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

YUCCA MOUNTAIN PROJECT

Approach to Resolving Geomechanical-Related Key Technical Issues

Presented to:
NRC-DOE Appendix 7 Meeting At The Center for Nuclear Waste Regulatory Analyses

Presented by:
Kirk Lachman, DOE
Mark Board, BSC
Steven Beason, USBR
Larry Costin

Introduction - Objective/Purpose of Meeting

- **Objective**
  - Establish open/interactive approach with the U.S. Nuclear Regulatory Commission (NRC) toward the resolution of RDTME KTIs
  - Present program for the path forward for the resolution of geomechanically-related RDTME KTI Agreements
- **Purpose**
  - Introduce proposed technical approach
  - Discuss logic behind the approach
  - Discuss how the approach will be used in the Repository Design process
  - Discuss how the approach may impact Performance Assessment and how it will be considered

Introduction - Geomechanical-Related Key Technical Issue (KTI) Agreement Summaries

- **Repository Design Thermal-Mechanical Effects (RDTME) 3.02**
  - Accountability for the critical combinations of in situ, thermal, and seismic stresses
- **RDTME 3.04**
  - Evaluation of currently available data, together with spatial and temporal variations and uncertainties, and acquisition of additional data as needed

Introduction - Geomechanical-Related Key Technical Issue (KTI) Agreement Summaries (Continued)

- **RDTME 3.05**
  - Accountability for the effects of lithophysae on the rock mass
- **RDTME 3.06**
  - Analysis of sensitivity and uncertainties of preclosure rock support system to design parameters
- **RDTME 3.07**
  - Accountability for the effect of sustained loading on intact strength

Introduction - Geomechanical-Related Key Technical Issue (KTI) Agreement Summaries (Continued)

- **RDTME 3.08**
  - Analysis of sensitivity and uncertainties of fracture patterns
- **RDTME 3.09**
  - Analysis of possible rock movement in the invert
- **RDTME 3.10**
  - Assessment of two-dimensional modeling applications, considering in situ stress field and fracture orientations

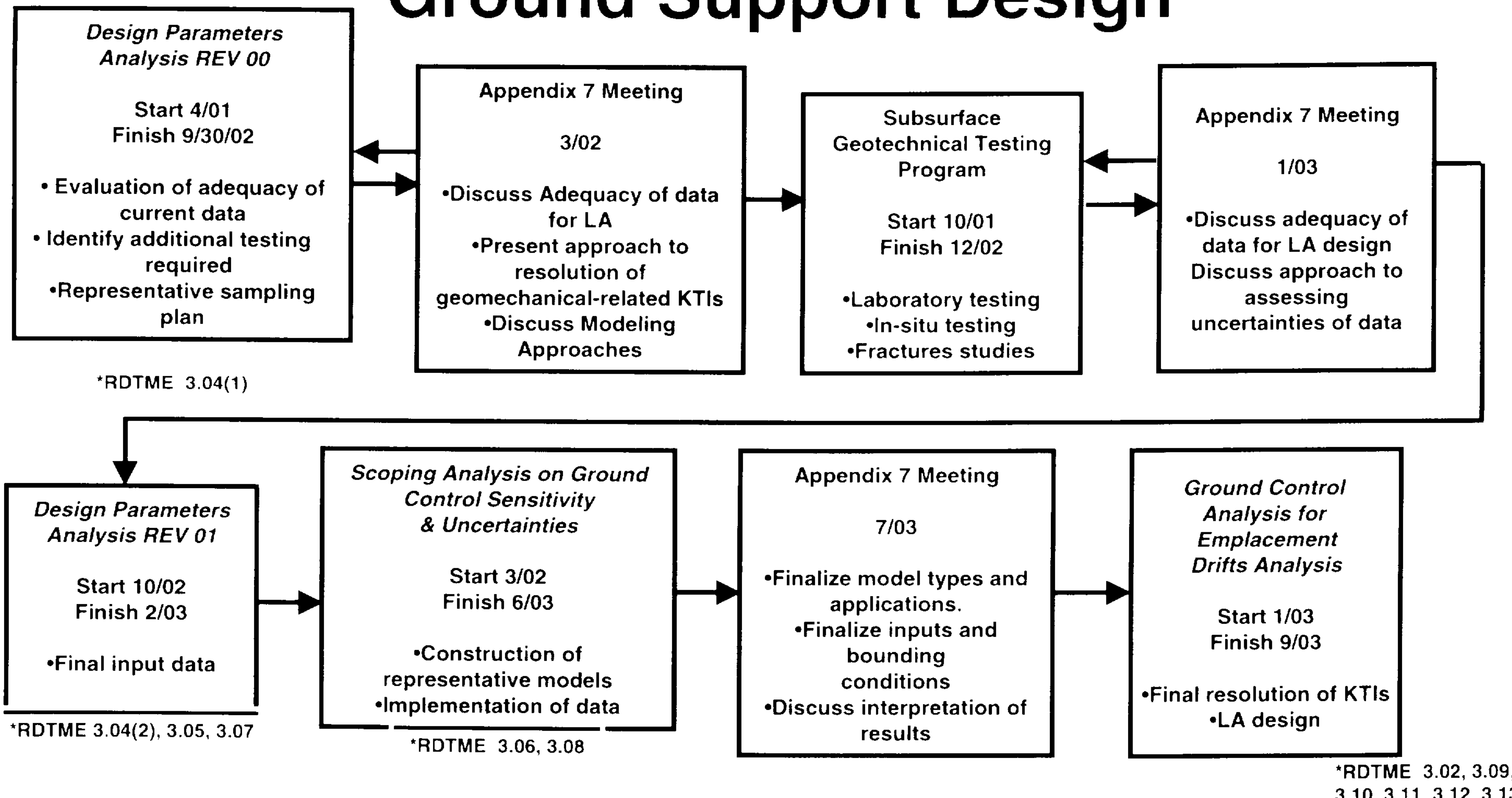
Introduction - Geomechanical-Related Key Technical Issue (KTI) Agreement Summaries (Continued)

- RDTME 3.11
  - Accountability for the long-term degradation of the rock mass and joint strength properties
- RDTME 3.12
  - Dynamic analysis using site-specific ground motion history
- RDTME 3.13
  - Technical justification for the bounding conditions used in modeling

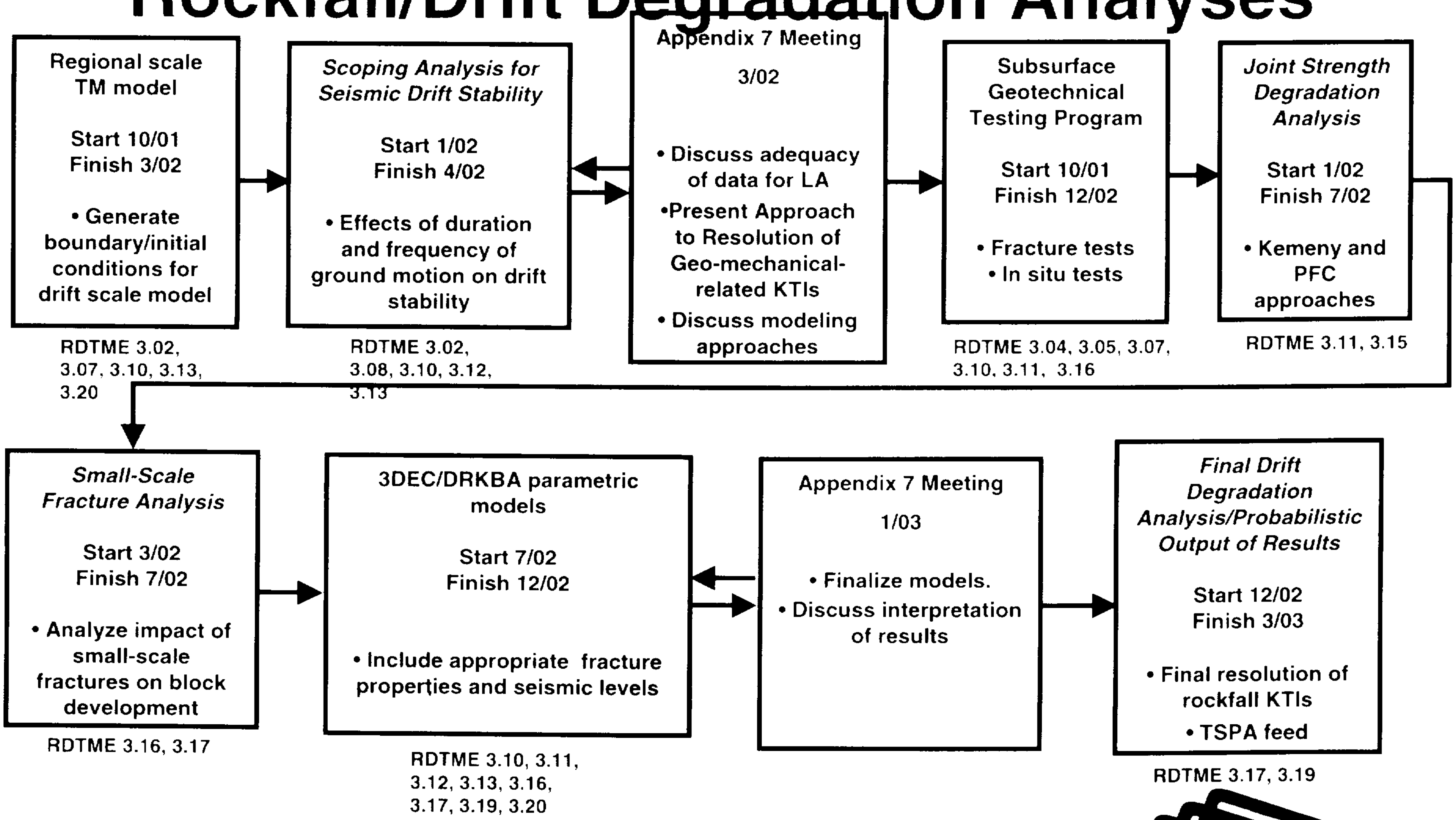
Introduction - Geomechanical-Related Key Technical Issue (KTI) Agreement Summaries (Continued)

- **RDTME 3.15**
  - Field data and analysis of rock bridges and joint cohesion
- **RDTME 3.16**
  - Technical basis for joint geometric representation used in modeling
- **RDTME 3.17**
  - Technical basis for maximum rock block size including consideration of the effect of variation of the joint dip angle
- **RDTME 3.19**
  - Acceptability of the process models that determine whether rockfall can be screened out

Introduction - Proposed Products, Meeting Actions for Resolution of KTIs Pertaining to Ground Support Design



Introduction - Proposed Products, Meeting Actions for Resolution of KTIs Pertaining to Rockfall/Drift Degradation Analyses

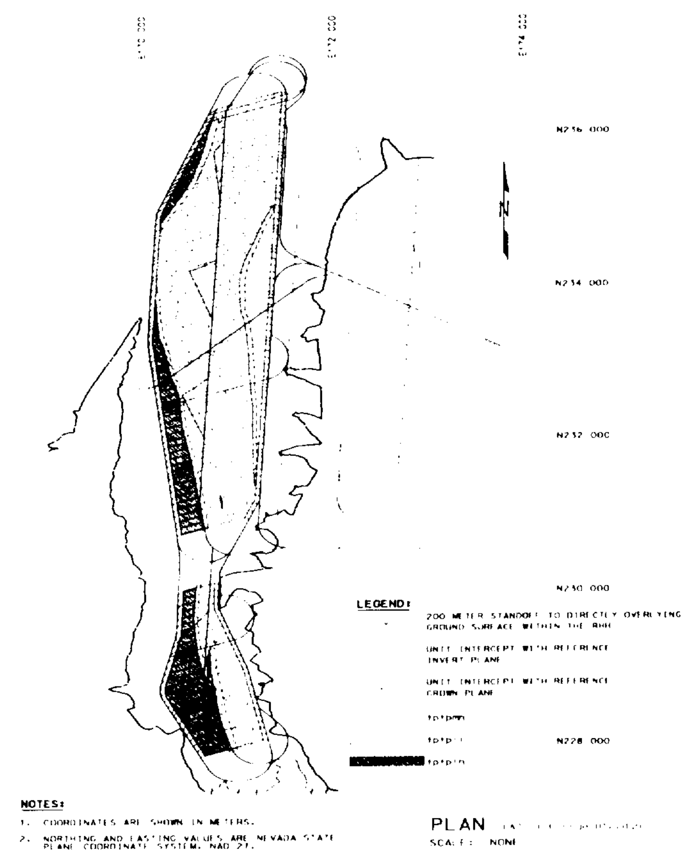


Overall Approach to KTI Resolution

- **Mark Board, BSC**

What are the Issues That Lead to the RDTME KTI's?

- Emplacement area currently about 80% in lithophysal rock, 20% in jointed non-lithophysal rock
- Difference between these rocks is primarily the "flaws" and their distribution - lithophysae in the upper and lower lithophysal units and jointing in the middle and lower non-lithophysal units
- Matrix material is approximately the same, minerologically. Groundmass between lithophysae is fractured, particularly in the lower lithophysal unit

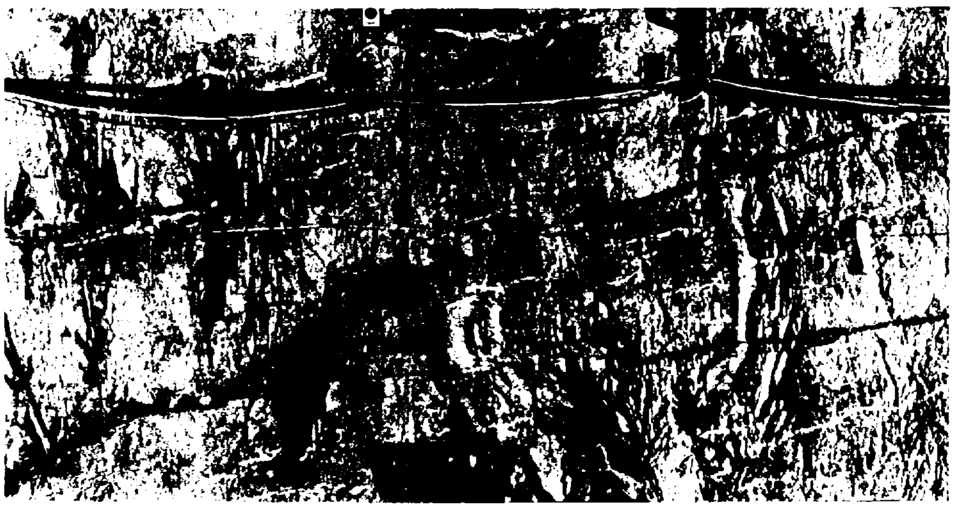


What are the Issues That Lead to the RDTME KTI's? - Lithophysal Rock

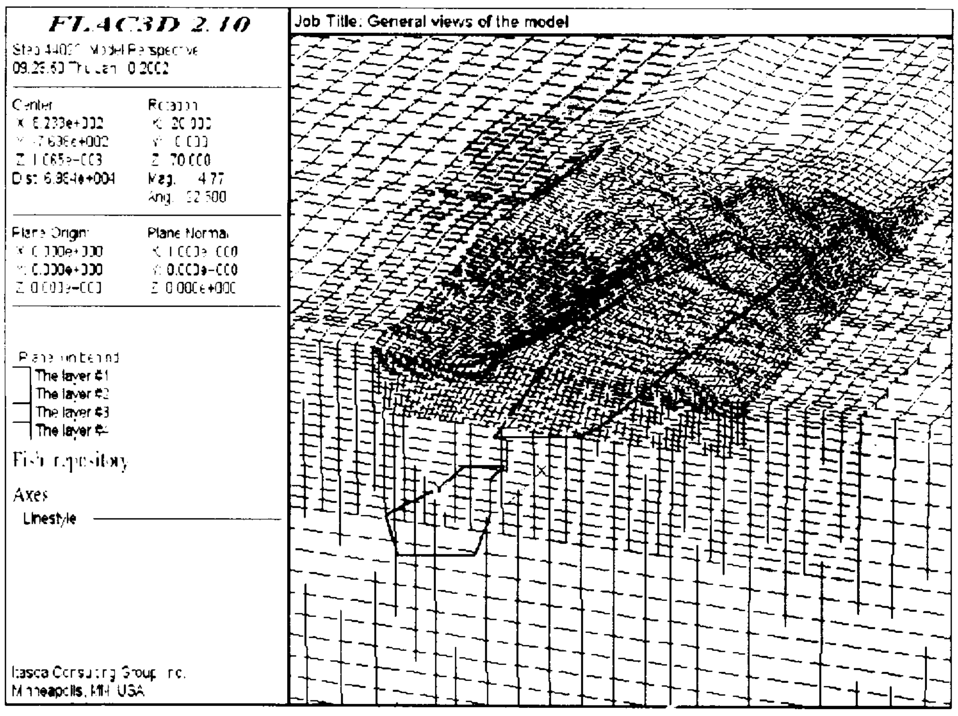
- **Lithophysal Rock Needs/Issues:**
  - Basic thermomechanical constitutive behavior needs to be defined - design property ranges need to be determined
  - Effect of variability of the properties as a function of lithophysal content and matrix fabric needs to be estimated
  - Strength degradation (static fatigue) effects as a function of loading needs to be defined
  - Scaling effects need to be considered due to lithophysae

What are the Issues That Lead to the RDTME KTI's? - Non-Lithophysal Rock

- **Non-Lithophysal rock:**
  - Analysis of geometric properties of jointing: small and large-scale roughness, joint terminations and rock bridges, joint continuity, spacing, dip and dip directions
  - Surface properties of joint samples
  - Joint shear constitutive behavior on a drift-scale
  - Fatigue strength of joints
  - Realistic, site-specific input to numerical models



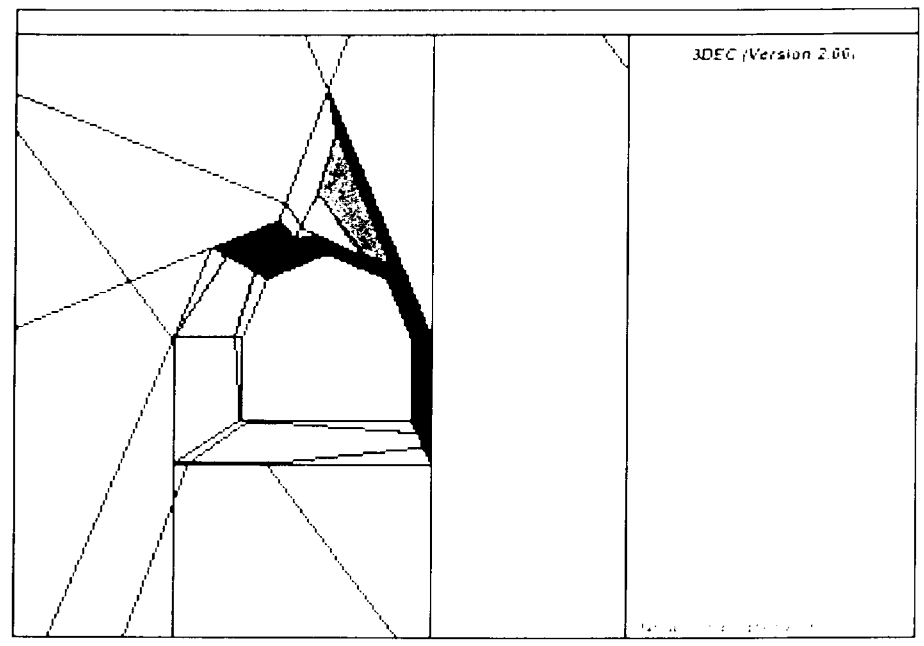
What are the Issues That Lead to the RDTME KTI's? - Boundary, Initial and Transient Loading Conditions



- **Loading applied to emplacement drifts:**
  - In situ stress on a mountain scale needed as initial condition for analysis
  - Thermal loading time history
  - Seismic loading from earthquake ground motions

What are the Issues That Lead to the RDTME KTI's? - Modeling Issues

- **What types of models or solution methods should be used?**
  - Need for site-specific models of jointed rock - models need to reasonably-reflect actual conditions
  - 2D vs 3D modeling for jointed rock masses and lithophysal rock?
  - Continuum vs discontinuum modeling?
  - Dynamic analysis using numerical models vs quasi-static keyblock methods?



What do These Issues Mean to Rock Mass Property Estimation?

