



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



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



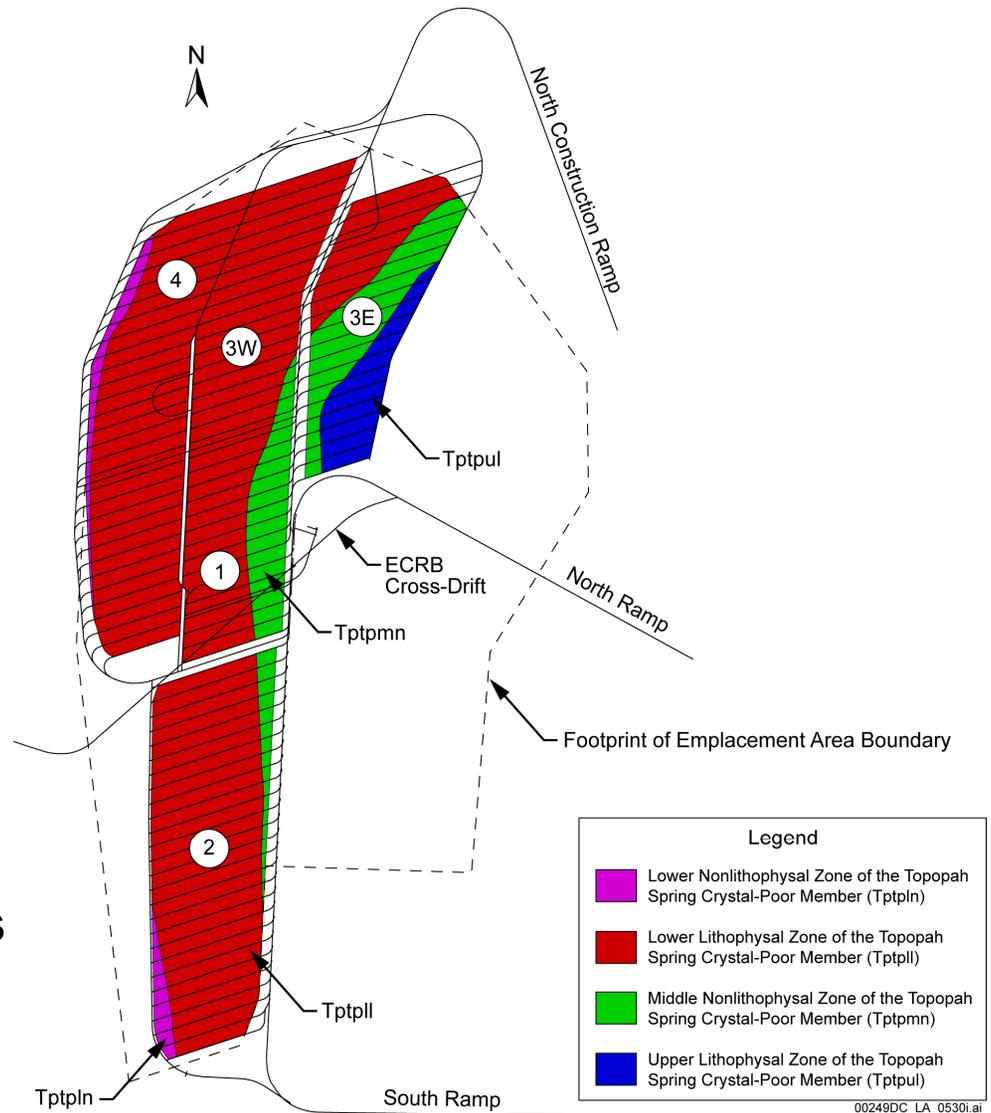
Outline

- **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



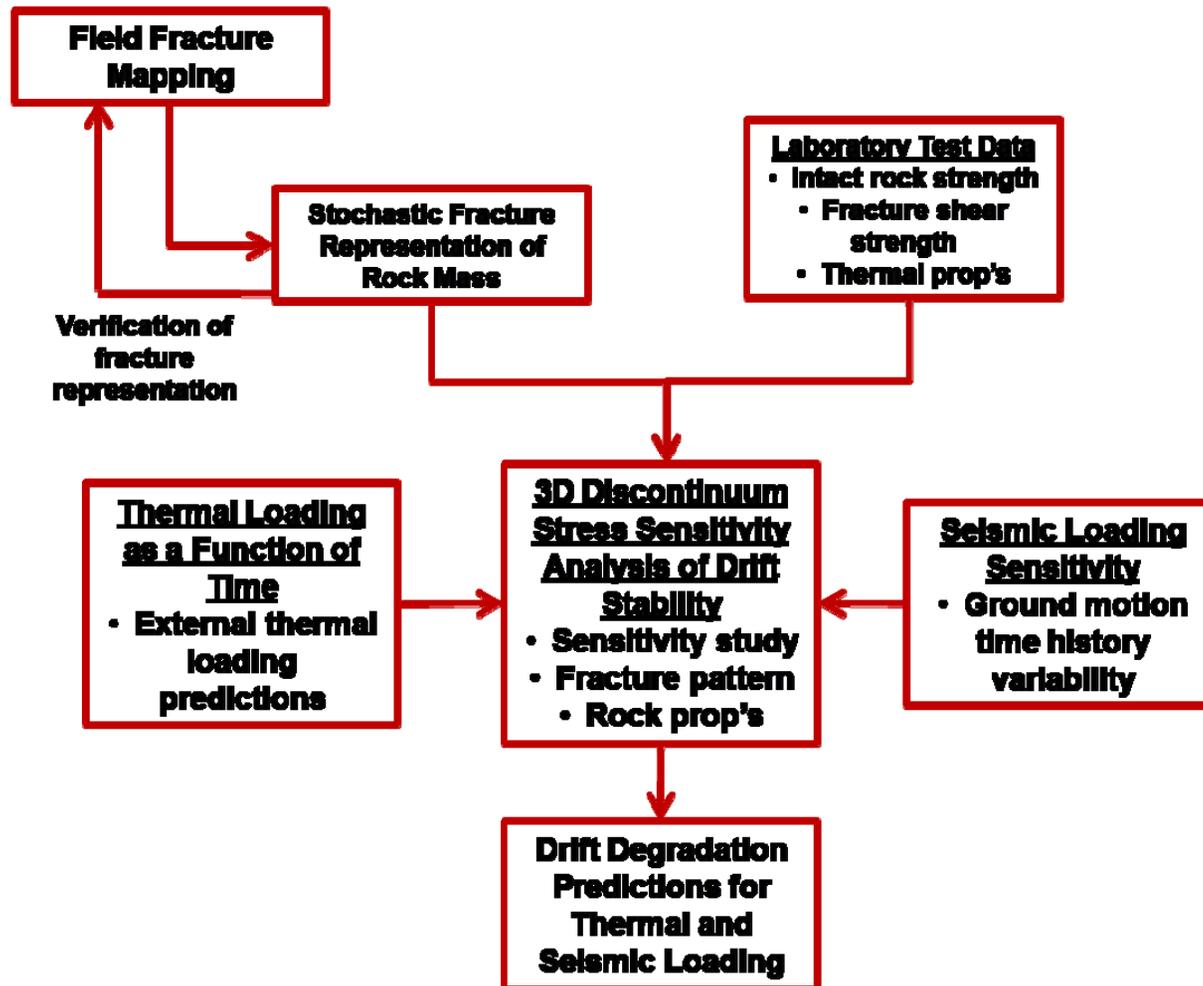
Nonlithophysal Tuff

- 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

ESF = Exploratory Studies Facility
ECRB = Enhanced Characterization of the Repository Block
[Drift]



