PMTurkeyCOLPEm Resource

From: Comar, Manny
Sent: Wednesday, October 03, 2012 7:58 AM
To: TurkeyCOL Resource
Subject: FW: DRAFT RAI Responses FPL Turkey Point 6 & 7 for eRAI 5896 Basic Geologic and Seismic Information
Attachments: Draft Revised Response for NRC RAI Letter No. 037 (eRAI 5896) 2.5.2-3.pdf; Draft Revised Response for NRC RAI Letter No. 037 (eRAI 5896) 2.5.2-5.pdf

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From: Franzone, Steve [mailto:Steve.Franzone@fpl.com]
Sent: Monday, September 24, 2012 2:33 PM
To: Comar, Manny
Cc: Franzone, Steve; Maher, William; Burski, Raymond
Subject: DRAFT RAI Responses FPL Turkey Point 6 & 7 for eRAI 5896 Basic Geologic and Seismic Information

Manny,

To support a future public meeting, FPL is providing draft revised responses for eRAI 5896 (RAI questions 02.05.02-3 and 02.05.02-5) in the attached files:

If you have any questions, please contact me.
Thanks
Steve Franzone
NNP Licensing Manager - COLA
"Three Rules of Work: Out of clutter find simplicity; From discord find harmony; In the middle of difficulty lies opportunity." Albert Einstein
561.694.3209 (office)
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Hearing Identifier: TurkeyPoint_COL_Public
Email Number: 671

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Subject: FW: DRAFT RAI Responses FPL Turkey Point 6 & 7 for eRAI 5896 Basic Geologic and Seismic Information
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NRC RAI Letter No. PTN-RAI-LTR-037

SRP Section: 02.05.02 - Vibratory Ground Motion

Question for Geosciences and Geotechnical Engineering Branch 1 (RGS1)

NRC RAI Number: 02.05.02-3 (eRAI 5896)

FSAR Subsection 2.5.2.4.4.3.1 describes summary information related to the SSHAC Level 2 study on new seismic source models for the Cuba and northern Caribbean region,. In accordance with NUREG-0800, Standard Review Plan, Chapter 2.5.2, "Vibratory Ground Motion", and Regulatory Guide (RG) 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion," please provide the complete SSHAC documentation detailing specifically:

a. Procedures and any assumptions made in developing the Caribbean seismic sources,
b. The questionnaire used in obtaining expert opinions,
c. The TI any advisory groups and/or peer reviewers used,
d. How the experts' opinions were integrated into the development of the final models. Discuss expert opinions and/or suggestions that were left out of the final model and justifications for doing so,
e. How conflicting opinions among the experts were dealt with,
f. How the final models represent the consensus of the informed community

FPL RESPONSE:

a) Procedures and any assumptions made in developing the Caribbean seismic sources

A seismic source characterization of Cuba and the northern Caribbean region for use in the Turkey Point Units 6 & 7 project was developed through the use of the Senior Seismic Hazard Analysis Committee (SSHAC) Level 2 process, defined in SSHAC (1997) (FSAR Reference 318). The SSHAC developed a formal process for conducting expert assessments and the use of expert judgment to incorporate uncertainties in probabilistic seismic hazard analysis (PSHA) (SSHAC 1997). The goal of the SSHAC process is to "represent the center, the body, and the range of technical interpretations that the larger informed technical community would have if they were to conduct the study" (SSHAC 1997, p. 21) (FSAR Reference 318). The SSHAC process also identifies a clear definition of ownership of the input parameters into the PSHA, and hence, ownership of the PSHA results. Ownership means intellectual responsibility such that the regulator will know the individuals who are responsible for developing the PSHA.

SSHAC (1997) (FSAR Reference 318) defines four levels of effort for capturing the range of uncertainty by the informed technical community (ITC). These are termed Levels 1 through 4. With each increasing level, there is increasing direct involvement of the ITC and, thus, increasing confidence and documentation that the center, body, and range of uncertainty in the ITC have been captured. Regardless of level of study, however, the goal of the SSHAC process is "to provide a representation of the informed scientific community's view of the important components and issues and, finally, the seismic hazard" (SSHAC 1997, p. 26) (FSAR Reference 318). Moreover, "regardless of the scale of the PSHA study, the goal remains the same: to represent the center, the body, and the range that the larger ITC would have if they were to conduct the study" (SSHAC 1997, p. 21) (FSAR Reference 318).

FSAR Subsection 2.5.2.4.4.3 describes the seismic source characterization for Cuba and the northern Caribbean region developed for the Turkey Point Units 6 & 7 project. Development of this seismic source characterization followed the SSHAC Level 2 process. According to SSHAC (1997, p. 23) (FSAR Reference 318), a Level 2 study is appropriate for issues with "significant uncertainty and diversity," and for issues that are "controversial" and "complex." The use of the SSHAC Level 2 process for the Turkey Point Units 6 & 7 project is consistent with other COL applications and regulatory guidance.

The SSHAC Level 2 process utilizes an individual, team, or company to act as the Technical Integrator (TI). In a SSHAC Level 2 study, the TI is responsible for reviewing data and literature and contacting experts who have developed interpretations or who have specific knowledge of the seismic sources. The TI interacts with these resource experts to identify issues and interpretations and to assess the center, body, and range of informed expert opinion. In other words, the role of the TI is to "evaluate the viability and credibility of the various hypotheses with an eye toward capturing the range of interpretations, their credibilities, and uncertainties" (SSHAC 1997, p. 27) (FSAR Reference 318).

The SSHAC Level 2 process performed for the Turkey Point Units 6 & 7 project began with a comprehensive literature search and review performed by the TI team. Based on this literature review, the TI team developed an initial straw man seismic source characterization. Also based on this literature review, the TI team identified resource experts with specialized knowledge of the region. These resource experts span a wide range of disciplines, including geology, seismology, geodesy, and geophysics. FSAR Table 2.5.2-216 provides a list of the resource experts contacted as part of this process. The TI team conducted interviews with resource experts regarding seismic sources in Cuba and the northern Caribbean. Parts (b), (d), and (e) of this response provide additional discussion of the TI team's interactions with experts. During the course of its development, the seismic source characterization was presented to, and discussed with, the project Technical Advisory Group (TAG). Part (c) of this response provides additional discussion of the TAG and their interactive review of the source characterization.

The seismic source characterization of the northern Caribbean region developed for the Turkey Point Units 6 & 7 project includes a number of assumptions, as described below. This source characterization is designed to include the seismic sources in the northern Caribbean region capable of generating frequent large or great earthquakes that, given the site-to-source distances, are assumed to be the contributors to the site hazard. The seismic source model for the Cuba and northern Caribbean region includes the Cuba areal source and segments of the plate boundary, but does not include background zones for the modern plate boundary region (FSAR Figure 2.5.2-217). At its closest approach, the North America-Caribbean plate boundary lies approximately 420 miles (680 km) from the Turkey Point Units 6 & 7 project site. Segments of the plate boundary were modeled as fault sources. However, it was assumed that distant background sources covering areas of relatively sparse seismicity would not contribute to site hazard. Therefore, with the exception of Cuba, areal background sources were not developed for the Caribbean plate boundary region. This is similar to PSHAs developed for many eastern U.S. sites that include the distant New Madrid seismic source but exclude some background sources that exist between the site and the New Madrid seismic source.

Additionally, it was assumed that the project Phase 2 earthquake catalog is the most appropriate earthquake catalog for use in seismic source characterization, determination of seismicity rates for Cuba, and calculating hazard at the site. As described in FSAR Subsection 2.5.2.1.3, there are many earthquake catalogs covering the Phase 2 seismicity investigation region, but no single published catalog includes everything for assessing earthquake occurrence. Thus, several regional and global catalogs were combined to make a new catalog supplement. These catalogs cover different time, space, and magnitude ranges with varying accuracy.

b) The questionnaire used in obtaining expert opinions

The TI team conducted interviews with resource experts by phone, email, and/or face-to-face discussions. To provide a framework and starting point for these discussions, resource experts were given a standard questionnaire pertaining to the initial straw man seismic source characterization and key issues regarding seismic sources in Cuba and the northern Caribbean. This questionnaire is provided here as Enclosure A. The interviews with resource experts were not a formal process of expert interrogation to obtain from each expert all of the specific parameters and weights to be used in the model. Instead, the resource experts were encouraged to speak to their own areas of expertise.

c) The TI and advisory groups and/or peer reviewers used

The TI team assembled to develop the seismic source characterization for Cuba and the northern Caribbean region for the Turkey Point Units 6 & 7 project comprised four William Lettis & Associates, Inc., geologists:

- Dr. Ross Hartleb
- Mr. Roland LaForge
- Mr. Scott Lindvall
- Dr. Steve Thompson

Peer review for this process was provided by the project TAG. At TAG meetings 1 through 3, TAG members included:

- Dr. Robert Kennedy (RPK Structural Mechanics Consulting)
- Dr. William McCann (Earth Scientific Consultants)
- Mr. Donald Moore (Southern Nuclear Operating Company)
- Dr. J. Carl Stepp (Earthquake Hazards Solutions)
- Dr. Robert Youngs (Geomatrix Consultants, currently AMEC)

Additional guidance and peer review were provided during TAG meeting 4. TAG meeting 4 was convened to discuss issues related to the update to FSAR Sections 2.5.1, 2.5.2, and 2.5.3, including re-evaluation of the seismic source characterization for Cuba and the northern Caribbean region. TAG meeting 4 differed from previous TAG meetings by including members with more specialized knowledge of the tectonics of Cuba, the Caribbean region, and the eastern United States. TAG members for meeting 4 included:

- Prof. Robert Hatcher (University of Tennessee at Knoxville)

- Prof. John Lewis (George Washington University, emeritus)
- Prof. Paul Mann (University of Texas at Austin, currently University of Houston)
- Dr. William McCann (Earth Scientific Consultants)
- Dr. J. Carl Stepp (Earthquake Hazards Solutions)

d) How the experts' opinions were integrated into the development of the final models. Discuss expert opinions and/or suggestions that were left out of the final model and justifications for doing so.

