

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

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9<sup>th</sup> Conference on the Mechanical Behavior of Salt

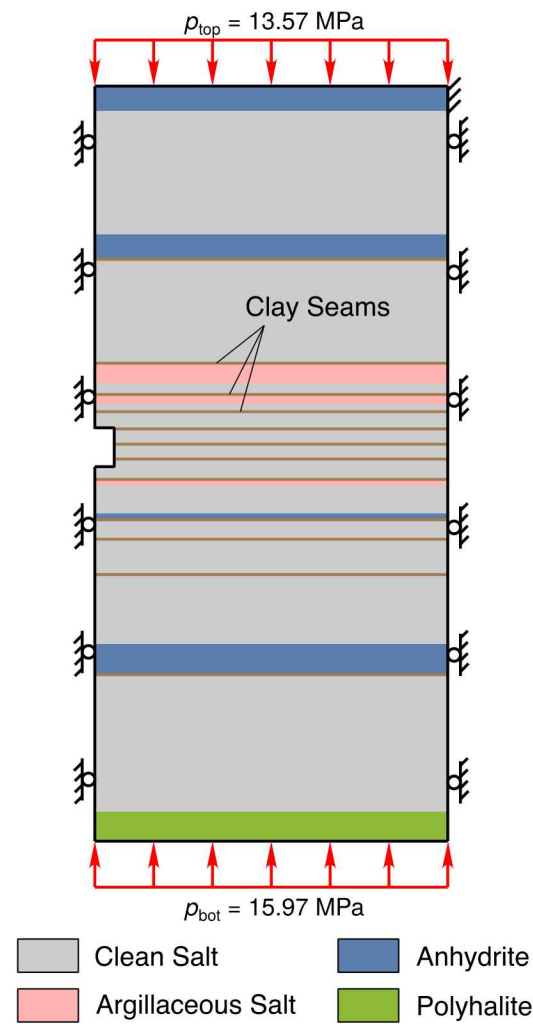
Hannover, Germany

September 12-14, 2018



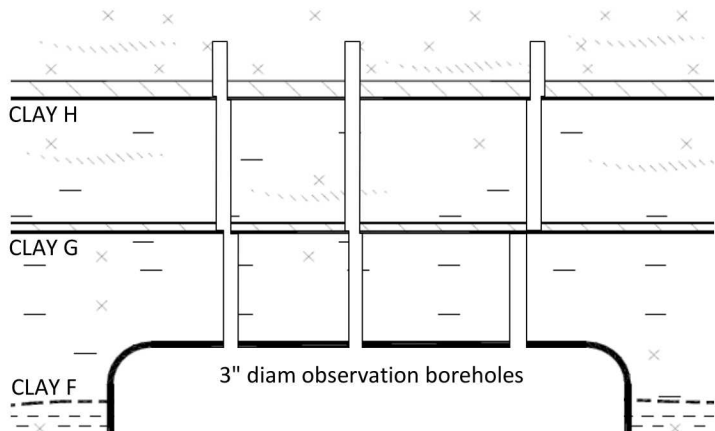
# Discontinuities in salt

- Influence of nonhomogeneities in repository performance identified as 1 of 4 key areas of the research agenda
- Examples include bedding interfaces, boundary shear planes, joints, and seams of non-halite materials such as anhydrite and clay
- Does shear strain create a permeable flow path along an interface or premature salt failure?
- Little existing lab or *in situ* data to characterize shear strength of salt interface and effects of shear on interface displacement and permeability

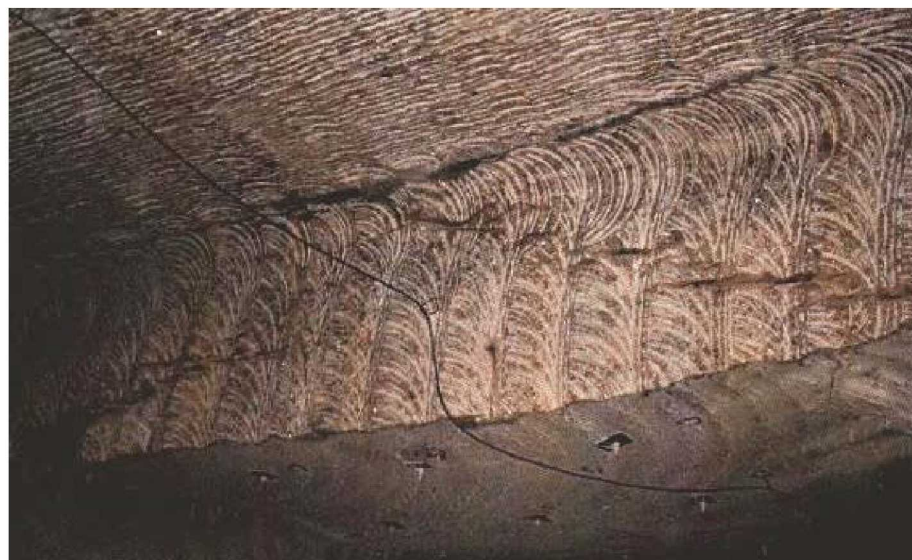


WIPP Stratigraphy

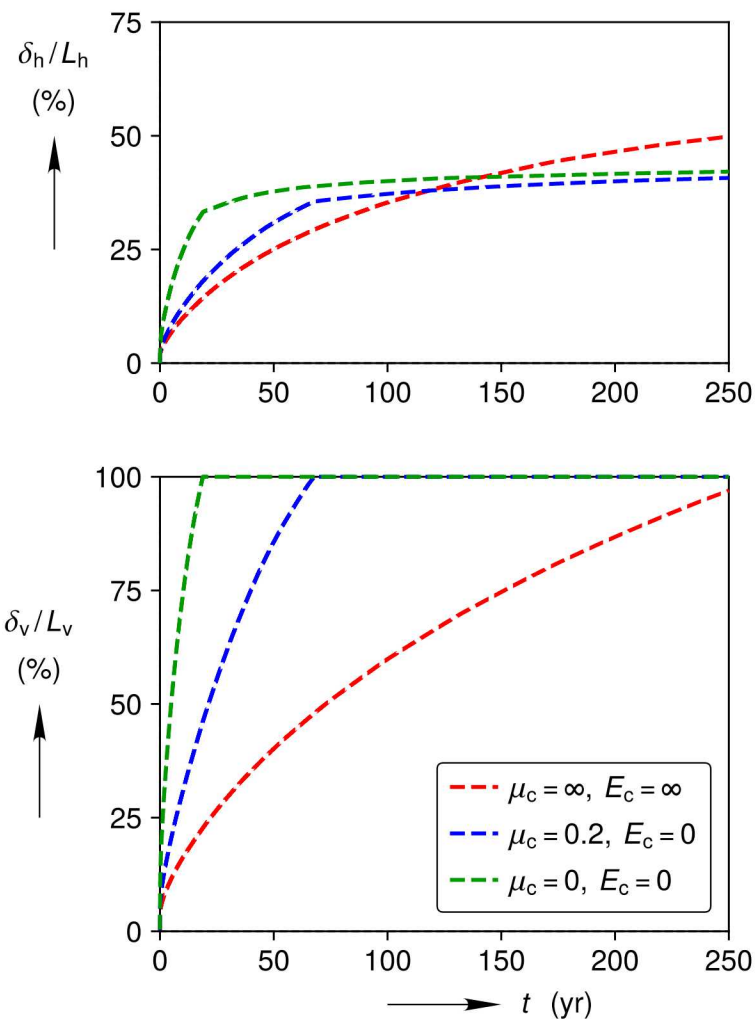
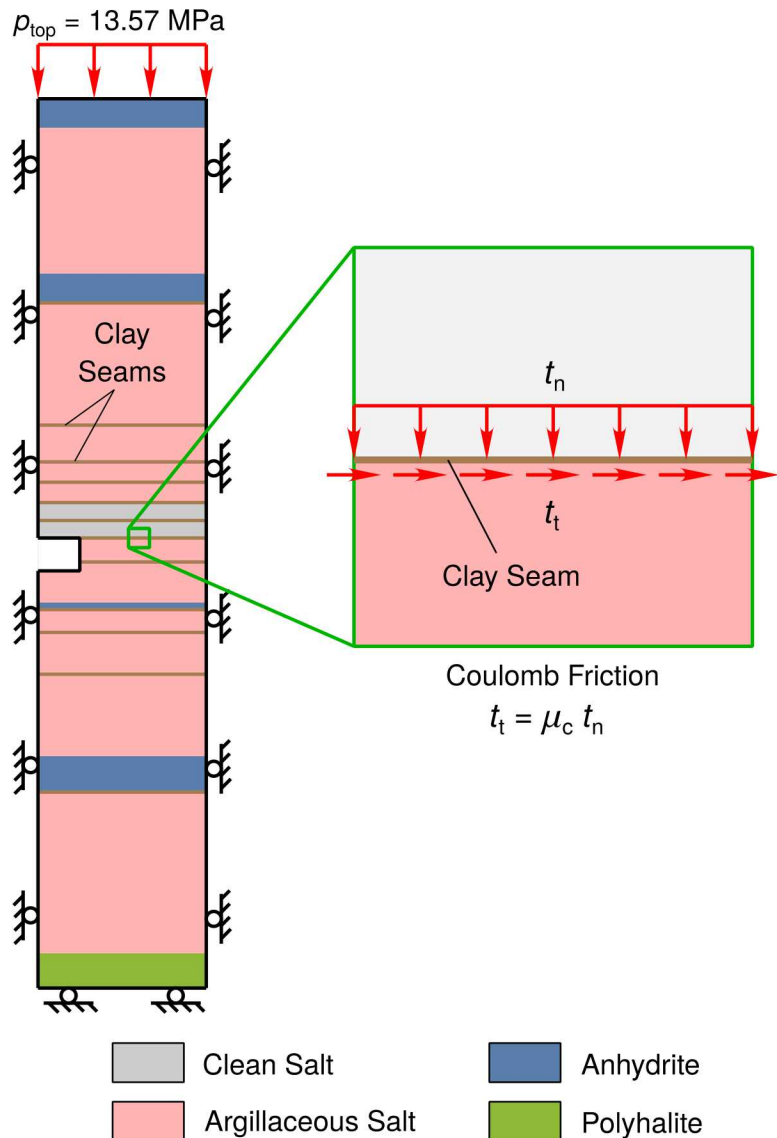
## Interface Sliding



