Palo Verde Nuclear Generating Station
Seismic Hazard Re-evaluation

NRC Public Meeting

Rockville, Maryland

June 9, 2015

Agenda

- **Introduction/Overview**
- **Seismic Source Characterization SSHAC**
  - *w/ Focus Area Questions*
- **Ground Motion Characterization SSHAC**
  - *w/ Focus Area Questions*
- **Site Response**
  - *w/ Focus Area Questions*
- **Probablistic Seismic Hazard Analysis**
- **Seismic Hazard Screening**

Overview

- Safety is a core value for APS and Palo Verde Nuclear Generating Station
  - New and extensive seismic hazard re-evaluation shows plant can safely withstand earthquakes
  - Seismic re-evaluation was performed with independent experts in a transparent and open process
  - Using new regulatory guidance, latest scientific methodologies and site-specific information, analysis demonstrates the plant's design is earthquake safe

SSHAC – Objectives

- Update Seismic Source Characterization (SSC) and Ground Motion Characterization (GMC) models for use in Probabilistic Seismic Hazard Assessment (PSHA)
- Site-specific SSC model developed following Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 guidelines
- Regional GMC model for the southwestern U.S. (SWUS) developed by SWUS GMC SSHAC Level 3 project
- Communication between SSC and GMC projects ongoing during development of models
- SSHAC guidelines are summarized in NUREG/CR-6372 and NUREG-2117
- Implemented PPRP data collection recommendations
  - Quaternary Geologic Mapping;
  - P-S Suspension Logging;
  - Spectral Analysis of Surface Waves;
  - Broad Band Seismic Array Installation

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Seismic Source Characterization SSHAC

SSHAC Workshops (SSC)

- Workshop 1: April 9-10, 2013
  - *Significant Issues and Data Needs*
  - Technical Integrator (TI) Team presentations, plus 14 Resource Expert presentations
- Workshop 2: September 24-25, 2013
  - *Alternative Interpretations*
  - TI Team presentations, plus 12 Proponent Expert presentations
- Workshop 3: April 23-24, 2014
  - *Preliminary Model and Hazard Feedback*
  - TI Team presentations, plus 2 Resource Expert presentations

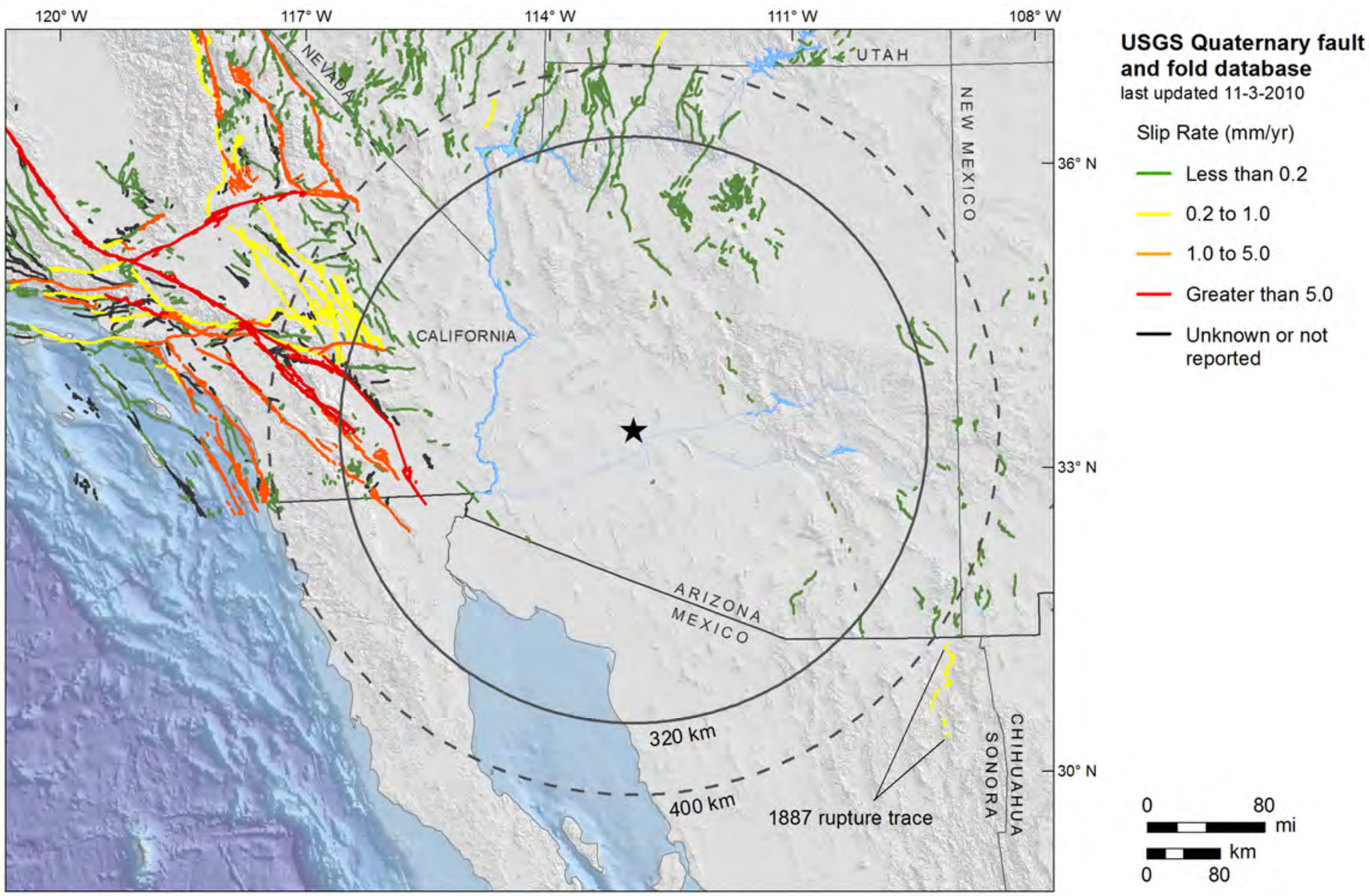
SSC - Participatory Peer Review Panel (PPRP) Interactions

- Project Kickoff Meeting: January 21, 2013
  - PPRP members, GMC Project Manager, and Project Sponsor
  - Review Project Plan, SSHAC training
- Working Meetings
  - PPRP members attended selected SSC TI Team working meetings throughout course of project
- PPRP Field Review of Geologic Mapping: February 4-6, 2014
- Update on SSC Activities (post-Workshop 3): June 18, 2014

Additional Interactions with SSC PPRP (cont'd)

- Final Briefing: July 10-11, 2014
- Update on SSC Activities: August 1, 2014
- Teleconference to Resolve Remaining Issues with SSC Report: February 19, 2015
- PPRP Closure Letter: February 26, 2015

Tectonic Setting of PVNGS



New Data, Models, and Methods for SSC

- New Data:
  - Compiled earthquake catalog for study region (400 km radius)
  - Quaternary geologic mapping of site vicinity (40 km radius), in collaboration with Arizona Geological Survey
  - Site geophysical data collection for site response analysis: borehole suspension logging and SASW
- New Models:
  - Uniform California Earthquake Rupture Forecast, Version 3 (UCERF 3) – USGS, CGS, SCEC – Field et al. (2013)
- New Methods:
  - Capture time-dependent behavior and uncertainties for high slip-rate strike-slip sources in CA (Equivalent Poisson Rates, or “EPR”)
  - Virtual faults within the areal sources

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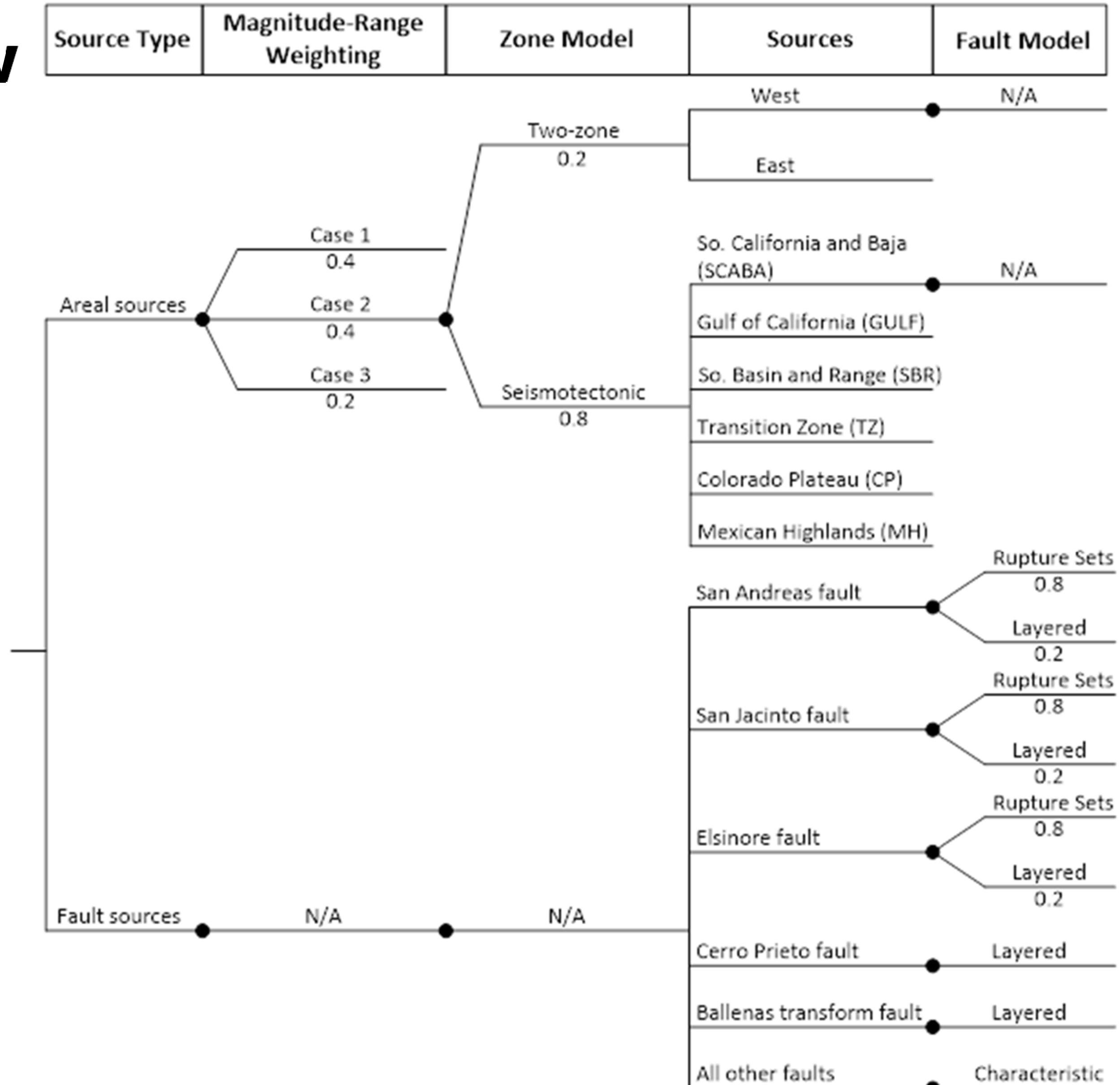
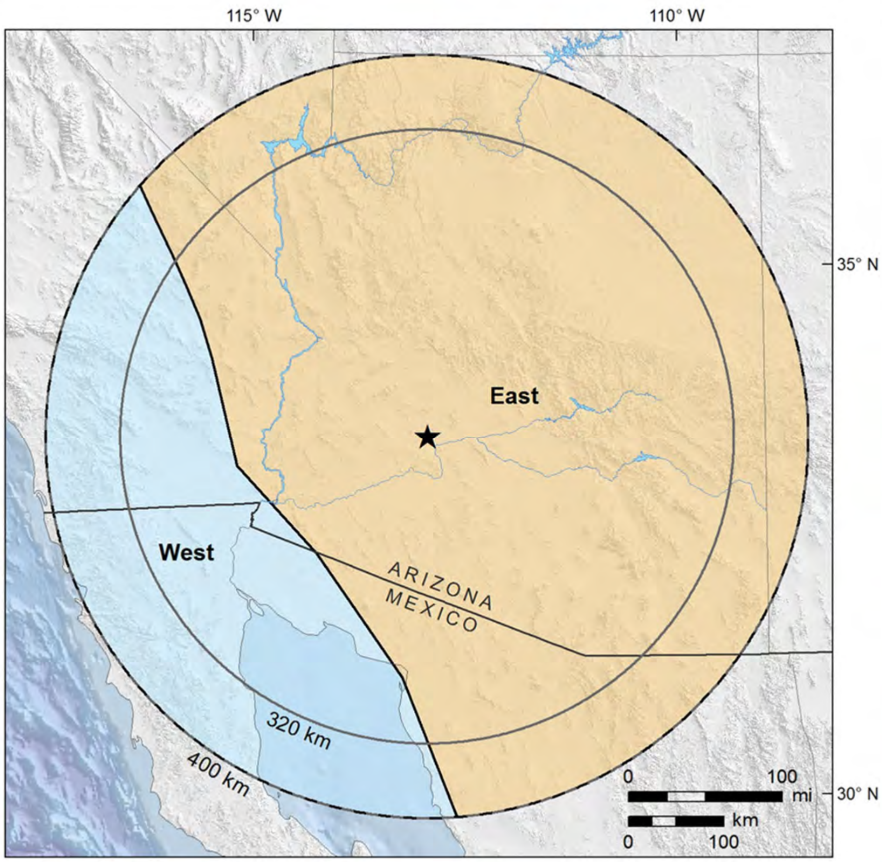
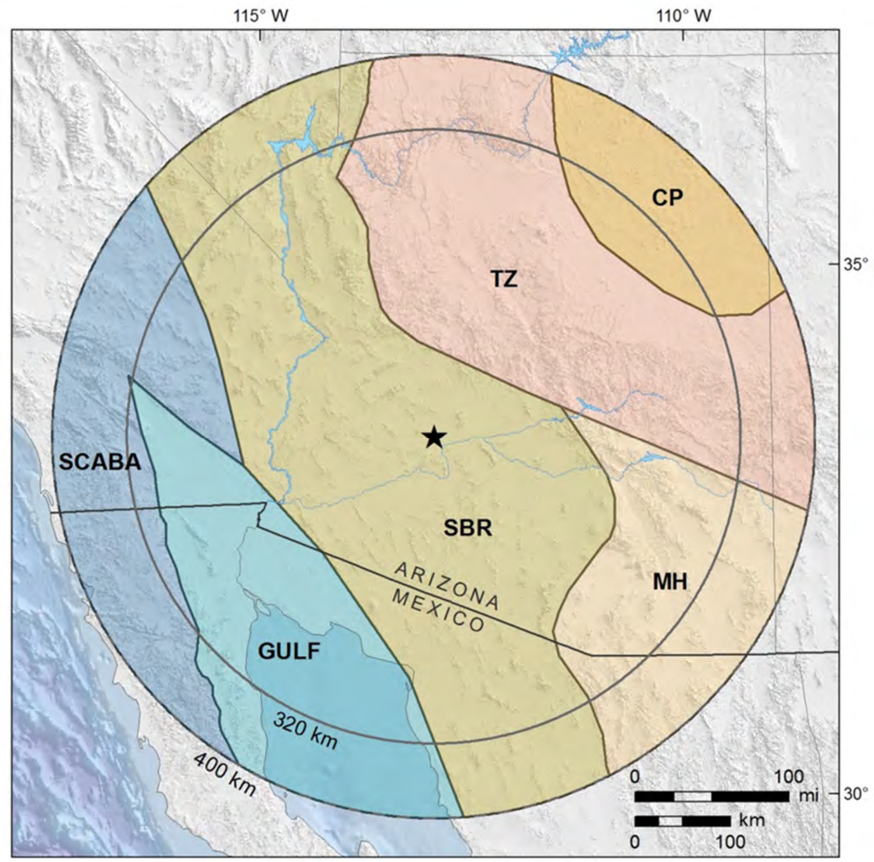
SSC Overview

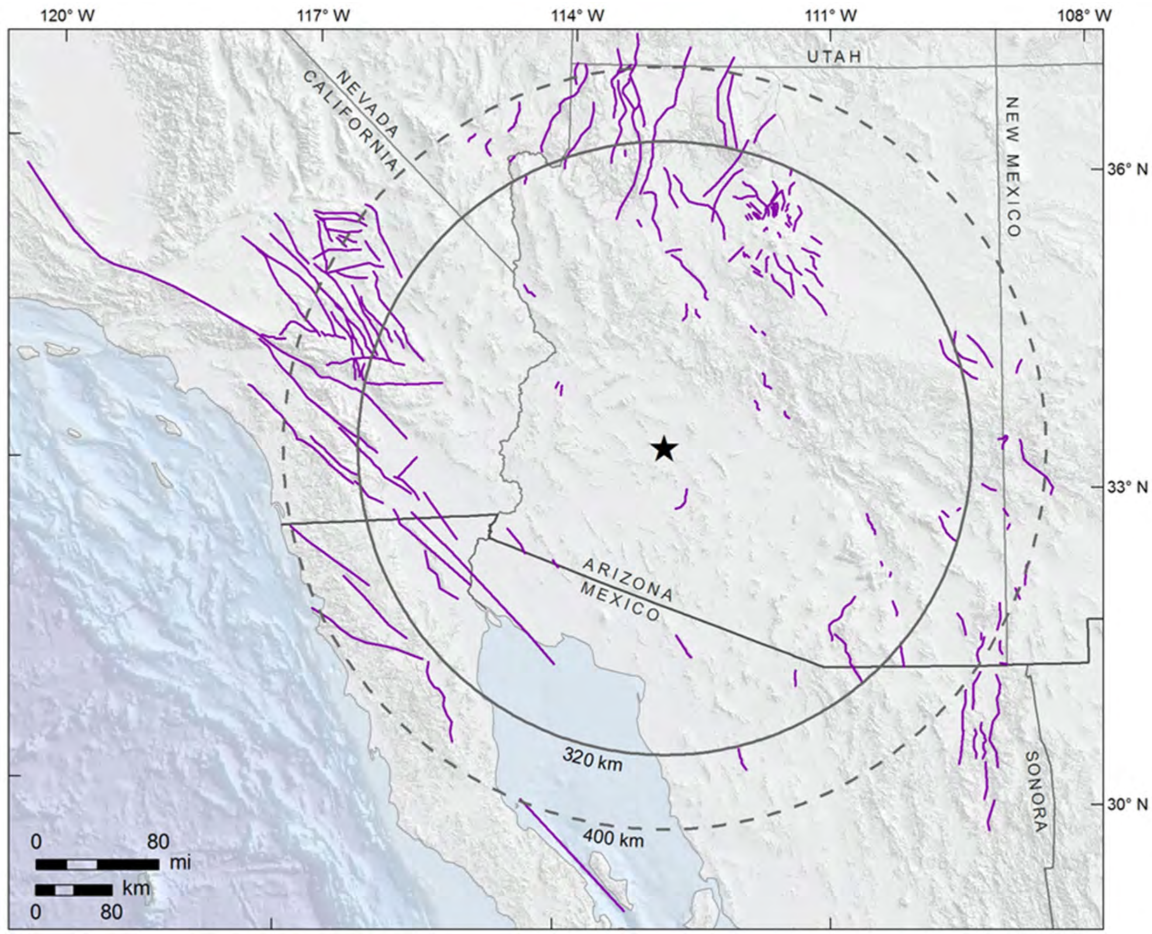


SSC: Areal Seismic Sources

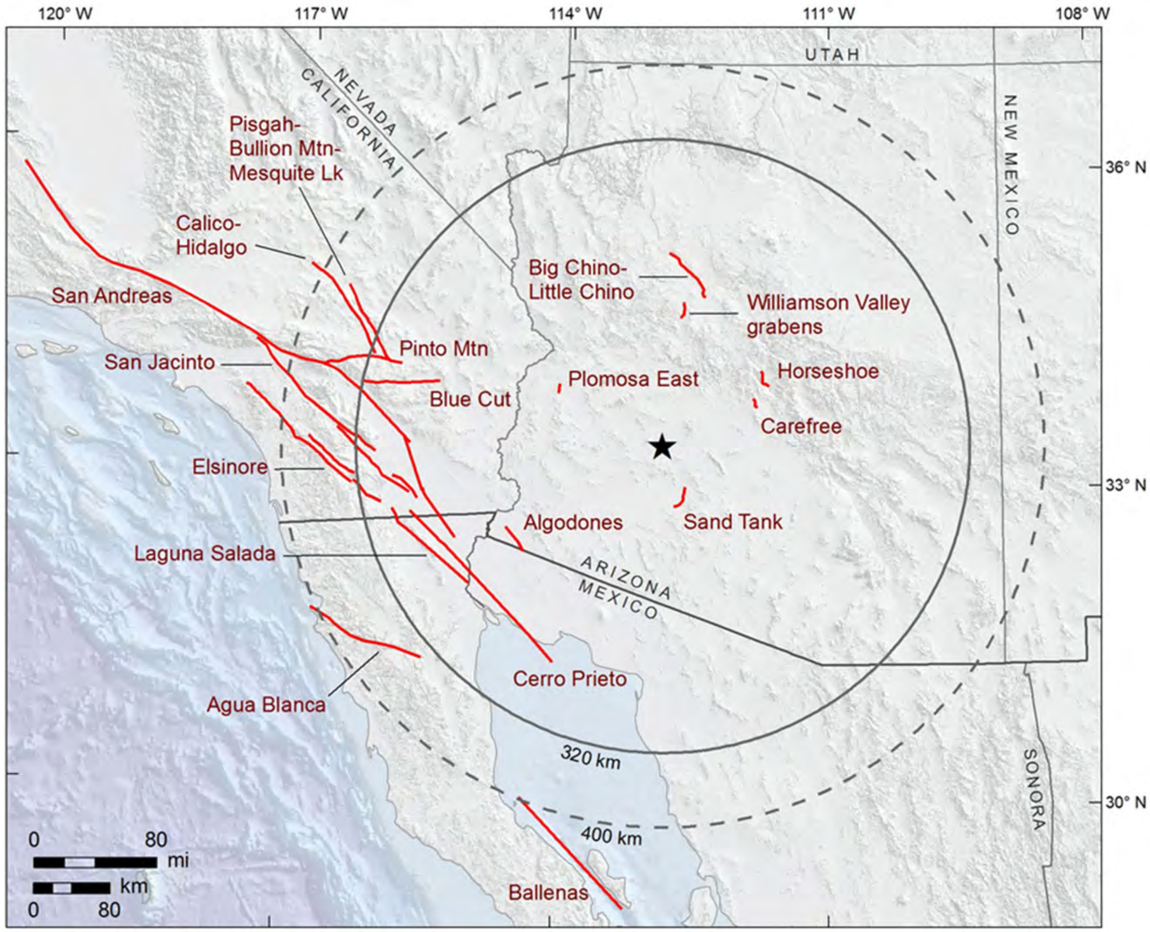




SSC: All Fault Sources



SSC: Hazard-Significant Fault Sources



SSC Focus Area Question 1

NRC SSC Q1: *Provide clarification on how the uncertainty derived from the difference in cumulative slip rates on Quaternary faults in Arizona in comparison to the geodetic slip rates in southern Arizona were evaluated and incorporated into the model. In addition, explain why faults that were originally part of the USGS National Seismic Hazard Mapping Project (NSHMP) and that are now part of the PVNGS SSC include alternative possibilities for geologic and geodetic slip rates while other PVNGS SSC faults that were not included in the NSHMP do not consider geodetic slip rates.*