As described above, the TI team developed an initial straw man seismic source model based on information available in the published literature. This initial straw man model and an accompanying questionnaire (Enclosure A) were transmitted to resource experts with specialized knowledge of the region for their review and comment. Based on discussions with, and guidance from, the resource experts regarding the initial straw man seismic source characterization, the TI team performed additional literature review and analysis and critical review of its initial straw man model. This new information was used by the TI team to revise the straw man model and to develop a preliminary seismic source characterization. The TI team then conducted follow-up interviews with some of the resource experts to modify or validate the preliminary seismic source characterization. Following this collection of additional data and information, the TI team conducted additional discussions with TAG reviewers at TAG meetings 1 through 3 to evaluate and finalize the proposed models for use in the PSHA. The TI team was responsible for combining the feedback from resource experts and TAG reviewers with data from the published literature to capture the range of technically defensible interpretations into the final seismic source characterization for Cuba and the northern Caribbean region.

The TI team presented the seismic source characterization, at varying stages of completion, at TAG meetings 1 through 3. The final seismic source characterization implemented in the PSHA was presented at TAG meeting 4 for review and comment. There were few conflicting opinions among resource experts and TAG reviewers involved in this SSHAC Level 2 effort. However, part (e) of this response (below) provides additional discussion of how conflicting opinions among experts were handled.

e) How conflicting opinions among the experts were dealt with

In general, there were few conflicting opinions among resource experts and TAG reviewers involved in this SSHAC Level 2 effort. The decision to model intraplate Cuba as an areal source, however, was a specific focus of interaction between the TI team and some resource experts. Likewise, this decision was an important topic of discussion between the TI team and the TAG, especially at TAG meeting 4.

In the initial straw man source characterization distributed to experts for their comments, Cuba was modeled using two areal sources and no fault sources, except along the modern plate boundary offshore of southernmost Cuba (Enclosure A). These two areal sources included a "West-Central Cuba" zone that covered most of the island and a "Southeast Cuba" zone that was restricted to the area of more concentrated seismicity in the southeastern-most portion of the island near the modern plate boundary (Enclosure A). This two-zone model for Cuba was subsequently revised for use in the FSAR such that intraplate Cuba was modeled as a single areal source with a uniform seismicity rate based on events listed in the project Phase 2 earthquake catalog for that area. The TI team's decision not to retain the separate Southeast Cuba zone is based on the significant distance from the site and that the modern plate boundary south of Cuba is modeled as individual fault sources.

In addition to the single areal source zone for Cuba, the model presented in the FSAR also includes multiple fault sources representing segments of the active North America-Caribbean plate margin south and east of Cuba (FSAR Figure 2.5.2-217). Most resource experts contacted provided little input and feedback regarding these modeling decisions for Cuba, citing lack of personal knowledge and/or the lack of available published information for Cuba.

In his role as a resource expert, Dr. Paul Mann suggested that the TI team consider the Pinar and La Trocha faults in Cuba as potential fault sources in the model. However, he also indicated to the TI team that, to his knowledge, slip rate and paleoseismic data are unavailable for these and other faults in Cuba. Dr. Mann informed the TI team that the Pinar fault is associated with a prominent and linear mountain front, but that he has walked along portions of the Pinar fault and did not observe any recent offsets along this fault zone. Based on this information, the TI team considered including the Pinar and La Trocha faults as seismic sources. Due to the lack of data regarding activity and slip rates for these faults, however, the TI team decided not to model these as independent fault sources.

In email correspondence to the TI team, one expert suggested that the TI team consider: (1) subdividing Cuba into numerous seismogenic zone sources (SZs), as described in Garcia et al. (2003) (FSAR Reference 254) and (2) implementing a smoothed seismicity approach for Cuba as described in Garcia et al. (2008) (FSAR Reference 255). Garcia et al. (2003) (FSAR Reference 254) present seismic hazard maps for Cuba that are based on SZs. Their SZs are elongated, areal seismic sources intended to represent potentially active faults or fault zones. The dimensions of these SZs vary, but are approximately 12–30 miles wide (20–50 km wide), with uncertainty in the boundaries that varies from zone to zone but that ranges from 1–10 km (0.6 to 6 miles) for sources in Cuba. Garcia et al.'s (2003) (FSAR Reference 254) assessments of seismicity rates for their SZs are not based on geologic- or geodetic-based fault slip rates because these data are lacking. Instead, Garcia et al.'s (2003) (FSAR Reference 254) SZs are large enough to envelop sufficient numbers of earthquakes to estimate separate rates of seismicity for each source from the earthquakes observed within that source. Maximum magnitude (Mmax) for their SZs varies from zone to zone and is based on either adding roughly 0.5 magnitude units to the largest observed earthquake in the zone or judgment informed by previous studies.

In all cases, Mmax for their SZs in intraplate Cuba ranges between M 5 and 7. With the exception of three SZs assigned Mmax of M 7, the remaining SZs are assigned only moderate Mmax values that range from M 5 to 6.5. Based on their SZ approach, Garcia et al. (2003) (FSAR Reference 254) present maps of expected levels of ground shaking with a 475-year return period. Garcia et al.'s (2003) (FSAR Reference 254) SZ approach predicts relatively high levels of ground shaking throughout much of southernmost Cuba near the modern plate boundary. In contrast, the "rest of the island is characterized by moderate values that do not represent the possibility of very severe damage at the specified annual probability level" (Garcia et al. 2003, p. 2,588) (FSAR Reference 254).

In a more recent study, Garcia et al. (2008) (FSAR Reference 490) present seismic hazard maps for Cuba that are based on a spatially smoothed seismicity approach, using correlation distances of 18 and 25 miles (30 and 40 km). According to Garcia et al. (2008) (FSAR Reference 490), the rationale for this change in approach is "to avoid drawing seismic sources in a region where the seismogenic structures are not well known" (p. 173) and "to avoid the subjective judgment involved when drawing SZs in a region where [it] is problematic to associate seismicity with tectonic features" (p. 178). Moreover, they state that "since the northern part of the Cuban region lies in an intraplate region and is characterized by a moderate seismicity, the association of earthquakes to faults is problematic and, consequently, the definition of SZs is based, in some cases, on subjective decisions" (p. 174). Garcia et al. (2008) (FSAR Reference 255) compare the results from the smoothed seismicity approach with those based on the Garcia et al. (2003) (FSAR Reference 255) SZ approach. To illustrate the differences between the two approaches, Garcia et al. (2008) (FSAR Reference 255) calculate the residual PGA with a 475-year return period between the smoothed seismicity approach and the SZ approach. The largest differences between the methods are located along the modern plate boundary near Hispaniola and in southernmost Cuba. Relative to the smoothed seismicity approach, the SZ approach yields equivalent or slightly higher values of PGA throughout most of Cuba away from the modern plate boundary, but these differences are "rather limited" (Garcia et al. 2008; p. 192) (FSAR Reference 255).

From this comparison, Garcia et al. (2008) (FSAR Reference 255) conclude that, relative to the smoothed seismicity approach, the SZ approach tends to result in slightly higher PGA values in northwestern Cuba. They indicate that "an improvement of the seismicity data collection would be welcome for a better knowledge of the seismicity in northwestern Cuba" (p. 193). Moreover, they indicate that "although the definition of SZs is positive because it focuses on understanding the regional tectonics, this exercise could be misleading when not supported by data. Consequently, a mixture of the two approaches would probably be the best solution: a seismotectonic approach for the more seismic areas and only seismicity elsewhere" (p. 174). According to Garcia et al. (2008) (FSAR Reference 255), "the northern intraplate region [of Cuba] is related to a moderate to low seismicity" (p. 182). This observation of low to moderate rates of seismicity in northern Cuba is consistent with observations made from the project Phase 2 earthquake catalog, which indicate a higher concentration of earthquakes and higher magnitudes in southernmost Cuba at and near the modern plate boundary. Therefore, the Garcia et al. (2003) (FSAR Reference 254) approach of defining SZs may not be applicable to the moderate-to-low seismicity areas of northern Cuba.

As part of the SSHAC Level 2 process, the TI team considered various modeling approaches for intraplate Cuba, including: (1) a seismogenic zone approach like that described in Garcia et al. (2003) (FSAR Reference 254), (2) the characterization of fault sources in Cuba, and (3) the characterization of a large areal zone or zones, with or without a smoothed seismicity approach. The TI team's decision not to implement an SZ approach was based on the recognition of the scant geologic data and few earthquakes in this region. The TI team's decision was also based on the assessment that the level of detail published on faults in Cuba was insufficient to confidently create SZs for the network of faults in intraplate Cuba and have confidence that the poorly located diffuse seismicity can be associated with a fault-like source or large areal sources. The primary reasons why the TI team did not define individual faults as fault sources are the lack of published slip rate information and the paucity of geologic data that could be used to independently estimate slip rates for fault sources.

Likewise, the TI team considered adopting a smoothed seismicity approach for Cuba as described in Garcia et al. (2008) (FSAR Reference 255). The TI team's decision not to implement the smoothed seismicity approach was based on: (1) the TI team's assessment that a simpler, uniform rate approach is appropriate for Cuba, given that the intent is to quantify seismic hazard at a distant site in southernmost Florida, and (2) the smoothed seismicity approach would isolate the higher rates of seismicity in southeastern Cuba and more distant to the site and could be viewed as a non-conservative modeling assumption.

