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

YUCCA MOUNTAIN PROJECT

Status on Repository Design - Geotechnical Considerations

Presented to:
Nuclear Waste Technical Review Board

Presented by:
Mark Board
Bechtel SAIC Company, LLC

May 8, 2002
Washington, D.C.

Outline

- Geotechnical Issues for License Application
- Issue Resolution Strategy
- Current Work Effort
- Summary

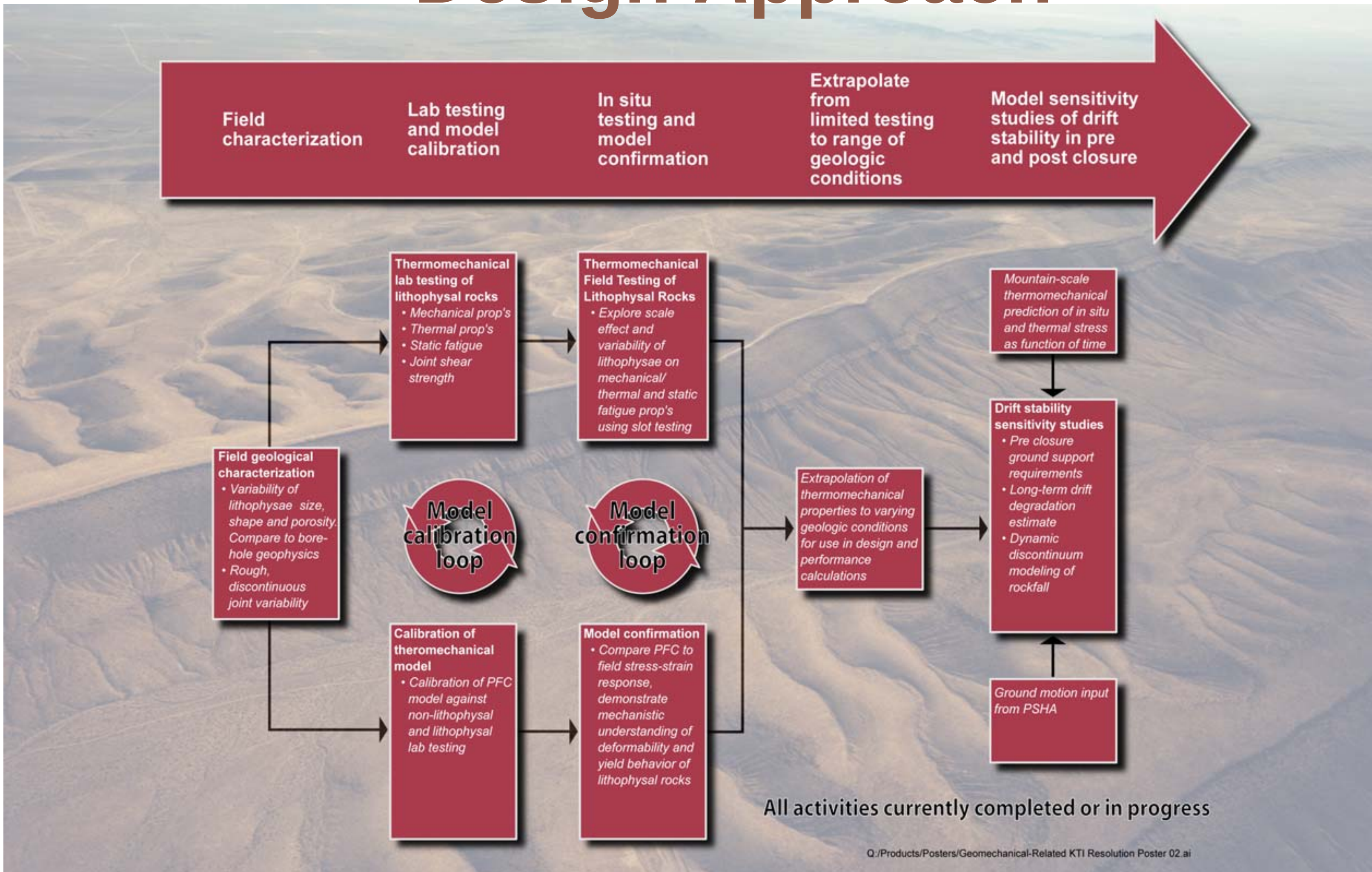
Repository Geomechanical Design Issues for License Application

- Thermomechanical properties of lithophysal rocks
  - Thermal conductivity and expansion
  - Strength and deformability (mechanical material behavior)
  - Thermal and mechanical coupling behavior and long-term strength degradation
  - Impact of variability of geologic structure on rock mass properties
- Pre-closure ground support specification
- Post-closure drift degradation and rockfall

