Used Fuel Disposition Campaign

A Reinvestigation into the Isothermal Room Closure Predictions at WIPP

Benjamin Reedlunn

Sandia National Laboratories

Annual UFD Working Group Meeting

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Acknowledgements / Collaborators

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  - Frank Hansen
  - Jim Bean
  - Courtney Herrick
  - Michael Schuhen
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  - Kirby Mellegard
  - Leo Van Sambeek
  - Kerry DeVries
  - Stuart Buchholz
- **Joint Project III and Joint Project WEIMOS**

Joint Project III and Joint Project WEIMOS

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- **Institute für Gebirgsmechanik**
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  - Kai Herchen
- **TU Braunschweig**
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  - Andreas Gährken
  - Christian Missal
- **Leibnitz Universität Hannover**
  - Reinhard Rokahr
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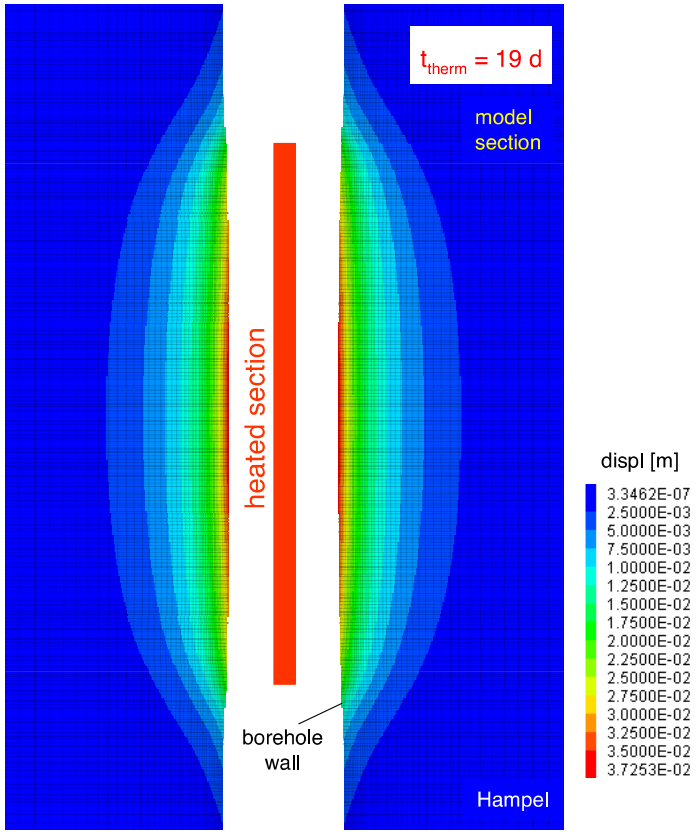
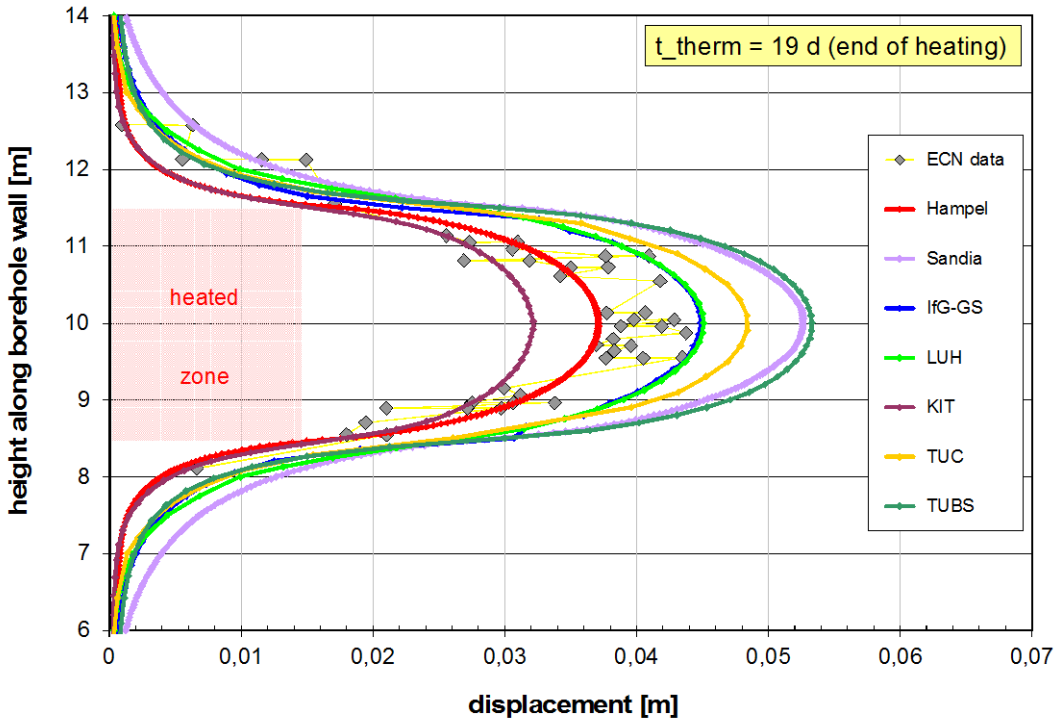
  - Alexandra Pudewillis
- **Sandia National Laboratories**
  - Frank Hansen
  - Lupe Arguello
  - Benjamin Reedlunn

Past Benchmarking Activity





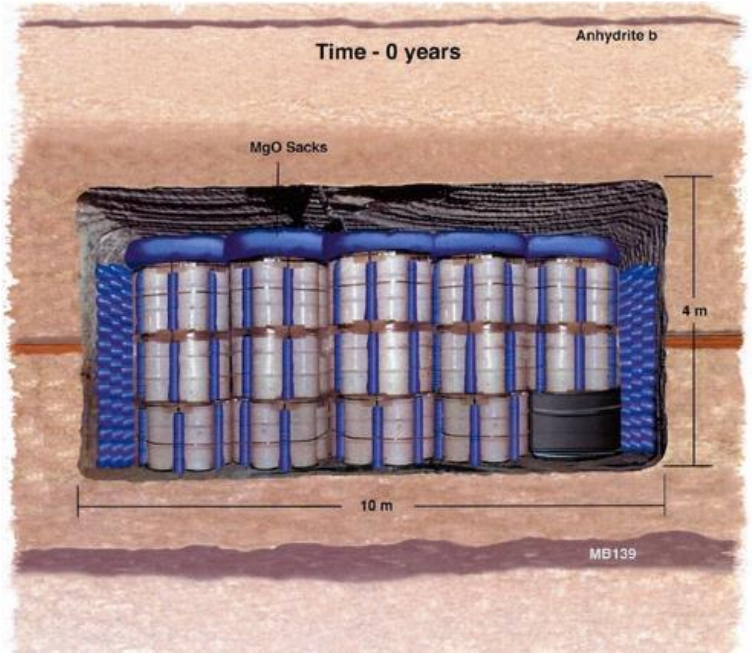
Outline

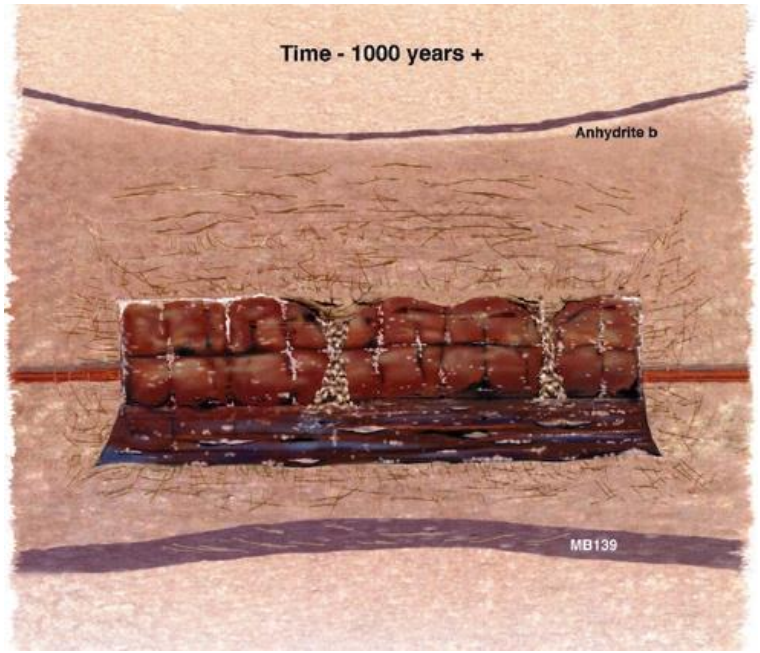
- **Background**
  - Motivation
  - WIPP Rooms B and D
- **Munson-Dawson Model**
- **Legacy simulations**
  - Munson's Changes
- **Legacy simulations recreated**
  - Resolving the numerics
- **Munson-Dawson model re-calibration**
  - New closure predictions
- **Open Questions**
- **Summary**

Background

Motivation: Post-Closure

How long until the waste is isolated?



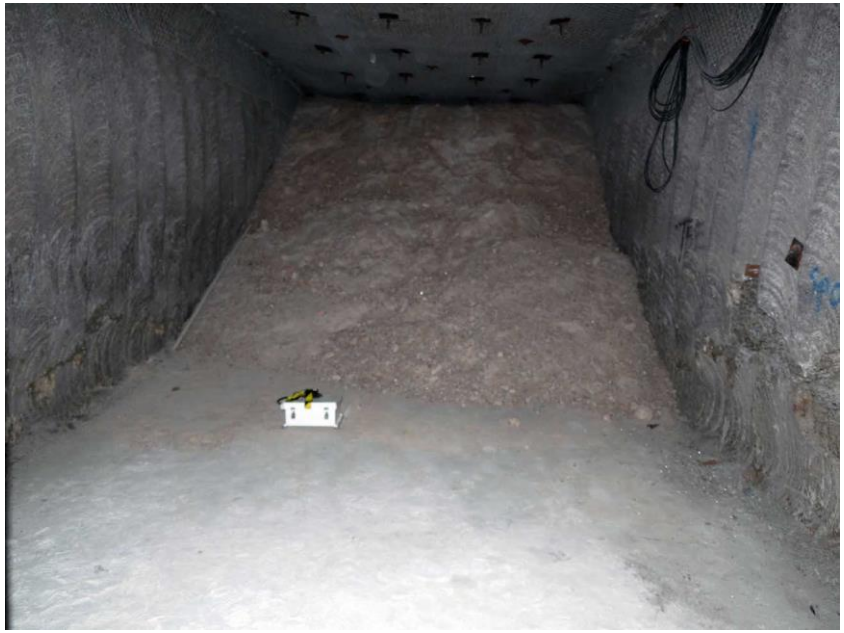


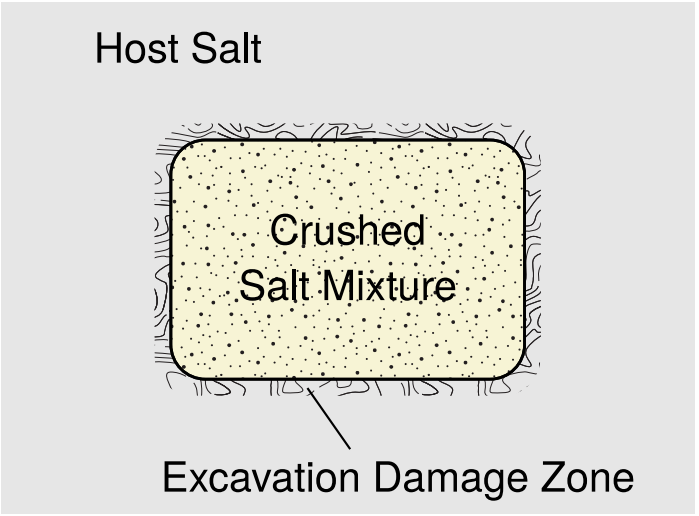
Motivation: Design and Operations

How long can we operate in an area?

Motivation: Design and Operations

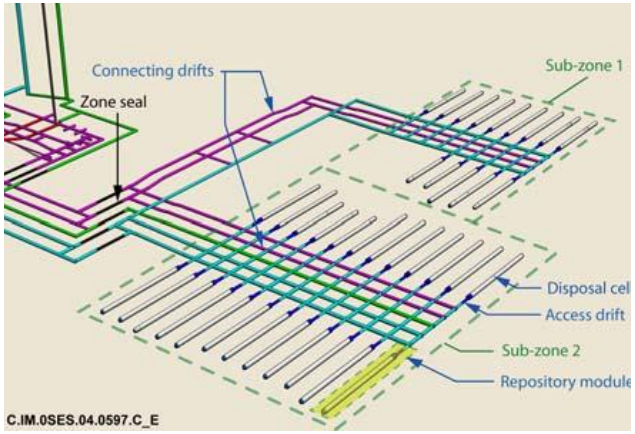
How long until a seal or panel closure matures?

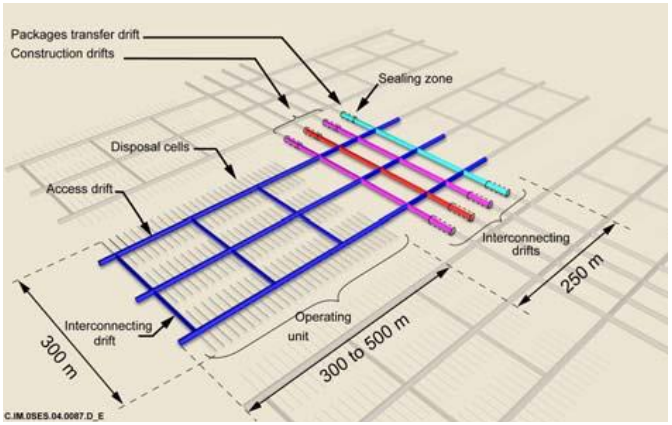




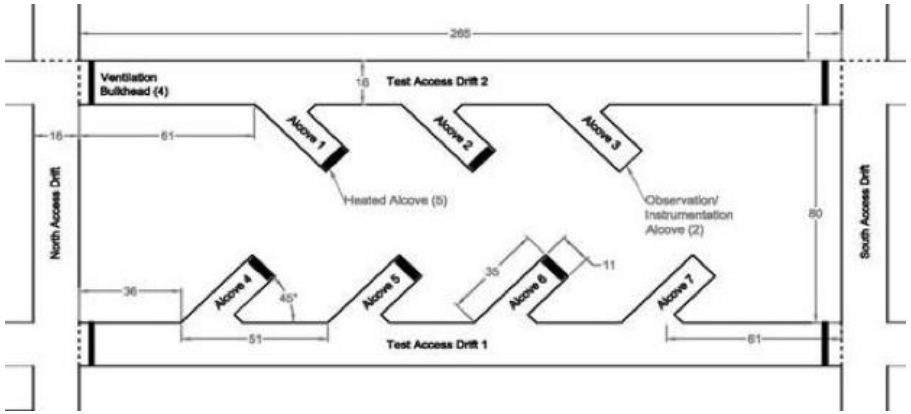
Motivation: Design

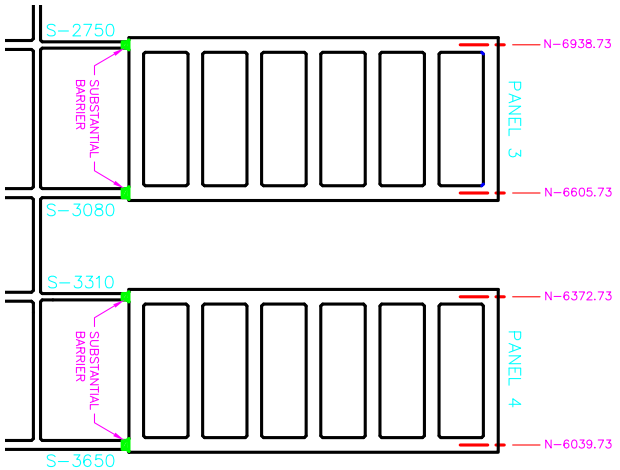
How do different designs compare?





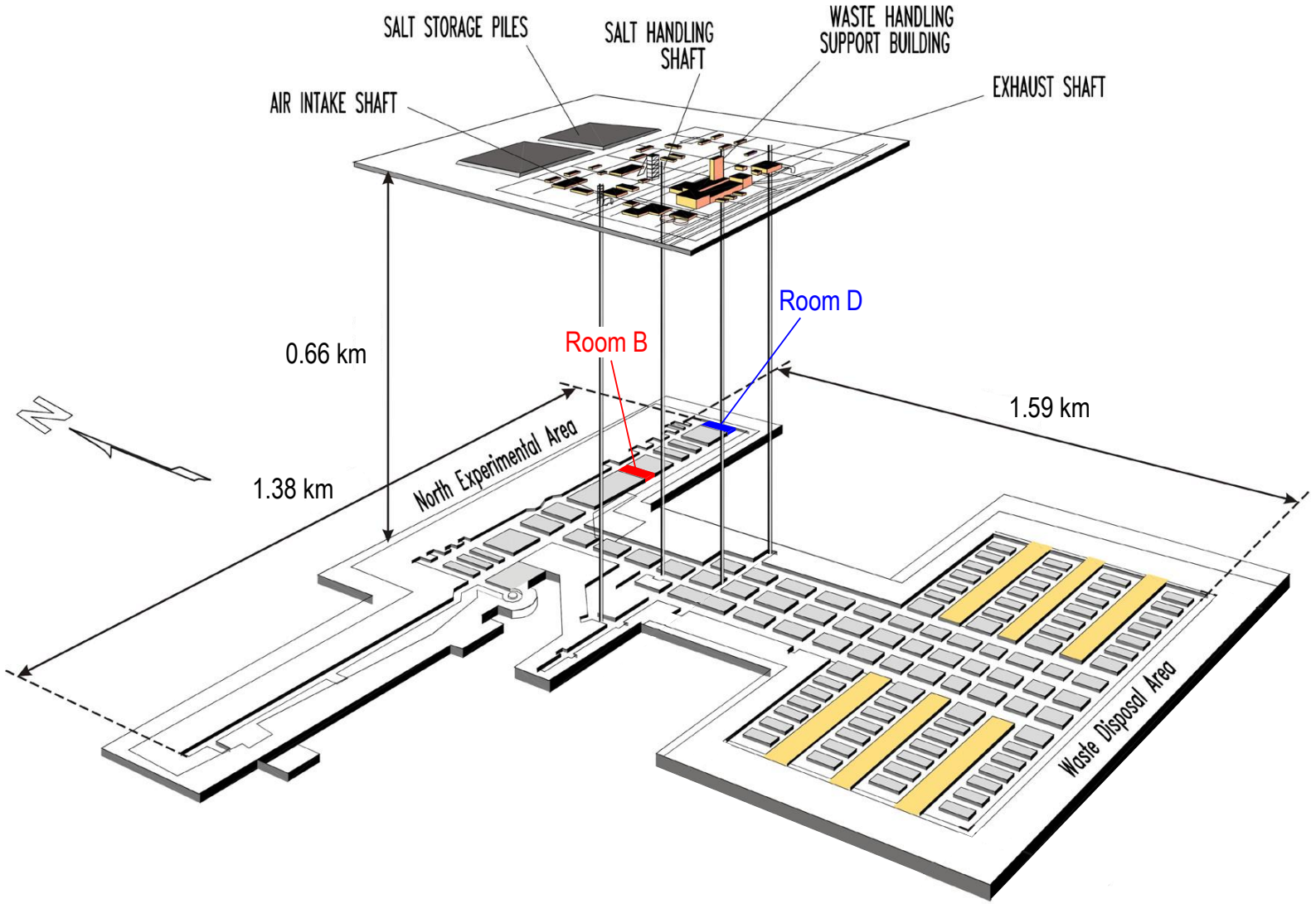
J. L. Gaussen, Geological repository layout for radioactive high level long lived waste in argilite. ENC 2005



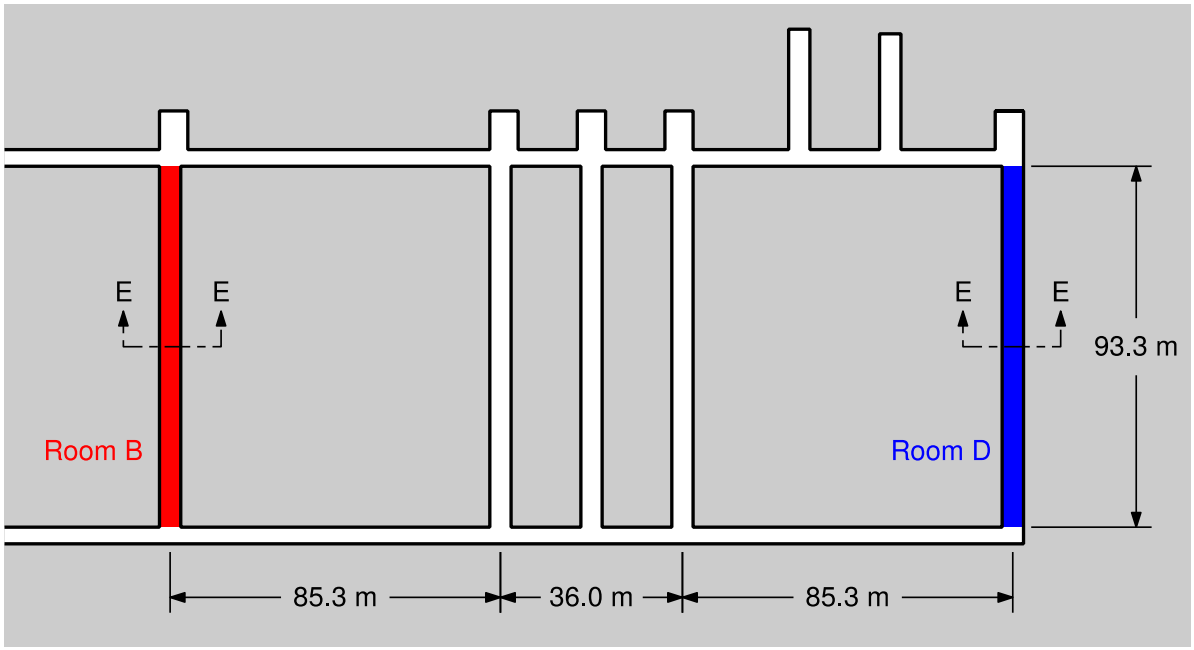


R. Nelson, Salt Disposal Investigations Proposal, DOE/CBFO-11-3470, June 2011

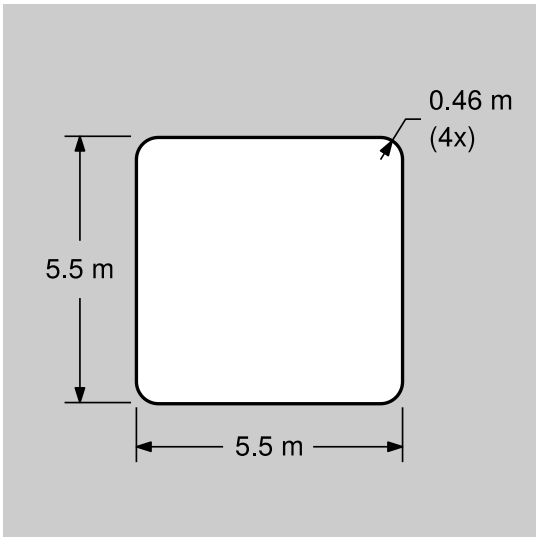
Room B and D at WIPP



Room B and D Dimensions



Plan View

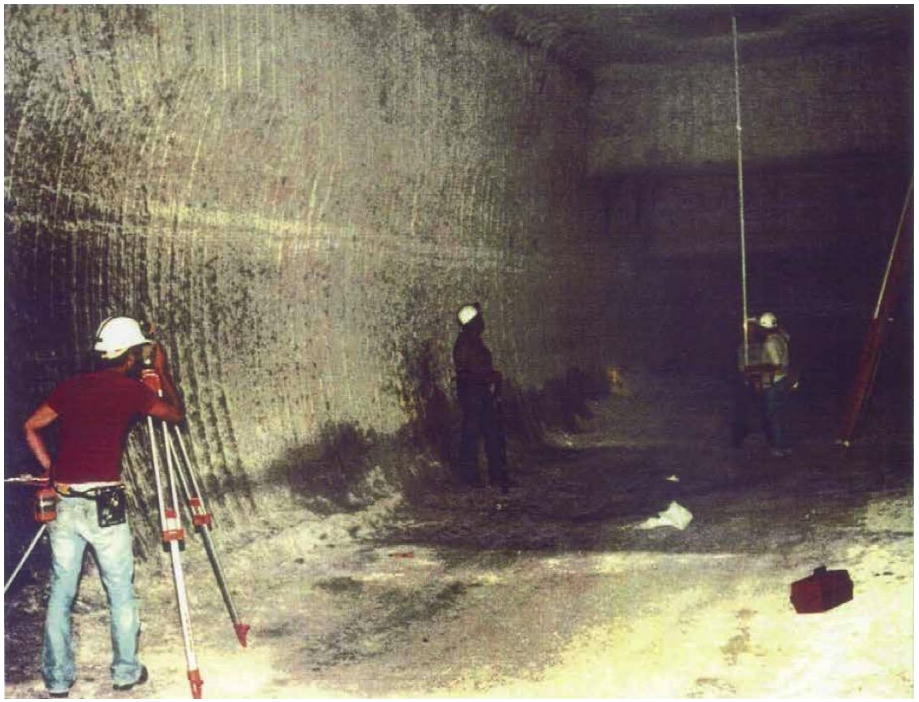


Section E-E

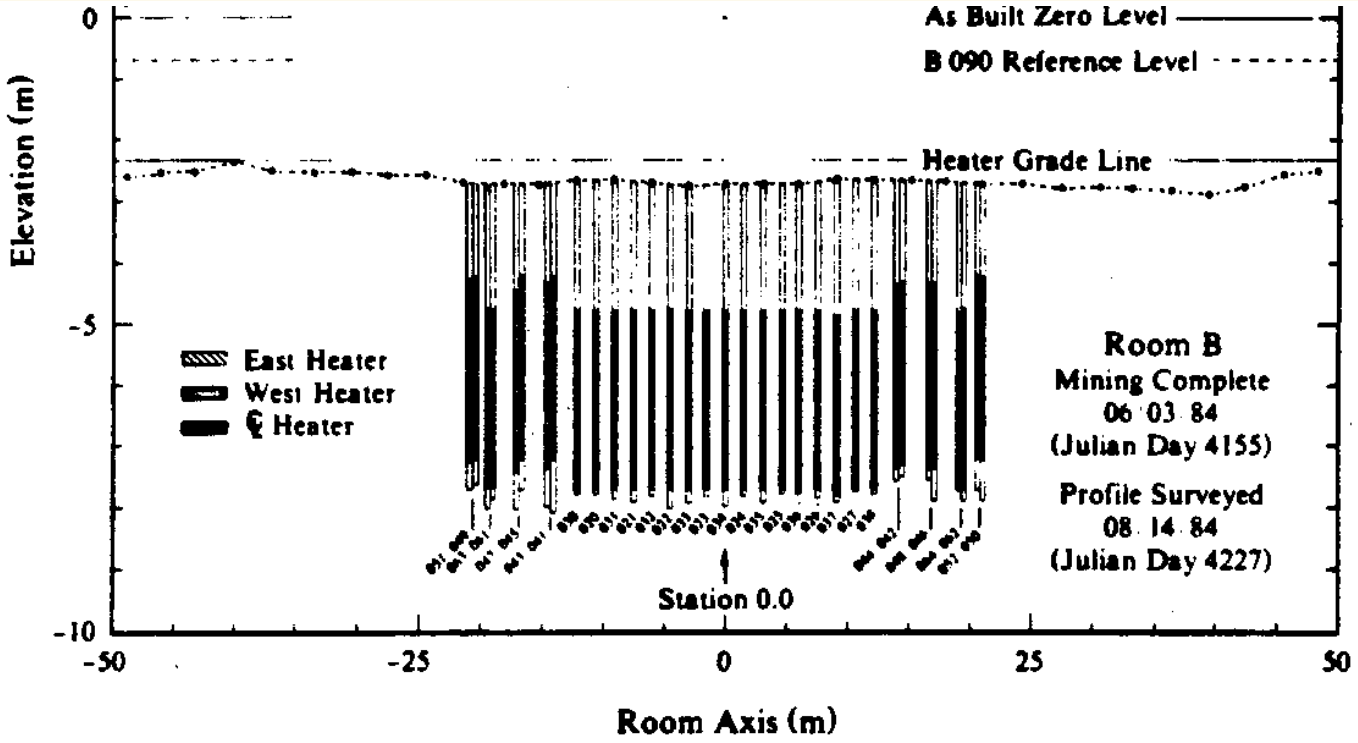
Photos of Room B and D

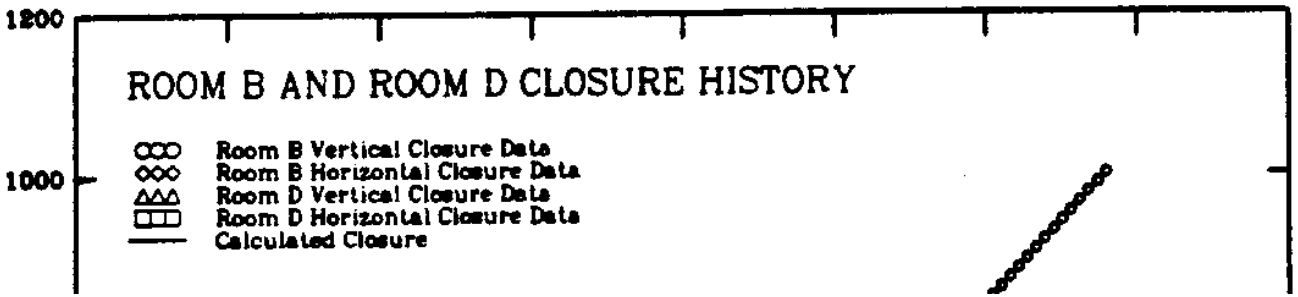
Room B

Room D



In-Situ Closure Measurements

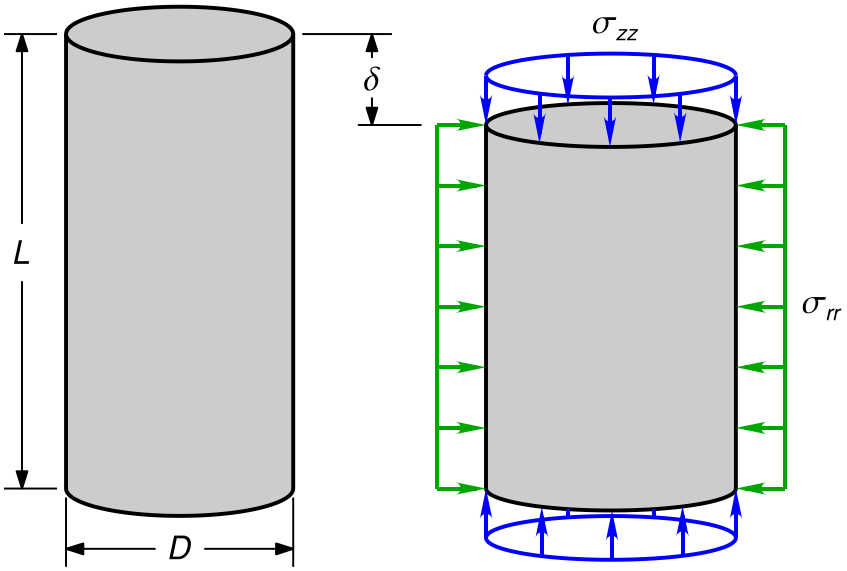




Munson, D., DeVries, K. Callahan, G. Comparison of Calculations and In Situ Result for a Large, Heated, Test Room at the Waste Isolation Pilot Plant (WIPP). 31st Symposium on Rock Mechanics. June 1990