The decision to model intraplate Cuba in the FSAR as a single areal source zone with a uniform seismicity rate was discussed during TAG meetings 1 through 3. This decision was confirmed by the reviewers at TAG meeting 4. At meeting 4, TAG member Prof. Robert Hatcher suggested that the TI team consider including fault sources for intraplate Cuba away from the modern plate boundary. At that time, Prof. Robert Hatcher indicated that he is neither an expert on source characterization nor an expert on the earthquake geology of Cuba. In the discussions that followed, the TAG at meeting 4 reached consensus that the single areal source approach is the most defensible, given: (1) the lack of knowledge regarding slip rates, geometries, and maximum magnitudes for individual faults in intraplate Cuba, and (2) the fact that this seismic source characterization is intended for use at a site in southern Florida, as opposed to a site in Cuba.

f) How the final models represent the consensus of the informed community

Through use of the SSHAC Level 2 process, the TI team developed a seismic source characterization of Cuba and the northern Caribbean region that is intended for use at the Turkey Point Units 6 & 7 site in southernmost Florida. The development of this characterization is based on literature reviews and interactions with both resource experts and the project TAG. The intent of this process was to represent the center, body, and range of technical interpretations that the larger ITC would have if they were to conduct the study.

There was general agreement among most of the resource experts, the project TAG, and published literature that the SSHAC Level 2 seismic source characterization presented in the FSAR represents the consensus of the ITC, especially with respect to the characterization of fault sources associated with the modern North America-Caribbean plate boundary. However, this seismic source characterization departs from some earlier published studies that quantify seismic hazard in Cuba from sources within and around Cuba. For example, Garcia et al. (2003) (FSAR Reference 254) and Garcia et al. (2008) (FSAR Reference 255) quantify seismic hazards in Cuba using a seismogenic zone approach and a smoothed seismicity approach, respectively.

The TI team's decision to not model individual faults in Cuba as seismic sources was due to a lack of geologic slip rate information. The TI team also did not choose to model faults as narrow SZs, and establish rates by counting seismicity within those zones, similar to the approach used by Garcia et al. (2003) (FSAR Reference 254). For the portions of northern Cuba within the site region and for much of Cuba well beyond the site region there is little geologic information and seismicity with which to characterize fault or SZ sources. Garcia et al. (2008) (FSAR Reference 255) caution that the SZ approach can be misleading in areas of scant geologic data and few earthquakes. They also suggest that the SZ approach is more applicable for "more seismic areas" like southernmost Cuba nearest the modern plate boundary. For southernmost Cuba where the SZ approach may be more applicable according to Garcia et al. (2008) (FSAR Reference 255), the TI team retained a single areal source zone and decided not to model fault or SZ sources due to the significant distance from the site. The TI team's characterization of the modern plate boundary south of Cuba as individual fault sources is in agreement with published literature and expert judgment captured by the SSHAC Level 2 process.

This response is PLANT SPECIFIC.

References:

None

ASSOCIATED COLA REVISIONS:

The following COLA changes are identified as a result of this response:

The text in FSAR Subsection 2.5.2.4.4.3.2.1, third paragraph, will be revised as follows in a future update of the FSAR:

Recent peer-reviewed literature provides support for the assessment of the lack of knowledge regarding the state of fault mapping in Cuba. For example, Cotilla-Rodriguez **et al.** (Reference 321, p. 327) state~~s~~, "...the detailed association between destructive earthquakes and active tectonic features is extremely complex and not known in depth [...] there is not a close correlation of seismic events with individual faults in Cuba." Furthermore, **Cotilla-Rodriguez** et al. (Reference 321, p. 331) state~~s~~, "...most [historical, pre-instrumental earthquakes] have scarce data and do not permit a clear association to a seismic zone. There is no uniform knowledge about the historical seismicity of Cuba." ~~Additionally, recent peer-reviewed seismic hazard studies of Cuba describe a shift from a probabilistic approach that defined individual faults and source zones (Reference 254), to newer studies (Reference 255) performed by many of the same researchers that use spatially smoothed seismicity in place of source zones. The rationale for this shift is, "...to avoid drawing seismic sources in a region where the seismogenic structures are not well known" (Reference 255, p. 173). Moreover, "...since the northern part of the Cuban region lies in an intraplate region and is characterized by a moderate seismicity [sic], the association of earthquakes to faults is problematic and, consequently, the definition of [seismic sources] is based, in some cases, on subjective decisions" (Reference 255, p. 174).~~

Garcia et al. (Reference 254) present seismic hazard maps for Cuba that are based on seismogenic zone (SZ) source zones. Their SZs are narrow, elongated, areal seismic sources intended to represent potentially active faults. Seismicity rates for these "fault-like" SZs are not based on geologic- or geodetic-based fault slip rates because these data do not appear to exist. Instead, Garcia et al.'s (Reference 254) SZs are large enough to envelop sufficient numbers of earthquakes to estimate separate rates of seismicity for each source from the earthquakes observed within

that source. In a subsequent publication, Garcia et al. (Reference 255) compare the results of their earlier SZ approach with those obtained by their implementation of a smoothed seismicity approach to hazard. Relative to the results obtained from their smoothed seismicity approach, Garcia et al. (2008) conclude that the seismotectonic zone approach tends to result in slightly higher PGA values in northwestern Cuba. They indicate that "an improvement of the seismicity data collection would be welcome for a better knowledge of the seismicity in northwestern Cuba" (Reference 255, p. 193). Moreover, they indicate that "although the definition of SZs is positive because it focuses on understanding the regional tectonics, this exercise could be misleading when not supported by data. Consequently, a mixture of the two approaches would probably be the best solution: a seismotectonic approach for the more seismic areas and only seismicity elsewhere" (Reference 255, p. 174). According to Garcia et al. (2008) (Reference 255, p. 182), "the northern intraplate region [of Cuba] is related to a moderate to low seismicity." This observation of low to moderate rates of seismicity in northern Cuba is consistent with observations made from the project Phase 2 earthquake catalog, which indicates a higher concentration of earthquakes and higher magnitudes in southernmost Cuba at and near the modern plate boundary relative to the rest of the island. Therefore, Garcia et al.'s (Reference 254) seismotectonic zone approach may not be applicable to the moderate to low seismicity areas of northern Cuba.

ASSOCIATED ENCLOSURES:

Enclosure A – SSHAC Caribbean Questionnaire, dated May 19, 2008

Enclosure A

SSHAC Caribbean Questionnaire

3 Pages (including cover)

PREAMBLE:

As a preliminary "straw man" model, we have identified the following six seismic sources in the northern Caribbean region as relevant to seismic hazard in southern Florida (see attached figure):

(1) West-central Cuba (area source)

(2) Southeastern Cuba (area source)

(3) Oriente fault zone west, between Cuba and the Cayman spreading center

(4) Oriente fault zone east, directly south of Cuba

(5) Septentrional fault, between the northern Dominican Republic and eastern Cuba

(6) North Hispaniola thrust fault, north of the Dominican Republic

(7) Swan Island fault zone, west of the Cayman spreading center

(8) Walton fault zone, between Jamaica and the Cayman spreading center

(9) Plantain Garden-Enriquillo fault zone, between southern Dominican Republic and Jamaica

It is our assessment that faults in Cuba are not sufficiently characterized to warrant fault (line) sources. The source zone boundaries for Cuba are defined by tectonic landforms, geology, and seismicity (see figure).

QUESTIONS:

1) Are all possible sources of magnitude 7 or greater events within ~1,000 km of south Florida included? If not, what are other potential sources?

2) For each fault source, in your opinion:

a) What is the maximum magnitude the fault is capable of generating?

b) What is the maximum seismogenic depth of each fault?

c) Do you have or know of any estimates of recurrence times for large ($M \geq 7$) events on any or all of these faults?

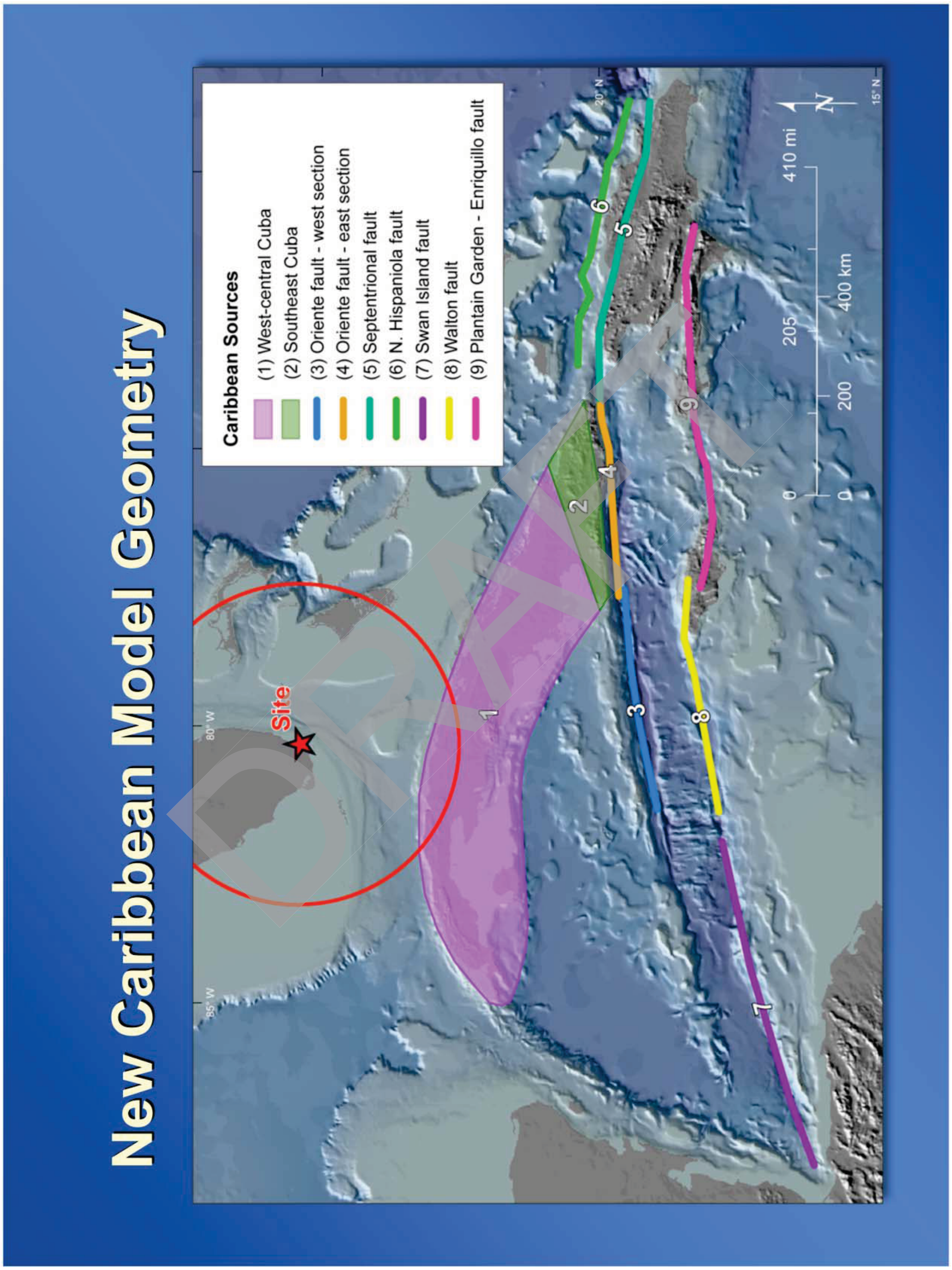
d) What is the magnitude distribution of large events on any or all of these faults?

