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U.S. Department of Energy
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Emplacement Drift Stability

Presented to:
Nuclear Waste Technical Review Board

Presented by:
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Lead Laboratory
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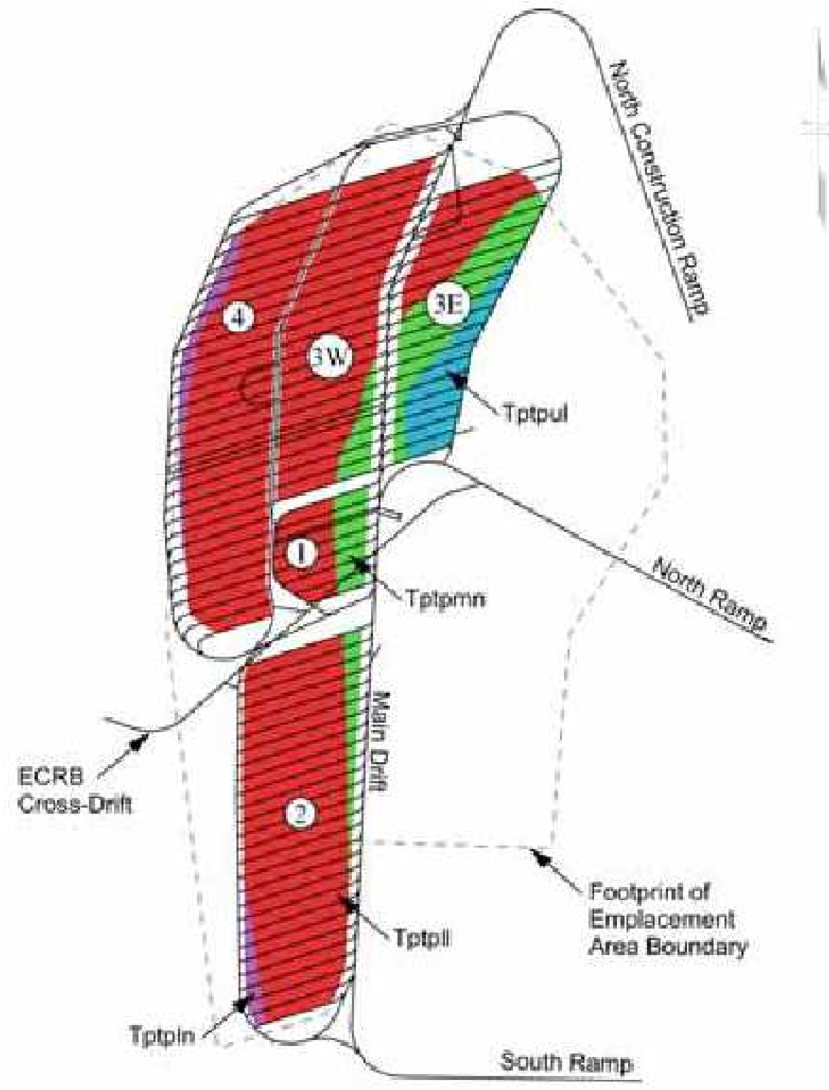
Las Vegas, Nevada

Outline

- **Summary of the general approach used for assessment of emplacement drift stability analysis under in situ, thermal and seismic loading**
- **Estimation of the thermal and mechanical properties and strength of tuff**
  - **nonlithophysal rock**
  - **lithophysal rock**
- **Numerical model for drift stability assessment and its validation**
- **Drift stability predictions at anticipated repository temperatures and stresses – comparison of results to practical mining experience**
- **Seismic response of drifts**

Repository Layout

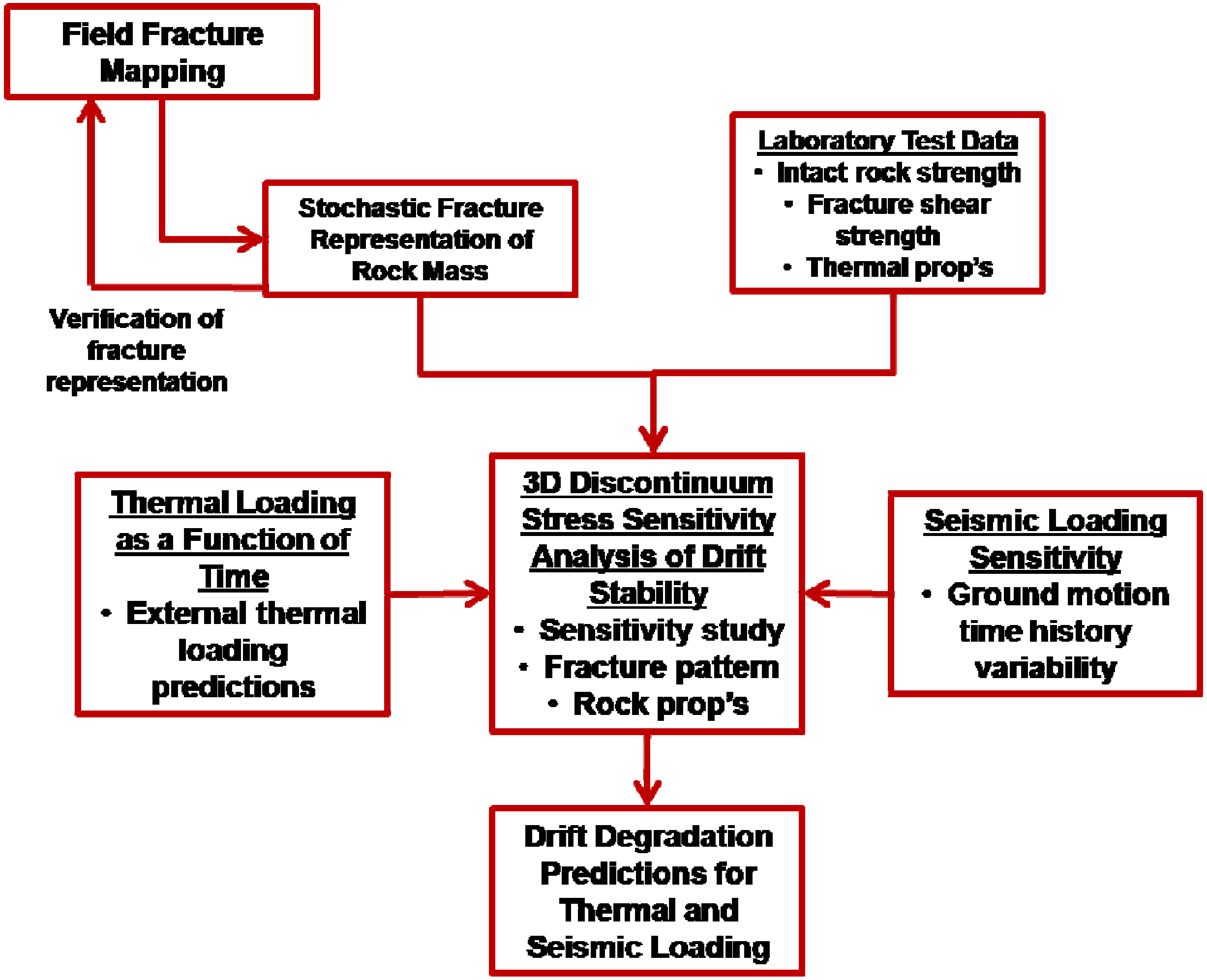
- The proposed repository is constructed in two basic units of the Topopah Spring tuff: lithophysal and non-lithophysal rock
  - ~85% of repository drifts in lithophysal tuff
  - ~15% of repository drifts in non-lithophysal tuff
- Depth of repository approx. 300m
- Vertical gravitational stress is maximum, approx. 7.8MPa



Nonlithophysal Tuff

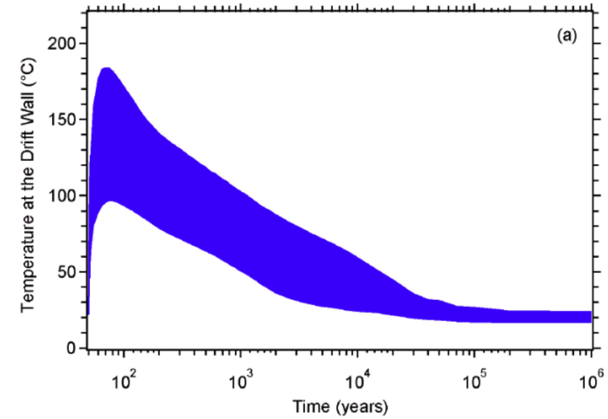
- **Good quality, fine-grained, strong rock**
- **Fracture sets mapped in detail throughout ESF and ECRB. Four well-developed, short trace length (less than drift diameter) fracture sets – generally discontinuous in nature**
- **Approximately 500 unconfined and confined lab compression strength tests have been completed, including testing to 200°C and saturated conditions**
- **Fracture strength determined from direct shear testing on joints**
- **Rock strength estimates:**
  - **Unconfined *intact* rock strength approximately 200 MPa**
  - **Unconfined rock *block* strength estimated to be approximately 70-75 MPa**

