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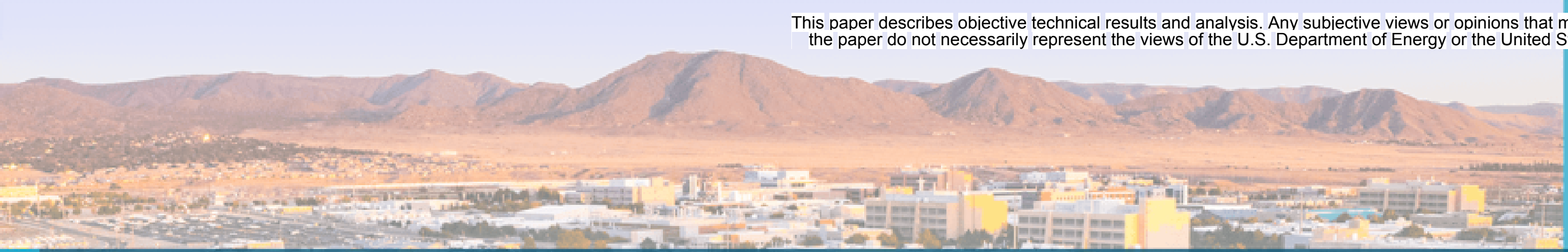

WEIMOS: Shear Behaviors of Bedded Salt Clay Seams and Their Impact on Disposal Room Porosity

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Joint Project WEIMOS:

Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt

Work Packages

WP 1: Deformation behavior at small deviatoric stresses

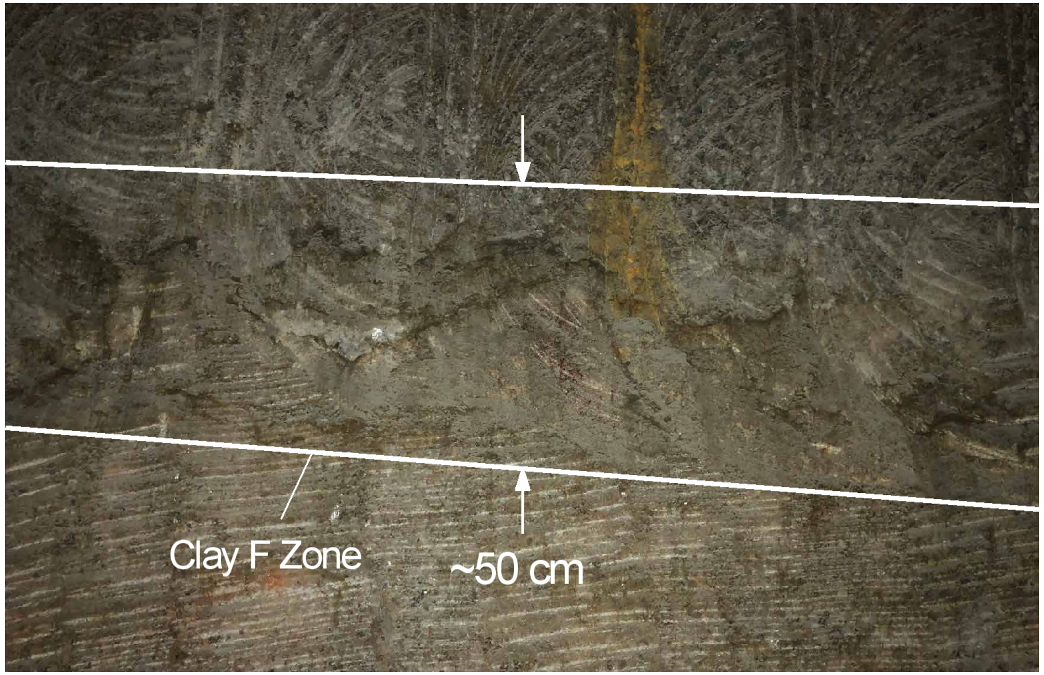
WP 2: Influence of temperature and stress state on damage reduction (“healing”)

