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Ongoing Research Related to Open Room Closure

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Sandia National Laboratories

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Outline

- Improvements to Creep Closure Modeling
- Mechanical Behavior of Bedding Plane Interfaces
- Damage and Fractures
- Healing, Reconsolidation, and Permeability

Geomechanics Research Plans

- Reconsideration of Mechanisms for Room Closure at WIPP
  - Experimental Investigation: TP 17-02
  - Analytical Investigation: AP-178
- Update of the WIPP Constitutive Model for Intact Salt
  - Experimental Investigations: conducted in Germany and the US
  - Modeling Investigation: AP-179
- Mechanical Behavior of Bedding Plane Interfaces
  - Experimental Investigation: TP 17-03
  - Analytical Investigation: in preparation
- Granular Salt Reconsolidation
  - Experimental Investigation: TP 17-04
  - Analytical Investigation: in preparation

Geomechanics Research Plans

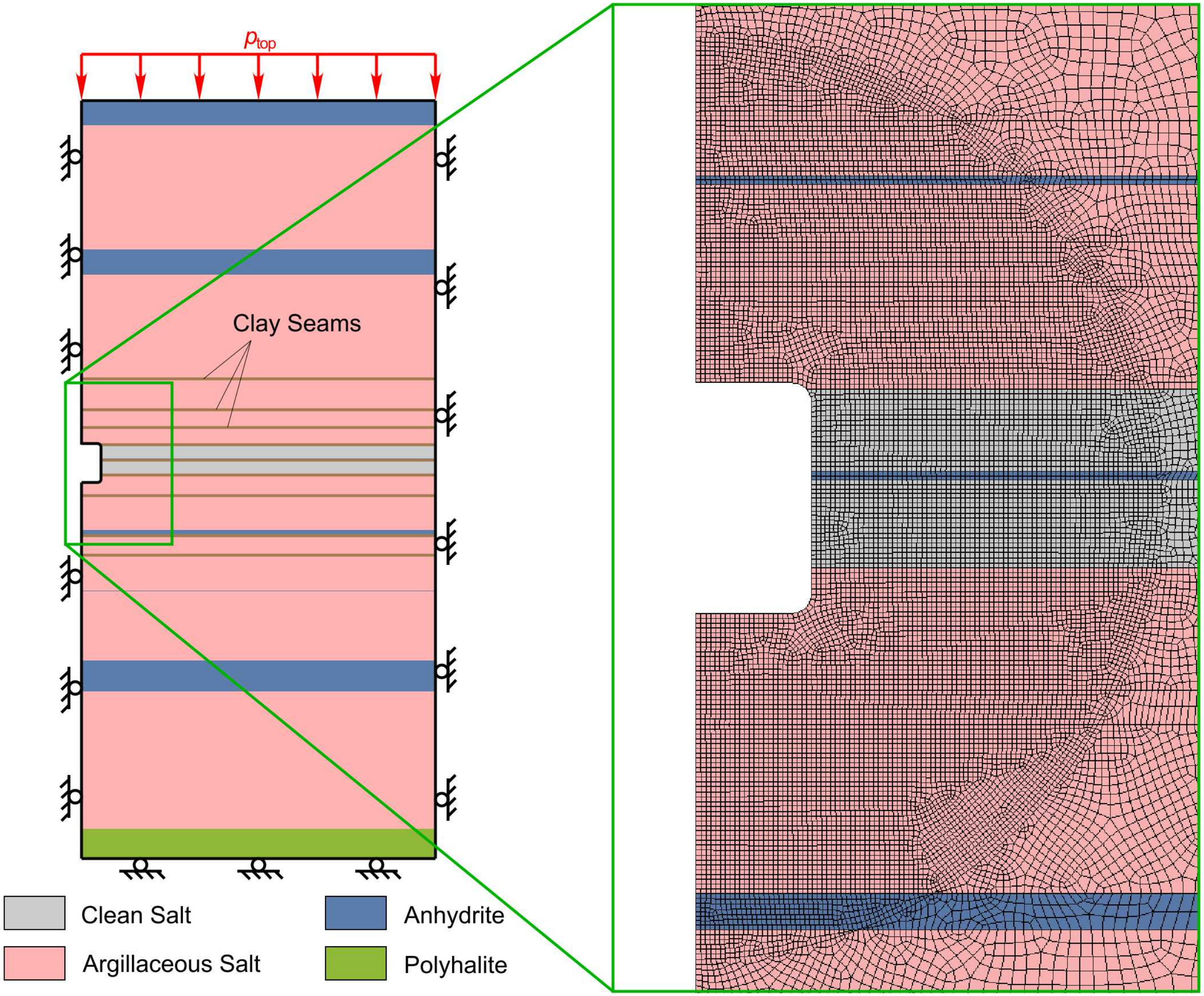
- Waste Constitutive Model
  - Experimental Investigation: TP 08-01
  - Analytical Investigation: AP-180

Improvements to Creep Closure Modeling

History of WIPP Creep Closure Modeling

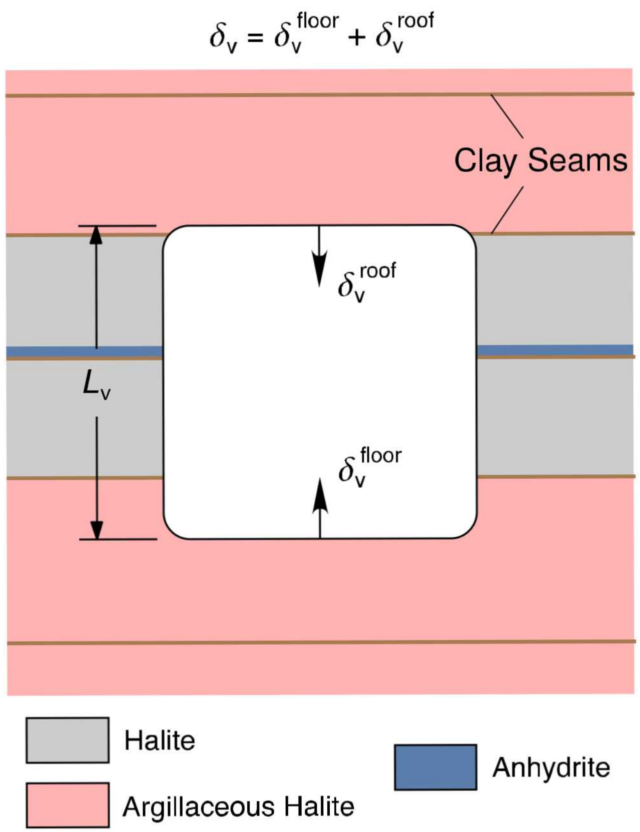
- In the 1980's, creep closure models calibrated against laboratory experiments under-predicted closure by roughly 3X.
  - Elastic stiffness reduced by 12.5X.
- Munson et al. (1989) tuned the geomechanical model to match Room D's closure.
  - Six different changes to the model, including neglecting anhydrite layers.
- Further research into creep closure came to a halt in early 1990's.
- Interest in creep closure reignited recently by US/German Joint Projects on Salt Geomechanics.

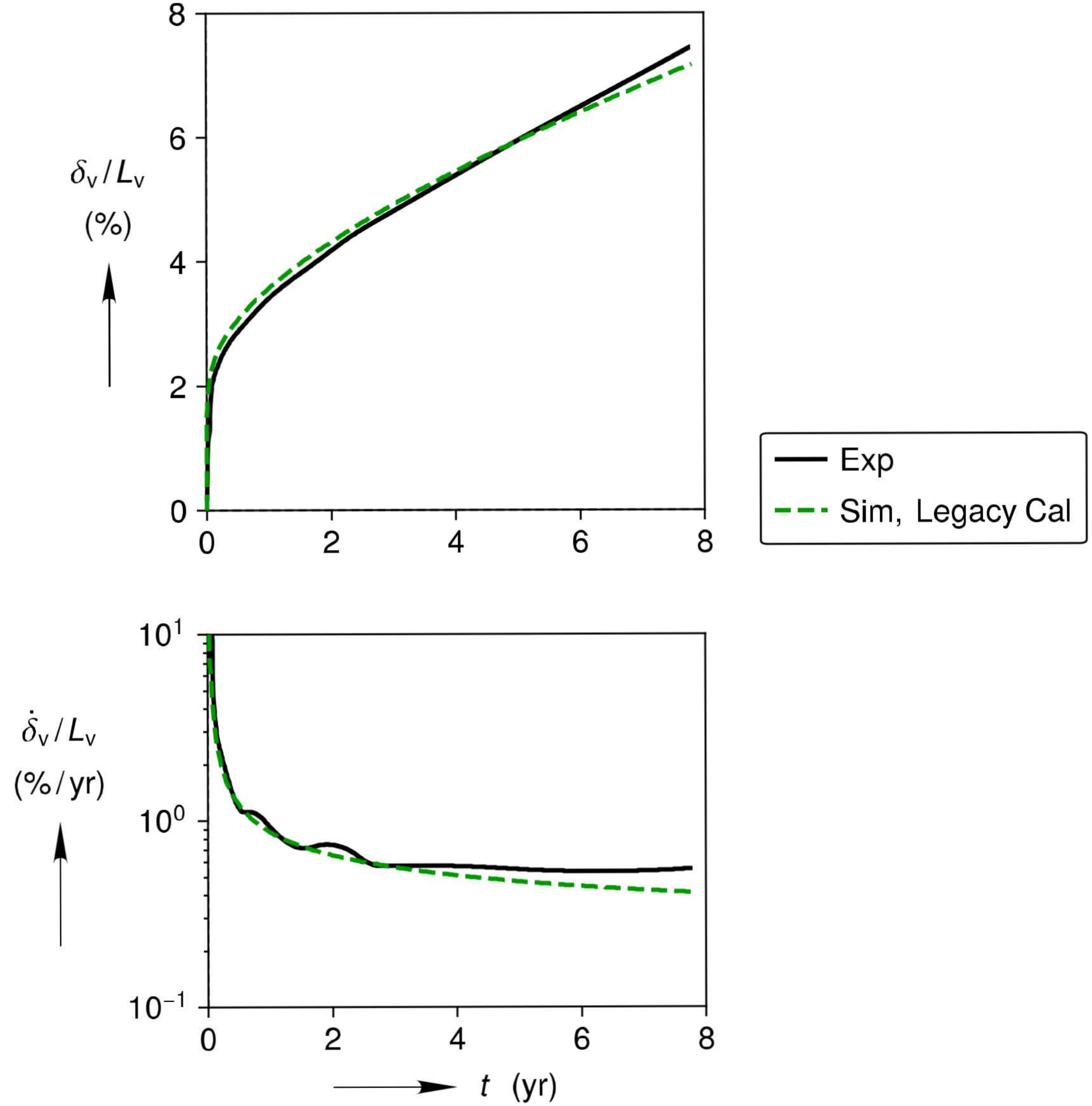
Room D Simulation Setup



Reedlunn, B., October 2016. Reinvestigation into closure predictions of Room D at the Waste Isolation Pilot Plant. Tech. Rep. SAND2016-9961, Sandia National Laboratories, Albuquerque, NM, USA.

Room D Simulations





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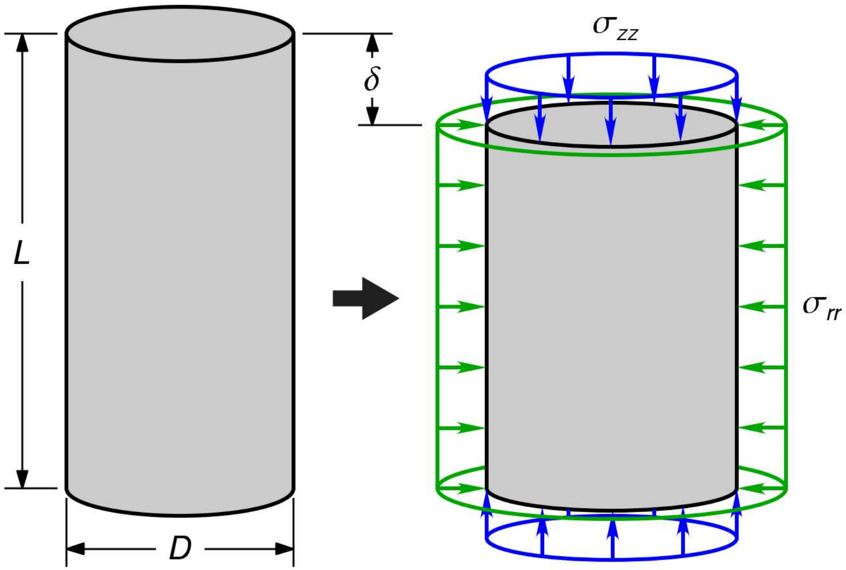
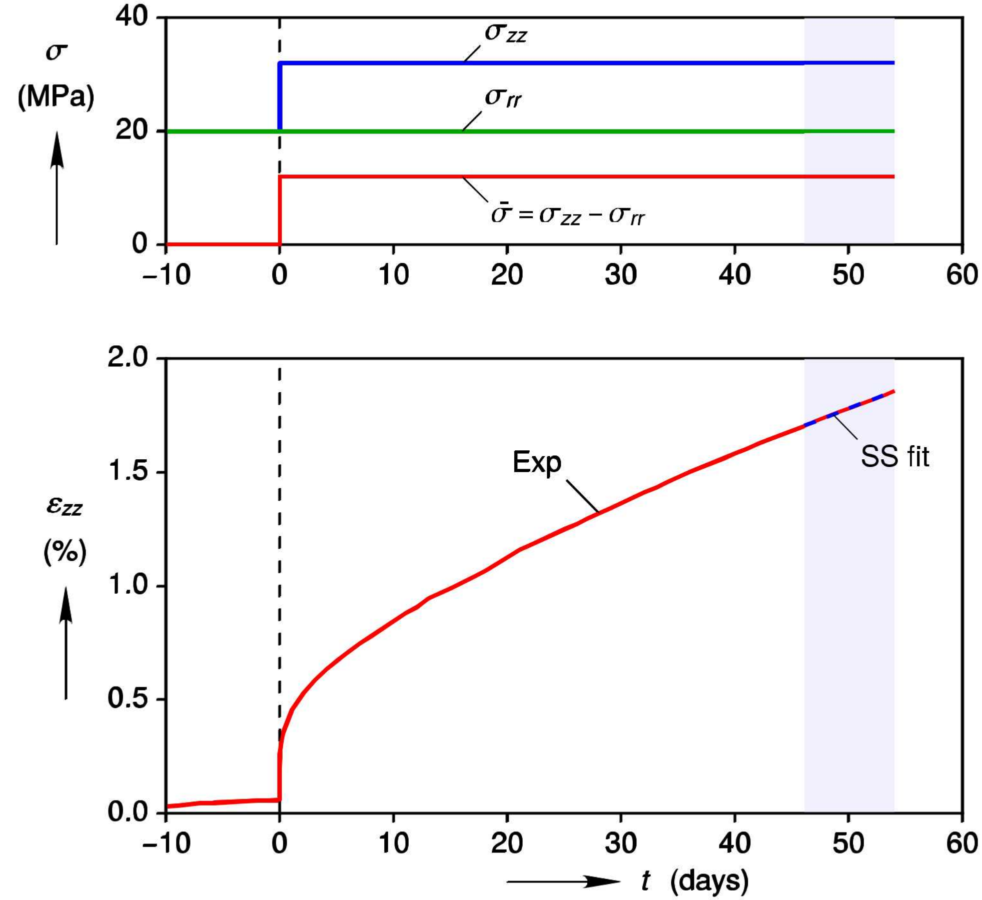
Laboratory Creep Tests



$$\frac{L}{D} = 2$$

$$\varepsilon_{zz} = \ln\left(1 + \frac{\delta}{L}\right)$$



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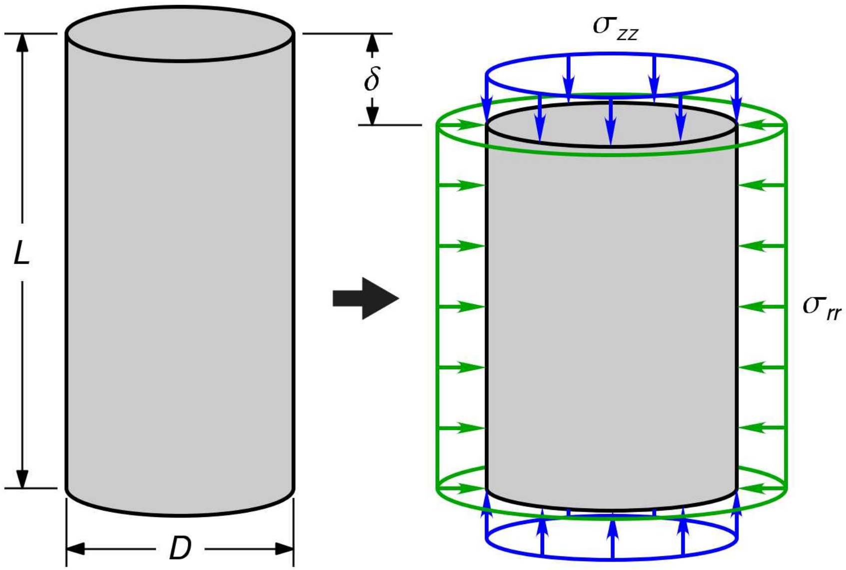