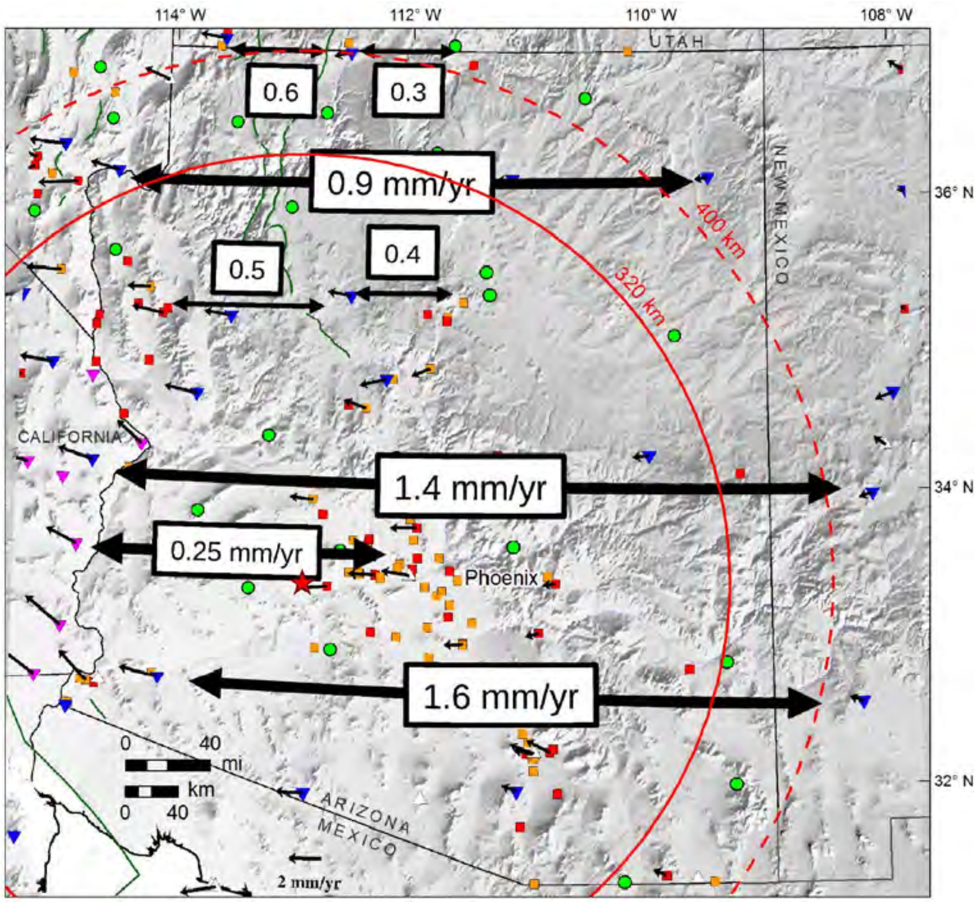
SSC Focus Area Q1 Response

The differences in geologic and geodetic rates were <u>evaluated</u> in the following manner:

- Obtain E-W geodetic extension rates from Resource and Proponent Expert Corne Kreemer
- Compared to transect in central NV where fault slip rates and geodesy match (Koehler and Wesnousky, 2011)
- Evaluated the likelihood that faults are not expressed geomorphically (How many faults can hide in landscape? At what rates?)
- Evaluated how many faults required to produce geodetic extension rate
- Compared geodetic extension rates to strain rates implied by seismicity in source zones

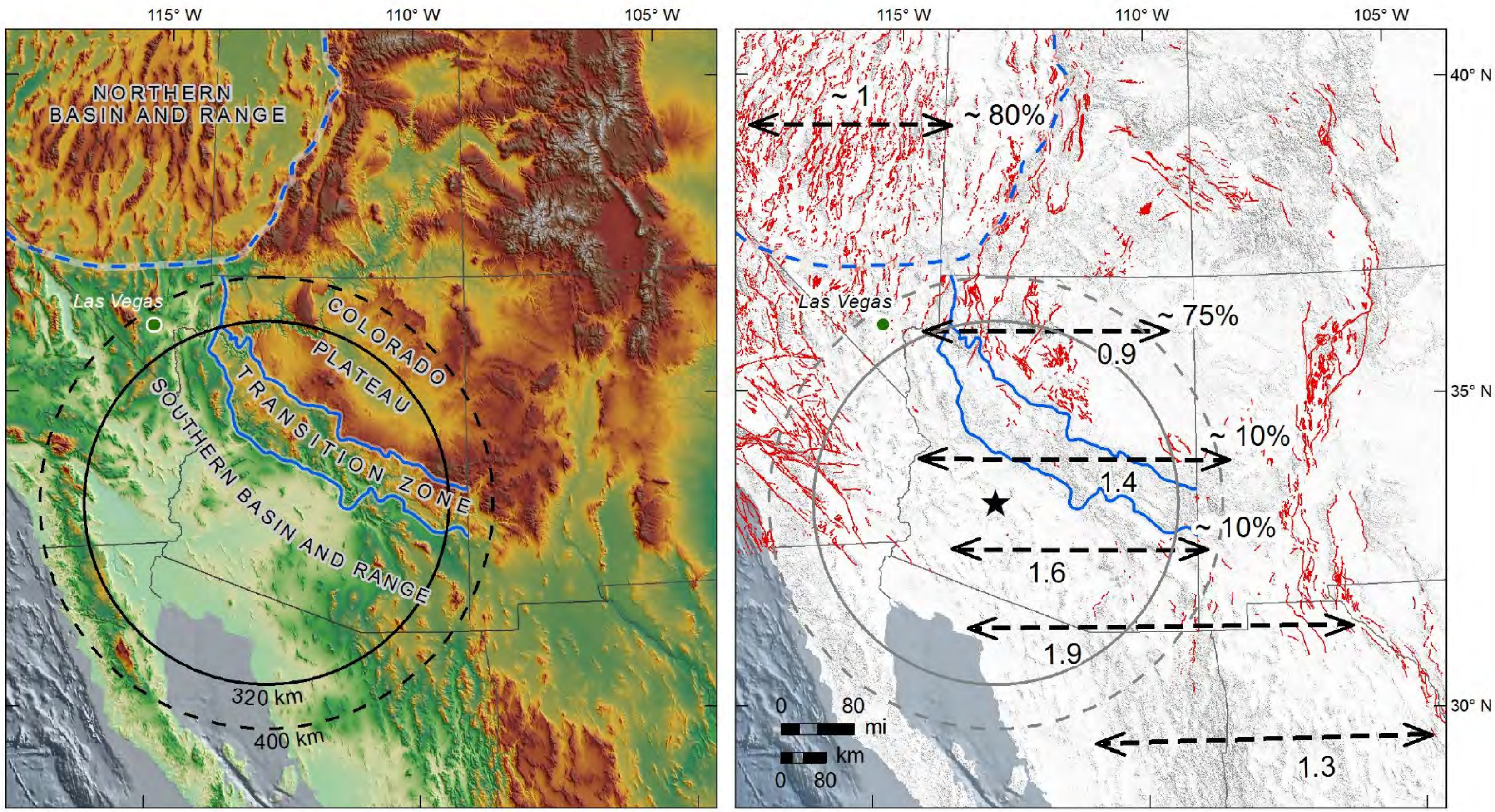
SSC Focus Area Q1 Response

Transects of geodetically based east-west extension rates (in mm/yr) from Kreemer



SSC Focus Area Q1 Response

Geodetic Extension Rates (in mm/yr) and % of extension that can be explained by fault slip rates



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SSC Focus Area Q1 Response

Could faults contribute to geodetic rate, but remain undetected in landscape?

Preservation and degradation of fault scarps in the desert landscape, modified after dePolo and Anderson (2000)

Slip rate (mm/yr)	RI (kyr) 1 m scarp	Degrade time (kyr) 1 m	Time w/o scarp	RI (kyr) 2 m scarp	Degrade time (kyr) 2 m	Time w/o scarp	RI (kyr) 4 m scarp	Degrade time (kyr) 4 m	Time w/o scarp
0.001	1,000	25	98%	2,000	100	95%	4,000	400	90%
0.005	200	25	88%	400	100	75%	800	400	50%
0.01	100	25	75%	200	100	50%	400	400	0%
0.02	50	25	50%	100	100	0%	200	400	0%
0.05	20	25	0%	40	100	0%	80	400	0%
0.2	5	25	0%	10	100	0%	20	400	0%

Notes:
RI: Average recurrence interval, in thousands of years (kyr).
Degrade Time: scarp degradation time, in thousands of years (kyr).

SSC Focus Area Q1 Response

How many normal faults required to produce geodetic extension rate?

Number of normal faults required to explain an east-west extension rate of 1.4 mm/yr (assumes various vertical separation rates and all faults are normal, strike north-south, and dip 50°)

Fault Vertical Separation Rate (mm/yr)	Fault Dip (assumes NS strike)	E-W Extension Rate for single fault (mm/yr)	No. of Normal Faults Required
0.001	50	0.00084	1667
0.005	50	0.0042	333
0.01	50	0.0084	167
0.02	50	0.017	82
0.05	50	0.042	33
0.2	50	0.17	8
1	50	0.84	2

SSC Focus Area Q1 Response

How many strike-slip faults required to produce geodetic extension rate?

Number of N40°W strike-slip faults required to explain an east-west extension rate of 1.4 mm/yr (assumes various dextral rates and all faults are strike-slip, strike N40°W, and dip 90°)

Dextral Fault Slip Rate (mm/yr)	Fault Strike (assumes vertical dip)	E-W Extension Rate for single fault (mm/yr)	No. of Strike-Slip faults Required
0.001	N40°W	0.00064	2188
0.005	N40°W	0.0032	438
0.01	N40°W	0.0064	219
0.1	N40°W	0.064	22
0.5	N40°W	0.32	4
1	N40°W	0.64	2

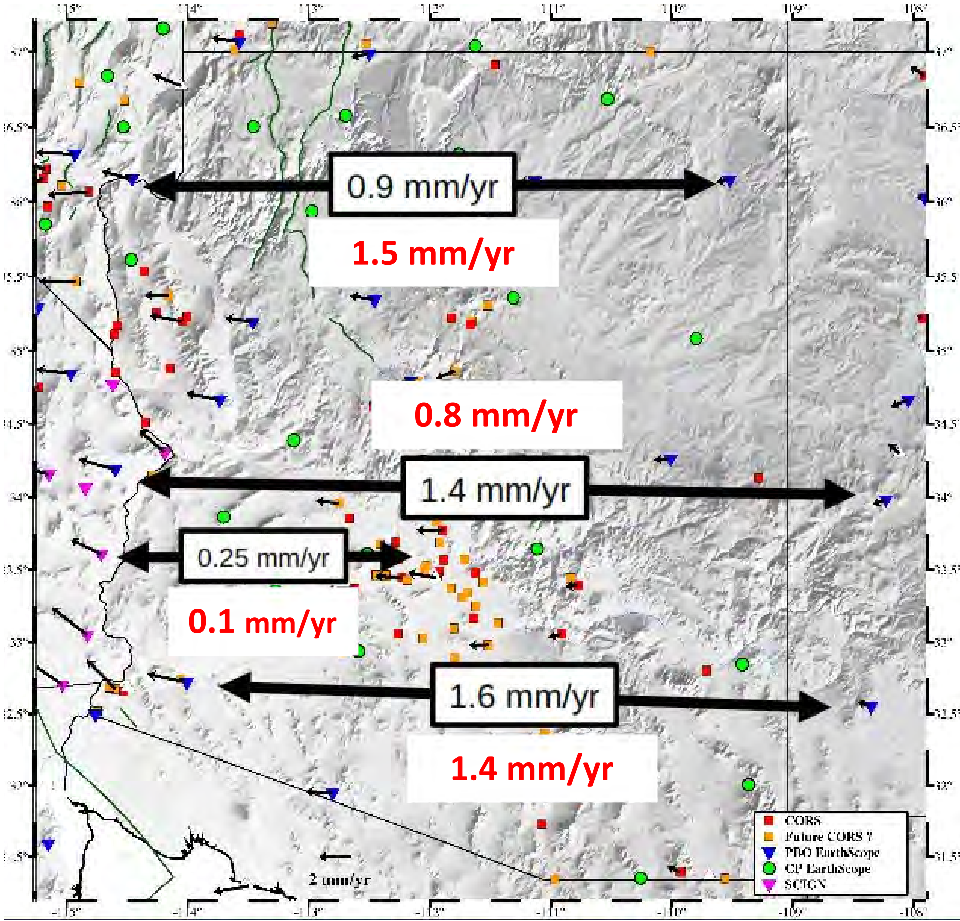
SSC Focus Area Q1 Response

Strain explained by source-zone recurrence rates

- Earthquakes in source zones also generate geodetic strain
- Calculation steps:
  - Recurrence parameters in each source-zone cell → Moment Rate in cell
  - Moment Rate in cell, cell volume, etc. → strain rate in cell
  - Integration of strain rate along a transect → deformation rate along transect

SSC Focus Area Q1 Response

Comparison to Kreemer's Extension Rates



Black:
GPS extension rates derived by Kreemer

Red:
Extension rates from earthquakes in areal source zones

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SSC Focus Area Q1 Response

Petersen et al. (2013) attempted to include geodetic rates in NSHMP SSC model

- Concluded not to use in off-fault or background zones
- Excluded block models (for faults), since they include no internal deformation and yield high rates
- Included two fault-based combined inversion models (Bird; Zeng and Shen), but gave them a low weight (0.2)
- Low weight since data and models are relatively new, and are based on the limited understanding of why certain areas and models yield much higher short-term geodetic measurements when compared to longer-term geologic rates

SSC Focus Area Q1 Response

Summary of Geologic vs Geodetic Rate Evaluation

- Multiple assessments were made to understand if geologic data could allow, support, or even explain the relatively high geodetic extension rates
- The TI Team judged the geodetic rates were anomalously high compared to other technically defensible, long-term rate information for faults
- The distributed seismicity in the source zones generates deformation rates that are roughly consistent with the measured extension rates, and may help explain the difference between geological and geodetic slip rates on faults
- Unresolved questions regarding the applicability of using geodesy to model earthquake potential (temporal signals or perturbations, short-term vs long-term rates, seismogenic vs aseismic) led the TI Team to question the usefulness of directly applying the geodetic rates in the SSC
- To include a component of geodetic rates for fault sources, the geodetic rate applied to NSHMP fault sources by the USGS was incorporated directly into the PVNGS SSC

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SSC Focus Area Q1 Response

PVNGS SSC model included geodetically-derived rates for only NSHMP fault sources

- This approach added a geodetic component of rate to the major faults that are common to both models
- Incorporates results of detailed study performed by USGS and other researchers for NSHMP
- TI Team did not include a geodetically-modeled rate on other faults in PVNGS SSC
- TI Team does not consider geodetic models to be as viable a representation of seismogenic strain accumulation as those models based on geologic slip-rate data

SSC Focus Area Question 2

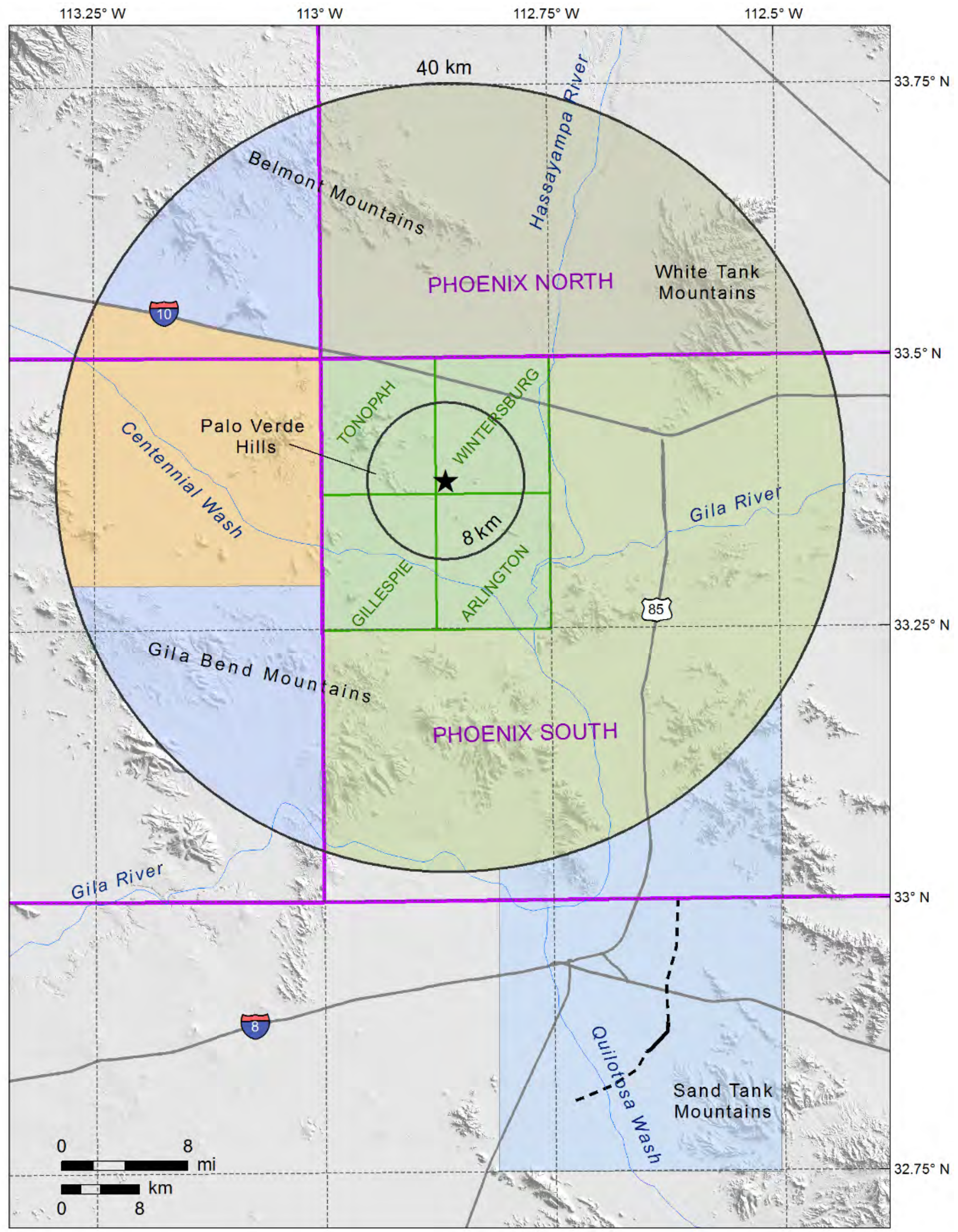
NRC SSC Q2: *With respect to the geologic mapping project, provide clarification regarding the stratigraphic correlation of Quaternary units used throughout the site area and site vicinity maps, please explain:*

a) how the 16 Quaternary units on the site map resolve into five units on the site vicinity maps

b) the rationale for singling out the river terrace unit (Qorh) as a stand-alone unit

c) the apparent mismatch of units between the site area map and the site vicinity map along the north-south trending Qorh river terrace (along the eastern side of the site area map) with the Qi1 alluvial fan surface (to the north and the south of the Qorh unit on the site vicinity map)

SSC Focus Area Q2 Response



SSC Focus Area Q2a Response

NRC SSC Q2a: *explain how the 16 Quaternary units on the site map resolve into five units on the site vicinity maps*

Response

- The site area map displays 16 Quaternary alluvial units and was mapped in more detail than the site vicinity maps
- The site vicinity maps display five Quaternary alluvial units, which represent a coarser grouping of the surficial deposits and was designed to place an emphasis on units that are approximately tens to hundreds of thousands of years and older that can then be interrogated for the presence of fault scarps and other signs of tectonic deformation
- The following table shows the general grouping of the site area map units within the generalized site vicinity map units

SSC Focus Area Q2a Response

Site Vicinity Map Unit (40-km)	Site Area Map Units (8-km)
Qy – Holocene alluvium, undiff.	Qyc – Modern stream channel deposits Qy2 – Late Holocene alluvium Qy1 – Holocene alluvium Qyf – Fine-grained Holocene alluvium Qy – Holocene alluvium undiff. Qye – Quaternary eolian deposits Qyp – Fine-grained deposits in playas
Qi3 – Late Pleistocene alluvium	Qi3 – Late Pleistocene alluvium Qi – Middle and late Pleistocene alluvium , undiff.
Qi2 – Middle to late Pleistocene alluvium	Qi2 – Middle to late Pleistocene alluvium Qi – Middle and late Pleistocene alluvium , undiff.
Qi1 – Middle Pleistocene alluvium	Qi1 – Middle Pleistocene alluvium Qorh Early to middle Pleistocene alluvium (of highest terraces along Hassayampa River) Qi – Middle and late Pleistocene alluvium, undiff.
Qo – Early Pleistocene alluvium	Qo – Early Pleistocene alluvium

SSC Focus Area Q2b Response

NRC SSC Q2b: *explain the rationale for singling out the river terrace unit (Qorh) as a stand-alone unit*

Response

- The Qorh unit delineates deposits associated with the highest terraces along the Hassayampa River. The Hassayampa River and additional Qorh deposits are located east of the site area map boundary
- Qorh is singled out to distinguish this specific type of deposit from other alluvial deposits of similar age (Qi1) that are not associated with the Hassayampa River
- Qorh appears on Pearthree et al.'s (2006) geologic map of the Wintersburg quadrangle

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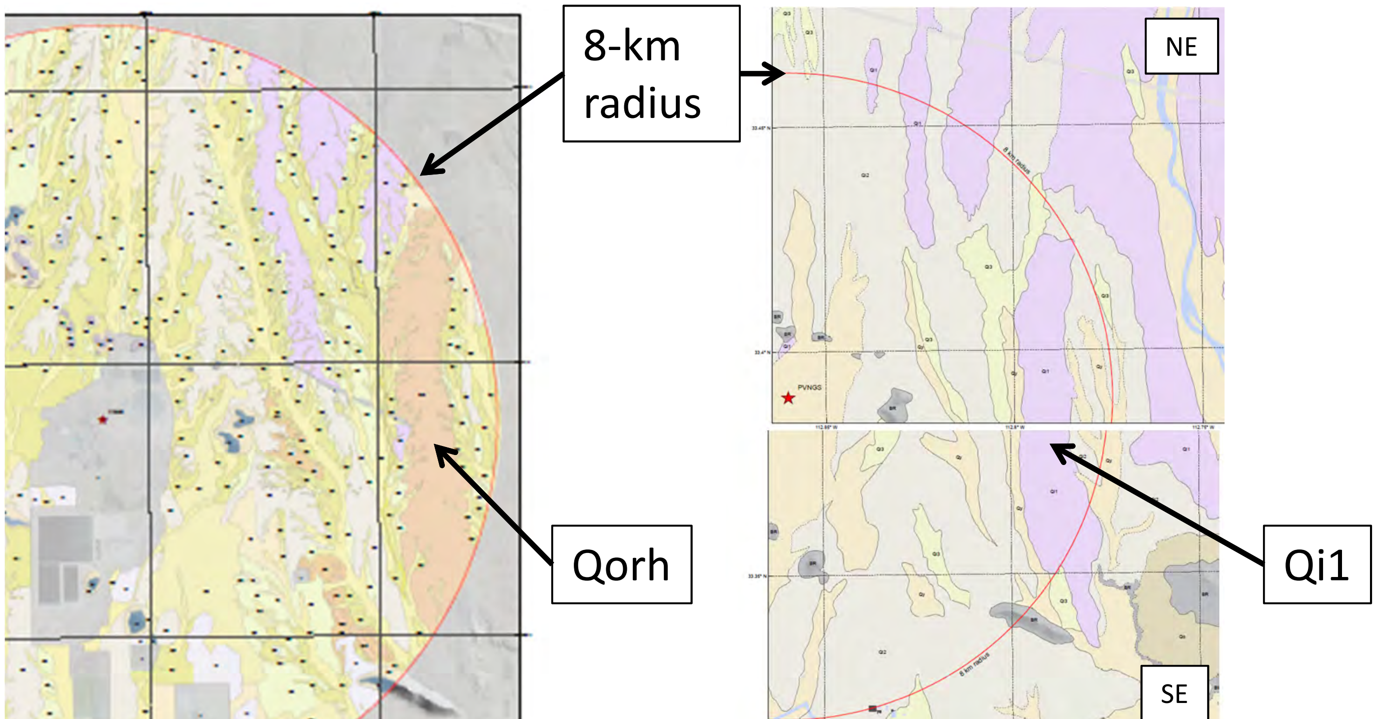
SSC Focus Area Q2c Response