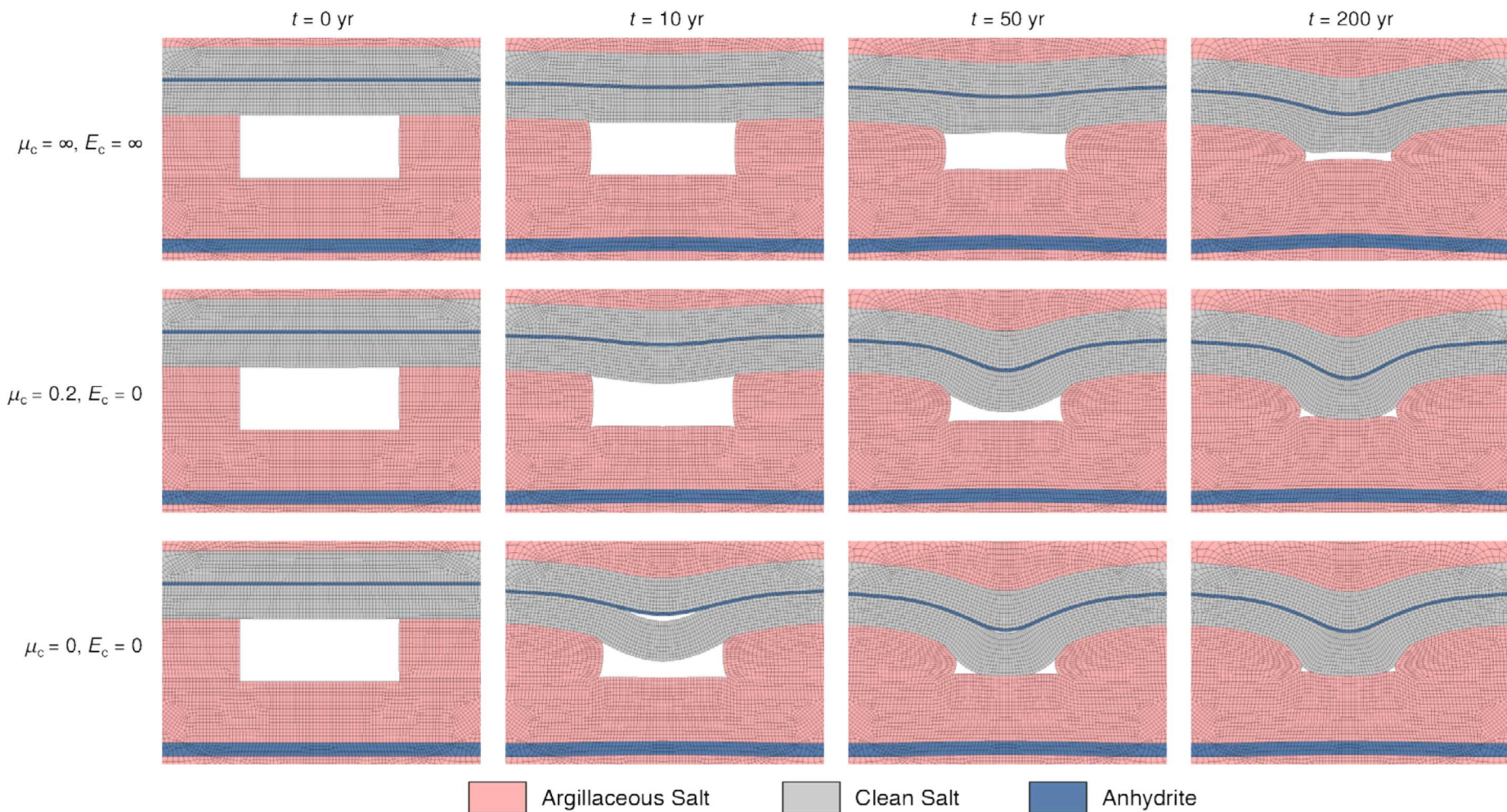
## Interface Separation



# Clay Seam Impact

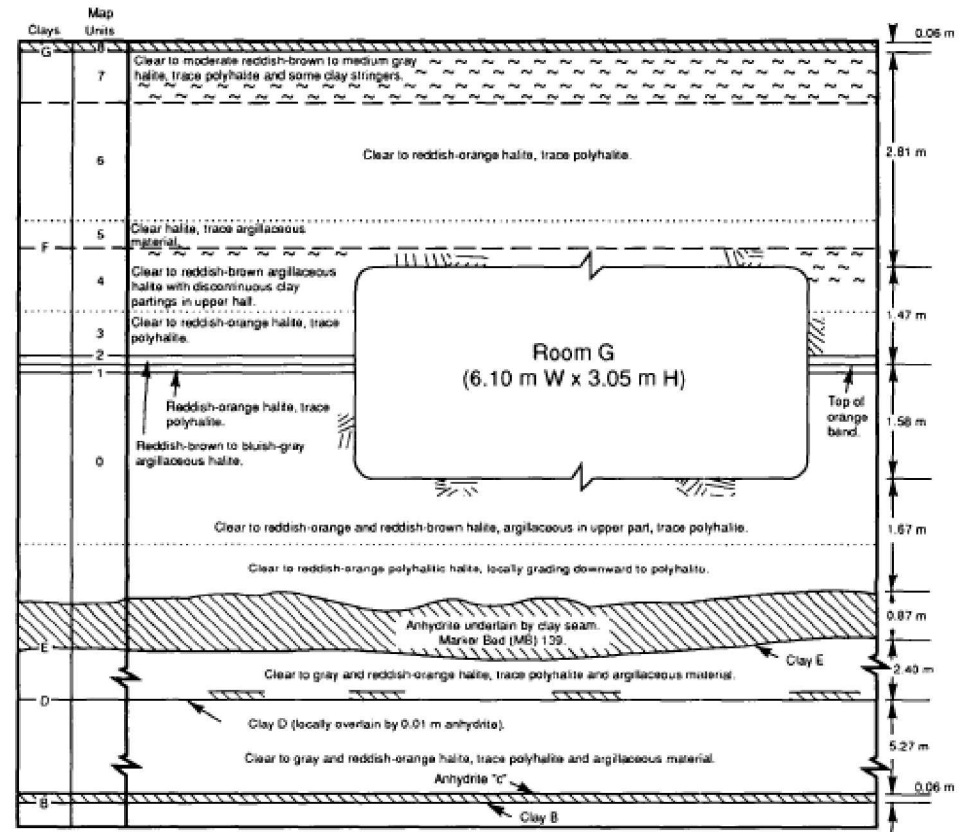


# Clay Seam Impact



# Early test proposed for WIPP

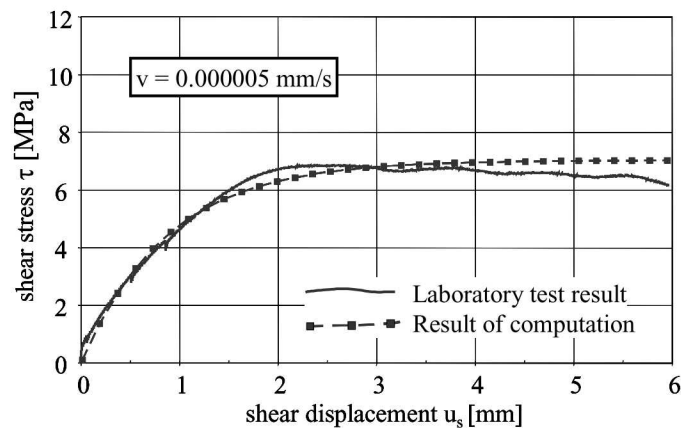
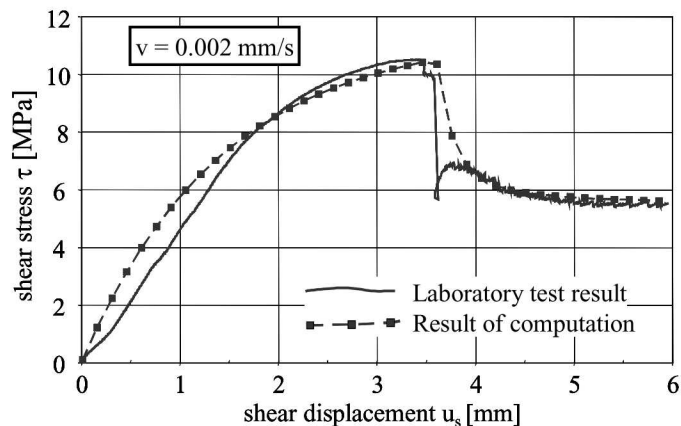
- Munson & Matalucci (1983) proposed in situ test with direct shear across clay seam.
- 1 X 1-m block in wall containing representative clay seam would be isolated by cutting around it in place in one of the drifts.
- Flatjacks installed in slots cut around the block to apply shear and normal stresses.
- Displacements along and across the seam would be measured as function of applied stress.
- **This proposed test never occurred.**



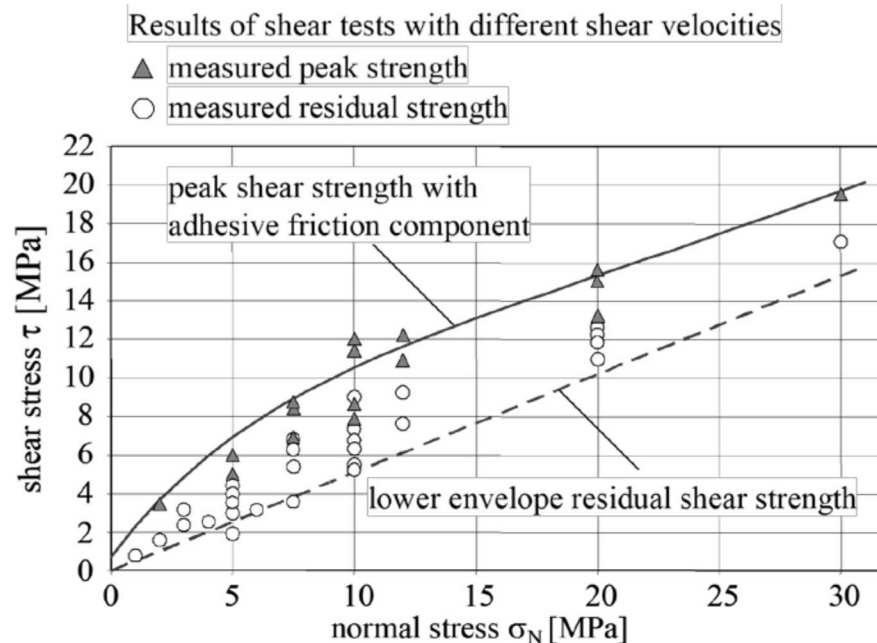
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# Carnallite on Salt Direct Shear Results