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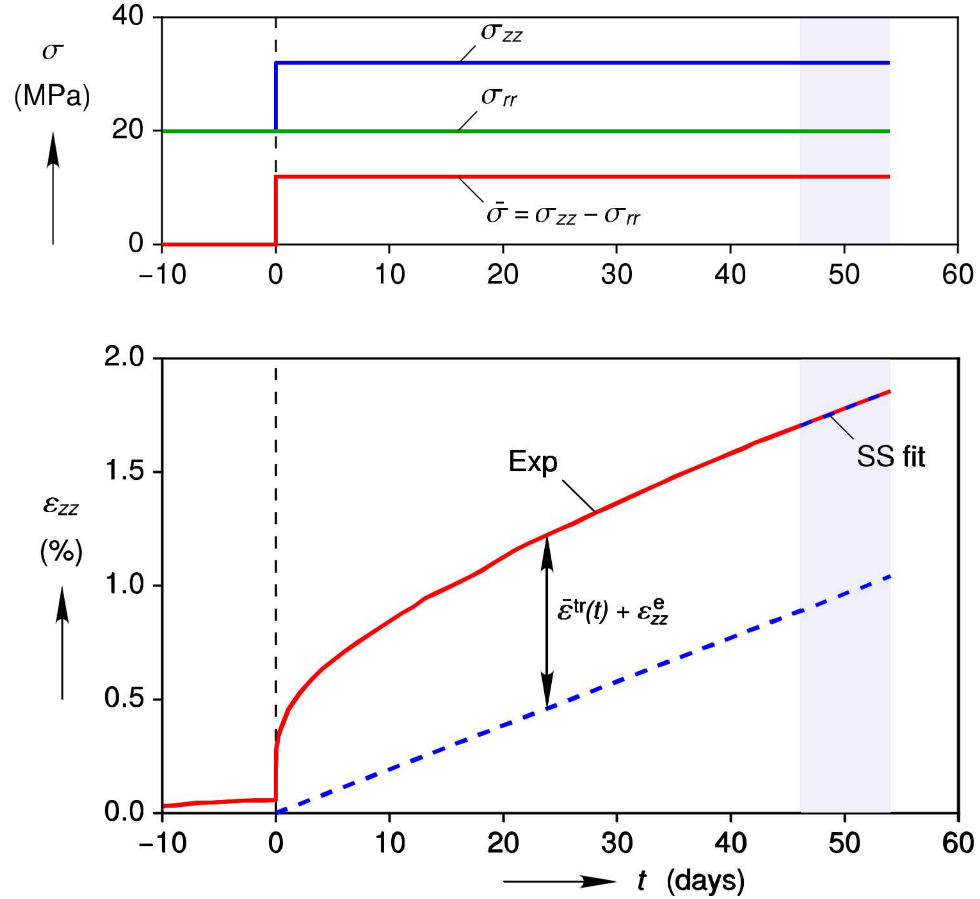

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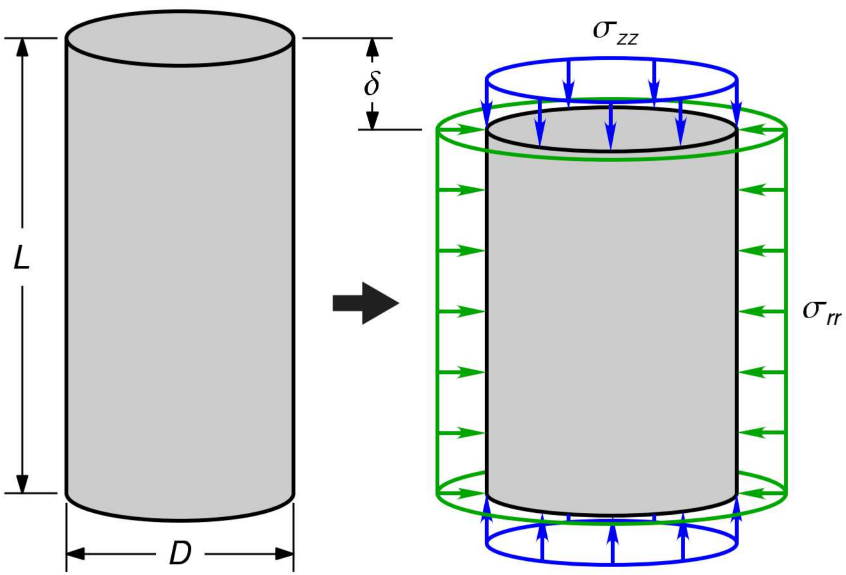

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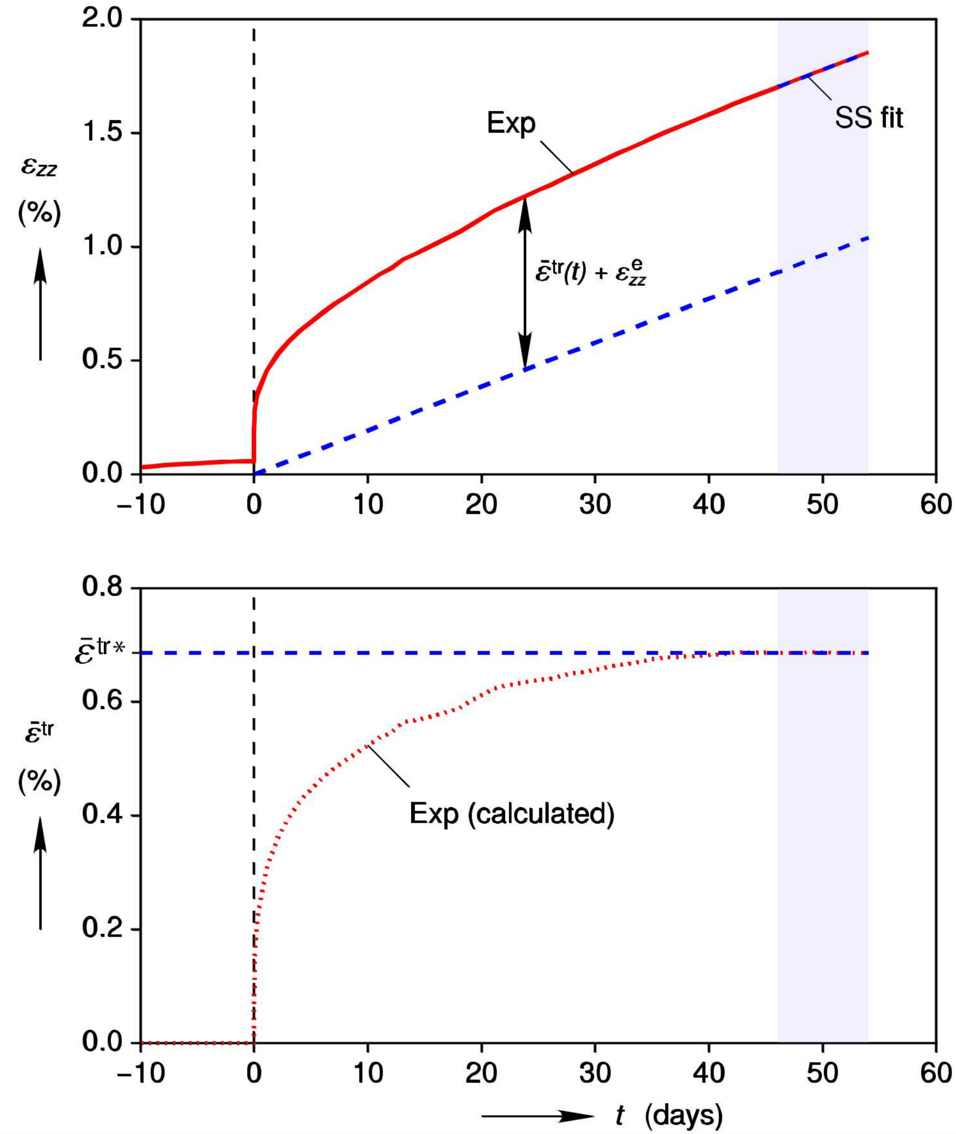

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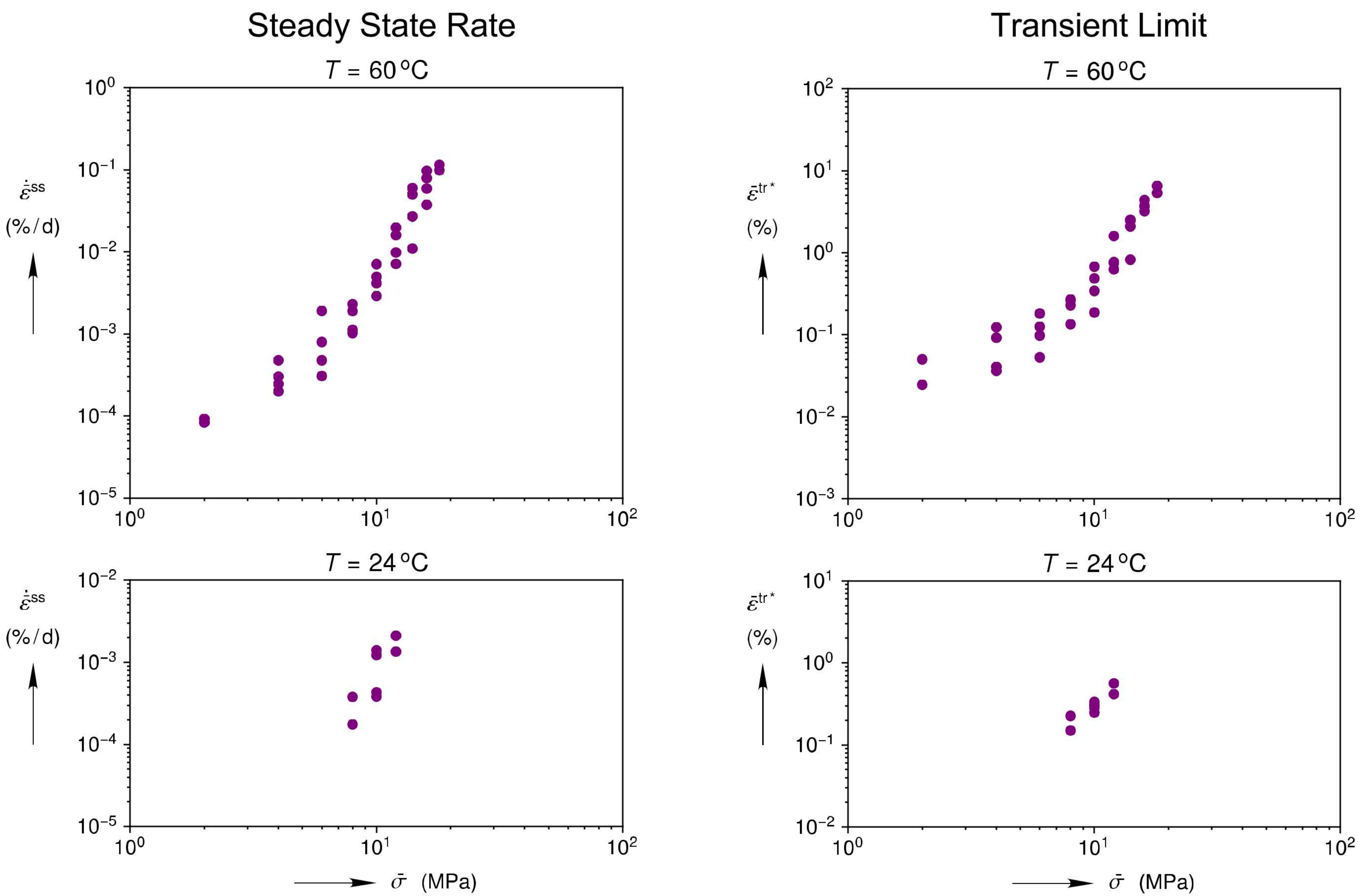
Creep Model Calibrations



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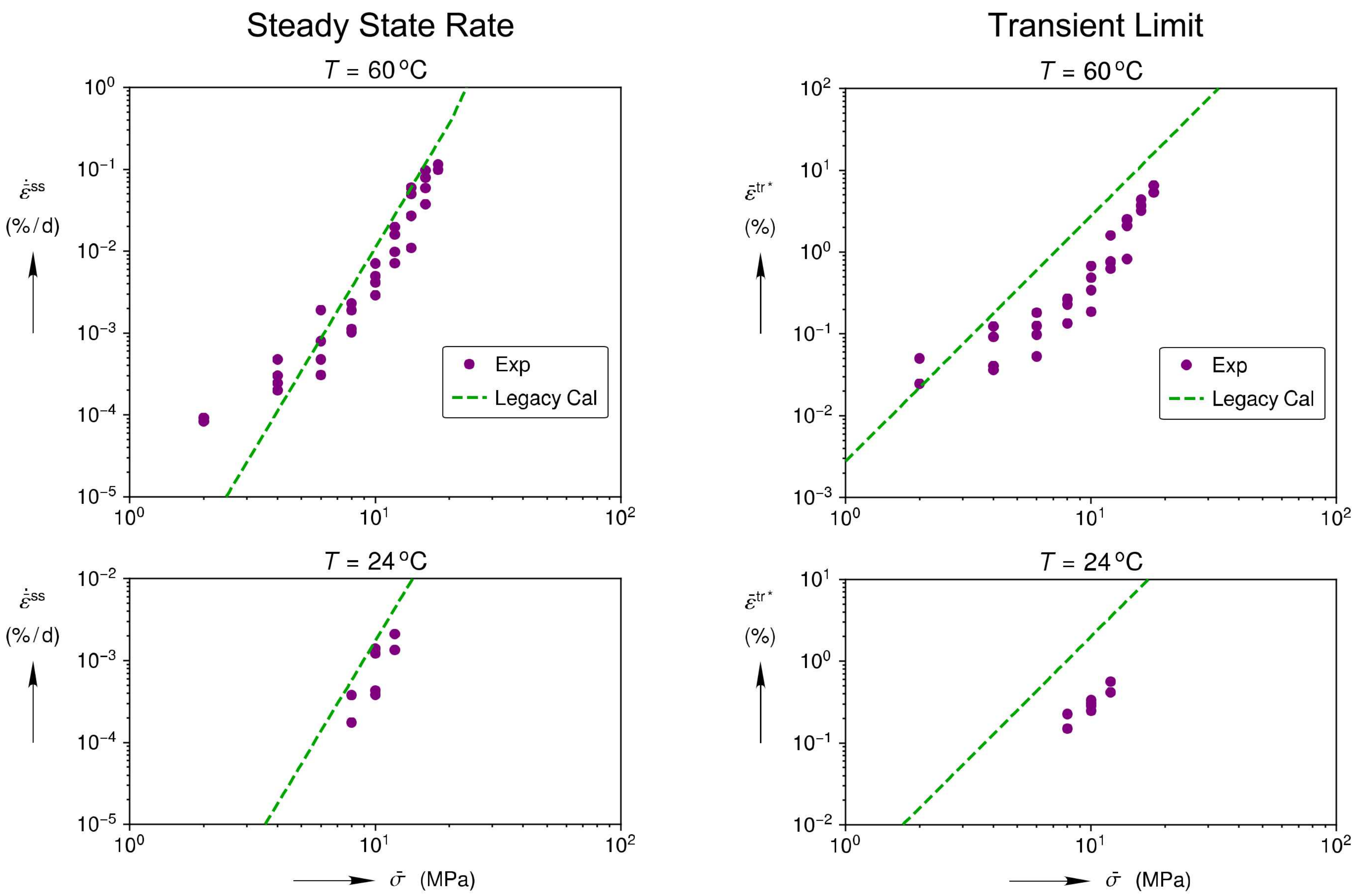

