U.S. Department of Energy
Office of Civilian Radioactive Waste Management
www.ocrwm.doe.gov

Update on Seismic Activities at Yucca Mountain, Nevada

Presented to:
Nuclear Waste Technical Review Board

Presented by:
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DOE/USBR

September 20, 2004
Las Vegas, NV

Yucca Mountain Seismic Hazard Analyses

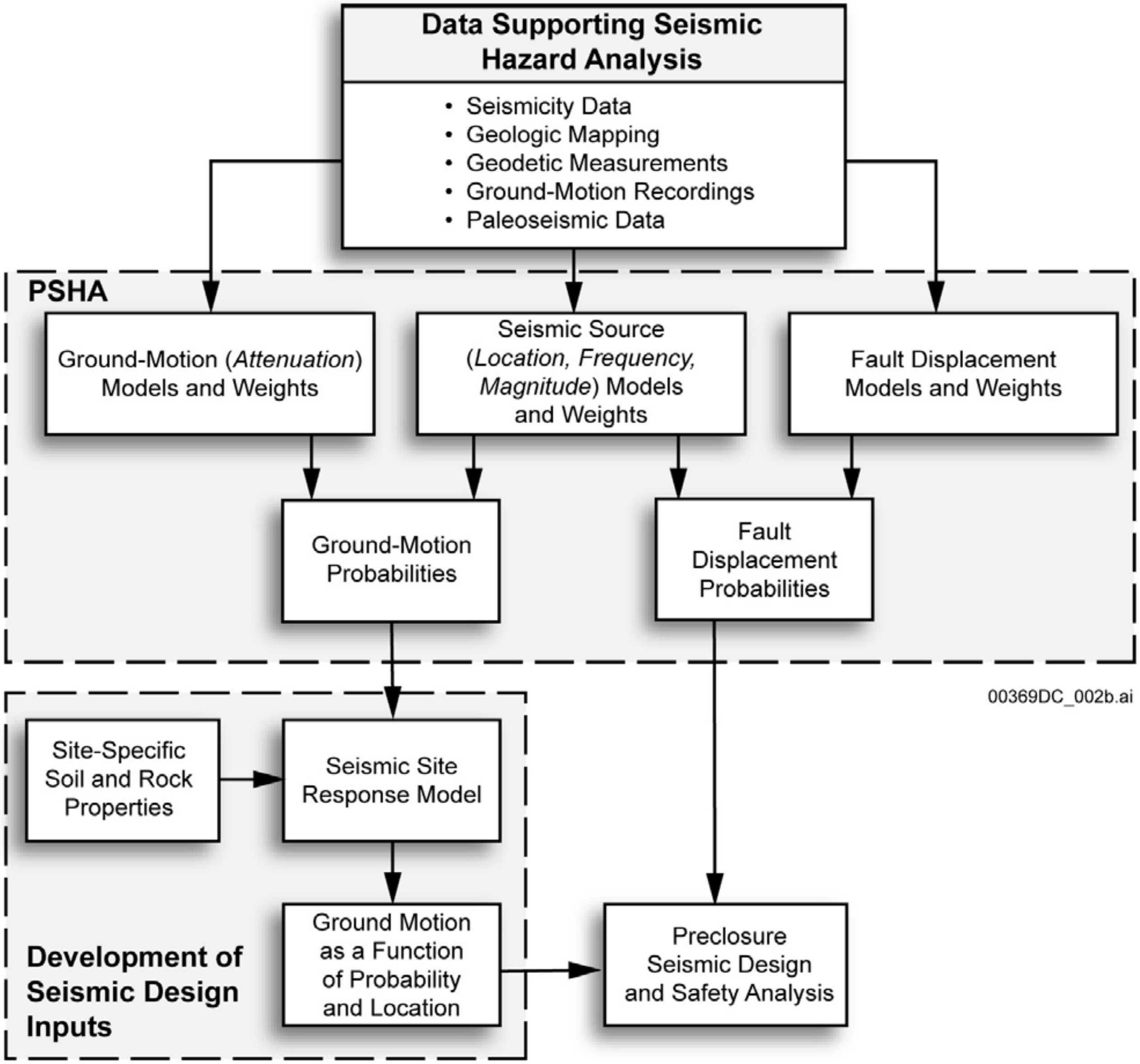
- **Summary of studies to date**
- **Development of realistic low probability ground motions (peak ground velocity)**

Background

- **Yucca Mountain Probabilistic Seismic Hazard Analysis (PSHA) conducted using state-of-the-art expert elicitation methodology by Senior Seismic Hazard Analysis Committee (SSHAC)**
  - Reviewed by National Academy of Sciences (NAS), accepted by Nuclear Regulatory Commission (NRC) for application in nuclear facility licensing, consistent with NRC Branch and Staff technical position
  - Includes epistemic uncertainties and aleatory variability in seismic sources and ground motions
  - Aleatory variability in ground motion attenuation is unbounded lognormal distribution
  - Anticipated focus on annual frequencies greater than 10^{-5} to 10^{-6} based on experience with nuclear power plants (pre 10 CFR 63)
  - Mean seismic hazard used for design and performance confirmation

Yucca Mountain PSHA

- **Source Characterization: 6 teams of 3 members**
- **Ground Motion Evaluation: 7 experts**
- **Develop hazard curves for ground motions and fault displacement for specific locations**
- **Focus on incorporation of uncertainty**



Data Supporting Seismic Hazard Analysis
• Seismicity Data
• Geologic Mapping
• Geodetic Measurements
• Ground-Motion Recordings
• Paleoseismic Data
PSHA
Ground-Motion (*Attenuation*) Models and Weights
Seismic Source (*Location, Frequency, Magnitude*) Models and Weights
Fault Displacement Models and Weights
Ground-Motion Probabilities
Fault Displacement Probabilities
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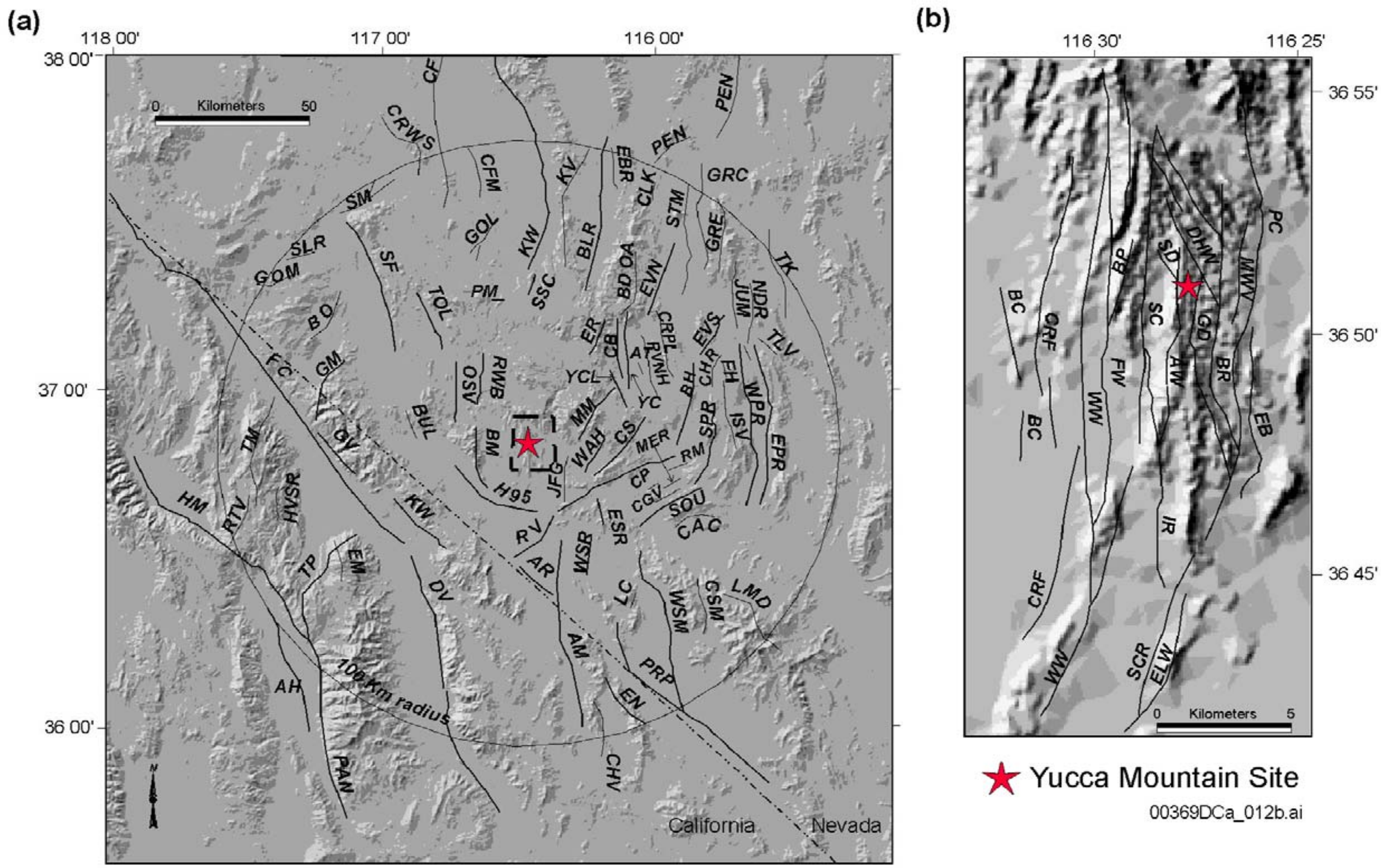
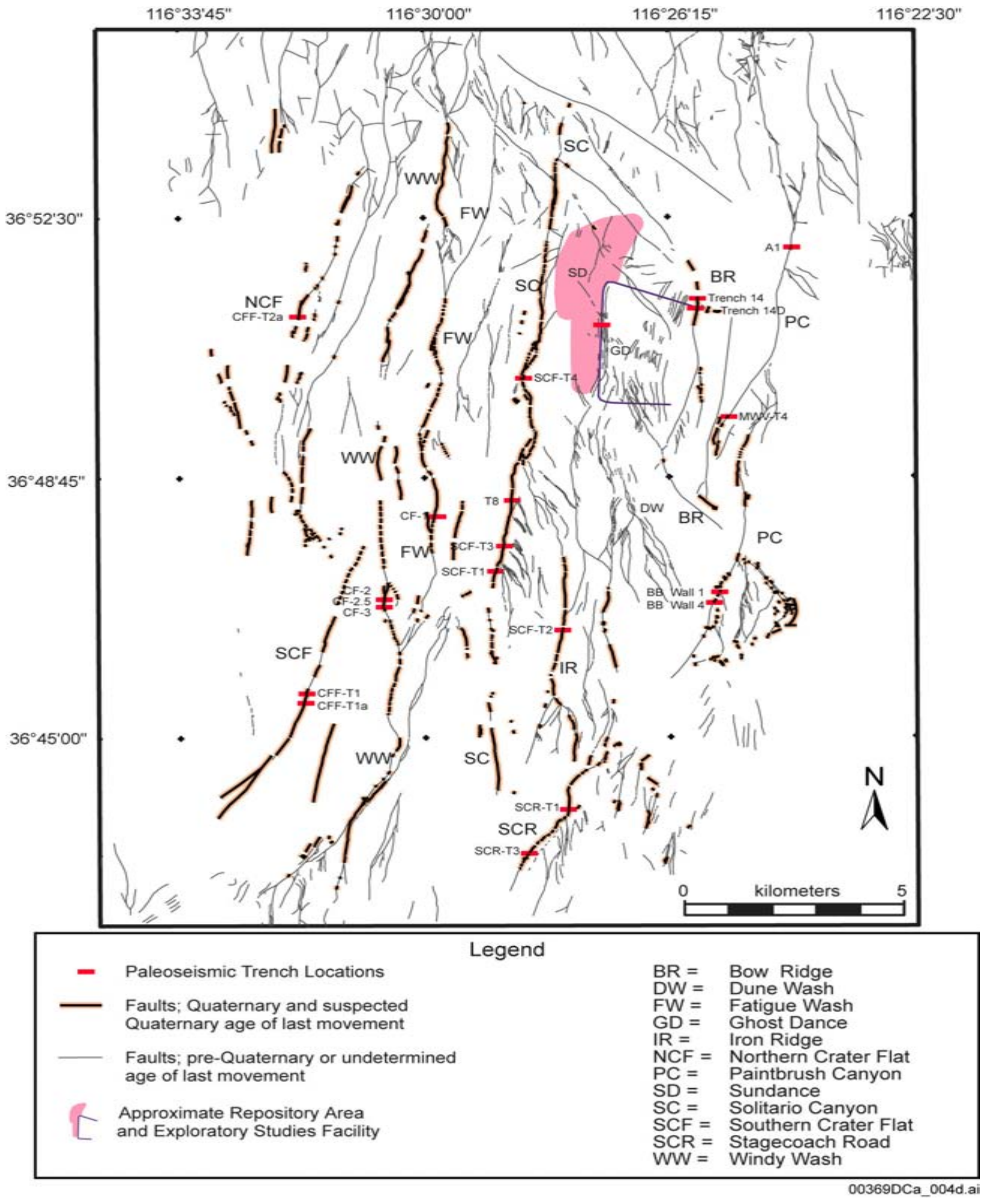
Site-Specific Soil and Rock Properties
Seismic Site Response Model
Ground Motion as a Function of Probability and Location
Preclosure Seismic Design and Safety Analysis
Development of Seismic Design Inputs

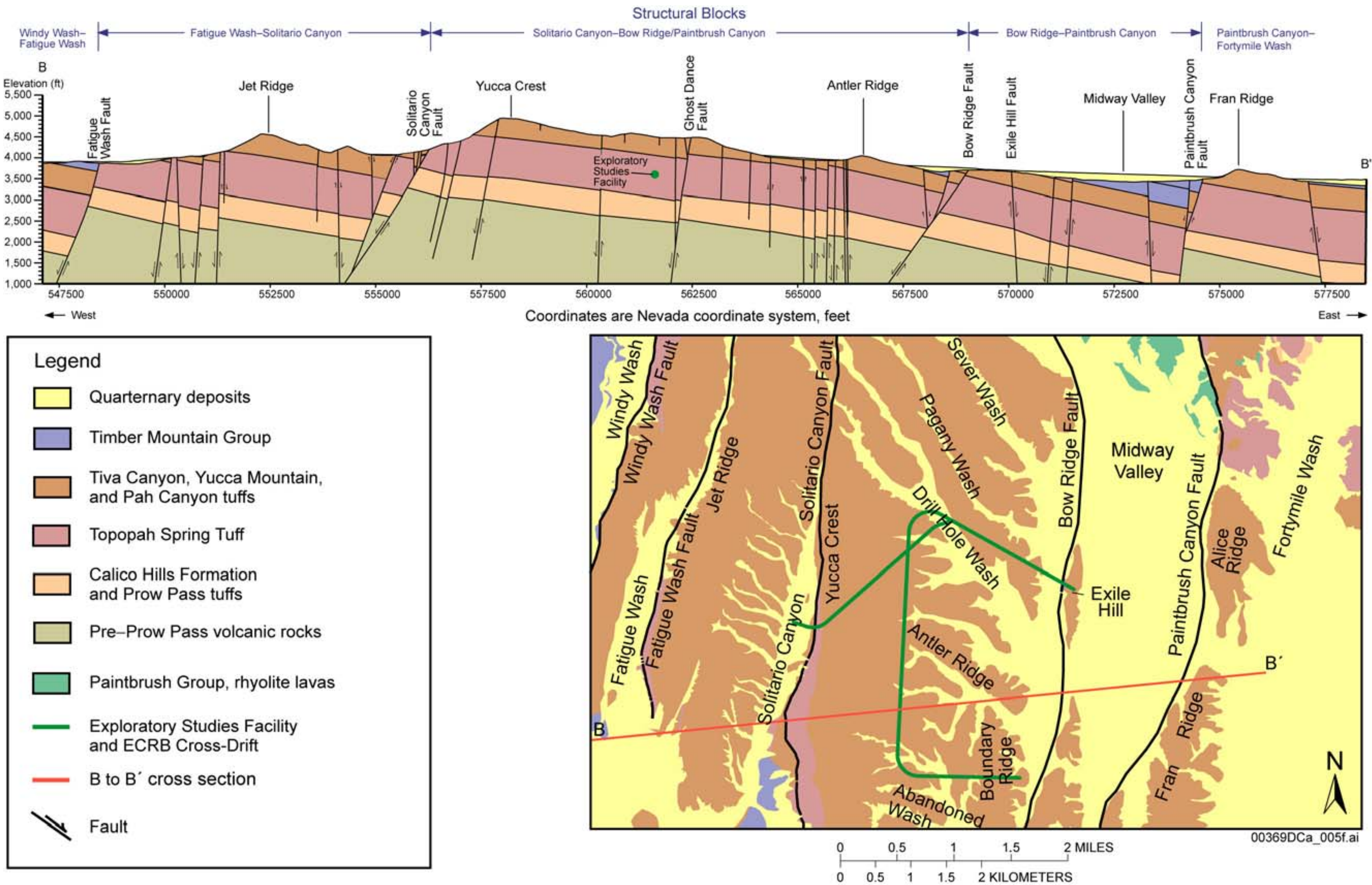
Regional and Local Faults





PSHA:

- **Source characterization**
- **Evaluation of local and regional fault sources in PSHA, supported by studies in numerous trenches**
- **Empirical and theoretical ground motion estimates**


Structural Blocks
Windy Wash–Fatigue Wash
Fatigue Wash–Solitario Canyon
Solitario Canyon–Bow Ridge/Paintbrush Canyon
Bow Ridge–Paintbrush Canyon
Paintbrush Canyon–Fortymile Wash
B
B'
Elevation (ft)
5,500
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
Fatigue Wash Fault
Jet Ridge
Solitario Canyon Fault
Yucca Crest
Ghost Dance Fault
Exploratory Studies Facility
Antler Ridge
Bow Ridge Fault
Exile Hill Fault
Midway Valley
Paintbrush Canyon Fault
Fran Ridge
547500
550000
552500
555000
557500
560000
562500
565000
567500
570000
572500
575000
577500
West
Coordinates are Nevada coordinate system, feet
East
Legend
Quarternary deposits
Timber Mountain Group
Tiva Canyon, Yucca Mountain, and Pah Canyon tuffs
Topopah Spring Tuff
Calico Hills Formation and Prow Pass tuffs
Pre–Prow Pass volcanic rocks
Paintbrush Group, rhyolite lavas
Exploratory Studies Facility and ECRB Cross-Drift
B to B´ cross section
Fault
Windy Wash
Windy Wash Fault
Jet Ridge
Solitario Canyon Fault
Sever Wash
Pagany Wash
Bow Ridge Fault
Midway Valley
Paintbrush Canyon Fault
Fortymile Wash
Alice Ridge
Drill Hole Wash
Exile Hill
Yucca Crest
Fatigue Wash
Fatigue Wash Fault
Solitario Canyon
Antler Ridge
B´
B
Boundary Ridge
Fran Ridge
Abandoned Wash
N
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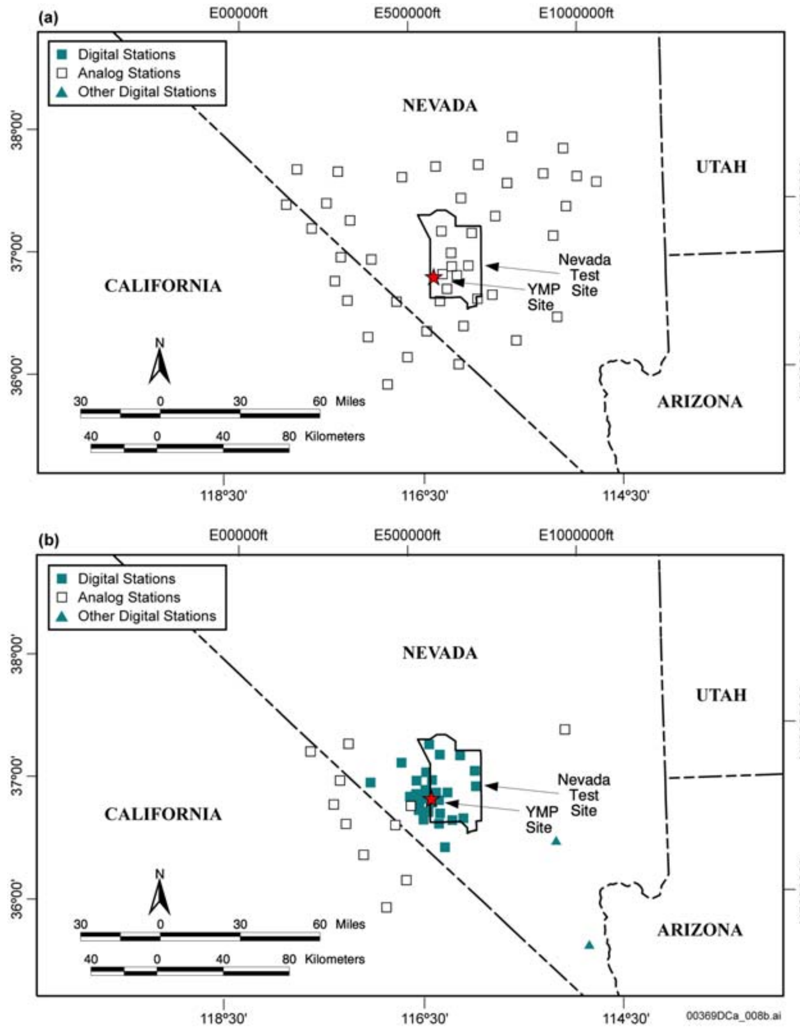
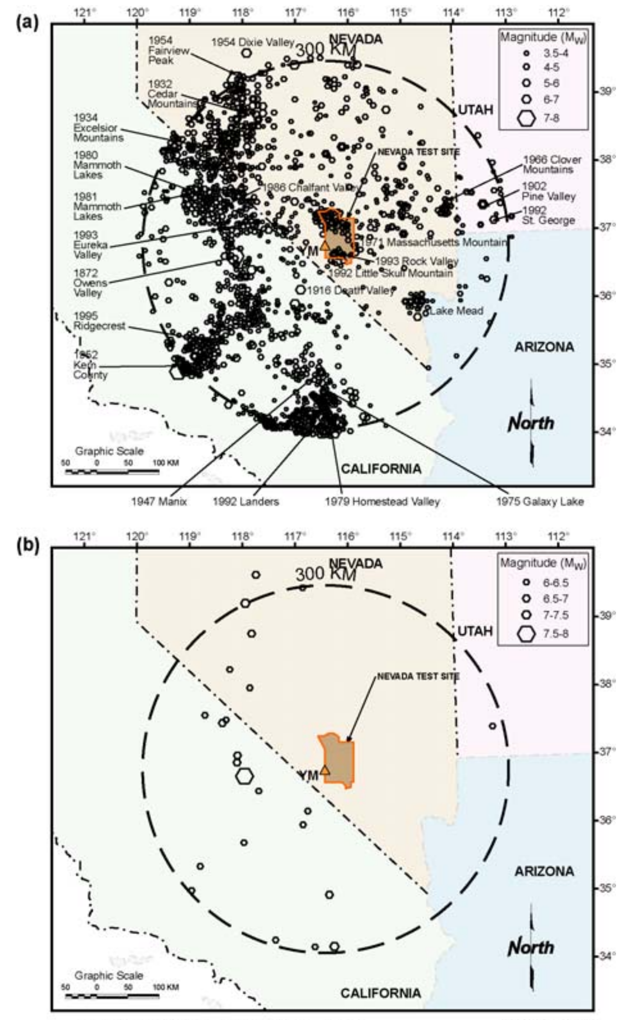
0 0.5 1 1.5 2 MILES
0 0.5 1 1.5 2 KILOMETERS

