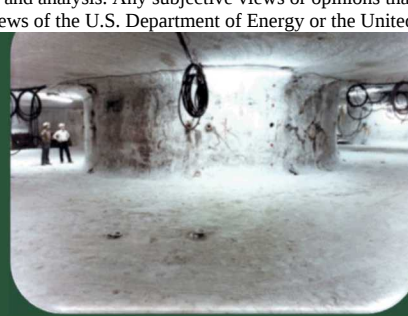
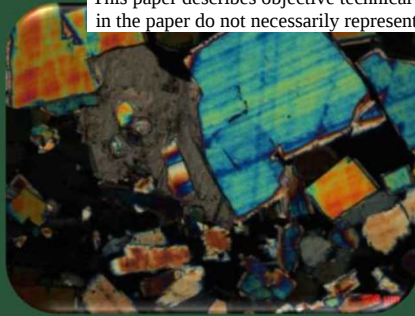
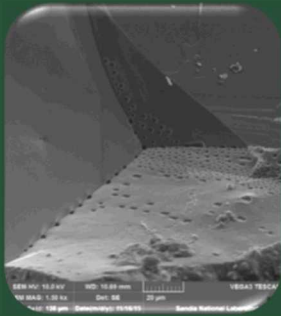




Mechanical Behavior of Bedded Salt Interfaces and Clay Seams Subjected to Shear

9th US/German Workshop on Salt Repository Research, Design, and Operation

Steven R. Sobolik & Ben Reedlunn, Sandia National Laboratories, Albuquerque, New Mexico, USA

Stuart Buchholz, Evan Keffeler, and Scyller Borglum, RESPEC, Rapid City, South Dakota, USA

Hannover, Germany

September 10-11, 2018

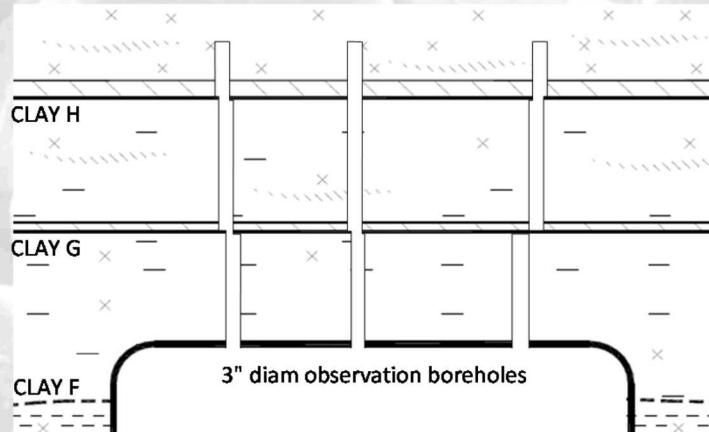


Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S. Department of Energy.

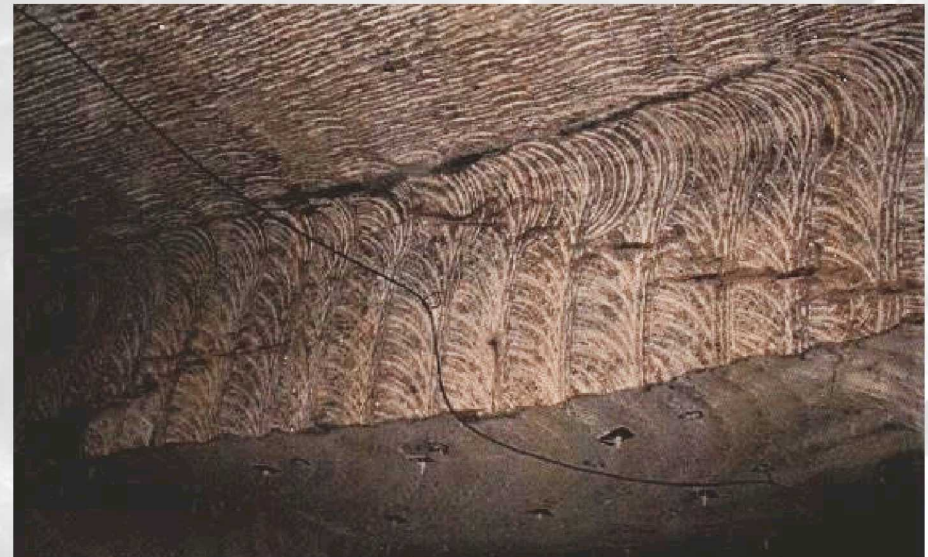
Examples of Interface Sliding and Separation



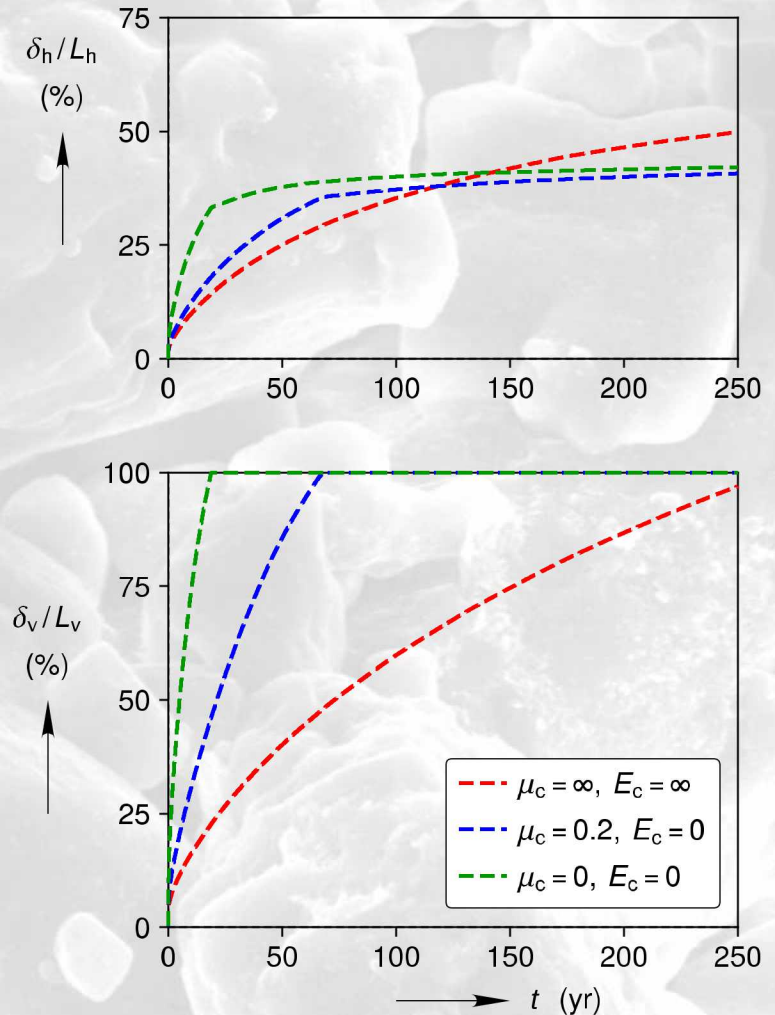
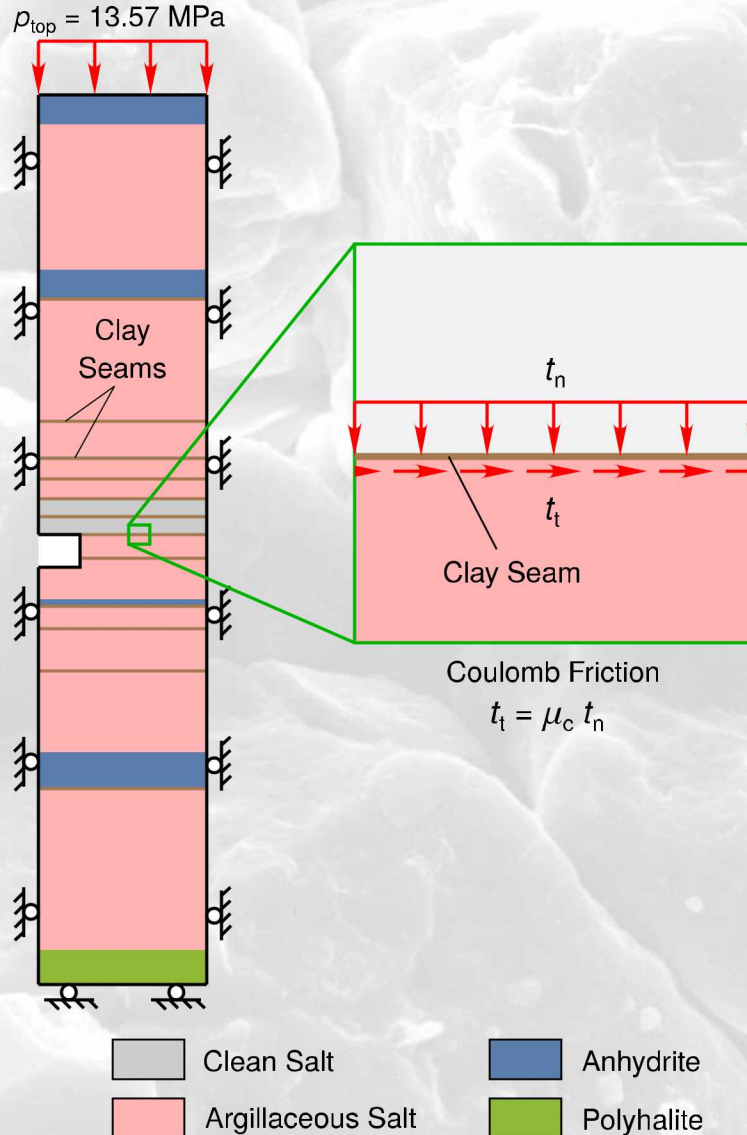
Interface Sliding



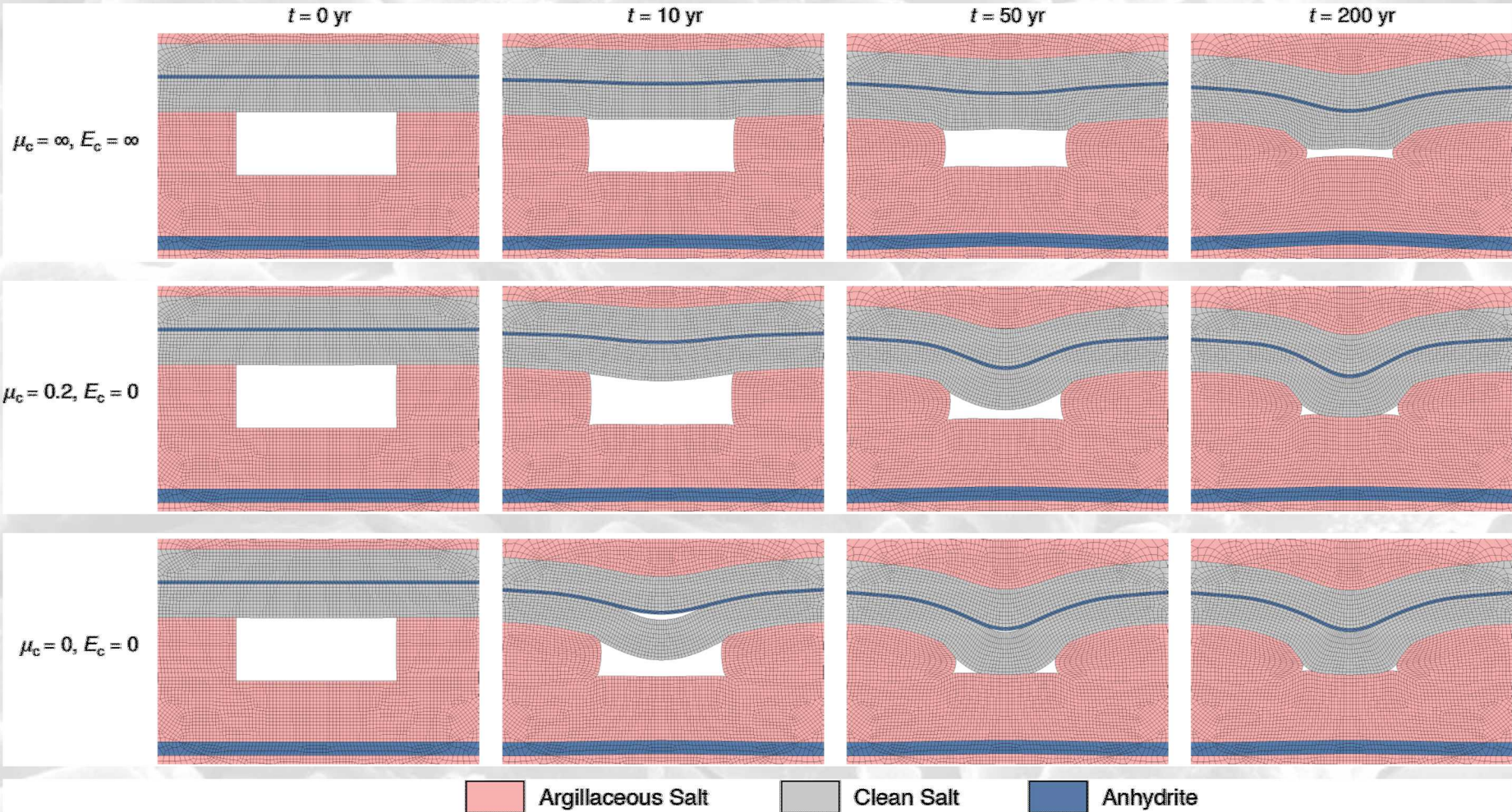
Interface Separation



Clay Seam Impact



Clay Seam 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.