NRC SSC Q2c: *explain the apparent mismatch of units between the site area map and the site vicinity map along the north-south trending Qorh river terrace (along the eastern side of the site area map) with the Qi1 alluvial fan surface (to the north and the south of the Qorh unit on the site vicinity map)*

Response

- The 8-km site area map is based on Pearthree et al.'s (2006) mapping of the Wintersburg quad, expanded to cover the entire site area
- The eastern portion of the 40-km site vicinity map is based on 1:100k mapping by the AZGS, modified by Phil Pearthree for this project. The western portion is based on original mapping
- The apparent mismatch between units is a function of comparing maps produced at two different scales with two different levels of detail
    - Simplification and lumping of units in the site vicinity map
    - Site vicinity map does not include small polygons and thin "veneers"

SSC Focus Area Q2c Response



Portion of site area (8-km radius) map

Portion of site vicinity(40-km radius) map

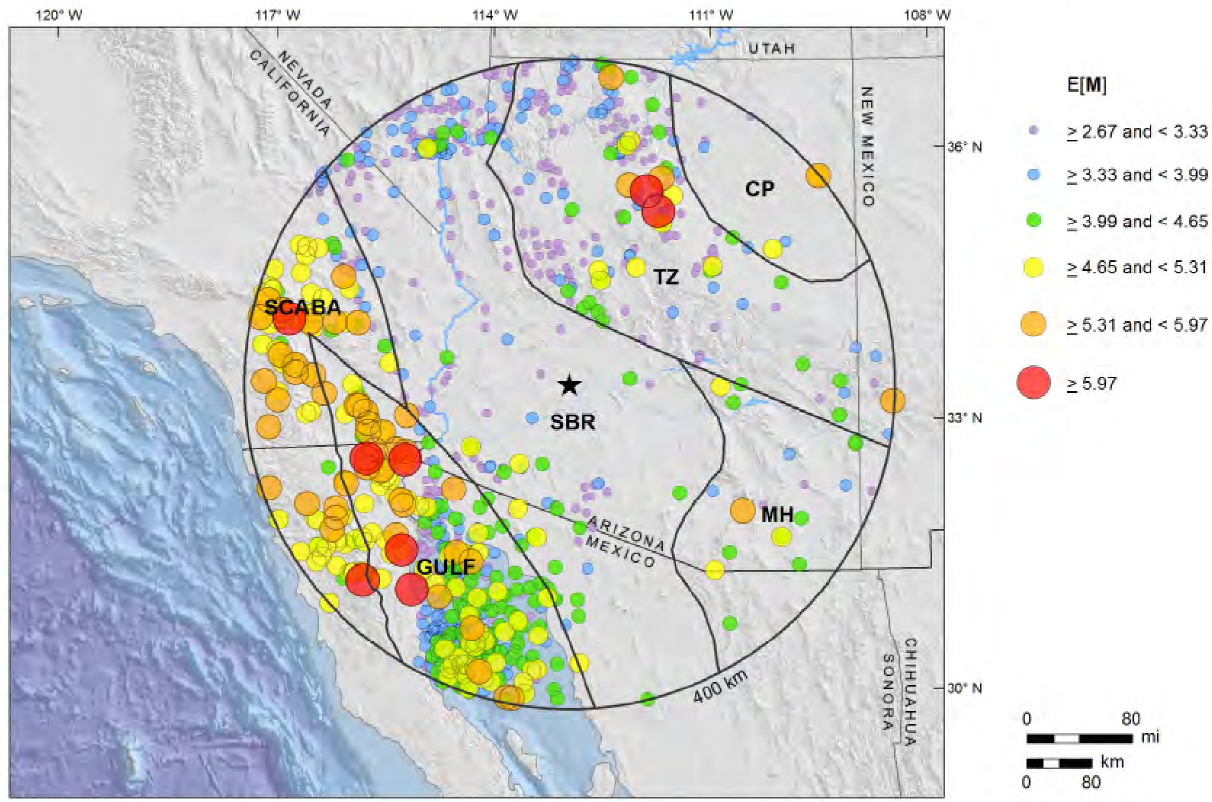
SSC Focus Area Question 3a

NRC SSC Topic 3a: *With respect to the areal source zones, provide the rationale for*

a. *choosing to model the spatial variation of the recurrence rate using variable, but continuous and relatively smooth seismicity rather than using uniform rates similar to the previously completed SSHAC Level 2 PVNGS SSC*

SSC Focus Area Q3a Response

Spatial pattern of earthquakes in SBR source zone is not consistent with the assumption of uniform seismicity



Map showing the PVNGS catalog (color coded by magnitude bin) and Seismotectonic sources

SSC Focus Area Q3a Response

SSC TI Team adopted three alternative sets of magnitude weights, which yield different degrees of smoothness and are consistent with spatial distribution of the catalog data (representing the "center, body, and range" of technically defensible interpretations regarding degree of smoothing)

SSC Focus Area Question 3b

NRC SSC Q3b: *With respect to the areal source zones, provide the rationale for*

b. not using a floor during the smoothing analysis of recurrence parameters as the host zones and other zones have cells with a rate of zero

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SSC Focus Area Q3b Response

- The cells with zero rate occur only in alternative realizations of the recurrence maps (as a way to represent uncertainty in rate), **not in the mean recurrence maps**
- The penalized likelihood approach introduces a “natural floor” by modeling the entire likelihood function of the rate

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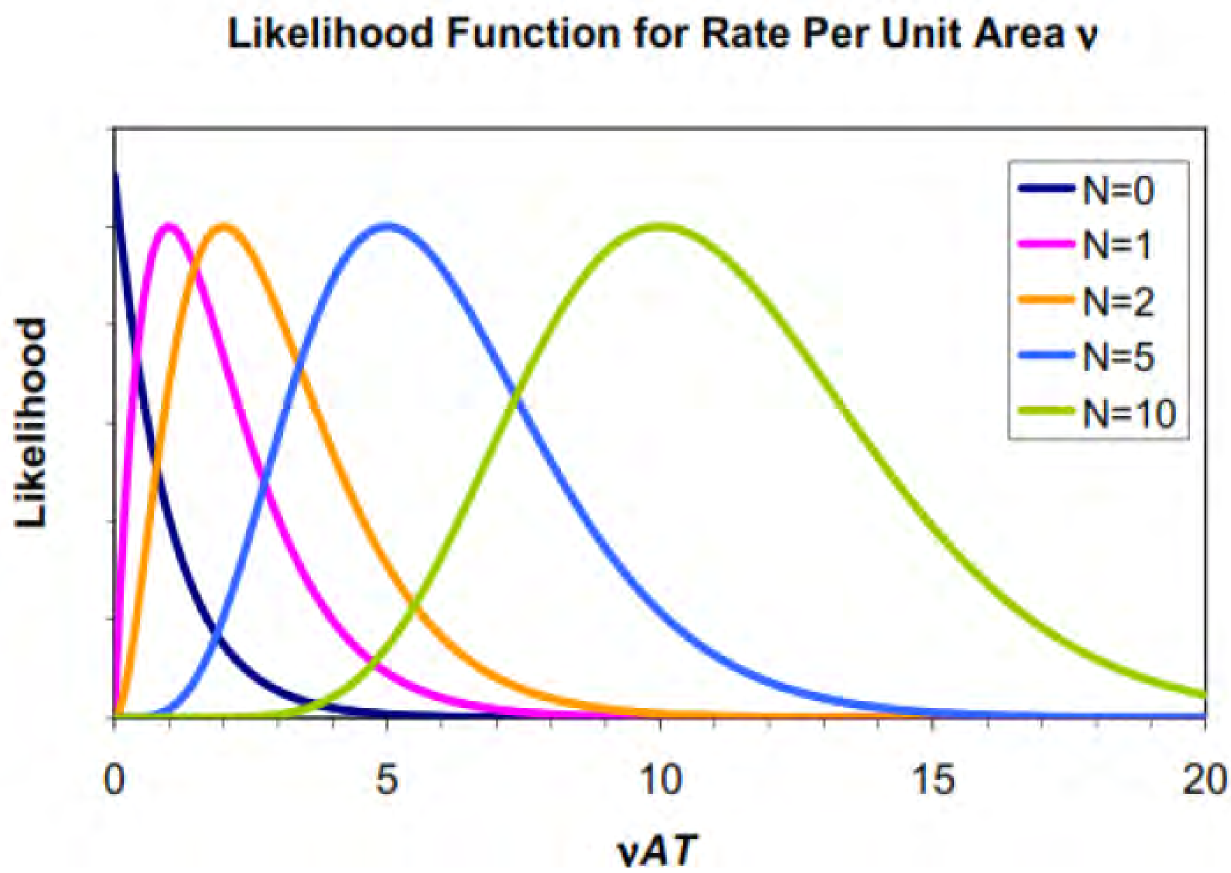
SSC Focus Area Q3b Response

<u>Natural Floor</u>

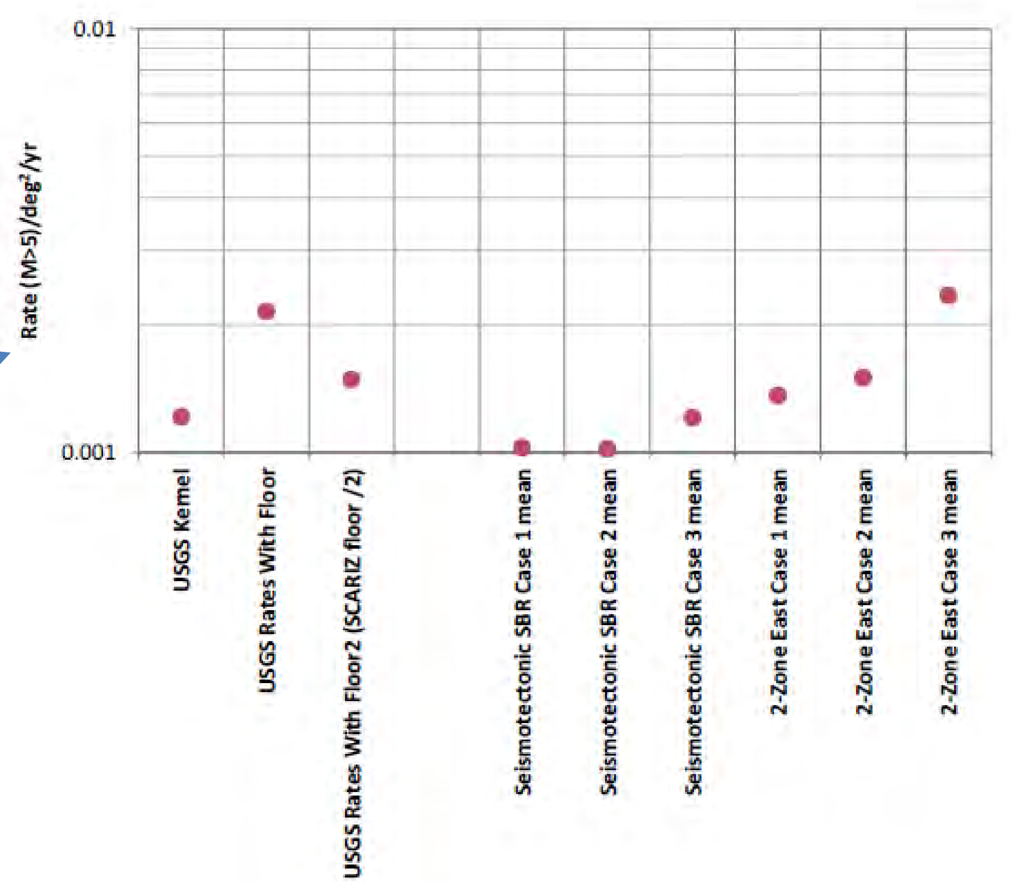
Even when the earthquake count is zero, the likelihood function takes non-zero values (dark blue curve)



SSC Focus Area Q3b Response

Comparison to USGS, 2014

Recurrence rate (**M**>5) in host cell



SSC Focus Area Question 3c

NRC SSC Q3c: *With respect to the areal source zones, provide the rationale for*

c. *not using earthquakes with magnitudes lower than M4.67 to determine the recurrence parameters for the Eastern source zones*

SSC Focus Area Q3c Response

The SSC model used **M**3.33 and greater data for eastern source zones and **M**4.67 and greater for western sources (more abundant data)

SSC Focus Area Q3c Response

Typographical error in SSC Report Captions

Table 9-4. Magnitude-dependent weights for eastern (SCABA, GULF, and West) source zones.

Case	M 2.67-3.33	M 3.33-4.0	M 4.0-4.67	M 4.67-5.33	M 5.33-6.0	M > 6.0
1	0	0.8	1	1	1	1
2	0	0.3	1	1	1	1
3	0	0.2	0.5	1	1	1

Table 9-5. Magnitude-dependent weights for western (SBR, TZ, CP, MH, and East) source zones.

Case	M 2.67-3.33	M 3.33-4.0	M 4.0-4.67	M 4.67-5.33	M 5.33-6.0	M > 6.0
1	0	0	0	1	1	1
2	0	0	0	0.5	1	1
3	0	0	0	0.3	0.5	1

Note: SSC Report is not a “docketed” report

Ground Motion Characterization
SSHAC

SSHAC Workshops and Working Meetings (GMC)

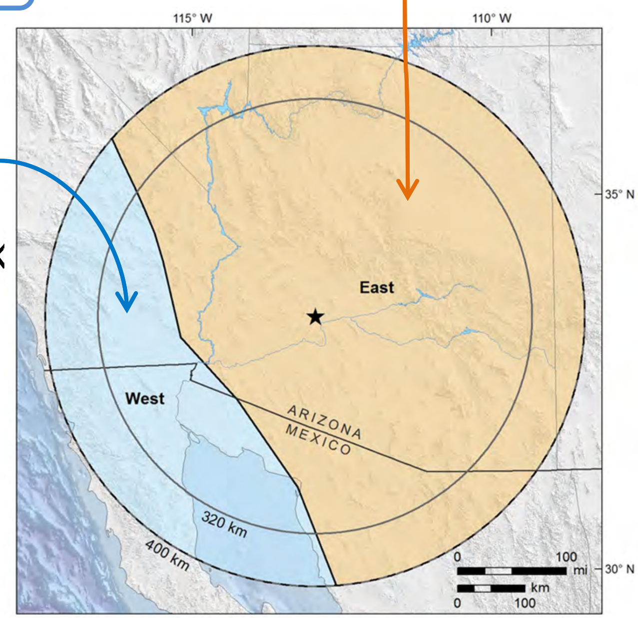
- Workshop 1: March 19-21, 2013
  - *Critical Issues and Data Needs*
  - TI Team presentations, plus several Resource Expert presentations
  - SSHAC Training
- Workshop 2: October 24-25, 2013
  - *Proponent Models and Alternative Interpretations*
  - TI Team presentations, plus several Proponent and Resource Expert presentations
- Workshop 3: March 23-24, 2014
  - *Preliminary GMC Model and Hazard Feedback*
  - TI Team presentations, with inputs from several Resource Experts
- 17 Formal Working Meetings
  - 2 planning meetings and 1 extended meeting with Resource Expert presentations

Additional Interactions with GMC PPRP

- Project Kickoff Meeting: August 27, 2012
  - TI Team, Project Technical Integrators, PPRP members, Hazard Analysts, Management and Project Sponsor attended in person
  - Review Project Plan, discuss interface with SSC and Site Response
- Working Meetings
  - PPRP members attended all GMC TI Team working meetings in person or via webinar throughout course of project
- PPRP Briefings (post-Workshop 3)
  - Pre-Briefing on May 14, 2014 and Final Briefing on July 17-18, 2014
  - PPRP members attended in person
- Review of Technical Report
  - Several written and oral communications with PPRP members while resolving PPRP's comments and finalizing the Technical Report
  - Endorsement letters received on February 24, 2015 and March 10, 2015

Ground-Motion Characterization Models

- Reference rock ground-motion model (regional SWUS GMC SSHAC project)
  - Median ground motion (two different source regions: Greater AZ and California/Mexico aka Regions 1, 2 & 3)
  - Aleatory variability
- Interface with Site Response
  - Accounting for: (1) differences in the rock conditions, and (2) site amplification
- Capture uncertainty in each part
  - Epistemic uncertainties
  - Avoid double-counting



New Data, Models and Methods for GMC

- Data:
  - NGA-West2 strong-motion data set (PEER)
  - European strong-motion data set (RESORCE)
  - Taiwanese data (Lin et al., 2011)
  - Arizona Database (PEER)
  - Finite-fault simulations (SCEC)

	NGA-West2	RESORCE	PEER-Arizona	Lin et al (2011)	Finite-Fault Simulations
Median for Greater AZ sources	SS and NML events	SS and NML events			
Kappa for Arizona rock site (Univ. Research task)			Earthquakes in Arizona		
Median for California/Mexico sources			Earthquakes in California /Mexico (200-400 km)		
Single-Station Sigma	X	X		X	
Single path-to-region Sigma for California/Mexico sources			Earthquakes in California /Mexico (200-400 km)		
HW scaling					X

New Data, Models and Methods for GMC (Cont'd)

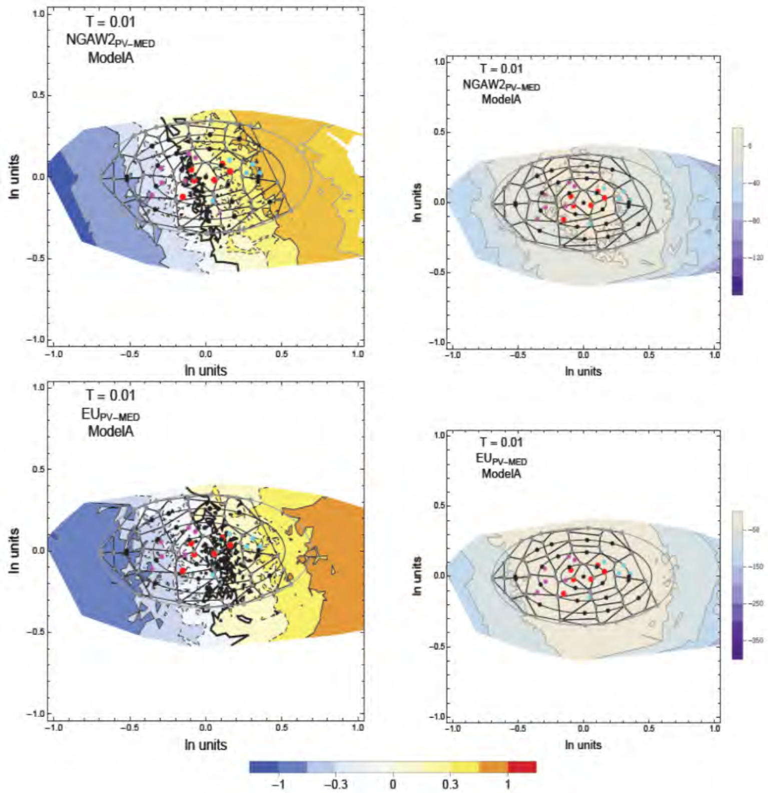
- Models:
  - Candidate median GMPEs: NGA-West2 and European GMPEs

	PVNGS - Greater Arizona Sources	PVNGS - Distant California & Mexico Sources
Abrahamson et al (2014)	X	X
Boore et al (2014)	X	X
Campbell and Bozorgnia (2014)	X	X
Chiou and Youngs (2014)	X	X
Idriss (2014)		X
Akkar et al (2014a, 2014b)	X	
Bindi et al (2014a, 2014b)	X	

  - Adjustment for path effects
  - Aleatory variability for residuals fatter than Gaussian distribution tail (Mixture model)

New Data, Models and Methods for GMC (Cont'd)

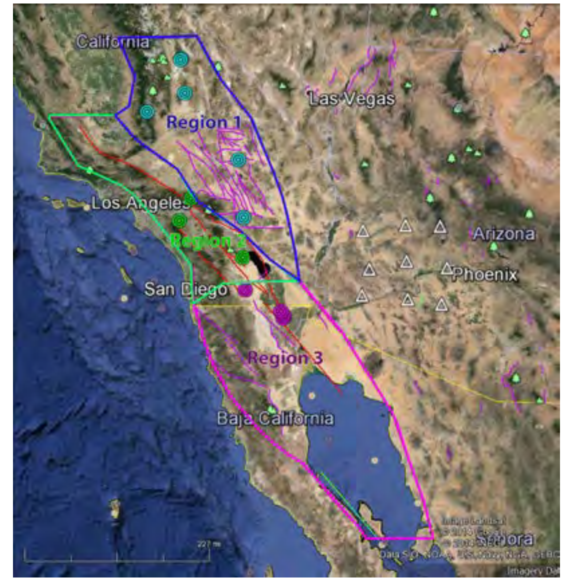
- Methods:
  - Sammon's map approach to develop weights to GMPEs, including comparison with empirical data
  - Treatment of additional epistemic uncertainty
  - Single-station sigma and single path-to-region sigma approaches

