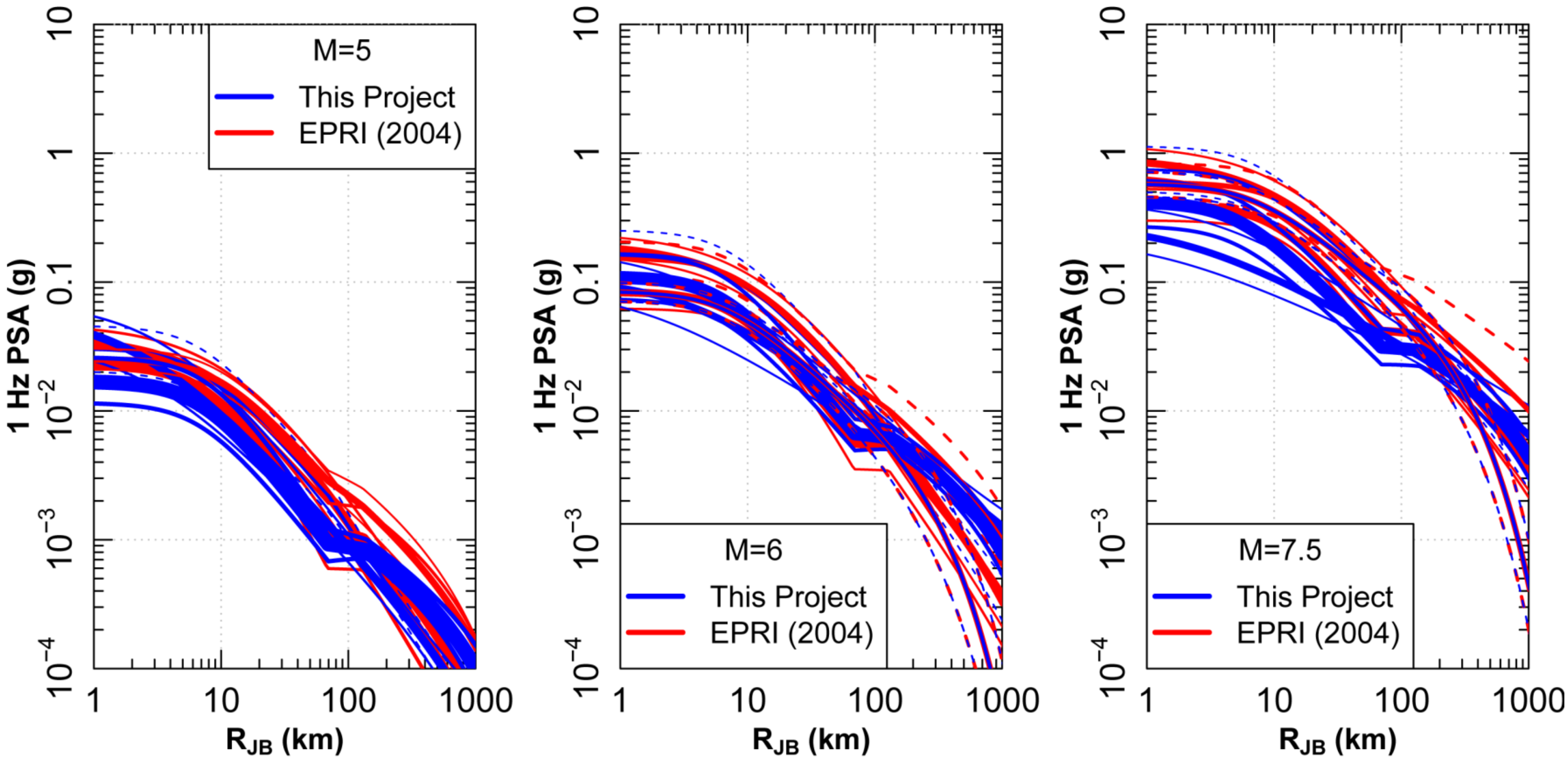

Figure 8.10-6. Comparison of updated and EPRI (2004) GMMs for 1 Hz spectral acceleration

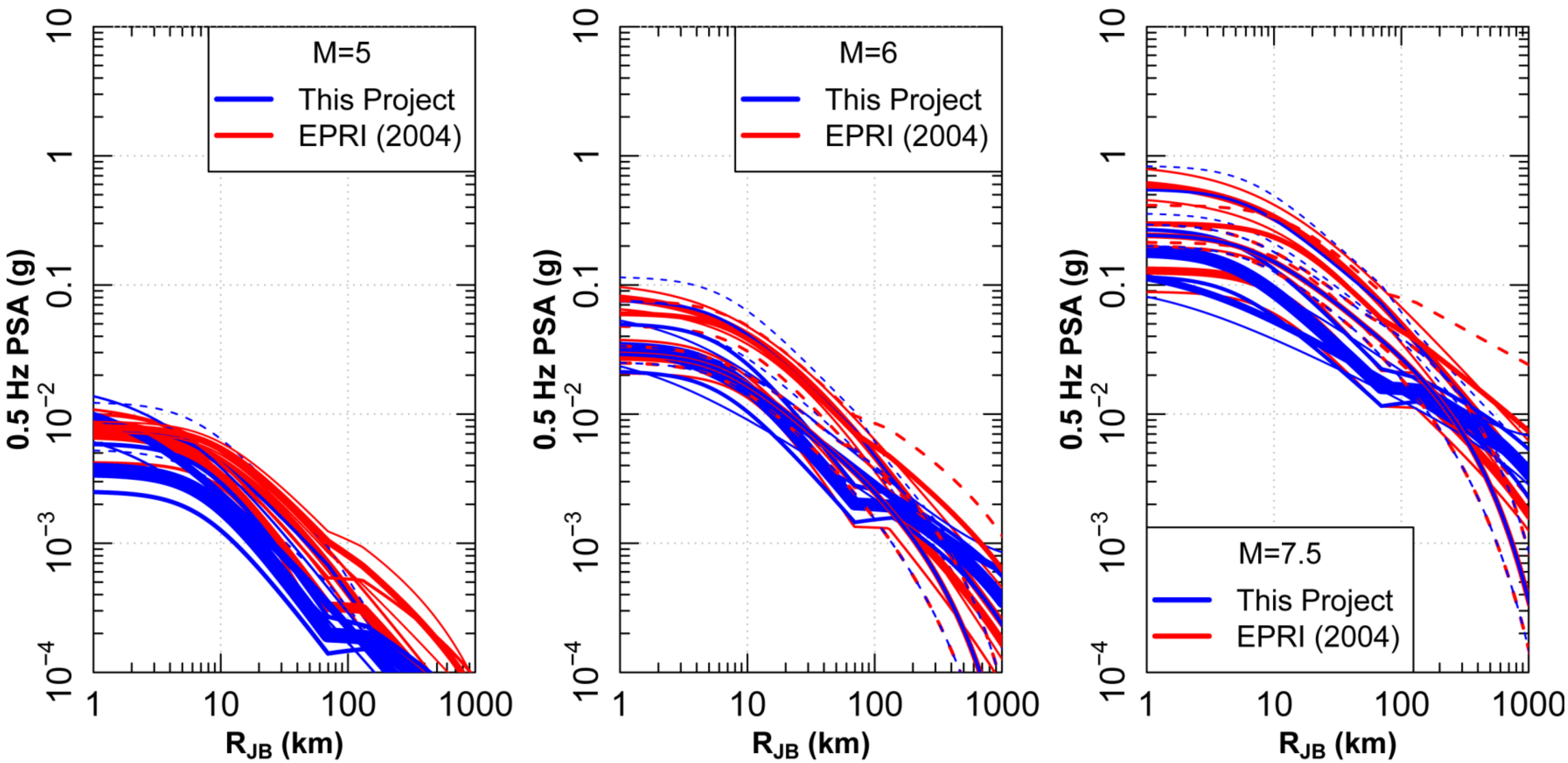

Figure 8.10-7. Comparison of updated and EPRI (2004) GMMs for 0.5 Hz spectral acceleration

10

CHAPTER 10 USE OF THE UPDATED EPRI (2004, 2006) GMM IN PSHA

10.1 Overview

This chapter provides instructions on how to implement the Ground Motion Model (GMM) developed in this project. Section 10.2 (together with the computer files referenced therein) defines the model in sufficient detail that they can be coded by a knowledgeable practitioner, even one with no direct involvement with this project. Section 10.3 provides guidance for the hazard analysts who may use the GMM.

A hazard input document (HID; see also Appendix G) was prepared to provide the documentation necessary for users to implement the EPRI (2013) GMM in PSHA calculations for future applications. The HID contains all of the information required for a future user to exercise the model within a PSHA, but it does not include the technical basis or justification for the elements of the model. This chapter contains no arguments or data in support of the model, and no cross-references to portions of the report where these arguments and data are provided. The purpose of the HID is to ensure that the expert assessments made by the TI Team are captured fully and accurately and delivered for use by the hazard analyst for a PSHA at a specific site. For the EPRI (2004, 2006) GMM Review Project, the HID was used by the hazard analyst to carry out hazard calculations at seven (7) demonstration sites as summarized in Chapter 9.

10.2 Hazard Input Document (HID)

10.2.1 Cluster and Curve Weights

The cluster weights are given in Table 10.2.1-1, for both RLME and area sources. More details regarding RLME and area sources are provided in Section 10.3.3 below.

As in EPRI (2004), there are three alternative branches for each cluster (denoted low, median, and high), with weights 0.185, 0.63, and 0.185, respectively.

10.2.2 Definition of Mid-Continent and Gulf Regions

The map on Figure 10.2.2-1 defines the revised definition of the Mid-Continent and Gulf regions. The coordinates of the Gulf-region polygon is provided as file

CEUS_gulfsourceregion.dat. More details regarding the choice between the Mid-Continent and Gulf GMPEs are provided in Section 10.3.2 below.

10.2.3 Functional Form of GMPEs (Mid-Continent and Gulf)

Clusters 1 and 3 use one functional form (with 15 coefficients), Cluster 2 uses another form (with 14 coefficients), and Cluster 4 uses a third functional form (the same functional form used in EPRI, 2004).[1] The functional forms for Clusters 1 through 3 are coded in file *EPRI_medians.f* and key portions are listed below. Unless indicated otherwise, all magnitudes are moment magnitudes[2] and all distances are Joyner-Boore distances (Rjb).

Equations for Clusters 1 and 3

```
dpth = exp(C(12)+C(13)*amag)
rr = sqrt(Rjb**2 + dpth**2)

gamma = C(10)+C(11)*amag

R1 = min(rr,C(14))
R2 = max( min( rr/C(14),C(15)/C(14) ), 1.)
R3 = max( rr/C(15) ,1. )
R1 = LOG(R1)
R2 = LOG(R2)
R3 = LOG(R3)

term = C(1)+C(2)*amag+C(3)*amag**2
geom = (C(4)+C(5)*amag)*R1 +
. (C(6)+C(7)*amag)*R2 +
. (C(8)+C(9)*amag)*R3

EPRI_2012_median_C1C3 = term + geom + gamma*rr
```

Equations for Cluster 2

```
CC = exp(c(11) + c(12)*min(amag,c(14)) + c(13)*max(0.,amag-c(14)))
rr = rjb + CC

gamma = c(8) + c(9)*min(amag,c(14)) + c(10)*max(0.,amag-c(14))

term = c(1)+c(2)*amag+c(3)*amag**2 + c(4)*amag**3

slope = c(5)+c(6)*min(amag,c(14)) + c(7)*max(0.,amag-c(14))
geom = slope*log(rr)

EPRI_2012_median_C2 = term + geom + gamma*rr
```

[1] See Equation identified as F4 on page F-3 of EPRI (2004).
[2] Magnitudes are denoted by M or **M**, or by `amag` in the source-code segments.