Geomechanical Data to Support Design and Performance Assessment

- **Existing rock properties and fractures data base (lab and in situ) is extensive for non-lithophysal rocks**
- **Currently developing (through lab and field testing) expanded data base of:**
  - **Thermomechanical properties of the lithophysal rocks**
    - **Importance of porosity-dependence and size effect**
  - **Evaluation of the geometric properties of joints and lithophysae and their variability**
    - **Ensuring that our models are based on site-specific geology**
  - **Time-related degradation effects (static fatigue) on lithophysal and non-lithophysal rocks**
- **Currently developing postclosure site-specific earthquake ground motions**

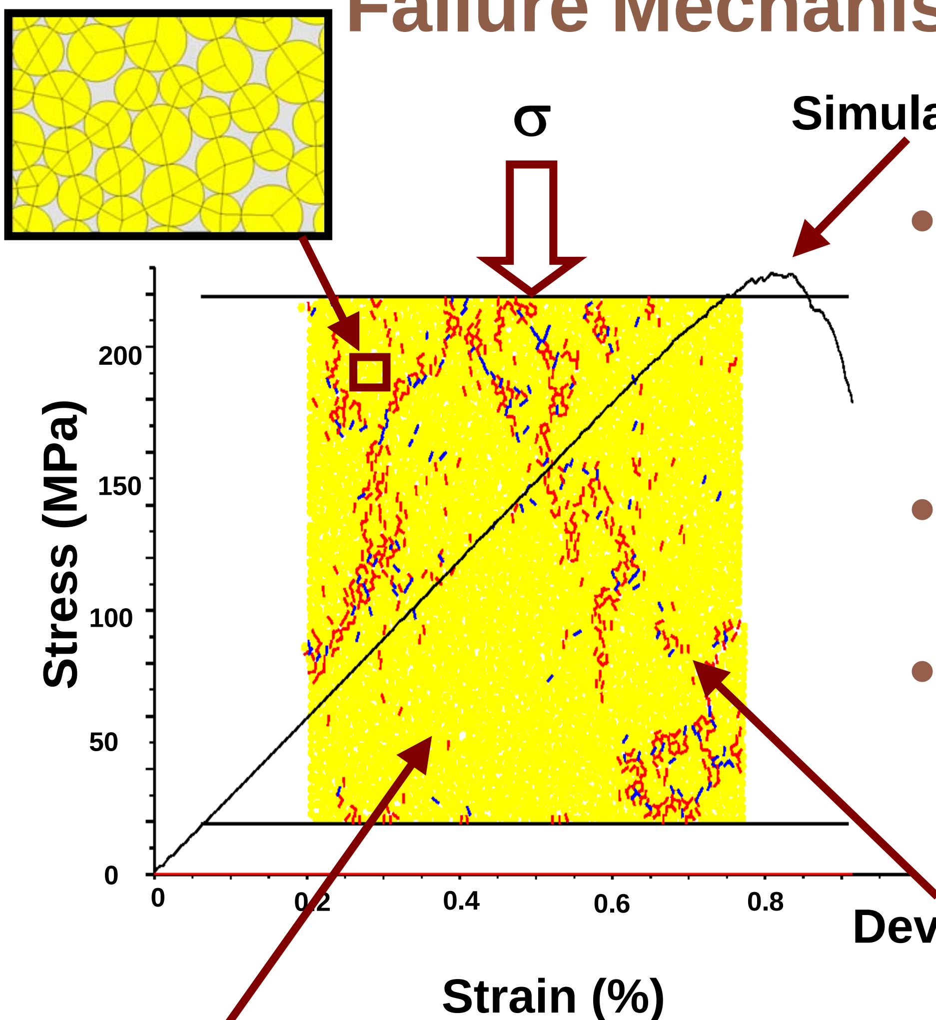
Rock Properties Estimation and Design Approach



Increasing Confidence, Reduction in Level of Uncertainty

Example of Properties Extrapolation Process Model Calibration - Effects of Lithophysal Porosity on Failure Mechanism and Strength

