U.S. Department of Energy
Office of Civilian Radioactive Waste Management

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Update on Development of Seismic Inputs for Yucca Mountain, Nevada

Presented to:
Nuclear Waste Technical Review Board

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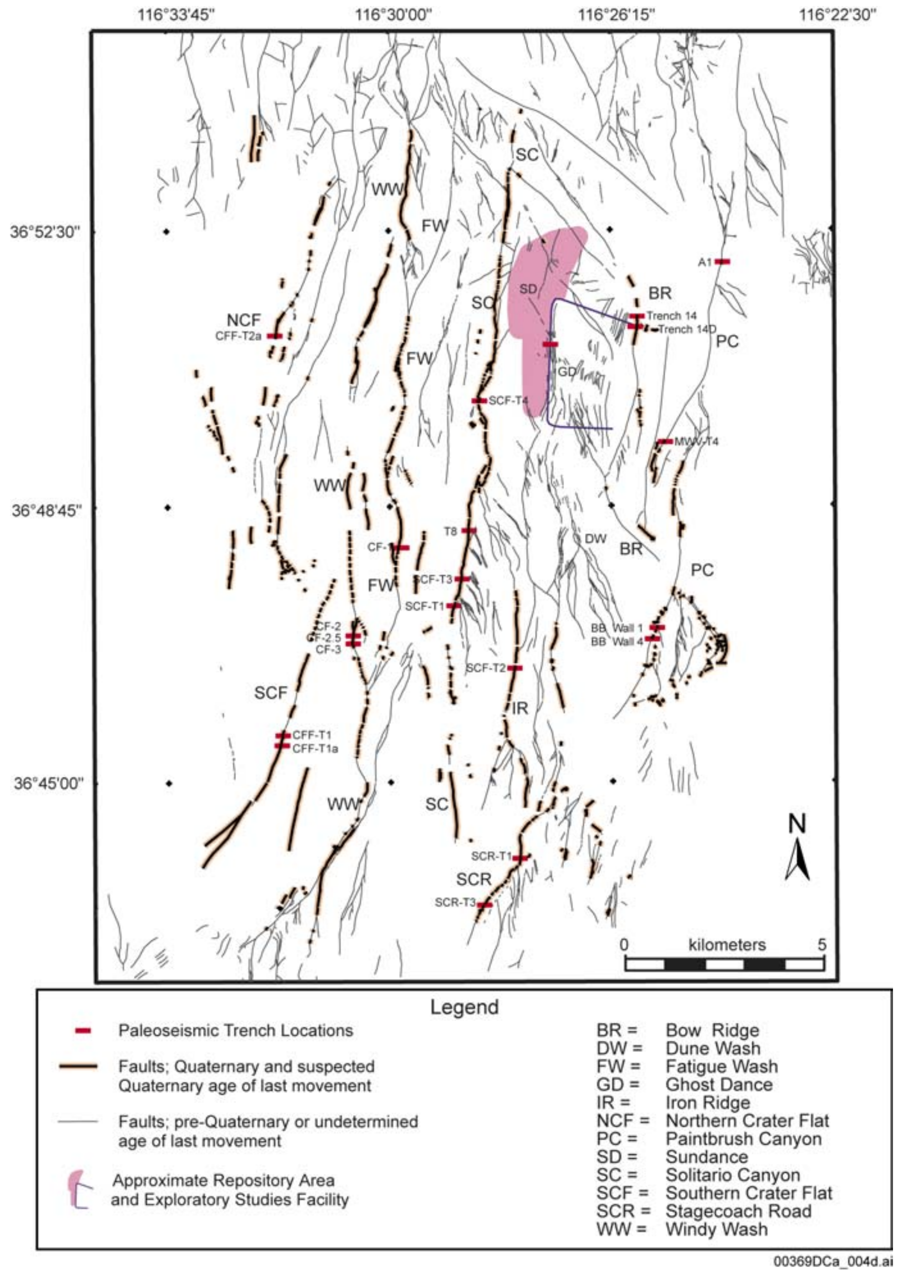
Washington, DC

Yucca Mountain Ground Motions

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

Background

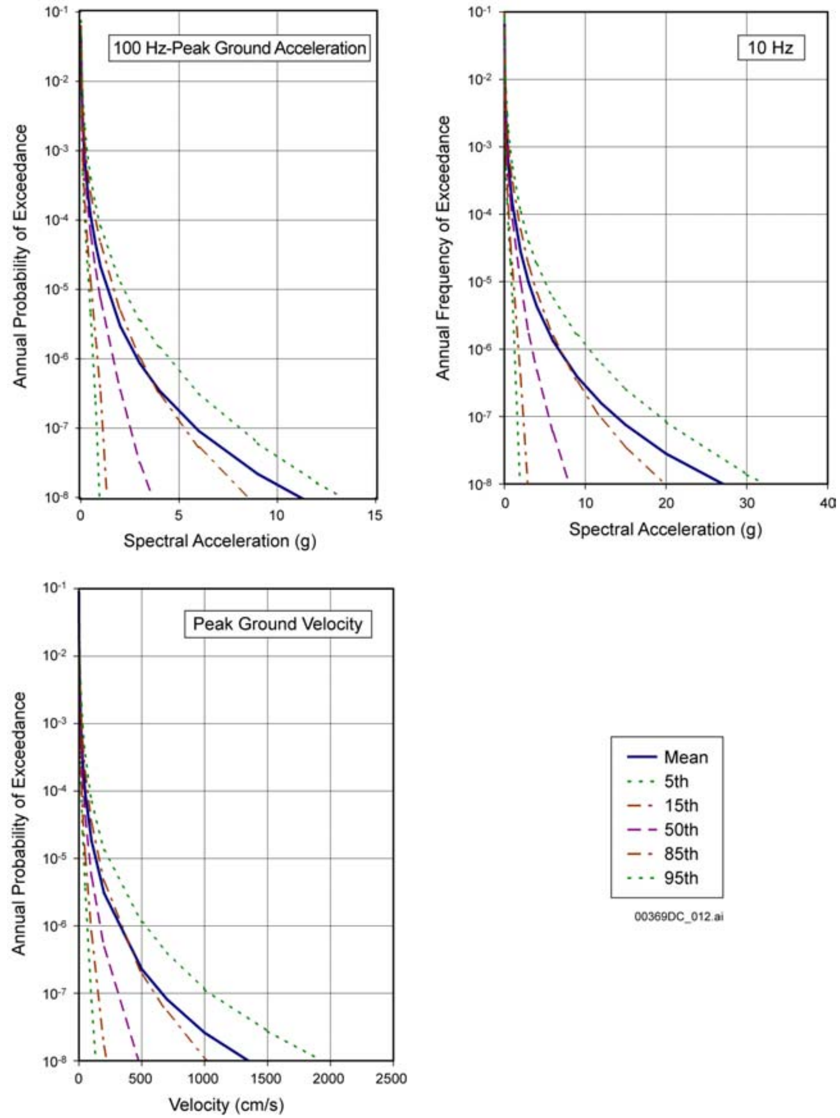
- **Yucca Mountain Probabilistic Seismic Hazard Analysis (PSHA) is based upon good science conducted using state-of-the-art expert elicitation (SSHAC Level 4) methodology**
  - **Reviewed by NAS, accepted by NRC for application in nuclear facility licensing, consistent with NRC Branch and Staff technical position**
  - **Includes epistemic uncertainties and aleatory variability in seismic sources and ground motions**
  - **Aleatory variability in ground motion attenuation is unbounded lognormal distribution, a highly conservative approach**
  - **Fundamental basis for preclosure and postclosure ground motion assessment**
  - **Anticipated focus on annual frequencies greater than 10^{-5} to 10^{-6} based on experience with nuclear power plants**
  - **Mean seismic hazard used for design and performance confirmation**