- Empirically-based rock mass properties estimates, common in mining and construction are probably not immediately applicable in lithophysal rock
- The rock mass properties are *scale-dependent* and *location-dependent*. It is not possible to define rock properties and their variations from a standard "statistical"- type laboratory testing program
- Rock mass property variation best defined by a combined program of geotechnical characterization, lab and field testing, and numerical model verification and extrapolation. Need to demonstrate an understanding of the basic contributing mechanisms of rock mass deformability and yield

Proposed Approach To Geomechanics Properties Resolution

- **Additional geological characterization of:**
  - Joint geometry in the middle and lower non-lithophysal units
  - Lithophysae characterization in the ECRB
  - Correlation of borehole geophysical logs and tomography studies of the Mountain to lithophysal mapping to estimate variability across site
- **Laboratory testing of thermomechanical properties of large cores of lithophysal and non-lithophysal rocks from the ESF and ECRB**
  - Direct shear of joints in the middle and lower non-lithophysal zones
  - Compression testing of the upper and lower lithophysal zones

Proposed Approach To Geomechanics Properties Resolution (continued)

  - Static fatigue testing of the lower lithophysal zone
  - Thermal expansion testing of the lower lithophysal zone
- In situ thermal/compression testing of lithophysal rocks
- Confirmation of PFC mechanical model of lithophysal rock and "excavation-scale" joint constititutive response
- Extrapolation of mechanical response of rock mass and joints using validated model and geologic characterization to variable conditions within repository block - directly ties to site specific geology

Overall Strategy to Geomechanical-Related KTI Resolution

Field Characterization → Lab Testing and Model Calibration → In Situ Tesing and Model Confirmation → Extrapolate from Limited Testing to Range of Geographic Conditions → Define Equivalent Material Model for Lith for Design/Performance → Model Sensitivity Studies of Drift Stability in Pre- and Post-Closure

Geotechnical/Geological Characterization of Tptp

- *Lithophysal Rocks*
  - Variability of shape, size, distribution and porosity of lithophysae. Compare to borehole geophysics
  - Natural and mining-induced fracturing in groundmass
- *Non-Lithophysal Rocks*
  - Variability of joint geometric parameters - dip/dip direction, continuity, scale-dependent roughness, terminations and rock bridges

RDTME 3.04, 3.05, 3.07, 3.08, 3.11, 3.15, 3.17

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Thermomechanical Lab Testing

- *Lithophysal Rocks*
  - Mechanical constitutive behavior and properties
  - Thermal prop's
  - Static fatigue
- *Non-Lithophysal Rocks*
  - Large existing data base
  - Shear behavior of joints
  - Shear strength of rock bridges
  - Static fatigue

Model Calibration Loop

Model Calibration

- *Lithophysal Rocks*
  - PFC model lab-scale calibration against results of uniaxial compression and static fatigue testing
- *Non-Lithophysal Rocks*
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RDTME 3.04, 3.05, 3.07, 3.11

In Situ Testing of Lithophysal Rock

- Flatjack compression testing of 1m+ cubes
  - Deformability
  - Strength Character.
- Determine Stress-strain response

Model Confirmation Loop

Model Confirmation

- Compare model to field stress-strain response
- Develop understanding of mechanisms of mechanical behavior and influence of lithophysae
- Adjust model properties to achieve validation

RDTME 3.04, 3.05

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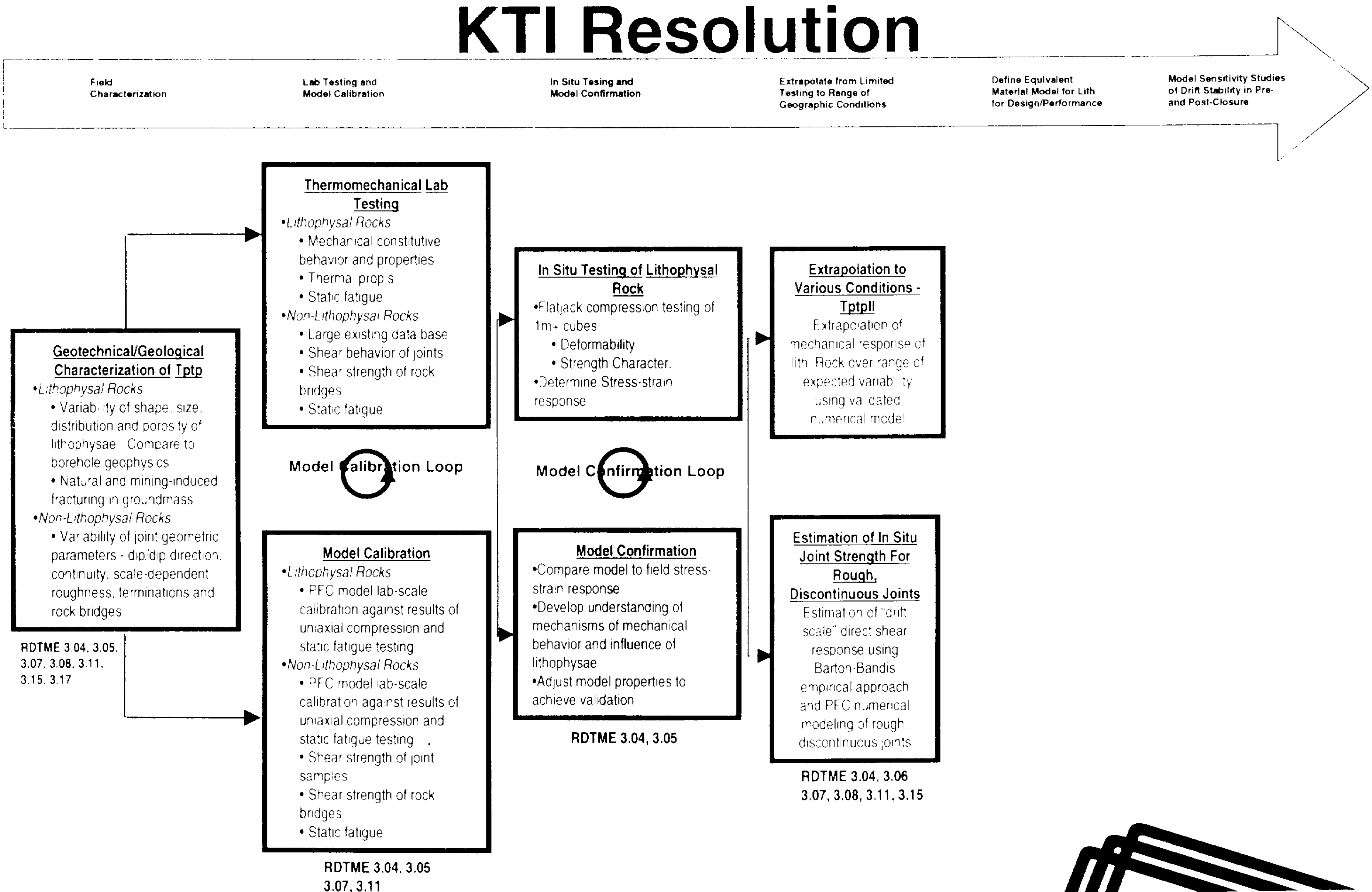
Overall Strategy to Geomechanical-Related KTI Resolution



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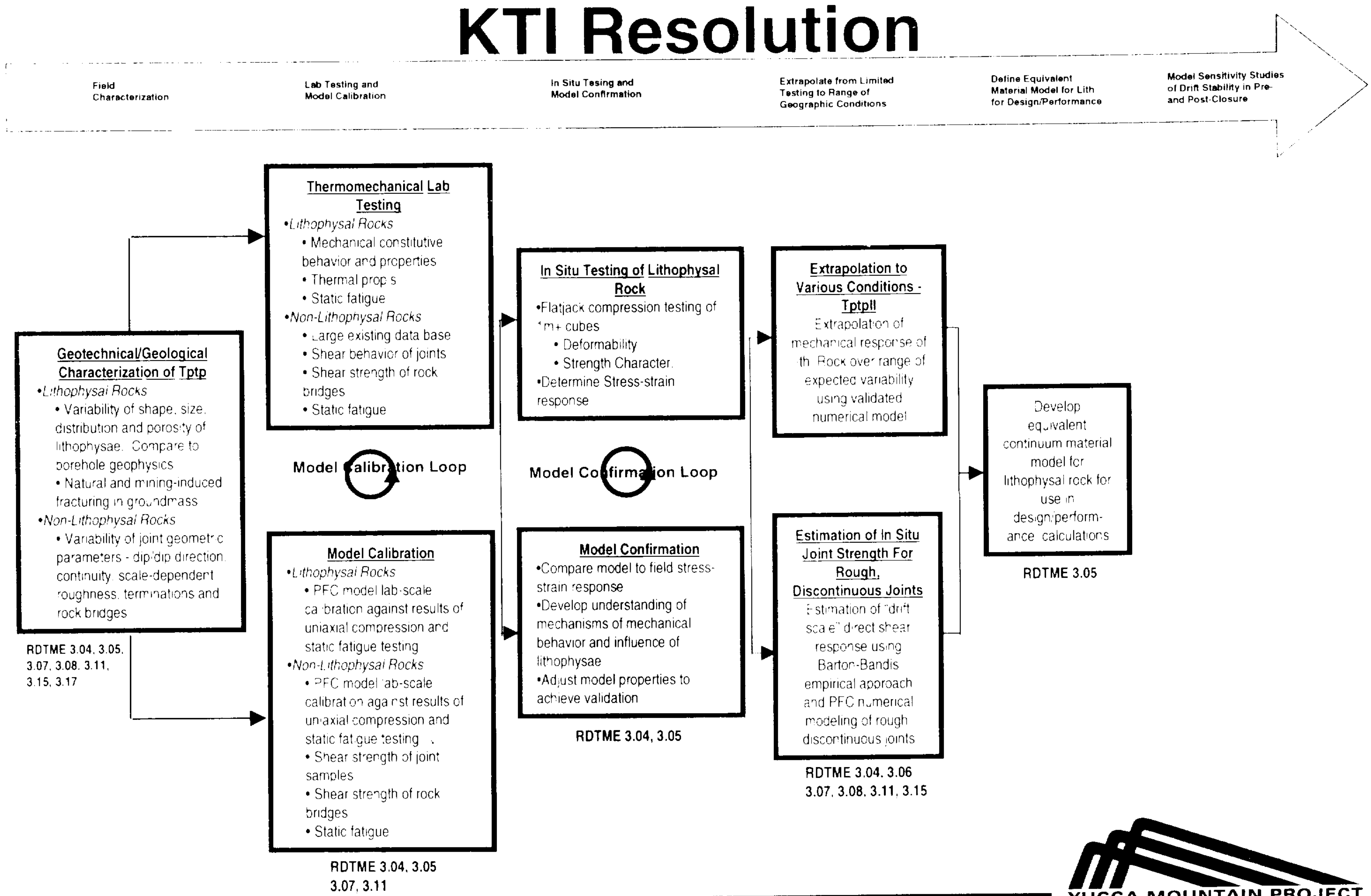
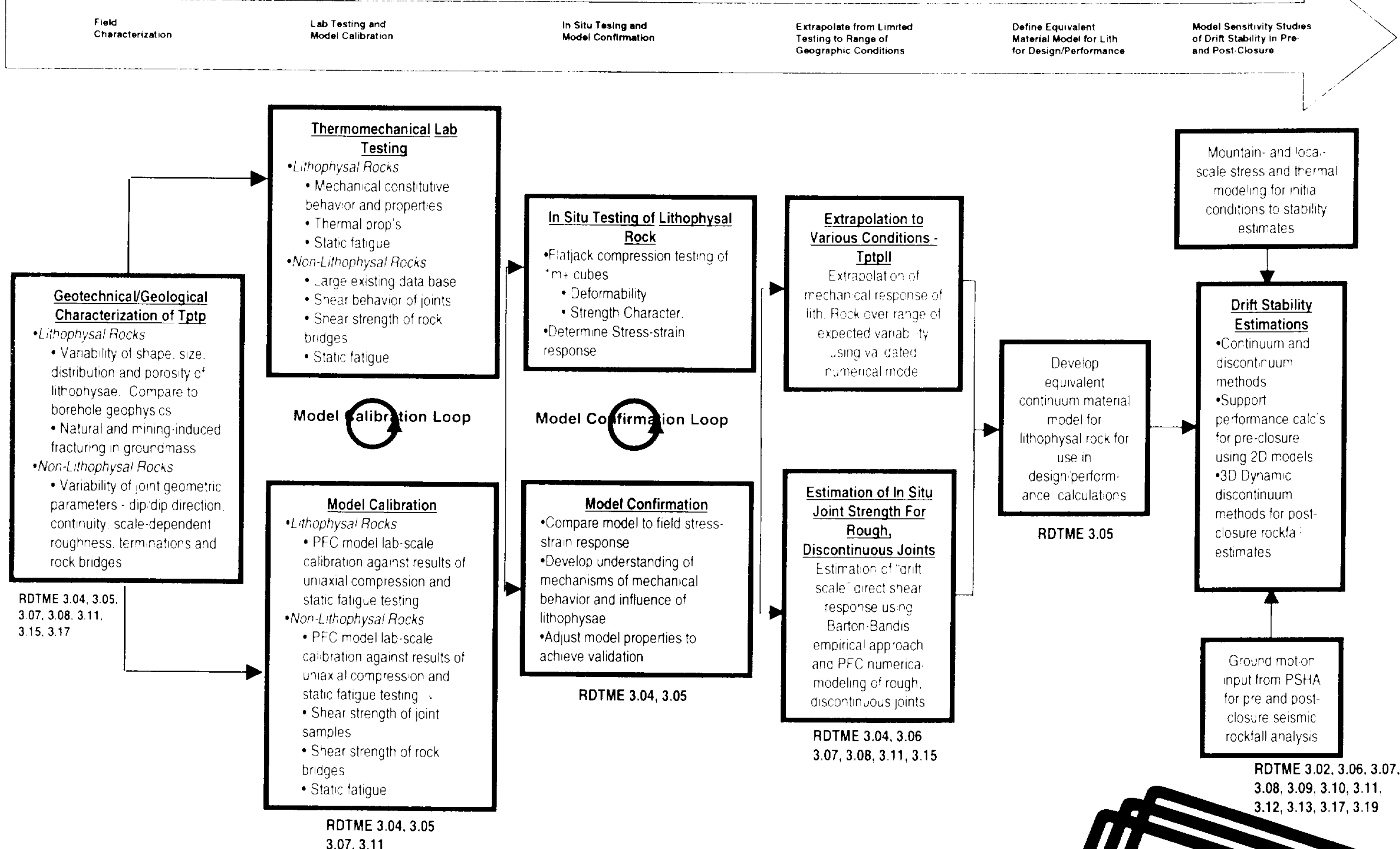
Overall Strategy to Geomechanical-Related KTI Resolution



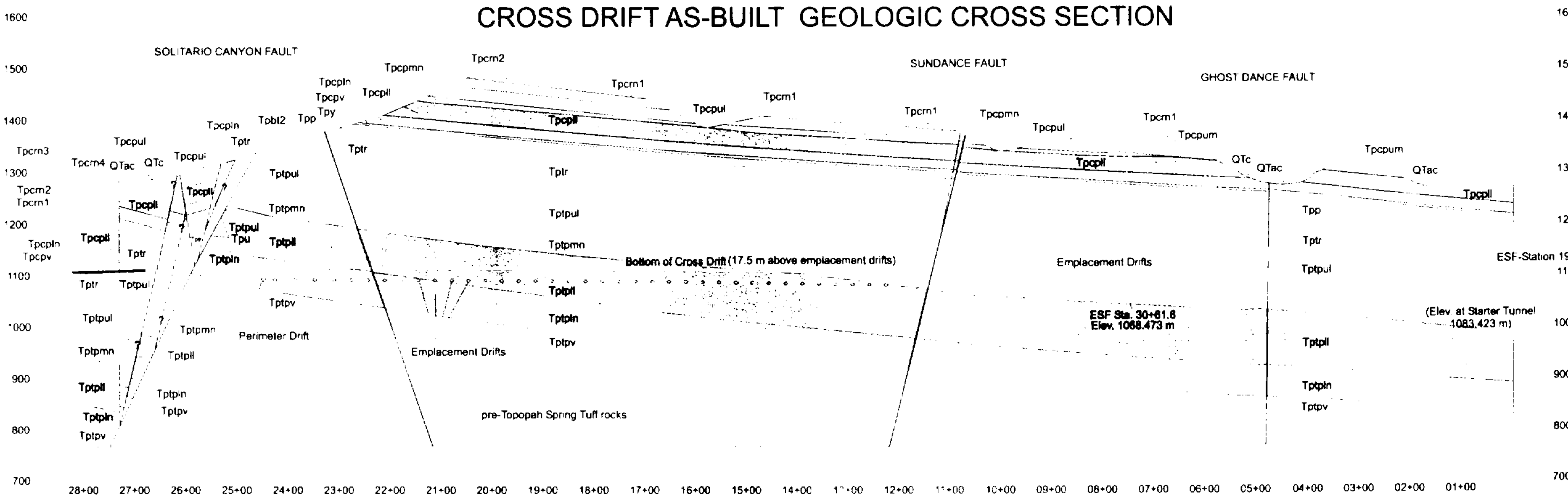
Overall Strategy to Geomechanical-Related KTI Resolution



Geology and Geotechnical Characterization of the Topopah Springs Formation

- **Steven Beason, United States Bureau of Reclamation (USBR)**

Geologic Cross-Section through the ECRB Cross Drift



EXPLANATION

Quaternary

QTac	Alluvial and colluvial deposits
QTc	Colluvial deposits

Tiva Canyon Tuff
Crystal rich member

Tpcrn4	Subvitric transition subzone
Tpcrn3	Pumice-poor subzone
Tpcrn2	Mixed pumice subzone (Tpcrn2, Tpcrl2)
Tpcrn1	Crystal transition subzone (Tpcrn1, Tpcrl1)

Crystal-poor member

Tpcpul	Upper lithophysal zone
Tpcpum	Upper lithophysal zone and middle nonlithophysal zone undivided
Tpcpmn	Middle nonlithophysal zone
Tpcpll	Lower lithophysal zone
Tpcpln	Lower nonlithophysal zone
Tpcpv	Vitric zone

Tpy	Yucca Mountain Tuff includes pre-Tiva Canyon Tuff bedded tuff (Tpbt4)
Tpp	Pah Canyon Tuff non- to moderately welded, includes pre-Yucca Mountain Tuff bedded tuff (Tpbt3)
Tpbt2	Pre-Pah Canyon bedded tuff
Tpu	Undifferentiated Paintbrush Tuff

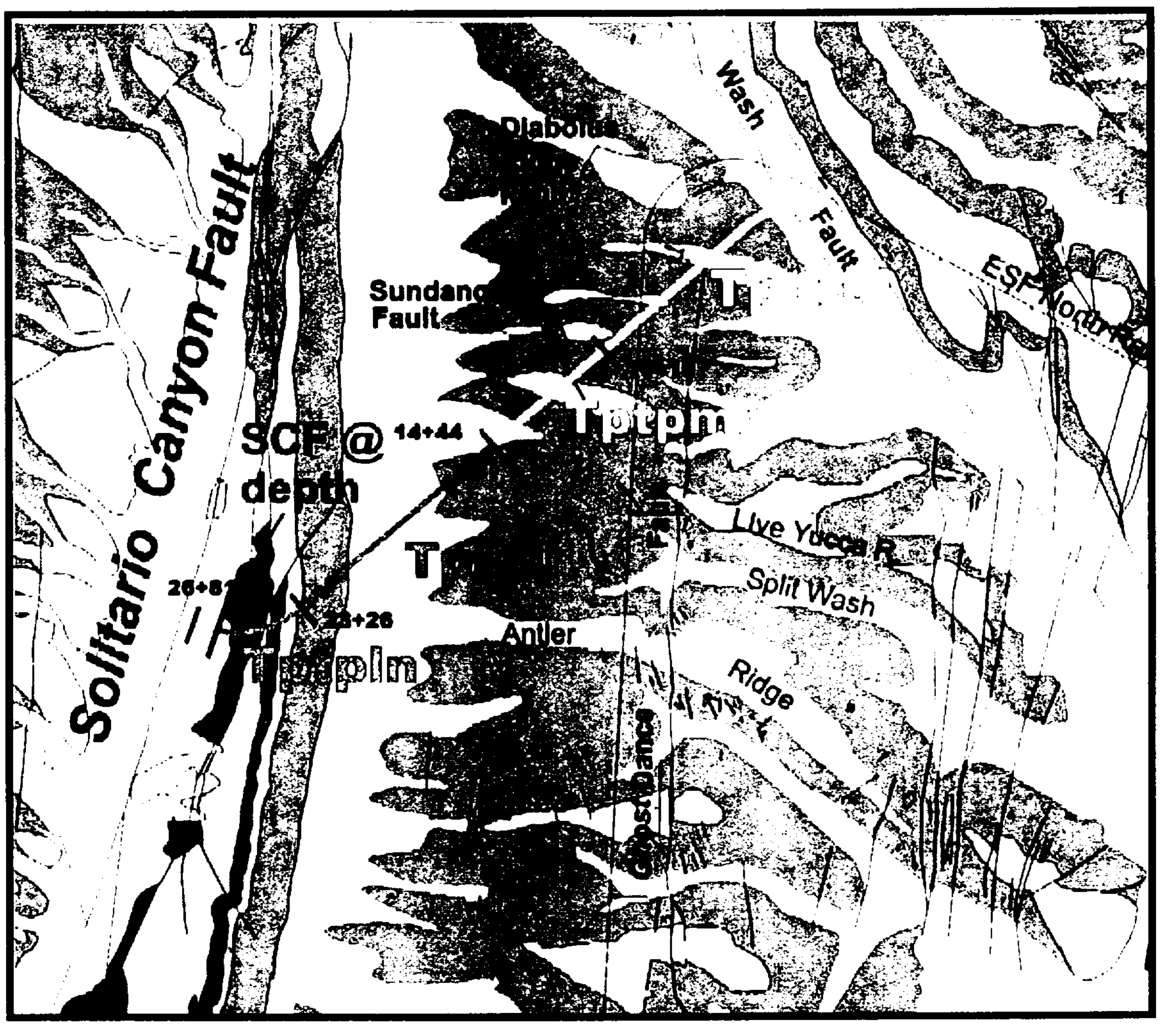
Topopah Spring Tuff
Crystal-rich member

Tptr	Crystal-rich zone

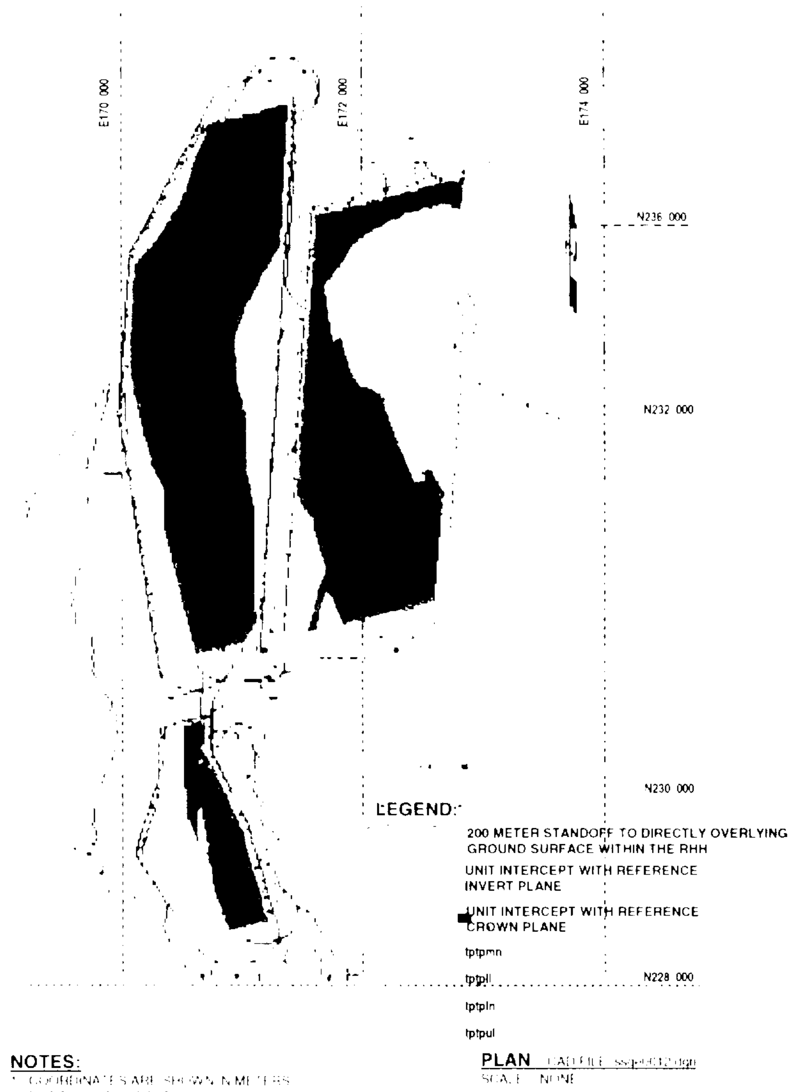
Crystal-poor member

Tptpul	Upper lithophysal zone
Tptpmn	Middle nonlithophysal zone
Tptpll	Lower lithophysal zone
Tptpln	Lower nonlithophysal zone
Tptpv	Vitric zone

Geologic Map of the Central Block Area



Repository Host Horizon Geologic Units



- Repository Host Horizon Rocks Expected to be Encountered by Present Repository Layout - Other emplacement regions are also under consideration