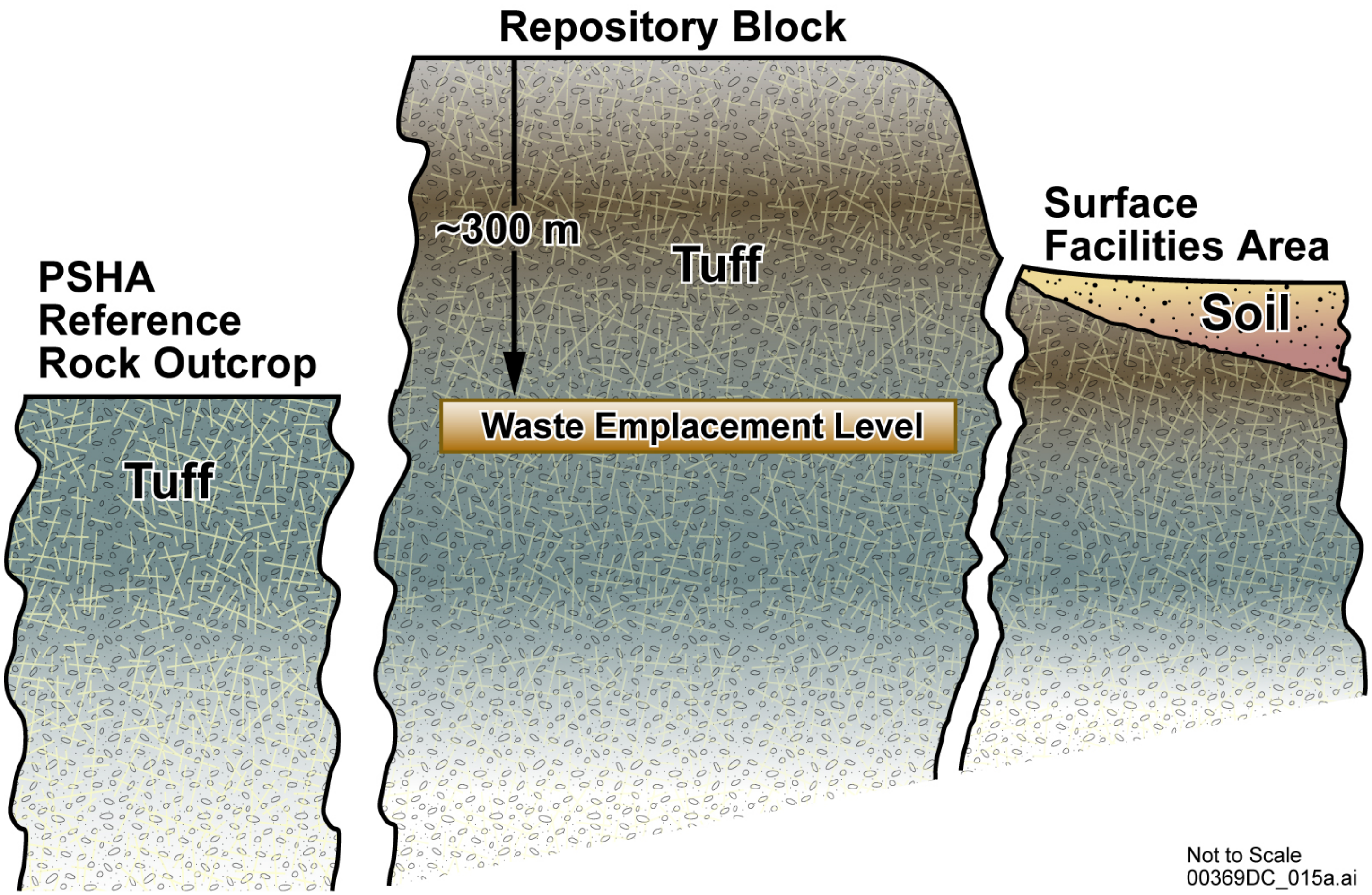
Seismicity



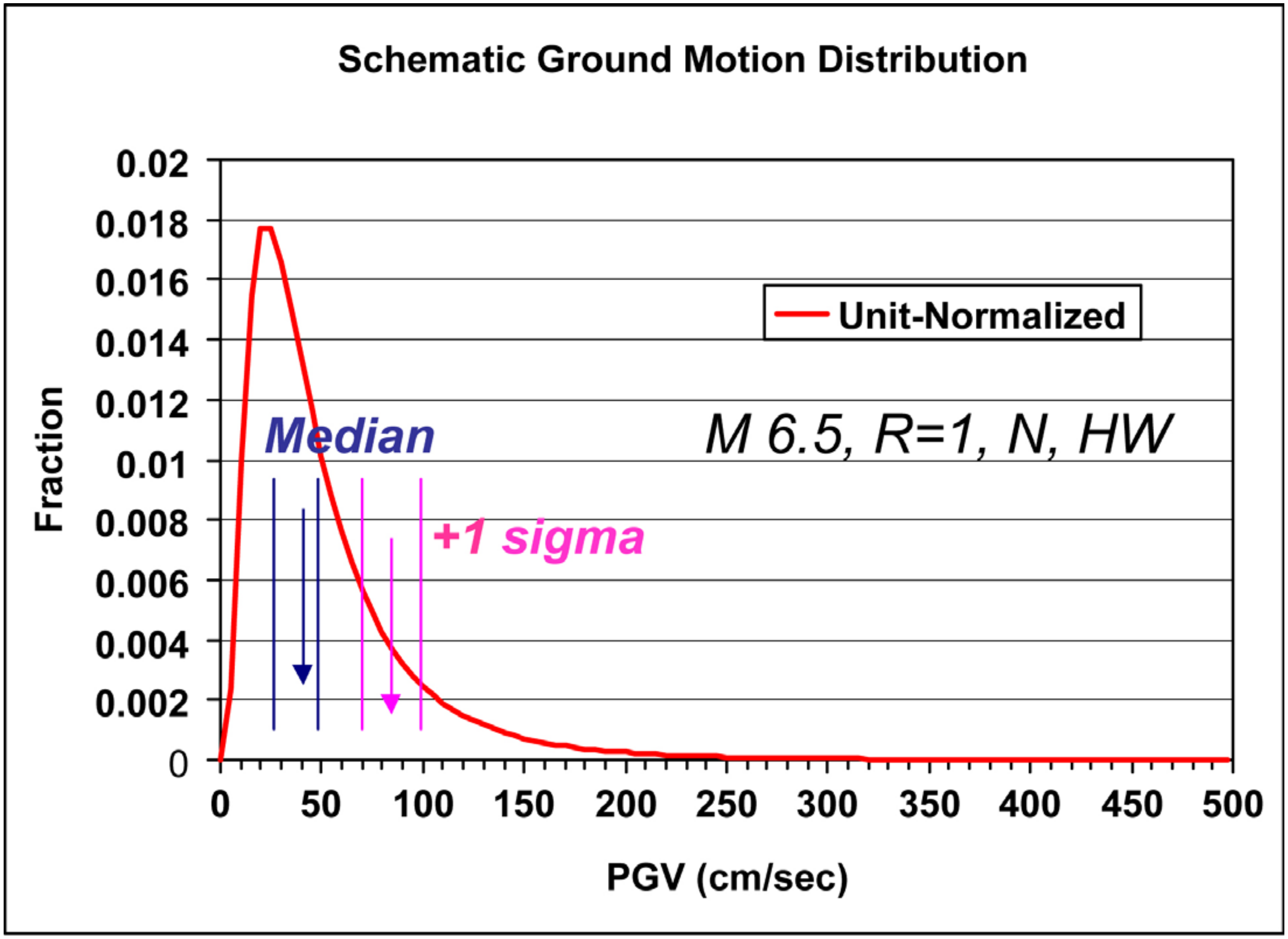


MAGNITUDE GREATER OR EQUAL TO 6.0
WITHIN 300 KM OF YUCCA MOUNTAIN.
1868-1996

Site Specific Ground Motions



Uncertainty in Ground Motions



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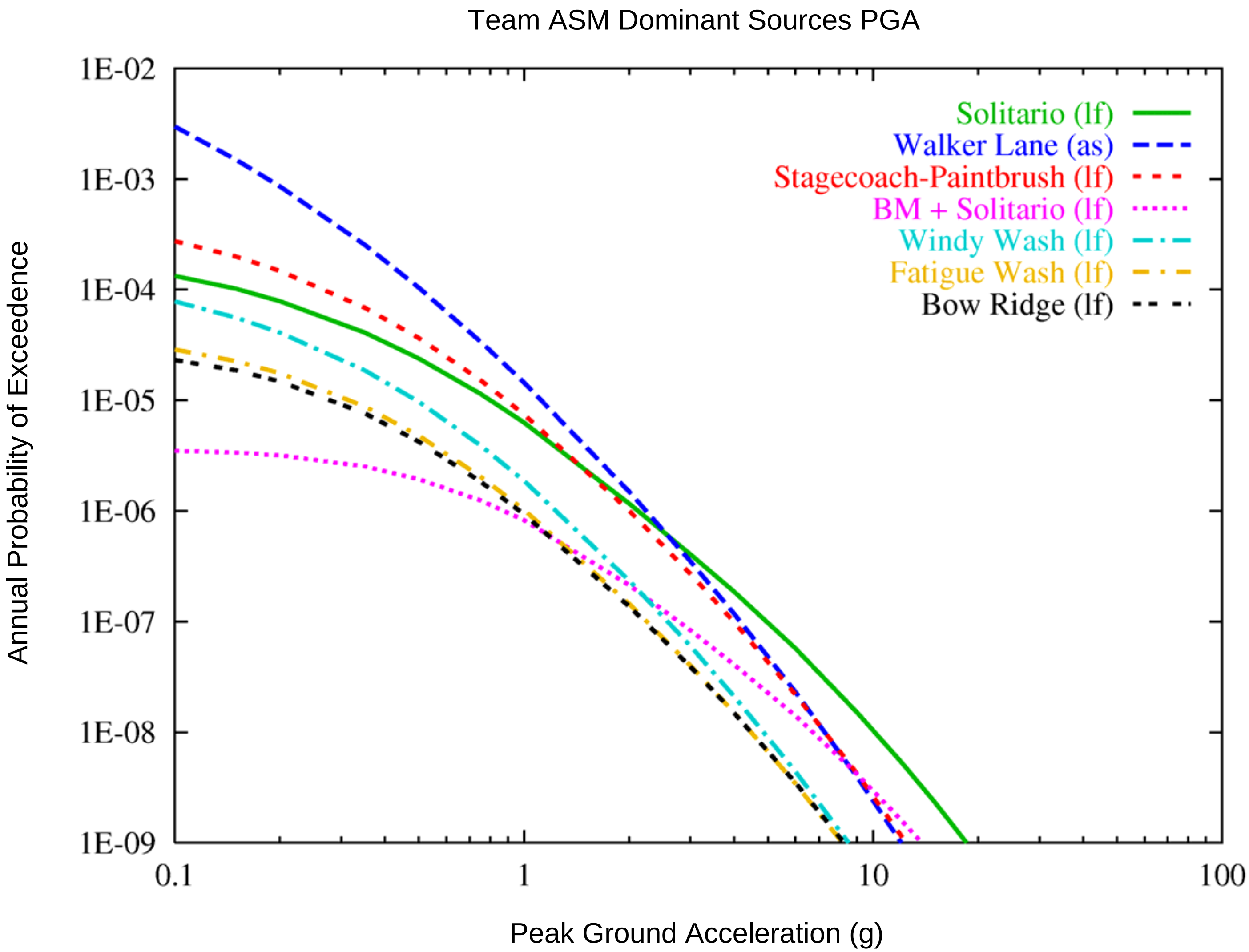
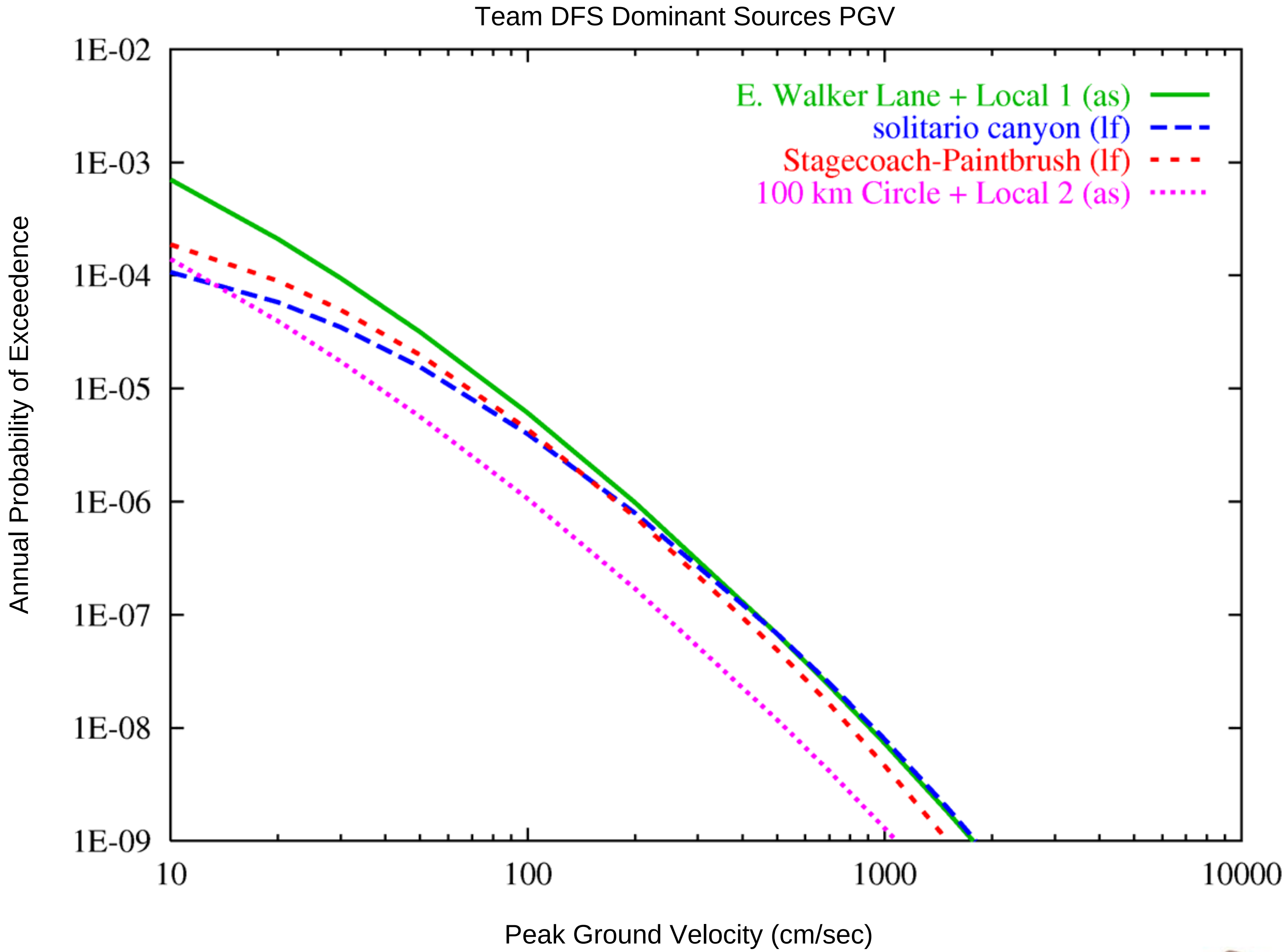
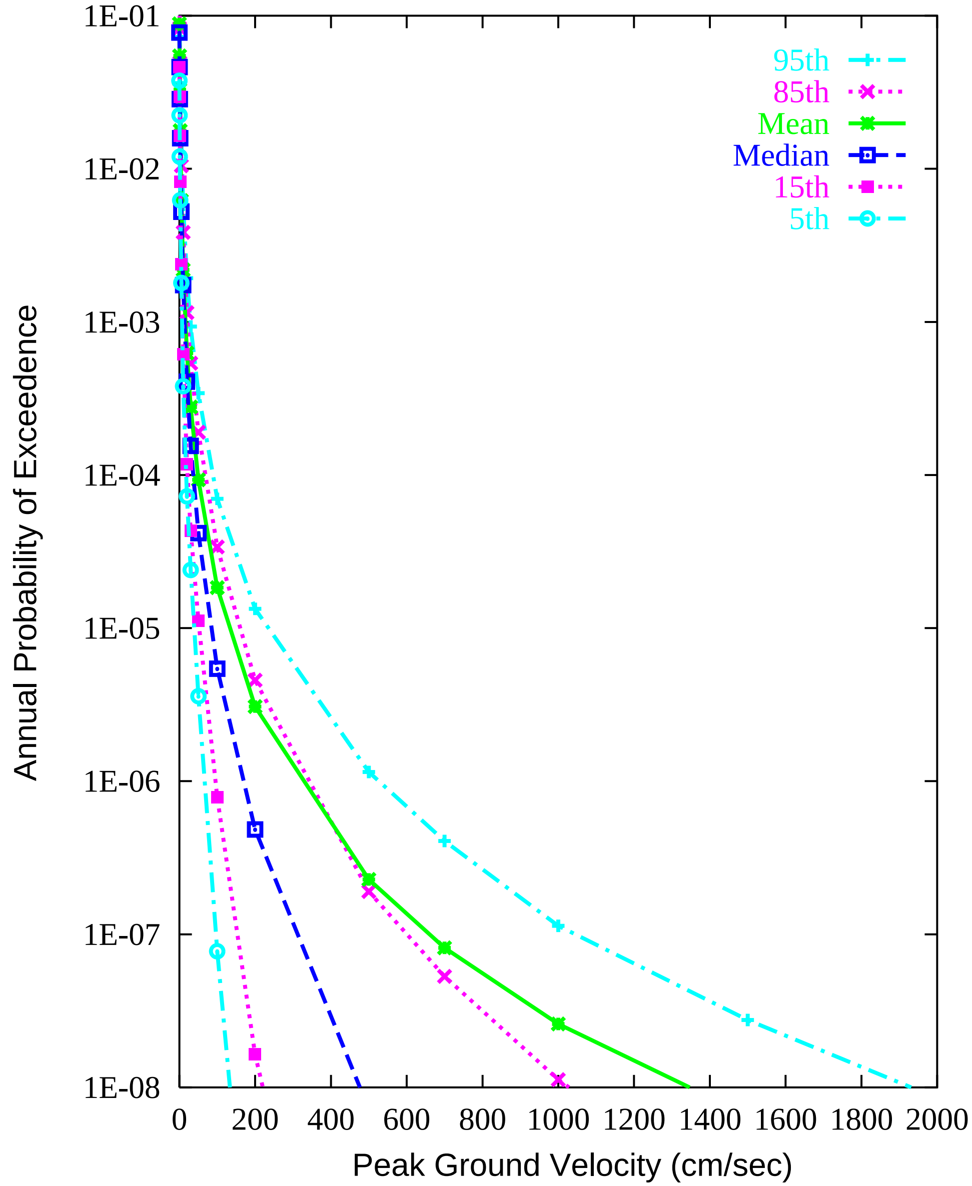
Ground Motion Results



Ground Motion Results (continued)

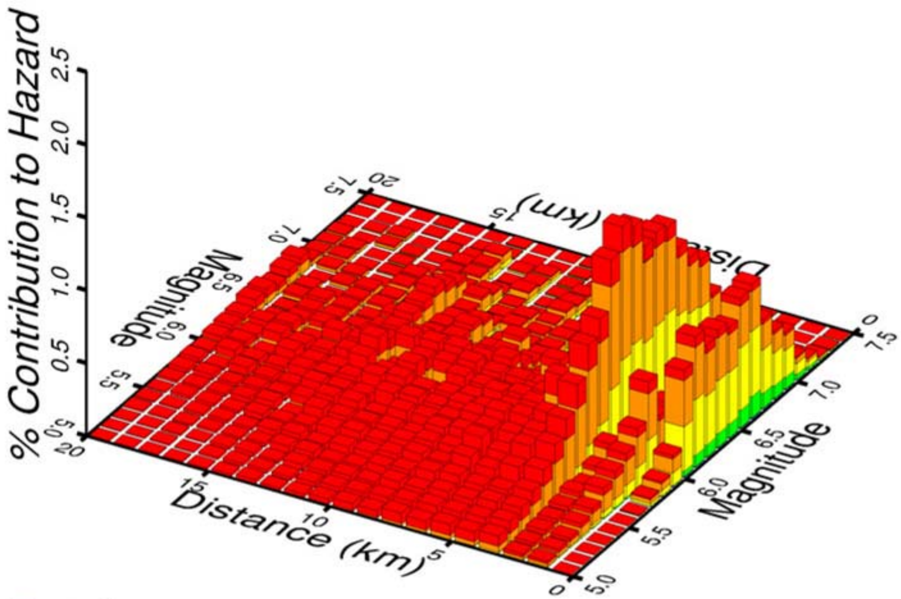


Ground Motion Hazard Results



PSHA
Reference Rock
Outcrop: Point A

1E-4 Hazard,PGV Horiz., All Teams



- ε: 2+
- ε: 1 to 2
- ε: 0 to 1
- ε: -1 to 0
- ε: -2 to -1

ε = Log (GM)-mean Log (GM)
GM = Ground Motion

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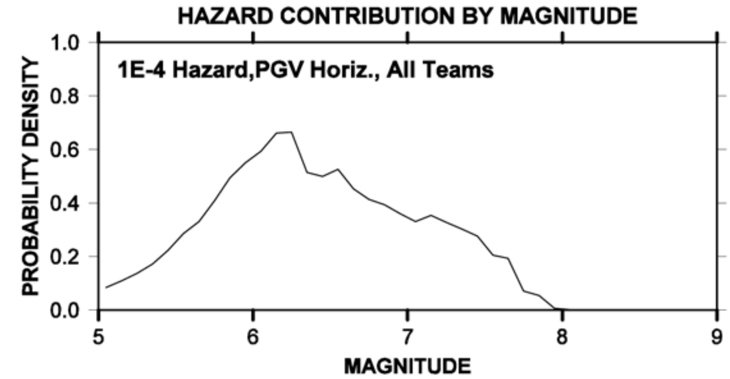
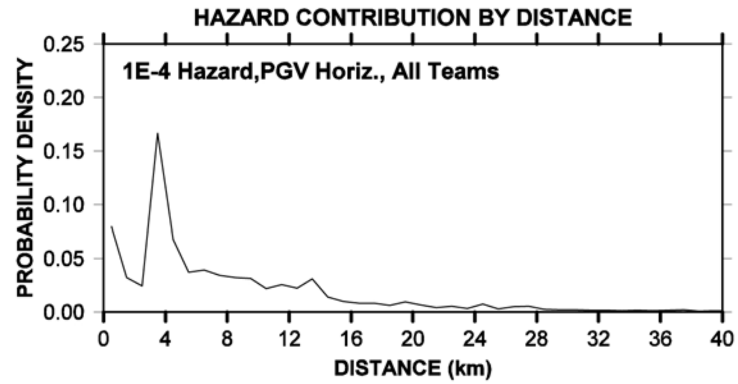
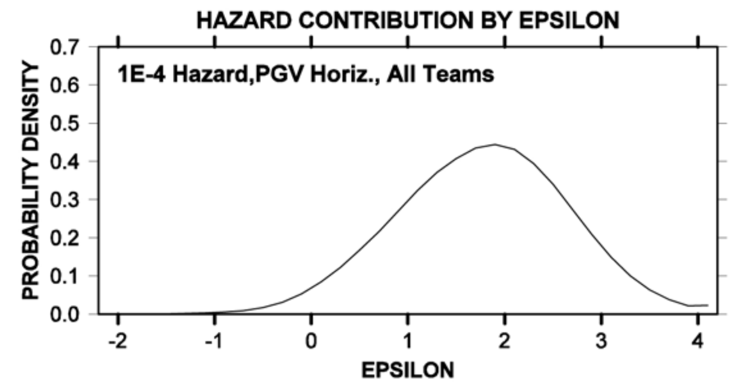
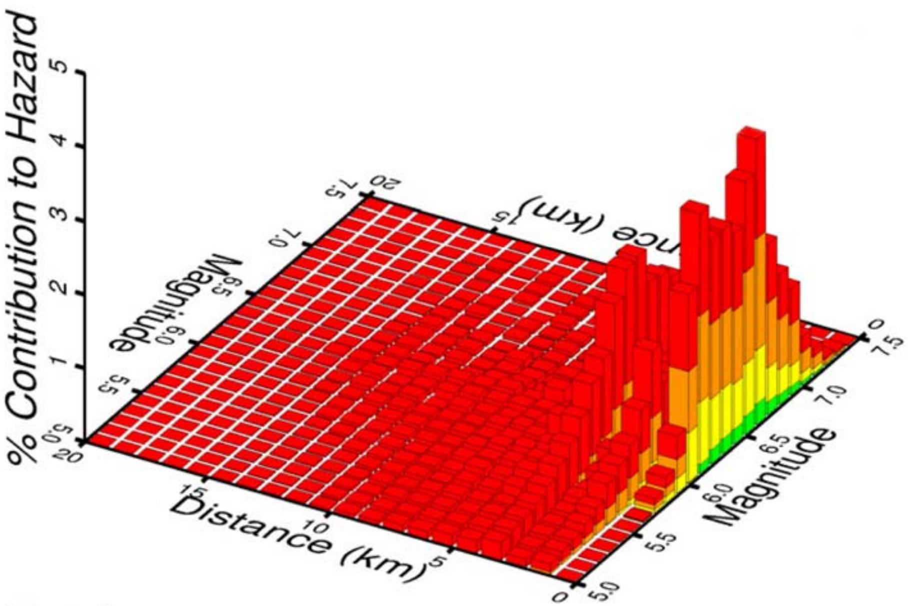






