SAND2019-4233PE

Assessment of Meshless Methods for Simulation of Empty Room Closure at the Waste Isolation Pilot Plant

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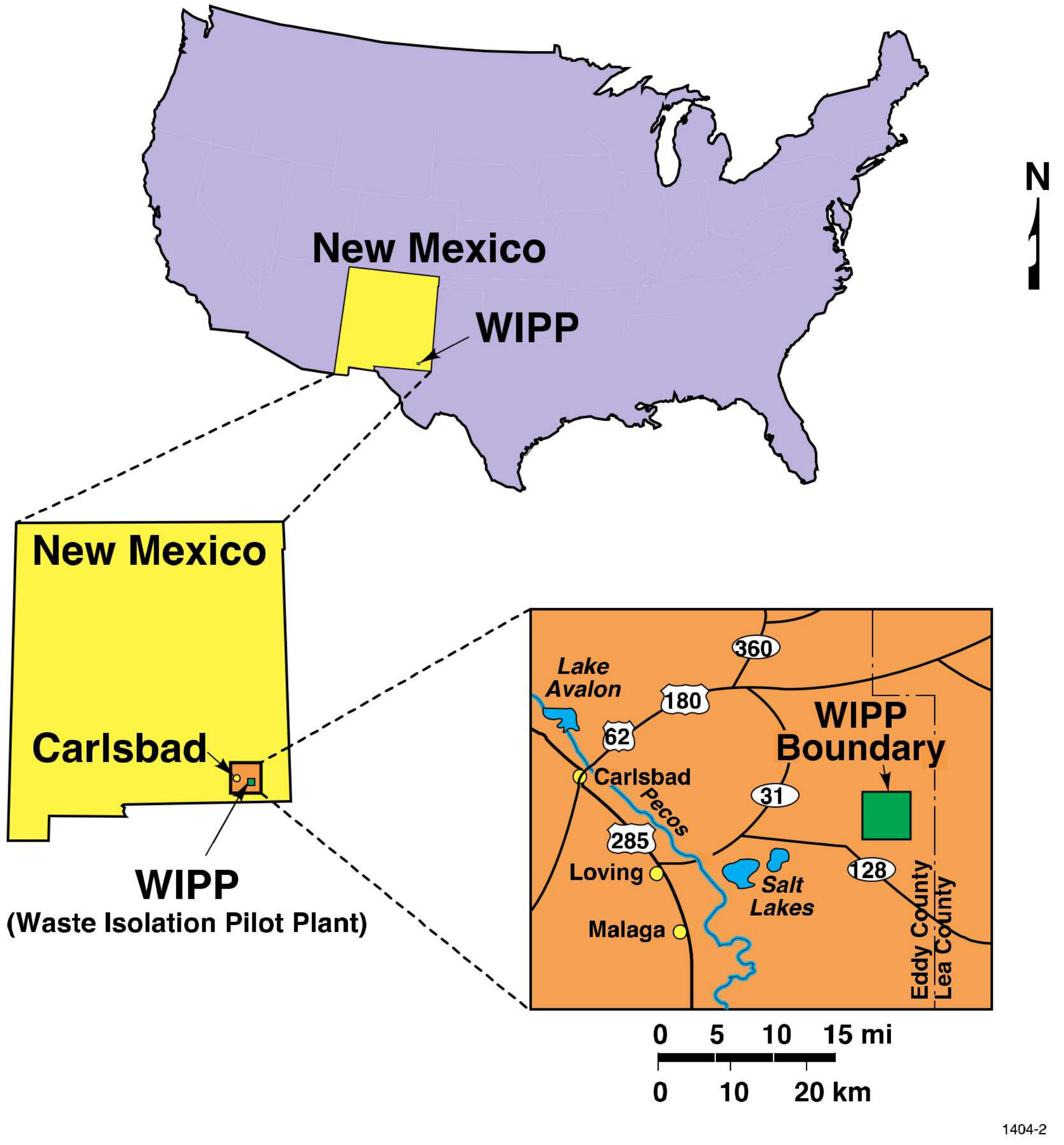
Outline

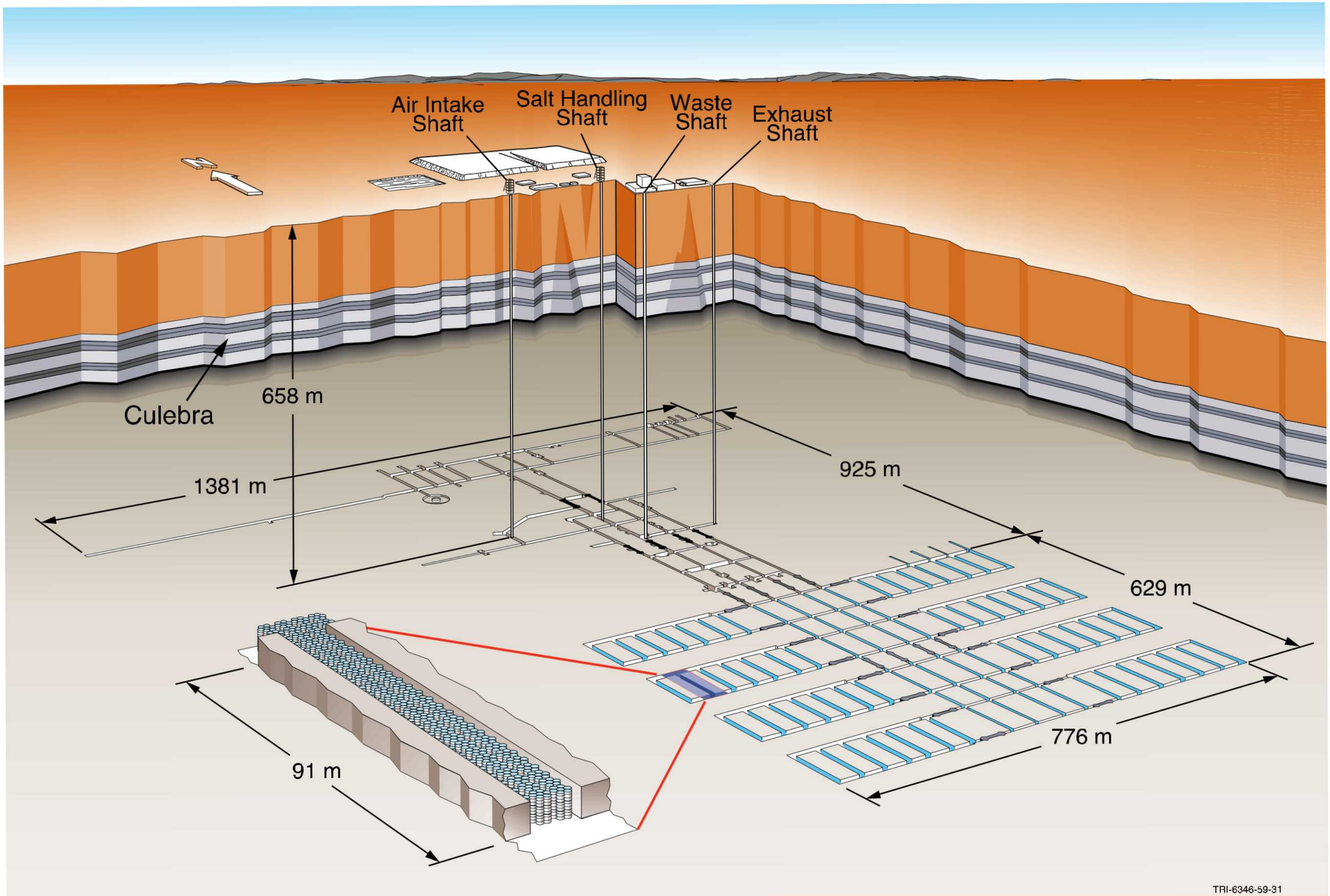
1. Background
   a. General WIPP Information
   b. Filled vs. Empty Room Closure
2. Project Scope
3. Problems
   a. Creep Closure
   b. Damage and Fracture
   c. Rubble Pile Compaction
4. Time scaling
5. Dates and Deliverables