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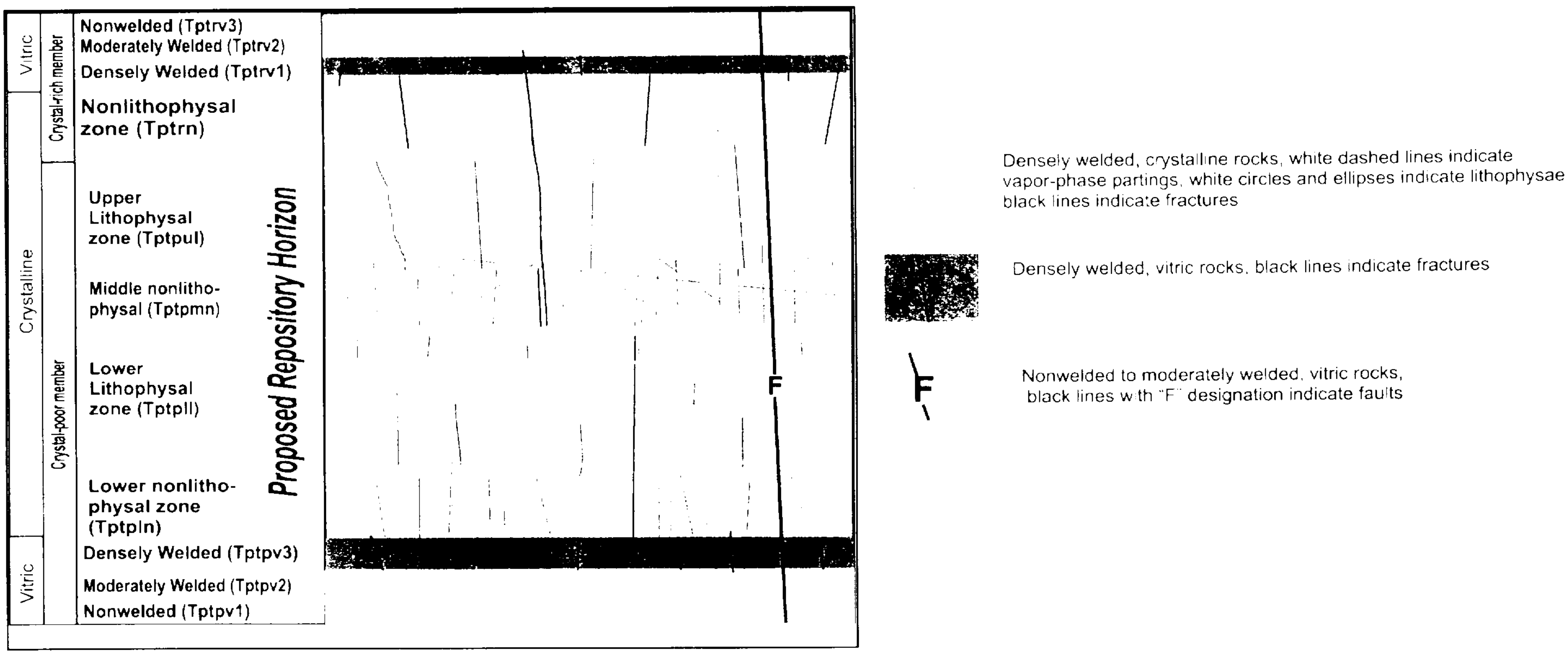
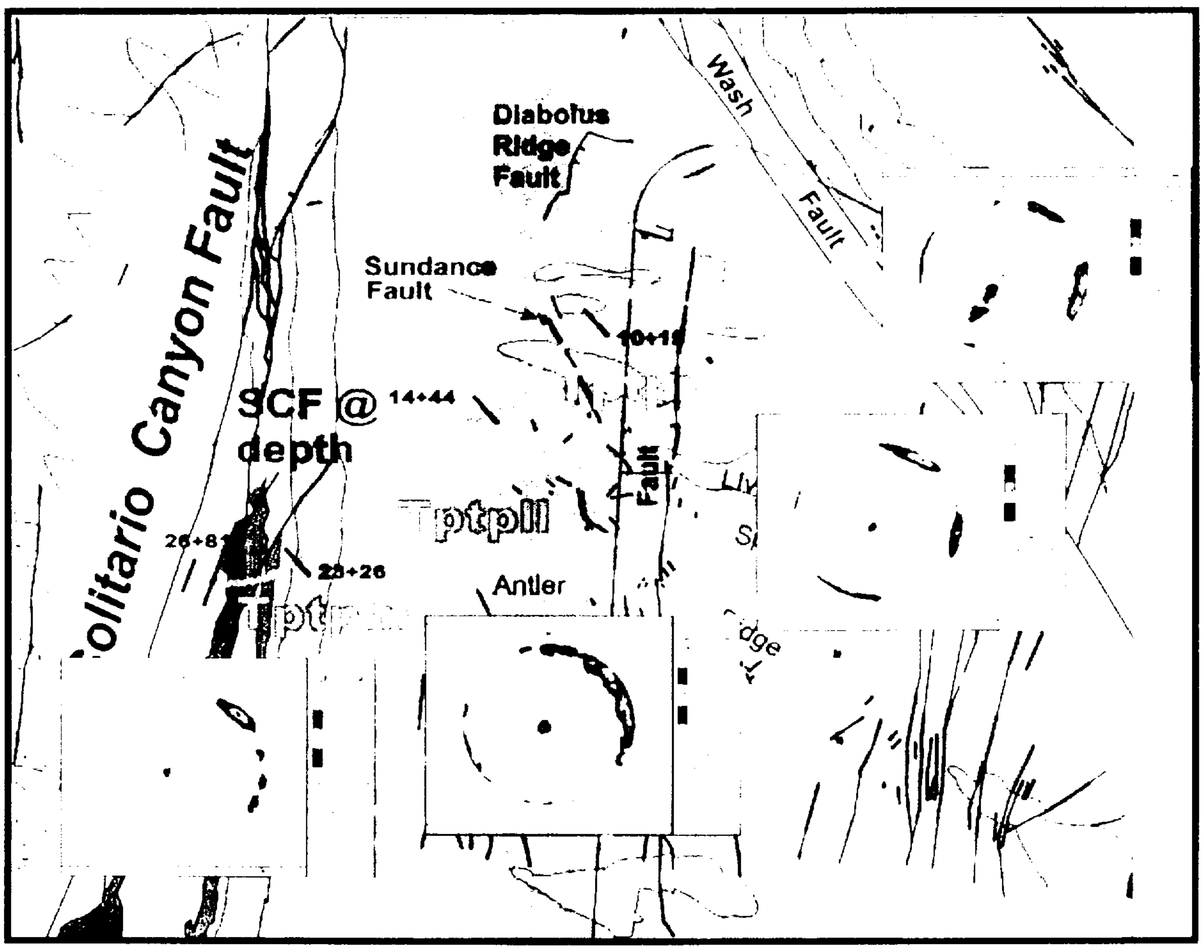
Fracture Characteristics: Variations with Lithostratigraphy*



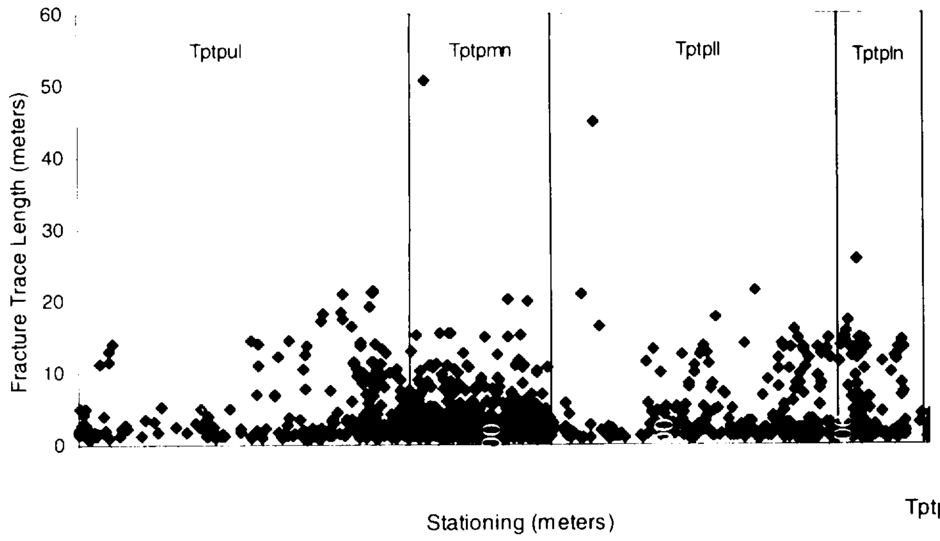
NTS

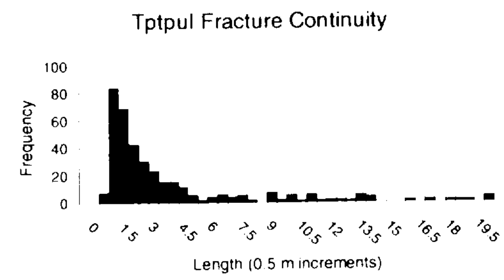
***Schematic illustration based on fractures with trace lengths greater the 1 meter. Groundmass in lithophysal units ubiquitously fractured on a small, inter-lithophysae scale**

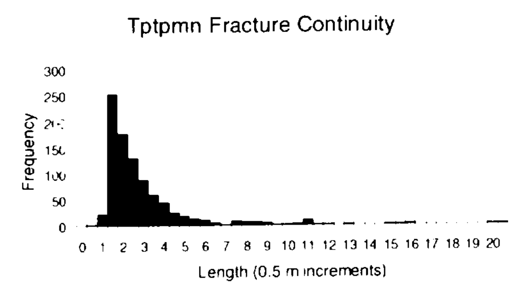
Fracture Patterns of Central Block Area

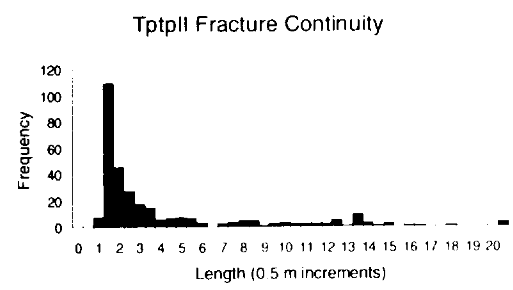


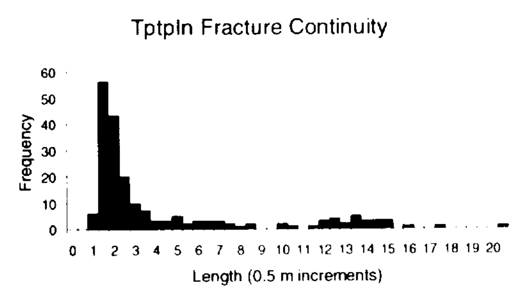
Fracture Continuity (all data from ECRB Detailed Line Survey)



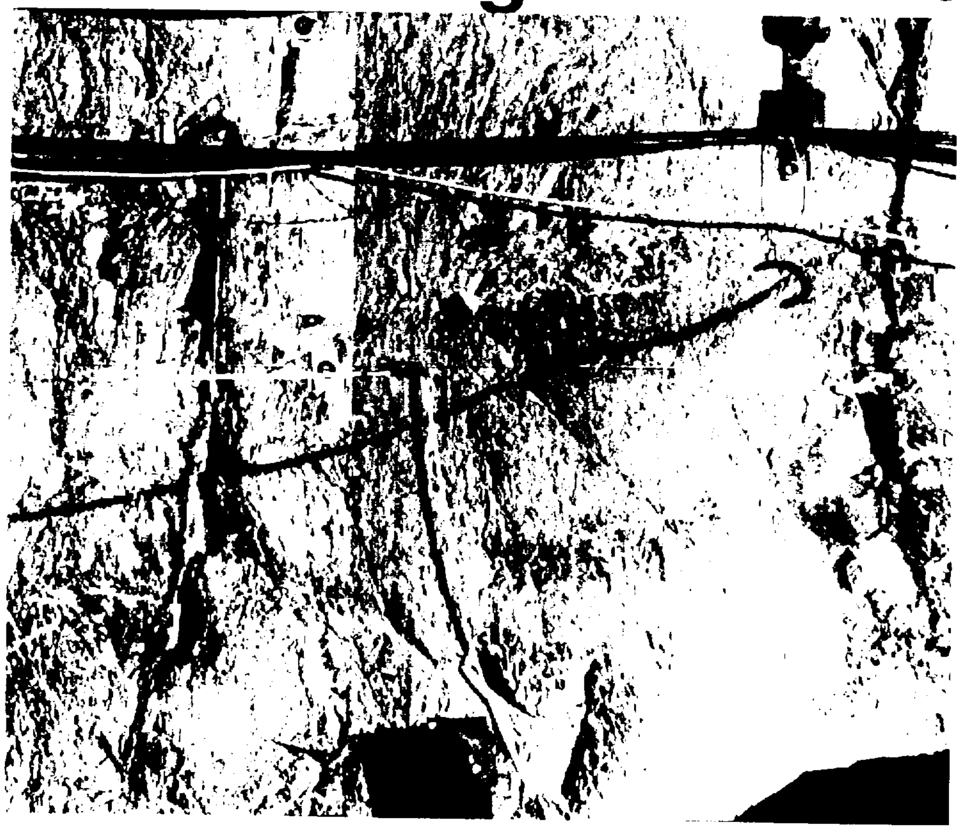








Fracture Surface Topography in the Middle Non-lithophysal Zone Drift-scale Roughness and Rock Bridges

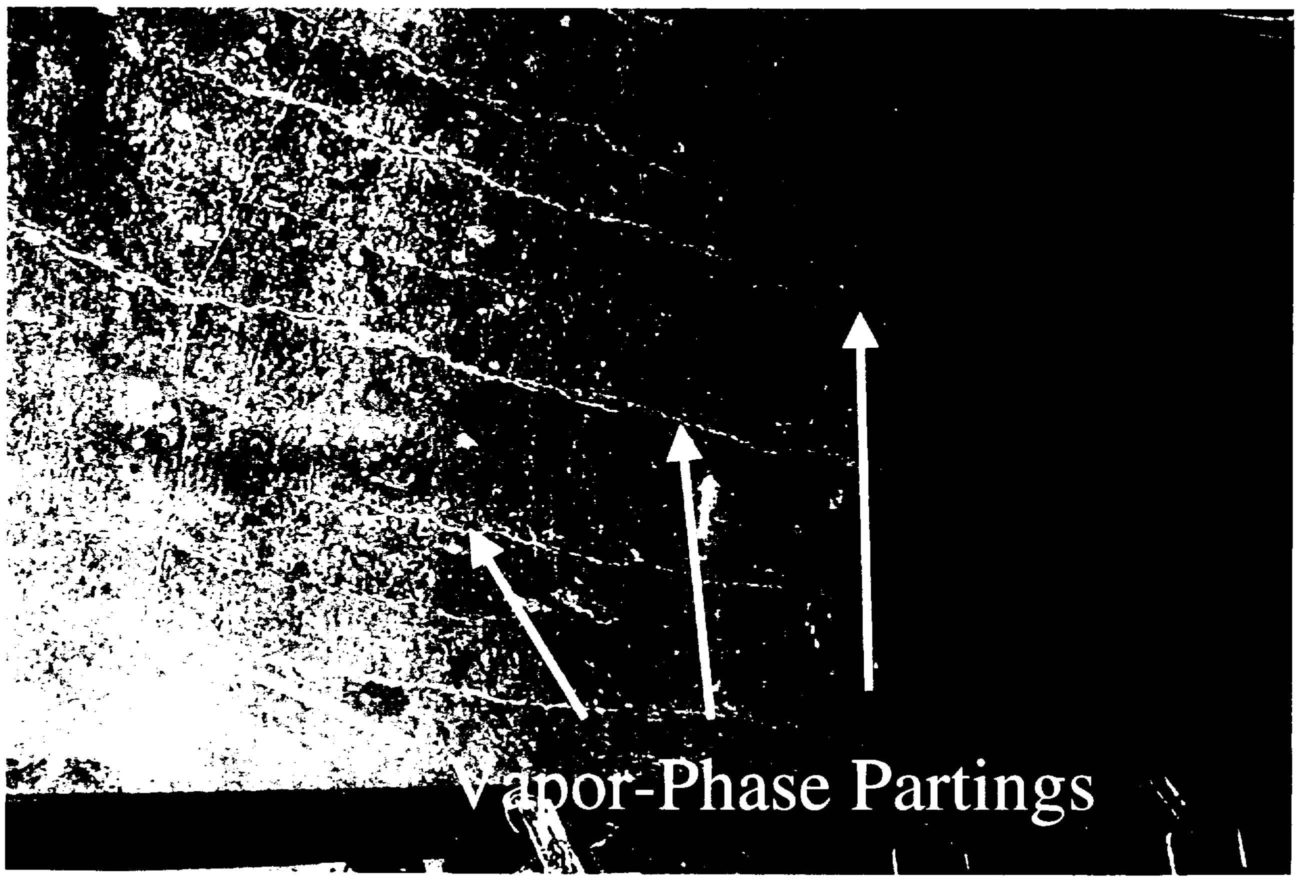


- Fractures often have curved surfaces with large-amplitude (10's of cm's) asperities and wavelength of meters
- Fractures often terminate in solid rock with discontinuous interconnection to adjacent joint tracks
- Fractures often terminate against other joints

Vapor-Phase Partings

- Subhorizontal partings, consisting of concentrations of vapor-phase mineralization (primarily tridymite and cristobalite) which form continuous discontinuities subparallel to the dip of the rock unit.

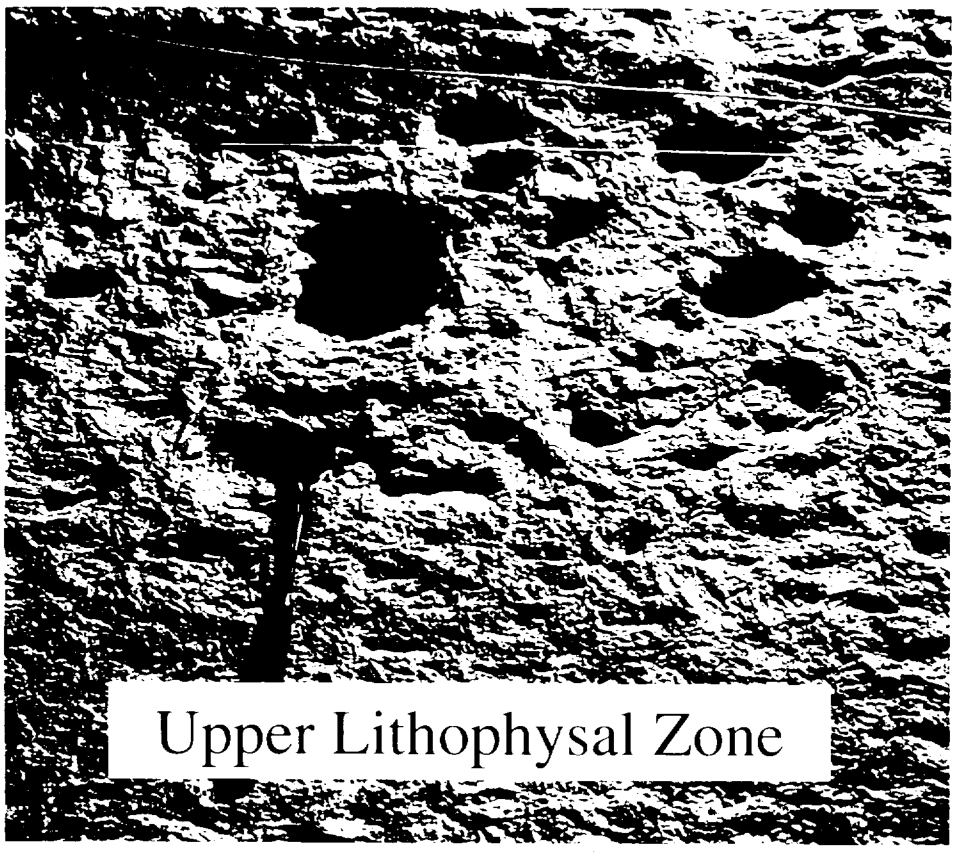
Vapor-Phase Partings
(Continued)



Fractures in the Middle Non-Lithophysal Unit

- Three major joint sets can combine to form removable rock wedges
- Fractures can form the bounding planes of wedges
- There are a *total of six recognizable wedges* throughout the existing 10+ kilometers of tunnels in the ESF and ECRB