Research Plan

- Laboratory Experiments (TP 17-03)

- Extraction Sites

- Salt/Potash mine in the Permian Basin
 - WIPP drifts

- Samples

- 10 cm diameter cylinders
 - Various bedding plane constituents

- Tests

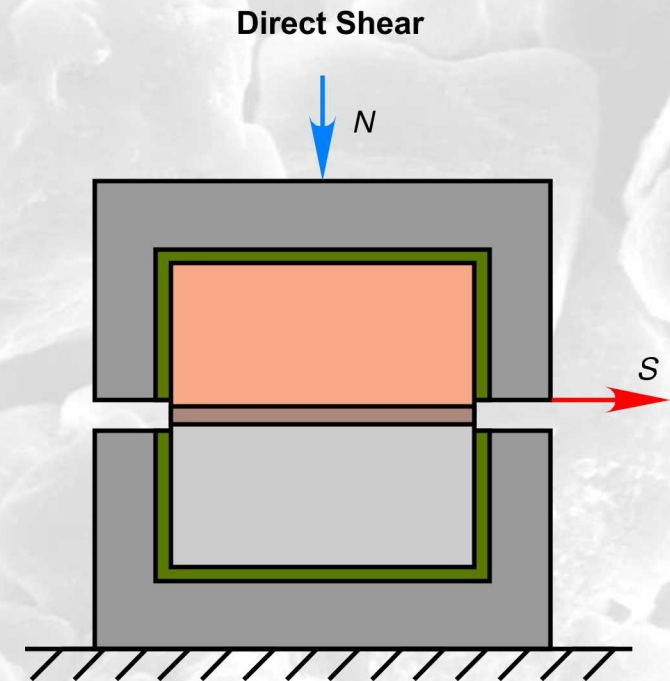
- Direct shear and/or triaxial cell tests
 - Tensile strength

- Modeling

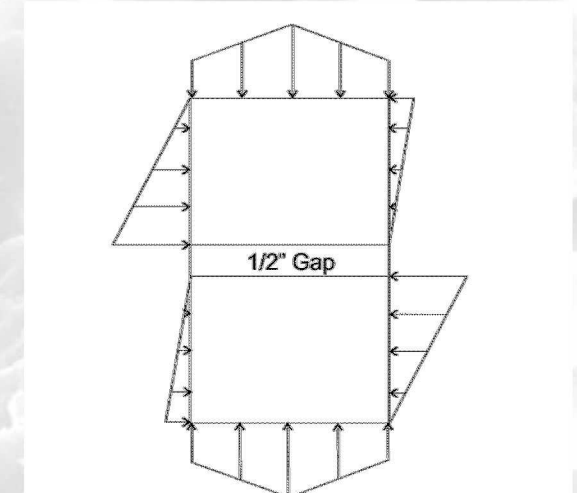
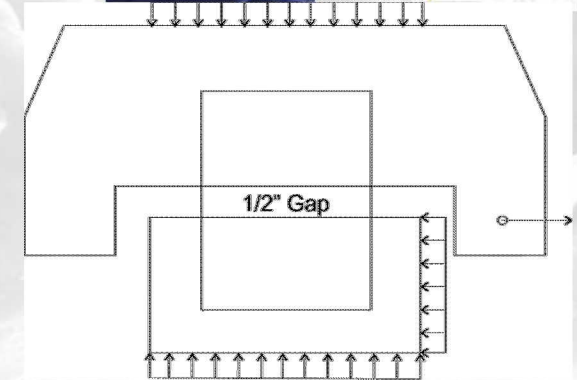
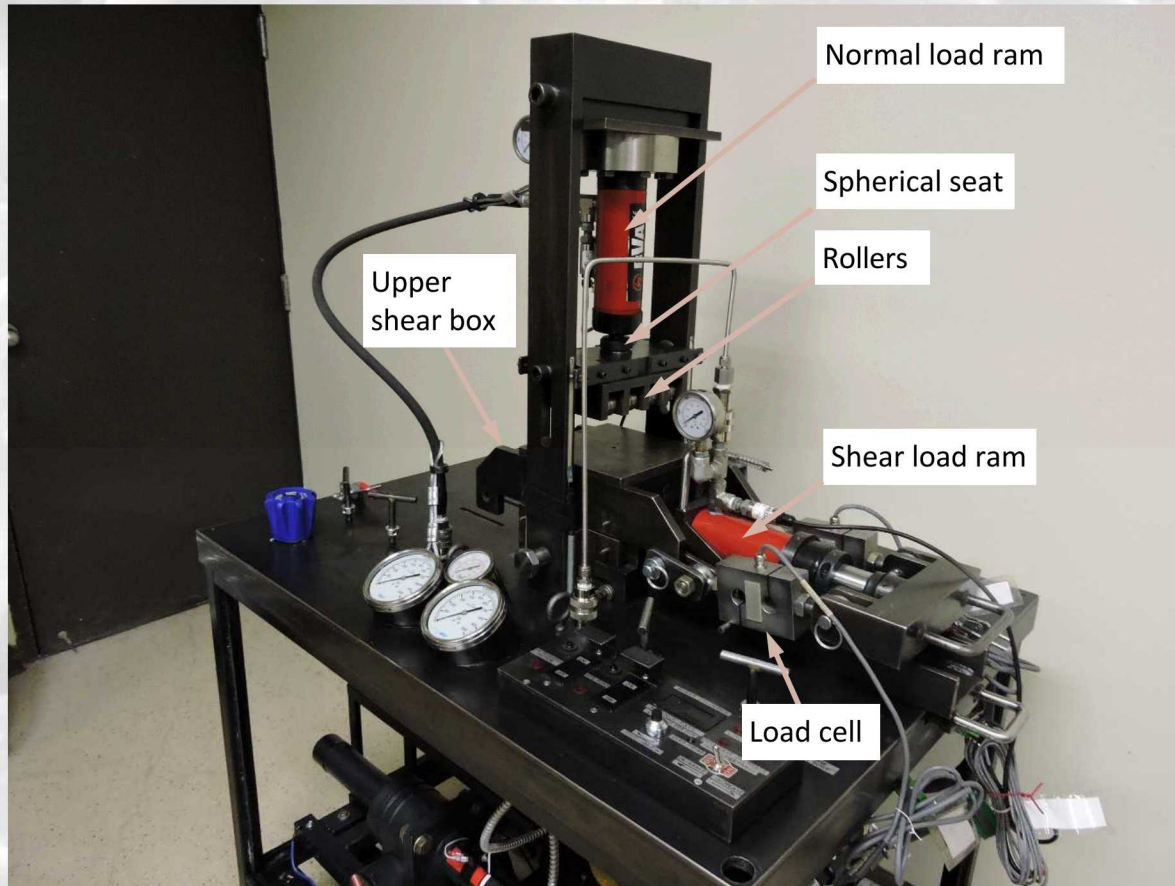
- Construct constitutive model(s) with Joint Project WEIMOS

- In-Situ Experiment

- ~1 m cube to quantify size effects
 - Validate models against in-situ test.

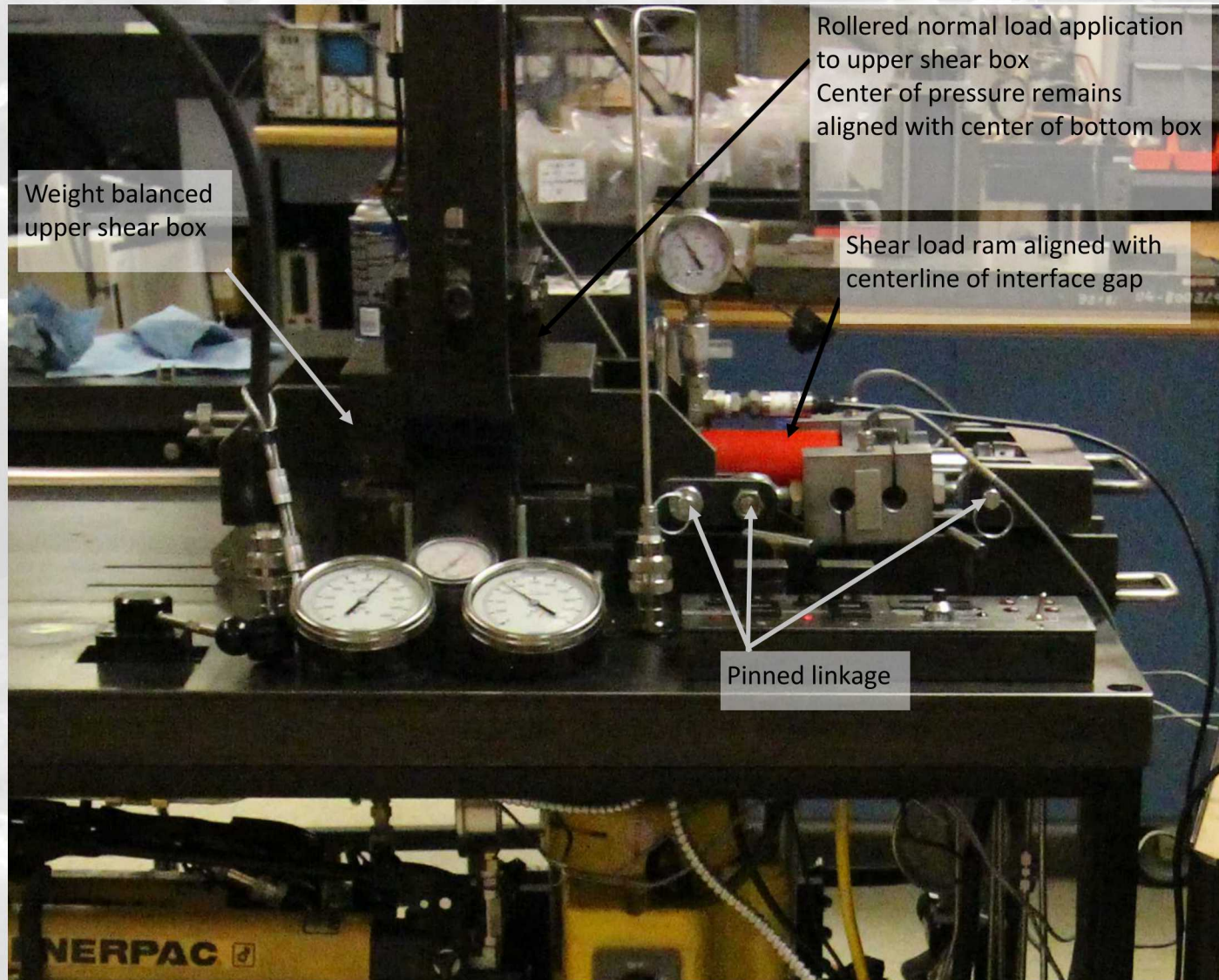


Direct Shear Test Setup



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

Shear Test Setup (Actual Test)



