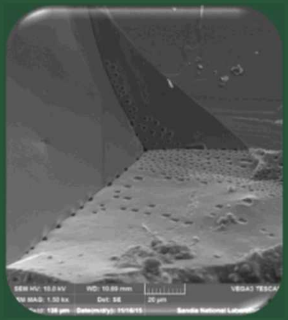
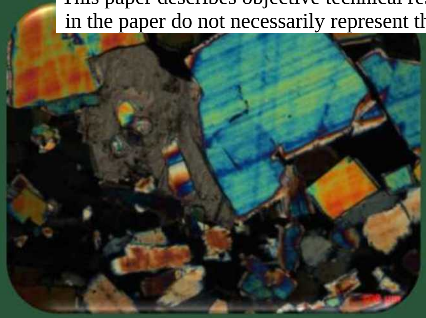
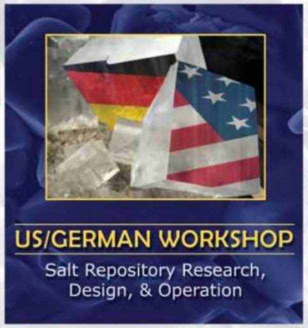




SAND2016-8560C

Reinvestigation into Closure Predictions of Room D at the Waste Isolation Pilot Plant



Benjamin Reedlunn
Sandia National Laboratories

Washington, DC
September 7-9, 2016

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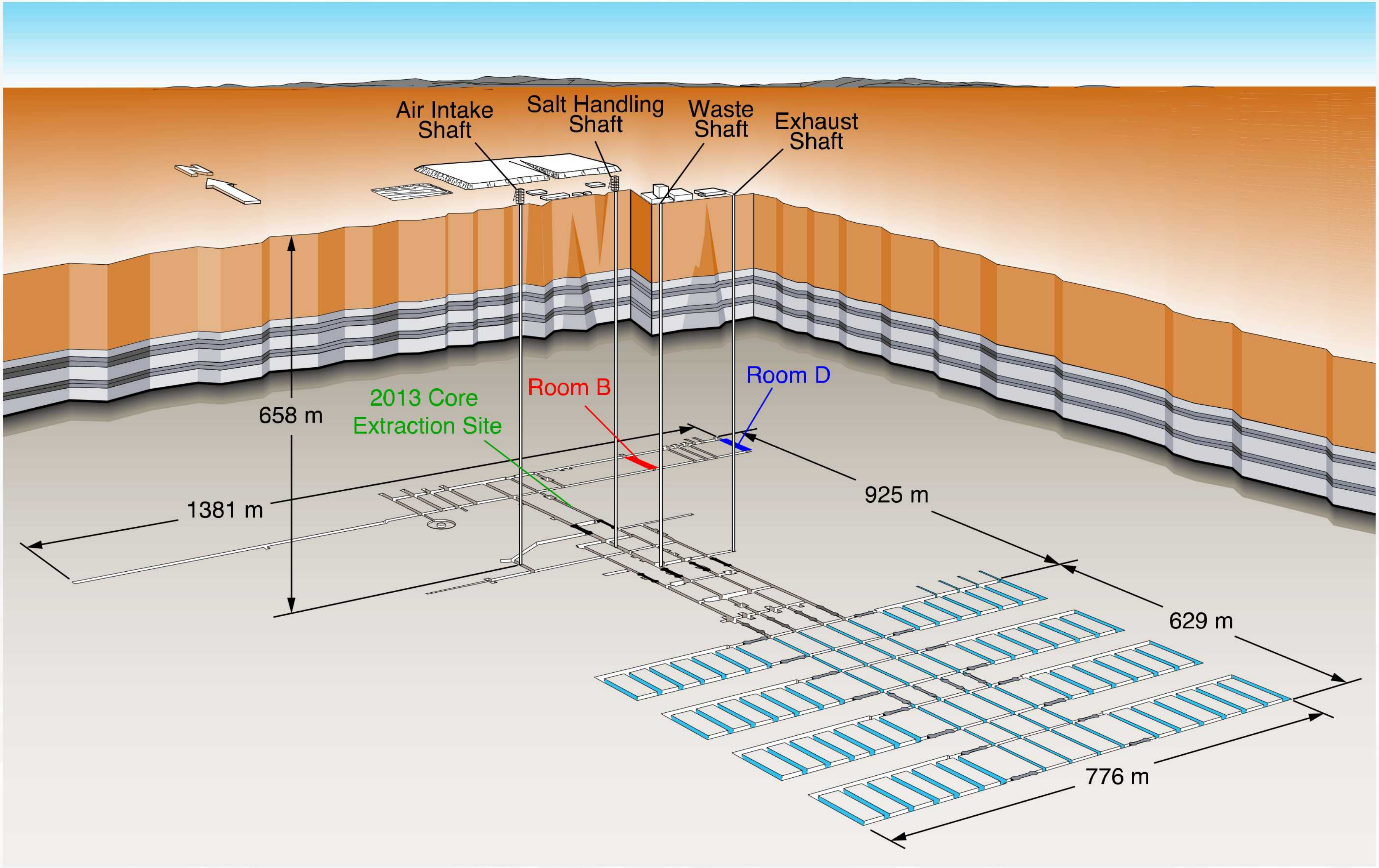
Outline

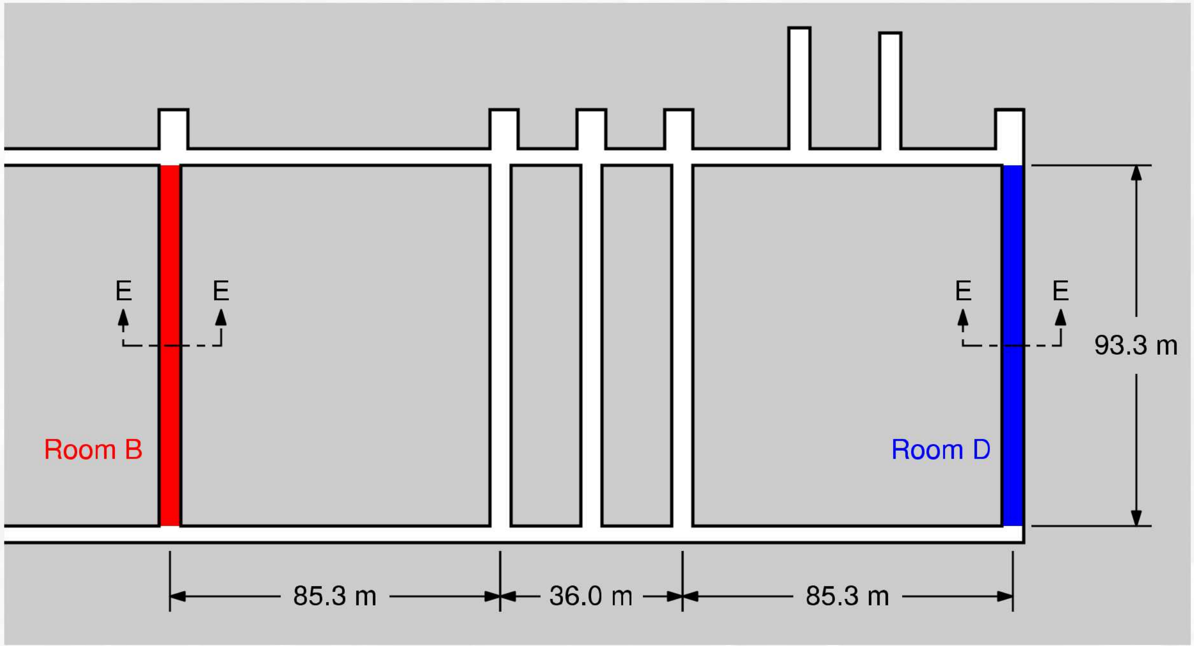
- Background
  - WIPP Room B and D
  - Munson-Dawson Model
  - Legacy Simulations
- Reinvestigation
  - Resolving the numerics
  - Munson-Dawson Model Recalibration
  - New predictions
- Summary