Simulated Stress-Strain Response



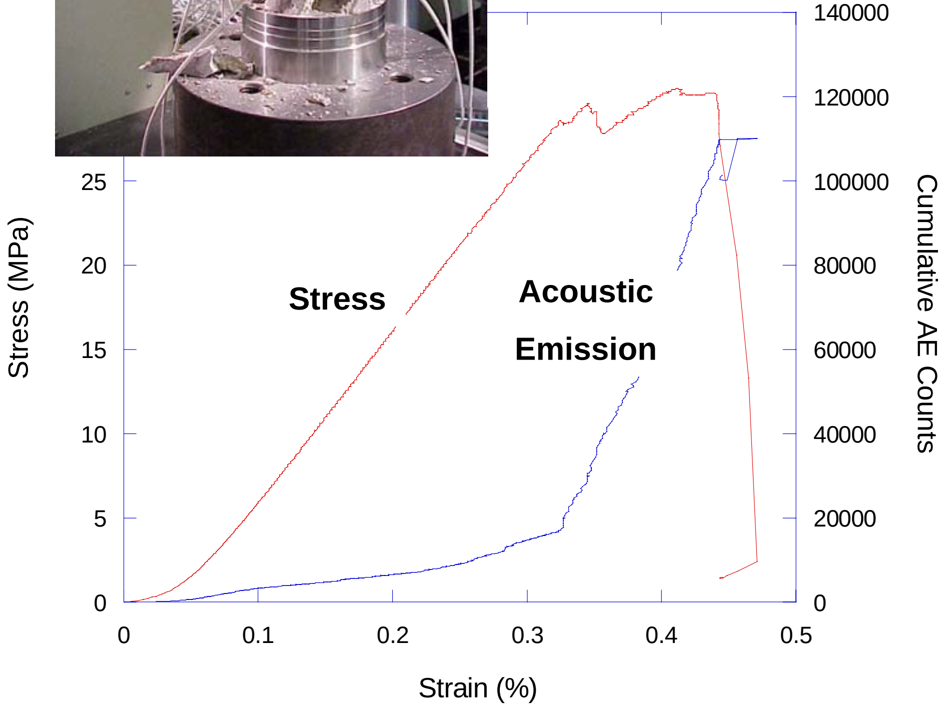
- **Particle Flow Code (PFC) model of uniaxial compression test on middle non-lithophysal rock**
- **Calibrate stress-strain behavior against lab tests**
- **Assistance of Itasca Consulting Group - P.Cundall, D. Potyondy, Leads**

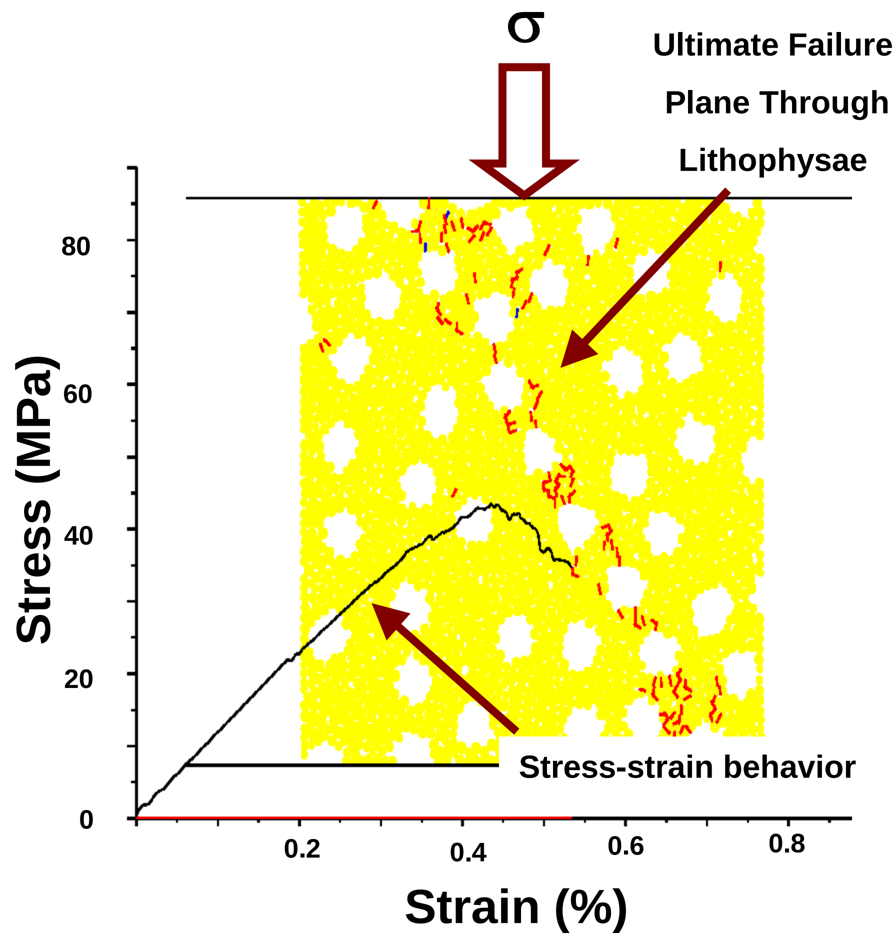
Development of macroscopic shear failure plane