Background

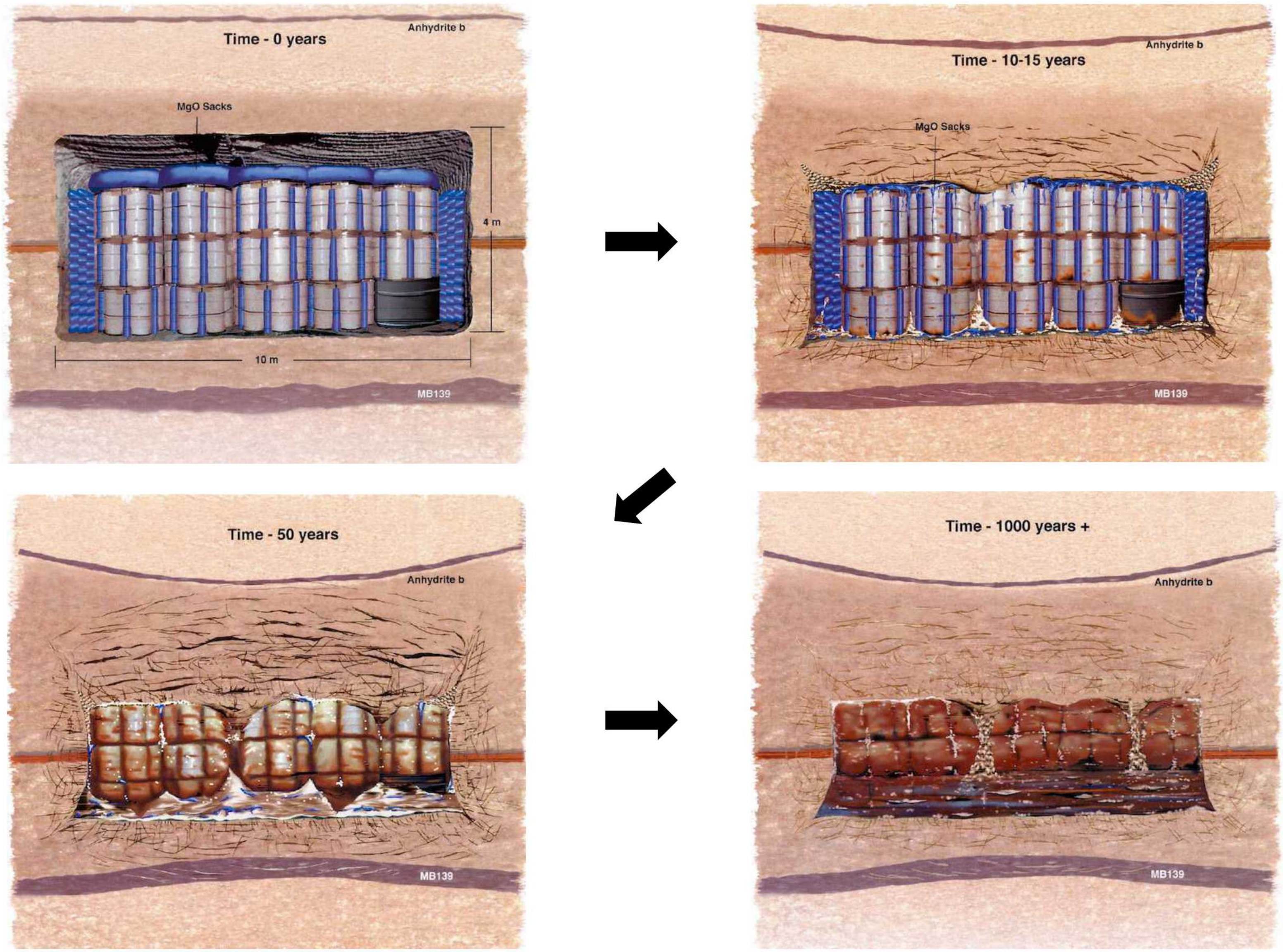
WIPP Location



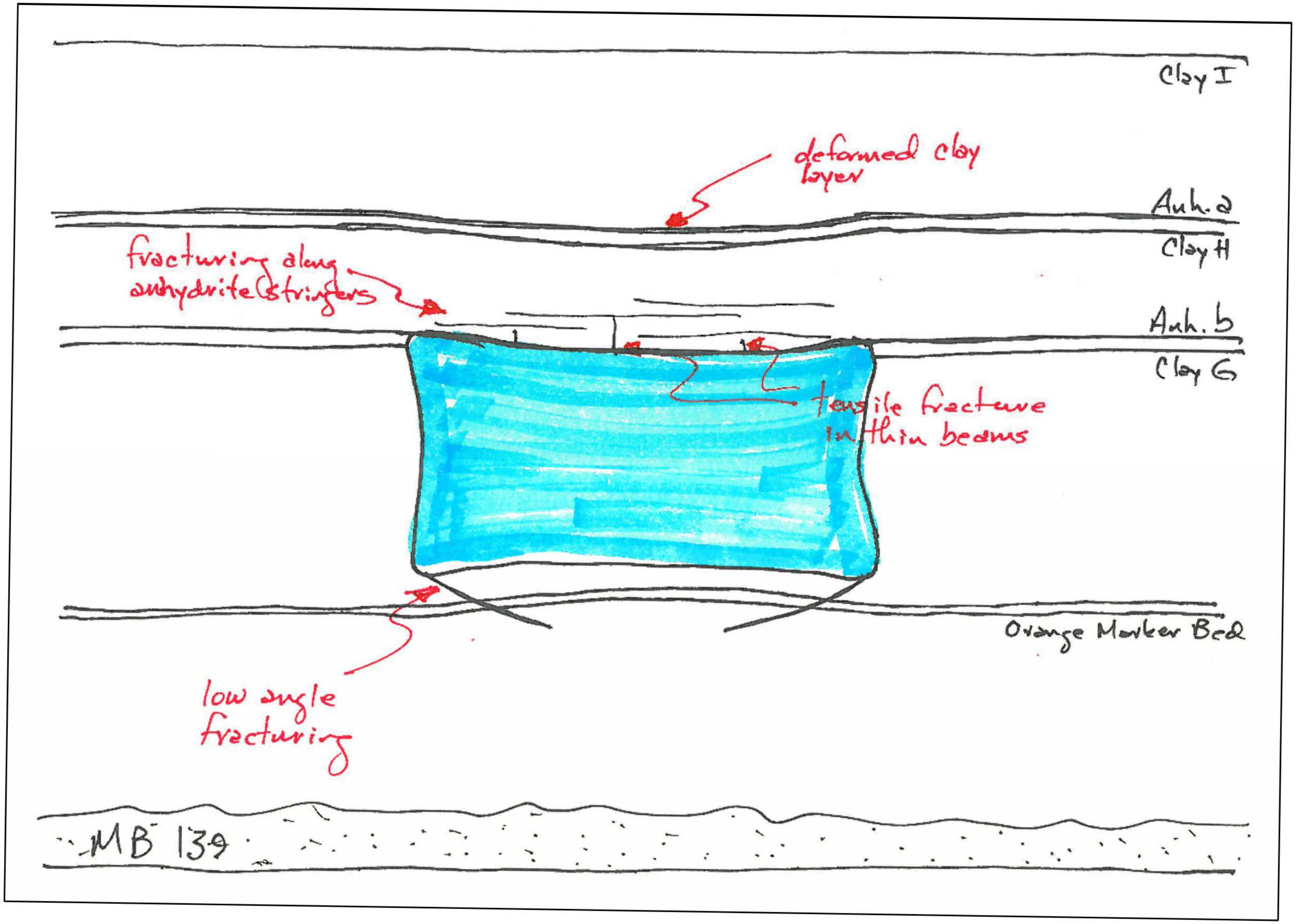
WIPP Layout


Air Intake Shaft
Salt Handling Shaft
Waste Shaft
Exhaust Shaft
Culebra
658 m
1381 m
925 m
629 m
776 m
91 m
TRI-6346-59-31