1E-6 Hazard, PGA Horiz., All Teams



- ε: 2+
- ε: 1 to 2
- ε: 0 to 1
- ε: -1 to 0
- ε: -2 to -1

ε = Log (GM)-mean Log (GM)
GM = Ground Motion

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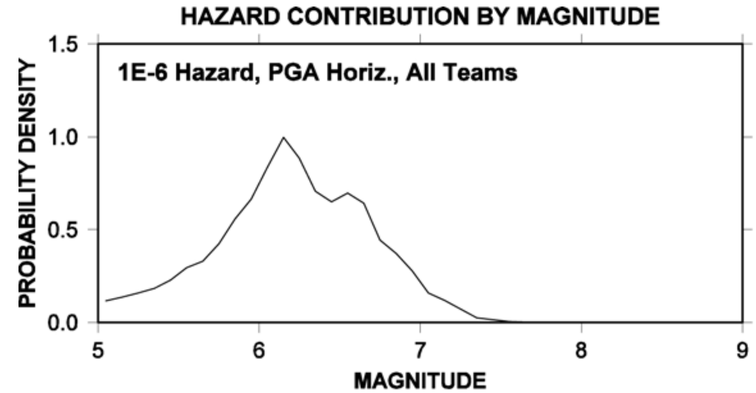
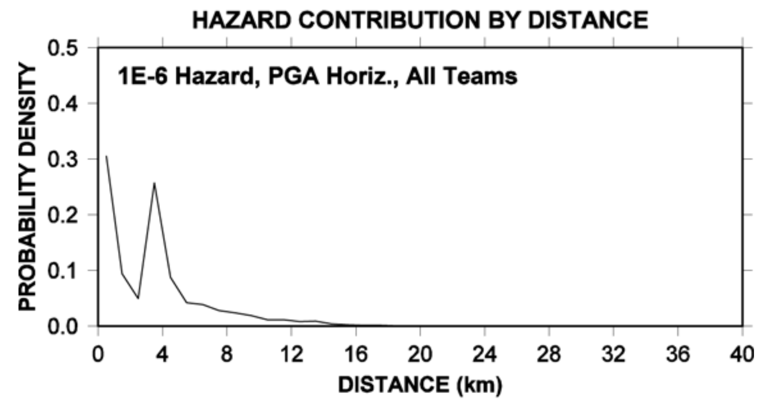
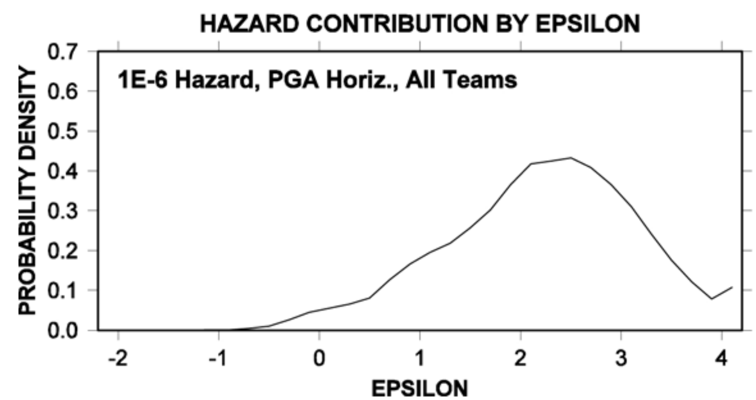
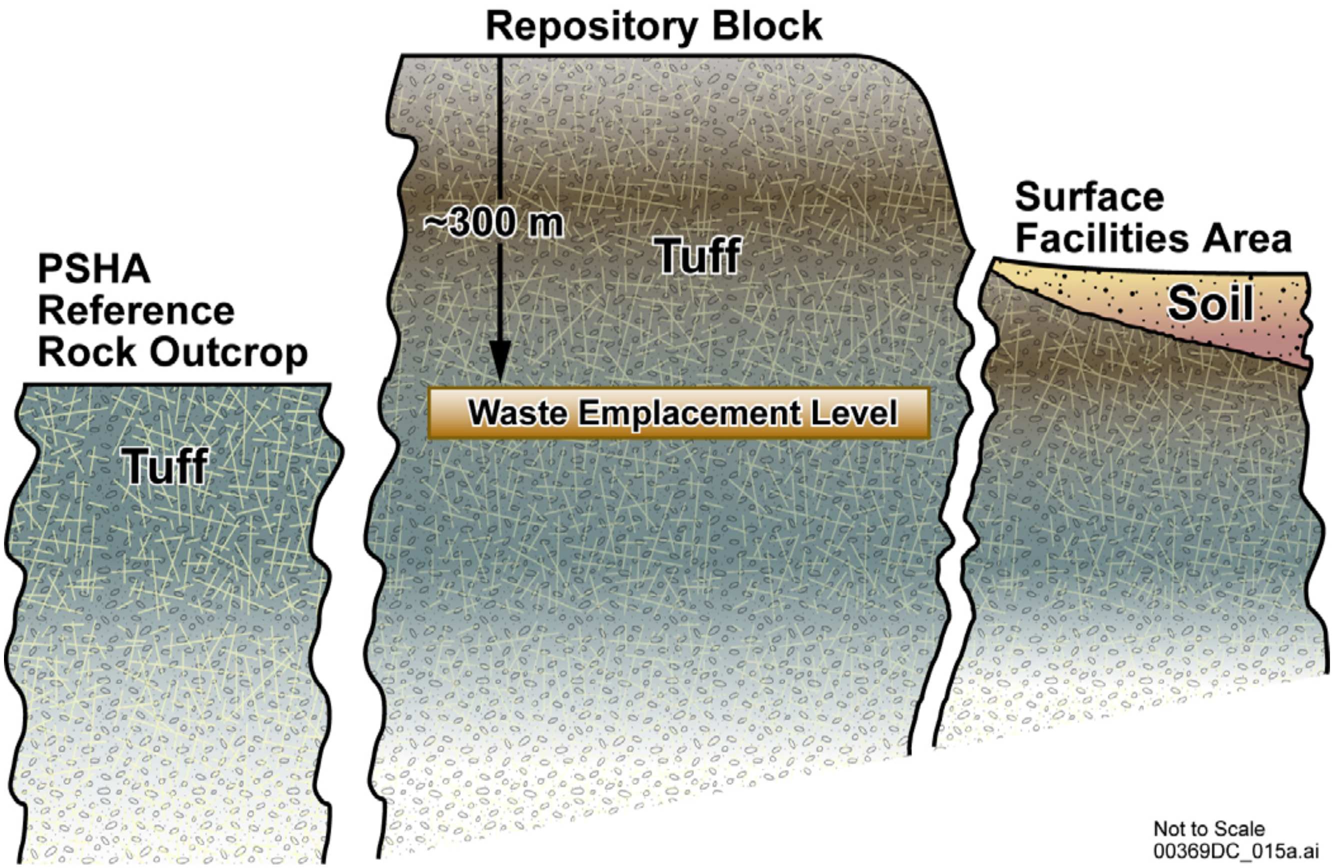






Site Specific Ground Motions



Site Response

- PSHA ground motion calculations developed for hypothetical Point “A”
- For post closure analyses need motions at depth (Point “B”)
- For pre closure design need motions at the top of soil column
- Need to incorporate deaggregation results
- Strong emphasis on incorporation of uncertainty in material properties

Analysis of Results

- **Very large ground motions and highly asymmetric probability distribution for low Annual Probability of Exceedence (APE)**
- **Back-calculation of source parameters consistent with low probability ground motions suggests physically unrealistic values**
- **Seismic inputs developed for low APE with site-response model produce very large strains (inconsistent with observed rock strength)**
- **NWTRB has indicated similar reservations in correspondence to DOE**

Motivation of PGV Study

- In the PSHA, aleatory variability in ground motion was characterized by unbounded lognormal distributions
- Very large epistemic uncertainty expressed for median ground motion from large and close events that control low-probability ground motions
- Calculated ground motion values at low exceedence probabilities reach levels that are physically unrealistic and not credible
- Per 10 CFR 63.102(f) only credible inputs to TSPA should be included

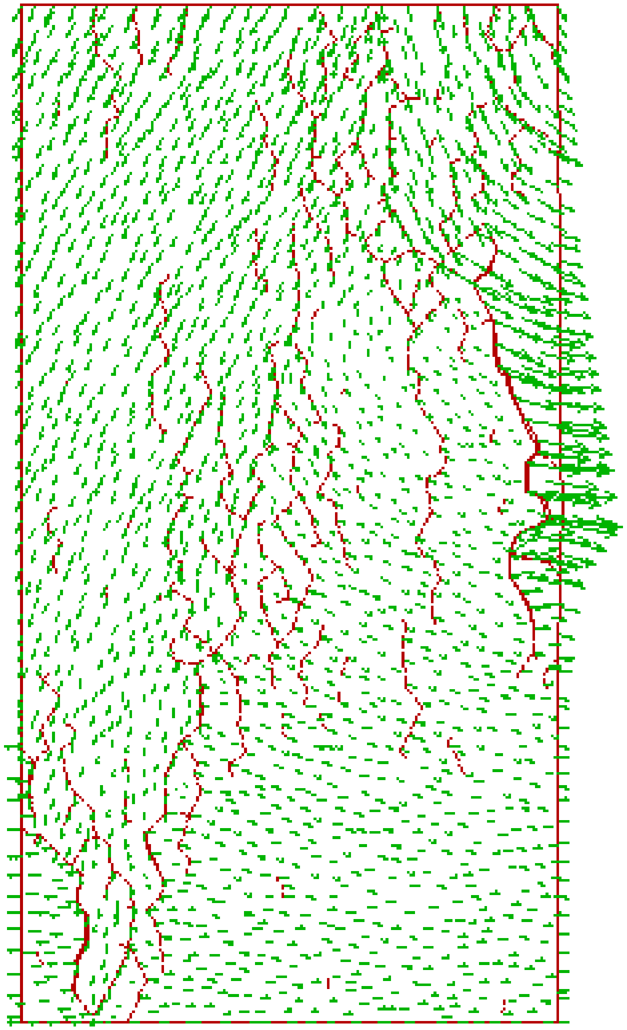
Purpose of PGV Study

- **Determine a physically realistic bound on peak horizontal ground velocities (PGVs) at the repository waste emplacement level (Point B)**
- **Characterize bound as a probability distribution to reflect uncertainties in the assessment**
- **Use bound to generate modified Point B hazard curve for use in total system performance assessment (TSPA) abstraction of seismic consequences (shaking effects on engineered components and rockfall)**

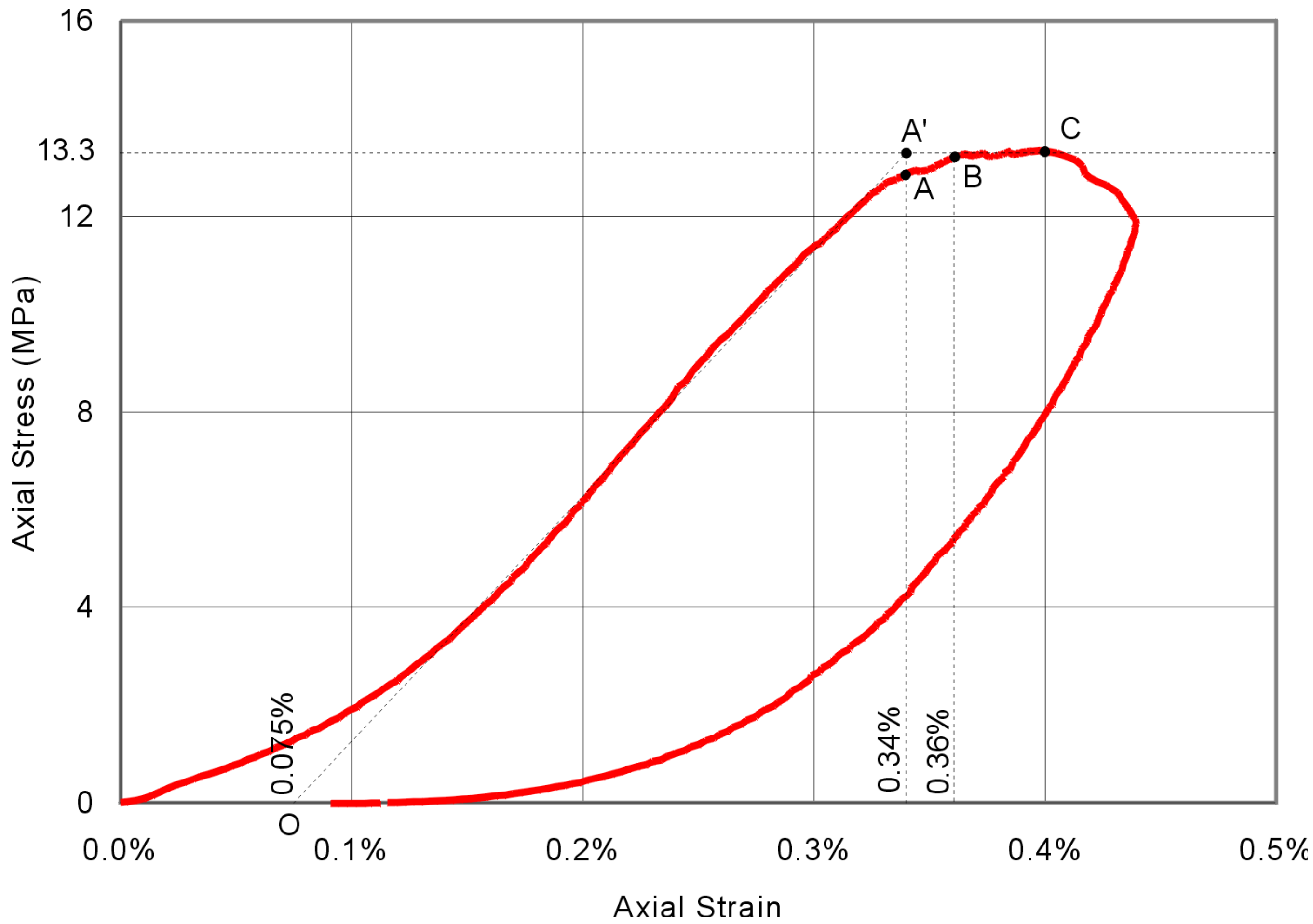
Study Outline

- **A fundamental constraint: Ground motion amplitudes limited by the strength of the materials through which they propagate**
- **Establish shear strain limits that produce wide-spread obvious failure/fracturing in lithophysal tuff units**
- **Shear strain-fracturing criteria needs to be consistent with resolution of geologic observations**
- **Calculate ground motions (PGV) consistent with strain threshold**

Comparison of Model Failure Mechanism at Large Core-Scale



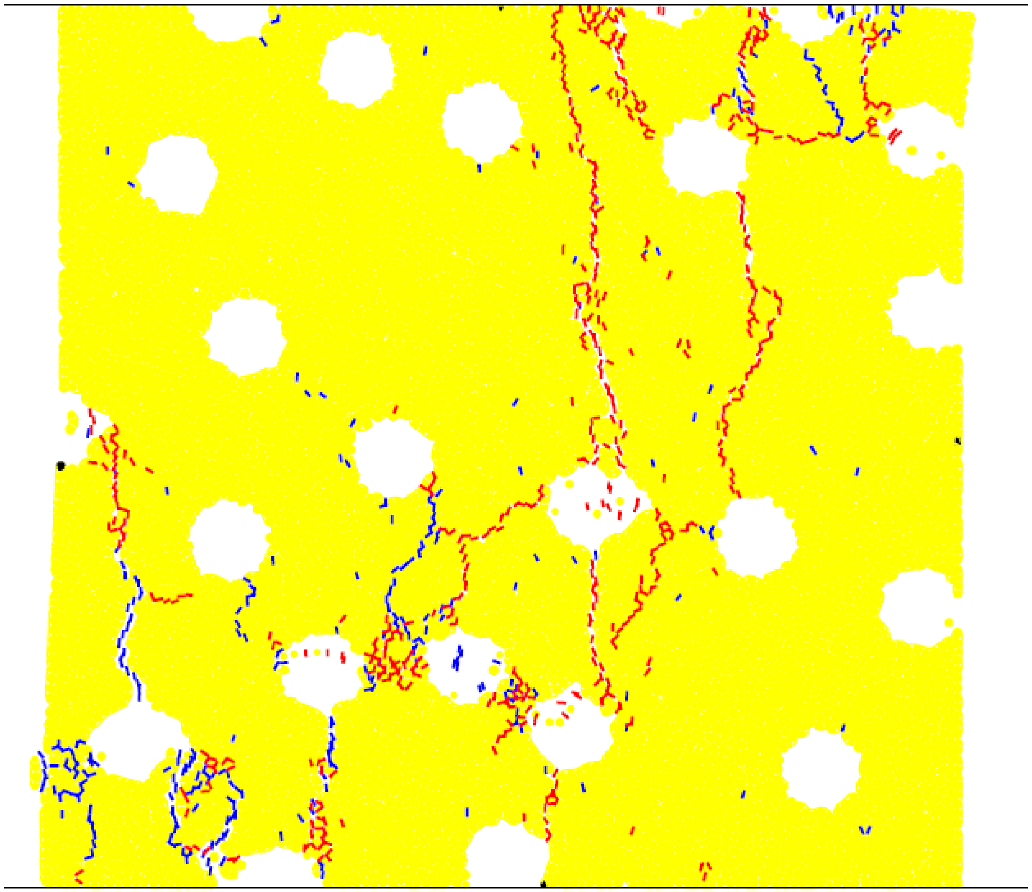
Stress-strain curve for 288-mm sample of Lower Lithophysal tuff at surface conditions