e) What is the best estimate of slip rate and seismic coupling on these faults?

3) In regards to seismic hazards on the island of Cuba:

a) Do you know of any individuals of groups that are studying and/or have published reports on active faulting on the island of Cuba? If so please provide names and references.

b) Do you have any knowledge or opinions regarding seismic hazards on Cuba?


New Caribbean Model Geometry
Caribbean Sources
(1) West-central Cuba
(2) Southeast Cuba
(3) Oriente fault - west section
(4) Oriente fault - east section
(5) Septentrional fault
(6) N. Hispaniola fault
(7) Swan Island fault
(8) Walton fault
(9) Plantain Garden - Enriquillo fault
Site
0 205 410 mi
0 200 400 km

NRC RAI Letter No. PTN-RAI-LTR-037

SRP Section: 02.05.02 - Vibratory Ground Motion

Question for Geosciences and Geotechnical Engineering Branch 1 (RGS1)

NRC RAI Number: 02.05.02-5 (eRAI 5896)

FSAR Subsection 2.5.2.1.3.1 states that **M**w was used as the uniform magnitude measure in Phase II (Caribbean region) earthquake catalog development efforts. Phase I earthquake catalog (EPRI updates), on the other hand, uses mb as the uniform magnitude measure. In accordance with NUREG-0800, Standard Review Plan, Chapter 2.5.2, "Vibratory Ground Motion," and Regulatory Guide (RG) 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion", please explain the rationale for selecting **M**w as the uniform magnitude measure for the Caribbean earthquake catalog rather than mb. Discuss what impact, if any, this choice had on the number of earthquakes listed in the Caribbean earthquake catalog. Were there any earthquakes with mb of 3.0 (or perhaps larger) that did not make the **M**w >= 3.0 cut used in Phase II catalog development?

FPL RESPONSE:

Introduction

The rationale for selecting moment magnitude ($\mathbf{M}_w$) as the uniform magnitude scale for the Phase 2 earthquake catalog, as is discussed below, is because $\mathbf{M}_w$ gives a better measure of the energy released for a greater range of magnitudes, including the very large earthquakes occurring in the Caribbean. The total number of earthquakes of body-wave magnitude (m_b) greater than or equal to 3.0 or of $\mathbf{M}_w$ greater than or equal to 3.0 in the Caribbean earthquake catalog depends on details of magnitude conversion among many different magnitude scales given in many different parent catalogs. Using the FSAR magnitude conversion process for earthquakes in the Caribbean region, no earthquakes of m_b 3.0 or larger were excluded by adopting $\mathbf{M}_w$ to characterize the size of Caribbean earthquakes. Alternative magnitude conversion schemes could lead to more or fewer earthquakes of magnitude 3.0 or greater for either choice of magnitude, m_b or $\mathbf{M}_w$. As an example of this, magnitude scale conversion relations used for the recently published central and eastern United States seismic source characterization (CEUS SSC) model (EPRI et al., 2012) are found to lead to more earthquakes of $\mathbf{M}_w$ greater than or equal to 3.0 for the Caribbean catalog but fewer earthquakes of $\mathbf{M}_w$ 5.0 and greater. The CEUS SSC magnitude conversion scheme, although specific to the CEUS and not presented here as applicable to the Caribbean, is investigated following a request from the NRC staff. The $\mathbf{M}_w$ scale that was used for the FSAR remains the preferred uniform magnitude scale

Rationale for Selecting $\mathbf{M}_w$ as the Uniform Magnitude Scale for the Phase 2 Catalog

Seismologists performing current conventional probabilistic seismic hazard analyses, as well as development of ground motion prediction equations [e.g., the 2008 USGS seismic hazard maps (FSAR Reference 300) and the 2008 Next Generation of Ground-Motion Attenuation models (Chiou et al., 2008)], prefer the use of $\mathbf{M}_w$ over other magnitude scales, including m_b scale, because it is a more direct indication of the seismic energy associated with an earthquake, particularly for both shallow and deep focus earthquakes with large fault dimensions and/or complex rupture mechanisms that occur in the Caribbean. The m_b

magnitude scale saturates, or is progressively insensitive to energy release beginning with magnitudes greater than about 5.0 due to the difference in the period and the seismic-wave type used to determine the magnitude size. While the magnitudes of earthquakes within the CEUS region have generally and traditionally been adequately represented by the m_b scale, the largest events in the Caribbean are not. This rationale for selecting moment magnitude was the basis for its use in developing the Phase 2 earthquake catalog.

Also, the update of the Phase 1 earthquake catalog was constrained to maintain the magnitude scale in m_b because both the EPRI-SOG seismicity catalog and recurrence characterization of the EPRI-SOG seismic sources already used the m_b scale.

The SRP [NUREG-0800] Section 2.5.2 and RG 1.206 specify that the earthquake catalog should include all earthquakes having Modified Mercalli Intensity (MMI) greater than or equal to IV or magnitude greater than or equal to 3.0 that have been reported within 320 km (200 miles) of the site. Large earthquakes outside of this area that would impact the SSE (in NUREG-0800) or the GMRS (in RG 1.206) should be reported. The Phase 1 and Phase 2 catalogs were developed to meet these requirements. The magnitude scale is not explicitly specified in these requirements, although, both documents later state that "magnitude designations such as m_b, M_L, M_s, M_w should be identified." There is no specification of the magnitude scale for the earthquake catalog given in RG 1.208.

The magnitude conversion relations between the moment magnitude scale and many other scales, such as m_b scale, show that the magnitudes less than about 4.5 (very short fault lengths) are assumed to be numerically equivalent to $\mathbf{M}_w$ and that the conversion relations are nonlinear at large magnitude values to reflect the saturation of some magnitude scales, specifically, m_b scale (Heaton et al., 1986). Therefore, in the development of the Phase 2 catalog, all small earthquakes of any magnitude scale less than 4.5 were assumed to be numerically equivalent to $\mathbf{M}_w$. As a result of this assumption for small events, the selected threshold magnitude scale $\mathbf{M}_w \geq 3.0$ for the Phase 2 earthquake catalog and m_b (or (E)mb) ≥ 3.0 for the Phase 1 earthquake catalog presents no inconsistency in terms of minimum size or minimum seismic energy of a given earthquake considered in the two catalogs. Therefore, under the process used to develop moment magnitudes for the Phase 2 catalog, all earthquakes of magnitude 3.0 and larger, regardless of characterization as moment magnitude or body-wave magnitude, are included in both Phase 1 and Phase 2 earthquake catalogs, and there is no impact on the number of earthquakes in the two earthquake catalogs associated with the different magnitude scales used in the two earthquake catalogs.

During a public meeting conference call with the NRC, there was a brief discussion on the matter of characterization of magnitudes for the Phase 2 catalog of earthquakes and the question of the correlation between m_b, and $\mathbf{M}_w$ was again raised with specific reference to new work on correlating these two scales as part of the recently completed study on seismic sources in the CEUS region. Both topics are discussed below.

Details of the FSAR Magnitude Conversion Process for Earthquakes in the Caribbean Region

The differences that exist among published seismotectonic region-specific magnitude conversion relations make the selection of appropriate relations for a given region important and, if such relations are not available, difficult. Seismic network operational histories are such that catalogs of events in a given region contain earthquakes located with different location programs. These programs use different station configurations and different crustal-velocity models with magnitudes calculated using different calibration. Therefore, conversions of diverse best estimates of magnitudes determined in different regions to a given uniform magnitude scale may show notable differences, dependent on tectonic setting (FSAR Reference 240).

In contrast to the CEUS tectonic environment considered for the Phase 1 earthquake catalog, the Caribbean region with its 1) different tectonic environments (e.g., plate boundary and near plate boundary shallow crustal faults and subduction zones), 2) different magnitude scales, and 3) different seismic network instrumentation and operational histories, required consideration of different global or regional magnitude conversion relationships for the Phase 2 earthquake catalog development.