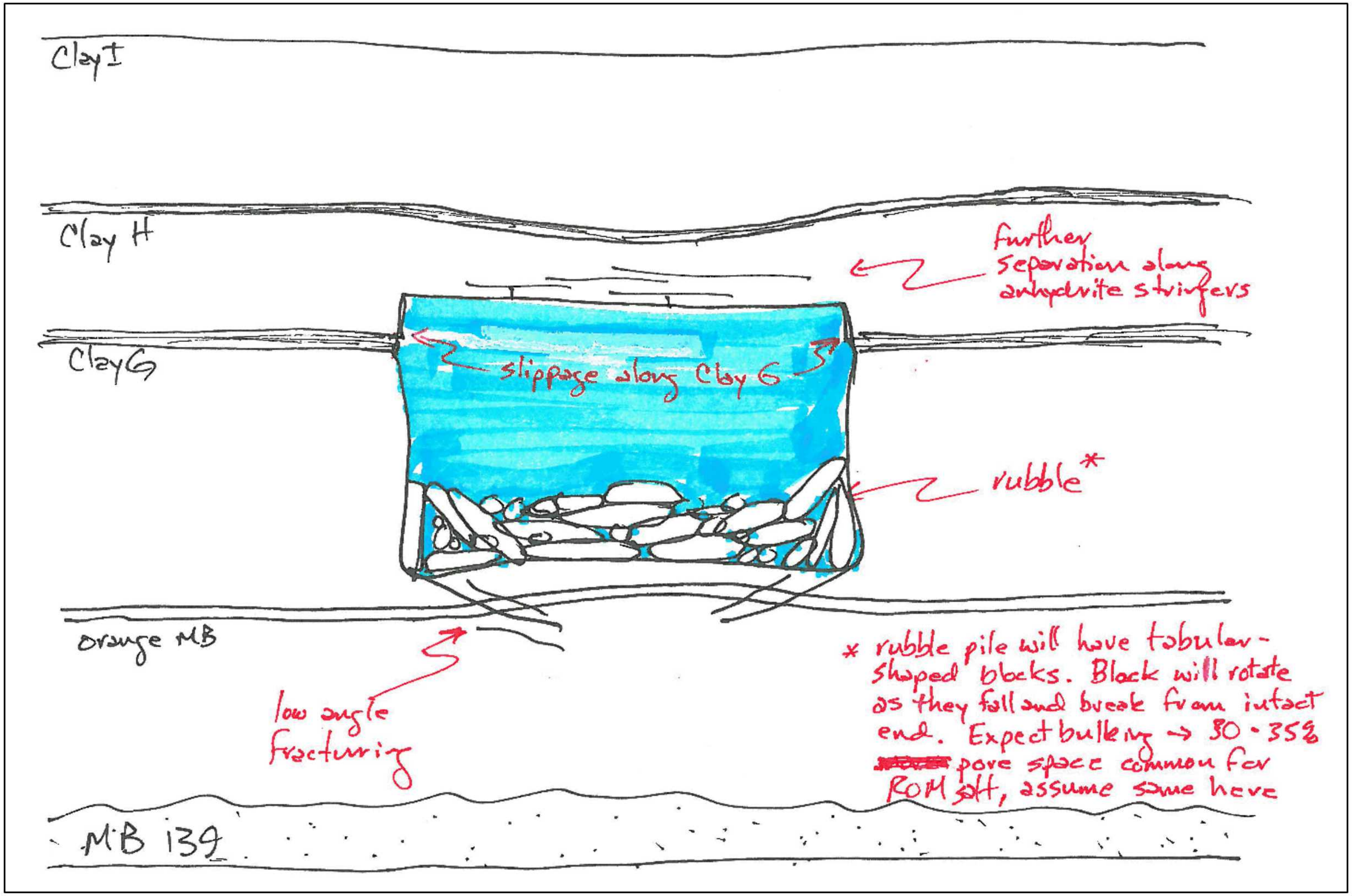
Filled Room Closure



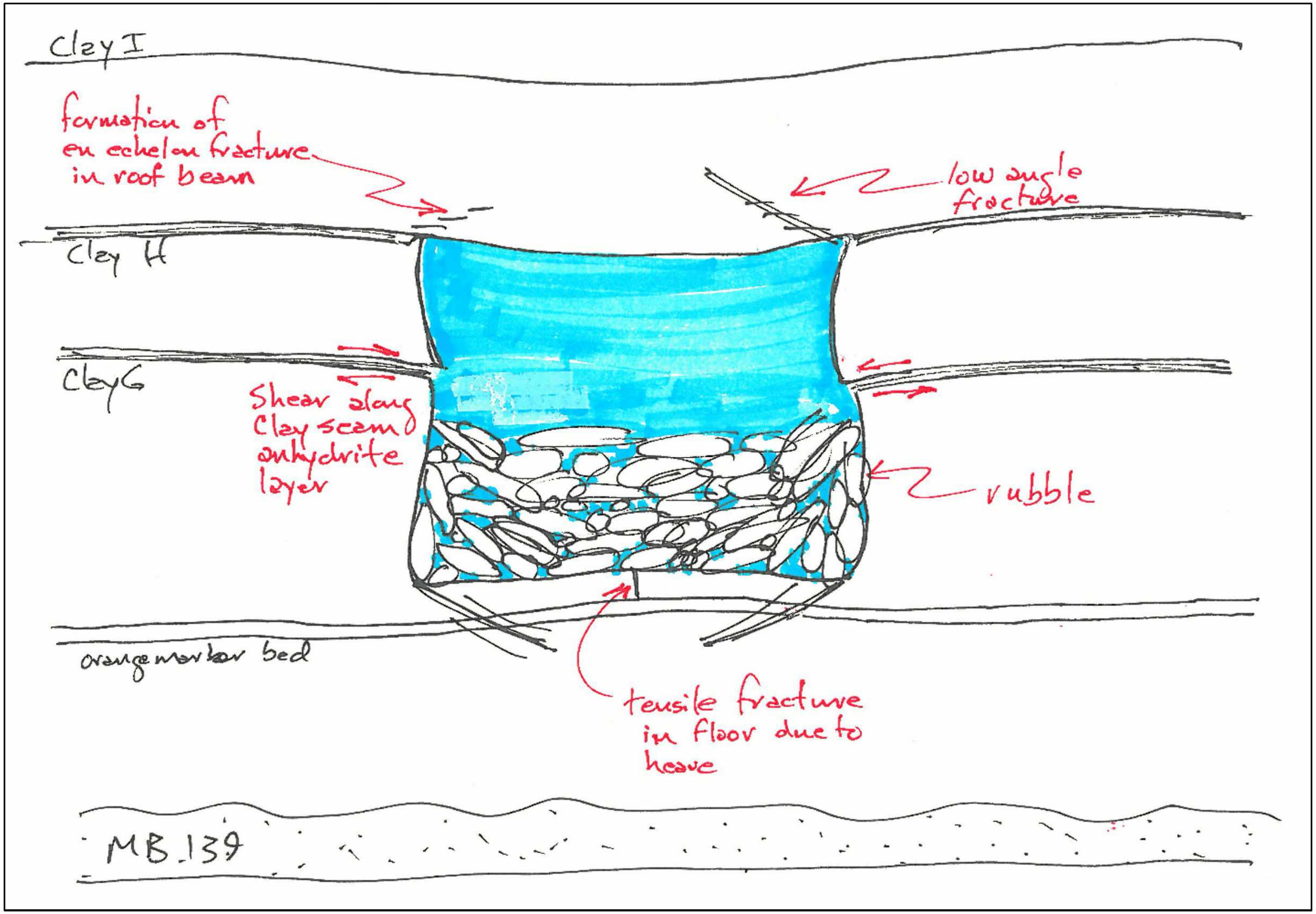
Empty Room Closure 1



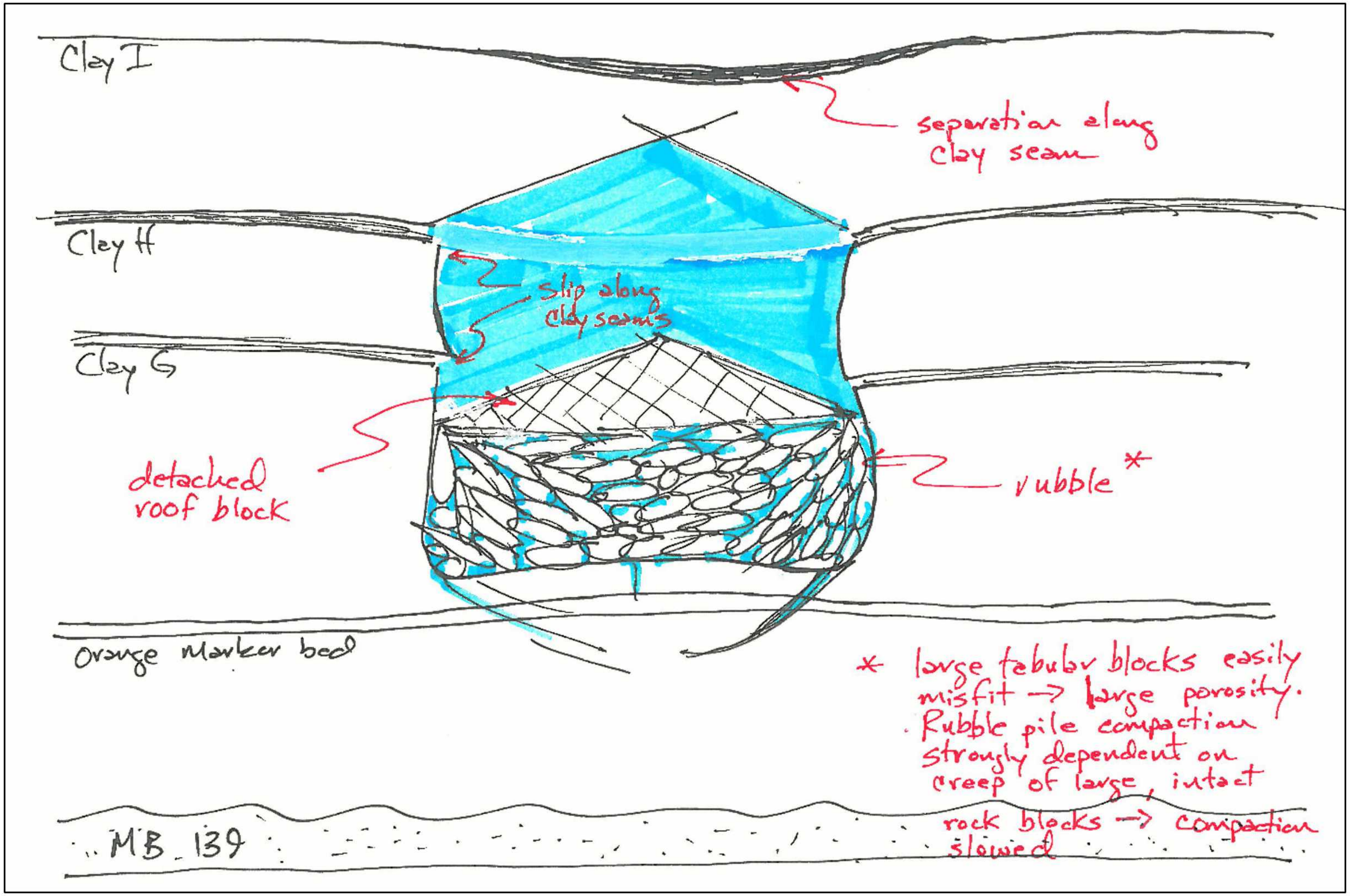
Empty Room Closure 2



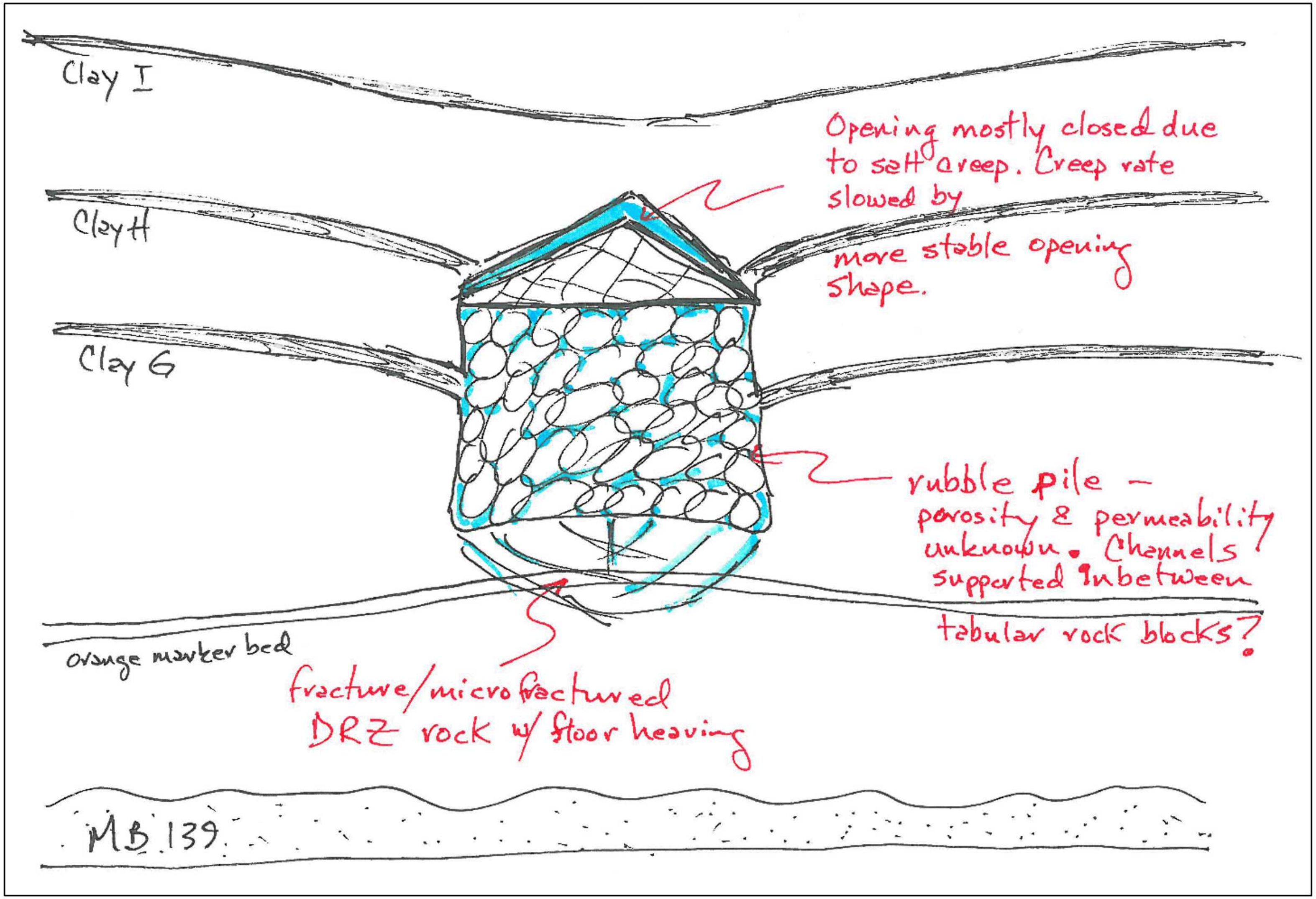
Empty Room Closure 3



Empty Room Closure 4



Empty Room Closure 5



Project Scope

Project Scope

1. Goal: Assess whether meshless methods are well suited to the simulation empty underground room closure in rock salt.
   a. Identify which approaches work and which do not

2. Capability demonstration, not intensive code development
   a. Minor code development is OK

3. Collaborate with Sandia to incorporate successful approaches into Sandia code(s).
   a. Approaches should be implemented with an eye on production

Creep Closure

Problem Statement

1. Supplied by Sandia:
   a. Creep material model
   b. Boundary value problem
   c. Finite element results
2. Assess whether a chosen meshless method can accurately simulate 2D room closure due to creep alone (no fracturing)
   a. Show discretization convergence
   b. Record total CPU time
3. Compare discretization converged meshless simulation against a finite element simulation
   a. Horizontal and vertical closure histories
   b. Room porosity histories

Simple Odqvist Creep Model

Strain Decomposition

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{\text{el}} + \dot{\boldsymbol{\varepsilon}}^{\text{vp}}$$

Isotropic, Linear, Hypoelasticity

$$\dot{\boldsymbol{\sigma}} = \mathcal{C} : \dot{\boldsymbol{\varepsilon}}^{\text{el}}$$

$$\mathcal{C} = (B - 2\mu/3)\, \boldsymbol{I} \otimes \boldsymbol{I} + 2\mu\, \mathcal{I}$$

Associated Flow Rule

$$\dot{\boldsymbol{\varepsilon}}^{\text{vp}} = \dot{\bar{\varepsilon}}^{\text{vp}} \frac{\partial \bar{\sigma}}{\partial \boldsymbol{\sigma}}$$

von Mises Equivalent Stress

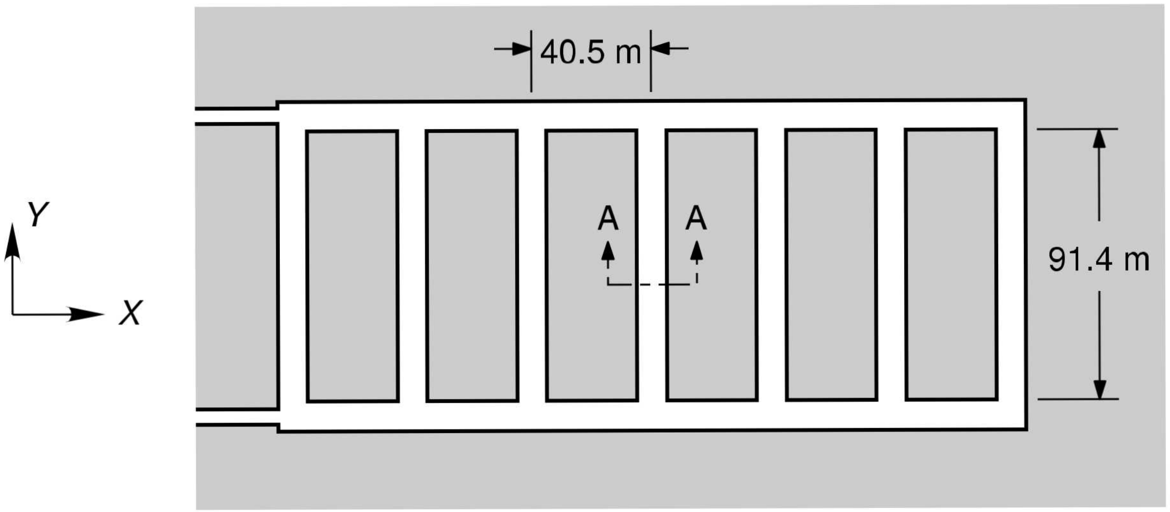
$$\bar{\sigma} = \sqrt{3\, J_2}$$

Equivalent Viscoplastic Strain Rate

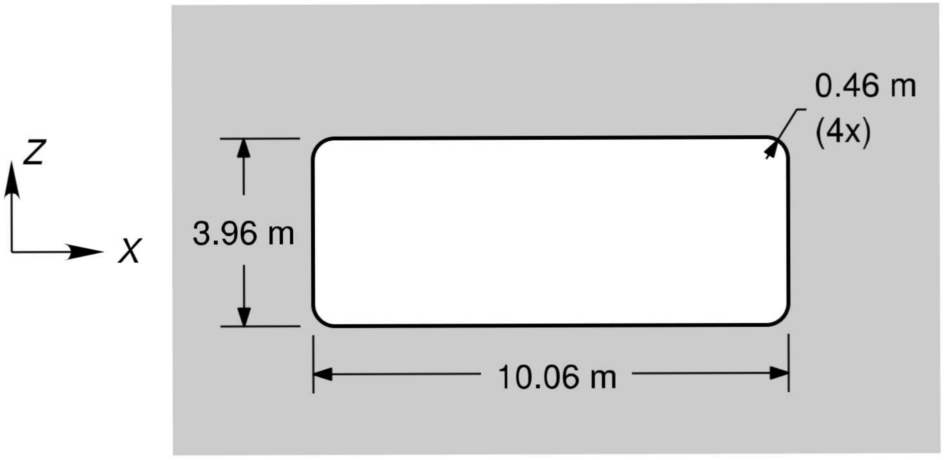
$$\dot{\bar{\varepsilon}}^{\text{vp}} = \sum_{i=1}^{2} A_i \left(\frac{\bar{\sigma}}{\mu} \right)^{n_i}$$