WIPP Room B and D

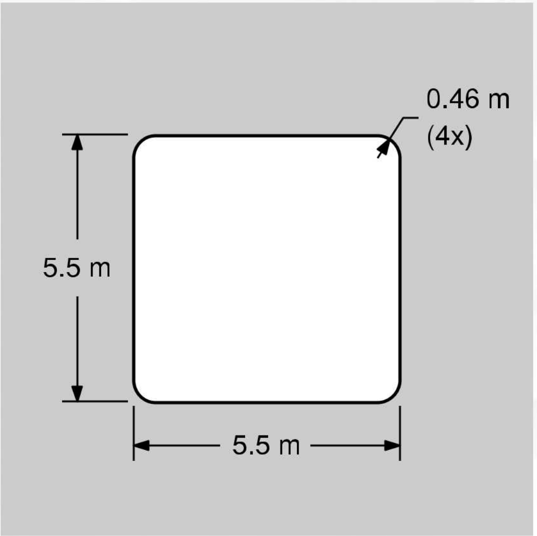
Rooms B and D at WIPP



Room B and D Dimensions



Plan View



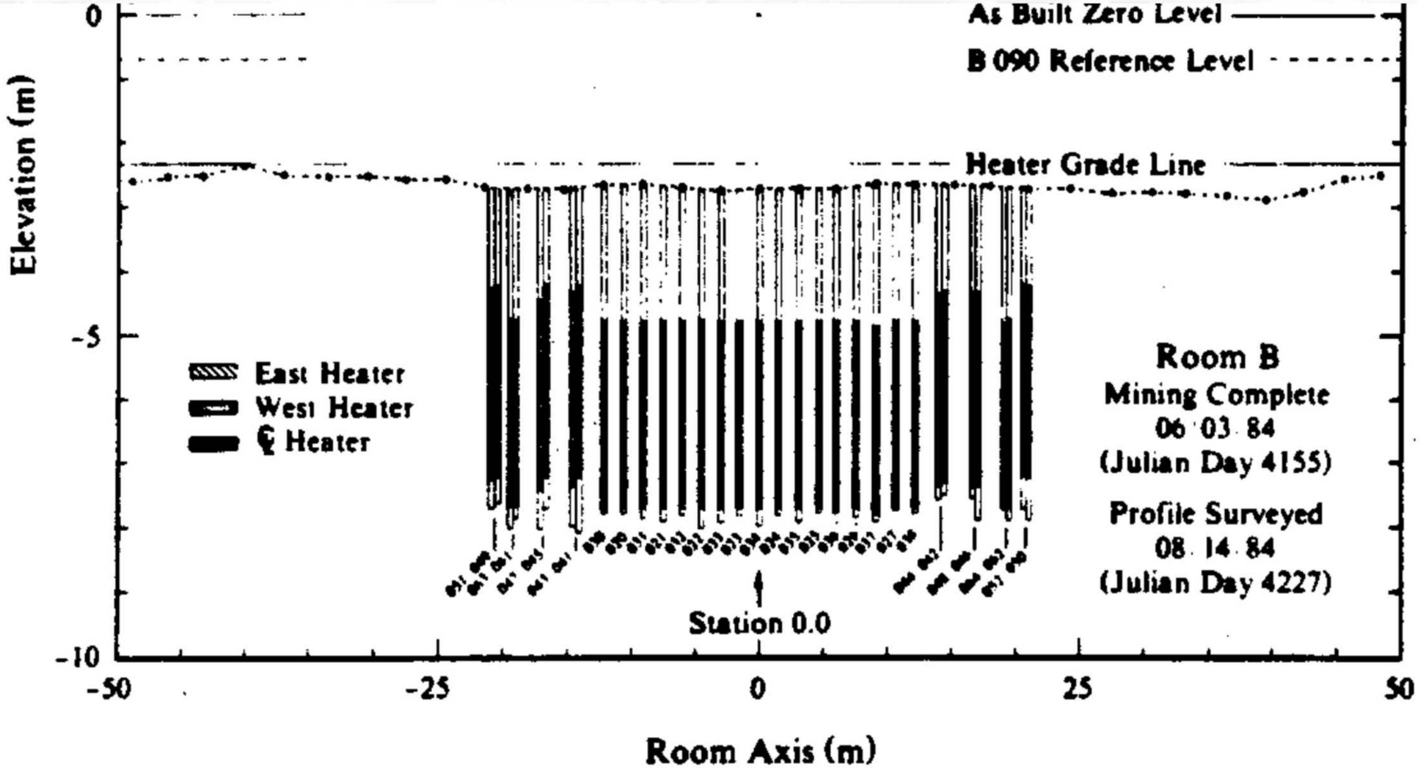
Section E-E

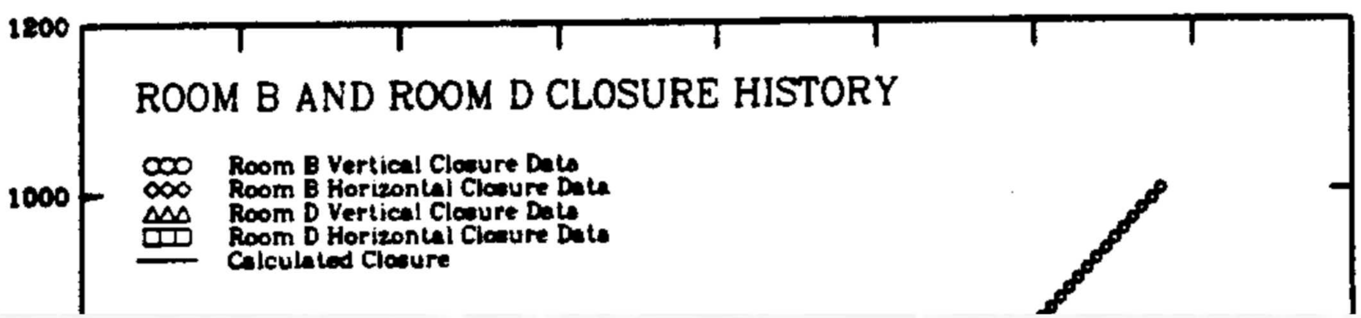
Photos of Room B and D

Room B

Room D

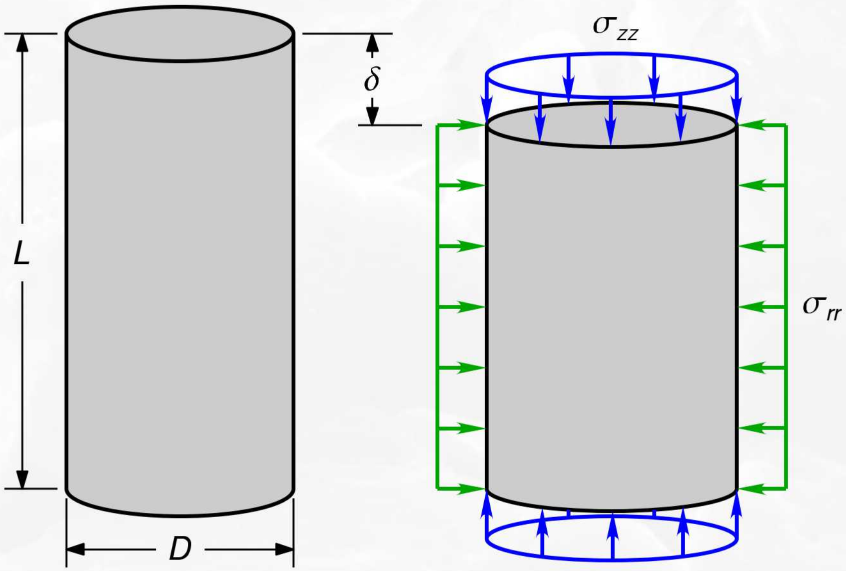
In-Situ Closure Measurements





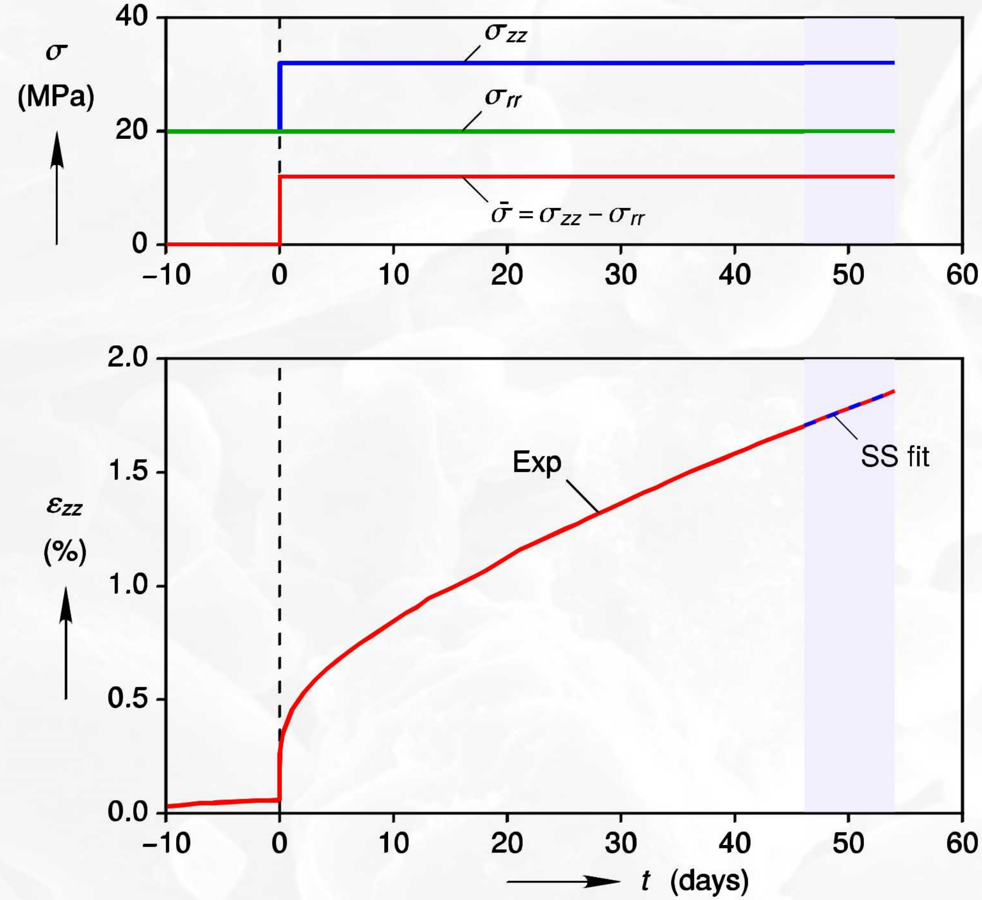
Munson-Dawson Model

Triaxial Creep Tests

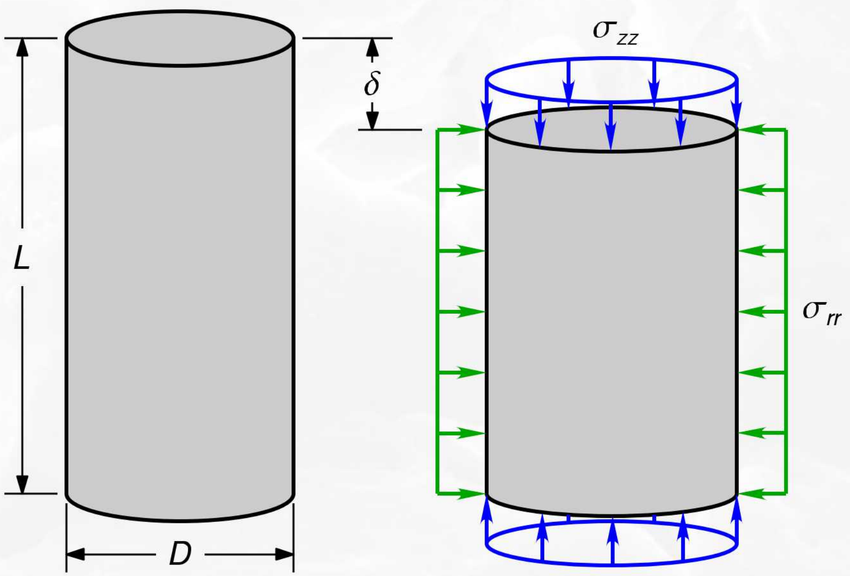


$$\frac{L}{D} = 2$$

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

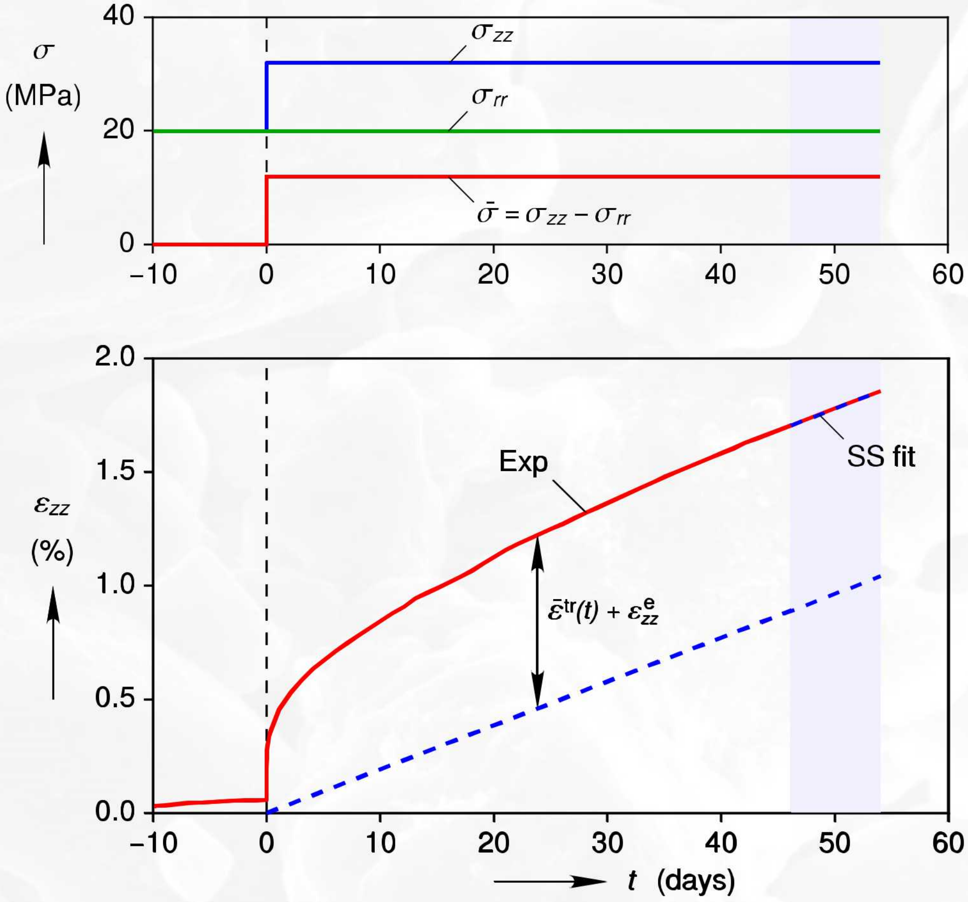


Triaxial Creep Tests

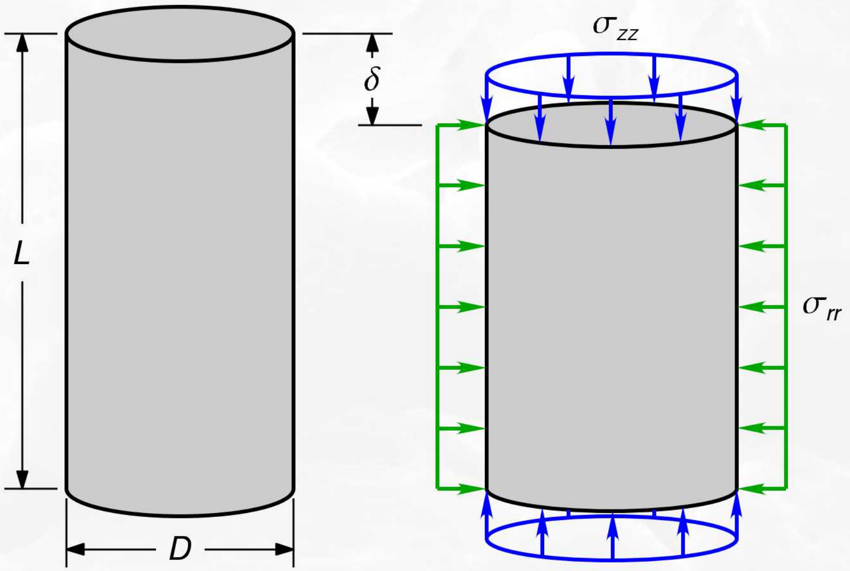


$$\frac{L}{D} = 2$$

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

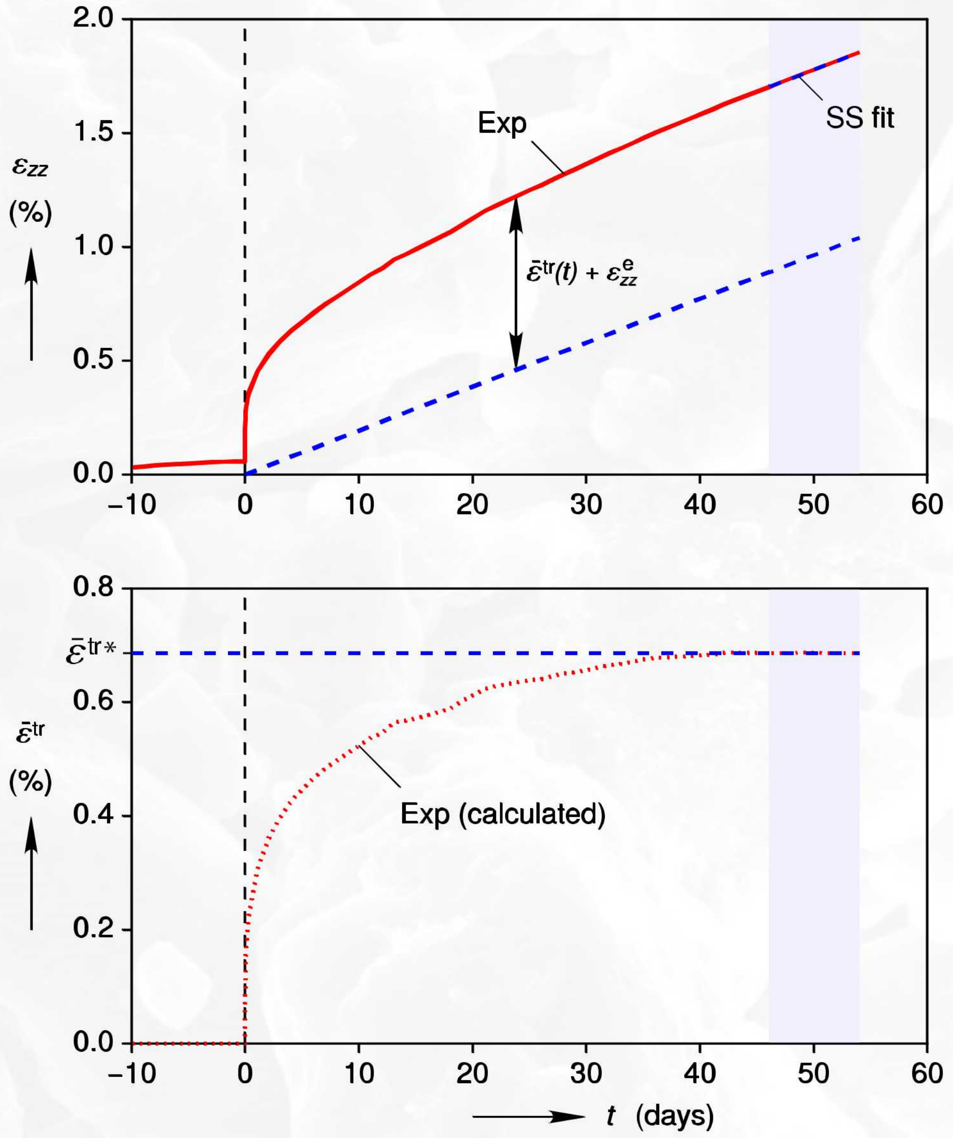


Triaxial Creep Tests

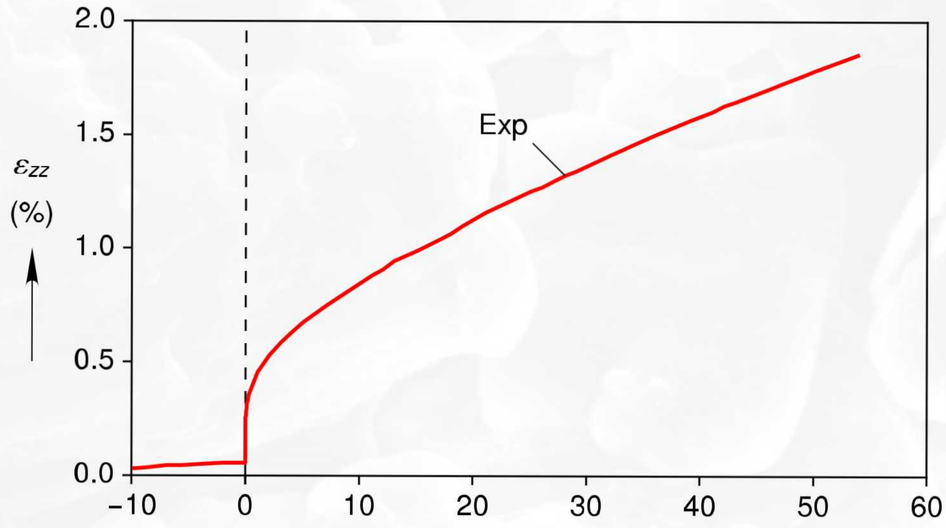


$$\frac{L}{D} = 2$$

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



Munson-Dawson Calibration



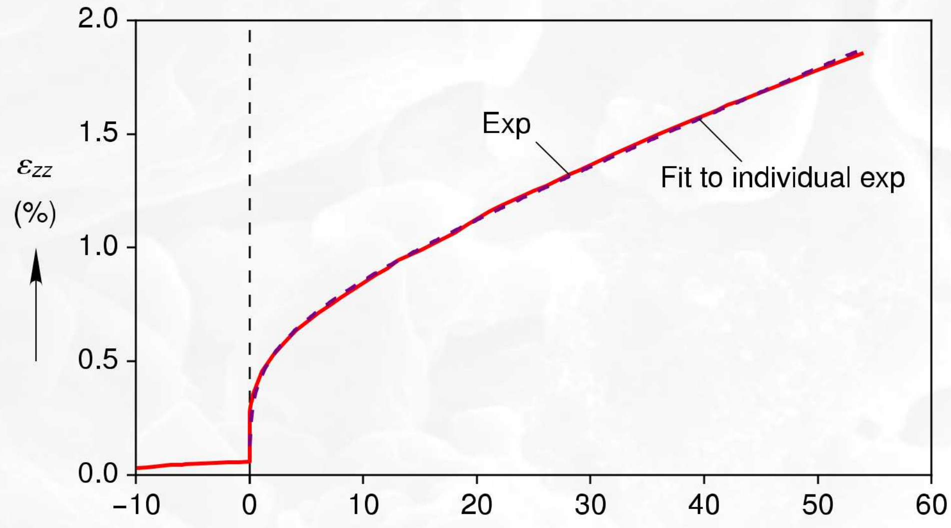
Transient Creep ODE

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

Munson-Dawson Calibration

Transient Creep ODE

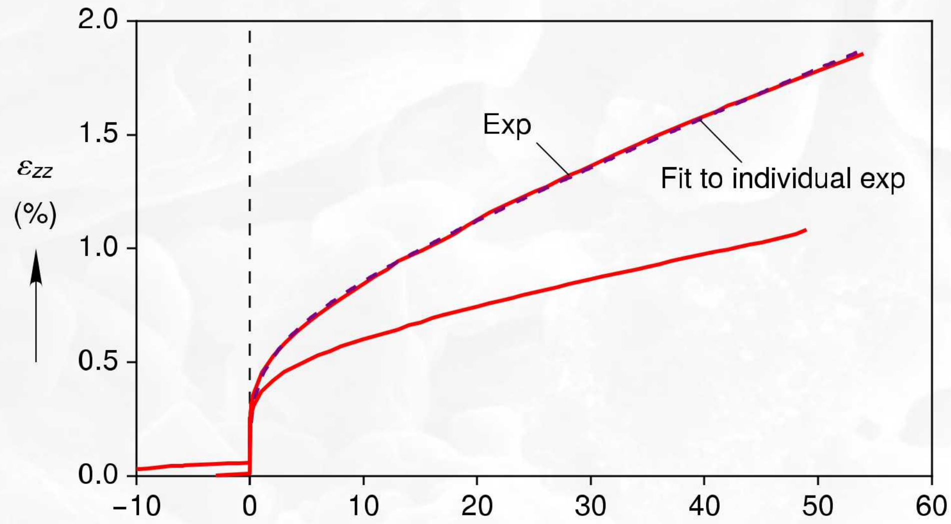
$$\dot{\bar{\varepsilon}}^{\mathrm{tr}} = \exp\left[\delta_{\mathrm{h}}\left(1 - \frac{\bar{\varepsilon}^{\mathrm{tr}}}{\bar{\varepsilon}^{\mathrm{tr}*}}\right)^2\right]\dot{\bar{\varepsilon}}^{\mathrm{ss}} - \dot{\bar{\varepsilon}}^{\mathrm{ss}}$$



Munson-Dawson Calibration

Transient Creep ODE

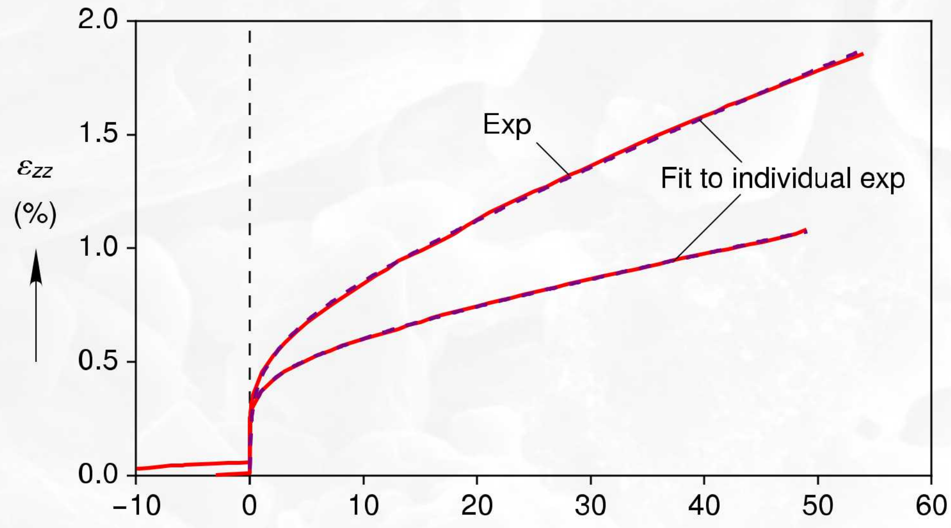
$$\dot{\bar{\varepsilon}}^{\mathrm{tr}} = \exp\left[\delta_{\mathrm{h}}\left(1 - \frac{\bar{\varepsilon}^{\mathrm{tr}}}{\bar{\varepsilon}^{\mathrm{tr}*}}\right)^2\right]\dot{\bar{\varepsilon}}^{\mathrm{ss}} - \dot{\bar{\varepsilon}}^{\mathrm{ss}}$$



Munson-Dawson Calibration

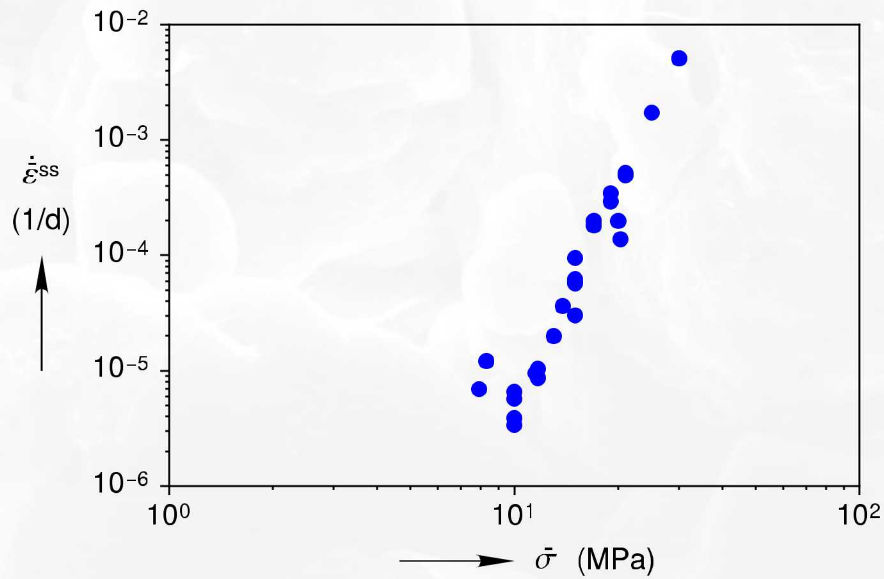
Transient Creep ODE

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

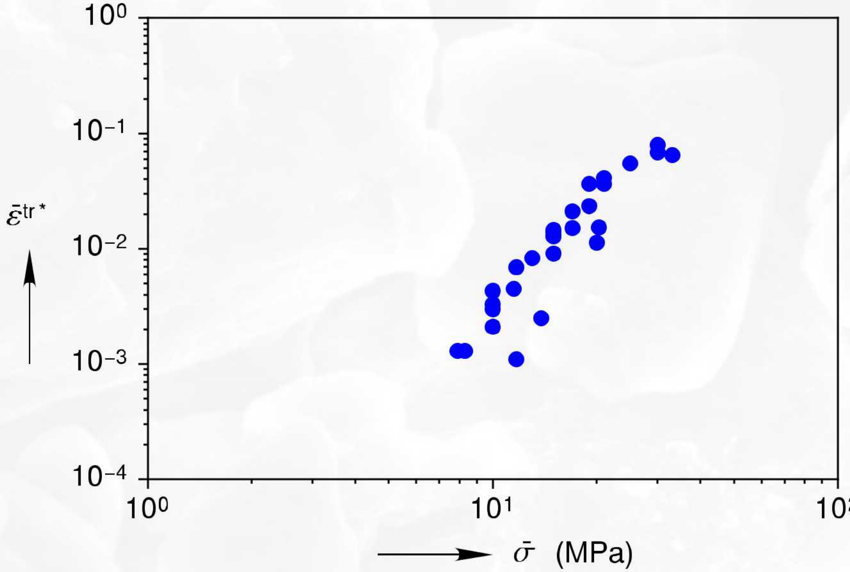


Munson-Dawson Calibration

Steady State Rate



Transient Limit



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

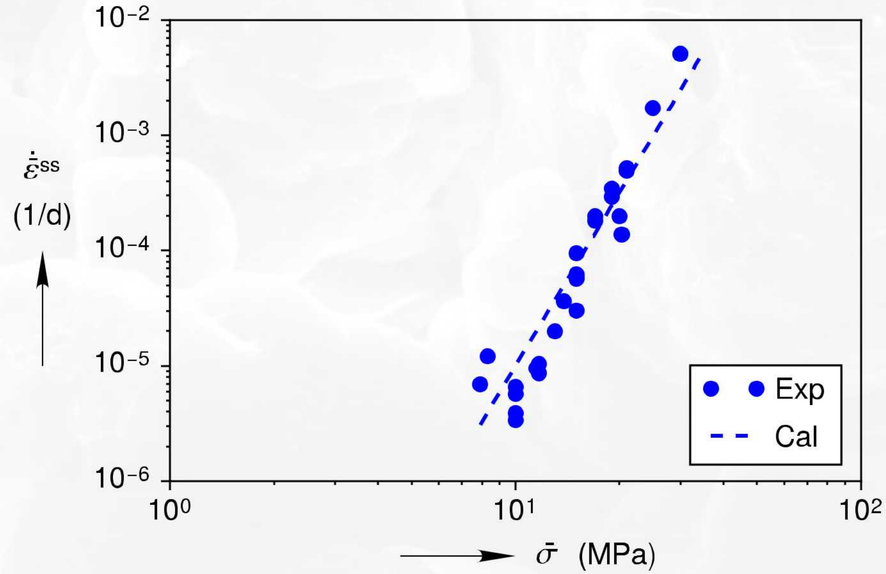
$$\bar{\varepsilon}^{tr*} = K_0 \exp\left(c\,T\right)\left(\frac{\bar{\sigma}}{\mu}\right)^m$$