In order to contrast the nature of earthquakes from the Caribbean region to the CEUS region, a magnitude conversion process was developed to consider the various magnitude scales used in the original source catalogs considered in the development of the Phase 2 earthquake catalog, and these various magnitude scales were converted to $\mathbf{M}_w$.

Among the various earthquake source catalogs used for compiling the Phase 2 catalog, there were 19 different magnitude types that needed to be converted to moment magnitude. These different magnitude scale conversions are discussed further below, but as discussed in the FSAR, the process was based on the following simplified process. First, magnitudes of any type less than 4.5, with reference to the Heaton et al. (1986) correlation plot described below, were assumed to be equivalent to $\mathbf{M}_w$ directly. For magnitudes of any type of 4.5 and larger, the following simplified process was followed:

- Moment magnitudes were, of course, already moment magnitudes, so no conversion was necessary.
- Surface-wave magnitudes M_s were converted to $\mathbf{M}_w$ considering the Ekstrom and Dziewonski (1988) relations (FSAR Reference 240) and the Kanamori (1977) relation (FSAR Reference 269).
- Body-wave magnitudes m_b were converted to M_s using the Garcia et al. (2003) relation (FSAR Reference 254), and then the above process of conversion from M_s to $\mathbf{M}_w$ was followed.
- Intensity-based magnitudes in the Cuba catalog were considered equivalent to M_s magnitudes (FSAR Reference 254) and then the above process of conversion from M_s to $\mathbf{M}_w$ was followed.

- All other magnitude types were considered equivalent to m_b and then the above process to convert from m_b to M_s to $\mathbf{M}_w$ was followed.

The Heaton et al. (1986) magnitude correlations, following similar work by Kanamori (1983), plot various magnitude scales relative to $\mathbf{M}_w$ for a seismotectonic setting [i.e., western US region or other active plate boundary regions] more similar to the Caribbean than the CEUS region, allowing conversion of Caribbean earthquake magnitudes in other scales into moment magnitude. These magnitude-scale plots graphically show relationships between the moment magnitude scale and several other magnitude scales, applicable magnitude ranges, and how they are nonlinear to reflect the saturation of some of the magnitude scales.

Following is a detailed summary of the approach that was used to provide specific magnitude scale conversions in order to estimate $\mathbf{M}_w$ for the Phase 2 earthquake catalog.

<u>*Specific Magnitude Scales Used in the Phase 2 Earthquake Catalog*</u>

The Phase 2 earthquake catalog developed for the Caribbean region contains 19 different measures of size for earthquakes that have occurred in notably different tectonic regions as compared to the CEUS region.

- Moment magnitudes ($\mathbf{M}_w$)

The moment magnitude scale, which provides an estimation of total energy released in an earthquake, was the preferred magnitude scale in the Caribbean Phase 2 catalog under the rationale given above. Therefore, for all earthquakes in Phase 2 earthquake catalog that were originally reported in the $\mathbf{M}_w$ magnitude scale, these $\mathbf{M}_w$ values were directly included in the catalog.

- Surface-wave magnitudes (M_s)

The surface-wave magnitude (M_s) scale is commonly used for shallow events larger than M_s 5.0 (Kanamori, 1983; Mueller et al., 1997) which, by definition, are earthquakes where surface waves may have been generated. Since the surface-wave magnitude gives the poorest results for small earthquakes or those deep or at intermediate depth, there are relatively few earthquakes of this type of magnitude scale in the Phase 2 catalog. For those reported earthquakes with M_s less than 4.5, these M_s magnitude scales were considered to be numerically equivalent to $\mathbf{M}_w$. For M_s values equal to or greater than 4.5, the 1988 global surface-wave magnitude to average seismic moment (M_o) conversion relation of Ekstrom and Dziewonski (FSAR Reference 240) and then the seismic moment to moment magnitude conversion relation of Kanamori (1977) (FSAR Reference 269) was used to convert surface-wave magnitudes to $\mathbf{M}_w$ in the Phase 2 earthquake catalog development.

- Body-wave magnitudes (m_b)

The Heaton et al. (1986) m_b-$\mathbf{M}_w$ magnitude correlation plot suggests that body-wave magnitude (m_b) less than about 4.5 are consistent with $\mathbf{M}_w$, and thus, they were assumed to be numerically equivalent to $\mathbf{M}_w$ for the Caribbean region. This consideration is also consistent with USGS Open File Report 97-464 (Mueller et al., 1997) for body-wave magnitudes in the western US region.

As may also be seen in the Heaton et al. (1986) magnitude correlation plot, there is an issue of saturation of the m_b scale beginning with magnitudes larger than about 5.0. The m_b scale stops increasing with increasing earthquake size at about magnitude 6.4 corresponding to a moment magnitude of about 7.5. Therefore, for m_b magnitudes of 4.5 and larger the magnitude conversion relation for m_b to M_s from the Garcia et al. study (FSAR Reference 254) was used, and then the M_s to $\mathbf{M}_w$ scaling, discussed above, was applied for these larger m_b values in the Caribbean Phase 2 catalog.

- Intensity-based magnitudes (M_I and M_k) in the Cuba catalog

The majority of earthquakes in the Cuba catalog have an estimate of intensity-based magnitude, M_I and M_k, as discussed in the Garcia et al. study (FSAR Reference 254). Both of these magnitude types are considered to be correlated to coda or duration magnitudes [see below]. For the FSAR, where there were no region-specific magnitude conversion relations for intensity-based magnitudes, as well as none for coda- or duration-magnitudes, to $\mathbf{M}_w$, these M_I and M_k magnitudes were taken as equivalent to $\mathbf{M}_w$ for magnitudes less than 4.5, following Heaton et al. (1986), and equivalent to M_s for magnitudes 4.5 and larger, following the Garcia et al. study (FSAR Reference 254). The M_s magnitude scale values were then converted to $\mathbf{M}_w$, as described above.

- Local, Duration, and Coda magnitudes (M_L, M_d, DR and M_c)

The local magnitude (M_L), duration magnitude (M_d) [sometimes designated “DR” or “M_D” in the National Geophysical Data Center database (NGDC), see FSAR 2.5.2] and coda magnitude (M_c) are three types of measurements for earthquakes that are used to determine the local magnitudes and are conventionally considered equivalent. The instrumental M_c and M_d are typically reported for small and moderate magnitude earthquakes less than about 6.0, while it is found that M_L is also reported for larger earthquakes up to about 7.0. These three magnitude scales in the Phase 2 earthquake catalog, which are provided by different seismic networks with varying operational histories and different station calibrations, are comparable on average to $\mathbf{M}_w$ for magnitudes less than 4.5 in the Phase 2 earthquake catalog (Mueller et al., 1997, Heaton et al., 1986). Nuttli and Herrmann (1982) report that M_L and m_b values are nearly equal in the western United States. Given the common equivalence of M_L, M_d, and M_c magnitudes, and the Nuttli and Herrmann observation, these magnitudes when larger than 4.5 are considered equivalent to m_b and converted to $\mathbf{M}_w$, as detailed above.

- Broad-band body-wave magnitudes (m_B).

There are also some earthquakes larger than 6.0 in the Phase 2 catalog that are designated broad-band body-wave magnitude (m_B). The main advantage of m_B magnitude scale rather than M_s is its applicability to both shallow and deep earthquakes. These m_B magnitude-scale events in the Phase 2 catalog are considered to be equivalent to M_s over the applicable magnitude range of events between about 6.0 and 8.0 (Heaton et al., 1986; Kanamori, 1983), and then converted to $\mathbf{M}_w$, as described above.

- Intensity-based magnitudes ($M(I_o)$), not in the Cuba catalog

These magnitudes are estimated from maximum intensity (I_o) using the Gutenberg-Richter (1956) relationship, which correlates to local magnitude M_L. Therefore, these earthquakes are converted from M_L to $\mathbf{M}_w$, as described above.

- Equivalent local and coda-duration magnitudes (m_l, m_2, fm, xm, MA, and m_t)

The Puerto Rico Seismic Network [PRSN] earthquake catalog, which locally collects the events in the Caribbean region, has recorded earthquakes whose magnitudes are determined using different local magnitude relations (m_1 and xm), as well as different magnitude-coda duration relations (m_2 and fm) – the xm and fm magnitudes are determined using the earthquake location program Hypoellipse (Lahr, 1999). An event less than magnitude 3.0, excluded from the Phase 2 catalog, is reported as a type MA magnitude, attributed to PRSN – it may be expected that this small magnitude is one of or an average of the other PRSN magnitudes. Also reported in the PRSN catalog are earthquakes from the Jamaica Seismic Network [JSN], which determines average coda magnitudes (m_t) based on the regression between standard m_b and log of the signal duration (Wiggins-Grandison, 2001).

As for local, duration, and coda magnitudes described above when greater than 4.5 these magnitudes are considered equivalent to m_b and are converted to $\mathbf{M}_w$.

- Unspecified magnitudes (nk and MG)

Finally, there are some earthquakes in the Phase 2 catalog with unknown magnitude scale labeled "nk" or " " (e.g., the computational method was unknown and could not be determined from published sources), as well as an unspecified magnitude scale labeled "MG" (e.g., magnitudes either have been reported by the contributor without listing the type [e.g., "MG 3.5"] or have been computed using procedures, which are not defined by the magnitude types routinely reported). These types of earthquakes were considered to be equivalent to m_b for small ($3 \leq \mathbf{M}_w < 4.5$) and moderate ($4.5 \leq \mathbf{M}_w < 6$) earthquake magnitudes in the Phase 2 catalog. Lamarre and Shah (1988) have plotted the unspecified magnitude scales versus M_L for the NGDC database used in the Phase 2 earthquake catalog, and have indicated that it is very closely approximated by the M_L and m_b for earthquakes in magnitude range less than about 5.0. Taken as equivalent to m_b, these magnitudes were converted to $\mathbf{M}_w$, as described above.