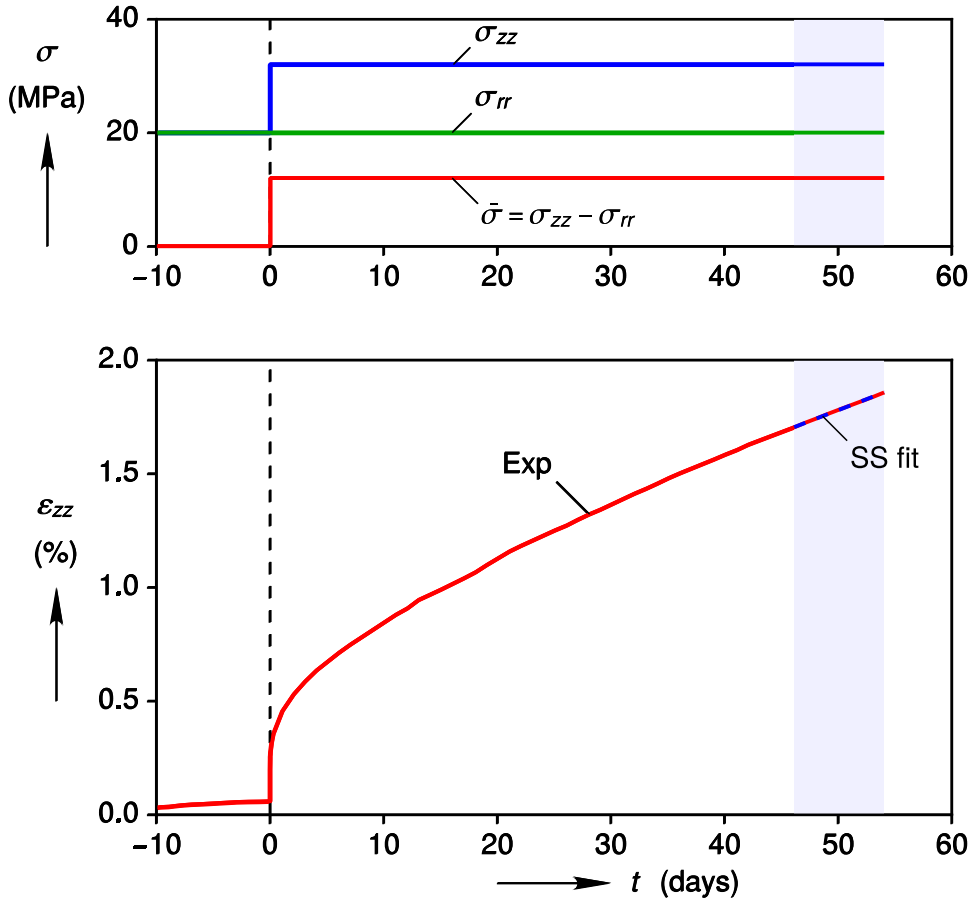
Munson-Dawson Model

Triaxial Creep Experiments

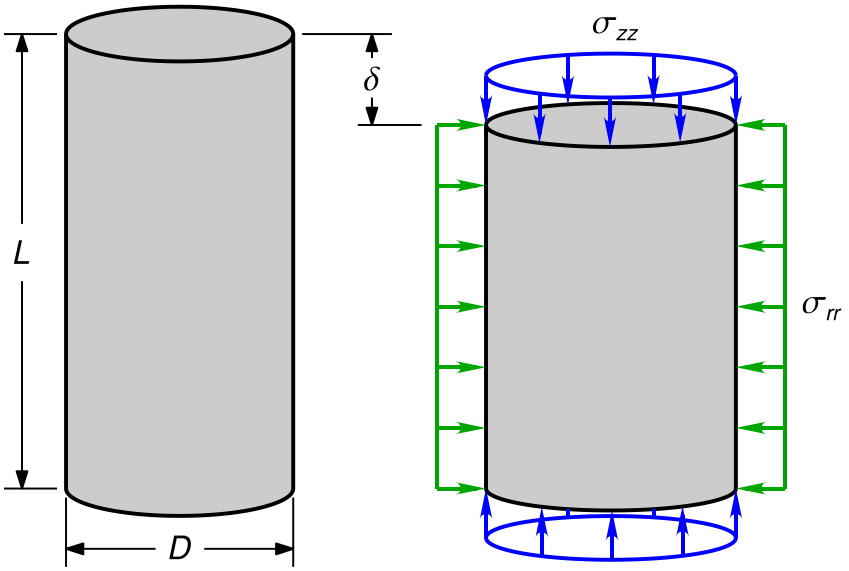


$$\frac{L}{D} = 2$$

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



Triaxial Creep Experiments



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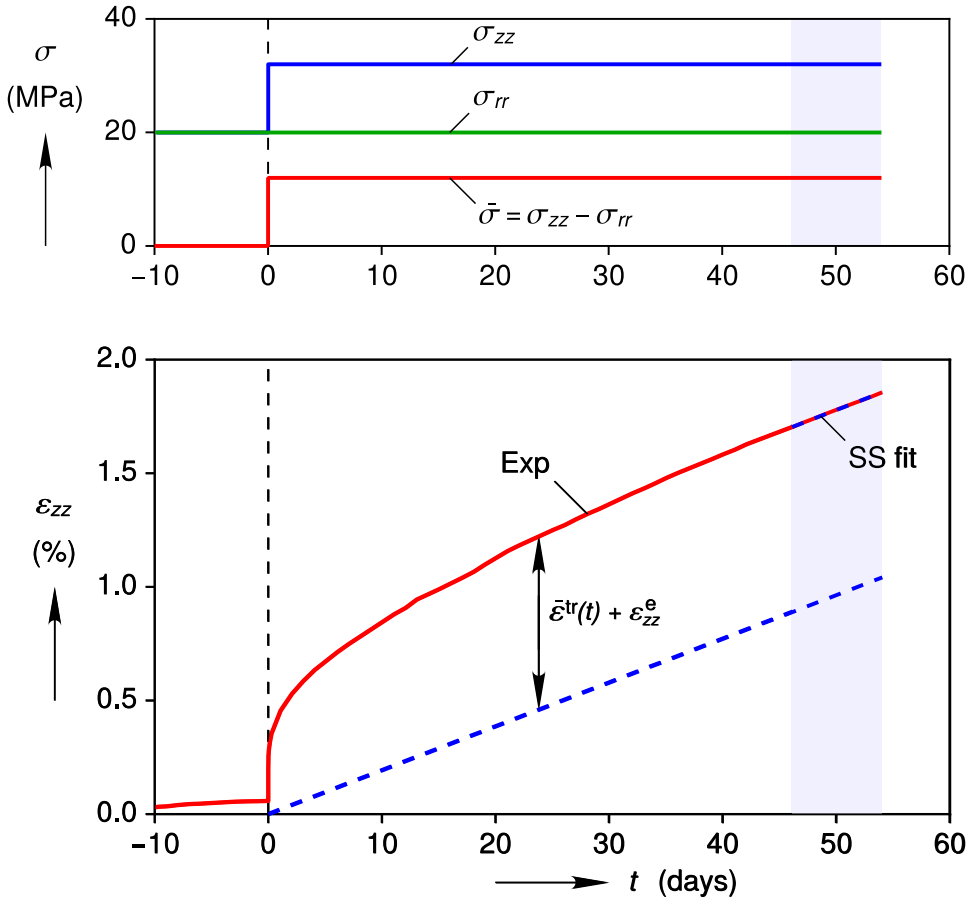

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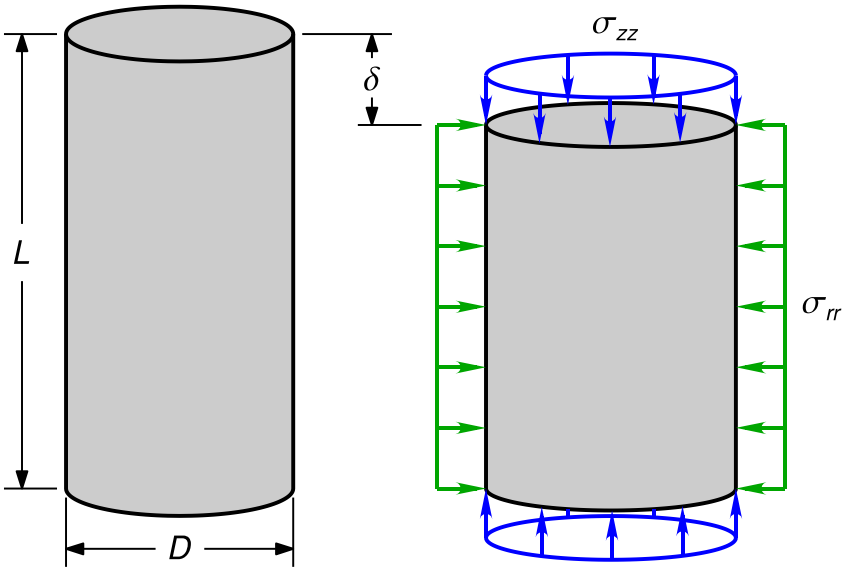

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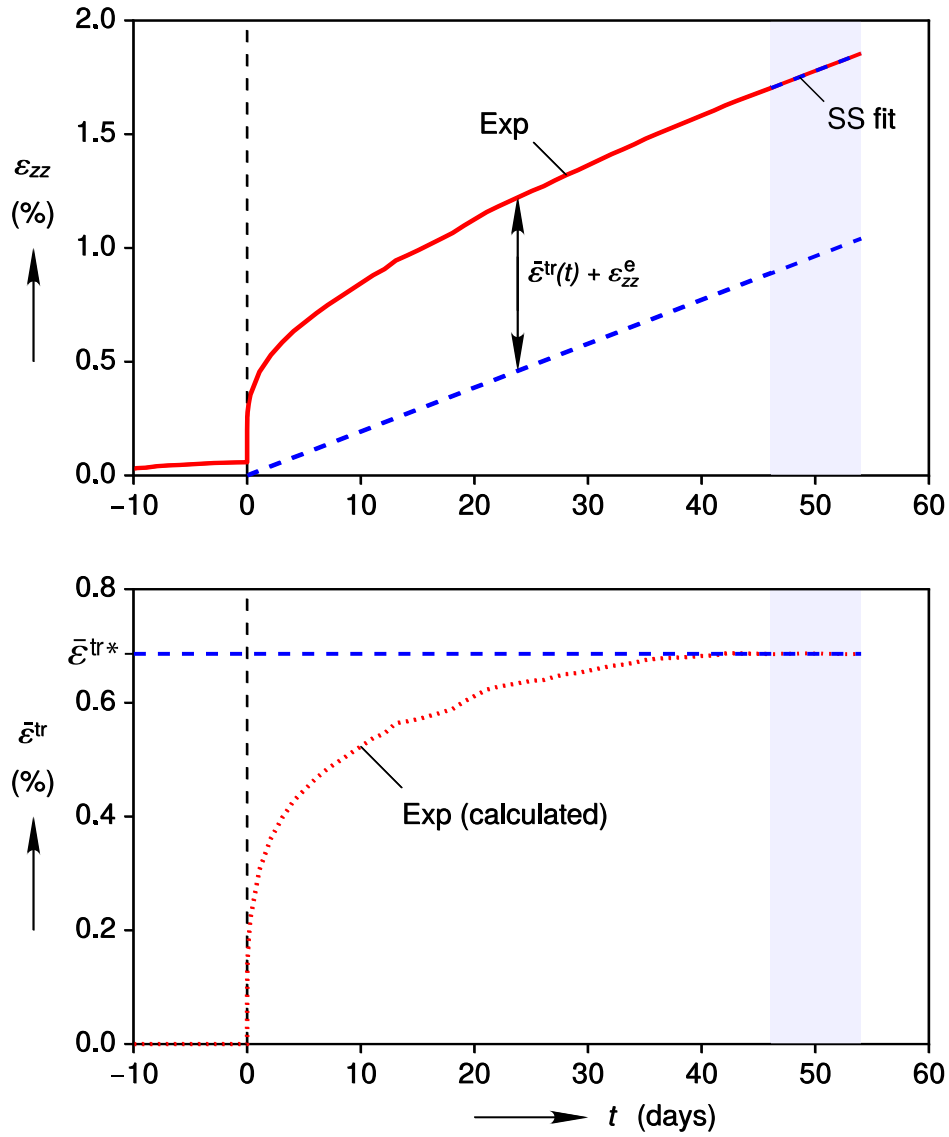
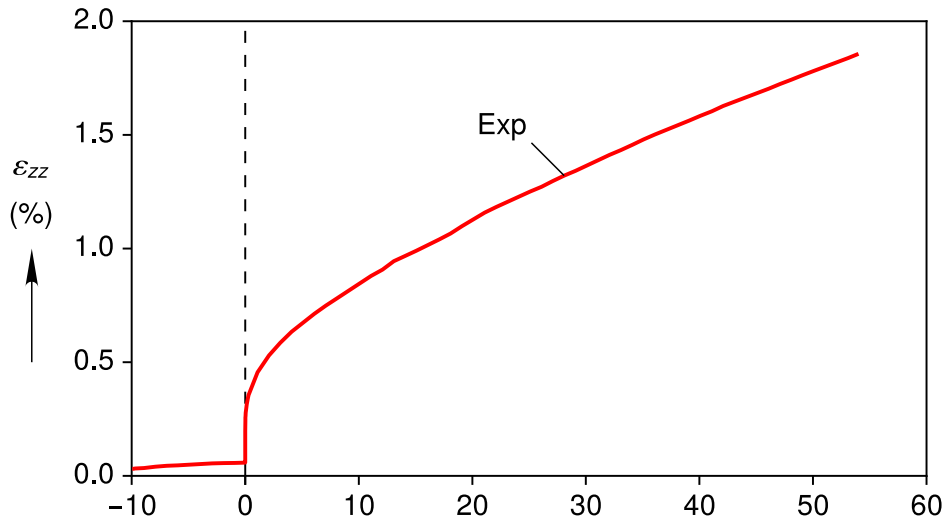


Munson Dawson Calibration



Transient Creep ODE

$$\dot{\bar{\varepsilon}}^{tr} = \exp\left[\delta_h \left(1 - \frac{\bar{\varepsilon}^{tr}}{\bar{\varepsilon}^{tr*}}\right)^2\right] \dot{\bar{\varepsilon}}^{ss} - \dot{\bar{\varepsilon}}^{ss}$$

Munson Dawson Calibration

Transient Creep ODE

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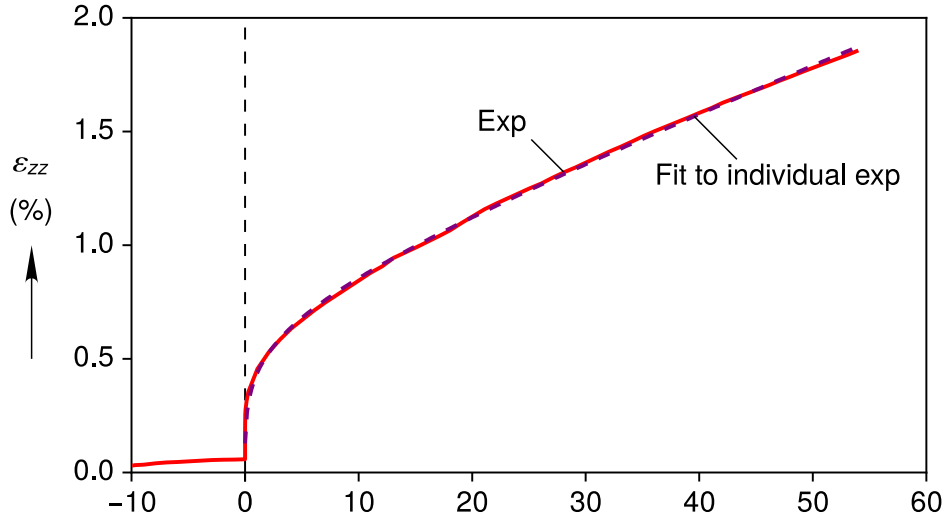

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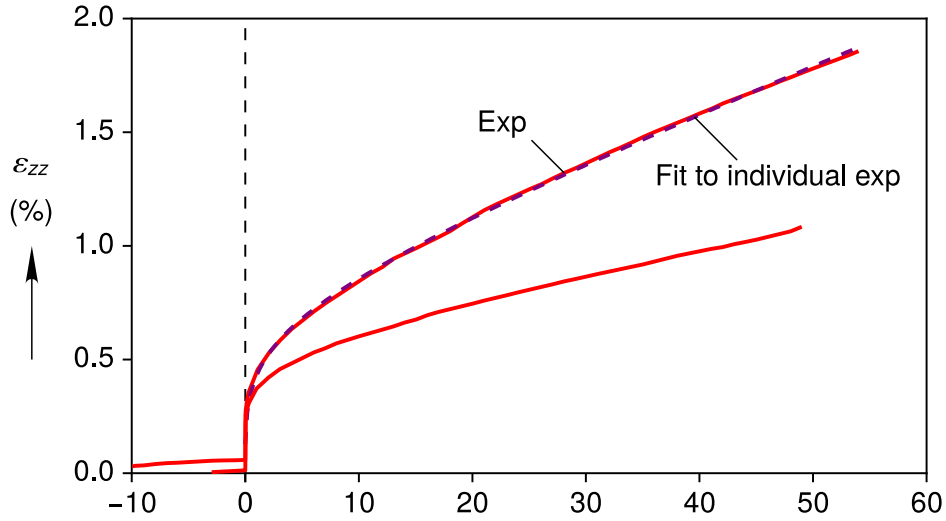

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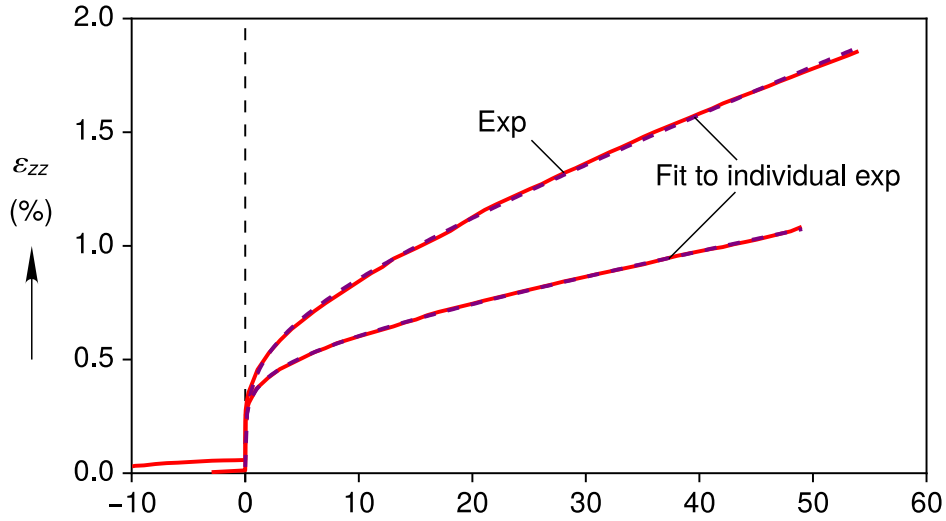
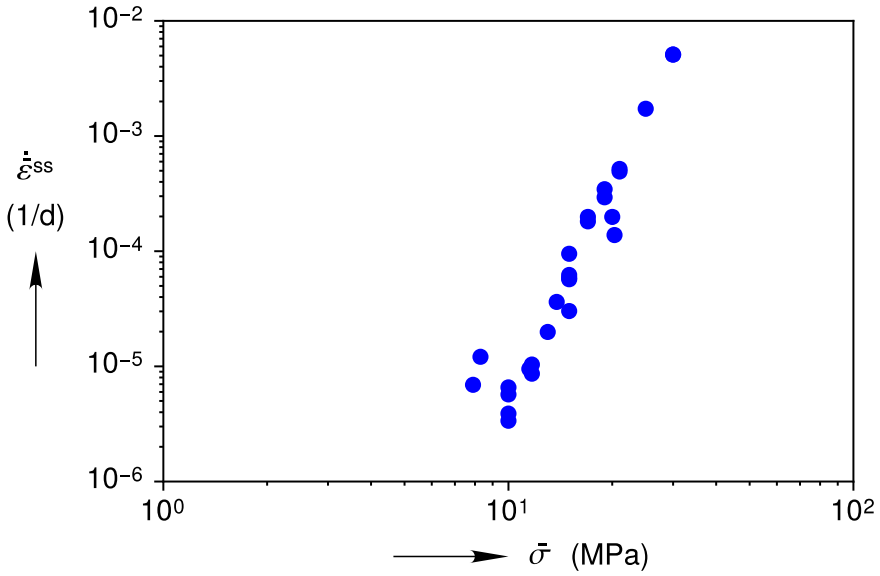


Munson Dawson Calibration (low stress, low temp)

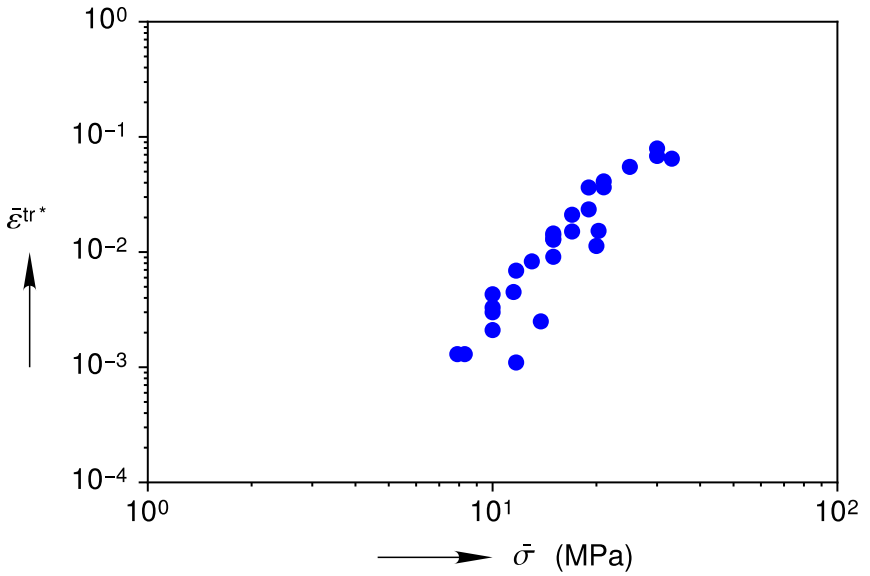
Steady State Rate



$$\dot{\bar{\varepsilon}}^{ss} = A \exp\left(-\frac{Q}{R\,T}\right)\left(\frac{\bar{\sigma}}{\mu}\right)^{n}$$

$$\log_{10}\left[\dot{\bar{\varepsilon}}^{ss}\right] = \log_{10}\left[A \exp\left(-\frac{Q}{R\,T}\right)\right] + n \log_{10}\left[\frac{\bar{\sigma}}{\mu}\right]$$

Transient Limit

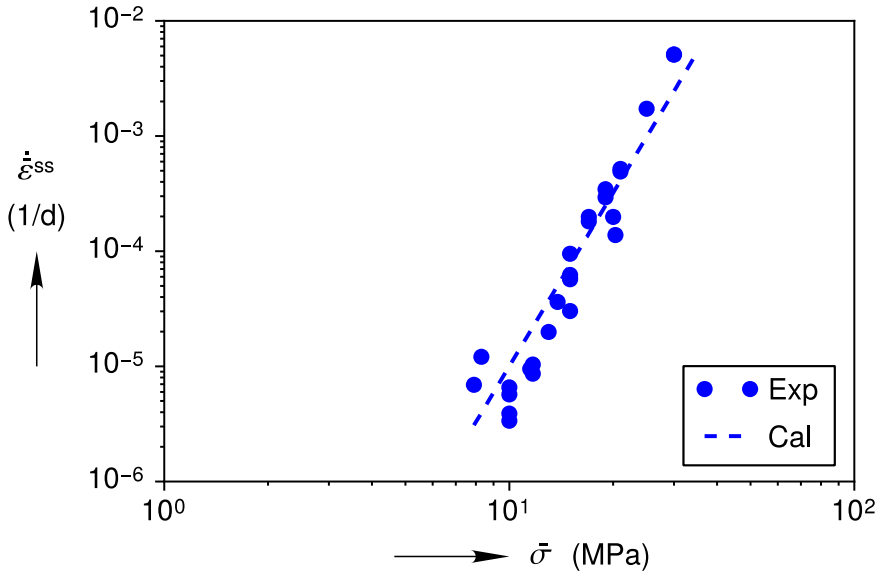


$$\bar{\varepsilon}^{tr*} = K_0 \exp\left(c\,T\right)\left(\frac{\bar{\sigma}}{\mu}\right)^{m}$$

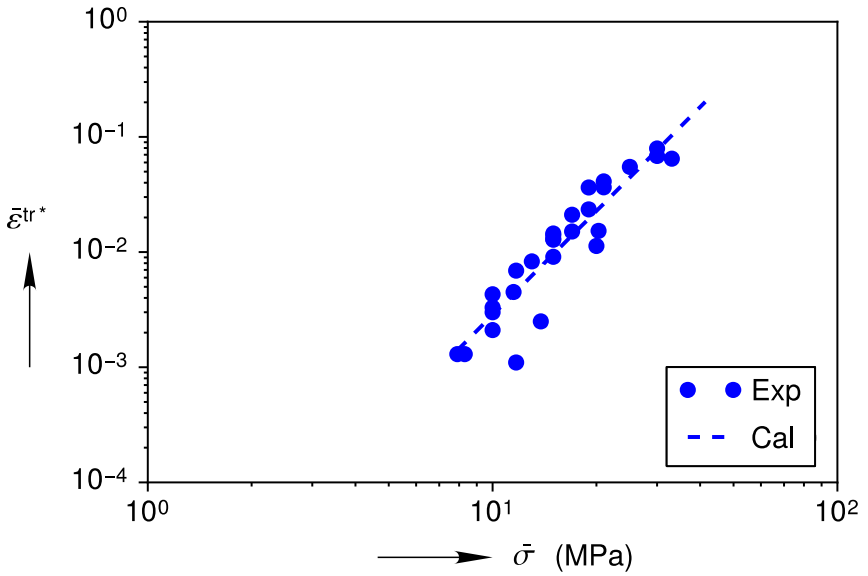
$$\log_{10}\left[\bar{\varepsilon}^{tr*}\right] = \log_{10}\left[K_0 \exp\left(c\,T\right)\right] + m \log_{10}\left[\frac{\bar{\sigma}}{\mu}\right]$$

Munson Dawson Calibration (low stress, low temp)

Steady State Rate



Transient Limit



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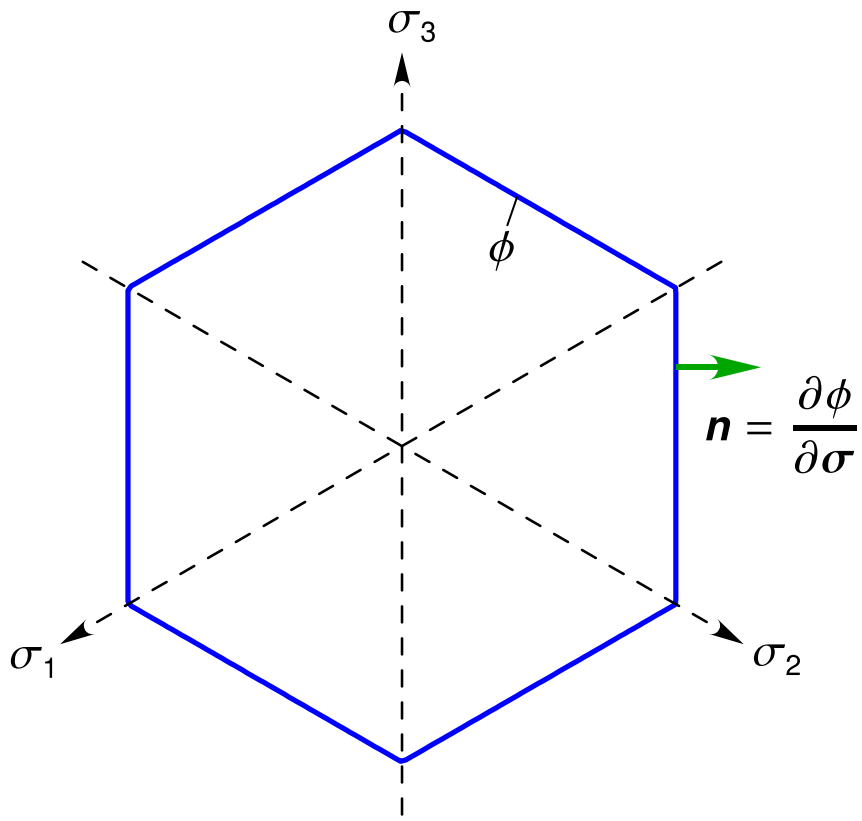
Munson Dawson: 3D Generalization

Tresca Flow Potential



$$\phi = \max\left(|\sigma_1 - \sigma_2|,\ |\sigma_2 - \sigma_3|,\ |\sigma_3 - \sigma_1|\right)$$