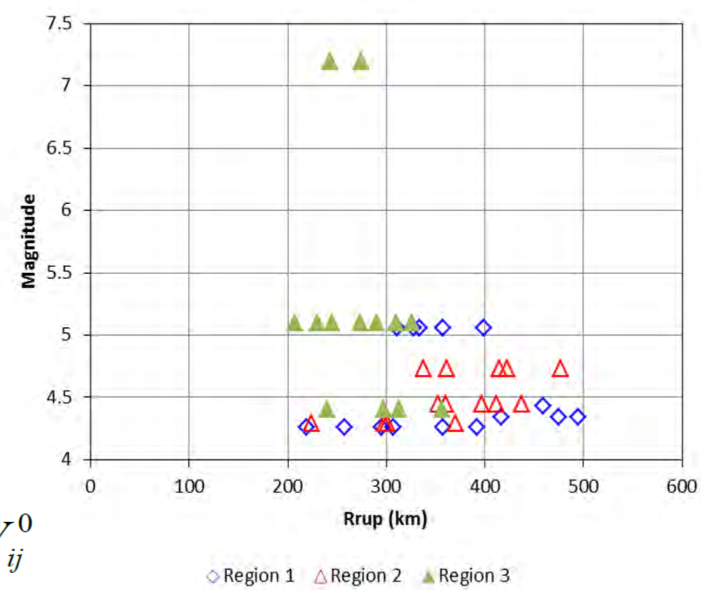


Regionalization of GMC Model: Greater AZ vs Regions 1, 2 & 3

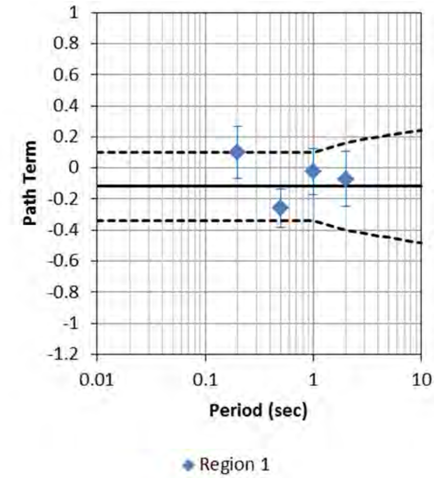
- Available Data:
  - 10 earthquakes from California and Mexico recorded by 9 stations in central Arizona
  - Systematic deviations from the average distance scaling for a given source-site pair
    - Path term is a regional term rather than site specific (single-path-to-region)
- Partially non-Ergodic GMC
  - Path effects can be estimated, removing the path term from the aleatory variability in the traditional ergodic approach

$$\ln SA_{obs}(M_i, Loc_i, Site_j) = \ln GMPE(M_i, R_{ij}, VS30_j)$$
$$+\delta L2L_l + \delta S2S_j + \delta P2P_{lj} + \delta B_i^0 + \delta W_{ij}^0$$

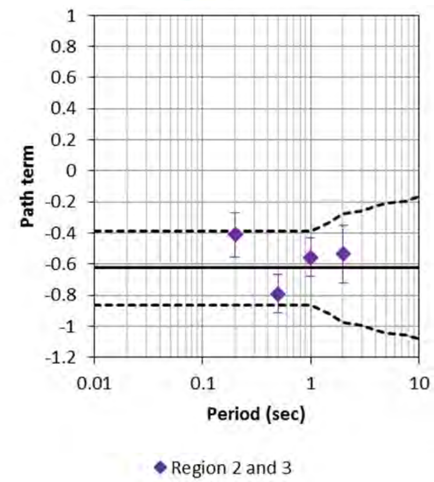


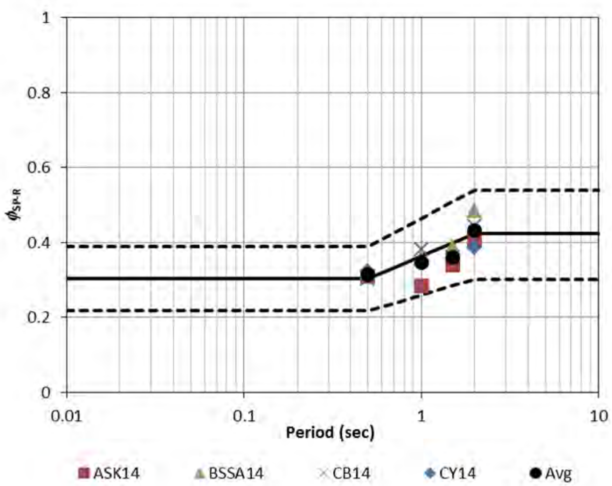


Treatment of Path Adjustment



- Mean Path Term Branches:
  - Upper and lower branches as mean path ± 1.6σ
  - Combine results for Regions 2 and 3
  - Additional epistemic uncertainty included at T > 1 sec
    - Scale the standard deviation at T > 2 sec by variance ratio of the Al Atik and Youngs (2014) additional epistemic variability with respect to its value at 2 sec

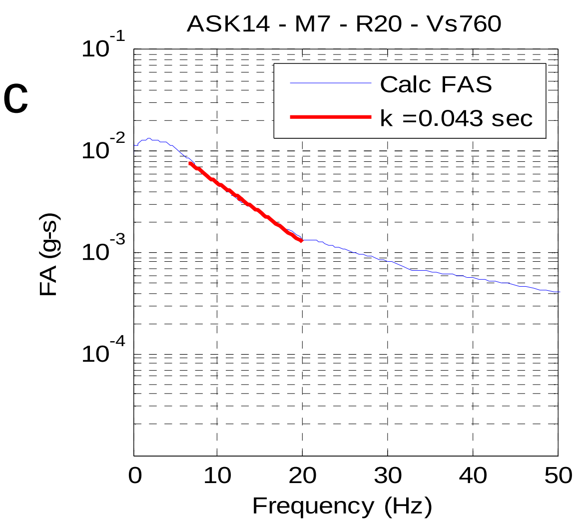


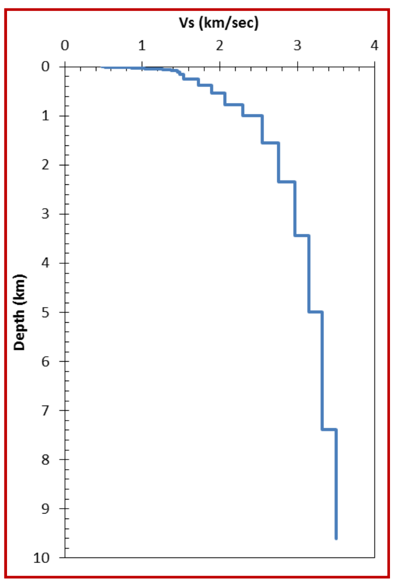


- PHI SP-R:
  - Evaluated at T = 0.5, 1 and 2 sec
  - Constant for T < 0.5 sec and T > 2 sec

GMC Inputs to PVNGS Site Response

- SWUS GMC host kappa value is 0.041 sec
  - Estimated using the inverse random vibration theory (IRVT) approach (Al Atik et al., 2013) for a reference V_{S30} of 760 m/sec
  - FAS HF slope for seven candidate GMPEs and nine short-distance scenarios





- SWUS GMC host profile (V_S and density)
  - Reference V_S profile for the host region is the Kamai et al. (2013*) profile for V_{S30} of 760 m/sec
  - Reference density compatible with reference V_S profile

**PEER Report 2013/12*

GMC Inputs to PVNGS Site Response (Cont'd)

- Target kappa value is 0.033 sec ($\sigma_{\kappa \ln}$ = 0.5)
  - PEER Report 2014/09
  - V_S profiles (2 generic profiles) for kappa estimates
    - From 11 profiles (10 SASW and 1 existing PVNGS)
    - One profile for stiff soil sites ($V_{S30} \leq 670$ m/s), and one profile for firm rock sites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PEER Arizona Strong-Motion Database and GMPEs Evaluation

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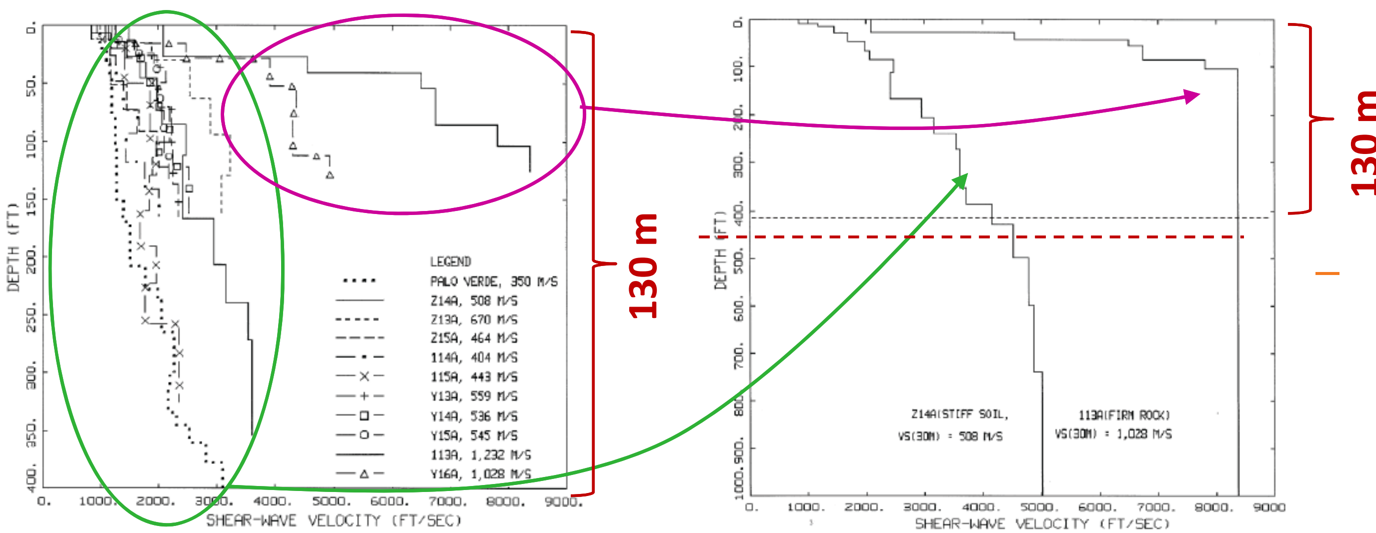
Chapter 4



- Extrapolated to source depth and merged into the host V_S profile at depth with V_S 3.5 km/s

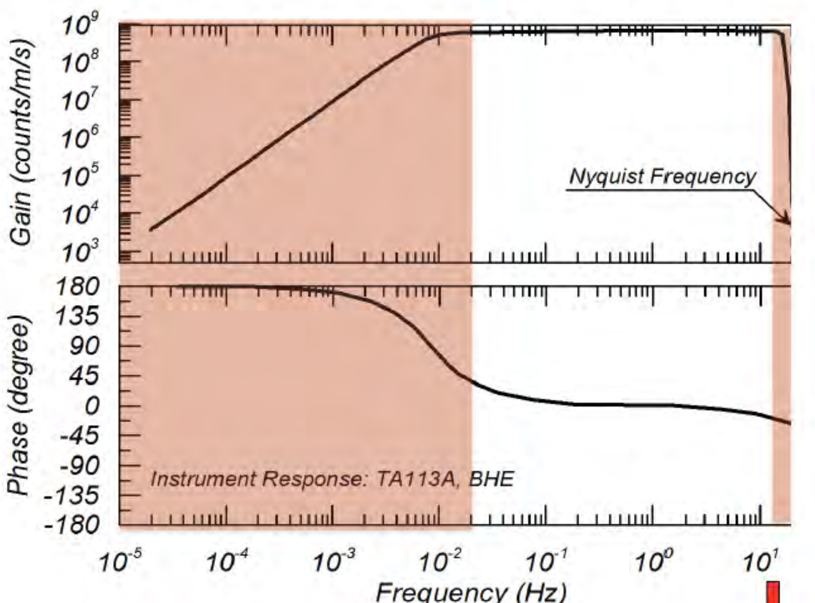
GMC Focus Area Question 1

NRC GMC Q1: *Considering the limited bandwidth of the data recorded by the TA array, provide additional detail on the process used to estimate the target site kappa values and their uncertainties. In addition, describe in more detail how the site amplification at the recording stations was accounted for in the estimates of site kappa.*

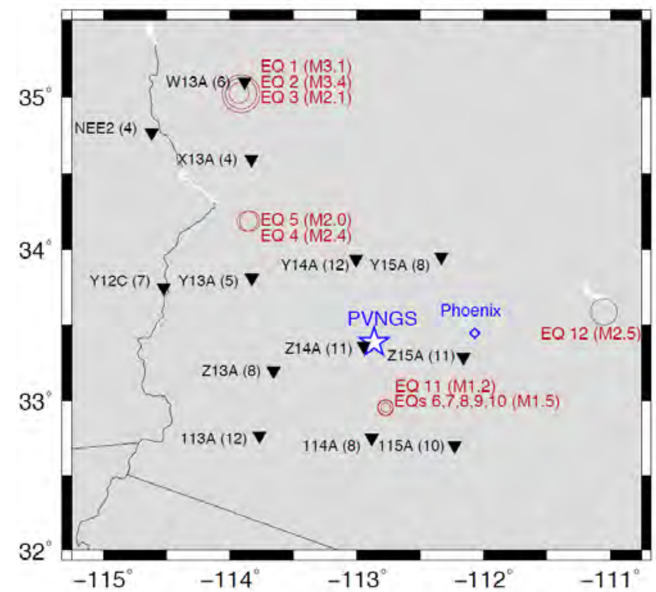
GMC Focus Area Q1 Response

Data Availability and Issues

- 12 earthquake in Arizona recorded by TA stations in central Arizona
  - M1.2-3.4; R 10-300 km



16 Hz



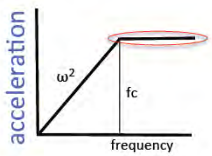
- TA bandwidth limitations
  - Sampling rate = 40 samples/sec
  - Max freq = 16 Hz (80% of Nyquist)

GMC Focus Area Q1 Response

AS and DS Methods

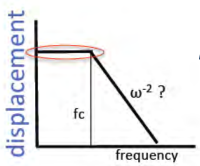
- Combine the two methods to capture uncertainty

K_{AS}



Anderson & Hough (1984)

K_{DS}
(K_{mini})



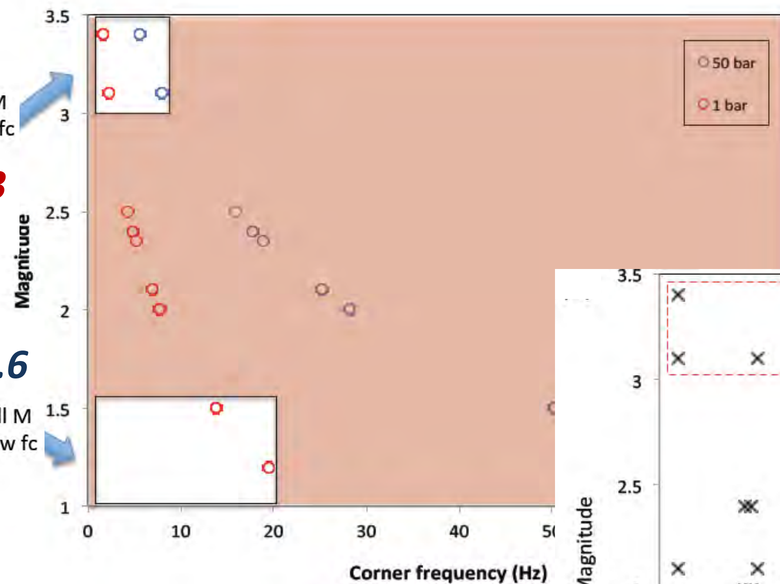
Biasi & Smith (2001)

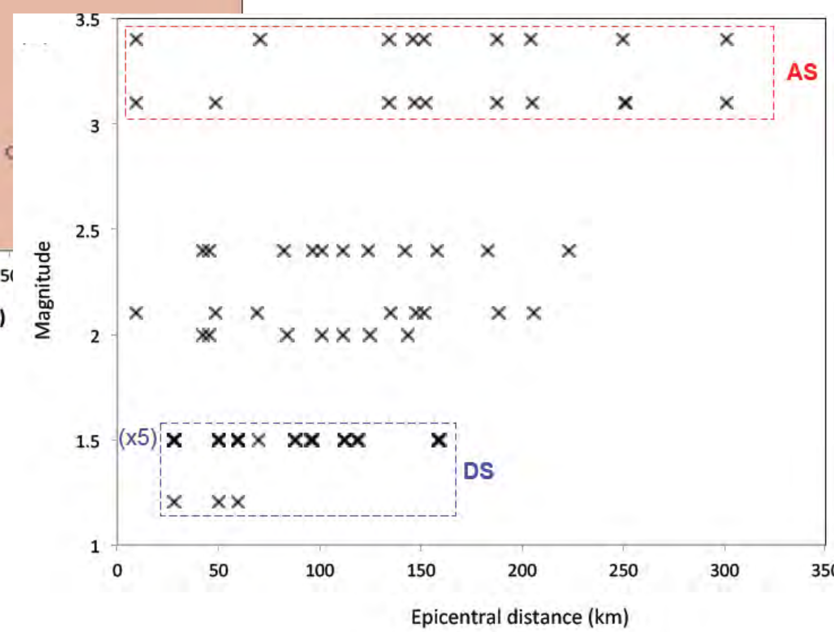
large M above fc

M > 3

M < 1.6

small M below fc





- K_{AS} computed between 9 and 16 Hz
- K_{DS} computed between 4 and 16 Hz

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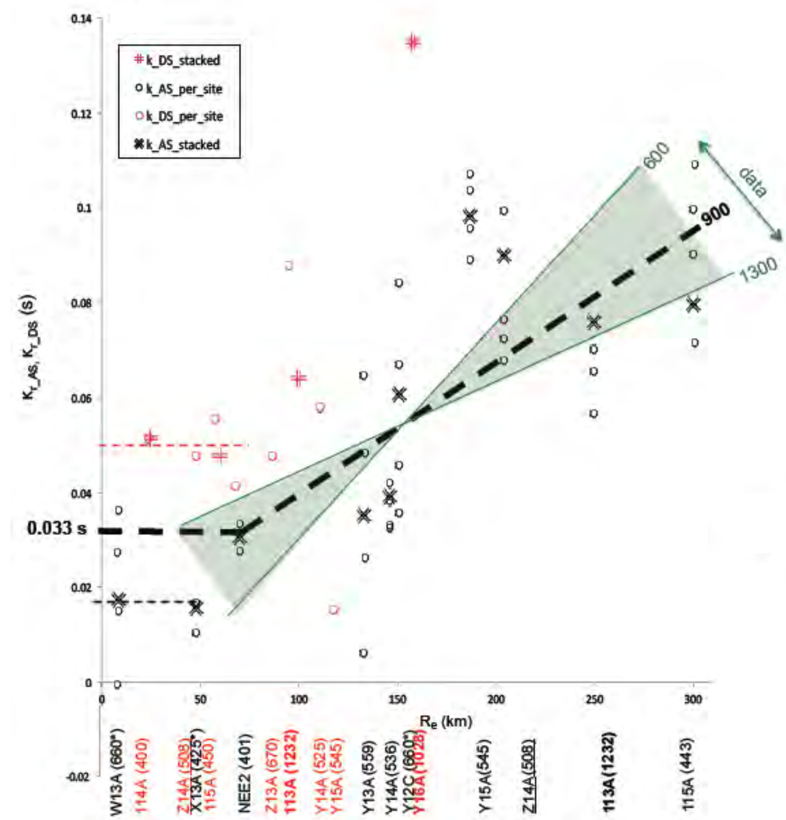
GMC Focus Area Q1 Response

AS and DS Methods: Results

- Mean κ_0 = 0.033±0.014 sec
  - Std. Deviation in 70 km
    - 13 msec for AS method
    - 6 msec for DS method
  - Mean frequency-independent regional Q = 900±300
  - κ_r estimates extrapolated to zero dist.
- DS estimates larger than AS
- Large scatter in individual κ_r
  - Not explained by distance or site stiffness
  - Possibly due to complex Q structure or shallow site resonance not accounted by average crustal amplification transfer function

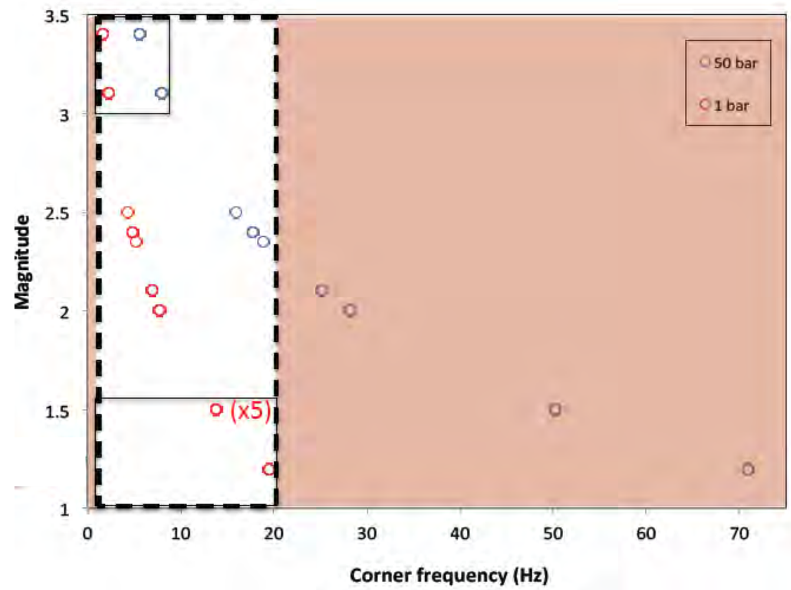


Result's scatter is associated with differences between AS and DS approaches

GMC Focus Area Q1 Response

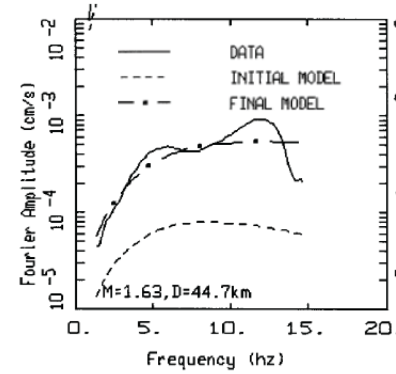
BB Method

- Uses all the events and sites simultaneously
- The FAS is inverted for κ_0, stress parameter, and **M**
  - Common crustal path damping parameter Q(f) and geometrical attenuation were used



κ_{BB}

Fits entire spectrum



- 1 starting model and 4 final models

		Q	η	mean κ_0(s)	mean M	Amplification
	Starting Model	200	0.68	0.040	1.97	rock/soil
Best estimate	Model 1	200	0.68	0.033	2.14	rock/soil
So. Cal Q(f)	Model 2	152	0.72	0.034	2.17	rock/soil
Freq. indep. Q	Model 3	1000	0.00	0.024	2.00	rock/soil
No crustal ampl.	Model 4	200	0.68	0.034	2.37	unity

Modified from PEER Report 2014/09

GMC Focus Area Q1 Response

BB Method: Results

- Mean κ_0 = 0.033 sec
- $\sigma_{\ln\kappa}$ = 0.5
  - Corresponds to 0.020-0.054 sec

Mean of individual inversion results for 14 sites from best estimate model (Model 1)

Site	κ0_BB (s) (Model 1)
113A	0.046
114A	0.030
115A	0.048
Y14A	0.023
Y15A	0.052
Z13A	0.058
Z14A	0.032
Z15A	0.015
NEE2	0.025
W13A	0.045
X13A	0.024
Y13A	0.015
Y12C	0.043
Y16A	0.051

- Scatter evaluated by sensitivity analyses

Variation in fixed input parameters

Parameter variations	Change in median κ0_BB (s)
Qo/1.5	κ/1.14
Qo•1.5	κ•1.03
η/1.5	κ/1.32
η•1.5	κ•1.21
RC/1.5	κ•1.02
RC•1.5	κ•1.03
κ/2	κ•1.01
κ•2	κ•1.01
$\Delta\sigma$•2	κ•1.09
$\Delta\sigma$/2	κ/1.06
amp/1.3	κ•1.03