WP 3: Deformation behavior resulting from tensile stresses

WP 4: Influence of inhomogeneities (layer boundaries, interfaces) on deformation

WP 5: Virtual demonstrator

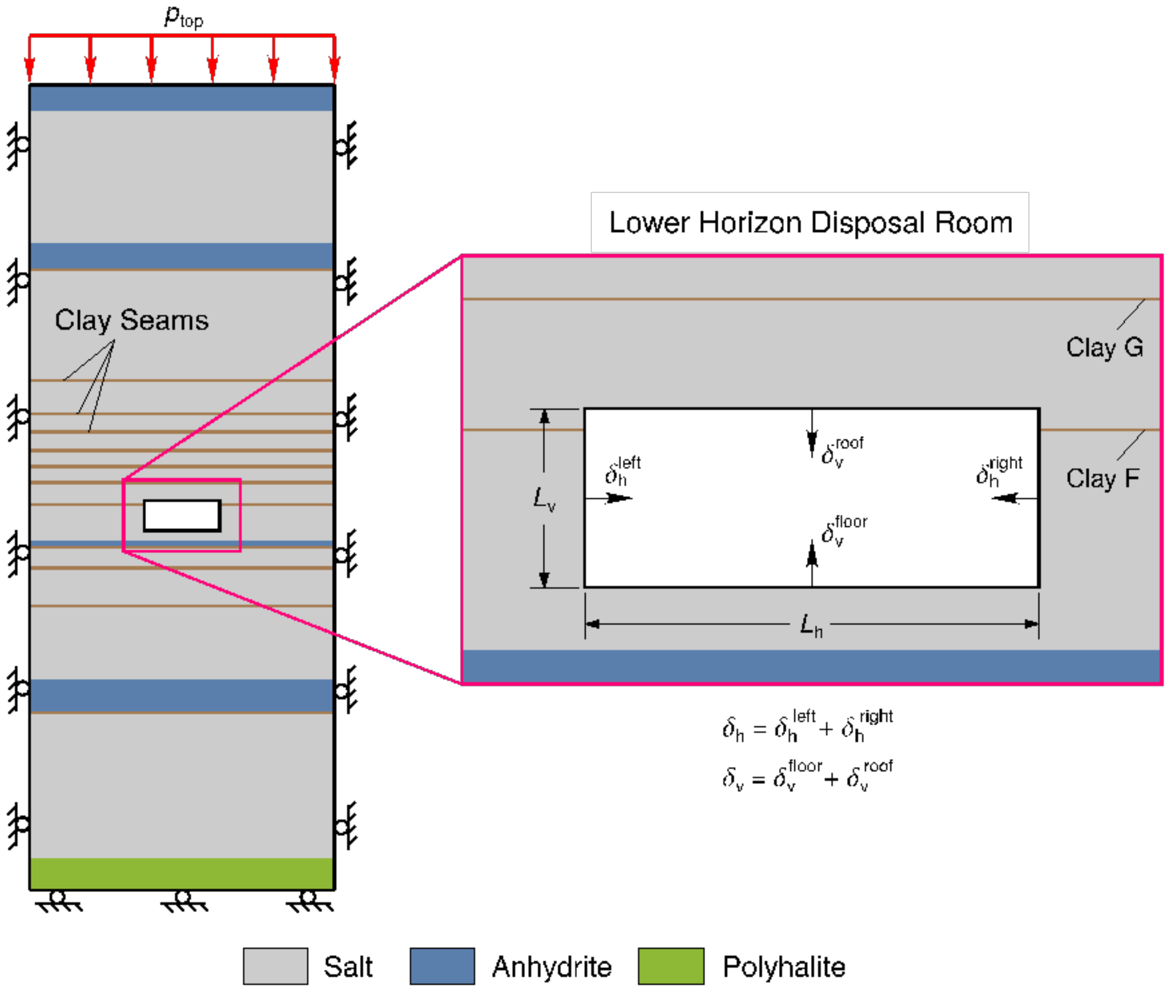
Pictures of Clay Seams at WIPP

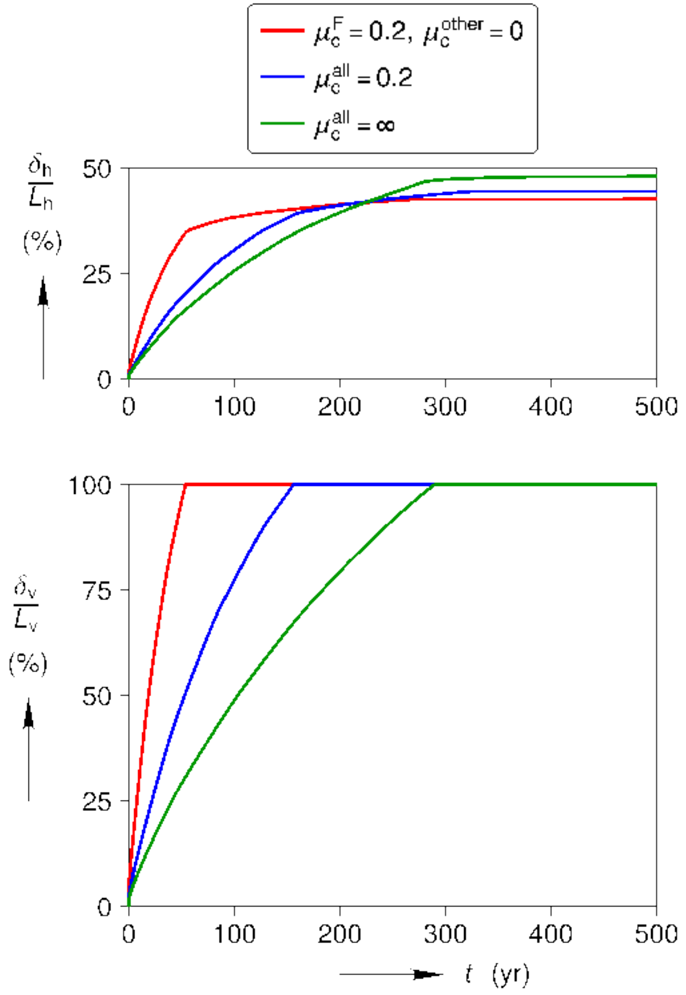


Clay seam G is thin (~8-25 mm), somewhat linear, contains clay and little else

Clay seam F is thick (up to 50 cm), wavy, contains clay + other materials, possibly has intersecting salt crystals

Influence of inhomogeneities (layer boundaries, interfaces)



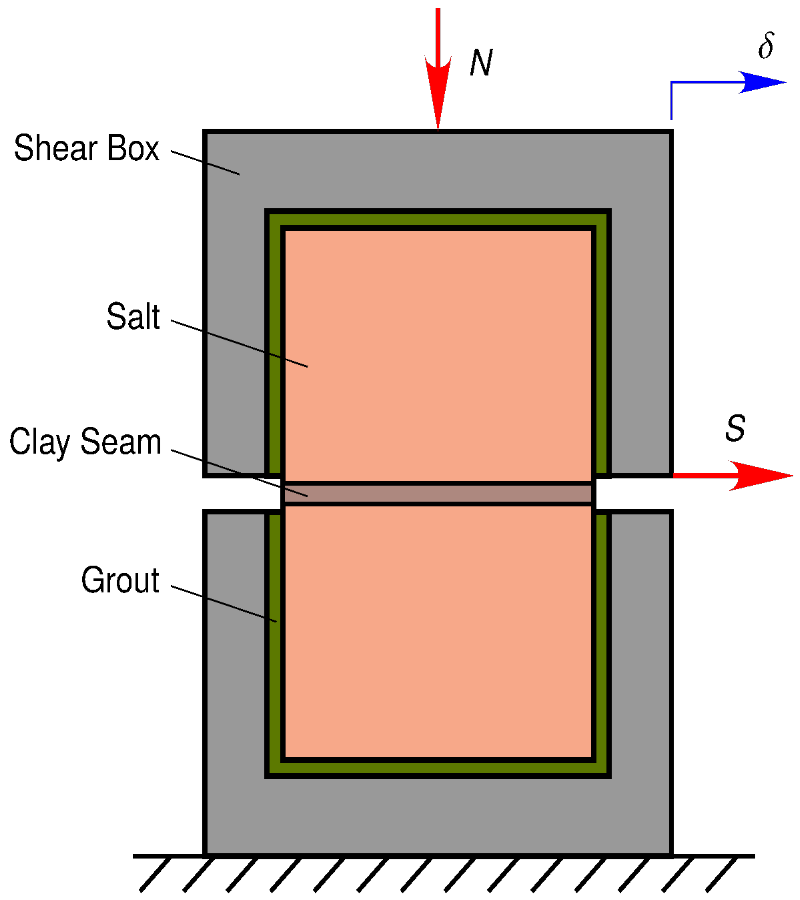


Predictions of empty room closure, without salt fracturing, are highly dependent on clay seam sliding behavior.

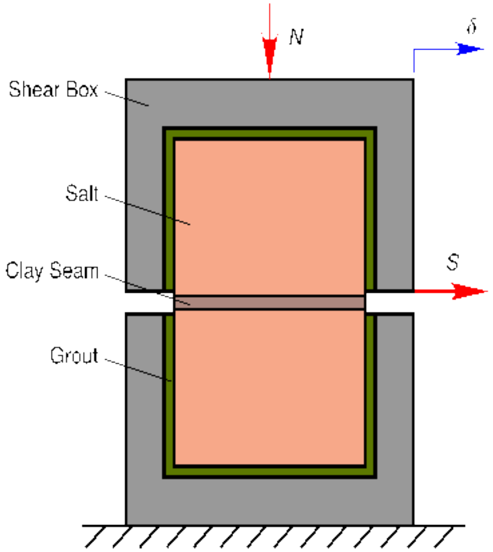
Reedlunn, B. and Bean, J. (2020). Impact of Properly Specifying the Clay F and Clay G Friction Coefficients in Disposal Room Closure Simulations at the Waste Isolation Pilot Plant. Memorandum. SAND202 -3575 CTF.