Additive Decomposition

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{\mathrm{e}} + \dot{\boldsymbol{\varepsilon}}^{\mathrm{in}}$$

Associated Flow Rule

$$\bar{\sigma} = \phi$$

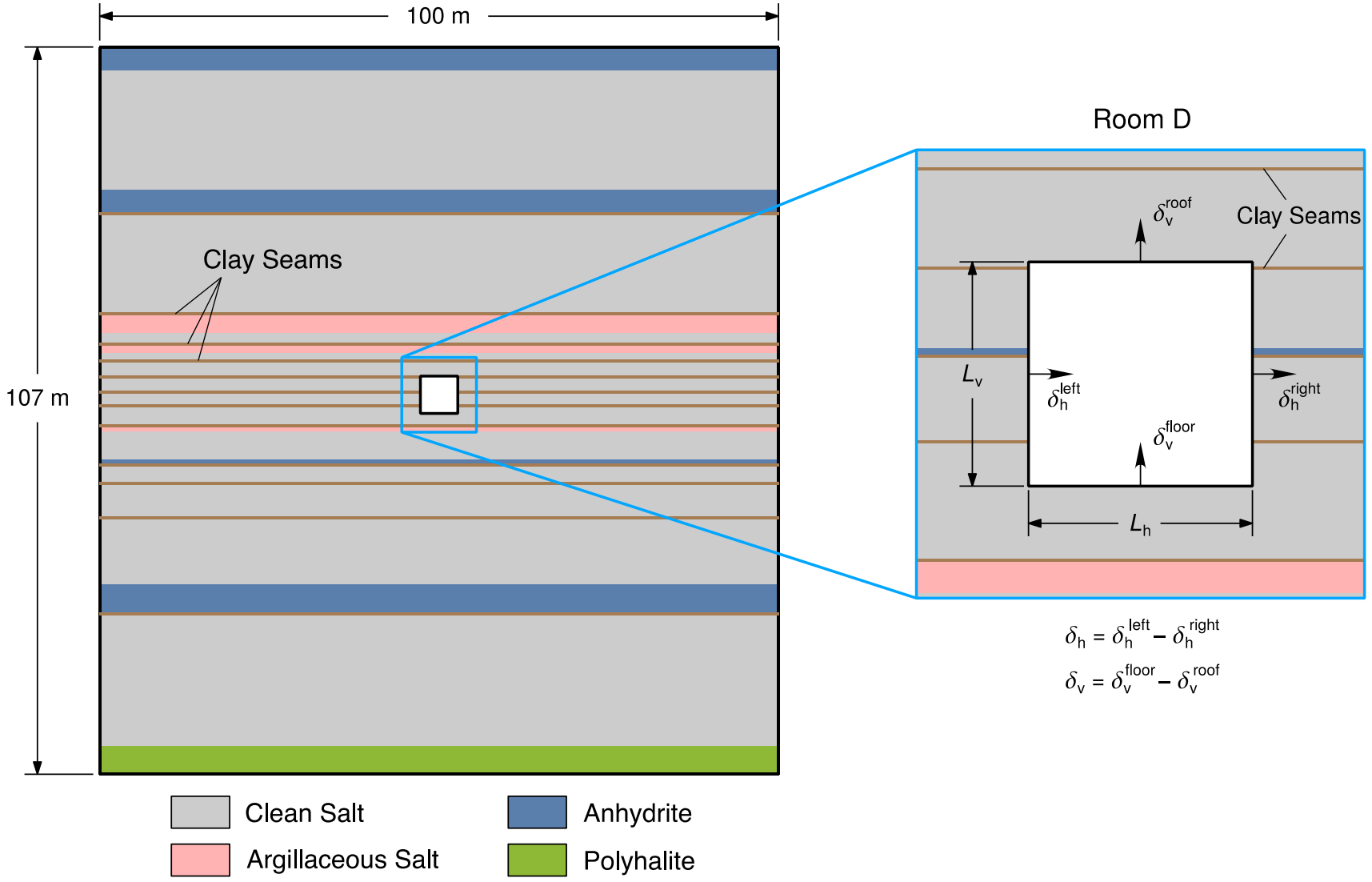
$$\dot{\boldsymbol{\varepsilon}}^{\mathrm{in}} = \left(\dot{\bar{\varepsilon}}^{\mathrm{ss}} + \dot{\bar{\varepsilon}}^{\mathrm{tr}}\right) \boldsymbol{n}$$

Generalized Hooke's Law

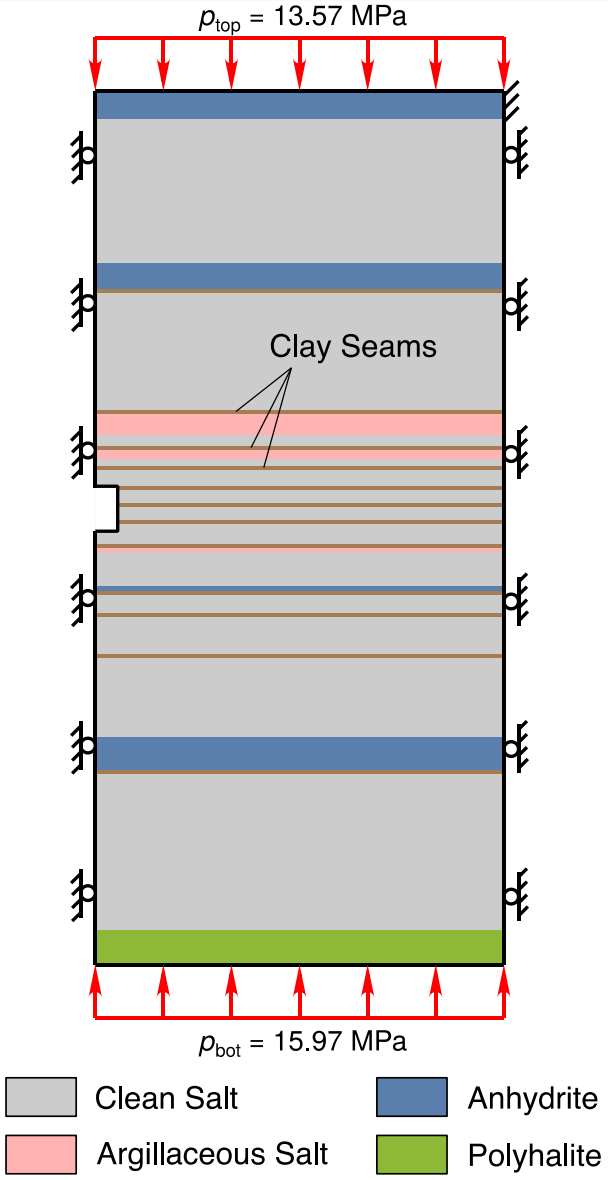
$$\dot{\boldsymbol{\sigma}} = \mathbb{C} : \dot{\boldsymbol{\varepsilon}}^{\mathrm{e}}$$

Legacy Simulations

Idealized Stratigraphy

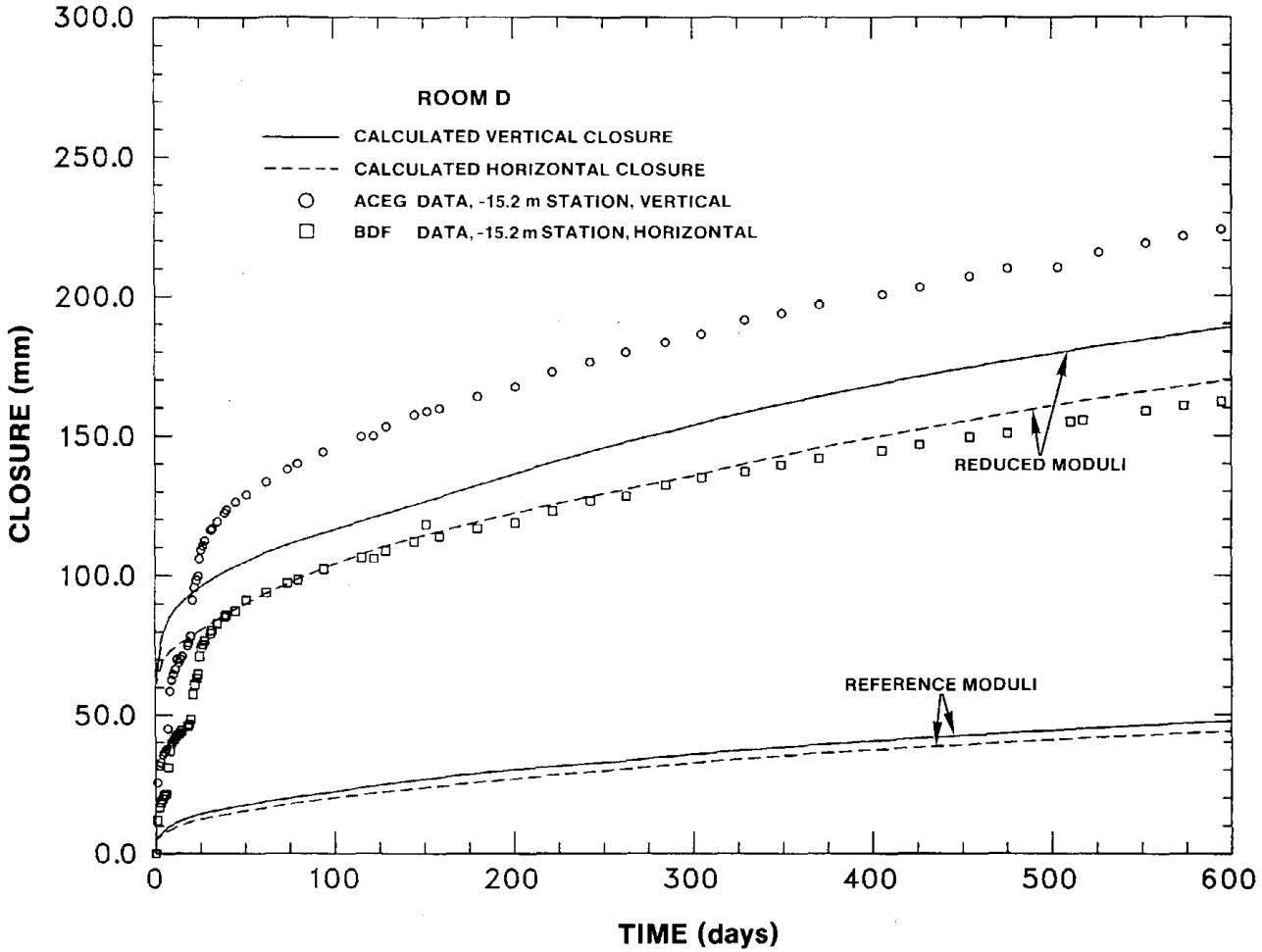


Model Setup



- **Clean and Argillaceous Salt**
  - Munson-Dawson model
  - Separate parameter sets
- **Anhydrite and Polyhalite**
  - Drucker-Prager model
  - Elastic perfectly plastic
  - Separate parameters sets
- **Clay Seams**
  - Coulomb friction

Legacy Simulations



Munson, D., Torres, T. Jones, R. Pseudostrain representation of multipass excavations in salt. 28th Symposium on Rock Mechanics. July 1987

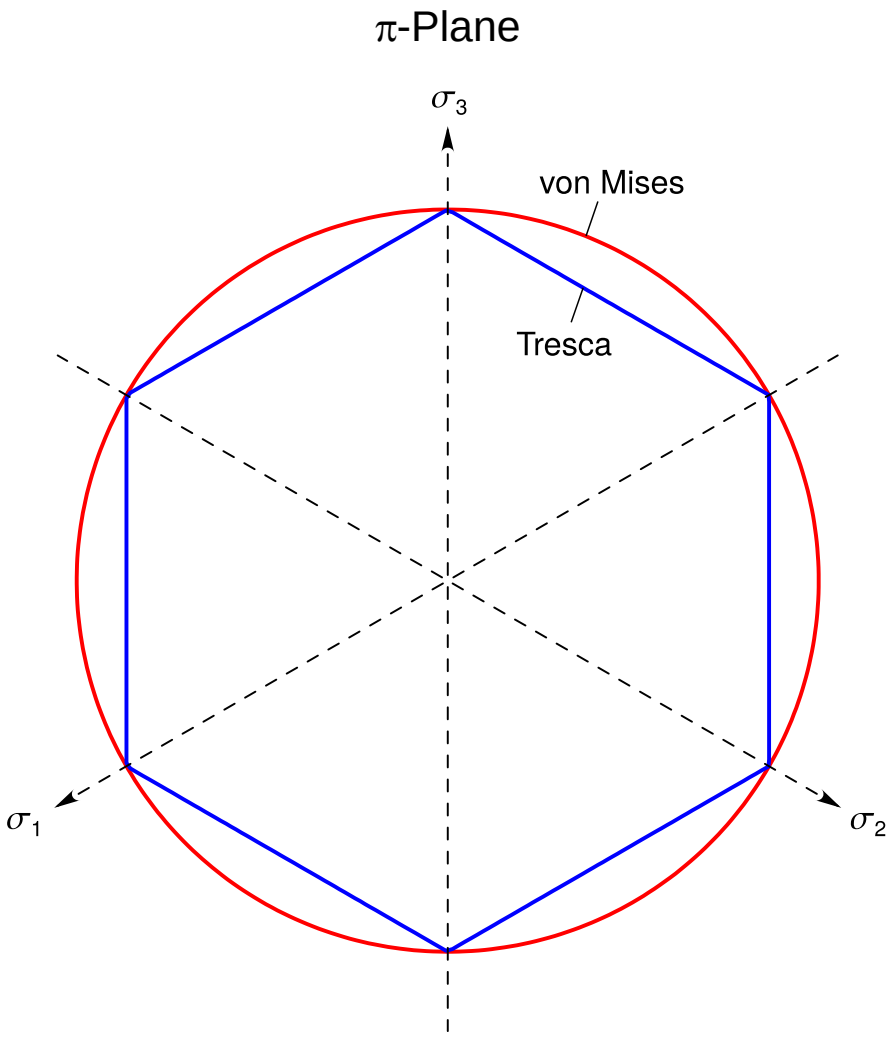
Steady State Creep Rate

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

Transient Creep Strain Limit

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

Changed the Flow Potential



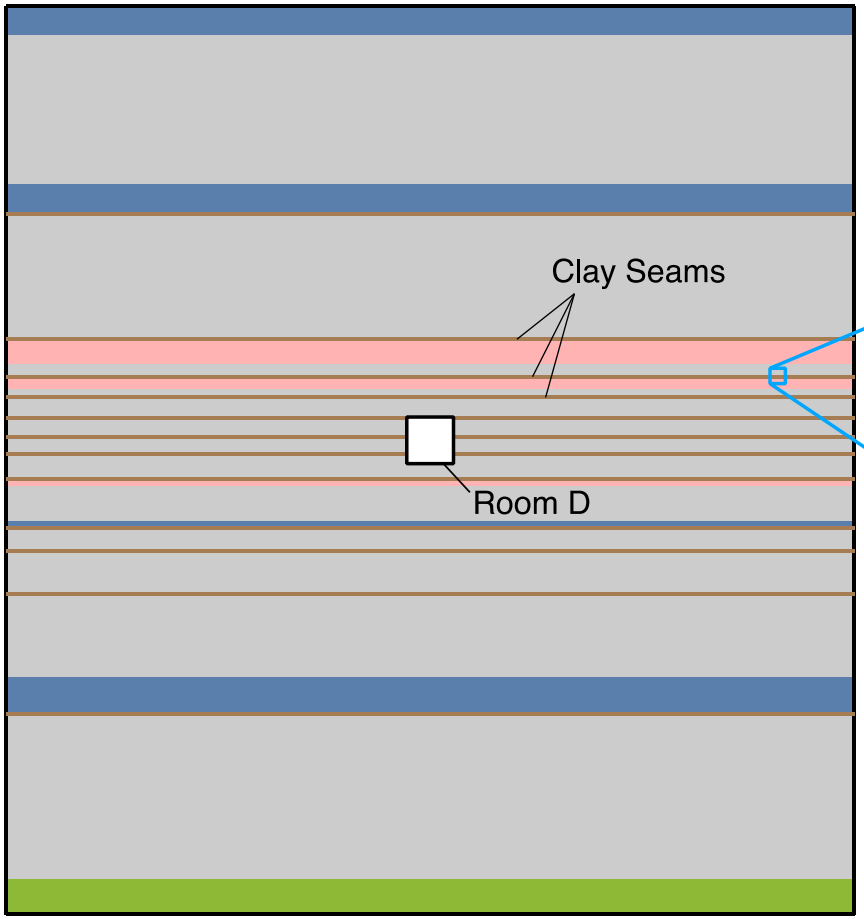
Steady State Creep Rate

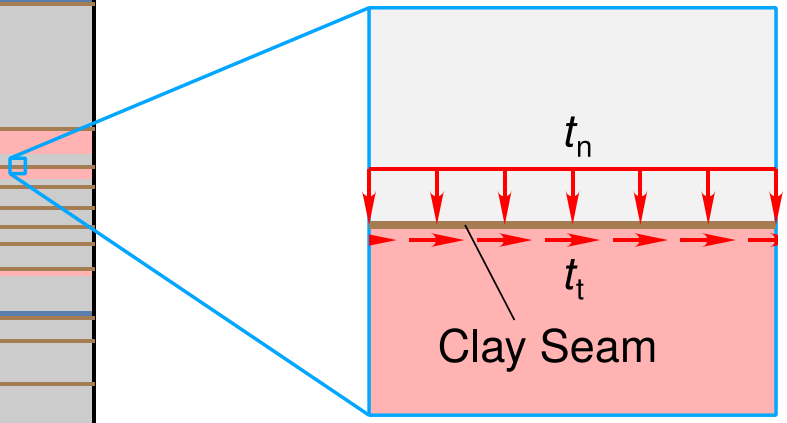
$$\dot{\bar{\varepsilon}}^{ss} \propto \left(\frac{\bar{\sigma}}{\mu}\right)^{n}$$

Transient Creep Strain Limit

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

Changed the Friction Coefficient





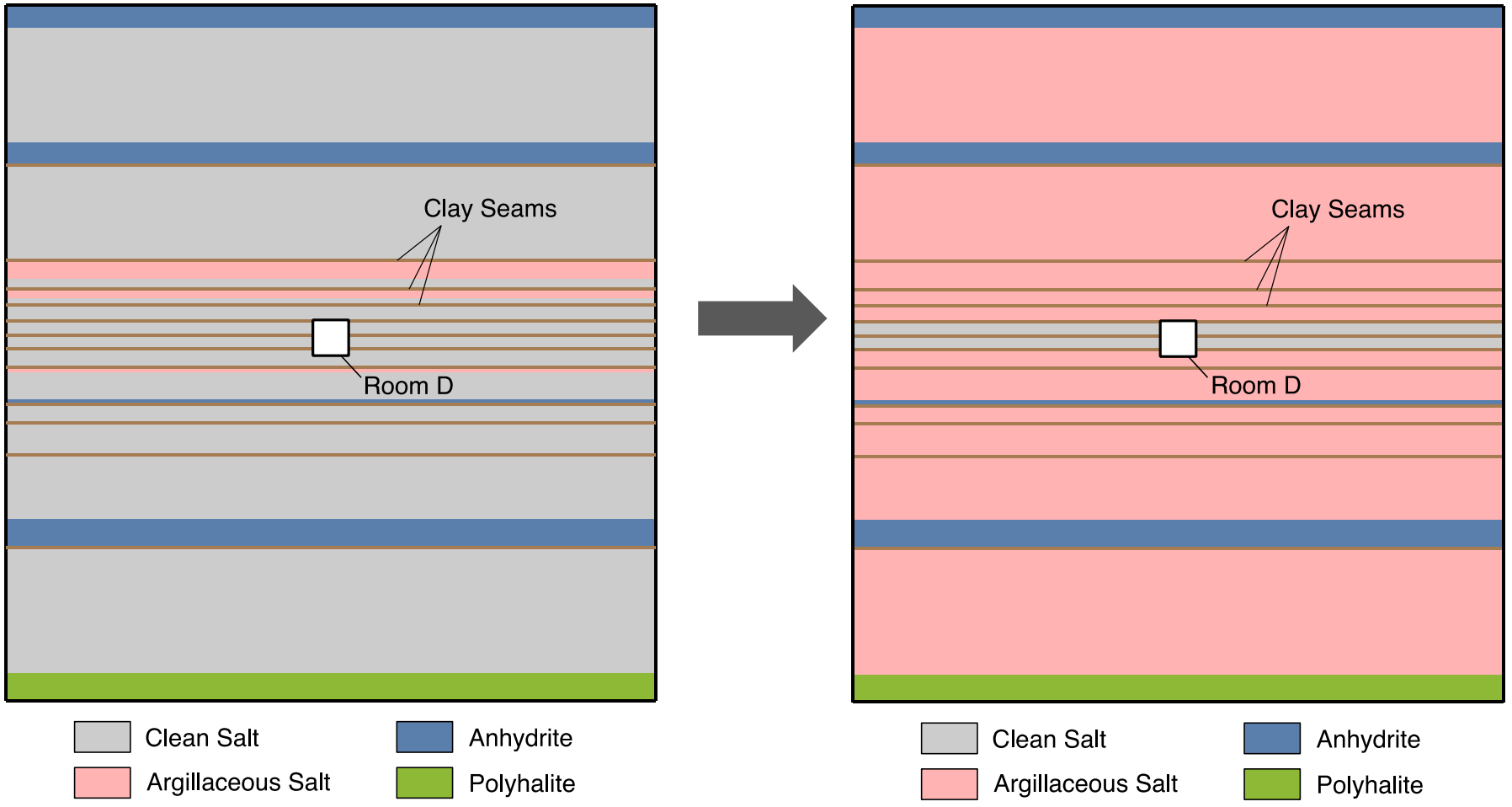
Coulomb Friction

$t_t = \eta\, t_n$

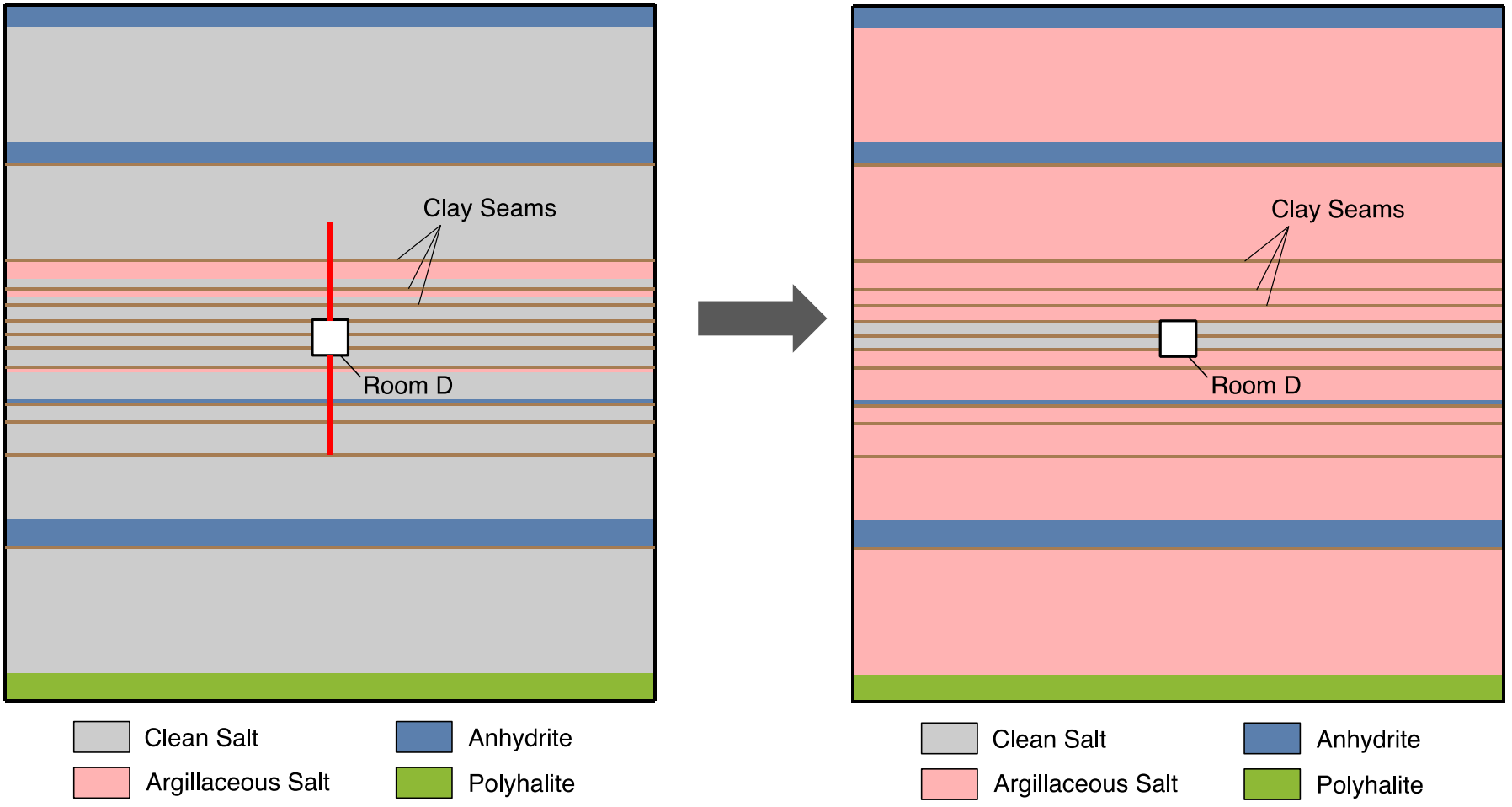
Friction coefficient treated as a free parameter

$\eta = 0.4 \rightarrow 0.2$

Changed the Stratigraphy

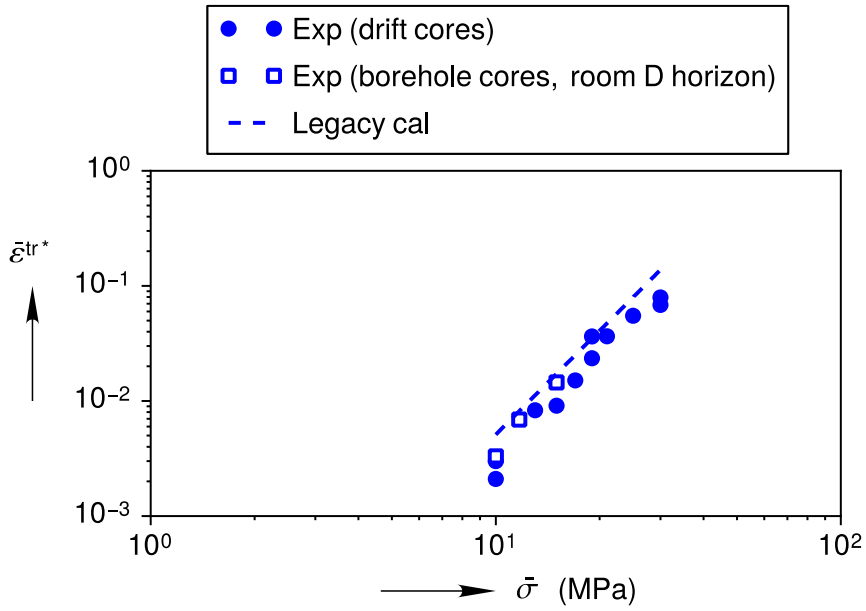


Changed the Stratigraphy

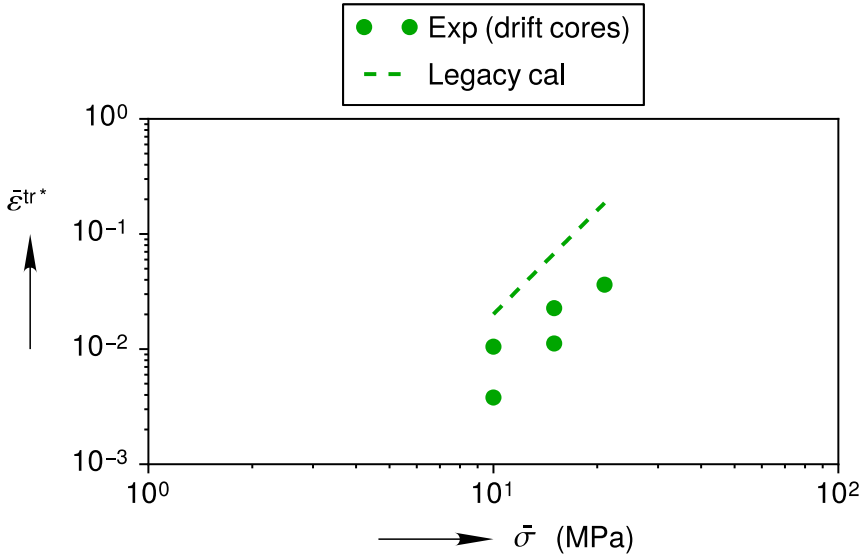


Changed the Material Parameters

Clean Salt



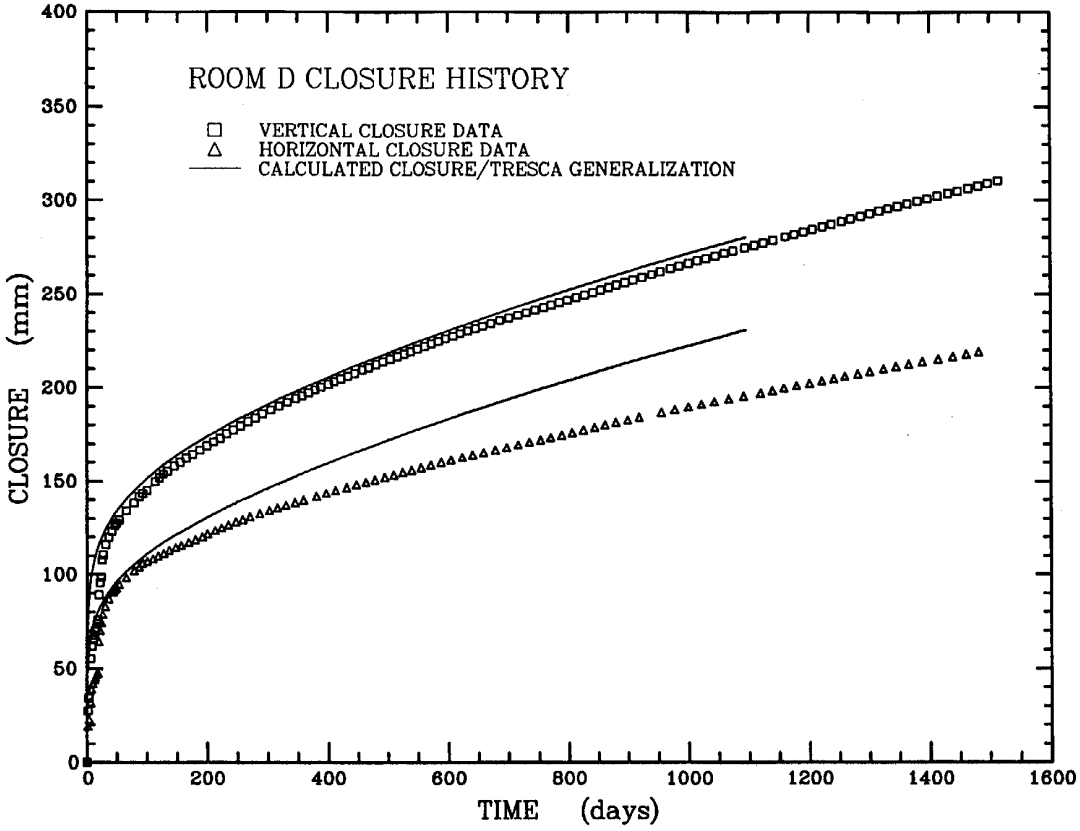
Argillaceous Salt



Argillaceous transient strain limit treated as a “free parameter”.