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

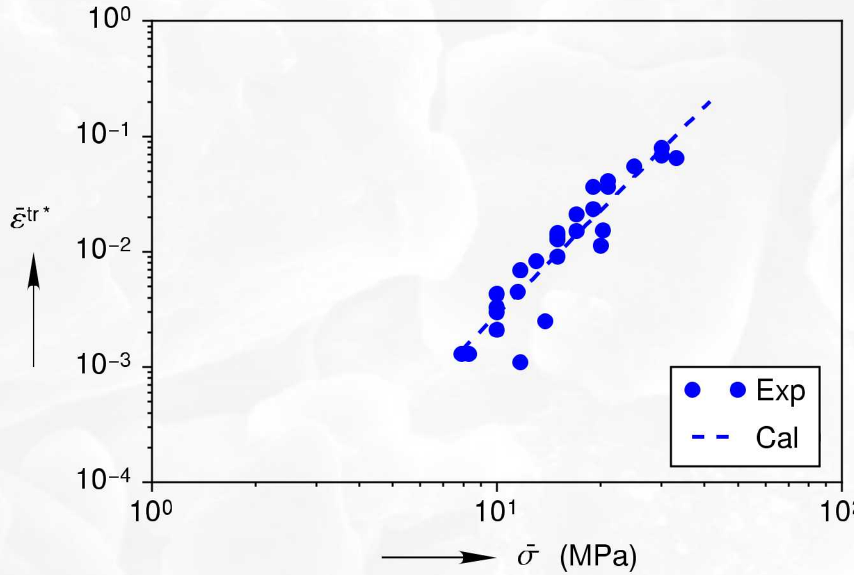
$$\log_{10}\left[\bar{\varepsilon}^{tr*}\right] = \log_{10}\left[\frac{K_0}{\mu^m}\exp\left(c\,T\right)\right] + m\,\log_{10}\bar{\sigma}$$

Munson-Dawson Calibration

Steady State Rate



Transient Limit



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

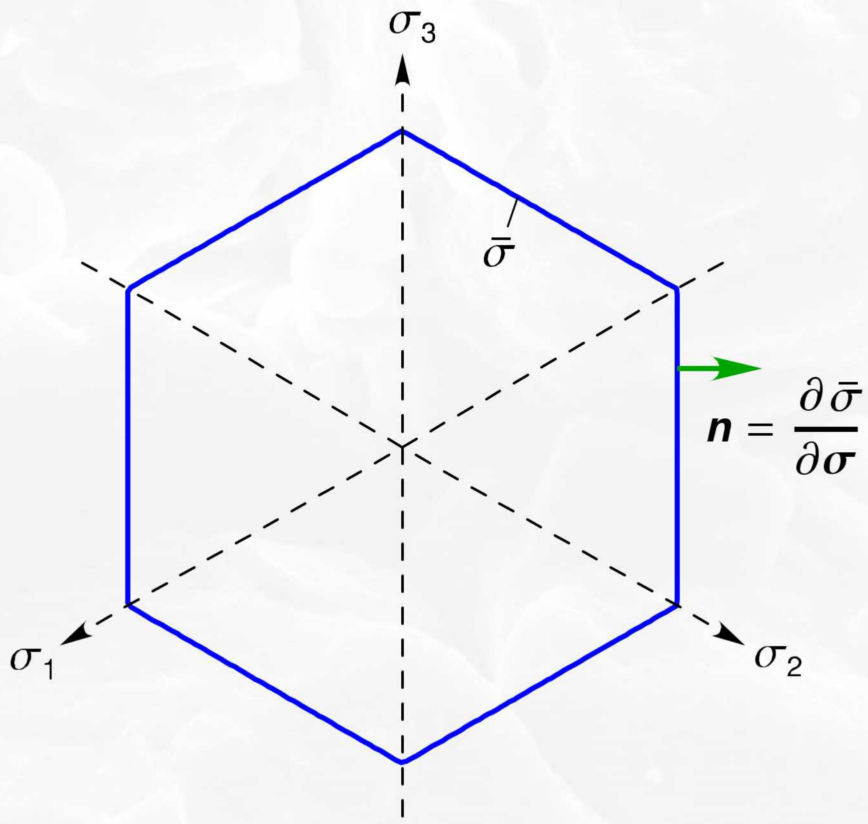
$$\log_{10}\left[\dot{\varepsilon}^{ss}\right] = \log_{10}\left[\frac{A}{\mu^{n}} \exp\left(-\frac{Q}{R\,T}\right)\right] + n \log_{10} \bar{\sigma}$$

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

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

Munson Dawson: 3D Generalization

Tresca Effective Stress



$$\bar{\sigma} = \max\left(|\sigma_1 - \sigma_2|,\ |\sigma_2 - \sigma_3|,\ |\sigma_3 - \sigma_1|\right)$$

Additive Decomposition

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

Associated Flow Rule

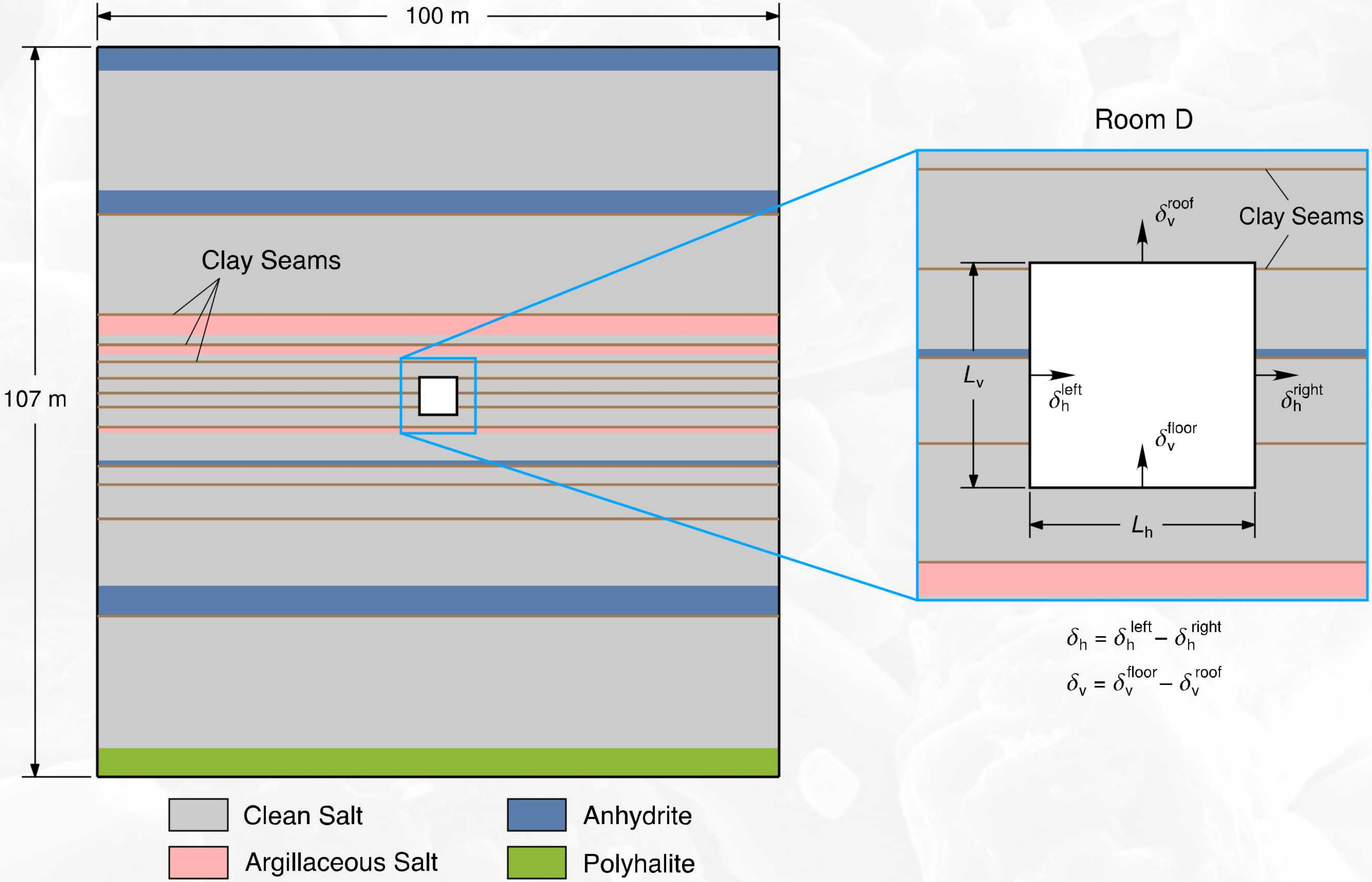
$$\dot{\boldsymbol{\varepsilon}}^{\mathrm{in}} = \left(\dot{\bar{\varepsilon}}^{\mathrm{ss}} + \dot{\bar{\varepsilon}}^{\mathrm{tr}}\right) \boldsymbol{n}$$

Generalized Hooke's Law

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

Legacy Simulations

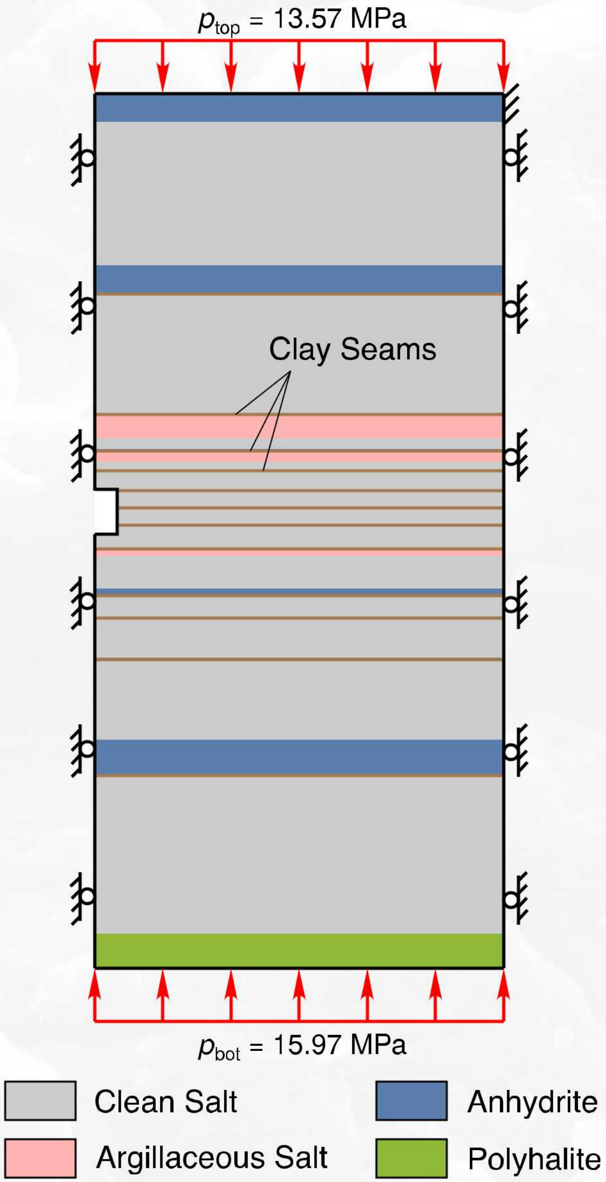
Idealized Stratigraphy



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

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

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

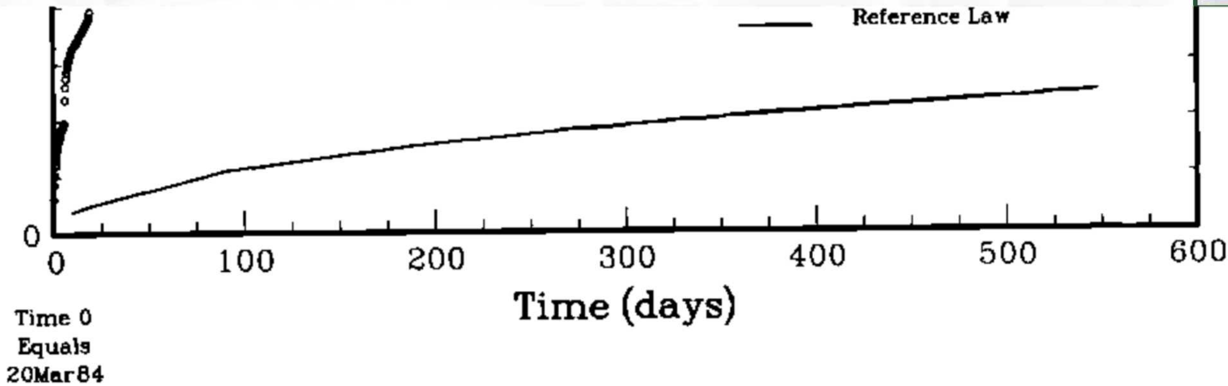
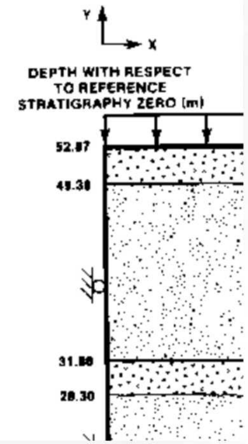


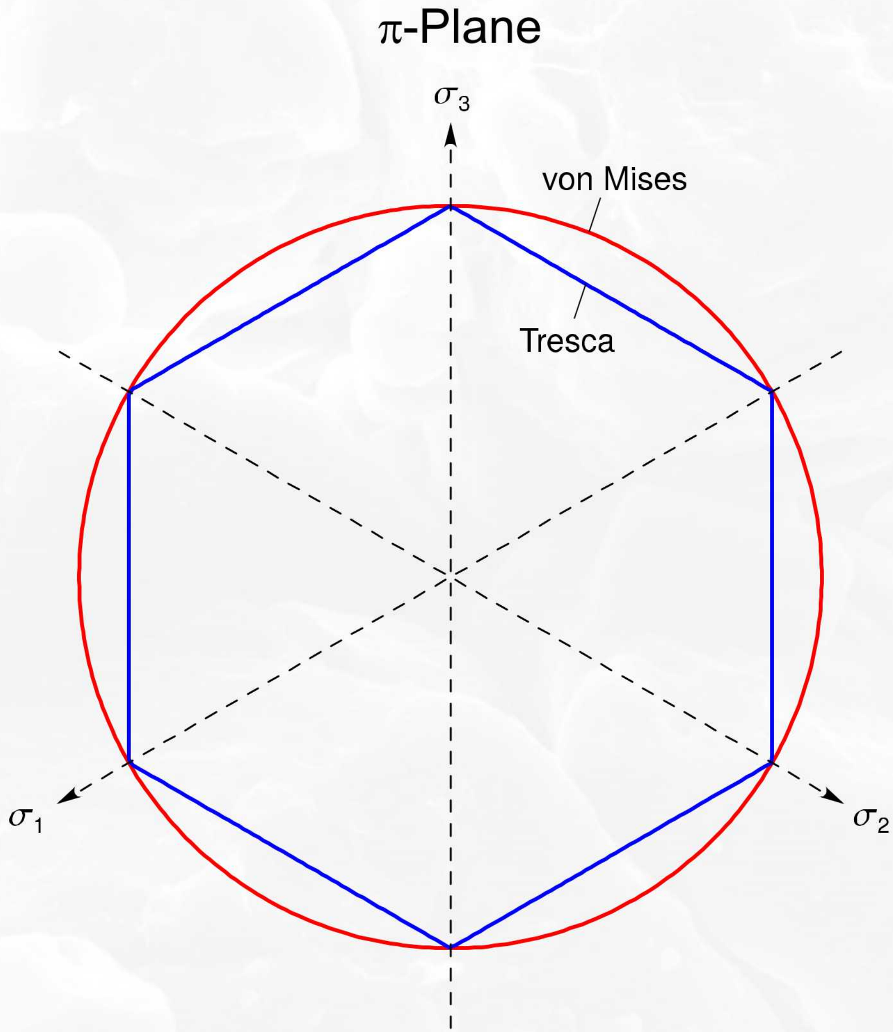
Figure 8. Manual and Remote Vertical Closure Data for Room D (and Reference Law Calculation)

instrument hole drilling. By preplanning the locations of the gages, manual and remote, it was reasonable to combine the plots, and maintain a continuous record of room closure. The zero station mining sequence measurements just described were located within 0.6 m of the remote measurements for room closure. In Figure 8 these two data sets are combined. It is important to emphasize that the data acquisition systems for the manually read mining sequence closure and the remotely read closure measurements were each made independently. Although a match between the two



Munson, DE, Torres, TM, & Blankenship, DA. 1986. Early results from the thermal/structural in situ test series at the WIPP. In: The 27th US Symposium on Rock Mechanics (USRMS). American Rock Mechanics Association.