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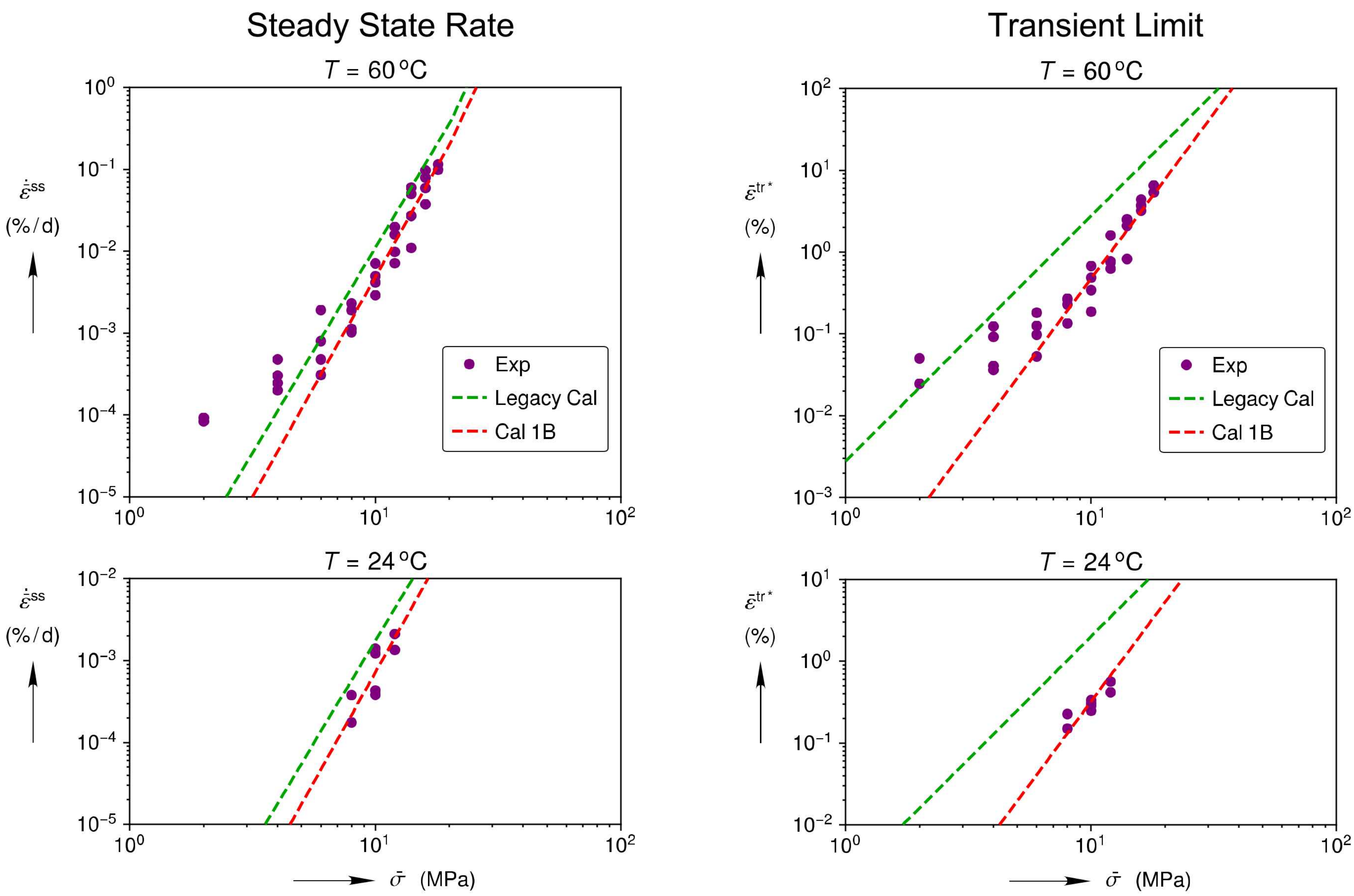

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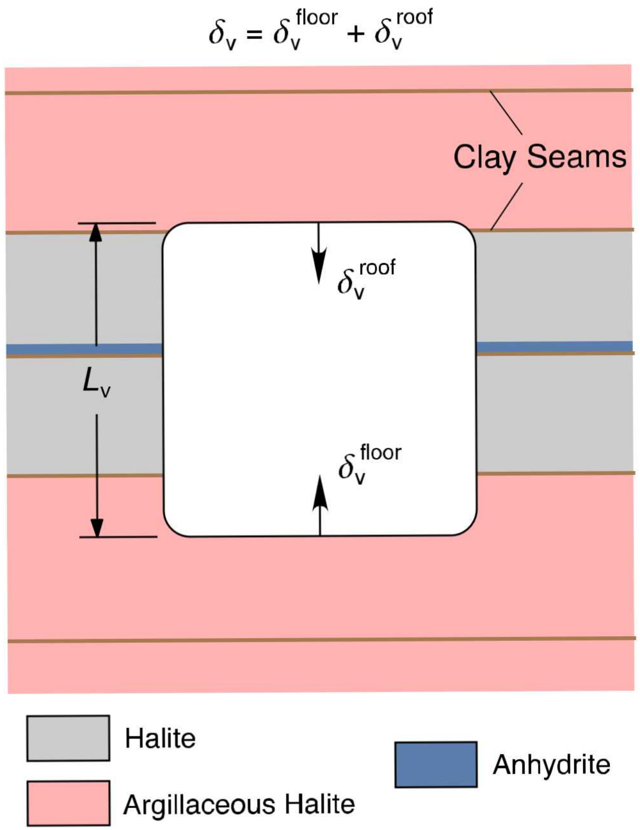
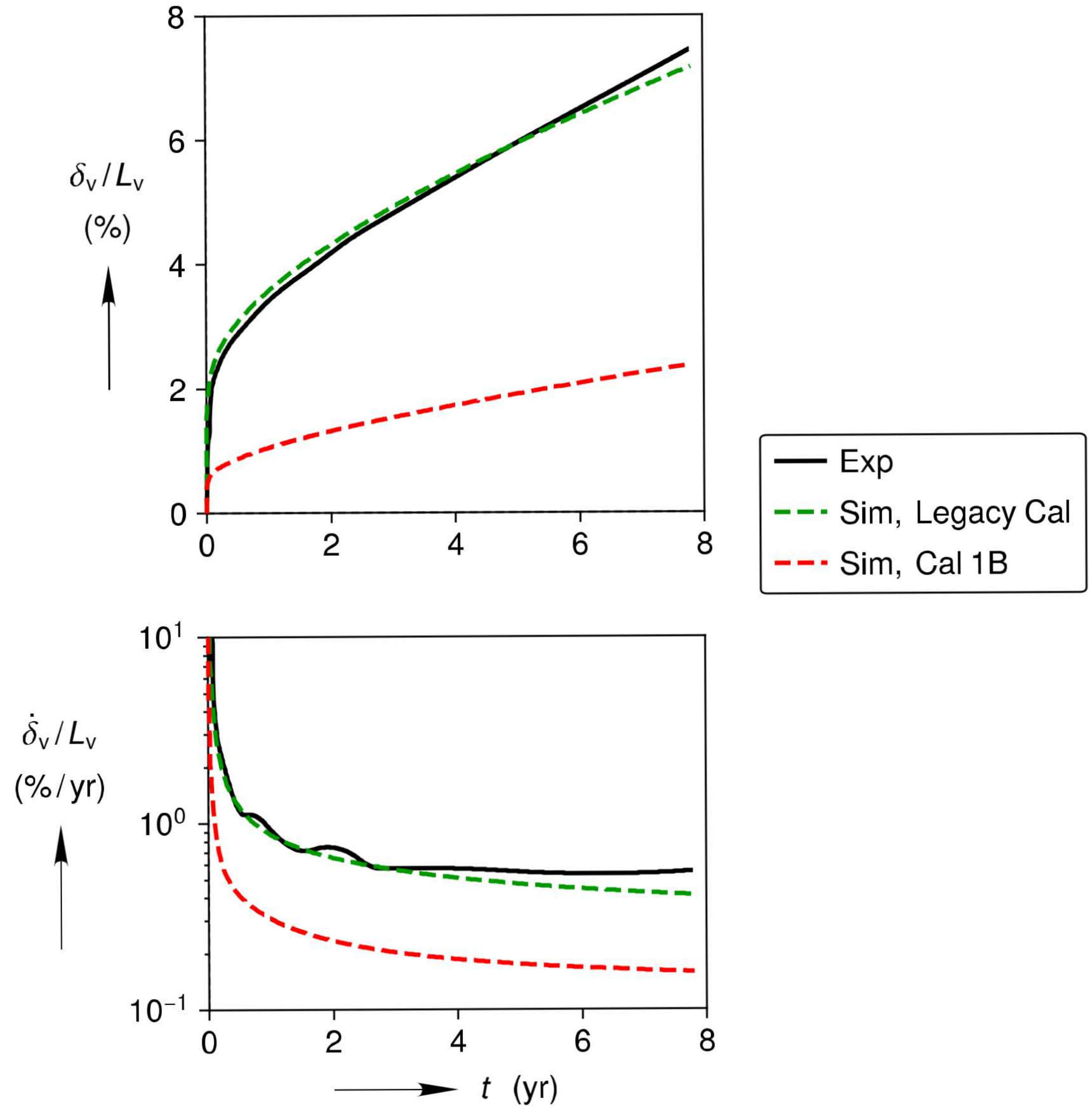
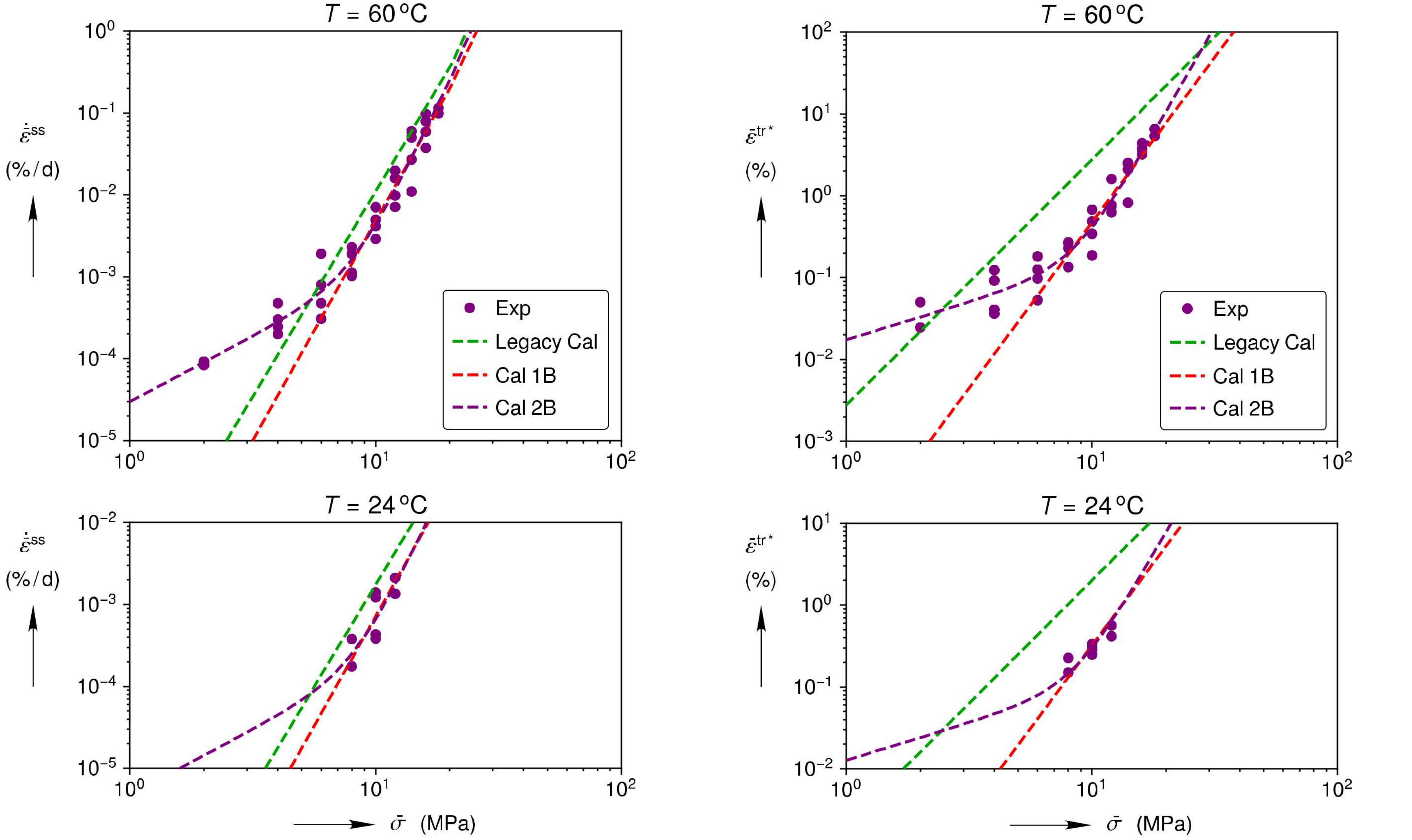
Room D Simulations





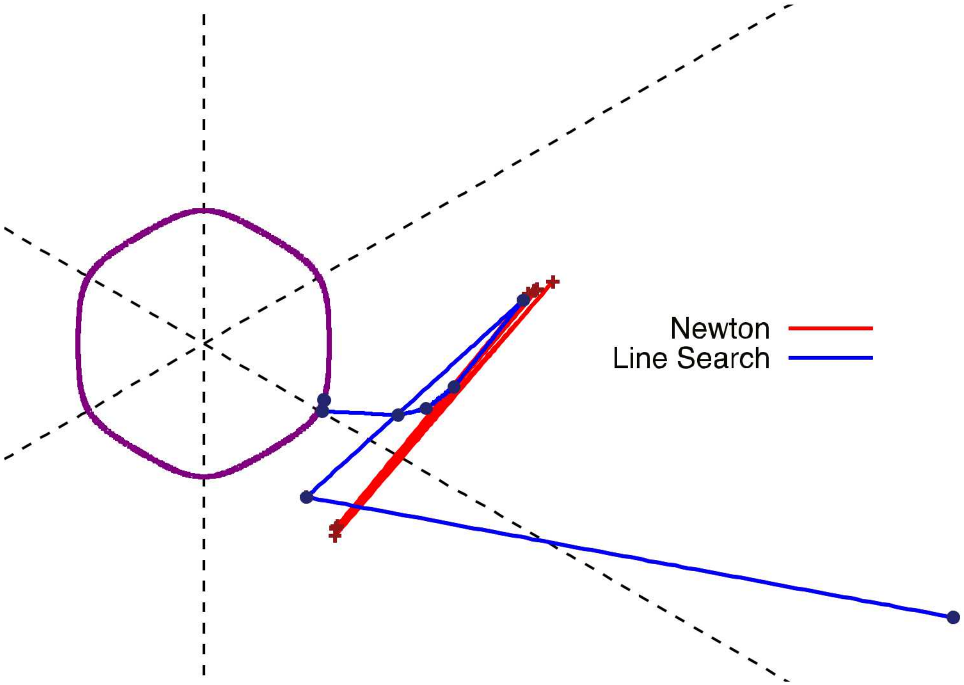
Creep Model Calibrations (AP-179)