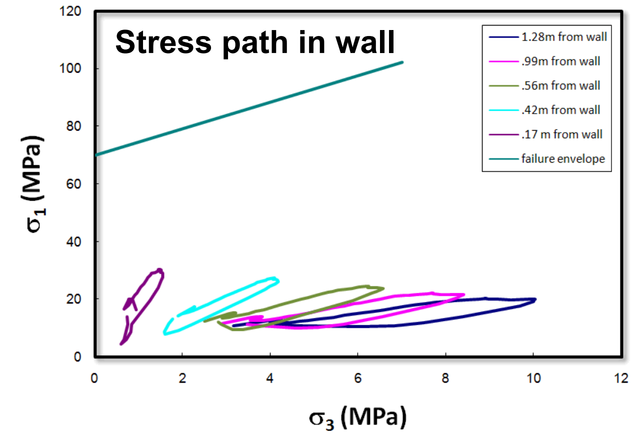
Approach to Drift Stability Assessment in Non-Lithophysal Rock

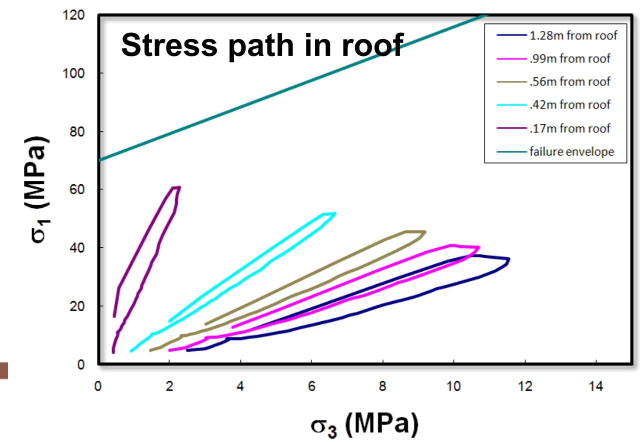


Thermal Drift Stability – Nonlithophysal Rock

- Maximum drift wall temperature approx 180C from realizations of multiscale thermal-hydrologic model (see upper figure at right)
- Thermal-mechanical sensitivity analysis conducted for emplacement drifts in non-lithophysal rock. Base case of 1.45 kW/m thermal load, 50 year preclosure ventilation
- Thermally-induced stresses in drift walls and roof (see stress paths with time in lower figures at right) are insufficient to fail rock blocks
- Minor rockfall due to dislodging of small blocks formed by natural rock joints around drift periphery (<0.1 m^3/m of drift length)



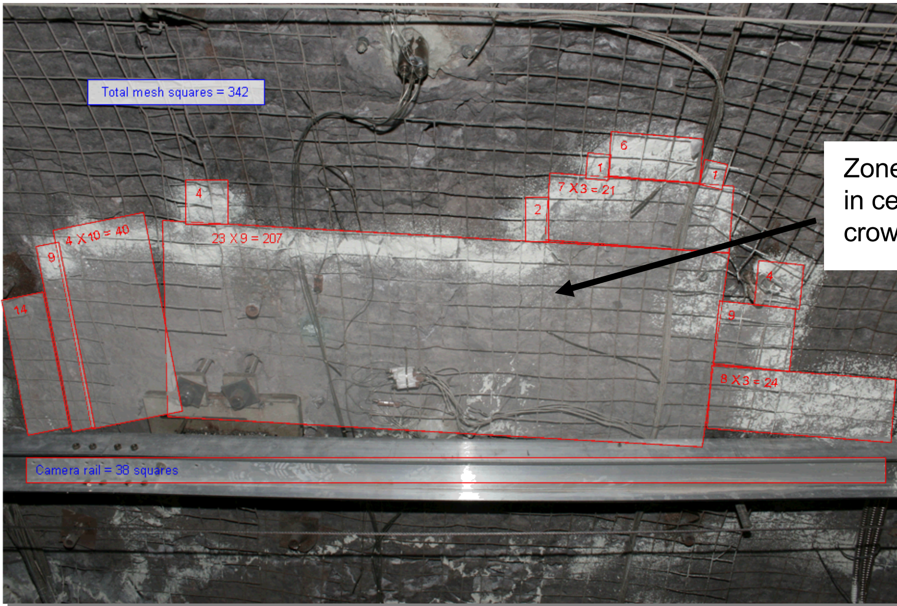


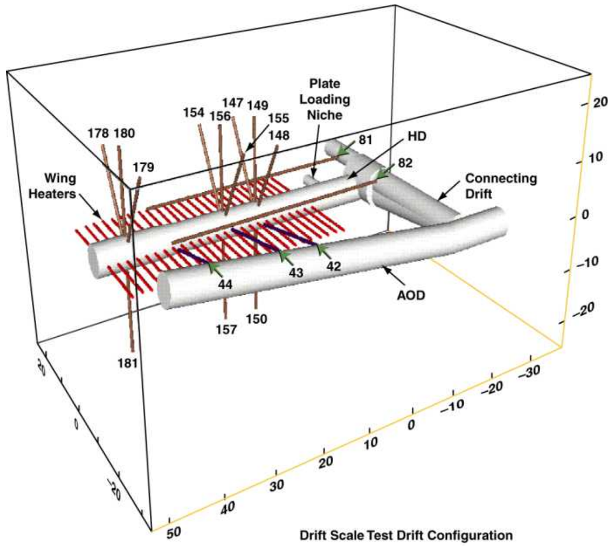


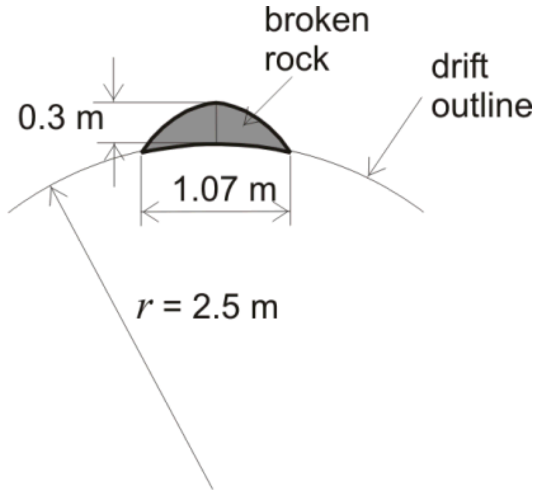
Verification of Predictions of Nonlithophysal Drift Thermal Response - Drift Scale Test

- Drift Scale Test (DST) is a full-scale heating experiment conducted in nonlithophysal rock mass
- Heaters are placed on the floor and in the walls (wing heaters) of 50 m long, 5 m diameter drift
- Heating started in 1997 and lasted for 4 years
- Subsequently there were 4 years of cool-down
- Drift wall temperature and stress driven to levels in excess of that for proposed repository
- Spalling of rock from the crown observed at several places along the drift after three years of heating

Observations of Crown Spalling During Thermal Overdrive – Drift Scale Test



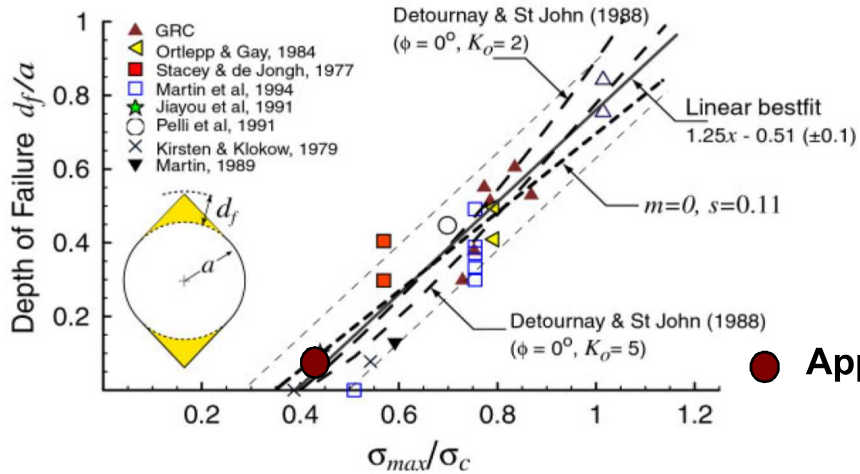




Estimated Shape of Spalled Zone

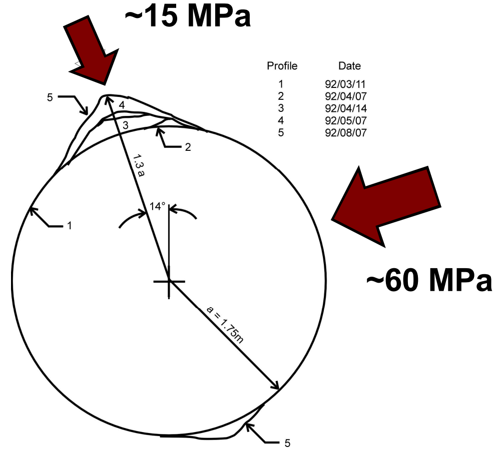
Comparison to Practical Observations of Spalling in Deep Mining