PSHA:

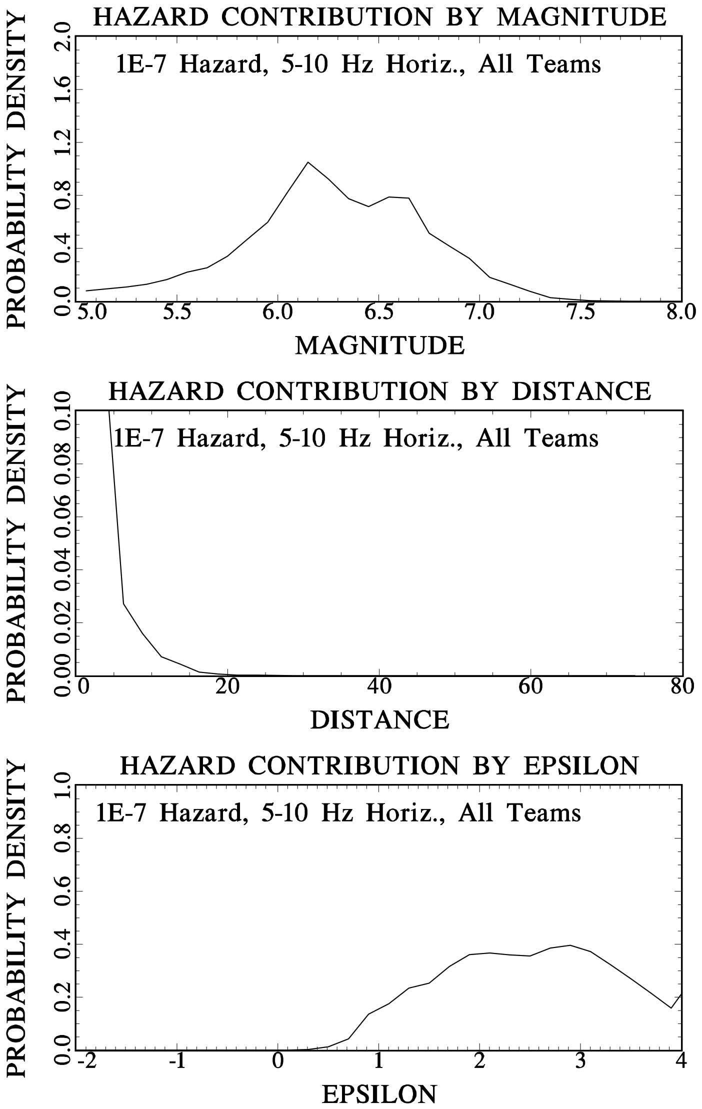
- Source characterization +Ground motion estimation
- Evaluation of local fault sources in PSHA, supported by numerous trenches
- Empirical and theoretical ground motion estimates

PSHA Seismic Hazard Curves



Ground Motion Hazard Results:

- Hazard deaggregation based on magnitude, distance, and epsilon
- For low annual probabilities, hazard from moderate magnitude nearby sources, and <u>high epsilon</u> dominates



Analysis of Results

- **Very large ground motions and highly asymmetric probabilities for low Annual Probability of Exceedance (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 in correspondence to DOE that this highly conservative approach produces unrealistic values**

Outline

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

Limits to Ground Motions

- Cutting edge research topic-Yucca Mountain and PEGASOS (Swiss) projects
- Absolute physical limits are difficult to define
- Approach as site-specific analysis within a probabilistic framework

Background

- Ground motion amplitudes at very low annual frequencies higher than observed worldwide and may be physically unrealizable
- Peak ground velocity (PGV) is ground motion measure of interest; related to EBS damage and rockfall
- Intact tuffs and delicate mineral deposits suggests no extreme ground motions have occurred at this site since deposition of repository rocks (~12Mya)
- DOE has decided to evaluate bounding ground motions (on PGV) using <u>site-specific physical arguments</u>

Site-Specific Investigations

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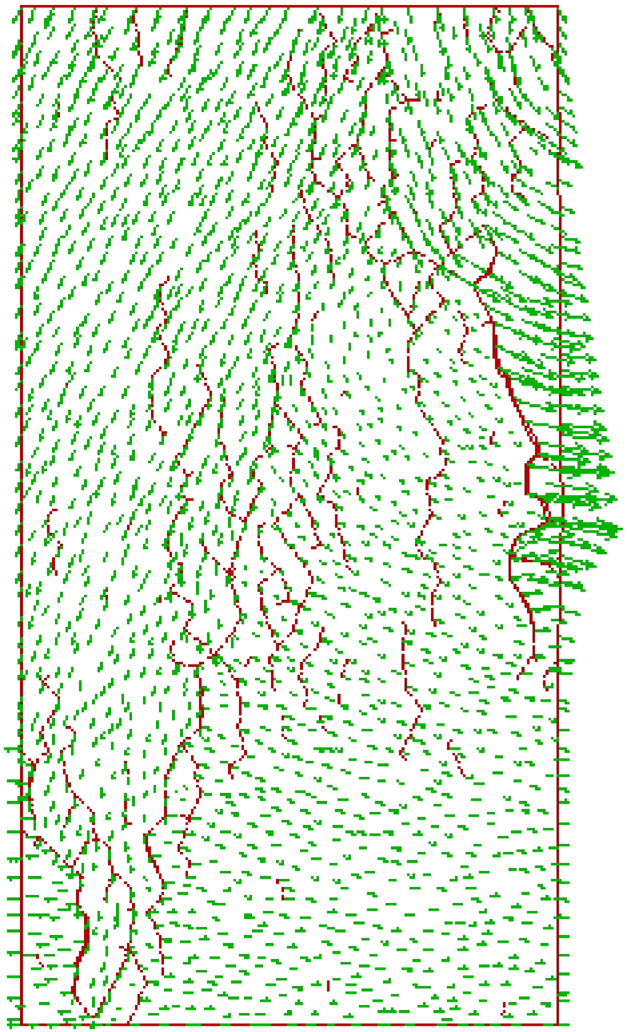
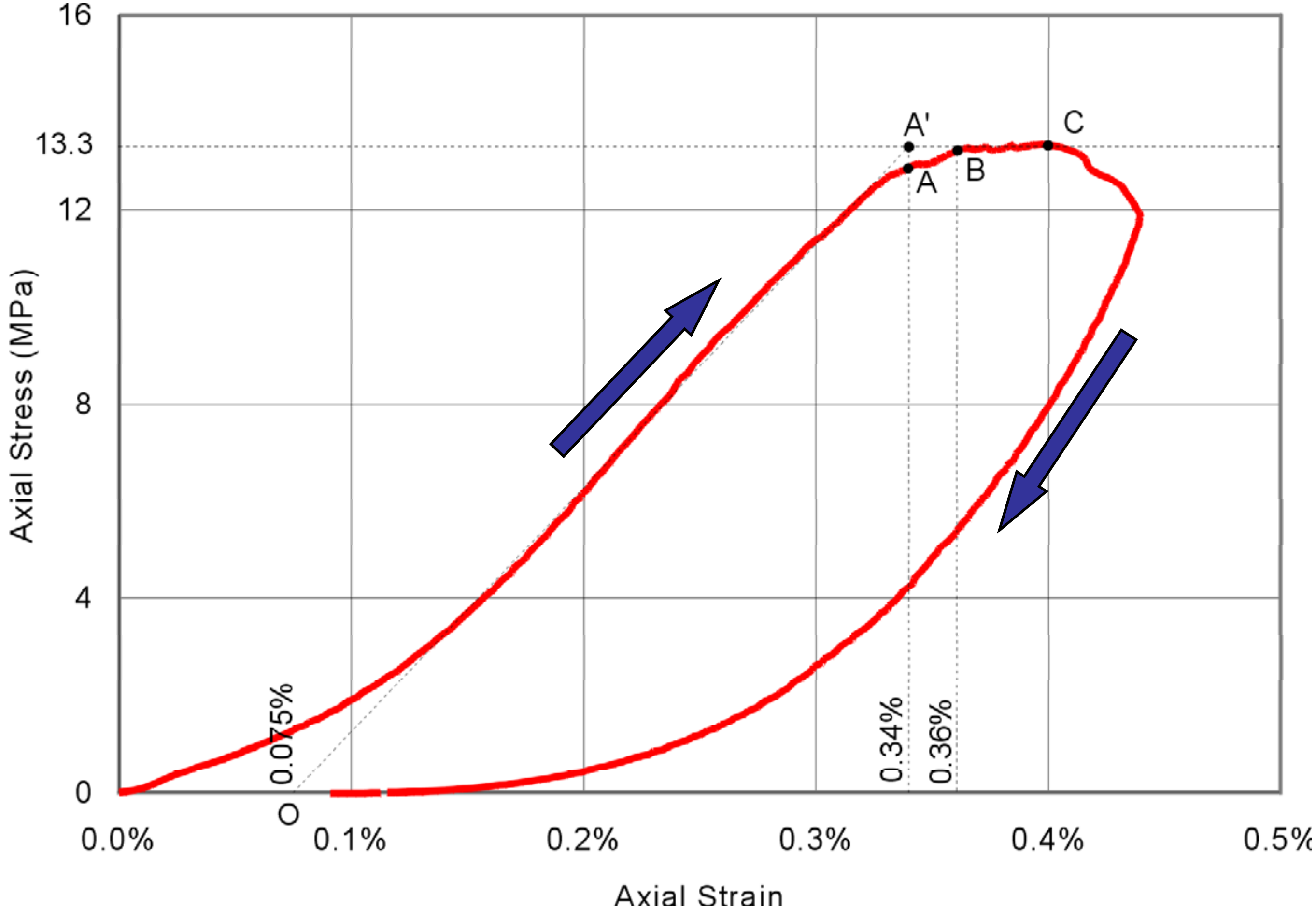
Geologic Observations of Fractures and Lithophysae