Summary of test series, application to model

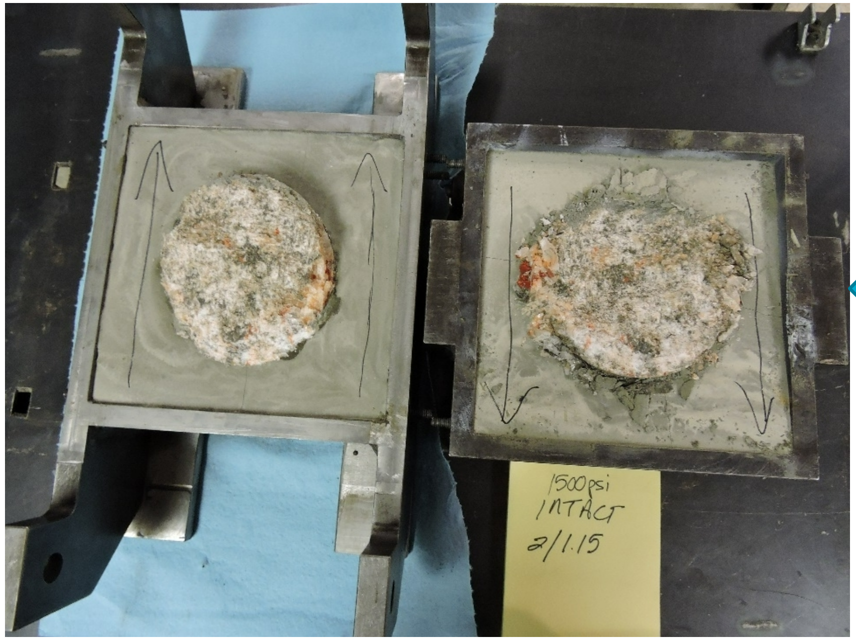
- **<u>First test series (2018-2019</u>**) – performed on representative salt core samples obtained from a potash mine near the WIPP.
  - Natural geologic contacts had intergrown halite crystals.
  - Residual shear strengths were like that of intact salt.
- **<u>Second test series (2020)</u>** – performed on samples with artificial clay seams prepared by mixing brine with bentonite.
  - Artificial clay seam residual shear behavior was similar to that of a saturated, highly consolidated clay.
- **<u>Model simulations (2022)</u>** – probed the sensitivity of WIPP disposal room porosity to clay seam shear behavior.
  - Weaker clay seams accelerated the decrease of room porosity within the first 300 years but had minimal impact on final room porosity.