The coefficients for the Mid-Continent (for clusters 1 through 3, all branches, and all frequencies) are given in files *XY_Model.csv*, where X indicates the cluster[3] (C1, C2p, or C3pp), and Y indicates the branch (l, m, or h, denoting low, median, and high, respectively). The coefficients for the Gulf region are given in files *XGY_Model.csv,* where X indicates the cluster (C1, C2p, C3pp, C4R, and C4NR[4]), Y indicates the branch (using the same convention as above), and G differentiates the Gulf coefficients from the Mid-Continent coefficients. Files with a csv extension may be opened and manipulated in Excel or as ASCII files. It may be convenient to combine them into one large file and possibly reorganize them by frequency.

Check values for all frequencies and curves and for selected magnitudes and frequencies (based on the original implementations in the R language) are given in file *GMPE_medians.xlsx* for the Mid-Continent and *GMPE_medians_Gulf.xlsx* for the Gulf.

10.2.4 Functional Form and Associated Sigma for Conversion from Epicentral Distance to Rjb

Use the functional form in Eq. G-1 of EPRI (2004; reproduced below) for all clusters.

$$r_{\text{Joyner-Boore}} = r_{\text{Epicentral}} \times \{1 - 1/\cosh(C_1 + C_2(\mathbf{M}-6) + C_3 \ln(r'))\}$$
$$r' = \sqrt{r^2_{\text{Epicentral}} + h'^2}, \quad h' = \exp\{C_4 + C_5(\mathbf{M}-6)\}$$

Equation G-1

The additional standard deviation in ln[ground-motion amplitude] is given by Eq. G-4 in EPRI (2004; reproduced below):

$$\sigma_{\text{Additional Epicentral Distance Aleatory}} = \exp\{C_1 + C_2(\mathbf{M}-6) + C_3(\mathbf{M}-6)^2\} \times [1 - 1/\cosh(f_A)] \times \frac{1}{\cosh(f_B)}$$
$$f_A = \exp\{C_4 + C_5(\mathbf{M}-6)\} + \exp\{C_6 + C_7(\mathbf{M}-6)\} \times r_{\text{Epicentral}}$$
$$f_B = \exp\{C_8 + C_9(\mathbf{M}-6)\} \times \ln(r'/h)$$
$$r' = \sqrt{r^2_{\text{Epicentral}} + h^2}, \quad h = \exp\{C_{10} + C_{11}(\mathbf{M}-6)\}$$

Equation G-4

File *Distance_ConversionCoefficients.xlsx* contains coefficients for both equations. There are separate sets of coefficients for each cluster, and for both random and centered epicenters. Note that, for the sake of consistency in the depth distributions used, the adjustments for Cluster 4 should use the coefficients in the above file, rather than the ones in EPRI (2004).

Check values for the distance conversion and for the associated standard deviations are contained in files *Conversion.xlsx* and *Additional_Sigma_from_Distance_Conversion.xlsx*

[3] No coefficients are provided for the Mid-Continent Cluster 4 GMPEs because these coefficients are unchanged from EPRI (2004).
[4] Two models (rifted and non-rifted, denoted as R and NR) are provided for Cluster 4. This is the same approach followed in EPRI (2004).

10.2.5 Aleatory Uncertainty

The model for aleatory uncertainty in ln[Amplitude] (sigma) contains two portions (namely a frequency- and magnitude-dependent portion and a distance-dependent portion), which should be combined with each other and with the aleatory uncertainty due to distance conversion (see above) using SRSS. The distance and frequency-dependent portion of sigma is tabulated for magnitudes 5, 6, and 7 in Table 10.2.5-1. It should be interpolated linearly in M between 5 and 6 or 6 and 7, and it should be treated as constant for magnitudes lower than 5 and greater than 7.

Values of the between-event (tau) and event-to-event (phi) components of this sigma have also been computed and are contained in the report. They are not included here because they are not needed for single-site PSHAs.

Figure 10.2.5-1 shows the frequency- and magnitude-dependent sigma, provides check values, and includes values from EPRI (2006) for comparison.

The distance-dependent portion of sigma (not shown on Figure 10.2.5-1) contains two branches, as follows:

1. No distance-dependent effect (weight 0.6).
2. Use Eq. 6-7 of EPRI (2006)[5] with a_1= 0.16 (weight 0.4).

This representation is a two-branch approximation to the three-branch model developed in EPRI (2006).

10.3 User Instructions

This section contains guidance regarding the use of the GMPEs described above when performing a PSHA study. The main topics are the selection between the Mid-Continent and Gulf GMPEs for a particular source and whether the Cluster 4 GMPEs should be used. In these and other matters of usage, the guidance provided in EPRI (2004) is generally followed.

10.3.1 Range of Applicability

The GMM presented here is applicable to moment magnitudes 5 to 8.5 and distances from 0 to 500 km. Although no data are available for magnitudes in the upper half of this magnitude range, the ensemble of selected models from the literature used inferences from other regions to constrain these estimates and provide a sufficiently wide range of epistemic uncertainty. It is also recognized that most of the hazard at CEUS sites and frequencies 5 Hz or greater comes from the lower half of this magnitude range.

[5] This equation indicates a constant value of a_1 for Rjb < 10 km, linear variation in ln(Rjb) between a_1 at 10 km and 0 at 20 km, and 0 for Rjb > 20 km.

Although magnitudes greater than 5 were emphasized, the GMM presented here may be also be used for magnitudes between 4 and 5, when required for hazard studies that use the CAV (Cumulative Absolute Velocity) filter. The GMM is also applicable to distances of 500 to 1,000 km, although the uncertainty is greater because less effort was spent on this distance range.

The GMM presented should not be used at distances greater than 1,000 km. The behavior of the selected models was not checked in this distance range and no comparisons to data beyond 1,000 km were performed. There are also indications that the data at these distances are affected by selection bias, where only unusually high recordings meet the signal-to-noise criteria and get processed.

10.3.2 Mid-Continent vs. Gulf Regions

The geographical boundary between the Mid-Continent and Gulf regions was presented in Section 10.2.2. In cases where a source is wholy or partially within one region and the site is within another, selection between the Mid-Continent model and Gulf model is not straightforward. It is recommended that the hazard analyst select the region that contains the majority of the travel path, which may be defined as the minimum distance from the source to the site.

10.3.3 Use of Cluster 4 GMPEs

Following EPRI (2004), this project recommends that Cluster 4 be used only for sources whose main contribution to hazard comes from magnitudes above 6.5.[6] In the context of the CEUS-SSC study (EPRI/DOE/NRC, 2012), this recommendation may be translated into the recommendation that Cluster 4 be used only for RLME sources.[7] There are two variants of the Cluster 4 GMPEs, which consider whether or not the source is rifted. The choice between these two should be based on knowledge of the tectonics of the RLME under consideration.

For sites affected by both source types, the approach illustrated on Figure 10.3.3-1 (modified from Figure 5.4 of EPRI, 2004) should be used for building the proper correlations into the ground-motion logic tree.

[6] EPRI (2004) refers to these as non-general seismic sources.
[7] Sources with repeated large-magnitude earthquakes.

Table 10.2.1-1. Cluster Weights

Cluster Number	Weight (RLME sources)	Weight (area sources)
1	0.11	0.127
2	0.27	0.310
3	0.49	0.563
4	0.14	0.000

Table 10.2.5-1. Aleatory Uncertainty (sigma) in ground-motion amplitude

Freq (Hz)	Sigma (M≤5)	Sigma (M=6)	Sigma (M≥7)
100	0.68	0.63	0.60
40	0.74	0.69	0.67
25	0.74	0.69	0.67
10	0.74	0.69	0.67
5	0.72	0.68	0.66
2.5	0.72	0.69	0.67
1	0.75	0.74	0.73
0.5	0.78	0.78	0.77
0.25	0.79	0.79	0.78

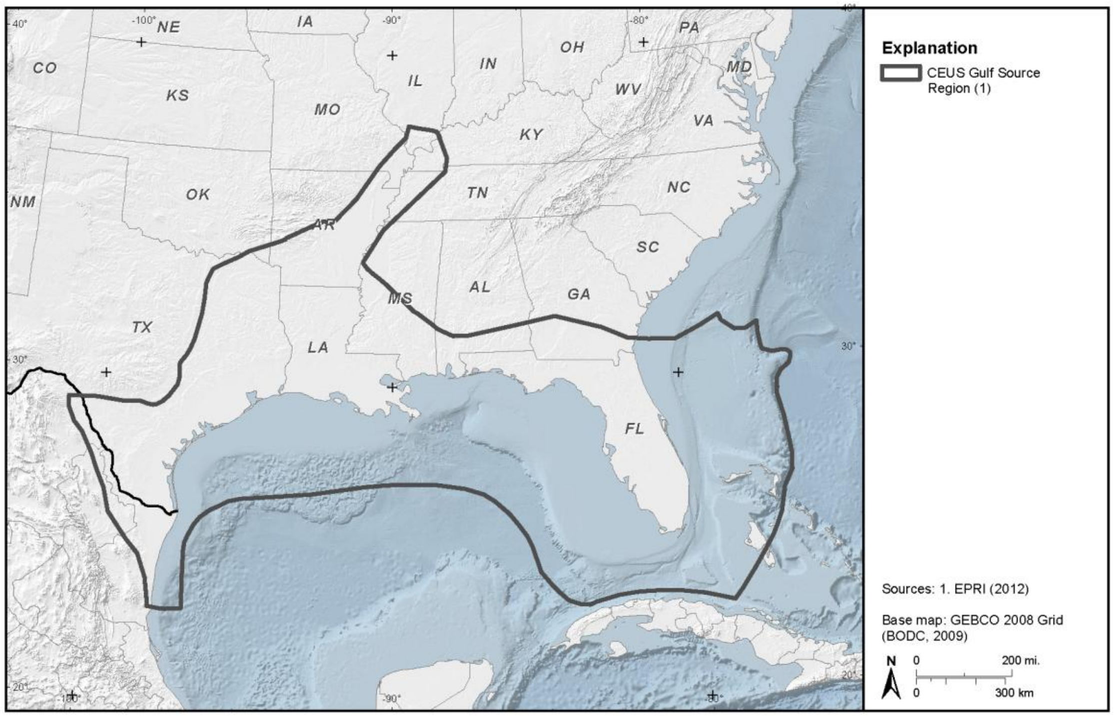

Figure 10.2.2-1. Map defining the Gulf Coast crustal region.

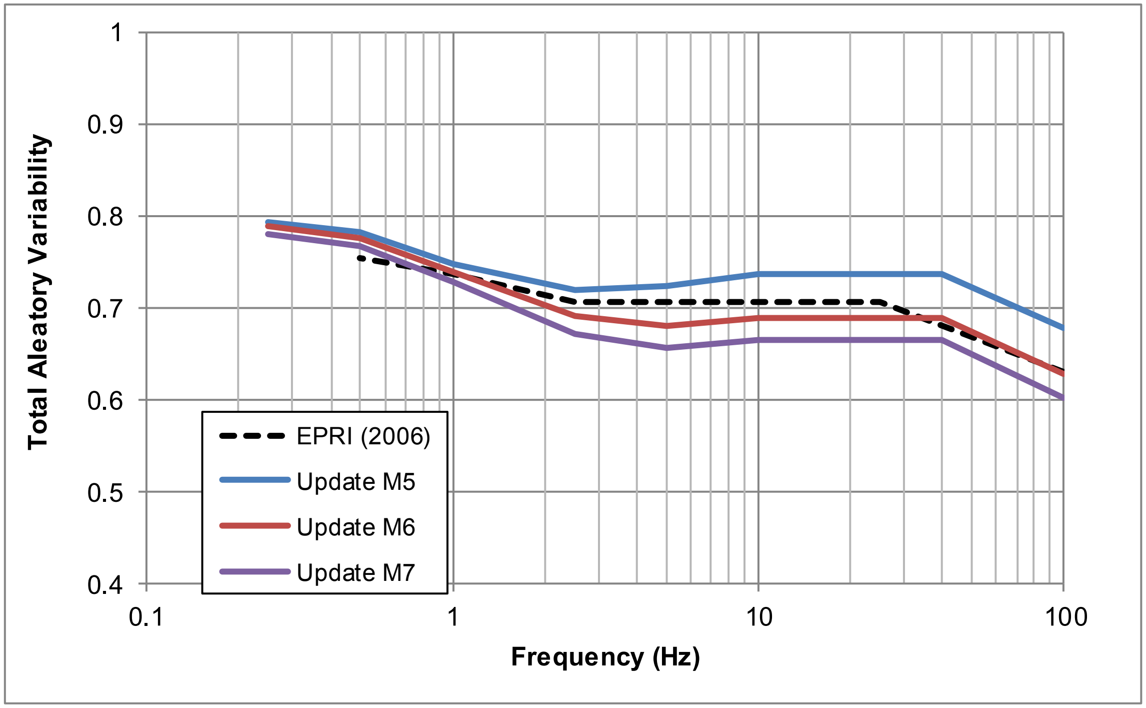

Figure 10.2.5-1. Frequency and magnitude-dependent portion of the aleatory uncertainty.