Panel Layout

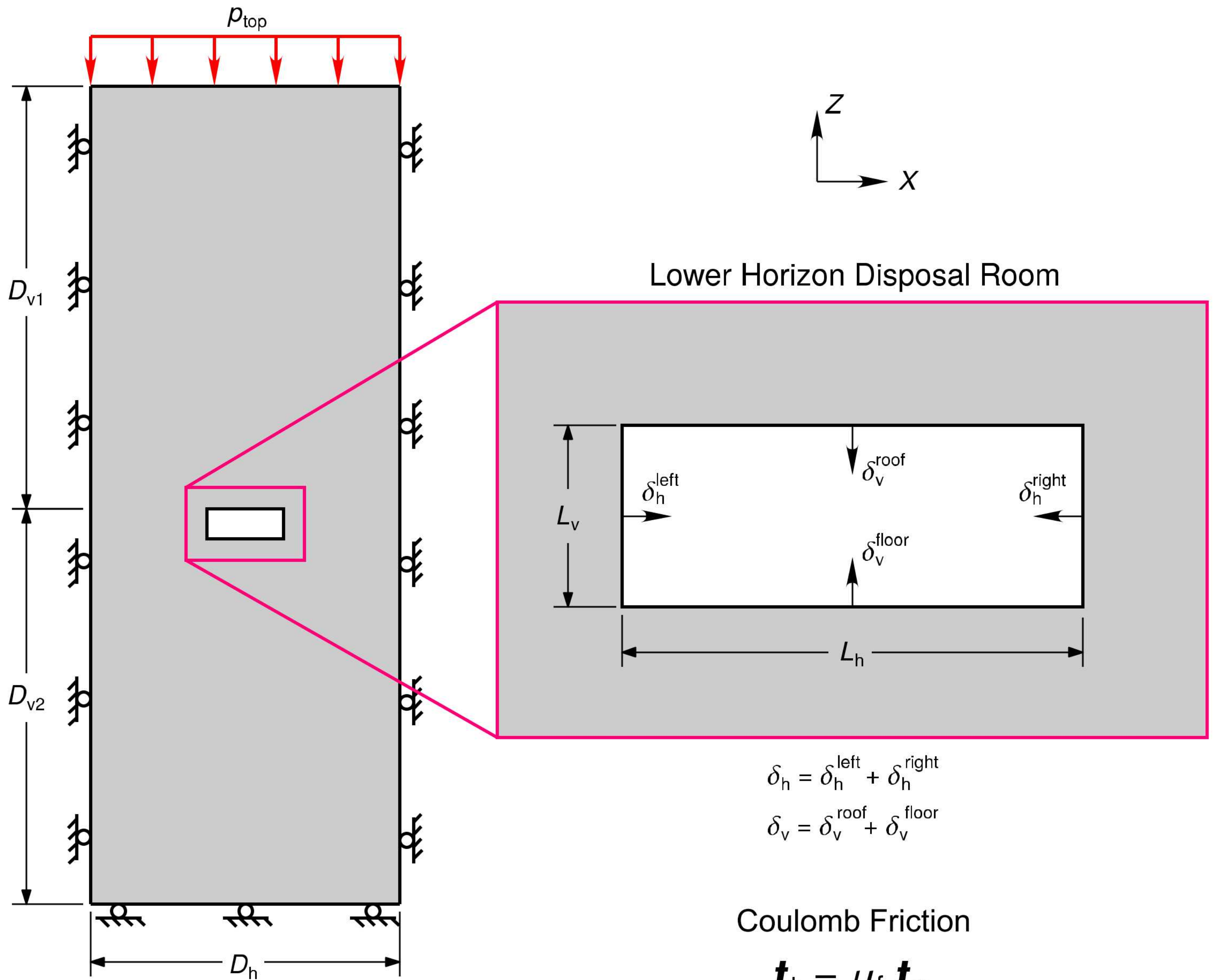
Plan View



Section A-A



Creep Closure Simulation Setup



$$\delta_h = \delta_h^{left} + \delta_h^{right}$$

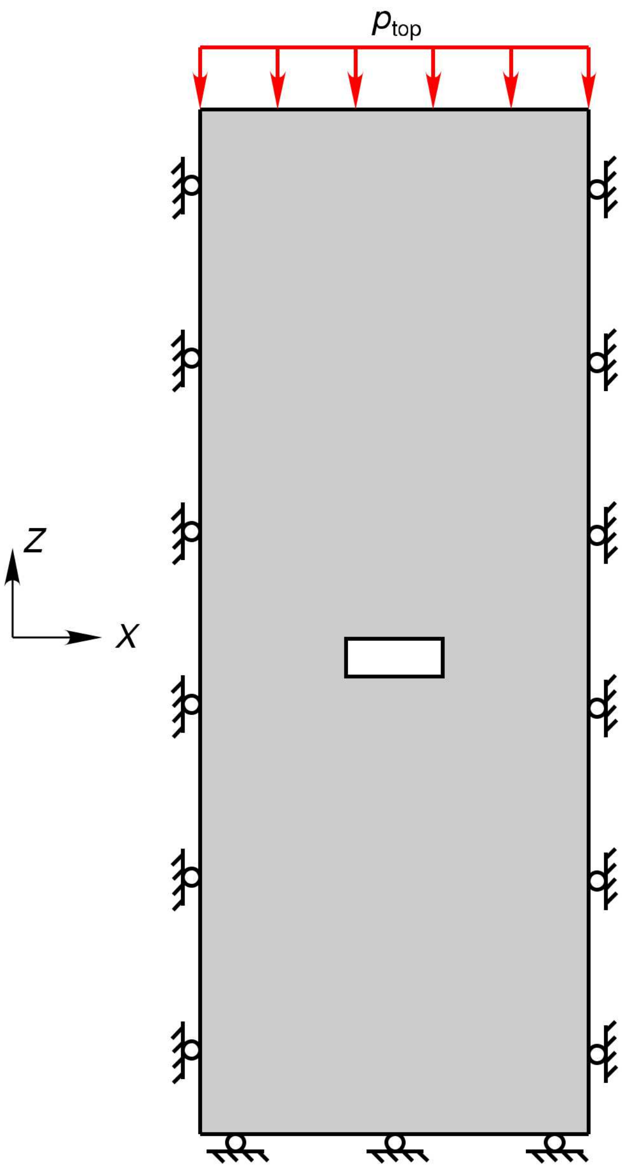
$$\delta_v = \delta_v^{roof} + \delta_v^{floor}$$

Coulomb Friction

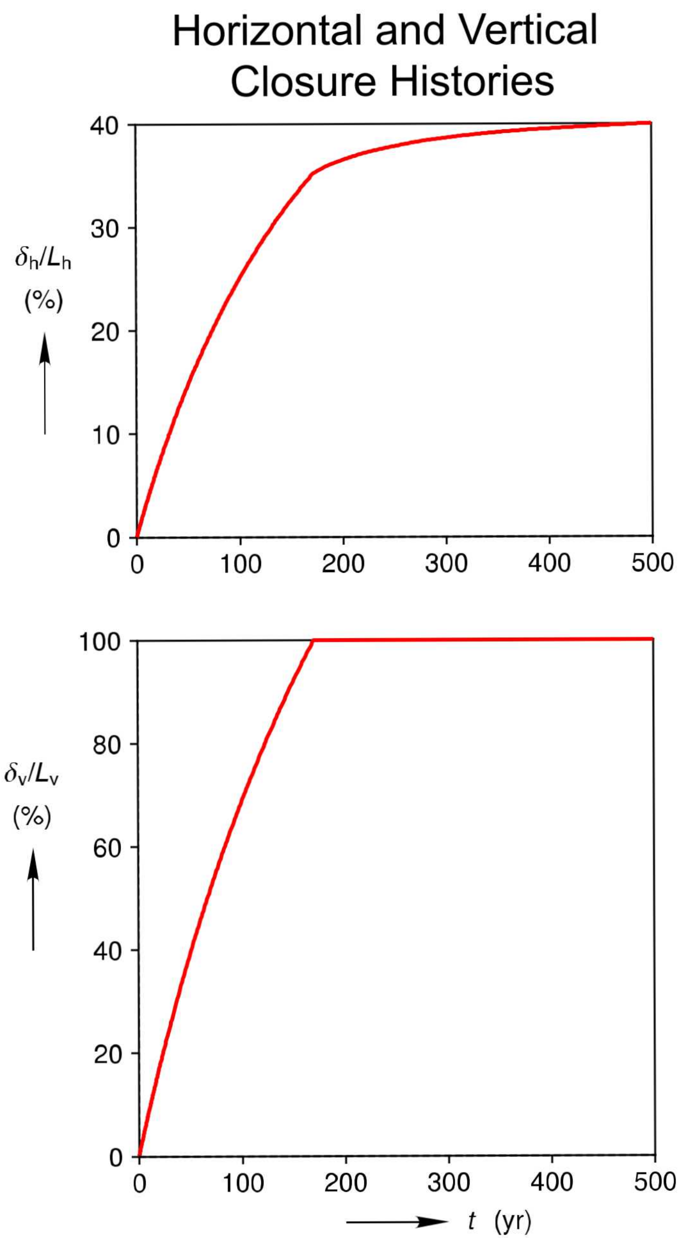
$$\boldsymbol{t}_t = \mu_f \, \boldsymbol{t}_n$$

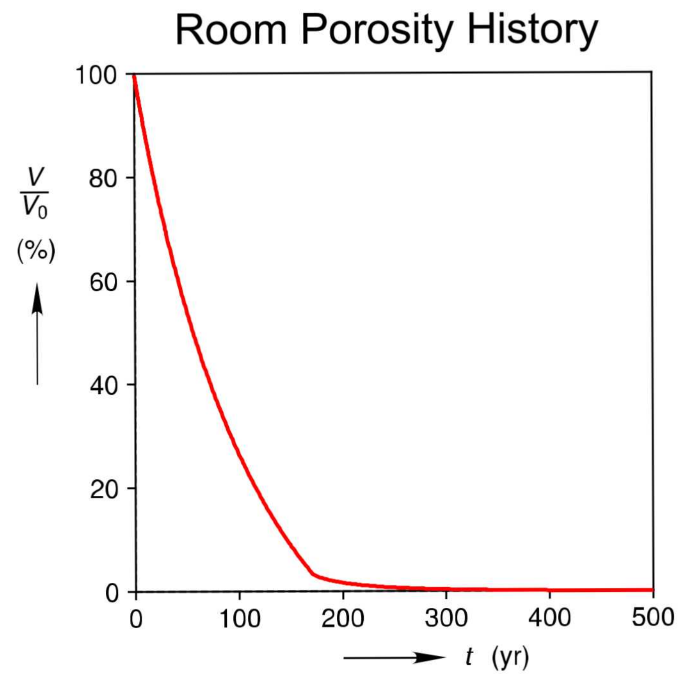
Simulation Initialization

1. Initialize rock mass with a lithostatic stress field.
2. Apply a lithostatic pressure to the surfaces of the room so that everything is in equilibrium.
3. Decrease the room pressure to zero over 0.01 seconds using a sinusoid function.