Approach to Drift Stability Assessment in Non-Lithophysal Rock



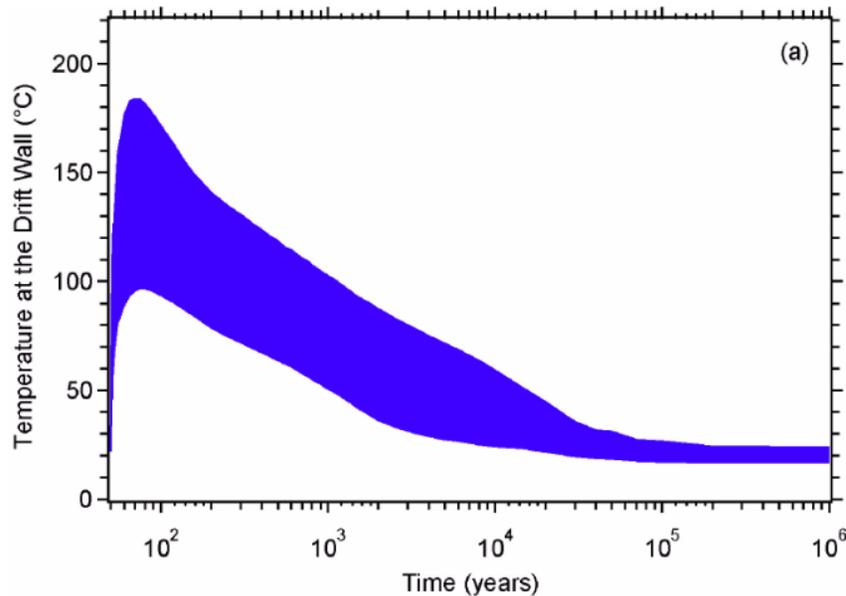
Summary of Modeling Results for Thermal Drift Stability – Nonlithophysal Rock

- **Maximum drift wall temperature approx 180C from realizations of multiscale thermal-hydrologic model (next page figure at left)**
- **Thermal-mechanical sensitivity analysis conducted for emplacement drifts in non-lithophysal rock. Heat load and thermal properties varied**
- **Thermally-induced stresses in drift walls and roof (see stress paths with time in right hand figures – next page) are insufficient to fail rock blocks**
- **Minor rockfall due to dislodging of small blocks formed by natural rock joints around drift periphery (<0.1 m³/m of drift length)**

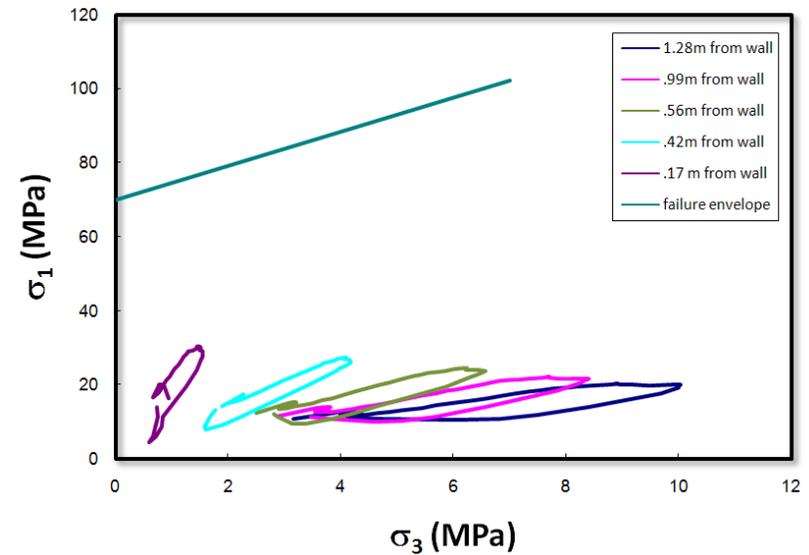


Temperature and Stress State in Emplacement Drift Wall – Nonlithophysal Rock

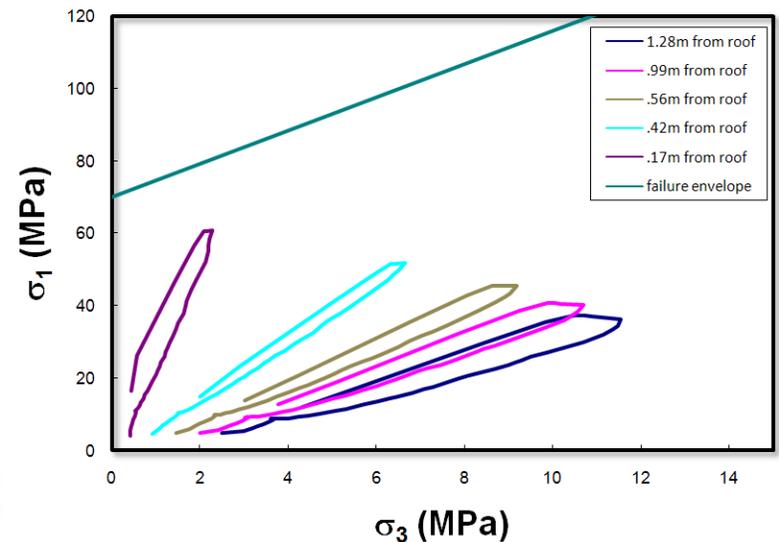
Range in transient temperature at drift wall