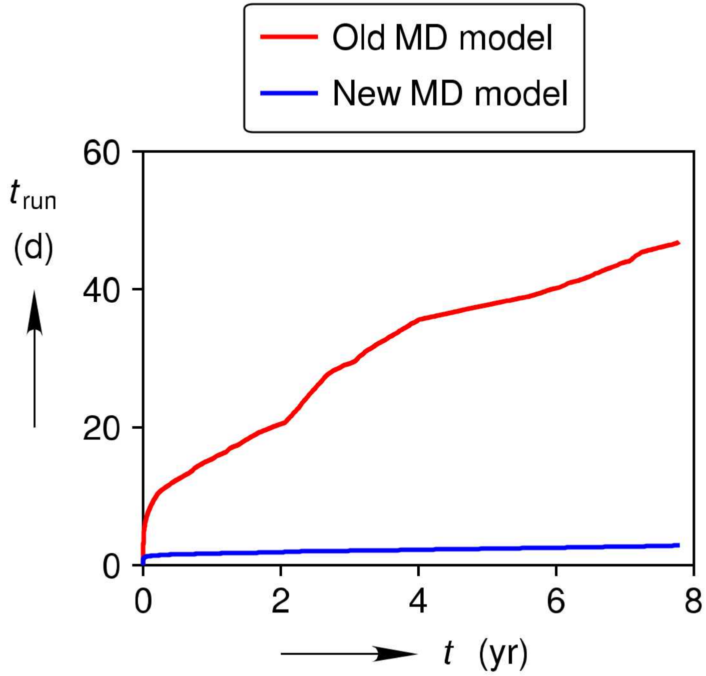
Steady State Rate | Transient Limit



Reedlunn, B., 2018. Joint Project III on the Comparison of Constitutive Models for the Mechanical Behavior of Rock Salt: Reinvestigation into Isothermal Room Closure Predictions at the Waste Isolation Pilot Plant. (Submitted to) Proc. 9th Conference on the Mechanical Behavior of Salt.

Numerical Algorithm Improvement (AP-179)

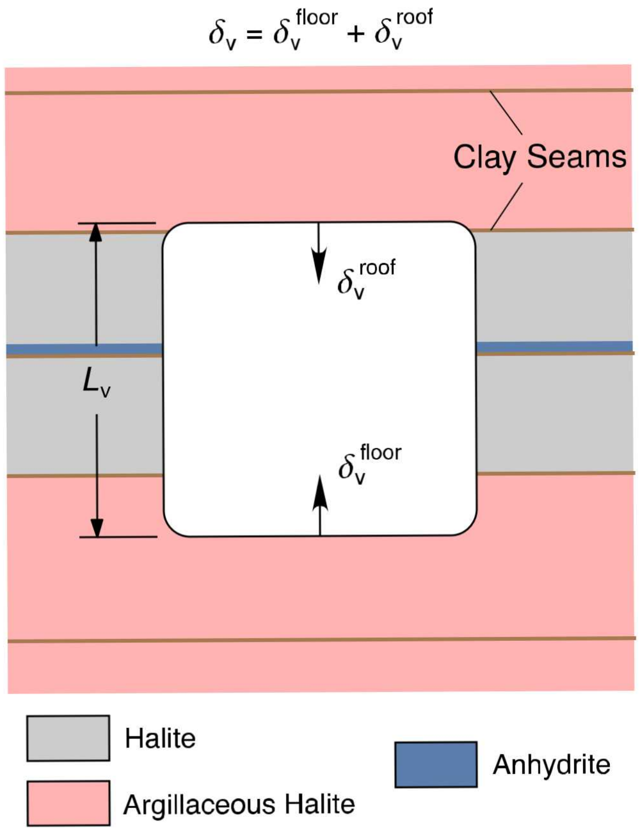


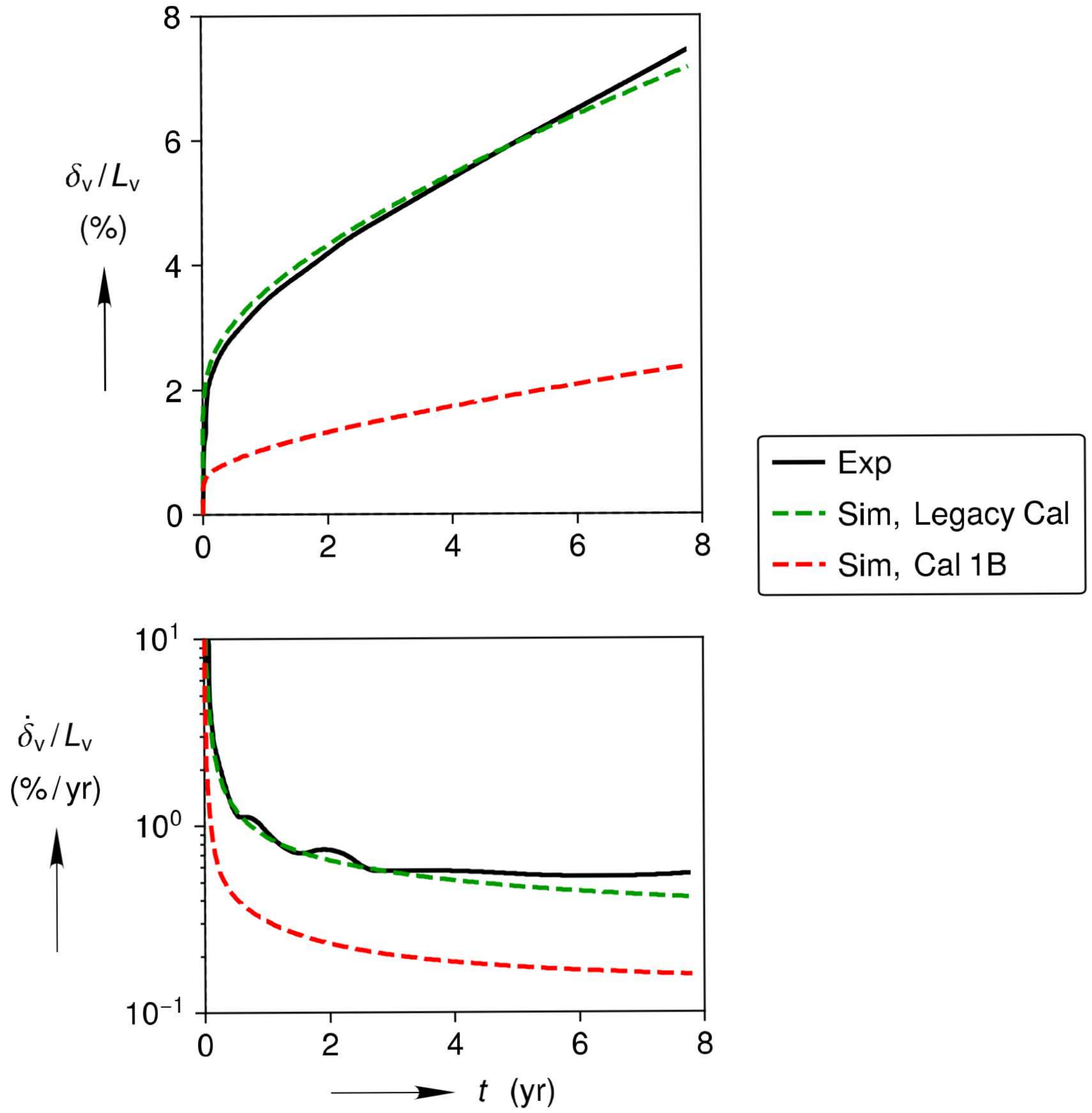


Scherzinger, W. M. 2017. A return mapping algorithm for isotropic and anisotropic plasticity models using a line search method. Computer Methods in Applied Mechanics and Engineering, 317, 526–553. (Modified)

Reedlunn, B., 2018. Joint Project III on the Comparison of Constitutive Models for the Mechanical Behavior of Rock Salt: Reinvestigation into Isothermal Room Closure Predictions at the Waste Isolation Pilot Plant. (Submitted to) Proc. 9th Conference on the Mechanical Behavior of Salt.

Room D Simulations (AP-178)





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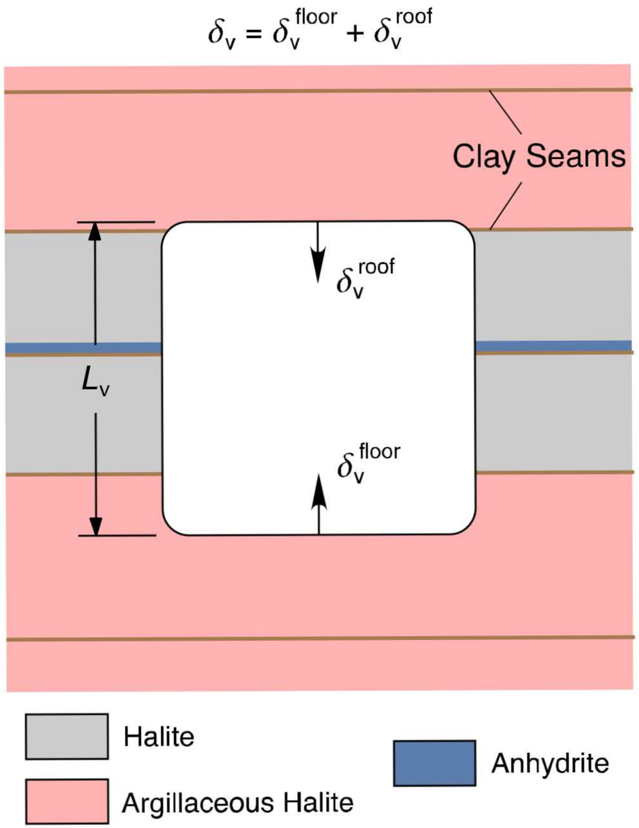
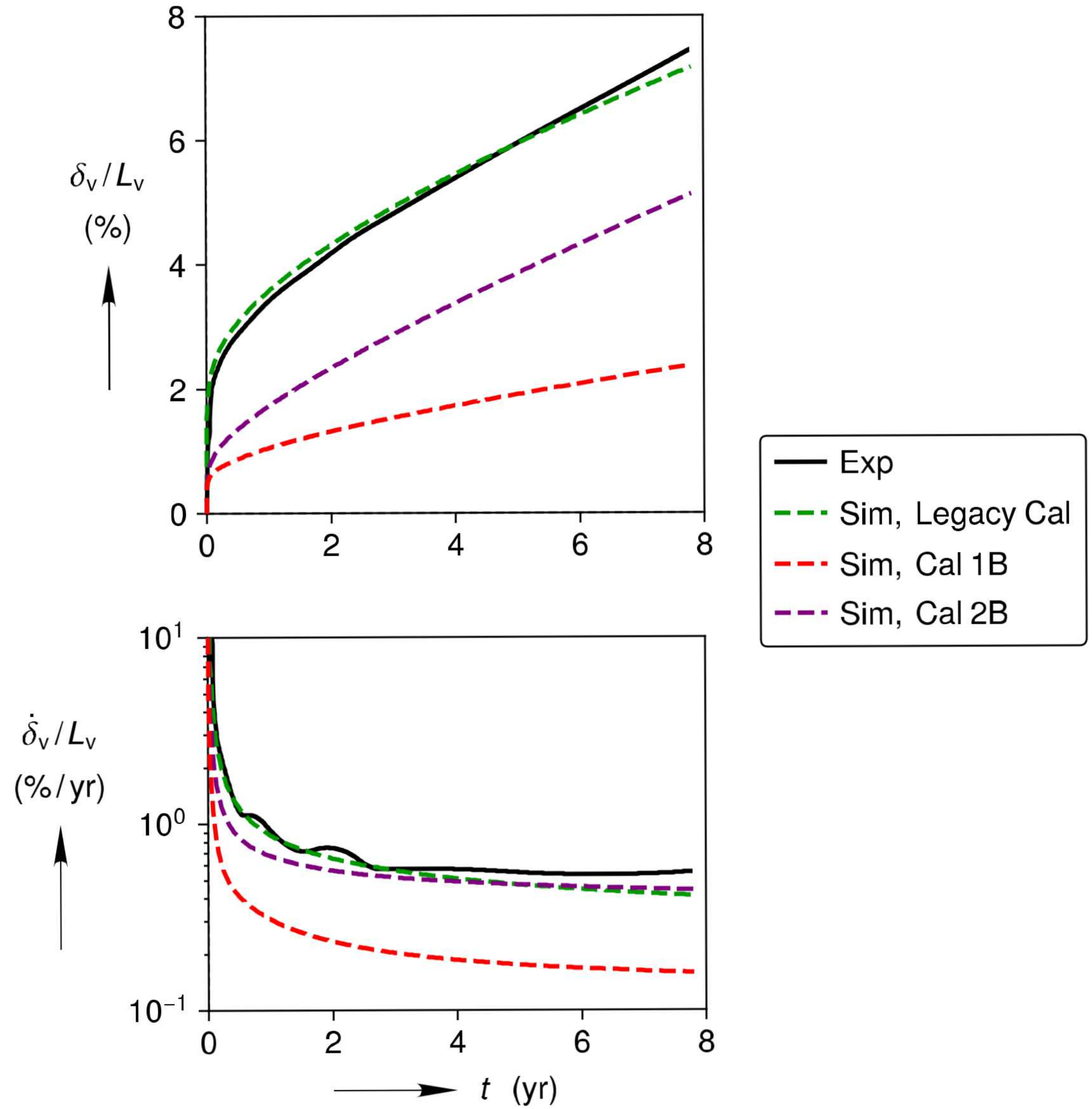




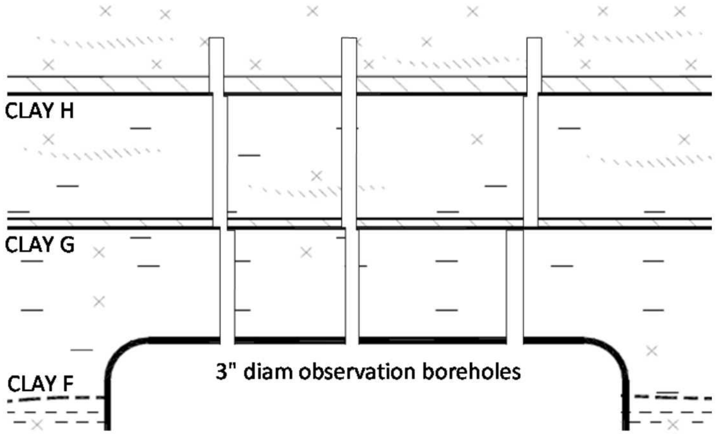
Future Research Topics

- Initial transient closure
  - Core extracted from drifts are not virgin.
- Simulation domain size
  - 50 m away from the room is not sufficient.
- Anhydrite model
  - Marker Bed 139 is too strong.
- Simulation robustness
  - Many simulations fail to converge due to contact interactions
- Behavior of bedding plane interfaces
  - Discussed in the next section…