Simulated rock sample, loaded in compression

Model Calibration - Effects of Lithophysal Porosity on Failure Mechanism and Strength - Simulation of Upper Lithophysal Test

Lab Test





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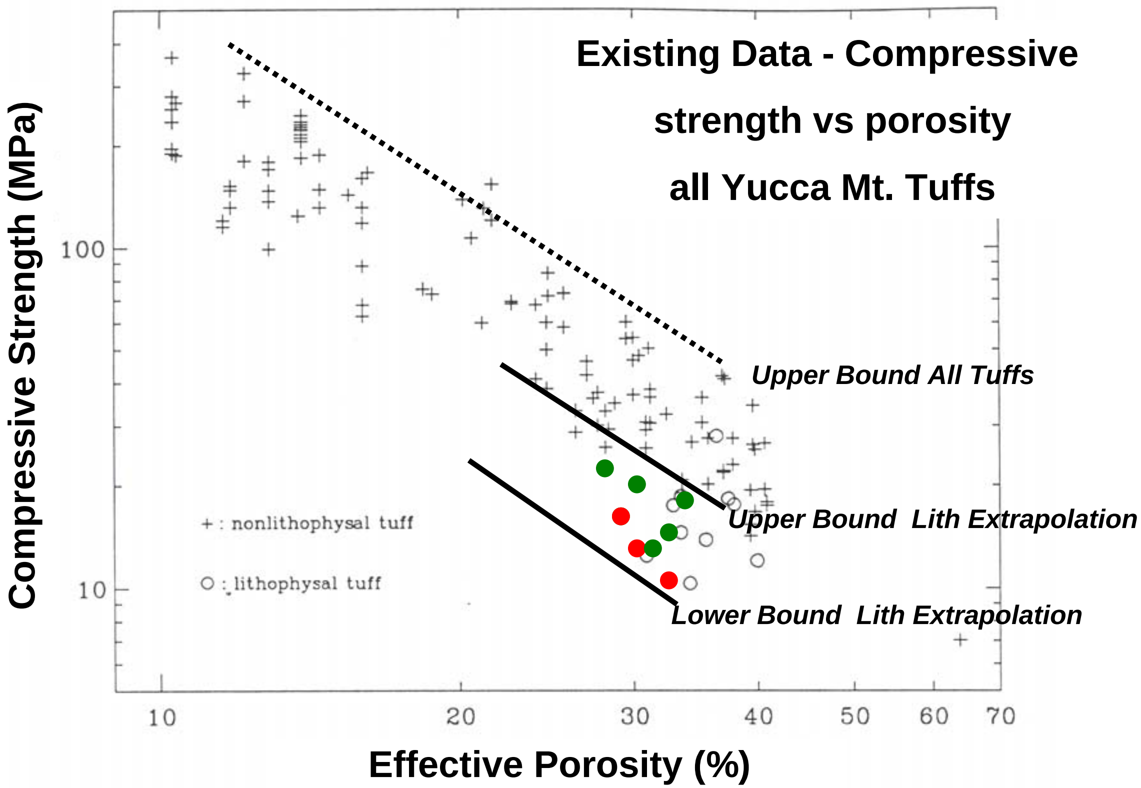
Developing Range of Rock Mass Design and Performance Properties - Establishing the Impact of Geologic Variability



- Generate ranges of rock properties from lab, field and numerical extrapolations that account for variability in the rock mass, porosity being the greatest contributor
- Produce variability and confidence limits for properties

Schematic **of the Approach to Incorporating Variability into Design Rock Properties**

- Lab Tests on Large cores
- In Situ Tests

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Ongoing Ground Support Evaluation Approach

- **Modeling to date indicates support loads and opening deformations expected to be relatively small during pre-closure**
  - **Time-dependent degradation under thermally-induced loads will need to be accounted for**
- **Estimated support function in pre-closure period**
  - **Retain potential raveling rock in lithophysal rock - "membrane"-type support well-suited**
  - **Support of "keyblocks" and possible surface spalling in jointed non-lithophysal rocks**

Ongoing Ground Support Evaluation Approach
(Continued)

- **Current studies for License Application Design**
  - Examining use of various support methods including rock bolts and mesh, steel sets, and shotcrete
  - Longevity of steel support, impact of thin layers of shotcrete on cement carbonation and water chemistry
  - Approach for observation and maintenance of support over pre-closure period

Approach to Post-Closure Rockfall Analysis

- Site-specific ground motions from PSHA
  - Walter Silva, Pacific Engineering; Carl Stepp, Consulting Seismologist; Allin Cornell, Stanford University
- 3D dynamic discontinuum analyses (3DEC) using site-specific joint geometries (non-lithophysal rocks) and site-specific lithophysae distributions (lithophysal rocks)
  - BSC, Itasca Consulting Group, USGS
- Development of probabilistic output of rockfall mass and velocity based on many discrete simulations of varying geologic conditions