Time-evolving stress path in wall of drift



Time-evolving stress path in roof of drift

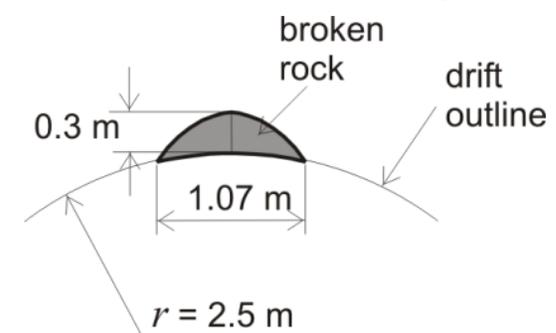
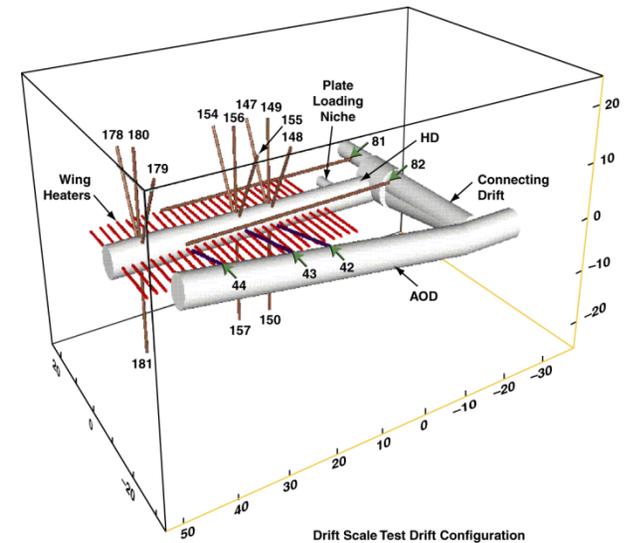
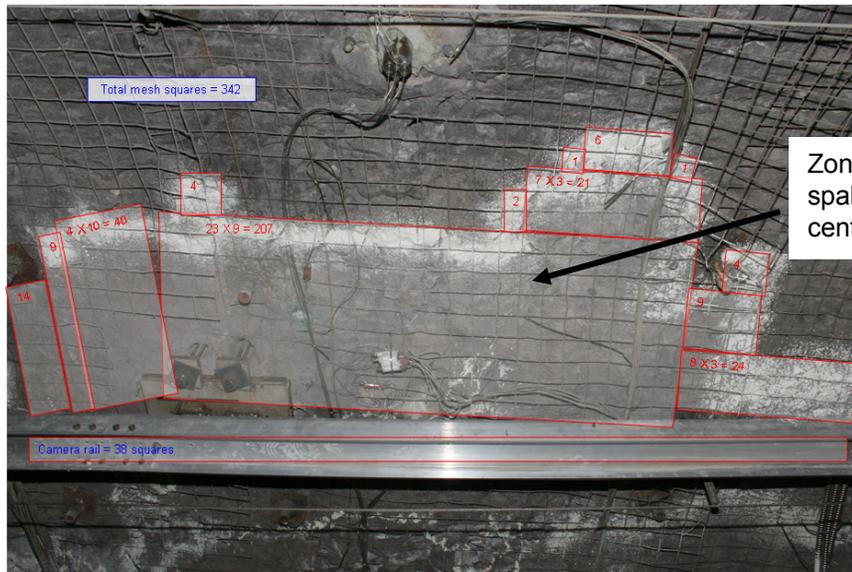


Verification of Predictions of Nonlithophysal Drift Thermal Response - Drift Scale Test

- **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

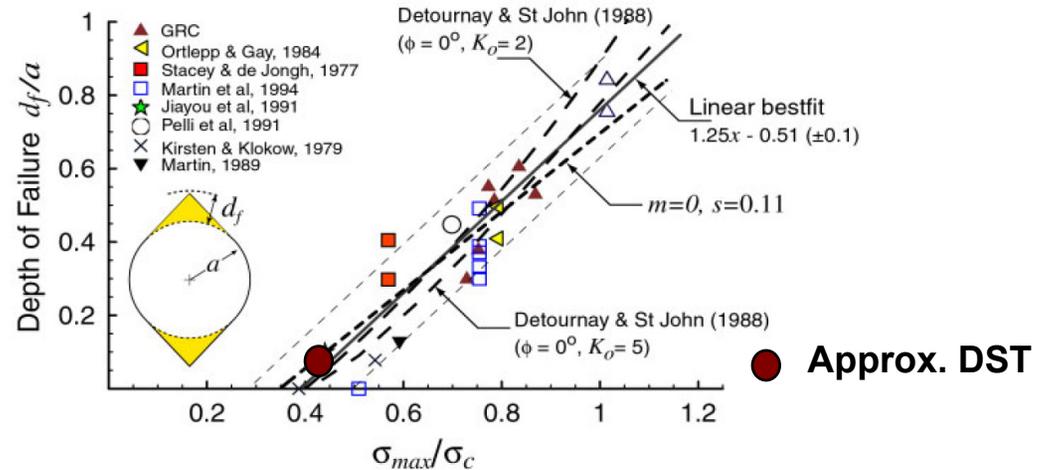


Estimated Shape of Spalled Zone

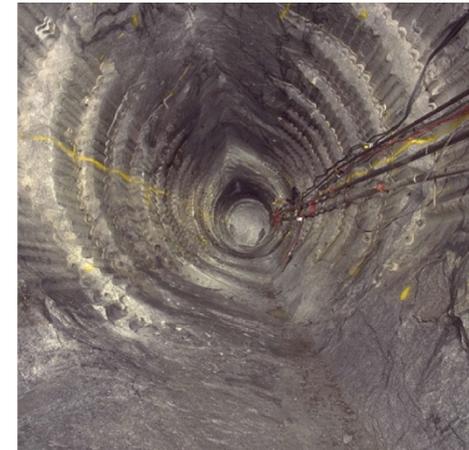
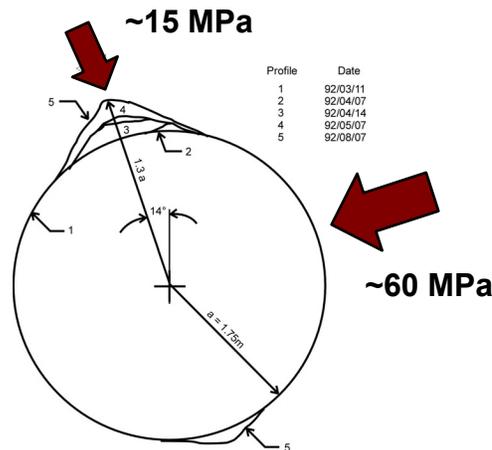


Comparison to Practical Observations of Spalling in Deep Mining

Case Examples of Spalling from Deep Mines Worldwide



Spalling Observed at the URL (Canadian Program in Granite)



Summary

Nonlithophysal Drift Thermal 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