Changed the Equivalent Stress



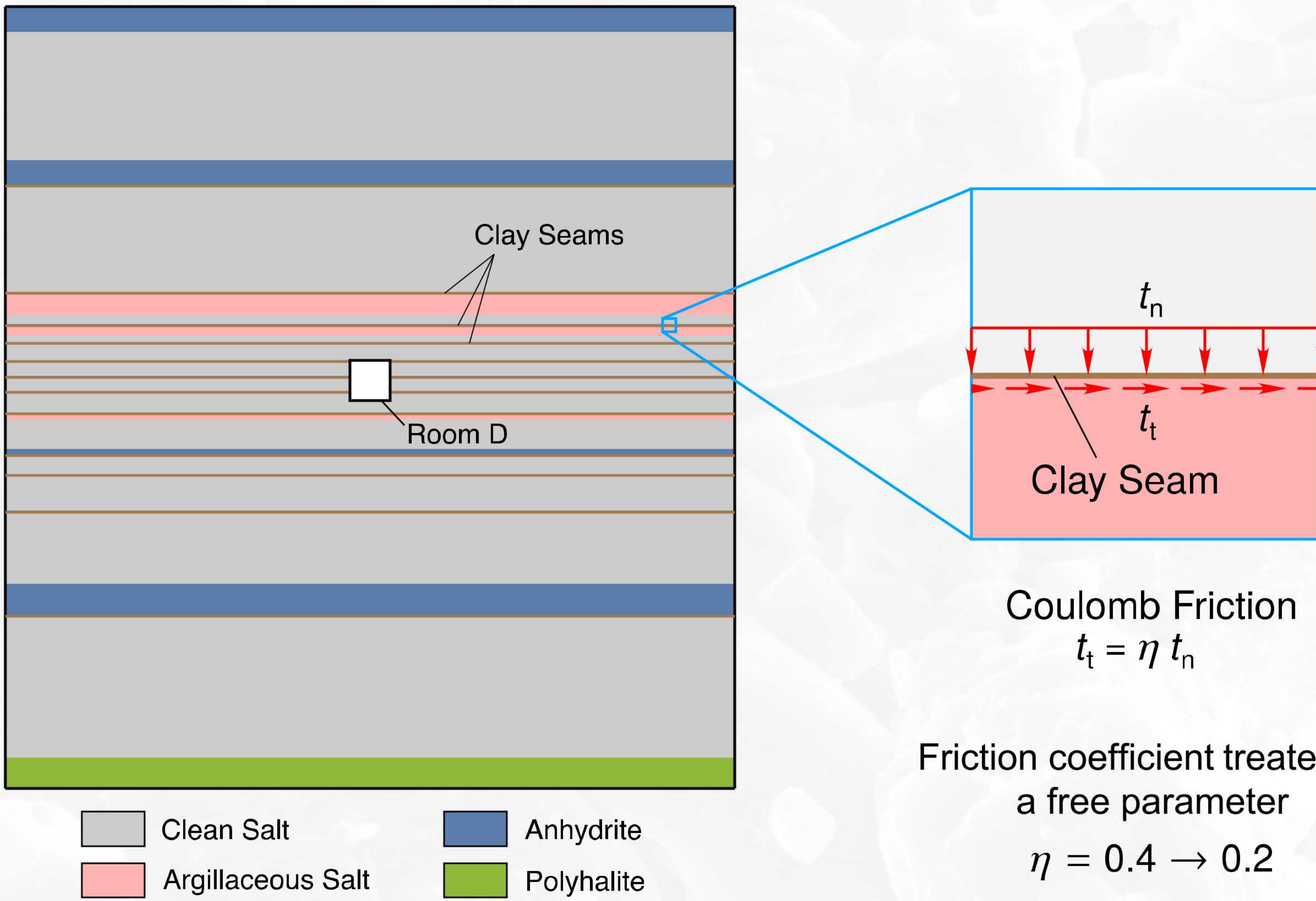
Steady State Creep Rate

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

Transient Creep Strain Limit

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

Changed the Friction Coefficient



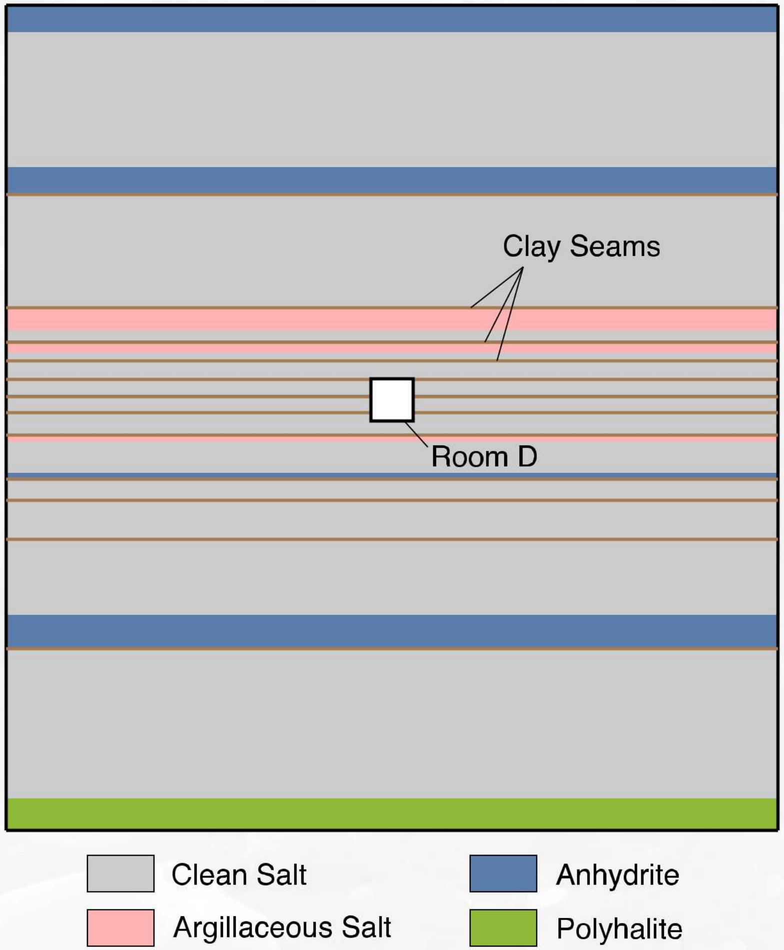
Coulomb Friction

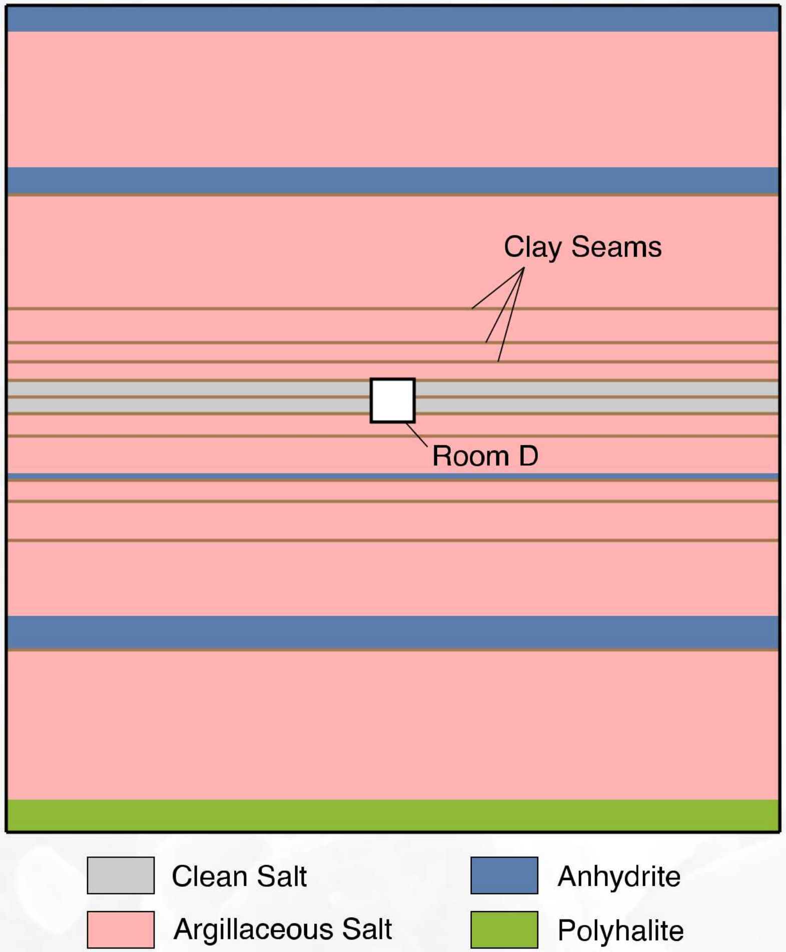
$t_t = \eta \, t_n$

Friction coefficient treated as a free parameter

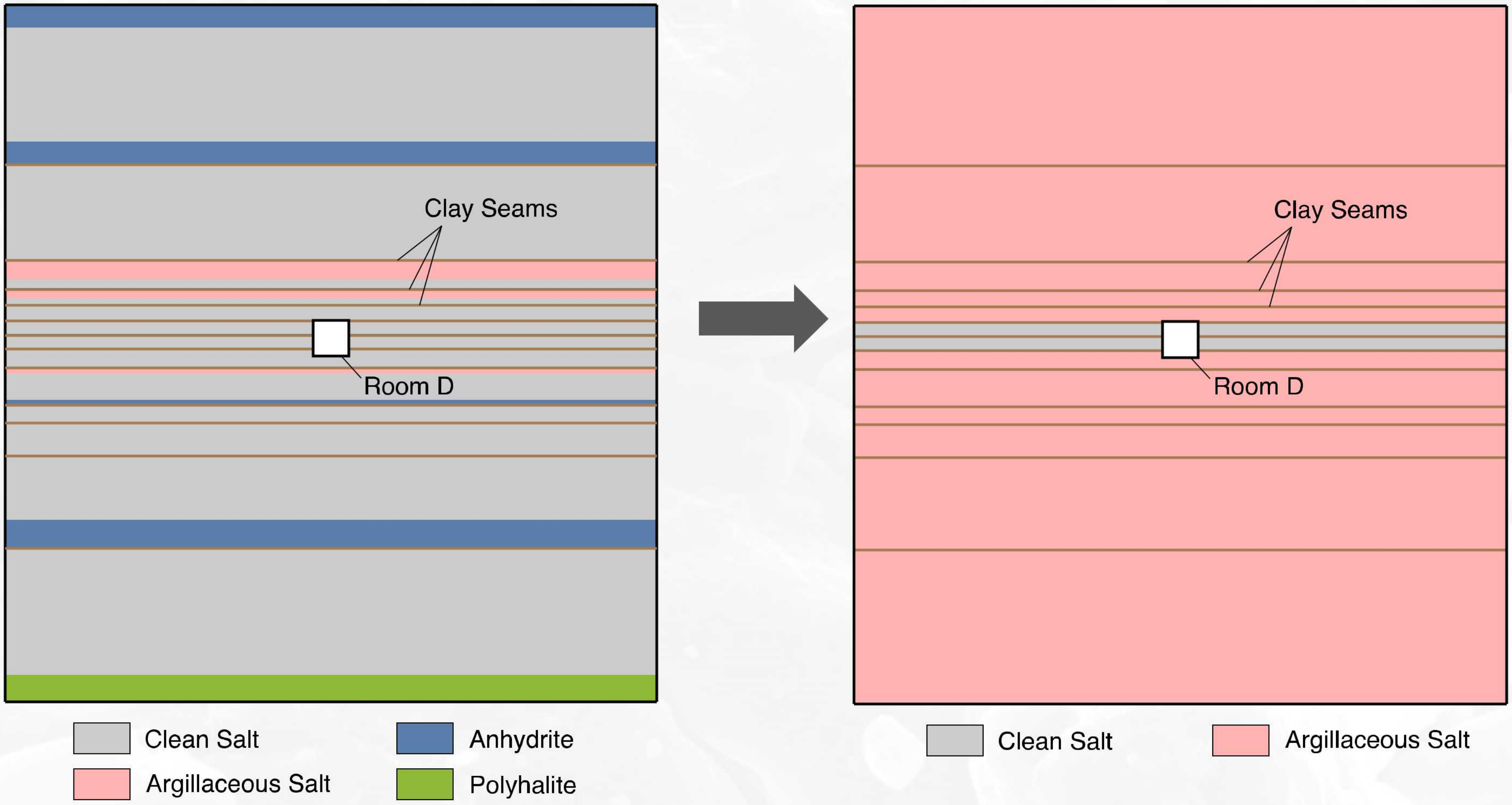
$\eta = 0.4 \rightarrow 0.2$

Changed the Stratigraphy

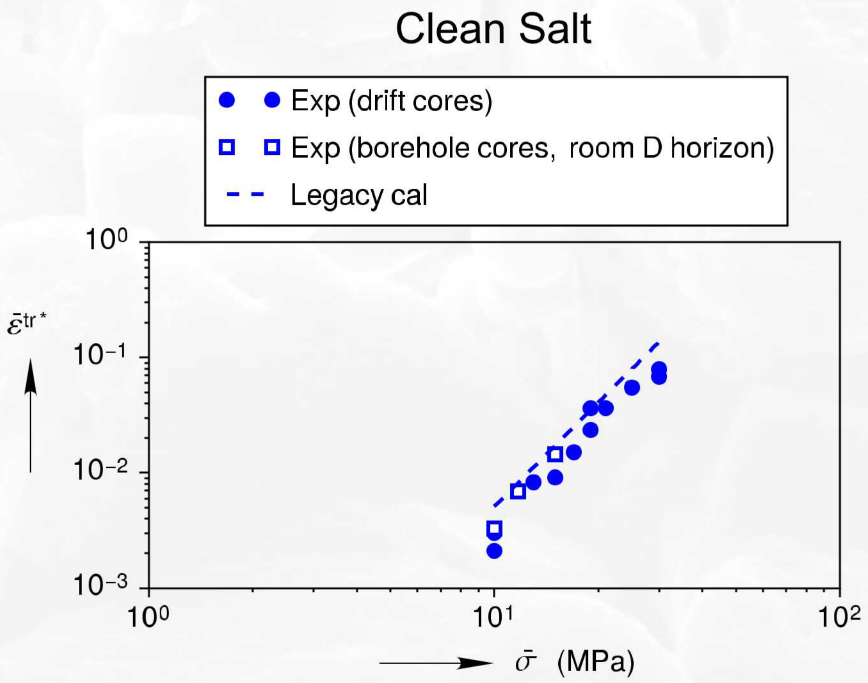


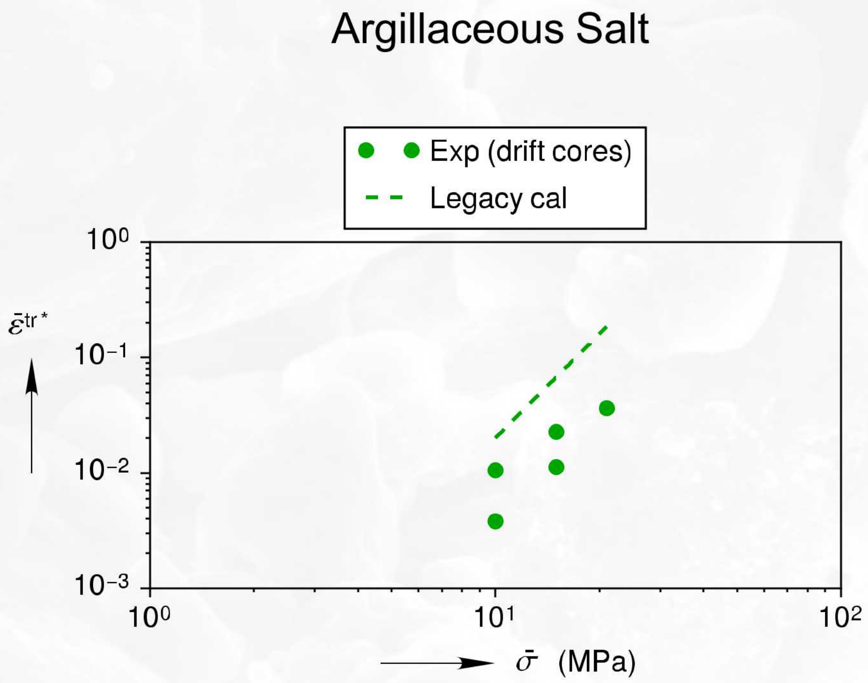


Changed the Stratigraphy



Changed the Material Parameters

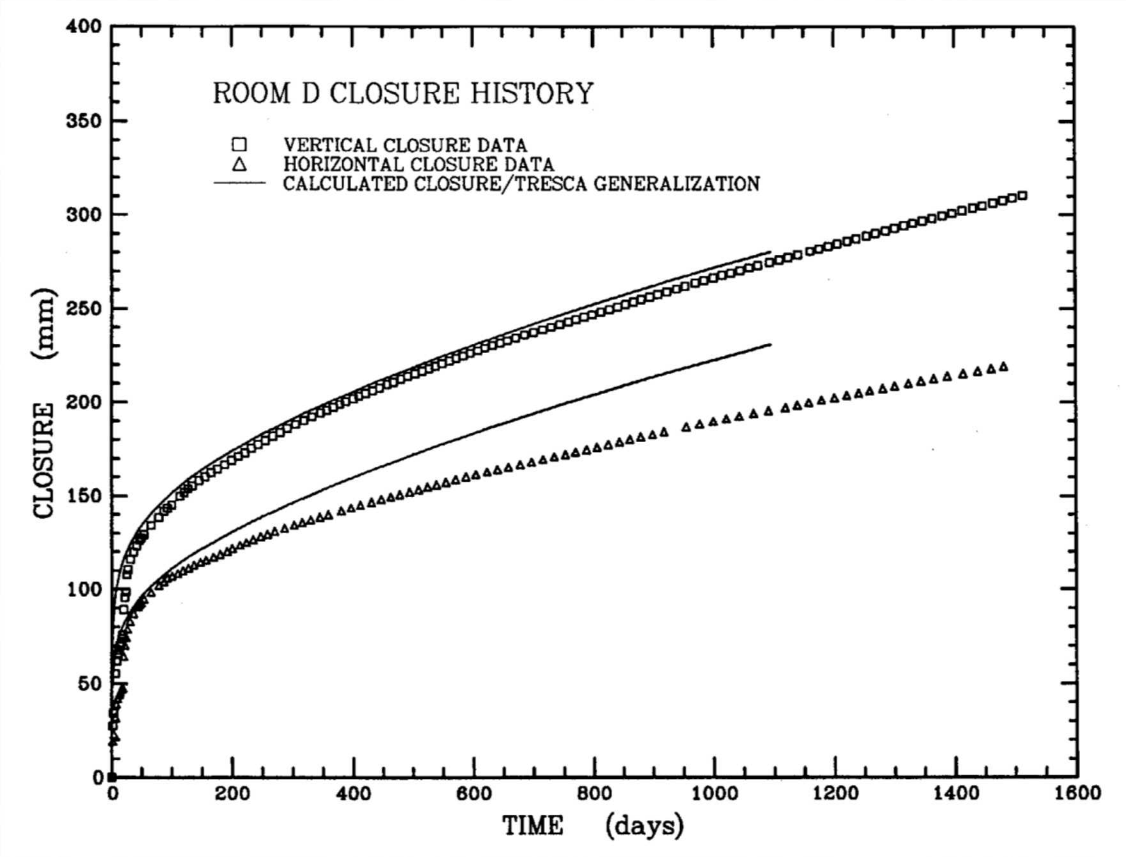




Argillaceous transient strain limit treated as a “free parameter”.