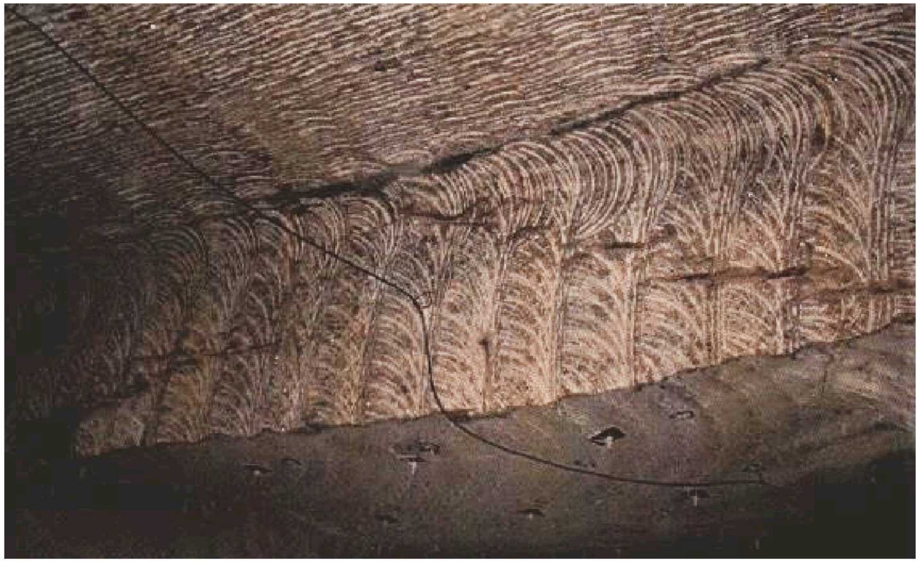
Mechanical Behavior of Bedding Plane Interfaces

Examples of Interface Sliding and Separation

Interface Sliding



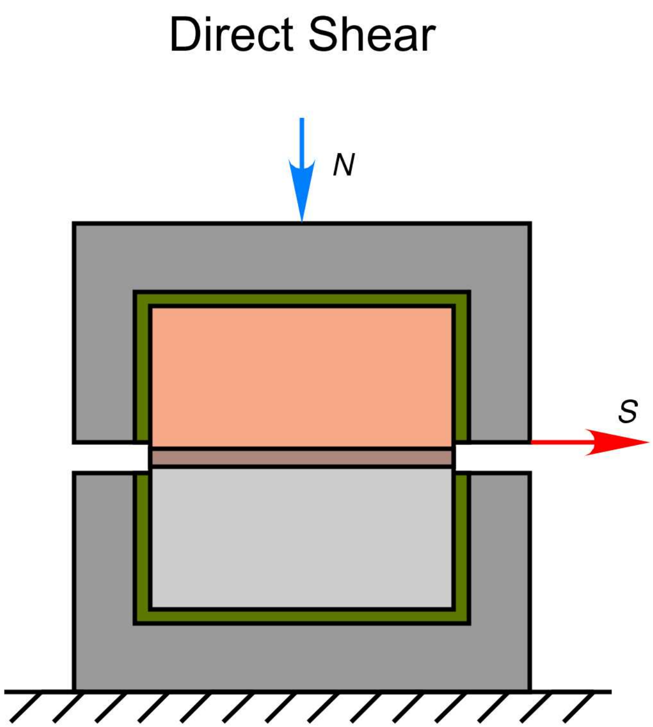
Interface Separation

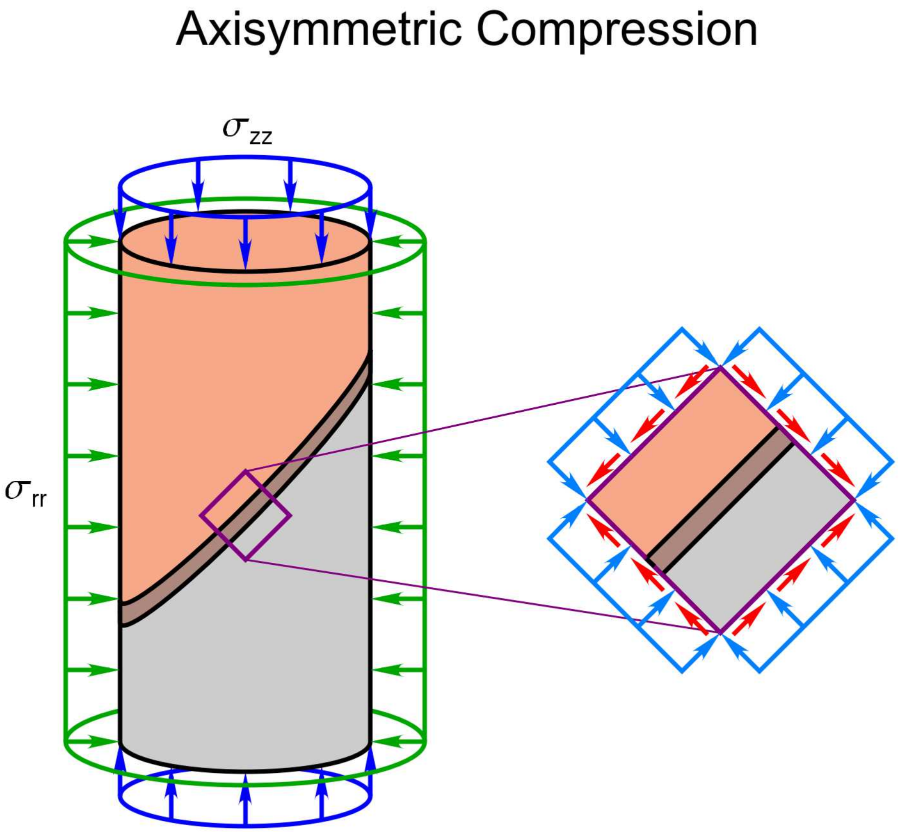


Research Plan

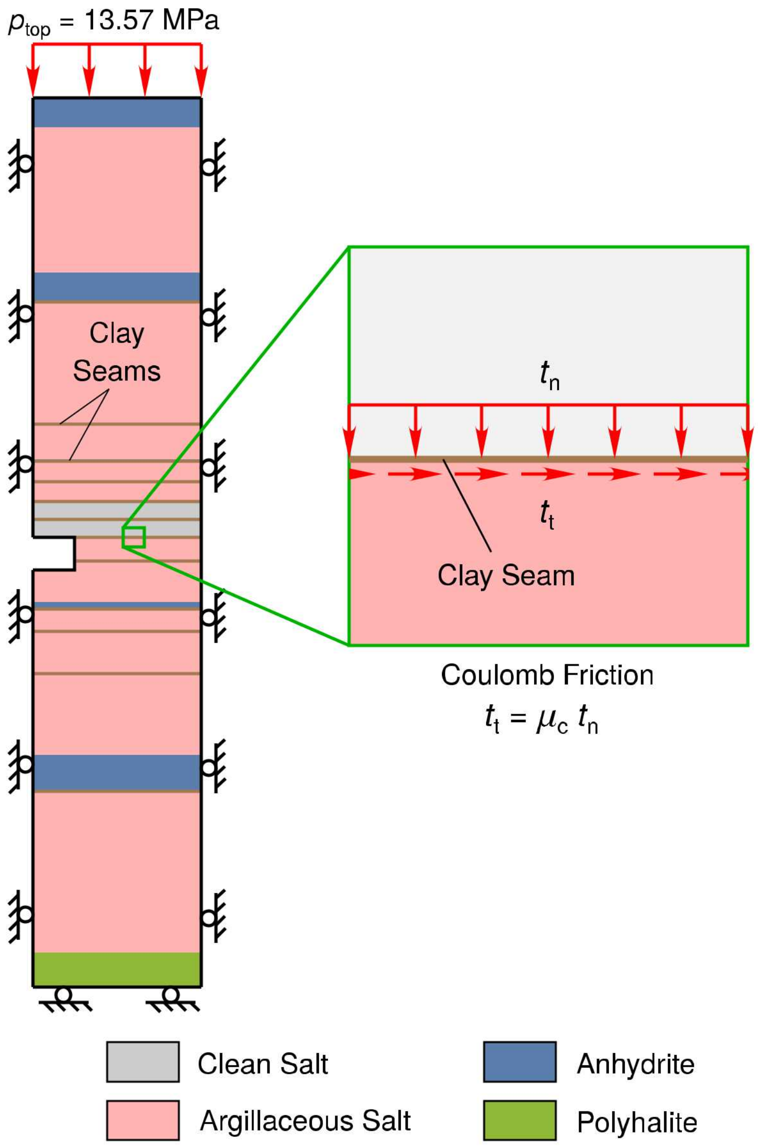
- Laboratory Experiments (TP 17-03)
  - Extraction Sites
    - Salt/Potash mines in the Permian Basin
    - WIPP drifts
  - Samples
    - 10 cm cubes or 10 cm diameter cylinders
    - Various bedding plane constituents
  - Tests
    - Direct shear machine and/or triaxial cell tests
    - Tensile strength
- Modeling
  - Construct constitutive model(s) with Joint Project WEIMOS
- In-Situ Experiment
  - ~1 m cube to quantify size effects
  - Validate models against in-situ test.

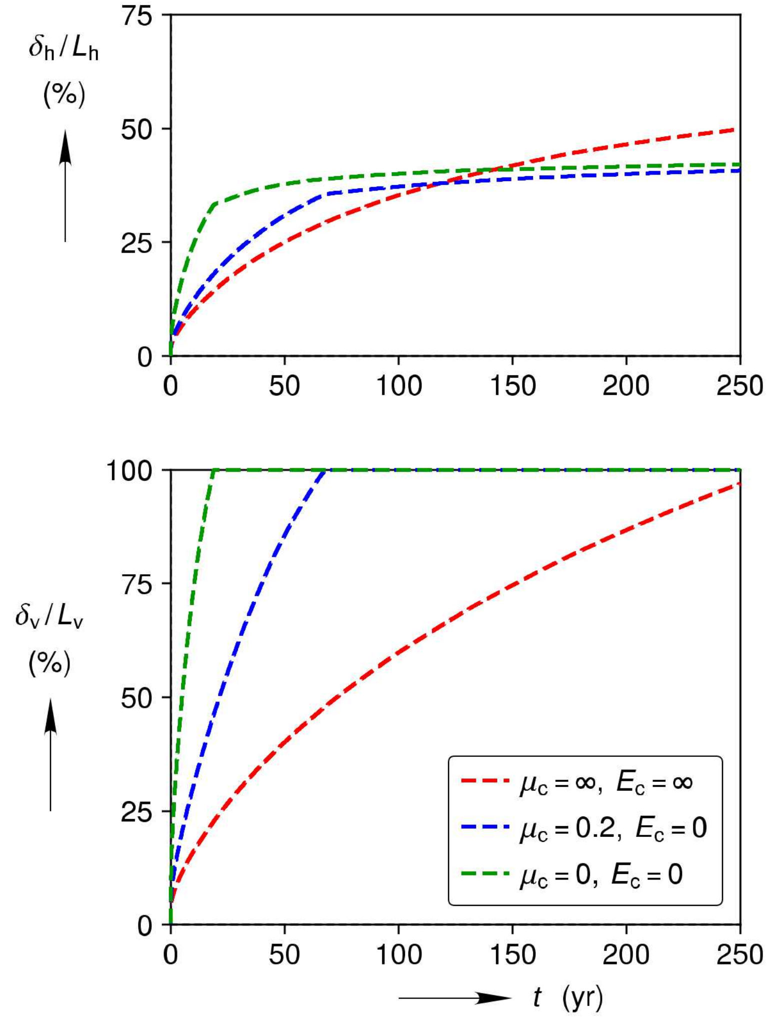
Experiment Types





Clay Seam Model Impact





Reedlunn, B. 2017. Geomechanical Simulations of an Empty WIPP Disposal Room using Explicit Dynamics and Time-Temperature Scaling. Memorandum to Distribution. SAND2017-13593 O.

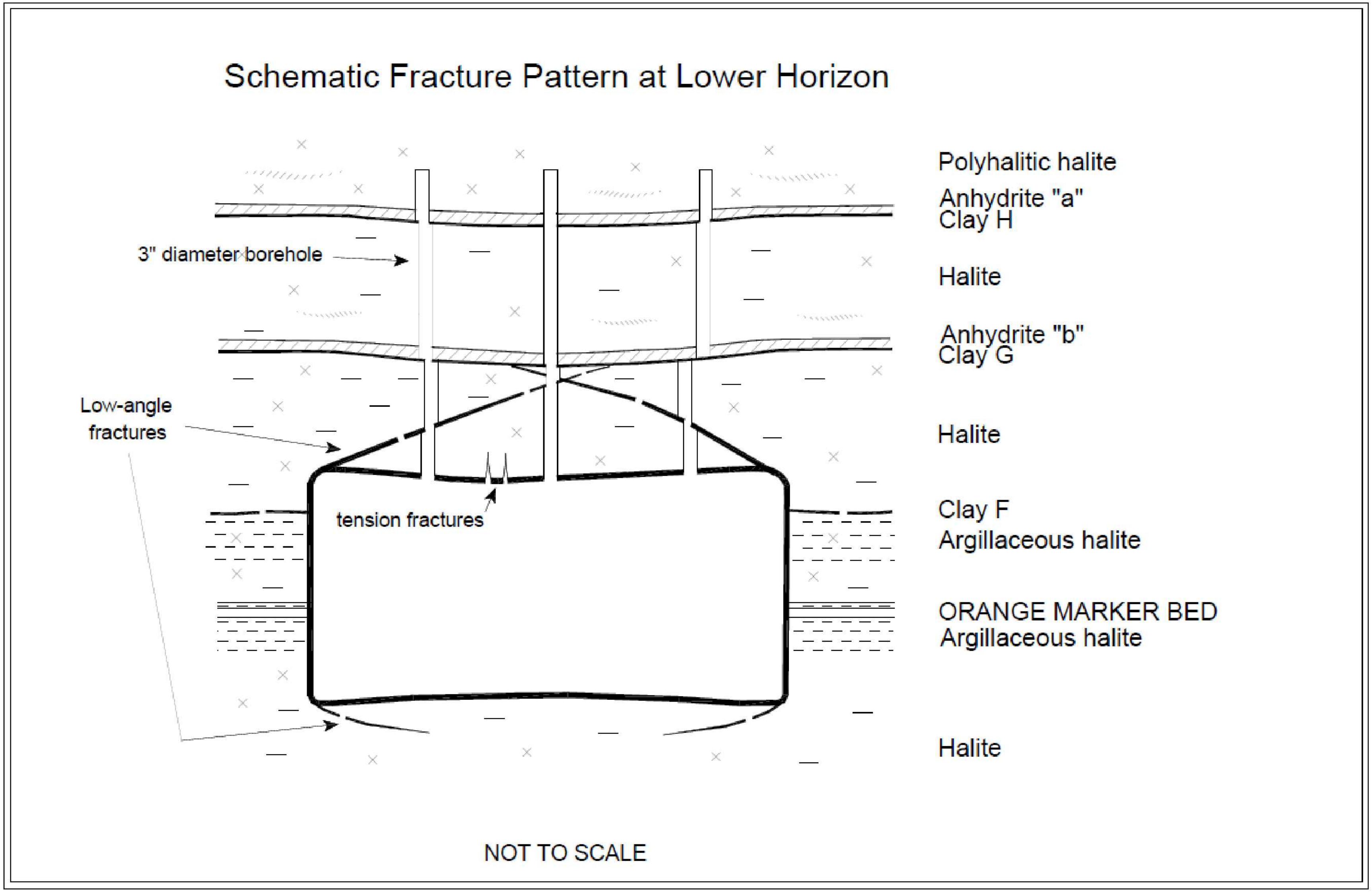
Damage and Fractures

Research Plan

- Laboratory Experiments
  - Joint Project III measurements of dilatancy and strength boundaries
  - Joint Project WEIMOS currently measuring healing behavior
  - Replicate open room closure on laboratory scale (TP 17-02)

- Modeling
  - Update Munson-Dawson model to capture damage and fracture (AP-179)
  - Validate against lab experiments and field observations (AP-178)