Strain increment adjusted for 250 m overburden = 0.2%

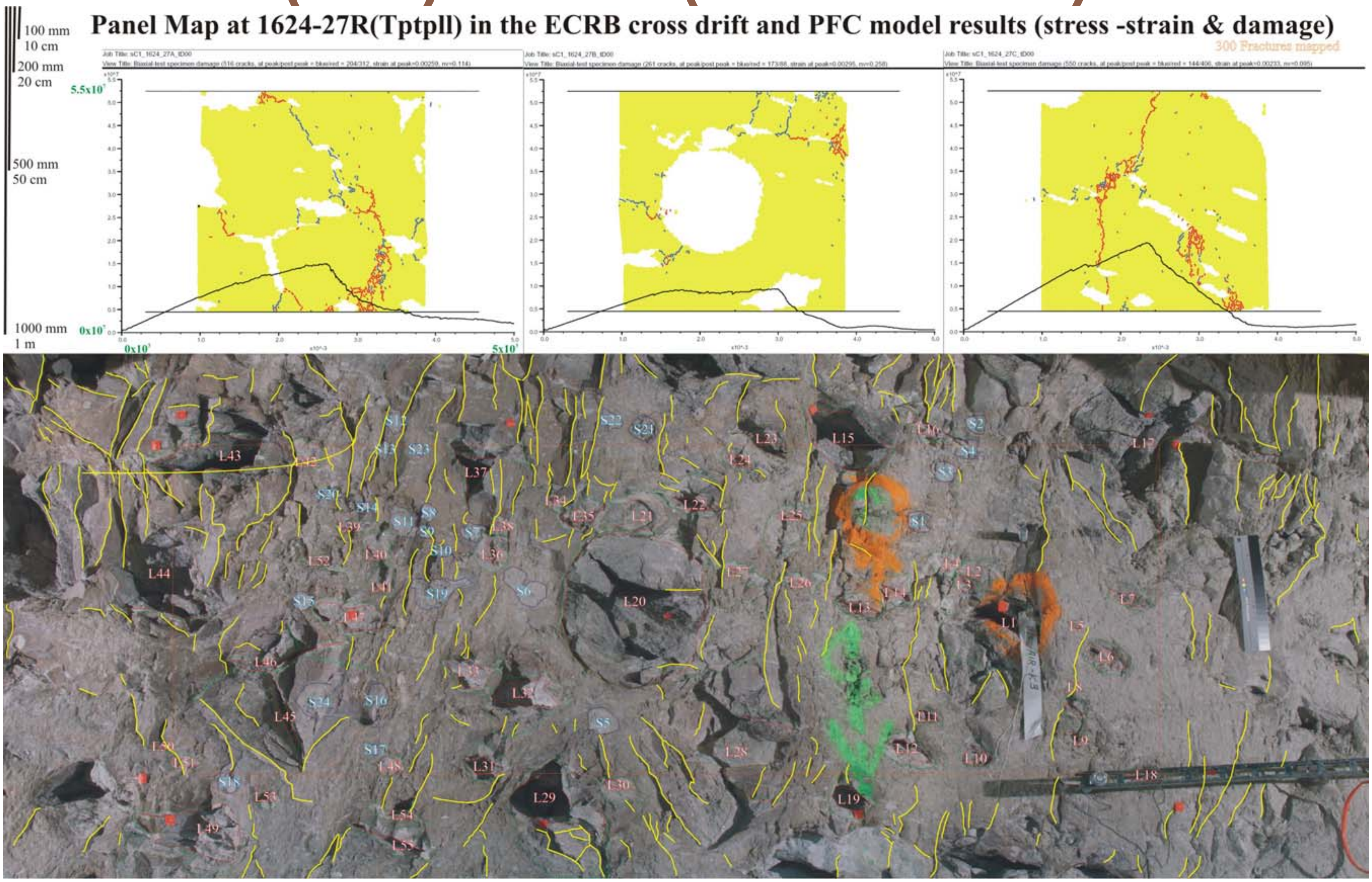
Modeled Deformation of Lithophysal Tuff

Fracturing of this magnitude inferred to be within observational limits of geologic mapping



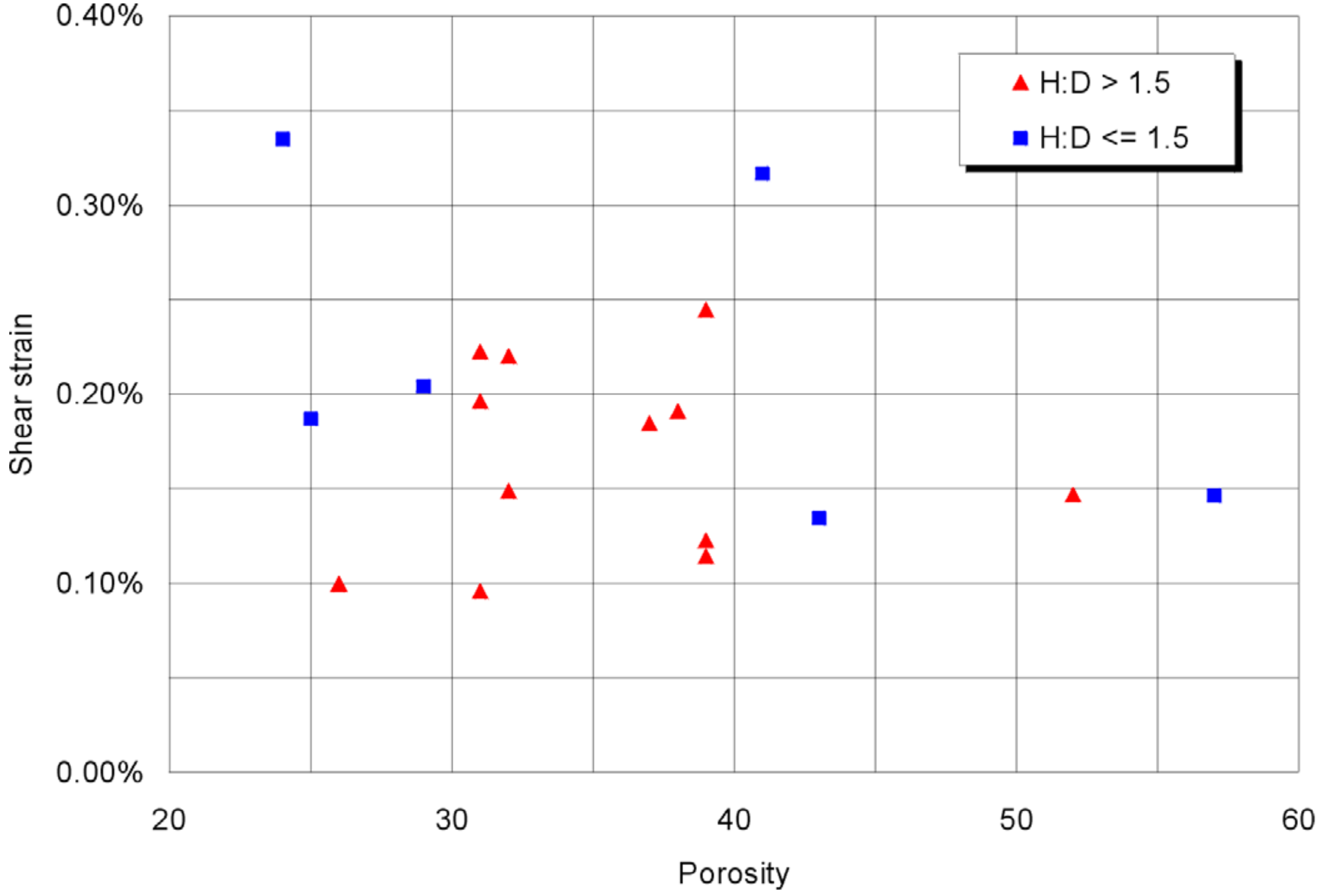
Fractures developed in lithophysal sample (blue = pre-peak, red = post-peak)

Panel Map 1624L and Particle Flow Code (PFC) models (300 fractures)



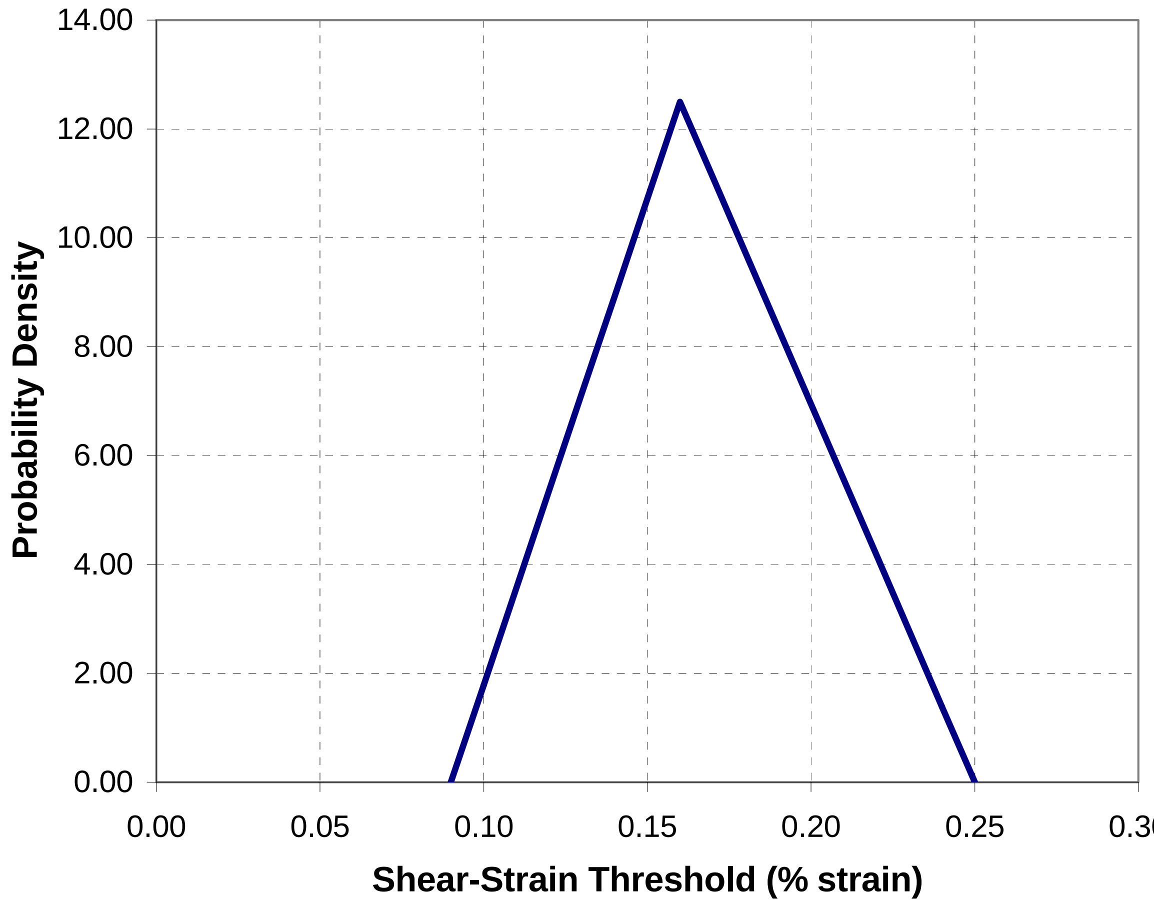
Experimental Results

Large Samples, Corrected for In situ Stresses at Overburden Depth of 250 m



Calculated shear strain limit for 288-mm diameter samples

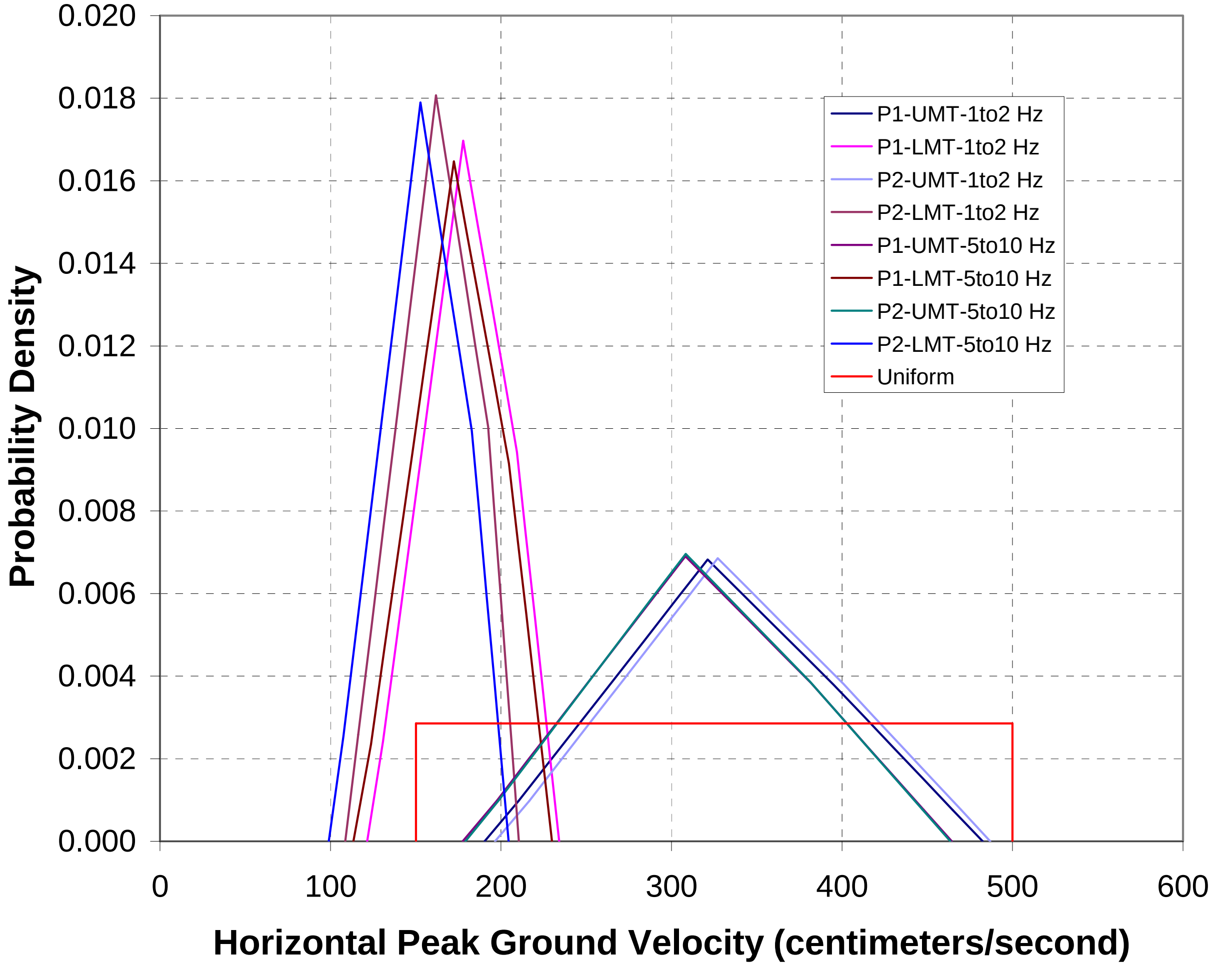
Assessed Probability Distribution of Threshold Shear Strain for Topopah Spring Lithophysal Rock



Ground Motion Calculation

- **Used full site response model to incorporate site specific properties, uncertainties, and variability**
- **Site response studies conducted over a broad range of amplitudes (consistent w/10^{-4} to 10^{-7} APE); One output of these model runs is the variation with depth of horizontal PGV and shear strain**
- **Results in probability distribution on bounding PGV**

Probability Distribution of Bounding PGV

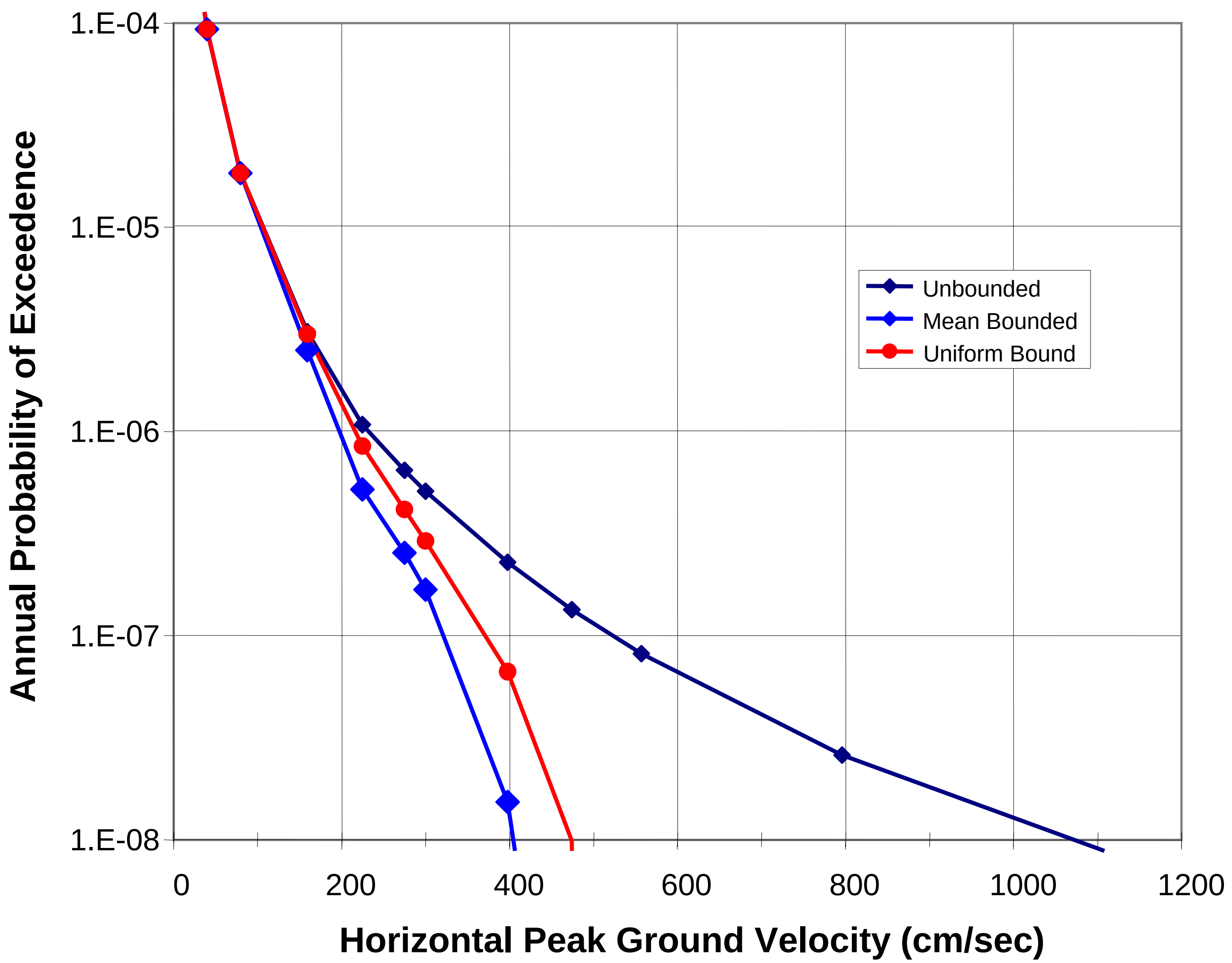


P1, P2 refer to velocity profiles, UMT, LMT to material property distributions, 1-2 Hz and 5-10 Hz to response spectrum frequency band