- 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

Comparison of Model Failure Mechanism at Large Core-Scale

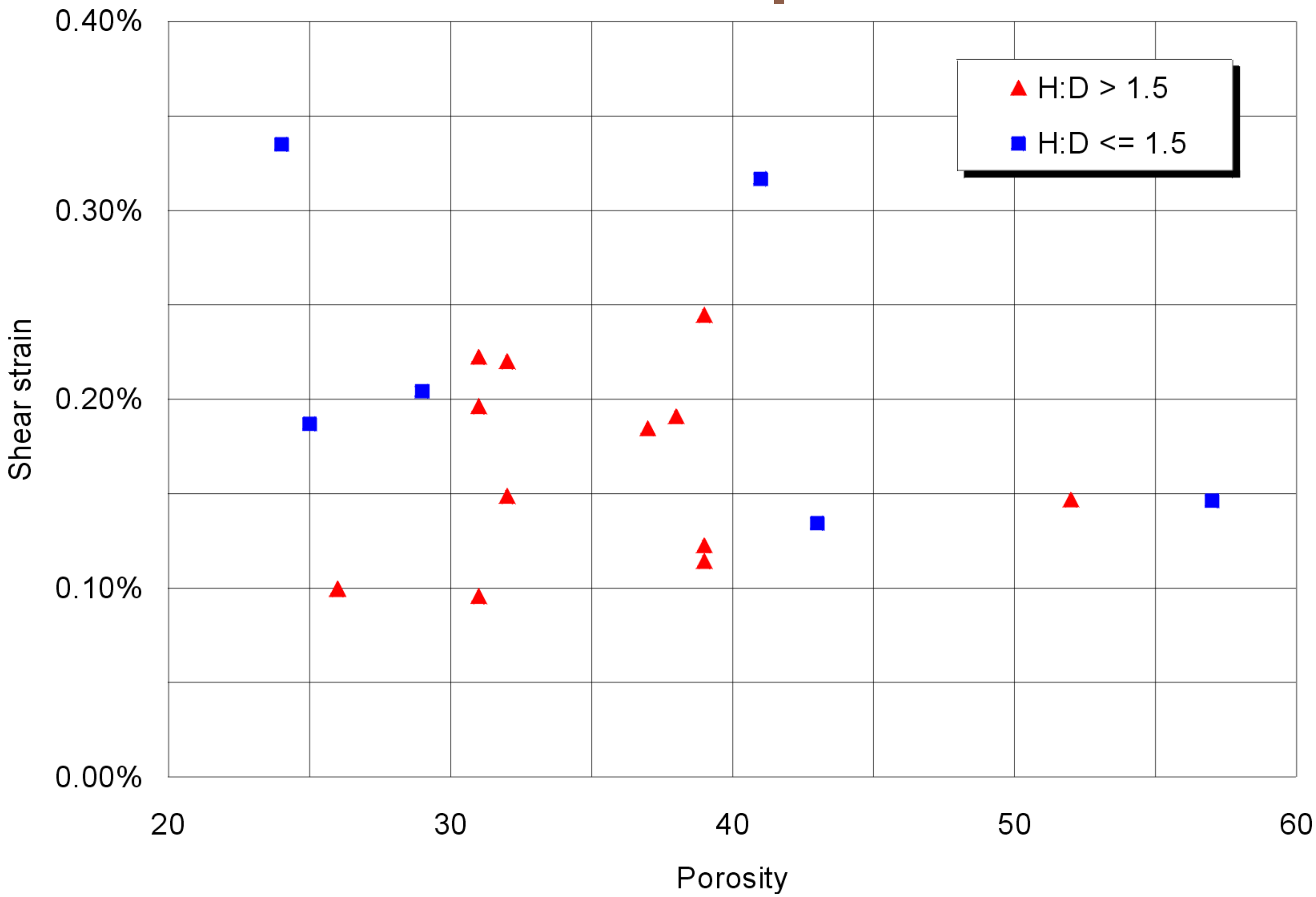


Stress-strain curve for 288-mm Sample of Lower Lithophysal Tuff at Surface Conditions