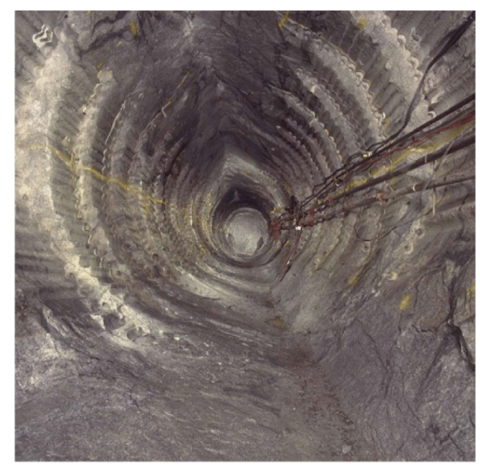
Case Examples of Spalling from Deep Mines Worldwide



Approx. DST

Spalling Observed at the URL (Canadian Program in Granite)





Summary
Nonlithophysal DriftThermal Response

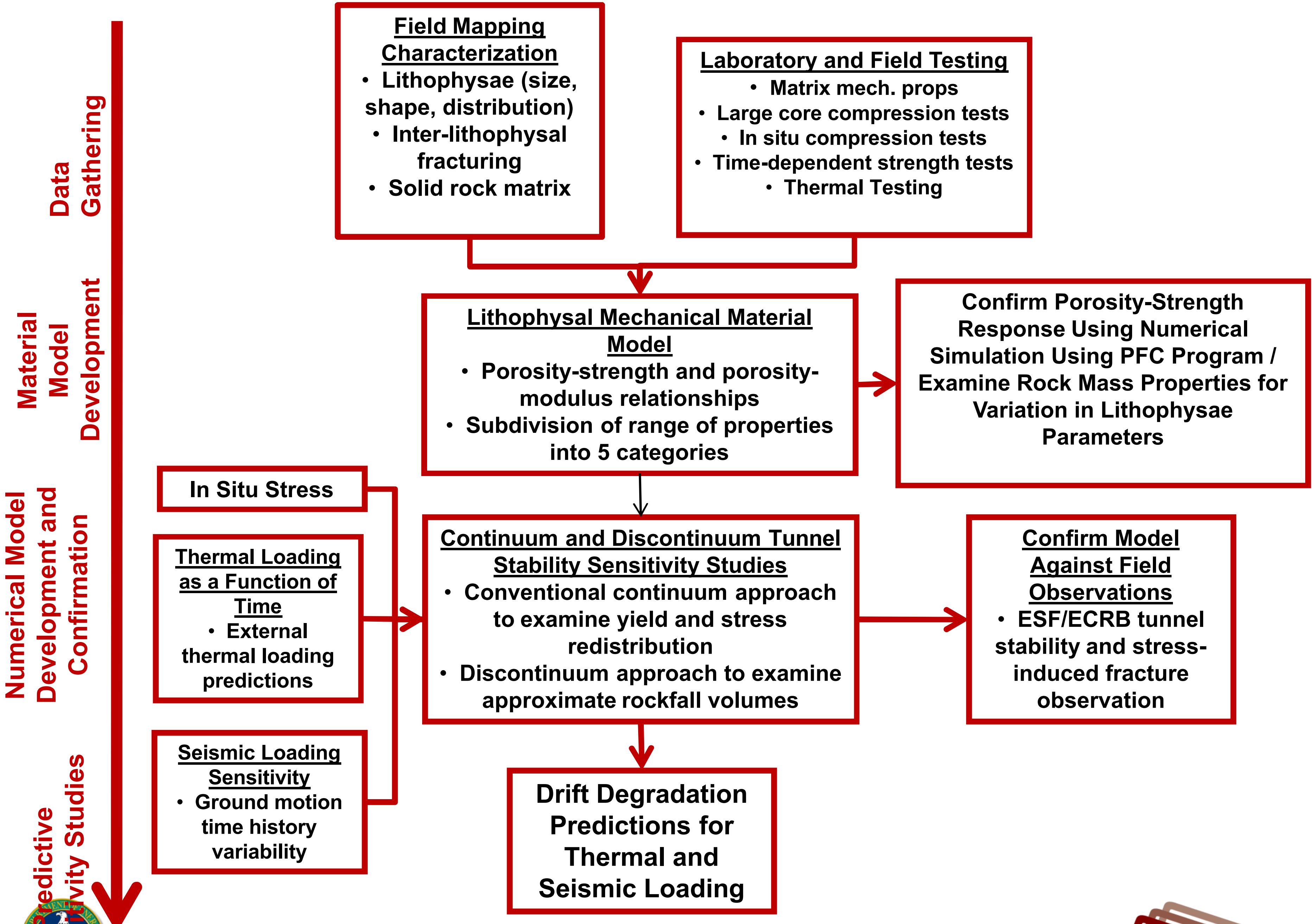
- Nonlithophysal rock mass is strong rock cut by short trace length fractures
- Maximum thermally-induced stresses indicate that a minor amount of rockfall is expected due to fall of small blocks around excavation periphery
- Stress-related spalling is not expected
- Minor spalling observed during the Drift Scale Test, thermal overdrive, agrees well with practical experience of spalling response in deep mine excavations

Lithophysal Tuff

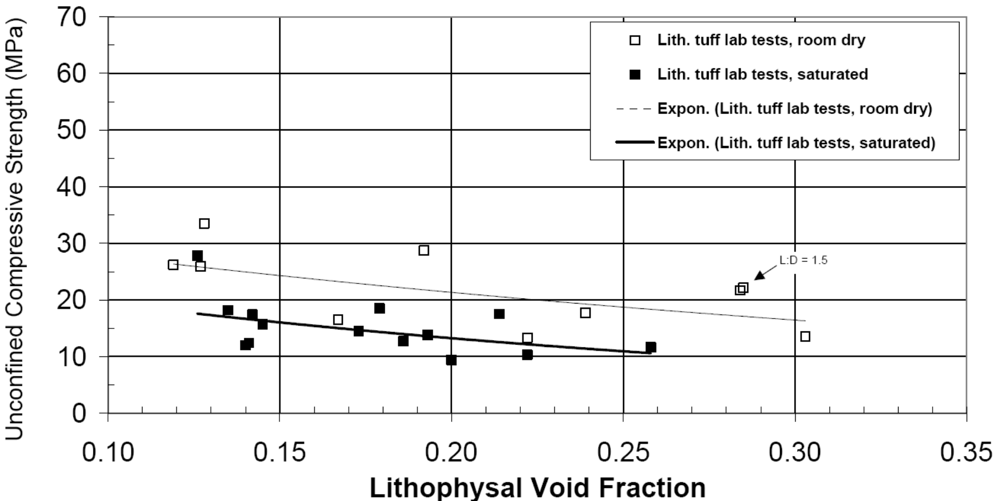
- Matrix material is mechanically similar to nonlithophysal rock
- Fracture sets are not as distinct as in nonlithophysal units and are discontinuous
- Fracture spacing is relatively small: less than 1 m, and very often of the order of 0.1 to 0.2 m; trace lengths are short
- Lithophysal porosity varies from ~ 10 to 30%
- Block sizes produced on failure expected to be roughly equal to average fracture spacing

Geotechnical Characterization of Lithophysal Unit

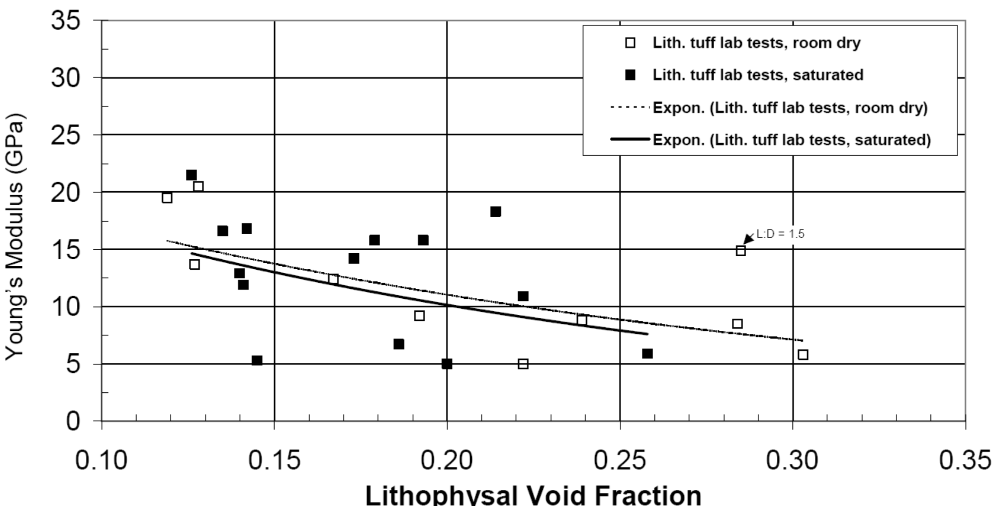
- **Mechanical Properties**
  - Approximately 500 uniaxial and triaxial compression tests on small (~2”) cores at temperatures to 200C and saturated conditions
  - 10.5” core samples from Busted Butte
  - 11.5” core samples from Tptpul and Tptpll [Exploratory Study Facility (ESF) and Enhanced Characterization of the Repository Block (ECRB)]
  - Approx. 30 time-dependent strength tests at 150C and saturated conditions conducted on tuff core matrix to determine time-to-failure as a function of applied stress
- **Thermal Properties**
  - Extensive laboratory testing of thermal conductivity, expansion and heat capacity as function of temperature
  - In situ heat probe tests to determine field effects of porosity
  - Verification of thermal properties from drift scale test and in situ block test