Laboratory tests to date



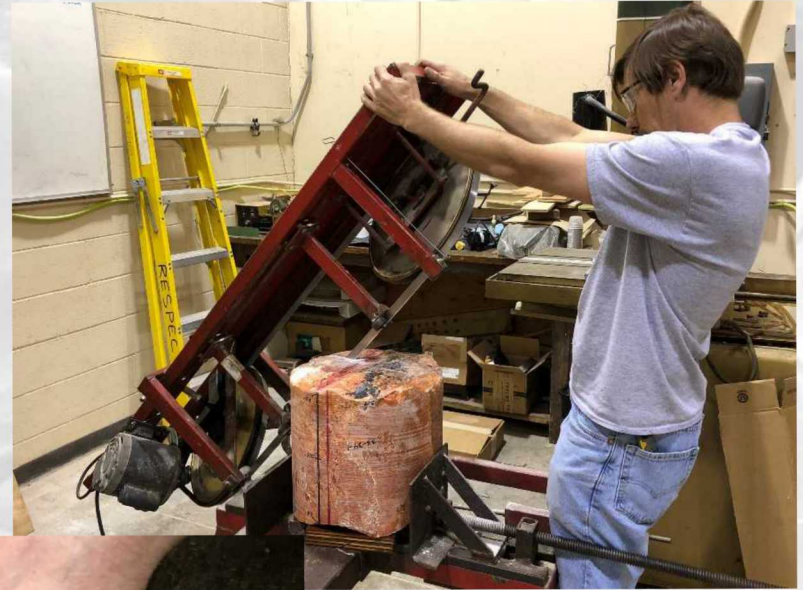
- 2018 laboratory tests include following:
 - 10-cm (4-in) cylindrical samples, with existing interface/contact
 - 3.4-16.6 MPa (500-2400 psi) stress capacity both in axial (compression) and shear loading
 - Fixed normal stress for tests
 - RESPEC direct shear machine (Capacity for 130 kN load, shear velocities 0.25-5 mm/min). Ram advance rate set at 0.25 mm/min for these tests.
- Analysis plan to develop constitutive, numerical model for shear slip at interface from results of 2018 lab tests.

List of tests performed

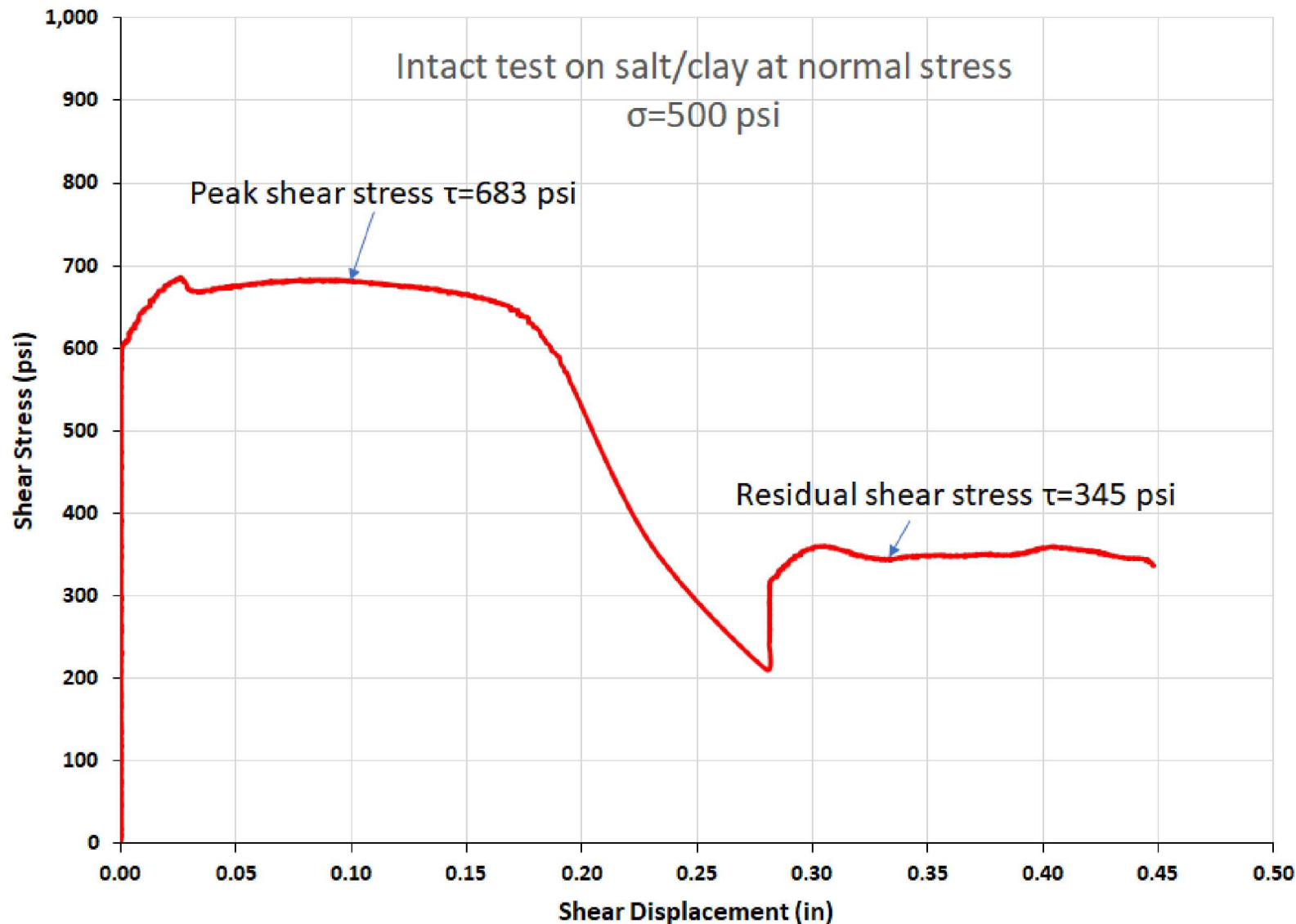


- 24 samples total, 4 intact tests/3 residual tests for each material type
- Normal pressures for intact tests were 500, 100, 1500, 2400 psi
- Post-intact residual tests at higher normal stresses for most samples
- Tests were performed on the following core samples:
 - Canadian halite with clay interface (to test out experimental procedure)
 - New Mexico core – Halite/polyhalite interface
 - New Mexico core – Halite/anhydrite interface
 - New Mexico core – Halite/clay interface
 - New Mexico core – “Pure salt” or “Closer salt” (Intact halite with no interface, 0-40 cm into drift wall; salt had more pure appearance)
 - New Mexico core – “Mixed salt” or “Deeper salt” (Intact halite with no interface, 50+ cm into drift wall; salt had more mixed appearance)