Strain increment adjusted for 250 m overburden = 0.2%

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



Calculated shear strain limit for 288-mm diameter samples

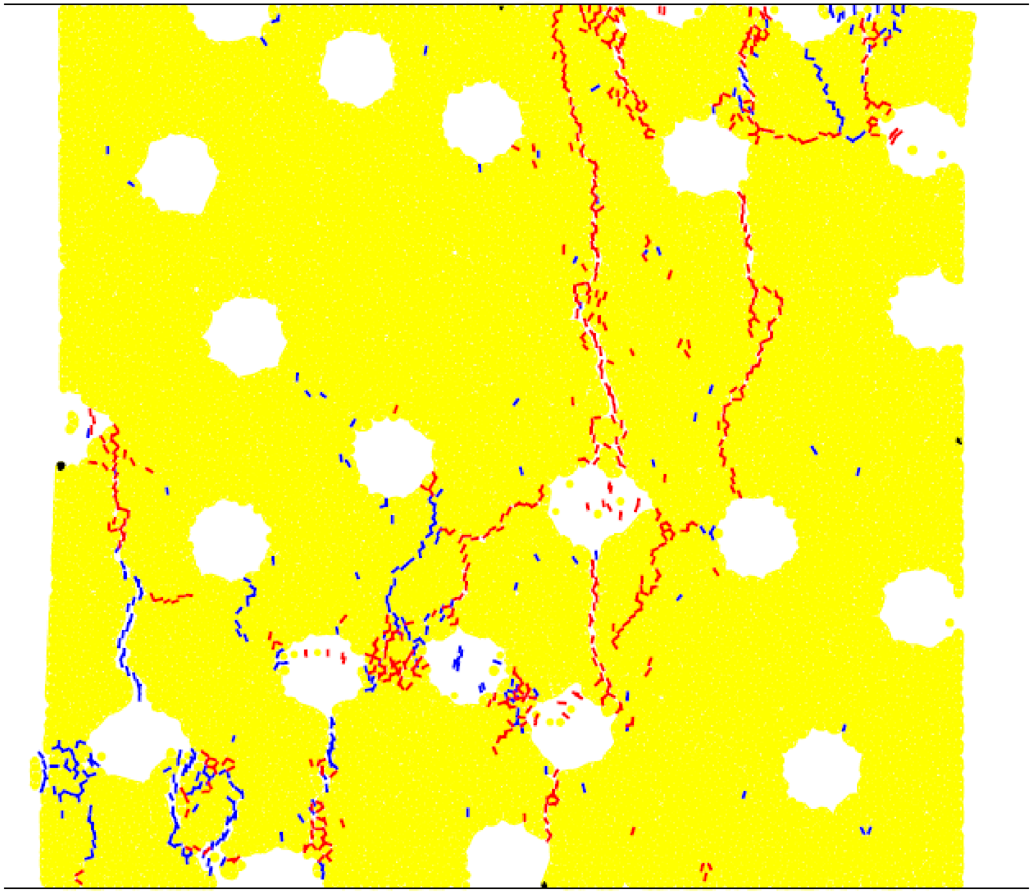
Testing and Modeling for Shear Strain Threshold

- Focus on lithophysal units, which would fail at lower strain levels
- Uniaxial compression tests, confined and unconfined, large and small samples
- Few cyclic tests
- Failure criteria: peak stress, volumetric strain reversal
- Modeling calibrated to test results

Modeled Deformation of Lithophysal Tuff

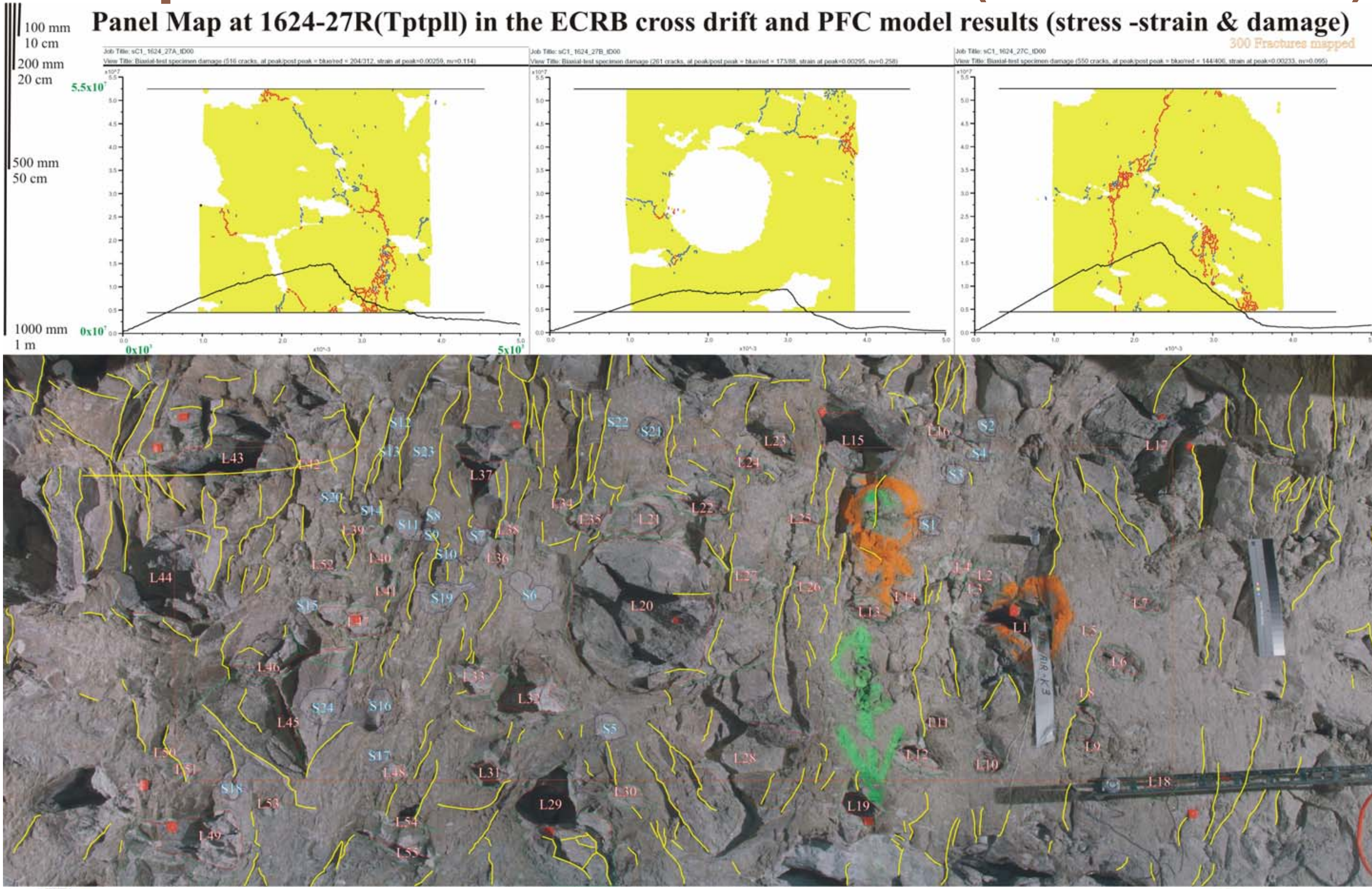
Fracturing of this magnitude inferred to be within observational limits of geologic mapping

Onset of Systematic Fracturing (OSF)



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

PMap 1624L and PFC Models (300 Fractures)