Finite Element Solution





Fracturing and Roof Falls

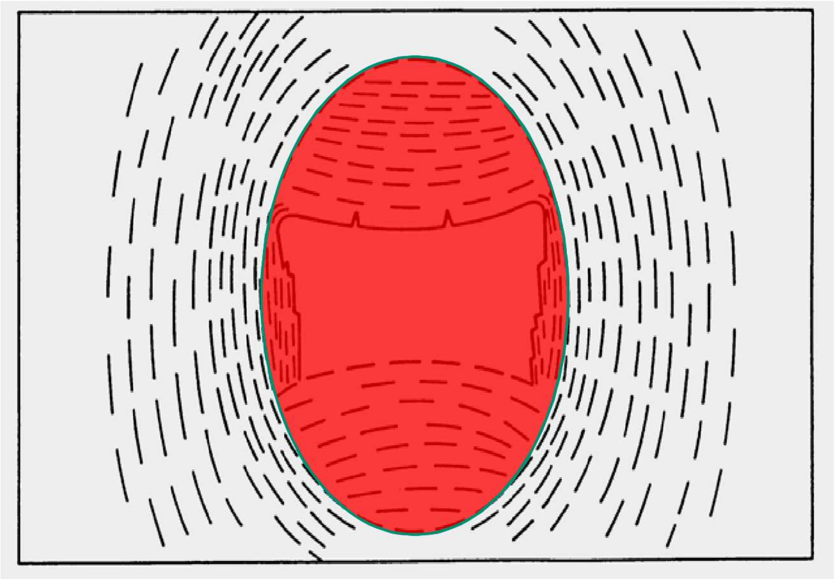
Examples of Fracture on Lower Horizon

Roof Fall on Lower Horizon

Roof Fall on Upper Horizon

Roof Fall on Upper Horizon

Fracturing around Empty Rooms

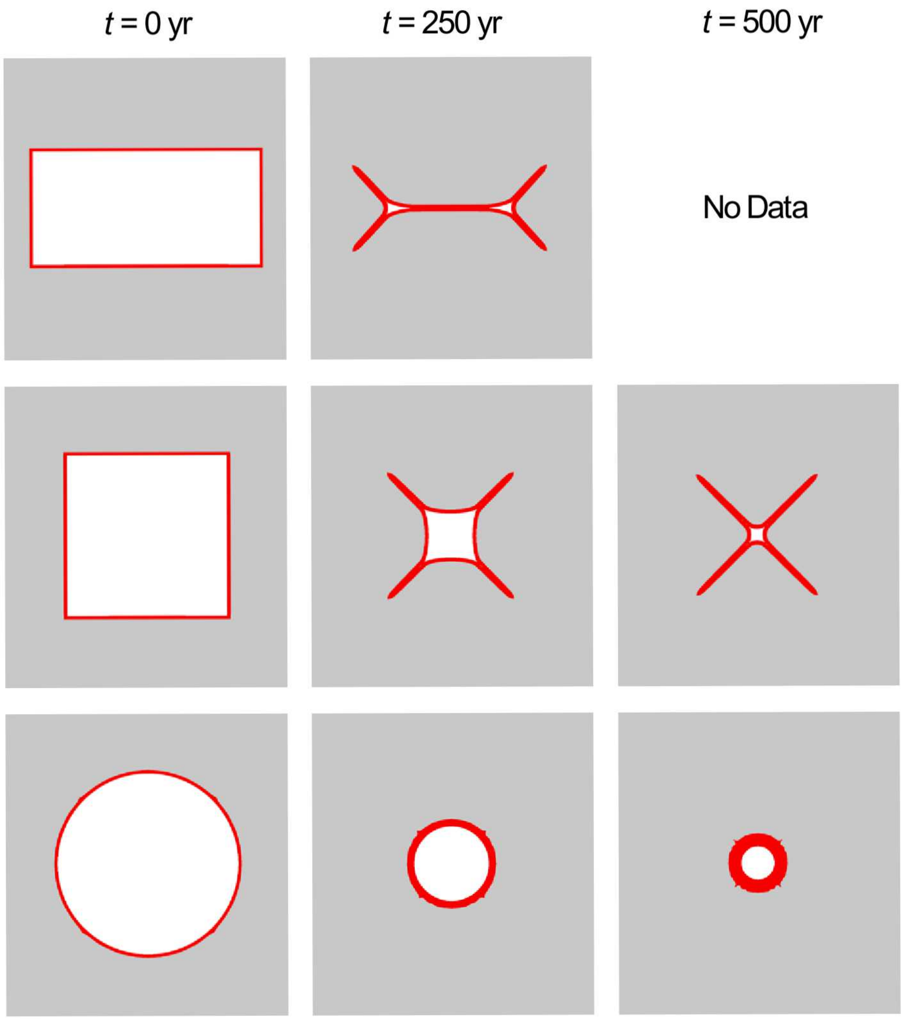


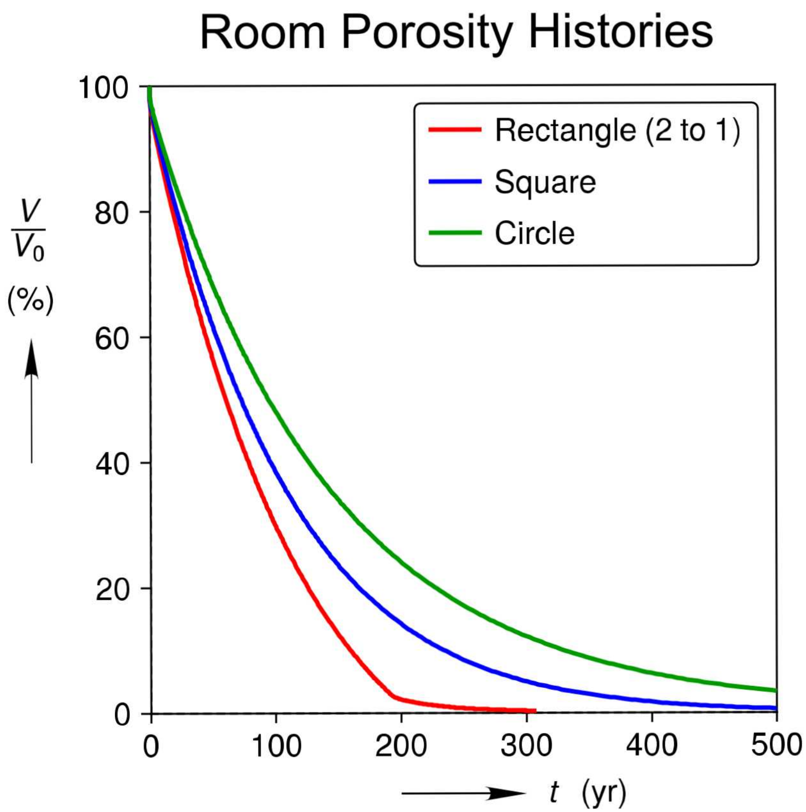
Modified after Borns, D.J. and J.C. Stormont. (1989). *Delineation of the Disturbed Rock Zone Surrounding Excavations in Salt*. SAND88-2230C. Sandia National Laboratories. Presented at the 30th U.S. Symposium on Rock Mechanics, 19-22 June 1989, Morgantown, WV, Paper ARMA-89-0353.

1. Controlling factors
   a. Deviatoric stress
   b. Confining pressure
   c. Layering
   d. Heterogeneity

2. Impact
   a. Changes the room cross-section from a rectangle to a more enduring, stable shape
   b. Causes a rubble pile with high permeability
      i. Pile size and character depend on type of roof fall

Effect of Room Shape on Creep Closure





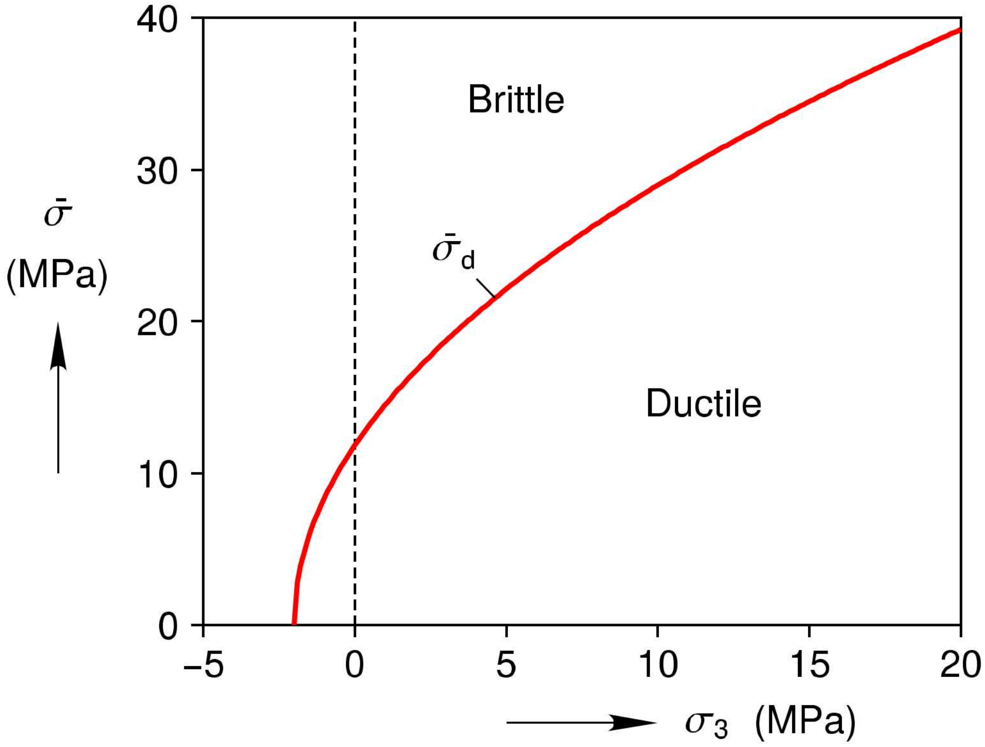
Problem Statement

1. Supplied by Sandia:
   a. Damage material model
   b. Boundary value problem

2. Assess whether a chosen meshless method can simulate 2D fracturing around a room and roof falls
   a. Show discretization convergence
   b. Record total CPU time

3. Demonstrate 3D fracturing around a room and roof falls
   a. Record total CPU time

Tentative Simple Damage Model

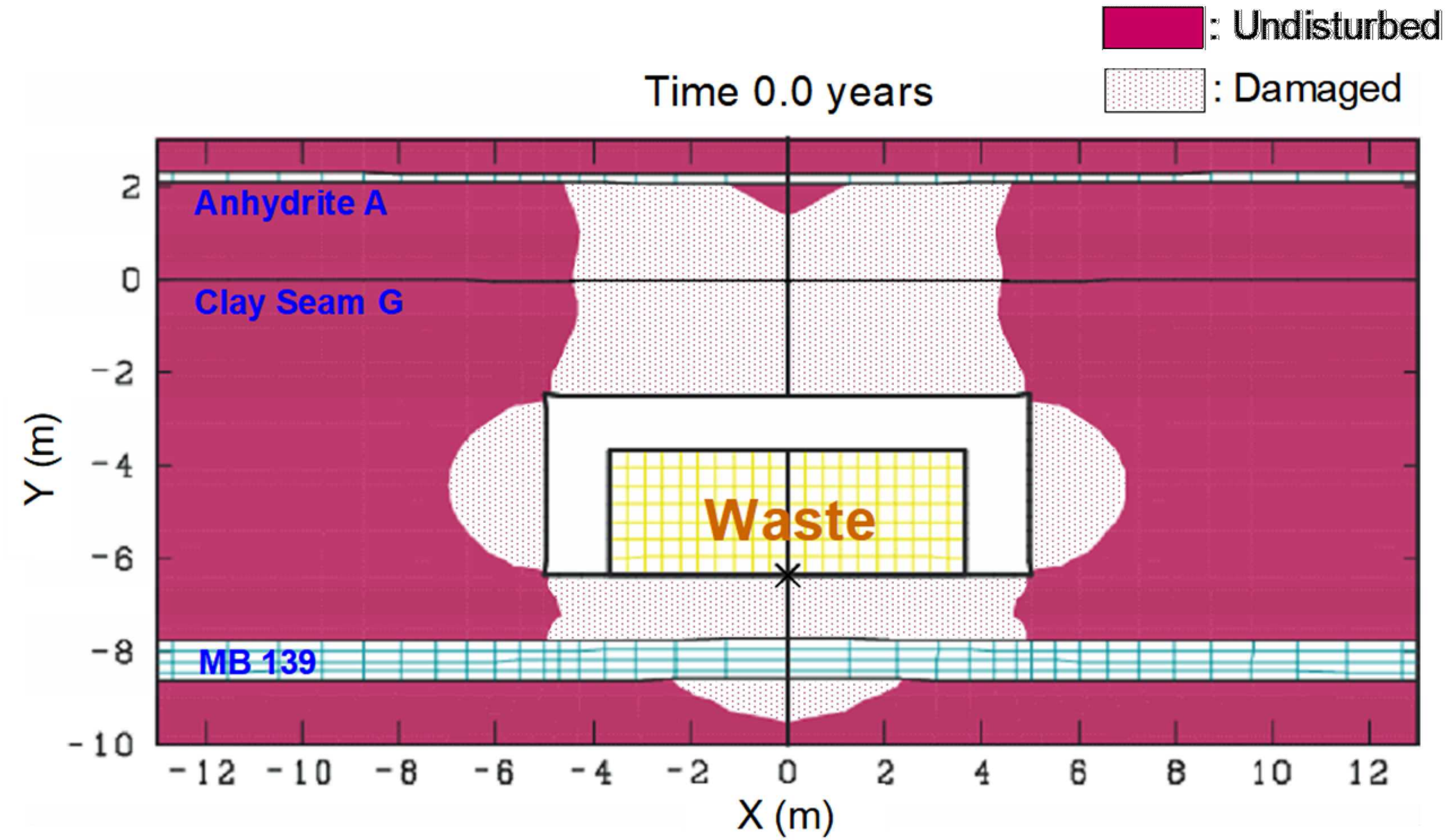


$$\bar{\sigma}_d = \sqrt{C(\sigma_3 - B)}$$

$$\dot{d} = \frac{\langle \bar{\sigma} - \bar{\sigma}_d \rangle \dot{\varepsilon}^{vp}}{D}$$

$$\dot{\varepsilon}^{vp} = \sum_{i=1}^{2} A_i \left[\frac{\bar{\sigma}}{\mu(1-d)} \right]^{n_i}$$