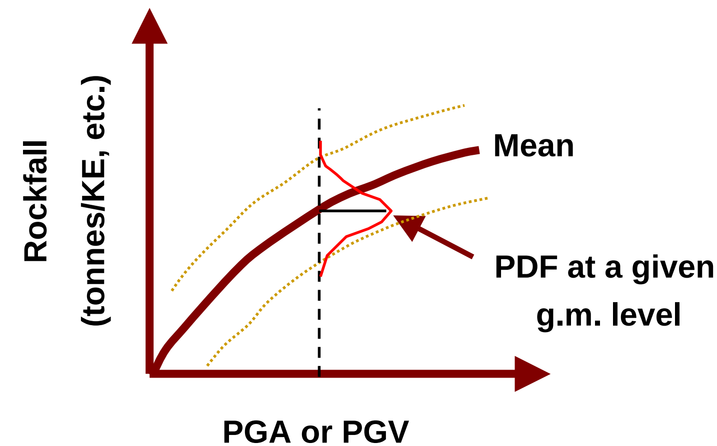
Rockfall Assessment Approach

Statistically-based
Geologic Input

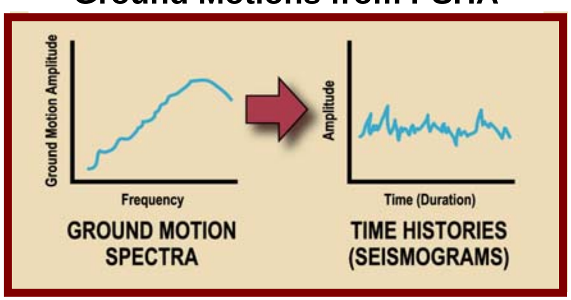
- Joint geometric parameter variations
- Lithophysae geometry variations
- Rock and joint property variations

3D Dynamic Discontinuum Modeling

Rockfall distribution to Drip Shield Analysis



Ground Motions from PSHA



Summary

- Major geomechanical issues
  - Preclosure ground support
  - Postclosure seismic stability
  - Increase data base of thermomechanical prop's, primarily of lithophysal rocks and assess variability across site
- Enhancing confidence
  - Additional laboratory and field testing of lithophysal rocks
  - Incorporation of site-specific geology into numerical model development
  - Continued validation of models against laboratory and field data - use of models for extrapolation of behavior to varying geology
  - Completion of ground support studies - load calculations and longevity estimates
  - Use of true 3D dynamic discontinuum simulations for rockfall estimation

Backup

Laboratory and Field Test Program

- Geotechnical program of detailed geometric documentation of jointing in middle non-lithophysal zone and lithophysae in upper and lower lithophysal zones
- Description of the PFC program used for evaluation of lithophysal rock mechanical constitutive behavior
- Thermal testing in the Lower Lithophysal Unit

Current Laboratory and Field Testing Program on Lithophysal Rocks

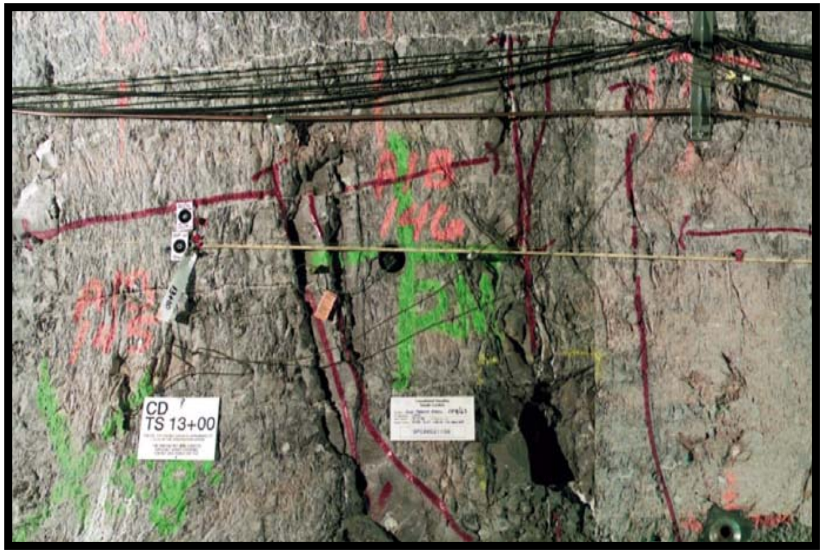
- **Laboratory Testing (Sandia and US Bureau Rec)**
  - **Thermal/Mechanical Prop's of large (12" diameter) core**
  - **Static Fatigue (time-dependency)**
  - **Joint Shear Strength**
  - **All as functions of temperature and saturation**

- **Field-Scale Testing in Exploratory Studies Facility and ECRB**
  - **Thermal/Mechanical Prop's ("Slot" flatjack compression)**
  - **Static Fatigue and thermal degradation by load cycling and long-period loadings**
  - **Heater testing in lower lithophysal unit for conductivity measurement**

Additional Geotechnical Investigations Now Underway - Joint Geometric Characterization

(Robert Lung, Steven Beason, US Bureau Rec.)