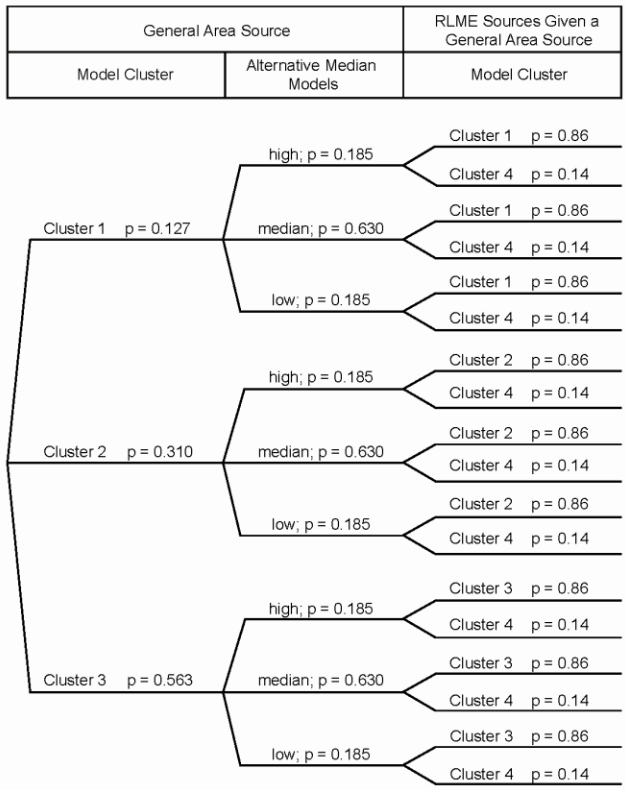

Figure 10.3.3-1. Logic tree for sites affected by both RLMEs and distributed-seismicity sources.

B

APPENDIX B

DOCUMENTATION FOR LITERATURE REVIEWS

B.1 References

- Table B-1 Atkinson, 2004a
- Table B-2 Atkinson, 2004b
- Table B-3 Campbell, 2004
- Table B-4 Tavakoli and Pezeshk, 2005
- Table B-5 Atkinson-Boore, 2006
- Table B-6 Douglas et al, 2006
- Table B-7 Sonley and Atkinson, 2006
- Table B-8 Atkinson et al, 2007
- Table B-9 Atkinson and Wald, 2007
- Table B-10 Kanth and Iyengar, 2007
- Table B-11 Atkinson, 2008
- Table B-12 Atkinson and Morrison, 2009
- Table B-13 Campbell, 2009
- Table B-14 Somerville et al, 2009
- Table B-15 Atkinson and Kraeva, 2010
- Table B-16 Boore et al. 2010
- Table B-17 Zandieh and Pezeshk, 2010
- Table B-18 Atkinson-Boore, 2011
- Table B-19 Atkinson et al, 2011
- Table B-20 Boatwright and Seekins, 2011
- Table B-21 Pezeshk et al, 2011
- Table B-22 Atkinson, 2012

- Table B-23 Boore, 2012

B.2 Introduction

Consistent with SSHAC guidelines, and considering new data, advances in methods, new proponent ground motion prediction equations (GMPEs), and the input from ground motion experts presented in Appendix B, it is prudent to examine and possibly update the EPRI (2004, 2006) Ground Motion Model (GMM) before site-specific PSHA calculations are performed. The EPRI (2004, 2006) GMM Review Project will incorporate an up-to-date assessment of the GMM (2004, 2006) GMM that has the following components:

- Assessment and incorporation of uncertainties,
- Structured and systematic evaluation of the range of diverse technical interpretations from the larger technical community and
- Up-to-date data, models and methods.

This approach will lead to a defendable GMM that can be used to respond to the NRC RFI letter dated March 12, 2012.

The second goal of Task 2 in the project plan is to compile a comprehensive bibliography on CEUS ground motions and related themes for review by the TI Team and other project participants to perform the above assessment of the current state of practice. The Literature Review tables that follow document the results of the reviews by the TI Team and demonstrate the structured and systematic evaluation of the range of diverse interpretations from the larger technical community. Full citations of references listed in the tables above are provided in the Table B and in Chapter XX – References.

B.3 Documentation Tables

Table B-1, Atkinson, 2004a

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Atkinson, Gail M. 2004a. ~~"~~Empirical Attenuation of Ground-Motion Spectral Amplitudes in Southeastern Canada and the Northeastern United States." *Bulletin of the Seismological Society of America* 94 (3) (June 1): 1079 –1095. doi:10.1785/0120030175.	This study preforms a regression analysis of CENA Fourier-amplitudes. Amplitude is found to decay as $R^{-1.3}$ over the first 70 km. Estimates of stress parameter increase with M for M<4.3, but attain a nearly constant value in the 100-200 bar range for larger events.	Hinged tri-linear model for geometric attenuation and a geometric-attenuation term, consider alternative hinge-point distances. Magnitude is characterized using the 1-Hz magnitude m1 (Chen and Atkinson, 2002), which is close to M.	1,700 digital seismograms (many of them vertical) obtained in hard-rock sites from 186 CENA earthquakes (M 2.5-5.0; 1990-2003)	None directly because does not include a full GMPE, but provides insights into many of the key issues. Also, results from this paper are used by Atkinson and Boore (2006).

Table B-2, Atkinson, 2004b

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Atkinson, Gail M. 2004b. ~~"~~Empirical Attenuation of Ground-Motion Spectral Amplitudes in Southeastern Canada and the Northeastern United States." *Bulletin of the Seismological Society of America* 94 (6) (December 1): 2419 –2423. doi:10.1785/0120040161.	This is an erratum to the Atkinson (2004a), which corrects for an error of 0.2 magnitude units in the equation for the 1-Hz magnitude m1.	Same as in Atkinson (2004a)	Same as in Atkinson (2004a)	None directly.

Table B-3, Campbell, 2004

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
K.W. Campbell (2004). ―Prediction of Strong Ground Motion Using the Hybrid Empirical Method and Its Use in the Development of Ground-Motion (Attenuation) Relations in Eastern North America.” *Bulletin of the Seismological Society of America* 94 (6) (December 1): 2418. doi:10.1785/0120040148.	Presents Erratum to Campbell (2003) paper on the hybrid GMPE for the CEUS	N/A	N/A	The modeling of the Campbell (2003) hybrid GMPE used in the EPRI (2004) was checked and found to have been done correctly.

Table B-4, Tavakoli and Pezeshk, 2005

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Tavakoli, Behrooz, and Shahram Pezeshk. 2005. ―Empirical-Stochastic Ground-Motion Prediction for Eastern North America.” *Bulletin of the Seismological Society of America* 95 (6) (December 1): 2283 –2296	Uses an empirical-stochastic model to modify Calif. Atten. using ENA source parameters. Uses double-corner source model. Calif. GM models are Abr-Silva 1997, Sadigh 1997, Campbell 1997.	Models Moho bounce, $\Delta\sigma$ = f(M), and equivalent point source for large M.	Compares to Kaka and Atkinson (2005) data for ENA, and to 5 published GM eqns.	Limited. Based on pre-NGA eqns in Calif, and to ENA data prior to 2005. Gives support to 2-corner source model. Compares well with EPRI (2003, same as EPRI 2004).

Table B-5, Atkinson-Boore, 2006

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Atkinson, Gail M., and David M. Boore. 2006. ~~"~~Earthquake Ground-Motion Prediction Equations for Eastern North America." *Bulletin of the Seismological Society of America* 96 (6) (December 1): 2181 –2205. doi:10.1785/0120050245.	Paper develops GMPE for hardrock and other site conditions using extended-source stochastic model and amplitude-decay assumptions from earlier studies by the same authors. Results are compared to response-spectrum data from 350 recordings.	Source: extended-source stochastic (EXSIM), with rupture dimensions given by Wells-Coppersmith (1994) worldwide relations for length and width, reduced by a random factor of ~0.6 (based on Somerville et al., 2001, source scaling). Stress parameter: 140 bar. Geometric spreading and Q based on Atkinson (2004a). Duration model from Atkinson-Boore (1995).	To investigate source scaling: historical and instrumental data (1811-2005; **M** 4.2-7.5). For GMPE validation: 350 records from CENA + Buhj (1925-2005; M 4.2 to 7.6)	GMPE is important because it includes effects similar to those of 2-corner models used in the past. Effect of source finiteness (relative to pint source) is large, but it is well supported. Original form of GMPE should not be used directly. 2001 revisions (AB06') should be used instead.

Table B- 6, Douglas et al, 2006

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Douglas, John, Hilmar Bungum and Frank Scherbaum, 2006. ―Ground-Motion Prediction Equations for Southern Spain and Southern Norway Obtained Using the Composite Model Perspective," *Journal of Earthquake Eng.,* 10, 1, 33-71.	GMPEs developed for So. Spain and So. Norway starting from 7 empirical relations from other regions. These were adjusted for M, R, and component definition to obtain common definitions, and were further using stochastic conversion factors to make target-region GM estimates. Equations were fit to these GM estimates to reflect local characteristics, both for median values and sigmas.	Need stress drop as f(M), geom. spreading, Q, path duration term, rock Vs, and site *K* in target region.	Started with eqns from: WNA(3) Europe (1) WNA+Europe (1) Japan (1) Italy (1)	Equations developed for So. Spain and So. Norway, equations not given, applicability of particular equations is low.

Table B-7, Sonley and Atkinson, 2006

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Sonley, Eleanor, and Gail M. Atkinson. 2006. ―Path-Specific Attenuation in Eastern Canada." *Bulletin of the Seismological Society of America* 96 (4A): 1375 – 1382.	Studied GM from 2400 waveforms, 400 EQs, in Charlevoix seismic zone. R<70 km for all records, to calculate b in R^{-b} attenuation.	---	2400 waveforms, 400 EQs in Charlevoix seismic zone.	Says b=-1.36 is consistent with A06, which found B=-1.3 in ENA. Perhaps adds weight to Moho bounce models.

Table B-8, Atkinson et al, 2007

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Atkinson, Gail M., and SanLinn I. Kaka. 2007. –Relationships Between Felt Intensity and Instrumental Ground Motion in the Central United States and California.” *Bulletin of the Seismological Society of America* 97 (2) (April 1): 497 –510.	Developed empirical relationships between instrumental GM amplitudes and MMI as measured by DYFI reports. Develops eqns to predict MMI based on PGV, PGA, PSA (0.5 Hz), and PSA (3.3 Hz).	Assumes no correction factors for site conditions.	29 EQs in central US, 2000—1005, with some stations in MS Embayment and some outside. **M** 1.8 to 4.6.	Limited. We will not be using MMI to calibrate or check GM eqns.