Legacy Predictions

- Changed from von Mises to Tresca equivalent stress
- 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



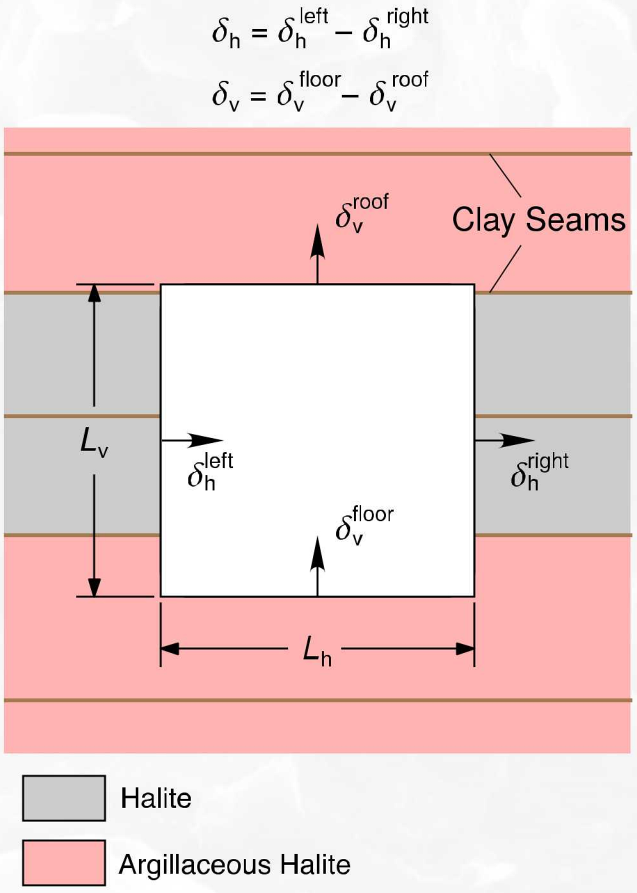
Munson, D., Fossum, A. Senseny, P., Advances in Resolution of Discrepancies Between Predicted and Measured In Situ WIPP Room Closures, SAND88-2948, 1988

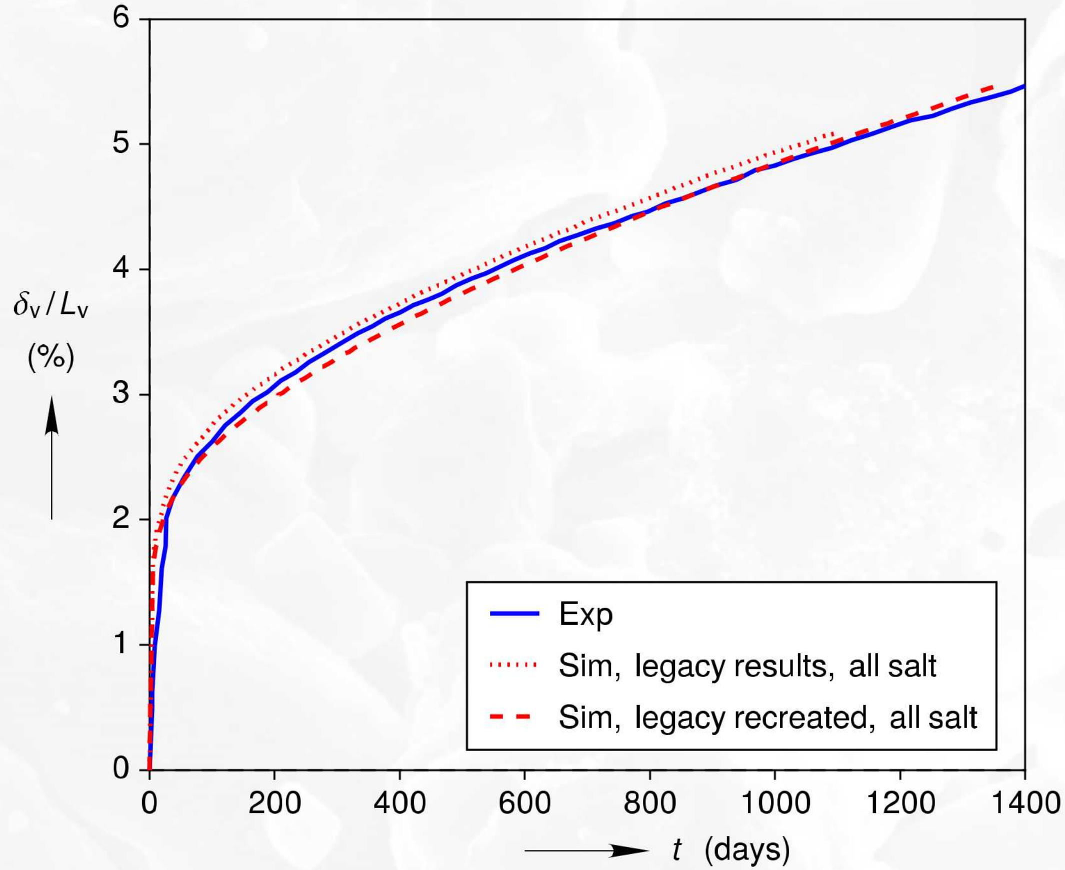
Legacy Predictions

- Tuning of model parameters is common industry practice
  - Tune against one *in-situ* measurement
  - Compare against other *in-situ* measurements
- Our goal is to predict **solely** from laboratory test data
  - Requires a stronger scientific basis
  - Allows one to predict what will happen in a new repository

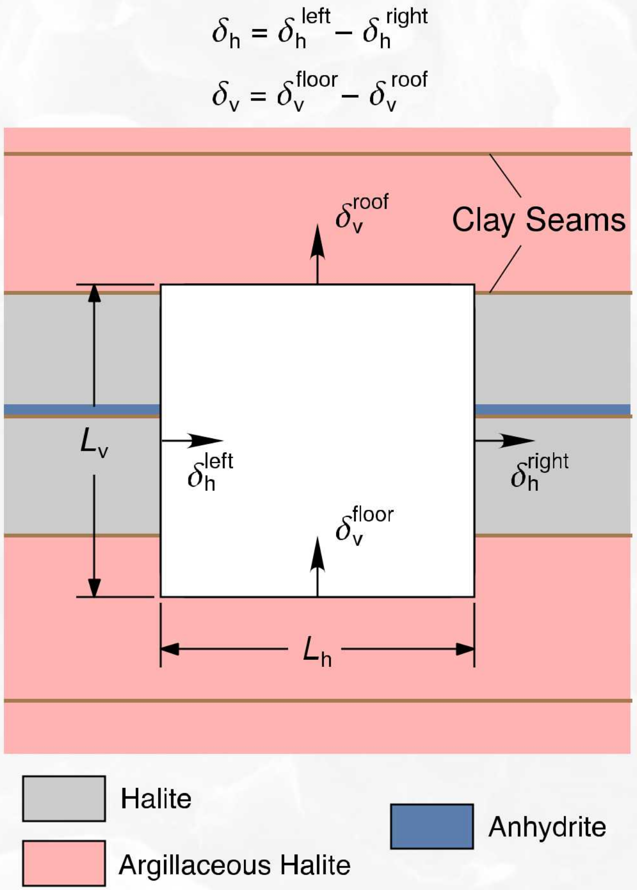
Updating the Legacy Simulations

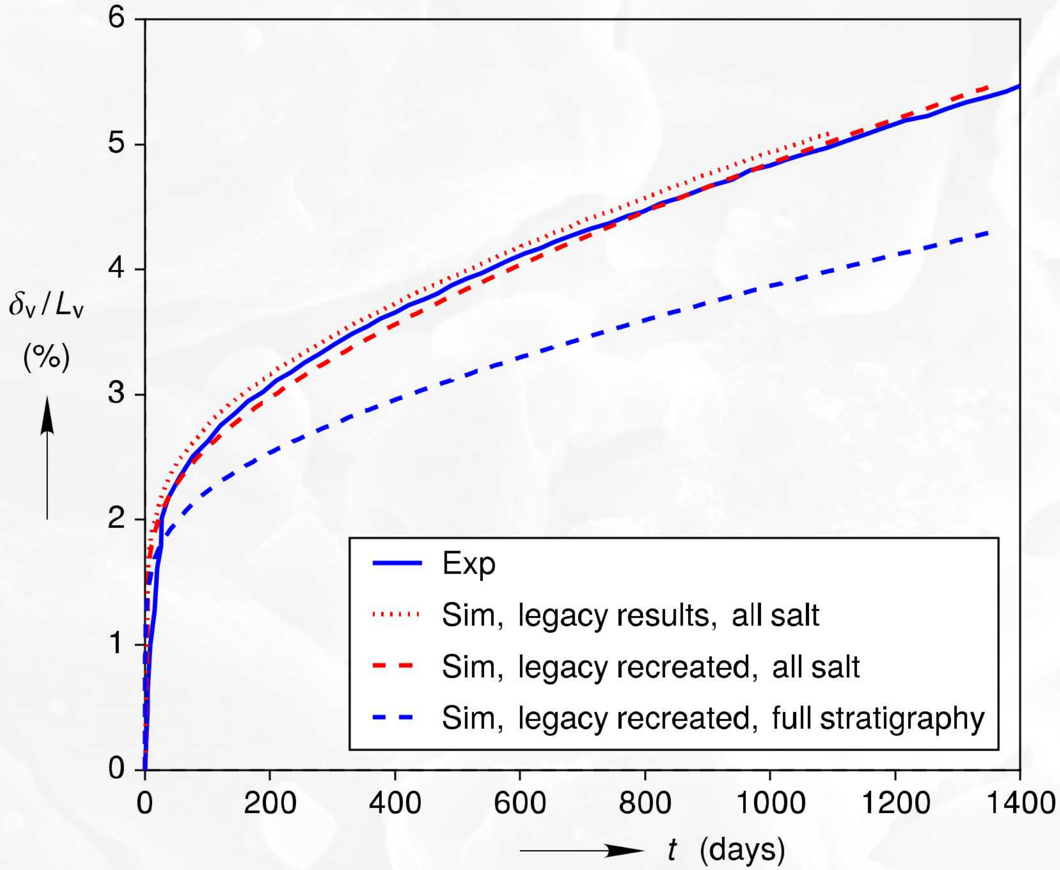
Recreation of Legacy Simulations





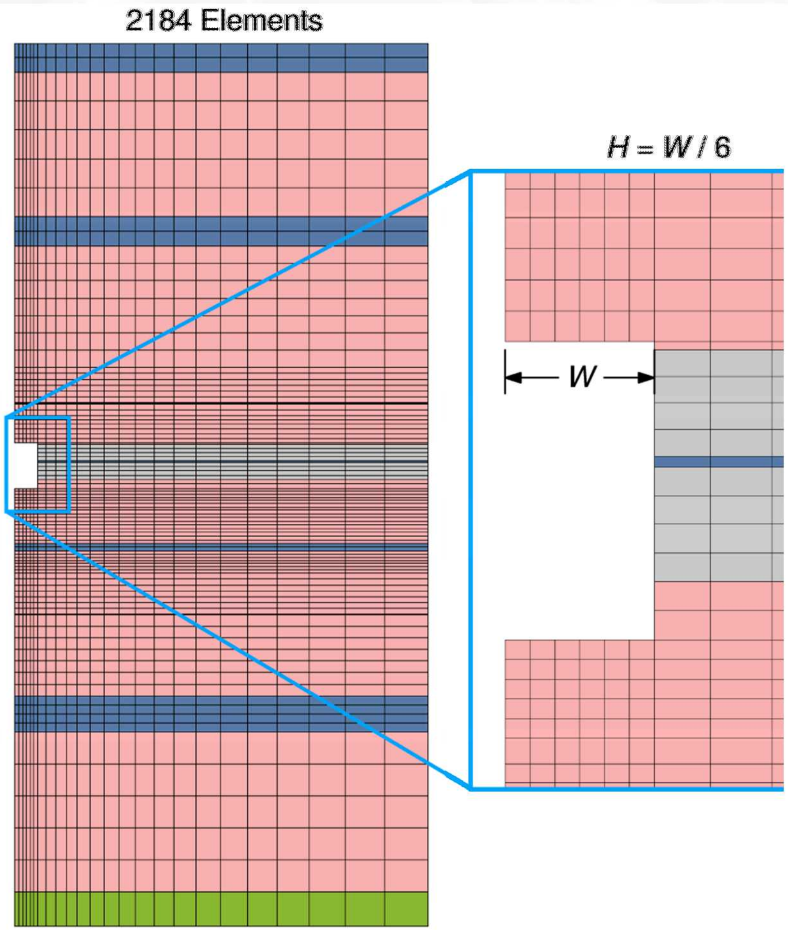
Recreation of Legacy Simulations



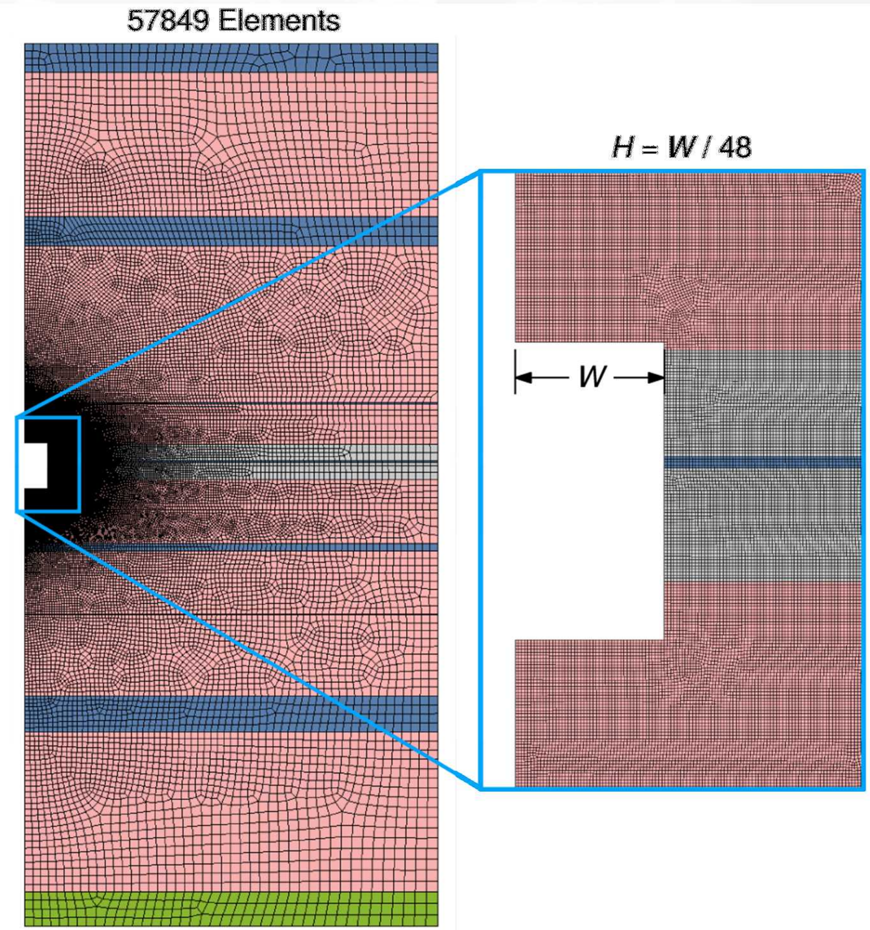


Changed the Mesh

Legacy Mesh

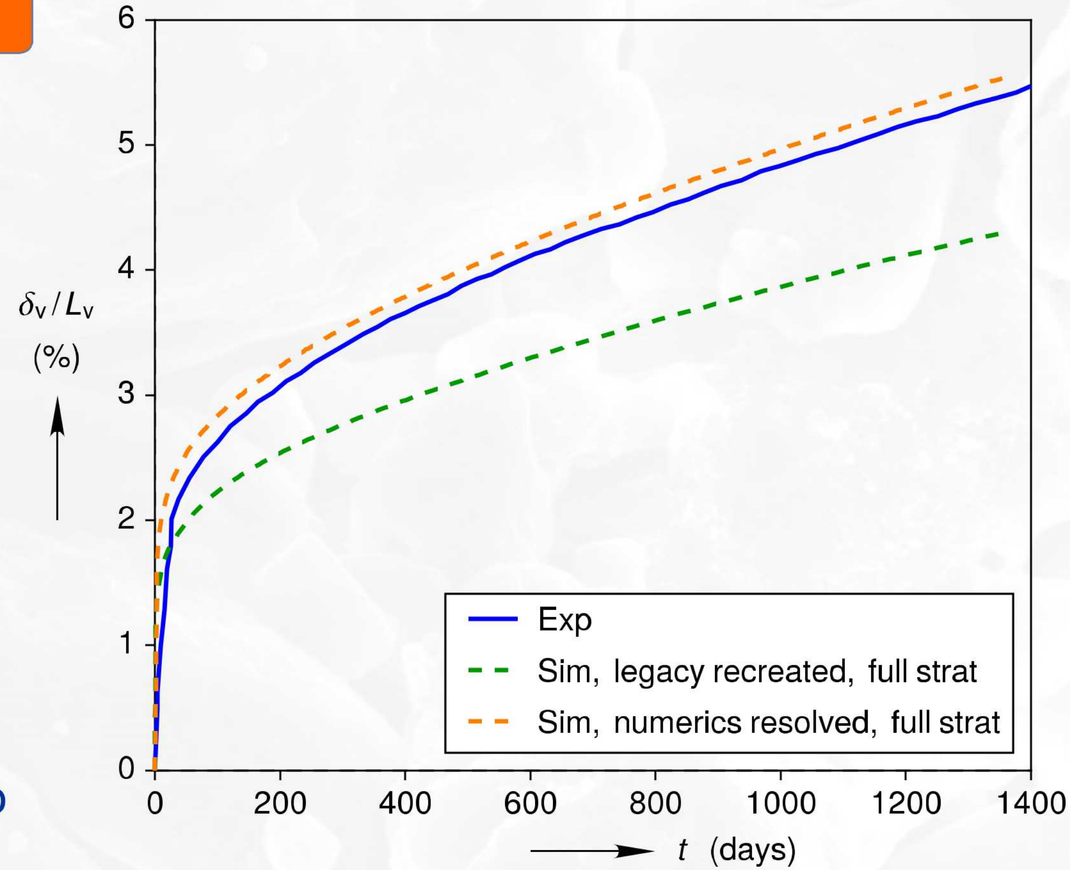


Current Fine Mesh



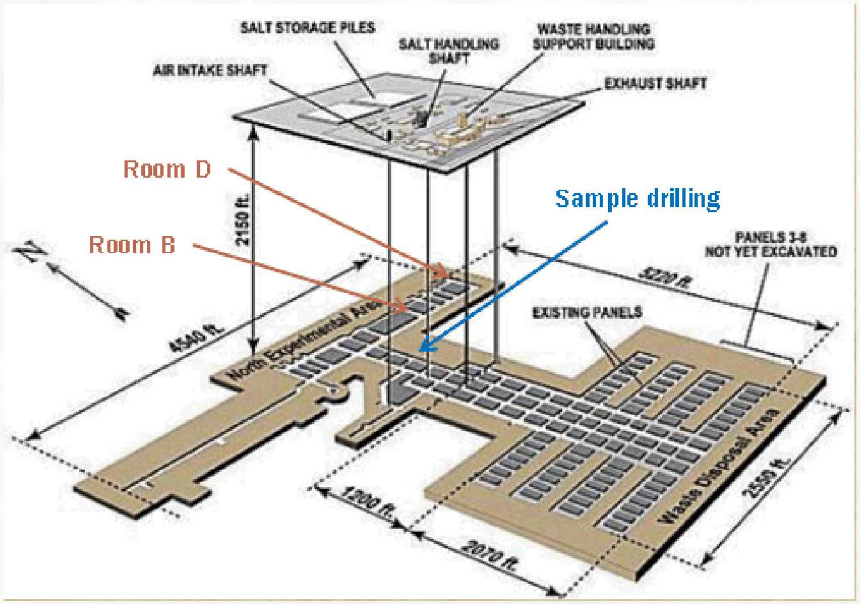
Resolving the Numerics

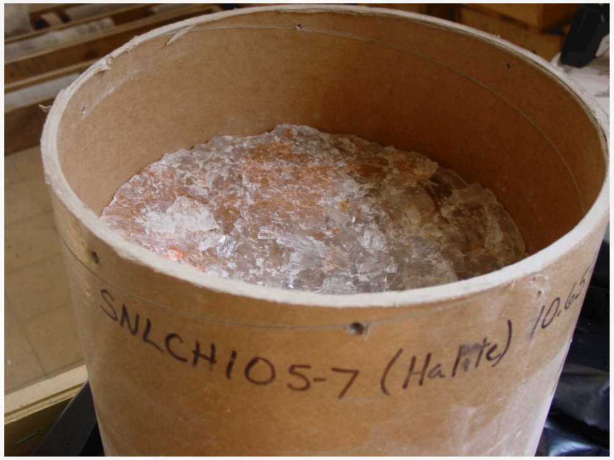
- Switched to a higher quality element type
- Changed the contact enforcement algorithm
- Switched from non-associated flow rule to an associated flow rule for the anhydrite
- Added a pressure ramp down to ease into the instantaneous excavation