Since the types of data used in determination of these magnitude scales are very different from region to region (e.g., observational errors and intrinsic variations in source properties), it is important to establish tectonically-similar regional magnitude scale correlations (Kanamori, 1983). Therefore, it should be emphasized that this magnitude conversion process was not incorporated into Phase 1 earthquake catalog that includes all events in the CEUS region with a notably different tectonic environment as compared to the Caribbean region (FSAR 2.5.1).

Application of CEUS-SSC Magnitude Conversion Relationships to the Phase 2 Catalog

While recognizing that, according to the findings of the CEUS SSC study (EPRI et al., 2012), the correlation between m_b and $\mathbf{M}_w$ is region-dependent, and that nothing in the CEUS SSC study addresses earthquakes in the Cuba and Caribbean region, an analysis was performed to investigate the hypothetical effect of the use of CEUS-SSC magnitude conversions (EPRI et al., 2012) on the number of earthquakes listed in the Phase 2 earthquake catalog.

In this section, an alternative methodology of magnitude conversion is considered using the magnitude conversion relations from the CEUS SSC report (EPRI et al., 2012), as proposed by the NRC staff.

Magnitude Conversion Using CEUS SSC Relations

In order to consider the impact on the Phase 2 earthquake catalog of using the CEUS SSC magnitude conversion relationships from CEUS SSC report (EPRI et al. 2012), there are two primary elements that need to be addressed. First, the 19 different magnitude types of the original earthquake catalogs have to be correlated to the magnitude conversion relationships available in the CEUS SSC report. Second, given the possibility that some of the CEUS SSC magnitude conversions could result in larger values of moment magnitude than obtained originally in the FSAR Phase 2 catalog, it is necessary to consider the smaller magnitude events that had been filtered in the development of the final Phase 2 earthquake catalog. This addresses the fundamental issue raised originally in RAI 02.05.02-5.

Given that the final Phase 2 earthquake catalog has been developed to include only independent events, it is necessary to perform cluster analysis on any additional smaller events that may arise for use of the CEUS SSC correlations. Therefore, the steps required for consideration of the CEUS SSC magnitude conversion relations are the following:

- Bring the smaller magnitude events back into the Phase 2 earthquake catalog that had been previously filtered out to obtain the final FSAR catalog of $\mathbf{M}_w$ 3.0 and greater.
- Perform de-clustering analysis to identify and remove dependent events among the added-in smaller magnitude events.
- Convert all magnitudes to moment magnitudes using the CEUS SSC relations.

These steps result in a ***modified*** Phase 2 earthquake catalog, where the CEUS SSC-derived moment magnitudes can be compared to those of the FSAR Phase 2 catalog.

Smaller Magnitude Events

As will be shown below, in order to capture any earthquake of moment magnitude 3 or greater converted using the CEUS SSC magnitude conversion equations, it is necessary to consider magnitudes of any type greater than 2.0. One exception could have been for earthquakes whose $\mathbf{M}_w$ would be developed from a very small M_s value. However, the smallest M_s magnitude in the preferred source catalogs from which a modified Phase 2 catalog $\mathbf{M}_w$ would be developed, is M_s 2.1, corresponding to a CEUS SSC $\mathbf{M}_w$ 3.5 (see below), Therefore, in practice the smallest M_s magnitude has been considered in this response.

De-clustering Analysis of the Smaller Magnitude Events

In order to consistently add any additional small earthquakes [2.0 ≤ magnitude < 3.0] to the FSAR Phase 2 catalog, dependent events (foreshocks and aftershocks) must be identified within this magnitude range and excluded from the modified Phase 2 earthquake catalog. For the purpose of de-clustering, the magnitudes of any type of the additional small events were considered equivalent to $\mathbf{M}_w$, similar to the methodology considered in the FSAR. As described in the FSAR, the Gardner and Knopoff (1974) de-clustering method (FSAR Reference 256) was used to identify dependent events among the added-in small magnitude events, which were then removed from the originally modified catalog.

Magnitude Conversion Using CEUS SSC Relations

In order to apply the limited number of types of CEUS SSC magnitude conversion relations, it is necessary to defensibly correlate the 19 magnitude types of the original Phase 2 catalog with the six magnitude types considered in the CEUS SSC report. Given the descriptions of the original 19 magnitude types above, Table 1 indicates the correlation of magnitude types used in this analysis.

Table 1. Correlation of the Original Magnitude Types to those in the CEUS SSC Report (EPRI et al., 2012)

Original Magnitude Types	**Corresponding CEUS SSC Magnitude Type**
m_b, MG, nk or {blank}	m_b
M_c, fm, MA, M_l, M_k, m_t, m_2	M_c
M_d, DR	M_d
M_L, xm, m_1, Io	M_L
M_s, m_B	M_s
$\mathbf{M}_w$	$\mathbf{M}_w$

1) <u>m_b-$\mathbf{M}_w$ magnitude conversion</u>

Using the m_b-$\mathbf{M}_w$ magnitude conversion from CEUS SSC report (EPRI et al., 2012, Table 3.3-1 in Chapter 3) – as specified for midcontinent, exclusive of the northeast region and Canada, and exclusive of recordings from the Geological Survey of Canada – to convert body-wave magnitudes in the Phase 2 earthquake catalog to moment magnitudes:

$$\mathbf{M}_w = m_b - 0.316 \quad (1)$$

leads to a smaller estimate of moment magnitude than considered in the FSAR – see Figure 1. For example, if the CEUS-SSC magnitude conversion relations had been considered for the Phase 2 catalog, the moment magnitude equivalent to m_b 3.0 would be about $\mathbf{M}_w$ 2.7, instead of the $\mathbf{M}_w$ 3.0 in the FSAR.

2) (M_c, M_d, M_L)-$\mathbf{M}_w$ magnitude conversion

The CEUS SSC report (EPRI et al., 2012) (M_c, M_d, M_L)-$\mathbf{M}_w$ magnitude conversion equation is:

$$\mathbf{M}_w = 0.762\,[M_c, M_d, M_L] + 0.869 \qquad (2)$$

Figure 1 indicates that for about $\mathbf{M}_w$ 3.5 and greater, the CEUS SSC leads to smaller converted $\mathbf{M}_w$ magnitudes, notably so for the largest magnitudes. For $\mathbf{M}_w$ less than about 3.5 the CEUS SSC magnitude conversions lead to slightly larger $\mathbf{M}_w$ magnitudes. Further, considering the intent of presenting the Phase 2 catalog as $\mathbf{M}_w$ 3.0 and greater, the CEUS SSC magnitude conversions would add some additional events which the FSAR catalog would have considered $\mathbf{M}_w$ 2.8 to 3.0.

3) M_s- $\mathbf{M}_w$ magnitude conversion

Using the quadratic M_s- $\mathbf{M}_w$ magnitude conversion from CEUS SSC report (EPRI et al., 2012),

$$\mathbf{M}_w = 2.654+0.334\,M_s+0.04\,M_s{*}\,M_s \qquad (3)$$

leads to very similar estimates of moment magnitude for earthquakes larger than 4.5 as those that were considered in the FSAR (FSAR 2.5.2) – see Figure 1. For the relatively few events with M_s less than 4.5 in the Phase 2 catalog, the CEUS SSC magnitude conversion leads to larger $\mathbf{M}_w$ magnitudes than the conversion assumption of equivalence in the FSAR.

Conclusions

Using the FSAR magnitude conversion process for earthquakes in the Caribbean region, no earthquakes of m_b 3.0 or larger were excluded.

The impact on the number of Phase 2 catalog earthquakes of $\mathbf{M}_w$ 3.0 and greater, considering the CEUS SSC magnitude scale conversion relations in lieu of the relations used in the FSAR, is summarized in Table 2. The number of $\mathbf{M}_w$ 3.0 and greater events would increase from 8747 to 9212 when using the CEUS SSC relations. The number of $\mathbf{M}_w$ 5.0 and greater would decrease from 787 events to 552 events. Figure 1 graphically presents the related conclusion, that considering the CEUS SSC magnitude scale conversion relations, there would be an increase in the number of smallest magnitude events, while there would be an equivalence or decrease in magnitude for all events of FSAR $\mathbf{M}_w$ 4.5 and greater.

Table 2. Comparison of the Binned Seismicity for the Phase 2 Catalog Considering Moment Magnitudes as Determined in the FSAR as Compared to Application of the CEUS SSC (EPRI et al., 2012) Magnitude Conversion Relations.

Magnitude Range	Number of Events: FSAR	Number of Events: CEUS SSC
$3.0 \leq \mathbf{M}_w < 4.0$	5815	7150
$4.0 \leq \mathbf{M}_w < 5.0$	2145	1510
$5.0 \leq \mathbf{M}_w < 6.0$	541	333
$6.0 \leq \mathbf{M}_w < 7.0$	167	159
$7.0 \leq \mathbf{M}_w < 8.0$	73	56
$8.0 \leq \mathbf{M}_w$	6	4
$3.0 \leq \mathbf{M}_w$	**8747**	**9212**
$5.0 \leq \mathbf{M}_w$	**787**	**552**

The CEUS SSC magnitude conversion scheme, although specific to the CEUS and not presented here as applicable to the Caribbean, is investigated following a suggestion from the NRC staff. The $\mathbf{M}_w$ scale that was used for the FSAR remains the preferred uniform magnitude scale.