Typical Fracture Pattern at Lower Horizon



Examples of Damage and Fracture of Salt in Lower Horizon

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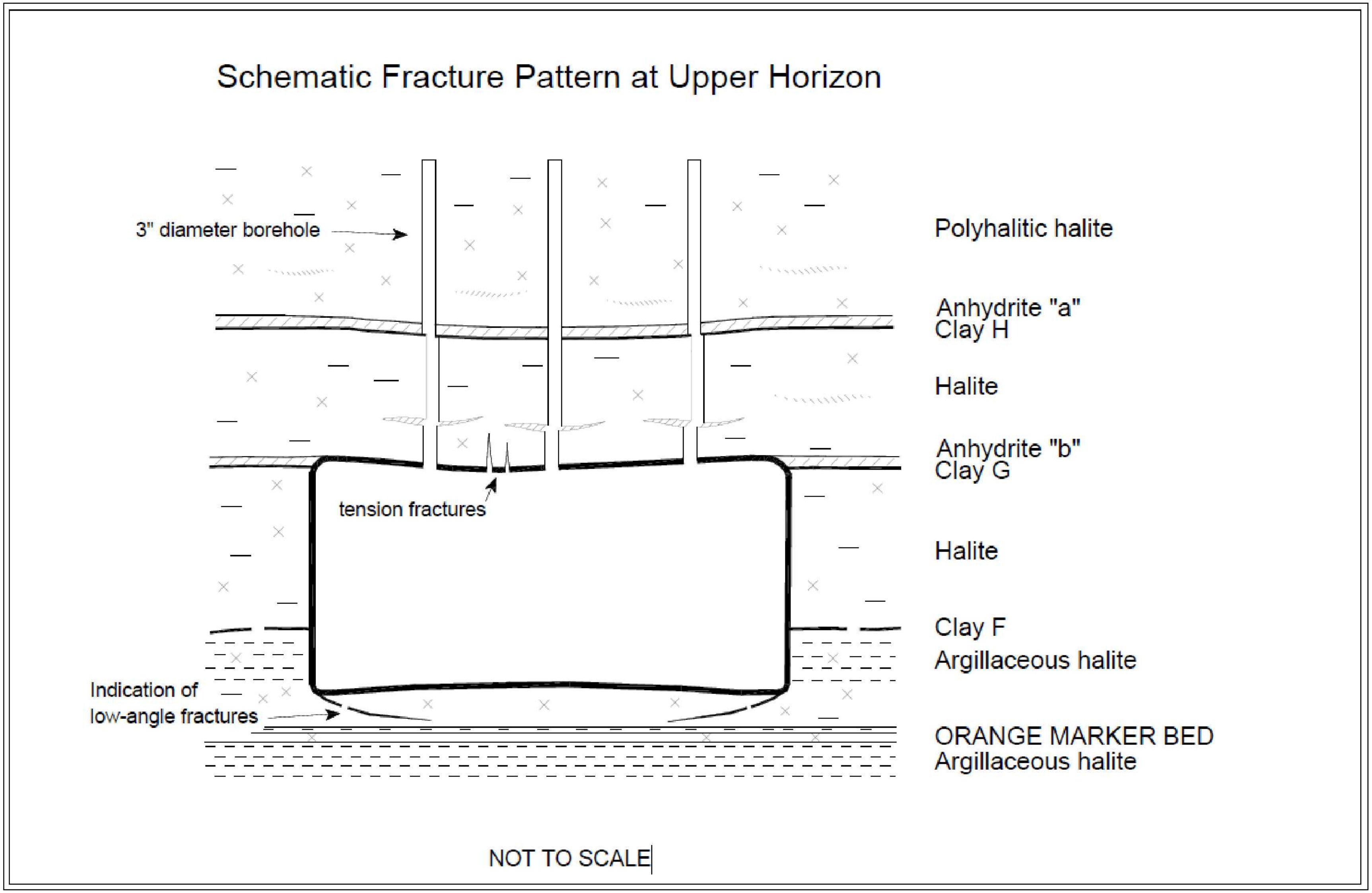
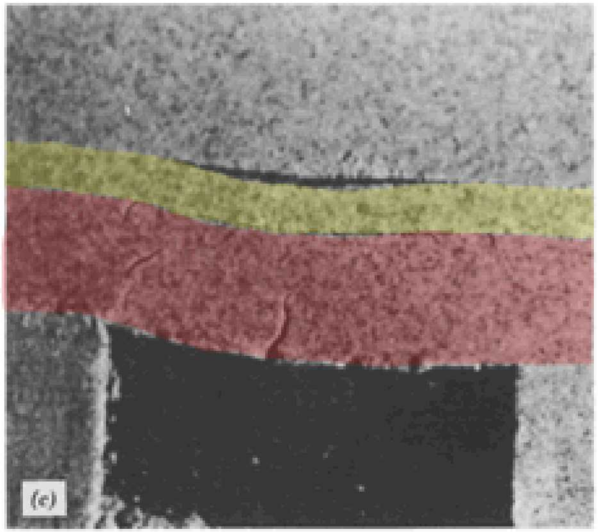
Typical Fracture Pattern at Upper Horizon

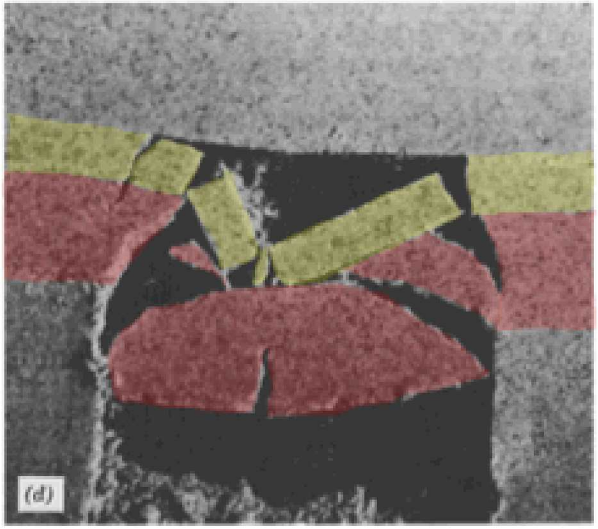


Roof Fall from Upper Horizon

Lab-Scale Open Room Closure (TP 17-02)

- Controlled structural-level experiments
- Improve understanding of failure processes
  - Upper vs. lower horizon
  - Discrete blocks vs. “deck of cards”
  - Evolution from rectangular to circular
  - Stabilization opening or slow down creep
- Validation of damage & failure portion of MD model

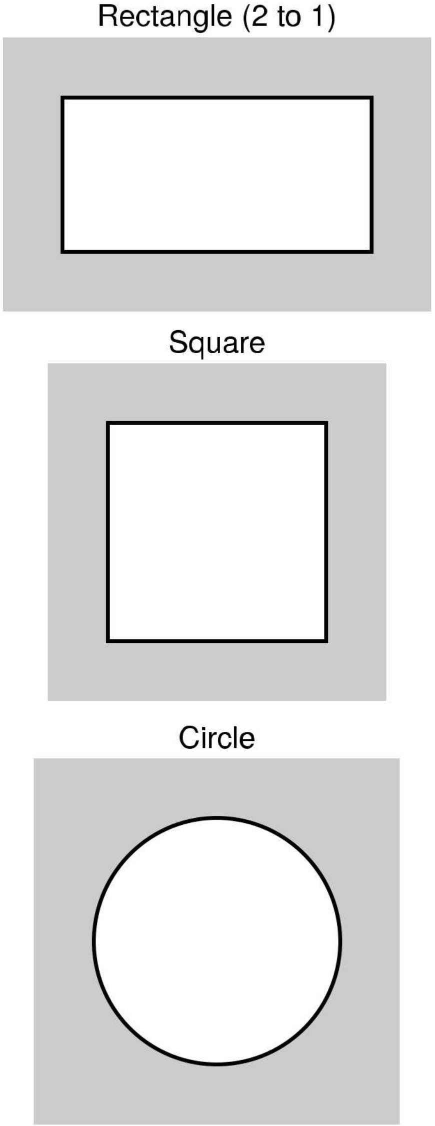




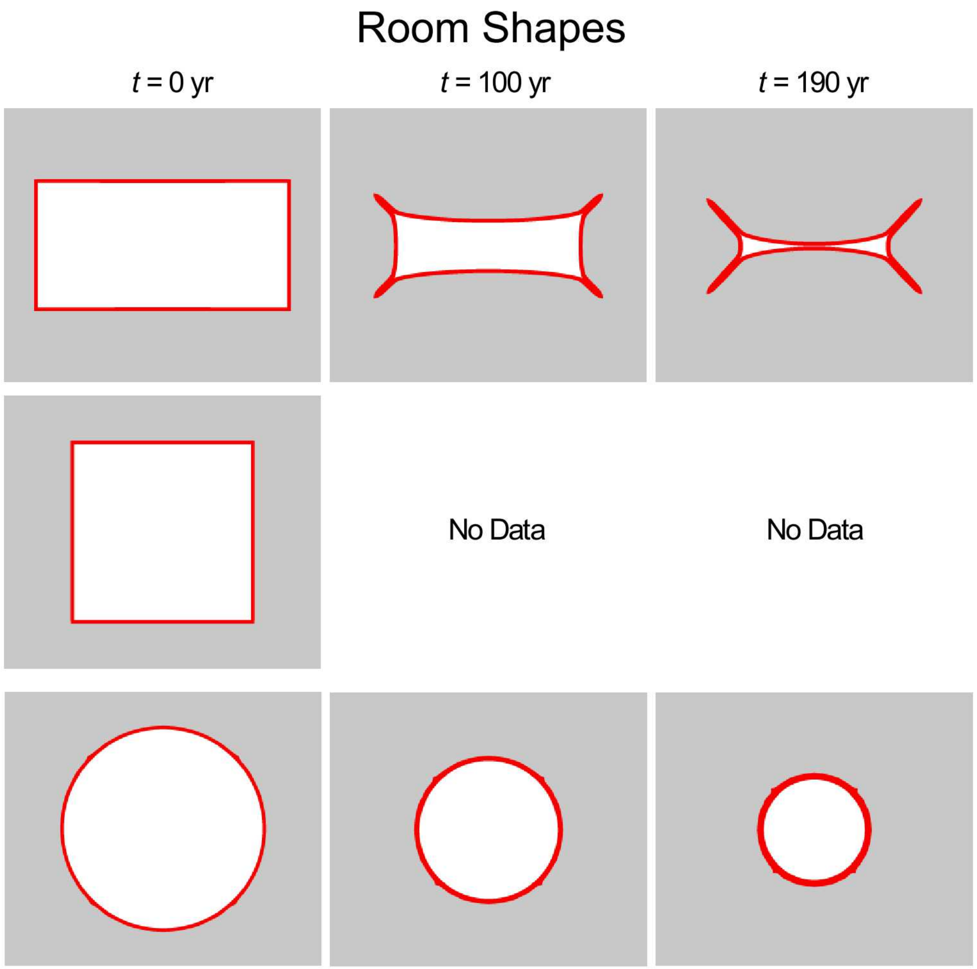
Goodman, (1989). Introduction to Rock Mechanics.

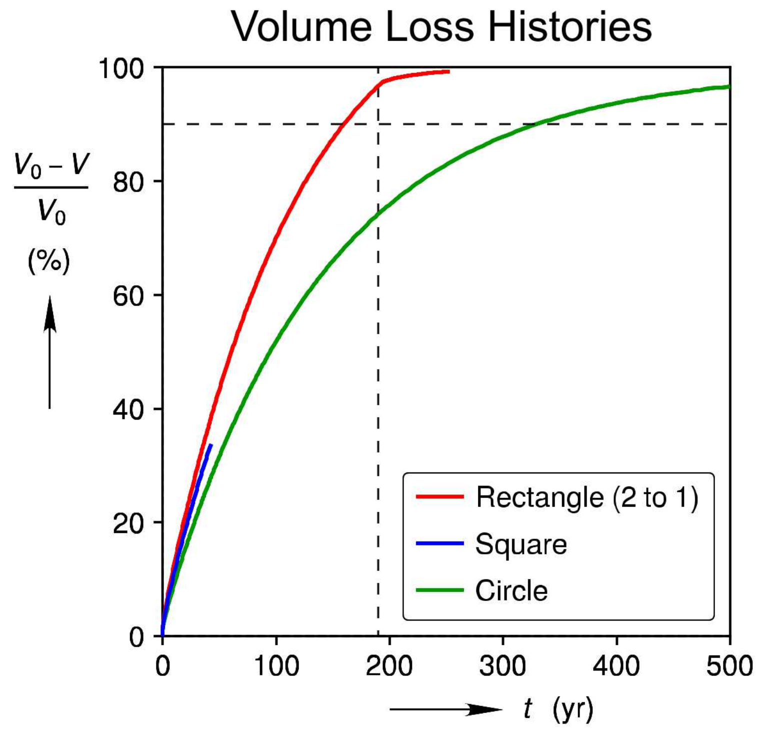
Impact of Room Shape

- Rough estimate of impact of fracturing and discrete events
- Fracturing changes the room shape
  - Three room shapes simulated
  - Long, slender, rooms (plane strain)
  - Same initial room area



Effect of Room Shape on Creep Closure





Preliminary simulations by B. Reedlunn (Unpublished)

Healing, Reconsolidation, and Permeability

Permeability and Porosity

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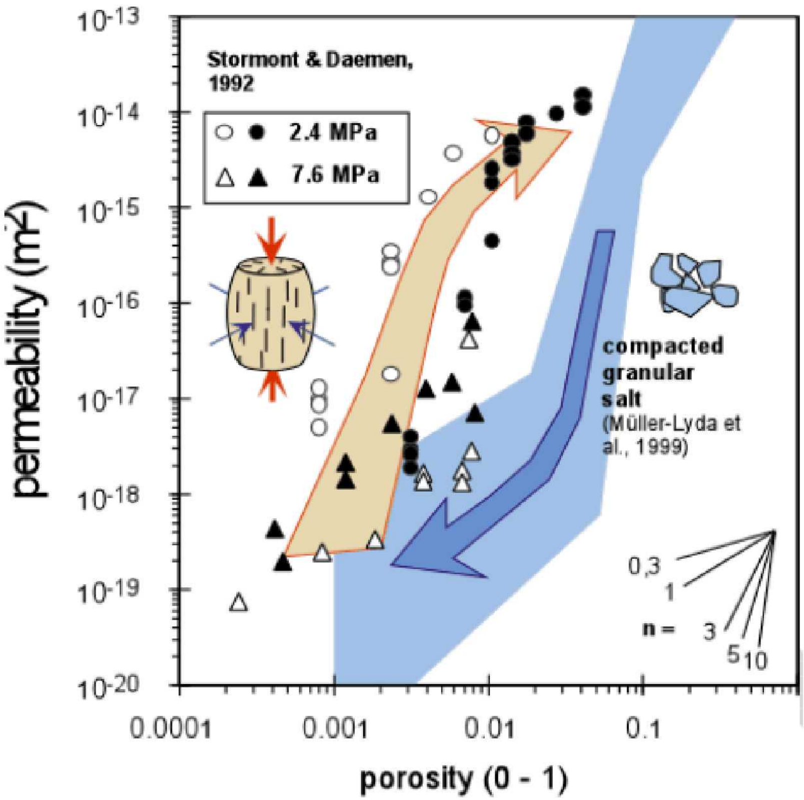
- Porosity: ϕ fraction of void space (0.1% – 40%)
- Permeability: k fluid flux due to driving force (>10 orders mag.)
  - k sensitive to pathways, ϕ is not (i.e., dead-end porosity)
  - k sensitive to fracture & grain surfaces, ϕ is not
- Permeability as a function of porosity $k(\phi)$
  - $k(\phi)$ different for granular, fractured, and "open channel" media
  - Granular materials $k(\phi)$ is simple down to low porosity
  - DRZ fracture k more pressure-sensitive than granular (David et al. 1994)
  - $k(\phi)$ relationships fit to data apply only to narrow ϕ range
- No one $k(\phi)$ valid for all parts of repository

David, C., T.-F. Wong, W. Zhu & J. Zhang. (1994). Laboratory measurement of compaction-induced permeability change in porous rocks: Implications for the generation and maintenance of pore pressure excess in the crust. Pure and Applied Geophysics, 143(1-3):425 456.