Q(f)=Qo*f^n

geo-spreading

κ

stress drop

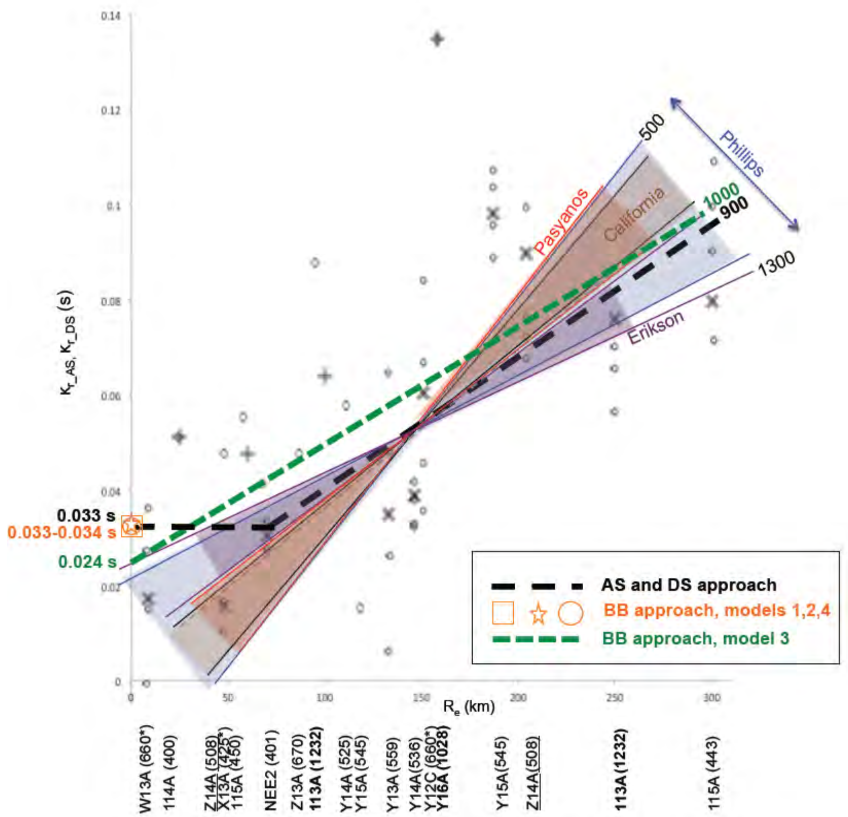
crustal amplification

- 32% change in median by varying fixed parameters (taken independently)
- Q_0, eta and k are coupled due to limited bandwidth and distance range
- A $\sigma_{\ln\kappa}$ = 0.5 in an appropriate value for epistemic uncertainty on median κ_0 estimate

Result's scatter is informed by sensitivity analyses

GMC Focus Area Q1 Response

Uncertainty in Target Kappa Estimate

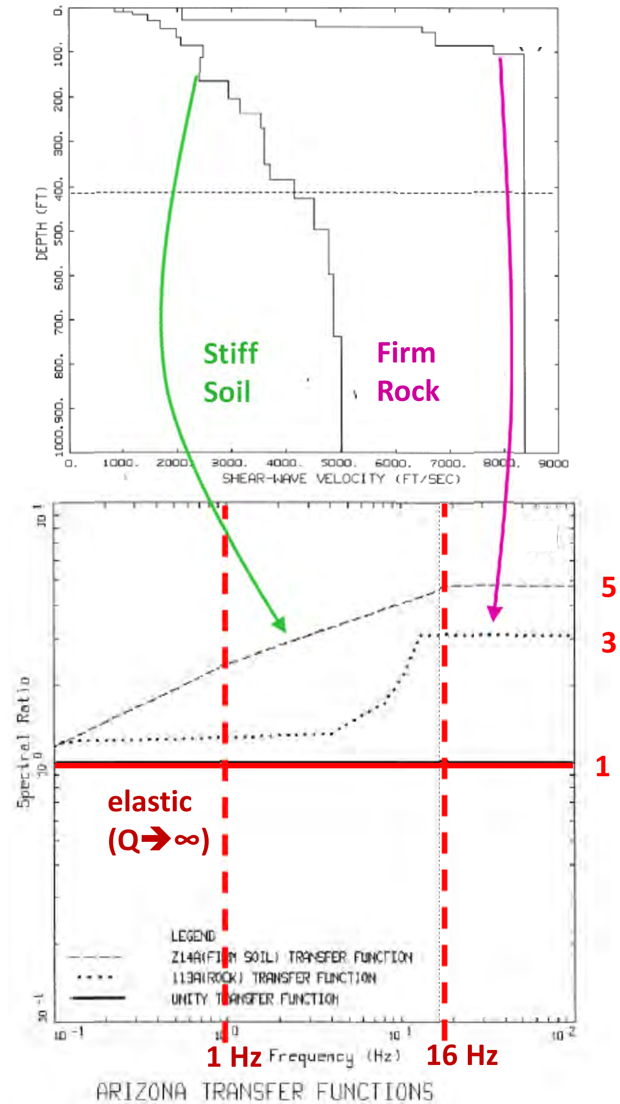


- Consistent mean κ_0 estimates
- Consistent scatter:
  - AS/DS: 0.033±0.014 sec
    - COV=0.014/0.033=0.43
    - $\sigma_{\ln\kappa}$=~0.41
  - BB: $\sigma_{\ln\kappa}$=0.5 (logarithmic range)
  - The BB Model 3's results (constant Q) are within the range of uncertainty from both approaches
- Consistent resulting Q (850-1050)
  - Within the scatter of independent estimates for the region

GMC Focus Area Q1 Response

Treatment of Site Amplification

- Transfer functions were computed from the two reference extrapolated profiles
  - They represent linear-elastic amplification, excluding any damping, from the source region (assumed to be at 10 km) to the surface at the site
- In all three approaches of kappa estimation (AS, DS, BB), the FAS are corrected for crustal amplification



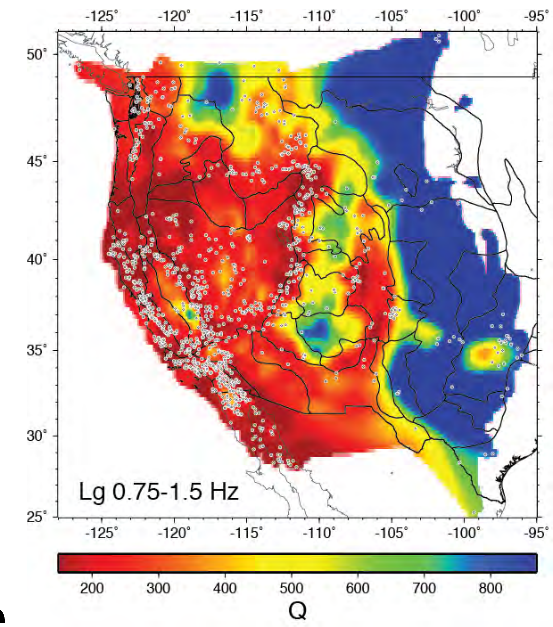
GMC Focus Area Question 2

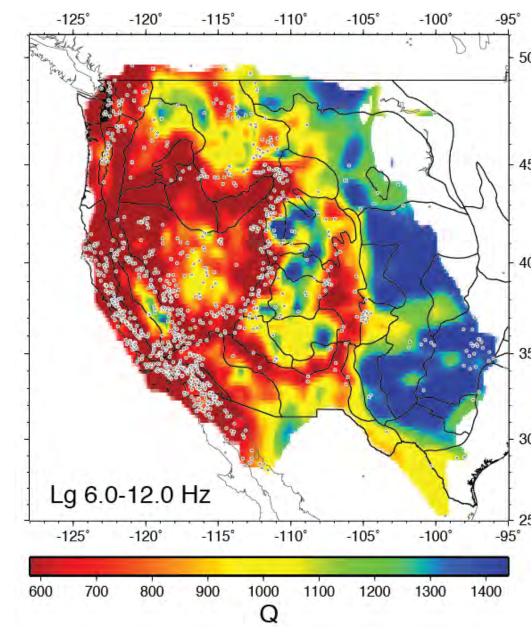
NRC GMC Q2: *Provide additional detail regarding the evaluation of candidate GMPEs for PVNGS for distant California and Mexico sources. Specifically, describe in more detail the evaluation of Kishida et al. (2014) of the potential effects of the Q differences on the ground motions, which provides justification for the conclusion that although there are differences in Q between California and Arizona, these differences do not lead to a significant discrepancy in the average distance attenuation over the distance range of 200-400 km.*

GMC Focus Area Q2 Response

Regional Q Evaluation:
Phillips et al. (2013) Model

- Inversion for Q in individual bands along with moment and corner frequency source parameters
  - Q(f) evaluated at 0.5 deg (50 km) grids
- Higher Q (lower attenuation) in Arizona (towards mid-west in general) as compared to California
  - Effect more pronounced at higher frequency



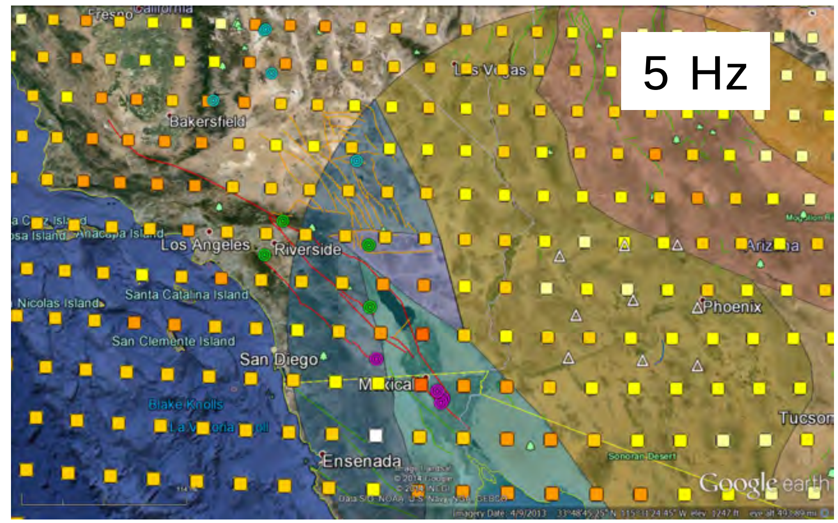


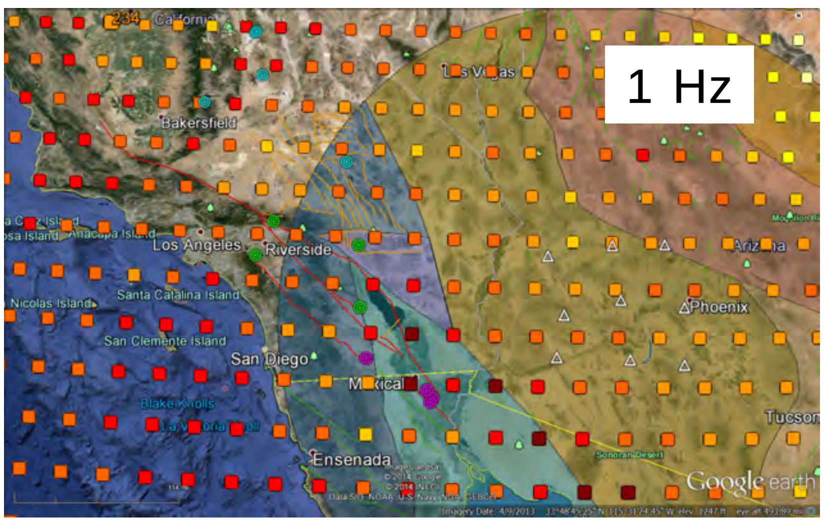
GMC Focus Area Q2 Response

Regional Q Evaluation: Phillips et al. (2013) Model (Cont’d)

- Zoom in at regional level:
  - Compute Q(f)=Qo*f^n at grid points
  - Q changes do not appear drastic
  - Look at ray-paths from CA events to central Arizona

Gridded values obtained from Phillips et al. (2013)





Q(f) ranges

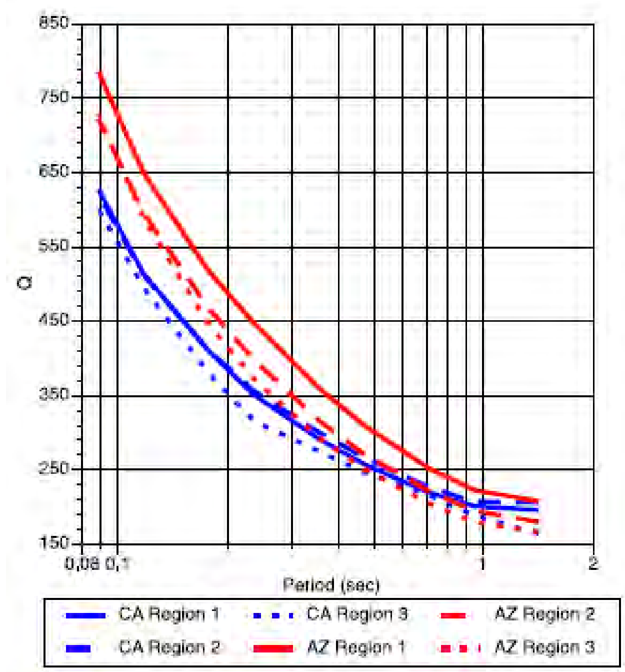
- Q(f) < 100
- 100 < Q(f) < 150
- 150 < Q(f) < 225
- 225 < Q(f) < 340
- 340 < Q(f) < 500
- 500 < Q(f) < 750
- 750 < Q(f) < 1150

GMC Focus Area Q2 Response

Regional Q Evaluation: Phillips et al. (2013) Model (Cont'd)

- Path weighted attenuation (sum of 1/Q) in the 200-400 km range
  - 14 NGA-West2 events with epicenters in CA recorded by stations in CA and AZ
  - Q differences between CA and AZ are visible for short periods, but disappear at longer periods
  - CA events contribute to PVNGS hazard at long periods (T > 0.5 – 1 sec)

Changes in Q between CA and AZ are negligible for hazard-significant frequencies



Comparison of *Q* values from earthquakes located in Regions 1, 2, and 3 to stations in California and Arizona at a rupture distance of 200–400 km.

From Kishida et al. (2015) – Chapter 5

GMC Focus Area Q2 Response

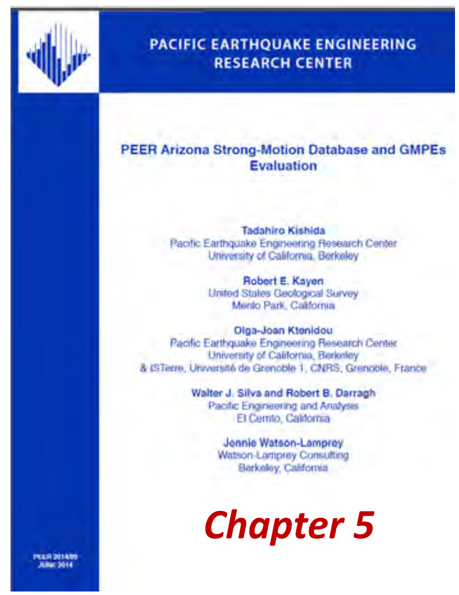
Adequacy of Attenuation with Distance

- Empirical check of evaluation:
  - 6 events in Region 1, 4 events in Region 2 and 4 events in Region 3
  - PEER report compares distance scaling for four periods (0.2, 0.5, 1 and 2 sec)
    - Data corrected for event term and V_{S30} scaling (500 m/s)
  - Focus of hazard is for low frequencies from CA earthquakes

Table 5.1 NGA-West2 earthquakes selected for analysis.

NGAW2 EQID	Hypocenter latitude	Hypocenter longitude	Depth (km)	Magnitude	Region
280	32.300	-115.267	0	7.2	3
1004	32.4105	-115.3120	18.65	5.1	3
1005	34.8118	-116.4227	9.33	5.06	1
1009	36.4011	-117.8397	7.419	4.73	1
1017	32.3362	-115.2425	17.16	4.63	3
1018	34.1081	-117.3062	14.795	4.45	2
1020	33.8776	-116.2019	10.062	4.26	2
1028	33.7328	-117.4921	10.018	4.73	2
1047	35.4744	-118.4262	6.678	4.43	1
1053	35.8373	-117.678	6.864	4.34	1
1058	32.707	-116.040	10.16	4.41	3
1067	33.2262	-116.1472	10.889	4.29	2
1182	36.3864	-117.8583	7.408	5.0	1
1186	36.4034	-117.8499	9.418	5.19	1

The attenuation from California to central Arizona is not different from the attenuation within California at low frequencies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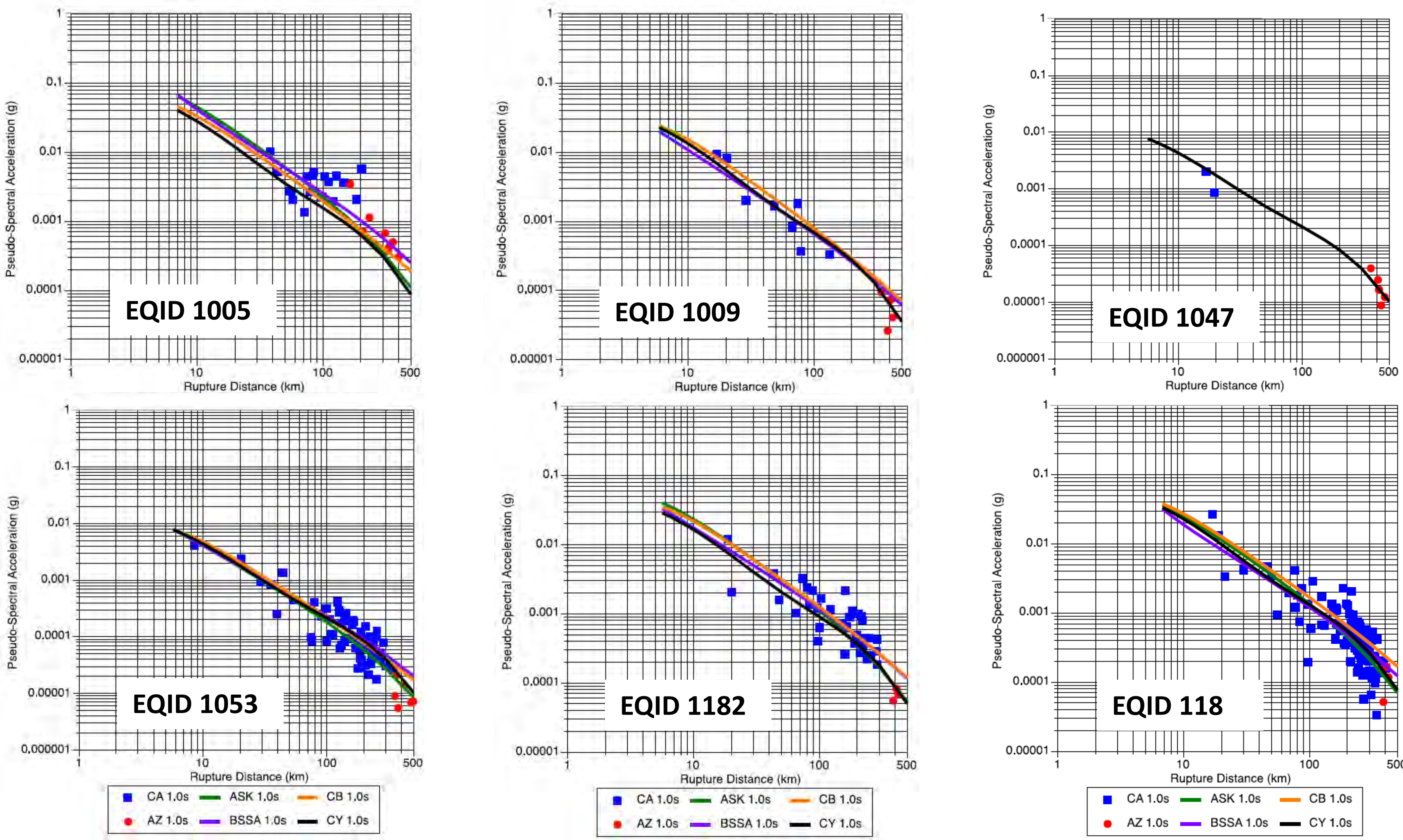
Watson-Lamprey Consulting
Berkeley, California

Chapter 5

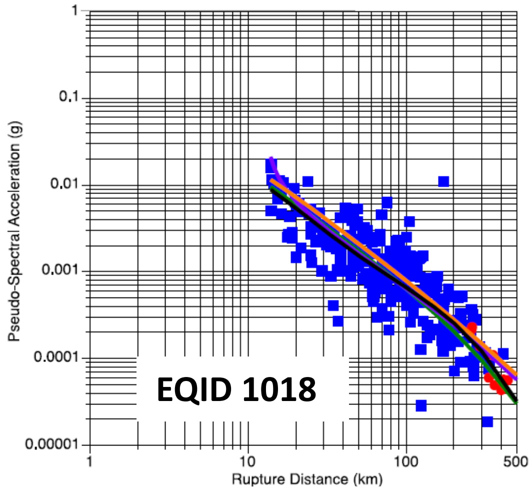
GMC Focus Area Q2 Response

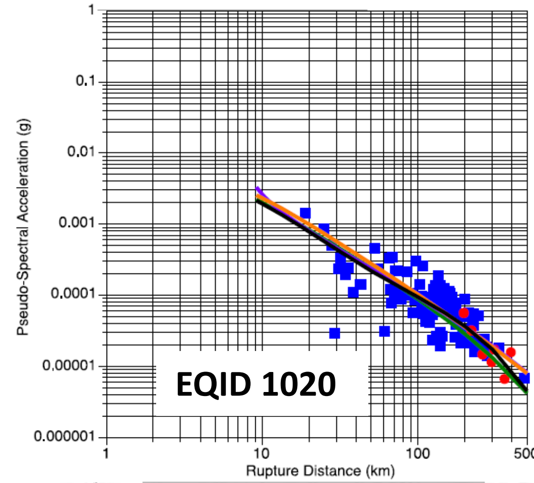
Attenuation with Distance: Region 1 (1 sec)

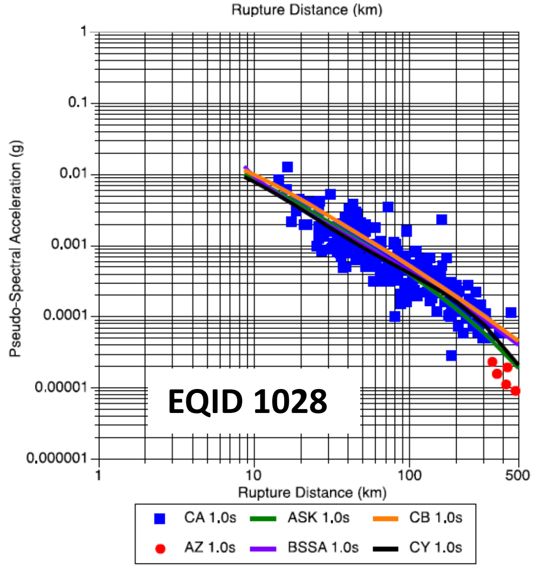


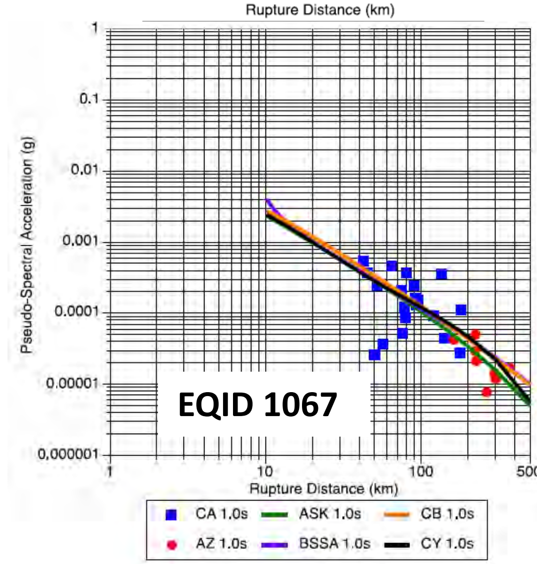
GMC Focus Area Q2 Response

Attenuation with Distance: Region 2 (1 sec)