Table B- 9, Atkinson and Wald, 2007

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Atkinson, G.M., and Wald, D.J., 2007, "Did You Feel It?" intensity data: A surprisingly good measure of earthquake ground motion: Seism. Res. Lett., v. 78, no. 3, p. 362-368.	This study uses data collected the Did You Feel It? (DYFI) system, which compiles online citizen responses to earthquakes, to compare ground-motion amplitudes in CEUS and in California. Regressions using data from multiple events indicate that CEUS motions have significantly higher intensity for a given magnitude, suggesting a factor of roughly 3 in stress drop. Comparisons for a pair of earthquakes indicate that CEUS intensities have faster decay with distance at short distances and slower decay at distances greater than 100 km. These former result is interpreted as supporting a $R^{-1.3}$ geometric decay at distances within 70 km.	The three key assumptions of this paper are as follows: (1) MMI is strongly correlated with instrumental amplitude, (2) the higher intensity in the CEUS are due mainly to higher stress parameter (as opposed to other differences such as site conditions, frequency content), and (3) the self-selection bias inherent in the system does not affect these comparisons.	More than 750,000 citizen responses obtained through the USGS DYFI system. Each response contains the answers to a simple multiple-choice questionnaire, which is designed to be diagnostic of the Modified Mercalli Intensity at the respondent’s location. The data volume is thought to compensate for its limitations in quality.	None directly, but it supports the assumption of higher stress drop in CEUS, which is an important consideration in evaluating or developing CEUS GMPEs. The suggestion of faster geometric decay is also a useful observation.

Table B- 10, Kanth and Iyengar, 2007

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Raghu Kanth, S.T.G. and R.N. Iyengar, 2007. ―Estimation of Seismic Spectral Acceleration in Peninsular India," *Jour. Earth Syst. Sci.,* 116, 3, June, 199-214.	Use stochastic model with Q for specific regions of India to predict GM, fit these predictions to a simple equation (4 constants) for prediction. Simple site correction terms are included.	GM can accurately be estimated with stochastic model, and can be fit with a simple predictive equation (using R-hypo).	Fig. 1 shows available SM records in India, ~19 records for M>5, R<300 km (5 EQs). Doesn't appear data were used for comparisons.	Not applicable, estimates are made for peninsular India. Value of fmax is inconsistent with reference-rock kappa.

Table B-11, Atkinson, 2008

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Atkinson, Gail M. 2008. ―Ground-Motion Prediction Equations for Eastern North America from a Referenced Empirical Approach: Implications for Epistemic Uncertainty." *Bulletin of the Seismological Society of America* 98 (3) (June 1): 1304 –1318	Starts with empirical GMPE from active region (BA-2008 NGA) and modifies it using data from ENA. Not meant to replace Atkinson-Boore 06. Simple correction factor based on ENA residuals. Fits to data are OK for M 5 but are low for M 6 (Saguenay data) and M 7 (Bhuj data).	---Magnitude scaling of GM is the same in both regions ---ENA predictions are based on residuals of ENA data from NGA equations	18 ENA EQs recorded by strong motion instruments. Use of Nahanni and Bhuj data ―questionable" for ENA.	Limited. This is an alternative GMPE to AB06. Not well-constrained at magnitudes $\geq$6. AB-11 below says it replaces this paper.

Table B-12, Atkinson and Morrison, 2009

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Atkinson, Gail M., and Mark Morrison. 2009. ―Observations on Regional Variability in Ground-Motion Amplitudes for Small-to-Moderate Earthquakes in North America." *Bulletin of the Seismological Society of America* 99 (4): 2393 –2409.	Compared ShakeMap data in California to NGA eqs, and No. Cal. to So. Cal. data. GM for **M**<5.5 are lower in NoCal than in SoCal for R 120-250 km. NGA eqs over-predict GMs for **M**<5.5, because observed GMs attenuate faster than NGA models	Few. GM data binned into **M** and R bins for comparison of different datasets and comparison with NGA eqs.	**M** 3.6—5.1 for Cal, Pacific NW, and BC.	Limited. Comparisons are for Calif, Pacific NW and BC.

Table B-13, Campbell, 2009

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Campbell, Kenneth W. 2009. ―Estimates of Shear-Wave Q and K0 for Unconsolidated and Semiconsolidated Sediments in Eastern North America." *Bulletin of the Seismological Society of America* 99 (4): 2365 –2392	Estimates K0 from a several methods: recordings using spectral decay/fitting, or from Q and Vs inferred at sedimentary sites. Concentrates on BC site profiles, finds K0 increases with increasing sedimentary thickness.	K0 can be estimated by integrating the product of $Qeff(z)^{-1}$ and $Vs(z)^{-1}$, which assumes that these quantities are adequately known as f(z).	Variety of recordings, profiles with estimated thicknesses, Vs, and Q.	Limited to BC soil profile. Uses K0=0.005 for hard rock in ENA (p. 2379). Finds K0=0.02 for BC, not K0-0.01 which USGS uses. Supports Silva K0 estimates for BC in ENA (p. 2388).

Table B- 14, Somerville et al, 2009

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Somerville, Paul, Robert Graves, Nancy Collins, S.G. Song, and Sidao Ni, and Phil Cummins. 2009. “Source and Ground Motion Models for Australina Earthquakes.” *Proc.,* Aus. EQ Eng Society Annual Meeting.	Developed ground motion simulations using region-specific source and attenuation functions, based on crustal velocity models from small EQ records. 2 models developed for cratonic and non-cratonic regions of Aus.	Used theoretical seismogram approach for low freq (<1 Hz), stochastic modeling for high freq ($\geq$1 Hz).	Finite fault rupture models using Meckering and Tennant Creek EQs. Compared to SM records from 1996 Thompson Reservoir EQ.	Not applicable, rupture area—M0 relations for Aus seem to be intermediate between WUS and ENA (Fig. 1). Cratonic model exhibits strong surface waves that are not anticipated in CEUS. Non-cratonic model has kappa value that is not applicable to reference site. Both models have Vs30 value of 865 m/s (much lower than reference rock).

Table B-15, Atkinson and Kraeva, 2010

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Atkinson, Gail M., and Nadia Kraeva. 2010. “Ground Motions Underground Compared to Those on the Surface: A Case Study from Sudbury, Ontario.” *Bulletin of the Seismological Society of America* 100 (3) (June 1): 1293 –1305	Compared surface ground motion records and records at depths of 1.4 and 2.1 km. Surface motions caused by local shallow mining events showed excitation of Rayleigh (Rg) waves at f~2 Hz that underground motions did not. Regional and teleseismic events showed surface amplification at f~0.8-1 Hz from	Few. Comparisons are made on basis of smoothed Fourier spectra.	GM records from local mine blasts, regional events, teleseismic events (2008 So. Illinois EQ, **M** 5.4). Records at surface and depths of 1.4 and 2.1 km.	Limited. Hazard effect restricted to mining blasts and rock falls that generate Rg phase locally.

Table B-16, Boore et al, 2010

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Boore, D.M., Kenneth W. Campbell, and Gail M. Atkinson, Determination of stress parameters for eight well-recorded earthquakes in eastern North America, *Bulletin of the Seismological Society of America* (August 2010), 100(4):1632-1645.	Reexamine stress drop $\Delta\sigma$ for 8 EQs studied by AB06, fitting PSA using a stochastic point-source model.	$\Delta\sigma$ depends on attenuation model assumed. They used 4 models, inc simple 1/R. Results depend on whether Saguenay EQ is included in analysis. Moho bounce effect is important. 1/R spreading adequate, found $\Delta\sigma \simeq 70$ bars.	8 EQs well-recorded in ENA.	Limited. No predictive equations included.

Table B-17, Zandieh and Pezeshk, 2010

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
A. Zandieh and S. Pezeshk (2010). ~~I~~Investigation of Geometrical Spreading and Quality Factor Functions in the New Madrid Seismic Zone." *Bulletin of the Seismological Society of America* 100 (5A) (October 1): 2185 –2195. doi:10.1785/0120090209.	Used recordings from 11 broadband stations in the upper Mississippi embayment to estimate geometric spreading and Q. The Fouier amplitude data were fit using a genetic algorithm that minimized the mean absolute value of the residuals (L1 norm). A tri-linear geometric spreading form was use with the large distance slope set to -0.5. Results show that geometric spreading terms did not show significant frequency dependence. Geometric spreading from 10 to 70 km is $R^{-1\pm0.15}$. From 70 to 140 km, the geometric spreading has a positive slope of +0.25. Q(f) could be fit by $614f^{0.32}$ for $f \geq 1$ Hz. However, a 3rd order polynomial that allows for an increase in Q at frequencies less than 1 Hz is needed for a wide frequency range. (Note that polynomial fit to data is not very good above 20 Hz, as show in Figure 4 of the paper). Source spectra for events in the range of Mw 3 to 4.1 can be modeled by Bruce source with stress drop of 50 bars.	Site effects are negligible for the vertical component. Geometric spreading at large distances set to $R^{-0.5}$.	Data consisted of 500 recordings from 63 earthquakes in the magnitude range M_W 2.5 to 5.2 and distance range of 10 to 400 km. Broadband data were recorded on a Guralp CMG40T instrument with a flat velocity response between 0.033 and 50 Hz. Data were recorded at 100 samples per second. Only the vertical component was used. Data was corrected for instrument response and then converted to acceleration and the method of Welsh (1967) was used to obtain the PSD of the acceleration spectrum. The noise PSD was calculated from the segment before the P arrival and subtracted from the PSD of the recording. Finally, data where the signal to noise ratio was less than 2 were discarded. The result was tables of Fourier amplitudes for frequencies from 0.2 to 30 Hz, with most of the data in the frequency range of 1 to 10 Hz.	Results show similar overall geometric spreading behavior to that obtained for SE Canada, although slope within 70 km is near -1. Results indicated lower Q than in SE Canada with similar frequency dependence.

Table B-18, Atkinson-Boore, 2011

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Atkinson, Gail M., and David M. Boore. 2011. “Modifications to Existing Ground-Motion Prediction Equations in Light of New Data.” *Bulletin of the Seismological Society of America* 101 (3) (June 1): 1121 –1135	Modifies the GMPEs developed by Atkinson (2008; A08) and Atkinson and Boore (2006) to use new ENA data. The resulting GMPEs are designated A08’ and BA06’. A08’ uses a distance correction based on residuals from BA-08 NGA predictions. AB06’ is implemented as AB06 with decreasing stress parameter.	Same as in Atkinson and Boore (2006) and Atkinson (2008).	“thousands more records” for ENA; inc 2005 Riviere-du-Loup **M** 4.7; 2007 Mount Carmel **M** 5.0; 2010 Val-des-Bois **M** 4.7.	Recommended to replace/update A08 and BA06 for ENA

Table B-19, Atkinson et al, 2011

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Atkinson, Gail M., Nadia Kraeva, and Karen Assatourians. 2011. “Ground-Motion Attenuation at Short Hypocentral Distances (<30 Km) Near Sudbury, Ontario.” *Bulletin of the Seismological Society of America* 101 (1) (February 1): 433 –437	Studied 12 shallow EQs near Sudbury, Ontario, for near-source (R<30 km) attenuation effects.	Events are all “shallow”, paper acknowledges that deeper EQs may have different attenuation with R.	12 shallow EQs recorded near Sudbury, Ontario, R<30 km, Mn 1.0—3.1.	Supports geom. spreading term of -1.3 for R<30 km, at least for small M and at least for H component. V component seems to have geom. spreading of -1.1.