Supporting Evidence

- **To place results in probability context, M 6.7 event at 1 km modeled as scenario event (consistent with PSHA deaggregation)**
- **Stochastic point-source/site-response model used to examine range of PGV that might occur at repository level, 5000 runs in sample, broad range of stress-drop, site and path properties**
- **Results: mean PGV ~31 cm/sec with σ_{ln}~0.71, suggests very low probability of PGV equal to derived bound**

Comparison of hazard curves at Point B resulting from the PSHA, the uniform bounding PGV distribution (used in TSPA), and the mean bounding PGV distribution



Conclusions

- PSHA for Yucca Mountain is fundamental basis for preclosure and postclosure ground motion assessment
- Represents state-of-the-art in seismic evaluation
- DOE has decided to evaluate bounding ground motions (PGV) using site-specific physical arguments
- Based on a lack of geologic deformation related to seismically induced strains in 10 Mya rocks at emplacement level
- Testing and modeling studies have been used to assess threshold shear strains and associated uncertainties
- Strength-limited PGV has been developed to ensure ground motions at very low annual frequencies are credible, physically realizable, and incorporate uncertainty (per 10 CFR 63.102(f))

Assessment of Bounding PGV

- **Fundamental physical constraint: Absence of geologic indicators of seismically-induced deformation in repository rocks at emplacement level**
  - **Geologic observations of fractures and lithophysae**
  - **Laboratory tests of shear strains causing failure**
- **Development of probability distribution on threshold shear strain**
  - **Ground motions associated with threshold shear strains**
- **Multiple lines of supporting evidence**
- **Assessment of bounding PGV expressed as probability distribution to reflect uncertainties**

Additional Slides

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Shattered rock, hanging wall, thrust fault

Courtesy of Jim Brune, UNR

Supporting Evidence

- **Seismic source constraints and observed ground motions (very low probabilities associated with combinations of source parameters consistent with very large motions)**
- **Consideration of extensional faulting and shattered rocks (large motions will fracture rocks)**
- **Lack of offset of fractures since mineralization**
- **Delicate crystals and coatings showing lack of dynamic deformation**
- **Consideration of strength of geologic units beneath repository limiting motions**
- **Precarious rocks on Yucca Mountain suggest that aleatory variability for given site is too large**

Summary of Statistics of Calculated Shear Strain Limits Based on Different Experimental Results

	Number of samples	Mean	Standard deviation
		%	%
288-mm diameter, H/D > 1.5	**13**	**0.16**	**0.05**
288-mm diameter, all	**19**	**0.18**	**0.07**
146-mm diameter	**16**	**0.20**	**0.04**
Busted Butte, 200-mm diameter	**5**	**0.13**	**0.03**

Price, 2004

Geologic Observations of Fractures and Lithophysae

Core and thin sections

- Small-scale (mm to cm),
- Development and confirmation of petrogenetic relations

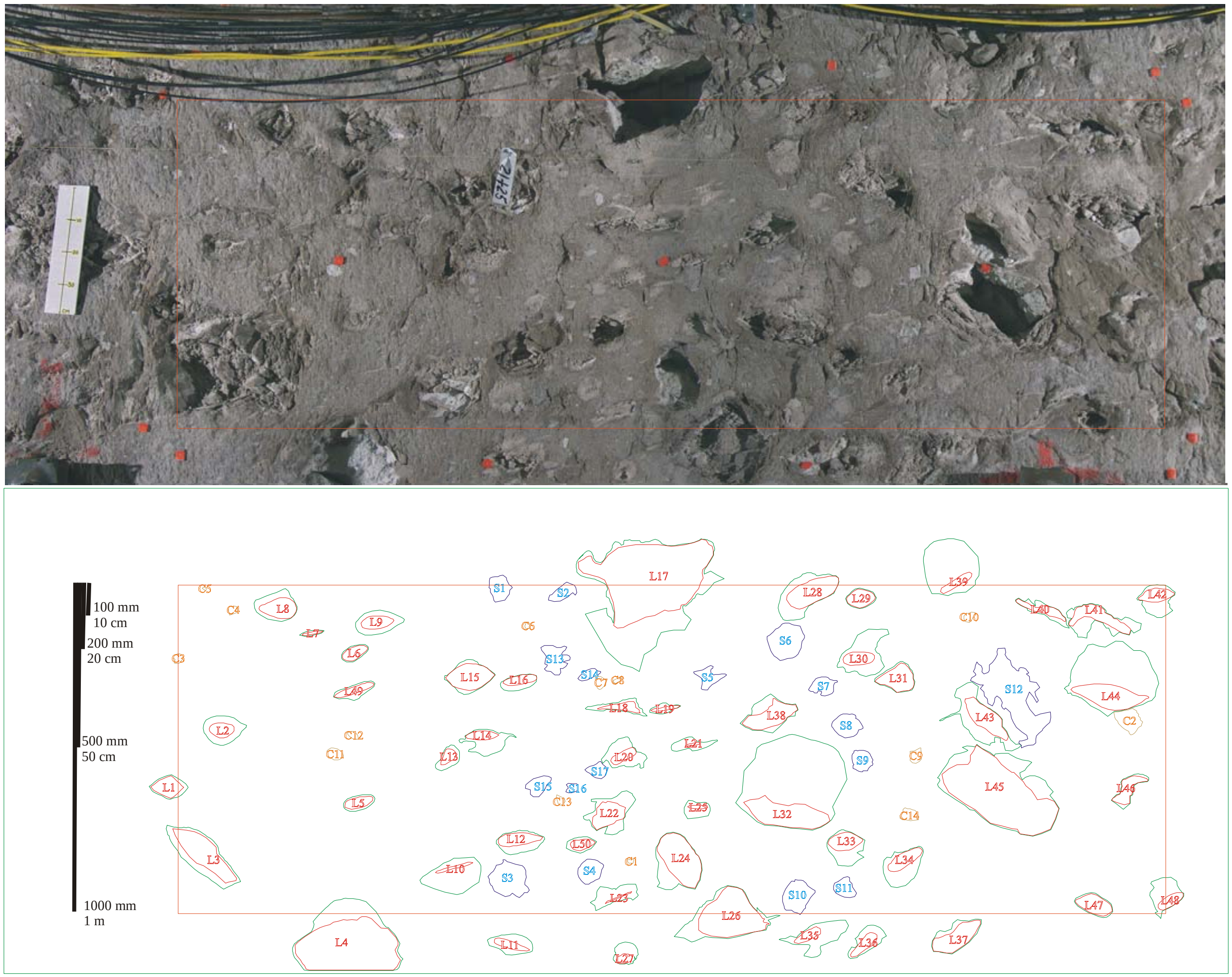
Detailed line surveys in ESF and ECRB

- Small- to large-scale (cm to km)
- Geometric and petrogenetic relations of discontinuities

Photogrametric lithophysae inventory in ECRB

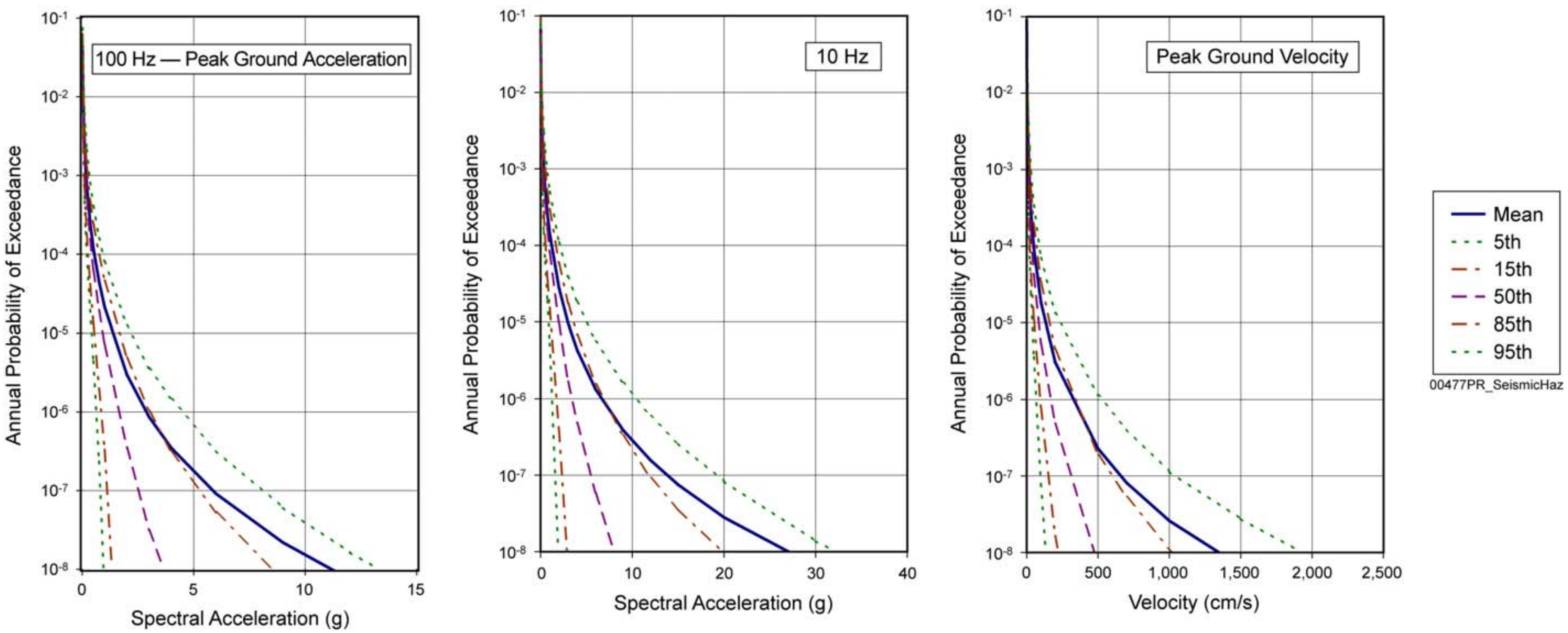
- Small- to intermediate-scale (mm to m)
- Shape of lithophysae as indicators (or lack) of deformation

PMap 21+25L

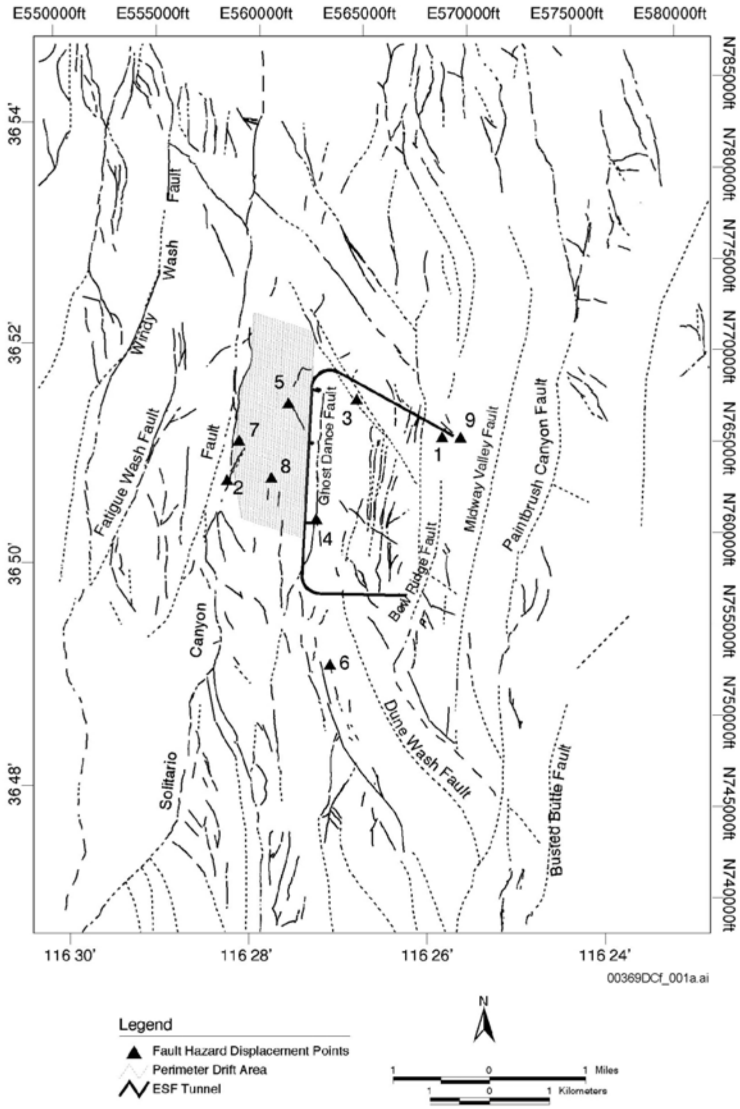


Lithophysae, spots, and clasts of Tptpll in panel map 2125 located on the left rib from station 21+25 to 21+28. Lithophysae have red “L” identifiers with cavities outlined in red and rims in green. Spots have blue “S” identifiers with cyan outlines. Lithic clasts have orange “C” identifiers with gold outlines.