Munson-Dawson Model Recalibration

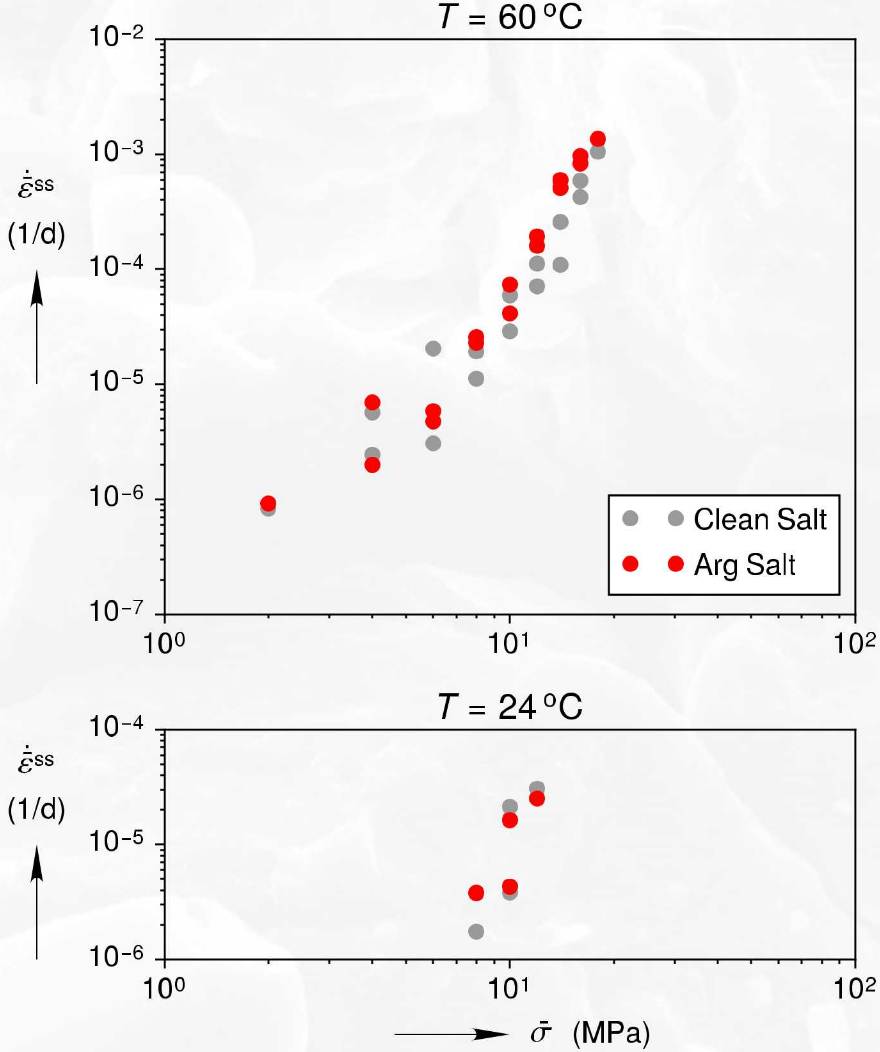
New Cores Extracted in 2013



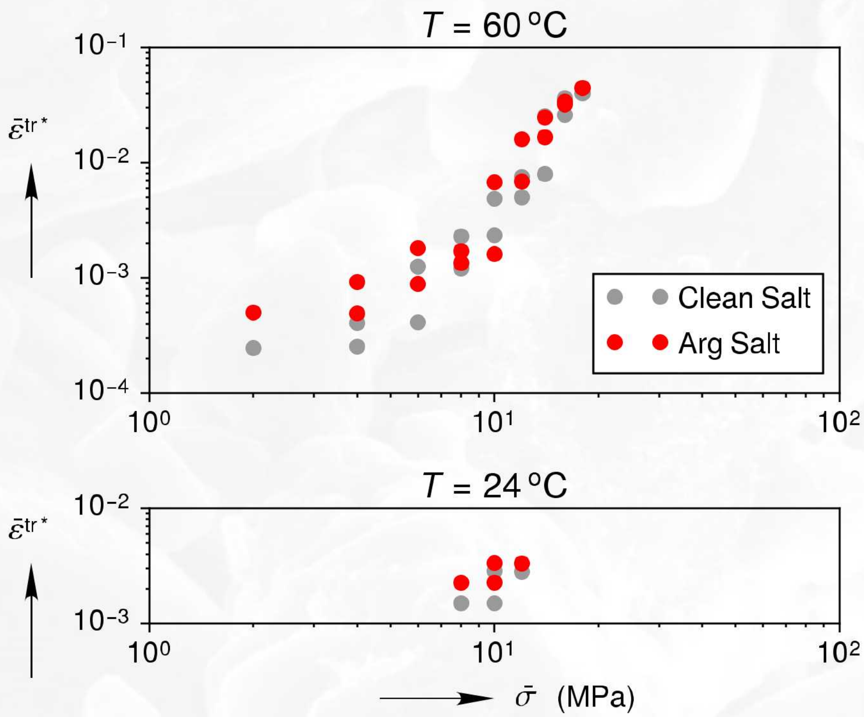


Clean vs. Argillaceous

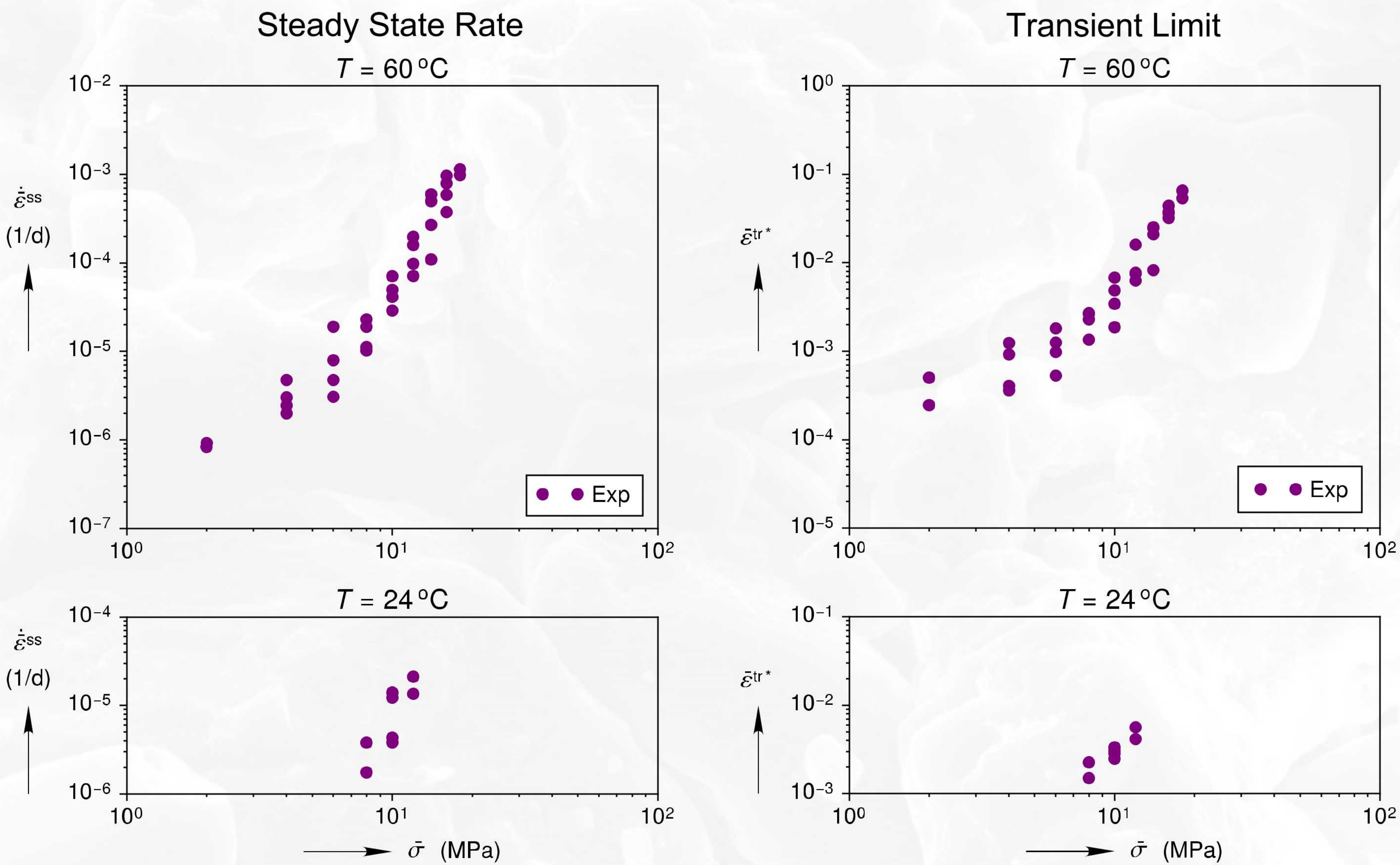
Steady State Rate



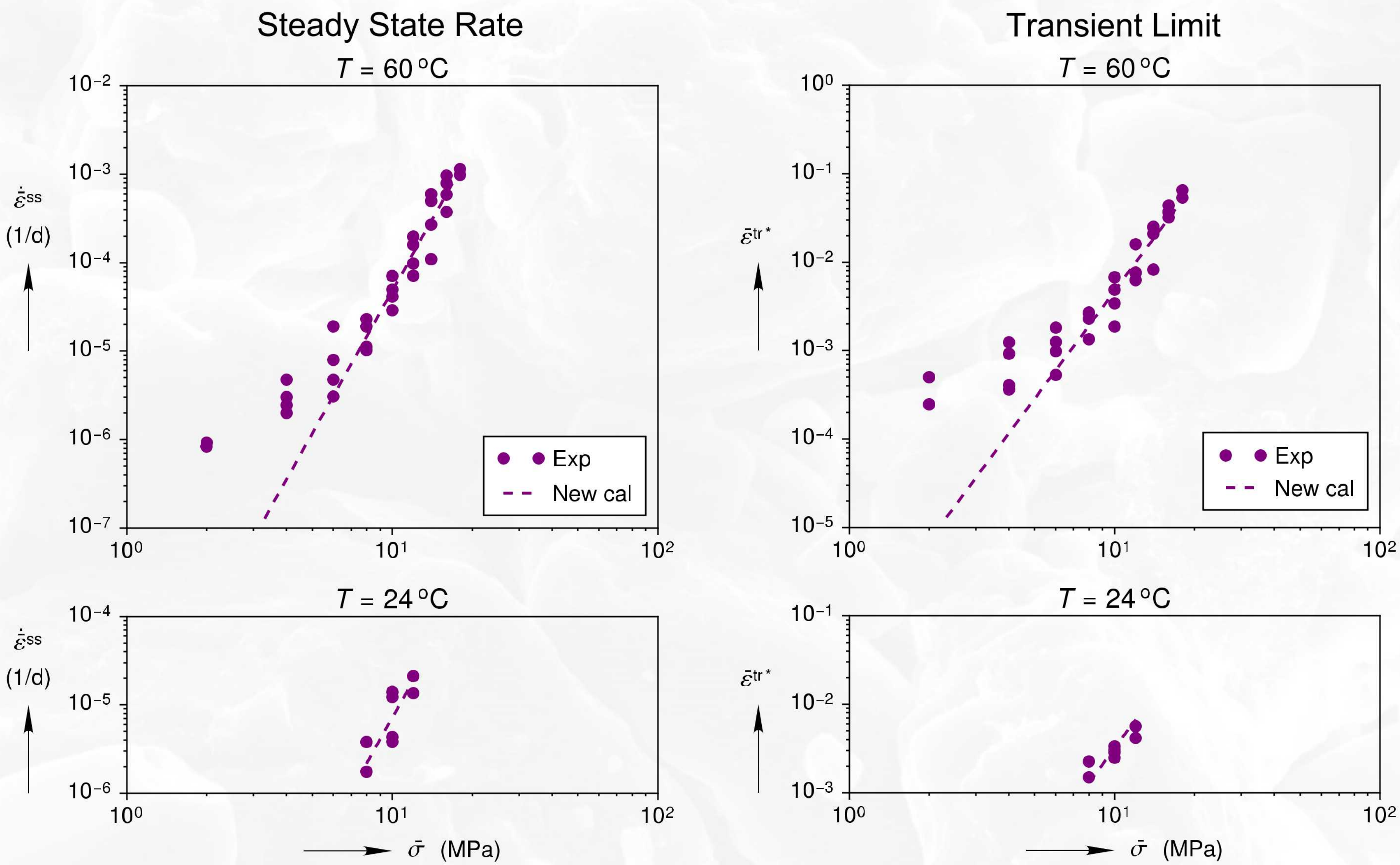
Transient Limit



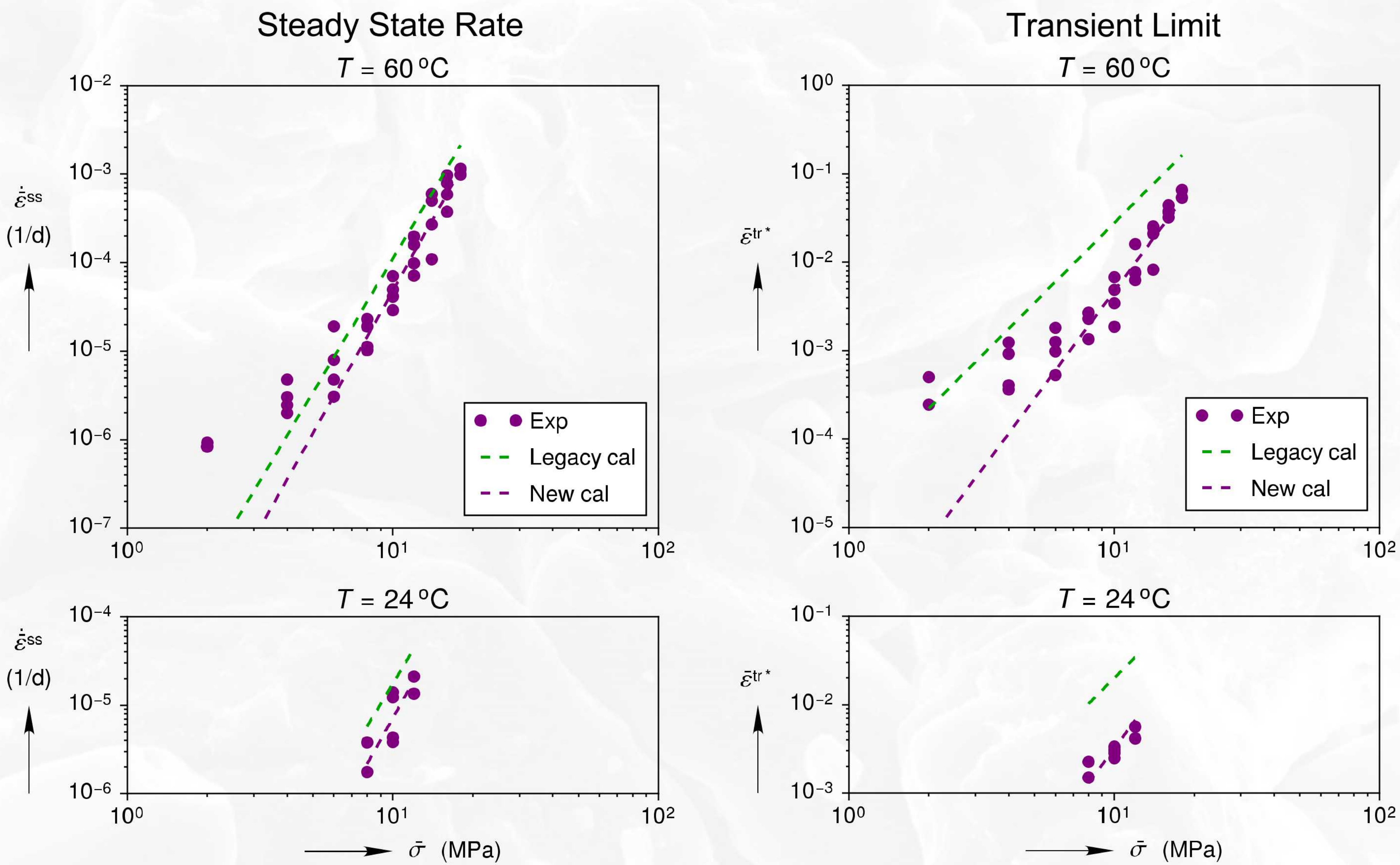
New Munson-Dawson Calibration



New Munson-Dawson Calibration



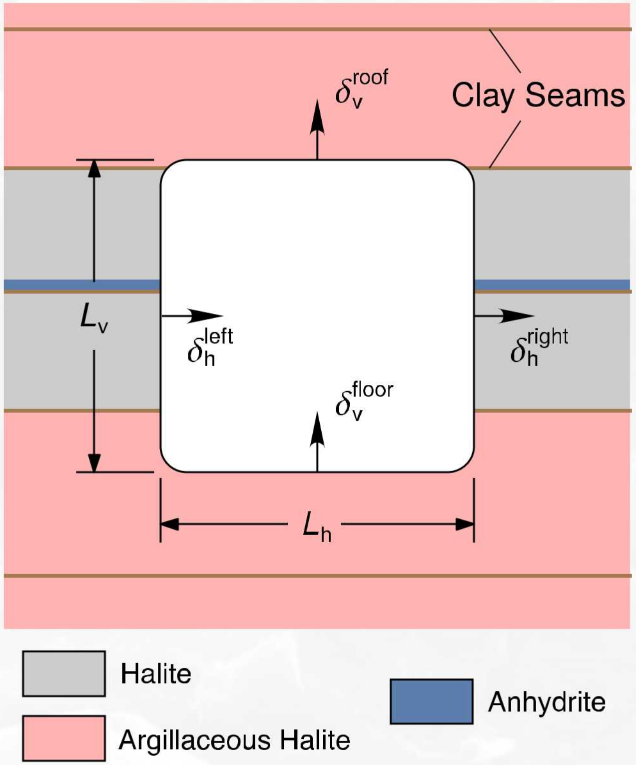
New Munson-Dawson Calibration

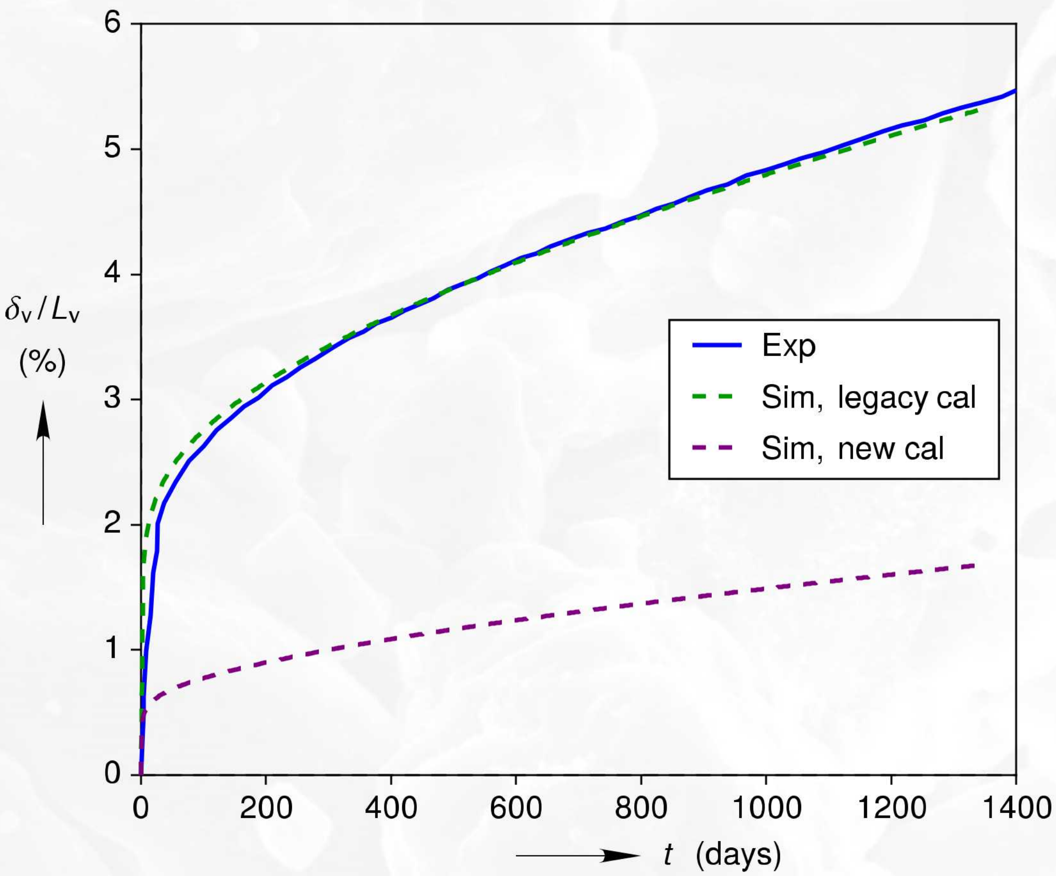


Closure Prediction with New Calibration

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

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





List of Open Questions

- Creep at low equivalent stresses
- Extent of simulation boundary
- Lost transient strains
- Creep of argillaceous vs. clean salt
- Sliding at clay seams
- Anhydrite material model
- Salt moisture content
- Reconstruction of closure measurements

Summary

Summary

- In 1987, the simulations under-predicted the room closure by roughly 4X. In 1989, Darrell Munson adjusted the model to match the experiments.