Lithophysae

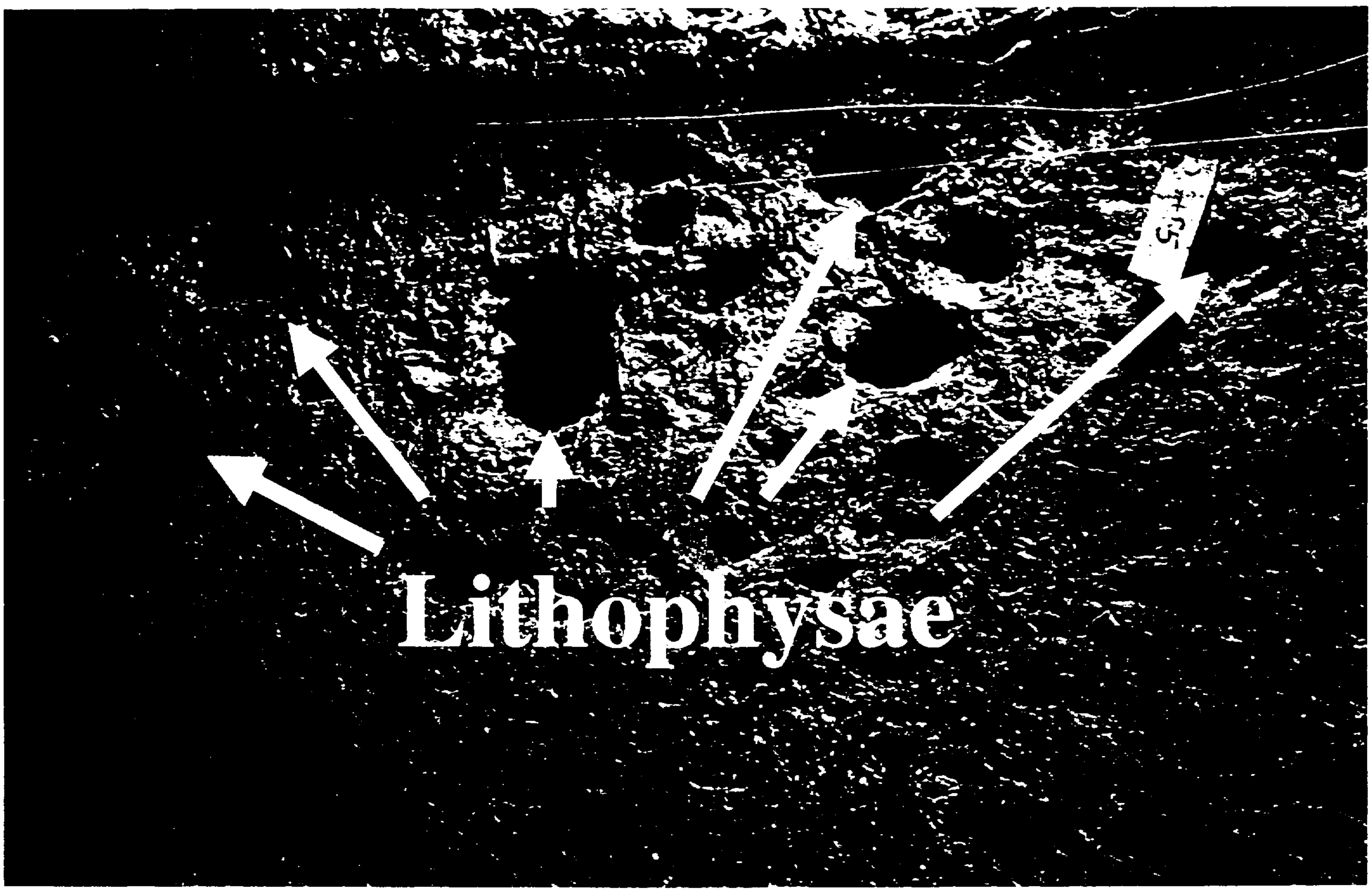


- **Hollow, bubblelike structures formed during the cooling of ash-flow tuffs**

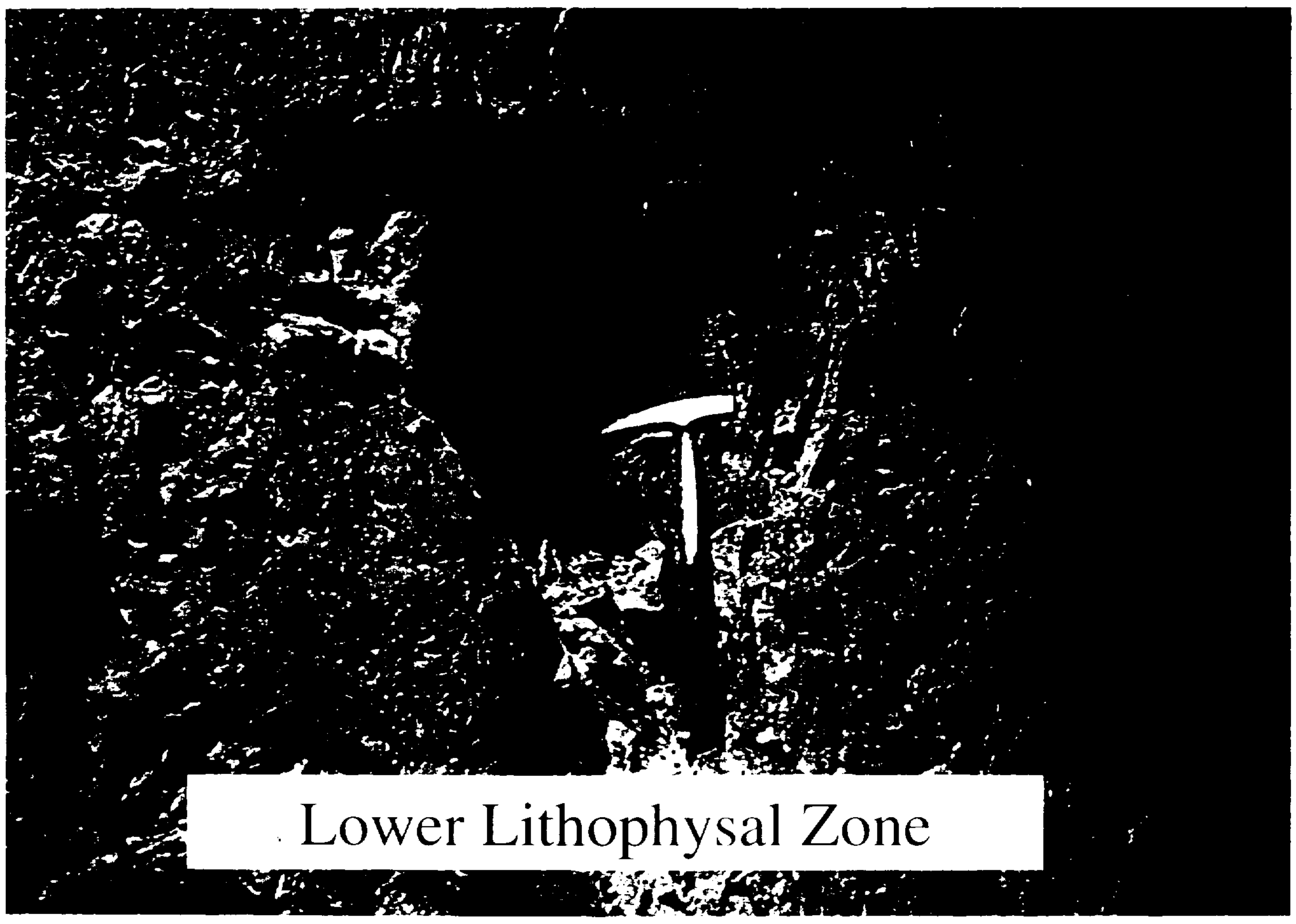
Variability of Lithophysae Within the Lower Lithophysal Unit

- ~1 cm to 1.8 m in size
- Shape is highly variable from smooth and spherical to irregular and sharp boundaries
- Infilling and rim thickness vary widely with vertical and horizontal spacing
- Volume percentage varies consistently with stratigraphic position
- Lithophysae are variable in shape and size, but stratigraphically-predictable

Typical Lithophysal Distribution in Lower Lithophysal Unit

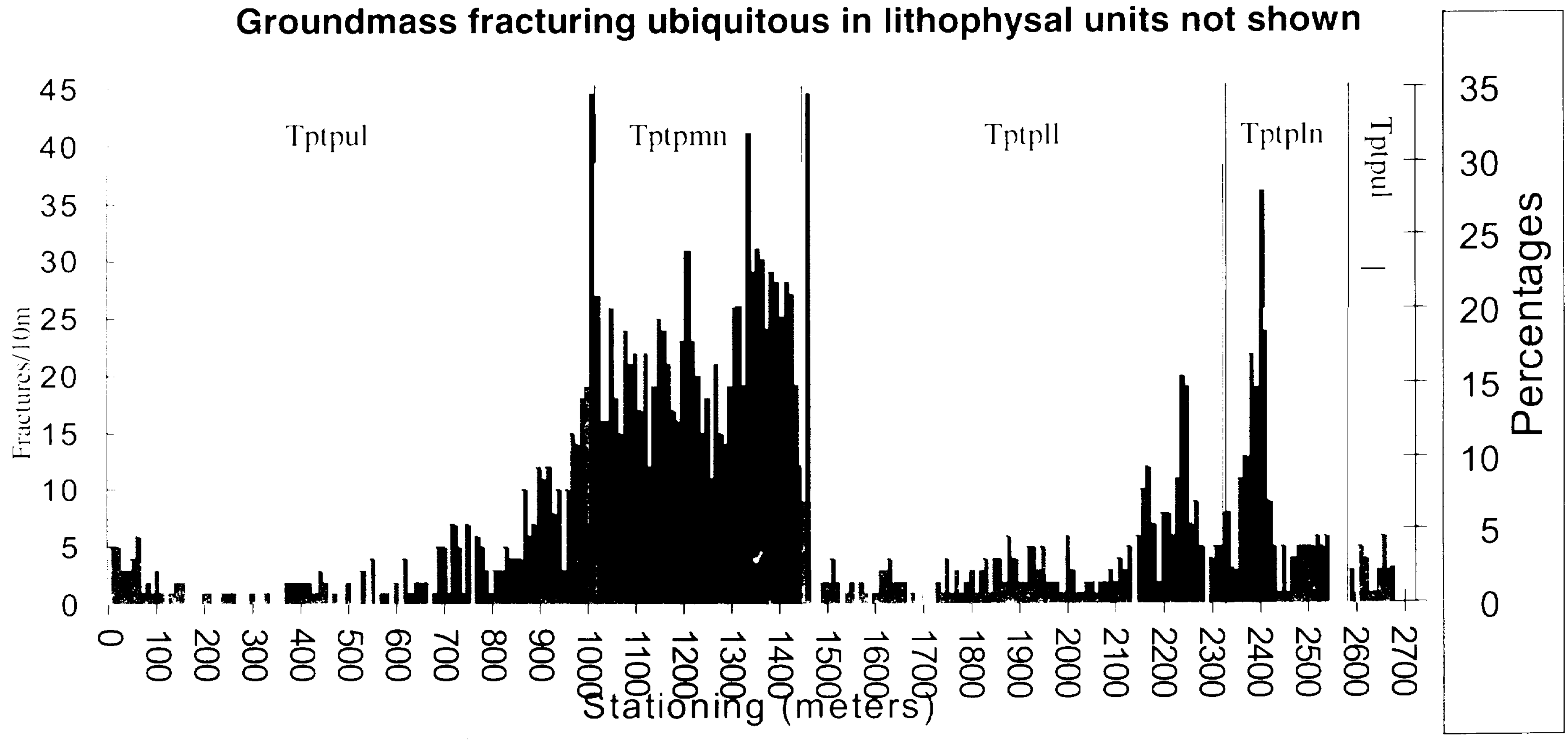


Example of Larger Lithophysal in Lower Lithophysal Unit



ECRB Fracture Frequency and Lithophysal Percentages*

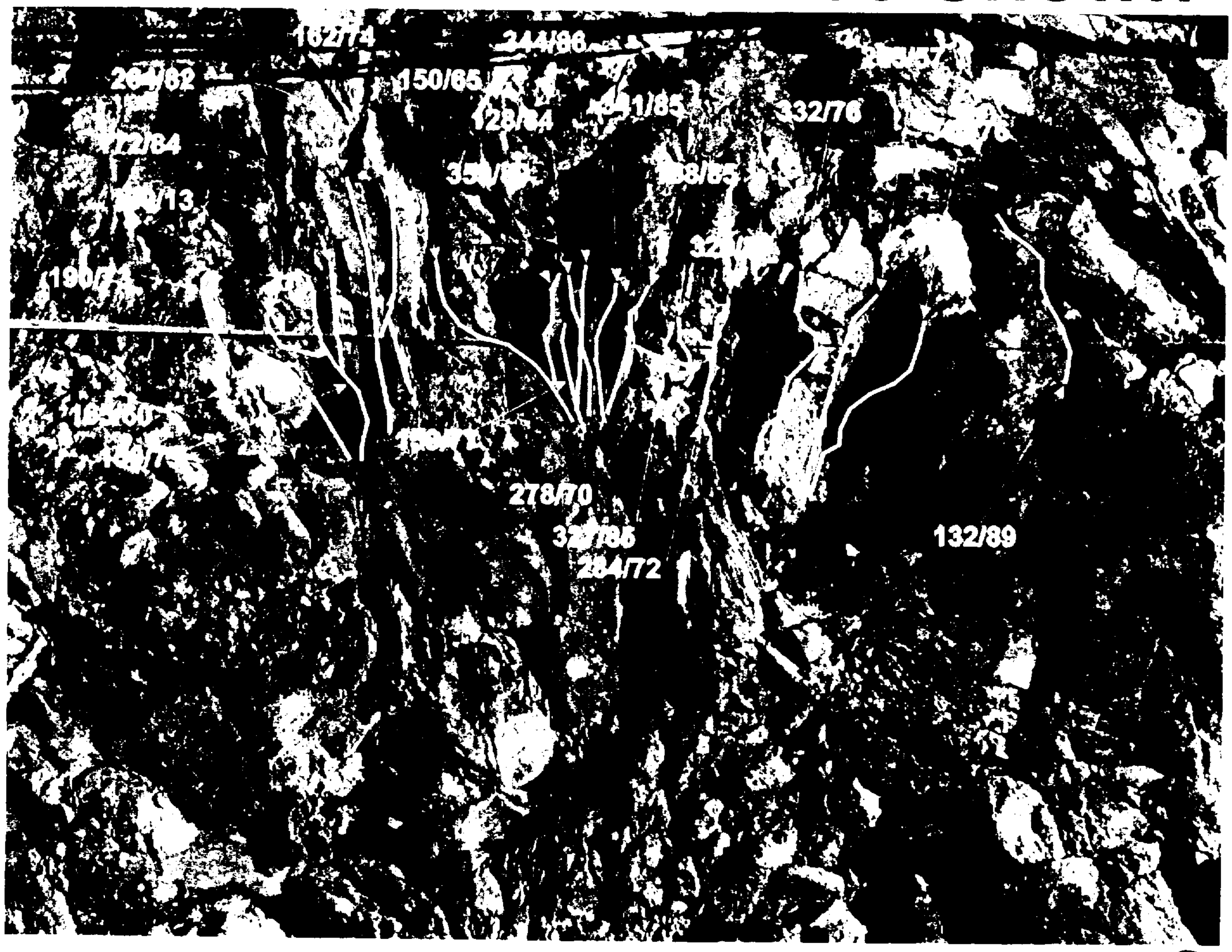
***Based on fractures with trace lengths greater than 1 meter**
Groundmass fracturing ubiquitous in lithophysal units not shown



Fracture frequency /

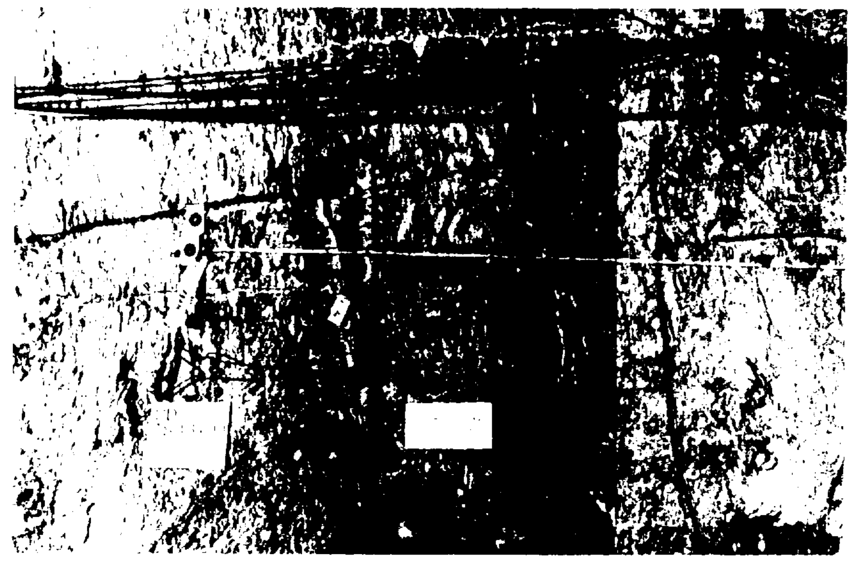
Close-up of ECRB Tunnel Wall in the Lower Lithophysal Unit

Close-up of ECRB Tunnel Wall in the ECRB With Small Fractures Shown



Additional Geotechnical Investigations Now Underway - Joint Geometric Characterization

- Study of Joint Geometry for Estimation of Joint Shear Constitutive Behavior and for Rockfall Model Input
- Re-examine joint geometric characteristics, 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



Additional Geotechnical Investigations Now Underway - Lithophysae Variability

- Geologic investigation of lithophysae in ECRB currently underway
  - Detailed mapping and description of study "panels" along ECRB
  - Linear traverses up ECRB using tape and angular measurements of lithophysal porosity
  - Shape, size, porosity, "rim" mineralization, spots, groundmass mineralogy and fracturing described
  - Variability of lithophysae will be documented in future AMR

Thermomechanical Characterization Program for Ground Support Design Analysis

- Larry Costin, SNL

Presentation Outline

- Basis for Testing
- Lithophysal versus Non-Lithophysal Rock
- Laboratory Test Program
- In Situ Test Program
- Data Integration

Basis for Design Characterization: Themomechanical Data Needs

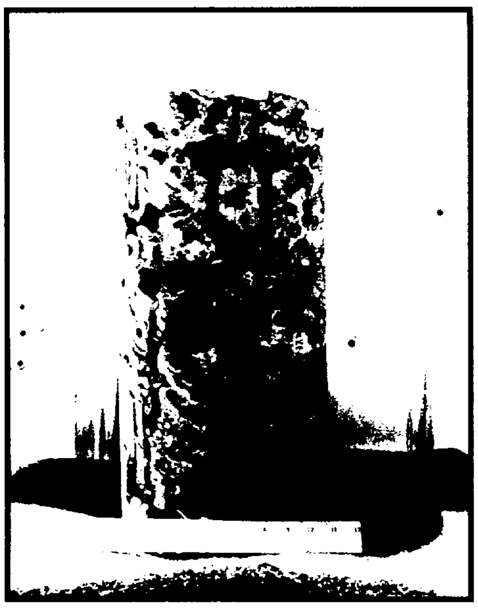
- Site Specific Rock and Rock Mass Data
- Model Parameters
  - Moduli
  - Strength
  - Joint stiffness, roughness, strength
  - Thermal conductivity, capacity
  - Thermal expansion
  - Static fatigue

Basis for Design Characterization: Thermomechanical Data Needs
(Continued)

- **Variables**
  - Location
  - Coupled effects T-M-H-C
  - Porosity, joints, fabric
  - Time
  - Deformation mode
  - Scale

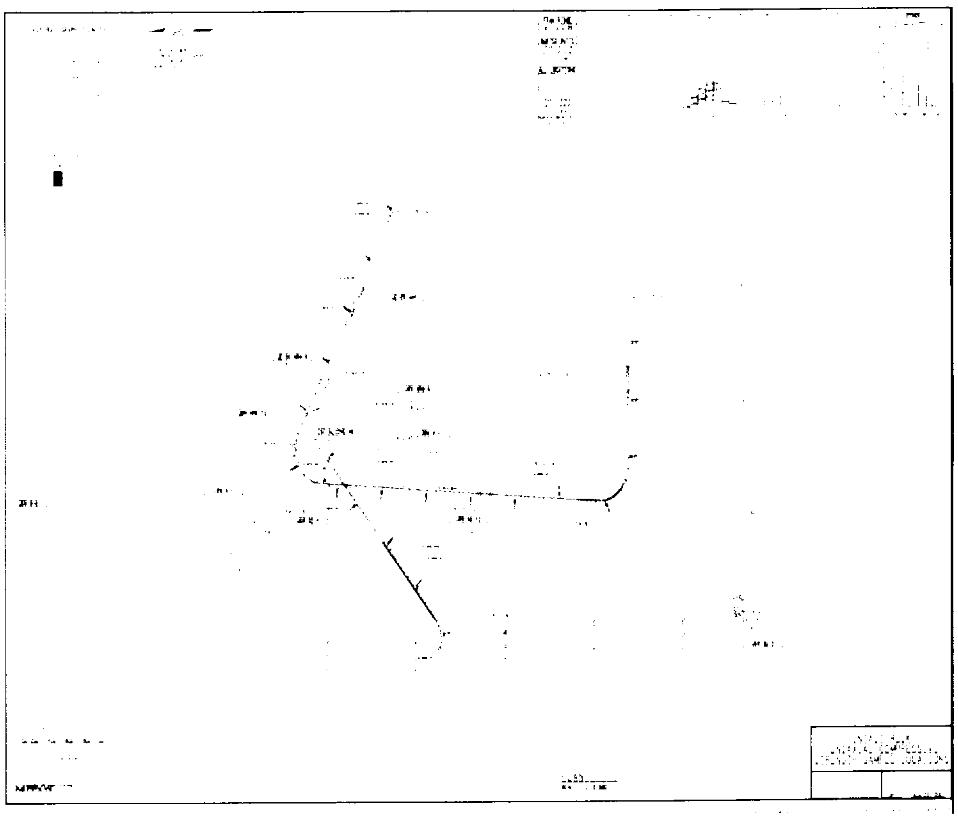
Addressing the Issues: Rock Mass Properties

Laboratory Measurements → Material Models → In Situ Property Estimates → In Situ Measurements → Model Sensitivity Studies

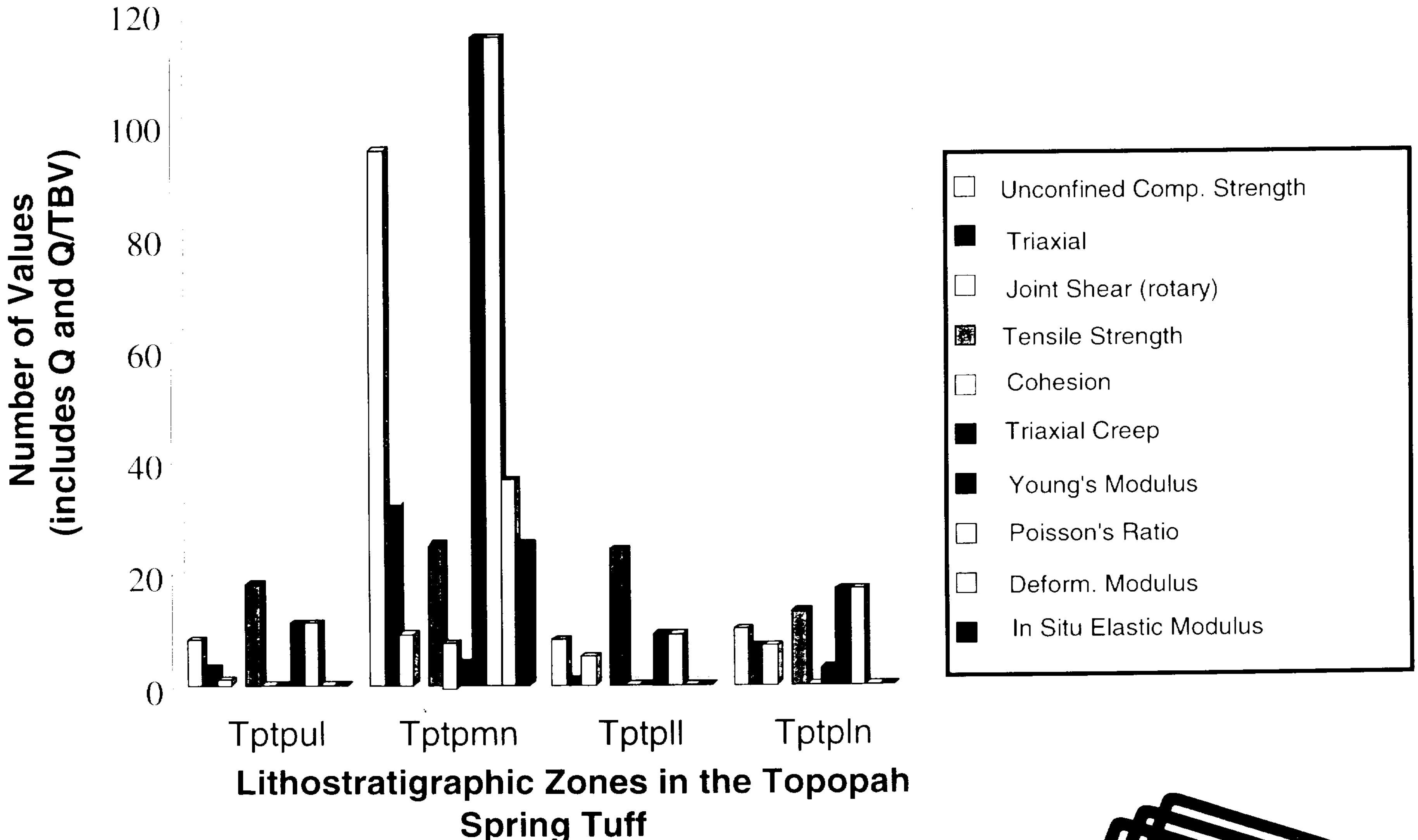


Addressing the Issues: Spatial Variability and Representativeness

- Assessment of current data
- Non-Lithophysal Data:
  - Address areas where existing data remains unqualified
- Focused effort on lithophysal rock