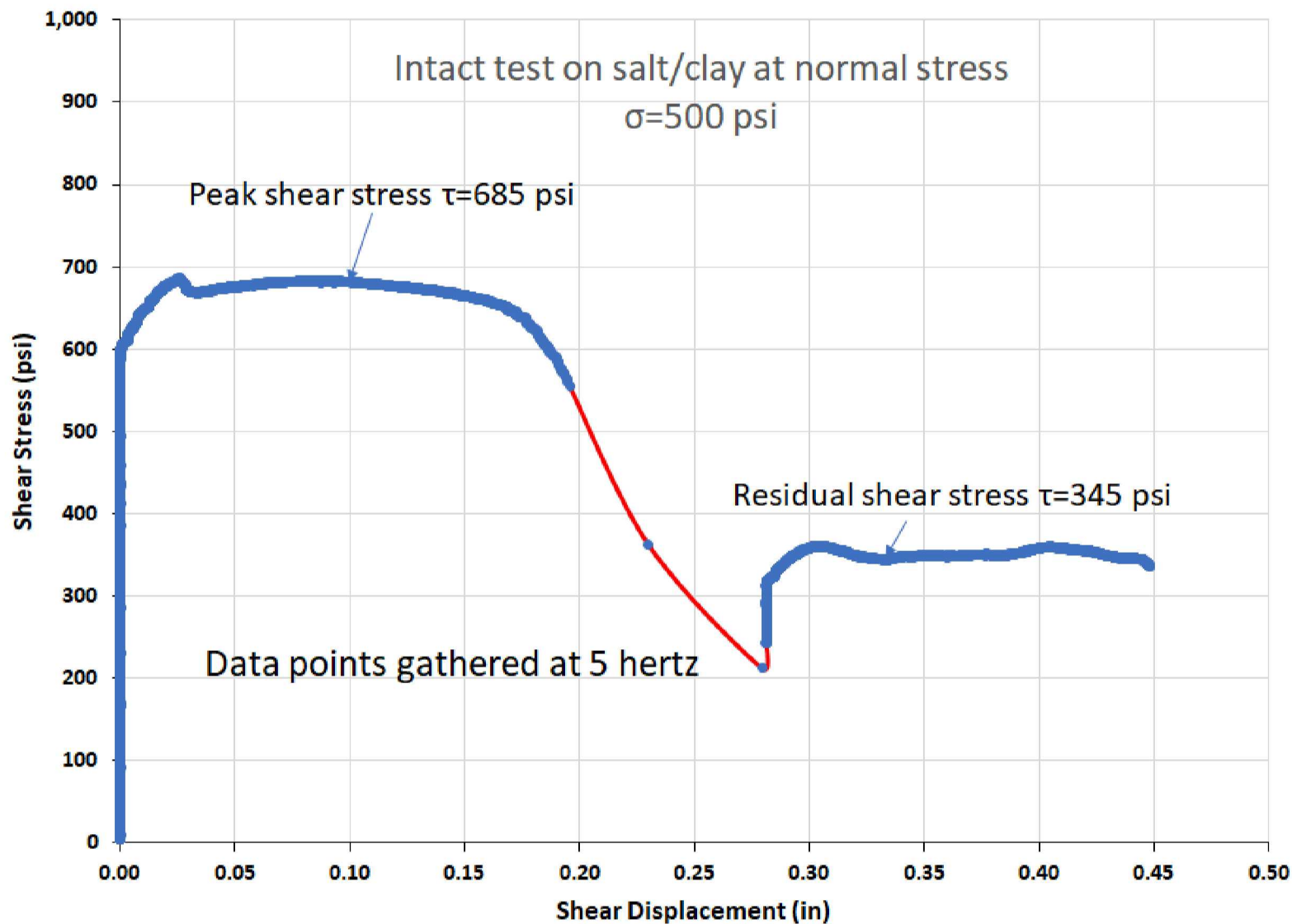
Cutting of Samples from Core



Typical test results



Typical test results



Closer salt tests



**Intact test,
 $\sigma_n = 1000$ psi**

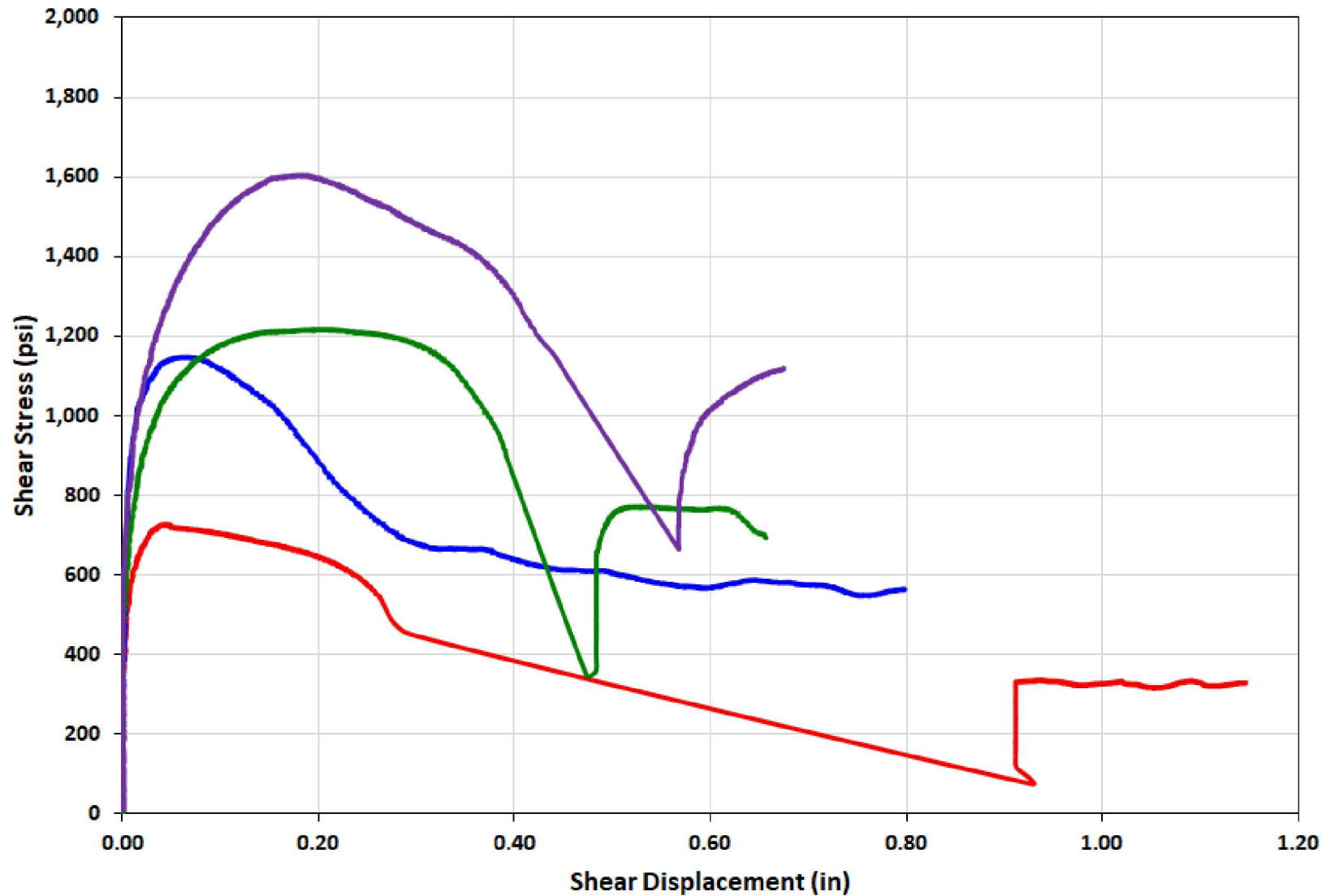
**Intact test,
 $\sigma_n = 1000$ psi,
side view**



Closer salt tests



— $\sigma=500$ psi — $\sigma=1,000$ psi — $\sigma=1,500$ psi — $\sigma=2,400$ psi



Salt/clay tests



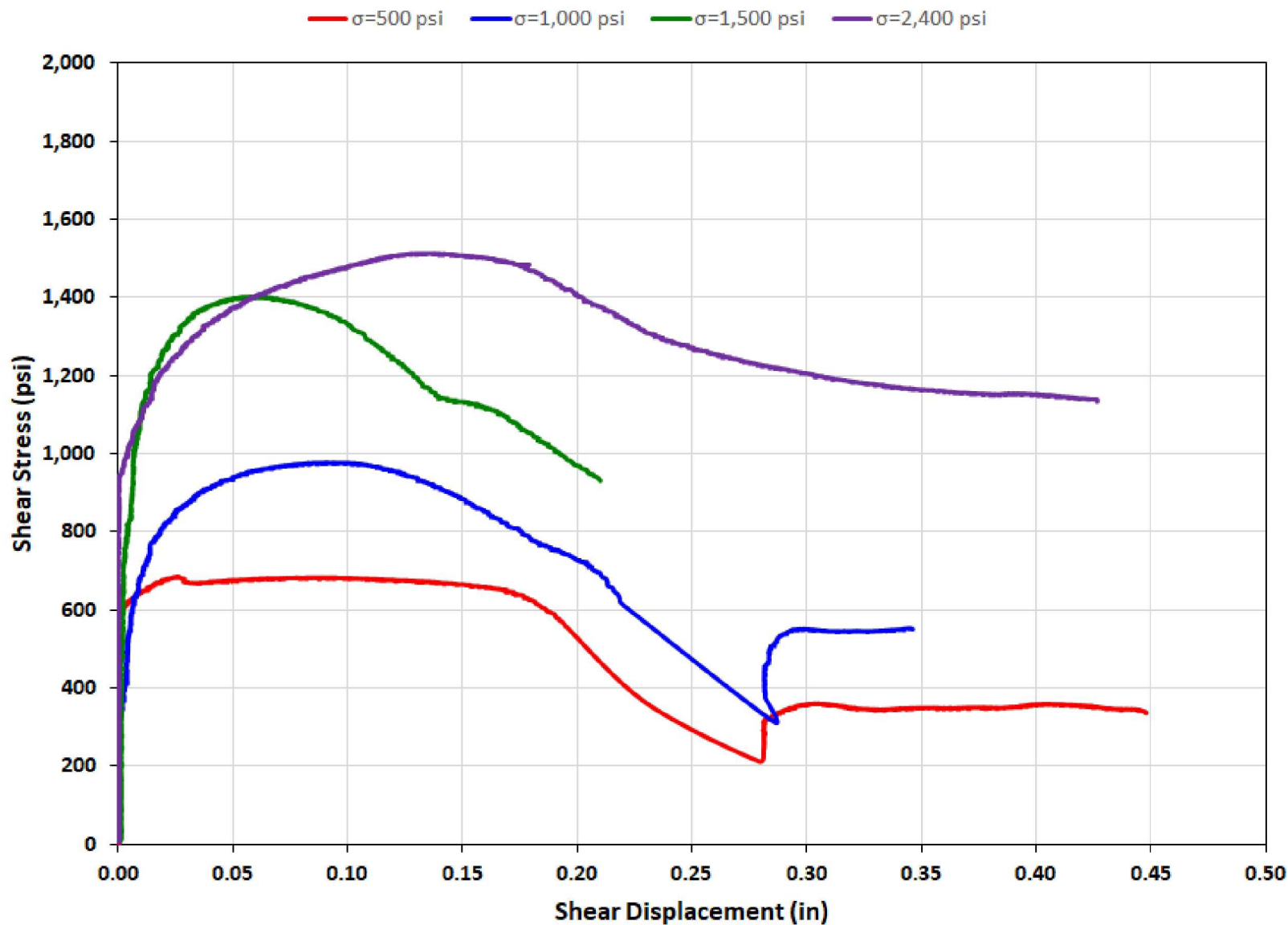
Intact test,
 $\sigma_n = 500$ psi,
side view



Intact test,
 $\sigma_n = 1500$ psi



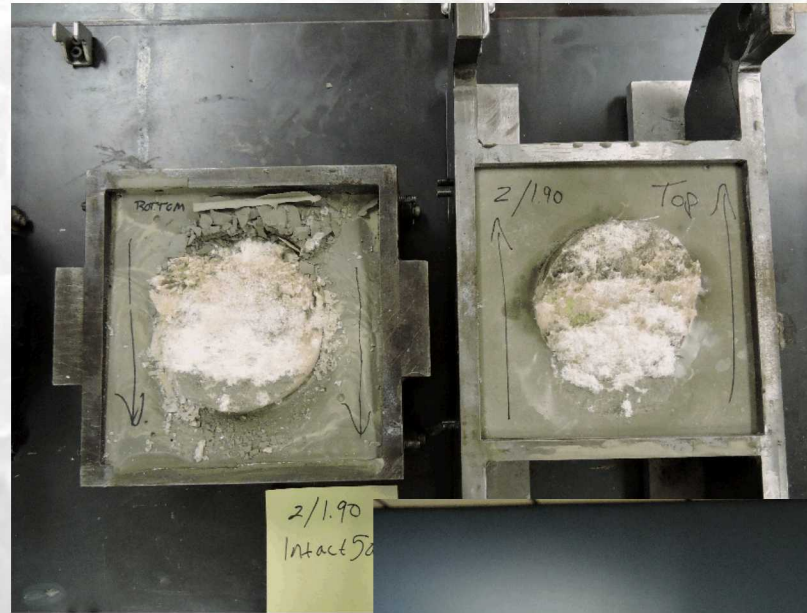
Salt/clay tests



Salt/anhydrite tests



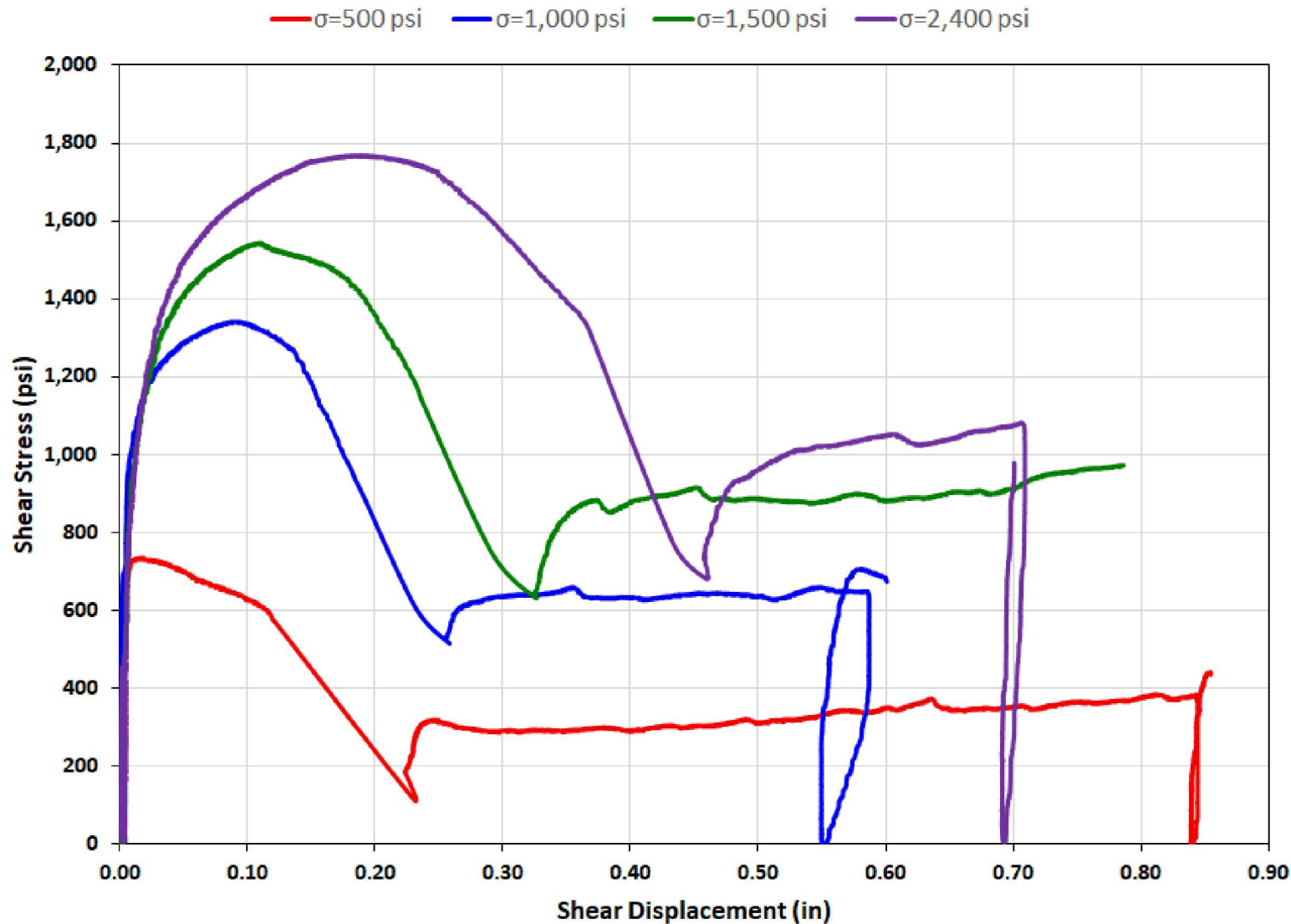
**Intact test,
 $\sigma_n=500$ psi,
side view**