DRZ Fracture Closure and Healing

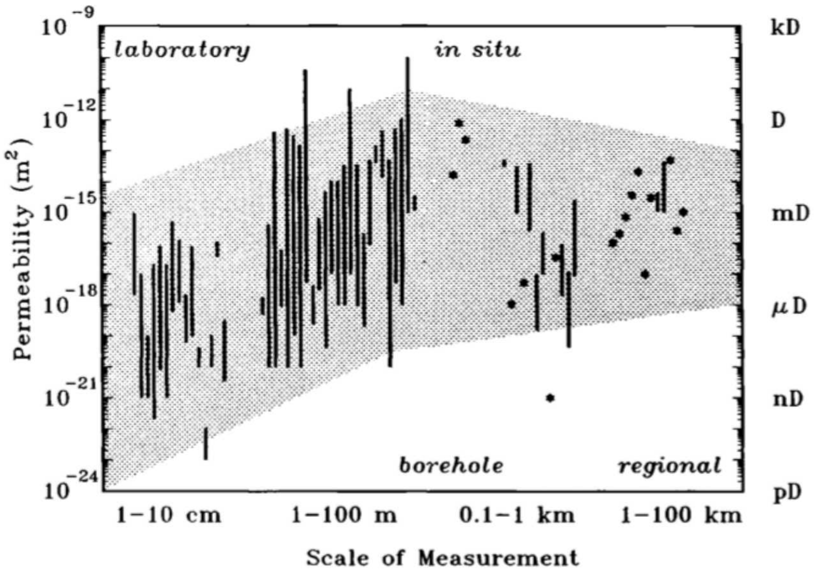
- $k(\phi)$ observed in salt
  - Reconsolidating granular (blue)
  - Fractured accumulating damage (tan)
  - Cases behave differently
  - Neither follows monomial power law
- Possible explanations
  - Concave-up (granular):
    - Multiple length scales
    - Both granular & fracture ϕ
  - Concave-down (fracture):
    - Mixture of "effective" and "ineffective" ϕ
    - Not all porosity is equal



Hansen, F., T. Popp, K. Wieczorek & D. Stuhrenberg, 2014. *Granular Salt Summary: Reconsolidation Principles and Applications*. SAND2014-16141R.

Permeability is Scale Dependent

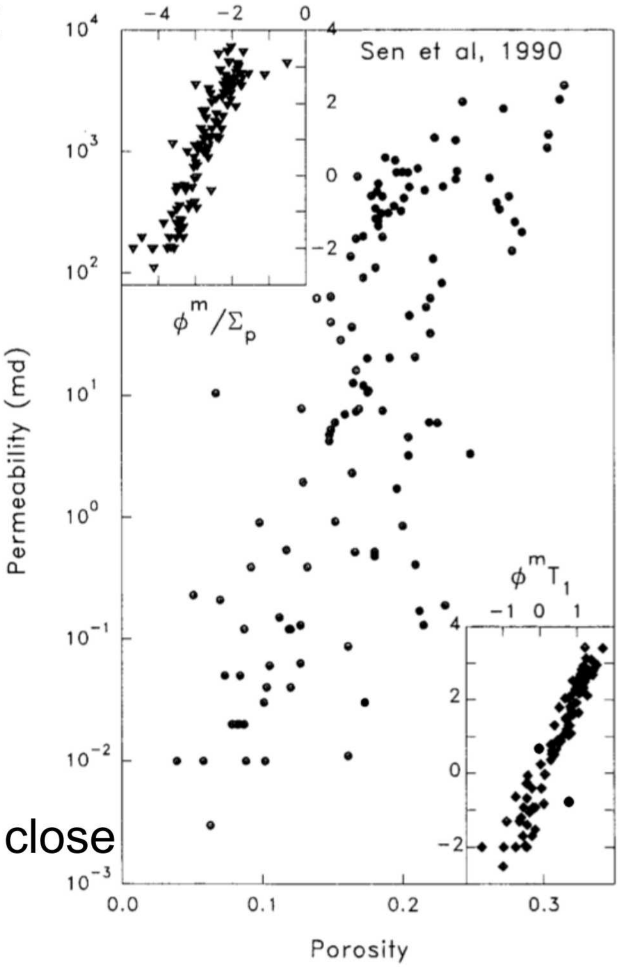
- k in fractured rocks
  - Entirely from fractures
  - Fractures are fractally distributed
- k is scale dependent
  - Lowest k observed in small samples
  - Highest k in regional numerical models
- Minimum k increases with scale
- Core-scale k << model k
- ϕ not really scale dependent



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

Permeability and Porosity in Lab

- Granular salt reconsolidation controlled by:
  - Applied effective stress
  - Temperature
  - Moisture content
  - Physical composition (grain size & mineral)
- $k = a\phi^m$ typical, but few data $\phi < 5\%$
- Other data useful for predicting k
  - Tortuosity, specific surface area (Σ_p)
  - Capillary pressures, pore-scale imaging
  - Geophysics: Nuclear Magnetic Resonance (T_1)
- Closure of DRZ fractures
  - Fractures favorably aligned with stress state will close
  - Exponential $k(\sigma)$
- Closure of open spaces
  - Rubble/debris in open space may behave like porous media at late time



Nelson, (1994). Permeability-porosity relationships in sedimentary rocks. The Log Analyst, 35(3):38 62

Research Plan

- Reconsolidation of granular salt (TP 17-04)
  - Some overlap with research program in Germany (Kröhn et al. 2017)
  - SNL will focus on complimentary aspects:
    - Explore characterization of other porous media metrics:
      - Tortuosity (i.e., formation factor)
      - Characteristic length scales (i.e., air-entry pressure, Hg-injection)
      - Modern pore-scale imaging (micro-CT, serial sectioning)
    - Control effects of composition on results (grain size + mineralogical)
    - Leverage WIPP samples from UNM NEUP project (Stormont et al. 2017)
  - Low porosity difficult to measure volumetrically in lab
- Two-phase flow in salt
  - Few relevant datasets (i.e., mostly for table salt)
  - Dissolution/precipitation complicates interpretation and test design
  - Hard to isolate flow problem from creeping, dissolving & precipitating
  - k and ϕ estimation from pore-scale imaging

Kröhn, K.-P., D. Stührenberg, M. Jobmann, U. Heemann, O. Czaikowski, K. Wieczorek, C. Müller, C.-L. Zhang, H. Moog, S. Schirmer & L. Friedenberg, 2017. *Mechanical And Hydraulic Behavior of Compacting Crushed Salt Backfill at Low Porosities, REPOPERM 2.* GRS-450, Braunschweig, Germany: Gesellschaft für Anlagenund Reaktorsicherheit.

Stormont, J., B. Lampe, M. Mills, L. Paneru, T. Lynn & A. Piya, 2017. *Improving the Understanding of the Coupled Thermal-Mechanical-Hydrologic Behavior of Consolidating Granular Salt.* Nuclear Energy University Partnership Fuel Cycle Research and Development, Project 13-4834.

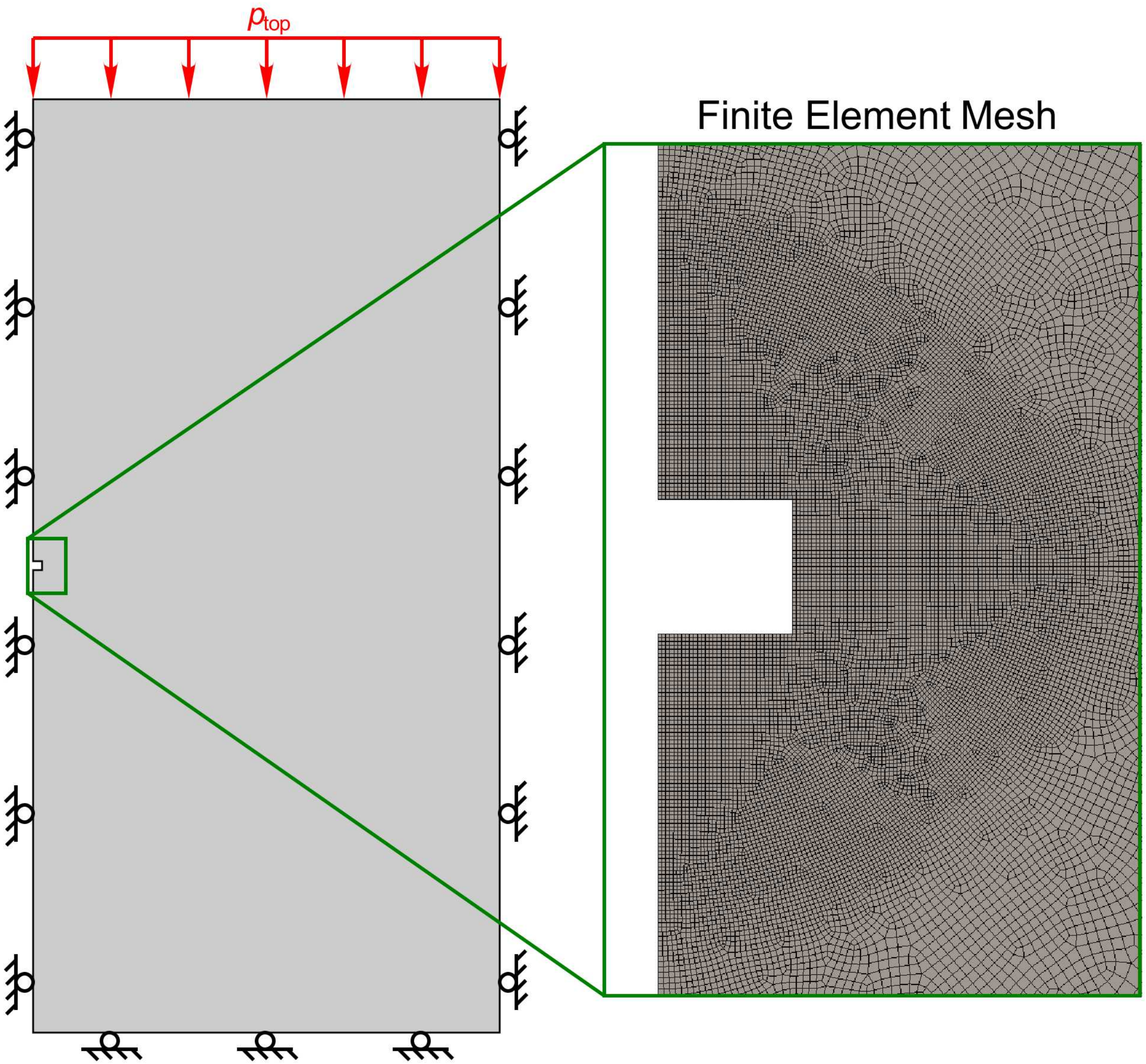
Summary

Summary

- Improved the scientific basis behind the creep closure modeling
- Bedding plane interface work is in-progress
- Damage and fracture research is restarting
  - Updates to the Munson-Dawson model
  - Validate against lab scale open room closure experiments
- Healing, reconsolidation, and permeability research
  - Probe at porosity-–permeability relationships on lab scale using novel measurement techniques

Extra Slides

Creep Closure Simulation Setup



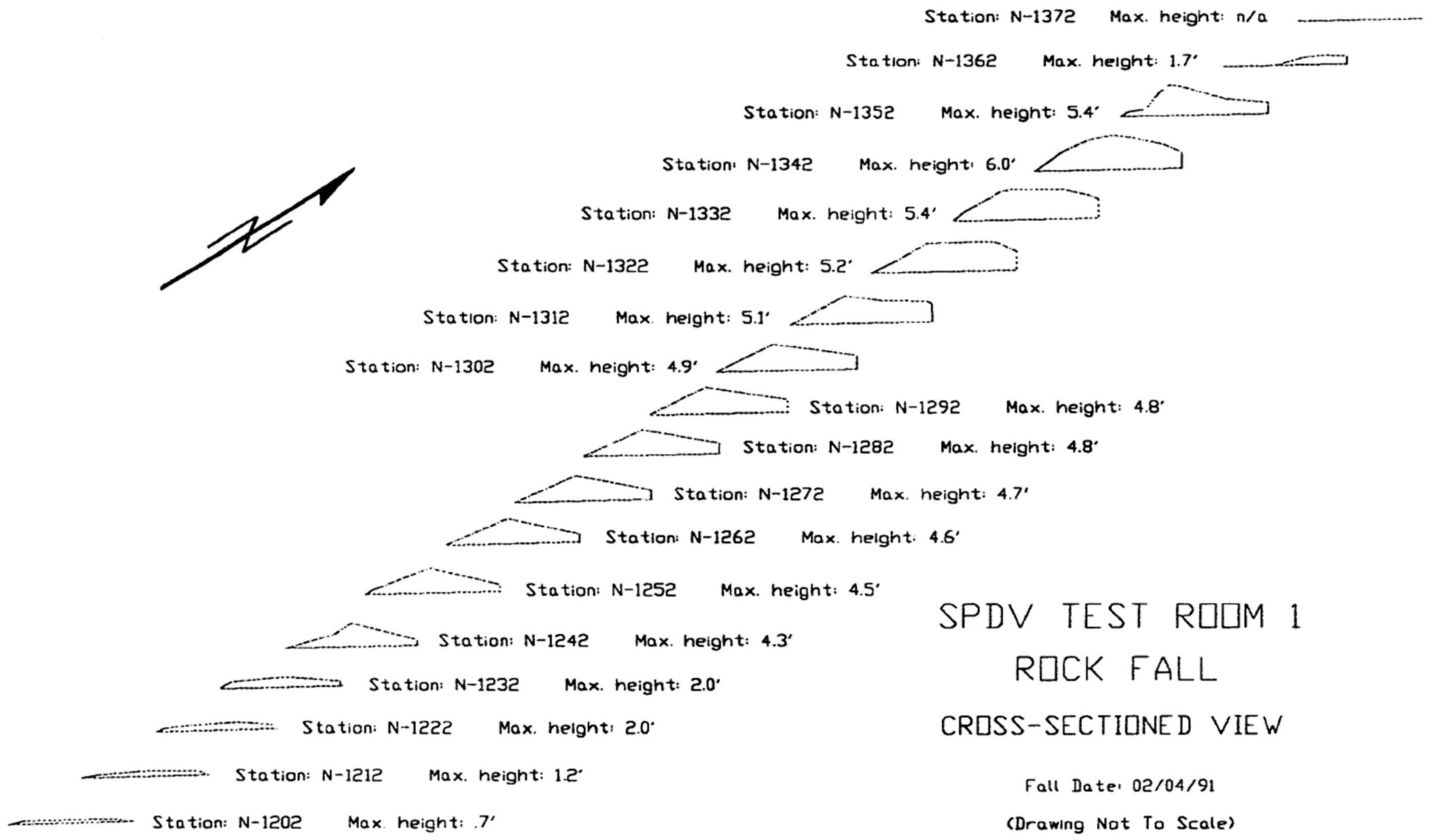
- Pure salt (No stratigraphy)
- Domain boundaries 200 m from room
- Latest Munson-Dawson Calibration (Cal 2B)
- Zero pressure inside room

Modeling Permeability and Porosity

- Changes in porosity from geomechanical model
  - Volumetric strain → porosity change
  - “Drained” poroelastic response
- Fluid pressure hydrofracs or slows room closure
  - Fluid pressure reduces effective stress
  - “Undrained” poroelastic response
- Reality is between these end members
  - Coupled thermal-hydro-mechanical model (difficult)

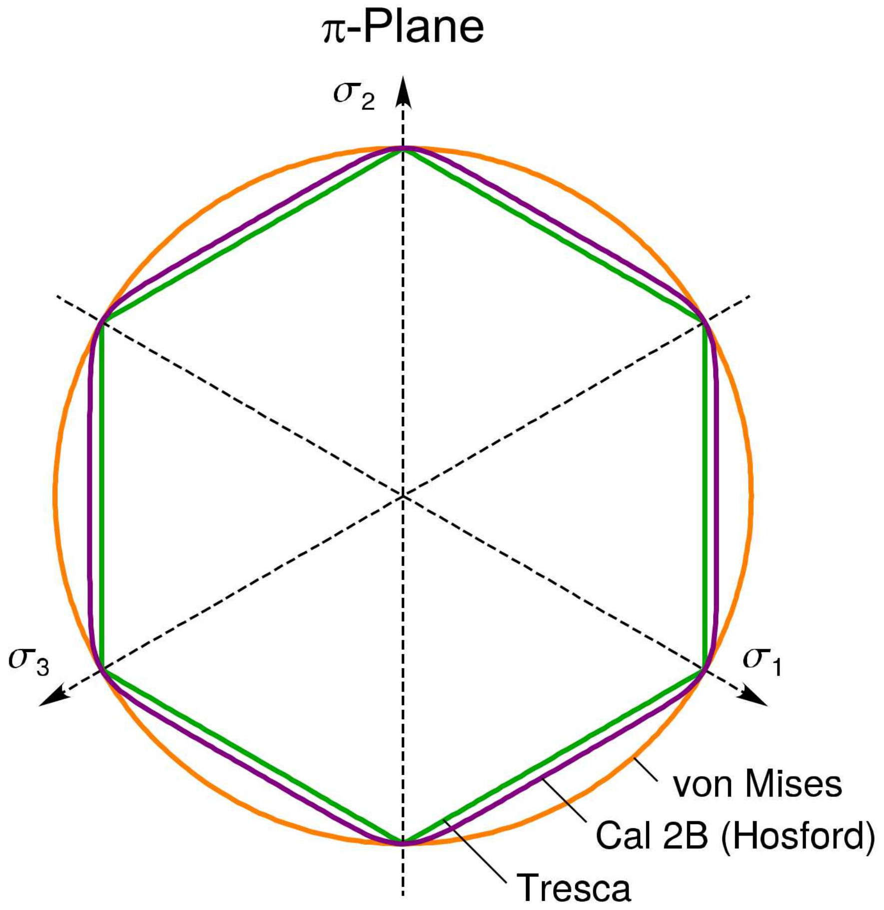
- Permeability and porosity change during life of repository
  - Reconsolidation of granular salt
  - Hydrofracture from high fluid pressure
  - Closure of DRZ fractures
  - Creep closure of open spaces

Fallen Block and Roof Gap 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.