Table B-20, Boatwright and Seekins, 2011

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Boatwright, John, and Linda Seekins. 2011. "Regional Spectral Analysis of Three Moderate Earthquakes in Northeastern North America." *Bulletin of the Seismological Society of America* 101 (4): 1769 –1782.	Studied 3 Canadian EQs **M** 4.4—5.0 for spectral shapes, correcting for attenuation and site response, to estimate source spectra. Also analyze source spectrum for 1988 **M** 5.8 Saguenay. Report Brune Δσ and "apparent" Δσ.	Data-driven study. Q=410 $f^{0.5}$.	Data from 1997 Cap-Rouge (13), 2002 Ausable Forks (30), 2005 Rivere-du-Loup (45), and 1988 Saguenay (12) EQs. (Nos. in parentheses are approx. no. of stations).	Finds "crossover distance" of Lg waves from R-1 to something slower to be at 50 km, not 100 km (as many assume). Brune source spectrum OK (single corner). Q=410 $f^{0.5}$.

Table B-21, Pezeshk et al, 2011

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Pezeshk, Shahram, Arash Zandieh, and Behrooz Tavakoli. 2011 "Hybrid empirical ground-motion prediction equations for eastern North America using NGA models and updated seismological parameters," Bulletin of the Seismological Society of America (August 2011), 101(4):1859-1870.	Uses hybrid empirical model and stochastic GM simulation starting from WUS NGA equations. For ENA uses single corner ω^{-2} source spectrum, $R^{-1.3}$ atten with a Moho bounce.	Key assumptions are single-corner source spectrum, Δσ=250 bars, Moho bounce, Q, Kappa, near-source saturation.	Data used but not described in detail.	GM predictions look similar to A06' model (Figure 2). Little reason to use this model if we use A06' (?).

Table B- 22, Atkinson, 2012

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Atkinson, Gail. 2012 —Empirical evaluation of aleatory and epistemic uncertainty in eastern ground motion," Seism. Res. L., Eastern Section, June 2012	Horizontal-component response spectra data for ground motions recorded on hard-rock sites in eastern North America (ENA) are used to explore the aleatory and epistemic uncertainty in ground-motion prediction equations (GMPEs).	This note investigates uncertainty in GMPEs in ENA from an empirical perspective. To evaluate ENA variability in a similar way to that used in Atkinson (2006), the author started with a database of PSA (pseudo-acceleration, 5% damped) observations obtained from six 3-component seismographs in the Charlevoix zone operated by the Geological Survey of Canada.	The author uses a database of ENA response spectra data (Assaourians and Atkinson, 2010; www.seismotoolbox.ca) to develop GMPEs for small-to-moderate events and explore their aleatory and epistemic uncertainty. The epistemic uncertainty in ENA GMPEs was evaluated by looking at the spread of predicted values from the various site-specific GMPEs for Charlevoix, Western Quebec (GAC, MNT, ALFO) and the lower St. Lawrence (ICQ) sites.	Aleatory variability in —site-specific GMPEs" has average values from 0.22 to 0.26. Overall, aleatory variability of ground motions in ENA is no larger than that for California, and may actually be smaller, at least for moderate events recorded on hard-rock sites. The overall epistemic uncertainty in ENA GMPEs should be at least 0.15 log units (as a standard deviation of the median GMPEs) in the magnitude-distance range where the prediction equations can be anchored by empirical data (magnitude less than 5.5, distances greater than 50 km). It should be larger than 0.15 units at large magnitudes and close distances.

Table B- 23, Boore, 2012

Citation	Short summary (~1-2 paragraphs)	Key Model Assumptions	Data Used	Assessment of Technical Value for this Project
Boore, D. M., Updated determination of stress parameters for nine well-recorded earthquakes in eastern North America, *Seismological Research Letters* (January 2012), 83(1):190-199	Used 10 attenuation models to study Δσ for 9 EQs in ENA, using various atten. models and PSA at 0.1 and 0.2 sec.	Data-driven study. Table 2 has a good summary of atten. models, R^{-c} models, hinge distances.	9 EQs including Nahanni **M** 6.8 to Cap Rouge **M** 4.4.	Δσ depends strongly on atten. model. Saguenay gives high Δσ, >600 bars in most cases. Mean Δσ for 9 EQs typically 50—100 bars w/o Saguenay. Δσ depends on R^{-c} assumption.

C

APPENDIX C

DOCUMENTATION FOR INTERVIEWS

C.1 Interviews

- Table C-1 Norm Abrahamson – June 21, 2012
- Table C-2 Gail Atkinson – July 6, 2012
- Table C-3 Jack Boatwright – October 4, 2012
- Table C-4 David Boore – June 26, 2012
- Table C-5 Kenneth Campbell – June 20, 2012
- Table C-6 Chris Cramer - July 3, 2012
- Table C-7 Arthur Frankel – July 31, 2012
- Table C-8 Bob Herrmann – September 11, 2012
- Table C-9 Shahram Pezeshk – June 26, 2012
- Table C-10 Walter Silva – July 17, 2012
- Table C-11 Paul Somerville – July 9, 2012

C.2 Questions to Resource Experts and Proponents

What are the key issues we should be considering in updating the model for median amplitudes (and the associated epistemic uncertainty) as a function of magnitude and distance?

Which data are the most relevant in addressing these issues?

Has your model (specific to each expert) which was used in EPRI (2004) superseded? If so, by which model?

What are the key issues we should be considering in updating the model for the aleatory uncertainty as a function of magnitude and distance?

In addition to your published papers, do you have any papers in preparation or under review that you can share with our project?

Do you know of interesting work in progress by other researchers?

Additional information from expert

C.3 Introduction

The goal of the SSHAC process is to represent the center, body, and range of technically defensible interpretations of the available data, models and methods. The EPRI (2004, 2006) GMM Review Project will incorporate an up-to-date assessment of the EPRI (2004, 2006) GMM that has the following components:

- Assessment and incorporation of uncertainties,
- Structured and systematic evaluation of the range of diverse technical interpretations from the larger technical community and
- Up-to-date data, models and methods.

This approach will lead to a defendable GMM that can be used to respond to the NRC RFI letter dated March 12, 2012.

The TI Team interviewed the resource experts and proponents listed above, who are working on CEUS ground motions and related topics, to obtain copies of papers under review or in press, and obtain an update on their ongoing work. To facilitate the interview process, the TI Team prepared the questions listed above to use during the interview. The resource expert and proponent interview tables that follow document the information obtained from the interviews and demonstrate the structured and systematic evaluation of the range of diverse interpretations from the larger technical community.

C.4 Documentation Tables

Table C-1

Expert Name: Norm Abrahamson	Date of Call: 6/21/2012
Prepared by: Gabriel Toro	Date Prepared: 7/1/2012

1. **What are the key issues we should be considering in updating the model for median amplitudes (and the associated epistemic uncertainty) as a function of magnitude and distance?**
    a. Single-corner point-source models should get less weight because they overestimate data (they may get some weight at high frequencies [>2 Hz] if weights are made frequency-dependent).
    b. Kappa value of 0.006 s is probably too low. Understands the need to keep value in this study, but should provide guidance on how to adjust on a site-specific basis
    c. Traditional hybrid-empirical models overestimate high-frequency motions: need to use Al-Atik et al. approach
    d. Stress parameters are probably OK
    e. Would not assign weights by cluster; would judge models instead
2. **Which data are the most relevant in addressing these issues?**
    a. Kappa:
        i. collect and analyze hard rock data (records) from around the world (this is being done by PEGASOS (PRP); will try to get report for us (may turn out to depend on Vs30 and on region)
        ii. Van Houtte et al.; problem: mostly soil data; real question is value of kappa for Vs30> 800m/s

b. For stress parameter: use NGA-East (some records too noisy) c. Mineral Aftershocks: some people (e.g., Archuleta SSA presentation) see $R^{-1.3}$, others do not (e.g., Herrmann).
3. Have your Abrahamson-Silva hybrid model of 2001 and your Toro et al model of 1997 (which were used in EPRI, 2004) superseded? If so, by which model? a. Would not use Abrahamson-Silva Hybrid models i. Based on obsolete WUS models ii. See earlier comments about hybrid models and kappa effects b. Would not use Toro et al. (see earlier comments about single corner) c. Somerville et al. (Norm also a co-author) not working well, especially for lower magnitudes (could be replaced by Atkinson's extended-rupture stochastic) d. We should look at residuals and eliminate models that don't work.
4. What are the key issues we should be considering in updating the model for the aleatory uncertainty as a function of magnitude and distance? a. Recommends that we follow the same EPRI (2006) framework but update the model using NGA (2008) results for sigma, some of which include magnitude-dependence.
5. In addition to your published papers, do you have any papers in preparation or under review that you can share with our project? a. Al-Atik et al. manuscript on kappa
6. Do you know of interesting work in progress by other researchers? a. Nothing that was not mentioned earlier.
7. Additional information from expert a. Some regional differences are becoming apparent: NGA East will consider 4 regions. This may be beyond the scope of EPRI Review project.

Table C-2

Expert Name: Gail Atkinson	Date of Call: 7/6/2012
Prepared by: Gabriel Toro	Date Prepared 7/7/2012

1. **What are the key issues we should be considering in updating the model for median amplitudes (and the associated epistemic uncertainty) as a function of magnitude and distance?**
   a. How to account for recent data
   b. How to treat Saguenay earthquake
   c. How to update models in EPRI (2004) clusters and how to include new ones
2. **Which data are the most relevant in addressing these issues?**
   a. For characterizing source, all data with **M**≥4
   b. For characterization of attenuation, all data with **M**>~3.4 (a lot more data than **M**≥4)
   c. Has used Mineral data only for ongoing Empirical Green's Function work with D. Boore
   d. Information on site conditions for the Ottawa region maintained by Dariush Motazedian (http://http-server.carleton.ca/~dariush/Microzonation/main.html)
3. **Have your 1995 two-corner model and your 2001 hybrid model (which were used in EPRI, 2004) been superseded? If so, by which model(s)?**
   a. Yes. Both models have been superseded. AB95 should be replaced by AB06' (AB06 with modifications in Atkinson and Boore, 2011, paper). The hybrid model should be replaced with A08' (Atkinson 08 with modifications in Atkinson and Boore, 2011, paper). Note that A08' is a Referenced Empirical rather than Hybrid Empirical (new method; uses empirical data more directly). Also likes the Pezesch hybrid model, which is a good recent hybrid-empirical GMPE.
      i. The magnitude saturation in the AB06 model is a consequence of source finiteness, which is characterized using 60% of the Wells-Coppersmith dimensions (based on Paul Somerville's work on source scaling). AB06' adds a decreasing stress parameter to mimic magnitude saturation seen in BA08'.
      ii. The magnitude saturation in the A08' model is adopted from WUS because this model changes only the absolute level and the distance dependence. Note that it is similar to the hybrid empirical model in this regard (that model also mimics WUS saturation).
4. **What are the key issues we should be considering in updating the model for the aleatory uncertainty as a function of magnitude and distance?**
   a. No problem in de-coupling the calculation of sigma from the calculation of the median GMPE and its epistemic uncertainty.
   b. Analysis of residuals in Atkinson (2012; see below) suggests that sigma may be similar or slightly lower than those in WUS.
5. **In addition to your published papers, do you have any papers in preparation or under review that you can share with our project?**
   a. Atkinson (2012). Empirical evaluation of aleatory and epistemic uncertainty in eastern ground motions, Submitted to Seism. Res. L., Eastern Section, June. (copy provided)
   b. Babaie Mahani, A., and G.M. Atkinson (2012). Moment Magnitude Estimates for Moderate Earthquakes in North America. Submitted to Bull. Seism. Soc. Am. (copy provided)
   c. Atkinson, G.M., and Gail M. Atkinson and A.Babaie Mahani (2012). Estimation of Moment Magnitude from Ground Motions at Regional Distances. For Submission to Bull. Seism. Soc. Am., May 2012. (copy provided)
   d. Work in progress with Dave Boore (will provide papers when submitted, scheduled for

	the end of the summer). Preliminary results suggest that geometric decay is different for different frequencies (this compensates for the higher stress drops one infers from the Empirical Green's functions).
6.	**Do you know of interesting work in progress by other researchers?** a. Motazedian, D., J.A. Hunter, A. Pugin, K. Khaheshi Banab, H.L. Crow (2011). "Development of a Vs30 (NEHRP) Map for the City of Ottawa, Ontario, Canada", Canadian Geotechnical Engineering Journal. doi:10.1139/T10-081. [NSERC and GSC].
7.	**Additional information from expert** a. H/V ratios (especially if calculated for more than one event) is a good diagnostic for unusual site response