Data Gathering
Material Model Development
Numerical Model Development and Confirmation
Predictive Sensitivity Studies
Field Mapping Characterization
• Lithophysae (size, shape, distribution)
• Inter-lithophysal fracturing
• Solid rock matrix
Laboratory and Field Testing
• Matrix mech. props
• Large core compression tests
• In situ compression tests
• Time-dependent strength tests
• Thermal Testing
Lithophysal Mechanical Material Model
• Porosity-strength and porosity-modulus relationships
• Subdivision of range of properties into 5 categories
Confirm Porosity-Strength Response Using Numerical Simulation Using PFC Program / Examine Rock Mass Properties for Variation in Lithophysae Parameters
In Situ Stress
Thermal Loading as a Function of Time
• External thermal loading predictions
Seismic Loading Sensitivity
• Ground motion time history variability
Continuum and Discontinuum Tunnel Stability Sensitivity Studies
• Conventional continuum approach to examine yield and stress redistribution
• Discontinuum approach to examine approximate rockfall volumes
Confirm Model Against Field Observations
• ESF/ECRB tunnel stability and stress-induced fracture observation
Drift Degradation Predictions for Thermal and Seismic Loading

Laboratory Testing on Large Samples



(a)



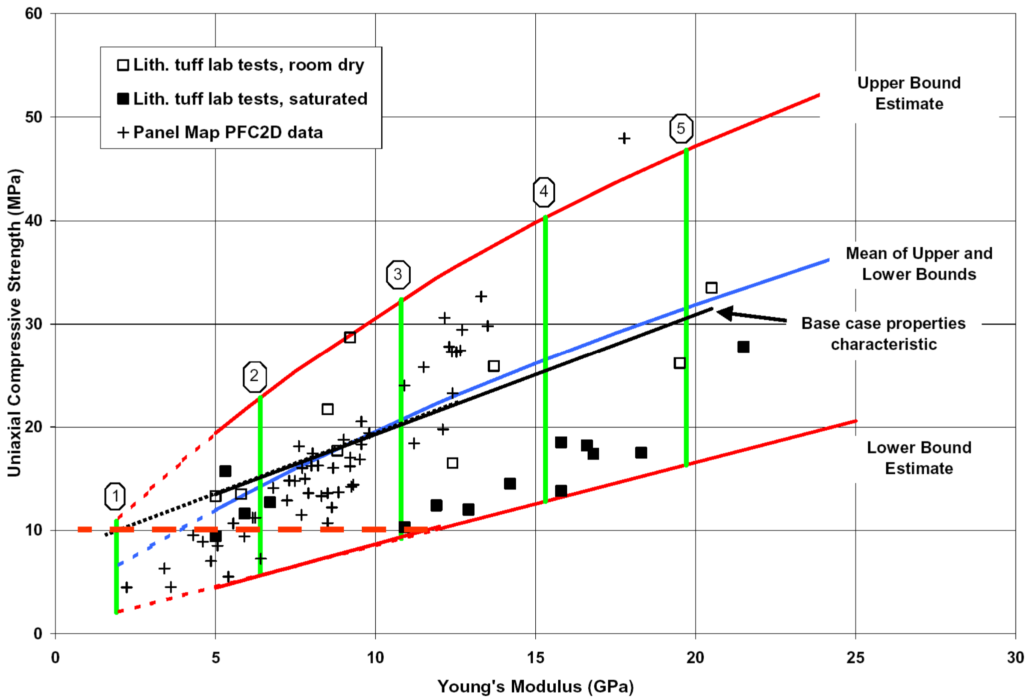
(b)

(a)

(b)

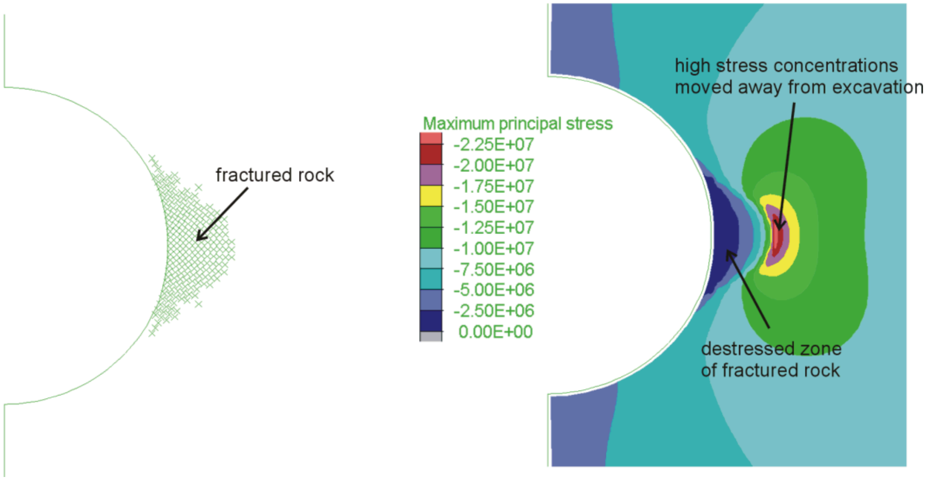
Range of Strength and Stiffness for Lithophysal Rock Mass Used in Drift Performance Analyses

Category	~ % of Tptpll	~% lith porosity
1	6	>25
2	15	20-25
3	26	15-20
4	27	10-15
5	26	<10



Modeling Approaches Used for Drift Stability Assessment in Lithophysal Rock

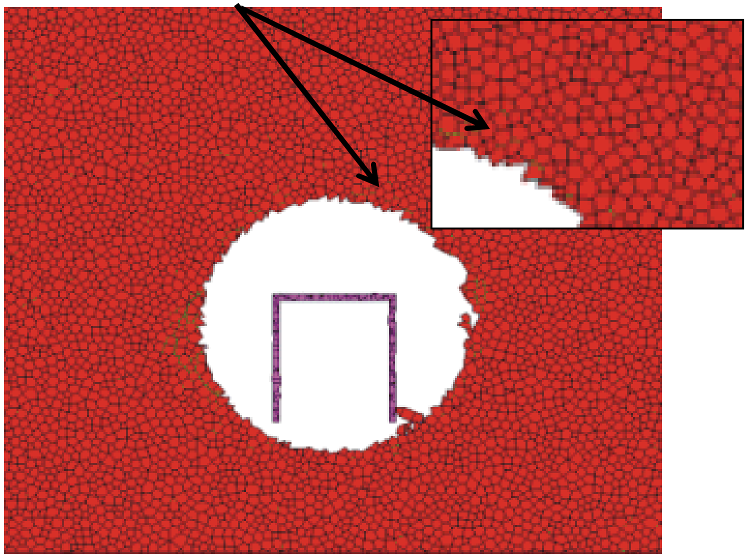
Continuum



- Material response represented as an elastic-plastic material with Mohr-Coulomb failure criteria defined by rock mass shear and tensile strength
- Rock mass progressively fails when stress state satisfies failure criteria
- Rock cannot dislodge and fall due to continuum assumption

Discontinuum

Yield represented by shear or tensile failure along "potential" surfaces



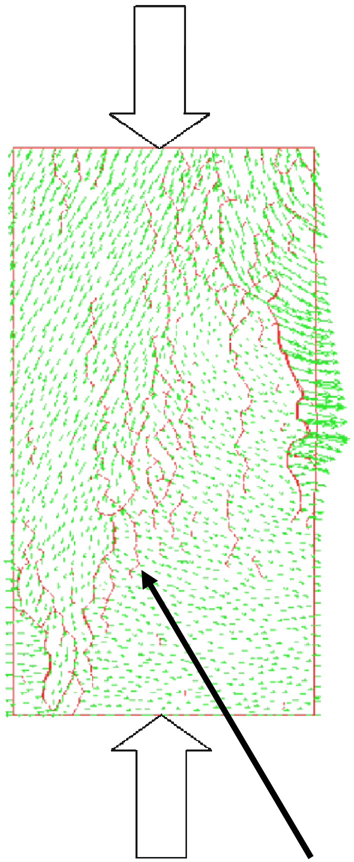
- Rock mass represented by a large number of small, randomly-shaped elastic blocks bonded at contacts with rock mass shear and tensile strength
- Bonds between blocks may progressively fail when stress satisfies failure criteria
- Rock blocks may dislodge and fall under gravity or seismic load – allows estimate of the ultimate equilibrium shape of the excavation and failed rock volume