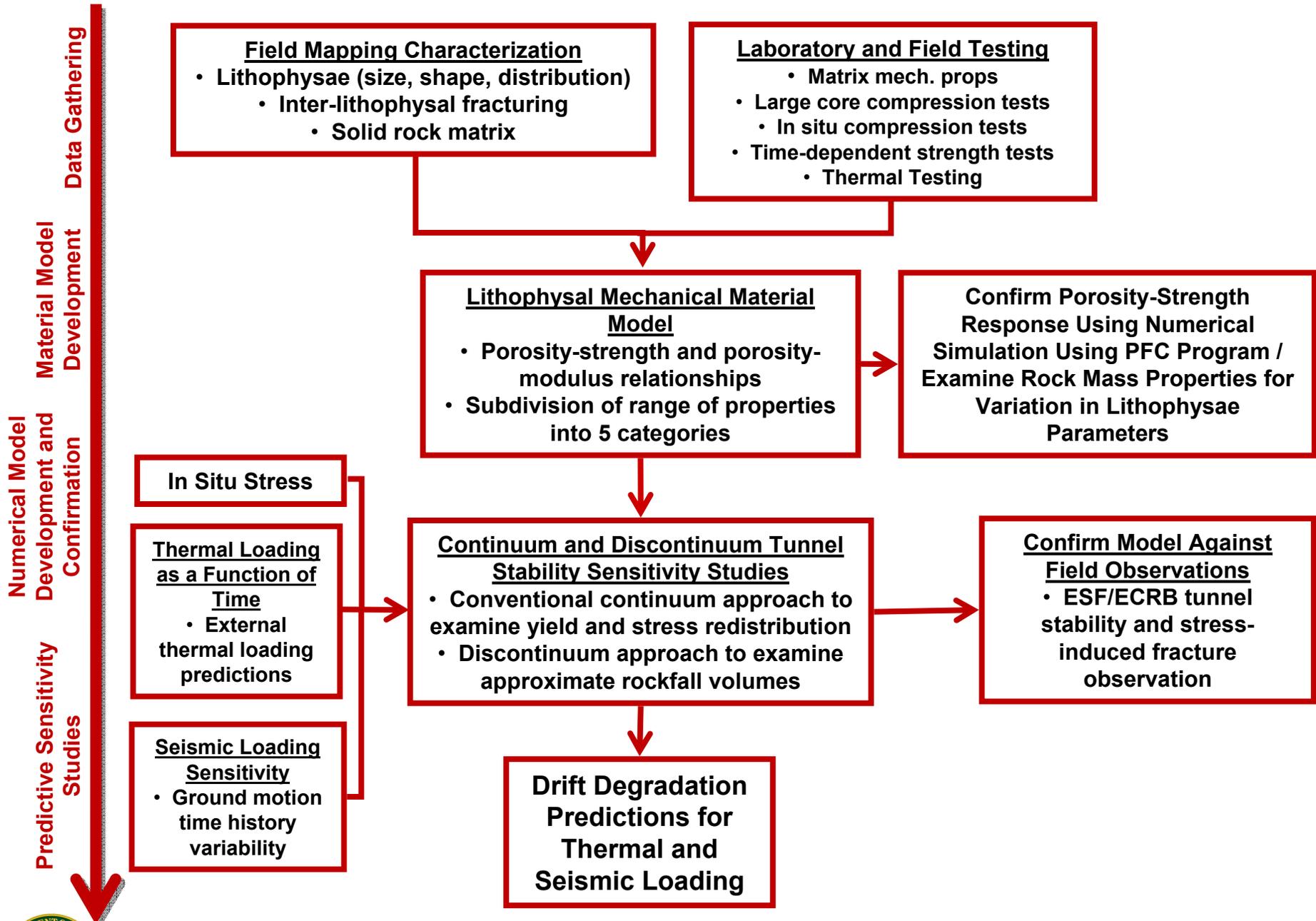
- **Mechanical Properties**

- Approximately 500 uniaxial and triaxial compression tests on small (~2") cores at temperatures to 200°C 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 150°C and saturated conditions conducted on tuff core matrix to determine time-to-failure as a function of applied stress

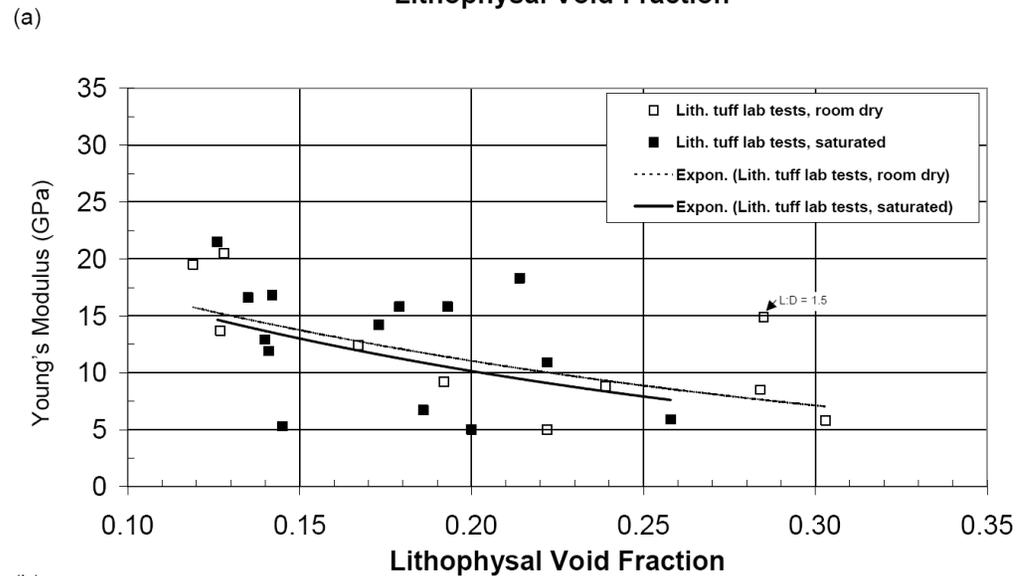
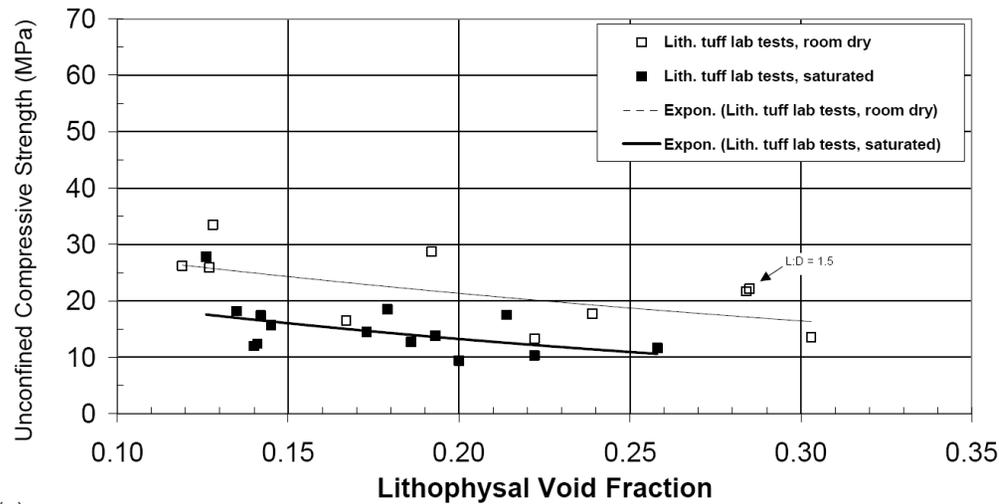
- **Thermal Properties**