**Intact test,
 $\sigma_n=500$ psi**



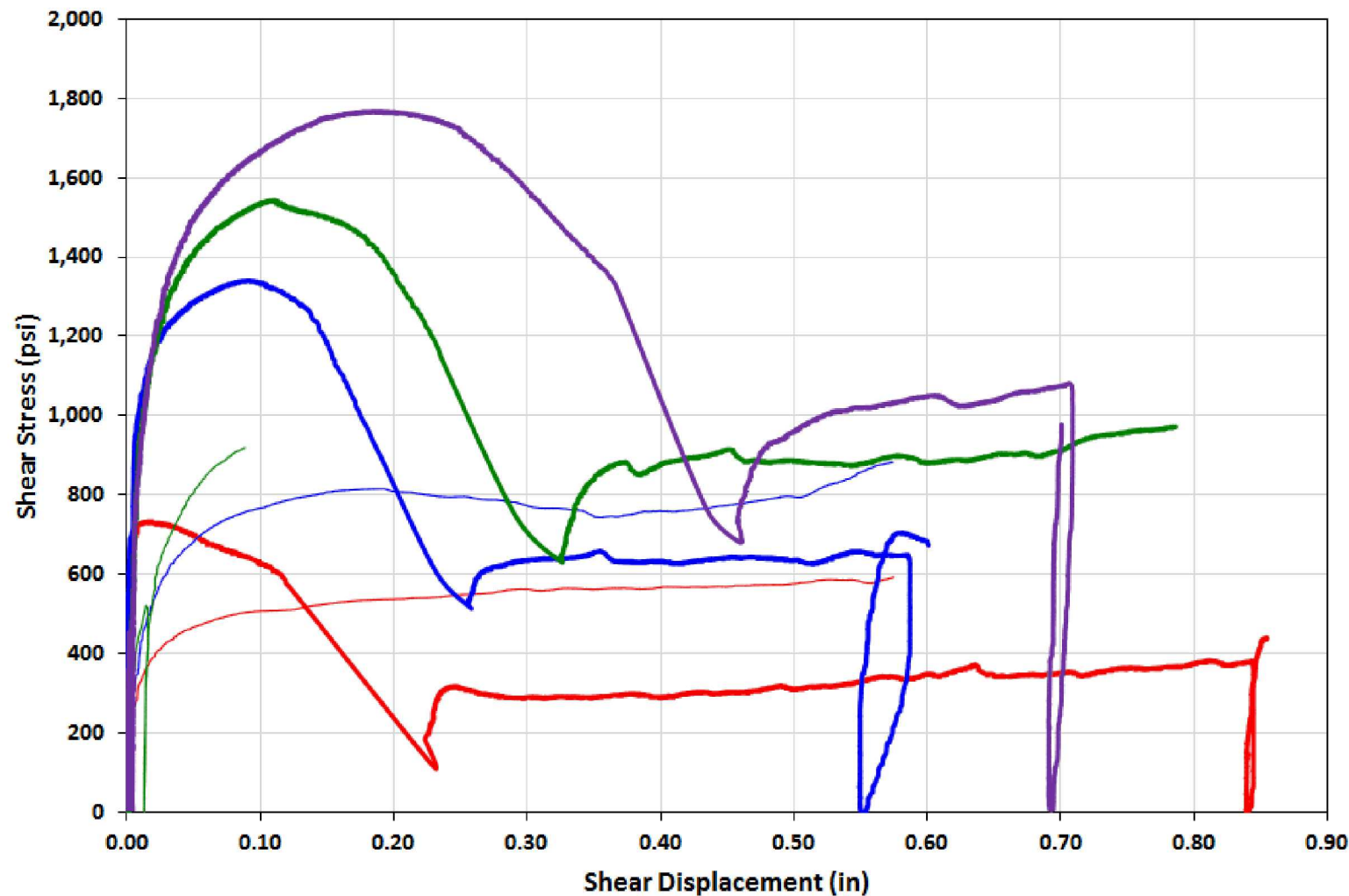
Salt/anhydrite tests

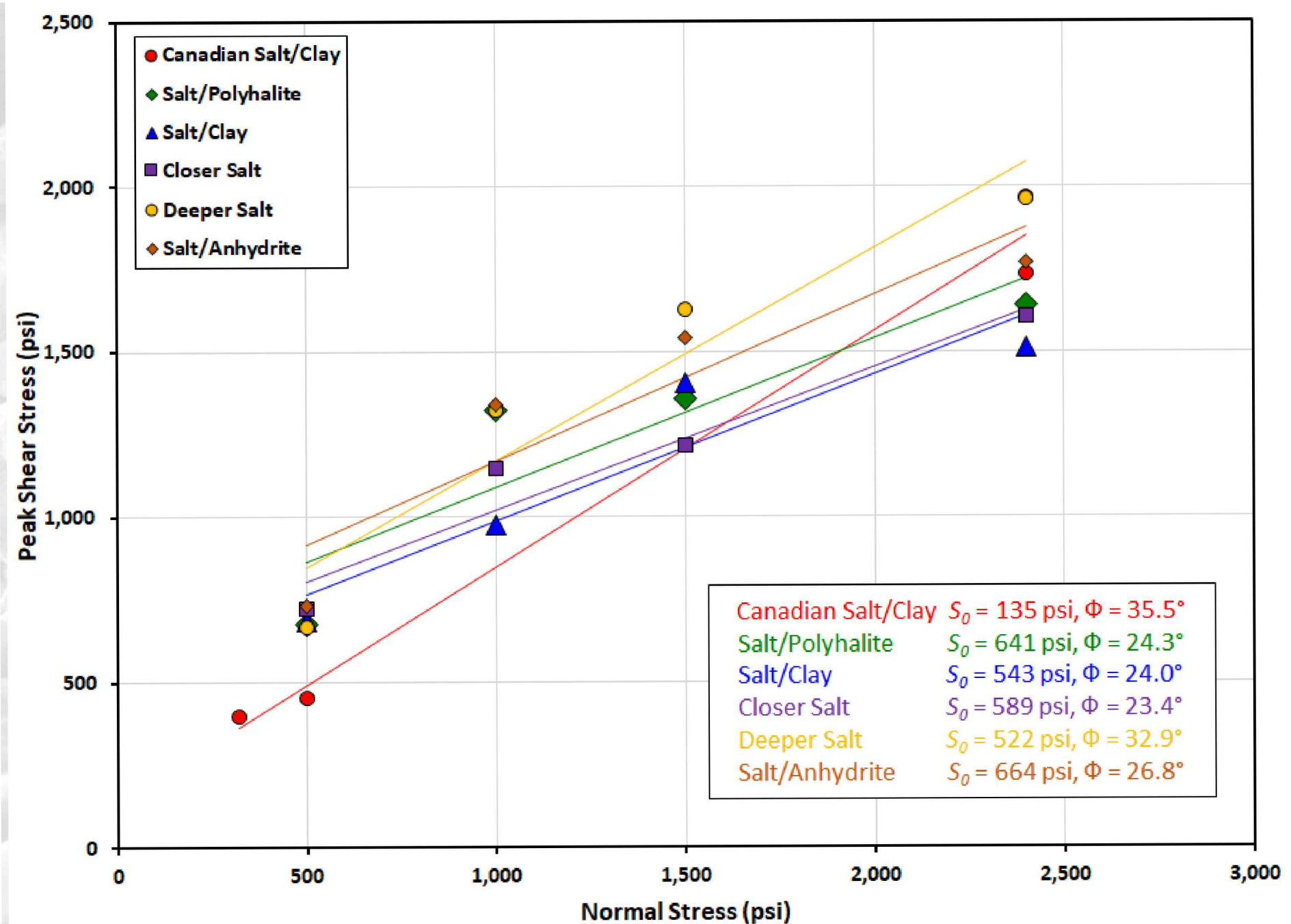


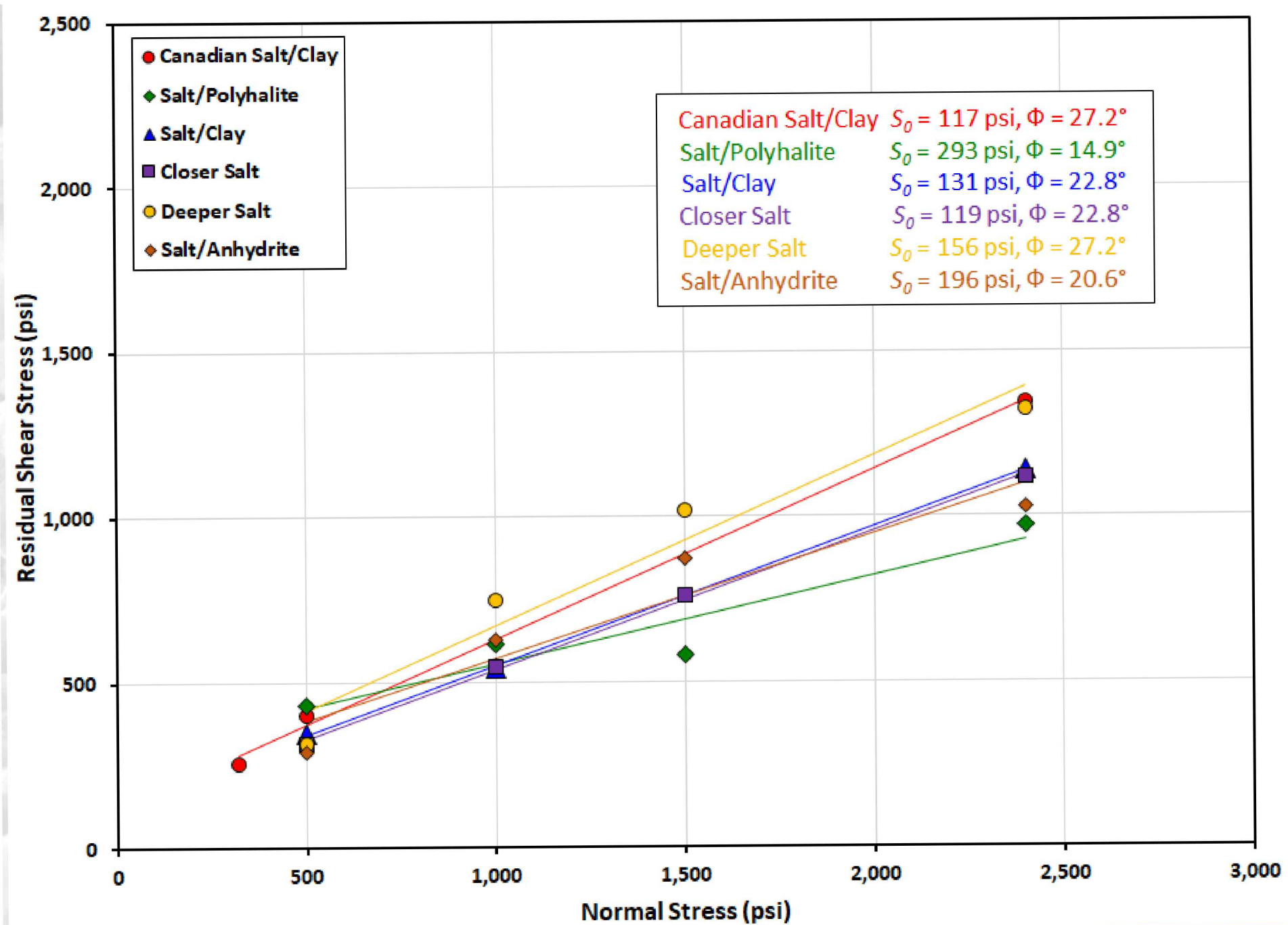
Salt/anhydrite tests (intact, post-intact)



