Wellbore & Seal Integrity

FWP FE-10-001

Experimental and Computational Studies of Coupled Geomechanical and Hydrologic Behavior of Wells and Caprock in Geologic Sequestration

Bill Carey

Los Alamos National Laboratory

Los Alamos, NM

U.S. Department of Energy

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Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS

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Outline & Motivation

- Experimental and computational studies of wellbore and seal integrity
- Why do wells leak?

Carey et al. (2007) Int. J. Greenhouse Gas Control

Benefit to the Program

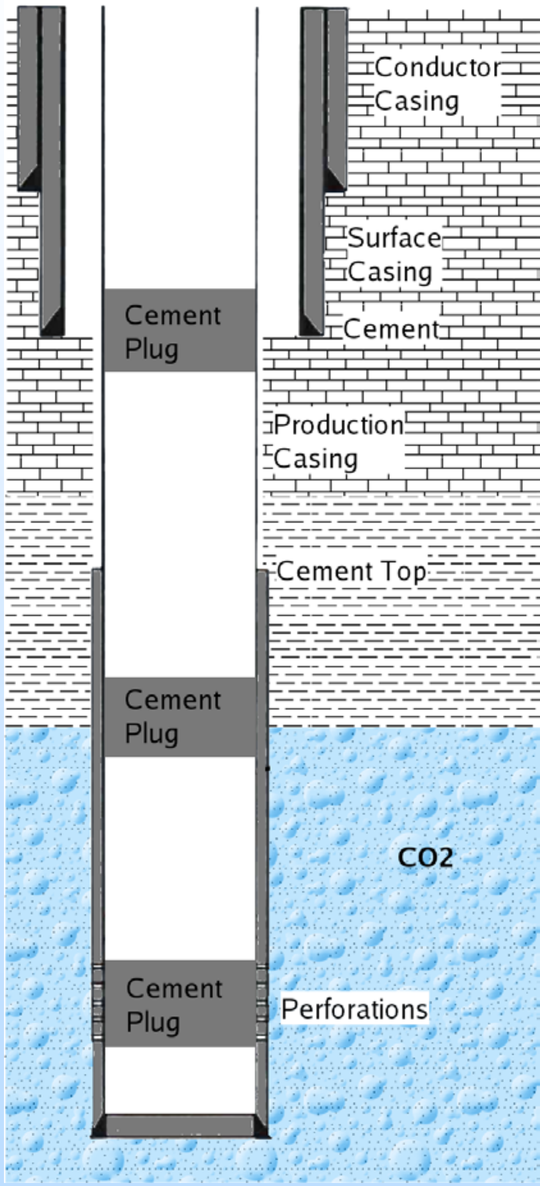
- Goal: Develop and validate technologies to ensure 99 percent storage
- Benefit: The research provides a basis for evaluating the long-term performance of wells, developing remediation strategies, facilitating use of reservoirs with numerous existing wells (i.e., EOR), and reducing risk in CO_2 storage projects

Project Overview: Goals and Objectives

- Project Goals
  - Conduct field studies to determine decade-scale behavior of wellbore systems
  - Conduct experimental studies to determine chemical and mechanical integrity of caprock and cement-steel-rock composites representing wellbore systems
  - Conduct computational studies to simulate chemical, mechanical, and hydrologic flow processes in wells and in caprock
  - Use collaborations to leverage research efforts
- Success Criteria
  - Complete 2-3 field studies of CO_2-exposed and CO_2-free wells
  - Complete experiments studying flow of CO_2 and brine in fractured caprock and cement-steel, cement-casing and cement-cement interfaces;
  - Complete a numerical model representing two-phase flow along wellbore interfaces and accounting for chemical and mechanical effects
  - Demonstrate consistency among field, experiment and numerical approaches to assessing wellbore integrity

Why Do Seals (Wells or Caprock) Leak?

- Pre-existing conditions
  - Inadequate well construction
  - Faults/fractures in caprock
  - Primary questions: how frequently does this occur and what are the consequences?
- CO_2 injection-induced damage
  - Chemical attack of materials
  - Geomechanical stress-induced permeability
  - Primary questions: what injection conditions create damage and what is the resulting permeability



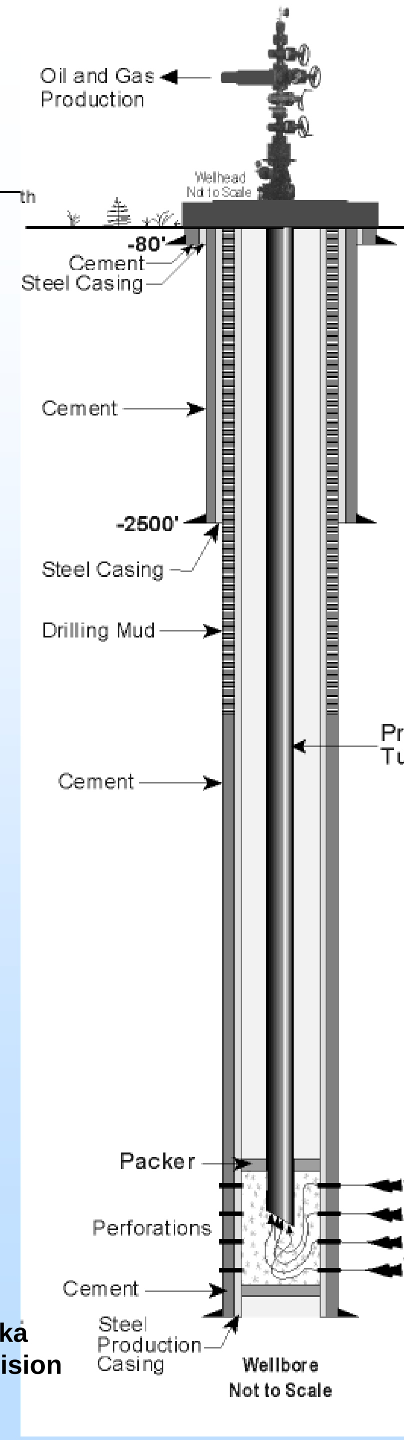
Why do wells leak?