- 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



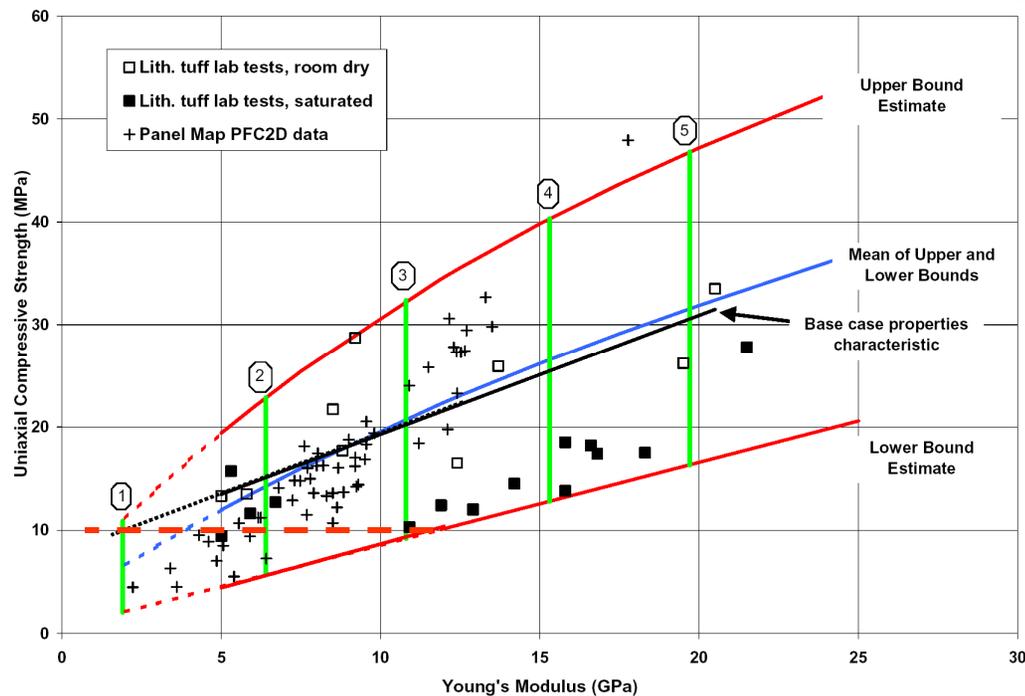


Laboratory Testing on Large Samples



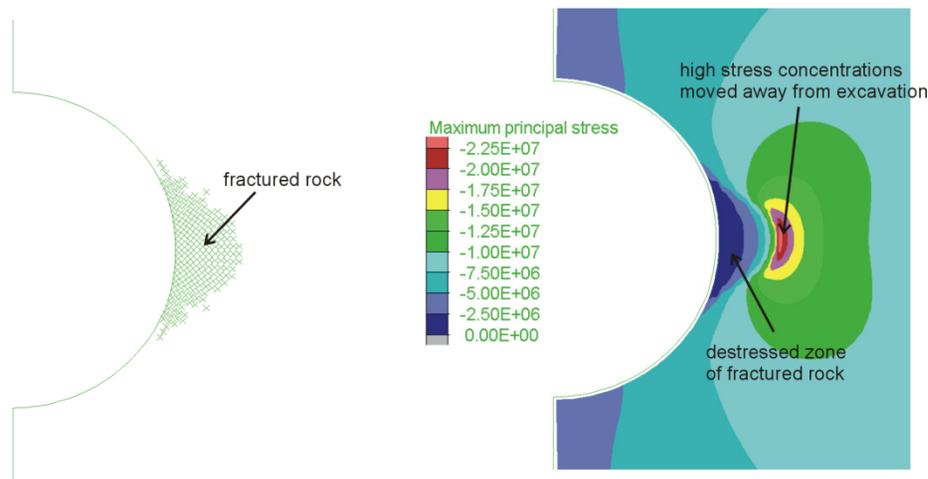
Range of Strength and Stiffness for Lithophysal Rock Mass Used in Drift Performance Analyses

Category	~ % of T _{tp11}	~% 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

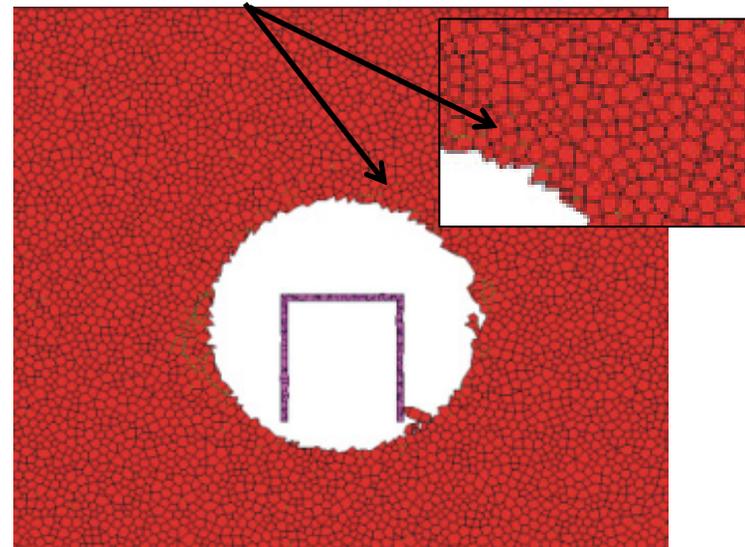
Continuum



- 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



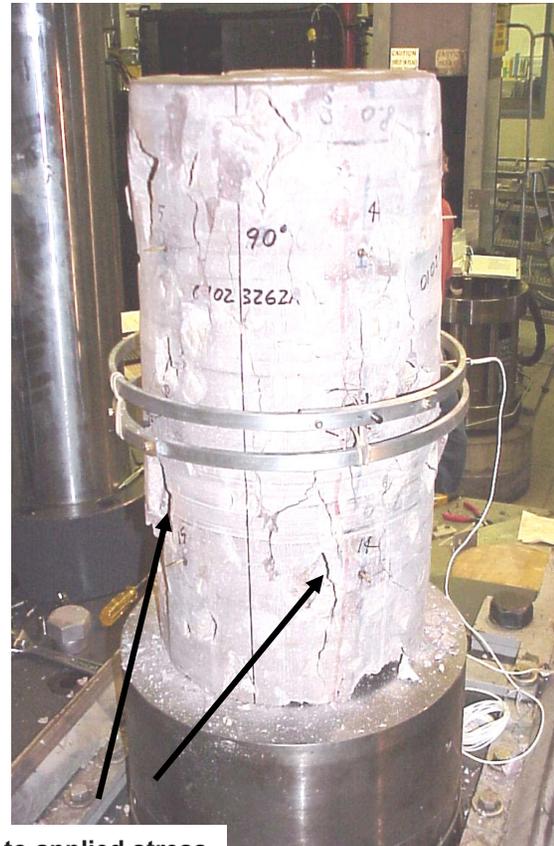
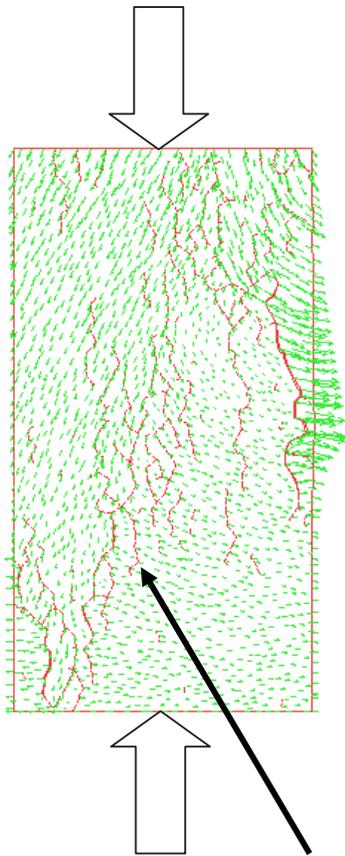
Discontinuum Model Calibrated to Stress-Strain Response in Unconfined Compression