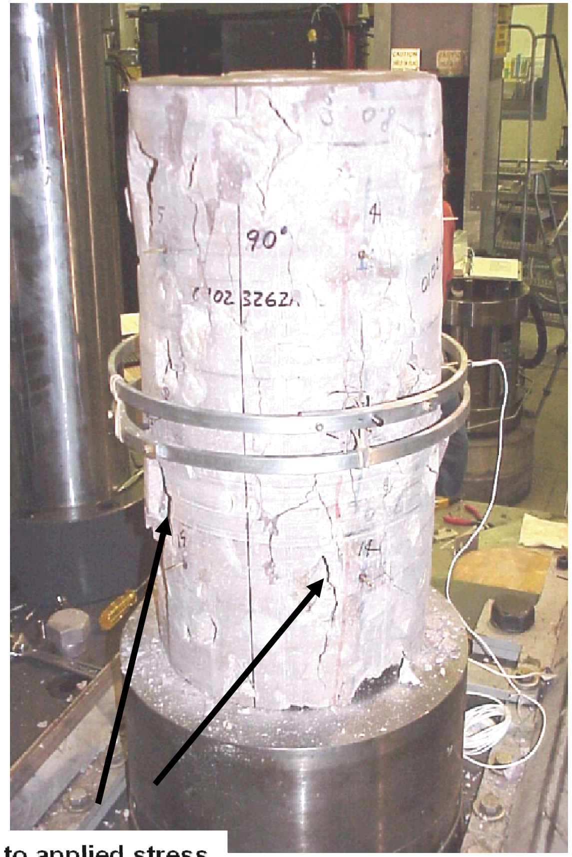
Discontinuum Model Calibrated to Stress-Strain Response in Unconfined Compression

- Three material parameters are of particular importance to stress level and mechanical stability of the drifts:
  - Modulus
  - Uniaxial Compressive Strength
  - Post-peak strength brittleness
- Model stiffness and block interface strength adjusted to achieve a calibration of the Young’s modulus and uniaxial compressive strength for range of lithophysal rock categories
- Post-peak behavior of rock mass is highly random and dependent on a large number of parameters (e.g., sample size)
- We do not attempt to specifically calibrate the model to post-peak behavior; instead we made sure that numerical model is more brittle than observed behavior from the tests as this conservatively predicts more extensive drift failure

Calibration of Lithophysal Model to Laboratory Compression Testing on Large Rock Compression Samples

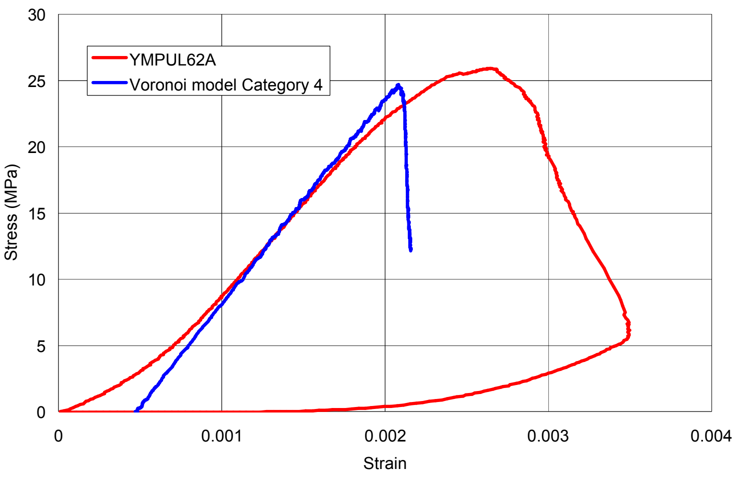
Applied Axial Load





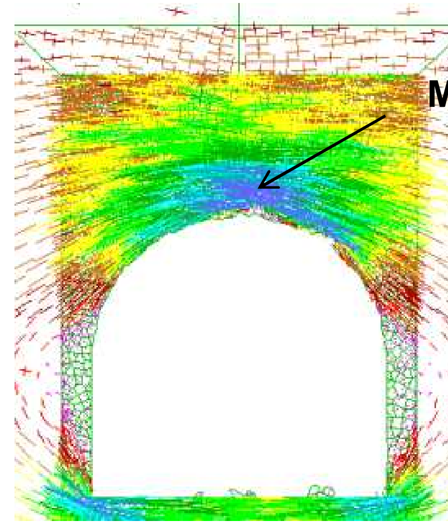
Axial splitting parallel to applied stress

Example of UDEC Model Calibration to Laboratory Compression Test



Comparison of Model Predictions to Observations of Fracturing and Drift Stability in the ECRB

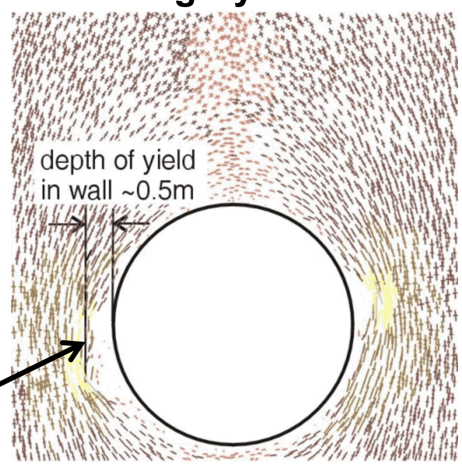
- **Model verified against observed DST roof spalling timing and extent during thermal overdrive**
- **Model verified against observations of depth of fracturing in approx. 60 large diameter boreholes in ESF and ECRB**

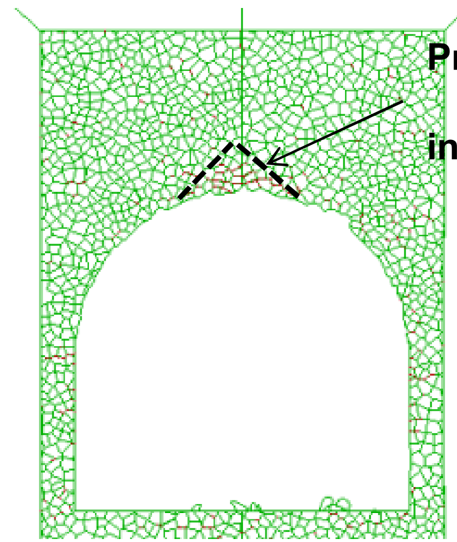


Max Stress = 80-90MPa

ESF South Ramp Sidewall Yielding

Prediction of Yield for Category 1 Rock





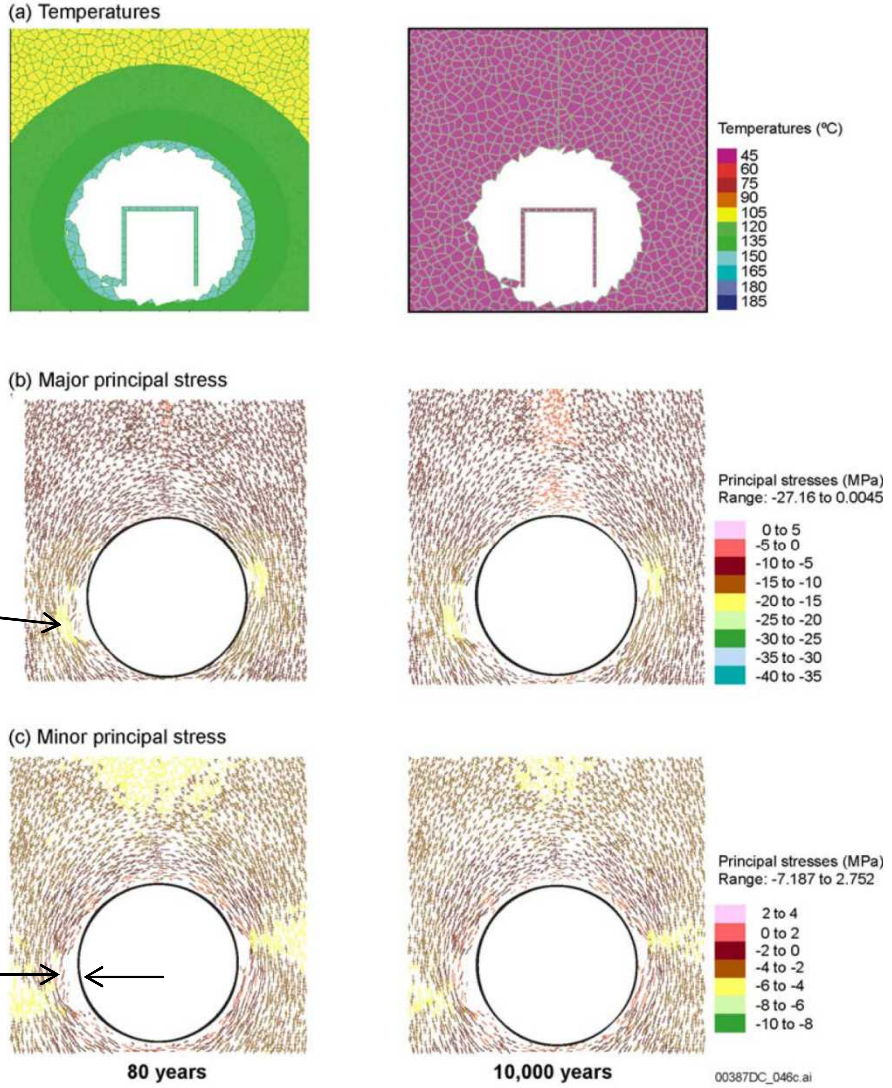
Predicted zone of stress-induced failure