## Two Individual Tests



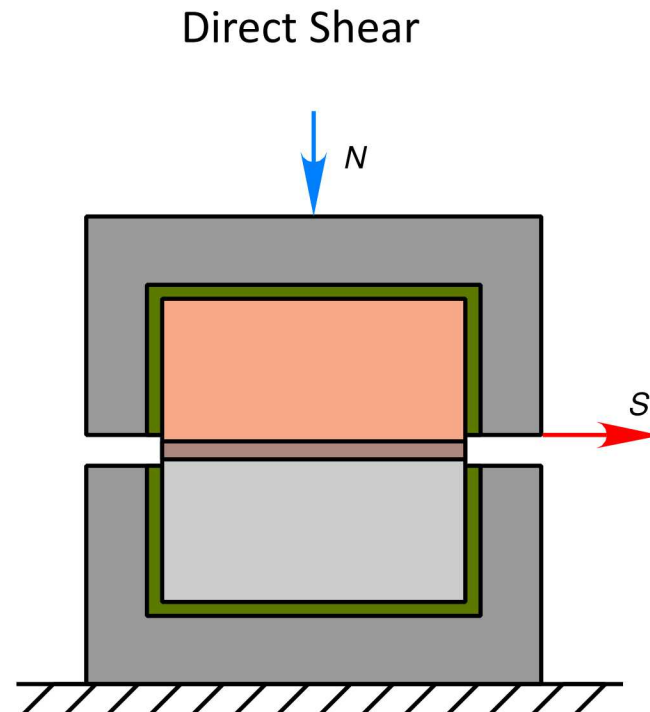
## Summary of Test Results



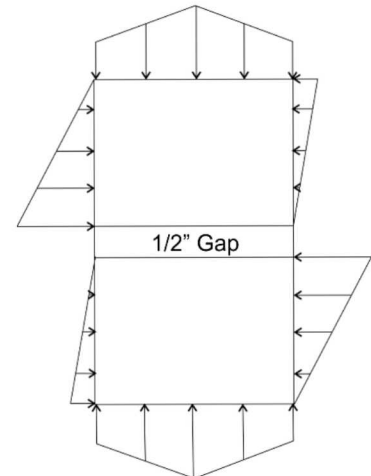
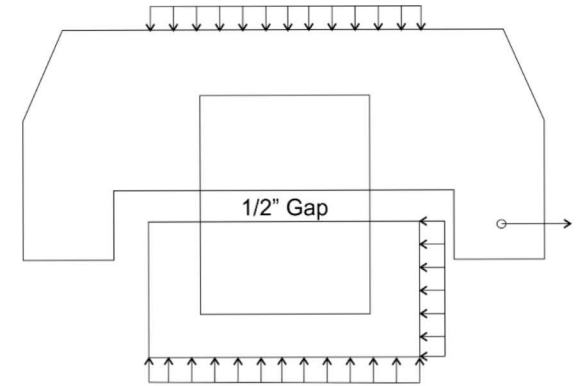
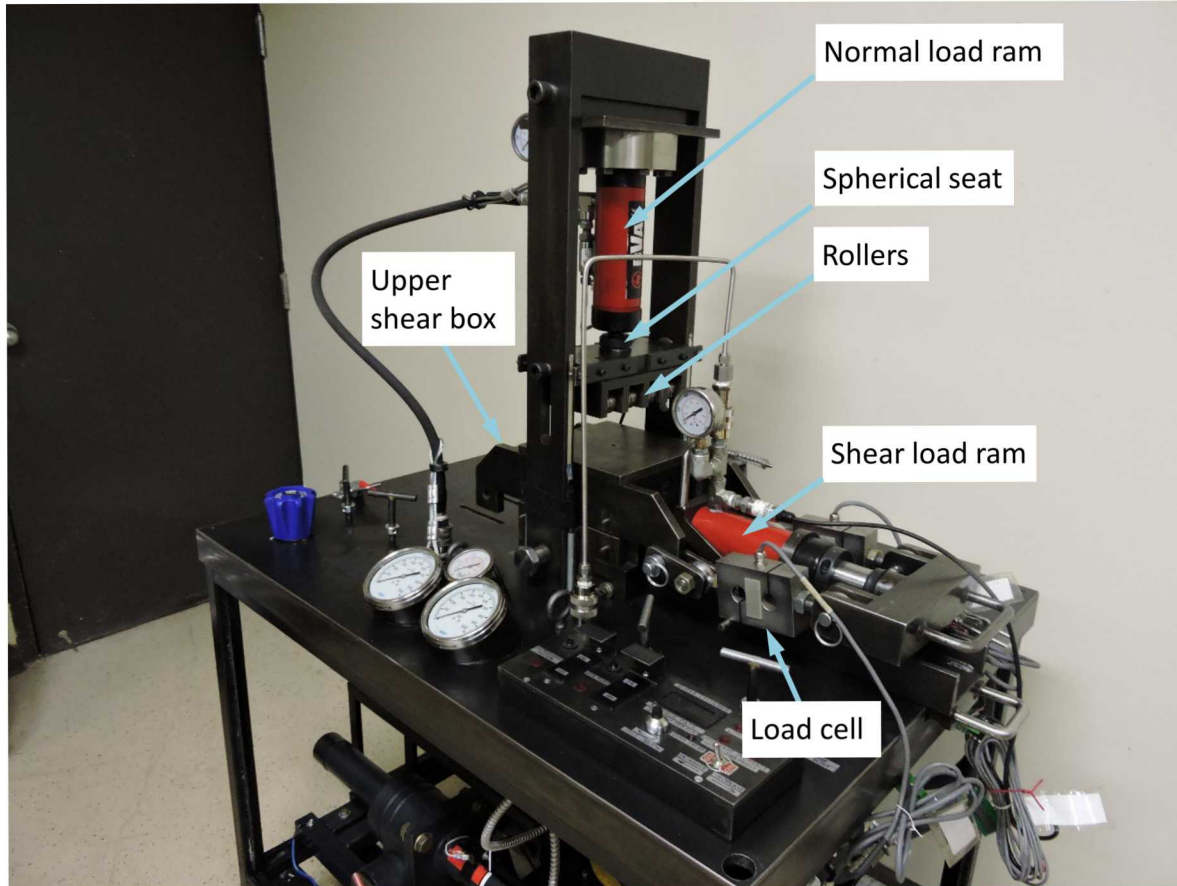
Coulomb Friction?

$$\tau = \mu_c \sigma_n$$

- 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

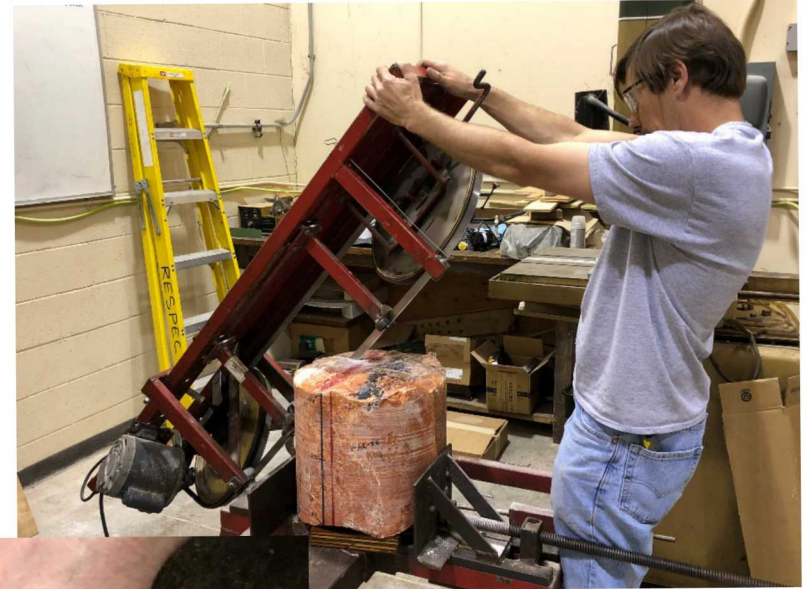


**Note:** All force profiles depend on contrast in stiffness between the specimen and grout.

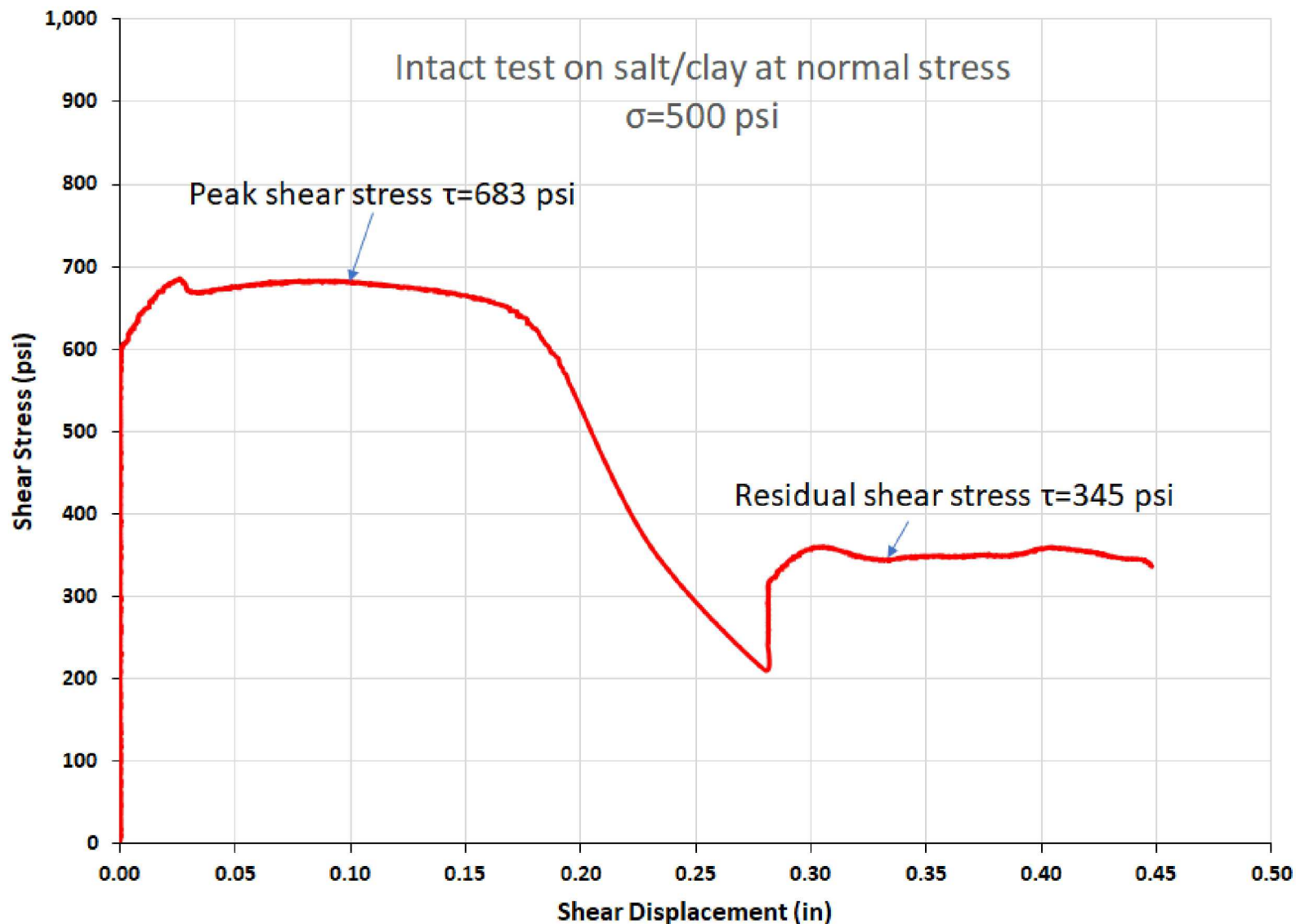
# Laboratory tests to date

- 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.)
- Analysis plan to develop constitutive, numerical model for shear slip at interface from results of 2018 lab tests.

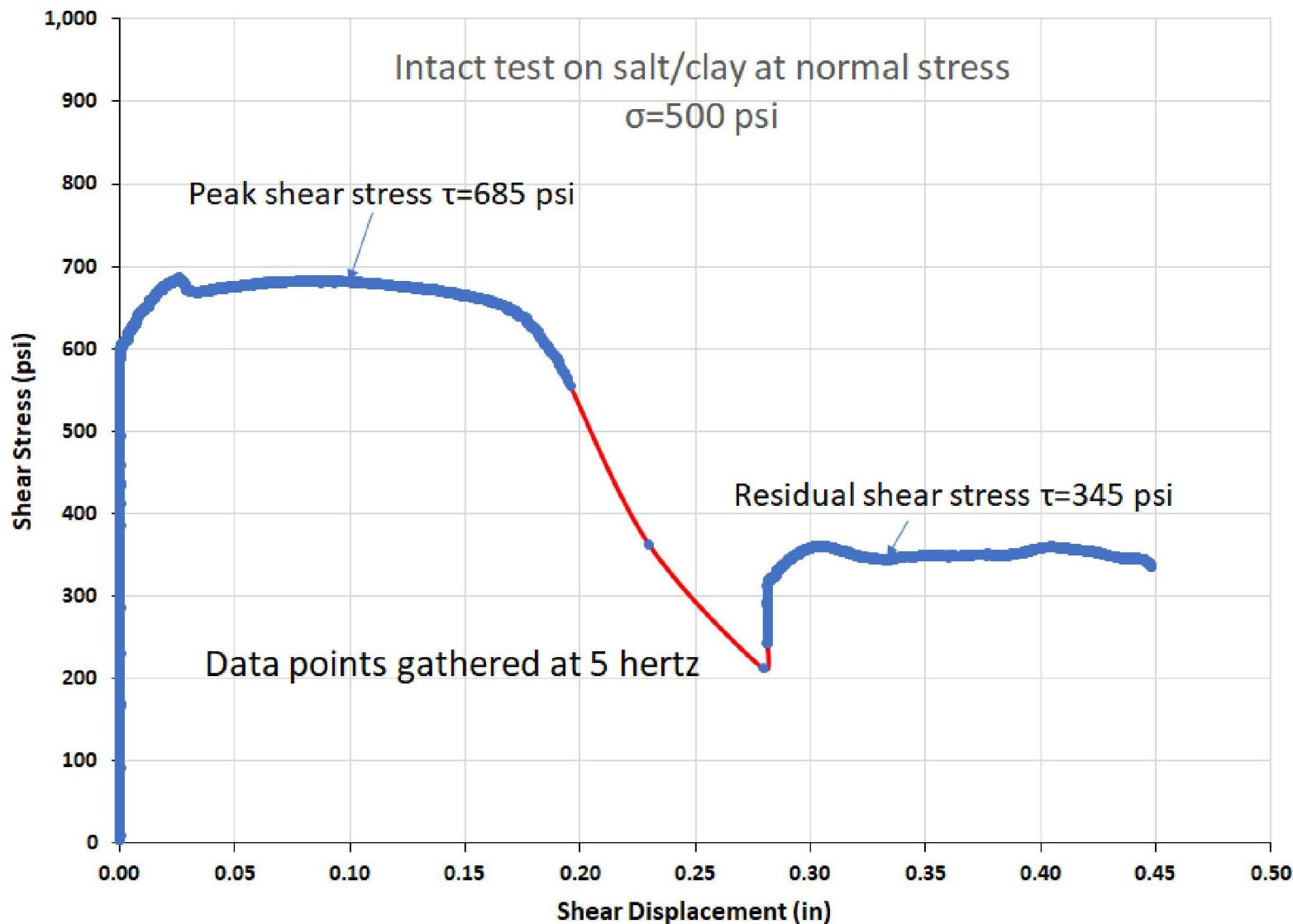
- 24 samples total, 4 intact tests/3 residual tests for each material type
- Normal pressures for intact tests were 500, 100, 1500, 2400 psi
- Post-impact residual tests at higher normal stresses for most samples
- Tests were performed on the following core samples:
  - Canadian halite with clay interface (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)