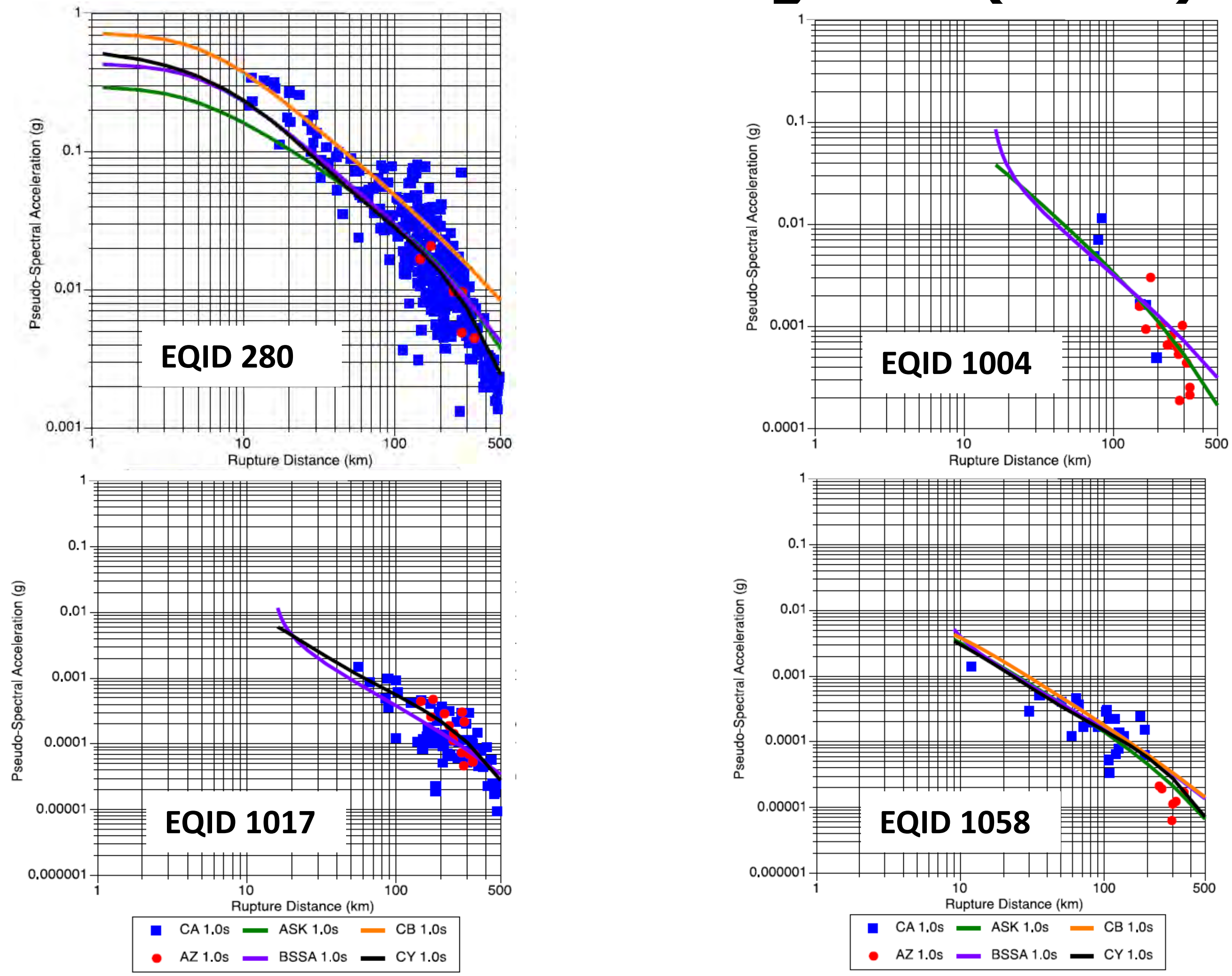






GMC Focus Area Q2 Response

Attenuation with Distance: Region 3 (1 sec)



GMC Focus Area Question 3

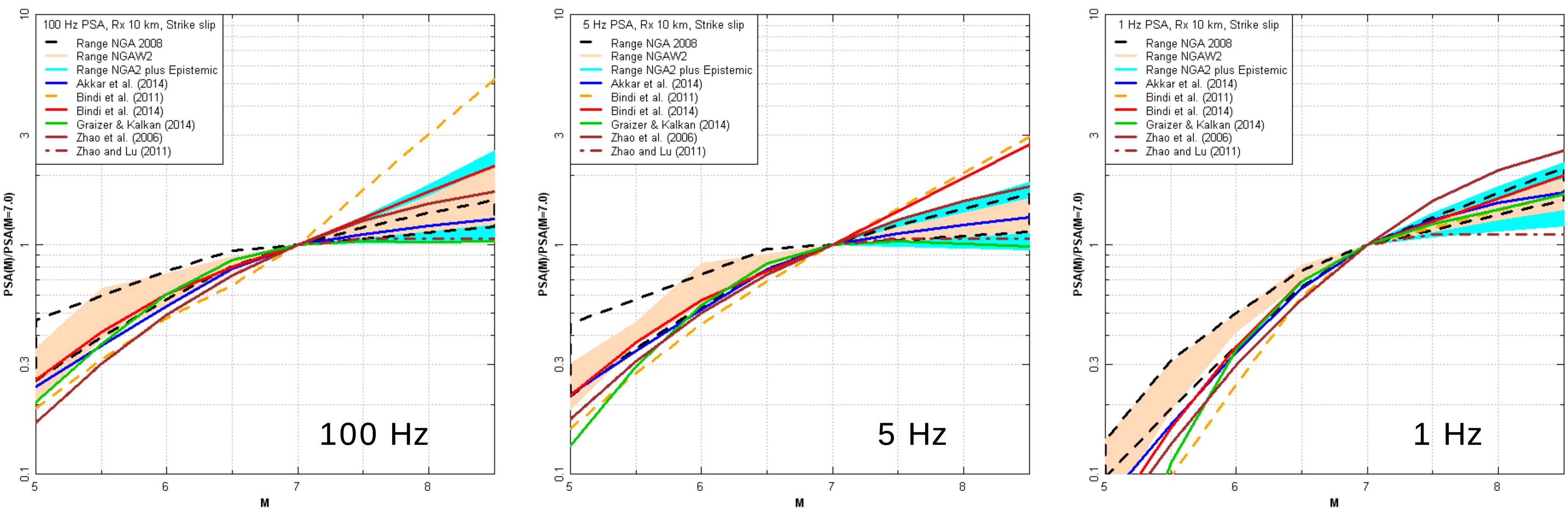
NRC GMC Q3: *With regard to the candidate GMPEs for PVNGS for the Greater Arizona Sources, provide additional rationale for limiting the use of the Bindi et al. (2014) for magnitudes greater than M7.*

GMC Focus Area Q3 Response

Limitations in Bindi et al. (2014) GMPE

- Problematic intermediate-frequency magnitude scaling (**M**>7):
  - Apparent in the 2011 version
  - Resolved for PGA in the 2014 version, but not for 5 Hz
  - Application limited at **M**7 for all periods

From TI Team's WS#3 presentation (Day 1)



GMC Focus Area Question 4

NRC GMC Q4: *Provide additional detail on the development of the common function form used to fit the candidate GMPEs. Specifically, please discuss how model parameters such as depth to Vs=1 km/s and 2.5 km/s (which are present in some of the candidate GMPEs) are accounted for in the final functional form.*

GMC Focus Area Q4 Response

Greater AZ Median Model: Common-form Functional Form

- Two Alternative Distance Metrics:
  - R_{RUP}-based common-form models (Model A)
  - R_{JB}-based common-form models (Model B) > no explicit Z_{TOR} scaling ($a_8=0$)

$$Ln\left(SA_A(M,R_{RUP},Z_{TOR},F,T)\right)=a_0(T)-a_7^2(T)R_{RUP}+a_8^2(T)Z_{TOR}-a_9^2(T)F_{NML}$$
$$+\left(a_4(T)+a_5(T)(M-5)\right)\ln\left(\sqrt{R_{RUP}^2+a_6^2(T)}\right)+a_{10}(T)F_{RV}$$
$$+\begin{cases}-a_1(T)+a_2(T)(M-5.5) & for\,M<5.5\\ a_1(T)(M-6.5) & for\,5.5\le M\le 6.5\\ a_3(T)(M-6.5) & for\,M>6.5\end{cases}$$

- Applicable Style-of-Faulting:
  - The common form is derived for SS and NML earthquakes only and a single REV factor is added at the end

GMC Focus Area Q4 Response

Common-form Models: Fitting

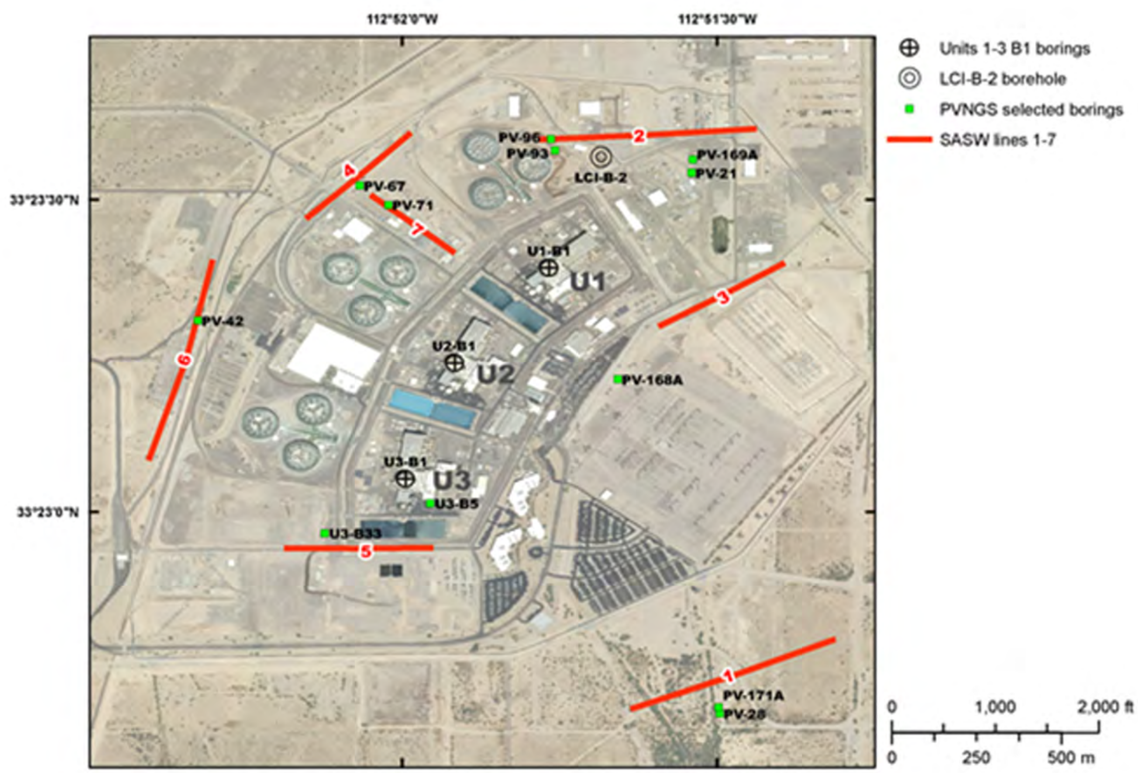
- Fitting Process:
  - V_{S30} = 760m/s, **M**5 to **M**7.5, R_X = -200 to 18 km (R_X>0 for R_{JB}=0km conditions), dip of δ = 50° (NML events)
  - Site parameters, $Z_{1.0}$ and $Z_{2.5}$ are set to their default values for V_{S30}=760 m/s by NGA developers
    - Basin depth is not a significant issue for soft-rock sites
  - HW model added to R_{RUP}-based common-form models
  - No HW model added to R_{JB}-based common-form models

Site Response

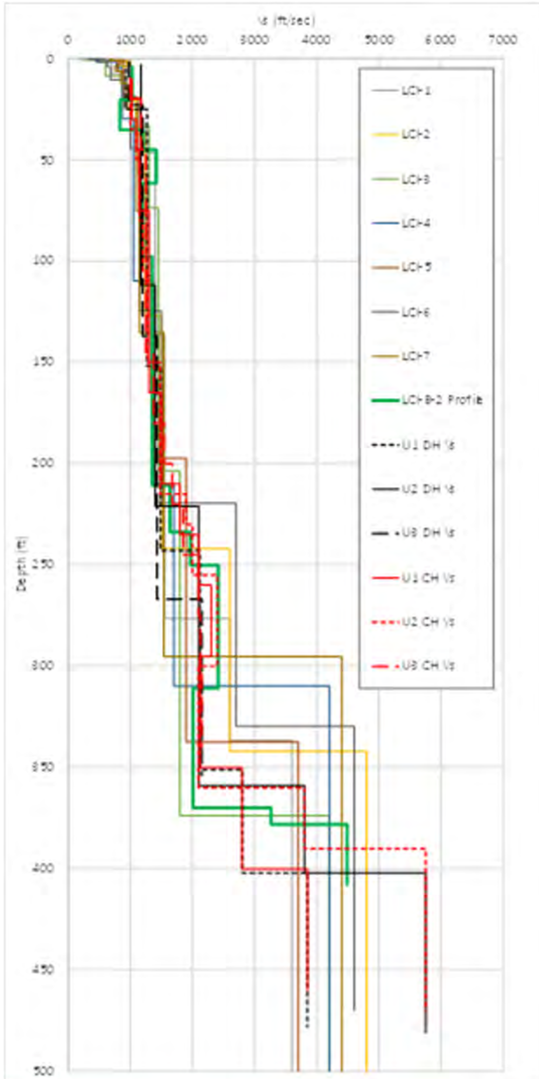
PVNGS Site Response

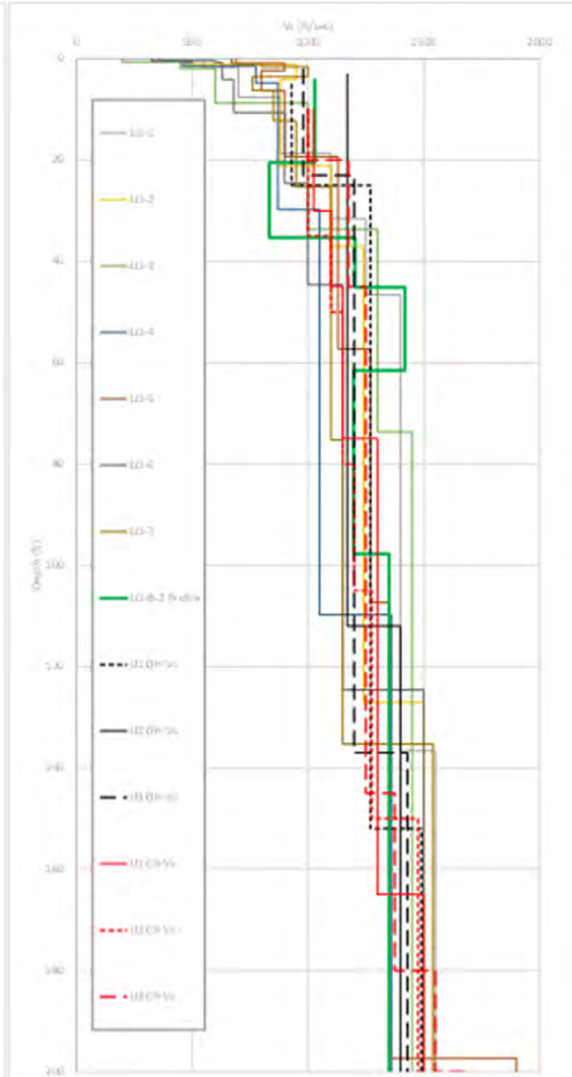
- Two elements
  - Adjustment of motions from SWUS Reference Rock to PVNGS rock
  - Site response proper (conversion of PVNGS rock motions to the surface, taking into account the effect of soils)

Site Geophysical Data Collection for Site Response Analysis



Vs Comparison (SASW, Suspension Logging, Downhole, and Cross-Hole)





Adjustment from SWUS Reference Conditions to PVNGS Rock (1)

- Inputs:
  - From SWUS Project: Reference (host) Vs and density profiles, host kappa; PVNGS (target) kappa, including uncertainty
  - From PVNGS PSHA Project: PVNGS (target) Vs and density profiles from local and regional data (*Deep Profile*)
- Approach (Vs-kappa adjustment)
  - Assume linear behavior
  - Use quarter-wavelength approach
  - Consider uncertainty in PVNGS profiles and kappa
  - Result: 9 adjustment factors (transfer functions in Fourier space*), with associated weights

* requires IRVT-adjustment-RVT for calculation of Spectral Acceleration

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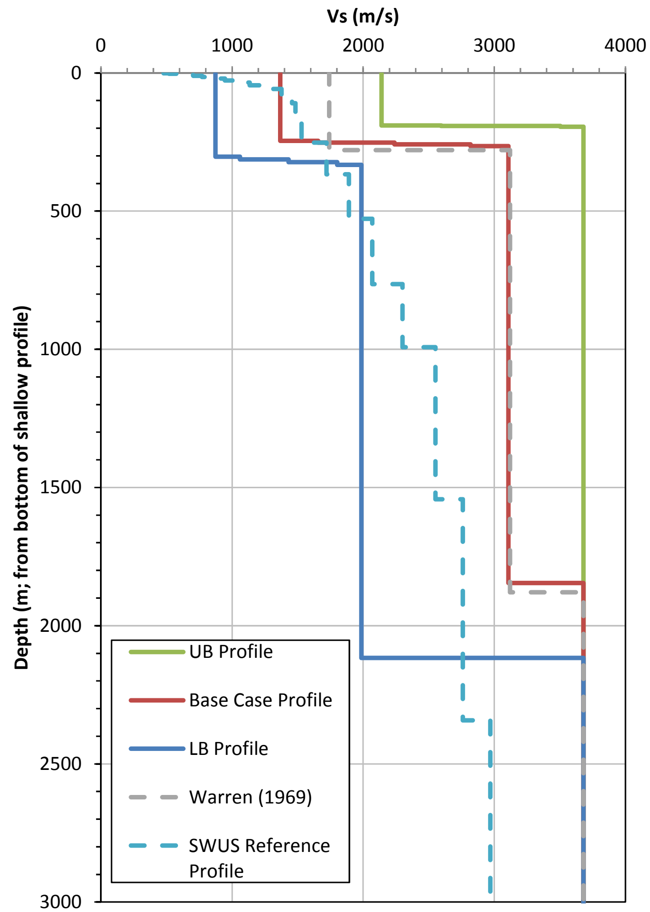
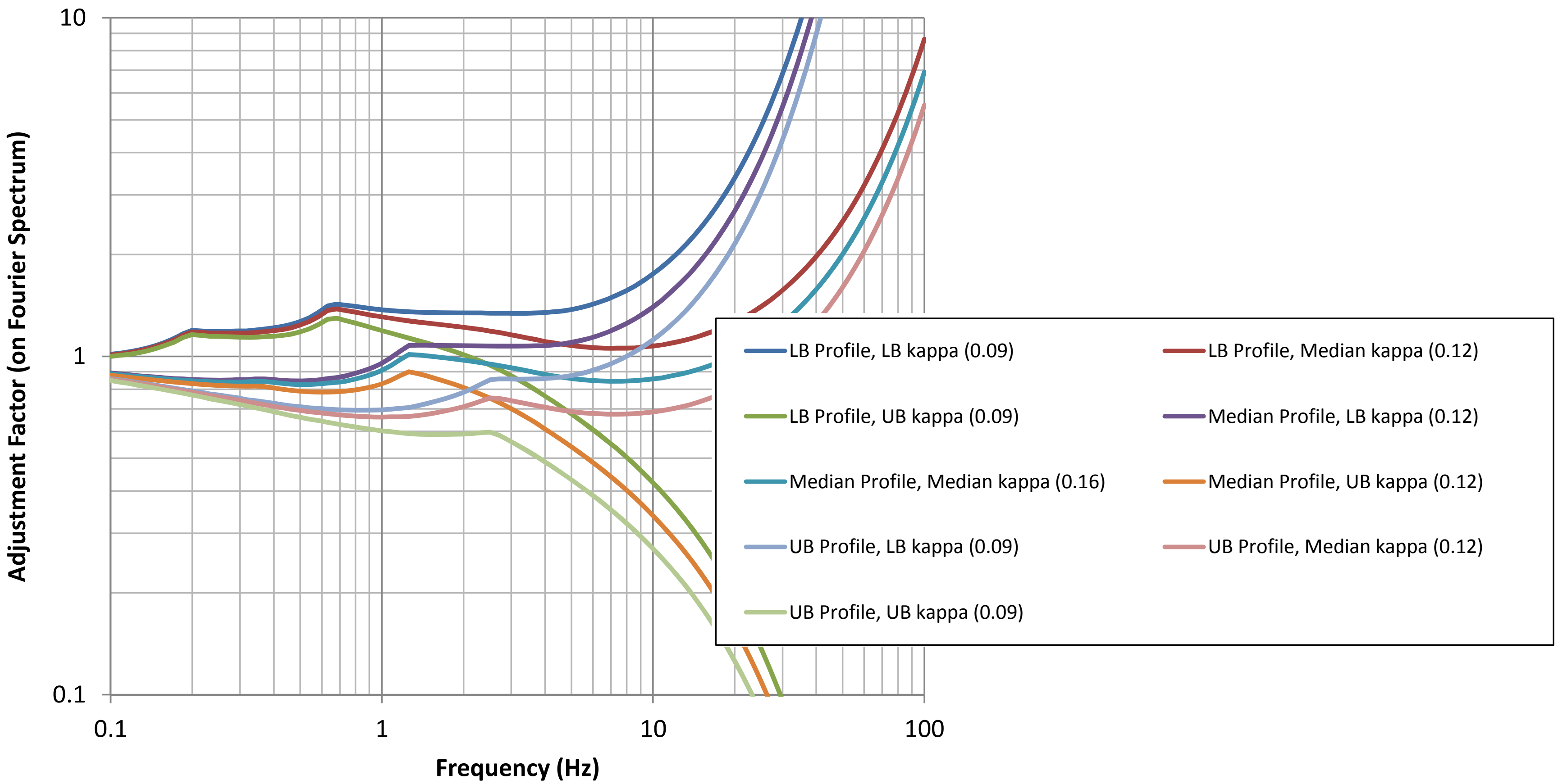
Adjustment from SWUS Reference Conditions to PVNGS Rock (2: Inputs)