DST Back-Analysis

Example of Discontinuum Analysis of Drift Stability Due to Thermally Induced Stresses – Lowest Lithophysal Strength Category

Stress concentration pushed into confined rock mass outside yield region

Depth of yield zone <0.5m

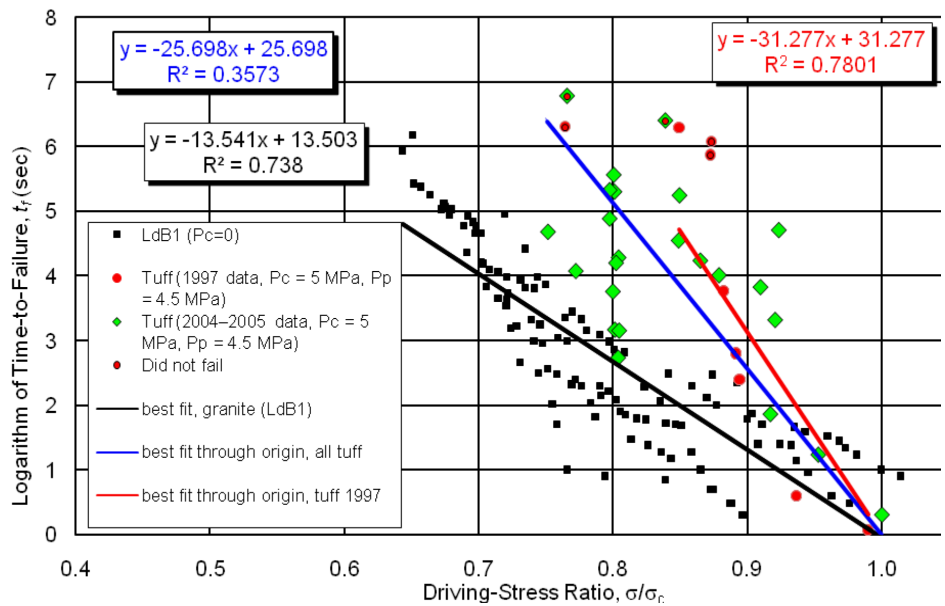


Summary – Thermal Stability of Drifts in Lithophysal Rock

- Thermal analysis indicates overall drift stability all rock strength categories at maximum temp/stress
- Drift yield and rockfall limited to immediate periphery of the drift
- Mechanism of stability is same as observed in deep tunnel conditions – rock mass yielding sheds high stresses into rock mass where confinement results in strengthening of the rock mass

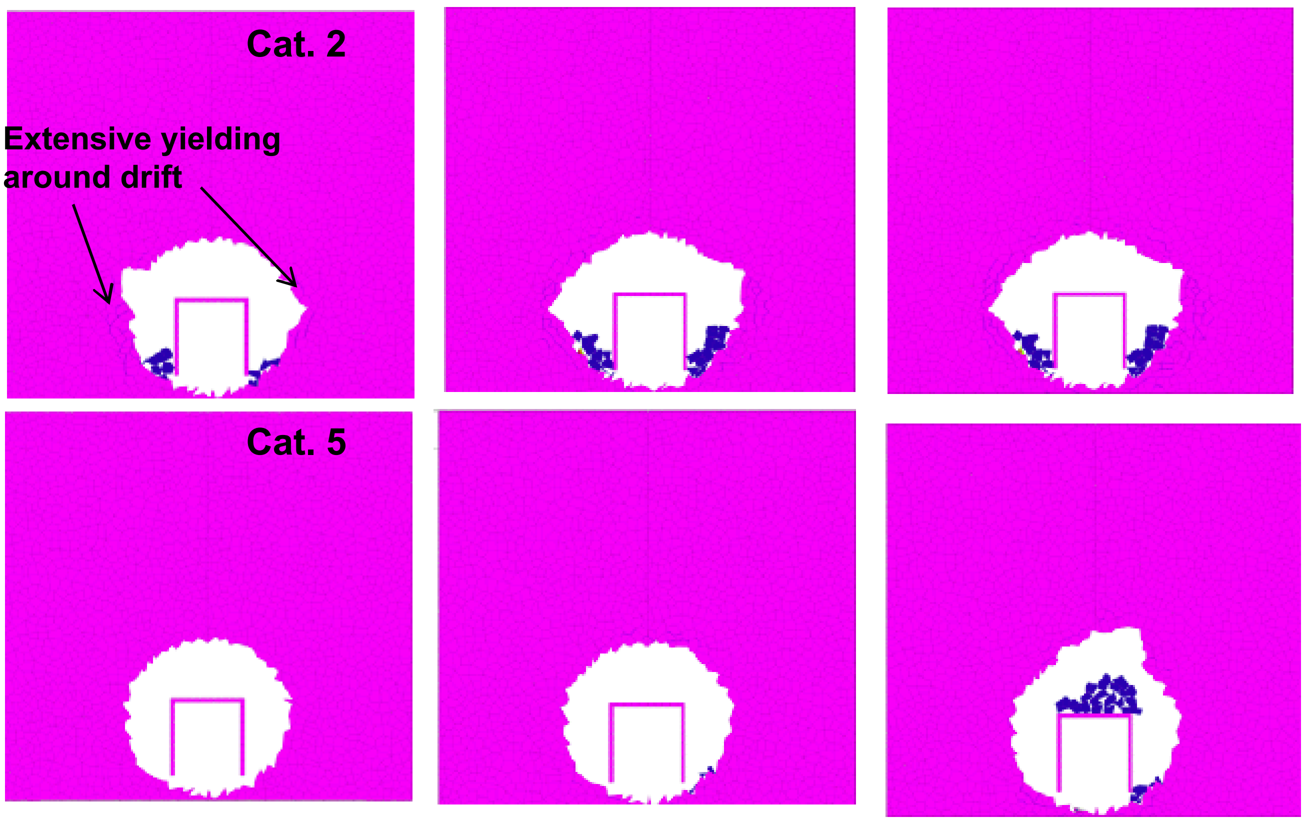
Impact of Time-Dependency on Drift Stability in Lithophysal Rock

- Time-dependent strength reduction of rock mass estimated from laboratory testing of time-to-failure for various ratios of applied stress to short term strength at 150C and saturated conditions
- Sensitivity study of drift stability conducted for range of lithophysal rock mass strength categories