2-1-90 Intact 500 psi 2-1-90 Residual 1,000 psi 3-2-30 Intact 1,000 psi 3-2-30 Residual 1,500
1-2-30 Intact 1,500 psi 1-2-30 Residual 2,400 psi 1-1-41 Intact 2,400 psi







Test observations

- Overall testing technique is good
- Two indications test setup might not be ideally rigid:
 - Fractures all tend to occur “top down”
 - Radial cracks in grout
- Able to obtain peak and residual stress curves from most samples



Conclusions and Next Steps



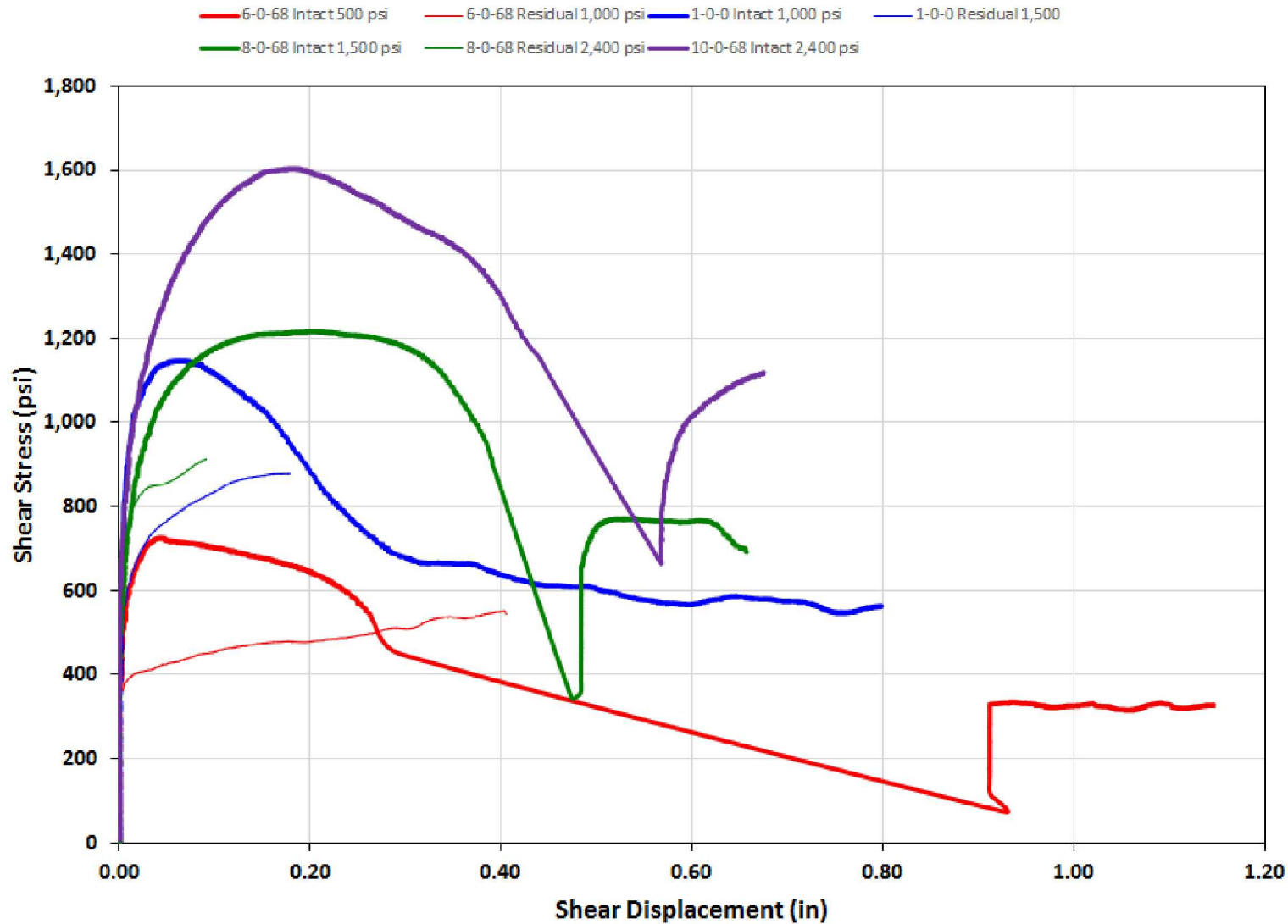
Conclusions

- Clay/salt contacts much stronger than anticipated
- Sample stiffness much higher than anticipated
- Consistent behavior among different samples on intact tests

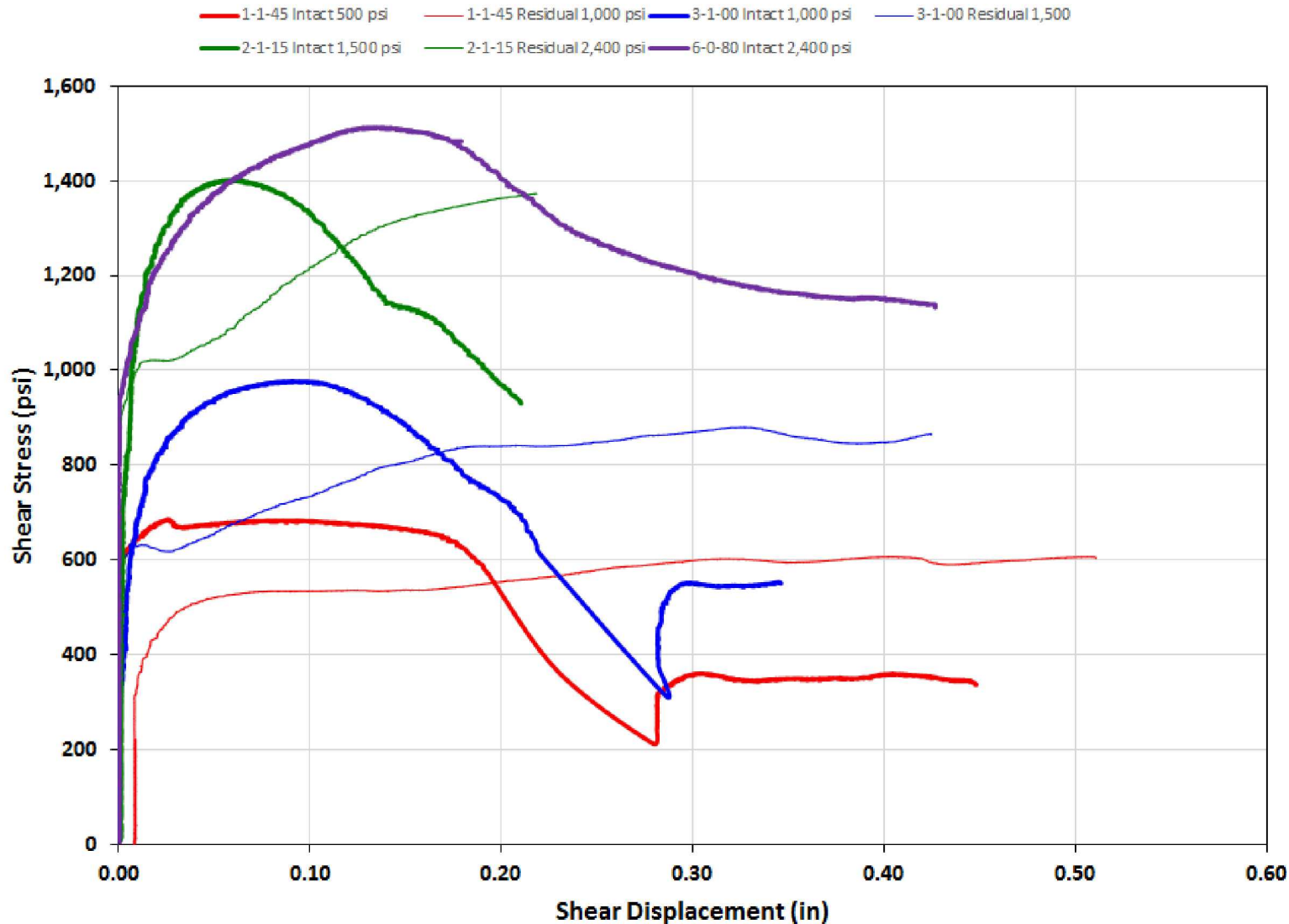
Next Steps

- Rerun a few selected tests to improve results
- Begin development of constitutive model based on test results
- Develop test for manufactured clay seam (bentonite?) which may be less stiff