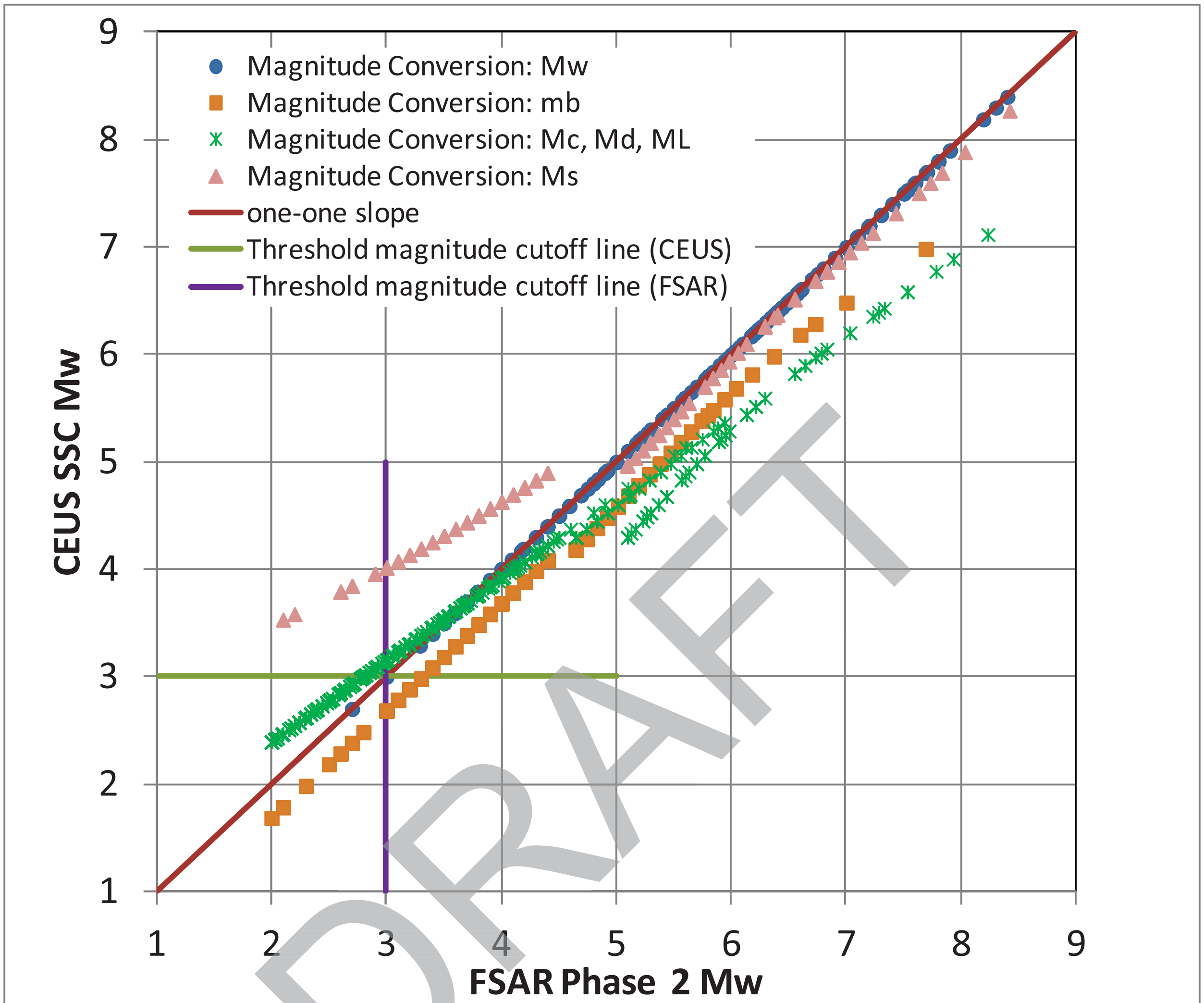


Figure 1. Comparison of converted magnitudes for the complete modified Phase 2 catalog: FSAR vs. CEUS SSC (EPRI et al., 2012). This figure represents the $\mathbf{M}_w$ correlation among 10,747 events.

This response is PLANT SPECIFIC.

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ASSOCIATED COLA REVISIONS:

The entire FSAR subsection 2.5.2.1.3.1 should be replaced with the following new text.

2.5.2.1.3.1 Uniform Magnitude M_w

In the Phase 2 earthquake catalog, Mw was used as the unifying magnitude because it is the most commonly used magnitude in recent seismic hazard studies.

Converting Various Magnitude Scales to Mw

Various magnitude scales may be available for a given event. Each available magnitude was considered in the evaluation of Mw for that event. If an Mw was available, it was adopted directly. Other magnitudes were converted to estimates of Mw using the Equation 2.5.2-8 (Reference 240).

Global average relationships between MS and log M0 (logarithm of the seismic moment) were used in which the independent variable is log M0 based on the assumption that the slope of the regression is 1 for small and 2/3 for large values of M0 (Reference 240). The following global log M0-MS relation was used to convert surface-wave magnitude (MS) to seismic moment (M0) for all events:

logM0 = 19.24 + MS   MS < 5.3   Equation 2.5.2-8
logM0 30.20 √92.45 11.4Ms   5.3 ≤ Ms ≤ 6.8
logM0 = 16.14 + 1.5MS   MS > 6.8

Moment magnitudes were estimated from seismic moment for all events as a linear transformation of the logarithm of the seismic moment, M0, given by (Reference 269):

Mw = (2/3) log M0 – 10.7   Equation 2.5.2-9

in which M0 is in dyne-cm units (10-7 Nm).

A new linear relationship to compute MS from mb, valid in the interval 4.0 < mb < 6.0 and 3.1 < MS < 6.7, was applied by the following linear regression (Reference 254):

MS = 1.37 mb - 2.34   Equation 2.5.2-10

In this section, the rationale for selecting moment magnitude (M_w) as the uniform magnitude scale for the Phase 2 earthquake catalog is discussed and the magnitude conversion process adopted for all events in the Cuba and Caribbean Phase 2 earthquake catalog is described in detail.

Rationale for Selecting M_w as the Uniform Magnitude Scale for the Phase 2 Catalog

Seismologists performing current conventional probabilistic seismic hazard analyses, as well as development of ground motion prediction equations (e.g., References 300 and 344), prefer the use of M_w over other magnitude scales, including m_b scale, because it is a more direct indication of the seismic energy associated with an earthquake, particularly for both shallow and deep focus earthquakes with large fault dimensions and/or complex rupture mechanisms that occur in the Caribbean. The m_b magnitude scale saturates, or is progressively insensitive to energy release beginning with magnitudes greater than about 5.0 due to the difference in the period and the seismic-wave type used to determine the magnitude size. While the magnitudes of earthquakes within the CEUS region have generally and traditionally been adequately represented by the m_b scale, the largest events in the Caribbean are not. This rationale for selecting moment magnitude was the basis for its use in developing the Phase 2 earthquake catalog.

Also, the update of the Phase 1 earthquake catalog, as discussed in subsection 2.5.2.1.2, was constrained to maintain the magnitude scale in m_b because both the EPRI-SOG seismicity catalog and recurrence characterization of the EPRI-SOG seismic sources use the m_b scale.

The SRP [NUREG-0800] Section 2.5.2 and RG 1.206 specify that the earthquake catalog should include all earthquakes having Modified Mercalli Intensity (MMI) greater than or equal to IV or magnitude greater than or equal to 3.0 that have been reported within 320 km (200 miles) of the site. Large earthquakes outside of this area that would impact the SSE (in NUREG-0800) or the GMRS (in RG 1.206) should be reported. The Phase 1 and Phase 2 catalogs were developed to meet these requirements. The magnitude scale is not explicitly specified in these requirements, although, both documents later state that "magnitude designations such as m_b, M_L, M_s, M_w should be identified." There is no specification of the magnitude scale for the earthquake catalog given in RG 1.208.

The magnitude conversion relations between the moment magnitude scale and many other scales, such as m_b scale, show that the magnitudes less than about 4.5 (very short fault lengths) are assumed to be numerically equivalent to M_w and that the conversion relations are nonlinear at large magnitude values to reflect the saturation of some magnitude scales, specifically, m_b scale (Reference 346). Therefore, in the development of the Phase 2 catalog, all small earthquakes of any magnitude scale less than 4.5 were assumed to be numerically equivalent to M_w. As a result of this assumption for small events, the selected threshold magnitude scale $M_w \geq 3.0$ for the Phase 2 earthquake catalog and m_b (or (E)mb) ≥ 3.0 for the Phase 1 earthquake catalog presents no inconsistency in terms of minimum size or minimum seismic energy of a given earthquake considered in the two catalogs. Therefore, under the process used to develop moment magnitudes for the Phase 2 catalog, all earthquakes of magnitude 3.0 and larger, regardless of characterization as moment magnitude or body-wave magnitude, are included in both Phase 1 and Phase 2 earthquake catalogs, and there is no impact on the number of earthquakes in the two

earthquake catalogs associated with the different magnitude scales used in the two earthquake catalogs.

Magnitude Conversion Process for Earthquakes in the Caribbean Region

The differences that exist among published seismotectonic region-specific magnitude conversion relations make the selection of appropriate relations for a given region important and, if such relations are not available, difficult. Seismic network operational histories are such that catalogs of events in a given region contain earthquakes located with different location programs. These programs use different station configurations and different crustal-velocity models with magnitudes calculated using different calibration. Therefore, conversions of diverse best estimates of magnitudes determined in different regions to a given uniform magnitude scale may show notable differences, dependent on tectonic setting (Reference 240).

In contrast to the CEUS tectonic environment considered for the Phase 1 earthquake catalog, the Caribbean region with its 1) different tectonic environments (e.g., plate boundary and near plate boundary shallow crustal faults and subduction zones), 2) different magnitude scales, and 3) different seismic network instrumentation and operational histories, required consideration of different global or regional magnitude conversion relationships for the Phase 2 earthquake catalog development.