# Typical test result



# Typical test result



# Closer salt tests



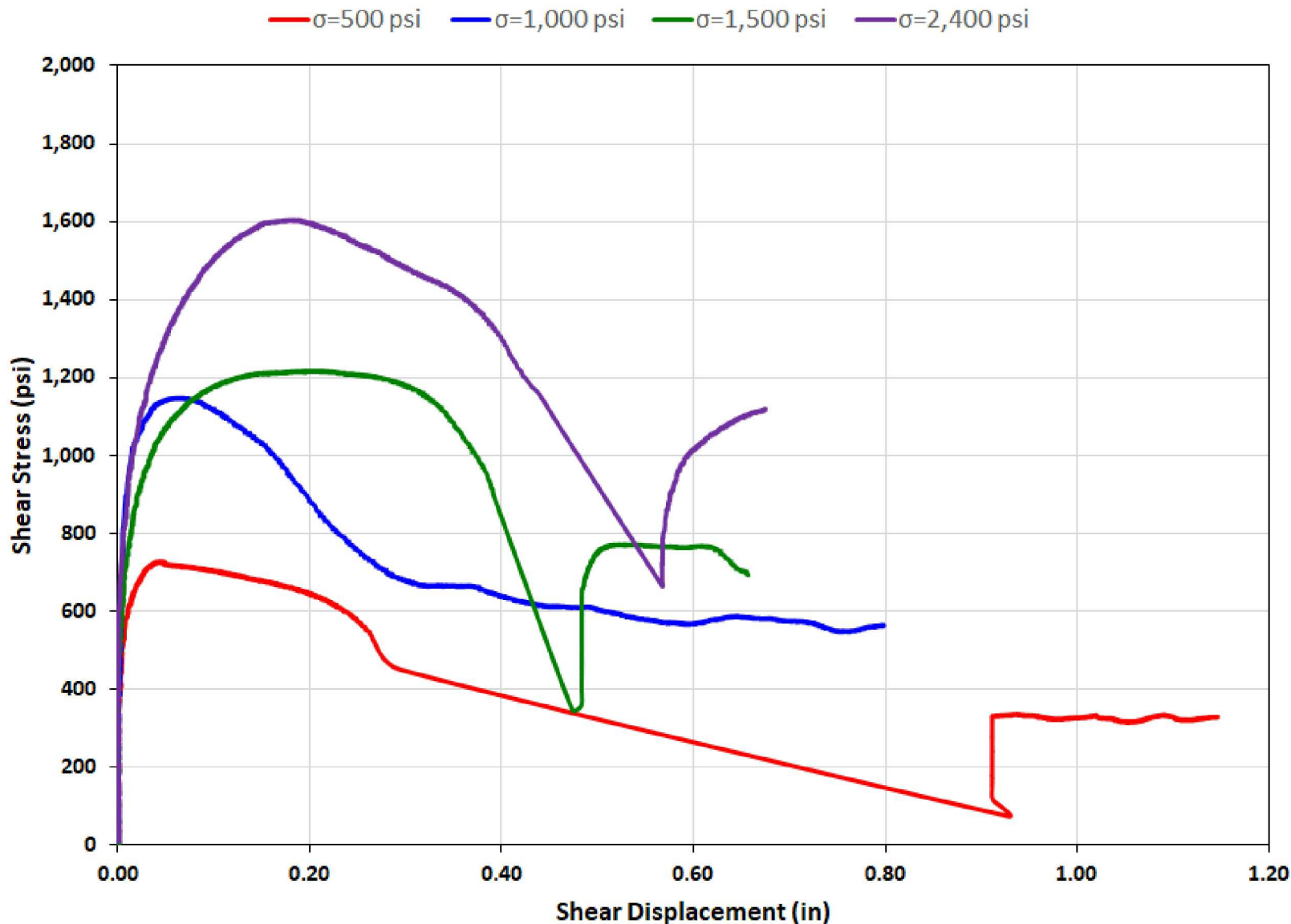
Intact test,  
 $\sigma_n = 1000$  psi,  
side view