- **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 lithophysical 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**



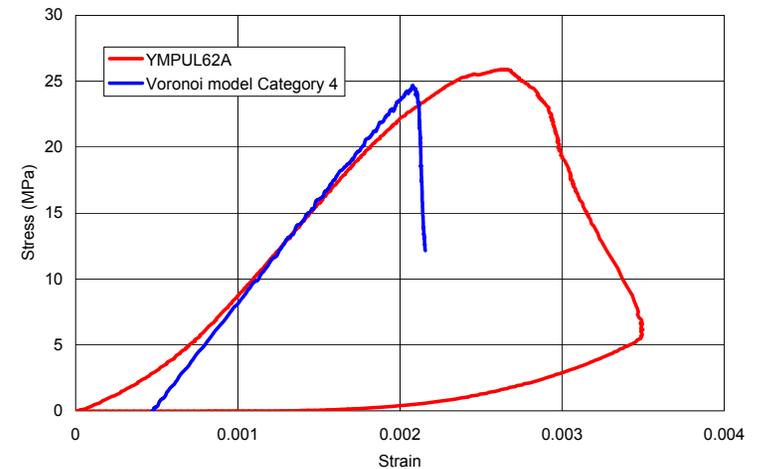
Calibration of Lithophysal Model to Laboratory Compression Testing on Large Rock Compression Samples

Applied Axial Load



Axial splitting parallel to applied stress

Example of UDEC Model Calibration to Laboratory Compression Test



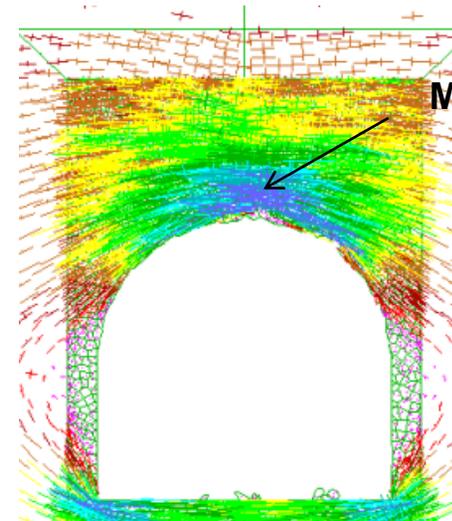
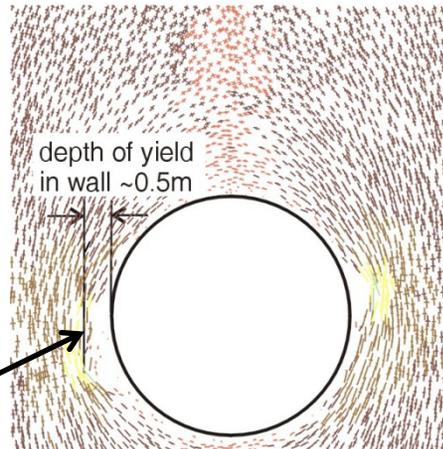
Comparison of Model Predictions to Observations of Fracturing and Drift Stability in the ECRB