Pure salt tests



Salt/clay tests



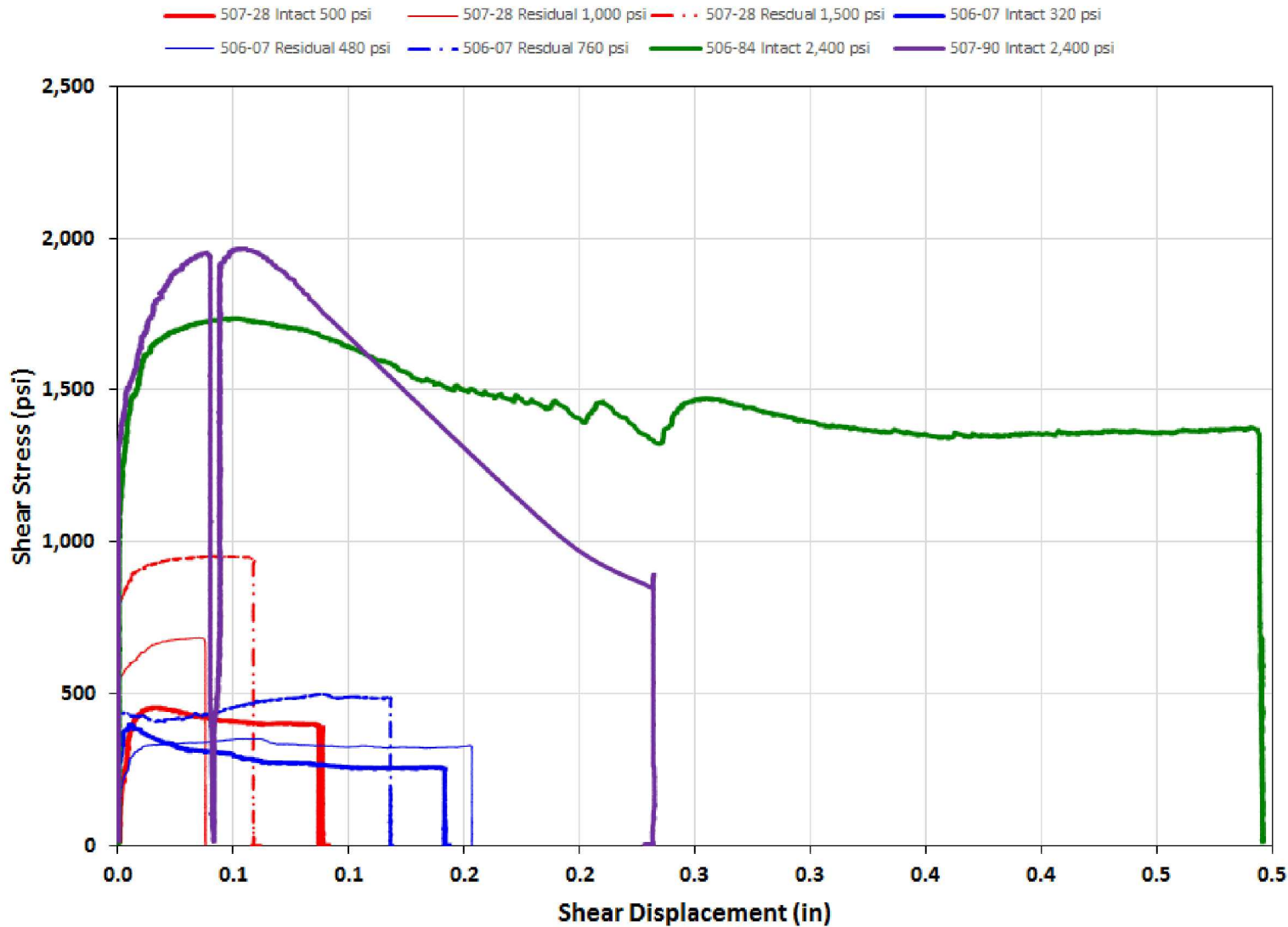
Canadian salt tests



Intact test, $\sigma_n = 2400$ psi



Canadian salt tests



Salt/polyhalite tests



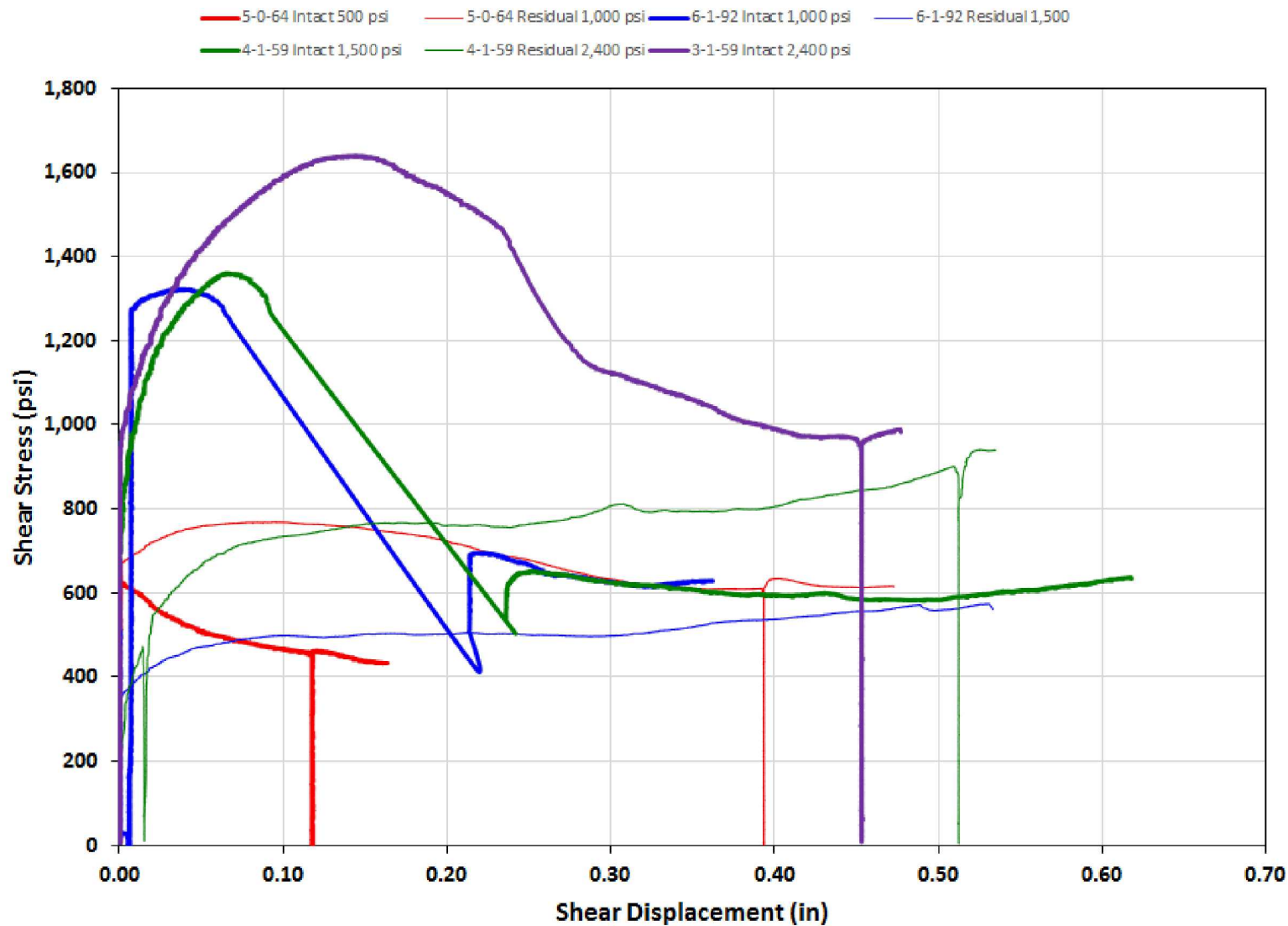
**Intact test,
 $\sigma_n=1500$ psi**



**Residual test,
 $\sigma_n=2400$ psi**



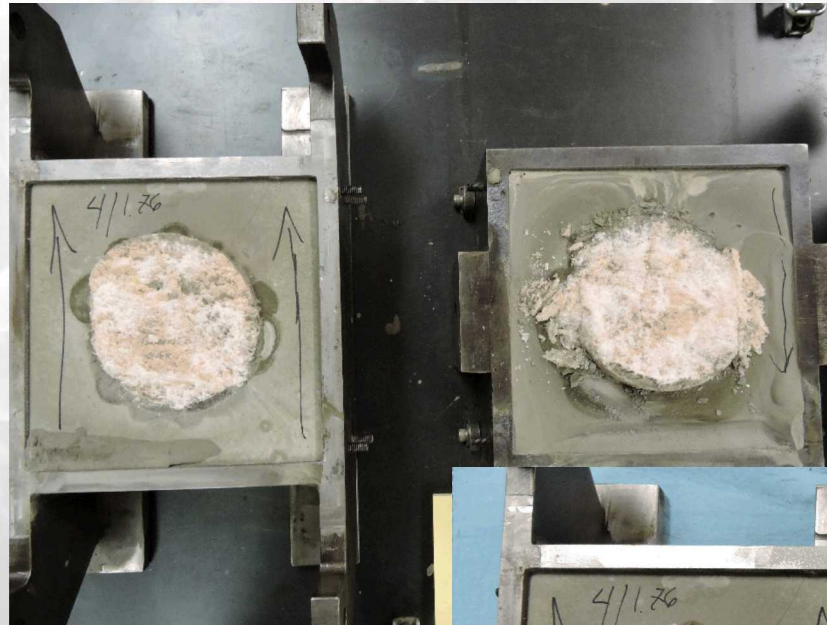
Salt/polyhalite tests



Mixed salt tests



**Intact test,
 $\sigma_n = 1500$ psi**



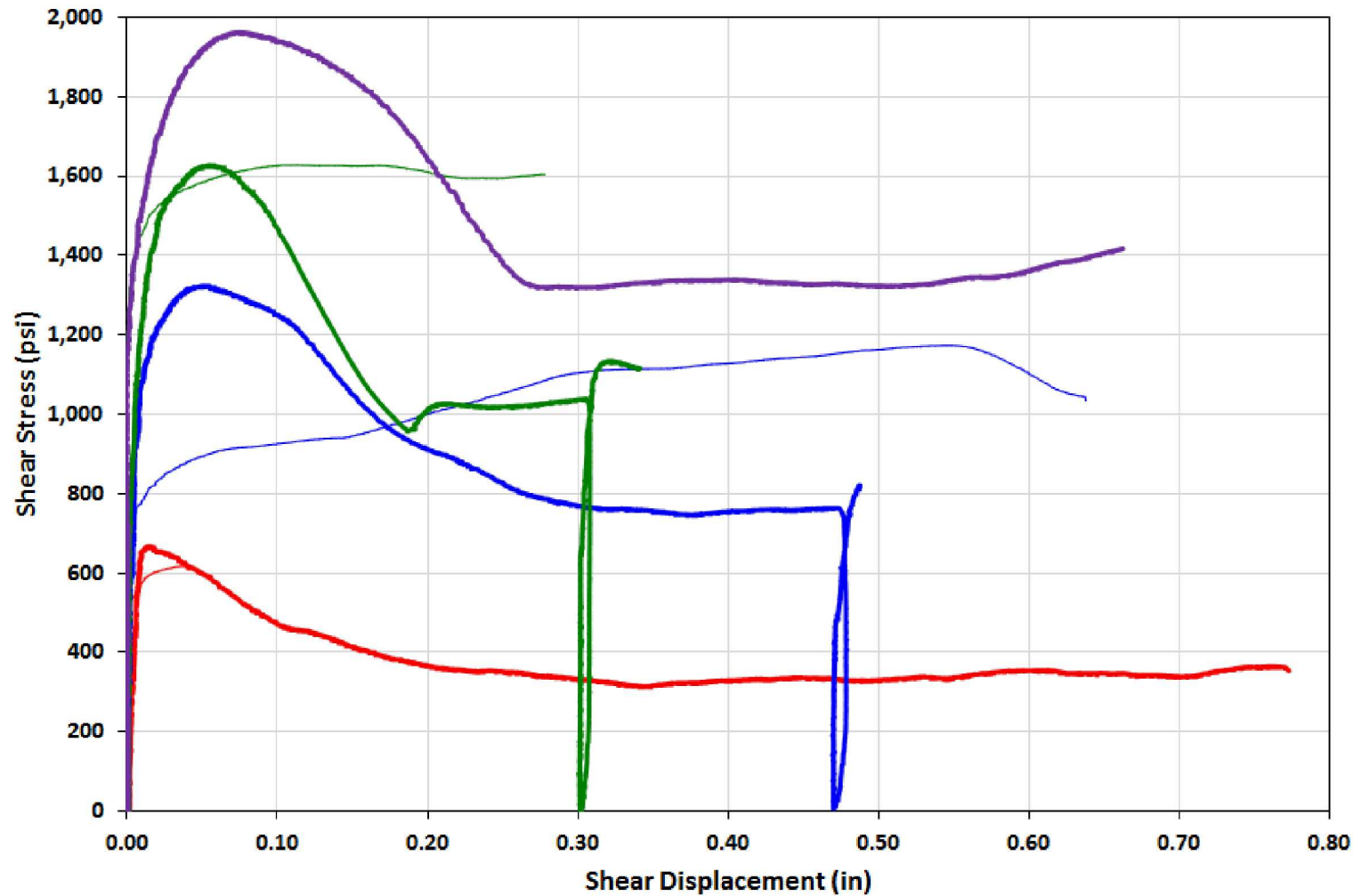
**Residual test,
 $\sigma_n = 2400$ psi**



Mixed salt tests



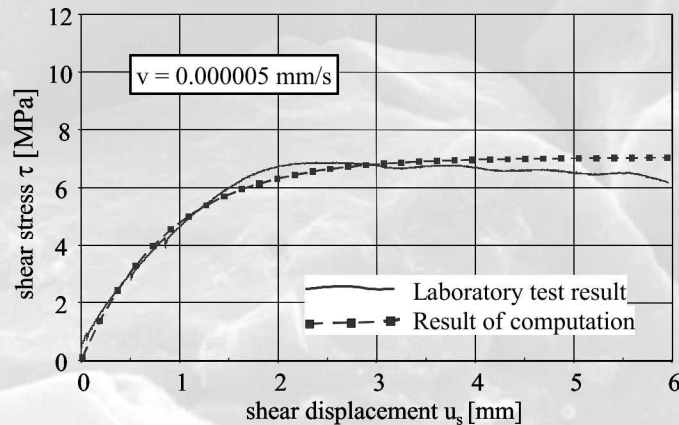
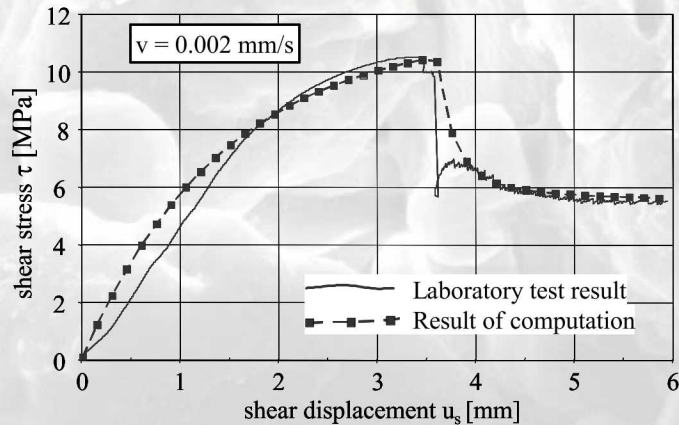
1-1-76 Intact 500 psi 1-1-76 Residual 1,000 psi 2-1-76 Intact 1,000 psi 2-1-76 Residual 1,500
4-1-76 Intact 1,500 psi 4-1-76 Residual 2,400 psi 5-1-76 Intact 2,400 psi