Legacy Predictions

- **Changed from von Mises to Tresca flow potential**
- **Changed the clay seam friction coefficient from 0.4 to 0.2**
- **Changed from mostly clean salt to mostly argillaceous salt**
- **Changed the material model calibrations**
  - Argillaceous strain limit treated as a free parameter



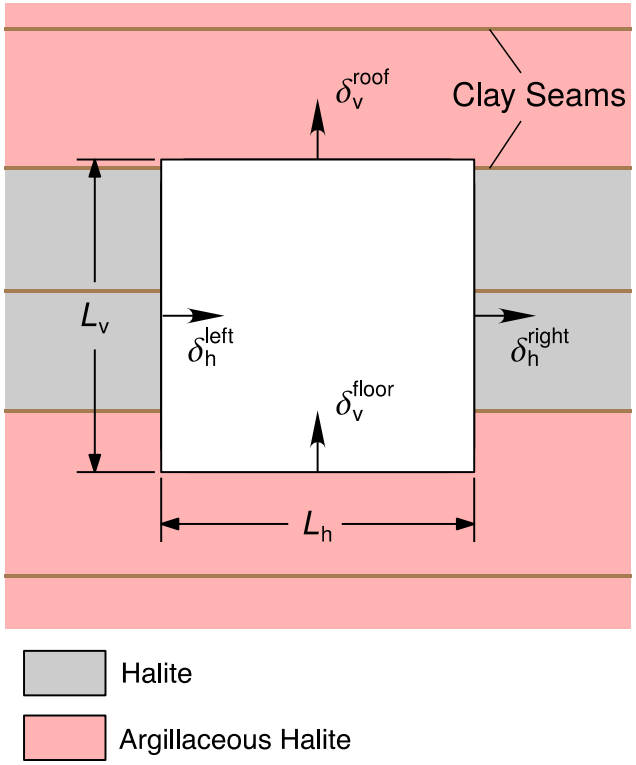
Munson, D., Fossum, A. Senseny, P., Advances in Resolution of Discrepancies Between Predicted and Measured In Situ WIPP Room Closures, SAND88-2948, 1988

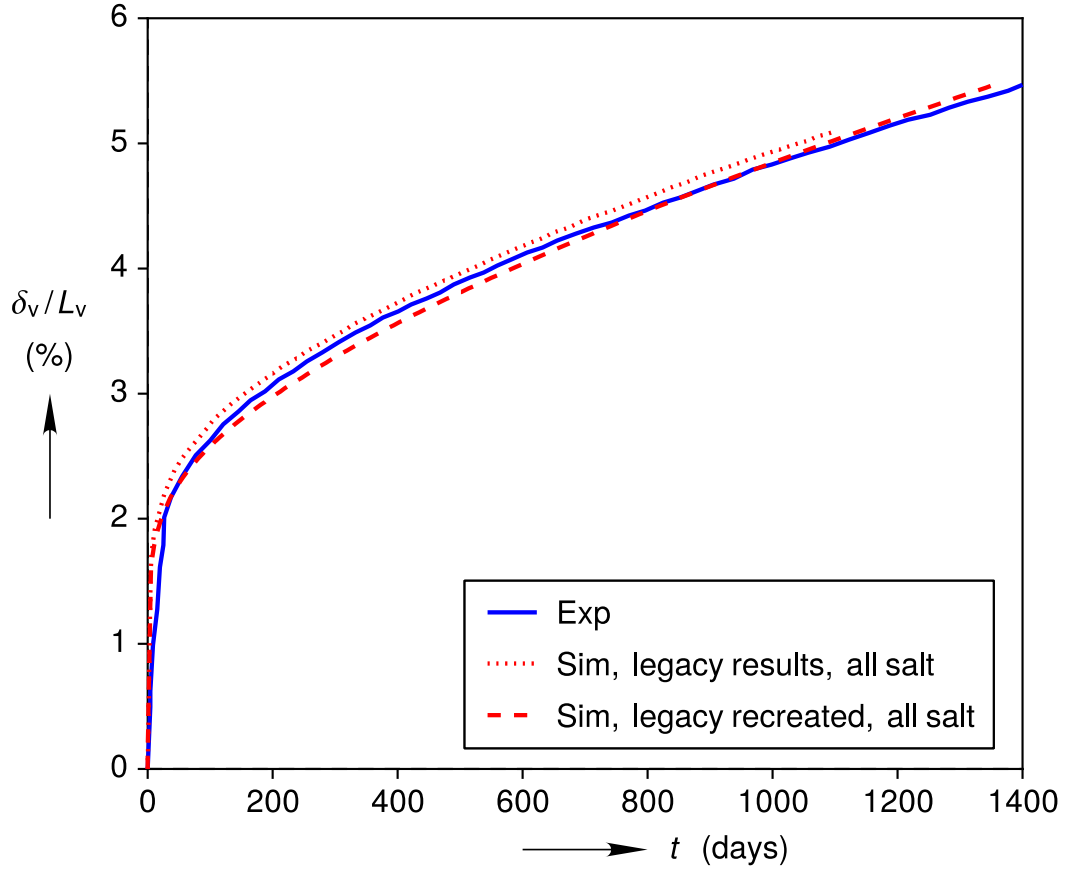
Legacy Simulations Recreated

Recreation of Legacy Simulations

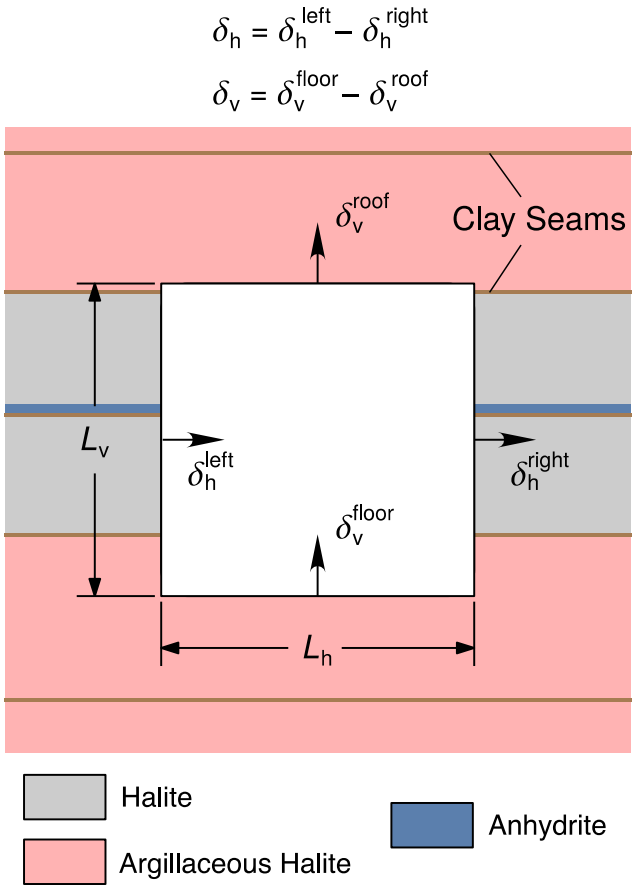
$$\delta_h = \delta_h^{left} - \delta_h^{right}$$

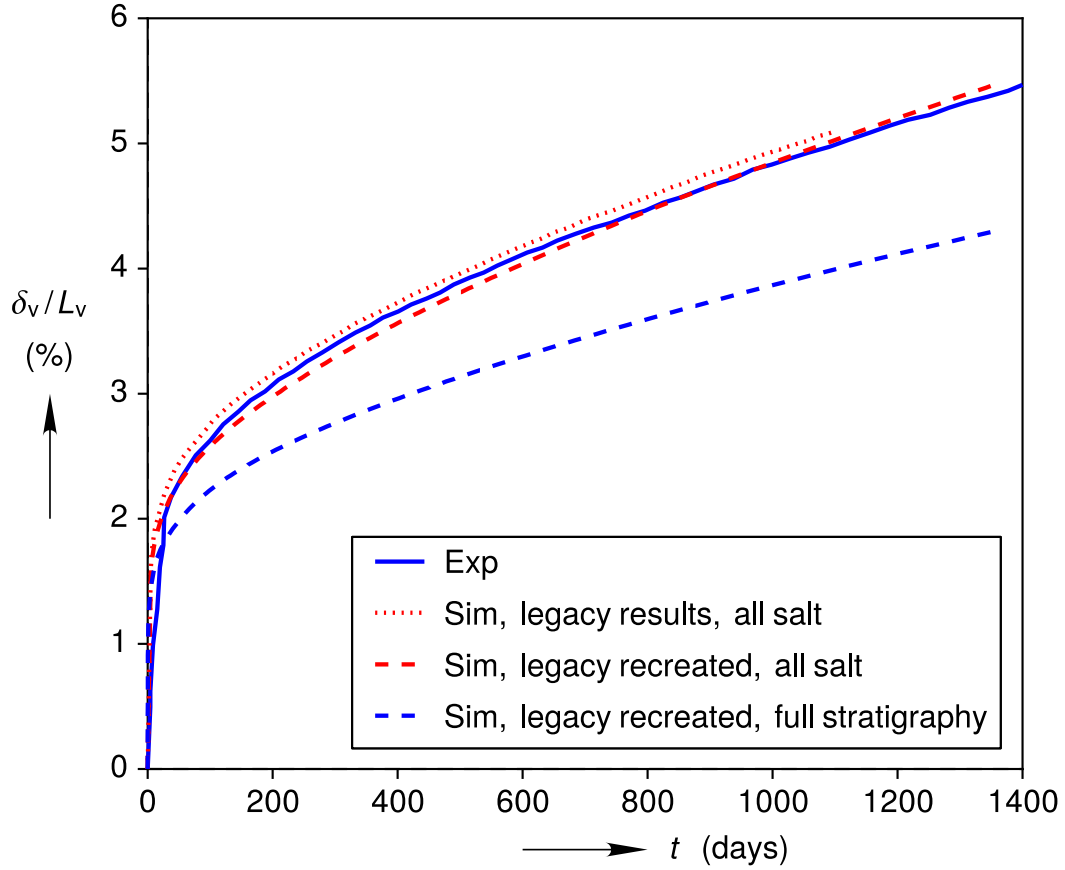
$$\delta_v = \delta_v^{floor} - \delta_v^{roof}$$





Recreation of Legacy Simulations

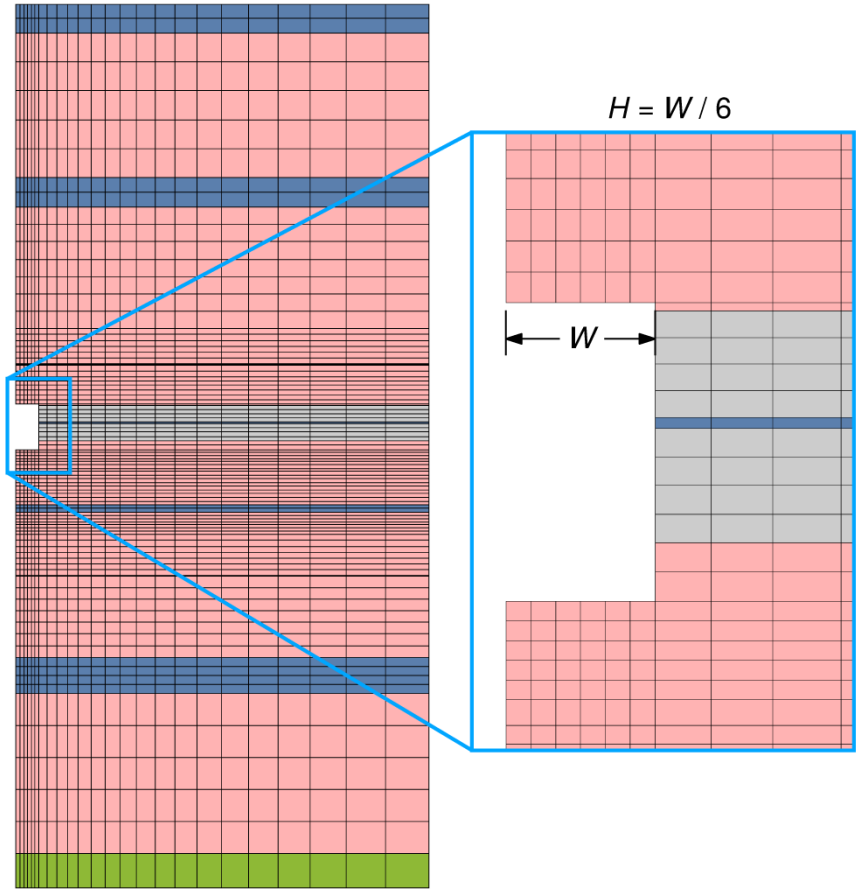




Changed the Mesh

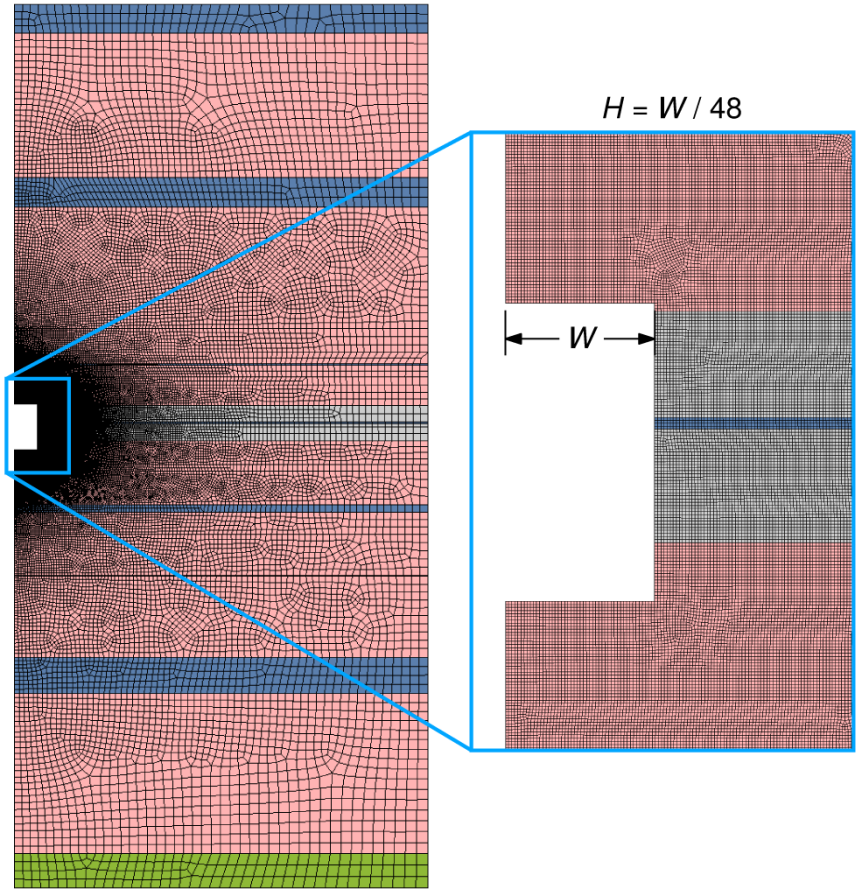
Legacy Mesh

2184 Elements



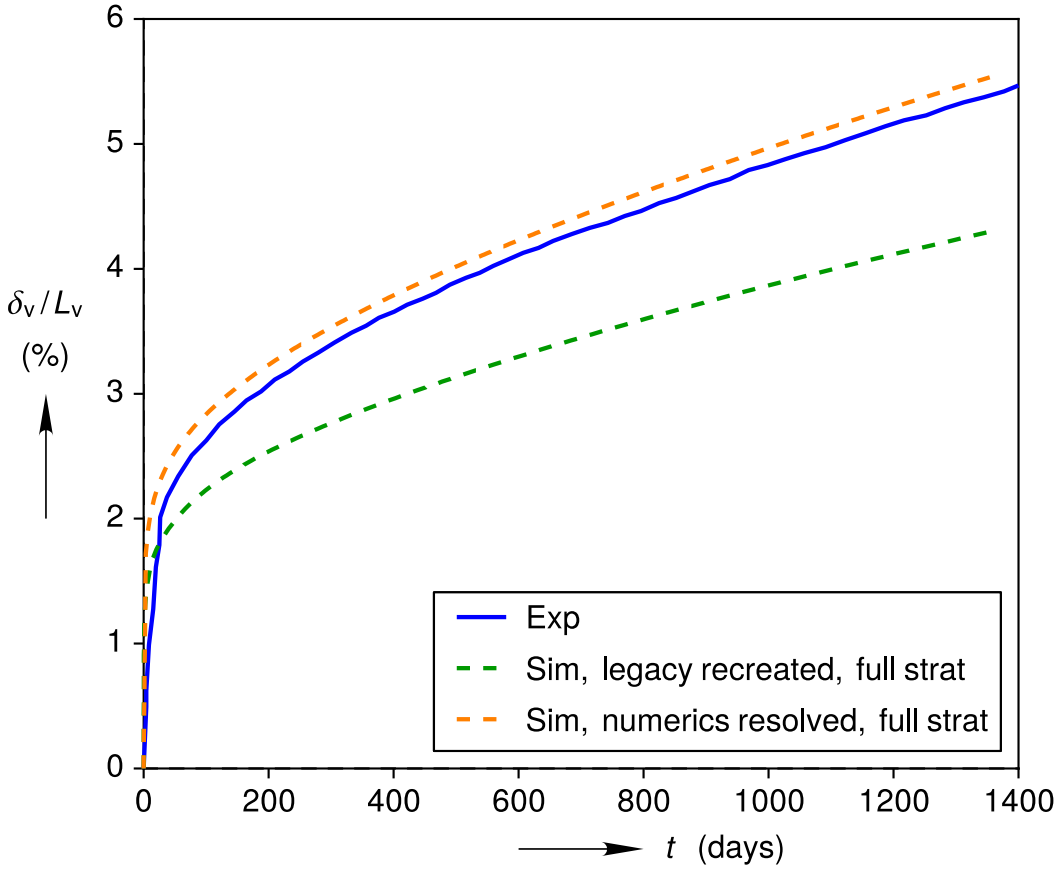
Current Fine Mesh

57849 Elements

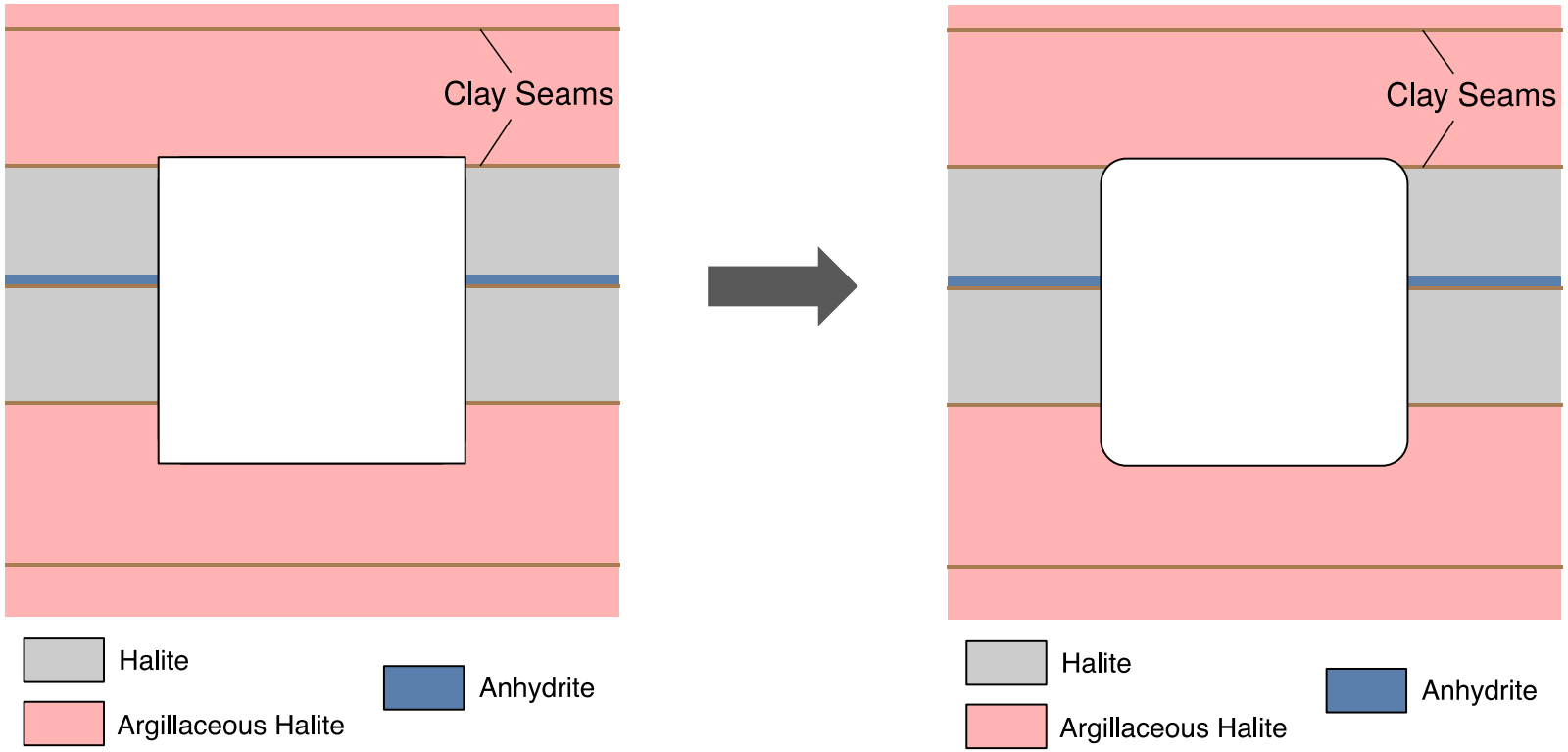


Impact of Resolving the Numerics

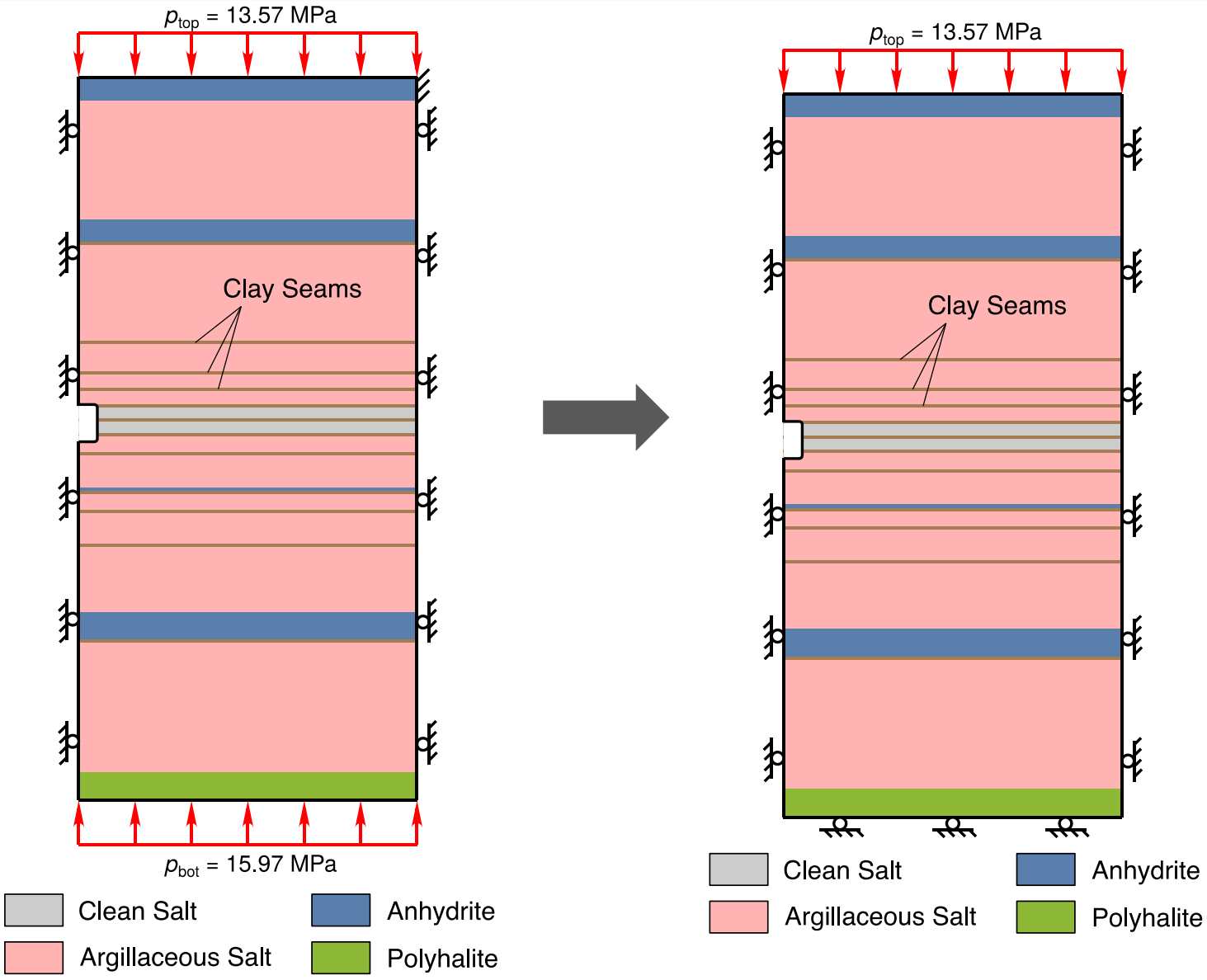
- **Change the Mesh**
- **Changed $R_{tol} = 10^{-3}$ to $R_{tol} = 10^{-5}$**
- **Switched to a higher quality element type**
- **Changed the contact enforcement algorithm**
- **Switched from non-associated flow rule to an associated flow rule for the anhydrite**
- **Added a pressure ramp down to ease into the instantaneous excavation**