Estimation of Excavation Damaged Zone

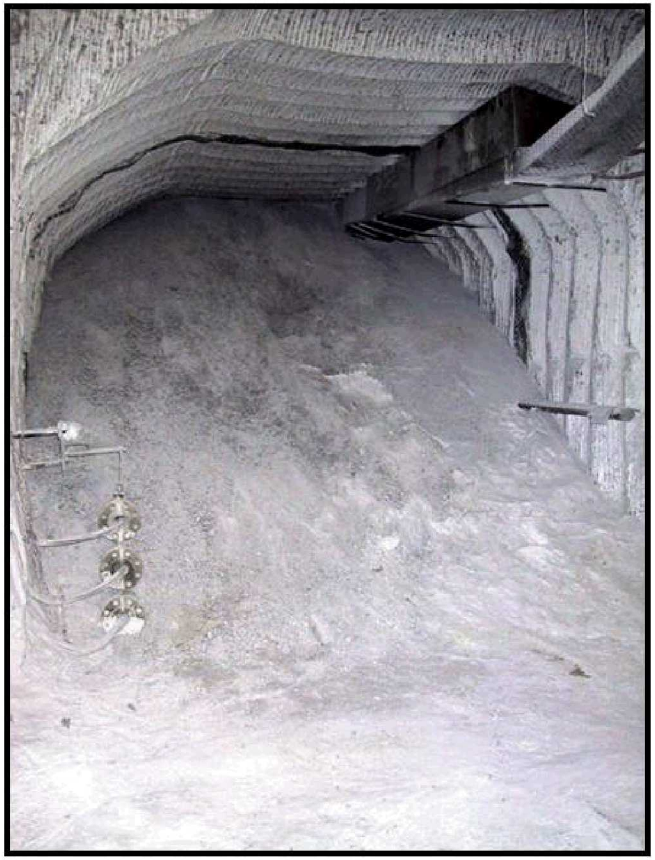


Herrick, C.G., et al. (2009). Estimating the Extent of the Disturbed Rock Zone around a WIPP Disposal Room. Paper ARMA 09-82. 43rd US Rock Mechanics Symposium, Ashville, NC. June 28 – July 1, 2009.

Rubble Pile Compaction

Crushed Salt vs. Rubble Pile

Crushed Salt

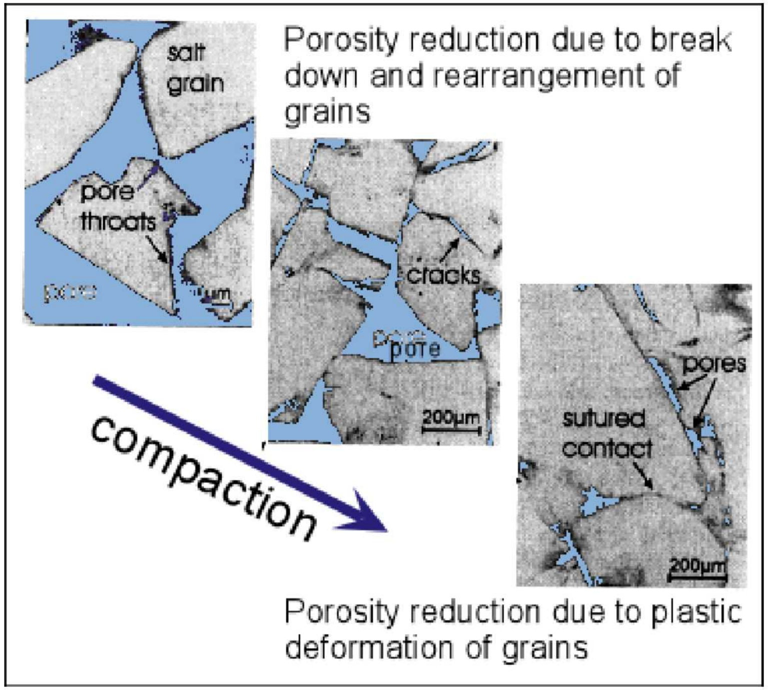


Bechthold, W., et. al. (2004). Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt (BAMBUS II Project), Final Report. European Commission, EUR 20621 EN

Rubble Piles

Rubble Pile Compaction

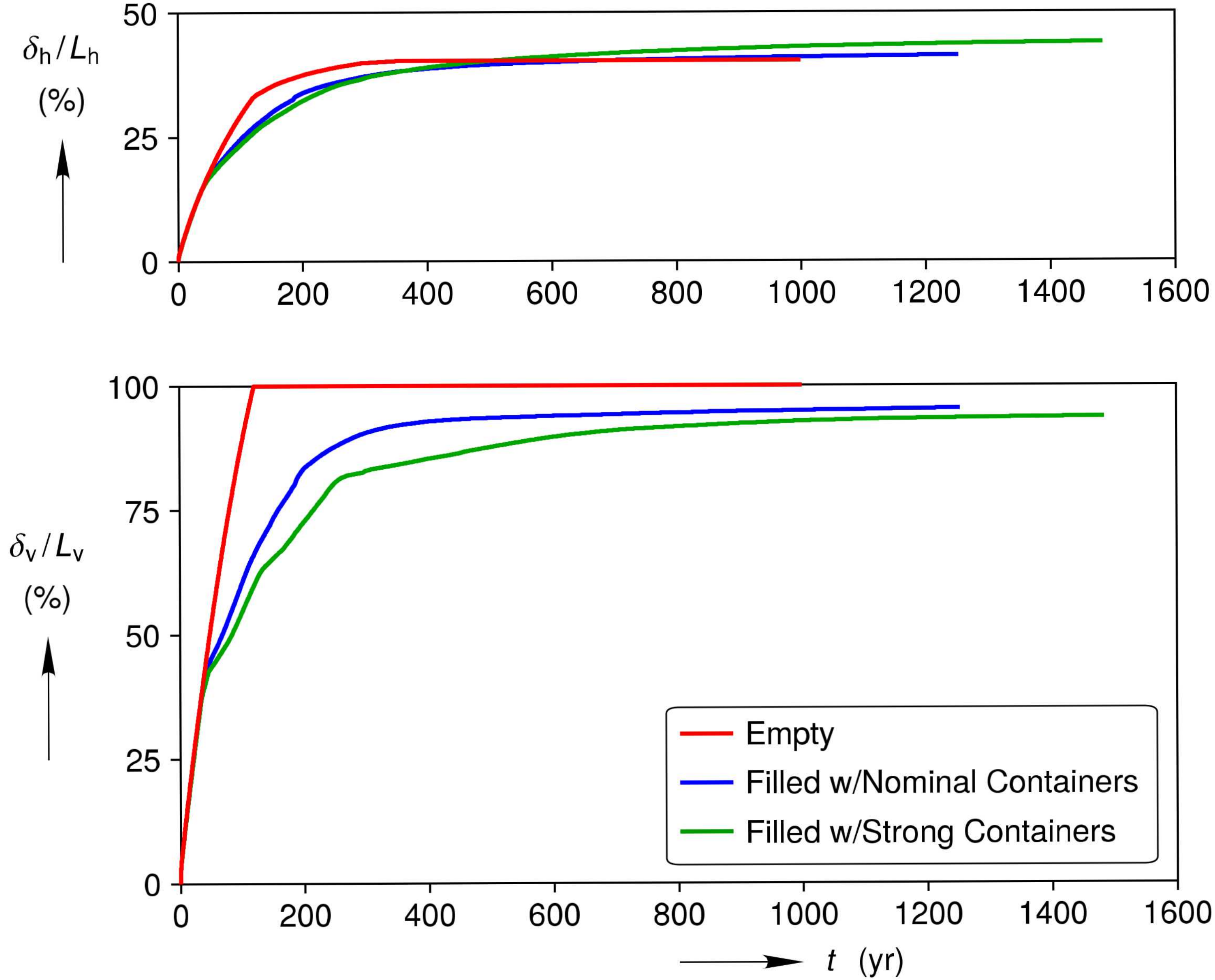
1. Important Processes
    a. Rubble reorganization
    b. Rubble fracture
    c. Dislocation Creep
    d. Pressure Solution Creep



Spangenberg (1998) (Modified)

2. Impact
    a. Compaction processes control flow pathways
        i. Two samples with same porosity can have different permeability
    b. Rubble pile supplies back pressure to surrounding rock formation
        i. Larger rubble likely compacts slower than smaller rubble

Filled Rooms Creep Closed More Slowly



Problem Statement

1. Supplied by Sandia:
   a. Boundary value problem

2. Assess whether a chosen meshless method can simulate 2D rubble pile compaction due to room closure
   a. Show room porosity discretization sensitivity
   b. Record total CPU time

3. Demonstrate 3D rubble pile compaction
   a. Compute room porosity history
   b. Record total CPU time

Time Scaling

Speeding up the Viscoplasticity

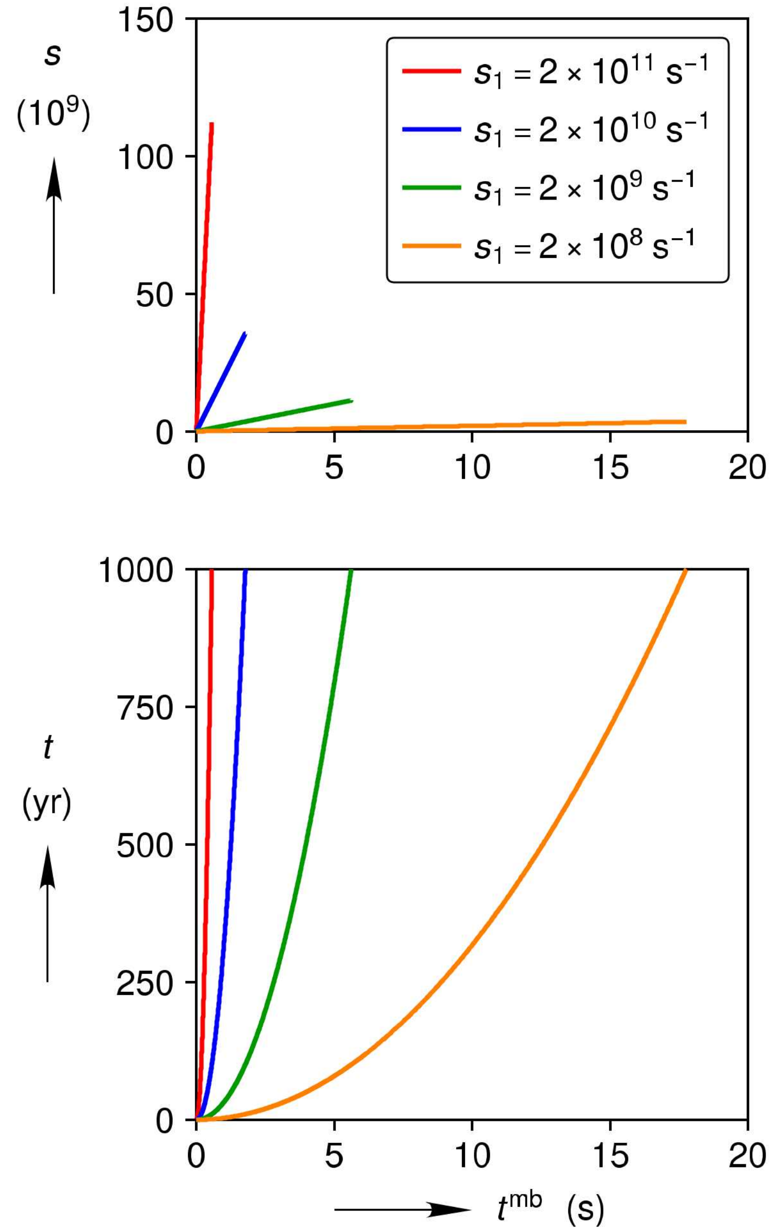
$$\dot{\varepsilon}^{\mathrm{vp}} = \sum_{i=1}^{2} A_i \left(\frac{\bar{\sigma}}{\mu}\right)^{n_i}$$