Pre-Production

- Formation damage during drilling (caving)
- Casing centralization (incomplete cementing)
- Adequate drilling mud removal
- Incomplete cement placement (pockets)
- Inadequate cement-formation bond
- Inadequate cement-casing bond
- Cement shrinkage
- Contamination of cement by mud or formation fluids

Production

- Mechanical stress/strain
  - Formation of micro-annulus at casing-cement interface
  - disruption of cement-formation bond
  - Fracture formation within cement
- Geochemical attack
  - Corrosion of casing
  - Degradation of cement
    - Carbonation
    - Sulfate attack
    - Acid attack



State of Alaska
Oil and Gas Division

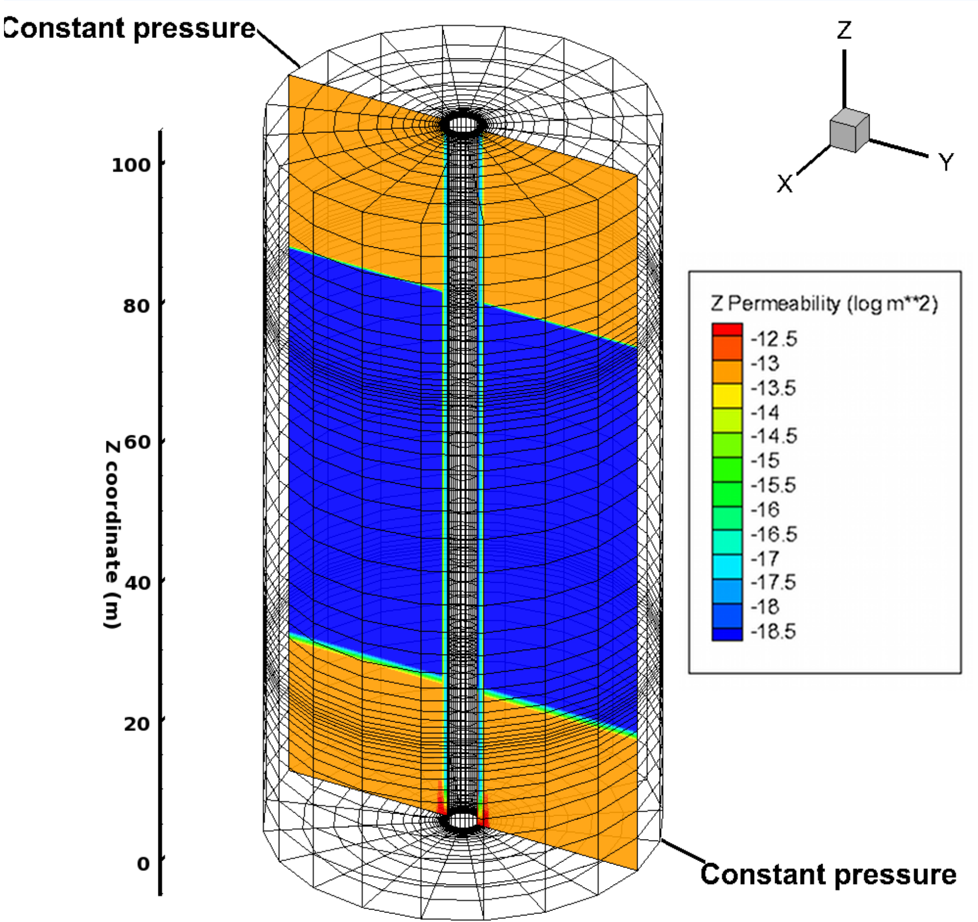
Geomechanics: Pathways Before Chemistry

Coupled Stress and Flow

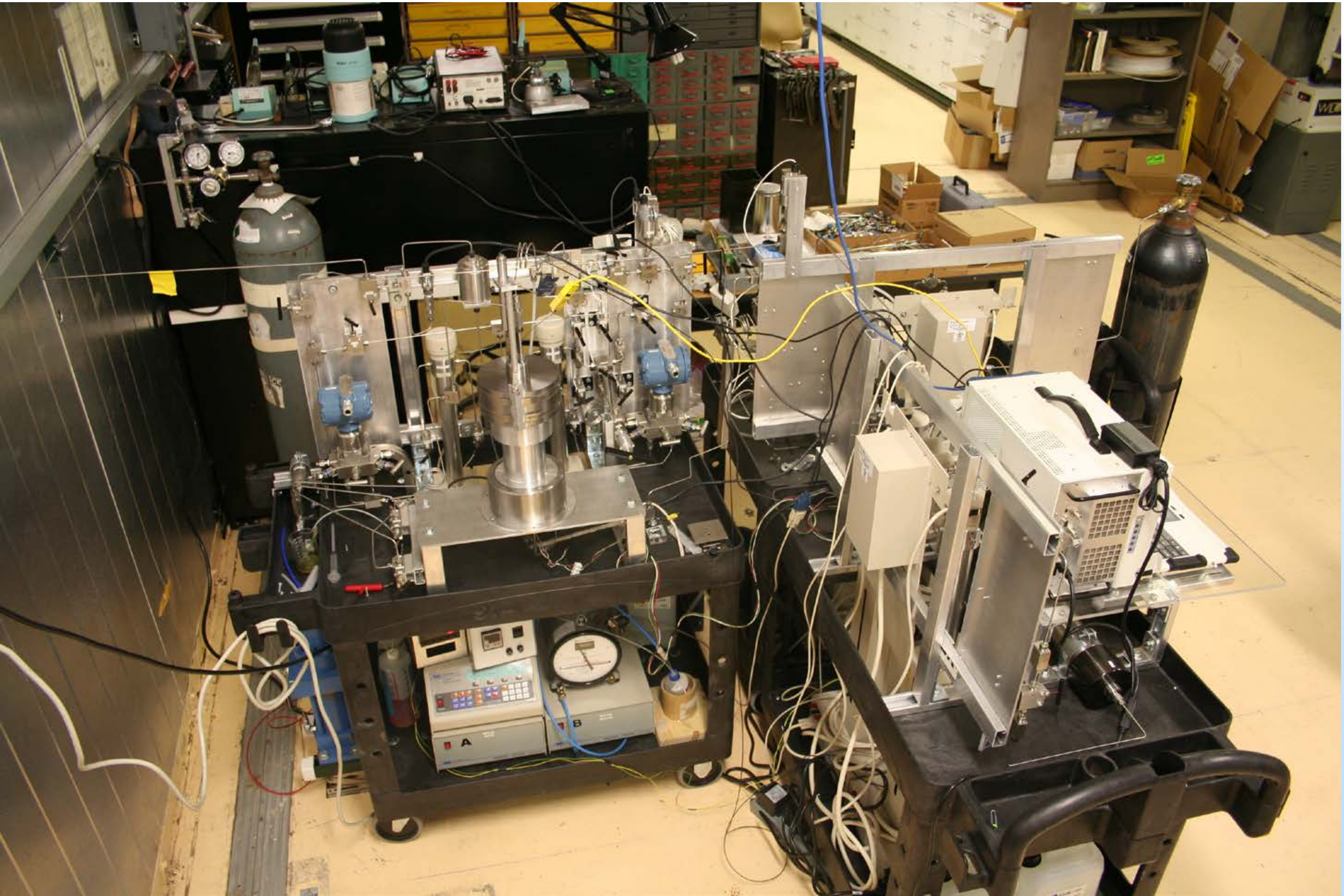
Experimental Studies

Computational Studies

X-ray CT of Anhydrite

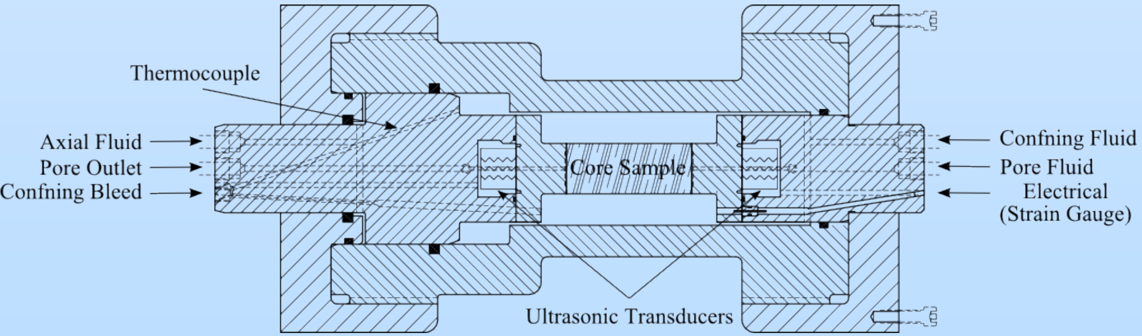


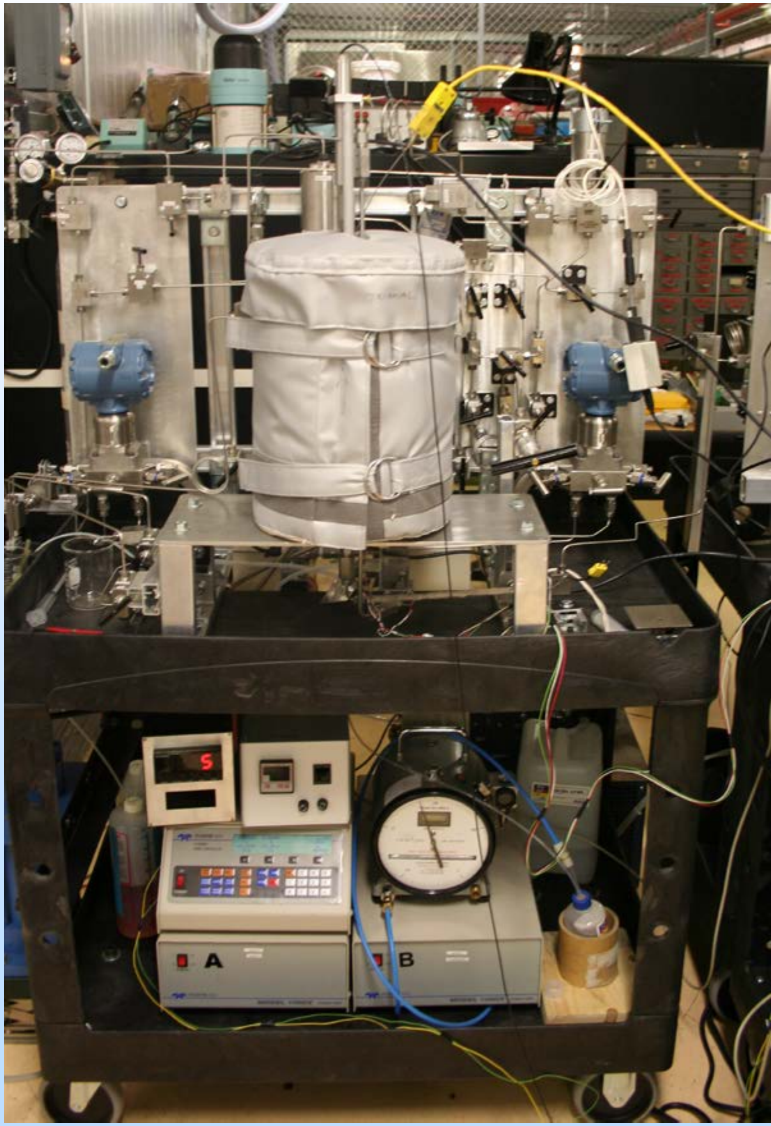
Experiments: Triaxial Coreflood



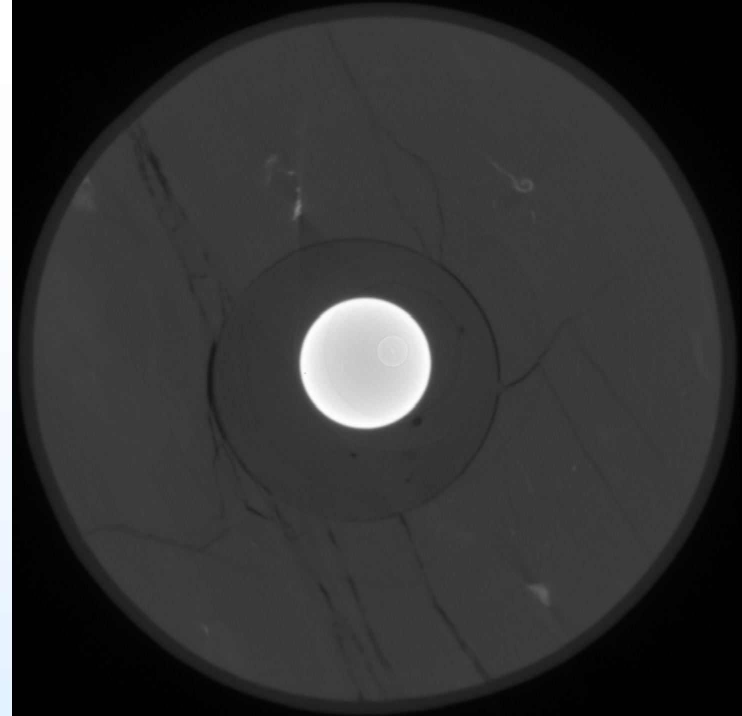
Measurement System

- Simultaneous axial load (fracture) and permeability data
- Strain data
- Acoustic properties
- Post (and soon *in situ*) tomographic observation