- 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

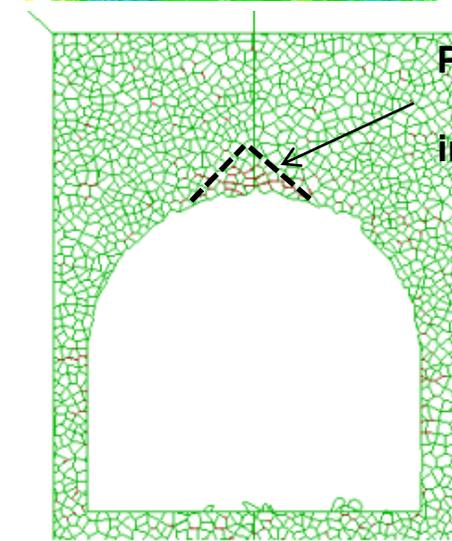
ESF South Ramp Sidewall Yielding



Prediction of Yield for Category 1 Rock



Max Stress = 80-90MPa

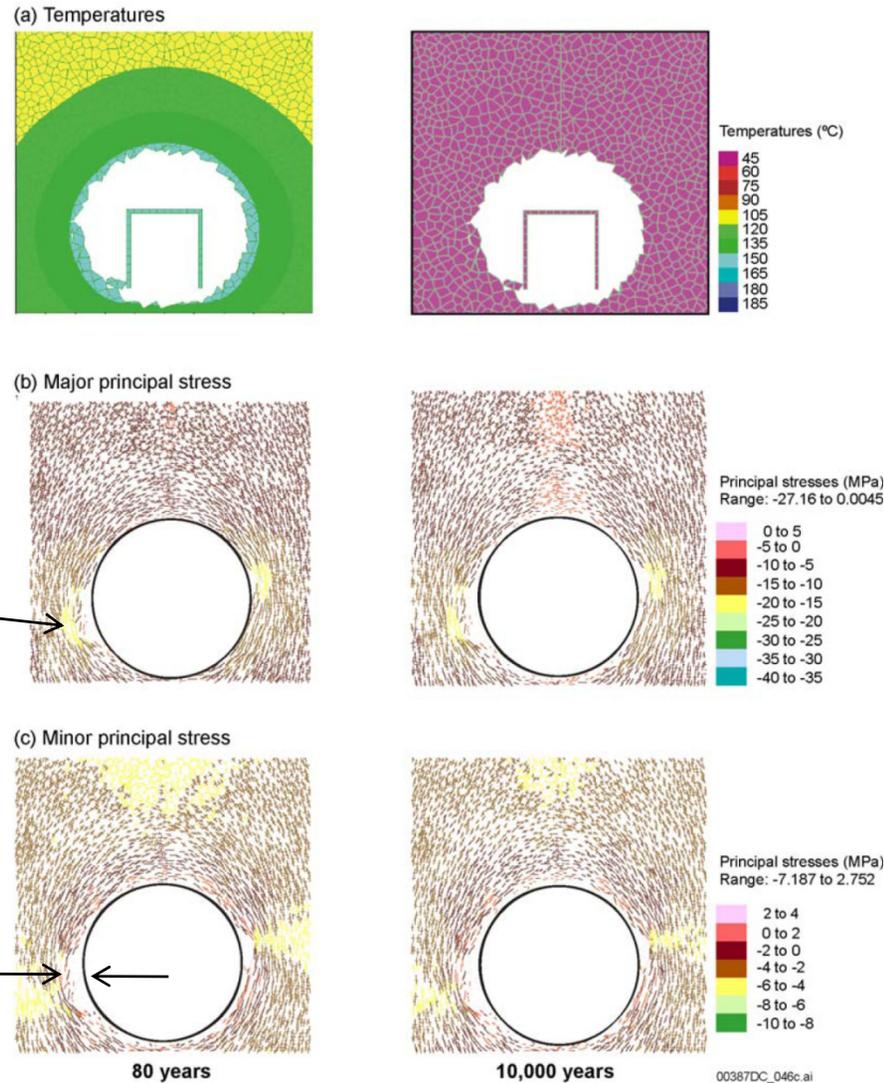


Predicted zone of stress-induced failure

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

Note: All analyses do not include ground support



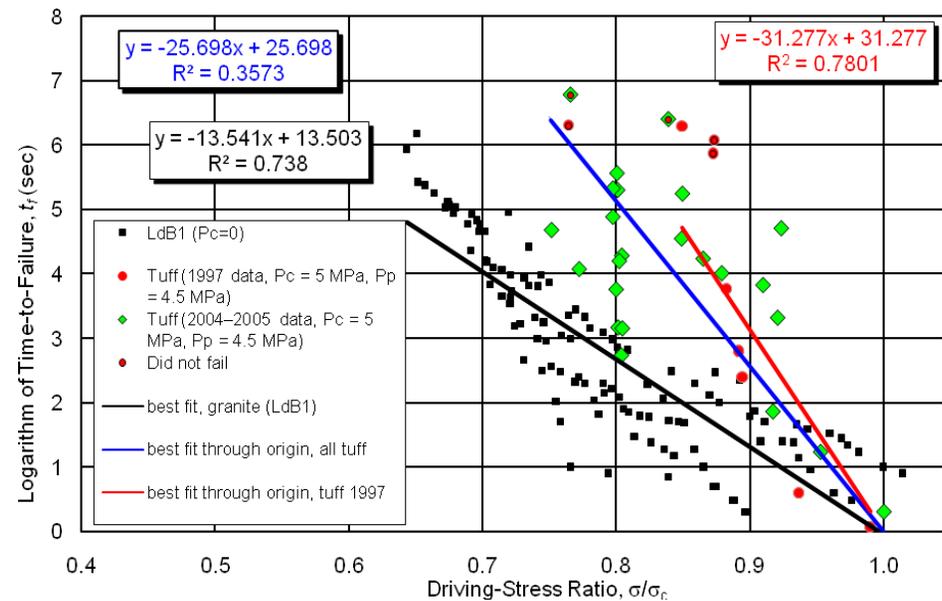
Summary – Thermal Stability of Drifts in Lithophysal Rock

- **Thermal analysis indicates overall drift stability for 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 150°C and saturated conditions
- Sensitivity study of drift stability conducted for range of lithophysal rock mass strength categories

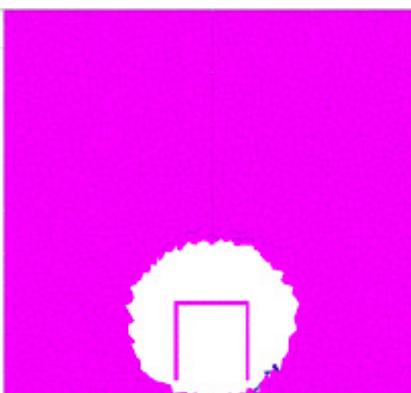
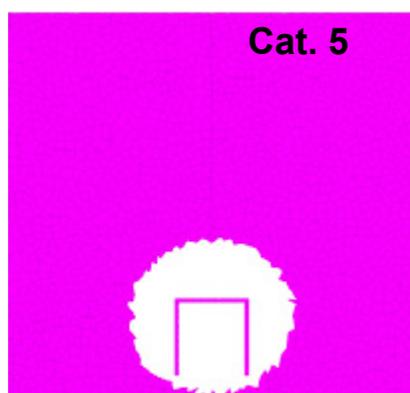
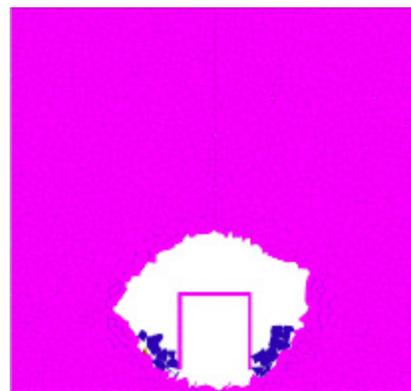
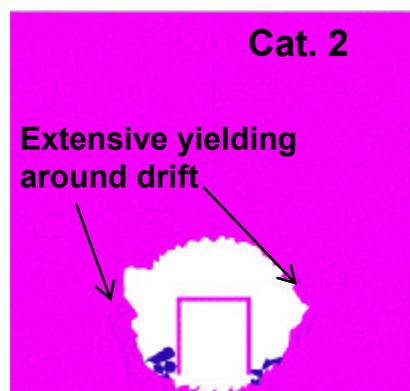