- Reference kappa
  - 0.041 s
- PVNGS kappa
  - Median: 0.033 s
  - $\sigma_{\ln[kappa]}$: 0.5



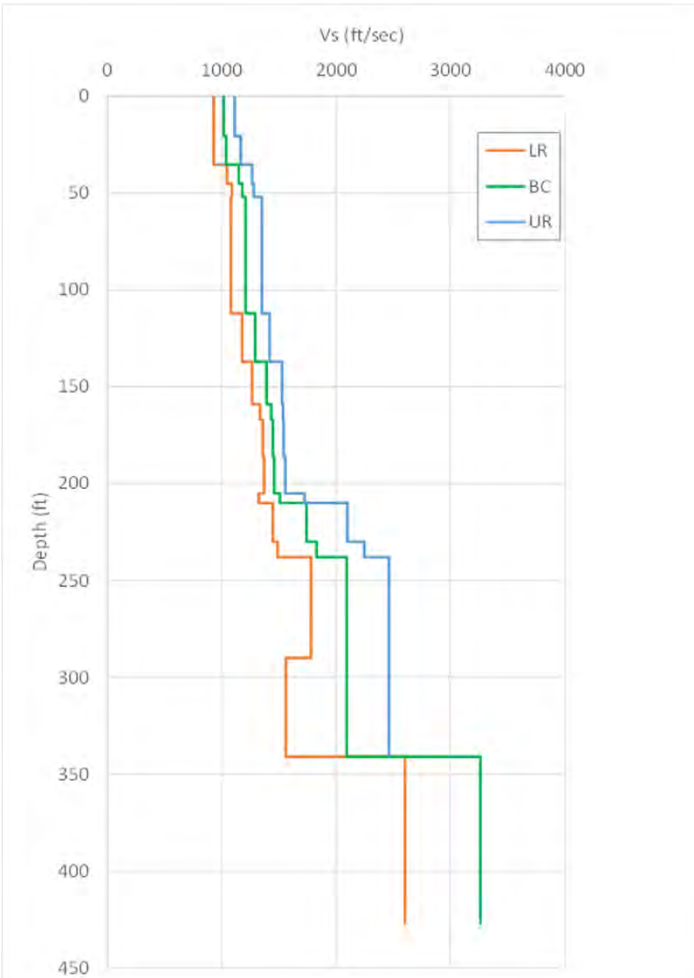
Adjustment from SWUS Reference Conditions to PVNGS Rock (3: Results)

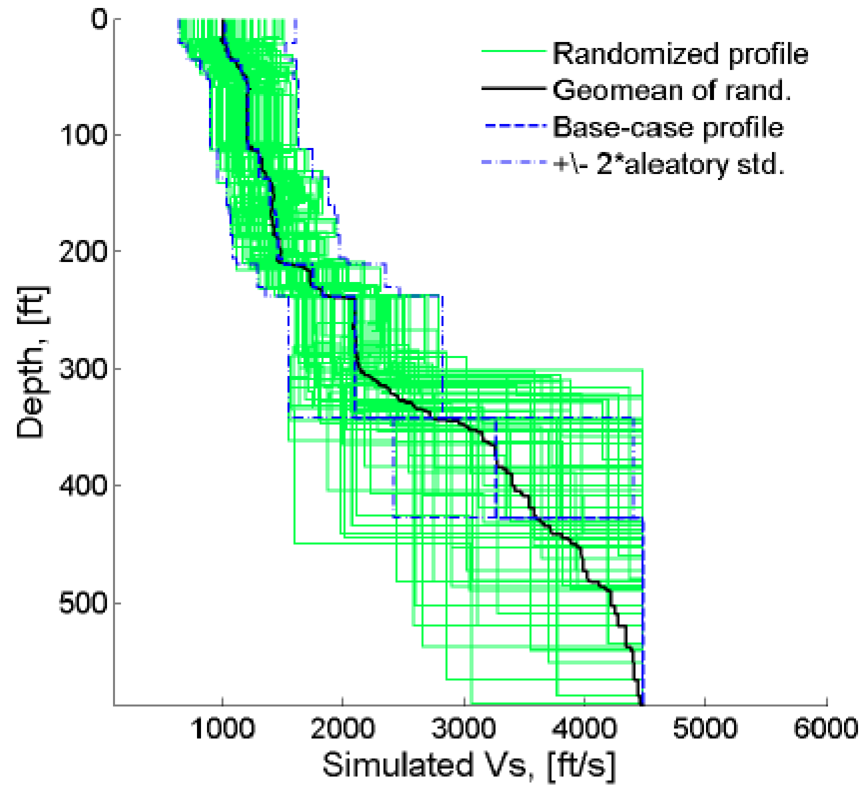


Site Response

- Inputs (shallow profile, range is representative of the 3 sites)
  - Stratigraphy from UFSAR and PSAR
  - Vs from suspension logging, SASW, and UFSAR
  - Degradation Curves
    - Sands: EPRI (1993) and Peninsular Range
    - Vucetic and Dobry with a broad range of PI
- Approach:
  - Profile randomization following SPID
  - Standard SHAKE-style calculation using RVT

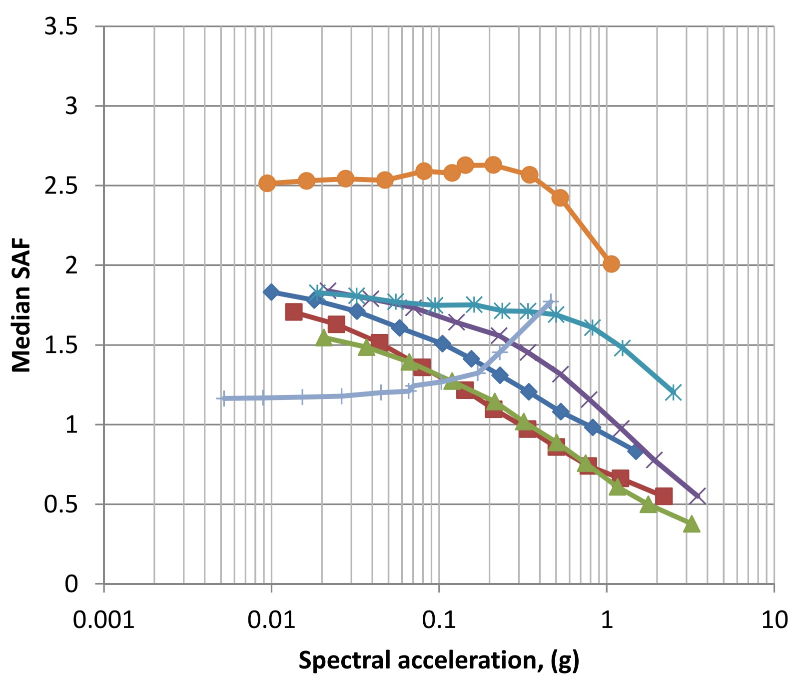
Site Response: Shallow Profile

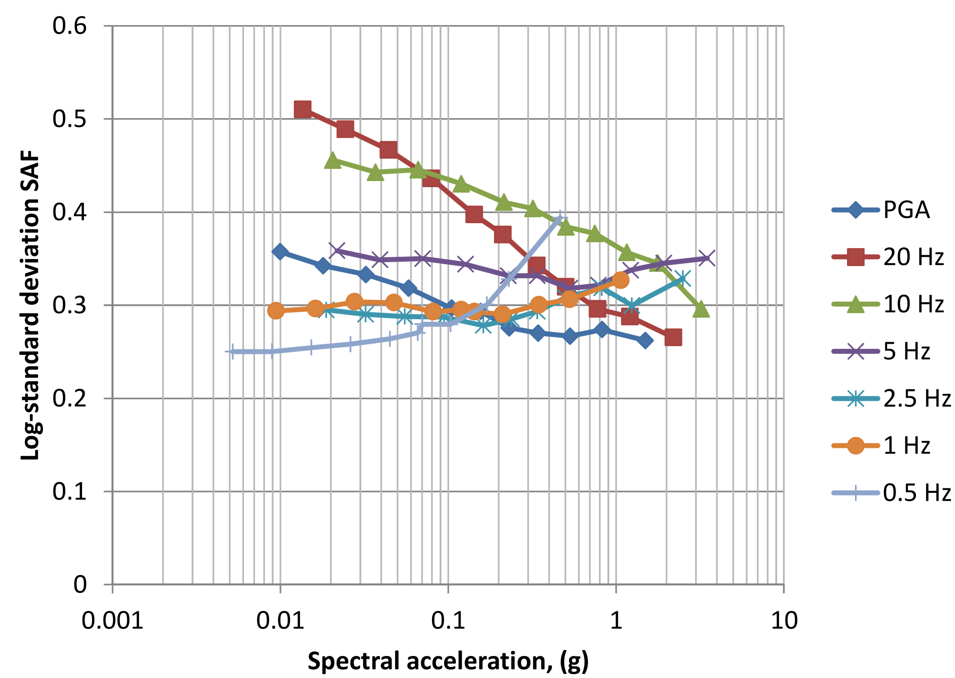




Randomized Vs profiles for base case (BC) median profile

Amplification Factors (Reference→Surface; base case)





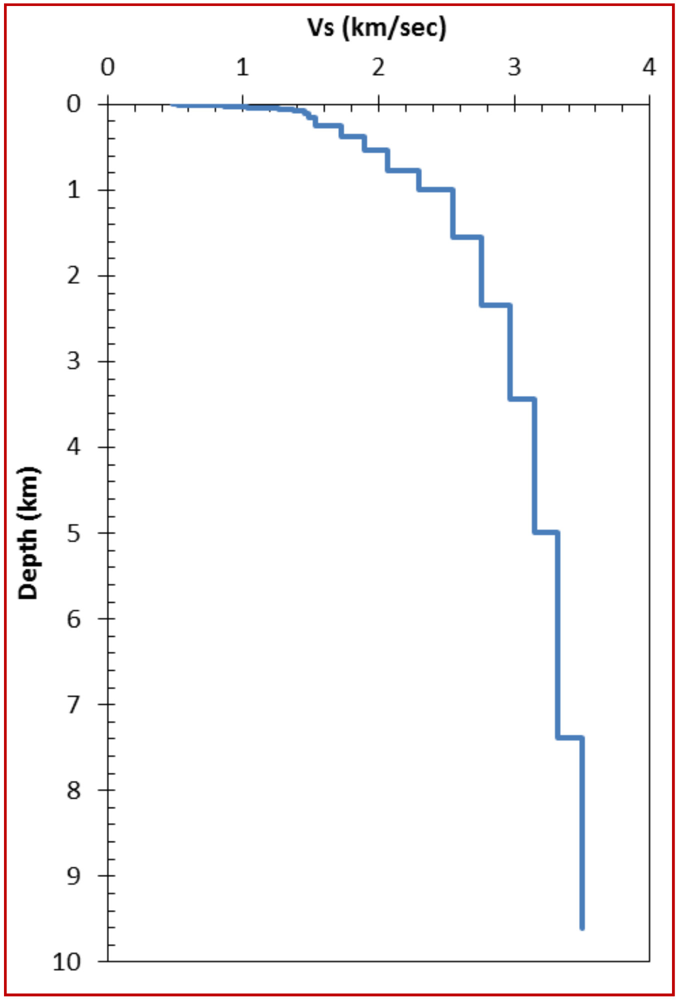
Site Response Focus Area Question 1a

NRC Site Response Q1a: *Provide additional detail regarding the Vs-kappa adjustment factors. Specifically, provide the bases for*

a. the host Vs profile

Site Response Focus Area Q1a Response

- SWUS GMC host profile (V_S and density):
  - Reference V_S profile for the host region is the Kamai et al. (2013*) profile for V_{S30} of 760 m/sec
    - Representative of NGA-West 2 rock sites
    - Consistent with Host kappa value of 0.041 s
  - Reference density compatible with reference V_S profile



*PEER Report 2013/12

Site Response Focus Area Question 1b

NRC Site Response Q1b: *Provide additional detail regarding the Vs-kappa adjustment factors. Specifically, provide the bases for*

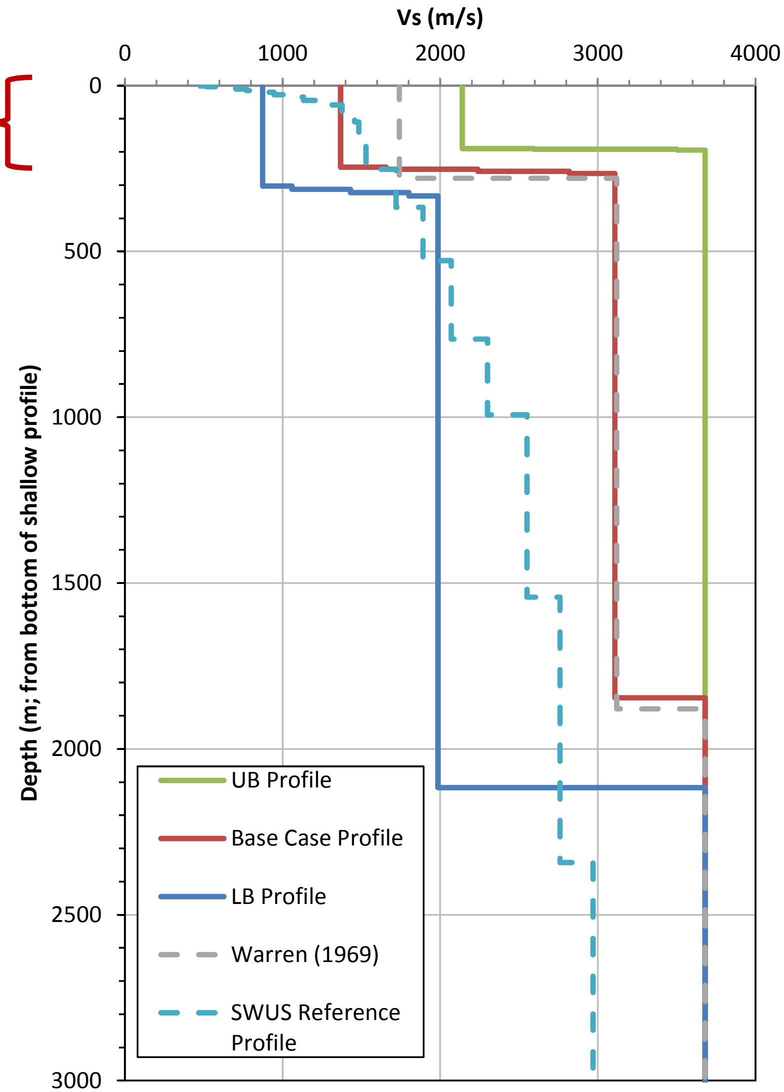
b. the target deep Vs profile (including the use of a logarithmic standard deviation of 0.35 to develop the upper and lower profiles)

Site Response Focus Area Q1b Response

Top portion (andesite, basalt, flow-breccia, and tuff)

- Vs from suspension-log data (LCI-B-2 profile)
- Thickness (& uncertainty) from UFSAR boreholes (consistent with Warren, 1969*)

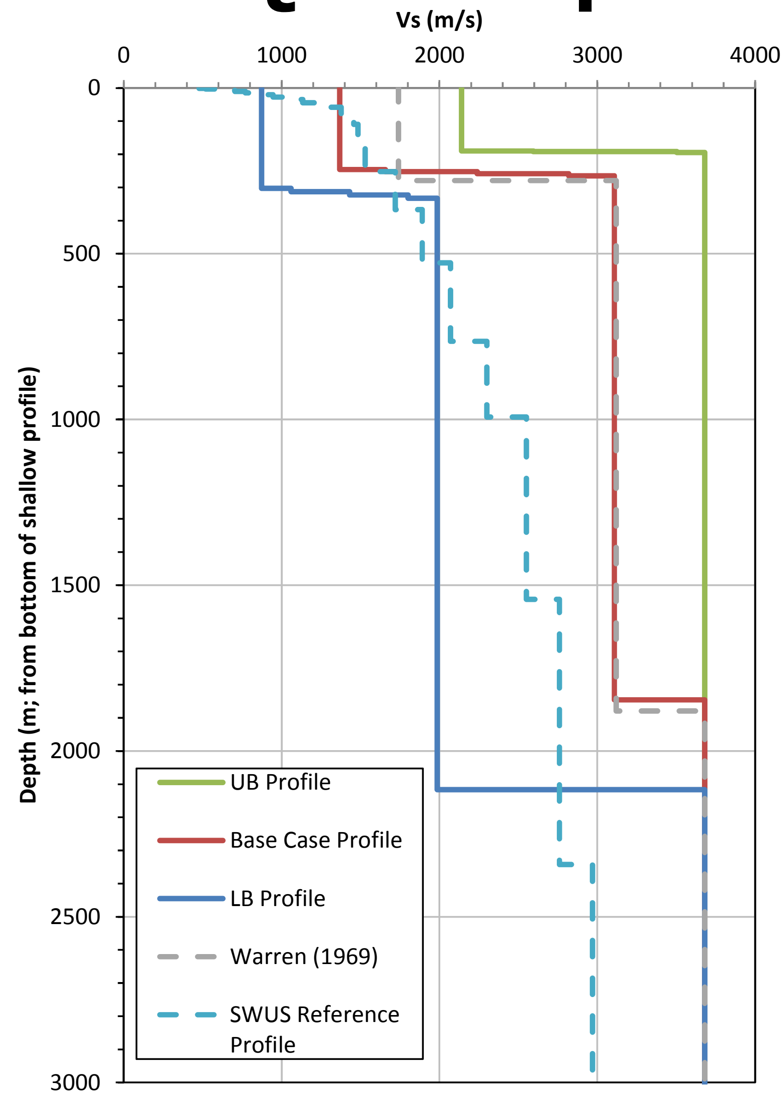
*Geological Society of America Bulletin, 80(2), 257-282; used by Lockridge et al. (2012) for earthquake location



Site Response Focus Area Q1b Response

Basement portion (granodiorite, metagranite)

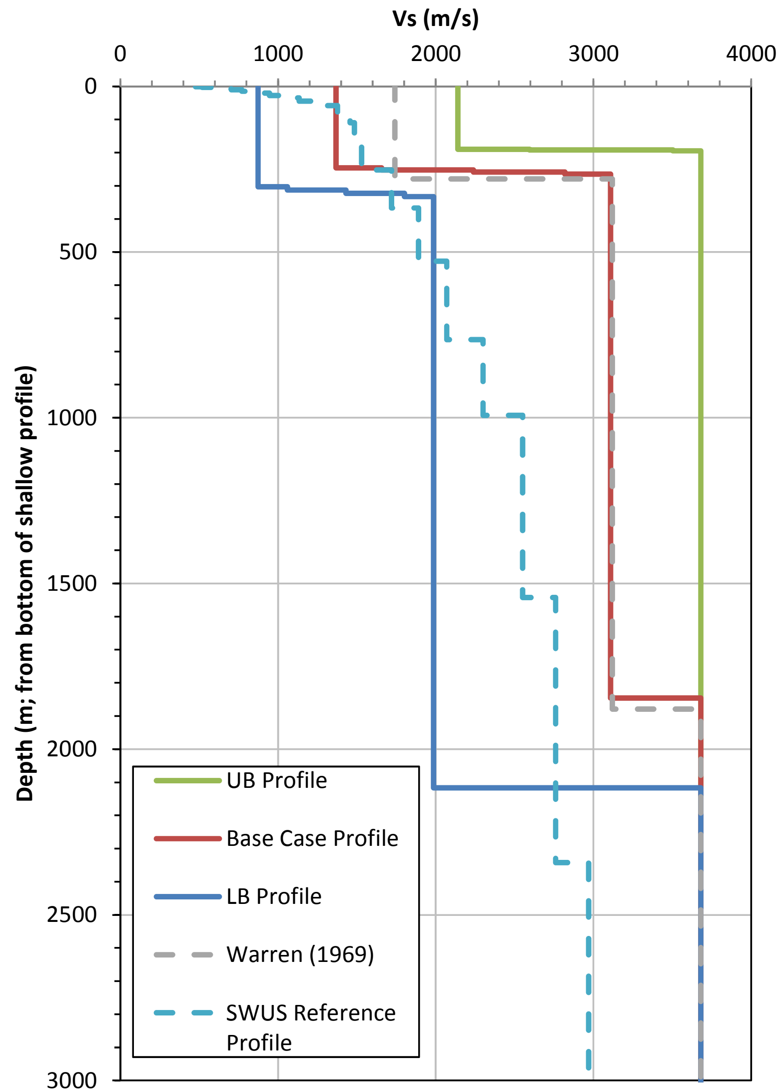
- Vs and thickness from Warren, 1969)
- Used 10% uncertainty for thickness of top basement layer



Site Response Focus Area Q1b Response

Rationale for 0.35 uncertainty in velocity:

Recommended by SPID (Section B.3.2) for "sites where geophysical information such as very limited shear-wave velocity data exists"



Site Response Focus Area Question 1c

NRC Site Response Q1c: *Provide additional detail regarding the Vs-kappa adjustment factors. Specifically, provide the bases for*

c. *the target kappa value used for the kappa adjustments and whether the input FAS were corrected to the site kappa of 0.033 sec or a lower baserock kappa value*

Site Response Focus Area Q1c Response

- Basis for target kappa value of 0.033 sec was provided in response to GMC Topic 1
- Input (Reference Rock) FAS were corrected to 0.033 sec ($\pm$uncertainty), which corresponds to Arizona rock

Site Response Focus Area Question 1d

NRC Site Response Q1d: *Provide additional detail regarding the Vs-kappa adjustment factors. Specifically, provide the bases for*

d. use of a logarithmic standard deviation of 0.5 to determine the upper and lower site kappa values

Site Response Focus Area Q1d Response

- Basis for logarithmic standard deviation was provided in response to GMC Topic 1
- Applied as follows:

Kappa (sec)	Weight
0.033*exp[-1.28*0.5]=0.0174	0.3
0.033	0.4
0.033*exp[+1.28*0.5]=0.0626	0.3

Site Response Focus Area Question 1e

NRC Site Response Q1e: *Provide additional detail regarding the Vs-kappa adjustment factors. Specifically, provide the bases for*

- e. *the scenario events (magnitudes and distances) used to develop the input spectra for the Vs-kappa adjustment factors*

Site Response Focus Area Q1e Response

- Vs-kappa adjustment was applied to each of the ground motion spectra used in the site-response calculations
- Spectral shapes are based on the 10^{-4}, 10^{-5}, and 10^{-6}, High- and Low-frequency Controlling Earthquakes, calculated using the approach in RG 1.208

Site Response Focus Area Q1e Response

Controlling Earthquakes

Motion	Magnitude (M_w)	Distance (km)
10^{-4} Low Freq.	7.5	210
10^{-4} High Freq.	6.1	18
10^{-5} Low Freq.	7.6	200
10^{-5} High Freq.	6.2	8.0
10^{-6} Low Freq.	6.8	8.0
10^{-6} High Freq.	6.4	6.0

Site Response Focus Area Question 1f

NRC Site Response Q1f: *Provide additional detail regarding the Vs-kappa adjustment factors. Specifically, provide the bases for*