1st test series samples

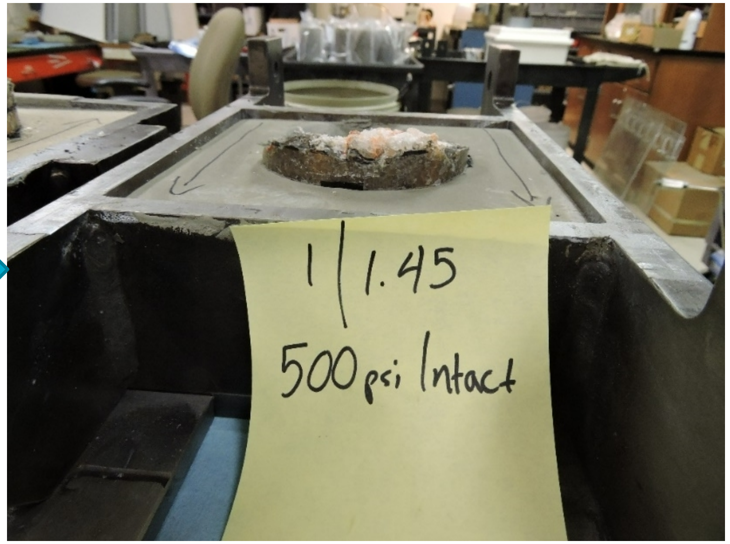


Salt/clay interface
Fracture shown is typical of all tests

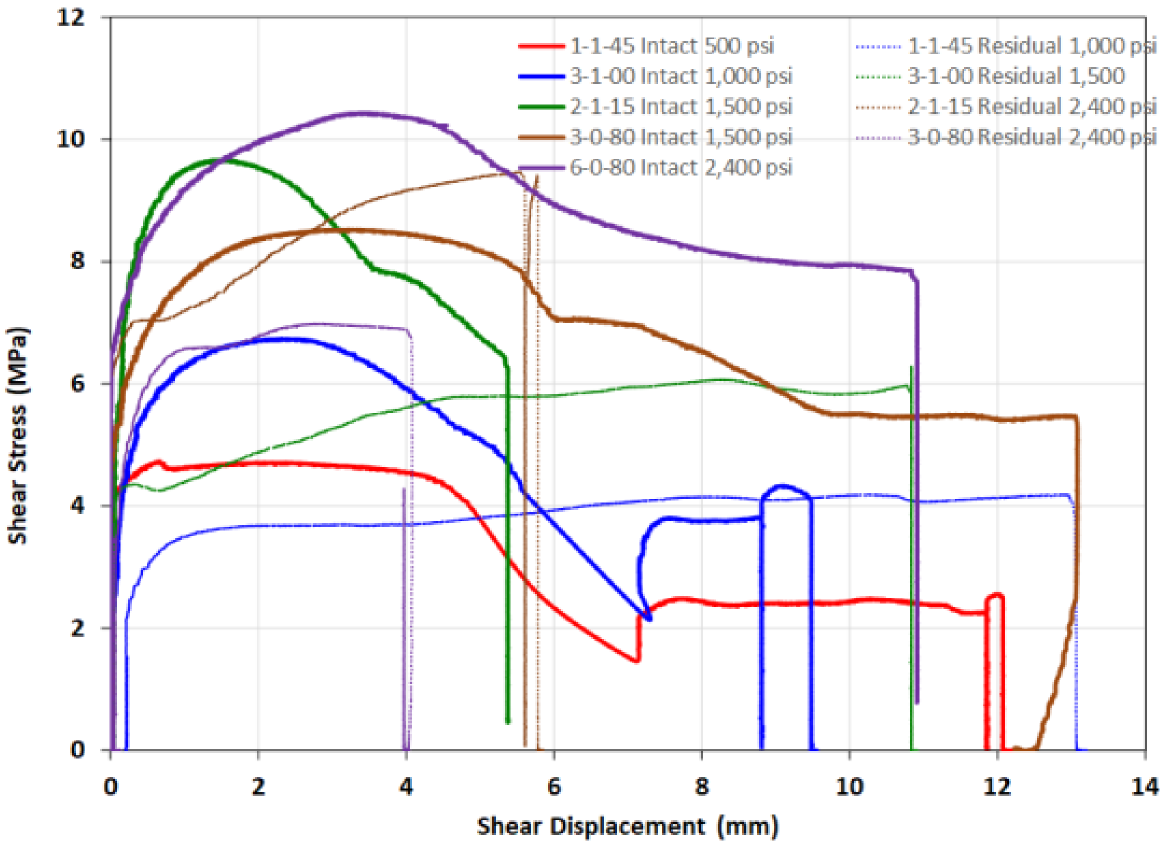


Intact test, σ_n=1500 psi (10.3 MPa); salt crystals cross through interface

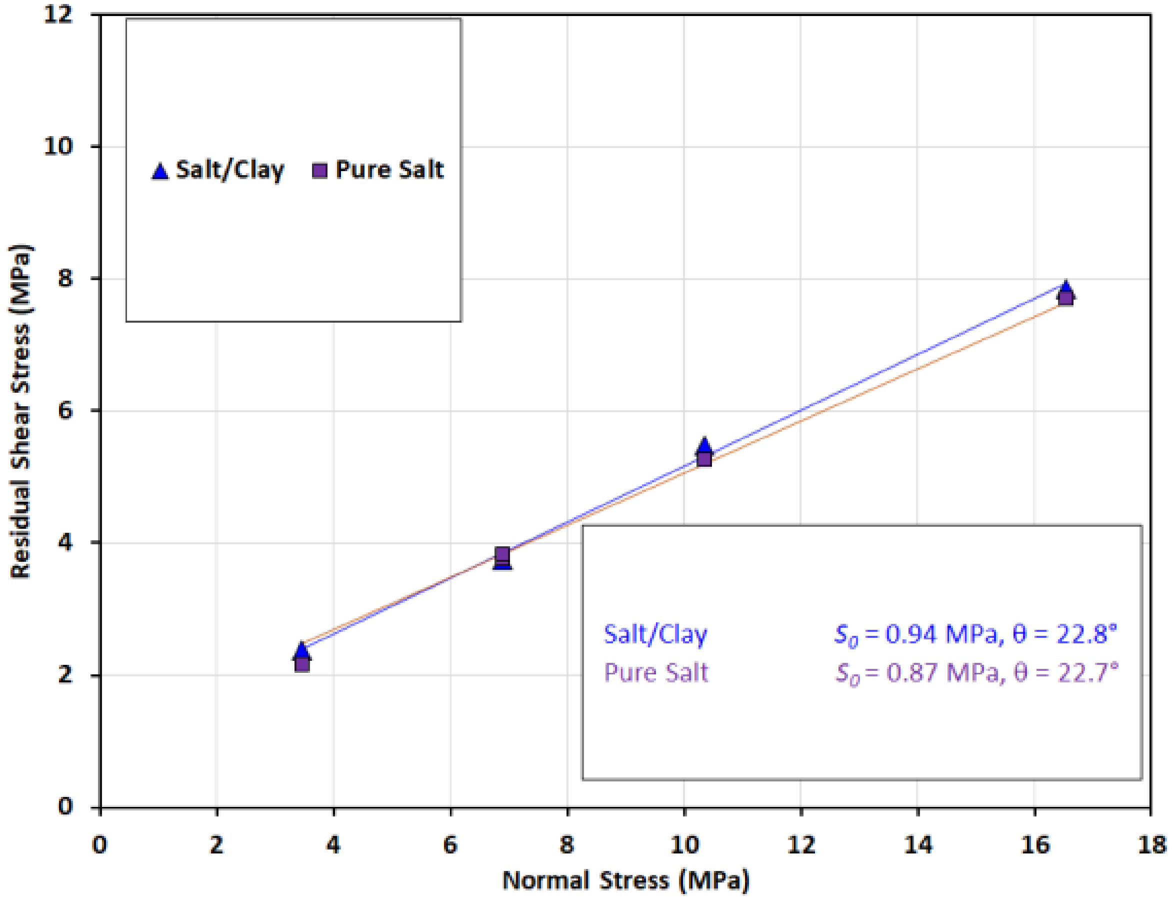
Intact test, σ_n=500 psi (3.4 MPa), side view



Natural layer boundaries, interfaces – First test series



Salt/clay interface responses

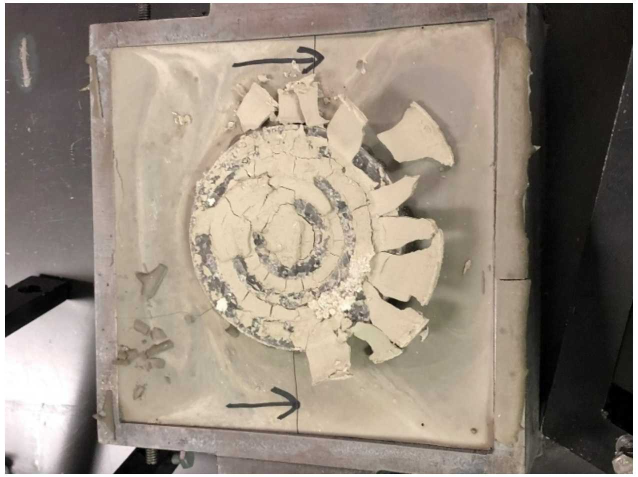


Shear tests were run at several normal stresses; shear displacement, shear load were measured, shear stress was calculated from the load.

Residual strength from these particular Salt/Clay interfaces are believed to represent an "upper bound".

Artificial clay seams – Second test series

- Goal: **Evaluate plausible frictional behavior** for strength and stiffness of clay seams in salt formations, including effect of seam thickness.
- Clay was made with mixture of bentonite, nearly-saturated brine.
- Post-consolidation seam height thicknesses: 12 mm (1/2”) down to 4.8 mm (3/16”); 6 mm (1/4”) down to 1.6 mm (1/16“).
- Normal pressures for tests: 3.4, 6.8, 10.3 MPa (500, 1000, 1500 psi).
- RESPEC direct shear test machine was used.
- Shear ram velocity 0.25 mm/min (0.004 mm/sec); this is believed to be much faster than “steady-state” slip would occur in an emplacement drift.



Specimen Construction – Samples from Core

Seam-side – where clay is applied

Outside – where normal stress is applied

Asperities were 1.3 mm deep, spaced 6 mm apart

Specimen Fabrication

4 specimens with initial seam thickness of 6 mm

4 specimens with initial seam thickness of 12 mm

Moisture content of clay pre-consolidation: 60% (1st batch), 54% (2nd batch)