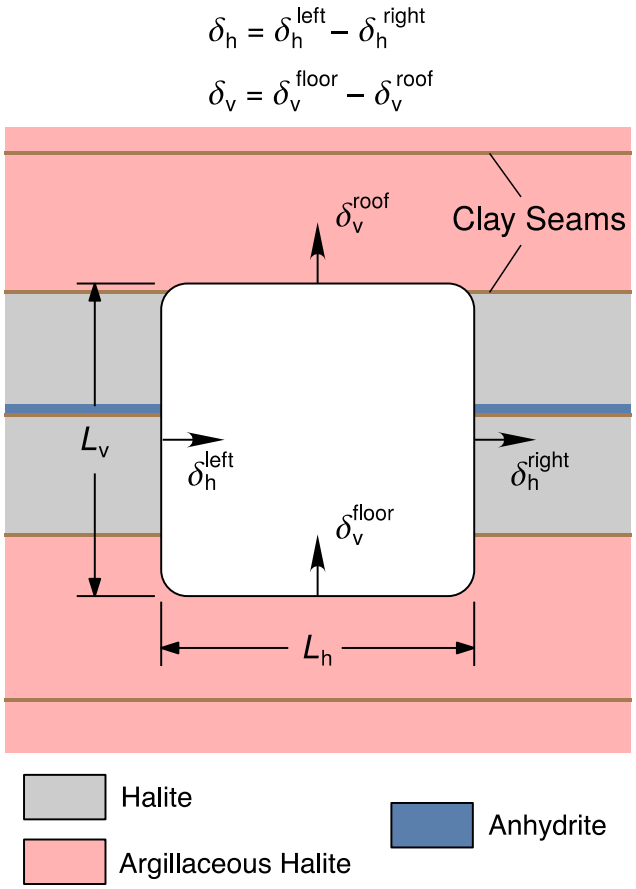
Rounded the Corners

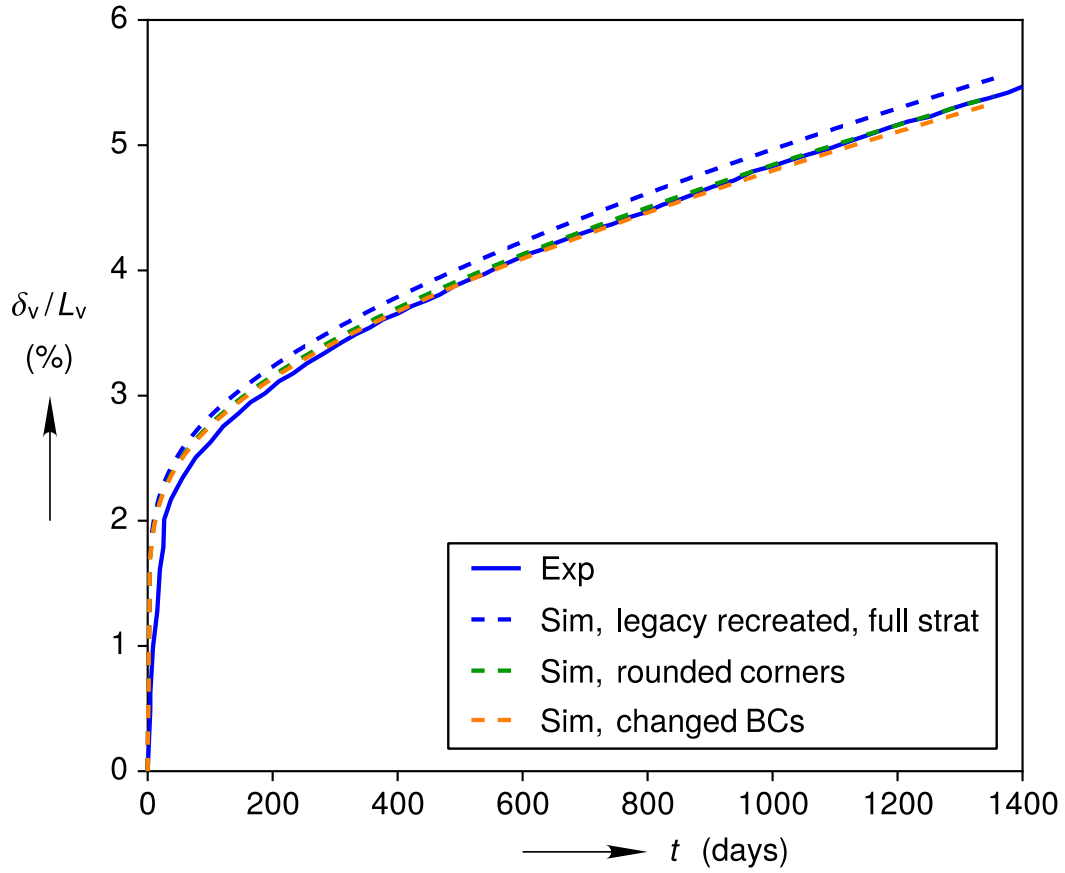


Change the Boundary Conditions



Change BCs and Round Corners

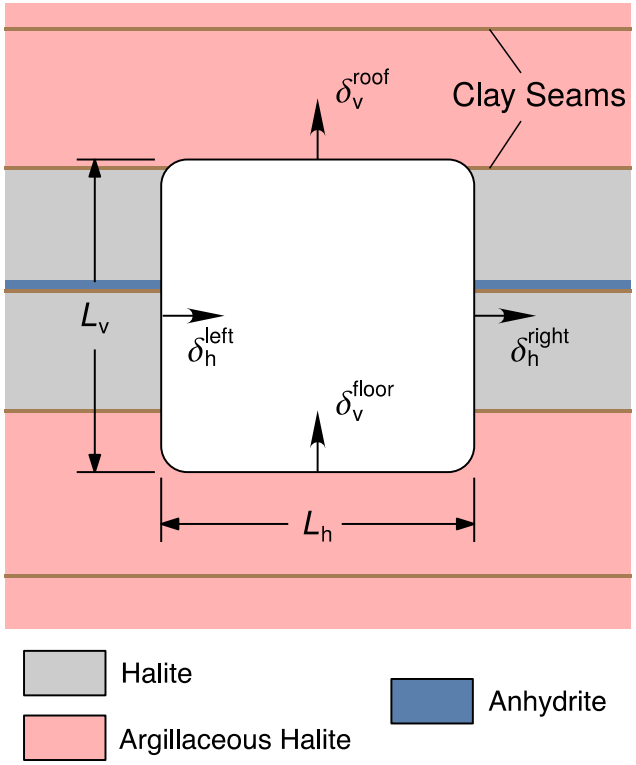


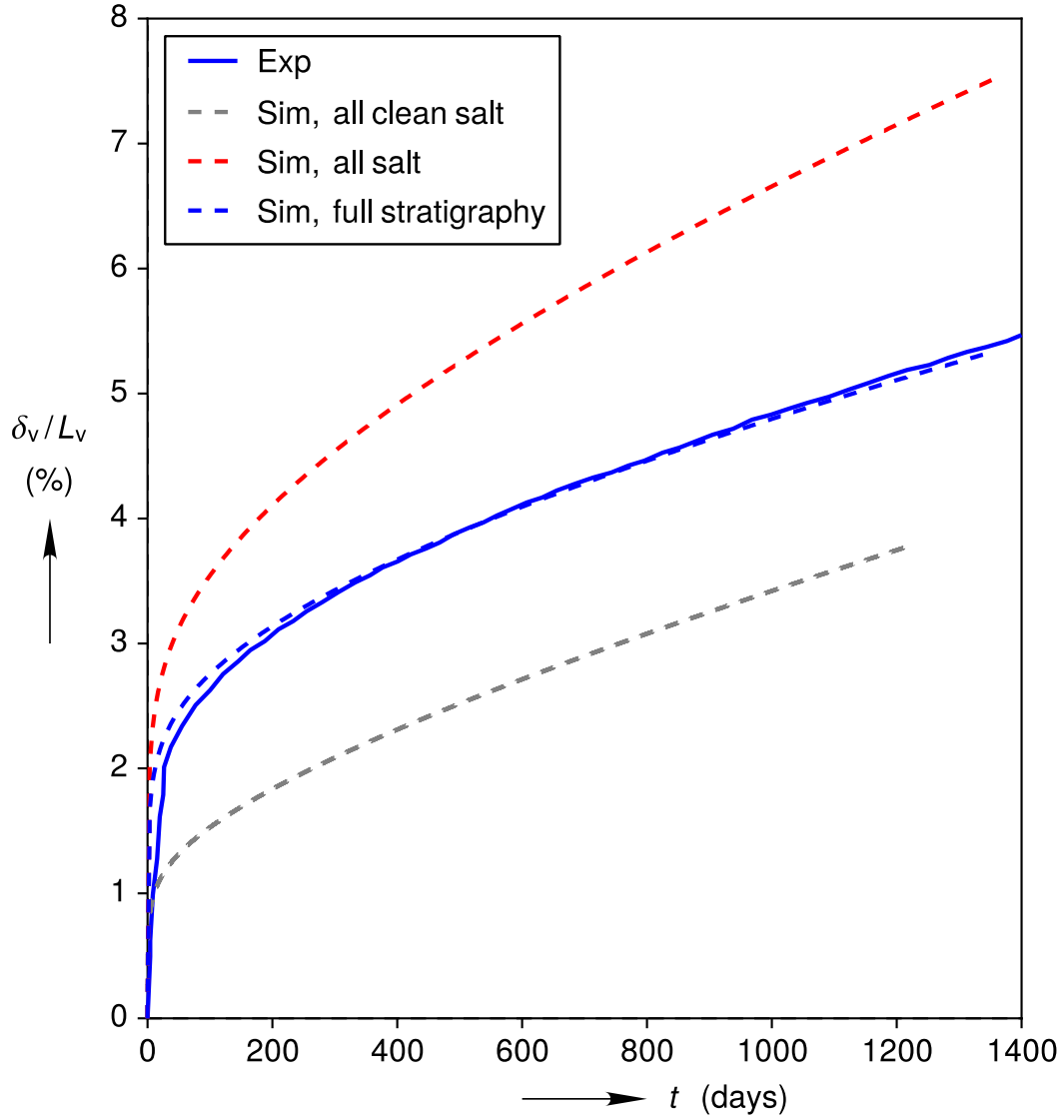


Sensitivity to Stratigraphy

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

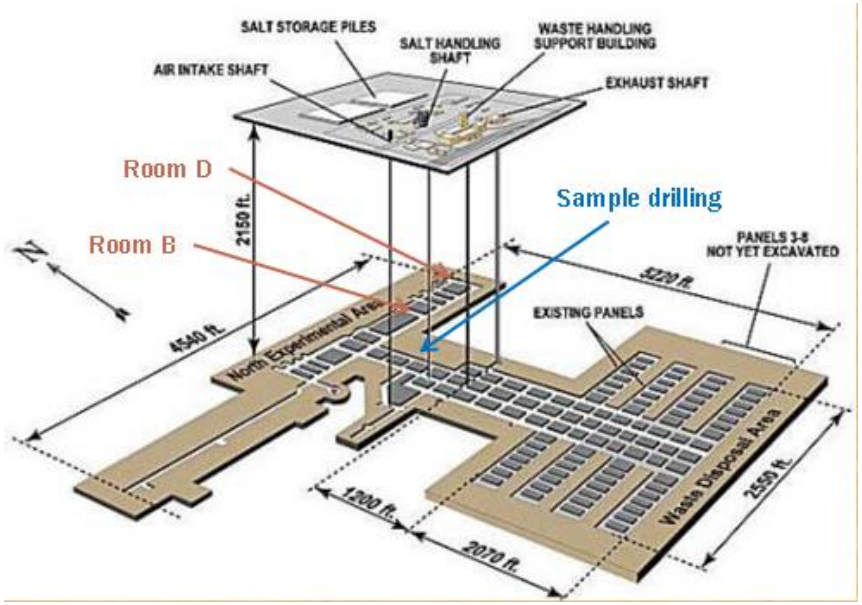
$$\delta_v = \delta_v^{floor} - \delta_v^{roof}$$

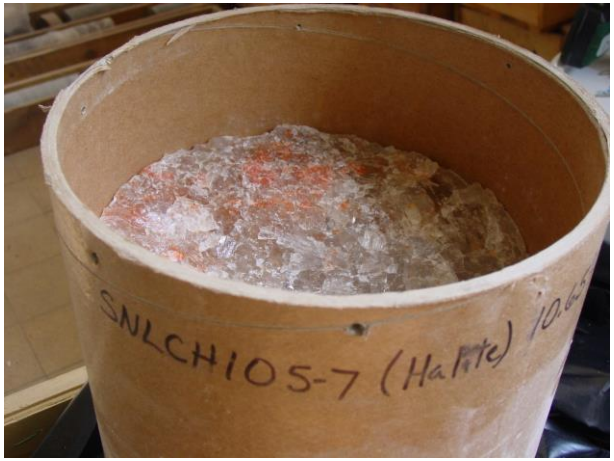




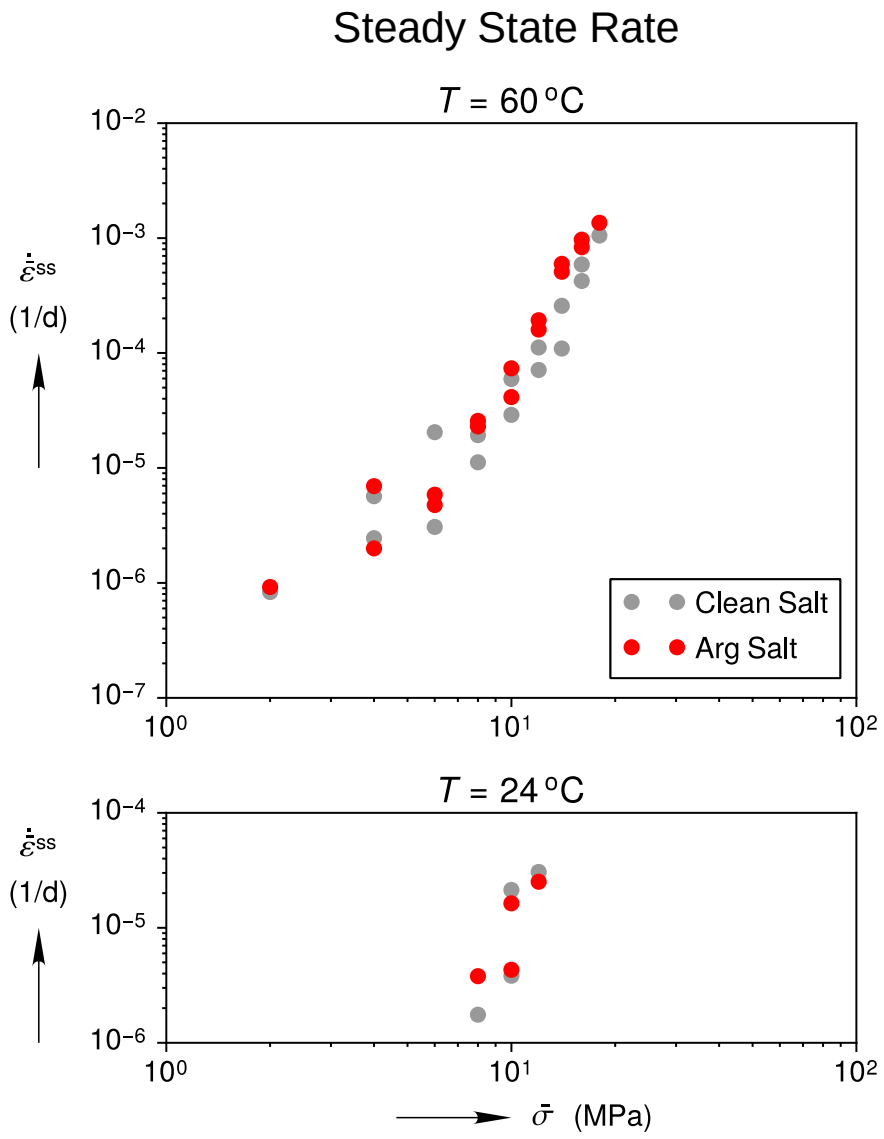
Munson-Dawson Model Re-Calibration

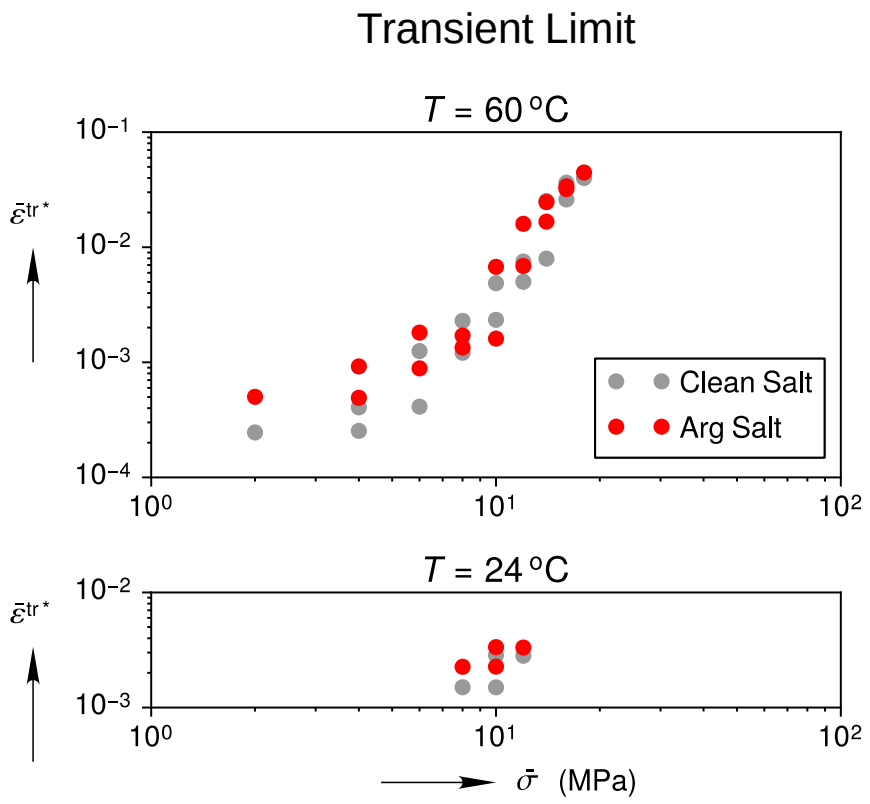
New Cores Extracted in 2013





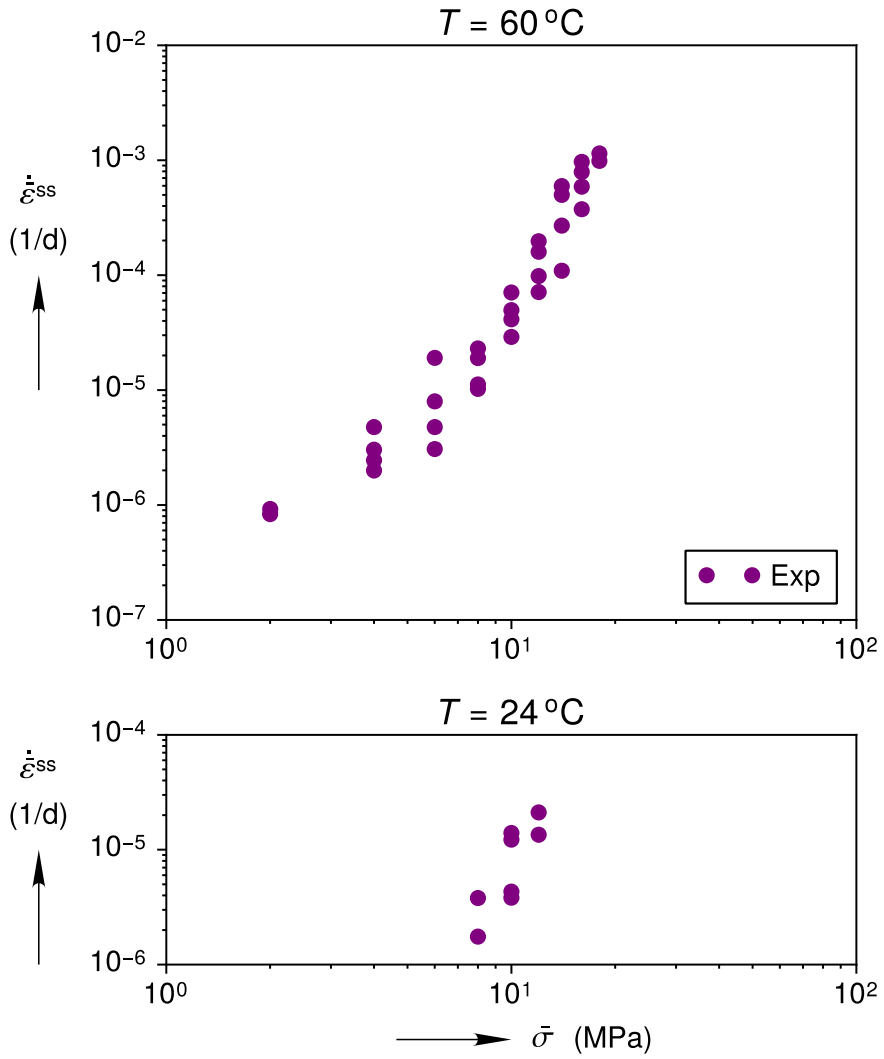
Clean vs. Argillaceous: JP III Experiments