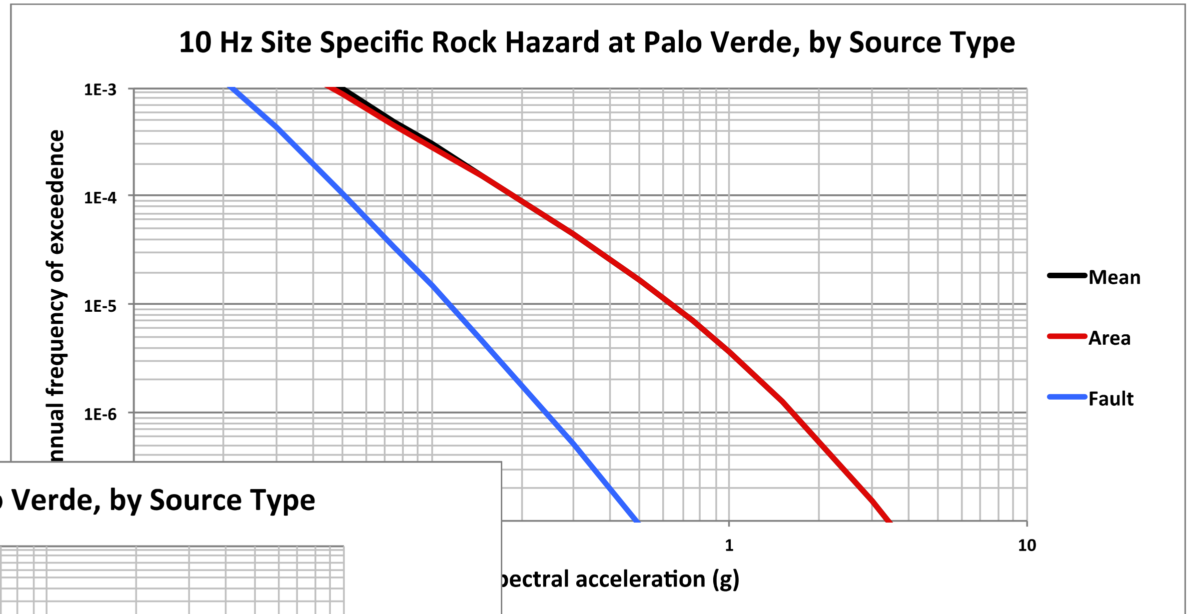
f. *not including the Vs-kappa adjustment factors as additional epistemic uncertainty on the median GMMs instead of capturing this variability as part of the variability in the site amplification functions*

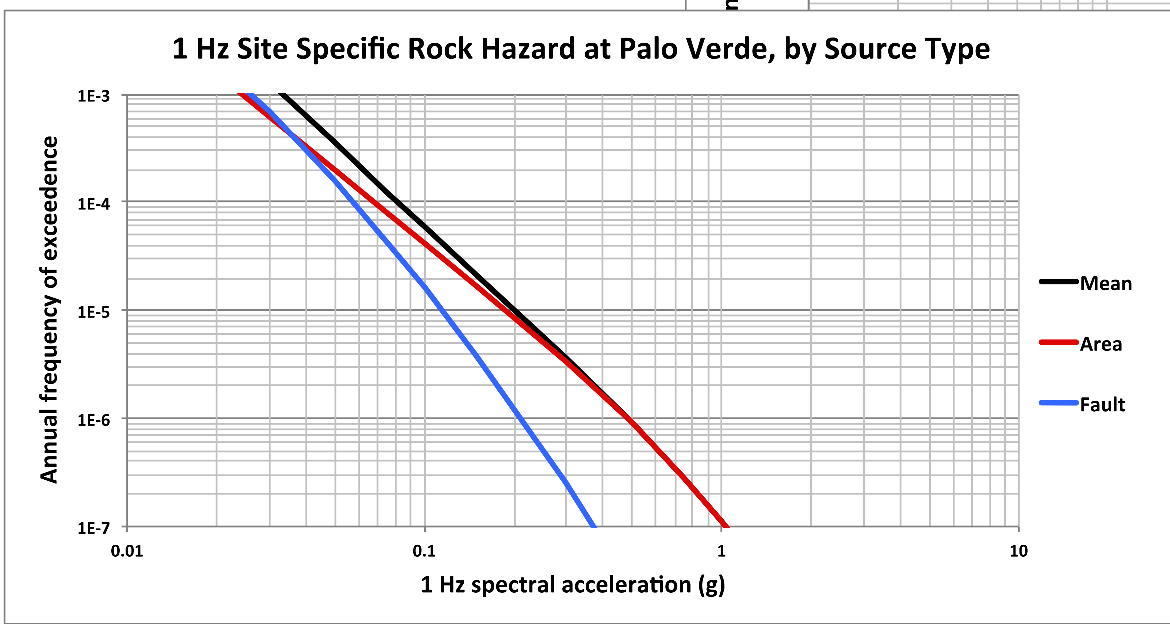
Site Response Focus Area Q1f Response

- Because NUREG/CR-6728 Approach 3 was used to convolve the rock hazard and site response, decision to include uncertainty in Vs-kappa adjustment factors as an uncertainty in the amplification functions has no effect on the mean hazard (→no effect on the GMRS)
- This decision was made for the sake of computational efficiency in hazard calculations

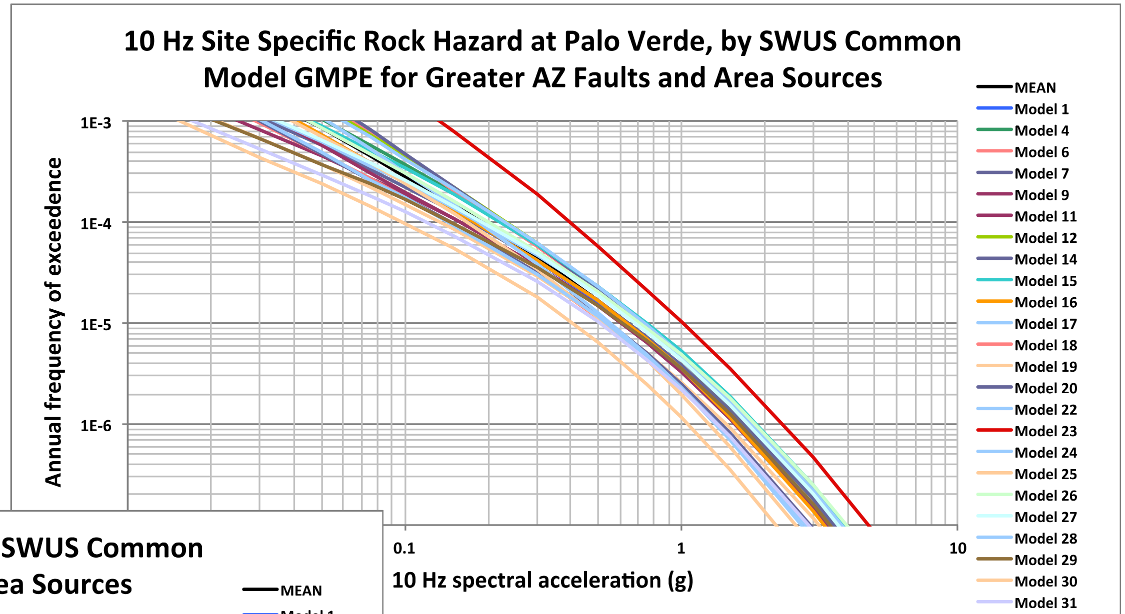
Probabilistic Seismic Hazard Analysis Results

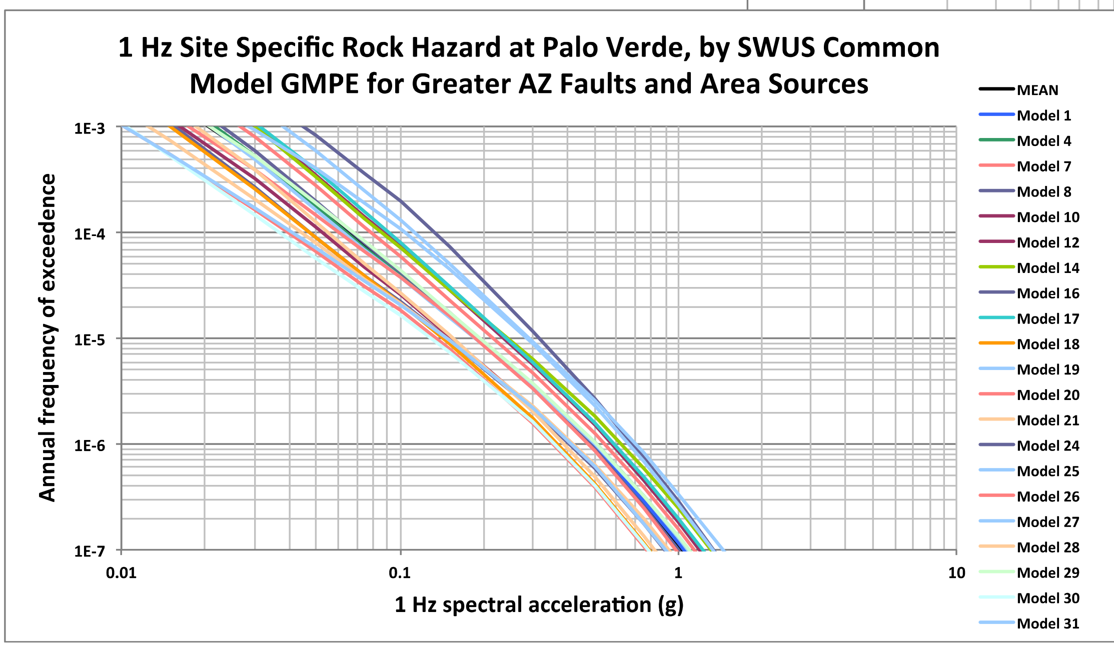
Hazard Sensitivities (rock)



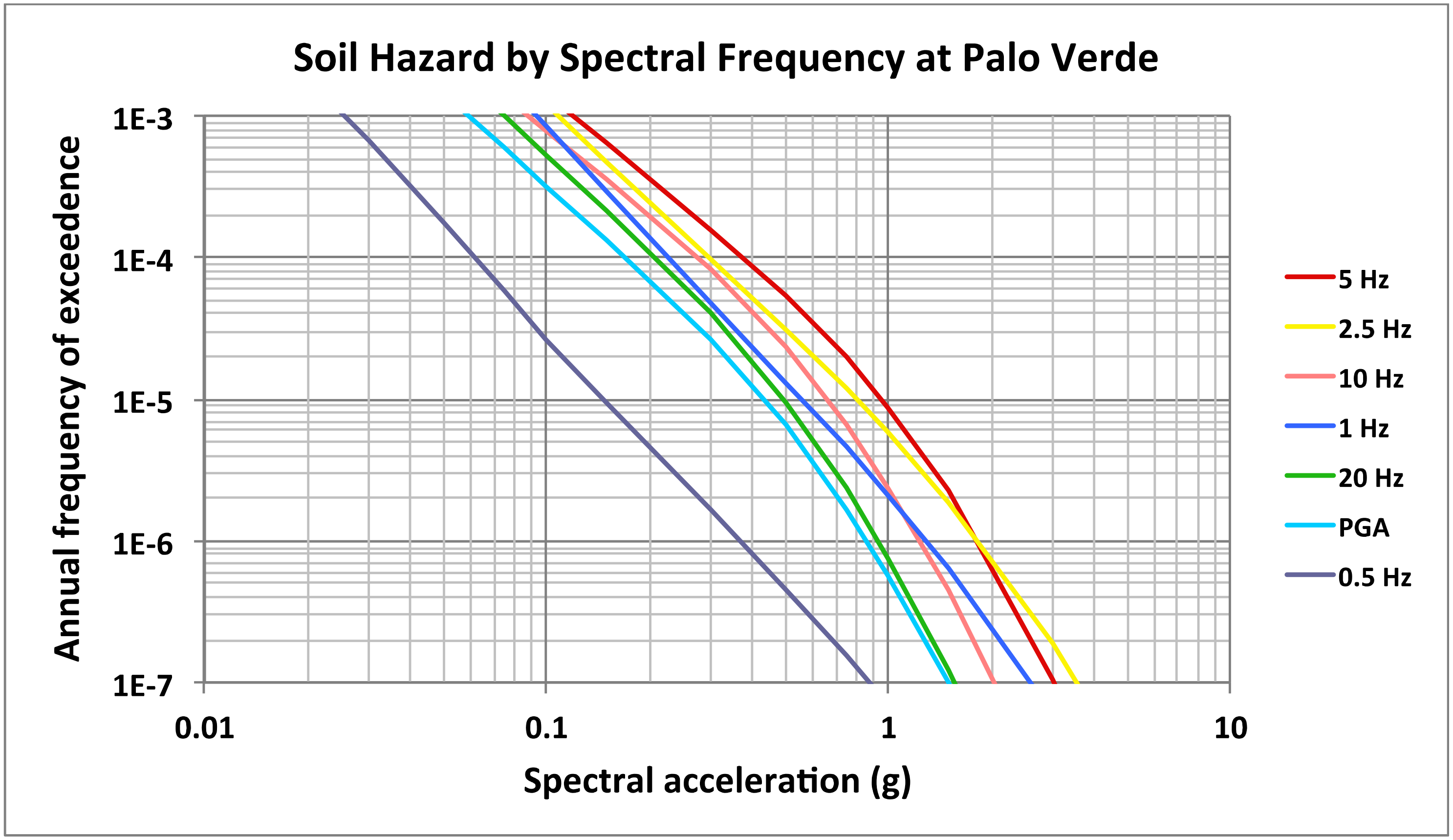


Hazard Sensitivities (rock; 2)

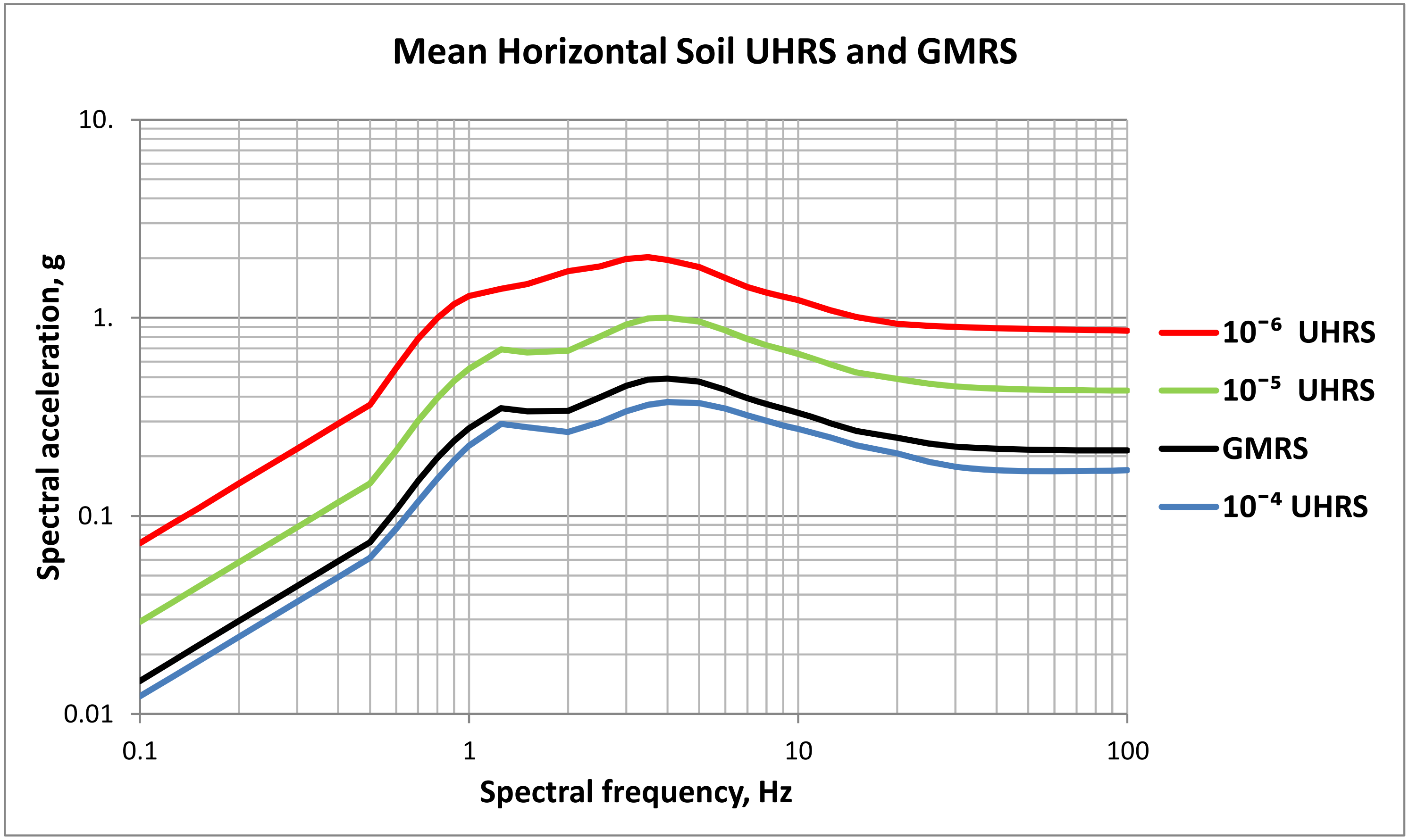




Hazard Results on Soil



Hazard Results on Soil (2)



PALO VERDE

PSHA Summary and Observations

- Approach and Scope
  - SSHAC Level 3 SSC and GMC Models
  - Site response used newly acquired site-specific SASW and suspension-logger data (as well as data from UFSAR), and followed Appendix B of SPID

→ Robust characterization of seismic hazard at PVNGS and its uncertainty

- Most important contributors to hazard
  - Area source zones (mainly SBR and East) dominant for 1 and 10 Hz and for 10^{-4}, 10^{-5}, 10^{-6}
  - Faults (mainly San Andreas, Cerro Prieto, and San Jacinto) important only at 1 Hz for 10^{-4}

PSHA Summary and Observations

Largest contributors to epistemic uncertainty in hazard

- GMC
  - Common-form models for Greater AZ
  - NGA-West 2 models for CA-MX faults (low frequencies only)
  - Path term for CA-MX faults (low frequencies only)
  - Additional epistemic uncertainty for CA-MX faults (low frequencies only)
  - Total sigma for CA-MX faults (low frequencies only)
- Site Response
  - Vs profile (BE, UR, LR) (low frequencies only)
  - Degradation Curves (high frequencies only)
- SSC
  - Mmax of SBR source (low frequencies only)

Seismic Hazard Screening

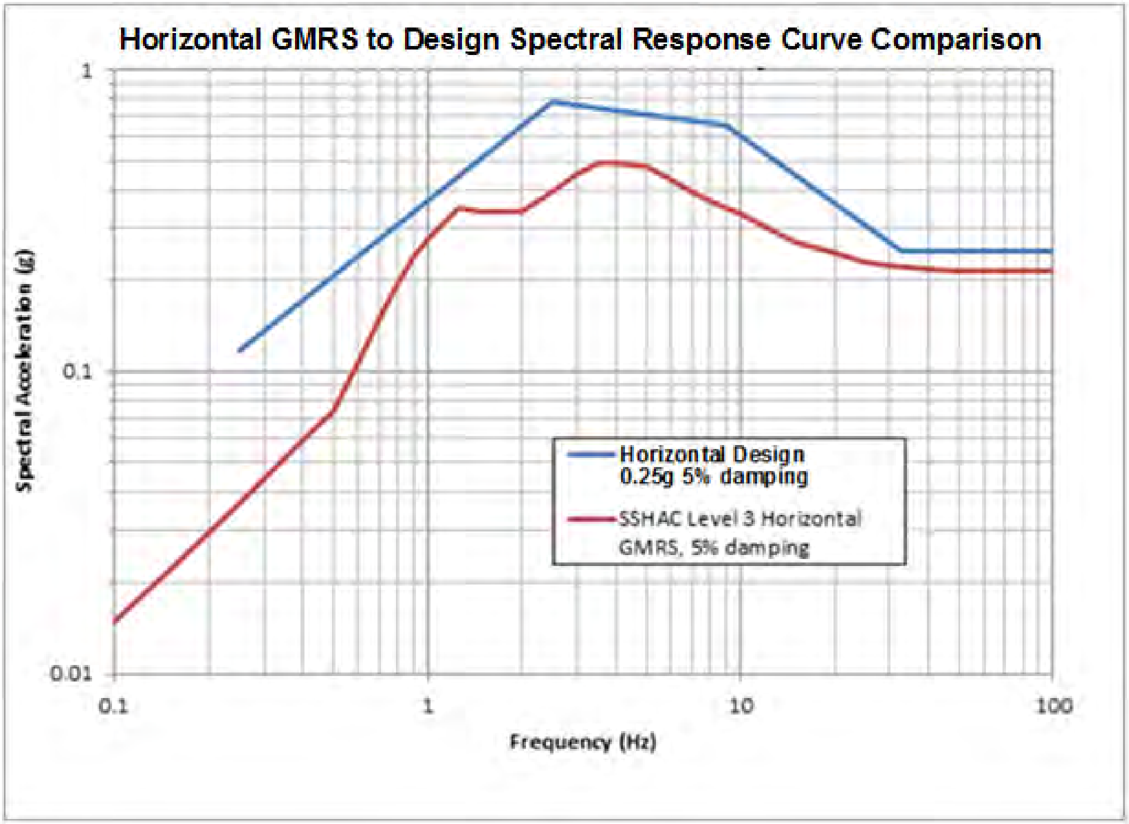
PVNGS Current Licensing Basis

- UFSAR Section 2.5 “Geology, Seismology, and Geotechnical Engineering”
  - 10 CFR Part 100, Appendix A, site characterization Safe Shutdown Earthquake (SSE) - 0.20g peak ground acceleration (PGA) value (UFSAR Figure 2.5-94)
- UFSAR Section 3.7 “Seismic Design”
  - Seismic Category I Structures, Systems and Components (SSCs) designed to spectral response curve anchored at 0.25g PGA (UFSAR Figure 3.7-1)
    - PVNGS Seismic Category I SSCs code-allowable seismic design based on 0.25g PGA spectra

Screening Evaluation

- In accordance with the 10 CFR 50.54(f) letter:
  - Re-evaluated Seismic Hazard Ground Motion Response Spectrum (GMRS) was developed for purpose of screening for additional evaluations
  - PVNGS screening evaluation performed based on comparison of Ground Motion Response Spectrum (GMRS) with Design Spectral Response Curve
- PVNGS 0.25g Design Spectral Response Curve bounds Re-evaluated Seismic Hazard GMRS curve

Screening Evaluation



- PVNGS Seismic Category I SSCs have code-allowable seismic capacities above re-evaluated GMRS

Screening Evaluation

- Risk Evaluation Screening (1 to 10 Hz, and >10 Hz)
  - Design Spectral Response Curve exceeds GMRS response curve
    - Not required to perform a Seismic Risk Evaluation
    - Not required to perform a Spent Fuel Pool Evaluation
    - Not required to perform the High Frequency Confirmation
- Interim Actions
  - PVNGS meets criteria in *Screening, Prioritization, and Implementation Details* (EPRI, 2013) for screening out
    - Interim actions are not required
- Conclusion
  - Further action is not required for NTTF Recommendation 2.1 Seismic Review

Questions

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