In order to contrast the nature of earthquakes from the Caribbean region to the CEUS region, a magnitude conversion process was developed to consider the various magnitude scales used in the original source catalogs considered in the development of the Phase 2 earthquake catalog, and these various magnitude scales were converted to M_w.

Among the various earthquake source catalogs used for compiling the Phase 2 catalog, there were 19 different magnitude types that needed to be converted to moment magnitude. These different magnitude scale conversions are discussed further below based on the following simplified process. First, magnitudes of any type less than 4.5, with reference to the Heaton et al. (Reference 346) correlation plot described below, were assumed to be equivalent to M_w directly. For magnitudes of any type of 4.5 and larger, the following simplified process was followed:

- **Moment magnitudes were, of course, already moment magnitudes, so no conversion was necessary.**
- **Surface-wave magnitudes M_s were converted to M_w considering the Ekstrom and Dziewonski relations (Reference 240) and the Kanamori relation (Reference 269).**
- **Body-wave magnitudes m_b were converted to M_s considering the Garcia et al. relation (Reference 254), and then the above process of conversion from M_s to M_w was followed.**

- **Intensity-based magnitudes in the Cuba catalog were considered equivalent to M_s magnitudes (Reference 254) and then the above process of conversion from M_s to M_w was followed.**
- **All other magnitude types were considered equivalent to m_b and then the above process to convert from m_b to M_s to M_w was followed.**

The Heaton et al. (Reference 346) magnitude correlations, following similar work by Kanamori (Reference 347), plot various magnitude scales relative to M_w for a seismotectonic setting [i.e., western US region or other active plate boundary regions] more similar to the Caribbean than the CEUS region, allowing conversion of Caribbean earthquake magnitudes in other scales into moment magnitude. These magnitude-scale plots graphically show relationships between the moment magnitude scale and several other magnitude scales, applicable magnitude ranges, and how they are nonlinear to reflect the saturation of some of the magnitude scales.

Following is a detailed summary of the approach that was used to provide specific magnitude scale conversions in order to estimate M_w for the Phase 2 earthquake catalog.

Specific Magnitude Scales Used in the Phase 2 Earthquake Catalog

The Phase 2 earthquake catalog developed for the Caribbean region contains 19 different measures of size for earthquakes that have occurred in notably different tectonic regions as compared to the CEUS region.

- **Moment magnitudes (M_w)**

The moment magnitude scale, which provides an estimation of total energy released in an earthquake, was the preferred magnitude scale in the Caribbean Phase 2 catalog under the rationale given above. Therefore, for all earthquakes in Phase 2 earthquake catalog that were originally reported in the M_w magnitude scale, these M_w values were directly included in the catalog.

- **Surface-wave magnitudes (M_s)**

The surface-wave magnitude (M_s) scale is commonly used for shallow events larger than M_s 5.0 (References 347 and 350) which, by definition, are earthquakes where surface waves may have been generated. Since the surface-wave magnitude gives the poorest results for small earthquakes or those deep or at intermediate depth, there are relatively few earthquakes of this type of magnitude scale in the Phase 2 catalog. For those reported earthquakes with M_s less than 4.5, these M_s magnitude scales were considered to be numerically equivalent to M_w. For M_s values equal to or greater than 4.5, the 1988 global surface-wave magnitude to average seismic moment (M_o) conversion relations of Ekstrom and Dziewonski (Reference 240) and then the seismic moment to moment magnitude conversion relation of Kanamori (Reference 269) was used to convert surface-wave magnitudes to M_w in the Phase 2 earthquake catalog development.

- **Body-wave magnitudes (m_b)**

The Heaton et al. (Reference 346) m_b-M_w magnitude correlation plot suggests that body-wave magnitude (m_b) less than about 4.5 are consistent with M_w, and thus, they were assumed to be numerically equivalent to M_w for the Caribbean region. This consideration is also consistent with USGS Open File Report 97-464 (Reference 350) for body-wave magnitudes in the western US region.

As may also be seen in the Heaton et al. (Reference 346) magnitude correlation plot, there is an issue of saturation of the m_b scale beginning with magnitudes larger than about 5.0. The m_b scale stops increasing with increasing earthquake size at about magnitude 6.4 corresponding to a moment magnitude of about 7.5. Therefore, for m_b magnitudes of 4.5 and larger the magnitude conversion relation for m_b to M_s from the Garcia et al. study (Reference 254) was used, and then the M_s to M_w scaling, discussed above, was applied for these larger m_b values in the Caribbean Phase 2 catalog.

- **Intensity-based magnitudes (M_I and M_k) in the Cuba catalog**

The majority of earthquakes in the Cuba catalog have an estimate of intensity-based magnitude, M_I and M_k, as discussed in the Garcia et al. study (Reference 254). Both of these magnitude types are considered to be correlated to coda or duration magnitudes [see below]. For the magnitude conversion process, where there were no region-specific magnitude conversion relations for intensity-based magnitudes, as well as none for coda- or duration-magnitudes, to M_w, these M_I and M_k magnitudes were taken as equivalent to M_w for magnitudes less than 4.5, following Heaton et al. (Reference 346), and equivalent to M_s for magnitudes 4.5 and larger, following the Garcia et al. study (Reference 254). The M_s magnitude scale values were then converted to M_w, as described above.

- **Local, Duration, and Coda magnitudes (M_L, M_d, DR and M_c)**

The local magnitude (M_L), duration magnitude (M_d) [sometimes designated "DR" or "M_D" in the National Geophysical Data Center database (NGDC)] and coda magnitude (M_c) are three types of measurements for earthquakes that are used to determine the local magnitudes and are conventionally considered equivalent. The instrumental M_c and M_d are typically reported for small and moderate magnitude earthquakes less than about 6.0, while it is found that M_L is also reported for larger earthquakes up to about 7.0. These three magnitude scales in the Phase 2 earthquake catalog, which are provided by different seismic networks with varying operational histories and different station calibrations, are comparable on average to M_w for magnitudes less than 4.5 in the Phase 2 earthquake catalog (References 346 and 350). Nuttli and Herrmann (Reference 351) report that M_L and m_b values are nearly equal in the western United States. Given the common equivalence of M_L, M_d, and M_c magnitudes, and the Nuttli and Herrmann observation, these magnitudes when larger than 4.5 are considered equivalent to m_b and converted to M_w, as detailed above.

- **Broad-band body-wave magnitudes (m_B).**

There are also some earthquakes larger than 6.0 in the Phase 2 catalog that are designated broad-band body-wave magnitude (m_B). The main advantage of m_B

magnitude scale rather than M_s is its applicability to both shallow and deep earthquakes. These m_B magnitude-scale events in the Phase 2 catalog are considered to be equivalent to M_s over the applicable magnitude range of events between about 6.0 and 8.0 (References 346 and 347), and then converted to M_w, as described above.

- **Intensity-based magnitudes ($M(I_o)$), not in the Cuba catalog**

These magnitudes are estimated from maximum intensity (I_o) using the Gutenberg-Richter (Reference 345) relationship, which correlates to local magnitude M_L. Therefore, these earthquakes are converted from M_L to M_w, as described above.

- **Equivalent local and coda-duration magnitudes (m_l, m_2, fm, xm, MA, and m_t)**

The Puerto Rico Seismic Network [PRSN] earthquake catalog, which locally collects the events in the Caribbean region, has recorded earthquakes whose magnitudes are determined using different local magnitude relations (m_1 and xm), as well as different magnitude-coda duration relations (m_2 and fm) – the xm and fm magnitudes are determined using the earthquake location program Hypoellipse (Reference 348). An event less than magnitude 3.0, excluded from the Phase 2 catalog, is reported as a type MA magnitude, attributed to PRSN – it may be expected that this small magnitude is one of or an average of the other PRSN magnitudes. Also reported in the PRSN catalog are earthquakes from the Jamaica Seismic Network [JSN], which determines average coda magnitudes (m_t) based on the regression between standard m_b and log of the signal duration (Reference 352).

As for local, duration, and coda magnitudes described above when greater than 4.5 these magnitudes are considered equivalent to m_b and are converted to M_w.

- **Unspecified magnitudes (nk and MG)**

Finally, there are some earthquakes in the Phase 2 catalog with unknown magnitude scale labeled “nk” or “ ” (e.g., the computational method was unknown and could not be determined from published sources), as well as an unspecified magnitude scale labeled “MG” (e.g., magnitudes either have been reported by the contributor without listing the type [e.g., "MG 3.5"] or have been computed using procedures, which are not defined by the magnitude types routinely reported). These types of earthquakes were considered to be equivalent to m_b for small ($3 \leq M_w < 4.5$) and moderate ($4.5 \leq M_w < 6$) earthquake magnitudes in the Phase 2 catalog. Lamarre and Shah (Reference 349) have plotted the unspecified magnitude scales versus M_L for the NGDC database used in the Phase 2 earthquake catalog, and have indicated that it is very closely approximated by the M_L and m_b for earthquakes in magnitude range less than about 5.0. Taken as equivalent to m_b, these magnitudes were converted to M_w, as described above.

Since the types of data used in determination of these magnitude scales are very different from region to region (e.g., observational errors and intrinsic variations in source properties), it is important to establish tectonically-similar regional magnitude scale correlations (Reference 347). Therefore, it should be emphasized that this magnitude conversion process was not incorporated into Phase 1

earthquake catalog that includes all events in the CEUS region with a notably different tectonic environment as compared to the Caribbean region (Section 2.5.1).

The following references will be added to FSAR subsection 2.5.2.7 in a future COLA revision.

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ASSOCIATED ENCLOSURES:

None