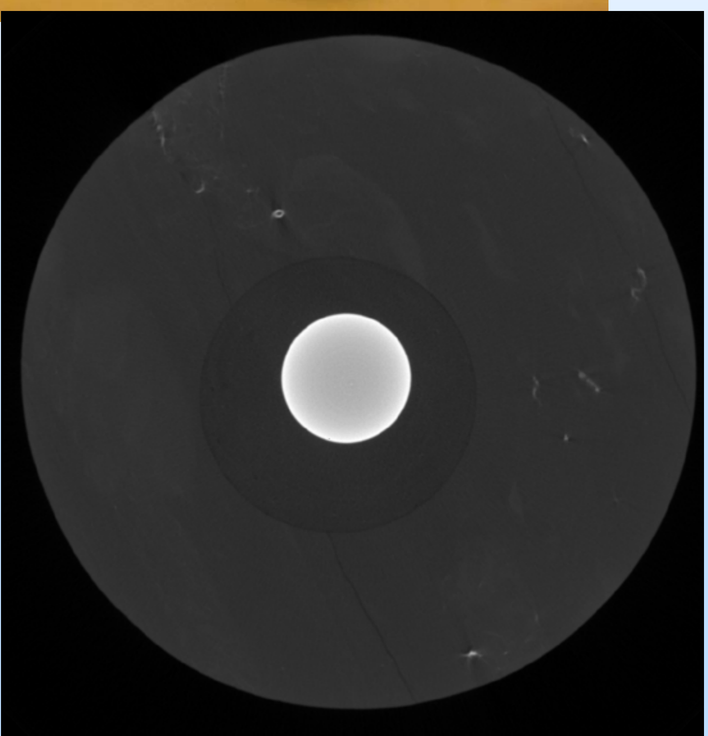




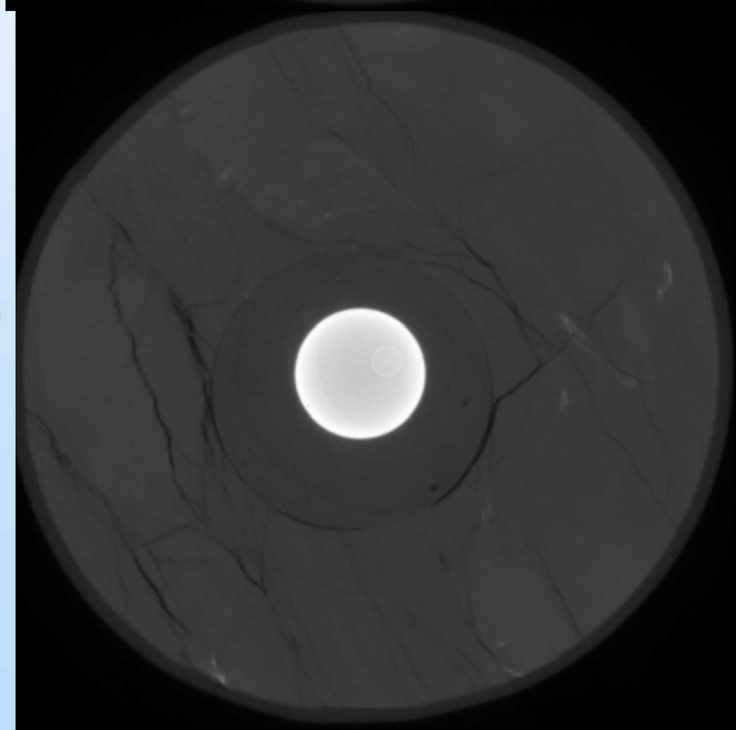
Synthetic Wellbore: Shale-Cement-Steel



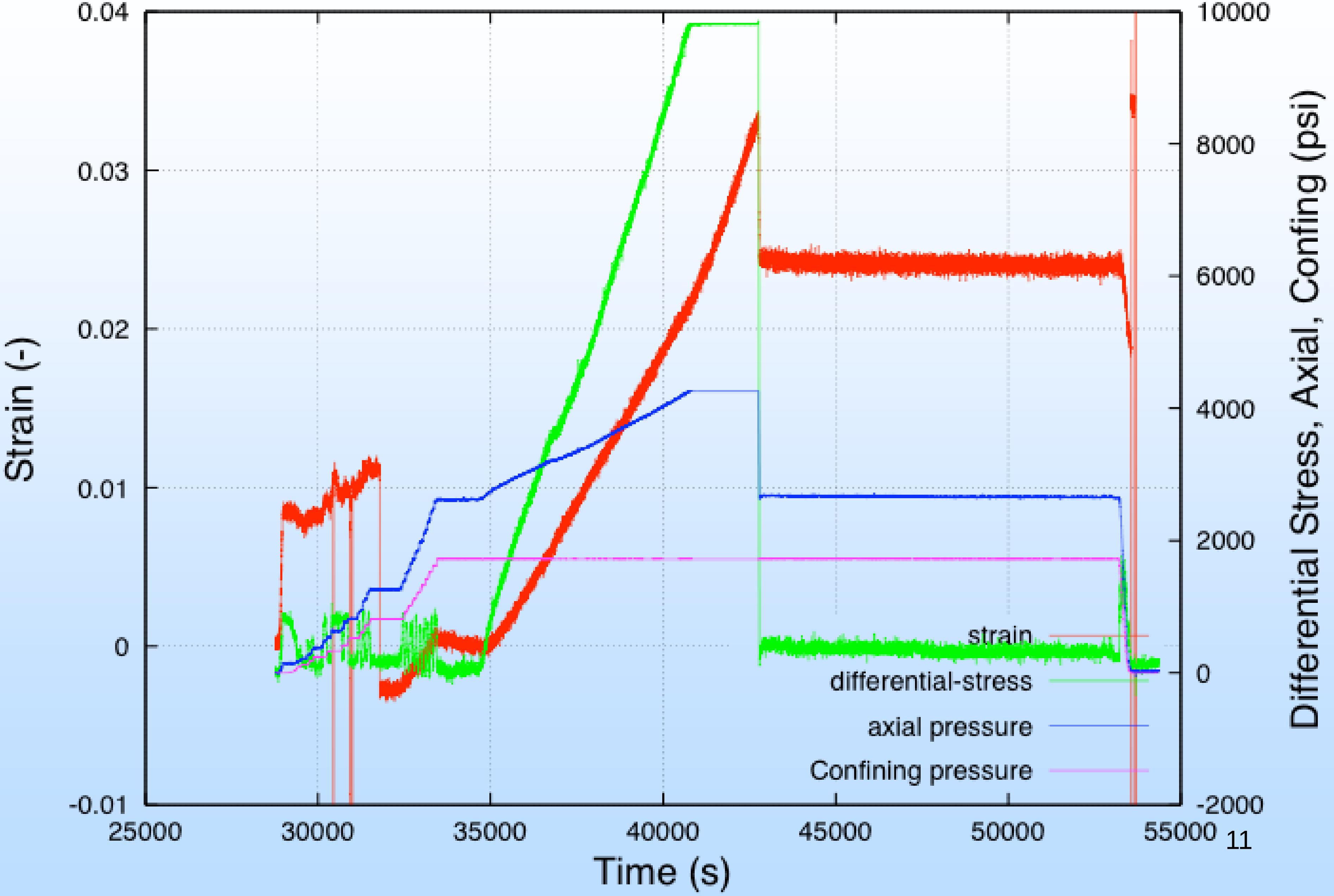
Pre



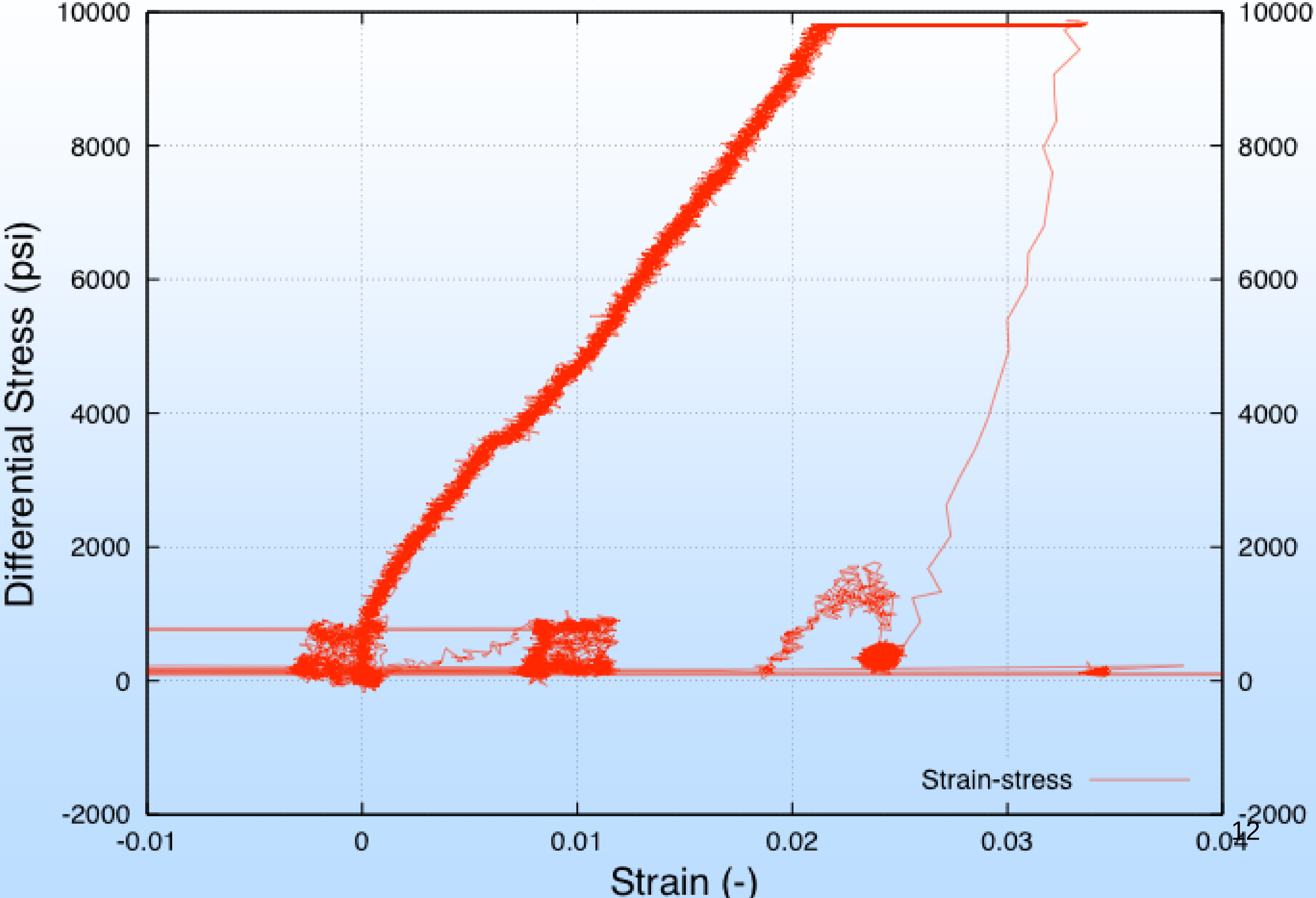