Consolidated

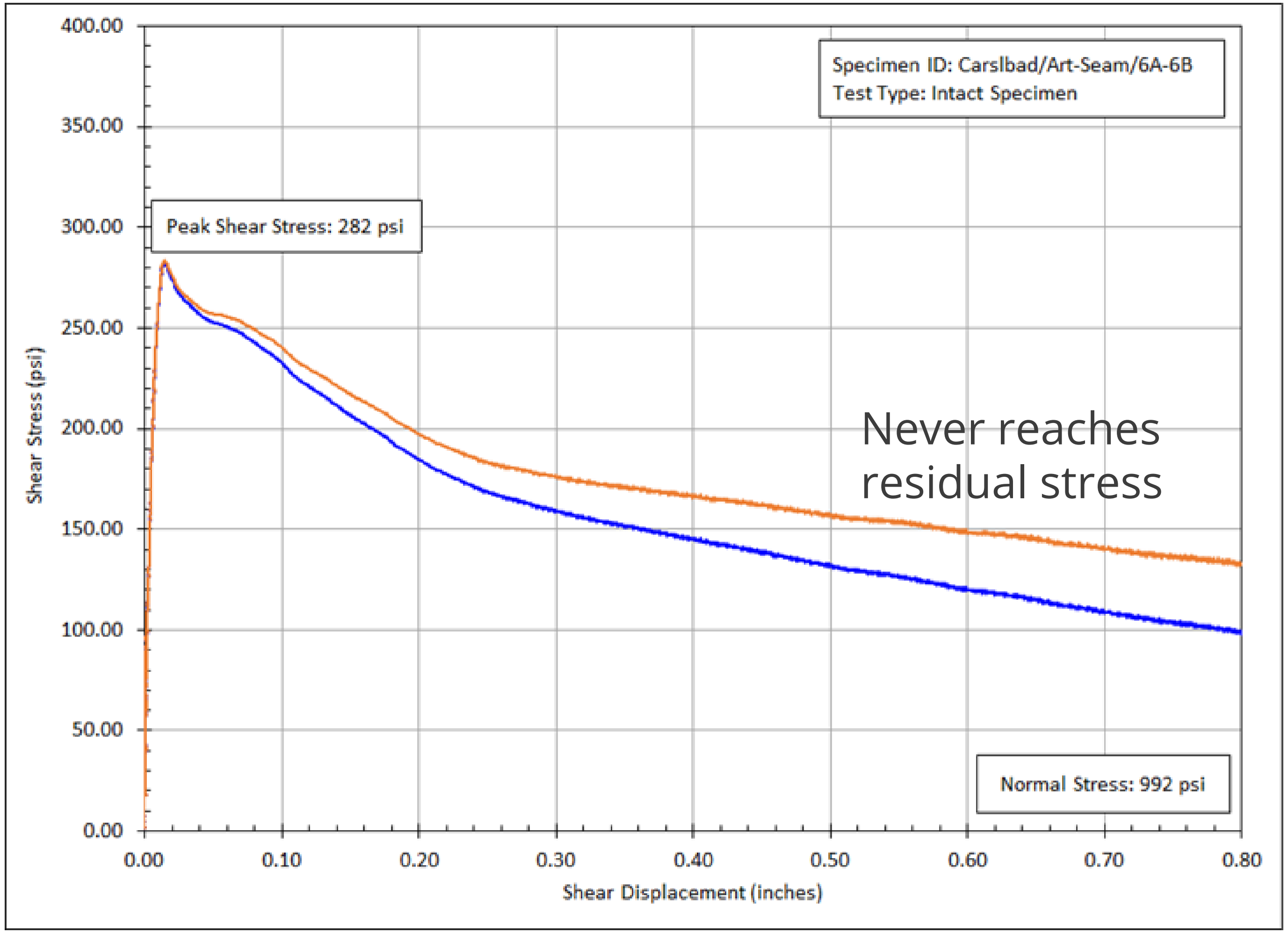
- 14 days at 20.7 MPa (3000 psi) hydrostatic stress and 21C
- Excess pore fluid vented

After consolidation

- Approximately 1/3 of pre-consolidation thickness
- Clay hardened
- Fresh water moisture content 13 to 17%
- No asperity-to-asperity contact

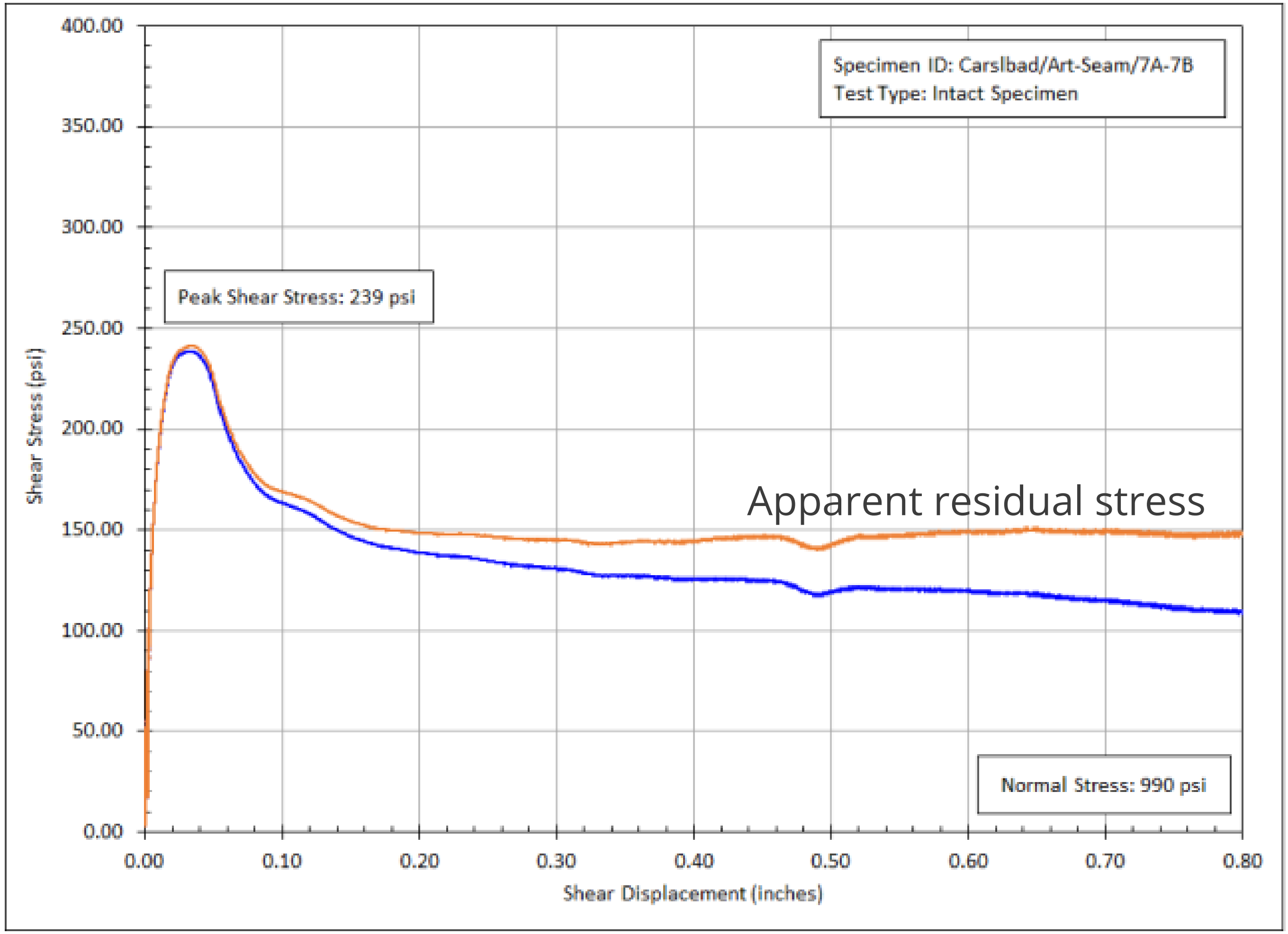



Shear Stress vs. Shear Displacement: Sample #6, 6-mm seam pre-consolidation, 6.89 MPa (1000 psi) normal stress