⬇

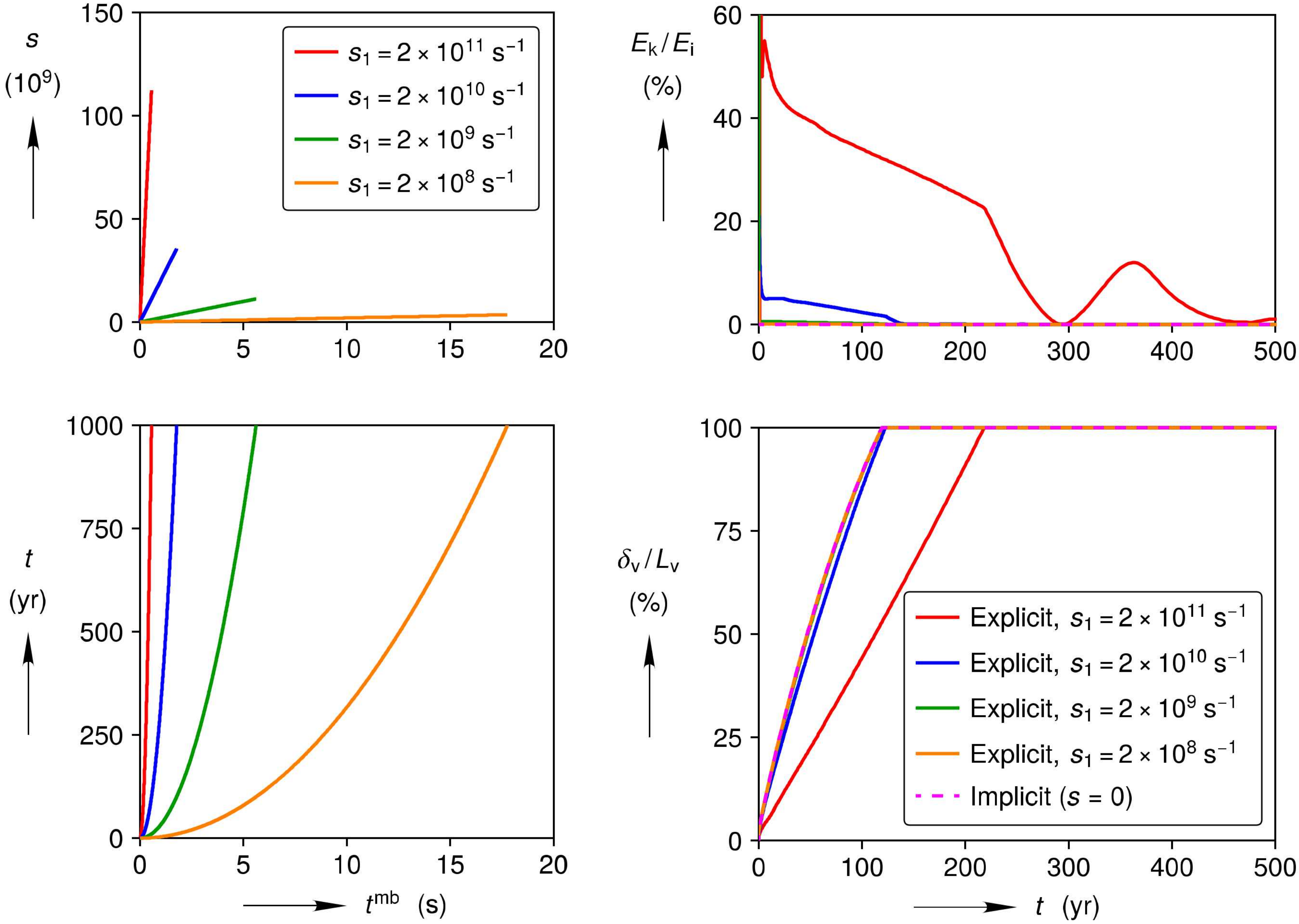
$$\dot{\varepsilon}^{\mathrm{vp}} = s \sum_{i=1}^{2} A_i \left(\frac{\bar{\sigma}}{\mu}\right)^{n_i}$$

$$\mathrm{d}t = s \, \mathrm{d}t_{\mathrm{mb}}$$

$$s = s_0 + s_1 \, t_{\mathrm{mb}}$$



Scaling Ramp Rate Selection



Dates and Deliverables

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1. WIPP Rock Mechanics Quarterly Review
   a. April 30th, 2019

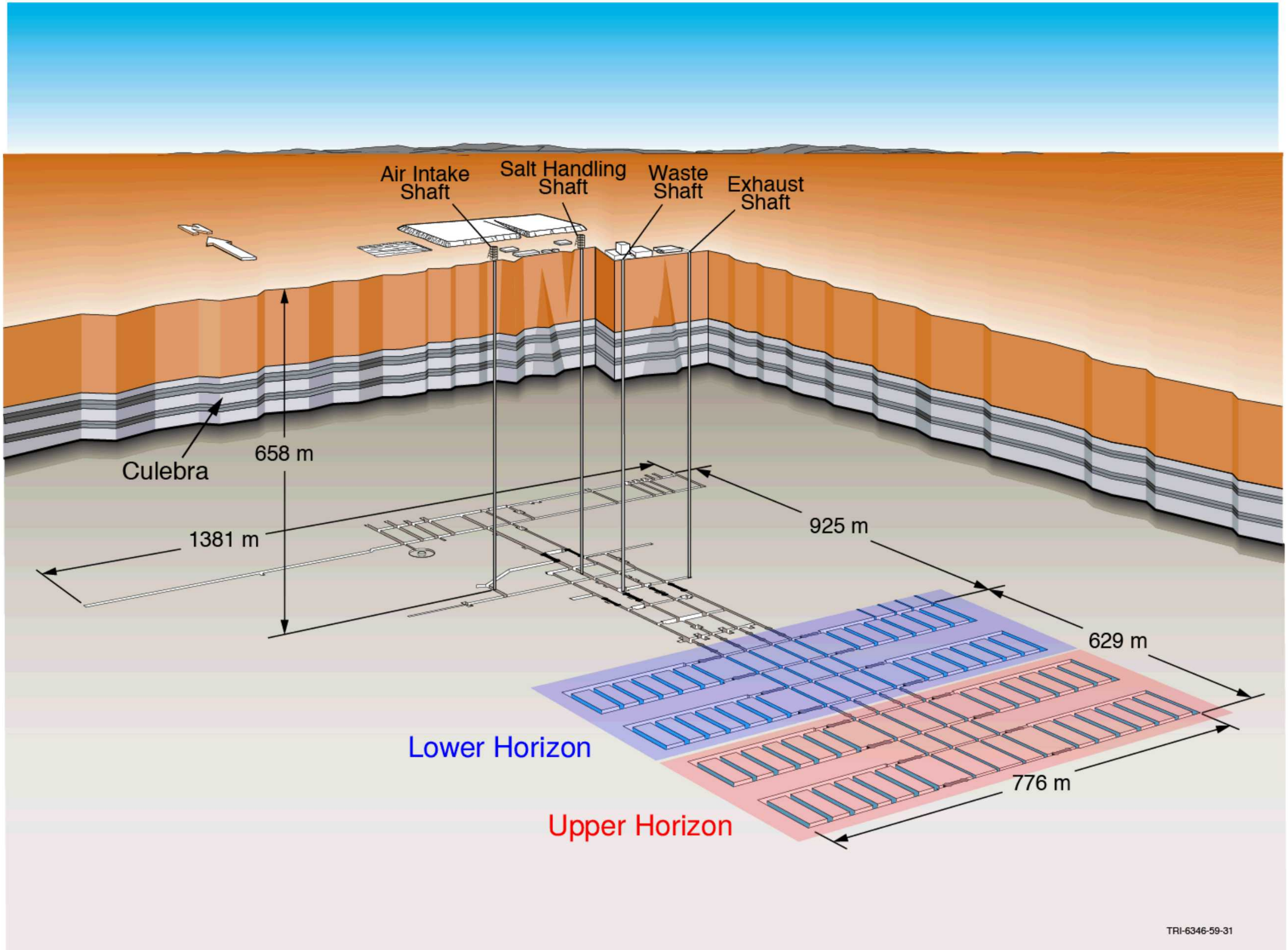
2. US / German Workshop on Salt Repository Research, Design, and Operation
   a. May 28th-30th, 2019

3. Final Report
   a. Sufficient detail to reproduce results at Sandia
   b. Due with final invoice on September 13th, 2019

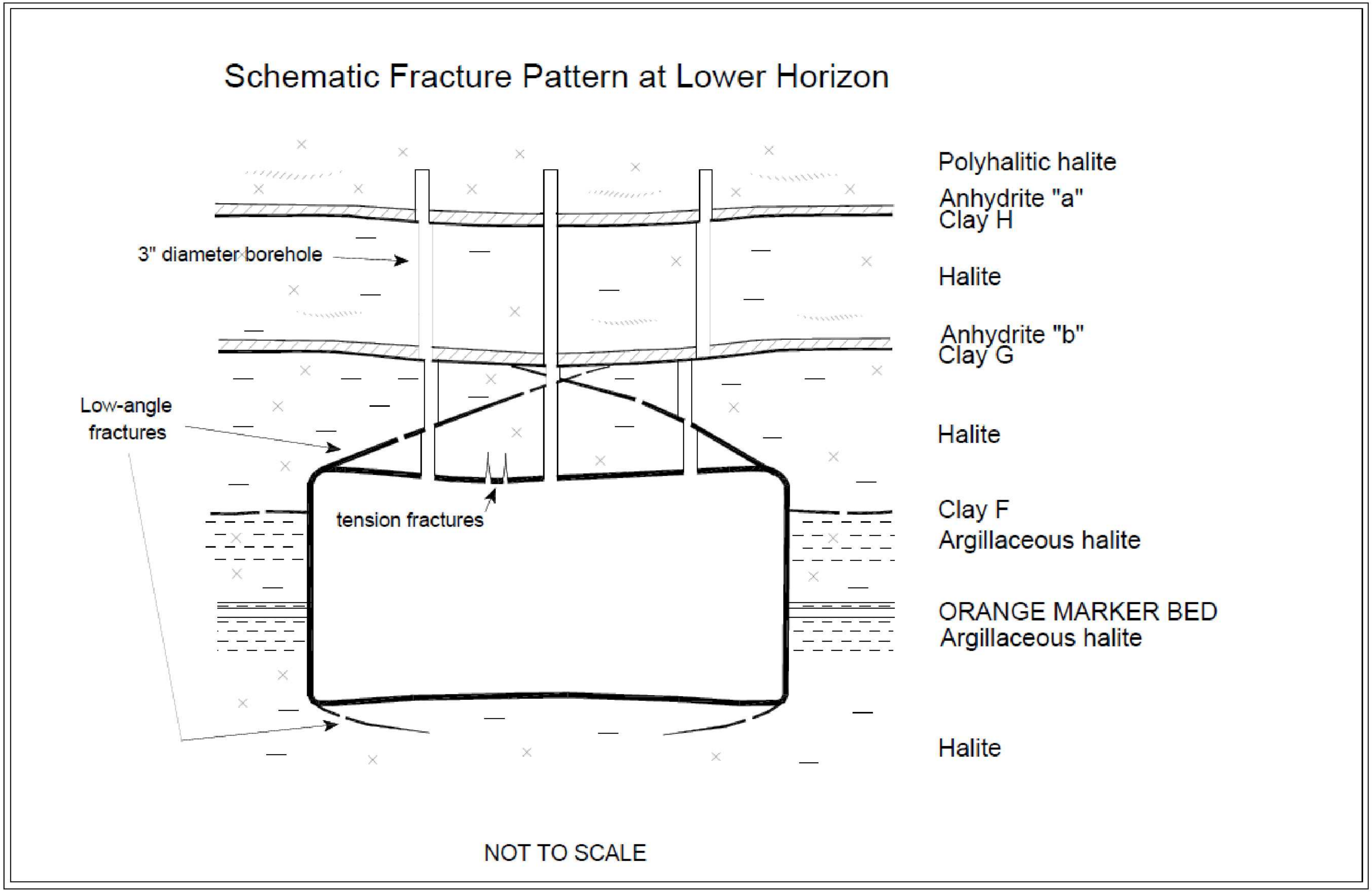
4. Present results at workshop in Albuquerque?
   a. Date?