Post



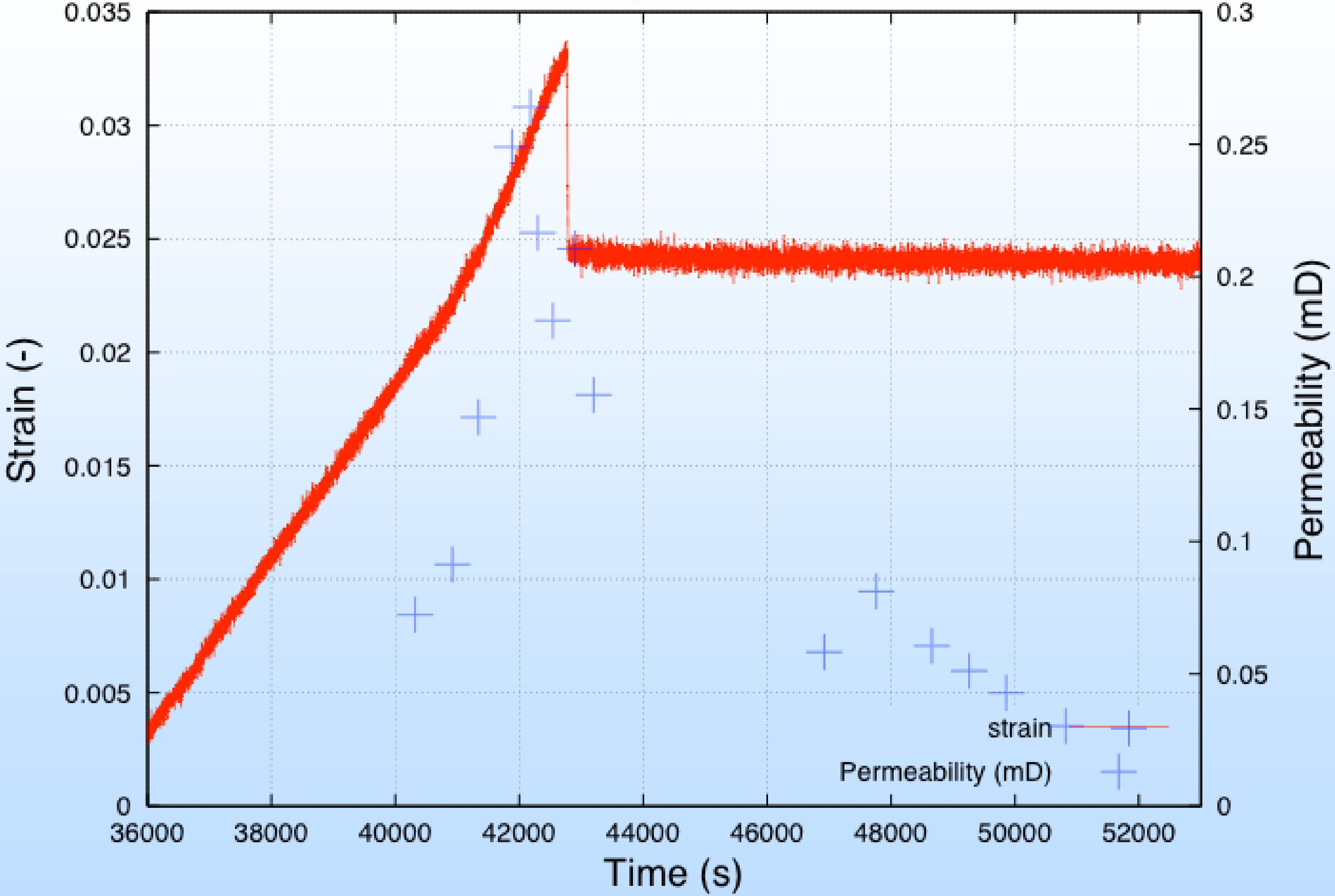
Differential Stress-strain: Synthetic Wellbore 5778-1