Intact test,  
 $\sigma_n = 1000$  psi



# Closer salt tests



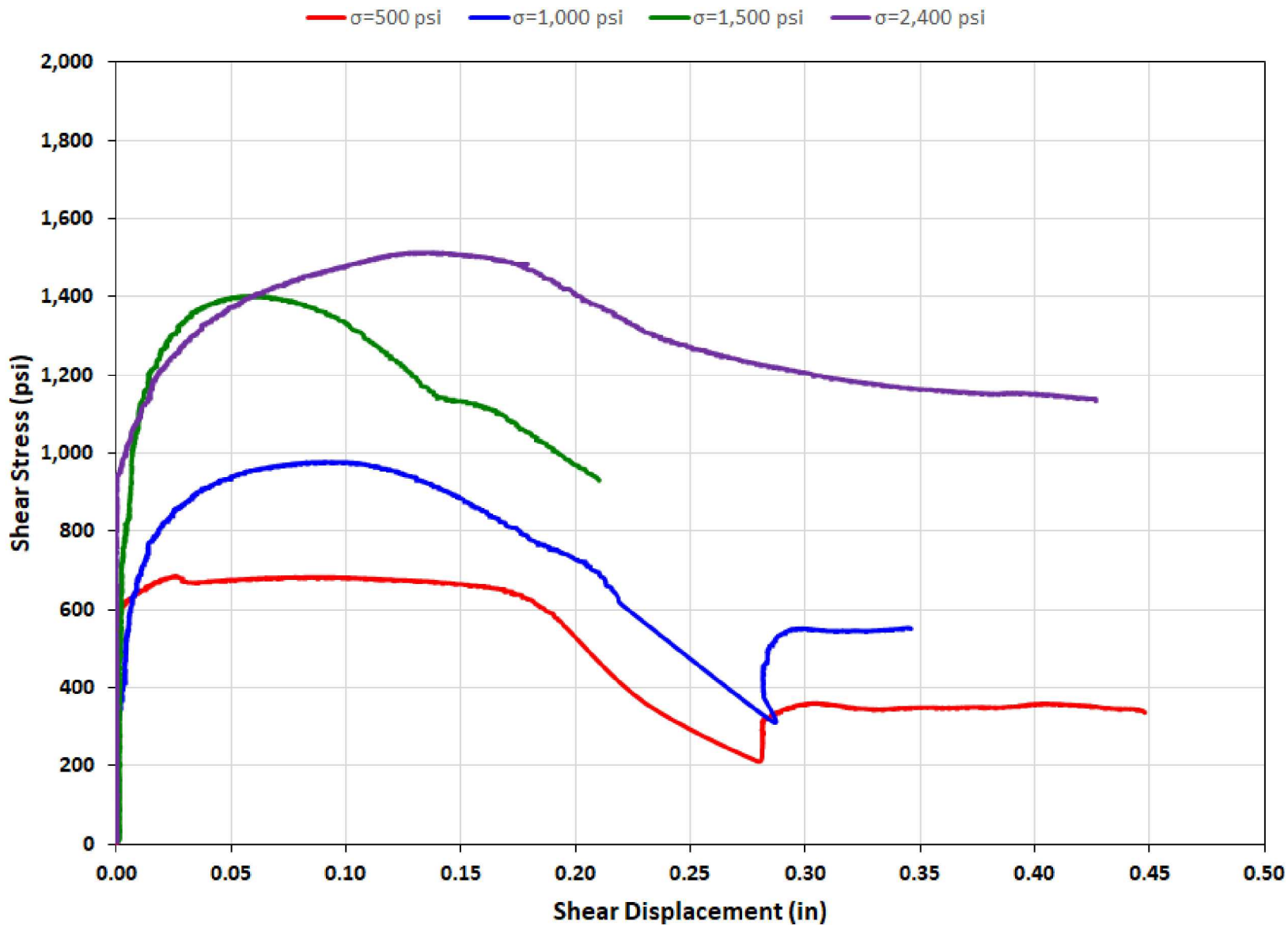


Intact test,  
 $\sigma_n = 1500$  psi

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



# Salt/clay tests



# Salt/anhydrite tests



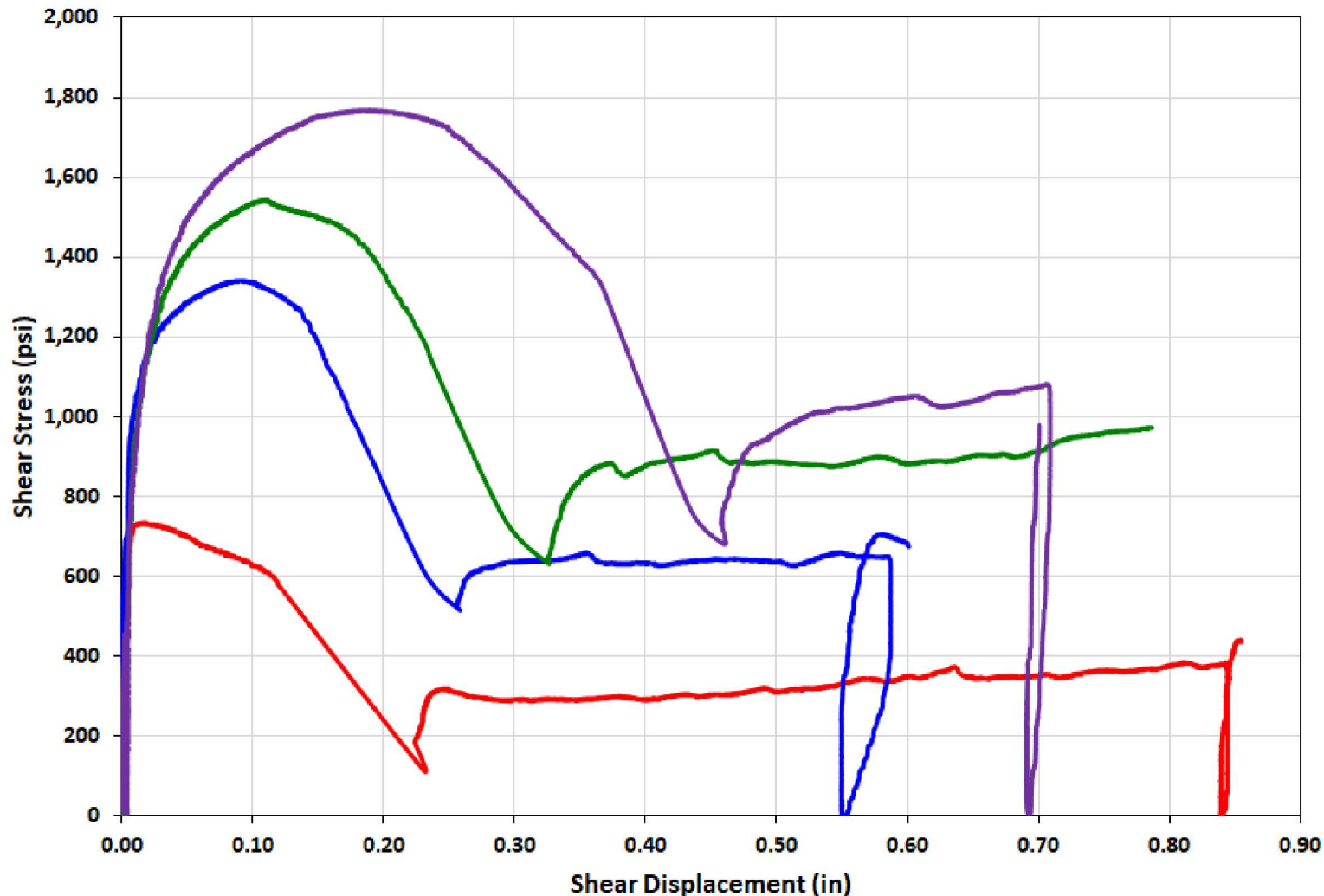
Intact test,  
 $\sigma_n = 500$  psi

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



# Salt/anhydrite tests

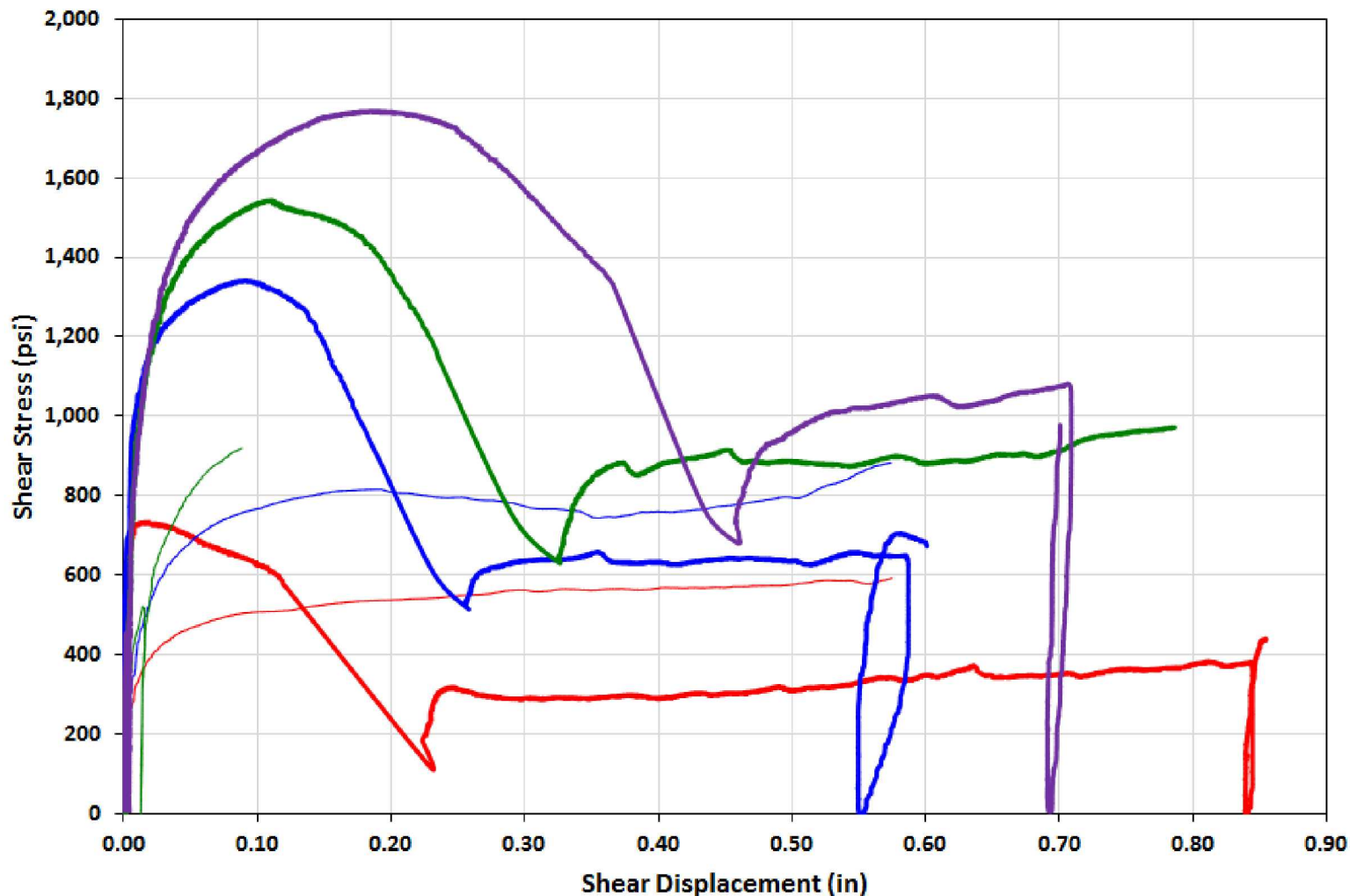
—  $\sigma=500$  psi   
 —  $\sigma=1,000$  psi   
 —  $\sigma=1,500$  psi   
 —  $\sigma=2,400$  psi