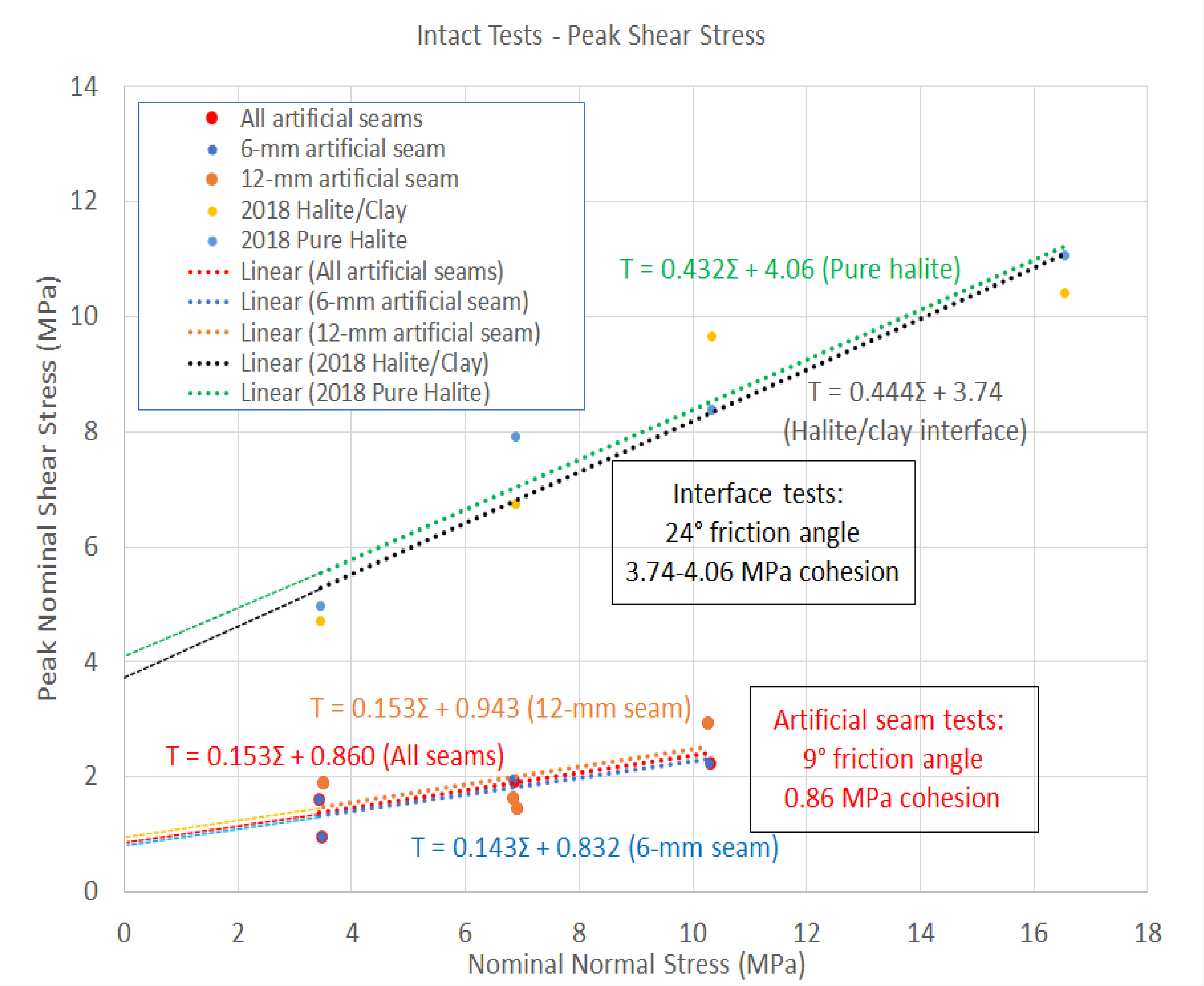
- Blue: Stress calculated with constant contact area
- Orange: Stress calculated with contact area modified by shear displacement
- Actual nominal normal stress = 992 psi (6.84 MPa)
- Peak shear stress = 282 psi (1.94 MPa)
- Never reached residual stress after initiation of shear movement
- Residual stresses were not achieved on 4 tests; for these cases, stress reached at 0.75” (19 mm) displacement used as “residual” stress

Shear Stress vs. Shear Displacement: Sample #7, 12-mm seam pre-consolidation, 6.89 MPa (1000 psi) normal stress



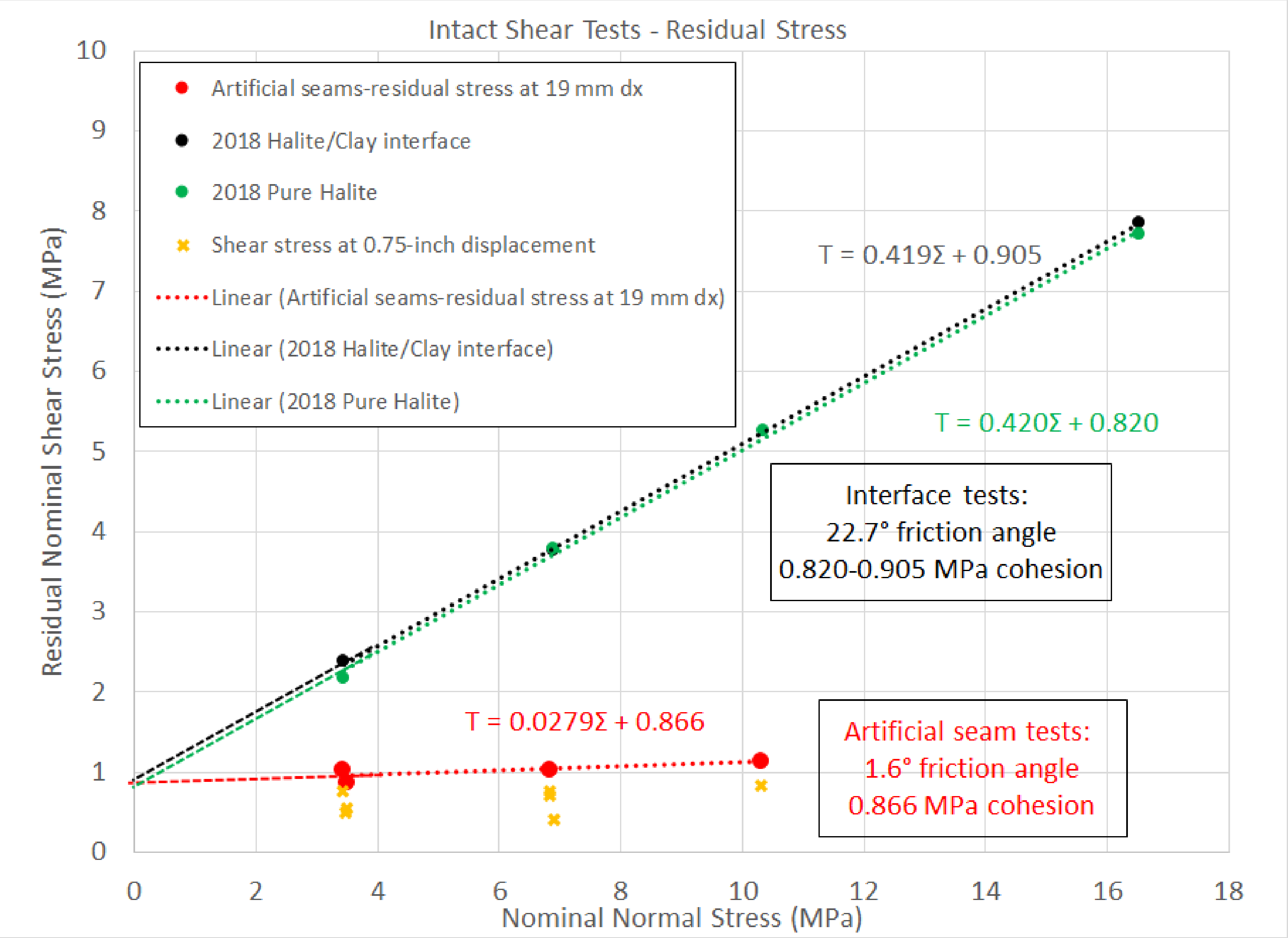
- Residual stresses were marginally achieved only on 4 tests
- Actual nominal normal stress = 990 psi (6.83 MPa)
- Peak shear stress = 239 psi (1.65 MPa)
- Reached apparent residual stress of ~150 psi (1.03 MPa) well before 0.75" (19 mm) shear displacement after initiation of shear movement
- "Apparent" residual stress because unchanging normal load, changing contact area mean changing normal stress