- **Study of Joint Geometry for Estimation of Joint Shear Constitutive Behavior and for Rockfall Model Input**
- **Re-examine joint geometric characteristics, and supplement existing work. Describe statistics of:**
  - Dip/dip direction
  - Trace length (continuity)
  - Terminations
  - Rock bridge lengths
  - Non-planarity (large scale roughness)
  - Index properties
- **Constitutive Behavior of Rough Joints - Barton-Bandis empirical joint shear constitutive model**



Joint geometry showing discontinuous, short trace lengths (shown as T-junctions on painted lines)

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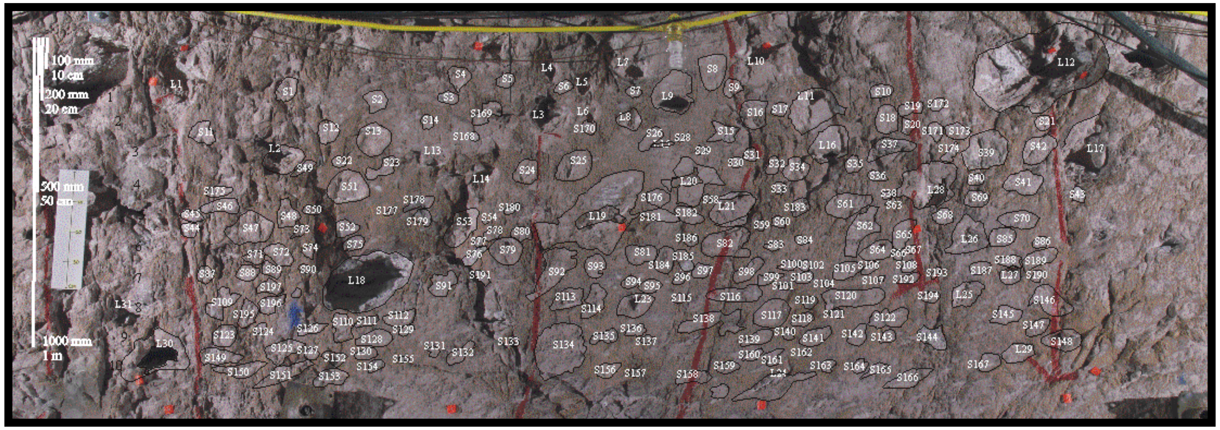
Additional Geotechnical Investigations Now Underway - Lithophysae Variability

(David Buesch, USGS)

- **Geologic investigation of lithophysae in Enhanced Characterization of the Repository Block (ECRB) currently underway**
  - **Detailed mapping and description of study “panels” along ECRB**
  - **Linear traverses up ECRB using tape and angular measurements of lithophysal porosity**
  - **Statistical description of shape, size, porosity, “rim” mineralization, spots, groundmass mineralogy and fracturing**
  - **Variability of lithophysae will be documented in future AMR**



ECRB Study Panel With Mapped Lithophysae

Description of the Particle Flow Code (PFC)

- PFC is a “micromechanical” discontinuum program written by P. Cundall of Itasca Consulting Group
- PFC is selected as it provides the ability to represent the basic physics of deformation and fracture of rock through use of a bonded particle assembly to represent the rock solid matrix, and represents lithophysae as physical voids in the model
- Provides a direct physical analogy to the actual rock - we do not have to make assumptions as to how to include geologic variation - it is done naturally in the model through direct inclusion of structure

Description of the Particle Flow Code (PFC)

(Continued)

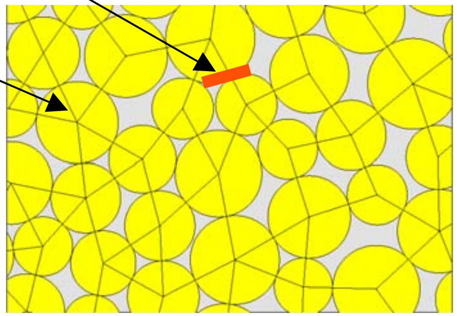
- Particle contact properties (strength, stiffness) are simple in nature and set via calibration against laboratory and/or field testing results. Complex constitutive behavior develops naturally
- Allows detailed study of the deformability and failure mechanisms of the rock, and how this is affected by lithophysae
- Provides simulation tool for extrapolation of thermal and/or mechanical response as function of geologic variation

Is Particle Flow Code in Widespread Use?