Differential Stress-strain: Synthetic Wellbore 5778-1

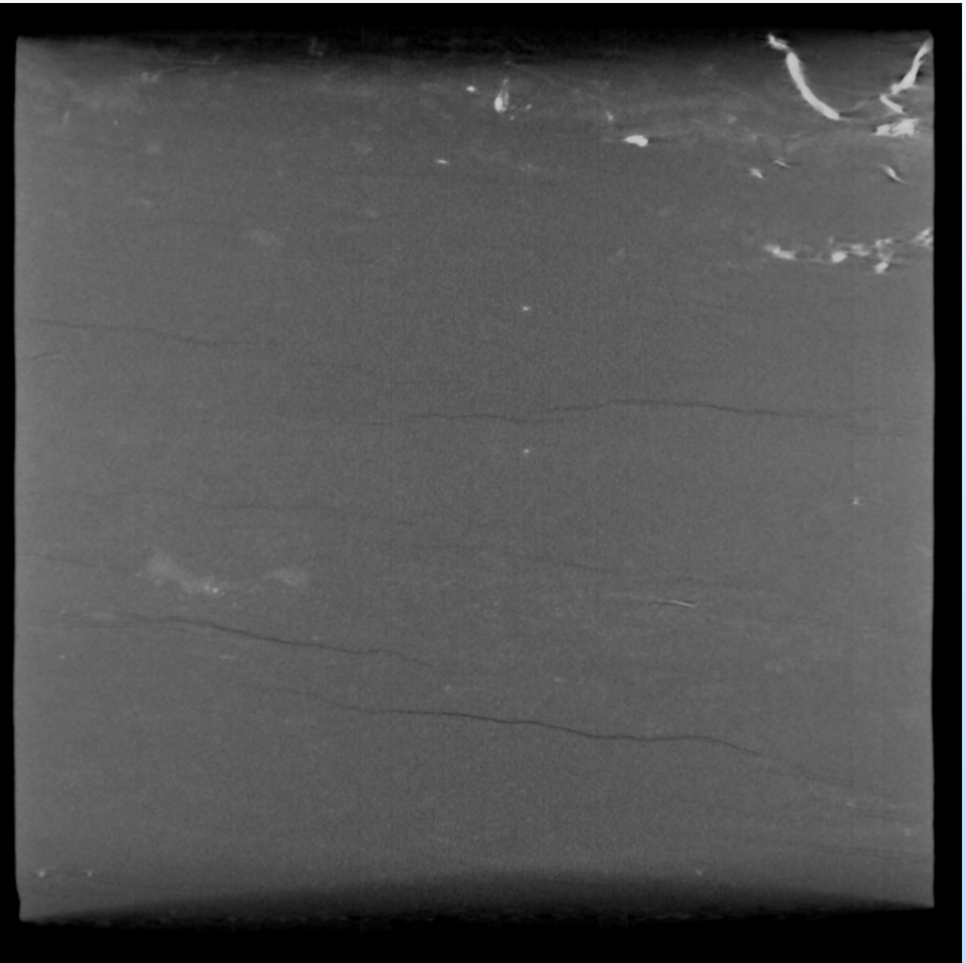


Strain-Permeability Relations: Synthetic Wellbore 5778-1: 8/13/2013