Drift Profiles for Combined Thermal and Time-Dependency

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



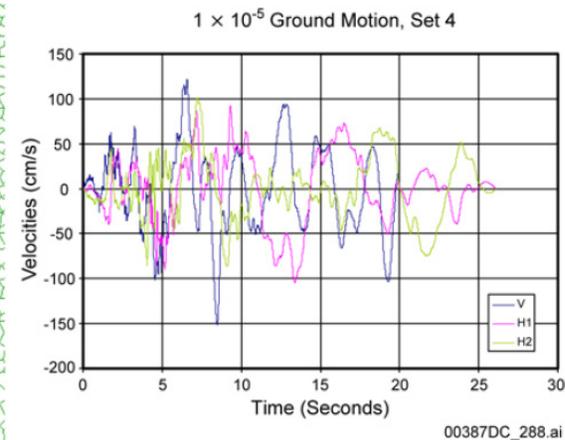
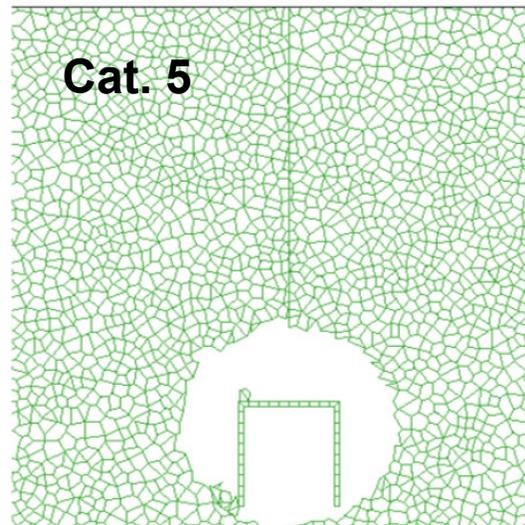
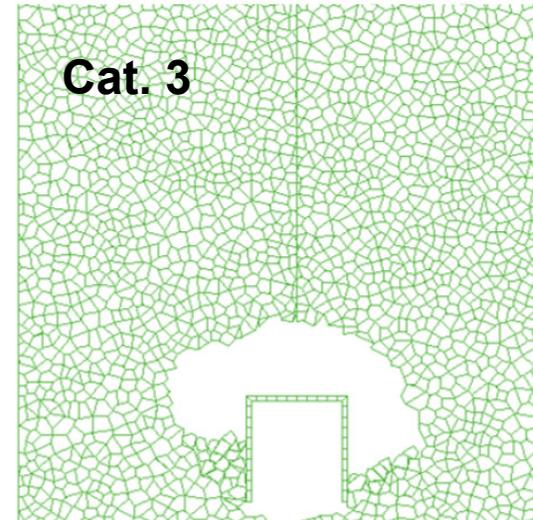
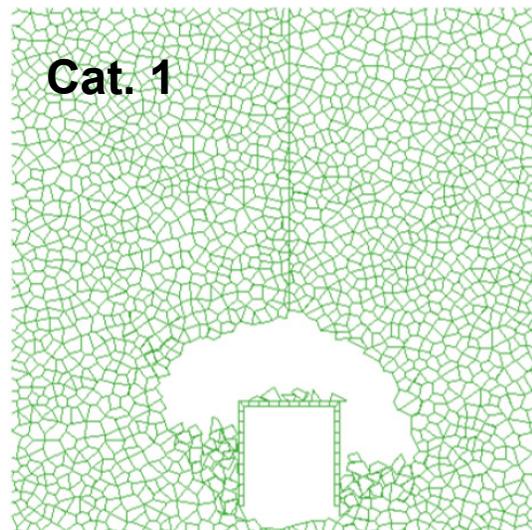
Seismic Response of Drifts in Lithophysal Rock

- **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**

PGV = Peak Ground Velocity

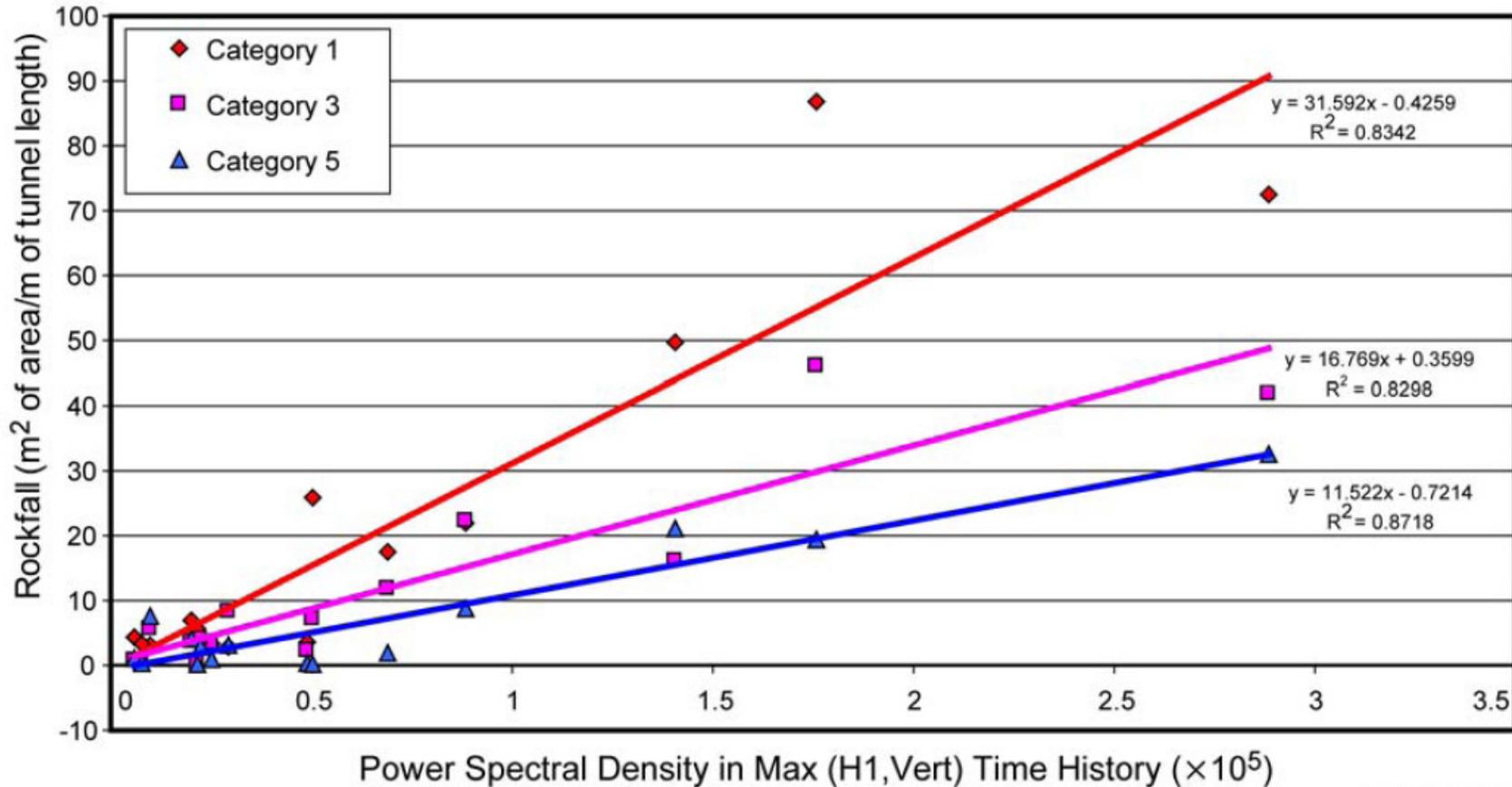


Example of Rockfall Predictions for a Ground Motion at the 1.05 m/s PGV Level



Predicted Rockfall as a Function of Seismic Energy

Damage Level (m² of rockfall) in Lithophysal Rock



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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