- After including the anhydrite and resolving the numerics, the predictions match the experiments.

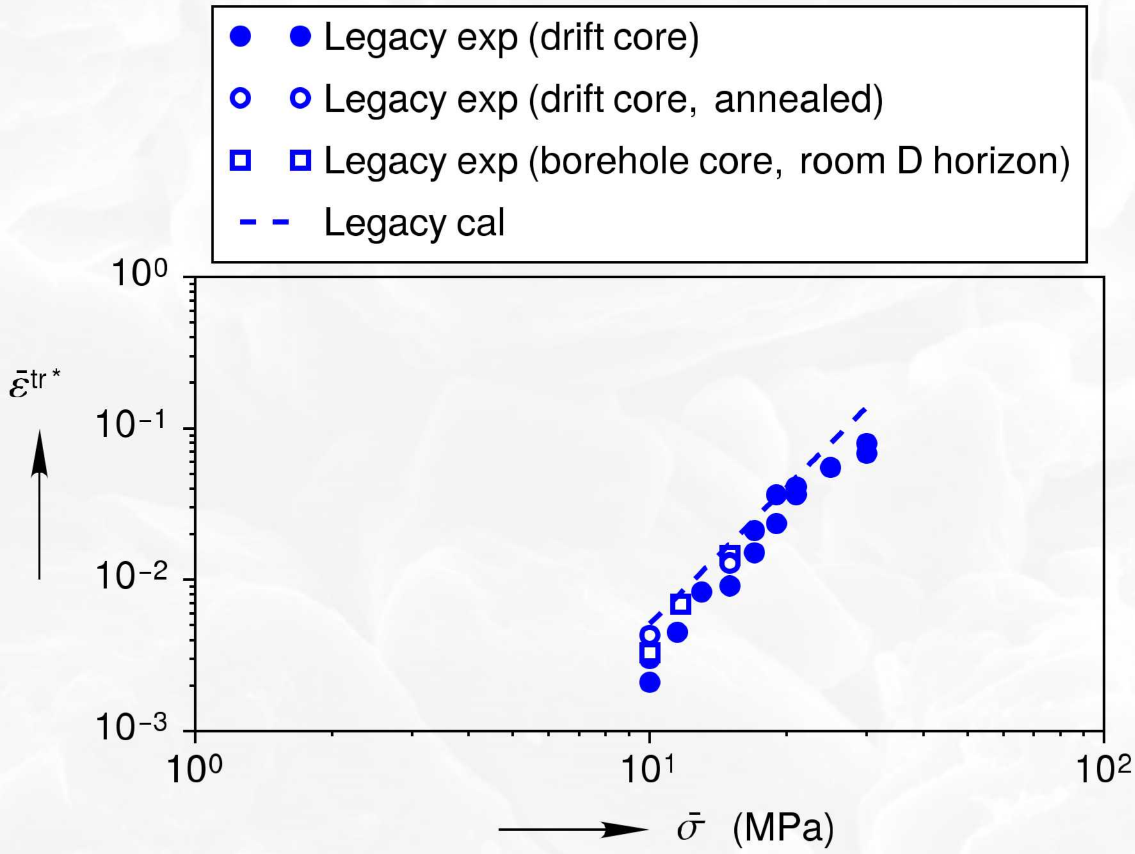
- New, laboratory based, salt calibration under-predicts the room closure by roughly 3X.

- Open questions remain
  - Creep at low equivalent stresses
  - Extent of simulation boundary
  - Lost transient strains
  - Creep of argillaceous vs. clean salt
  - Sliding at clay seams
  - Anhydrite material model
  - Salt moisture content
  - Reconstruction of closure measurements

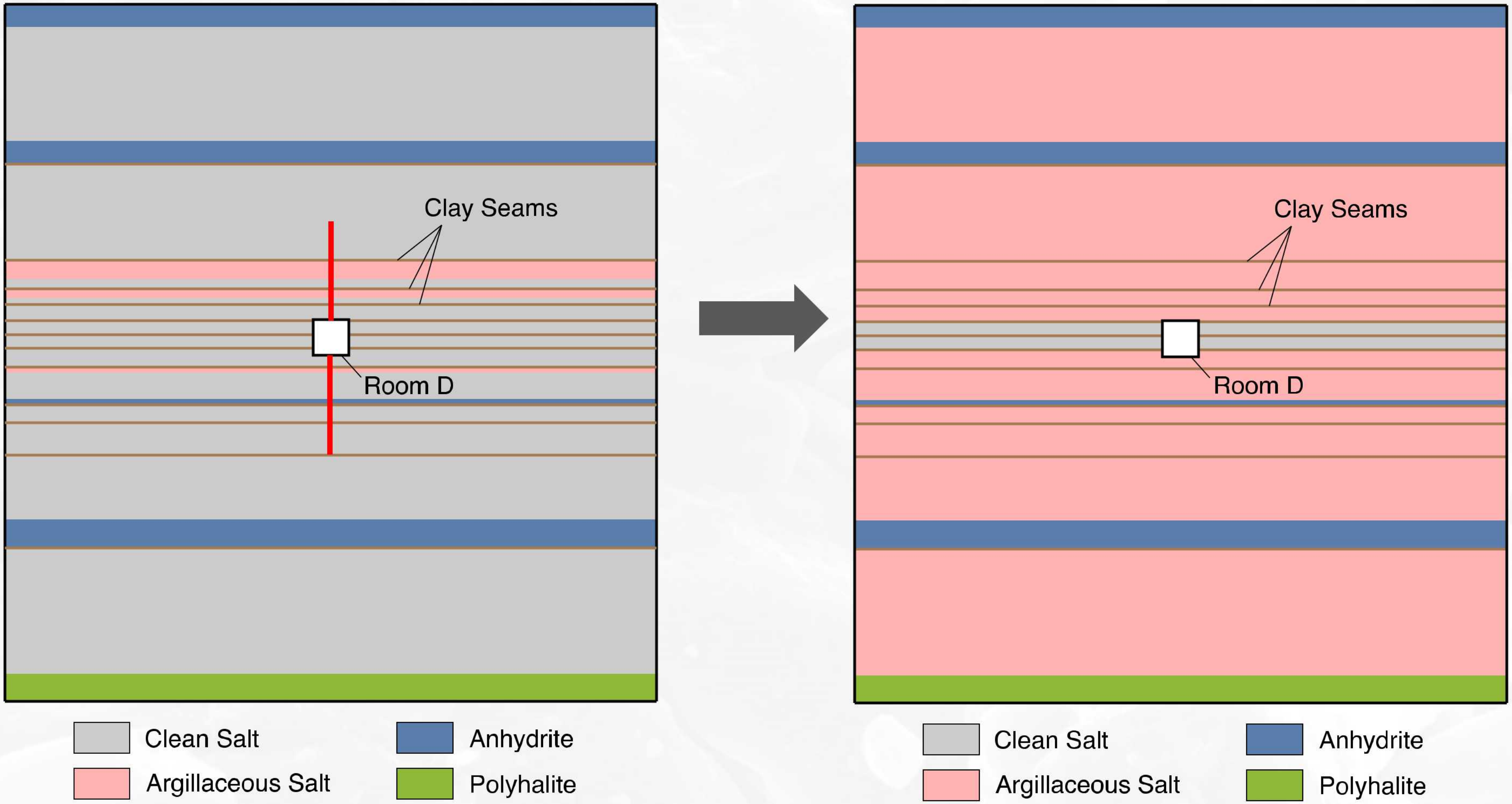
Thank you for your attention.

Extra Slides

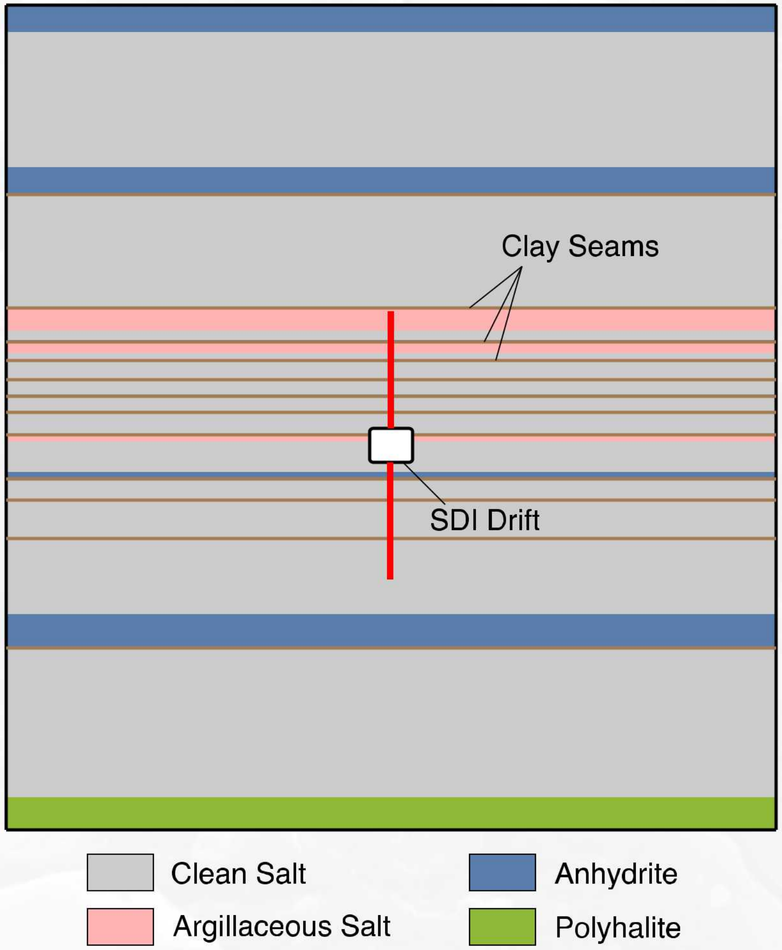
Lost Transient Strains



Changed the Stratigraphy



Stratigraphy Reassessment



Dennis Powers (Consulting Geologist):

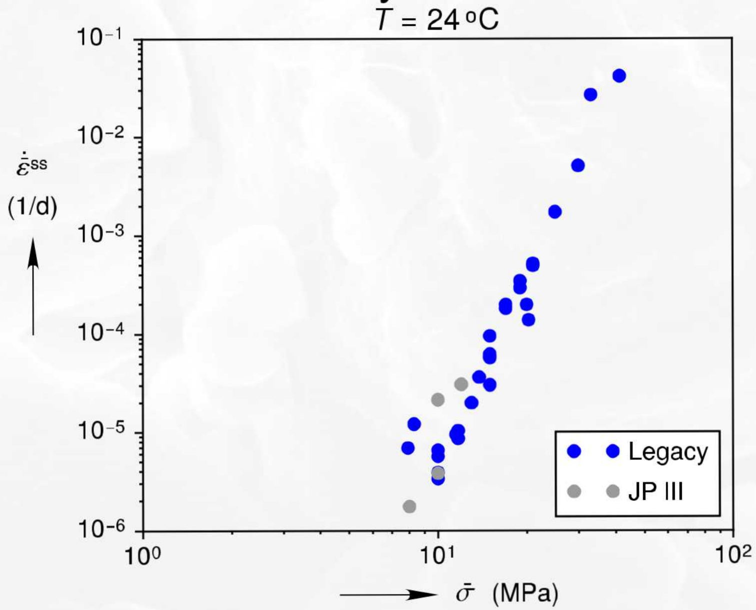
"This study does not sustain the assessment of Munson et al. (1989) that all of the halite within the reference stratigraphy, with the exception of halite above and below anhydrite a, could or should be treated as argillaceous halite."