Table C-3

Expert Name: John Boatwright	Date of Call:
Prepared by John Boatwright	Date Prepared 10/4/12
1. What are the key issues we should be considering in updating the model for median amplitudes (and the associated epistemic uncertainty) as a function of magnitude and distance? 1st We need to understand how to use small earthquakes (2.5 < M < 3.5) to help predict strong ground motion from large earthquakes. In particular, we need to include hypocentral depth as a third parameter. 2nd We need to model how directivity and radiation pattern can distort near-source ground motion. 3rd We need to be extremely careful in using regional data fro small earthquakes.	
2. Which data are the most relevant in addressing these issues? Fourier spectra, PGA, and PGV, from near-field to regional distance (500 km).	
3. What are the key issues we should be considering in updating the model for the aleatory uncertainty as a function of magnitude and distance?	
4. In addition to your published papers, do you have any papers in preparation or under review that you can share with our project? The Variation of Brune Stress Drop with Hypocentral Depth for Moderate Earthquakes in Northeastern North America, by Boatwright, MacDonald, and Seekins.	
5. Do you know of interesting work in progress by other researchers? “The Frequency Dependence of Q in Eastern North America” by Dineva, Mereu, and Atkinson shows that the present NENA ground motion data can be fit by a range of attenuation models.	
6. Additional information from expert	

Table C-4

Expert Name: David Boore	Date of Call: 6/26/2012
Prepared by: Gabriel Toro	Date Prepared: 7/7/2012
1. What are the key issues we should be considering in updating the model for median amplitudes (and the associated epistemic uncertainty) as a function of magnitude and distance? a. Geometric-decay rate in first 70 km: $R^{-1.3}$ or R^{-1}? This question makes a big difference in predictions. Unfortunately, no event contains good data over this distance range (best ones are Riviere de Loup). Faster geometric decay requires a higher value of stress parameter (higher amplitudes at short distances). b. Source: 1 vs. 2 corner. Choice is strongly tied to geometrical spreading. c. Geometric attenuation may be regionally dependent, contributing to epistemic uncertainty. d. Very important to maintain internal consistency.	
2. Which data are the most relevant in addressing these issues? a. See items 1 and 5 b. Any other thoughts, Dave?	
3. Has your Atkinson-Boore 1995 model (which was used in EPRI, 2004) been superseded? If so, by which model? a. It has been superseded by AB06' (Atkinson-Boore 2006 as revised by Atkinson and Boore, 2011). Reason for large difference in M scaling (M 5 to 7.5, as compared to Toro et al., 1977): finite source (EXSIM) and Atkinson-Boore 2011 decreasing stress parameter.	
4. What are the key issues we should be considering in updating the model for the aleatory uncertainty as a function of magnitude and distance? Any thoughts, Dave?	
5. In addition to your published papers, do you have any papers in preparation or under review that you can share with our project? a. Work in progress with Gail Atkinson using Empirical Green's Functions: provides constraints on stress parameters (considering Bal de Bois, Riviere de Loup, and Saguenay).	
6. Do you know of interesting work in progress by other researchers? a. Boatwright-Seekins paper in BSSA.	
7. Additional information from expert N/A	

Table C-5

Expert Name: Kenneth W. Campbell	Date of Call: Via email
Prepared by: Kenneth W. Campbell	Date Prepared: June 20, 2012
1. What are the key issues we should be considering in updating the model for median amplitudes (and the associated epistemic uncertainty) as a function of magnitude and distance? This is too complicated to discuss over the phone in a few minutes. Please see my recent literature on the subject (from a Hybrid Empirical modeling point of view) as listed, for example, in my Blue Castle presentation. If you don't have access to the Blue Castle presentation, I can send it to you.	
2. Which data are the most relevant in addressing these issues? This is too complicated to discuss over the phone in a few minutes. I would need some time to think about this issue.	
3. Has your model (Campbell, BSSA 2003) been superseded? If so, by which model? I would consider the Pezeshk et al. (2011) Hybrid Empirical model published in the BSSA to have superseded my 2003 model in that it uses virtually the exact same methodology but with updated seismological and empirical models. It is also consistent with the approach used in my 2007 NEHRP research report and subsequent conference papers (see Blue Castle presentation).	
4. What are the key issues we should be considering in updating the model for the aleatory uncertainty as a function of magnitude and distance? This is too complicated to discuss over the phone in a few minutes. I would need some time to think about this issue.	
5. In addition to your published papers, do you have any papers in preparation or under review that you can share with our project? There are some plots showing comparisons of Hybrid Empirical models in the Blue Castle presentation, which I intend to publish as a Comment to the Pezeshk et al. (2011) BSSA paper. My research on the PEER NGA-East Ground Motion project is too preliminary to share.	
6. Do you know of interesting work in progress by other researchers? There is a lot of interesting work being done as part of the PEER NGA-East Ground Motion project, but it is too preliminary to share. You will need to ask other experts in the field to see what new studies they are working on.	
7. Additional information from expert I have no additional information to provide.	

Table C-6

Expert Name: Chris Cramer	Date of Call: 7/3/2012
Prepared by: Gabriel R. Toro	Date Prepared: 7/10/2012

1. **What are the key issues we should be considering in updating the model for median amplitudes (and the associated epistemic uncertainty) as a function of magnitude and distance?**
    a. EPRI (2004) did not have enough separation between experts and TI Team. More independence needed.
    b. EPRI (2004) gave large weights to one Proponent Expert (Silva).
    c. Silva's single-corner model should be treated as a 2-corner model because the low Q value used with single-corner leads to identical predictions as double-corner. This is shown in Cramer (2006) BSSA paper.

2. **Which data are the most relevant in addressing these issues?**
    a. The NGA-East database.
        i. Comparisons presented at the NGA-East Workshops and poster at 2012 SSA meeting show interesting trends. Comparisons suggest that models over-predict at long periods.
        ii. Currently working on report for NGA-East project
        iii. Working with Christine Goulet of PEER on cleanup and QA.

3. **(If the expert's models were included in EPRI, 2004; see table on next page) Has your model of year xxxx been superseded? If so, by which model?**
    N/A

4. **What are the key issues we should be considering in updating the model for the aleatory uncertainty as a function of magnitude and distance?**
    a. No specific comments. EPRI (2006) did a good job at estimating sigma.

5. **In addition to your published papers, do you have any papers in preparation or under review that you can share with our project?**
    a. Cramer (2006) BSSA
    b. Cramer (2012) SSA Poster
    c. Cramer (2010) paper at US/Canadian Earthquake Conference (Toronto)

6. **Do you know of interesting work in progress by other researchers?**
    a. The NGA-East Source and Path working group is doing interesting work, but there is nothing ready.
    b. Vs measurement by USGS and others (Alan Yong, Rob Kayen, etc.)

7. **Additional information from expert**
    N/A

Table C-7

Expert Name: Art Frankel	Date of Call: 7/31/2012
Prepared by: Robert Youngs	Date Prepared: 8/02/2012

1. **What are the key issues we should be considering in updating the model for median amplitudes (and the associated epistemic uncertainty) as a function of magnitude and distance?**
   a. Geometrical spreading at distances less than 100 km: is decay steeper than 1/R observed widely across CEUS, is it perhaps a result of radiation pattern
   b. Moho bounce: is it as prominent in other areas as in southeastern Canada.
   c. Source spectra – single versus double corner: Although the single corner model is perhaps too simplistic, a good physical explanation of the basis for a double corner model is needed.
   d. The concept of a single corner type model with 1/R spreading (<100 km) and nearly constant stress should be given some weight in developing updated ground motion characterization. This model in point source form also has issues with overestimation of ground motions from large earthquakes at short distances.
   e. Modeling using finite faulting sources is an important step forward, but there should be a good physical basis for the source spectra (see c. above)
   f. Scaling of stress drop with seismic moment. Needs to be consistent with the faulting model. A finite-fault model with constant stress drop explains NGA west observations. CEUS median stress drop is higher than WUS.
   g. Characterization of site response in CEUS.
2. **Which data are the most relevant in addressing these issues?**
   a. Detailed studies of recent earthquake data, such as the Riviere du Loup event using careful time domain modeling
   b. Suggest consideration of coda normalization technique developed by Aki to remove site response and instrument response from data
3. **Has your Frankel et al. 1996 model (which was used in EPRI, 2004) been updated or superseded? If so, by which model?**
   It has not been updated or specifically superseded. In the early stages of an update. The basic characteristics of the model should be considered in CEUS ground motion characterization with the caveats mentioned in 1d above.
4. **What are the key issues we should be considering in updating the model for the aleatory uncertainty as a function of magnitude and distance?**
   No strong opinion about use of NGA West data, but suggest that NGA aleatory variability may be a minimum. The Saguenay earthquake suggests that there may be more source to source variability in CENA. There does not appear to be a Saguenay type earthquake in the NGA West database.
5. **In addition to your published papers, do you have any papers in preparation or under review that you can share with our project?**
   Nothing at this point
6. **Do you know of interesting work in progress by other researchers?**
   Believe that Hartzell and Mendoza are doing some work that may be relevant to the issue.
7. **Additional information from expert**

Table C-8

Bob Herrmann was interviewed on September 11, 2012. Bob Herrmann provided a paper entitled, "Ground Motions for Recent Earthquakes in Eastern North America," updated October 12, 2012 with highlights to document the interview. This paper provided an overview of data sets available for recent, significant earthquakes in eastern North America. The update adds the M_w=4.83 Northeast Texas earthquake of May 17, 2012. The ground motion at larger distances was demonstrably lower than any of the model predictions, which indicated the need for different ground motion scaling for paths in the Gulf Coastal Plain. Dr. Herrmann focused on this earthquake because of the large difference between observed and predicted intensities.

Dr. Herrmann suggested that one should entertain a California-like ground motion attenuation model for the Gulf Coastal Plain. Such a model may have a major effect on hazard calculations in this region. Plots in the paper raise another issue underlying any prediction model – the ability of the model to reflect the data sets in their creation. There is very little modern digital broadband data at distances less 100 km, and especially less than 20 km. Confidence in the model at these shorter distances would have to be based on other evidence, e.g., behavior of western U.S. data sets, or even theoretical wave propagation considerations.

Dr. Herrmann states in the paper that Dr. Martin Chapman has access to a unique data set acquired from the Mineral, Virginia aftershocks. A linear array with a station separation on the order of km's was deployed to about 70 km. This data set may elucidate the nature of geometrical spreading, for this one azimuth, for this type of source mechanism. Although we have better observations, Dr. Herrmann recommended that sponsoring agencies be proactive to acquire new data sets by deploying seismographs as earthquakes occur, so that we can acquire data sets to better constrain ground motion scaling.