Equivalent Stress Measure (AP-179)



Steady State Creep Rate

$$\dot{\varepsilon}^{ss} \propto \left(\frac{\bar{\sigma}}{\mu}\right)^n$$

Transient Creep Strain Limit

$$\bar{\varepsilon}^{tr*} \propto \left(\frac{\bar{\sigma}}{\mu}\right)^m$$

Hosford: $$\bar{\sigma} = \left\{\frac{1}{2}\left[|\sigma_1 - \sigma_2|^a + |\sigma_2 - \sigma_3|^a + |\sigma_1 - \sigma_3|^a\right]\right\}^{1/a}$$

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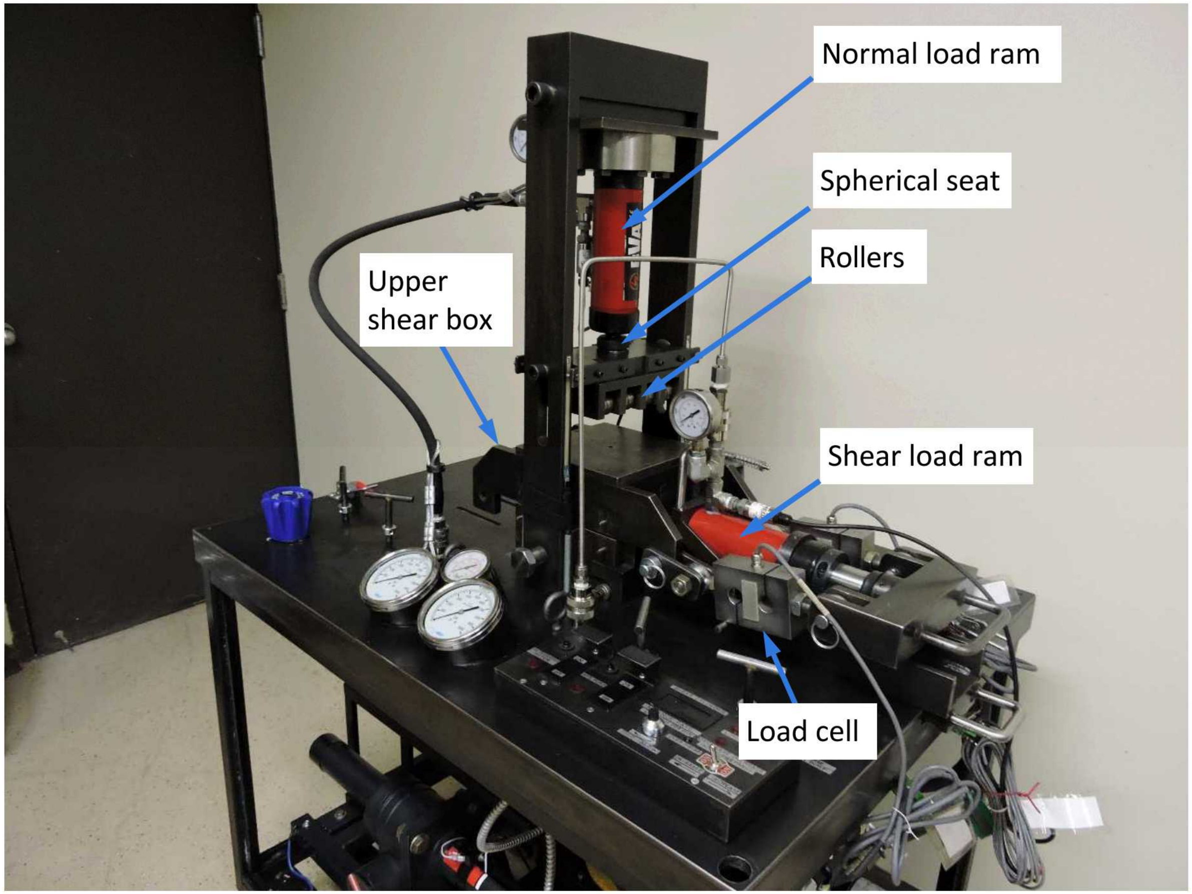
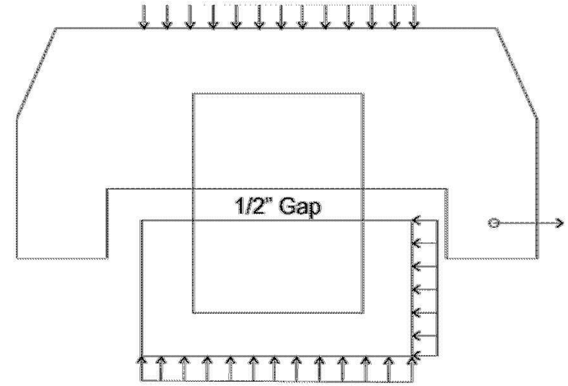
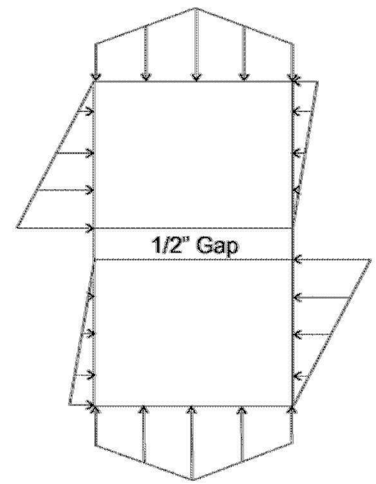
Direct Shear Test Setup (TP 17-03)



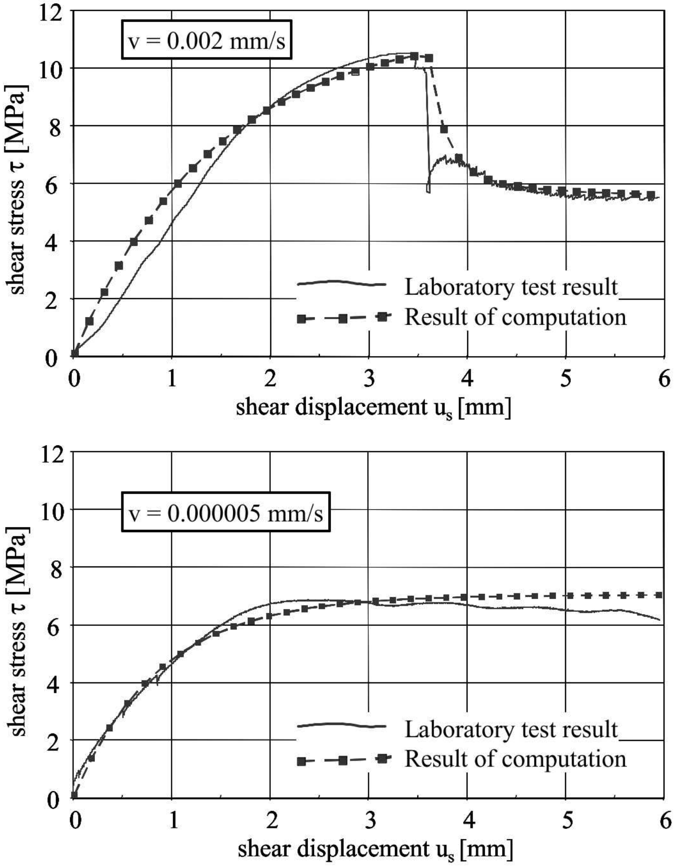




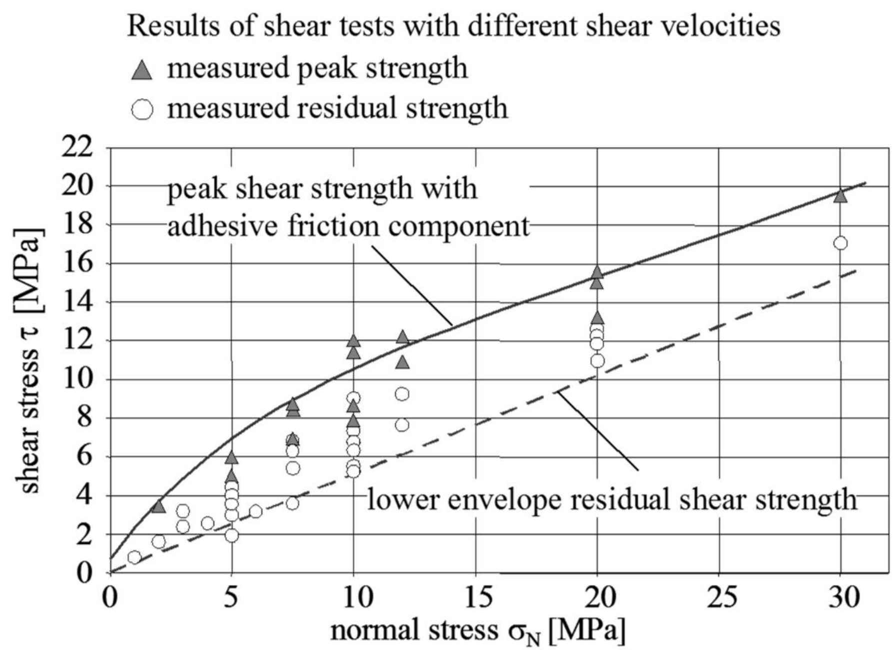
Note: All force profiles depend on contrast in stiffness between the specimen and grout.

Carnallite on Salt Direct Shear Results

Two Individual Tests



Summary of Test Results

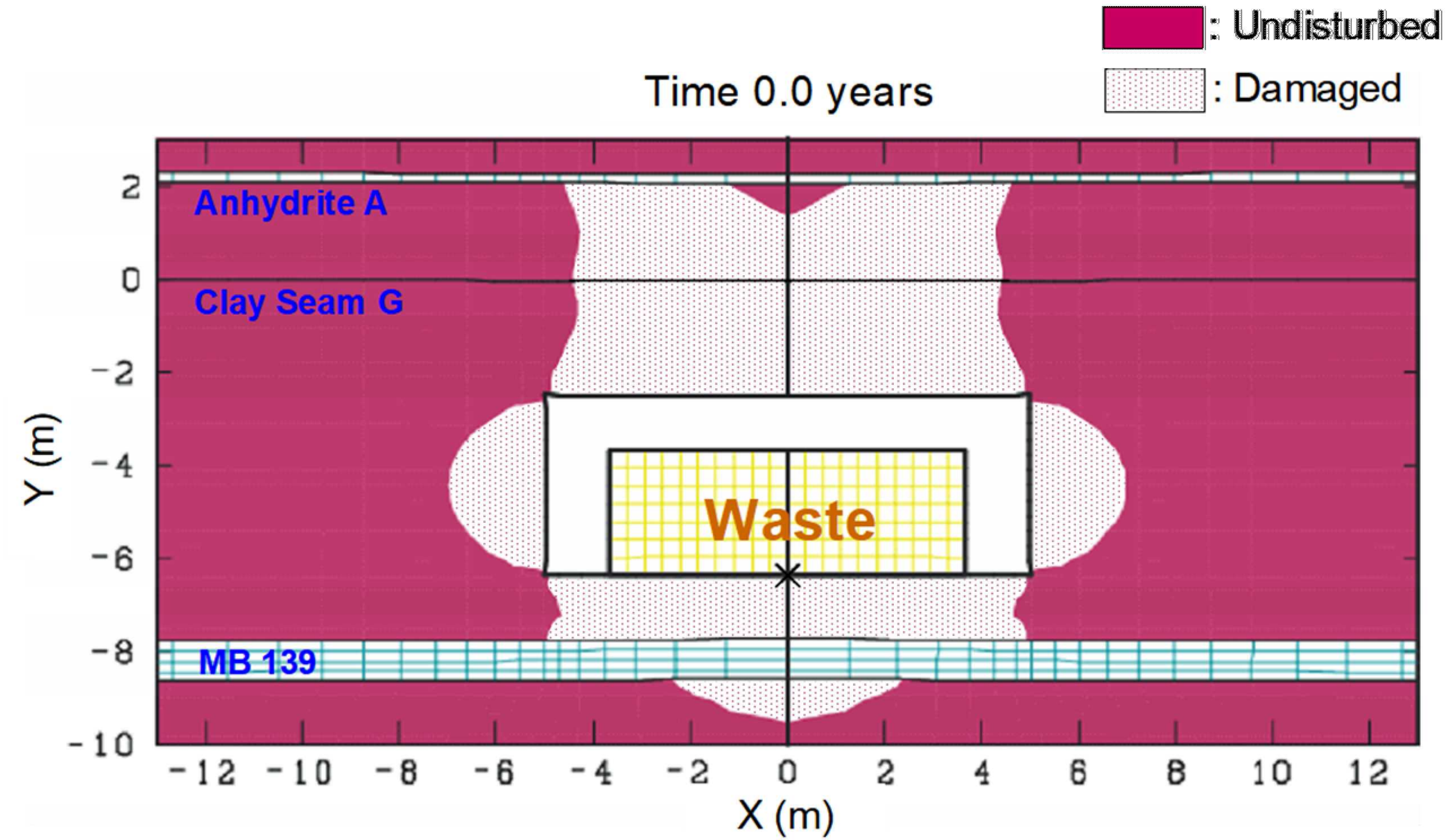


Coulomb Friction?

$$\tau = \mu_c \sigma_n$$

Minkley, W. and J. Mühlbauer. 2007. Constitutive Models to Describe the Mechanical Behavior of Salt Rocks and the Imbedded Weakened Planes. Wallner, M., K-H. Lux, W. Minkley, H.R. Hardy, eds. The Mechanical Behavior of Salt: Understanding of THMC Processes in Salt. Taylor & Francis/Balkema, Leiden, The Netherlands.

Estimation of Disturbed Rock 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.