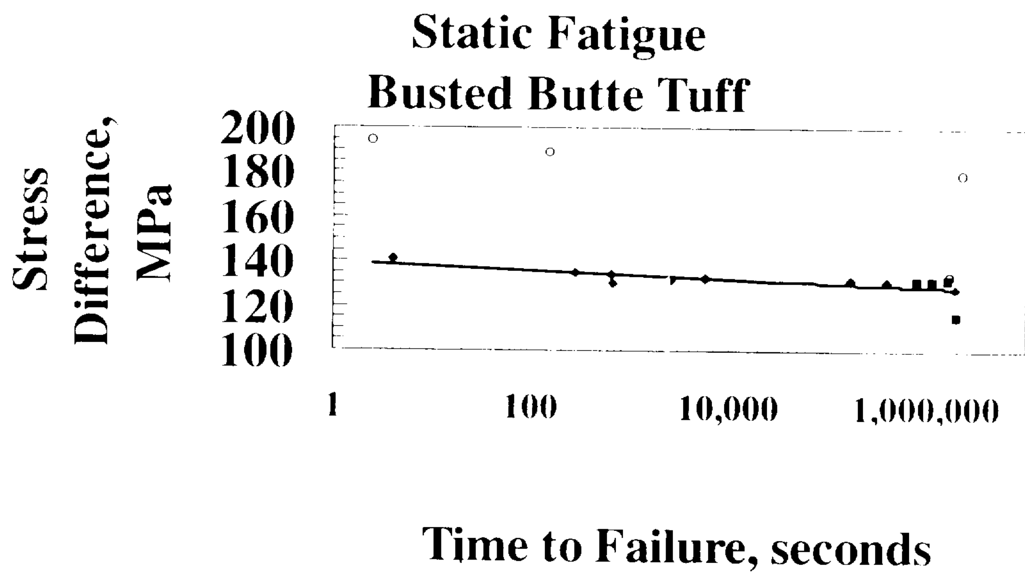


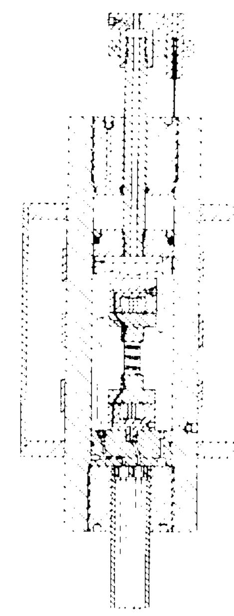
Existing Rock Mechanics Testing



Addressing the Issues - Time Dependent Creep

- Static Fatigue/Creep Testing of Intact Rock
- Time-dependent strength of joints
- Time-dependent deformation of the rock masses





time = $9 \times 10^{58} e^{-0.9584\sigma}$

At 100 MPa, time to failure of Tptpmn would be 7 billion years

Characterization and Modeling Approach

Different for lithophysal and non-lithophysal rock units

Non-Lithophysal Rock

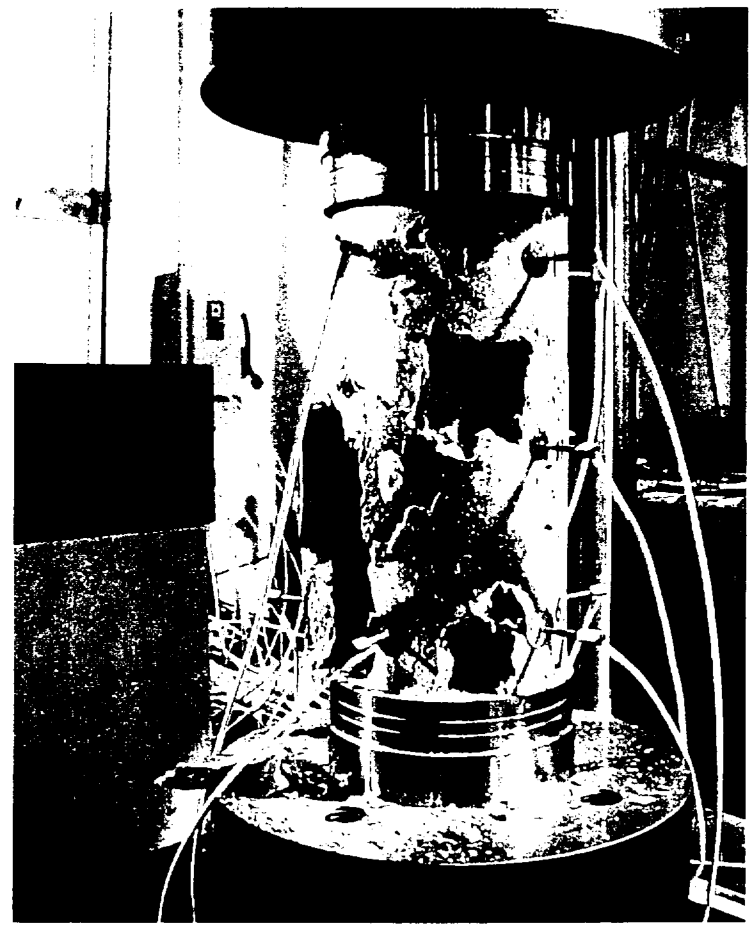
- Rock-mass deformation accommodated by joints
- Additional characterization of joint behavior
- Joint strength and stability
  - Joint roughness and condition, index correlations (JRC)
  - Time-dependent deformation and strength
  - Dependence on temperature, moisture
  - Cyclic loading

Lithophysal Rock

- Rock-mass deformation accommodated by voids and degree of fracturing between voids
- Understand the deformation mechanism
  - Lab-scale testing
  - Void porosity and distribution
  - Failure Mechanisms
  - Thermal effects

Approach
Lithophysal Rock

- Other aspects
- Thermal expansion
- Fracture/joint behavior
- Time-dependence
- Up-scaling
- Lab ⟶ In situ ⟶ Rock mass



Laboratory-Based Characterization

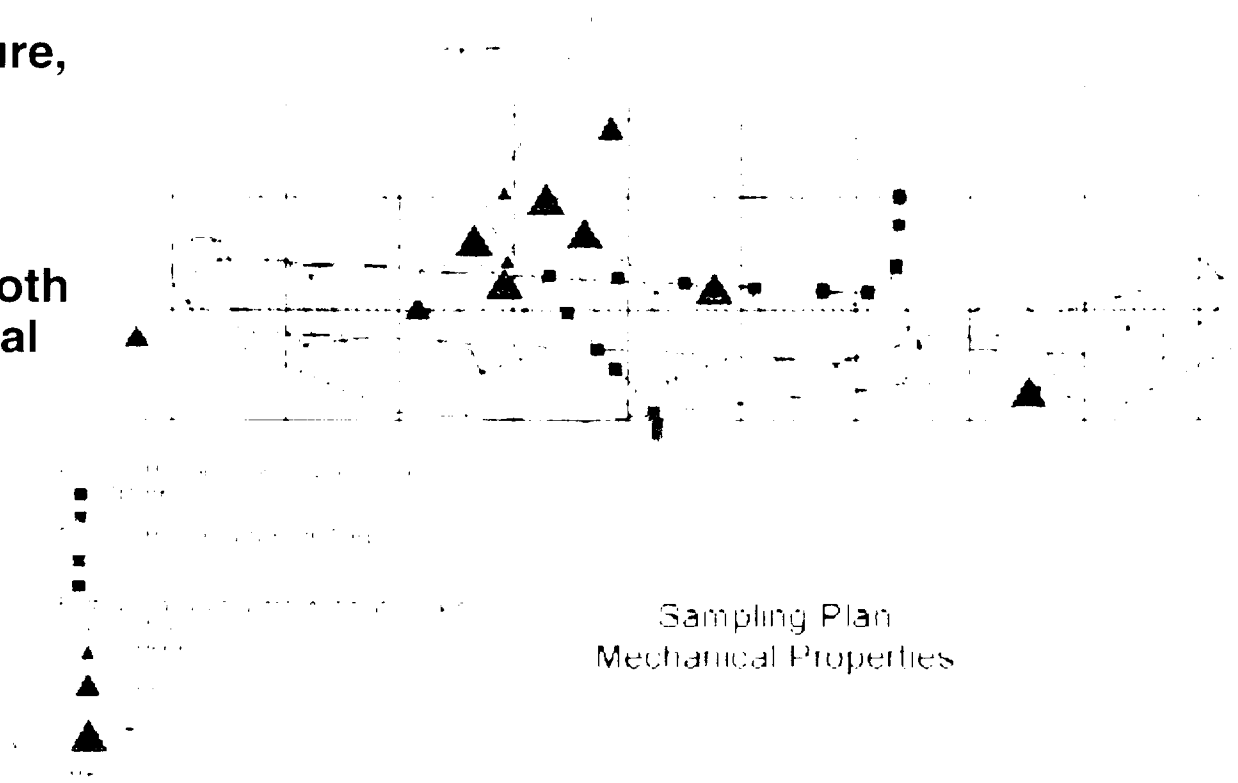
- **Exact numbers of tests and locations of sampling await completion of analysis of current data and development of sampling plans**
- **As much as practical, samples will be taken from in situ test locations**

Proposed Laboratory Testing Program for Lithophysal Rock

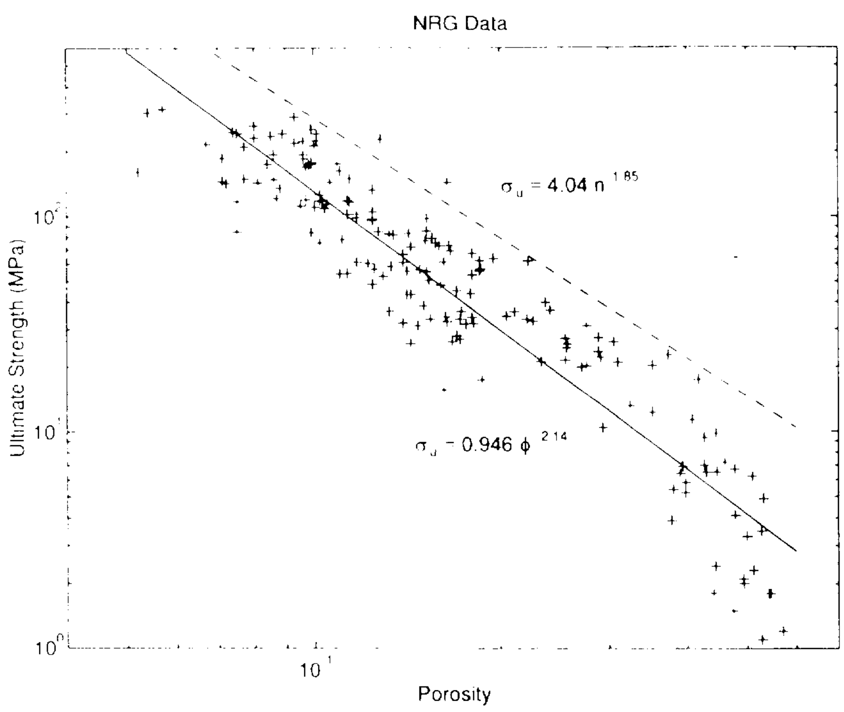
Study Type	Samples/locations	Parameters/conditions
Thermal expansion	TBD	Coefficient of thermal expansion
Temperature effects	TBD	Unconfined modulus, strength (to 200°C)
Saturation effects	TBD	Unconfined modulus, strength (dry and saturated)
Spatial variability	TBD	Unconfined modulus, strength
Static fatigue	TBD	Time to failure at 50%-90% unconfined strength.
Joint/fracture shear	TBD	Joint deformation properties
Joint fatigue	TBD	Time-dependent joint strength

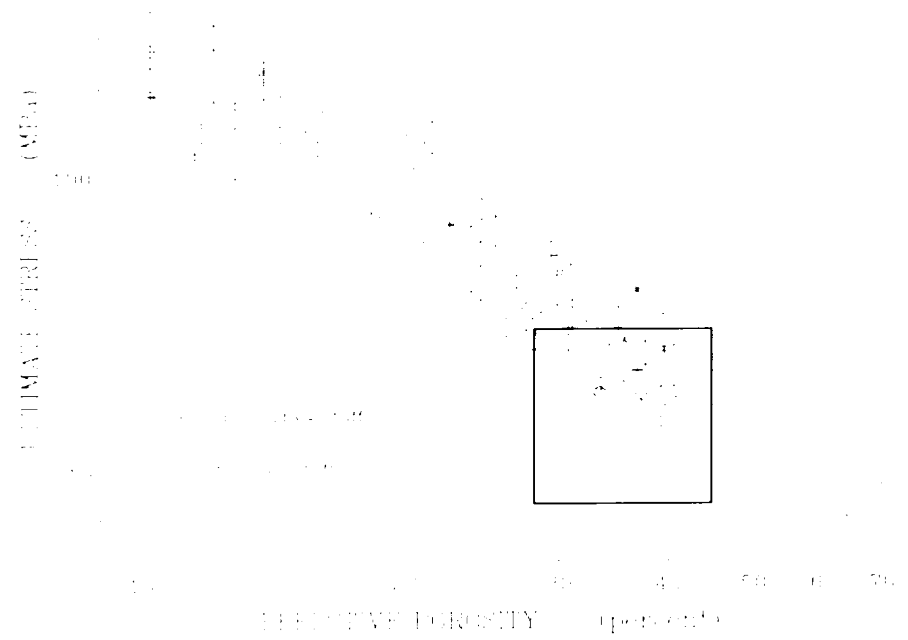
An Example of a Sampling Plan for Proposed Laboratory Testing in Lithophysal Rock

- Tests will vary Pressure, Temperature, Size
- Equally spaced sampling to address spatial variation in both horizontal and vertical
- Extend spatial coverage south and west

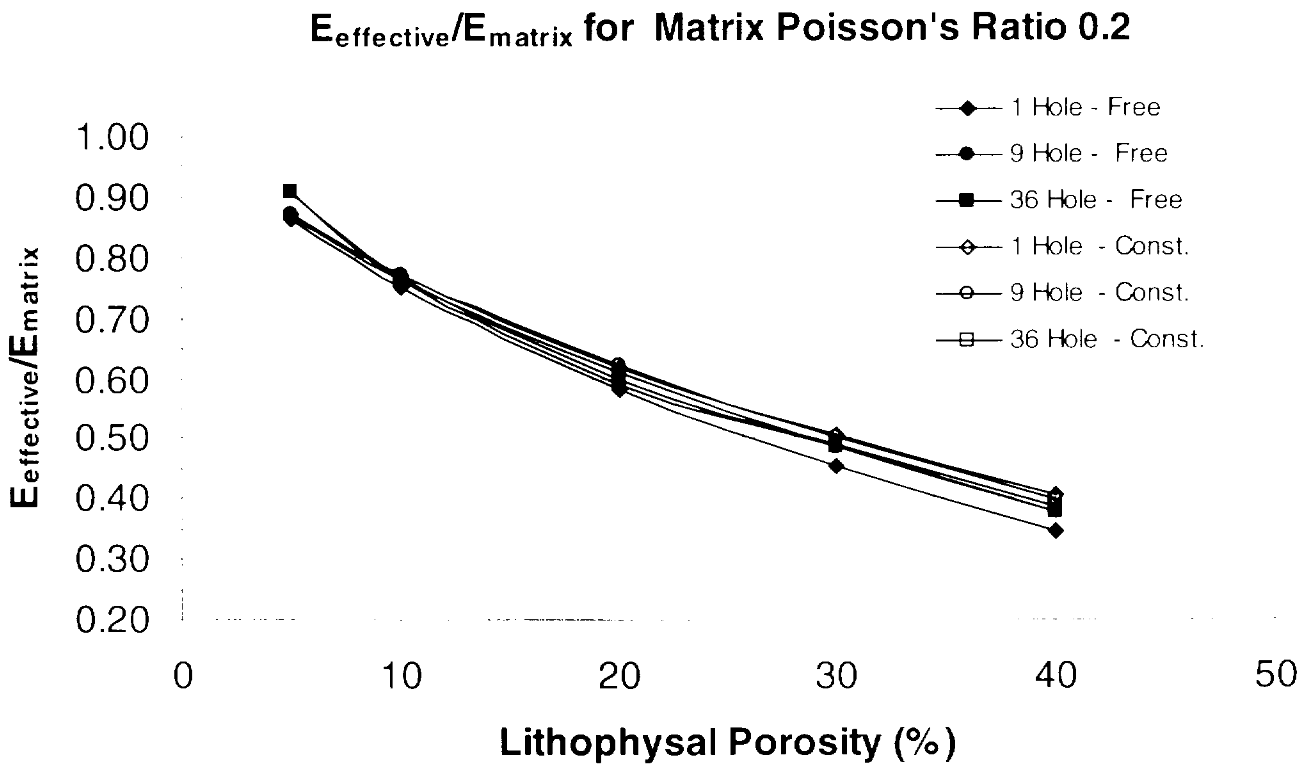


Laboratory-Based Characterization Generalizing Current Results





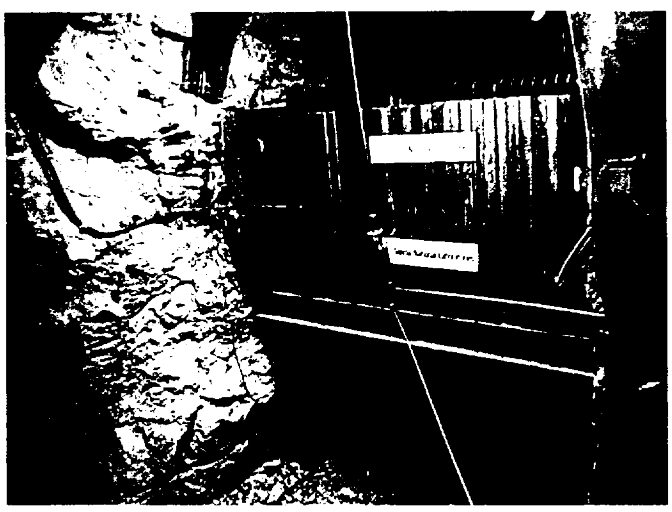
Laboratory-Based Characterization Numerical Analysis Results

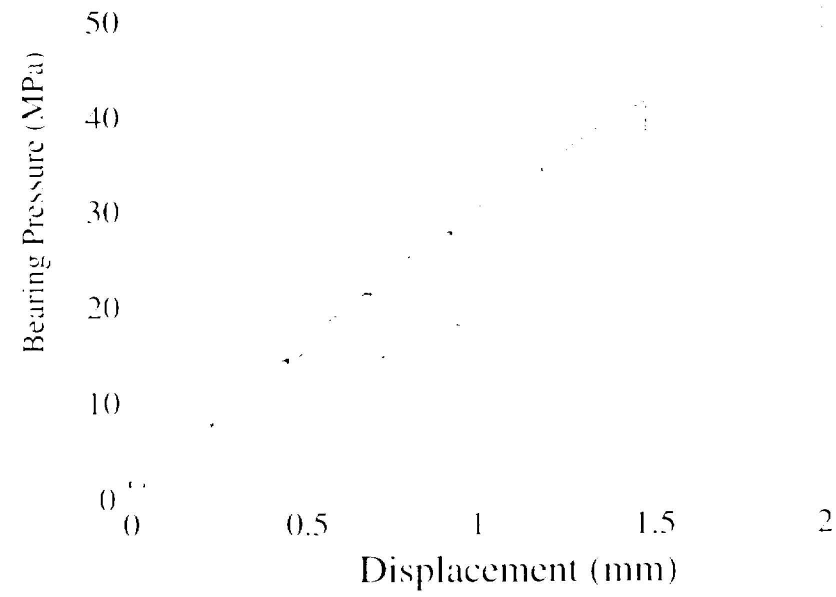


$E_{effective}$ = Young's Modulus of specimens containing lithophysal cavities
E_{matrix} = Young's Modulus of specimens without lithophysal cavities

In Situ Characterization Nonlithophysal Rock

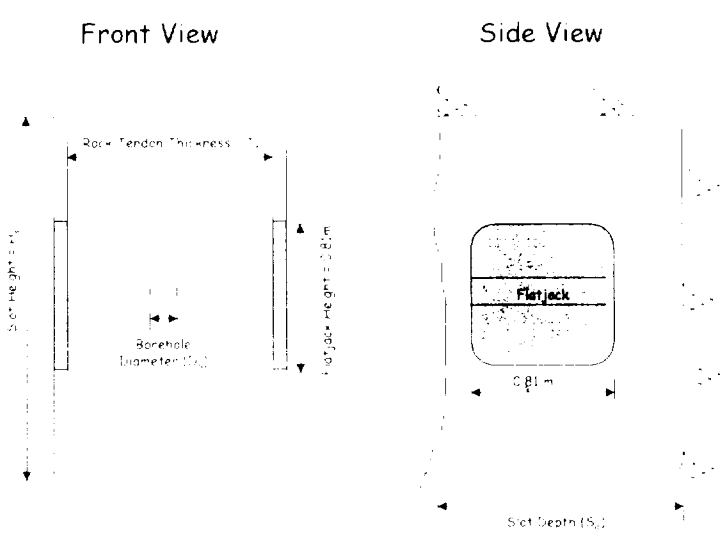
- Continue established test program
- Plate loading
- Continue analysis of Heated Drift Data
- Cooling Phase