Intact samples shear tests – Peak Stresses



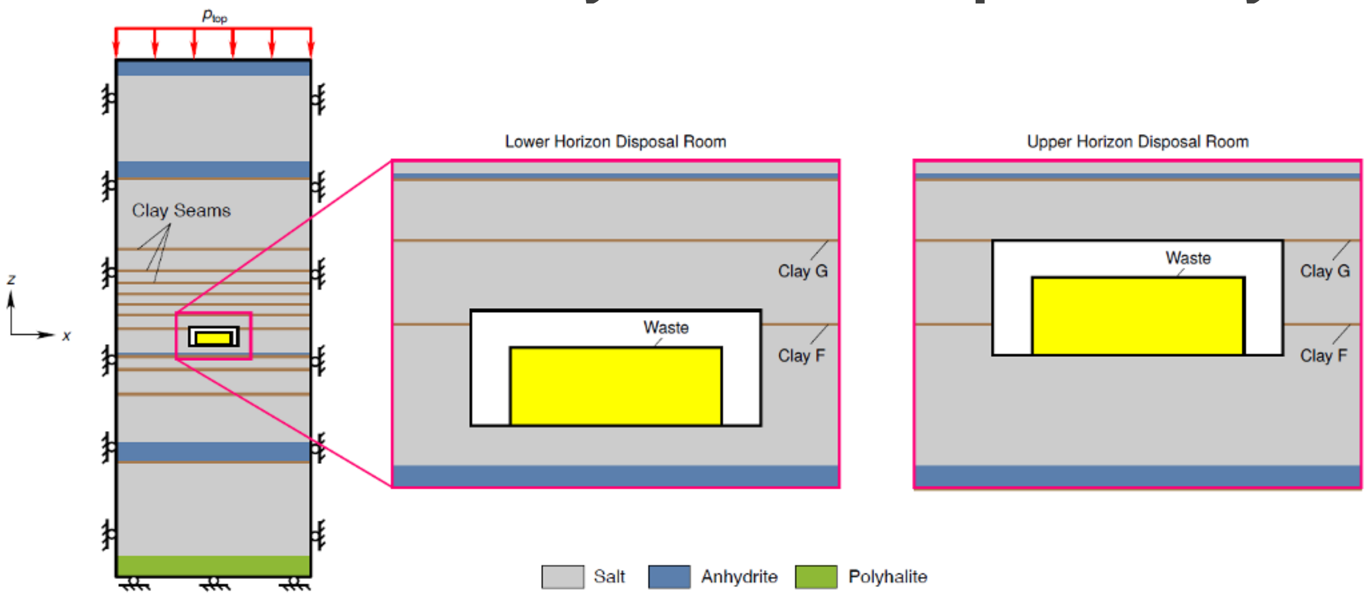
- Peak stresses occur when interface breaks or slides, shear stress sharply decreases
- For 2018 salt interface tests: friction angle 24°, cohesion 546 psi (3.74 MPa)
- For artificial seam shear tests; friction angle 8.7°, cohesion 125 psi (0.86 MPa)