Extra Slides

Upper vs. Lower Horizon

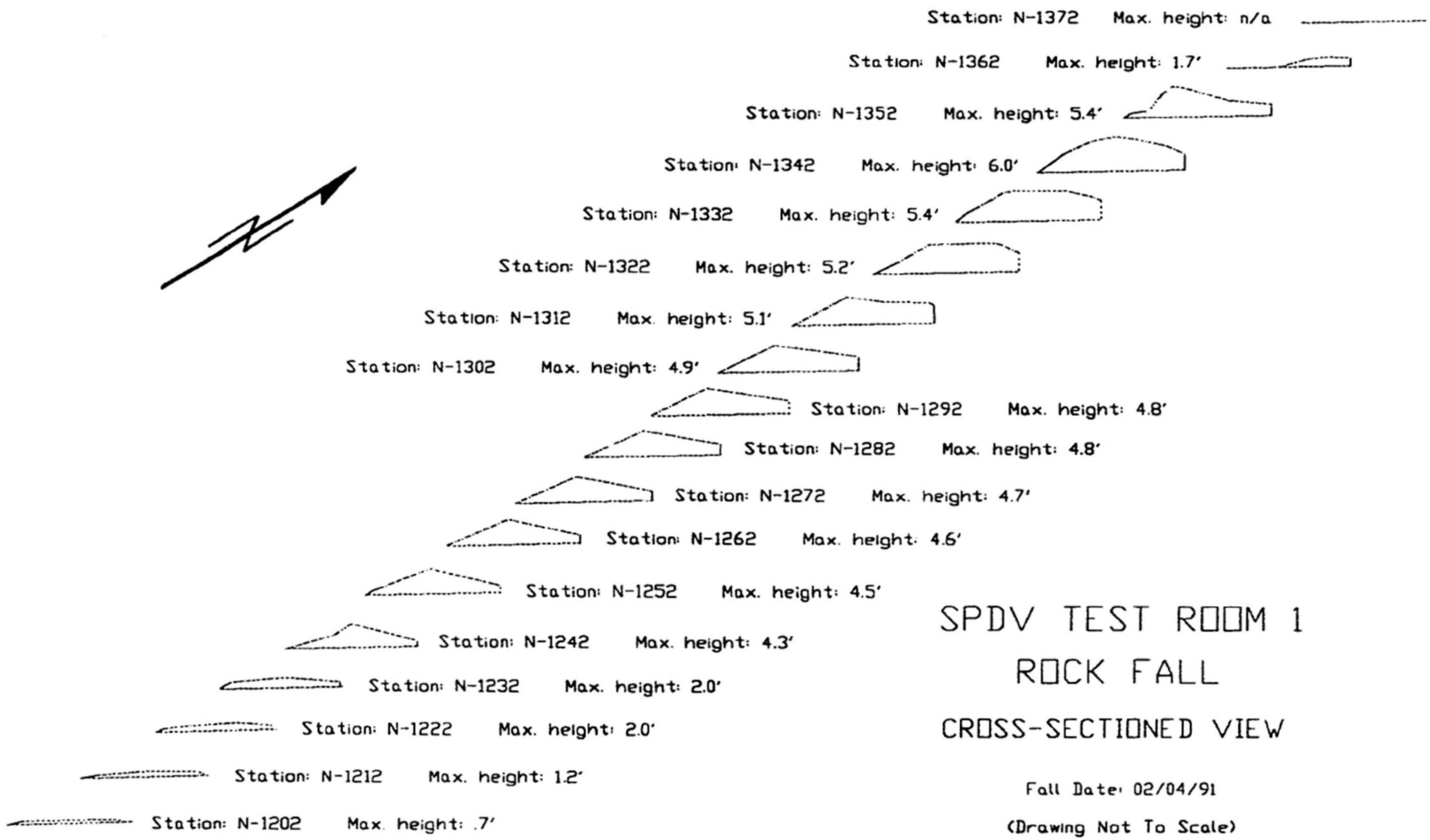


Typical Fractures on Lower Horizon



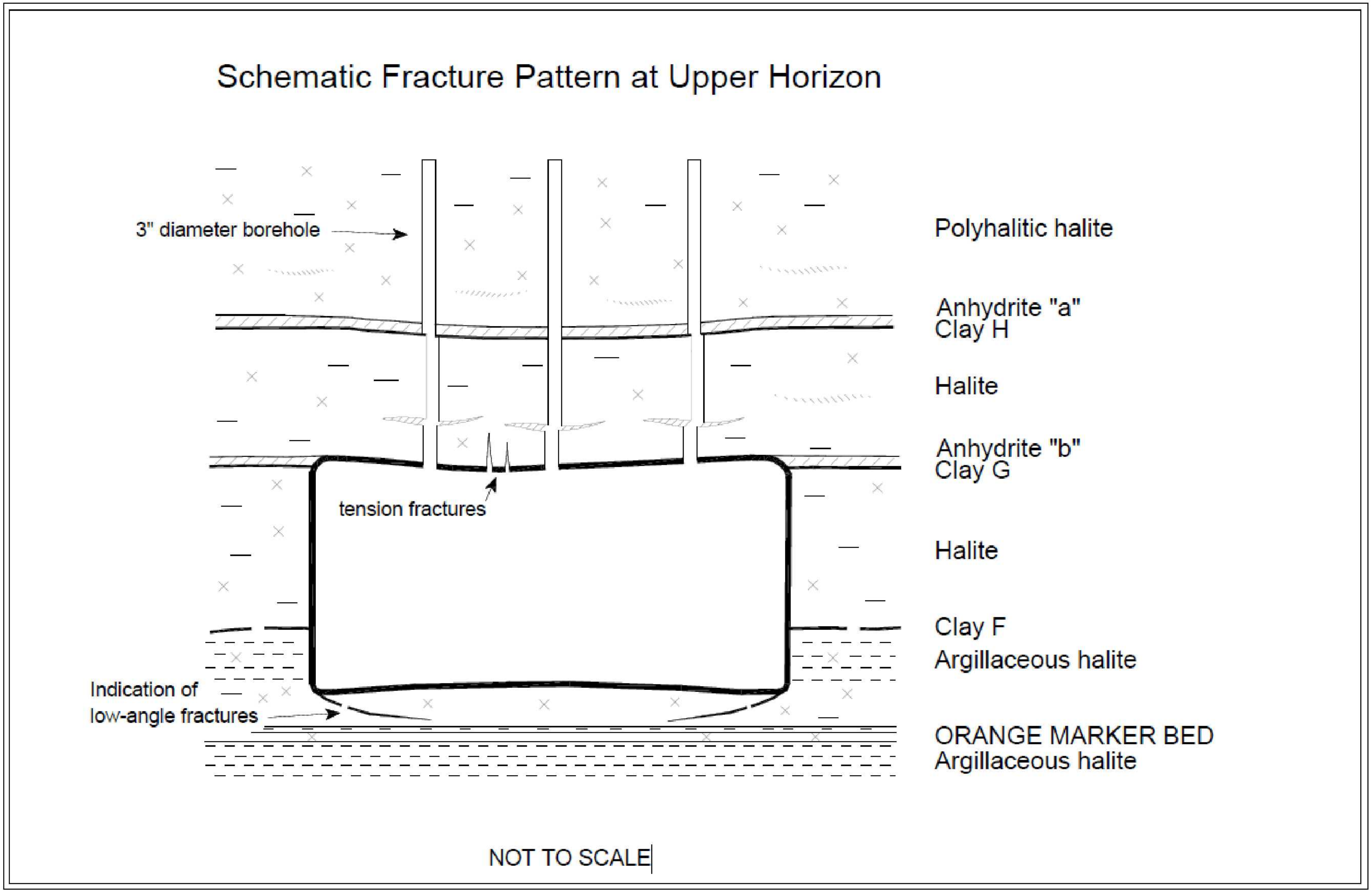
DOE (2016) Waste Isolation Pilot Plant Geotechnical Analysis Report, Vol. 1. DOE/WIPP-16-3569

Fallen Block Shapes



U.S. DOE. (1993). The Current Bases for Roof Fall Prediction at WIPP and a Preliminary Prediction for SPDV Room 2. DOE/WIPP 93-033.

Typical Fractures on Upper Horizon



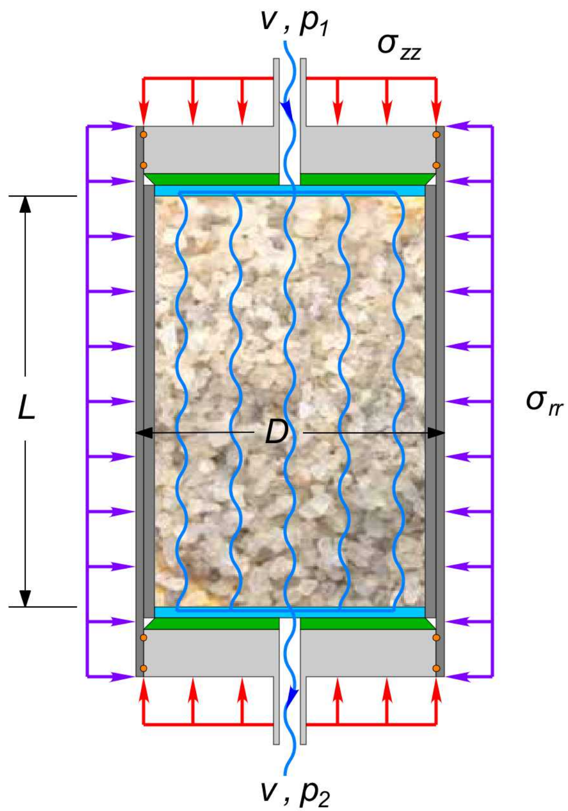
DOE (2016) Waste Isolation Pilot Plant Geotechnical Analysis Report, Vol. 1. DOE/WIPP-16-3569

Crushed Salt Laboratory Testing

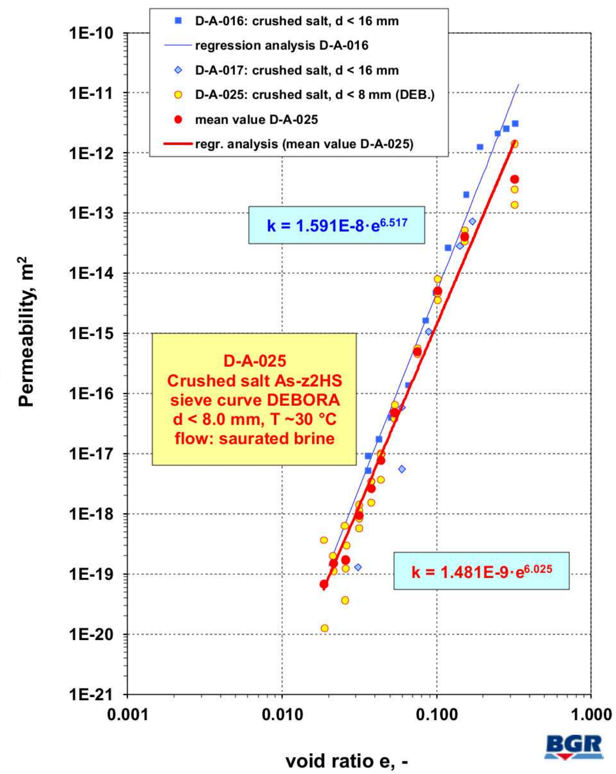
Specimen preparation

Photo courtesy of Scott Broome

Triaxial compression while measuring permeability



Permeability vs. Void Ratio (Porosity)

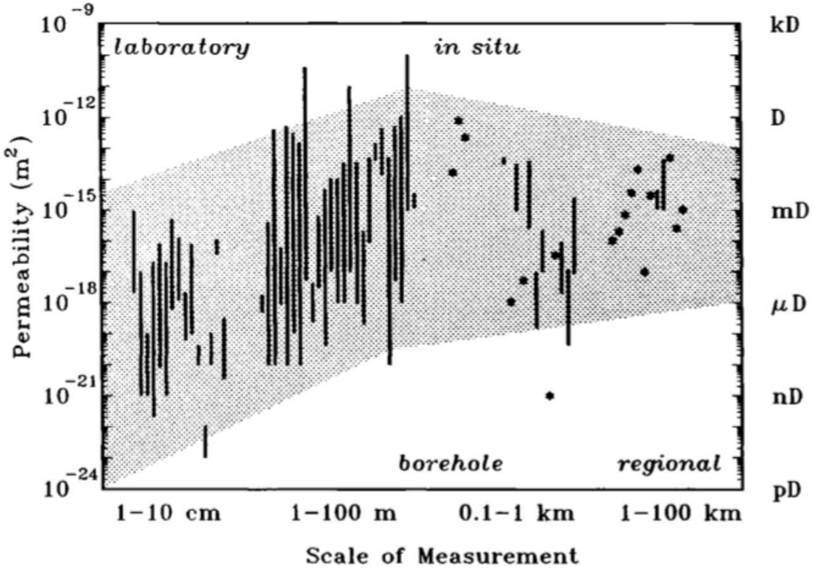


Kroehn, KP, et al. Mechanical and hydraulic behaviour of compacting crushed salt backfill at low porosities. Project REPOPERM. Phase 2. GRS GmbH. GRS – 450. 2017

Scale Effects

Compaction Scale Effect

Permeability Scale Effect



Clauser, C. (1992). Permeability of crystalline rocks. Eos, Transactions American Geophysical Union, 73(21), 233-238.