- PFC is used extensively worldwide, primarily as a research tool in rock constitutive modeling, rock fracture, granular materials research, powder research, rock dynamics, fluid flow in granular materials, rock cutting, etc.
- Following are some examples in rock mechanics in which program has been used to investigate similar problems to ours:
  - Compaction of porous chalk and acoustic emission in the Ekofisk Oil Field, North Sea
  - Borehole fracturing and breakout in deep wells
  - Mechanisms of shear constitutive behavior of faults and rough joints and comparisons to empirical joint models
  - Time-dependent stress corrosion fracture mechanisms in granite at the URL, Canada
  - Blasting and hydraulically-induced fracturing
  - Oil well stimulation and proppant injection/effectiveness

Description of the Particle Flow Code Program and How it Represents Rock

Rock Composed of Bonded Particles



Contact Properties

$F_n = k_n U_n$

$\Delta F_s = k_s \Delta U_s$

Deformability governed by contact stiffnesses

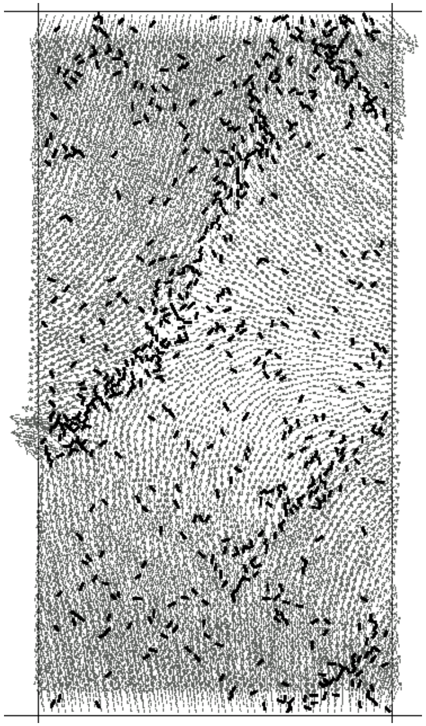
$F_s \leq \mu F_n$

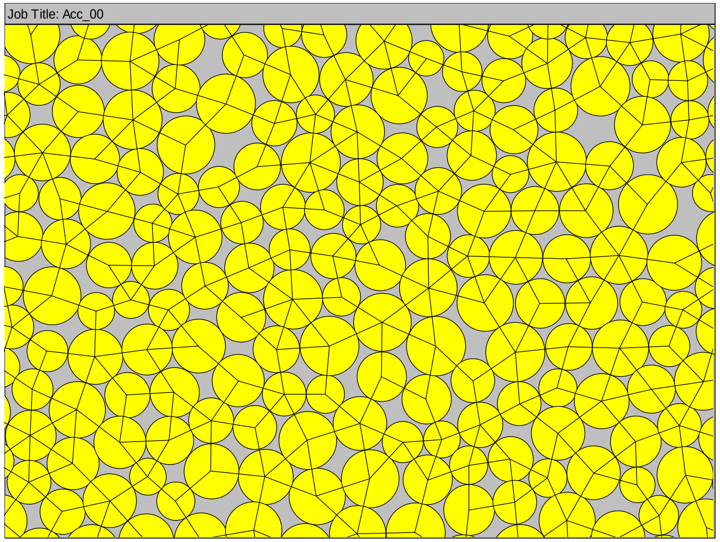
strength

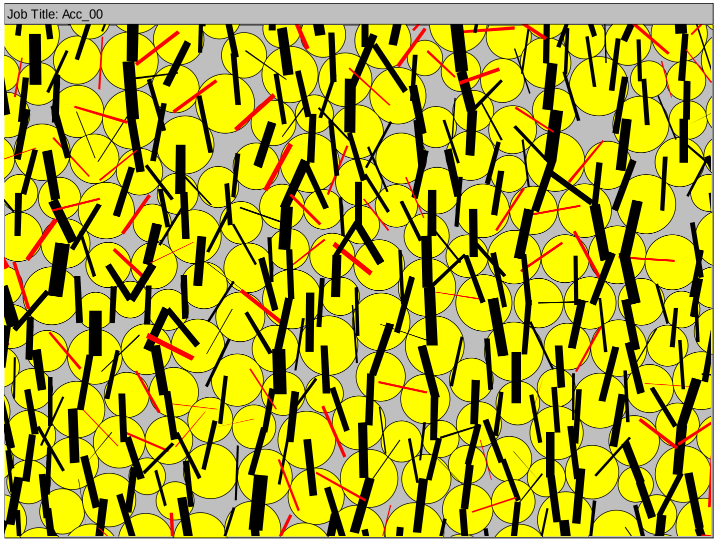
- PFC uses a fully-dynamic, micromechanical discontinuum approach that physically models pores as holes
- Rock modeled as series of bonded particles with shear and normal stress bonds
- Properties very simple - only shear and normal stiffness, tensile and shear strength of contacts, interparticle friction angle after bonded failure
- Non-linearity and complexity of response arises from geometry of particles and porosity
- Allows for determination of propagation of fractures in shear or tension, followed by frictional resistance
- Provides a direct physical analogy to porous rock, and allows direct input of lithophysae variation to model