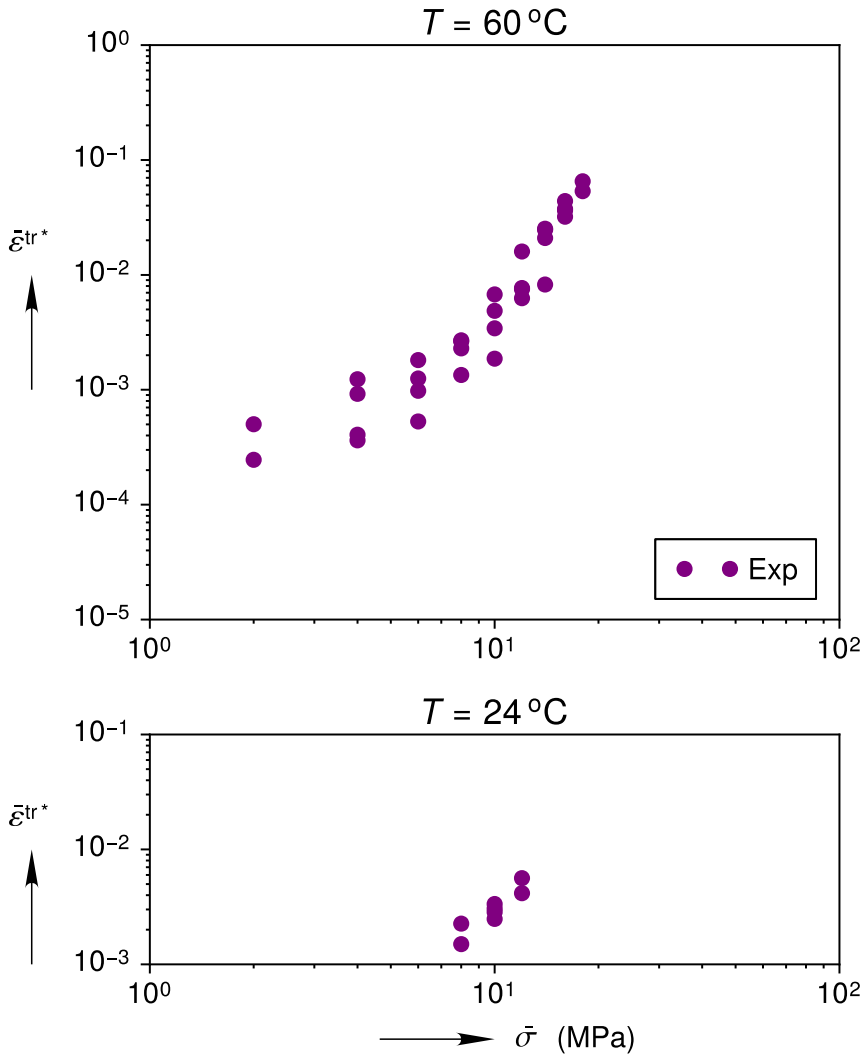


New Munson-Dawson Calibration

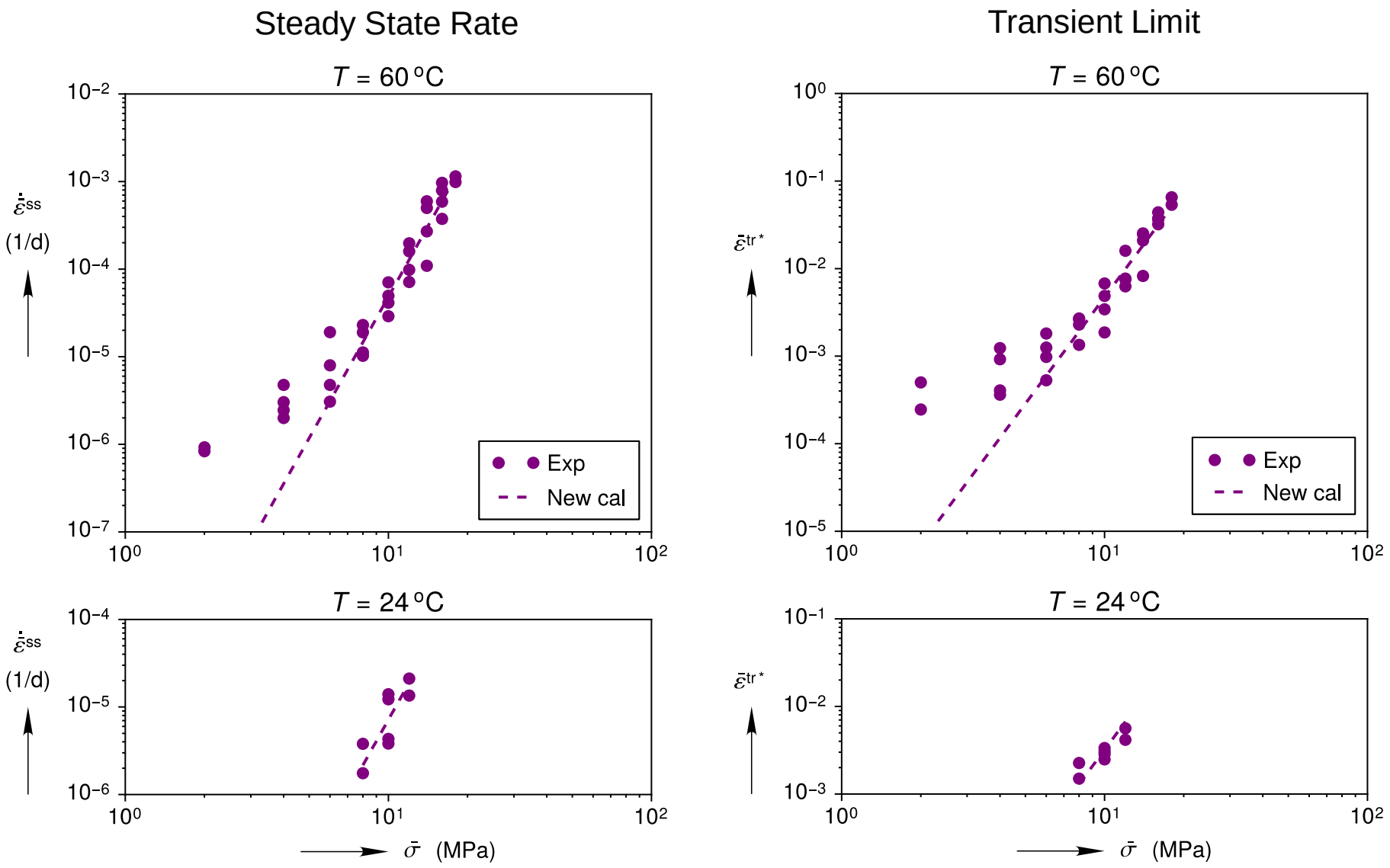
Steady State Rate



Transient Limit

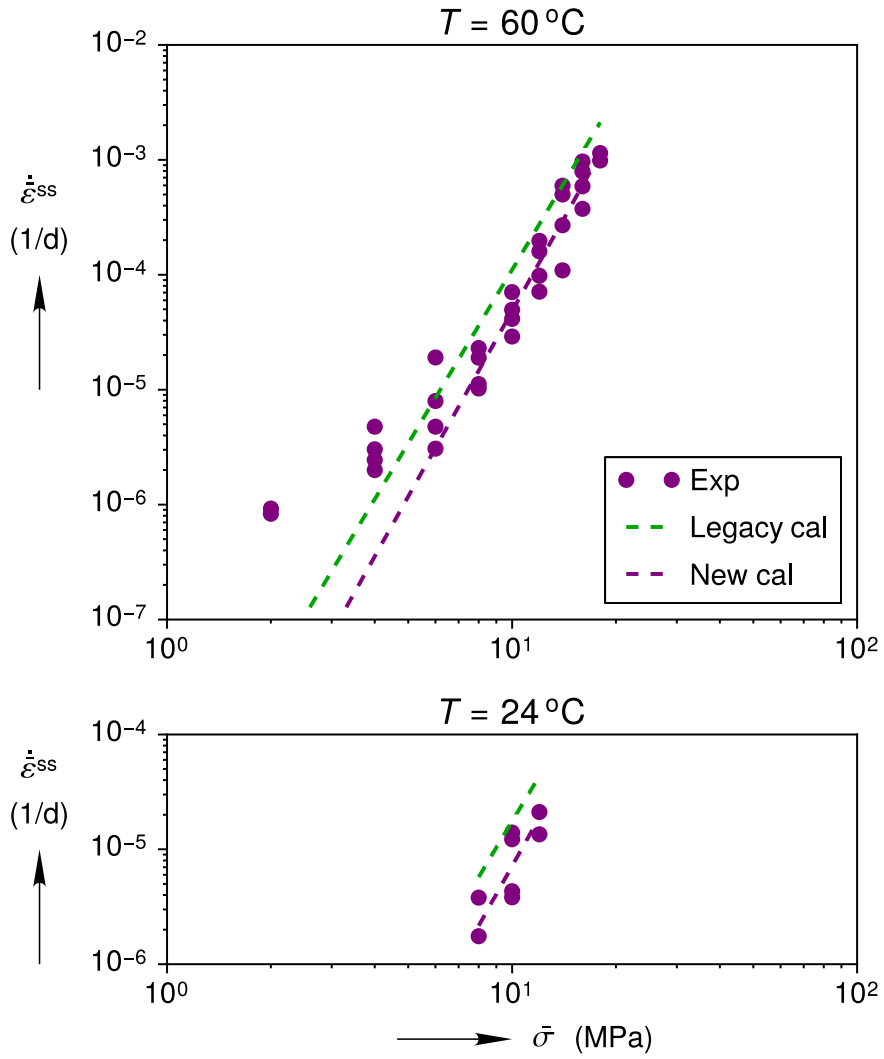


New Munson-Dawson Calibration

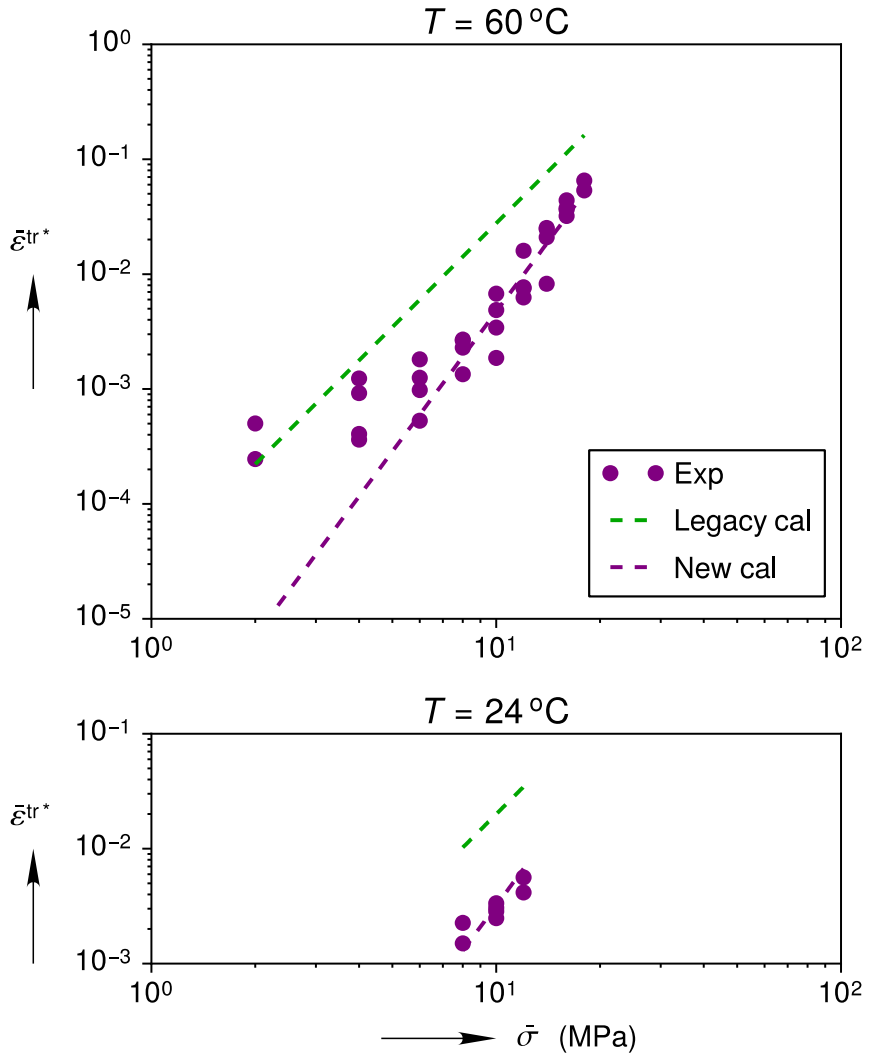


New Munson-Dawson Calibration

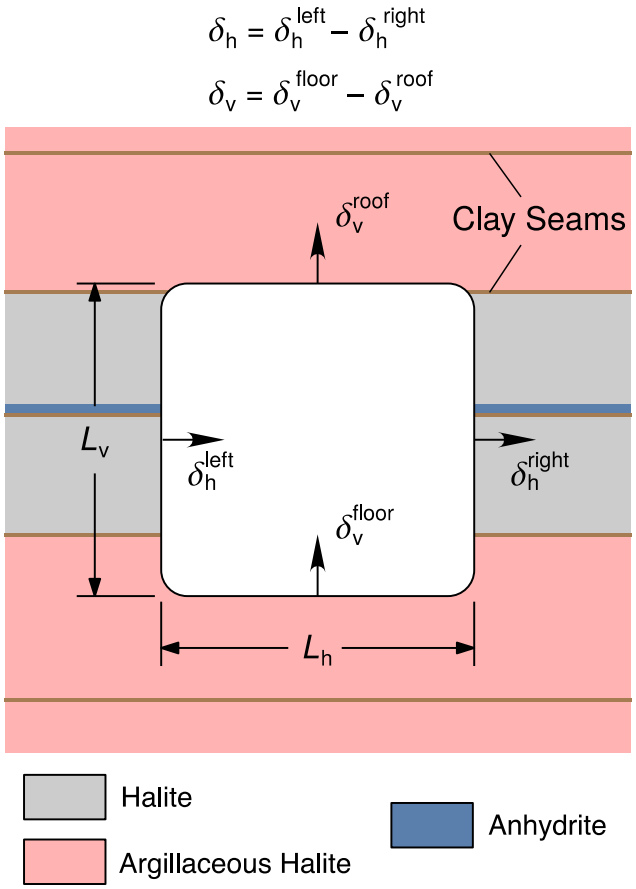
Steady State Rate

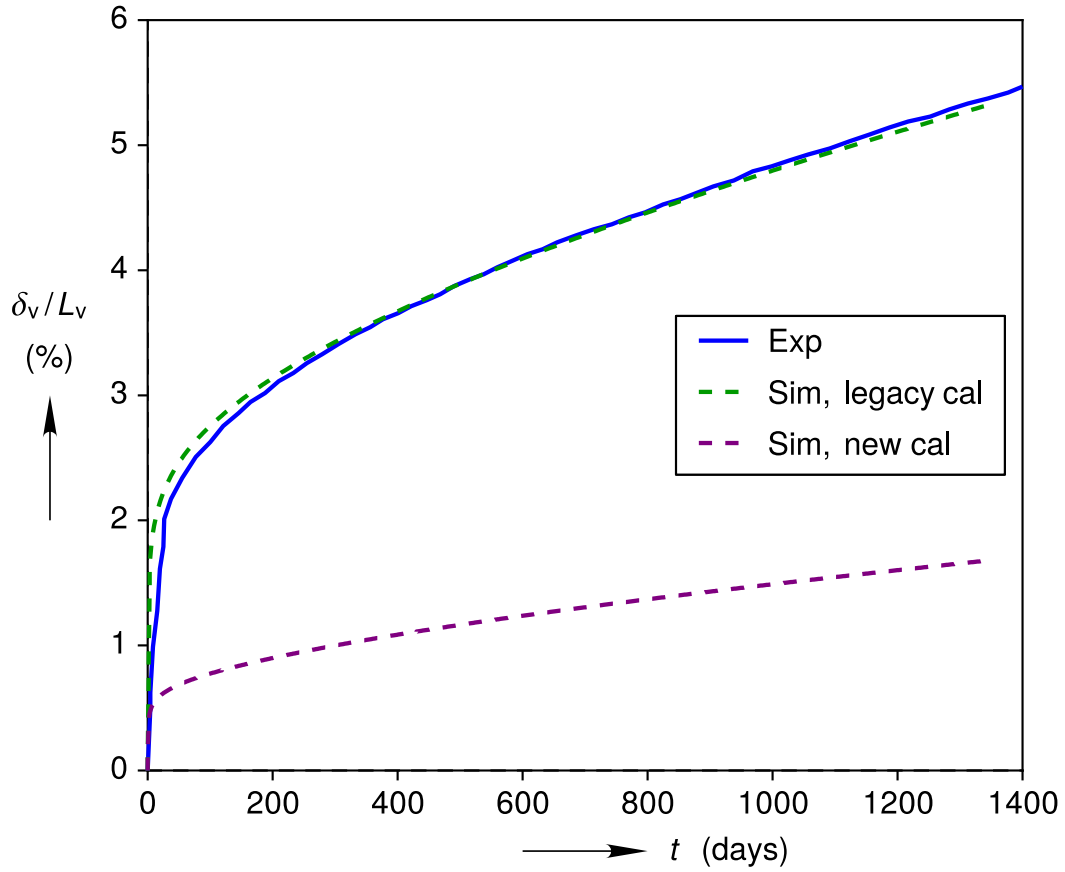


Transient Limit



Closure Prediction with New Calibration

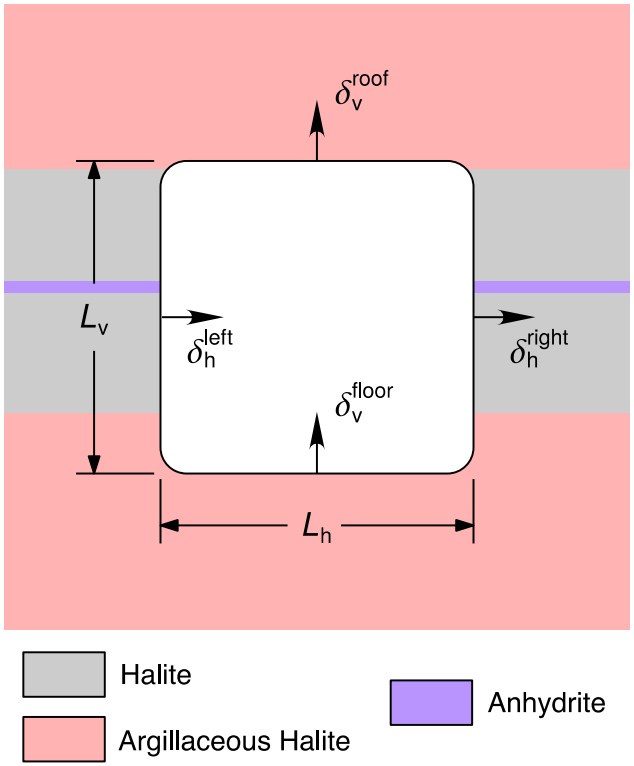


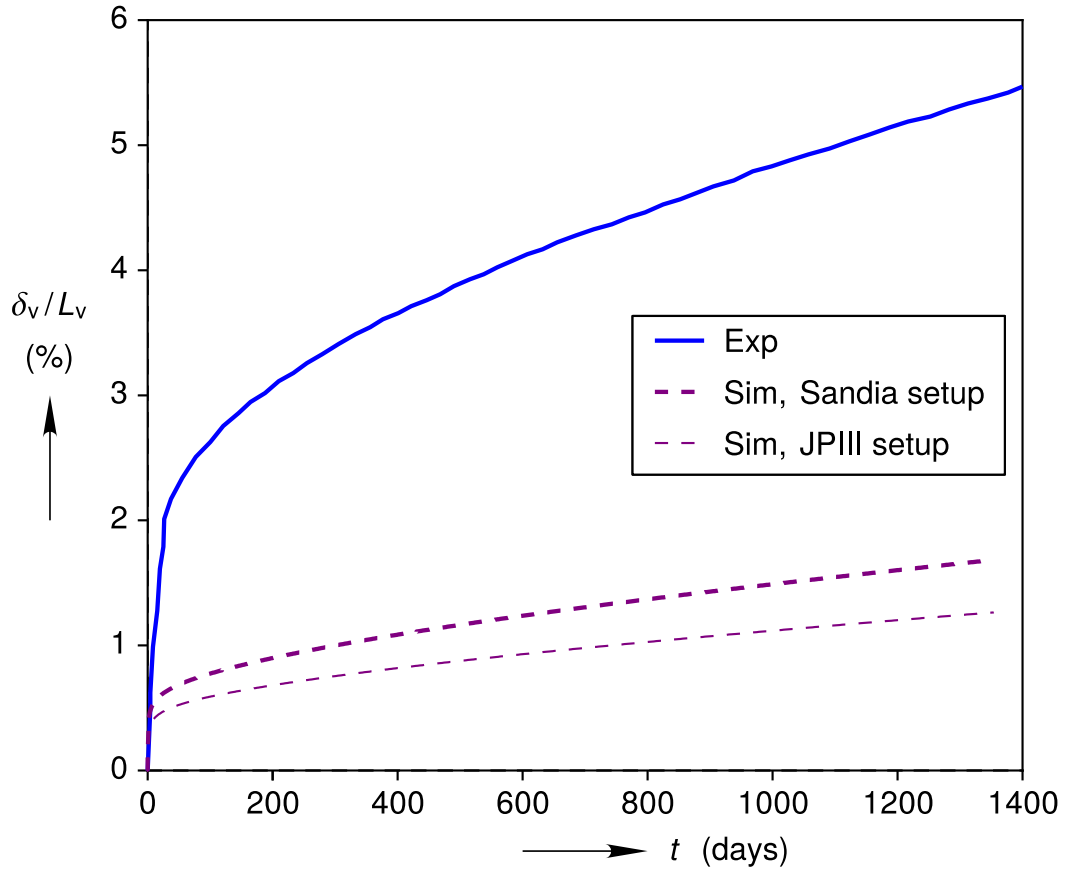


Switch To Joint Project III Setup

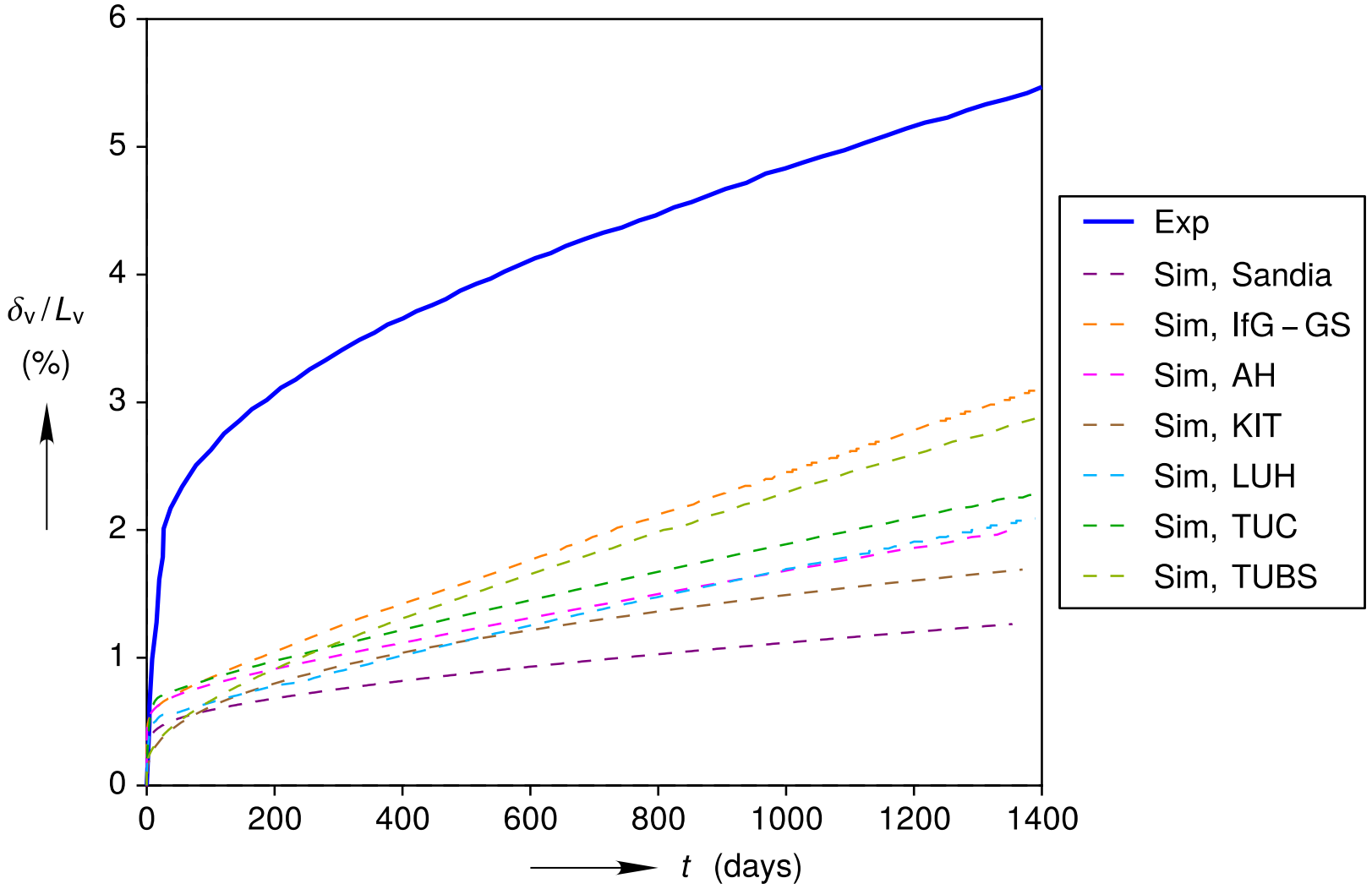
$$\delta_h = \delta_h^{left} - \delta_h^{right}$$

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



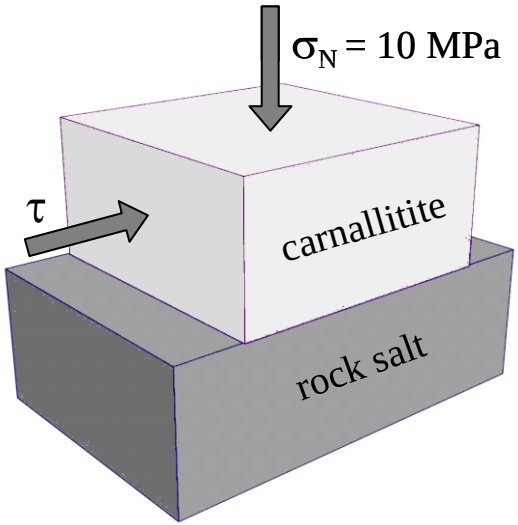


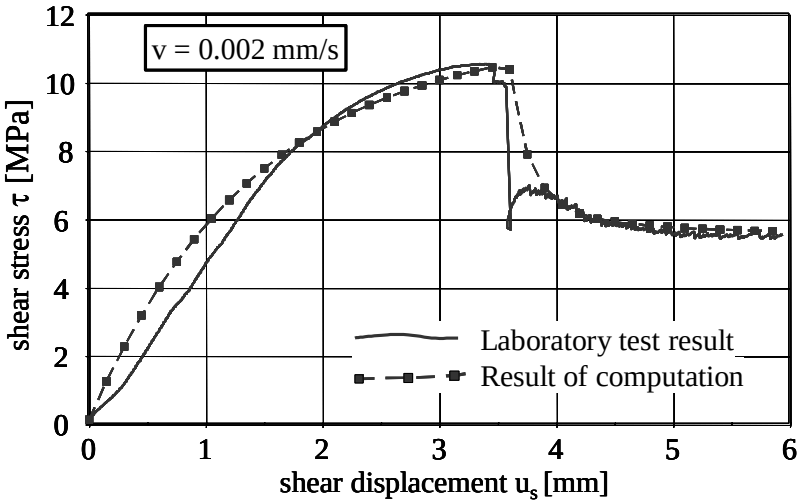
Joint Project III Predictions

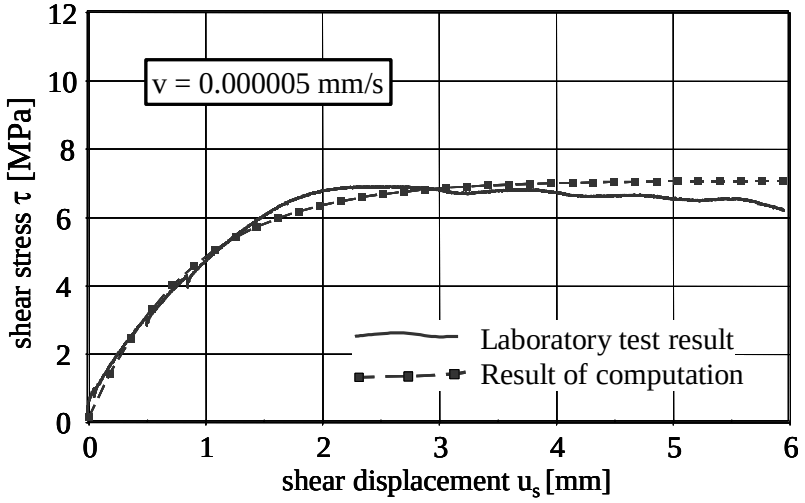


Open Questions

Clay Seam Behavior



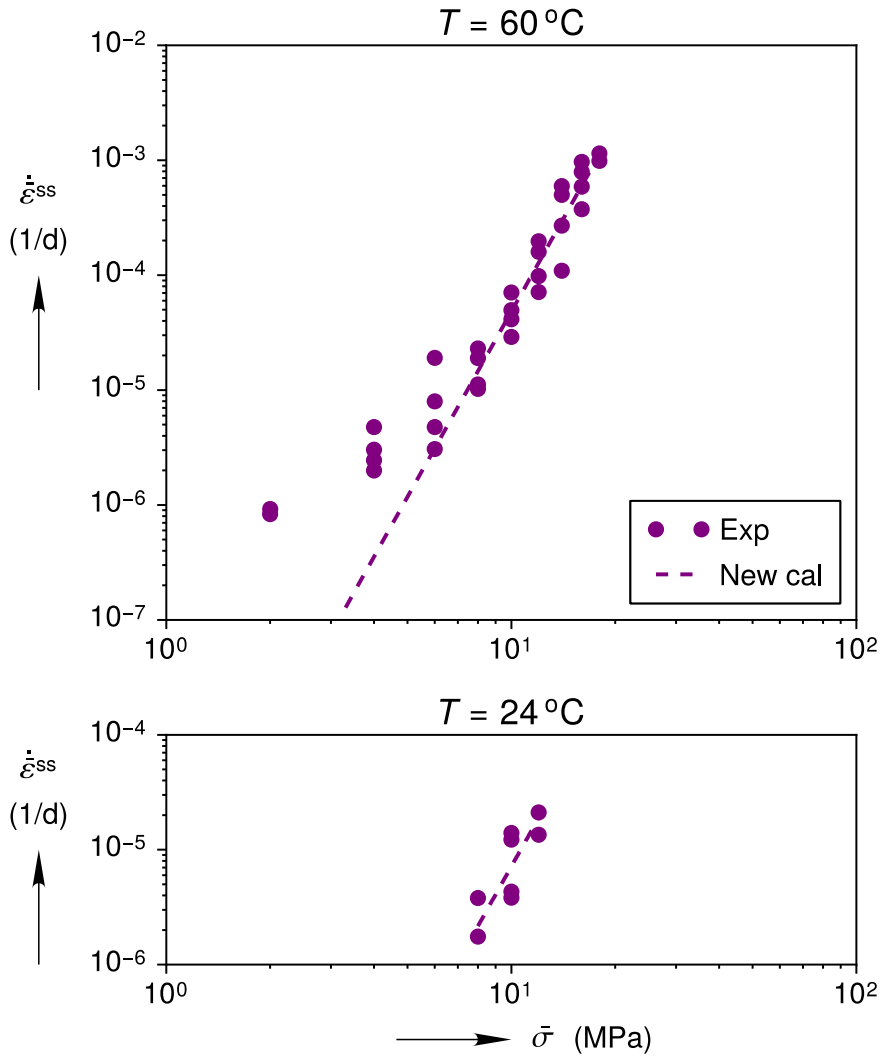




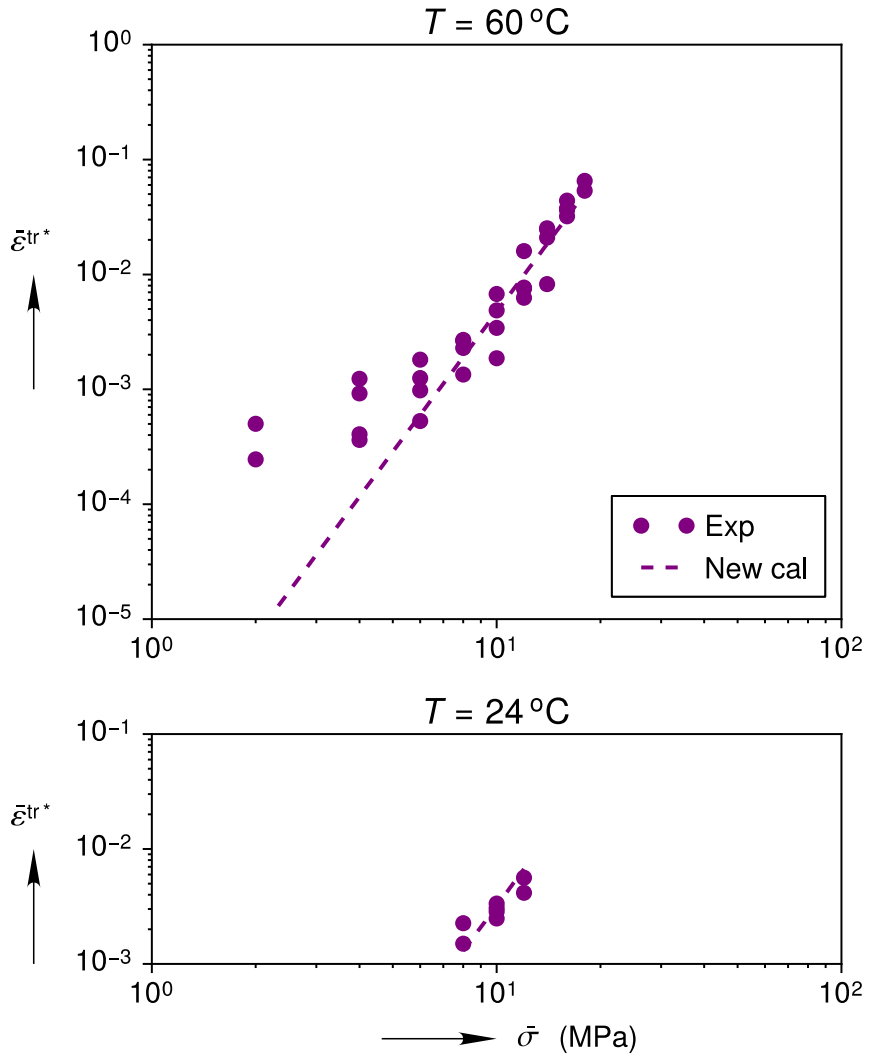
Minkley, W., Muehlbauer, J., "Constitutive models to describe the mechanical behavior of salt rocks and the imbedded weakness planes", SALTMECH6, 2007

Low Deviatoric Stresses

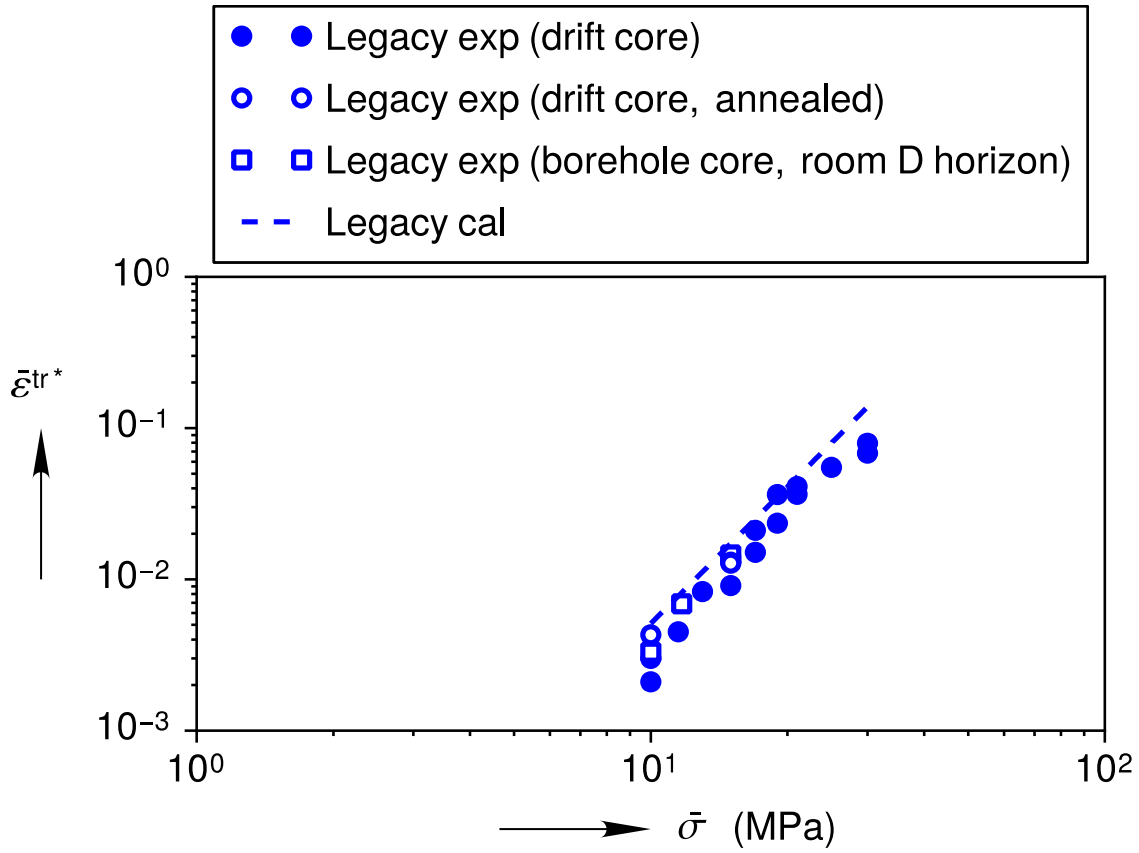
Steady State Rate



Transient Limit



Lost Transient Strains

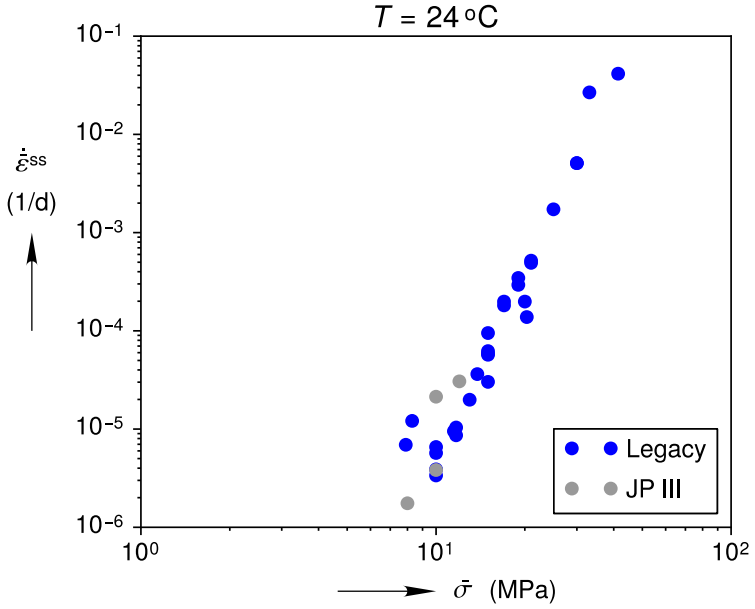


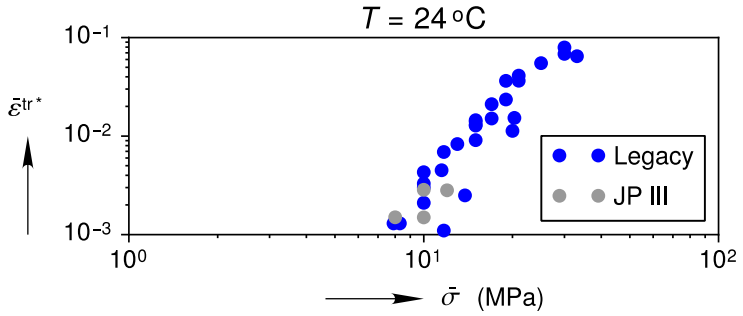
Argillaceous vs. Clean Salt

Steady State Rate

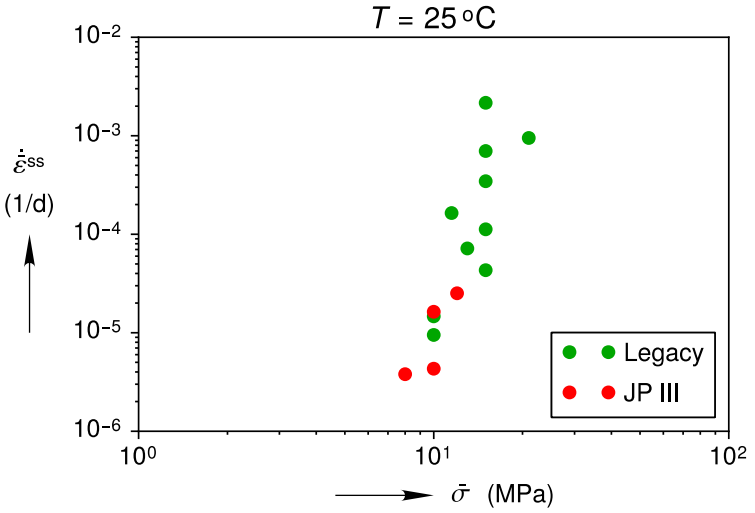
Transient Limit

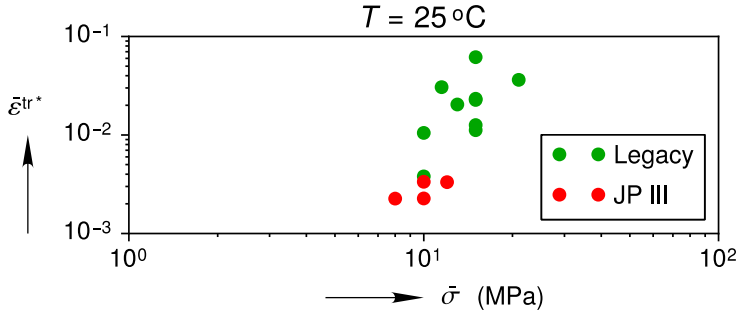
Clean Salt





Argillaceous Salt



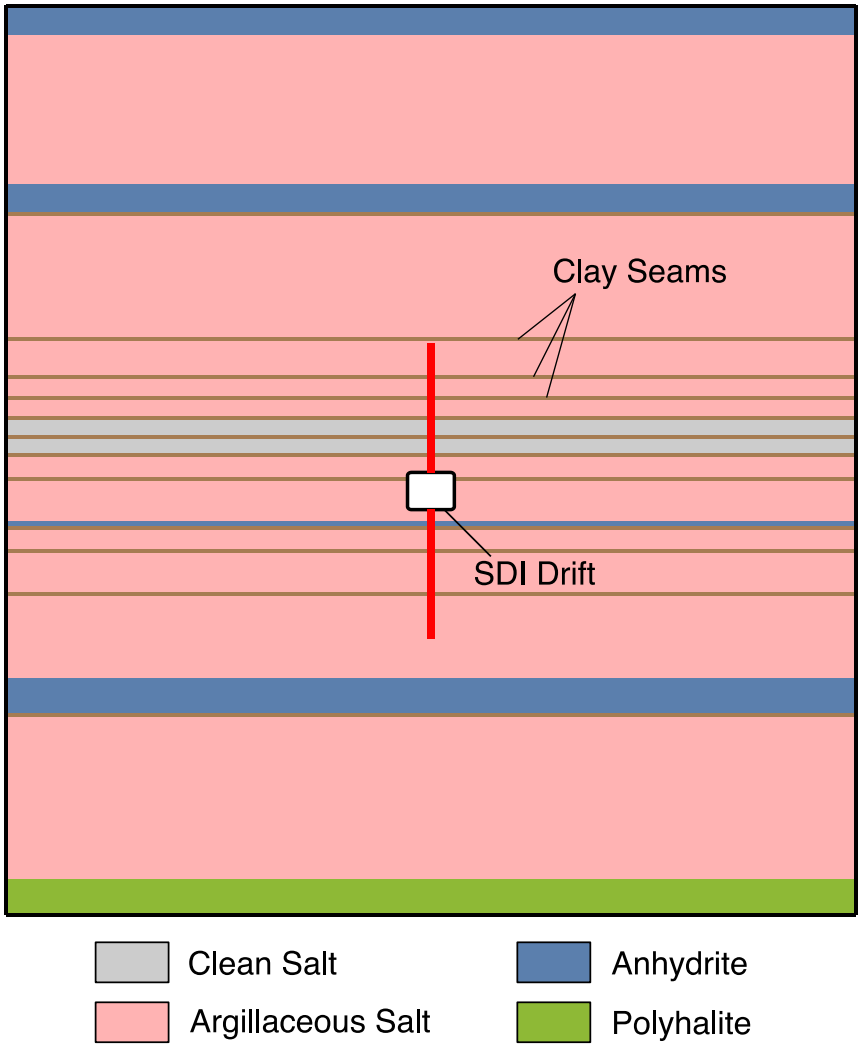


Legacy experimental data copied verbatim from SAND92-7291

Stratigraphy Reassessment

Dennis Powers (Consulting Geologist)

- "This study does not sustain the assessment of Munson et al. (1989) that all of the halite within the reference stratigraphy, with the exception of halite above and below anhydrite a, could or should be treated as argillaceous halite."
- "The general comparison to the [Krieg (1984) stratigraphy] for both cores is very good."