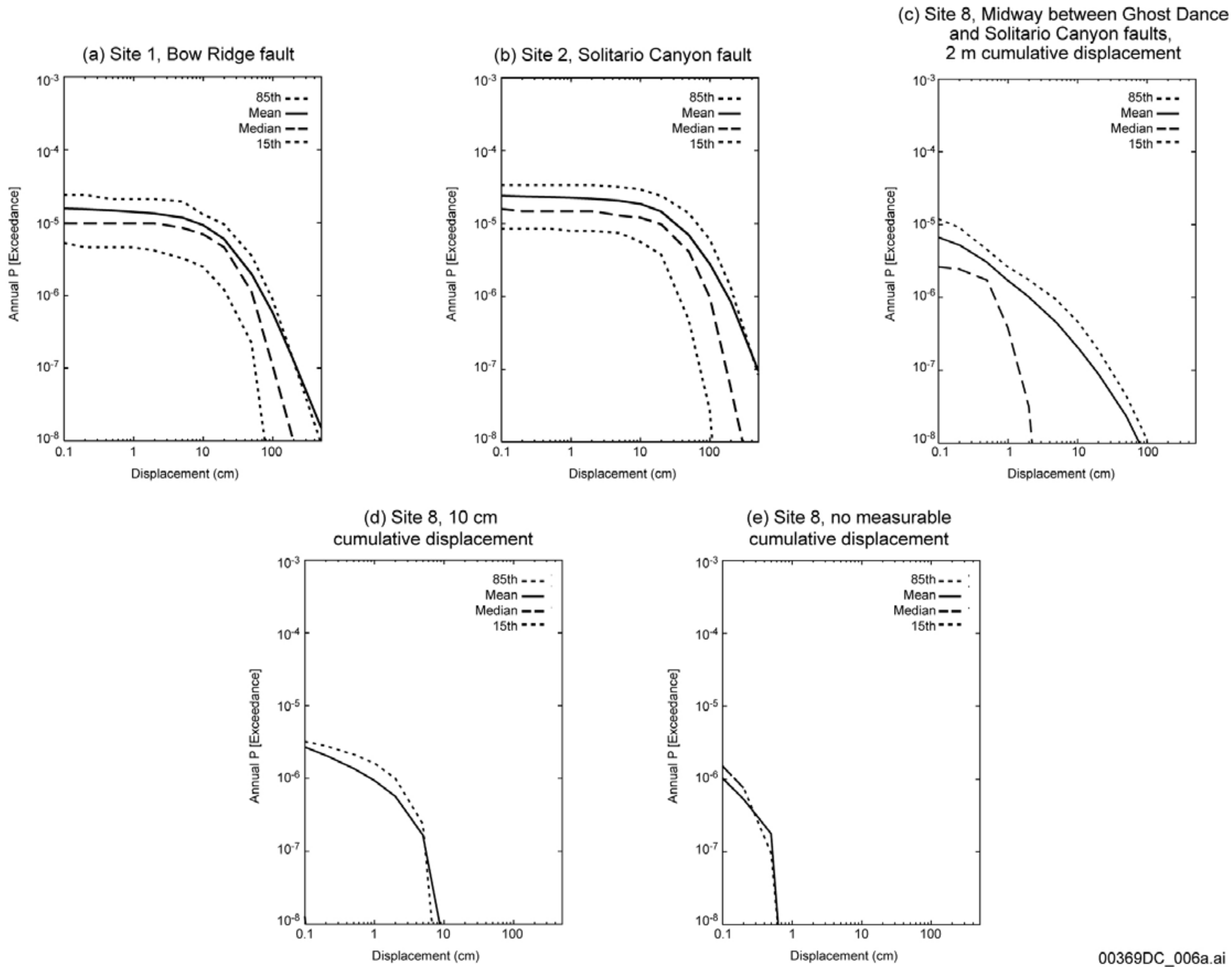
PSHA Seismic Hazard Curves



Probabilistic Fault Displacement Hazard



Fault Displacement Results



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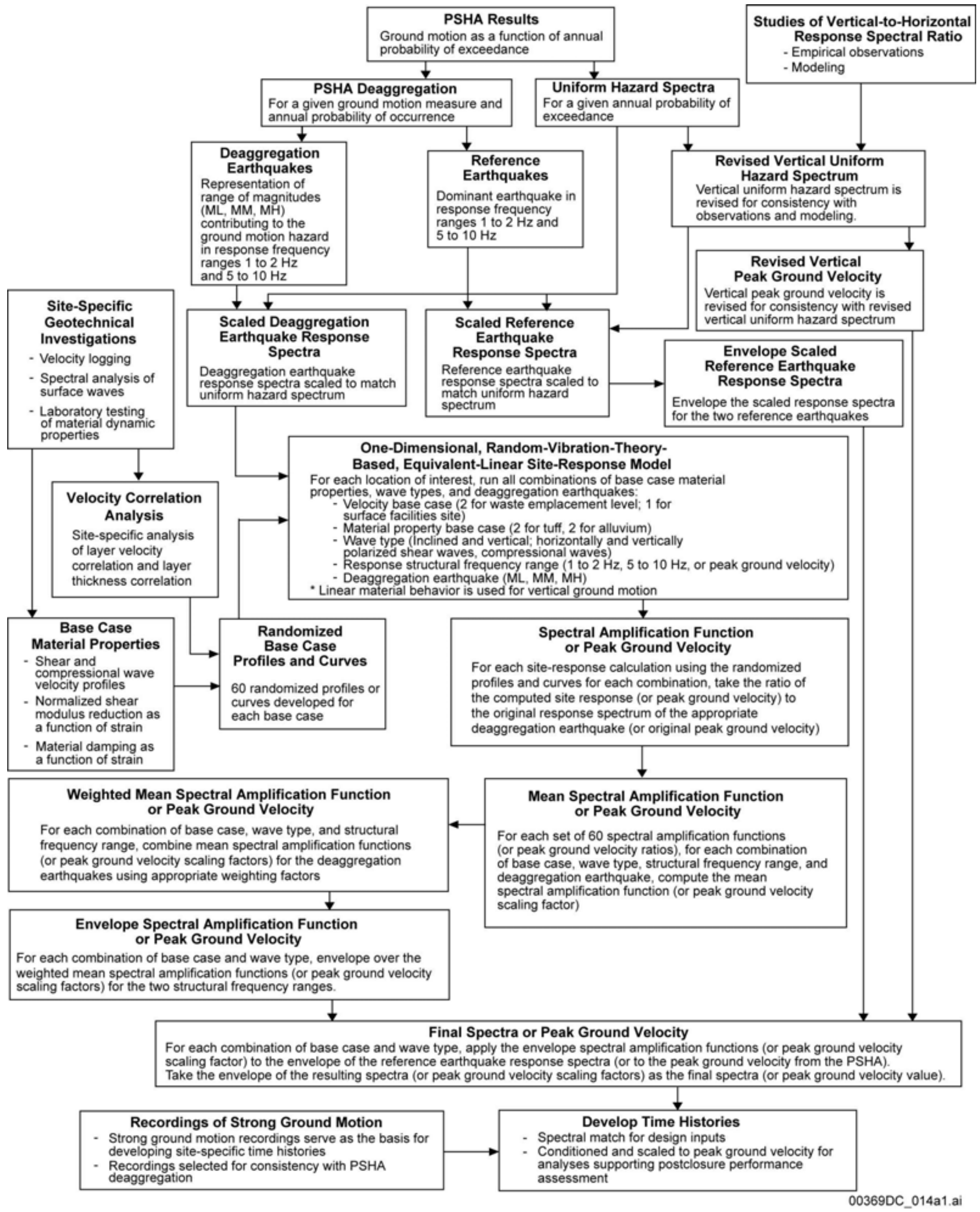
PSHA Results
Ground motion as a function of annual probability of exceedance
Studies of Vertical-to-Horizontal Response Spectral Ratio
- Empirical observations
- Modeling
PSHA Deaggregation
For a given ground motion measure and annual probability of occurrence
Uniform Hazard Spectra
For a given annual probability of exceedance
Deaggregation Earthquakes
Representation of range of magnitudes (ML, MM, MH) contributing to the ground motion hazard in response frequency ranges 1 to 2 Hz and 5 to 10 Hz
Reference Earthquakes
Dominant earthquake in response frequency ranges 1 to 2 Hz and 5 to 10 Hz
Revised Vertical Uniform Hazard Spectrum
Vertical uniform hazard spectrum is revised for consistency with observations and modeling.
Revised Vertical Peak Ground Velocity
Vertical peak ground velocity is revised for consistency with revised vertical uniform hazard spectrum
Site-Specific Geotechnical Investigations
- Velocity logging
- Spectral analysis of surface waves
- Laboratory testing of material dynamic properties
Scaled Deaggregation Earthquake Response Spectra
Deaggregation earthquake response spectra scaled to match uniform hazard spectrum
Scaled Reference Earthquake Response Spectra
Reference earthquake response spectra scaled to match uniform hazard spectrum
Envelope Scaled Reference Earthquake Response Spectra
Envelope the scaled response spectra for the two reference earthquakes
One-Dimensional, Random-Vibration-Theory-Based, Equivalent-Linear Site-Response Model
For each location of interest, run all combinations of base case material properties, wave types, and deaggregation earthquakes:
- Velocity base case (2 for waste emplacement level; 1 for surface facilities site)
- Material property base case (2 for tuff, 2 for alluvium)
- Wave type (Inclined and vertical; horizontally and vertically polarized shear waves, compressional waves)
- Response structural frequency range (1 to 2 Hz, 5 to 10 Hz, or peak ground velocity)
- Deaggregation earthquake (ML, MM, MH)
* Linear material behavior is used for vertical ground motion
Velocity Correlation Analysis
Site-specific analysis of layer velocity correlation and layer thickness correlation
Base Case Material Properties
- Shear and compressional wave velocity profiles
- Normalized shear modulus reduction as a function of strain
- Material damping as a function of strain
Randomized Base Case Profiles and Curves
60 randomized profiles or curves developed for each base case
Spectral Amplification Function or Peak Ground Velocity
For each site-response calculation using the randomized profiles and curves for each combination, take the ratio of the computed site response (or peak ground velocity) to the original response spectrum of the appropriate deaggregation earthquake (or original peak ground velocity)
Weighted Mean Spectral Amplification Function or Peak Ground Velocity
For each combination of base case, wave type, and structural frequency range, combine mean spectral amplification functions (or peak ground velocity scaling factors) for the deaggregation earthquakes using appropriate weighting factors
Mean Spectral Amplification Function or Peak Ground Velocity
For each set of 60 spectral amplification functions (or peak ground velocity ratios), for each combination of base case, wave type, structural frequency range, and deaggregation earthquake, compute the mean spectral amplification function (or peak ground velocity scaling factor)
Envelope Spectral Amplification Function or Peak Ground Velocity
For each combination of base case and wave type, envelope over the weighted mean spectral amplification functions (or peak ground velocity scaling factors) for the two structural frequency ranges.
Final Spectra or Peak Ground Velocity
For each combination of base case and wave type, apply the envelope spectral amplification functions (or peak ground velocity scaling factor) to the envelope of the reference earthquake response spectra (or to the peak ground velocity from the PSHA). Take the envelope of the resulting spectra (or peak ground velocity scaling factors) as the final spectra (or peak ground velocity value).
Recordings of Strong Ground Motion
- Strong ground motion recordings serve as the basis for developing site-specific time histories
- Recordings selected for consistency with PSHA deaggregation
Develop Time Histories
- Spectral match for design inputs
- Conditioned and scaled to peak ground velocity for analyses supporting postclosure performance assessment
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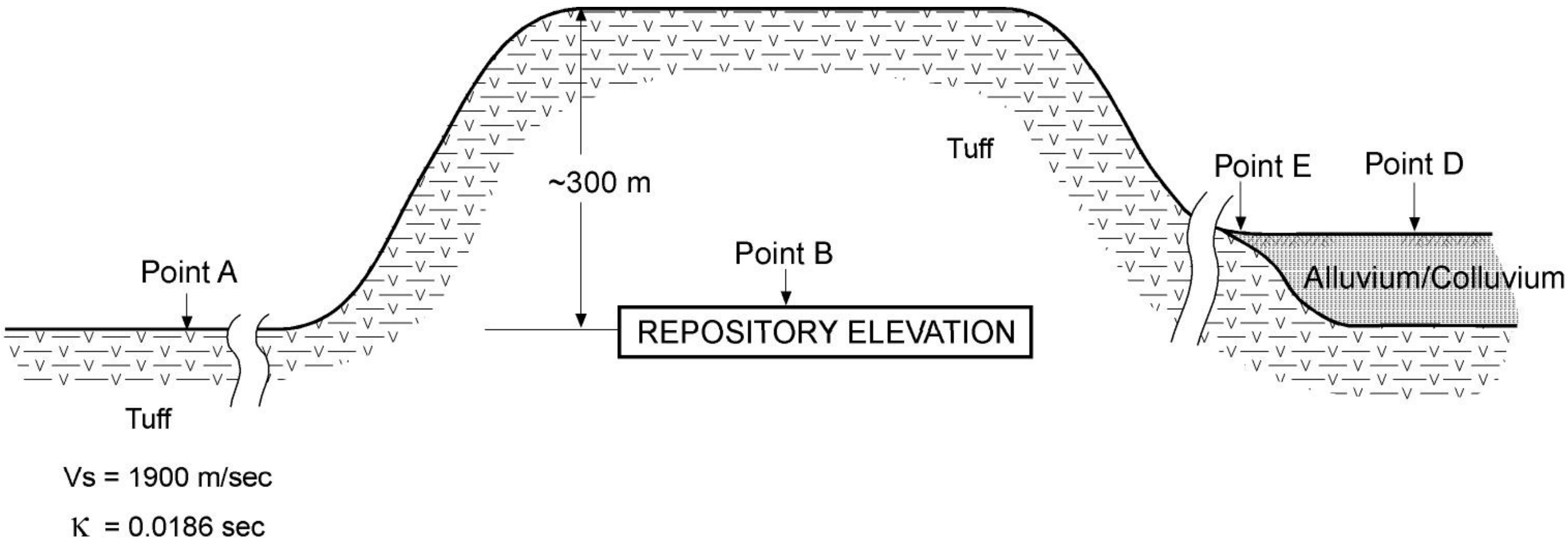
Ground Motion Hazard Results

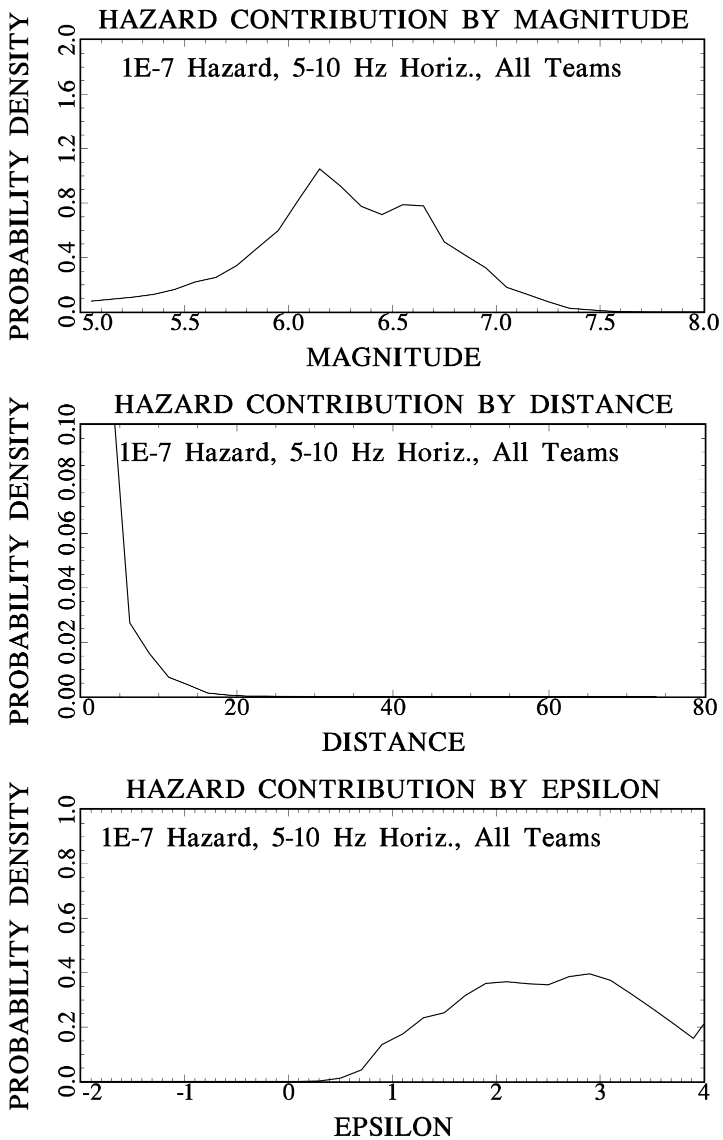


- **Ground motion hazard computed at control location (hypothetical point A), rock properties at control location are the same as those at repository elevation**
- **Aleatory variability of ground motion about the median motion for M and D not truncated**

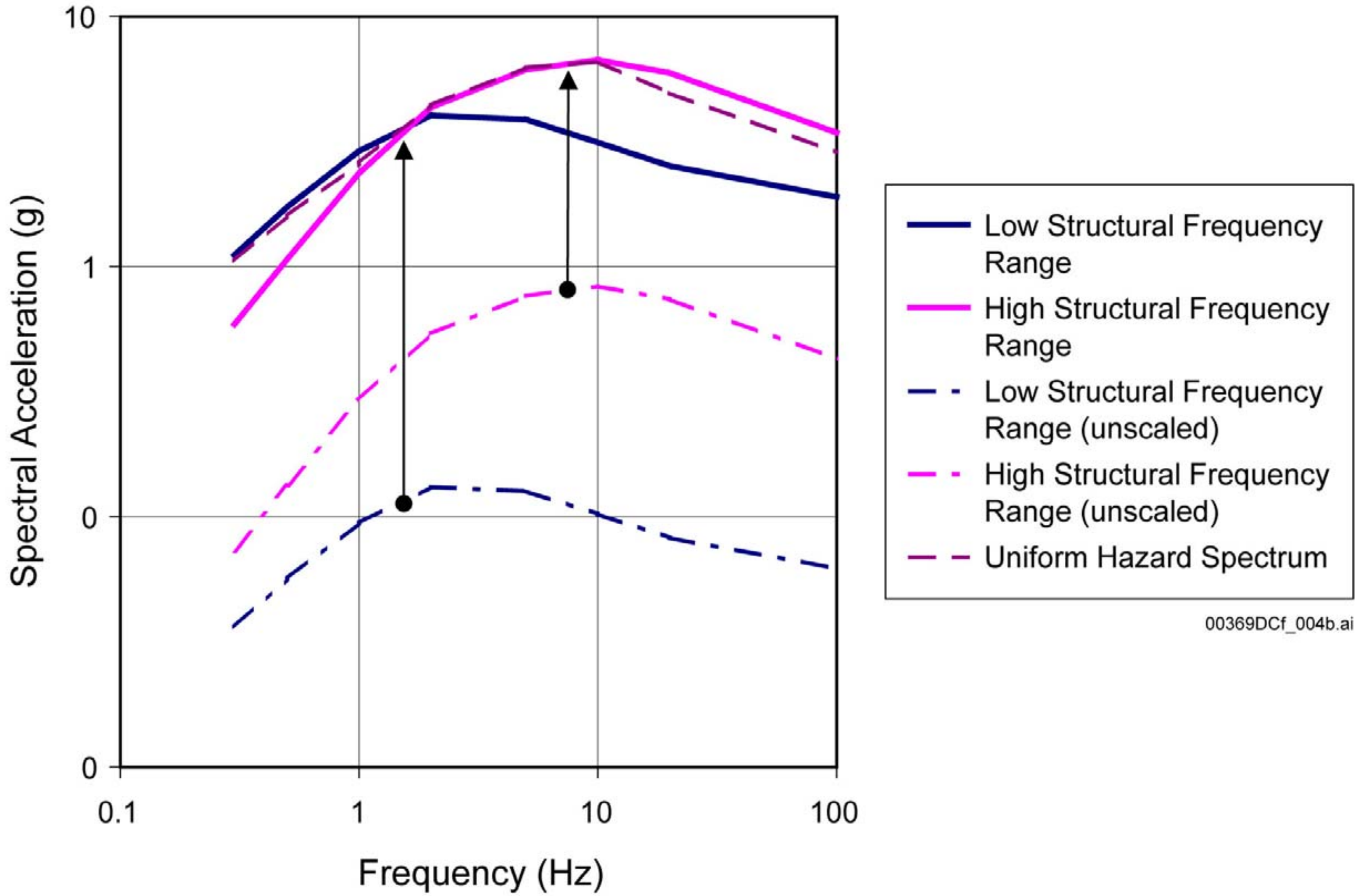
Ground Motion Hazard Results:

Hazard deaggregation based on magnitude, distance, and epsilon

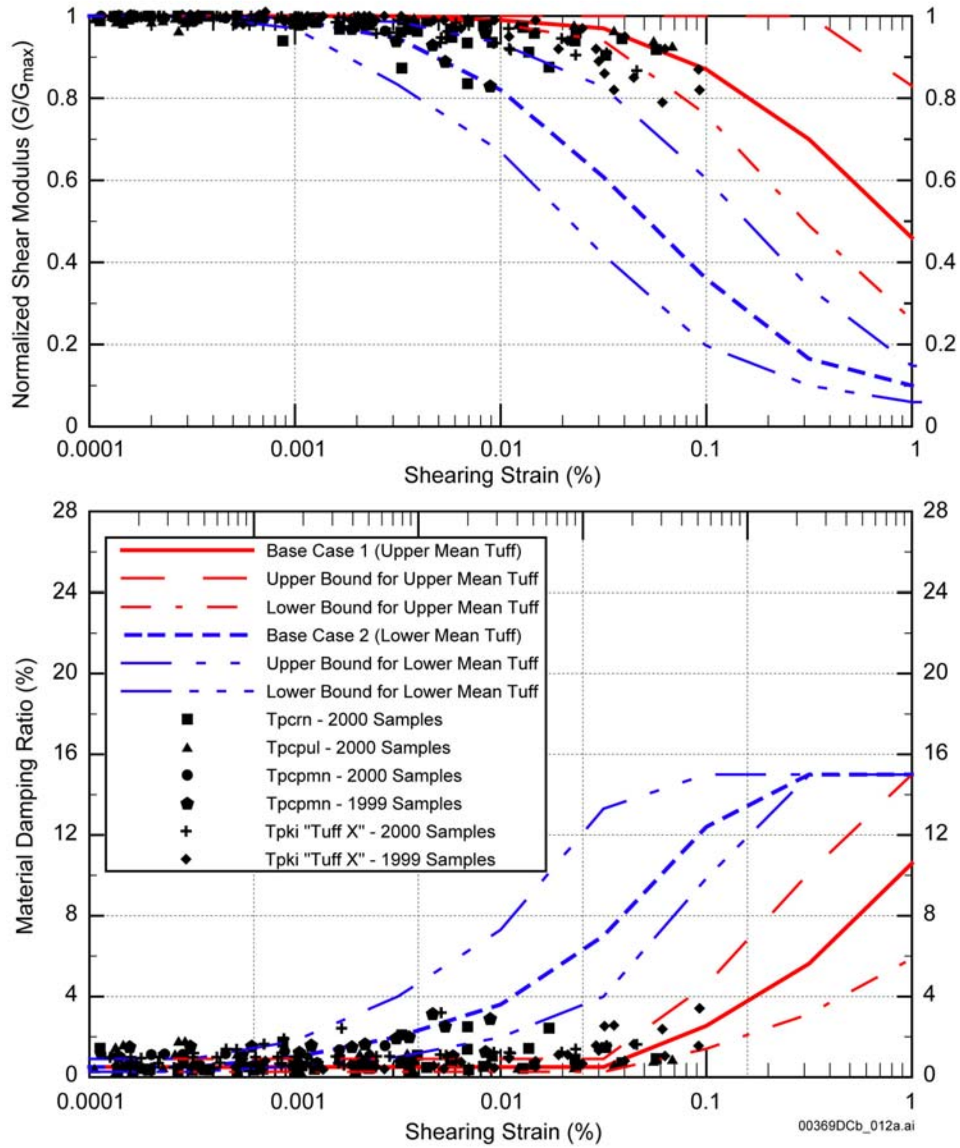
For low annual probabilities, hazard from moderate magnitude nearby sources, <u>high epsilon</u> dominates



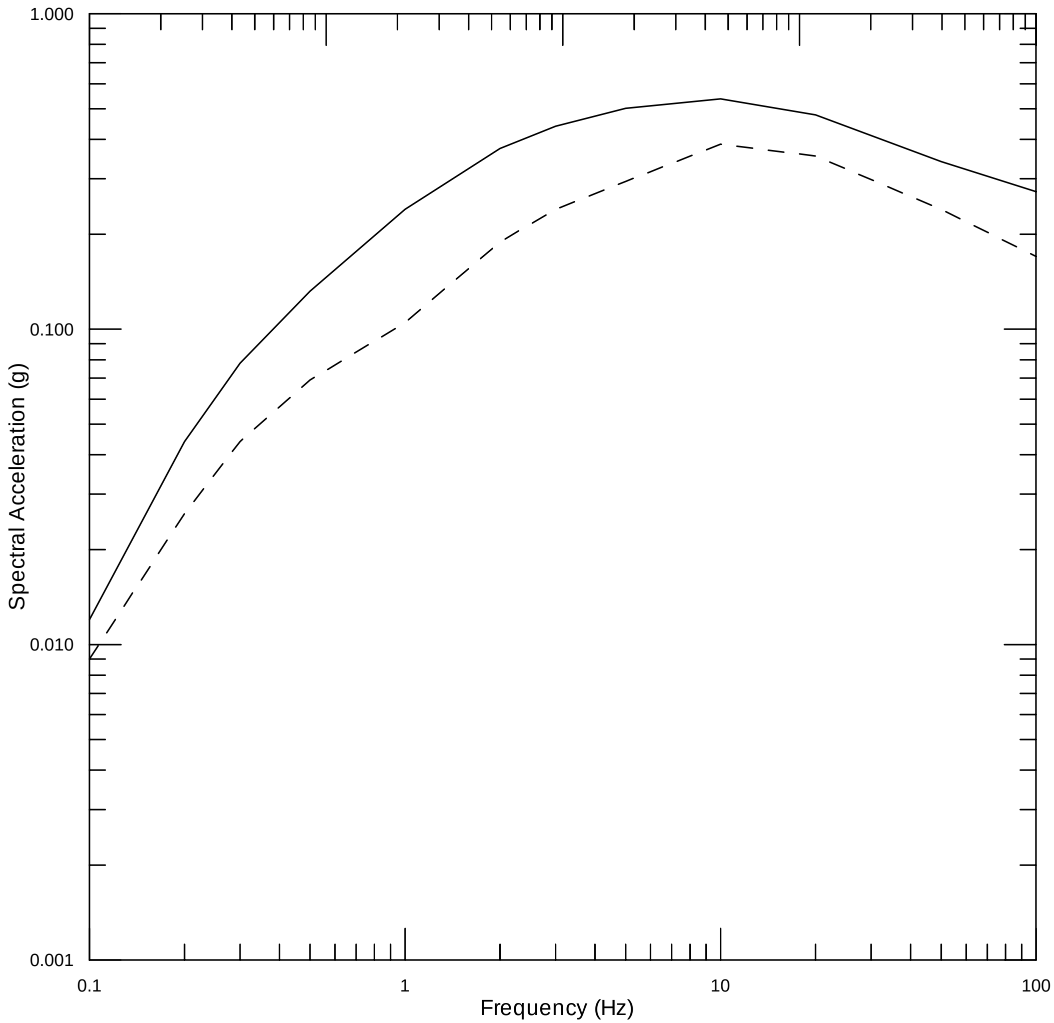
Deaggregation Earthquakes



Uncertainty in Dynamic Material Properties



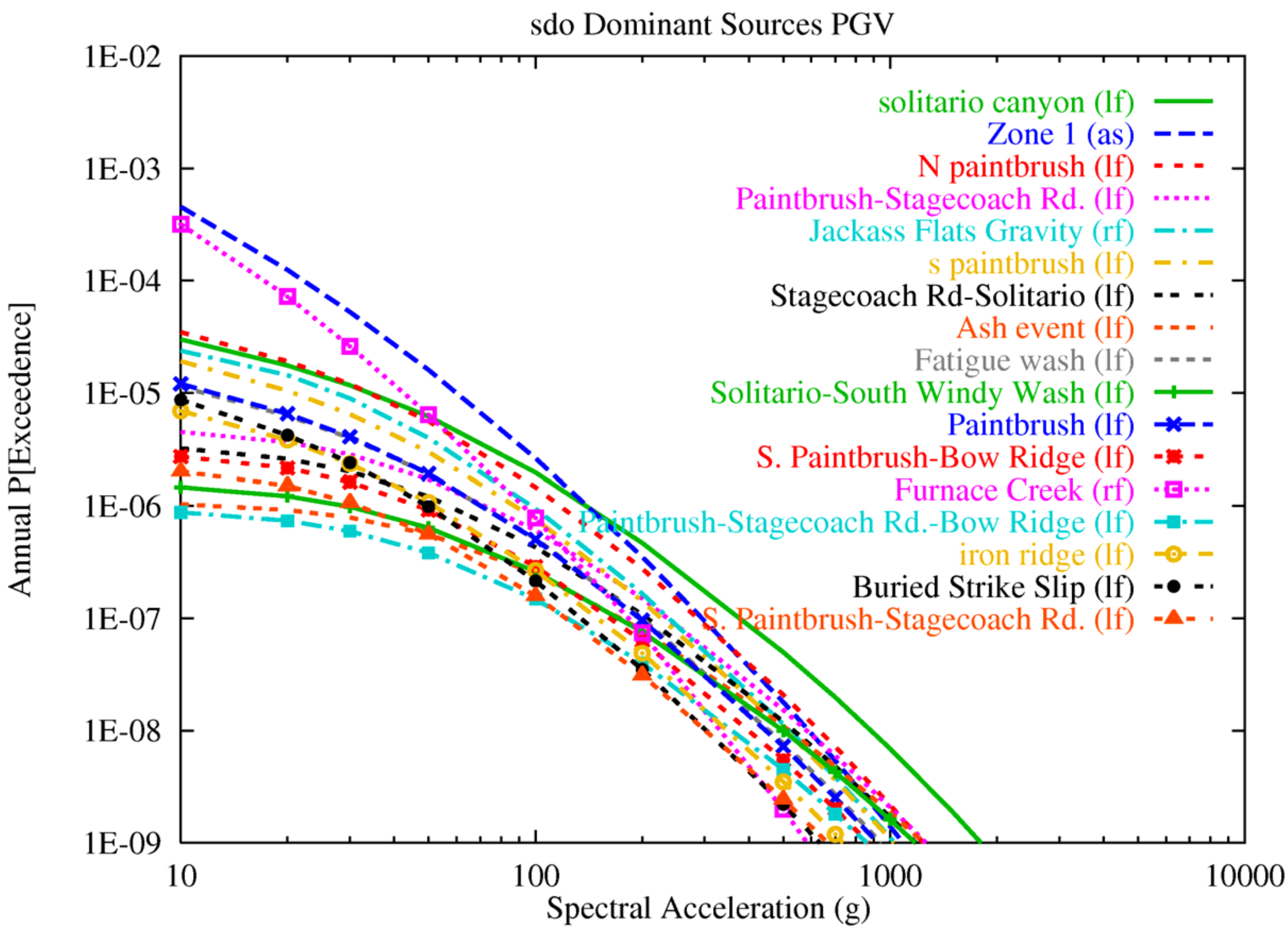
Uniform Hazard Spectra and Representative Events Used to Develop Time Histories



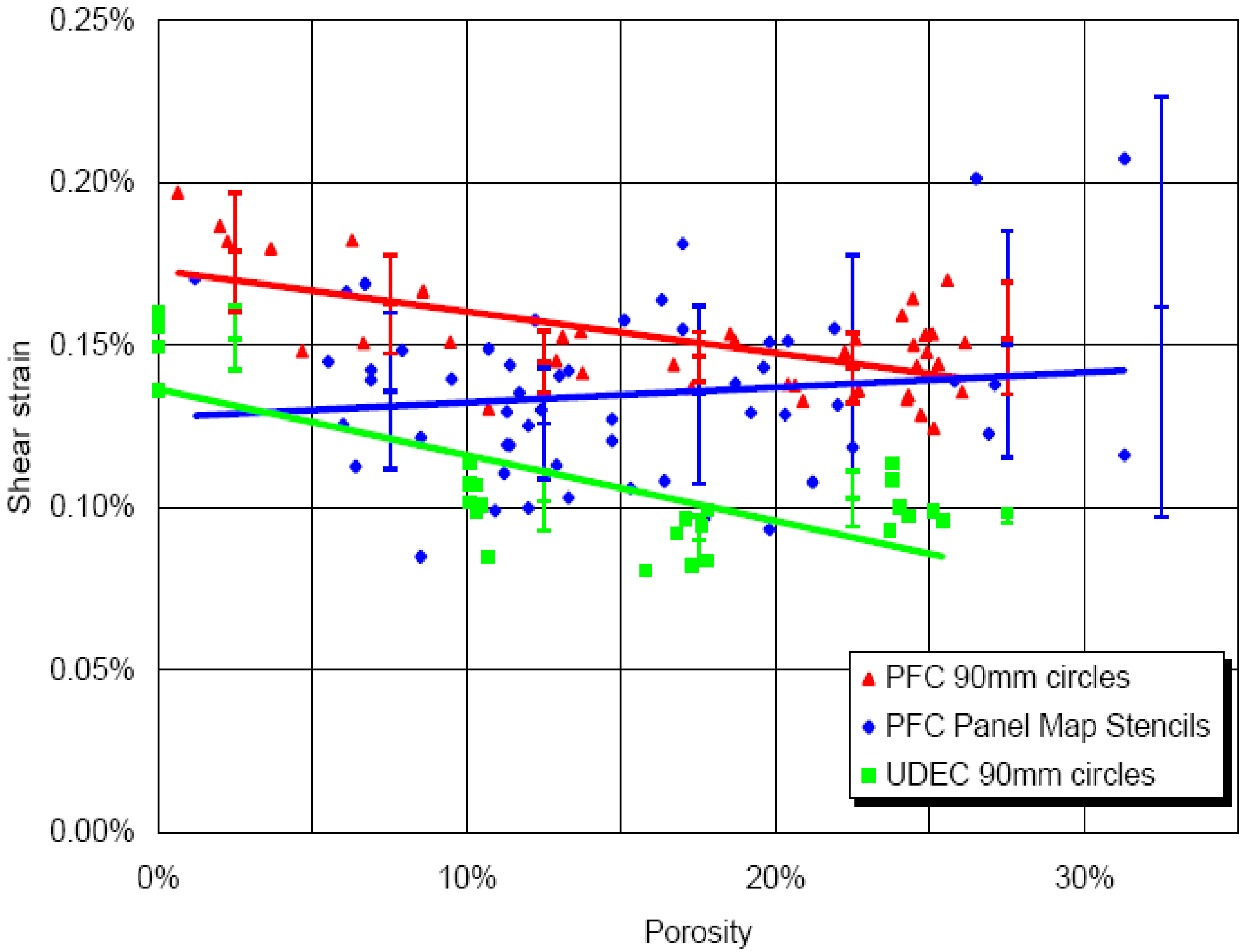
$5x10^{-4}$ AEP

LEGEND
——— HORIZONTAL, PEAK GROUND ACCELERATION (PGA) = 0.273 g (Acceleration due to gravity)
- - - - - VERTICAL, PGA = 0.170 g

Complex Source Models



Modeling Results



Shear strain vs porosity for peak-stress criterion; overburden = 250 m