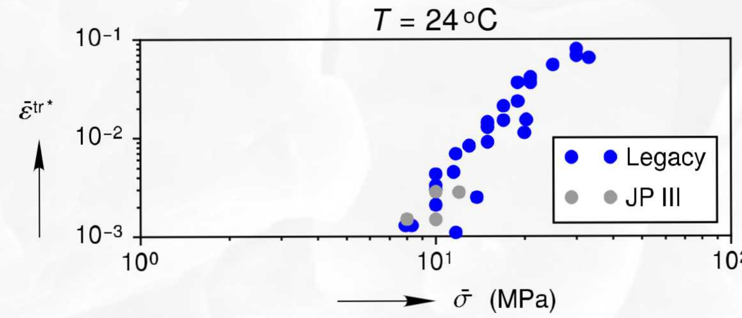
Argillaceous vs Clean Salt

Steady State Rate

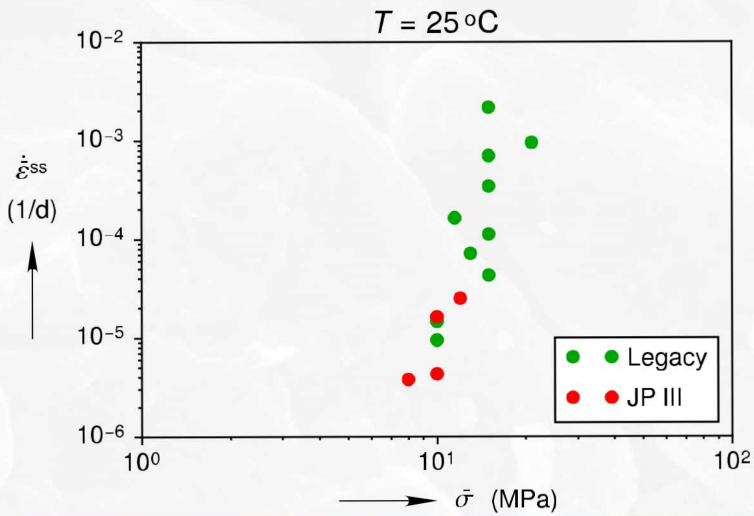
Transient Limit

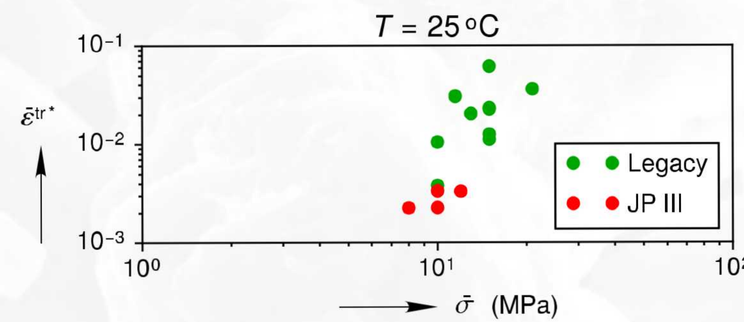
Clean Salt



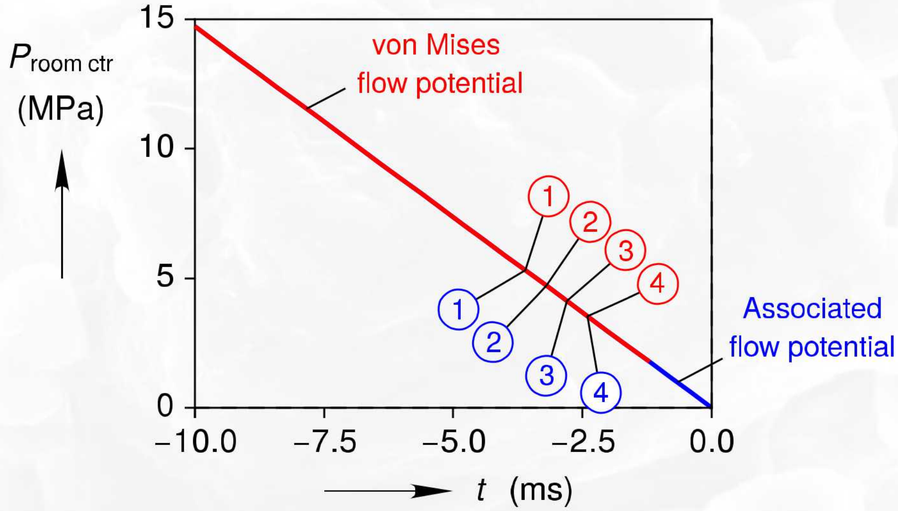


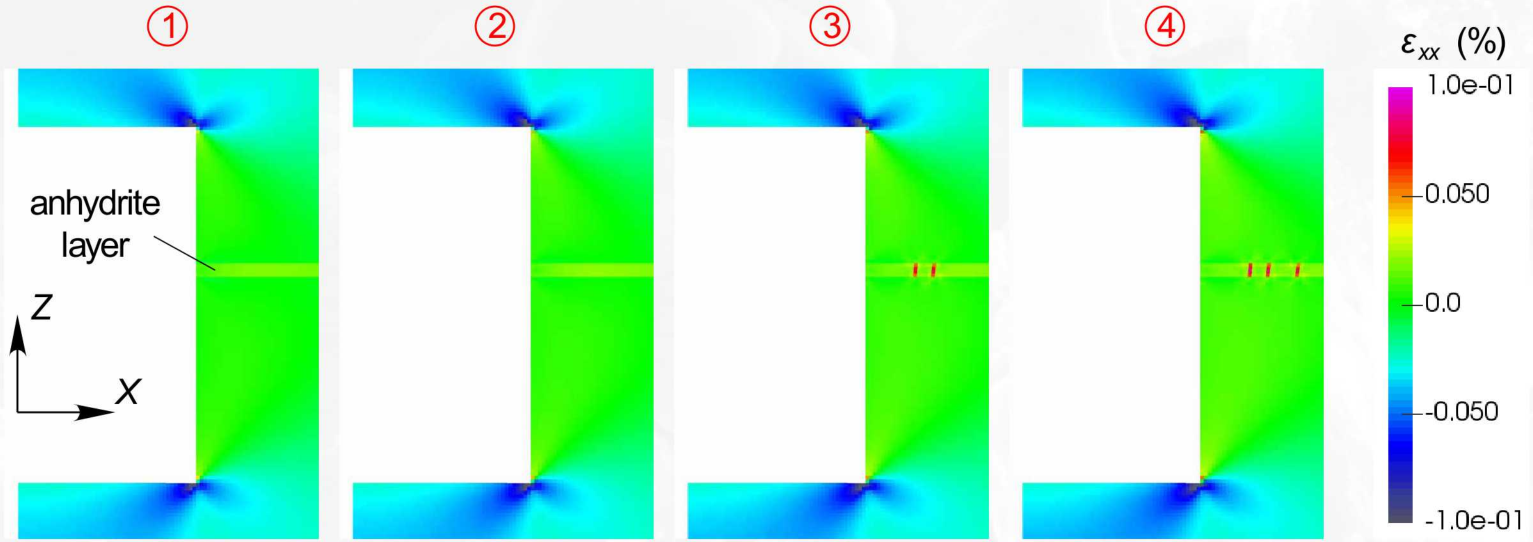
Argillaceous Salt



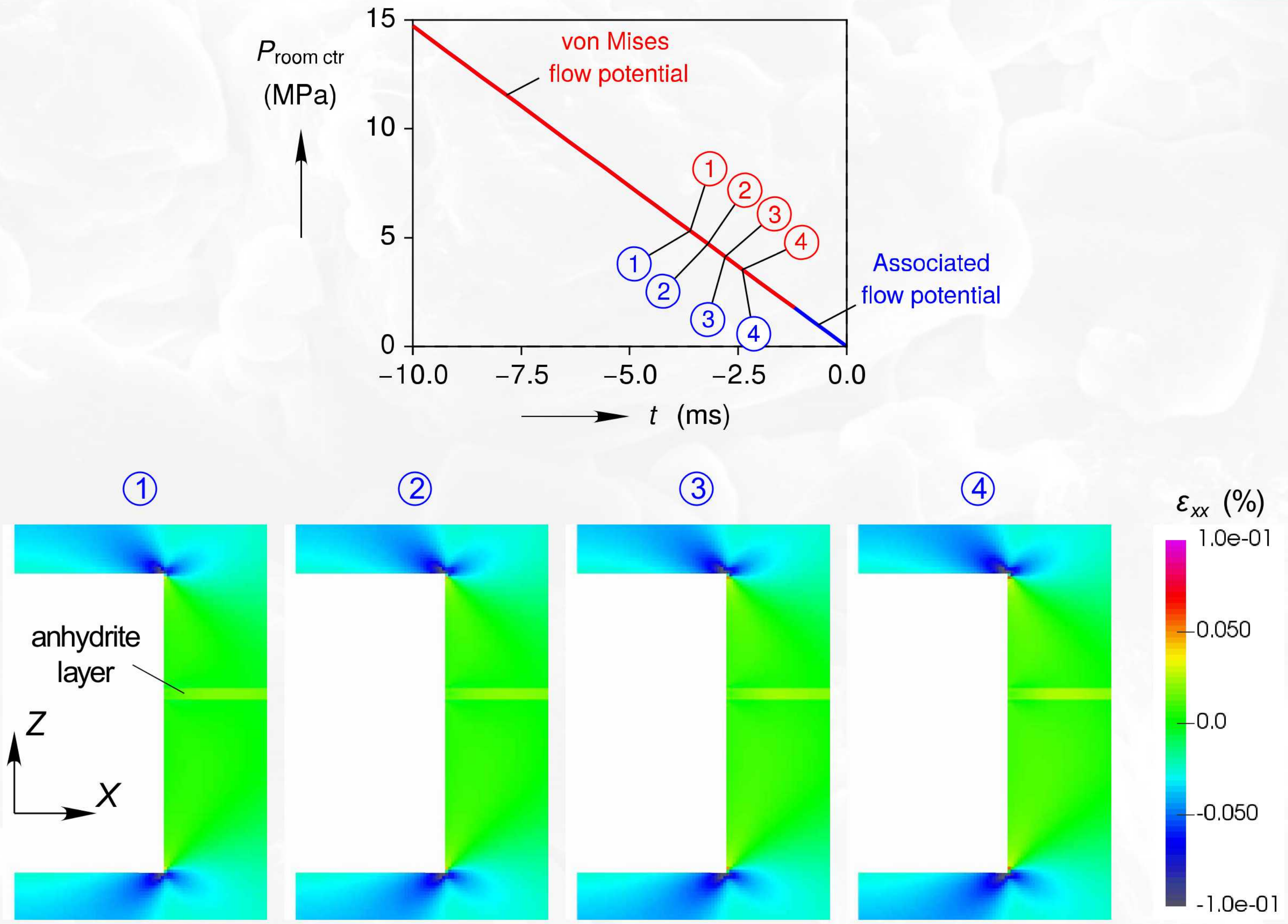


Anhydrite Issue

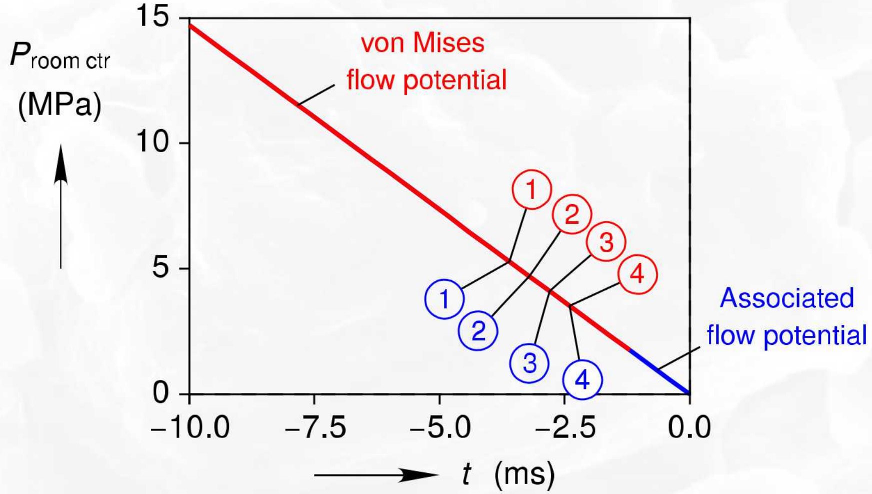


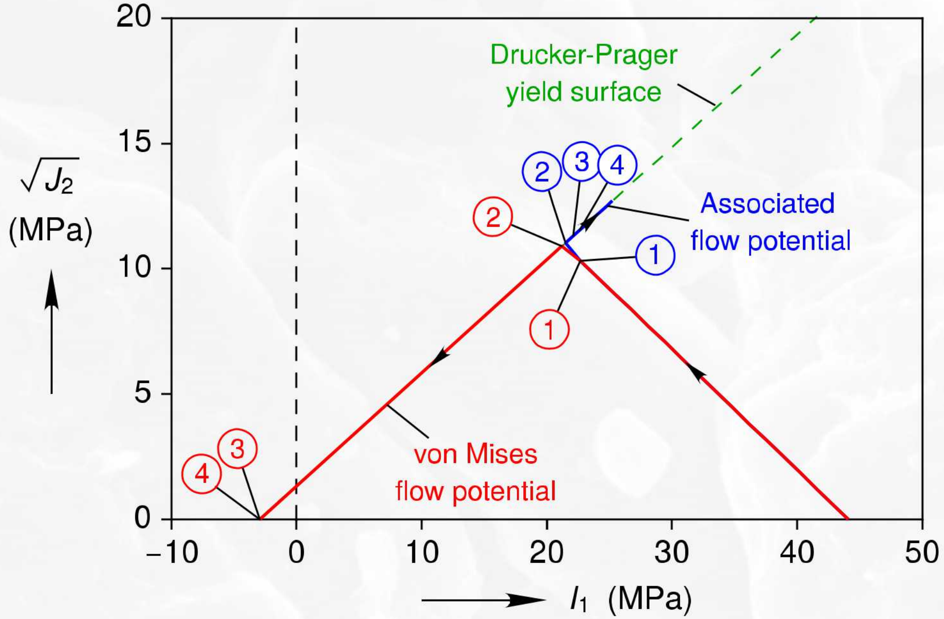


Anhydrite Issue

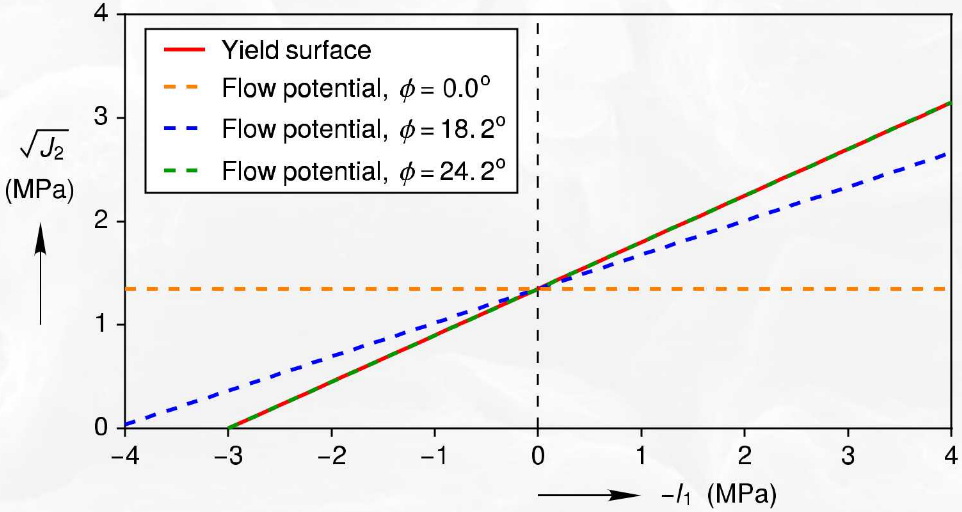


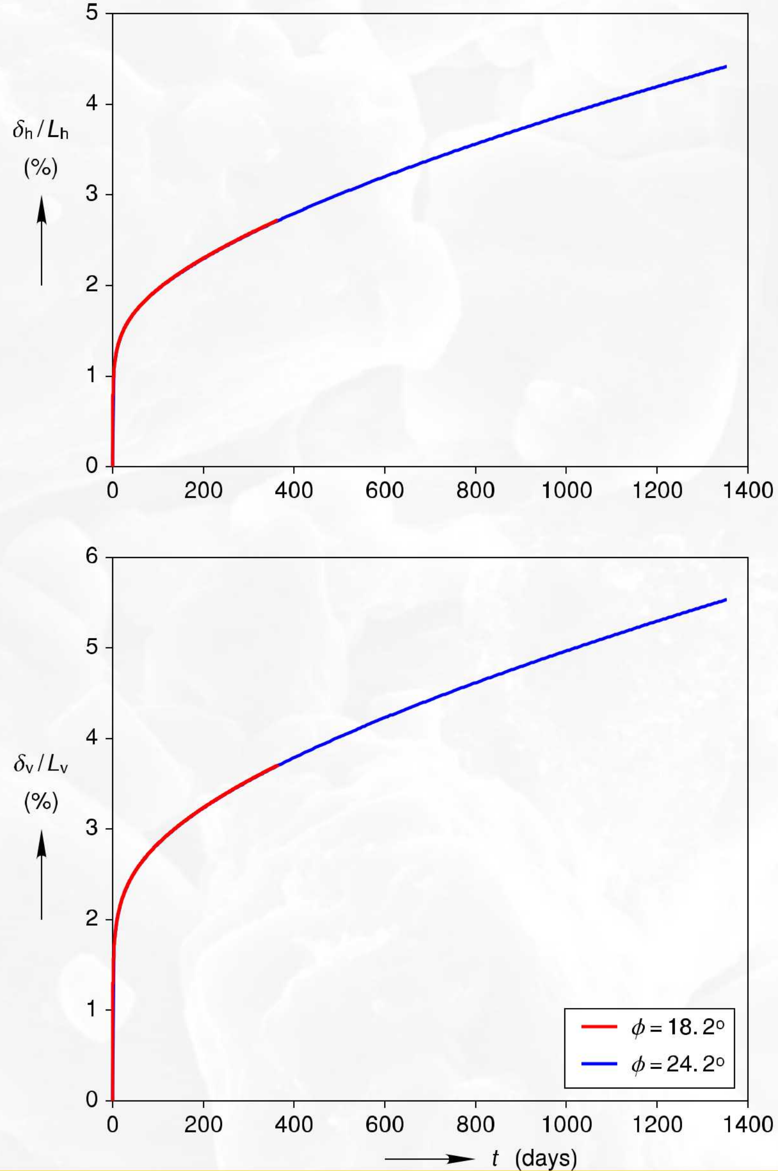
Anhydrite Issue



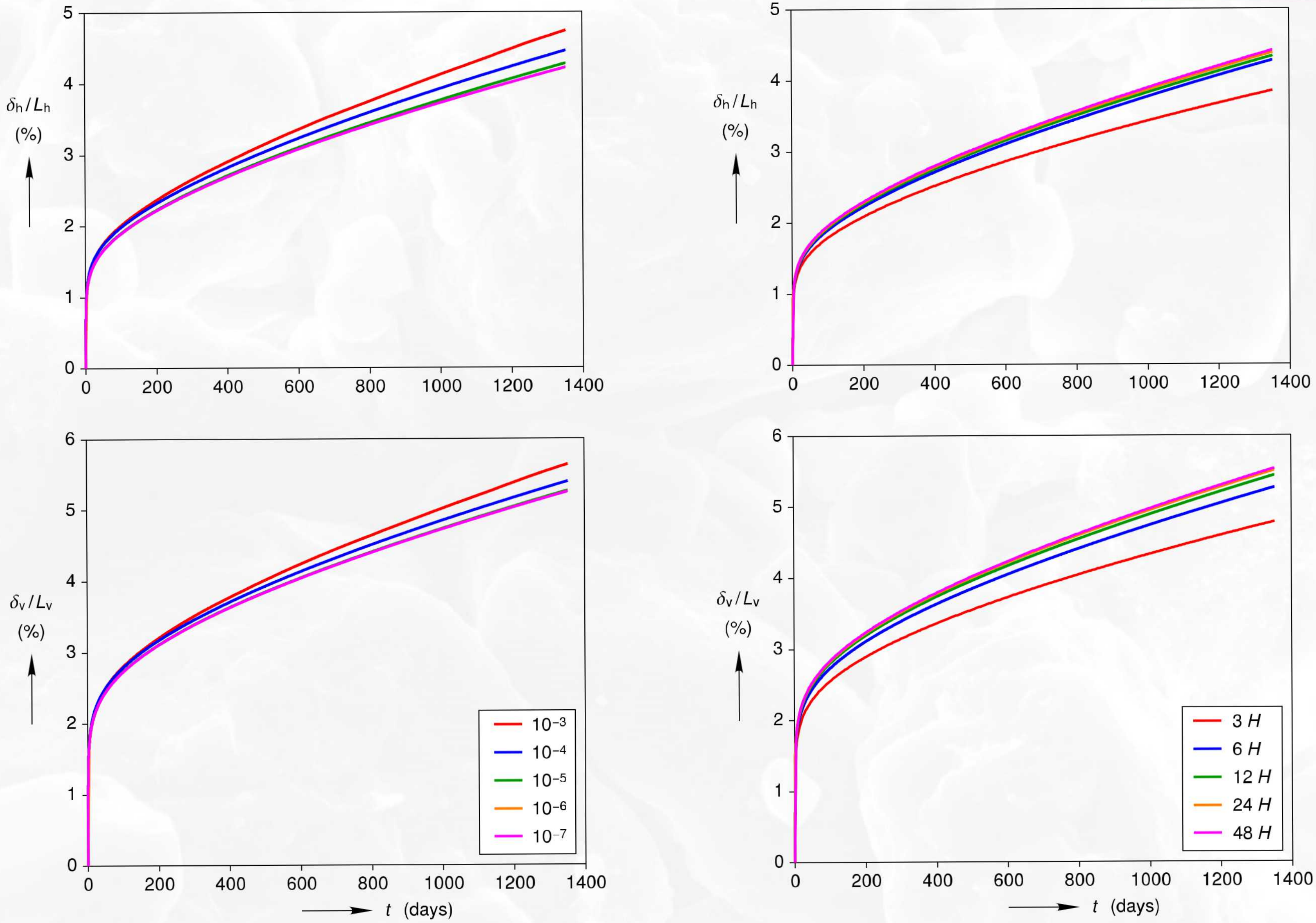


Anhydrite Dilatation Angle Sensitivity





Residual and Mesh Convergence



Creep at Low Equivalent Stresses