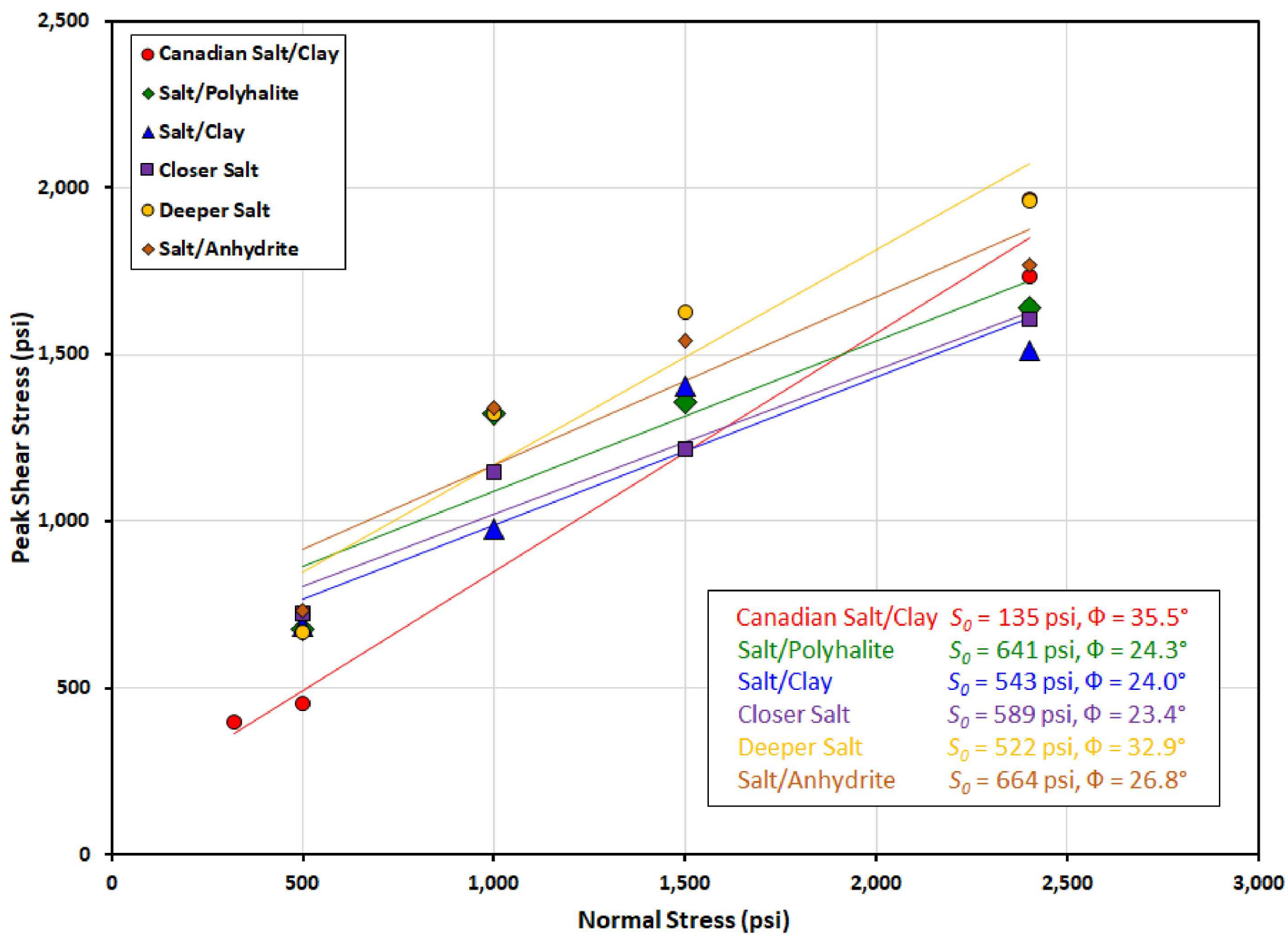


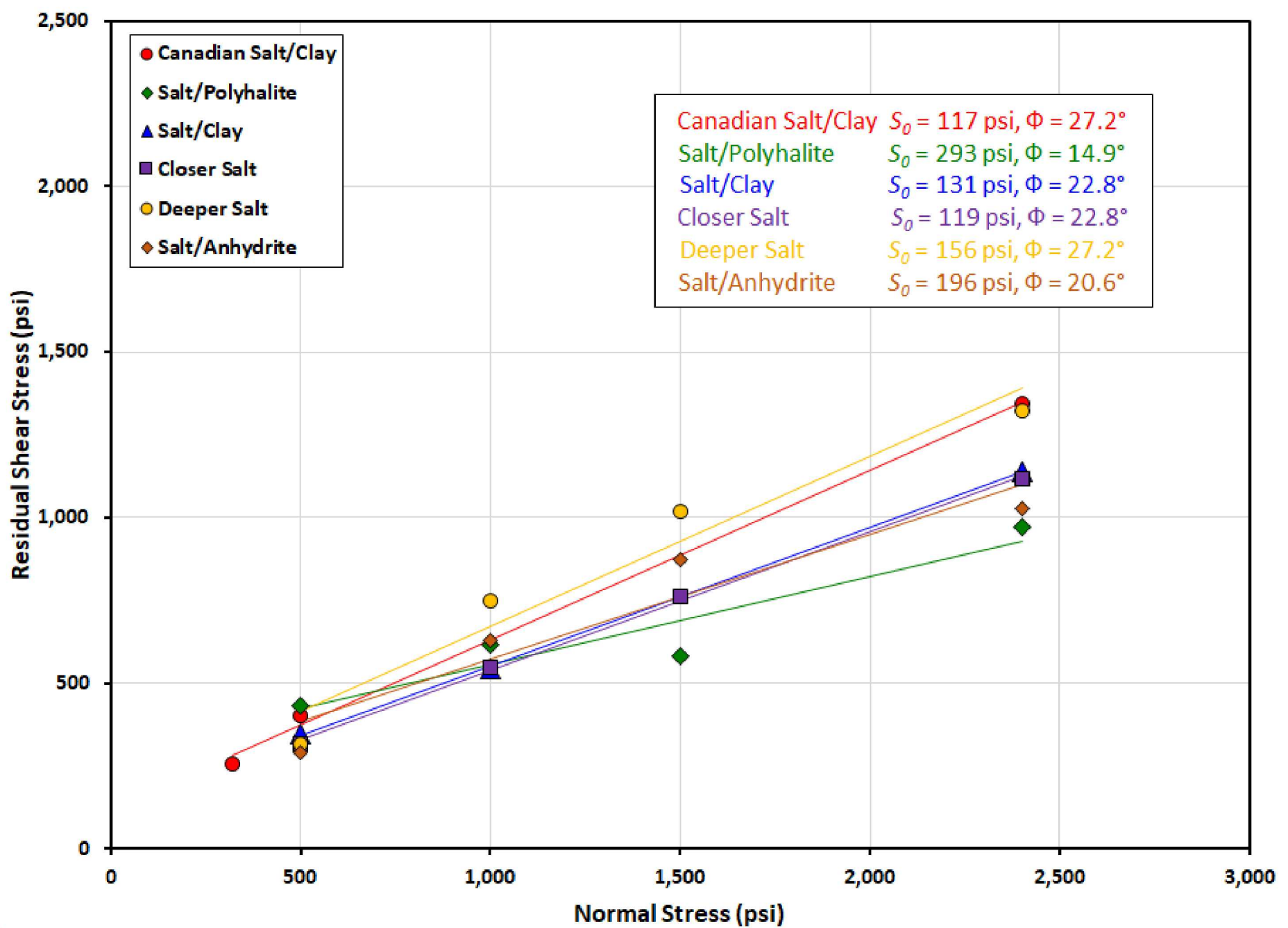


# Salt/anhydrite tests (intact, post-intact)

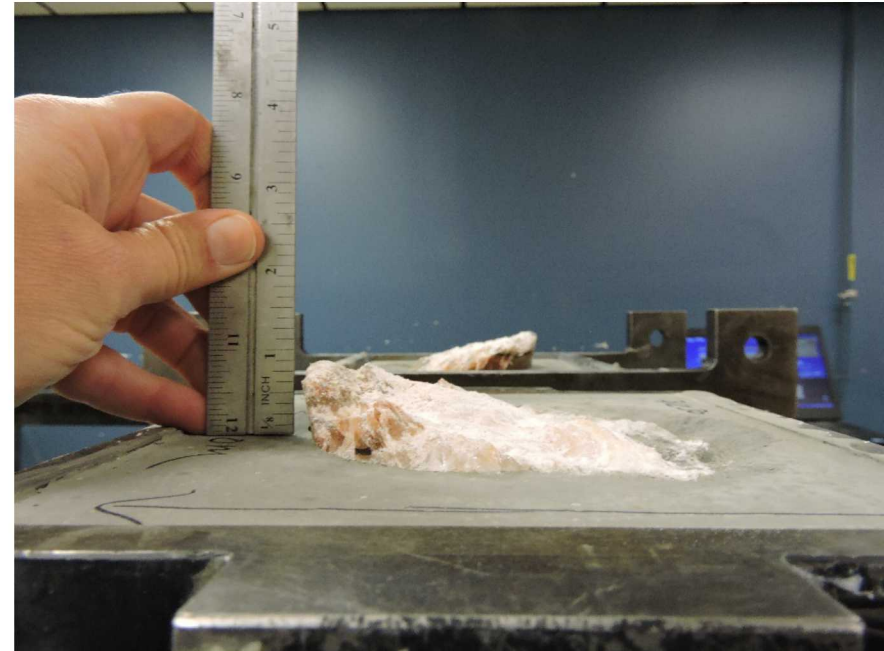
2-1-90 Intact 500 psi    2-1-90 Residual 1,000 psi    3-2-30 Intact 1,000 psi    3-2-30 Residual 1,500  
1-2-30 Intact 1,500 psi    1-2-30 Residual 2,400 psi    1-1-41 Intact 2,400 psi







- 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

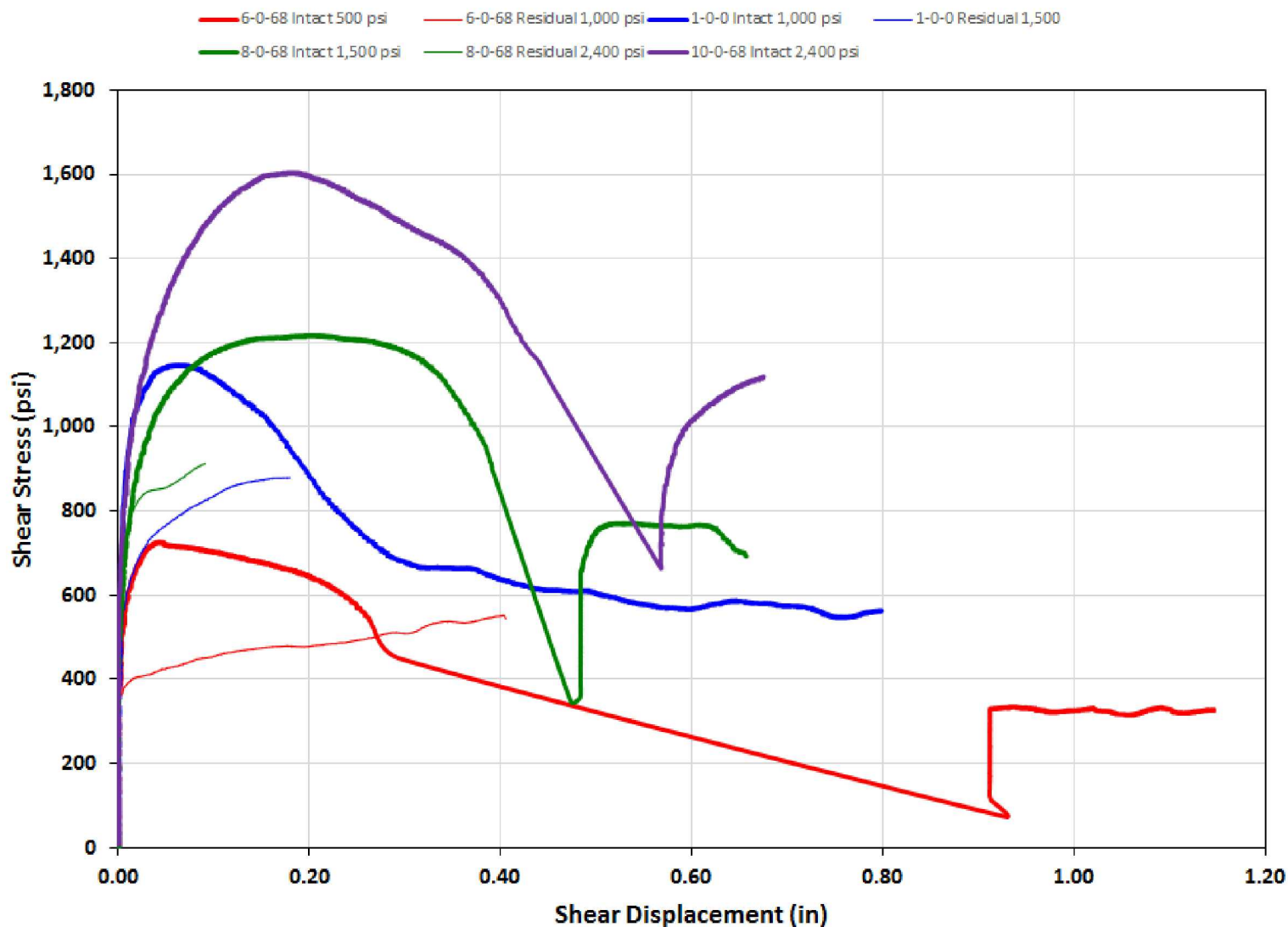
- Clay/salt contacts much stronger than anticipated
- Sample stiffness much higher than anticipated
- Consistent behavior among different samples on intact tests

## Next Steps

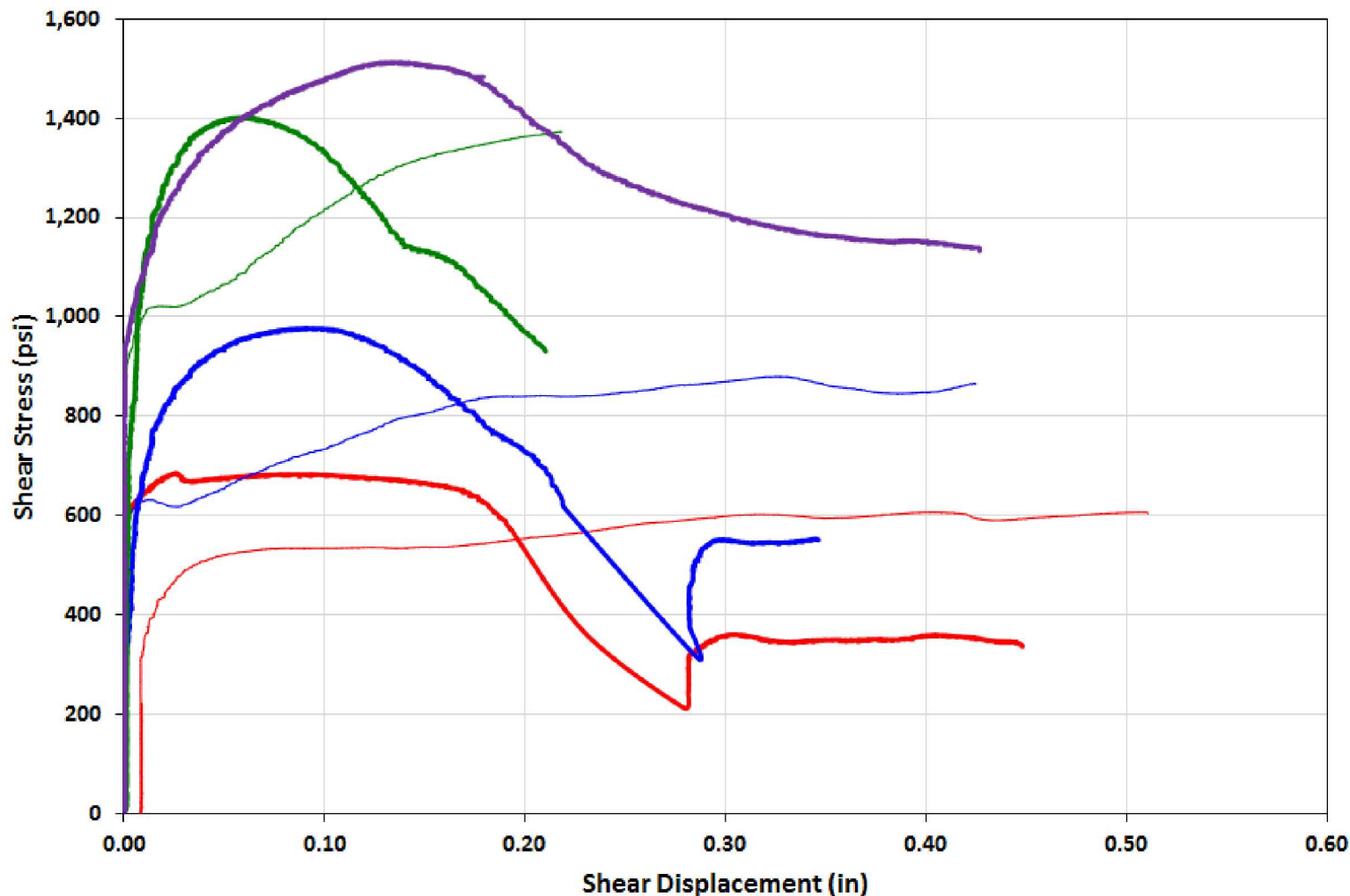
- Rerun a few selected tests to improve results
- Begin development of constitutive model based on test results
- Develop test for manufactured clay seam (bentonite?) which may be less stiff

Thank You!!