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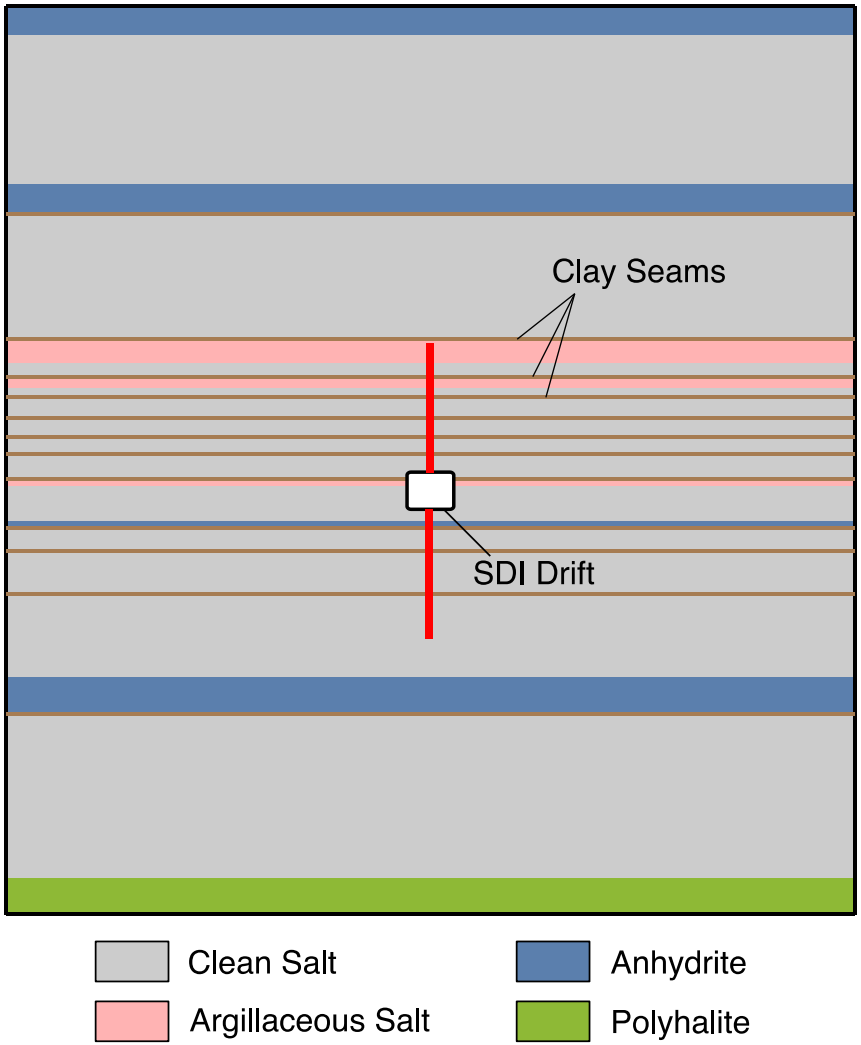


Summary

Summary

- **In 1987, the simulations under-predicted the room closure by roughly 3X. In 1989, Darrell Munson adjusted the model to match the experiments.**
- **After including the anhydrite and resolving the numerics, the predictions still match the experiments.**
- **New salt calibration under-predicts the room closure by roughly 3X.**
- **Open questions remain**
  - Argillaceous vs. clean salt
  - Low deviatoric stresses
  - Lost transient strains
  - Sliding at clay seams
  - Anhydrite material model
  - Simulation boundary
- **Model tuning is an acceptable engineering approach, but we must improve.**

Thank you for your attention!

Extra Slides

Munson-Dawson Model

Steady State Rate

$$\dot{\bar{\varepsilon}}^{ss} = \sum_{i=1}^{3} \dot{\bar{\varepsilon}}_i^{ss}$$

$$\dot{\bar{\varepsilon}}_1^{ss} = A_1 \exp\left(-\frac{Q_1}{R\,T}\right) \left(\frac{\bar{\sigma}}{\mu}\right)^{n_1}$$

$$\dot{\bar{\varepsilon}}_2^{ss} = A_2 \exp\left(-\frac{Q_2}{R\,T}\right) \left(\frac{\bar{\sigma}}{\mu}\right)^{n_2}$$

$$\dot{\bar{\varepsilon}}_3^{ss} = H(\bar{\sigma} - \bar{\sigma}_0) \left[B_1 \exp\left(-\frac{Q_1}{R\,T}\right) + B_2 \exp\left(-\frac{Q_2}{R\,T}\right)\right] \sinh\left(q\frac{(\bar{\sigma} - \bar{\sigma}_0)}{\mu}\right)$$

Transient Limit

$$\bar{\varepsilon}^{tr*} = K_0 \exp(c\,T) \left(\frac{\bar{\sigma}}{\mu}\right)^{m}$$

Transient Creep ODE

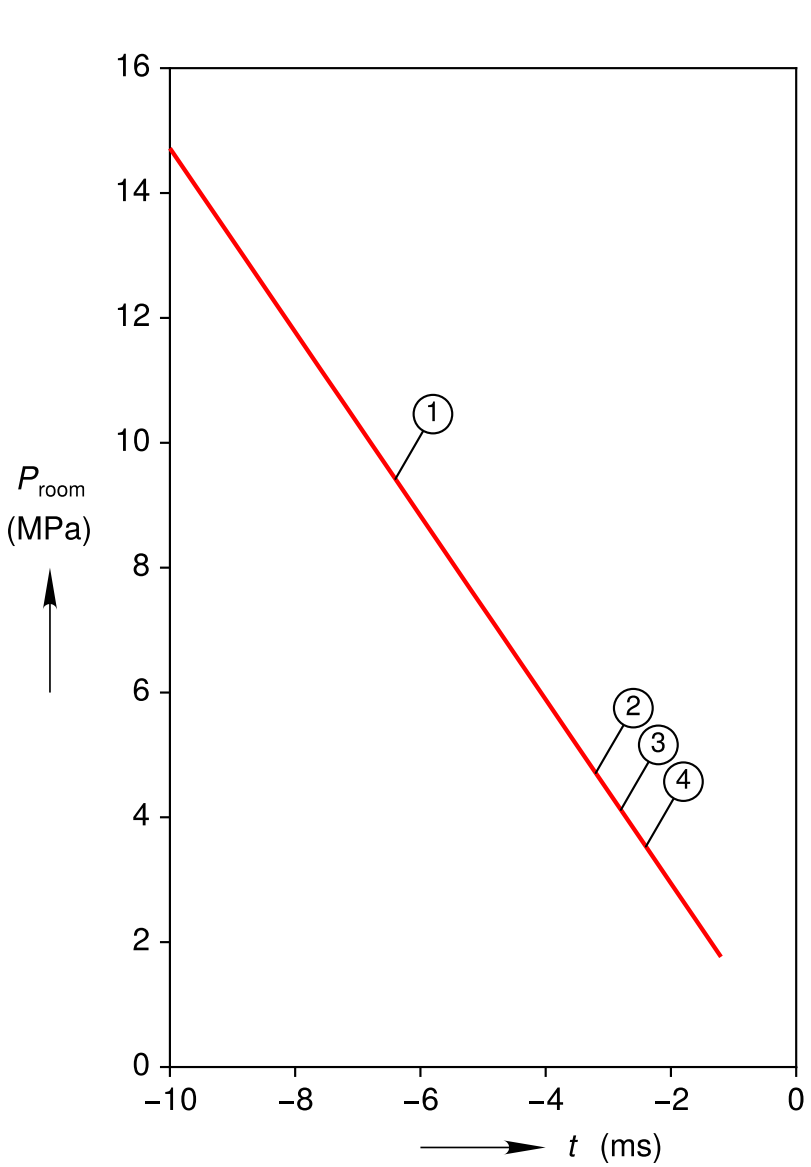
$$\dot{\bar{\varepsilon}}^{tr} = (F - 1)\ \dot{\bar{\varepsilon}}^{ss}$$

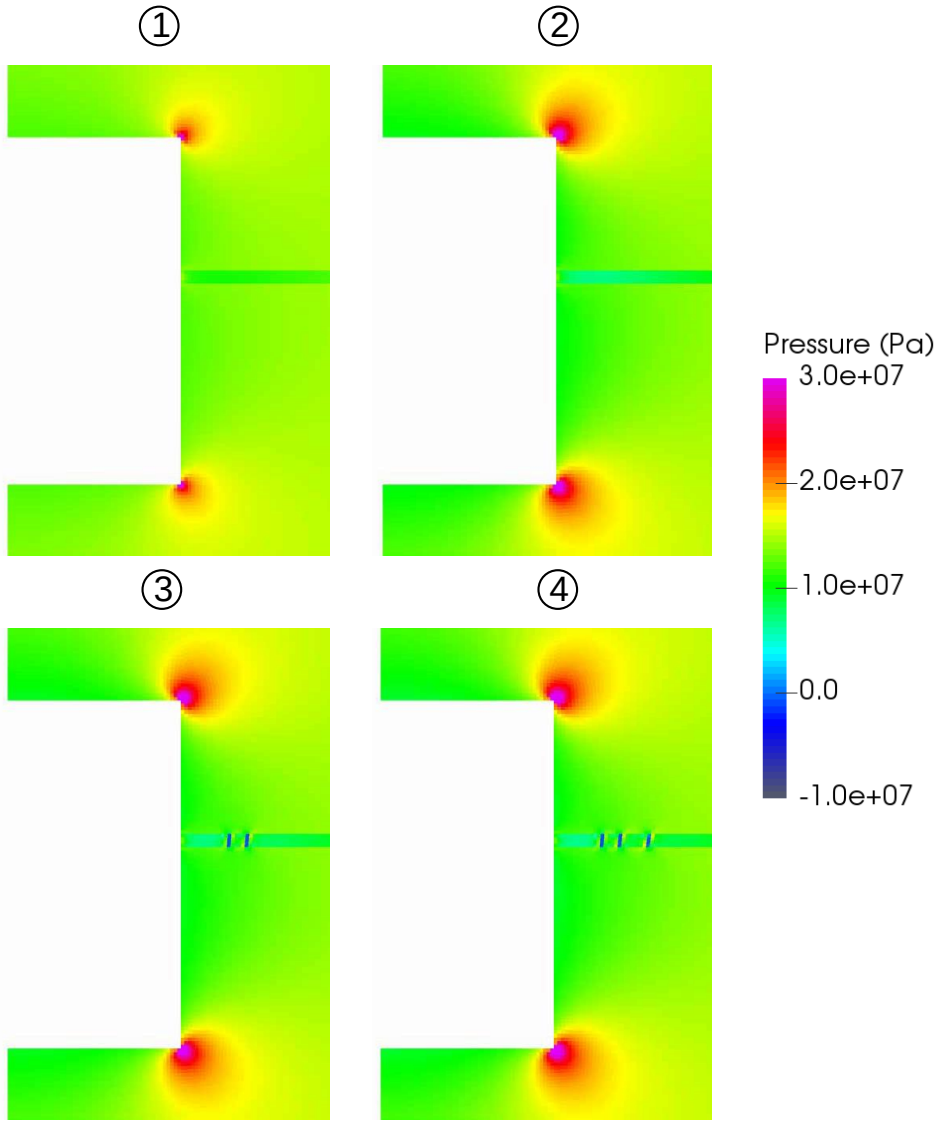
$$F = \begin{cases} \exp\left[\delta_h \left(1 - \frac{\bar{\varepsilon}^{tr}}{\bar{\varepsilon}^{tr*}}\right)^2\right] & \bar{\varepsilon}^{tr} \le \bar{\varepsilon}^{tr*} \\ \exp\left[-\delta_r \left(1 - \frac{\bar{\varepsilon}^{tr}}{\bar{\varepsilon}^{tr*}}\right)^2\right] & \bar{\varepsilon}^{tr} > \bar{\varepsilon}^{tr*} \end{cases}$$

$$\delta_h = \alpha_h + \beta_h \log_{10}\left(\frac{\bar{\sigma}}{\mu}\right)$$

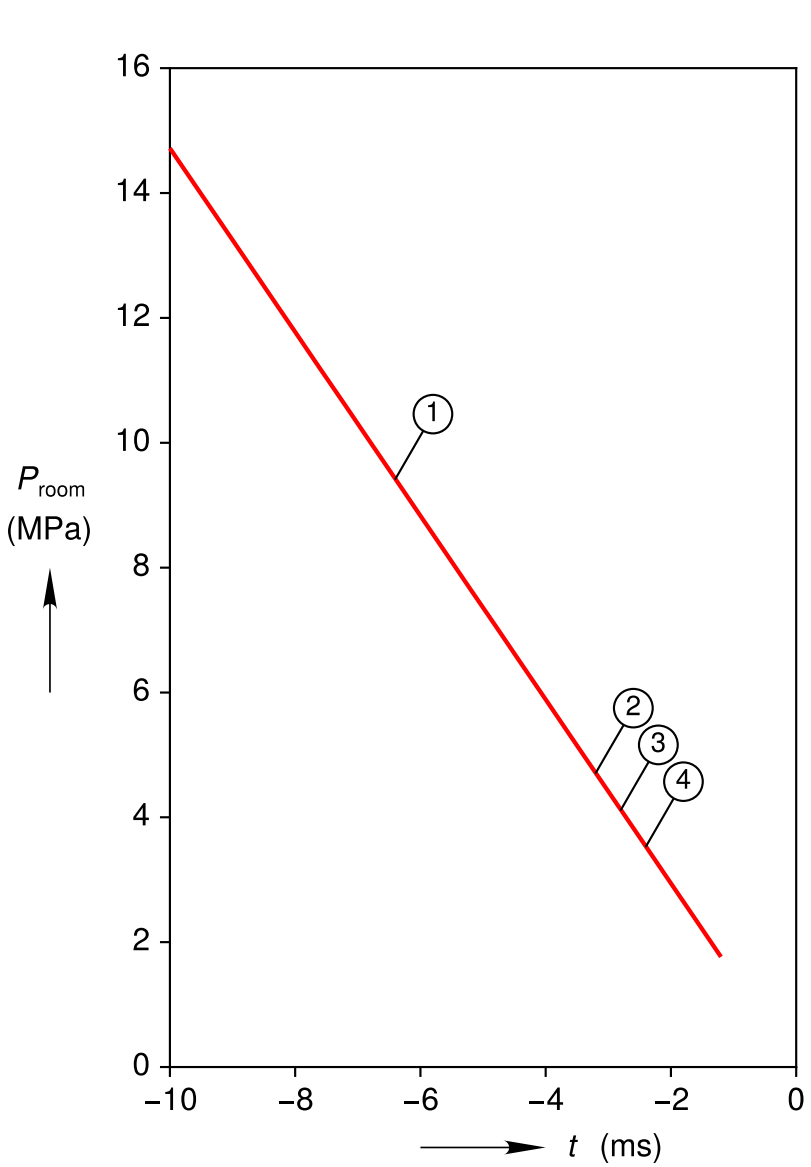
$$\delta_r = \alpha_r + \beta_r \log_{10}\left(\frac{\bar{\sigma}}{\mu}\right)$$