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

Assessment of Bounding PGV

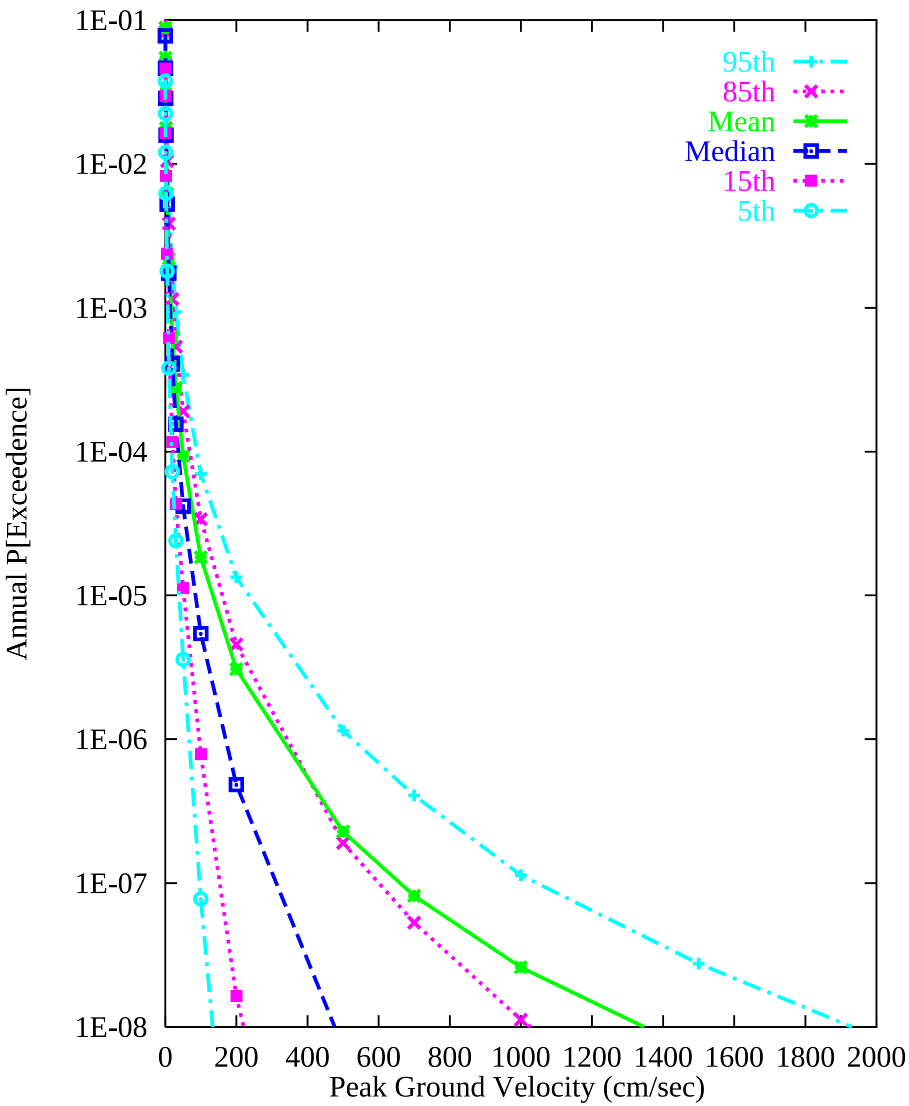
- Fundamental physical constraint: Absence of geologic indicators of seismically-induced deformation in repository rocks at emplacement level
  - Geologic observations of fractures and lithophysae
  - Laboratory tests of shear strains causing failure
- Development of probability distribution on threshold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

Distribution for Strain Consistent with OSF

- Truncated normal distribution
- Mean of 0.2%, sigma of 0.1%
- Limits at 0.05% and 0.4%

Ground Motion Hazard Results

Application in TSPA: Comparison of sampled mean PGV from existing hazard vs. strength-limited value



Ground Motion Calculation

- **PGV calculated for given shear strain threshold, and associated uncertainty distribution**
- **Using full site response model to incorporate site specific properties, uncertainties, and variability**
- **Results in probability distribution on mean bounding PGV**

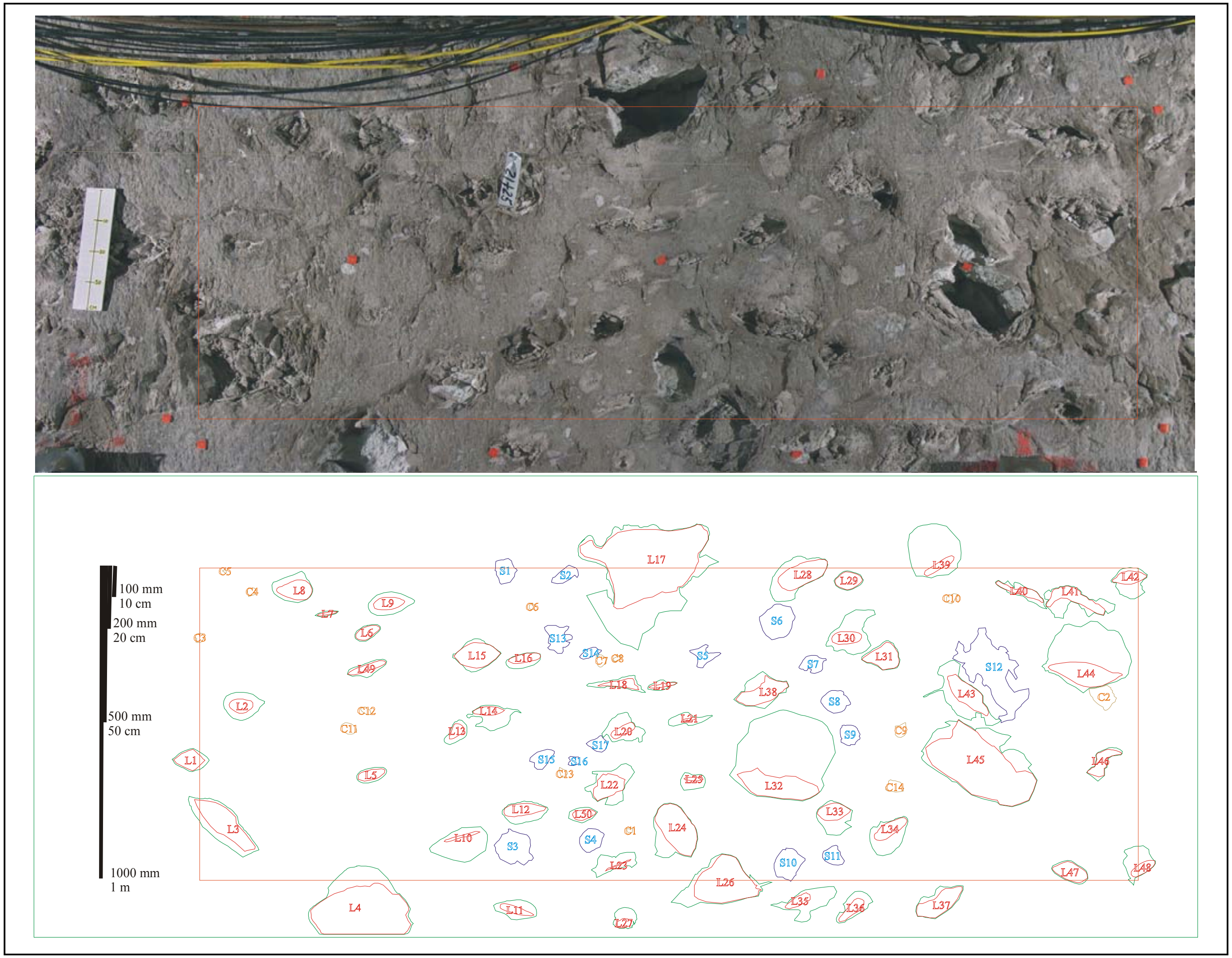
Supporting Evidence

- Seismic source constraints and observed ground motions
- Consideration of extensional faulting and shattered rocks (large motions will shatter 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