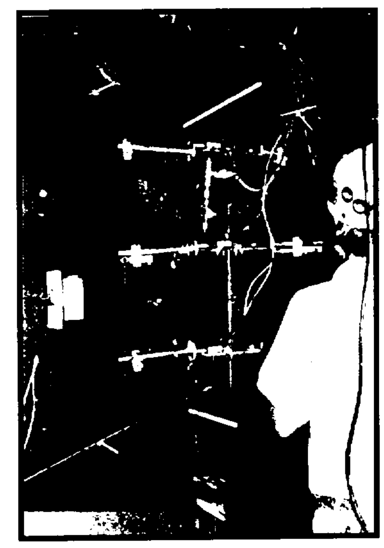


In Situ Characterization: Lithophysal Rock Slot Testing

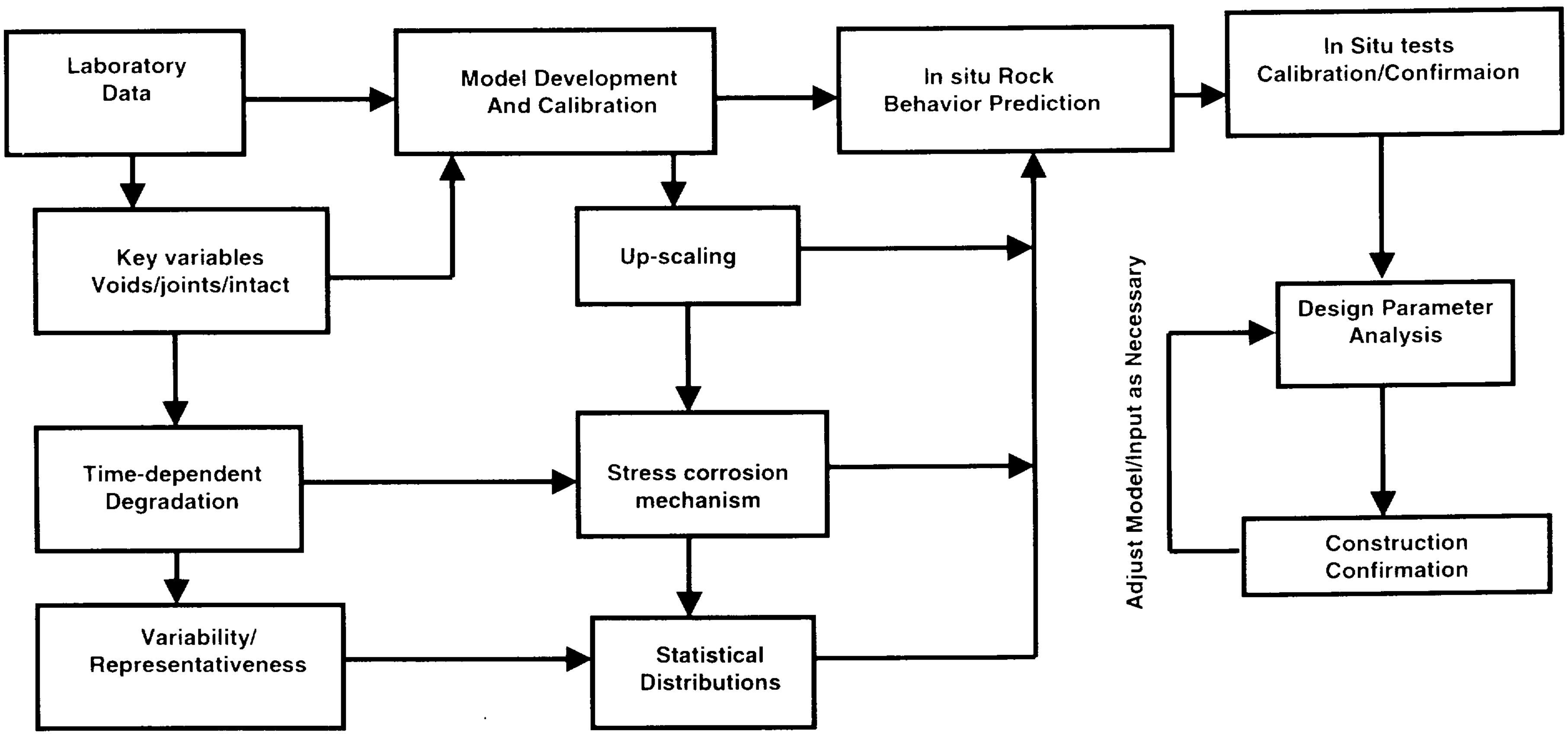
- Follows Roca, 1966
- Rock-mass modulus
- Strength
- Time-dependent deformation
- Flatjacks rated to 50 MPa
- Ambient and heated



- Three locations currently planned
- Range of rock conditions
- Options:
  - Central hole
  - Pressure holds
  - AE diagnostics
  - Thermal stresses



Data Integration



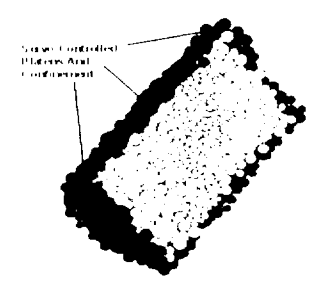
Summary
Characterization Testing

- Addresses time dependent degradation
- Develops rock-mass model and parameters through testing at different scales
- Broadens data base to evaluate variability and representativeness

Model Validation Strategy for Lithophysal Rock

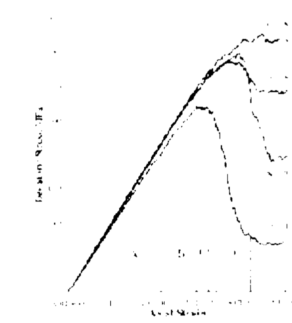
- Impossible to "statistically" test properties of lithophysal rocks - need to use another approach to bound range of properties
- Propose to validate a model(s) (*Particle Flow Code* and possibly others) that explicitly represents the mechanics of deformation and yield of lithophysal rock – we wish to demonstrate a thorough knowledge of the mechanical and thermal behavior of this material
- Validate model directly against field instrumentation data and observations
- Once validated, use model for extrapolation of mechanical behavior for expected range of lithophysal size, shape and porosity in repository block
- Embed proper constitutive model for lithophysal rock and into standard design code for further ground support performance studies

PFC 3D "Sample"

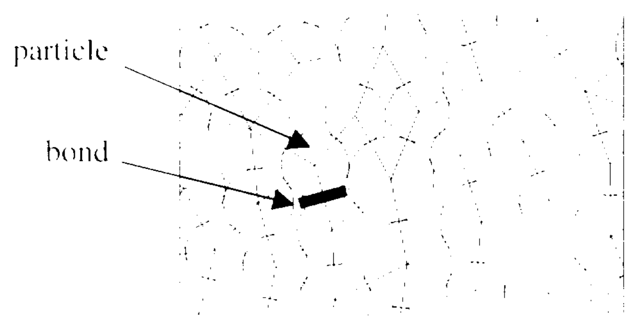


Failure Mechanism in Uniaxial Compression

Comparison Stress-Strain Response to Laboratory



Why use the PFC Model?



$$F_n = k_n U_n$$
$$\Delta F_s = k_s \Delta U_s$$

deformability

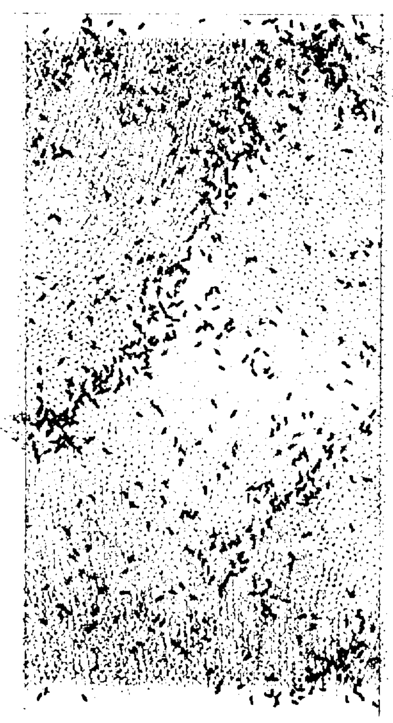
$$F_s \leq \mu F_n$$

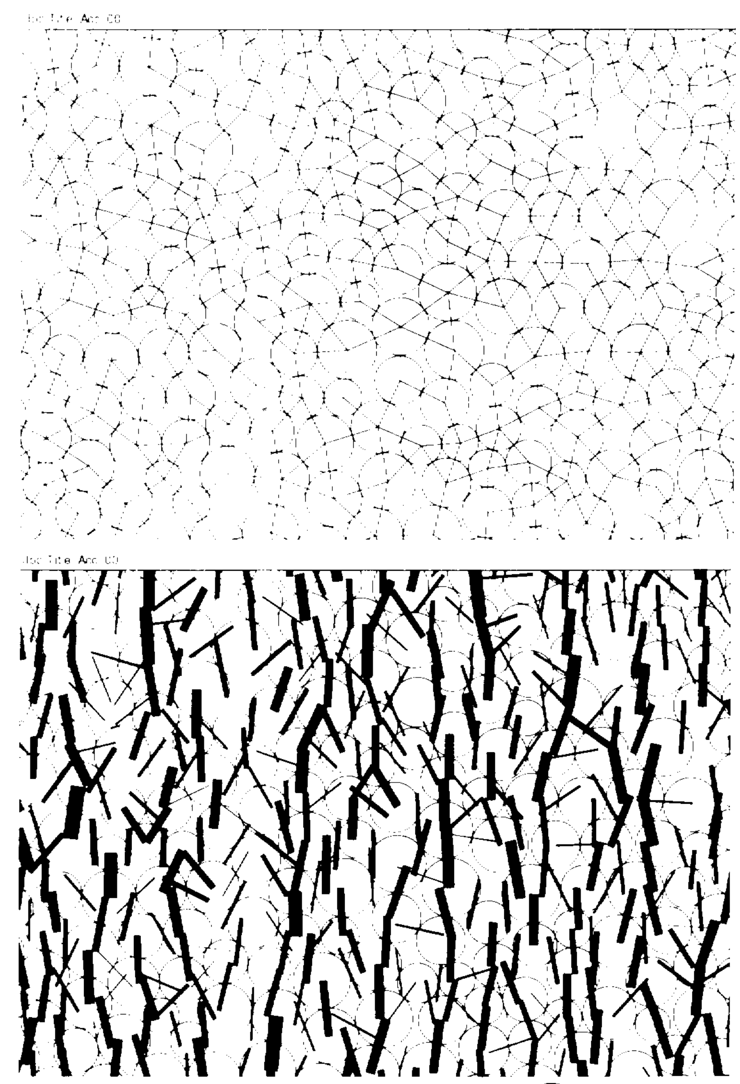
strength

- 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

Mechanical Behavior of Rock

- 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

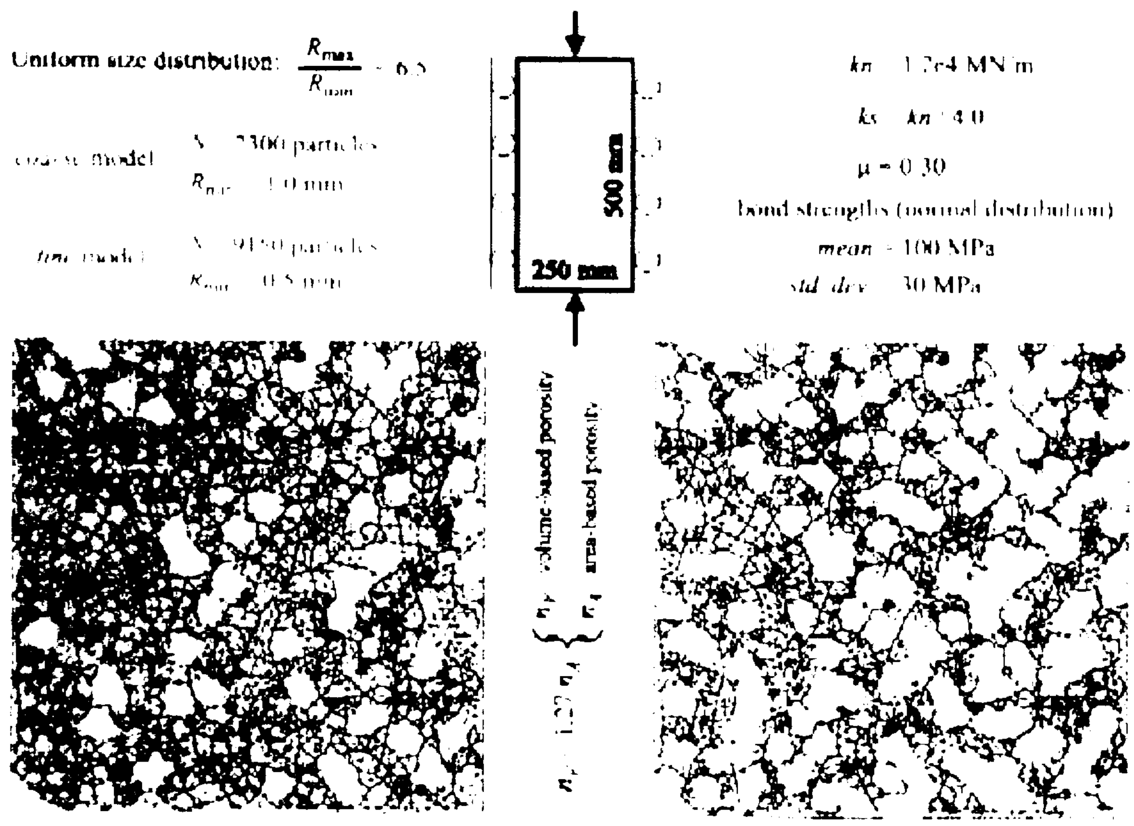




Is PFC in Widespread Use?

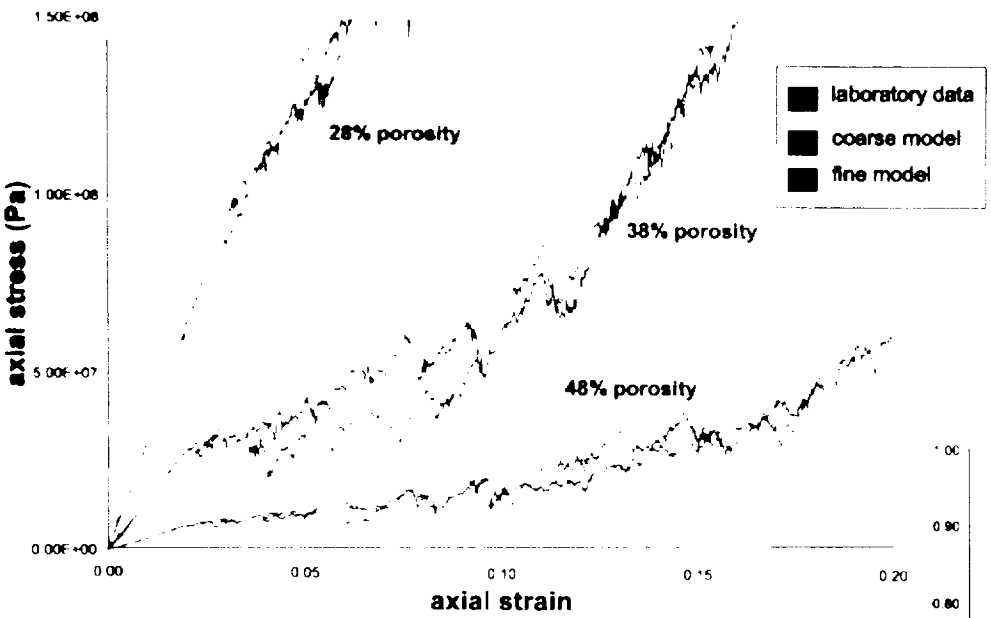
- PFC is used worldwide, primarily as a research tool in rock constitutive modeling, granular materials reasearch, powder research, rock dynamics, fluid flow in granular materials, rock cutting, etc
- Following are some examples in rock mechanics in which program has been used to investigate similar problems to ours:
  - Compaction of porous chalk in the Ekofisk Field, North Sea
  - Mechanisms of shear constitutive behavior of a rough joint
  - Time-dependent stress corrosion mechanisms in granite at the URL, Canada

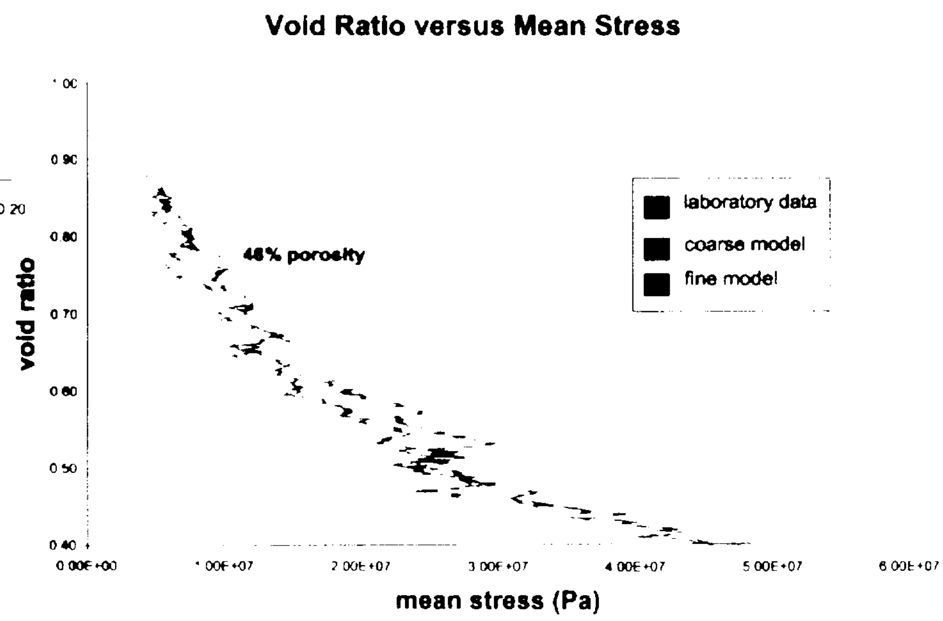
Example 1 - PFC Model Calibration of High-Porosity Chalk from the Ekofisk Reservoir, North Sea



coarse model (28% porosity)
coarse model (48% porosity)

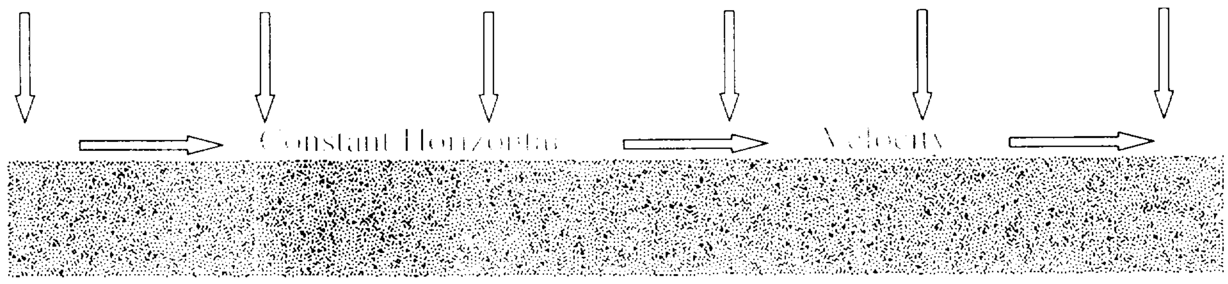
One-dimensional Compaction of Porous Chalk - Model Calibration



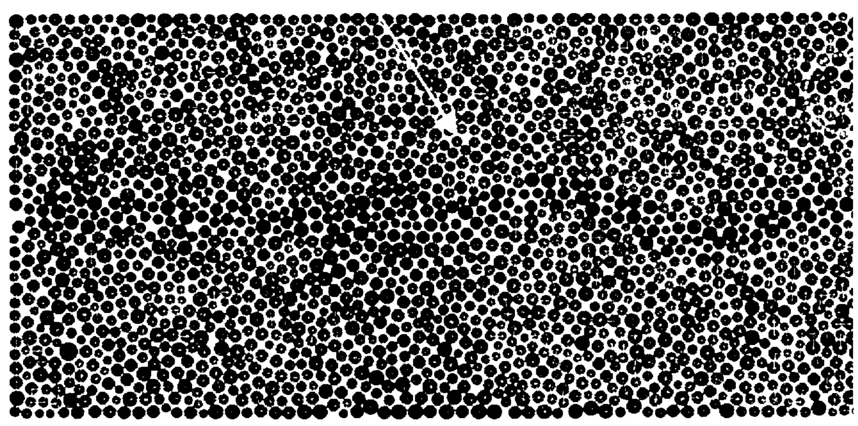


Example 2 - PFC Shear Box Test of Rough Joint

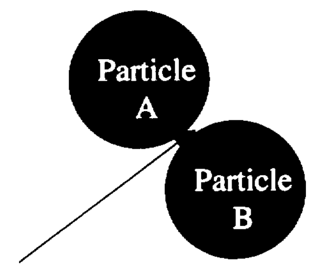
Constant Vertical (Normal) Stress



Numerical Experiment of Rough Joint in Shear



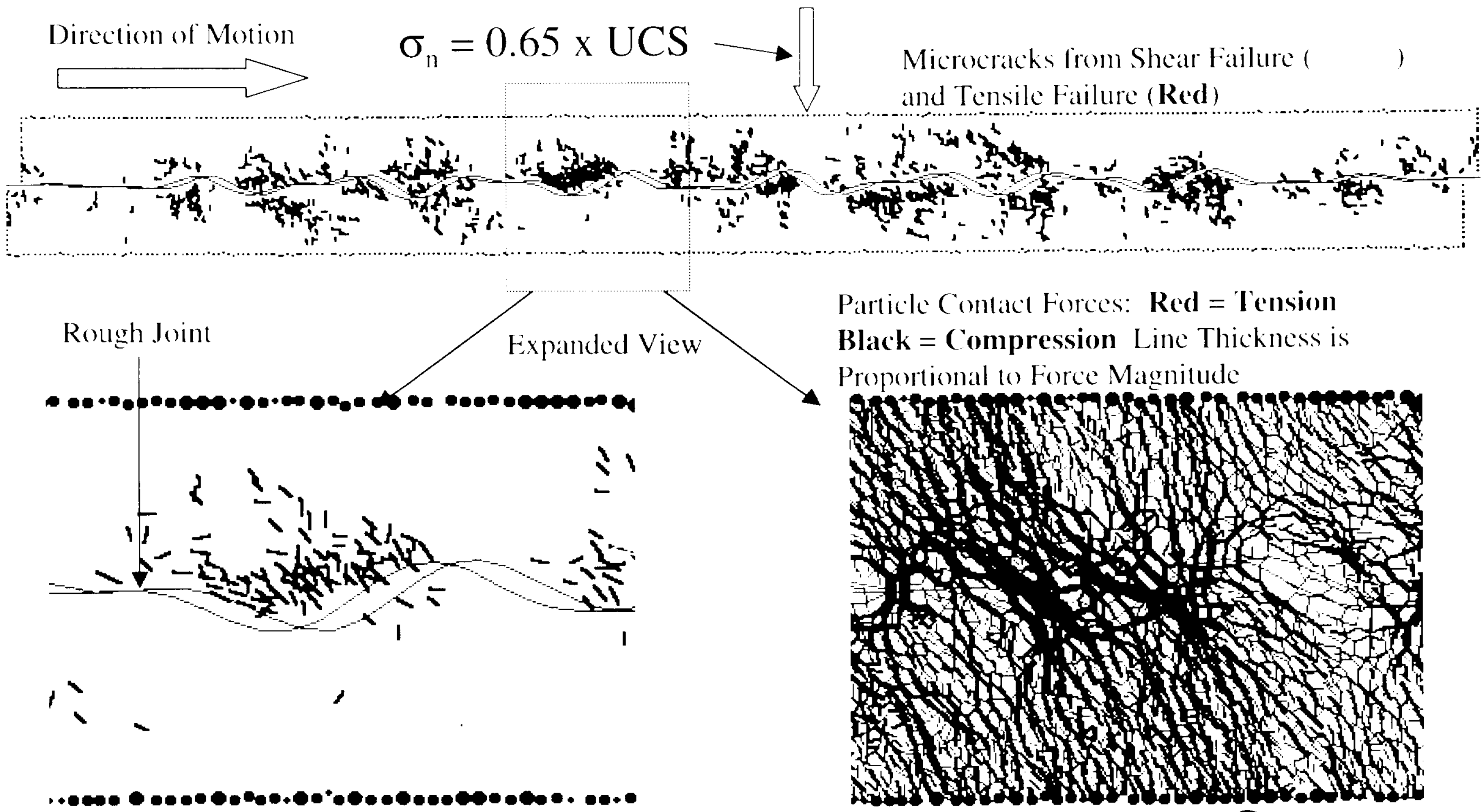
Black bonded particles representing shear box
Red unbonded particles representing joint
bonded particles representing intact rock



Contact & Bond Parameters:

- K_n - contact normal stiffness
- K_s - contact shear stiffness
- μ - contact friction coefficient
- F_n - normal bond strength
- F_s - shear bond strength

Numerical Shear Box Experiment on Rough Joints

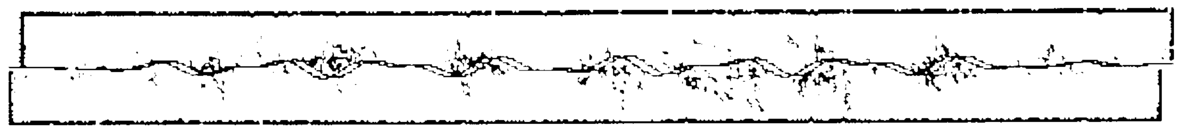


Applied normal stress

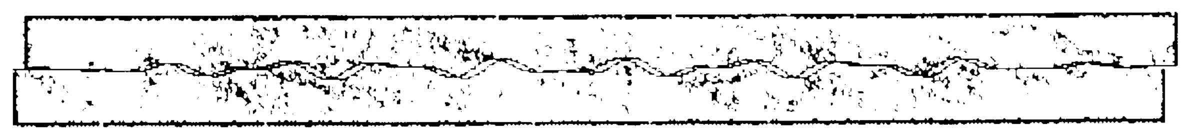
Micro-cracks induced during shearing -

25% of UCS

50% of UCS



87.5% of UCS



Notes:

1. States shown at displacement = 1% of box width
2. Red lines are tensile cracks; green lines are shear cracks
3. Material was calibrated (in another test) to determine the UCS (unconfined compressive strength).