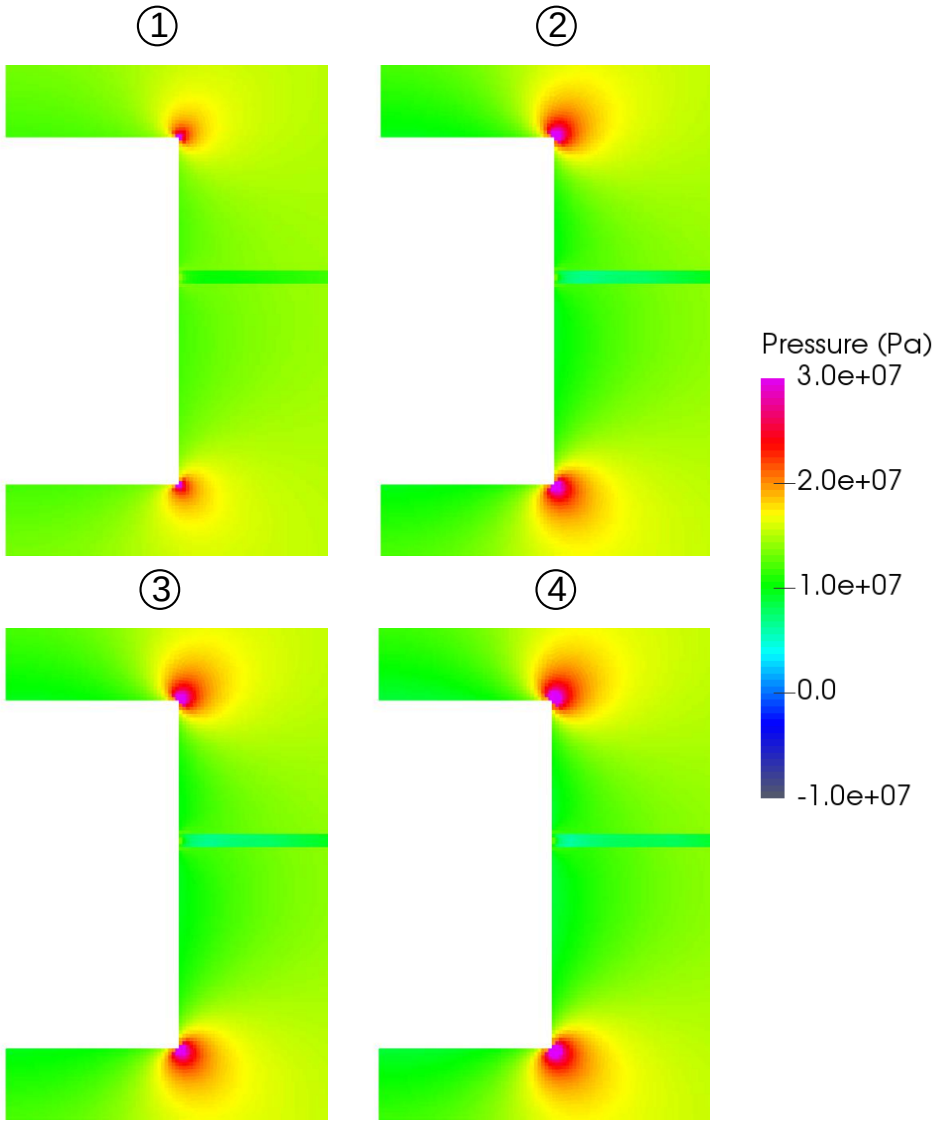
Anhydrite Issue



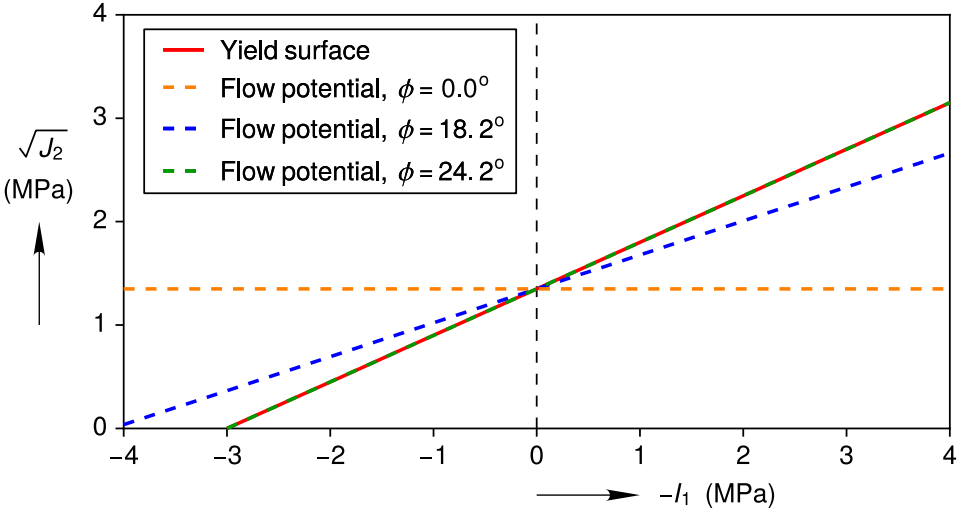


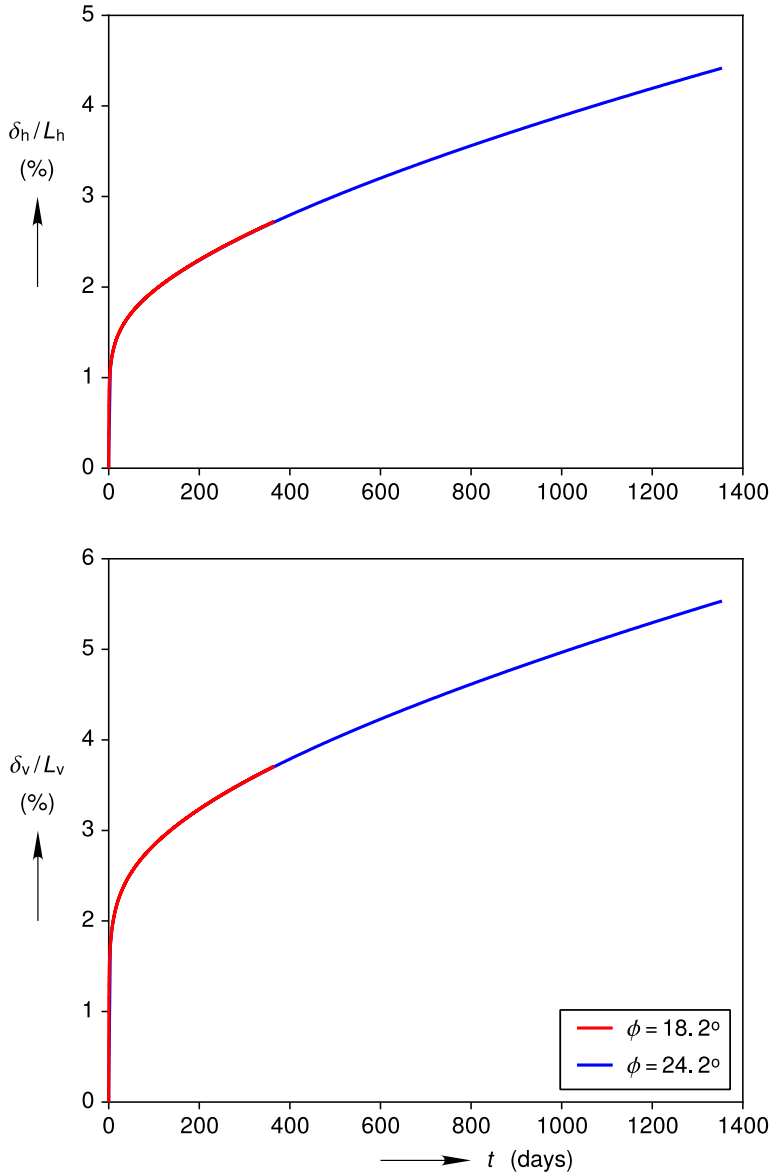
Anhydrite Issue Resolved



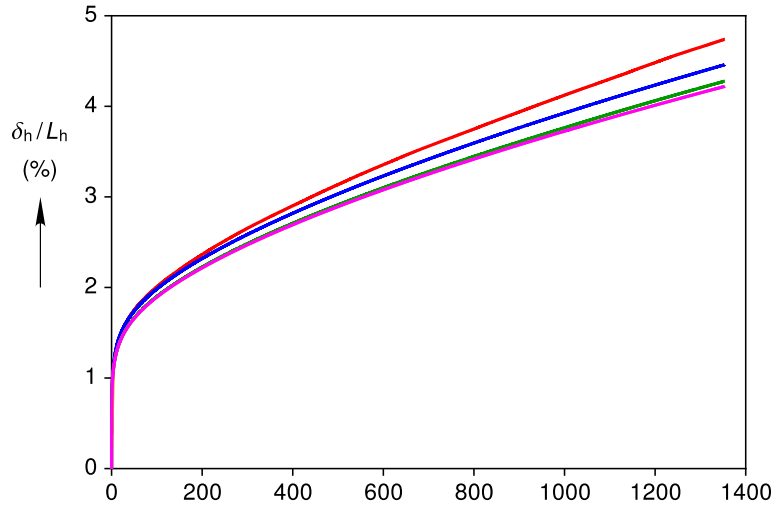


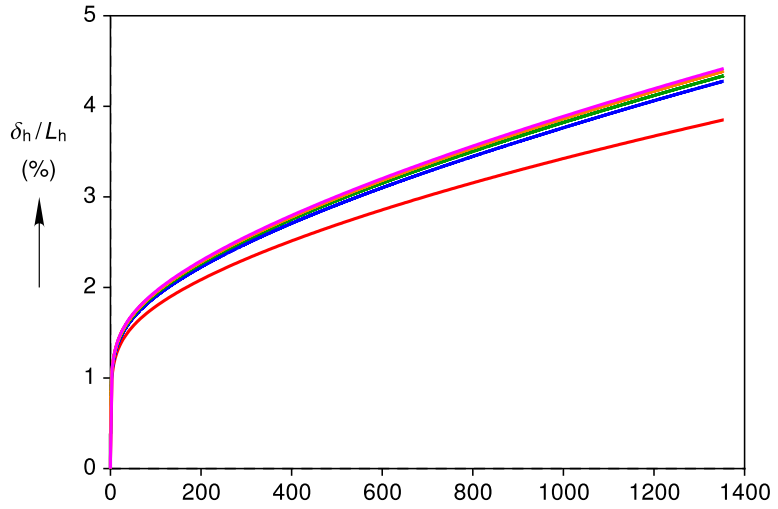
Anhydrite Dilatation Angle Sensitivity

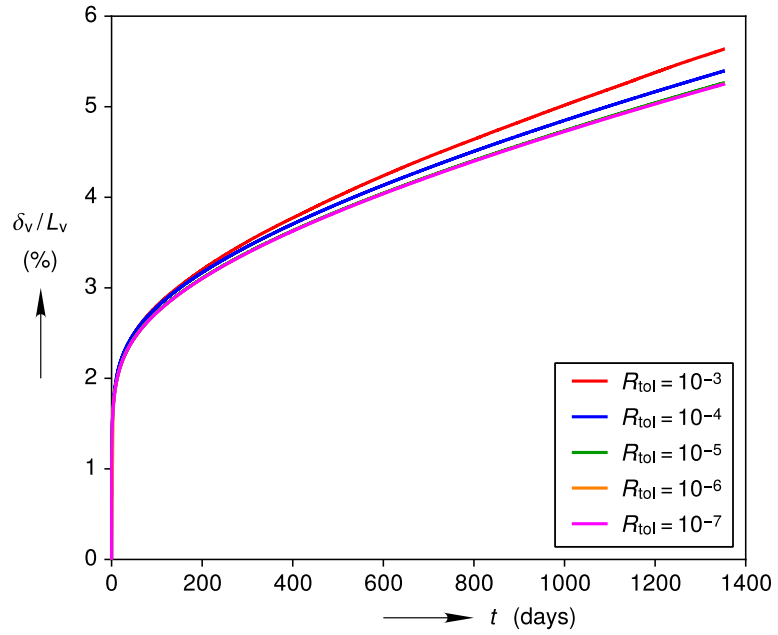


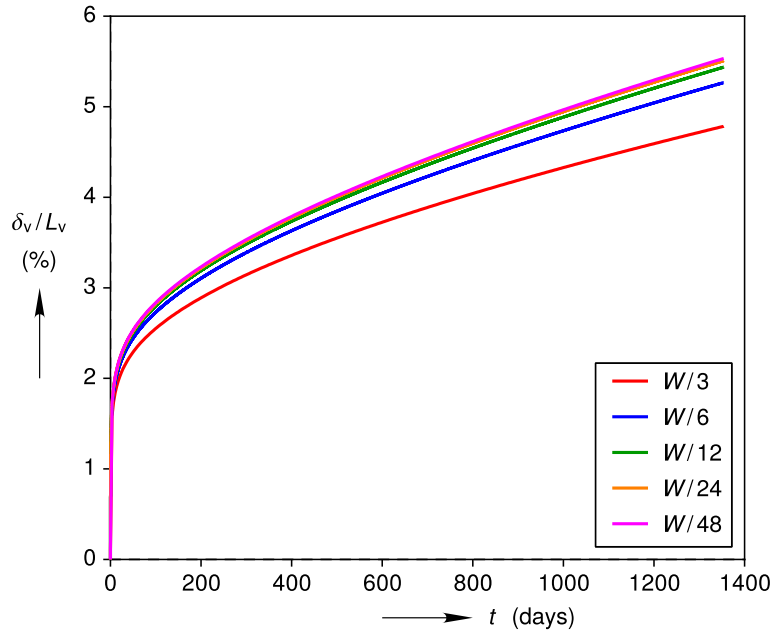


Residual and Mesh Convergence



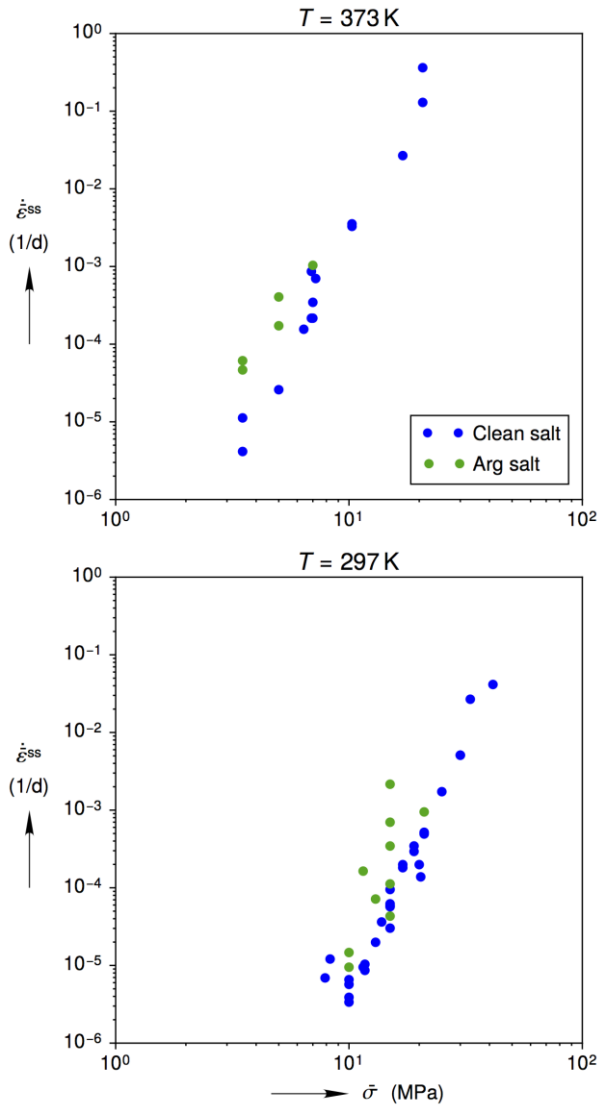




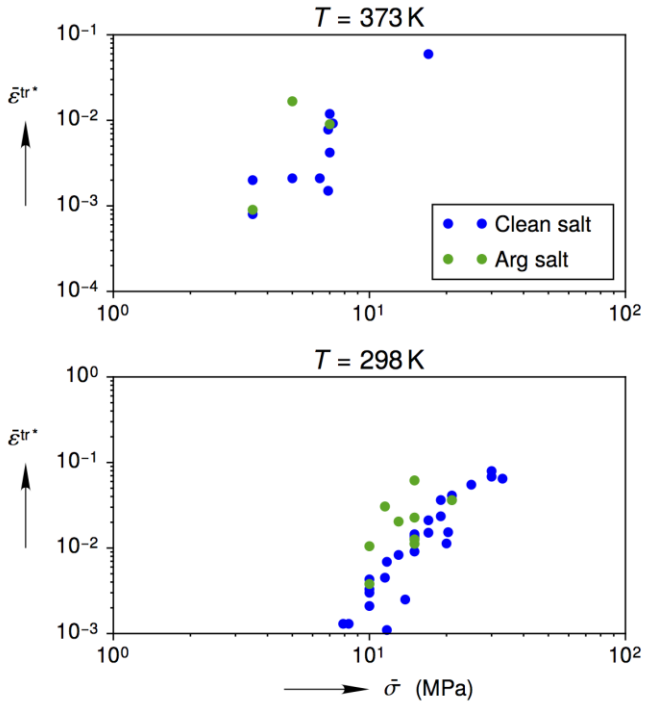


Argillaceous vs. Clean Salt, Legacy Experiments

Steady State Rate



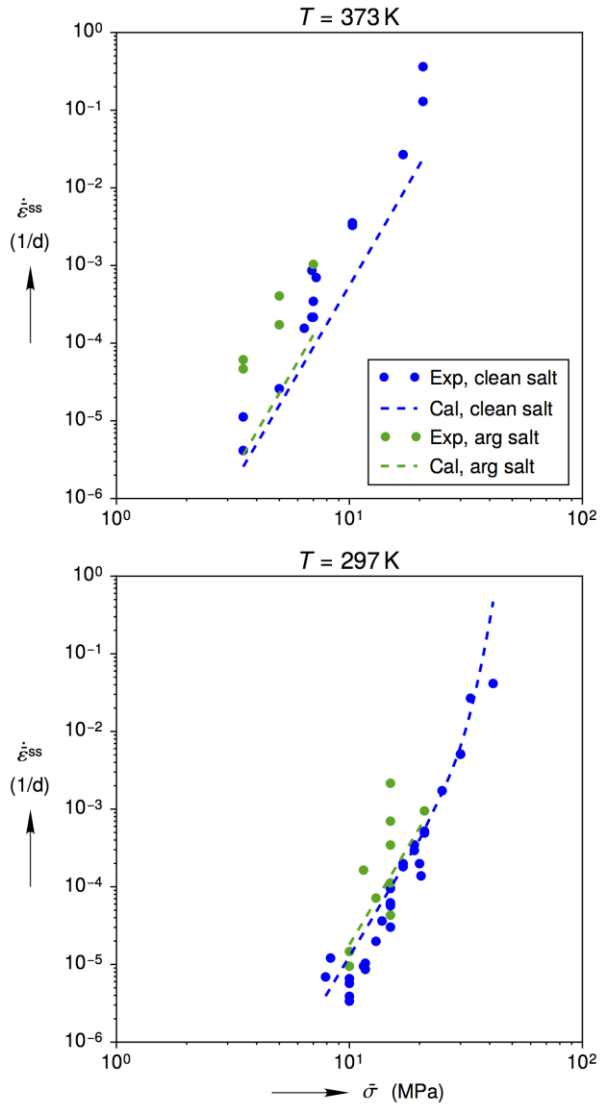
Transient Limit



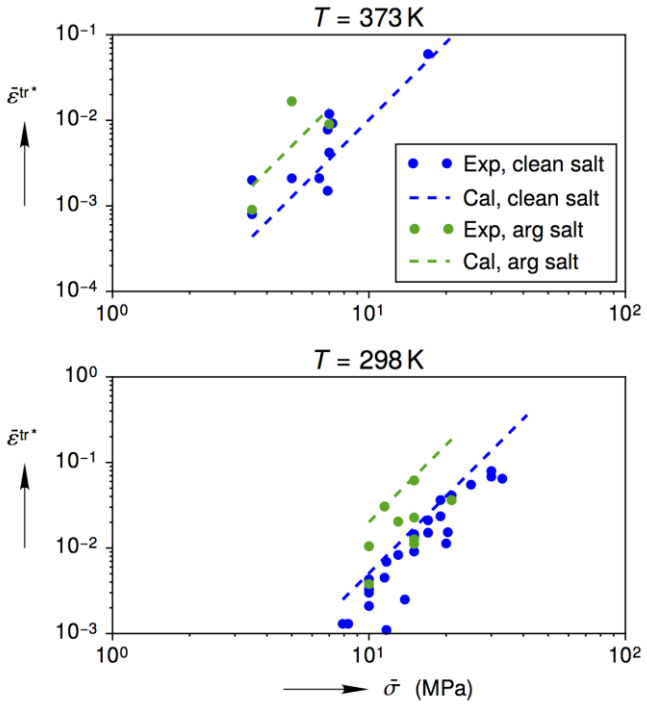
Legacy experimental data copied verbatim from Table 4-1 and 4-2 in Mellegard, K. and Pfeifle, T., Creep tests on clean and argillaceous salt from the Waste Isolation Pilot Plant, SAND92-7291, 1993

Argillaceous vs. Clean Salt, Legacy Experiments

Steady State Rate



Transient Limit

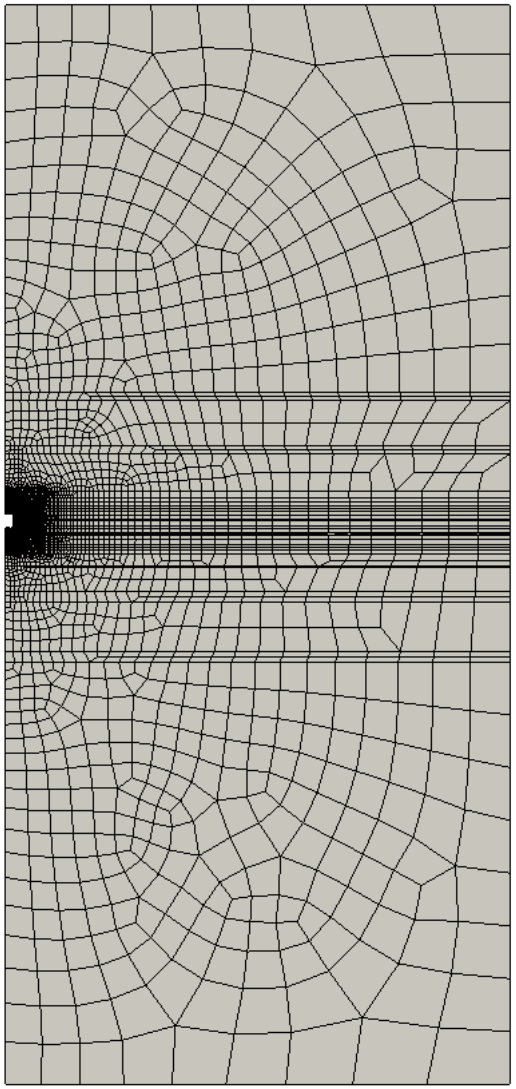


Legacy experimental data copied verbatim from Table 4-1 and 4-2 in Mellegard, K. and Pfeifle, T., Creep tests on clean and argillaceous salt from the Waste Isolation Pilot Plant, SAND92-7291, 1993

Simulation Boundary

Legacy (50 m)
Boundary

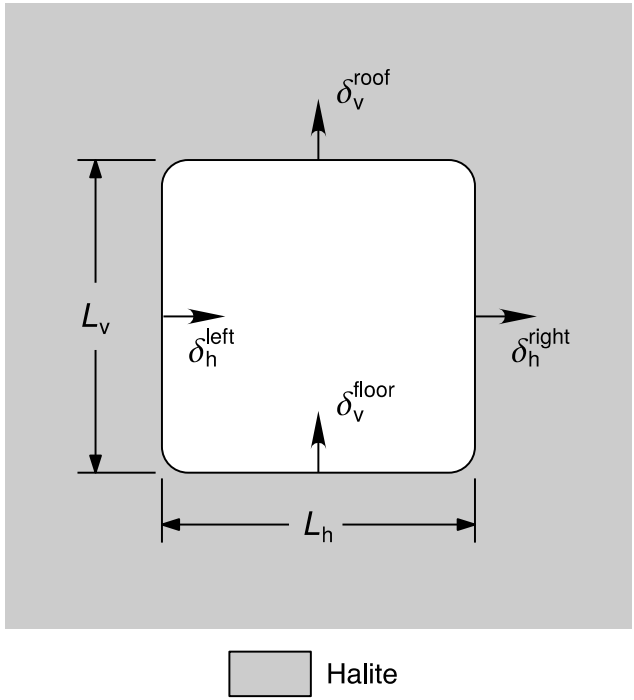
200 m Boundary



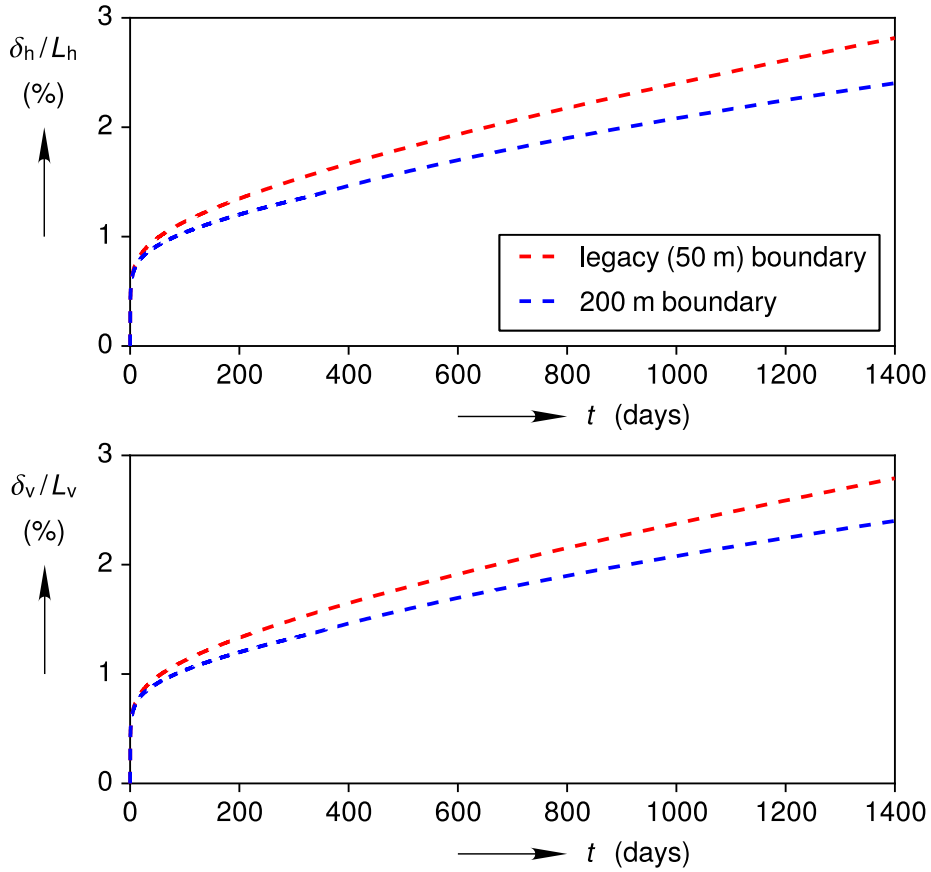
Simulation Boundary: Room Closure

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

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

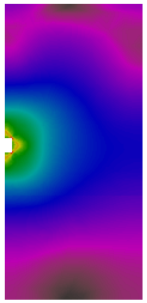


Legacy Clean Salt Calibration

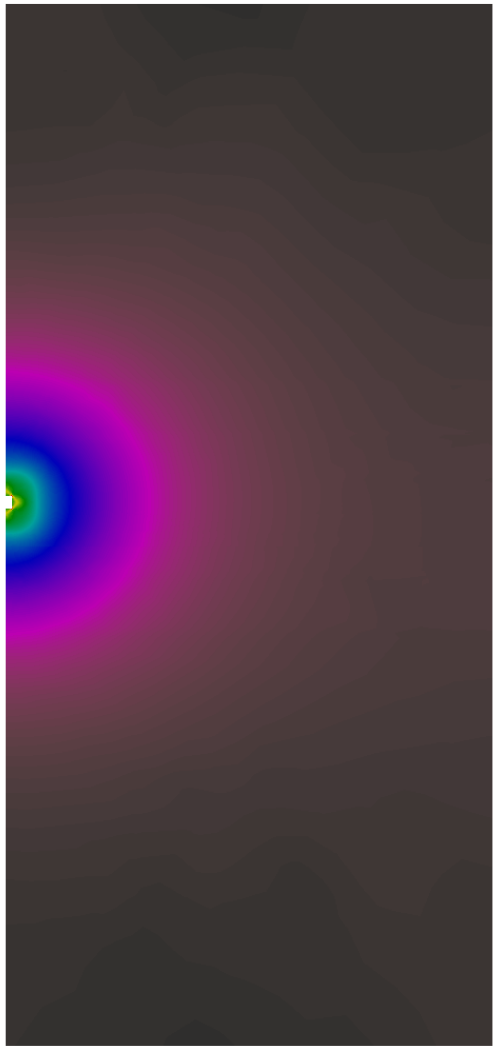


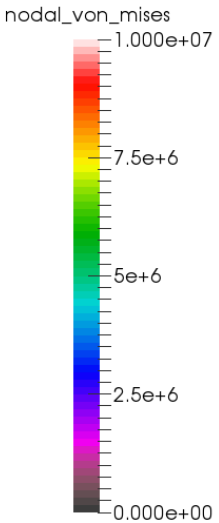
Simulation Boundary: von Mises Stress Fields

Legacy (50 m) Boundary



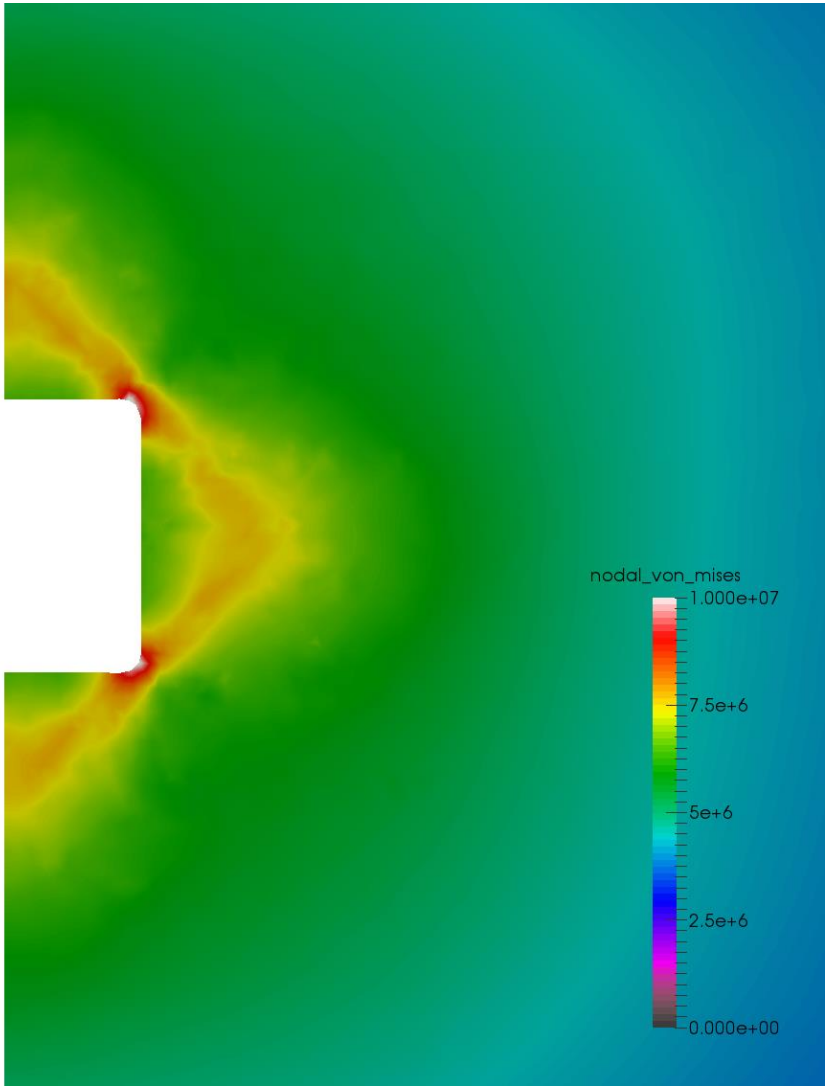
200 m Boundary



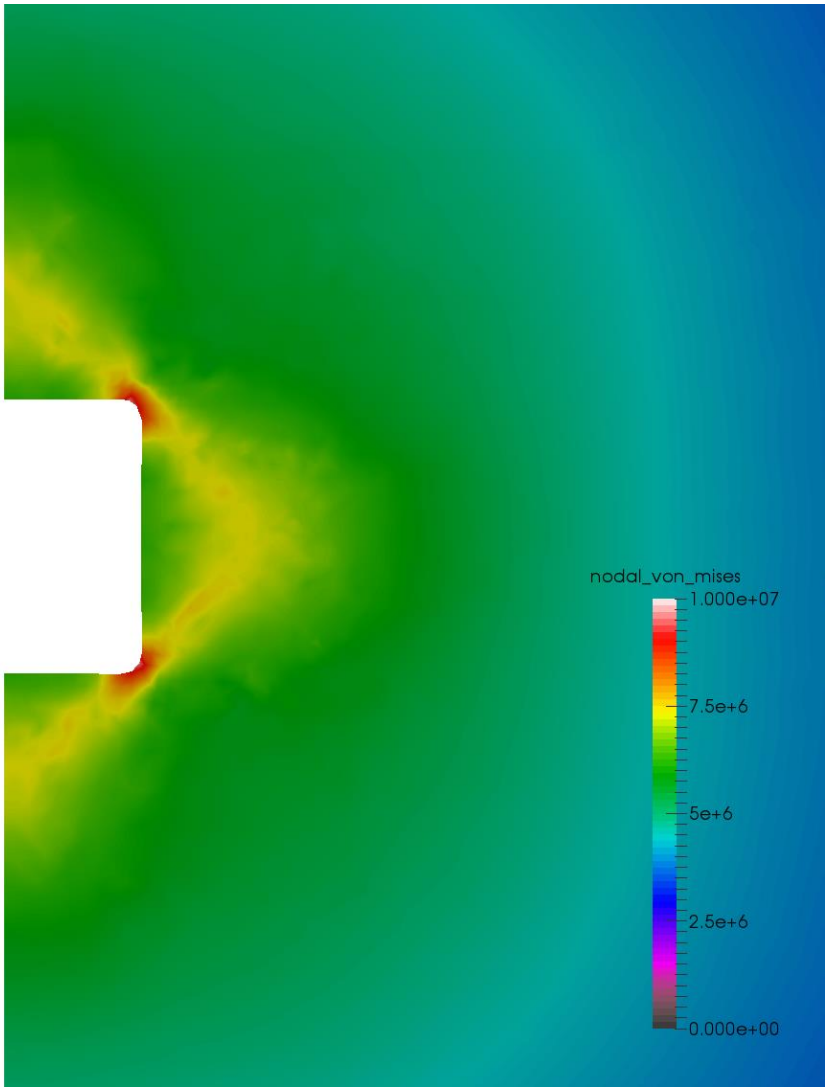


Simulation Boundary: von Mises Stress Fields

Legacy (50 m) Boundary

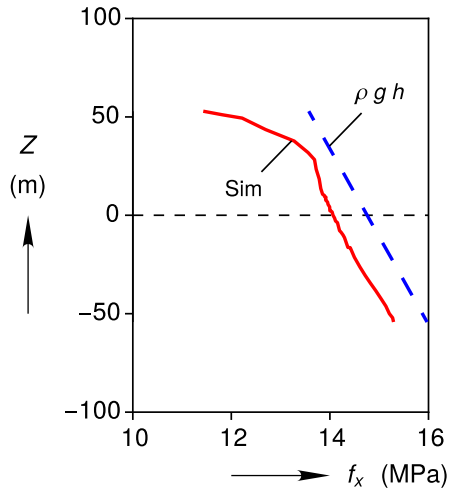


200 m Boundary

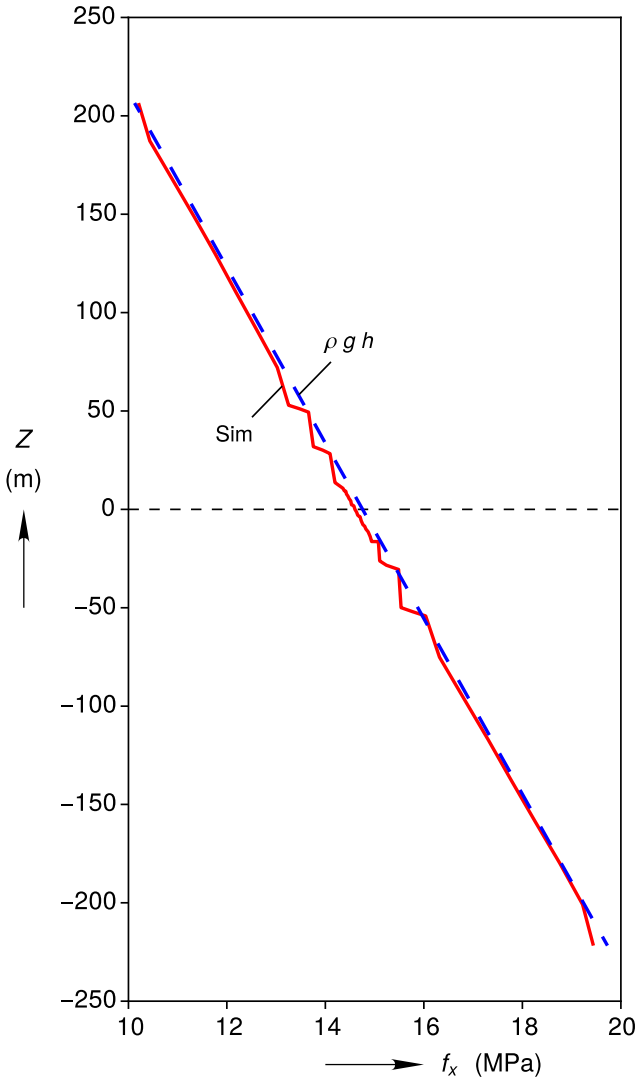


Simulation Boundary: Right Traction Distribution

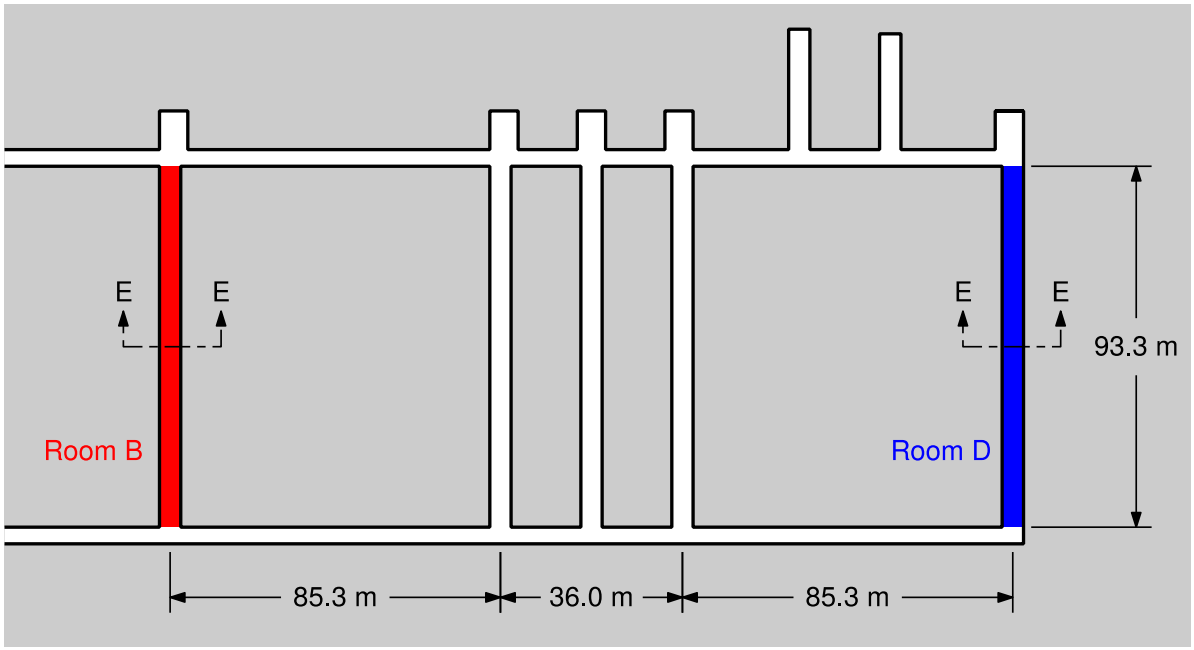
Legacy (50 m) Boundary



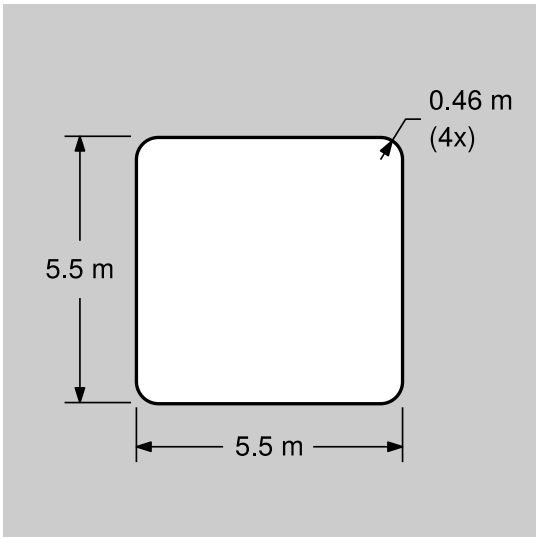
200 m Boundary



Simulation Boundary: Room Spacing



Plan View



Section E-E