Development of Yield Mechanisms in PFC

- When loaded in compression, bonded assemblies develop non-uniform force chains that induce the formation of axially aligned microcracks
- These microcracks coalesce into macroscopic fractures



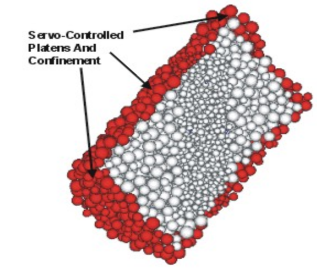




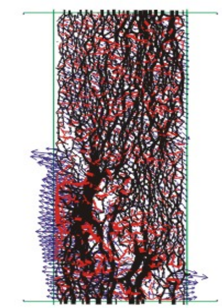
Model Validation Strategy for Lithophysal Rock

- Due to scale effects, difficult to conduct standard "statistically"-based test program for lithophysal rocks - need to use another approach to bound range of properties
- Validating model(s) *(Particle Flow Code)* that *explicitly* represent the mechanics of deformation and yield of lithophysal rock
- Validate model directly against lab and field instrumentation data and observations
- Once validated, use model for extrapolation of mechanical behavior and design properties for expected range of lithophysal size, shape and porosity in repository block

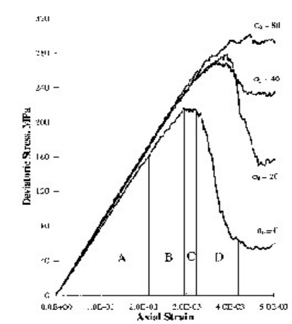
***PFC 3D* Model "Sample"**



Failure Mechanism in Compression



Comparison/ Calibration of Stress-Strain Response to Lab and Field Results



Thermal Conductivity Testing in the Lower Lithophysal Unit

- Lower lithophysal unit is characterized by voids, or lithophysae, which range in size from centimeters to meters, making a field program an effective method of measuring bulk rock properties
- Field tests will provide insitu measurements of thermal conductivity (K) and thermal diffusivity (k). Since $k=K/(\rho \cdot Cp)$, heat capacity (Cp) is also obtained
- In concert with the field program, a laboratory program is being developed to determine matrix properties of the material and to develop a relationship between thermal conductivity and void volume

Overview of Field Test Status

- Test 1: Single heater and single instrumentation borehole
  - Status: Completed, preliminary results reviewed in next slide
- Test 2: Array of 3 heaters, 3 instrumentation boreholes
  - Status: In progress
- Test 3: Single heater, 2 instrumentation boreholes
  - Status: In progress

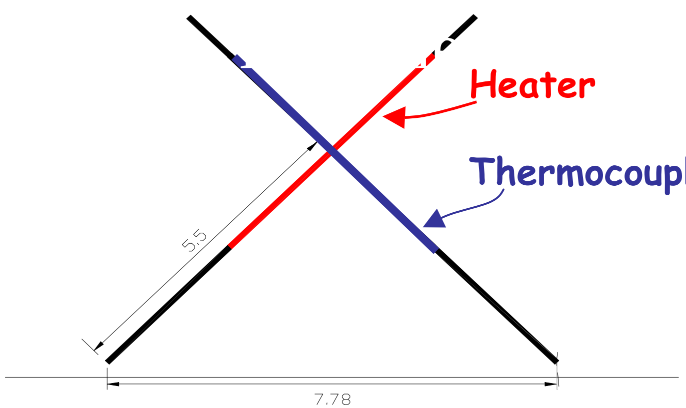
Field Thermal Conductivity Test 1

–***Purpose:*** Initial test; measure thermal conductivity and thermal diffusivity on field scale.

–***Test Configuration:*** Single heater and single instrumentation borehole.

Heater: 5 m long

Thermocouples: In instrumentation borehole. 30 thermocouples cover 5 m.



Testing: Ran heater at low power to remain below boiling; calculated thermal conductivity, thermal diffusivity under partially saturated conditions.