Comparison of PFC Model of Rough Joint to Empirical Barton-Bandis Shear Constitutive Model

Comparison to Barton-Bandis equations:

$$\tau = \sigma_n \tan\{\text{JRC}\log(\text{JCS}/\sigma_n) + \phi_r\}$$

$$d_n = \text{JRC}\log(\text{JCS}/\sigma_n)$$

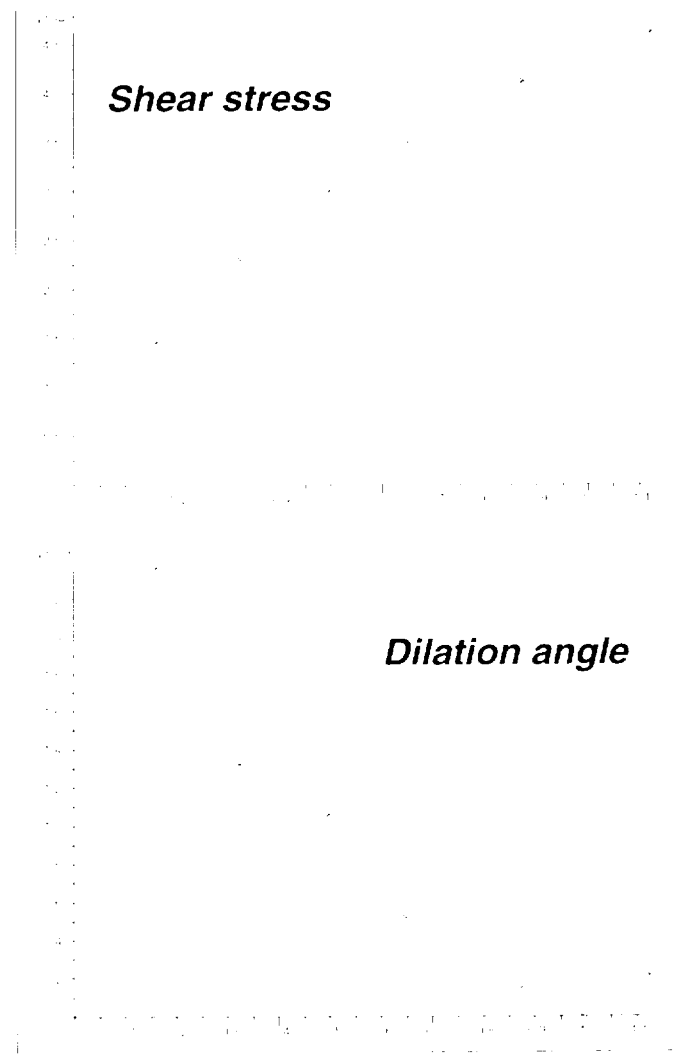
Solid curves show values calculated by these equations for:

$$\phi_r = 24^\circ$$

$$\text{JRC} = 20$$

$$\text{JCS} = \sigma_c \ \ (\text{UCS of solid})$$

Crosses show results from seven *PFC* simulations



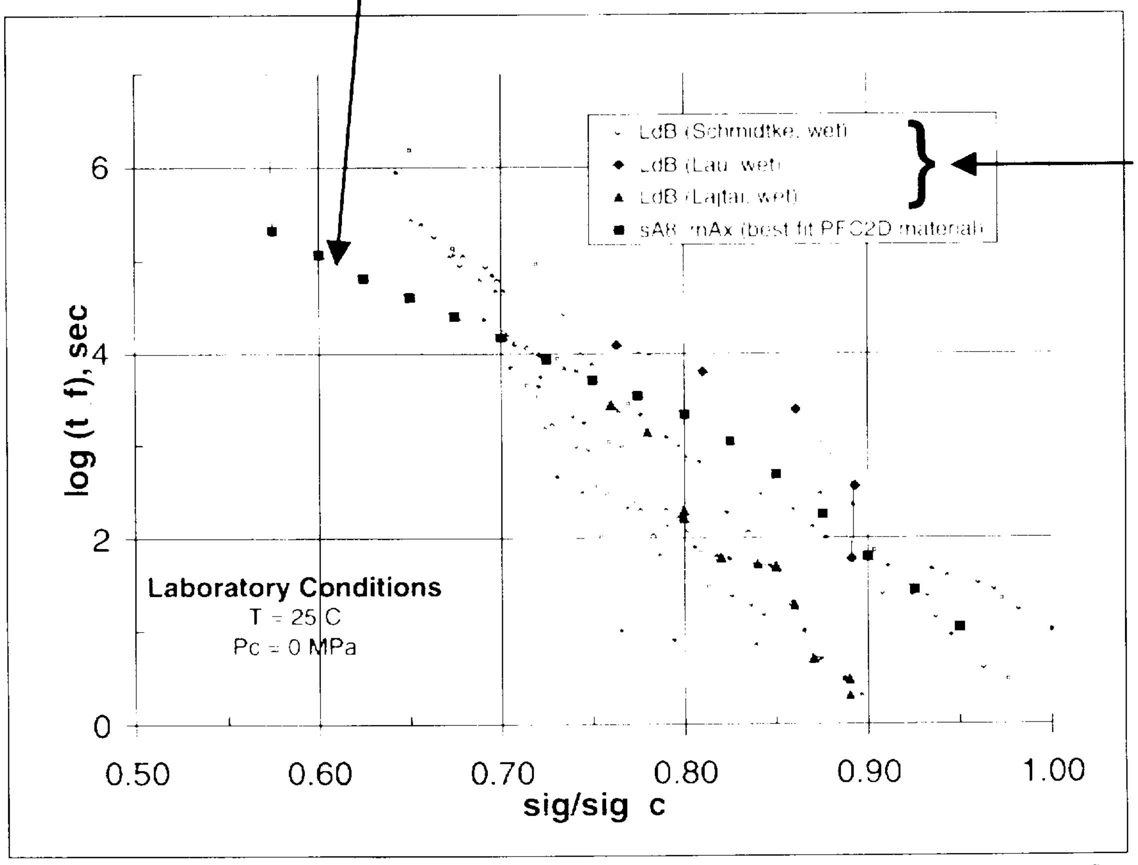
Static-fatigue Data for LdB granite

data used for PFC2D calibration

simulated results

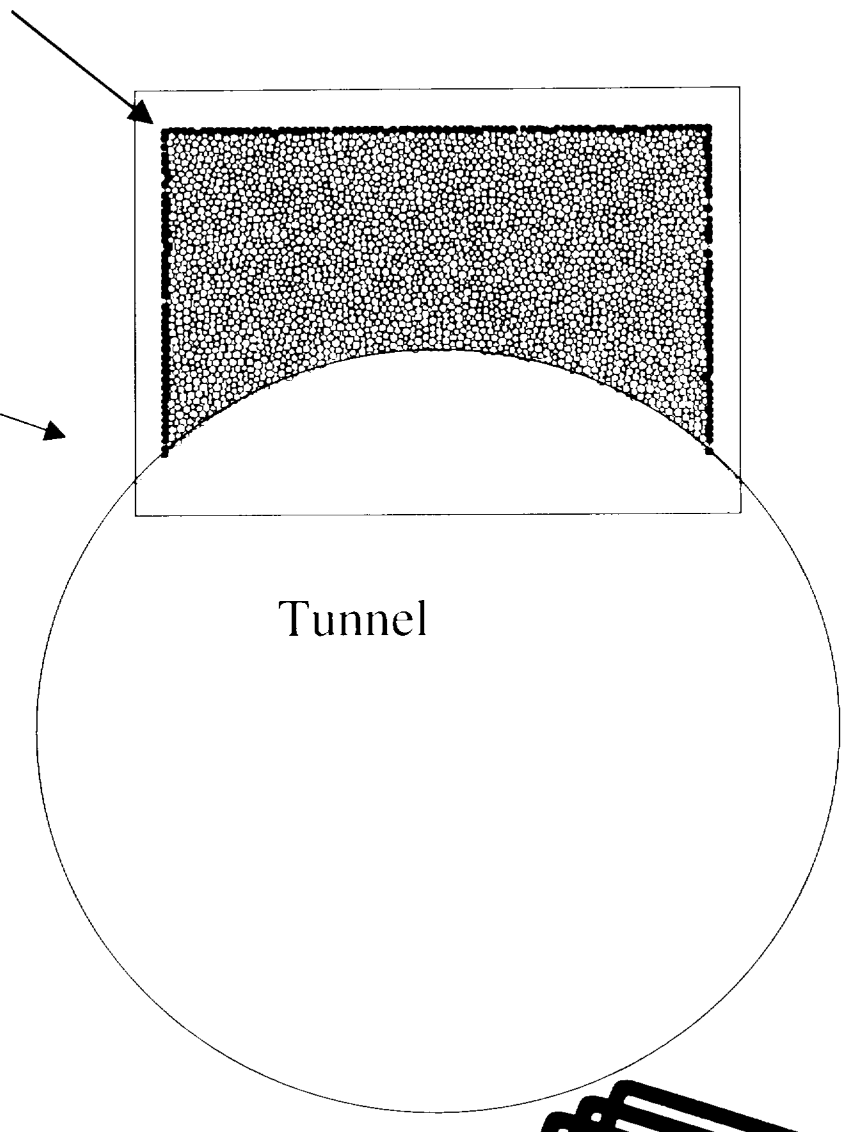
lab results

Time to failure (log scale)

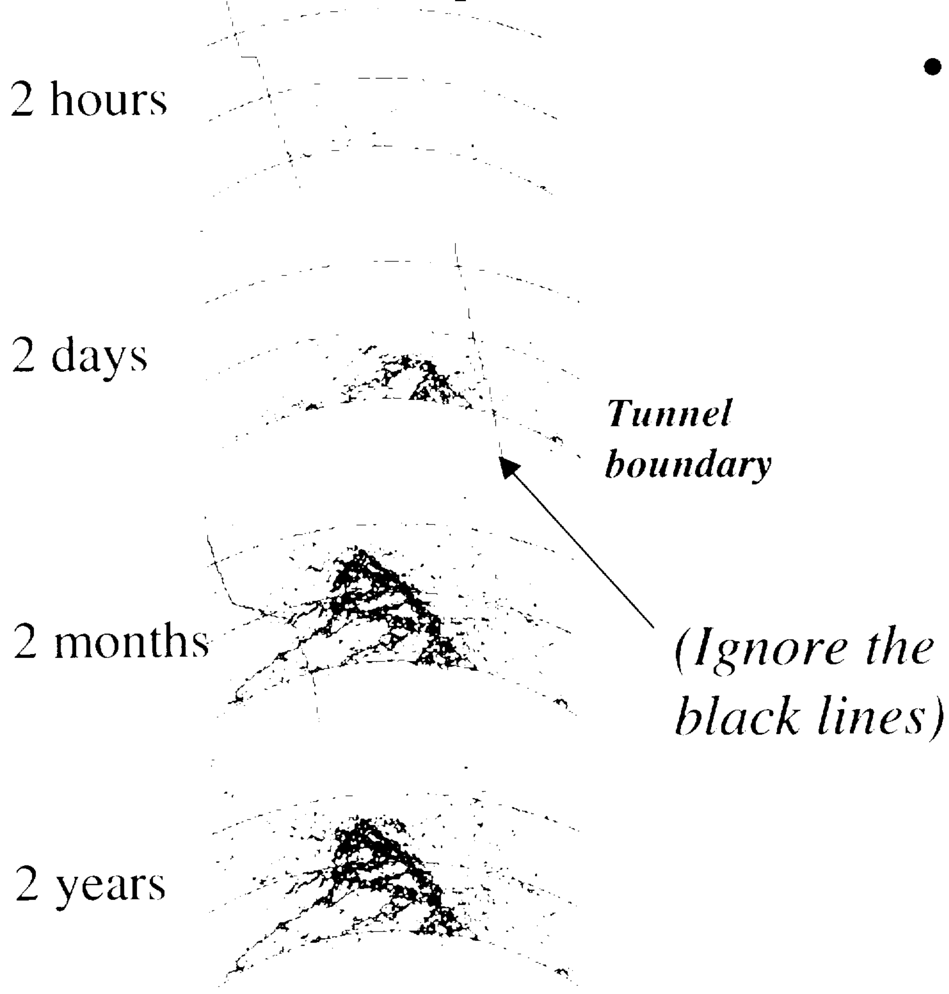


PFC Model of Tunnel Crown

- The near-field around the URL tunnel crown is modeled by a *PFC* region
- Everything else (including the far field) is represented by an elastic solution (using the *FLAC* code)
- After the initial, short-term stress adjustment, the model is solved by time-stepping. Cracks occur (due to stress corrosion), causing new stress distributions, and further cracks ...



Use of PFC to Simulate the Time-Dependent Evolution of Fracture Development in the Tunnel Crown



- **These results – simulated by *PFC* – show tensile cracks in** red, **and shear cracks in** blue

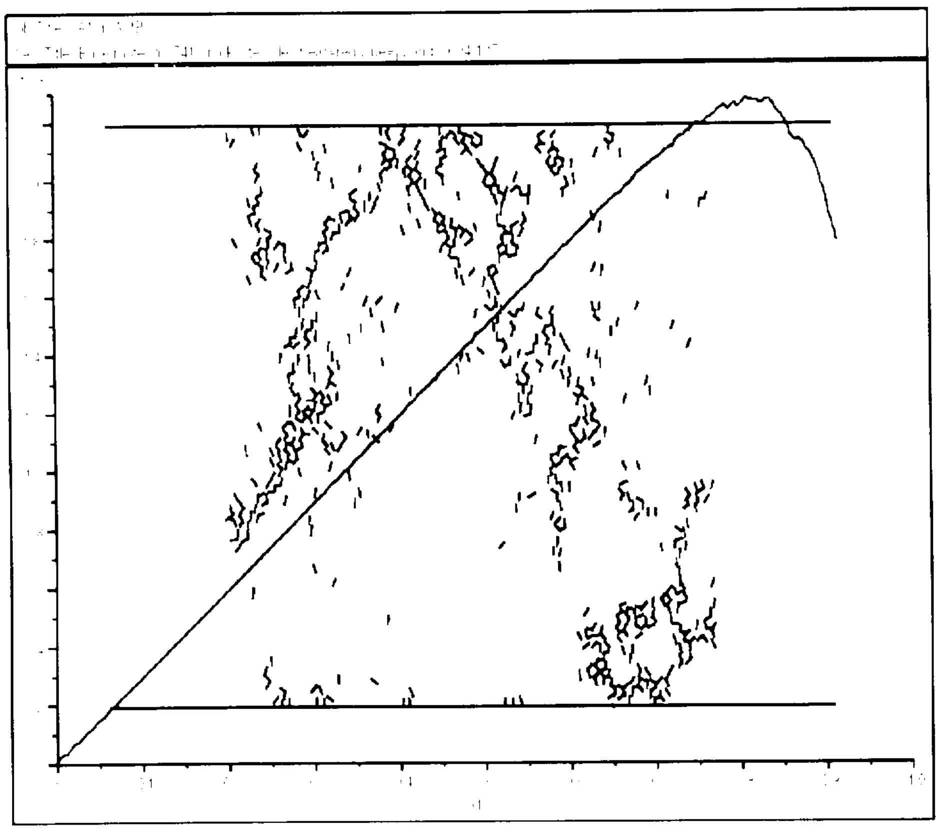
Additional Validation Via Comparison to Acoustic Emission

Since *PFC* is a dynamic code, each bond-break generates a pulse of kinetic energy. Several such pulses, correlated in time and space, are equivalent to a microseismic event

Field measurements ***of microseismic events (after Young & Hazzard, 2001)***

"Events" generated by the *PFC simulation*

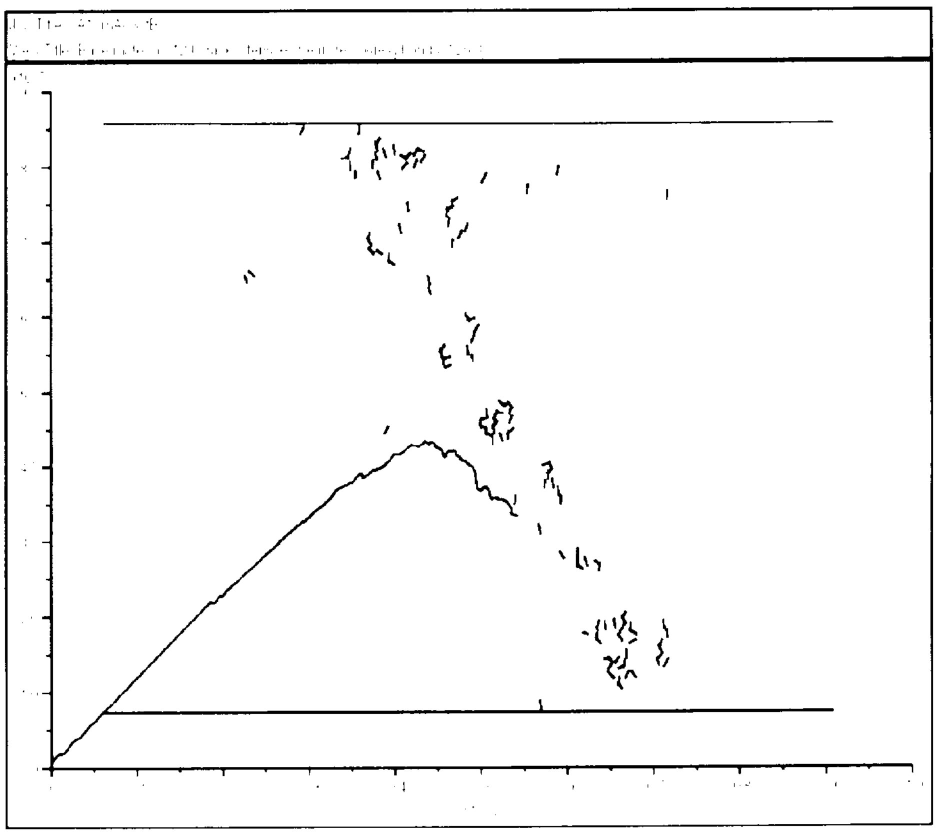
Example of Preliminary PFC Investigations Investigating Effects of Lithophysal Porosity on Failure Mechanism and Strength



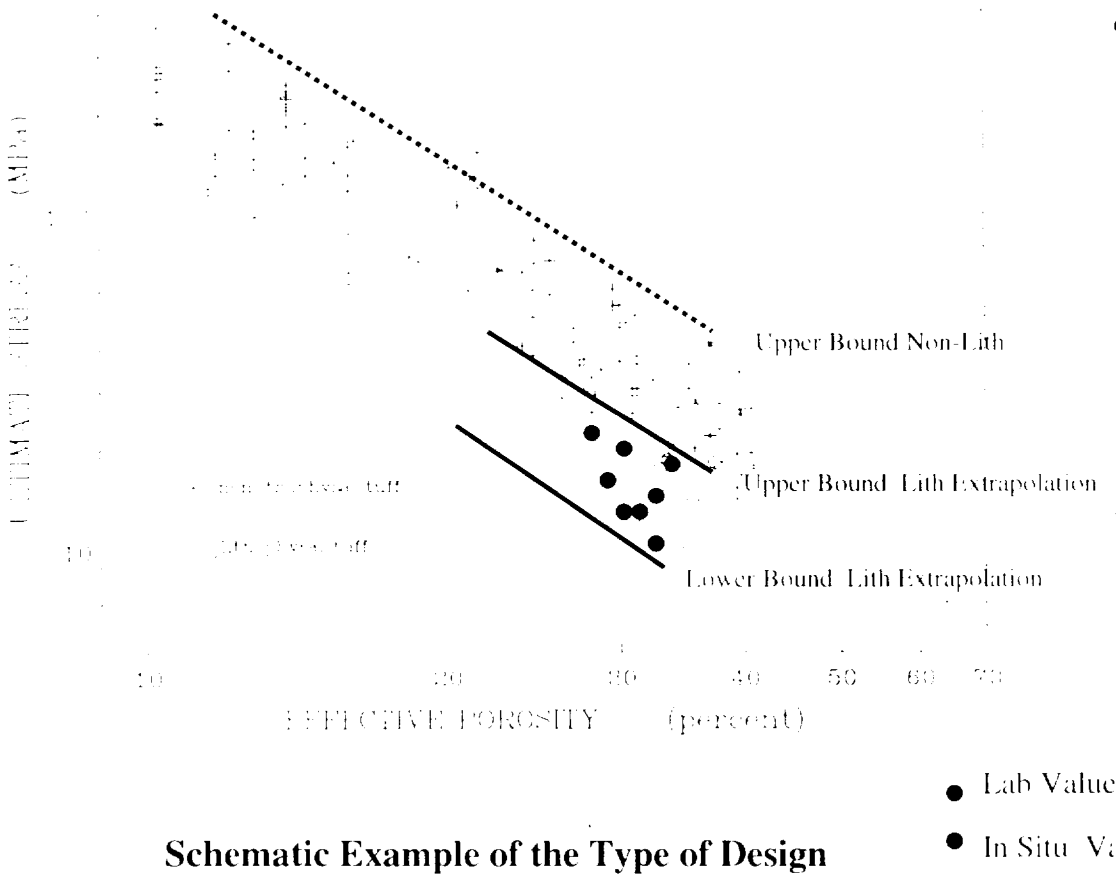
- Assistance of Itasca Consulting Group - P. Cundall, D. Potyondy, Leads
- Middle-non lith failure mode calibrated against lab test results
- High end of strength scale shown at left
- Failure mode in shear