Shattered Rock, Hanging Wall, Thrust Fault

Courtesy of Jim Brune, UNR

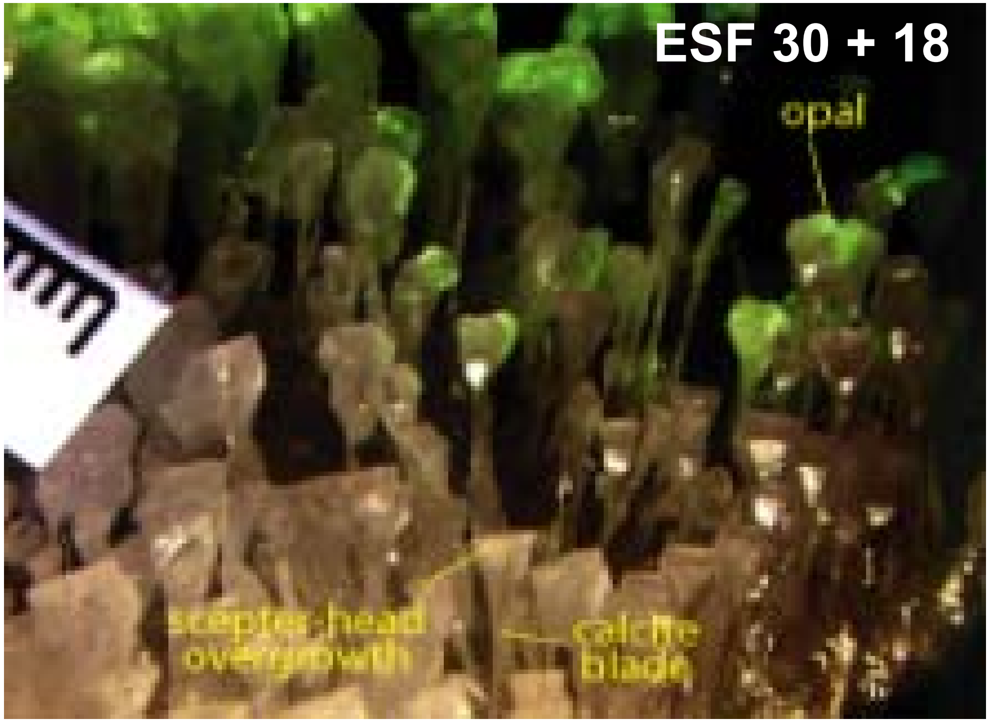
PMap 21+25L



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.

Preservation of Delicate Textures

- Exceptionally thin blades with top-heavy overgrowths
- Testing could be done to determine the minimum ground motions required to break them
- These late-stage features are relevant to ground motions during the past 2 to 4 million years



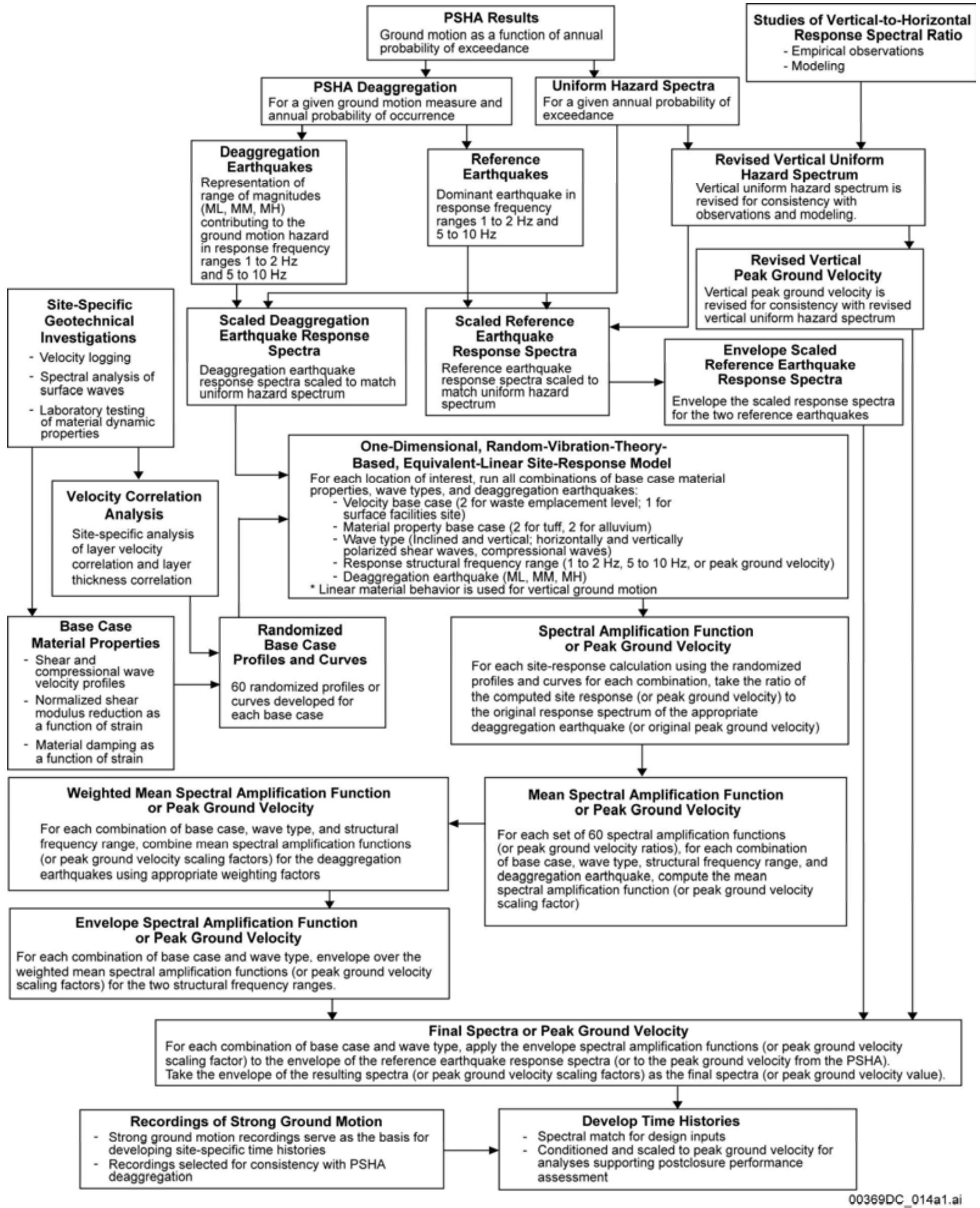
Conclusions

- PSHA for Yucca Mountain is fundamental basis for preclosure and postclosure ground motion assessment
- Strength-limited PGV being developed to ensure ground motions at very low annual frequencies are physically realizable and incorporate uncertainty
- Lack of geologic deformation related to seismically-induced strains in rocks at emplacement level
- Testing and modeling studies to assess threshold shear strains and associated uncertainties
- Documentation being developed for inclusion in License Application
- Supporting evidence

Follow Up

- **Currently Completing an analysis report that documents the assessment of PGV based on shear strain threshold (OSF)**
- **Additional work will be undertaken that further refines potential limitations to ground motions imposed by the seismic source and non-linear wave propagation**