# Pure salt tests

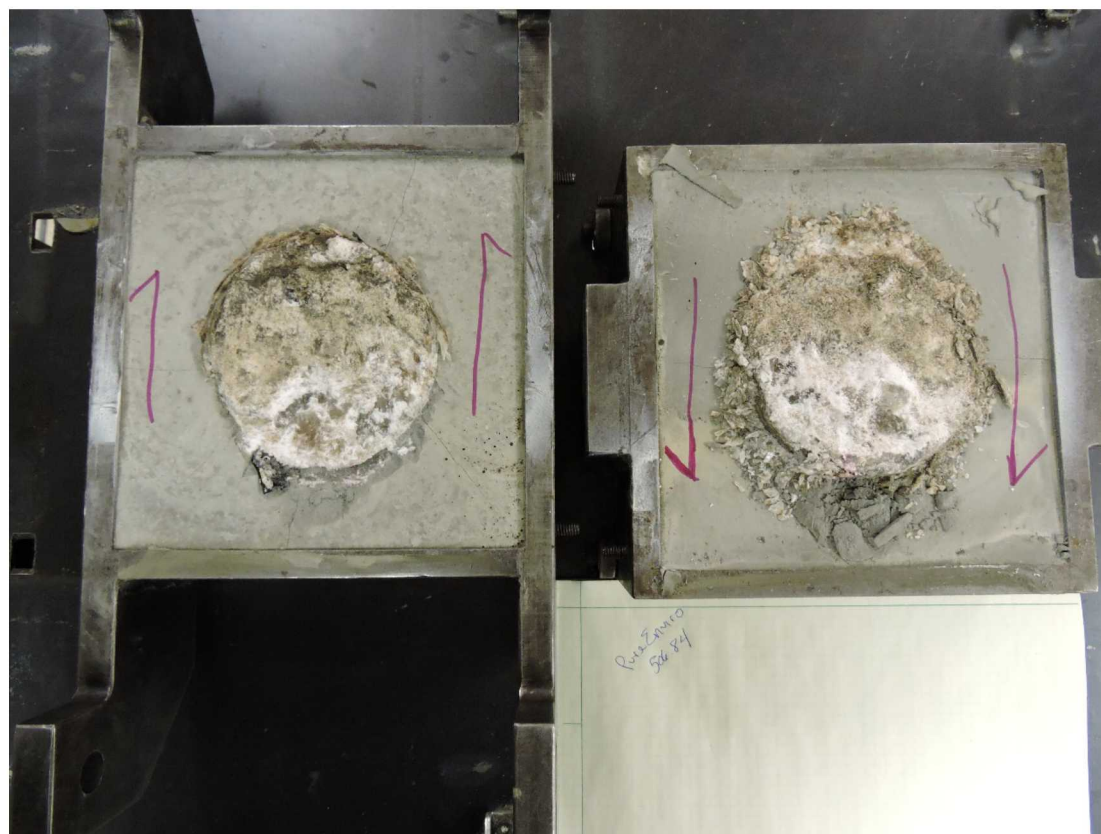


— 1-1-45 Intact 500 psi   
 — 1-1-45 Residual 1,000 psi   
 — 3-1-00 Intact 1,000 psi   
 — 3-1-00 Residual 1,500  
— 2-1-15 Intact 1,500 psi   
 — 2-1-15 Residual 2,400 psi   
— 6-0-80 Intact 2,400 psi

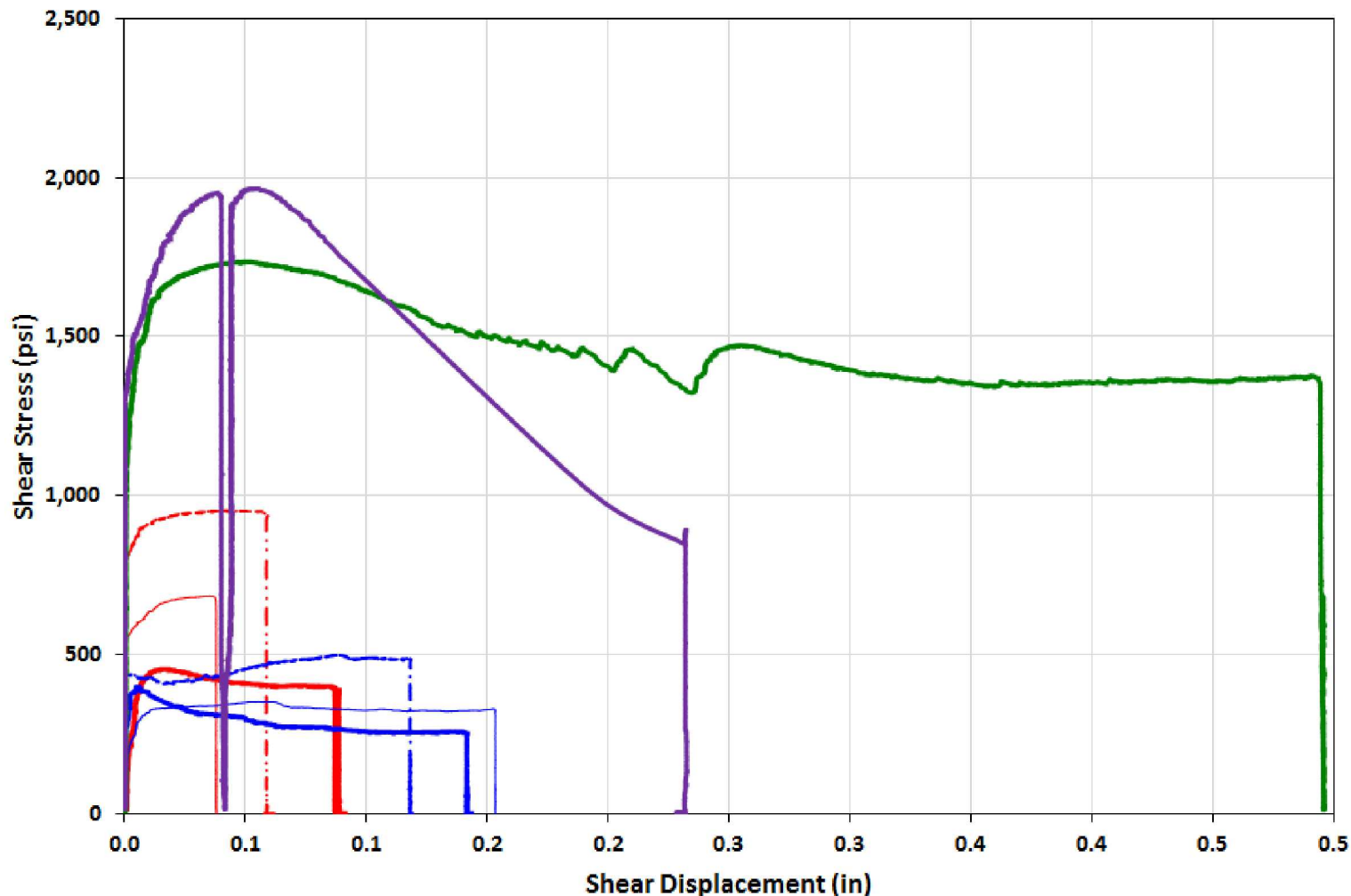




Intact test,  $\sigma_n = 2400$  psi



— 507-28 Intact 500 psi   
 — 507-28 Residual 1,000 psi   
 - - - 507-28 Residual 1,500 psi   
 — 506-07 Intact 320 psi  
— 506-07 Residual 480 psi   
- - - 506-07 Residual 760 psi   
— 506-84 Intact 2,400 psi   
— 507-90 Intact 2,400 psi



# Salt/polyhalite tests



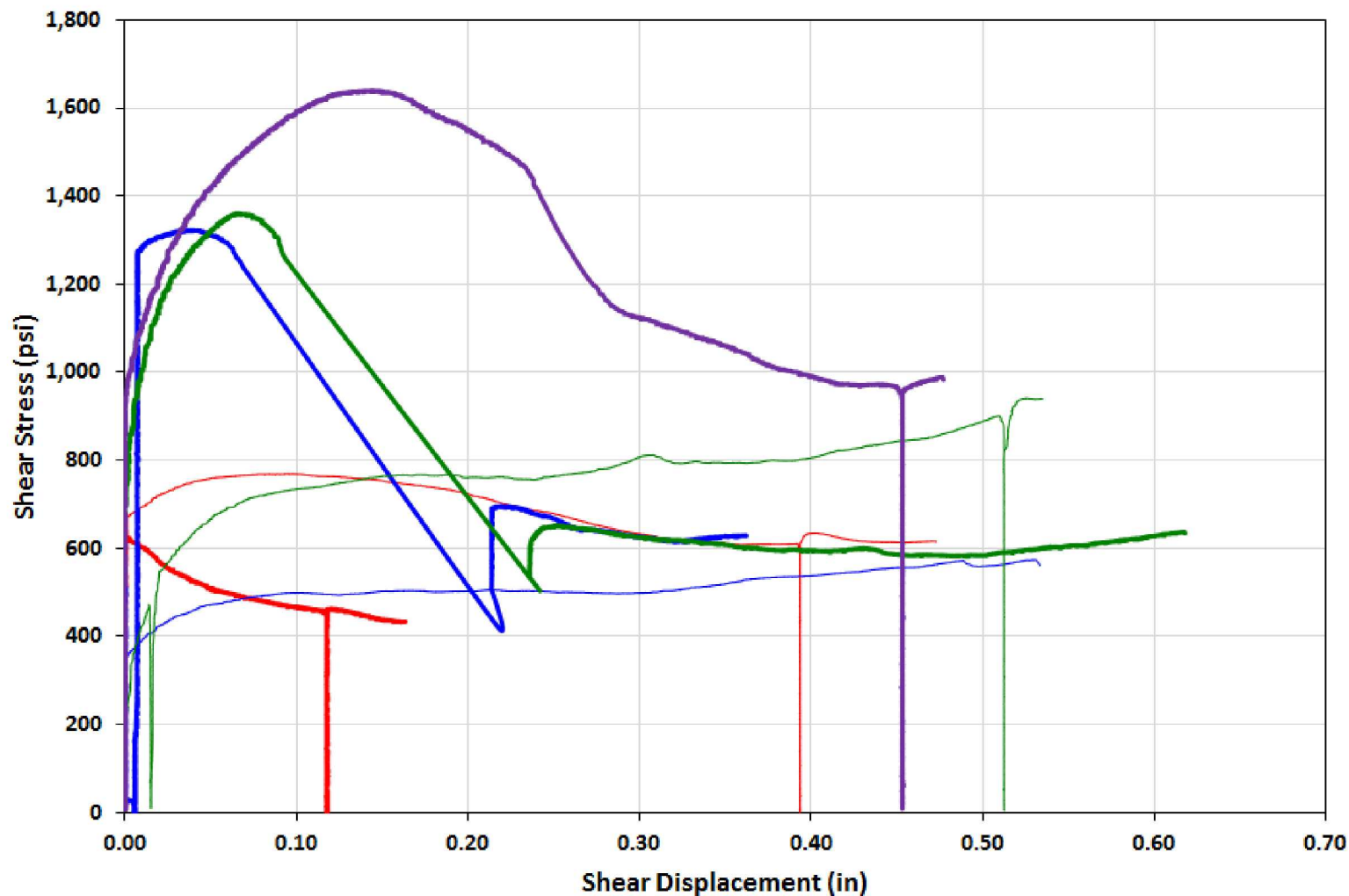
Intact test,  
 $\sigma_n = 1500$  psi

Residual test,  
 $\sigma_n = 2400$  psi



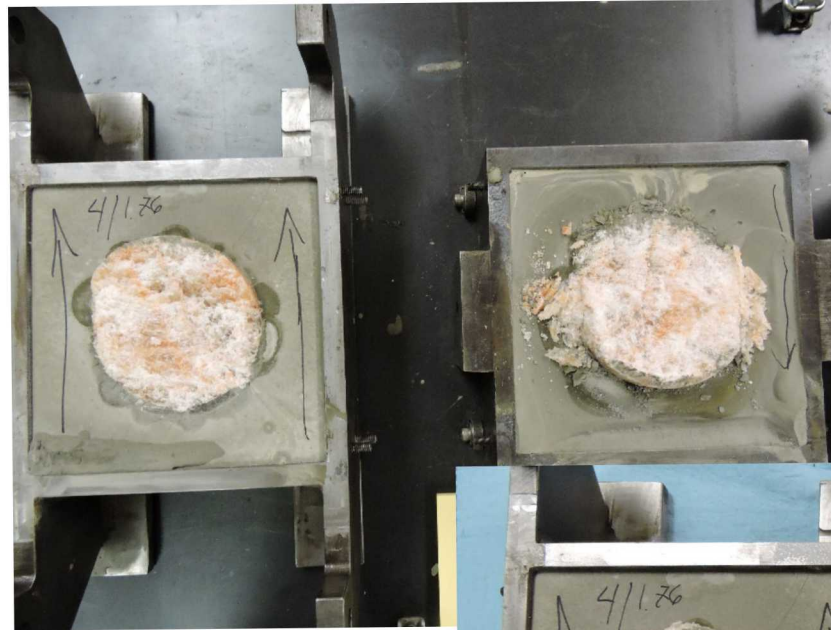
# Salt/polyhalite tests

— 5-0-64 Intact 500 psi   
 — 5-0-64 Residual 1,000 psi   
 — 6-1-92 Intact 1,000 psi   
 — 6-1-92 Residual 1,500  
— 4-1-59 Intact 1,500 psi   
 — 4-1-59 Residual 2,400 psi   
— 3-1-59 Intact 2,400 psi