Intact sample shear tests – Residual Stresses

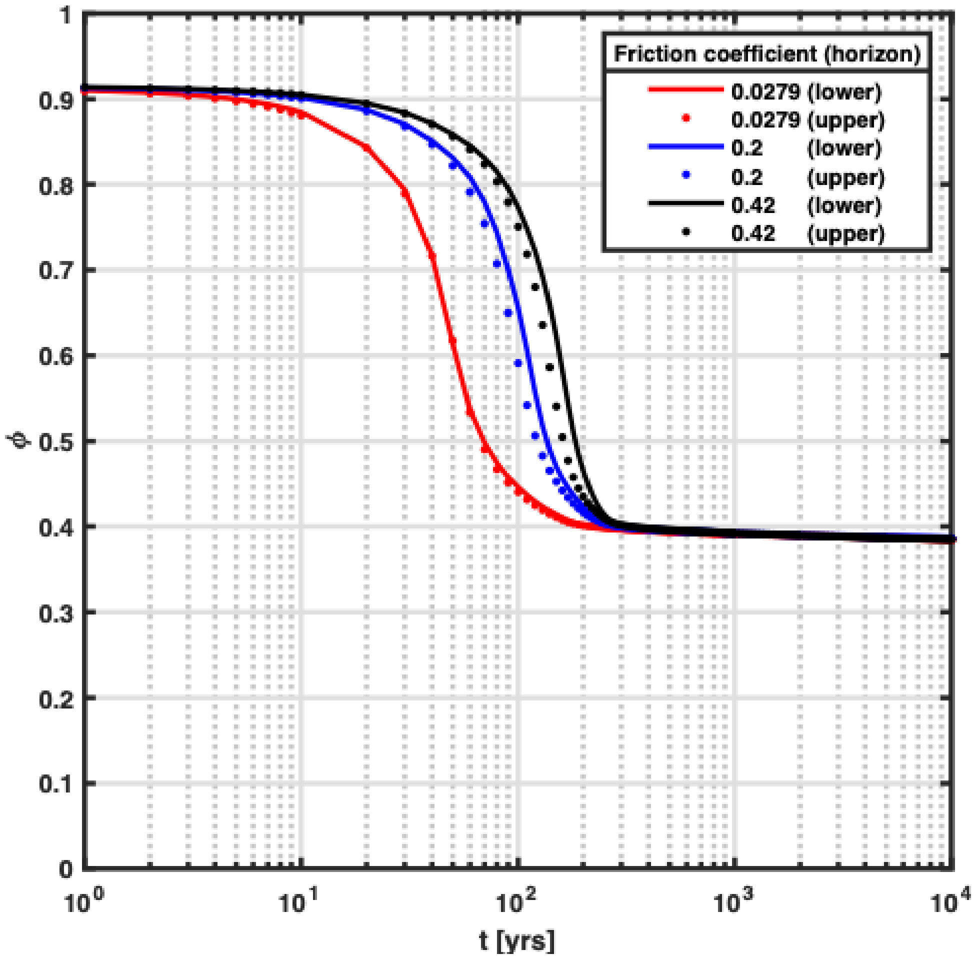


- For 2018 salt interface tests: friction angle 22.7°, cohesion 119-131 psi (0.82-0.91 MPa)
- Only 4 of 8 artificial seam shear tests attained apparent residual stresses after initiation of shear displacement
- For artificial seam tests: friction angle 1.6°, cohesion 125 psi (0.866 MPa)
- Values much lower than expected; softness of clay, salt asperity size may be factors
- Current assumption is that Clay Seam G test results will plot between interface and artificial seam results

Effect of clay seam on porosity response



- Coulomb friction model used.
- Friction coefficient for Clay F = 0.42 (upper bound); all other clay seams (including G) range from 0.0279 to 0.42.
- Disposal room porosity ϕ computed as void space volume divided by volume of room (void+waste).



- For t<300 y, room porosity is sensitive to seam sliding; upper, lower disposal rooms exhibit similar behaviors.
- For t>300 y, all scenarios asymptote to same value.

Artificial clay seam shear tests – Application to modeling

In situ WIPP clay seams F, G, others vary significantly in visual, tactile character.

Until tests on WIPP clay seams can be performed, individual seams will be characterized by photographs, borehole logs, other evidence in comparison to interface, artificial seam shear test samples.

Geological Society of America Bulletin, published online on 11 February 2011 as doi:10.1130/B30197.1

Geological Society of America Bulletin

Synsedimentary dissolution pipes and the isolation of ancient bacteria and cellulose

Robert M. Holt and Dennis W. Powers

Geological Society of America Bulletin published online 11 February 2011;
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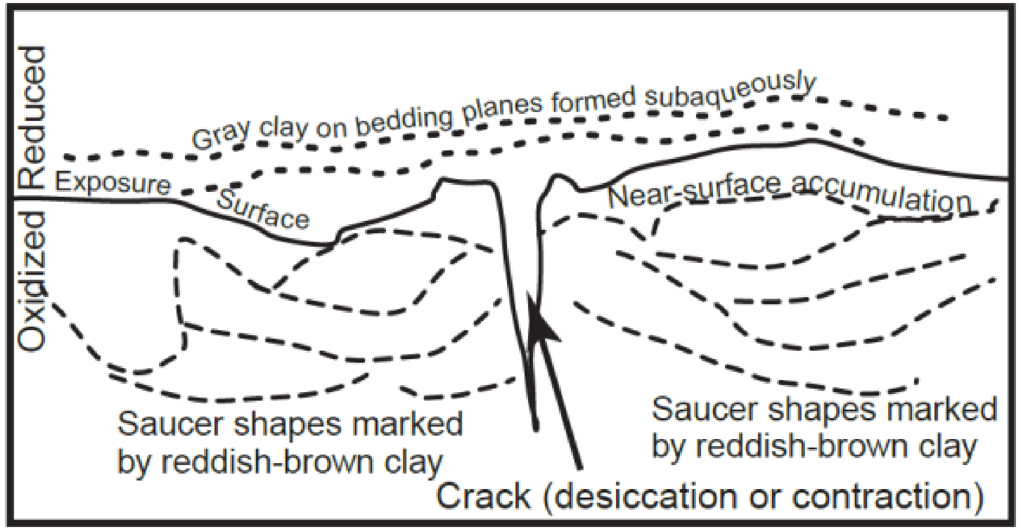

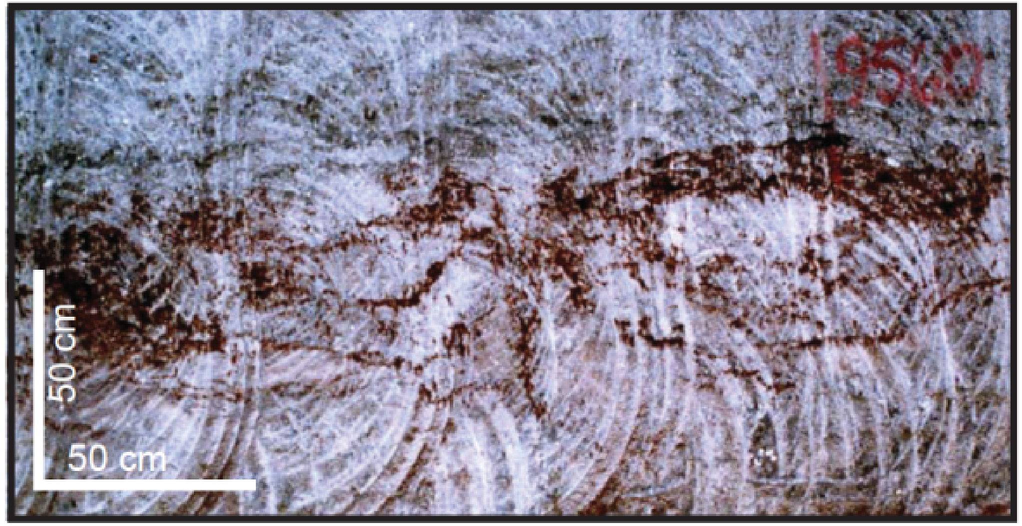

Figure 9. Desiccating-upward cycle is illustrated by a crack at the top of the cycle and clay along saucer shapes. This example is from map unit (MU) 4 (Fig. 4), which is not known to have developed pipes.

Artificial clay seam shear tests –Conclusions

- Eight samples of salt with artificial clay seams of two different thicknesses were subjected to displacement-controlled direct shear tests at three different normal loads.
- Maximum, final shear strength were determined for each test.
- Although none of the tests achieved a true residual stress plateau, the final shear stresses reasonably conformed to Mohr-Coulomb behavior.
- The Mohr-Coulomb parameters were similar to those of a highly consolidated, saturated clay, which is to say they were quite low.
- Upper and lower bounds from direct shear tests were used in simulations of waste compaction due to disposal room closure at the WIPP. This preliminary study found disposal room porosity was sensitive to clay seam sliding behavior during the first 300 years, yet became insensitive afterwards.
- Having a credible model for clay seam sliding is also important for validating models of room closure.

"Two things that remain eternally true and complement each other, in my view are: don't snuff out your inspiration and power of imagination, don't become a slave to the model; and the other, take a model and study it, for otherwise your inspiration won't take on material form."

To Theo van Gogh, The Hague, 5 November 1882

THANK YOU FOR YOUR ATTENTION!