Additional Slides



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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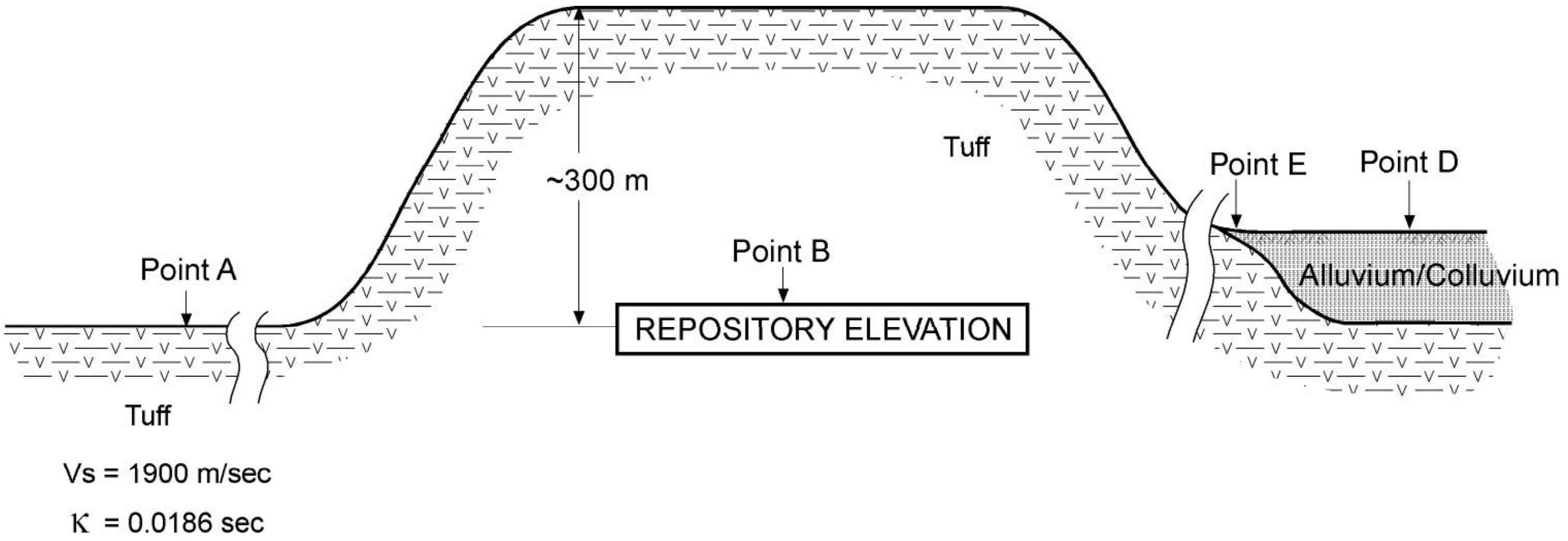
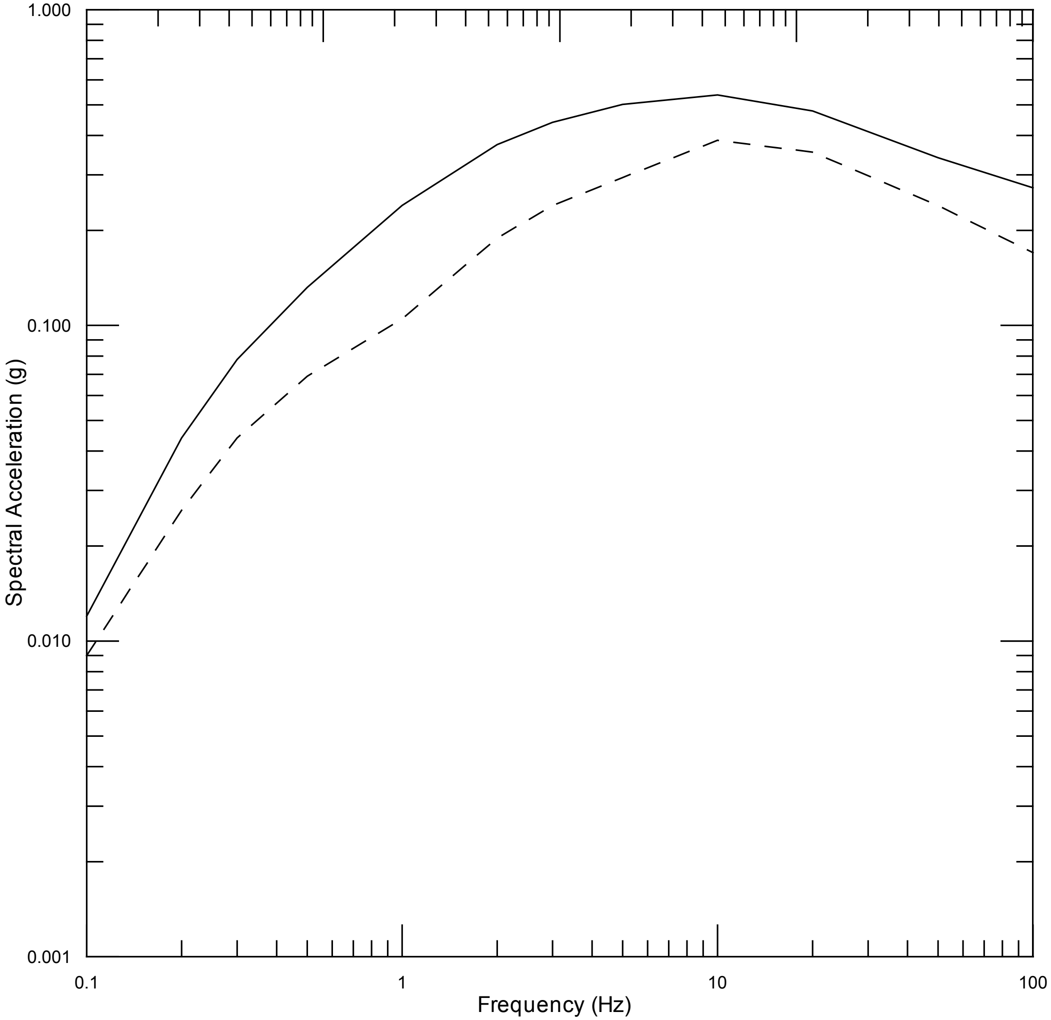
Ground Motion Hazard Results



- **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**

Uniform Hazard Spectra and Representative Events Used to Develop Time Histories



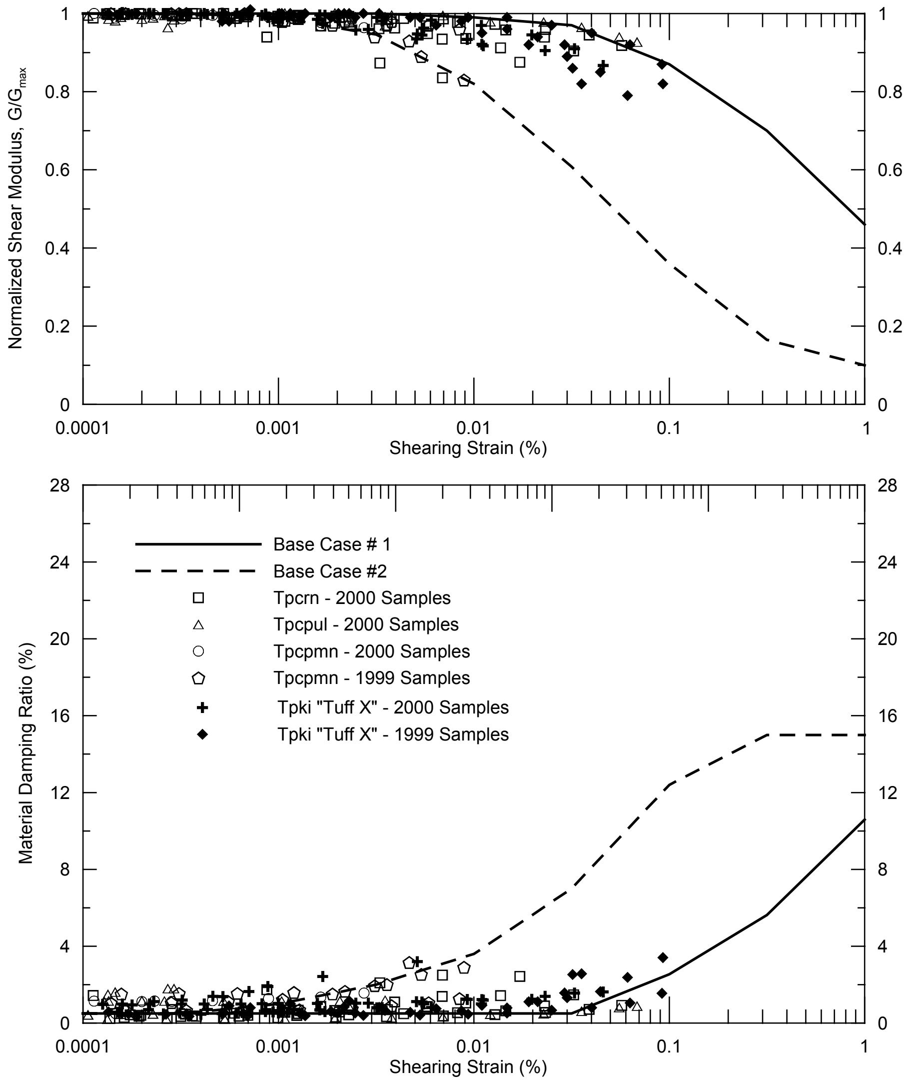
$5x10^{-4}$ AEP

LEGEND

HORIZONTAL, PEAK GROUND ACCELERATION (PGA) = 0.273 g (Acceleration due to gravity)