Drift Profiles for Combined Thermal and Time-Dependency

10 Years – no thermal load | 80 Years – thermal load | 1000 Years – thermal load

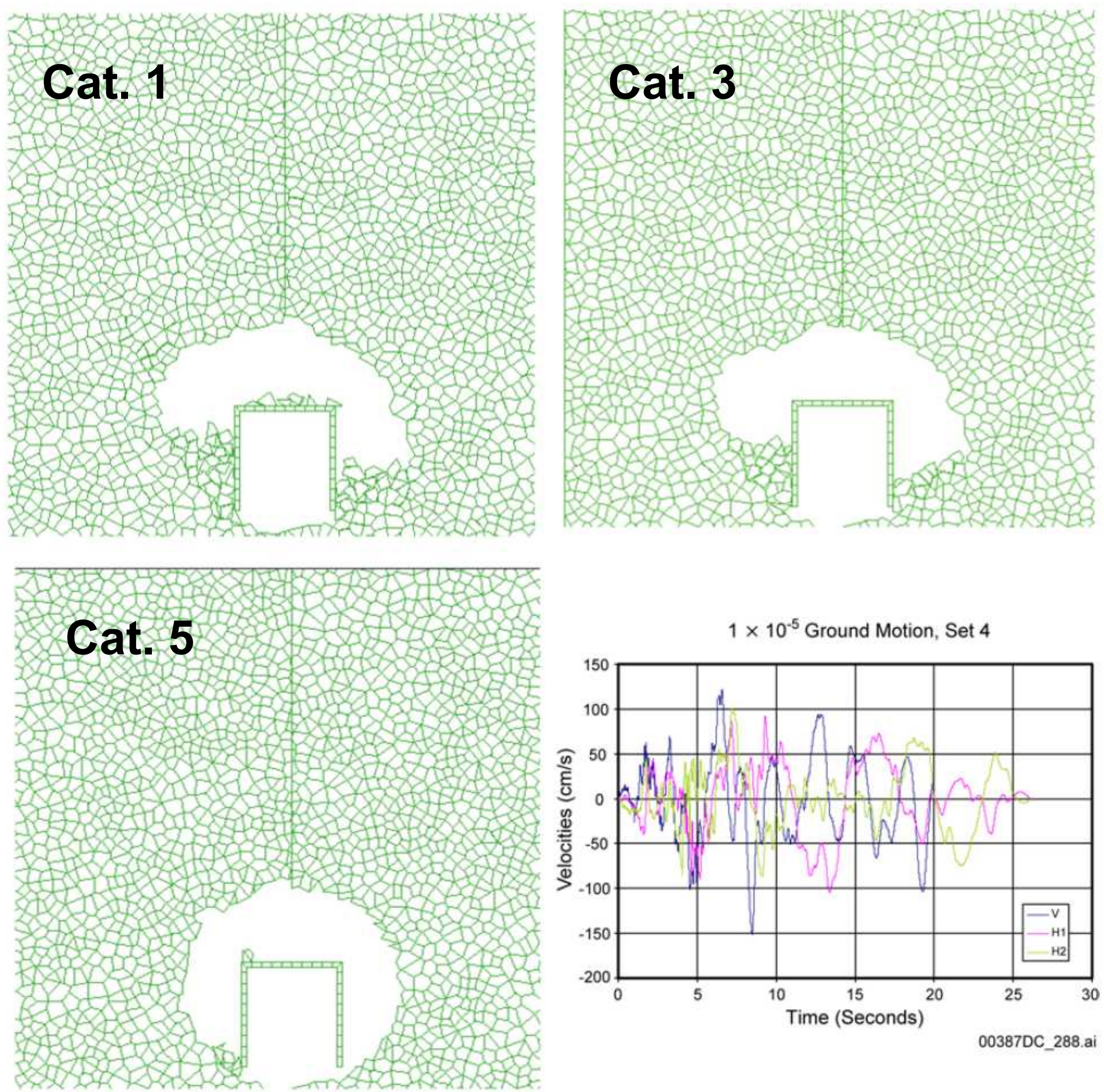


- Base-case for best fit to time-to-failure data
- Conservatism in assumed strength-loss with time can be seen in Category 2 results at 10 years – no drift instability and fracturing observed in ESF or ECRB

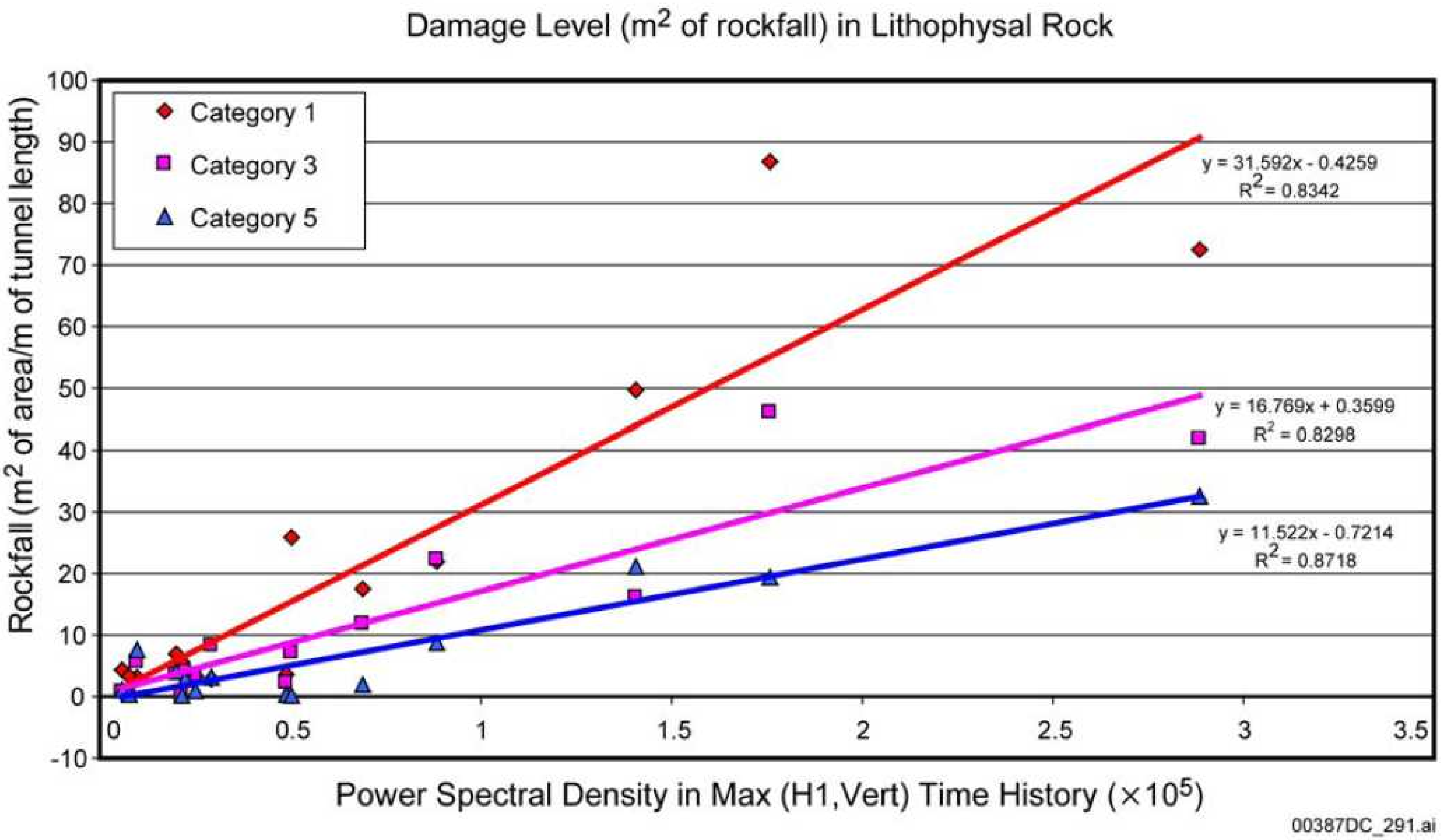
Seismic Response of Drifts in Lithophysal Rock

- **2D dynamic simulations of the drift subjected to seismic ground motions of different intensity were carried out**
- **Different PGV levels (0.4 m/s, 1.05 m/s and 2.44 m/s) and multiple ground motions at each PGV level were considered**
- **Analyses show minor rockfall at the 0.4 m/s PGV level and total drift collapse at the 2.44 m/s PGV level**
- **Transition is observed at the 1.05 m/s PGV level**

Example of Rockfall Predictions for a Ground Motion at the 1.05 m/s PGV Level



Predicted Rockfall as a Function of Seismic Energy



Conclusions

- Detailed underground mapping and lab and field testing of Yucca Mt. tuffs have been carried out at range of temperature and saturation conditions
- Numerical models have been validated against results from large-scale laboratory and field testing, and predictions are consistent with observations of drift response observed in the ESF and ECRB
- Multiple modeling approaches were used. Discontinuum approach is consistent with results of continuum methods, but also capable of predicting rockfall volume
- No significant rockfall predicted due to thermally induced stresses, time-dependency results in small amounts of rockfall through thermal pulse phase of repository
- No rockfall in lithophysal rock predicted for seismic ground motions from the 0.4 m/s PGV level; drift completely collapses at the 2.44 m/s PGV level

Backup Slides

Thermomechanical Data

Thermal Mechanical Unit	Thermal Conductivity (W/m°K)	
	T ≤ 100°C	T>100°C
TSw/PTn	1.06	0.46
TSw1	1.77	1.22
TSw2/TSw3	1.92	1.33
CHn1/CHn2	1.21	0.57

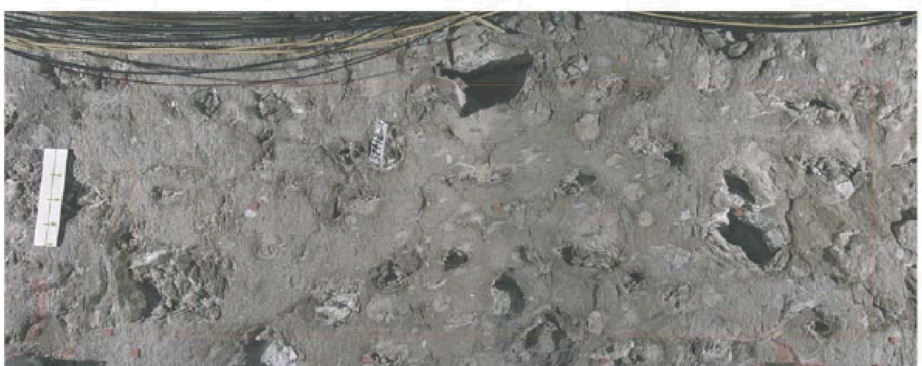
Thermal Mechanical Unit	Specific Heat (J/kg°K)		
	T ≤ 95°C	95°C <T ≤ 114°C	T>114°C
TSw/PTn	1300	9000	1000
TSw1	920	3200	990
TSw2/TSw3	910	3000	990
CHn1/CHn2	1300	840	1100

Thermal Mechanical Unit	Thermal Expansion Coefficient (/°C)			
	25°C < T ≤ 50°C	50°C < T ≤ 75°C	75°C < T ≤ 100°C	100°C < T ≤ 125°C
TCw	7.09×10^{-6}	7.62×10^{-6}	8.08×10^{-6}	10.34×10^{-6}
PTn	4.46×10^{-6}	4.28×10^{-6}	-1.45×10^{-6}	-30.42×10^{-6}
TSw1	6.56×10^{-6}	7.32×10^{-6}	6.83×10^{-6}	6.92×10^{-6}
TSw2	7.14×10^{-6}	7.47×10^{-6}	7.46×10^{-6}	9.07×10^{-6}