Table C-9

Expert Name: Shahram Pezeshk	Date of Call: 6/26/2012
Prepared by: Shahram Pezeshk, G. Toro	Date Prepared: 7/2-7/2012

1. **What are the key issues we should be considering in updating the model for median amplitudes (and the associated epistemic uncertainty) as a function of magnitude and distance?**
Since due to lack of data, the ground–motion must rely on numerical simulation, especially the stochastic simulations, following are the issues that should be considered in such a modeling:

Types of stochastic modeling and the combination

- Single-Corner point-source
- Double-Corner point-source
- Finite fault

Single-corner point-source and finite fault models have been updated in term of compatible seismological parameter and modeling procedure; however, the existing double-corner point-source models for CEUS have not been examined and updated for consistency with the newly recorded data.

The most critical issue in point source modeling is to use consistent seismological parameters corresponding to each source, path, and site terms. In other words, the correlations between these terms should be considered in modeling. This means that the stress drop being used for instance in the single-corner point-source modeling should be consistent with the choice of geometrical spreading and quality factor function (path effect) and also the site term.

Sensitivity analysis should be performed with different set of correlated parameters to prevent redundancy; therefore, decreasing the epistemic uncertainty. For instance, if two sets of correlated seismological parameters would result in similar estimation of ground motion, what is the point of using the two?

Another critical issue is the regionalization. Is the choice of seismological parameters the same in the New Madrid seismic zone and for example the southeastern Canada? Of course, lack of strong motion data is an obstacle to verify the regionalization; however, the small magnitude events may be used to detect regionalization. Again, if regionalization is detected, in each region consistent correlated seismological parameters should be used.

Another interesting issue is the geometric decay within 50-70 km. Some investigators see $R^{-1.3}$, others see R^{-1}. Could this be explained by regional differences?

The correlation between seismological parameters will affect the parametric uncertainty in the stochastic modeling. By using different sets of correlated seismologic parameters in a logic tree scheme the parametric uncertainty could be quantified appropriately.

The distance measure: Different modifications have been introduced for the distance measure used in the point-source modeling to mimic the effect of finite faults. These modifications are necessary when using the point-source method for ground motion estimation at close distances. However, if the distance modification is developed to make point-source simulations very close to finite fault modeling what is the point of using both models and maybe one is enough!

In CEUS, the reference site is a very hard rock. There are different site responses of the hard rock of CEUS based on different generic profiles, empirical H/V ratios, etc. Again, whatever the choice of site response would be, consistent seismological parameters for source and path should be used.

Data from recent earthquakes in CEUS such as Mt. Carmel, Arkansas, Kentucky, and Central Virginia can be used to evaluate different models (at least in the small to moderate magnitude range) and study possible regionalization.

Another modeling technique will be hybrid empirical modeling. Also, since hybrid empirical modeling uses stochastic simulation to map the empirically derived GMPEs from a host region to CEUS, the same issues for stochastic modeling are applicable. For Hybrid empirical modeling:

- The choice of stress parameter for both host and target region plays an important role in the HEM estimations, especially at high frequencies (PGA). For, the host region, this parameter can be constrained with empirical data. For the target region, due to lack of strong motions stress parameter is not well constrained. The issue is that whether the stress parameter from small event can be used for the large events as well. One alternative is to use the same magnitude scaling observed in the host to constrain the stress parameter in target. This procedure may result in using the same degree of magnitude scaling in both regions and cancel out this effect. On the other hand the purpose of using HEM is to map the same magnitude scaling observed in host to target. Therefore, by using, e.g., the small magnitude stress parameters for both WNA and ENA it can be assumed that the HEM does the rest and model the same magnitude scaling observed in the WNA for ENA.
- In WNA the dependency of stress parameters with magnitude is observed using a point-source stochastic model. This dependency might be weakened if higher order stochastic model, where the definition of stress parameter is different, is used to model ground-motions. Therefore, the choice of stress parameter should be exclusively limited to the specific stochastic model being used in HEM.
- The stress parameter is correlated with the choice of path effect in the inversion problem of going from observations to the stochastic predictions. Therefore, the choice of stress parameter should be consistent with the path effect being used in the stochastic simulations. On the other hand, based on the systematic difference between path effect between WNA and ENA, the choice of path effect, affect the shape of HEM estimations. Therefore, enough evidence and rationalizations should be used to select the path effect for both WNA and ENA. Using different alternatives with appropriate weighting to consider the epistemic uncertainty is recommended.

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APPENDIX F
BIOGRAPHIES OF PROJECT TEAM

EPRI Management

Robert P. Kassawara, PhD, is EPRI Senior Project Manager for the Structural Reliability and Integrity group at EPRI. Dr. Kassawara is responsible for the technical, financial, and administrative planning and management of EPRI's research and development for seismic engineering for commercial nuclear power plants. Projects include all aspects of the discipline from seismic hazard to equipment qualification. Before joining EPRI in 1985, he managed the engineering analysis section of the Plant Engineering Division of IMPELL in Melville, New York. In this position, he was responsible for performing structural engineering analyses predominantly for the nuclear power industry. Between 1970 and 1981, he managed and contributed to nuclear power plant design and analysis at Combustion Engineering in Windsor, Connecticut. Dr. Kassawara has a BS in civil engineering from the Polytechnic Institute of Brooklyn (1966), and an MS (1968) and PhD (1970) in civil engineering from the University of Illinois.

Jeffrey F. Hamel is Executive Director at EPRI. His current research activities focus on supporting deployment of advanced nuclear plants in the near term, while promoting areas of research to support long-term nuclear sustainability and growth. Specifically, Mr. Hamel oversees research on near-term deployment of advanced light-water-reactor nuclear plants, development of the Next Generation Nuclear Plant GEN IV technology, and technical and commercial support for an integrated spent-fuel management strategy. Before joining EPRI in 2007, he worked at General Electric as the manager of special projects and was responsible for managing and leading new growth for GE's nuclear business, particularly in pressurized water reactor and spent-fuel services. In addition, while at GE, he supported the commercial development of new nuclear power plant projects both domestically and internationally, including development of key engineering, mechanical and electrical equipment necessary for project execution. Mr. Hamel received a BS in marine transportation from the Massachusetts Maritime Academy in Buzzards Bay, Mass., along with a U.S. Coast Guard Merchant Marine license and U.S. Navy Reserve commission. He received his MBA from Santa Clara University in Santa Clara, California.

Project Manager

Lawrence A. Salomone, PE, is the Project Manager for the EPRI (2004, 2006) Ground-Motion Model (GMM) Review Project. He is a registered Professional Engineer with 42 years of experience in the environmental and earth sciences. He was the Site Chief Geotechnical Engineer at the Savannah River Site (SRS) in Aiken, S.C. for nineteen (19) years, where he developed and managed a $100 million geological, seismological, and geotechnical (GSG) characterization program to integrate geotechnical and geo-environmental work for mission-critical nuclear facilities at the SRS. He worked in 2011 with vendors interested in obtaining design certification for various Small Modular Reactor (SMR) designs. He has directed 35-person and 70-person multidisciplinary groups. He directed the licensing, site preparation, and foundation operations for the Hope Creek Generation Station. For the National Bureau of Standards (now National Institute of Standards and Technology), he performed research to advance geotechnical, earthquake engineering, and energy technology. Mr. Salomone was nominated by the National Capital Section of the American Society of Civil Engineers for the Walter L. Huber Civil Engineering Research Prize for his work in the area of thermal soil mechanics. His work was used to a) study backfills for the Yucca Mountain high level waste repository, b) develop Electric Power Research Institute (EPRI) design guidance for ground-coupled heat pumps, c) design underground electric transmission lines and develop mesoscale (severe) weather forecasting models. He currently serves as a consultant to the U.S. House of Representatives and the U.S. Senate on national energy policy issues. He has worked with the U.S. Congress on environmental and energy legislation, numerous federal agencies on geotechnical and energy-related research and Fortune 500 companies on environmental cleanup.

Mr. Salomone established the industry-government partnership to develop a new earthquake source model for the Central and Eastern United States (CEUS) and the industry-funded project to update the EPRI (2004, 2006) GMM for the CEUS. He served as the Project Manager for both national efforts that are currently being used to evaluate the seismic safety of the existing fleet of nuclear power plants in the CEUS. He served as the Department of Energy (DOE) representative supporting the NEI/EPRI New Plant Seismic Issue Resolution Program and interacted with the NRC for its update of Regulatory Guide 1.208 and the related sections of the Standard Review Plan, NUREG-0800. Currently, he is a member of the Seismic Lessons Learned Panel that advises the DOE Nuclear Facility Safety Program, and he is the EPRI representative on the Joint Management Committee (JMC) for the Next Generation Attenuation–East Project. He has provided support for the DOE Nuclear Power 2010 program and the 2006 National Electric Transmission Congestion Study. He served on the New Carolina Nuclear Power Policy Subcommittee. He is the author or co-author of over 43 published papers and many technical reports. Mr. Salomone earned his BCE in civil engineering from Manhattan College in Riverdale, N.Y., and his MS in geotechnical engineering from the University of California, Los Angeles.

TI Team

Robin K. McGuire, PhD, is the founder of Risk Engineering, Inc., of Boulder, Colorado, and is currently Vice President of Fugro William Lettis & Associates, Inc. For 30 years he has consulted in seismic hazard analysis, earthquake engineering, and the application of probabilistic methods to engineering problems. He has conducted seismic hazard analyses at sites of major engineering facilities at over 100 locations within the United States and at over 30 locations in foreign countries, in a range of technical environments. In addition, he has developed earthquake hazard software that is used around the world in engineering, insurance, risk management, government, and research for seismic hazard estimation. Dr. McGuire is the author of over 100 papers and articles on these topics that have been published in technical journals or as technical reports, as well as *Seismic Hazard and Risk Analysis*, a monograph published by the Earthquake Engineering Research Institute (EERI) in 2004. He is a past president of the Seismological Society of America (SSA) and has served on the Board of Directors of both SSA and EERI. Dr. McGuire was elected to the National Academy of Engineering in 2007. He holds degrees in structural engineering from MIT (SB and PhD) and the University of California, Berkeley (MS).

Gabriel R. Toro, PhD, Senior Principal Engineer with Fugro William Lettis & Associates, Inc., has more than 30 years of experience in PSHA for critical facilities and other applications of probabilistic and statistical methods to the engineering analysis of natural hazards. His project experience includes a number of significant studies that have advanced the state of practice in PSHA. In the EPRI-SOG study, Dr. Toro designed and developed the software for the PSHA calculations and was a key member of the group selecting the ground motion models. As a member of the SSHAC staff, he was a major contributor to the chapter on ground motions, as well as contributing to the chapter on source characterization and to four appendices. He also directed and coordinated the PSHA calculations for the Yucca Mountain and PEGASOS Level 4 PSHA studies. Dr. Toro has made significant contributions to multiple areas of PSHA, including the development of ground motion models for regions with limited data such as the CEUS, the treatment of uncertainty in PSHA inputs, models for temporal clustering in the New Madrid region, and the probabilistic modeling of soil profiles for use in site-response calculations. He has also served as reviewer for PSHA and risk studies in Asia, Africa, and the Americas. Awards he has received include the Fulbright Travel Grant, the OMAE Award from ASME, and the EERI Outstanding Paper Award. Dr. Toro has a civil engineer's degree from the National University of Colombia, and a Master's and PhD in civil engineering from M.I.T.

Robert R. Youngs, PhD, a Principal Engineer at AMEC Geomatrix, Inc., has more than 35 years of consulting experience, with primary emphasis in hazard and decision analysis. He has pioneered approaches for incorporating earth sciences data and their associated uncertainties into probabilistic hazard analyses. The focus of this work has been on developing quantitative evaluations of hazard by combining statistical data and expert judgment. Dr. Youngs has considerable experience in assessing earthquake hazards in central and eastern North America and implementing SSHAC processes. He was a member of the research teams that developed EPRI's seismic hazard assessment for nuclear power plants in the CEUS and EPRI-sponsored research projects to assess ground motions (1993) and maximum magnitudes (1994) for the CEUS. He was also a member of the project team for the NRC project to develop response spectral shapes for analysis of nuclear facilities (NUREG/CR-6728) in 2001 and the EPRI project to characterize ground motions in the CEUS for analysis of nuclear facilities in 2004. Dr. Youngs has completed seismic hazard analyses of existing and proposed nuclear power plants throughout the United States (including in Alabama, Florida, Louisiana, Michigan, and North Carolina) and internationally, including in Ontario, Canada and Switzerland (PEGASOS project). He earned his BS in civil engineering at California State Polytechnical University, Pomona (1969), and his MS and PhD in geotechnical engineering at the University of California, Berkeley (1982).