VERTICAL, PGA = 0.170 g

Variation in Normalized Shear Modulus and Damping Ratio with Shearing Strain (Tuff)



Secondary Mineral Evidence of Past Seismicity

- **Drift Degradation AMR predicted future seismicity could produce extensive damage to emplacement drift walls**
- **Observational evidence from the secondary calcite and silica deposits in fractures and cavities shows some tuff fragmentation but it is restricted to the early history of the tuffs**

Secondary Mineral Evidence of Past Seismicity
(Continued)

- Three types of textural evidence of past seismicity:
  - Tuff fragments incorporated into secondary mineral coatings
    - Possible analog to degradation of drift walls
  - Preservation of delicate bladed textures
  - Undisturbed weakly attached fracture coatings
- The last two could provide paleo-seismoscopes

Incorporation of Tuff Fragments

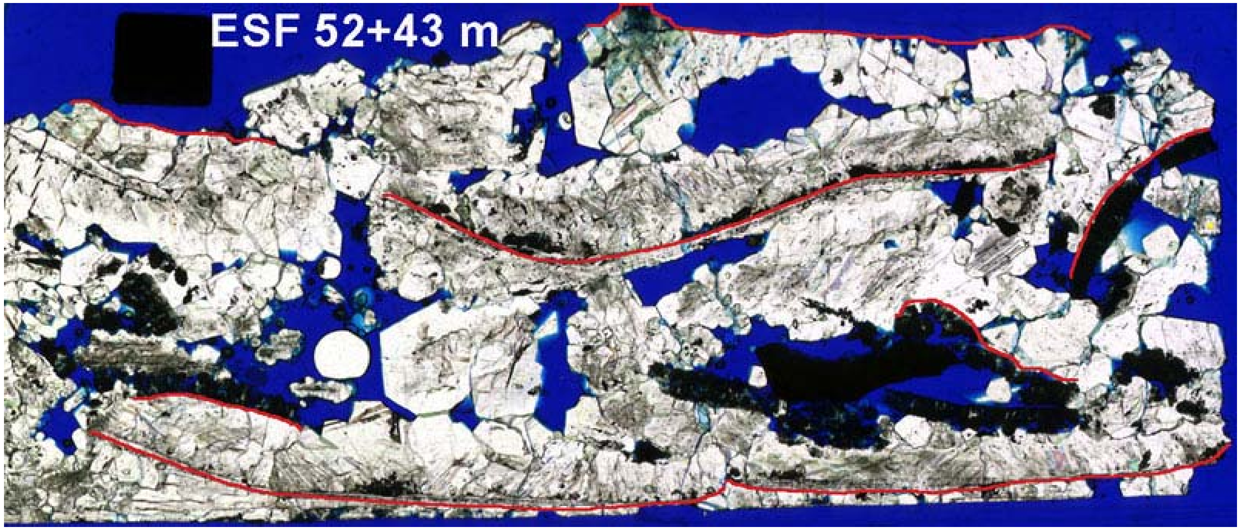
Mineral coatings have incorporated tuff fragments

- Common in the early stage (>6 to 8 Ma)
- Less common in the intermediate stage
- Rare in the late stage (last 2 to 4 million years)

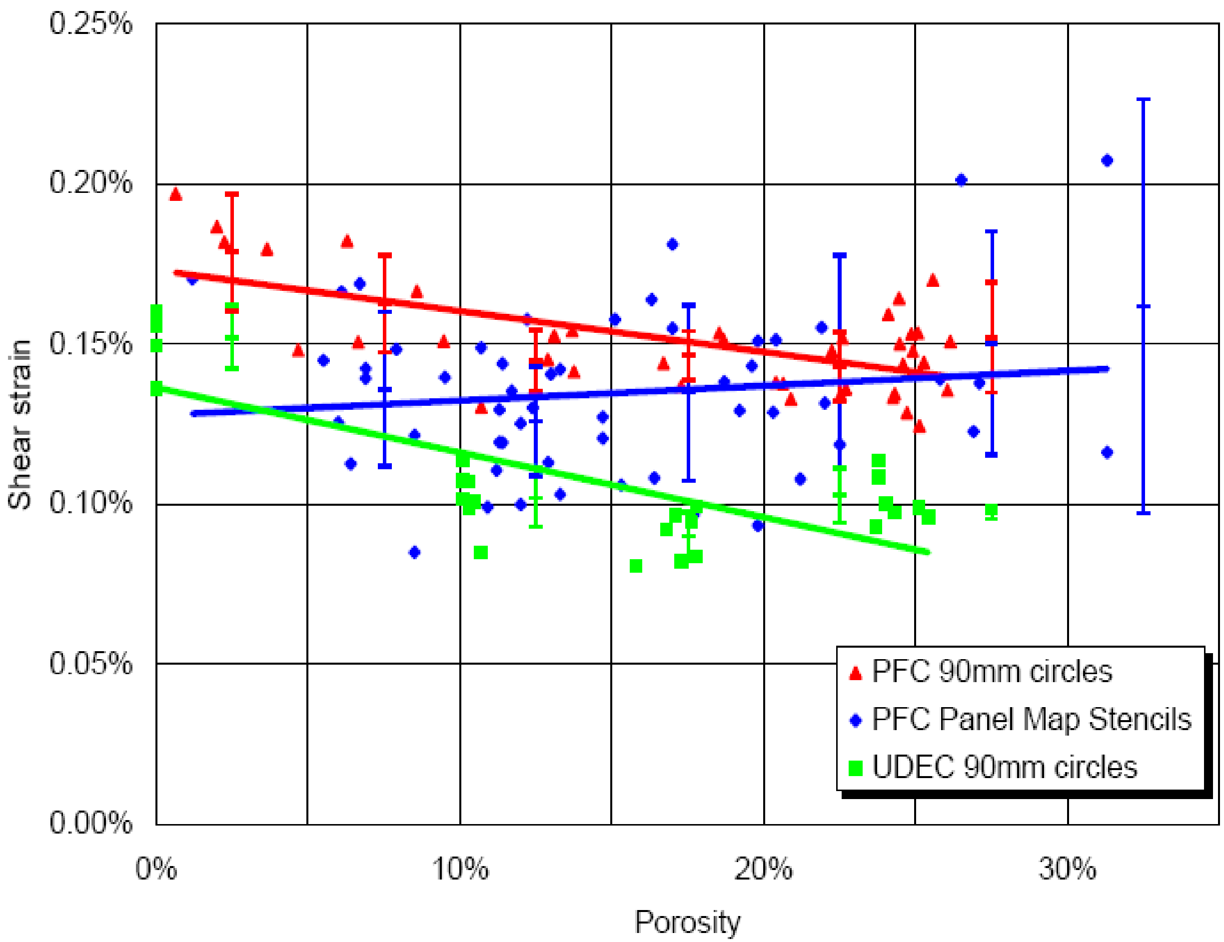
Implies processes resulting in tuff fragmentation have become less common with time

Preservation of Weakly Attached Fracture Coatings

- Some fracture coatings are so weakly attached that they can be removed by hand or with a pocket knife
- Some, as shown in this thin section photograph, have been disturbed and are now re-cemented masses of coating fragments
- Such features may be useful in estimating peak ground motions



Modeling Results



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