Preliminary PFC Investigation

- Upper Lithophysal Zone
- Evenly-distributed lithophysal porosity
- Presence of lithophysae facilitates extension fractures between holes resulting in global shear failure mechanism - lithophysae act as flaws
- Same matrix material as the previous middle non-lith example



General Objective - Use of Model to Supplement Testing and Help Establish Rock Mass Variability

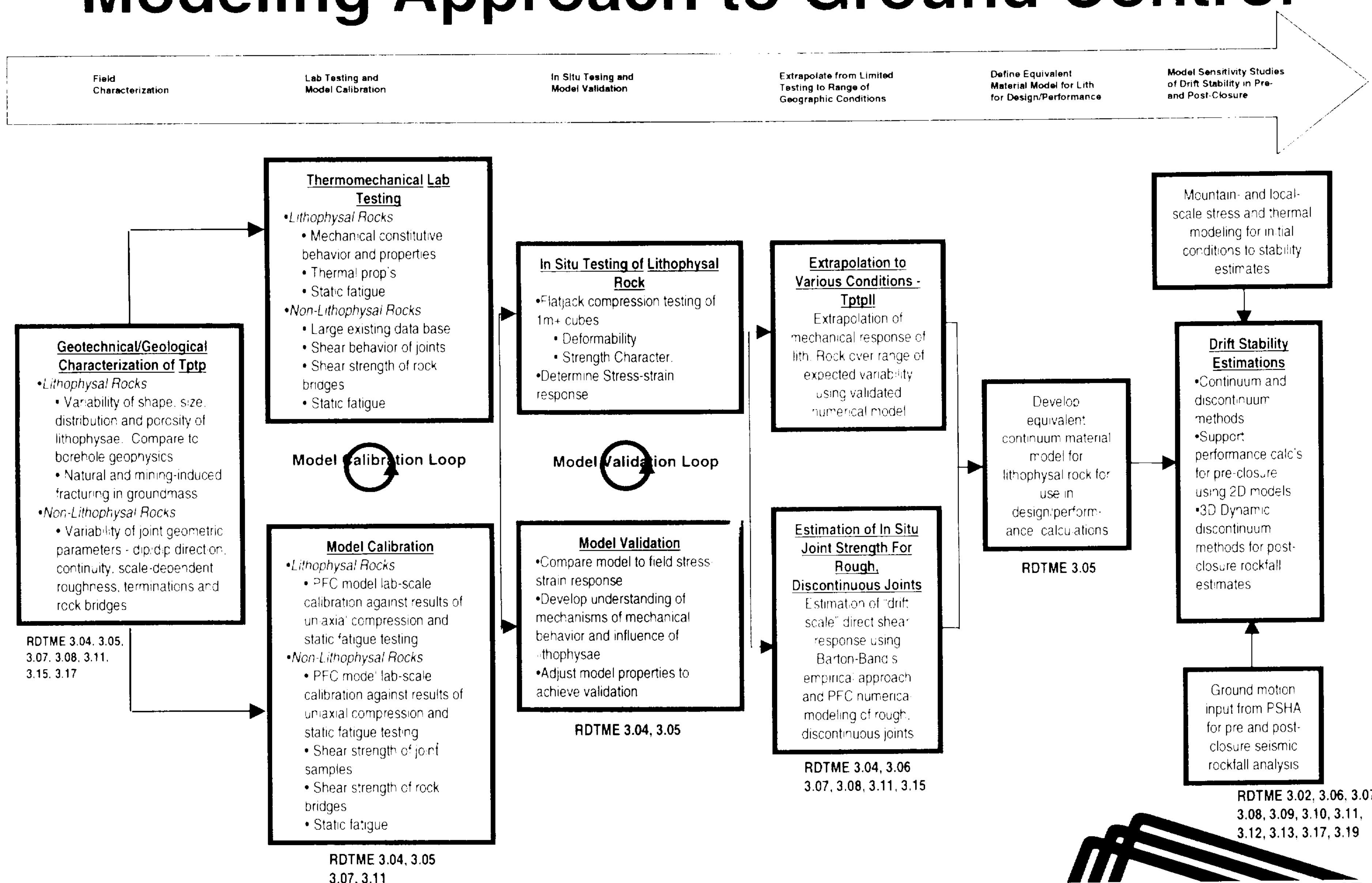


Schematic Example of the Type of Design Information We Would Like to Produce - Impact of lithophysae on Compressive Strength

- 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

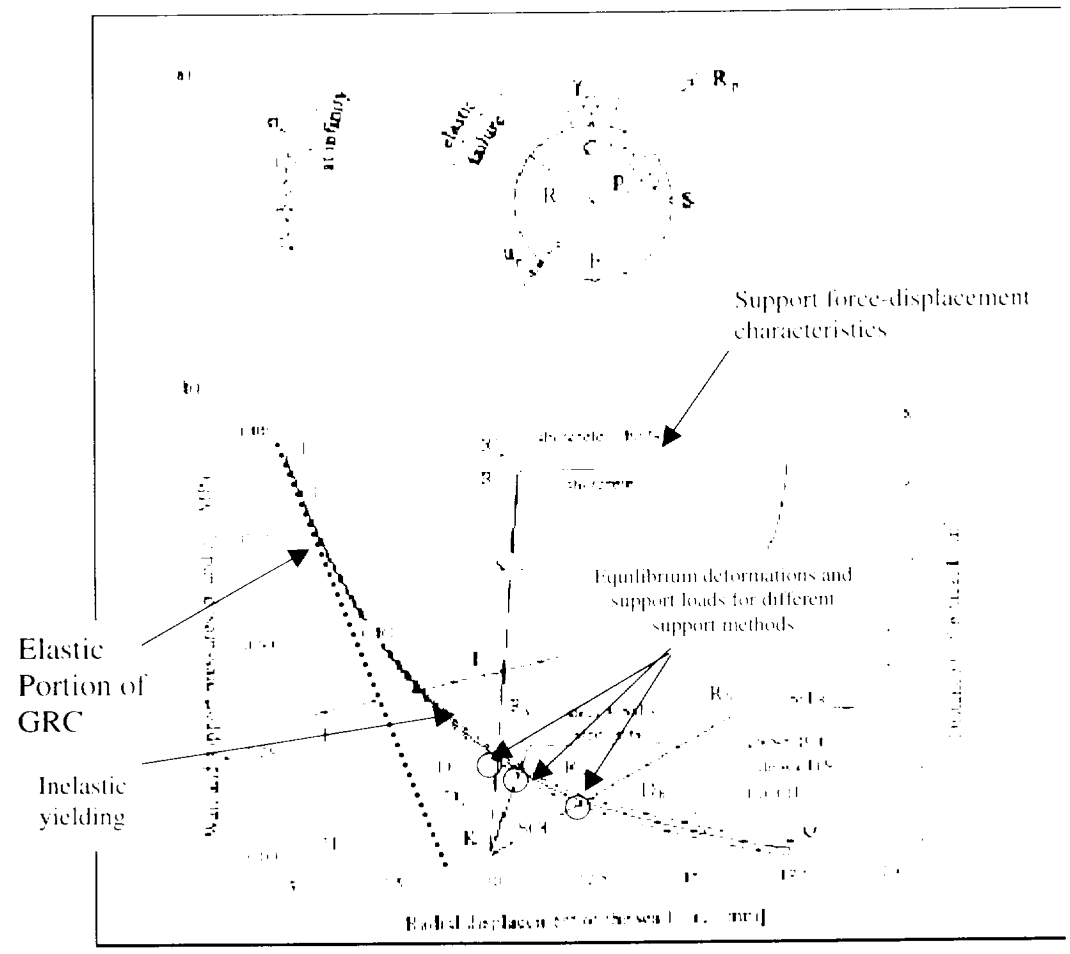
YUCCA MOUNTAIN PROJECT

Modeling Approach to Ground Control

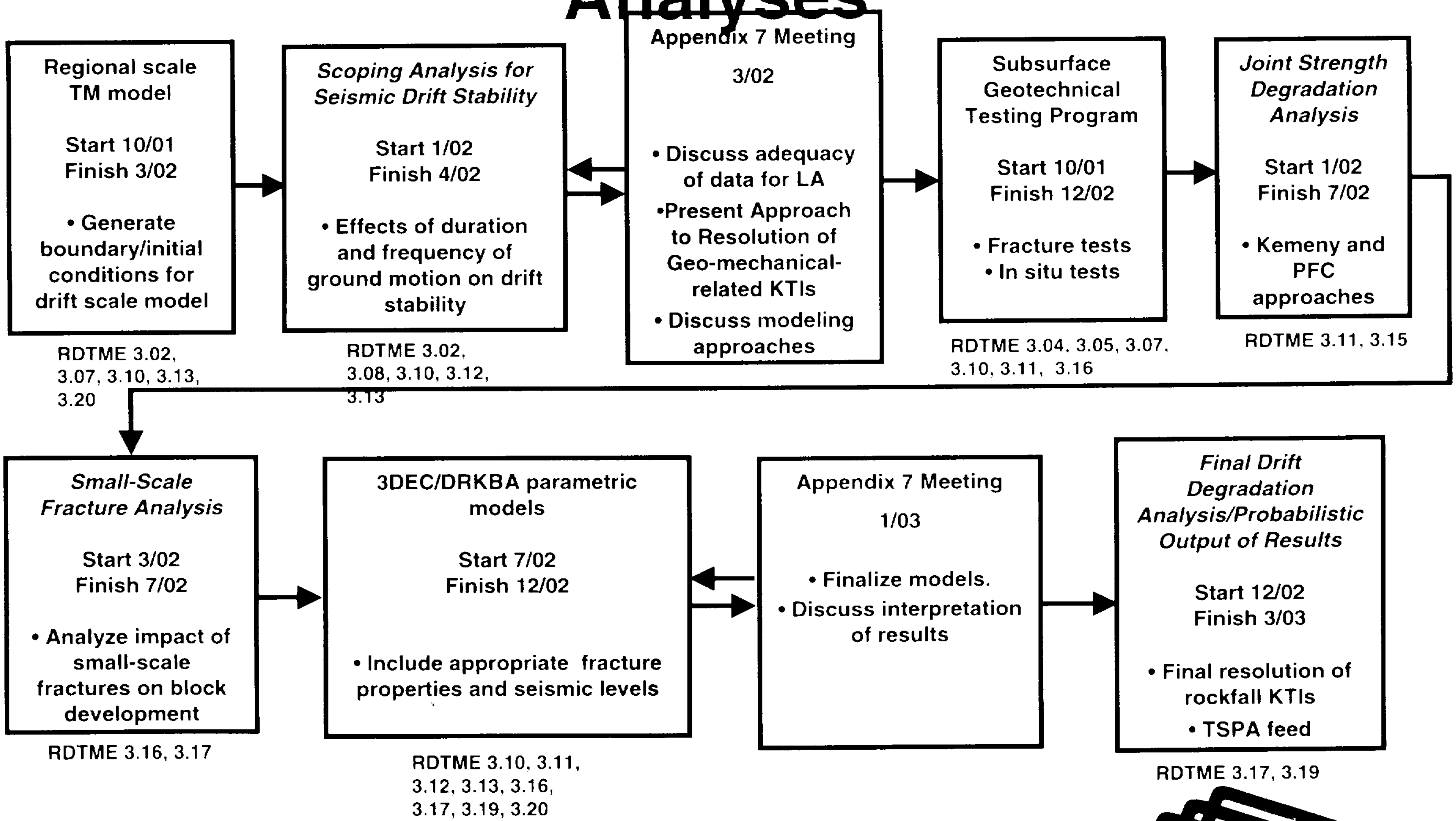


Approach to Pre-closure Ground Support Analysis

- Use of range of input properties defined from testing and validated model
- Rely on 2D models for analysis of failure potential and deformation
  - Continuum (FLAC) with equivalent mechanical behavior for lithophysal rocks
  - Discontinuum (UDEC) for non-lithophysal rocks
- Parametric analyses of time-related in situ, thermal, seismic response
  - Develop a series of ground reaction curves that describe the rock mass deformability and yield and interaction with the support. Determine support characteristics necessary for ground control as a function of time in pre-closure
  - Determine, under these given loading conditions, and along with support longevity studies, whether candidate methods are suitable



Review - Resolution Strategy for KTIs Pertaining to Rockfall/Drift Degradation Analyses

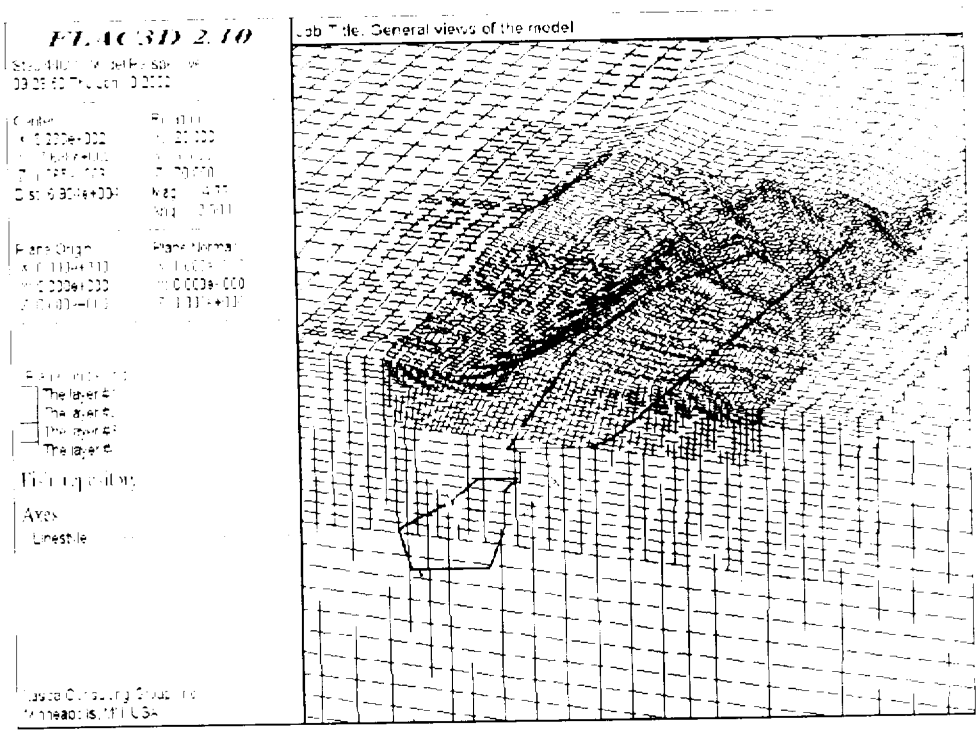


Approach to Post-Closure Rockfall

- **Approach is evolving at present. Formed post-closure seismic working group to assist in planning and review. Group consists of:**
  - Allin Cornell (PSHA and probabilistic structural analysis methods), Stanford University
  - Carl Stepp, Seismologist, PSHA, consultant
  - Walt Silva, Seismologist, ground motion determination
  - Kevin Coppersmith, Rich Quittmeyer, BSC Disruptive Events Group
  - Ivan Wong, URS Seismologist
  - Peter Cundall, Branko Damjanac, rock mechanics dynamics modeling, Itasca Consulting Group
  - Mark Board, Dwayne Kicker, Ming Lin, BSC rock mechanics
  - William Boyle, DOE
  - Personnel from Engineered Barriers, Waste Package and Performance Assessment groups

Approach to Post-Closure Rockfall

- ***Step 1 - Provide initial conditions to emplacement drift model.*** **Conduct mountain-scale thermomechanical simulations as a function of time (provides in situ and mining-induced stress and temperature variations vs time)**



FLAC3D mountain-scale model of SR Design

YUCCA MOUNTAIN PROJECT

Approach to Post-Closure Rockfall

- *Step 2 - Define post closure ground motions from PSHA currently being developed by Disruptive Events group, Carl Stepp, Lead.* **Approach is to examine ground motion impacts from pre-closure annual exceedance limits to as yet determined levels. Will investigate limits at which significant damage occurs**
- **Currently performing simple, conservative 2D analyses to define effects of spectral shape, duration and acceleration as well as rock joint geometry and strength on damage to identify important ground motion parameters to rockfall**
- **Identifying performance measure of rockfall most suitable for interface to WP/DS - ie, rock mass, energy (velocity and mass), etc**

Approach to Post-Closure Rockfall

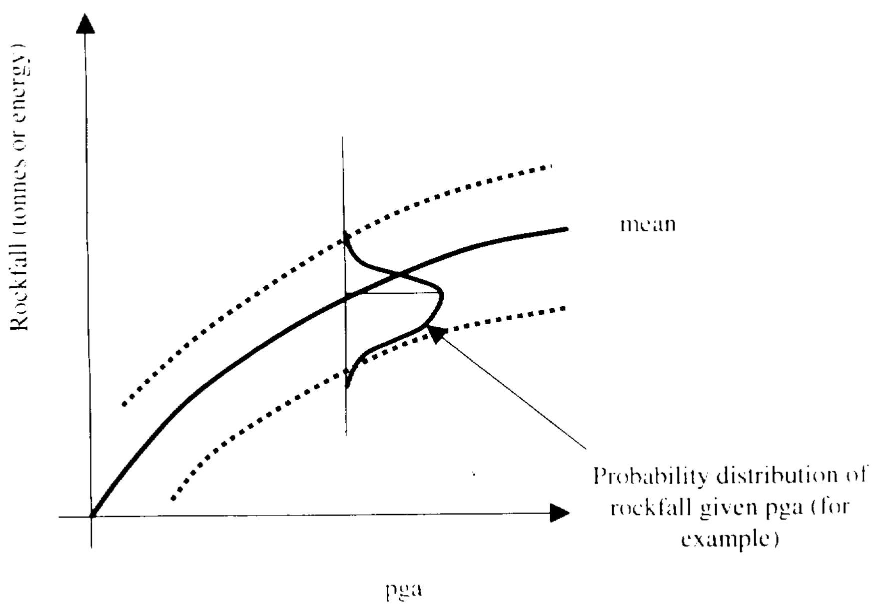
- ***Step 3 - Define rock mass parameters that need to be varied in the rockfall analyses, and range of variation***
  - Joint geometry variables - dip/dip direction, spacing, trace length, terminations
  - Joint strength and surface properties - range of constitutive properties based on lab and numerical extrapolations - friction angle, dilation angle, cohesion (including presence of "rock bridges")
  - Lithophysal rocks strength properties (deformation modulus, cohesion and internal friction angle)
- **Current testing program and geotechnical/geological characterization feeds the above.**

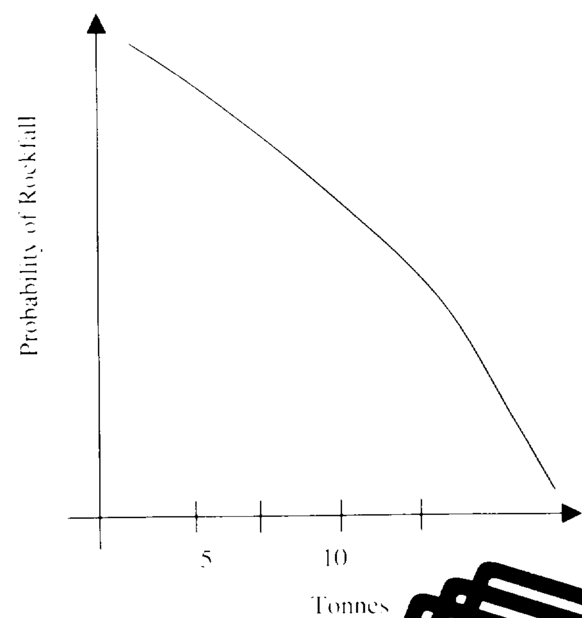
Approach to Post-Closure Rockfall

- Step 4 - 3D dynamic discontinuum analyses of rockfall using 3DEC program, Branko Damjanac, Itasca Lead. Conduct series of simulations using a number of ground motions, varying rock mass parameters, determining rockfall mass, velocities
  - Issues
    - Will use a "fragility" approach to cast rockfall in probabilistic framework commensurate with PSHA and WP/DS analysis
    - Number of deterministic simulations necessary to properly cast in probabilistic framework
    - Continuity of joints and method of accounting for rock bridges and terminations
    - Duration of events, multiple events
    - Number of discrete points in time analyses that need to be conducted

Output

- **Produce a probabilistic output of rock mass (and velocity) based on a "fragility" approach - ie, a probability density function relating rockfall size and/or energy to probability. Schematic of output method envisioned:**





Output

(Continued)

- This probabilistic output will be used in analysis of distribution of rock sizes and velocities that will impact the drip shield
- Used as input to the Engineered Barrier Systems for structural analysis of of the drip shield/waste package, and ultimately to the TSPA process models

Summary

- **Approach to resolving geomechanical-related KTI agreements**
  - Developing resolution plans for technically-related KTIs
  - Presenting plan to key technical staff within the NRC and CNWRA for feedback
  - Keeping NRC abreast of developments toward resolution of KTIs through Appendix 7 meetings at key junctures The issues that lead to the RDTME KTIs related to ground support design and rockfall analysis
  - The proposed technical approach to the resolution of these issues
  - The logic behind the approach
  - How the approach will be used in the repository design and performance assessment

Summary (continued)

- **Resolution Plan**
  - **Proposed approach to determining geomechanical properties of lithophysal and non-lithophysal rock types involves:**
    - additional geological characterization of the jointing and lithophysae variations within the proposed repository horizon
    - laboratory and field thermomechanical testing of lithophysal rock and joints
    - calibration and validation of numerical models in conert with lab and field testing
    - use of model as a numerical "laboratory" for extrapolation of mechanical response over estimated geologic variability