Physical Interpretation of Rock Strength Categories

- Category 3 (~20% lith porosity)

- Category 4 (~13% lith porosity)



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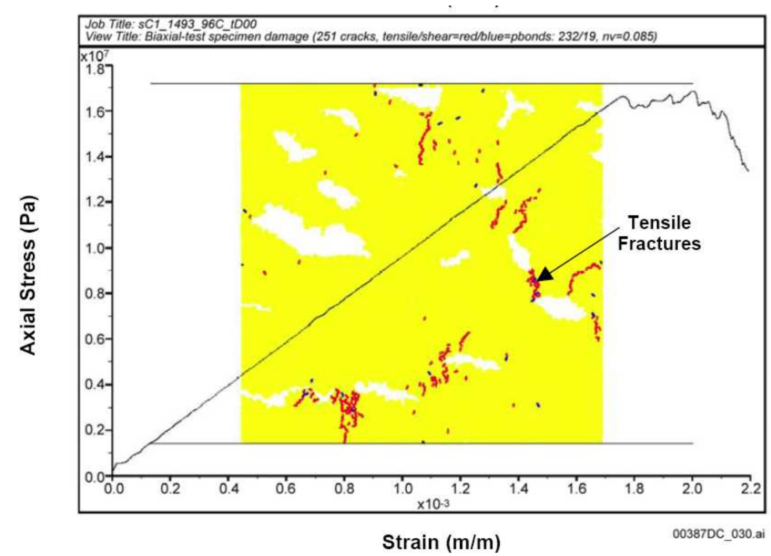
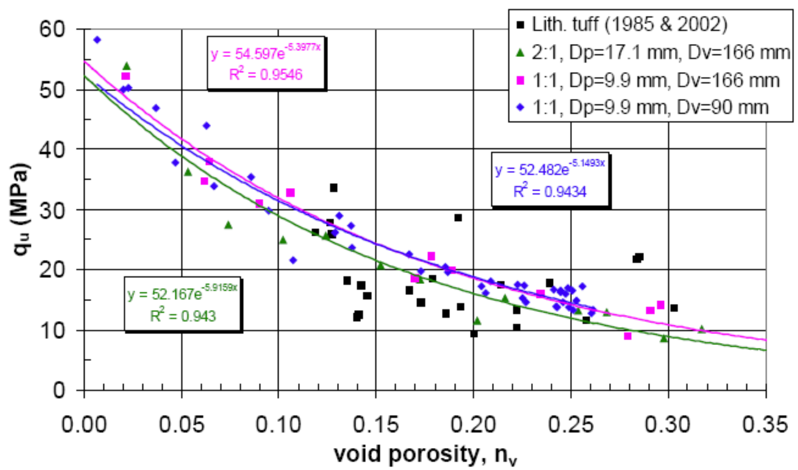
- Category 5 (~8.5% lith porosity)

These 3 categories comprise roughly 90% of the lithophysal rock mass in the Tptpll

Confirmation of Material Response of Lithophysal Rock - Particle Flow Code (PFC) Modeling

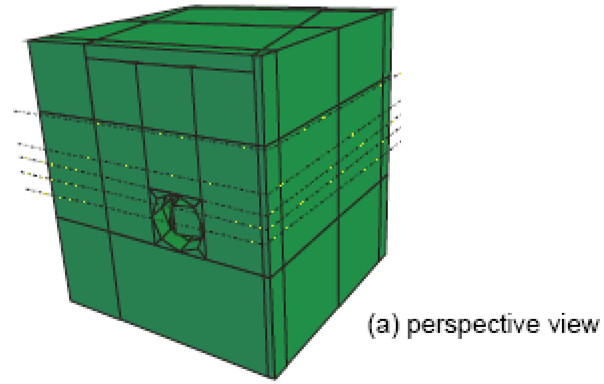
- Bonded particle model used to understand the mechanical impact of lithophysal voids on constitutive response of rock mass
- Rock represented as a large number of particles bonded together with shear and tensile strengths. Bonds may break when stress state dictates.
- Shear and tensile strength properties of matrix calibrated to nonlithophysal laboratory testing (upper figure)
- Numerical simulations of compression on simulated lithophysal samples, failure mechanisms and properties estimated (lower figure)
- Comparison to large-sample laboratory testing and extension to various lithophysal shapes and porosities (next page)



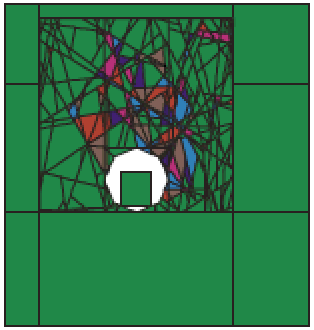


Seismic Analysis of Drift Stability in Nonlithophysal Rock

- Field mapping data in ESF/ECRB used to develop a stochastic description of fracture geometry in nonlith using Fracman program
- A 100mx100mx100m volume of synthetic rock mass developed with representative fracture geometry
- 15 sets of ground motions selected from annual probability of exceedance of $1x10^{-4}$, $1x10^{-5}$, $1x10^{-6}$ and $1x10^{-7}$ as seismic input
- 50 random pairings of one of the 15 ground motions to one of approx. 100 tunnel locations within the synthetic rock mass chosen for analysis at each ground motion level
- Dynamic simulations of tunnel stability and block fallout determined for each simulation

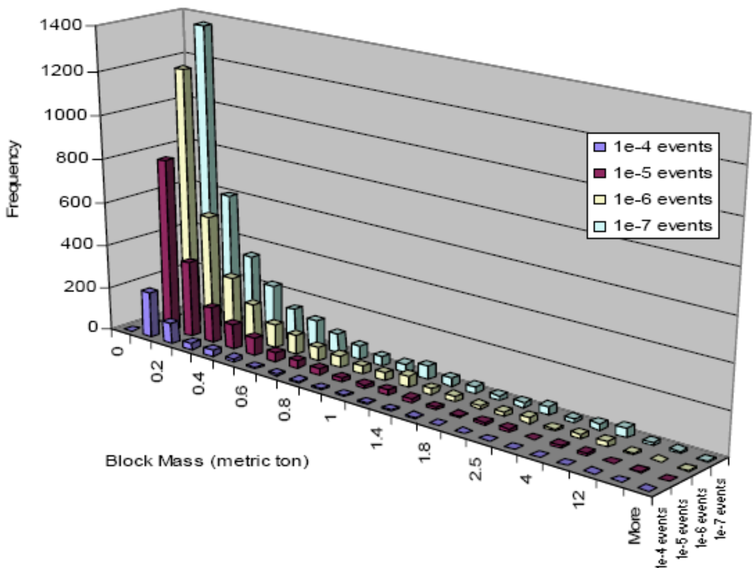


Perspective view of model

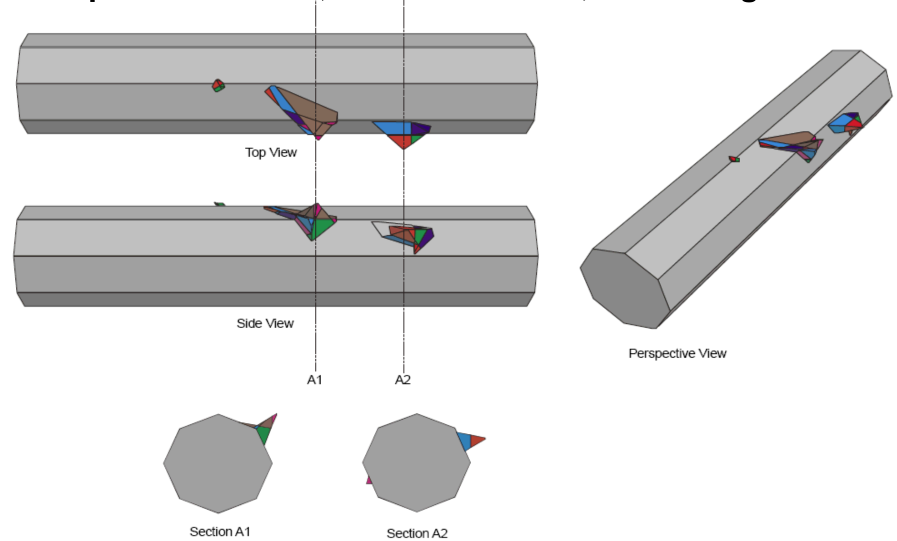


Vertical section through drift showing block structure

Summary of Seismic Rockfall Analysis in Nonlithophysal Rock



Example – 10^{-5} Event, Median Rockfall, 25 m Long Drift



Summary Seismic Rockfall Statistics for Nonlithophysal Drifts

Statistic	Ground Motion			
	10^{-4}	10^{-5}	10^{-6}	10^{-7}
Mean	0.22	0.35	0.43	0.50
Median	0.10	0.12	0.13	0.15
Standard Deviation	0.33	0.93	1.30	1.43
Skewness	3.47	10.03	11.61	8.81
Range	2.69	19.04	28.19	28.26
Minimum	0.02	0.02	0.02	0.02
Maximum	2.72	19.07	28.22	28.29
Sum	95.00	615.97	1200.43	1699.57