Martin Chapman– biography will be provided later

Technical Support

J. Carl Stepp, PhD, is Senior Advisor for the EPRI (2004, 2006) GMM Update Project. Dr. Stepp has more than 40 years experience developing PSHA methods and developing probabilistic seismic design bases, primarily for nuclear power generation plants and other critical facilities. During his professional career he has been a research seismologist for the U.S. Coast and Geodetic Survey for approximately 10 years; he was chief of the Geology, Seismology, and Geotechnical Engineering Branch at the NRC, in charge of the application of seismic hazard assessment in nuclear facilities seismic regulation for 7 years; he headed research and development of seismic hazard, seismic design, and seismic regulation technologies for 10 years as director of the Seismic Center at EPRI; and he provided consulting services in seismic hazard assessment and seismic safety regulation for approximately 20 years. At the NRC, he supervised early implementation of the nuclear seismic regulation 10 CFR, Part 100, Appendix A for reviews of 53 nuclear power plant construction and operating license applications, and the development of geology, seismology, and geotechnical engineering sections of the NRC's Standard Review Plan. At EPRI, Dr. Stepp managed a broad program of nuclear plant seismic safety research and technology development, including methods for probabilistic seismic hazard assessment and for predicting earthquake-generated ground motion. He was technical lead for EPRI, interacting with both the NRC and industry to incorporate the integrated results of EPRI's seismic research and technology development into seismic regulations, including the 10 CFR Part 100.23 Rule Making and the development of Regulatory Guide 1.165 and Revision 3 of the related Standard Review Plan sections.

Dr. Stepp directed development of the PSHA for the Yucca Mountain, Nevada, high-level nuclear waste site; he chaired the development of Pre-closure Seismic Design Methodology for a Geologic Repository at Yucca Mountain, and he chaired the Seismic Review Panel for development of the Yucca Mountain license application. He served as a member of the EPRI Technical Review and Advisory Group, supporting the NEI/EPRI New Plant Seismic Issue Resolution Program and interacting with the NRC to develop Regulatory Guide 1.208 replacing Regulatory Guide 1.165, and to update related sections of the Standard Review Plan. He served as Chairman of the PPRP for the BC Hydro PSHA Project and as a member of the Seismic Lessons Learned Panel that advises the DOE Nuclear Facility Safety Program. Dr. Stepp holds a BS in geology from Oklahoma State University, an MS in geophysics from the University of Utah, and a PhD in geophysics from Pennsylvania State University.

Charles Mueller– biography will be provided later

Database Manager

Serkan Bozkurt, MCP, is a Principal GIS Analyst and IT Manager at Lettis Consultants International, Inc. He has 15 years of work experience in GIS, information management, and Internet technologies. The focus of his work has been the utilization of spatial models; 3-D visualizations; GIS analysis; remote sensing and database technologies to support geosciences projects such as seismic hazards analysis for proposed or existing nuclear power plants, oil facilities, offshore platforms, pipelines, bridges dams, levees, and other critical facilities. Some of his recent project work includes GIS and information management services for SSHAC Level 3 studies and for sites in the United States, Canada, and South Africa and Combined License

(COL) Applications for New Nuclear Reactors in United States. Prior to joining Lettis Consultants International Mr. Bozkurt worked at the U.S. Geological Survey on the Earthquake Hazards Team as a GIS analyst and Web developer. He has contributed to more than 50 scientific publications related to seismic hazard studies by utilizing GIS and data base technologies. He earned a BS in urban and regional planning from Istanbul Mimar Sinan University (1996) and an MCP in GIS and city planning from the Istanbul Mimar Sinan University (2000) focusing Disaster Management and GIS technologies.

Participatory Peer Review Panel

Walter J. Arabasz, PhD, is Chairman of the PPRP for the EPRI (2004, 2006) Ground Motion Model Review Project. He has worked since 1974 as a seismologist at the University of Utah, where he is now Research Professor Emeritus of Geology and Geophysics. From 1985 to June 2010 he was Director of the University of Utah Seismograph Stations. He has more than 40 years of professional experience in research, project management, consulting, and occasional teaching in seismology, seismotectonics, and earthquake hazard assessment. He is the author or co-author of 46 published papers, 94 published abstracts, and many technical reports. In addition, he has served on numerous national and state advisory and policy-making committees for earthquake risk reduction and U.S. network seismology.

Since 1977 Dr. Arabasz has routinely provided professional consulting services and peer review on earthquake hazard assessments for dams, nuclear facilities, and other critical construction, including services for engineering firms, the International Atomic Energy Agency, DOE, the U.S. Bureau of Reclamation, EPRI, Los Alamos National Laboratory, and the state of Utah, among others. He has had broad experience in implementing PSHA, beginning with participation as a member of the PSHA methodology team in the original EPRI seismic hazard characterization of the CEUS (1985–1987). As a member of the National Research Council's Panel on Seismic Hazard Evaluation (1992–1996), he observed the development of and formally reviewed recommendations for PSHA made by the Senior Seismic Hazard Analysis Committee (SSHAC). Honors include the U.S. Geological Survey's John Wesley Powell Award, the Western States Seismic Policy Council Lifetime Achievement Award in Earthquake Risk Reduction, and the [Utah] Governor's Medal for Science and Technology. Dr. Arabasz earned a BS in geology at Boston College (1964), an MS in geology at the California Institute of Technology (1966), and a PhD in geology and geophysics at the California Institute of Technology (1971).

Brian Chiou – biography will be provided later

Richard Quittmeyer – biography will be provide later

Robert B. Whorton, PE, is a Consulting Engineer with South Carolina Electric & Gas Company. He has over 40 years experience in seismic analysis, seismic design, seismic qualification, and seismic hazard assessment of nuclear power plant structures, systems, and components. He has provided technical leadership through EPRI and NEI in many areas, such as implementation of the seismic margin assessment methodology, the methodology for response to individual plant examination of external events (IPEEE) for seismic activity, industry guidance for seismic instrumentation and plant shutdown requirements, and development of industry guidance for response to the Fukushima Near Term Task Force Recommendations.

Mr. Whorton was a member of the EPRI industry task group that provided NRC comments on new regulations and regulatory guides for COLs. He also participated as an industry lead in the review of the shield building seismic analysis of the Westinghouse AP1000. He is a member of the NEI Seismic Issues Task Force and the EPRI Structural Reliability & Integrity Group, which are involved in resolving seismic issues with operating plants and COLs. He provided the Technical Interface for South Carolina Electric & Gas Company for the seismic portion of the Summer Unit 2/3 COL, including technical presentations to the NRC ACRS and Commissioners. Mr. Whorton holds a BS in engineering (civil/structural) from the University of South Carolina. He is a licensed Professional Engineer in South Carolina.

Observer Reviewers

Jon P. Ake, PhD, is currently Senior Seismologist in the Office of Research, Division of Engineering of the NRC. His duties include overseeing research on a broad range of seismic related issues for hazard assessment and integration with risk analyses. Dr. Ake began his career conducting research on explosively generated ground motions, the dynamic response of earth media, and applications of signal analysis to ground shock problems. He subsequently worked as a consulting geophysicist with responsibility for operating a 21-station seismic network in central Colorado and performing high-resolution seismic refraction and reflection studies and other engineering geophysical investigations (magnetic, electrical, and gravity). In 1989 he joined the U.S. Bureau of Reclamation, where his responsibilities included conducting, reviewing, and coordinating probabilistic seismic hazard studies, integrating the results with engineering analyses, and incorporating them into quantitative risk assessments. Dr. Ake served as a member of the expert panel that characterized seismic sources for a PSHA for the proposed high-level waste repository at Yucca Mountain. He also served in a liaison role to the DOE on seismic hazard issues for the Yucca Mountain Project, in which he assisted in the coordination and preparation of documents on disruptive events that became part of the license application to the NRC.

Dr. Ake has served on the Dam Safety Advisory Team to the U.S. Bureau of Reclamation; the Federal Interagency Committee on Dam Safety; the U.S.-Japan Panel on Wind and Seismic Effects; the Consortium of Strong Motion Operators (COSMOS); and ANS/ANSI Committees 2.27 (Criteria for Investigations of Nuclear Facilities Sites for Seismic Hazard Assessments), 2.29 (Probabilistic Seismic Hazard Analysis), and 2.20 (Seismic Instrumentation for Nuclear Facilities). He has acted as a peer reviewer for the University of California Campus Earthquake Safety Program, BC Hydro, U.S. Army Corps of Engineers, DOE, California Department of Water Resources, Federal Energy Regulatory Commission, and the USGS, among others. He is currently a member of the DOE Seismic Lessons Learned Panel and Next Generation Attenuation–East projects. Dr. Ake obtained a BA in geology and physics from Western State College in Colorado and an MS and PhD in geophysics from the New Mexico Institute of Mining and Technology.

Jeffrey K. Kimball is a Technical Specialist (Seismologist) on the staff of the Defense Nuclear Facilities Safety Board. He is responsible for technical issues involving natural phenomena hazards, nuclear facility safety and design, and general oversight of defense nuclear facilities. He has 30 years of experience with the evaluation and characterization of natural phenomena hazards and the design of critical facilities to resist these hazards. He has full knowledge of a wide range of nuclear facility regulations, regulatory guides, standards, manuals, guides, and review plans associated with nuclear facility design and evaluation. From 1990 to 2006, Mr. Kimball was the group lead for engineering design in the DOE National Nuclear Security Administration. He supervised technical staff responsible for technical review of nuclear facility designs and safety analysis. He led the development of seismic site characterization at numerous DOE sites, including the definition of the design basis earthquake, and led preparation of DOE standards and guides to define requirements and procedures to complete assessment of natural phenomena hazards.

Mr. Kimball was the DOE sponsor for the program that led to the “Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts,” commonly referred to as the SSHAC guidelines. From 1987 to 1990, he was a geophysicist in the DOE Office of Radioactive Waste, responsible for establishing the baseline site characterization plan for the Yucca Mountain high-level waste repository site. Before that, from 1984 to 1987, he was a senior geophysicist with Roy F. Weston Inc., participating in the review and development of environmental assessments for nine candidate high-level waste sites, and comparing and ranking sites for site characterization. From 1980 to 1984, he was a geophysicist with the NRC, participating in the review of safety analysis reports and developing appropriate sections of those reports. Mr. Kimball holds a BS in atmospheric and oceanic sciences and an MS in geosciences (geophysics/seismology), both from the University of Michigan.

Clifford G. Munson, PhD, is Senior Technical Advisor in the Division of Site and Environmental Reviews, Office of New Reactors for the NRC. He is the principal reviewer of new nuclear plant siting applications in the areas of geology, seismology, and geotechnical engineering for the NRC. He has developed and updated several regulatory guidance documents pertaining to siting, including Chapter 2.5 of NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants”; Regulatory Guide 1.206, “Combined License Applications for Nuclear Power Plants (LWR Edition)”; and Regulatory Guide 1.208, “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion.” Dr. Munson joined the NRC in 1995 as a geophysicist, becoming a senior geophysicist in 2003, then a branch chief in 2008 until he took his current position in November 2009. He has a BS in statistics (1987) from Brigham Young University and an MS (1991) and PhD in geophysics (1995) from the University of Wisconsin–Madison.