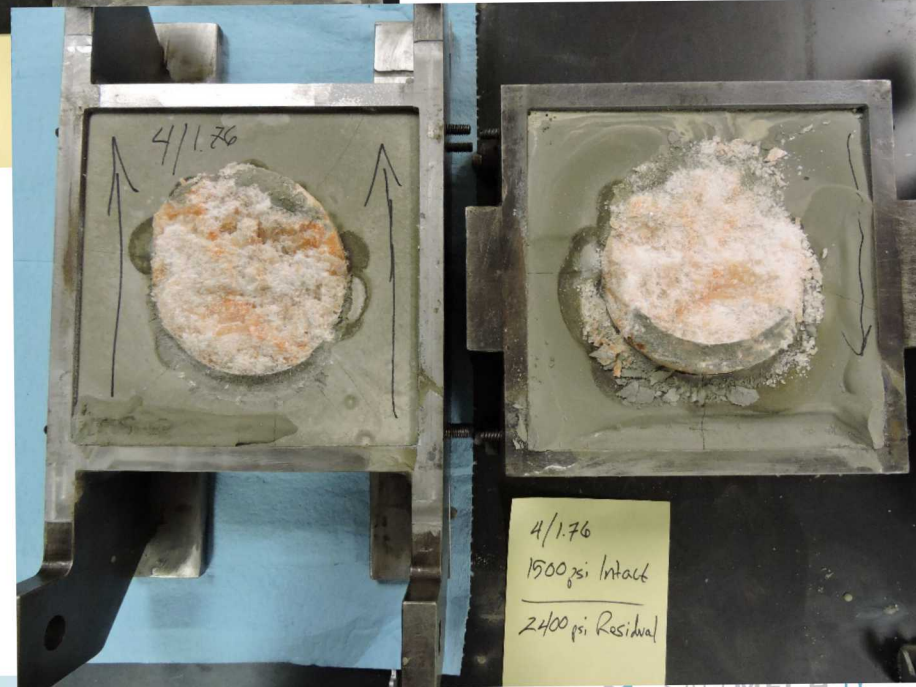


# Mixed salt tests

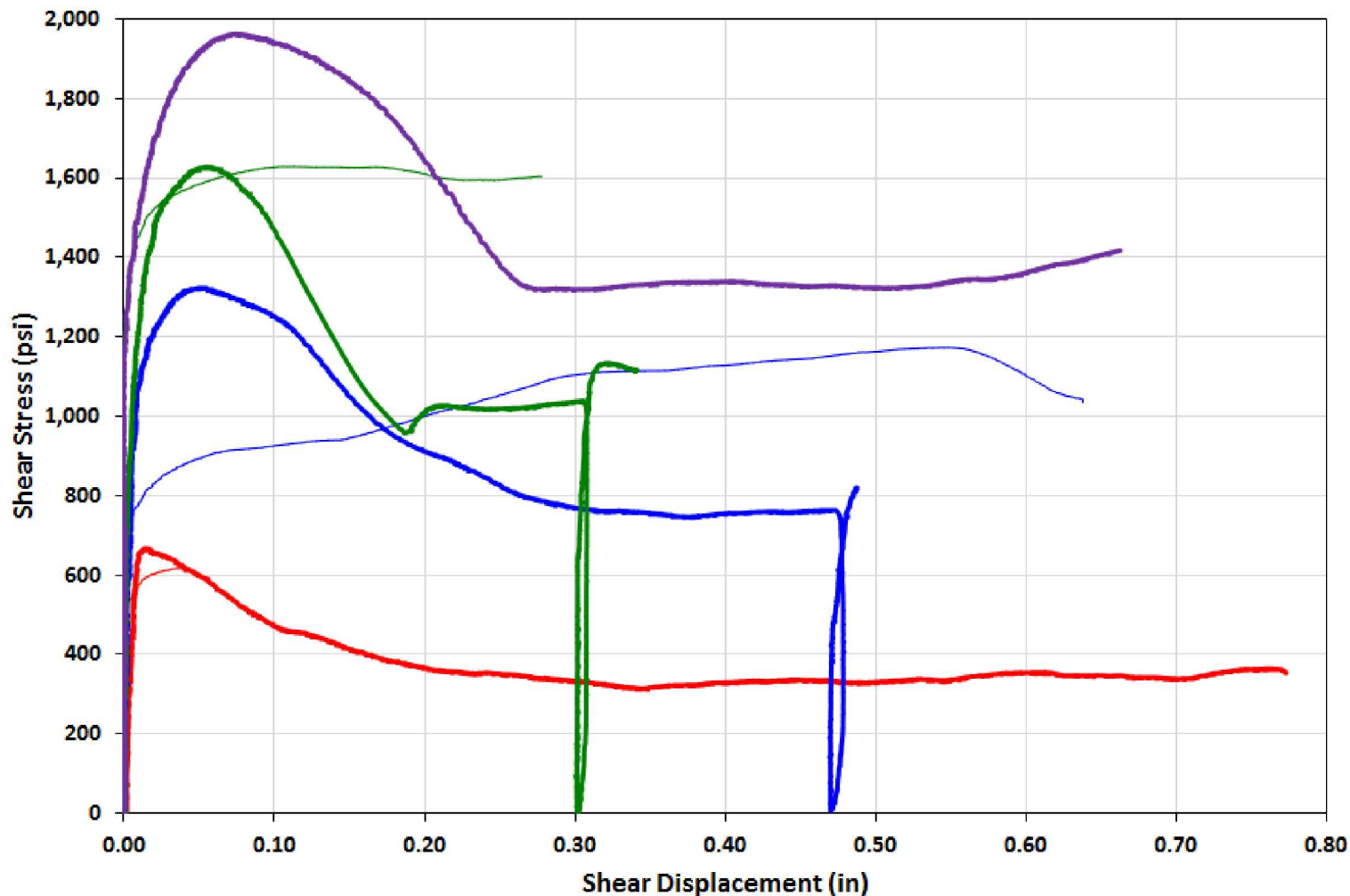
Intact test,  
 $\sigma_n = 1500$  psi



Residual test,  
 $\sigma_n = 2400$  psi



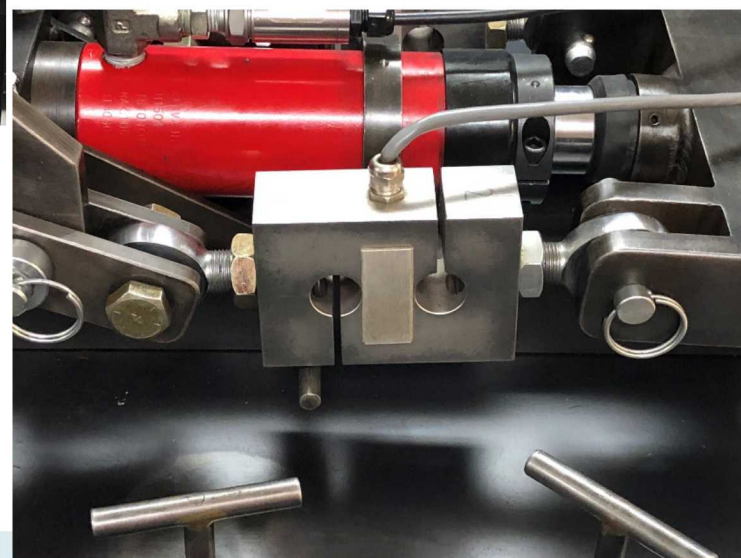
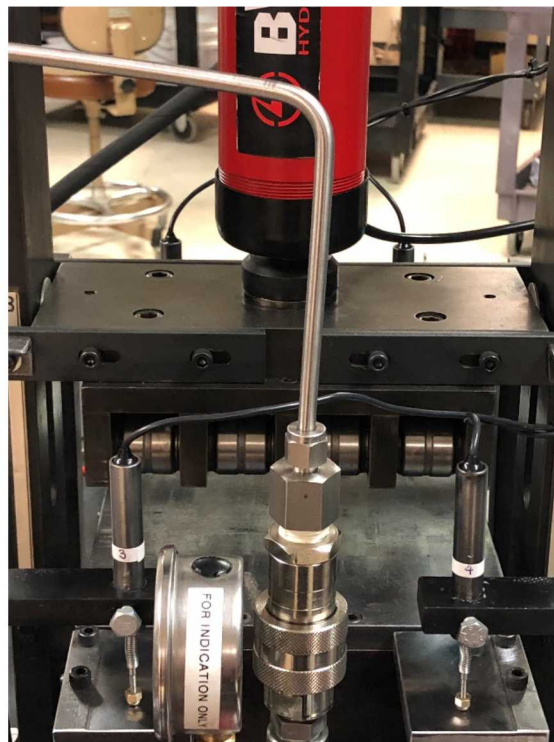
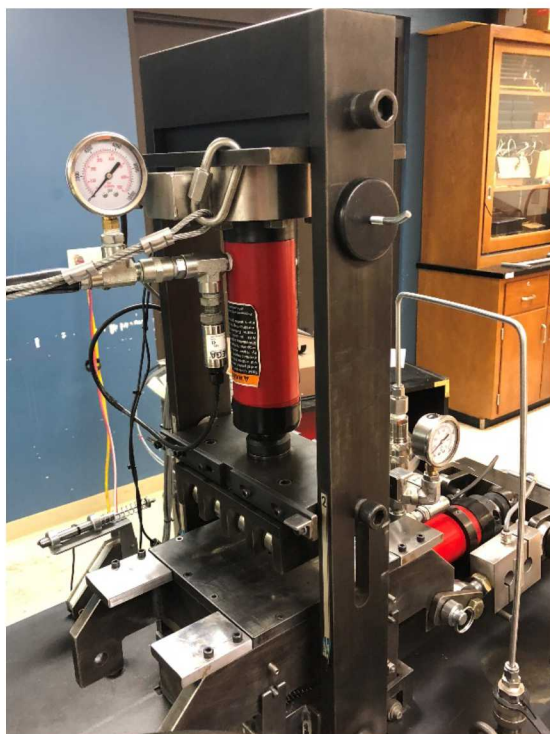
— 1-1-76 Intact 500 psi   
 — 1-1-76 Residual 1,000 psi   
 — 2-1-76 Intact 1,000 psi   
 — 2-1-76 Residual 1,500  
— 4-1-76 Intact 1,500 psi   
 — 4-1-76 Residual 2,400 psi   
— 5-1-76 Intact 2,400 psi



# 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