Carnallite on Salt Direct Shear Results



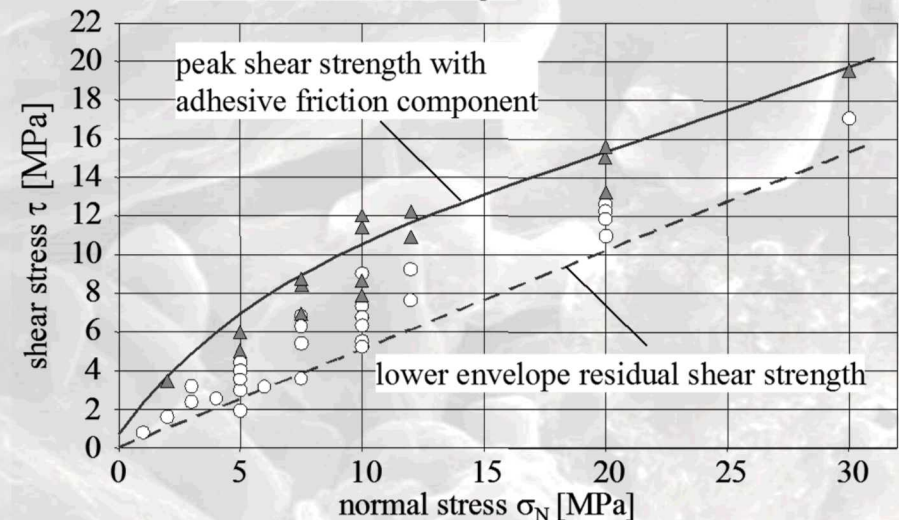
Two Individual Tests



Summary of Test Results

Results of shear tests with different shear velocities

- ▲ measured peak strength
- measured residual strength



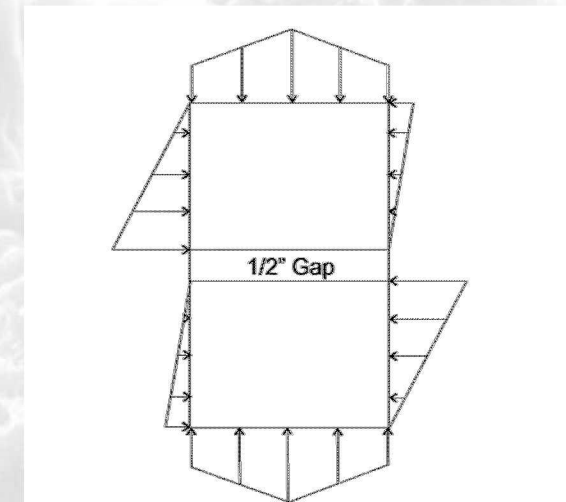
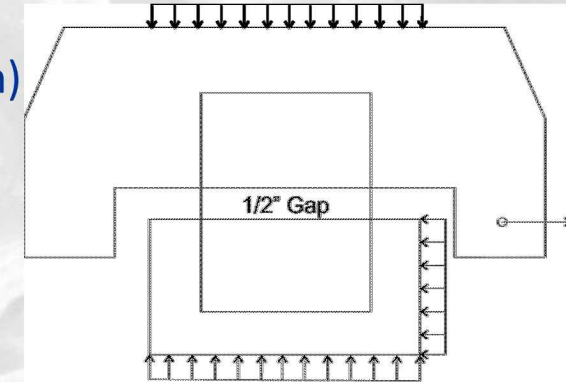
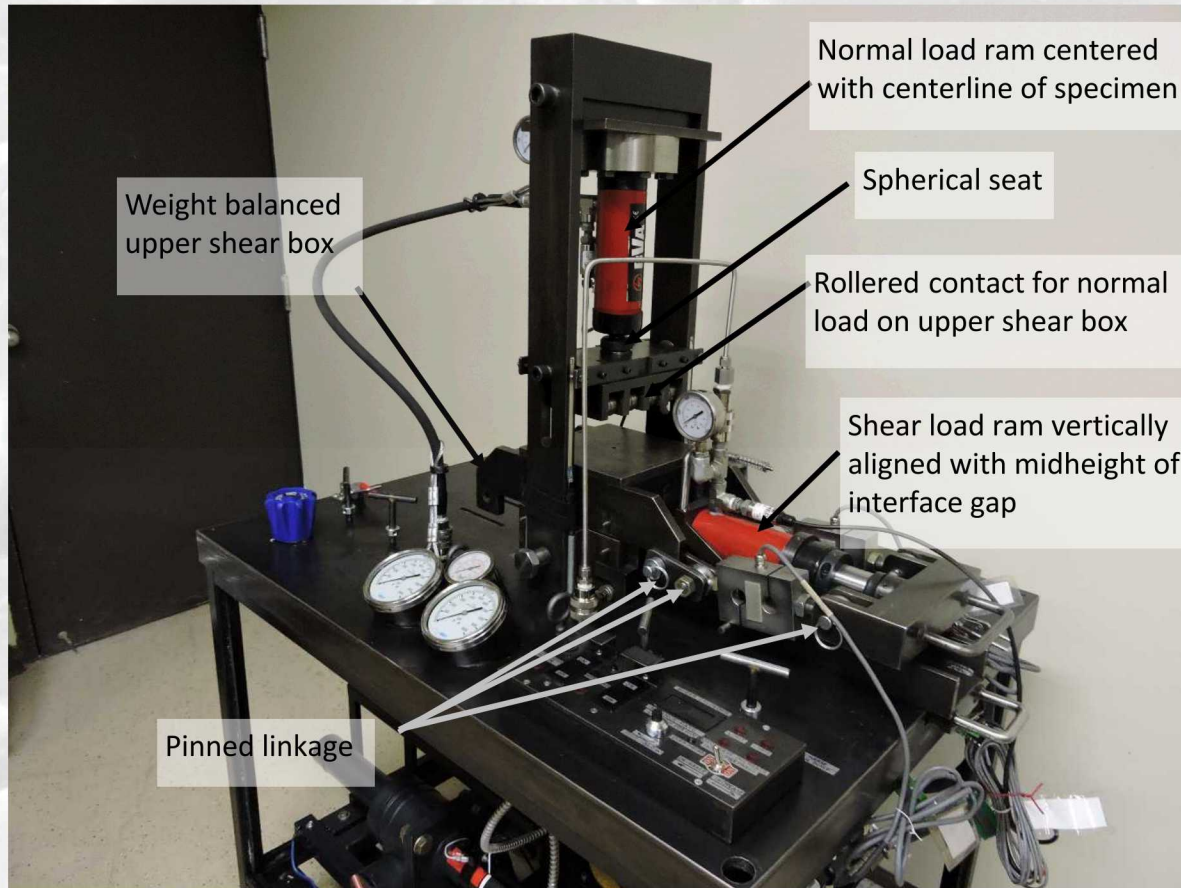
Coulomb Friction?

$$\tau = \mu_c \sigma_n$$

Shear Test Setup



- Similar to Minkley test setup
- RESPEC direct shear machine
- Eliminates bending force due to shear (box that holds specimen)



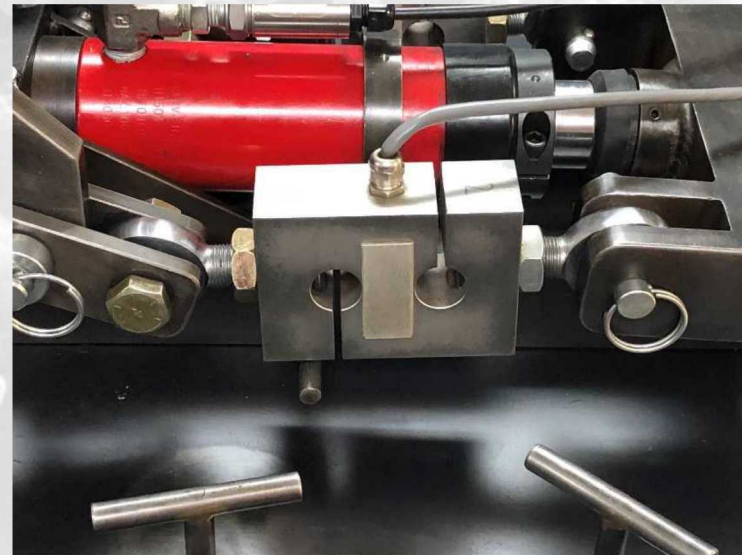
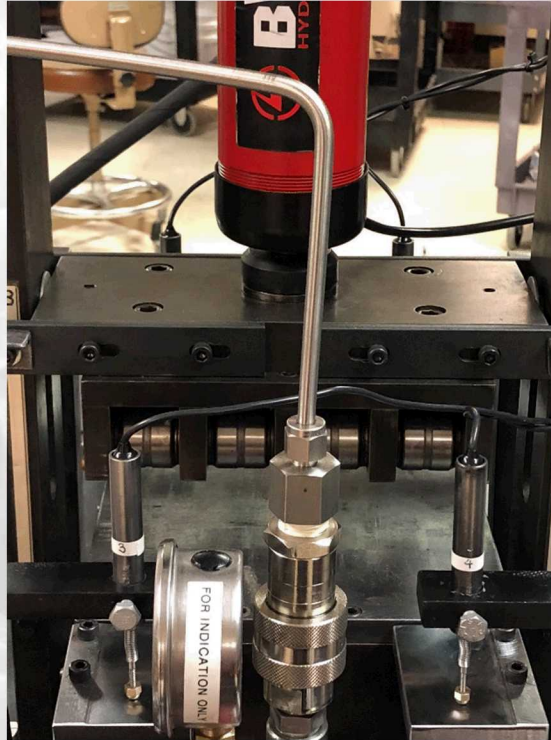
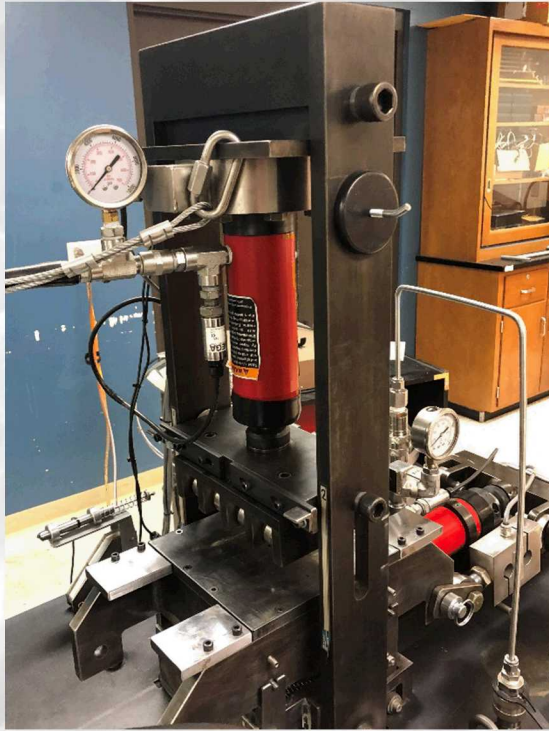
Note: All force profiles depend on contrast in stiffness between the specimen and grout.

Additional tests to be run



- Rerun halite/polyhalite intact tests for 500, 1000 psi normal stress
- Rerun halite/clay intact test for 1500 psi
- Rerun pure salt test for 1000 psi
- Rerun mixed salt test for 500 psi
- Rerun halite/anhydrite test for 500 psi
- Others upon request from WEIMOS participants
- Many more test samples have been made – saving some for possible tension tests
- Not doing rate dependence test, as apparatus cannot operate at slower speeds

Direct shear test machine



- S-shaped load cell – gaps opened during some tests
- 4 normal displacement gages, average displacement used to calculate stiffness

4 clay test samples



500 psi intact test sample

1,000 psi intact test sample

1500 psi intact test sample

2,400 psi intact test sample