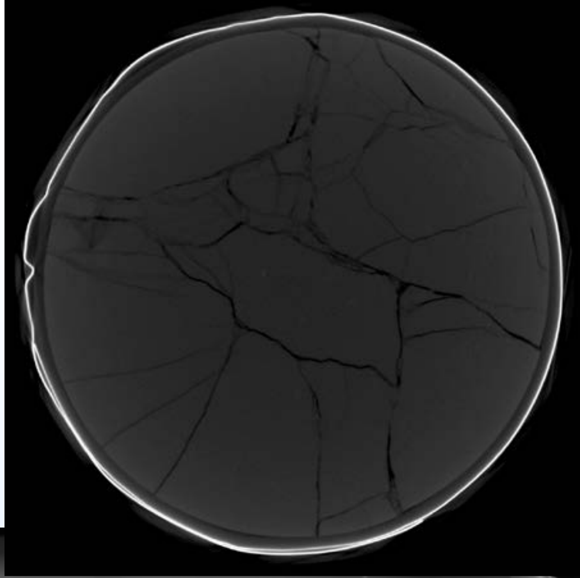


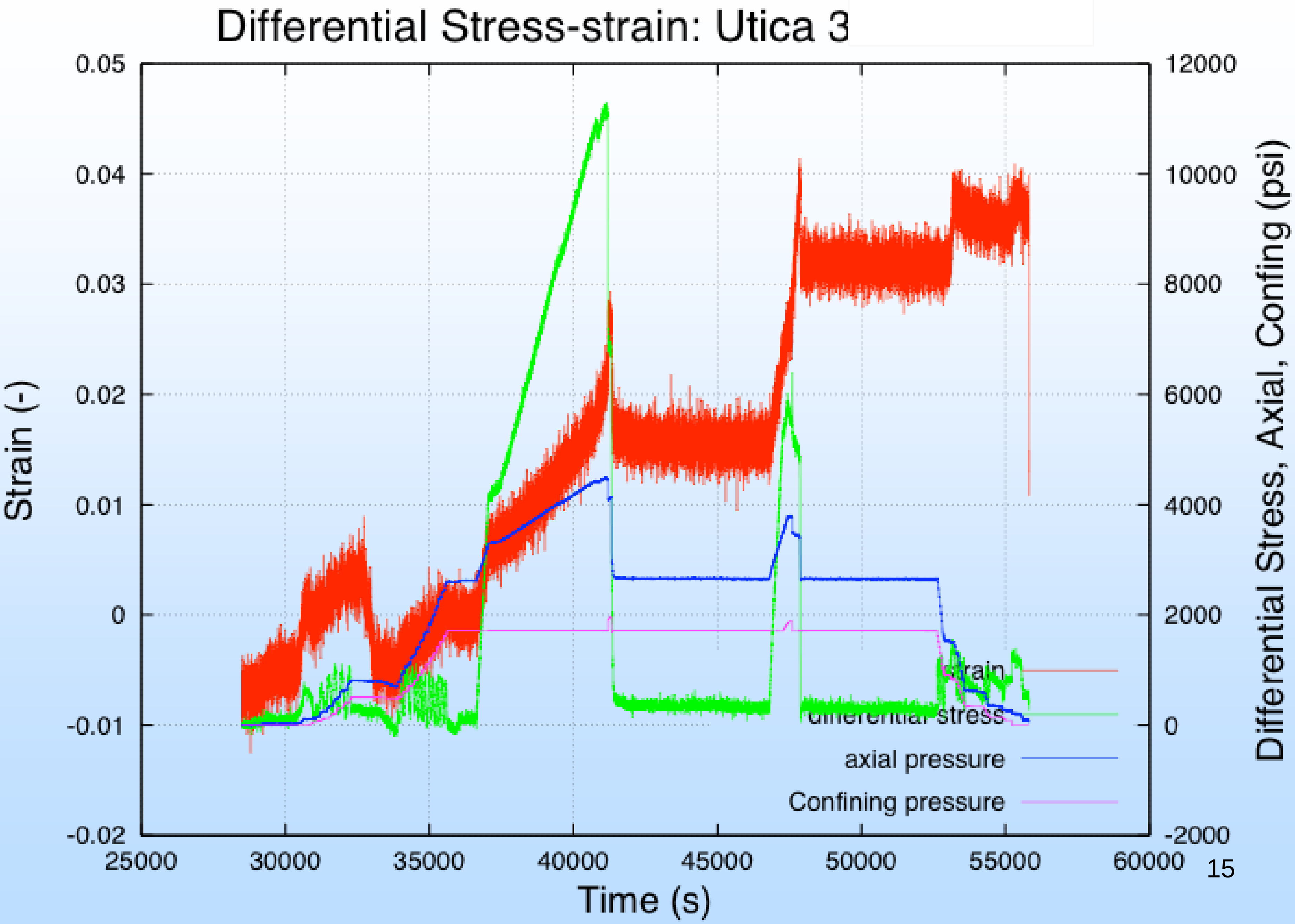
Caprock Studies: Utica Shale

Pre-stress



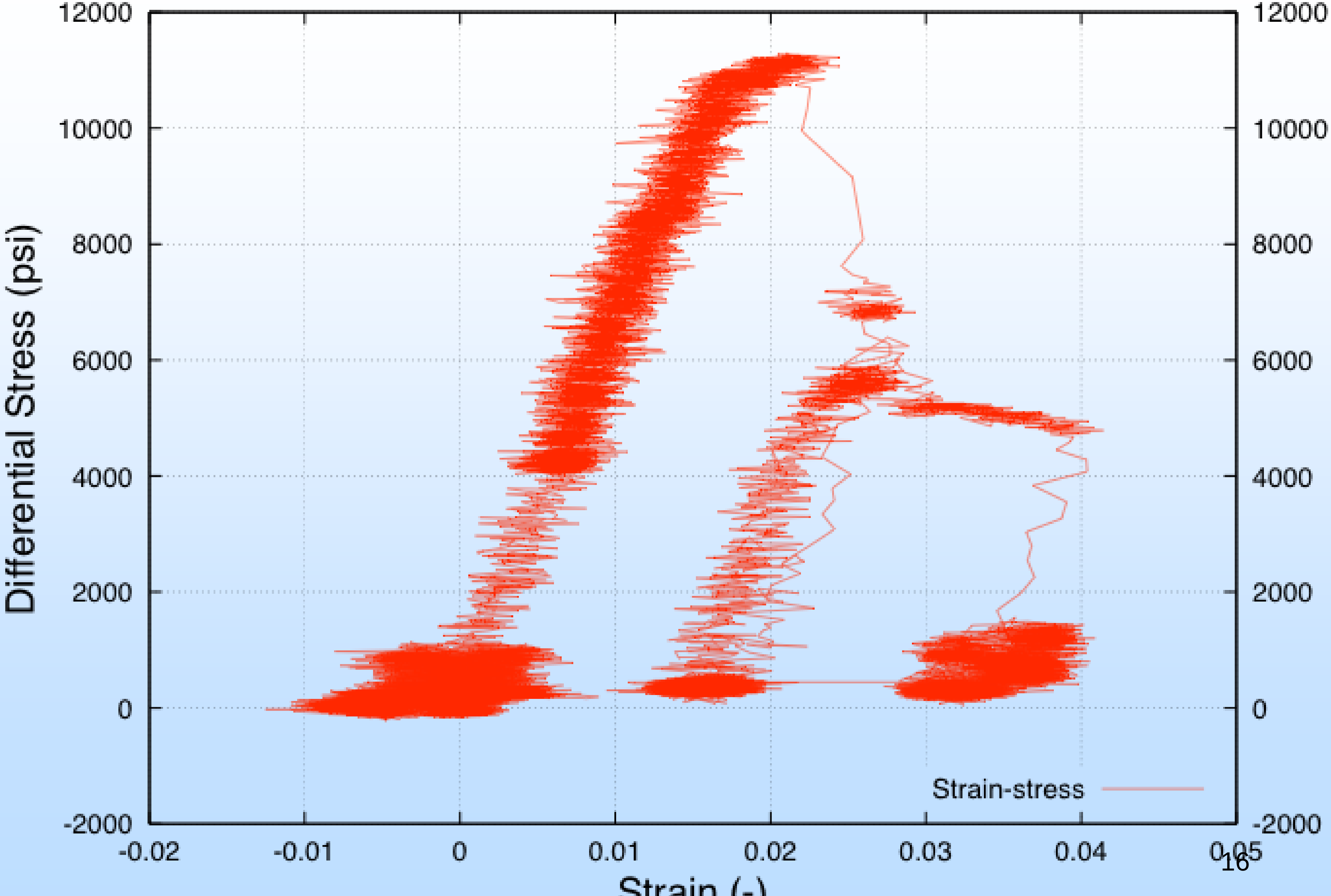
Post-stress



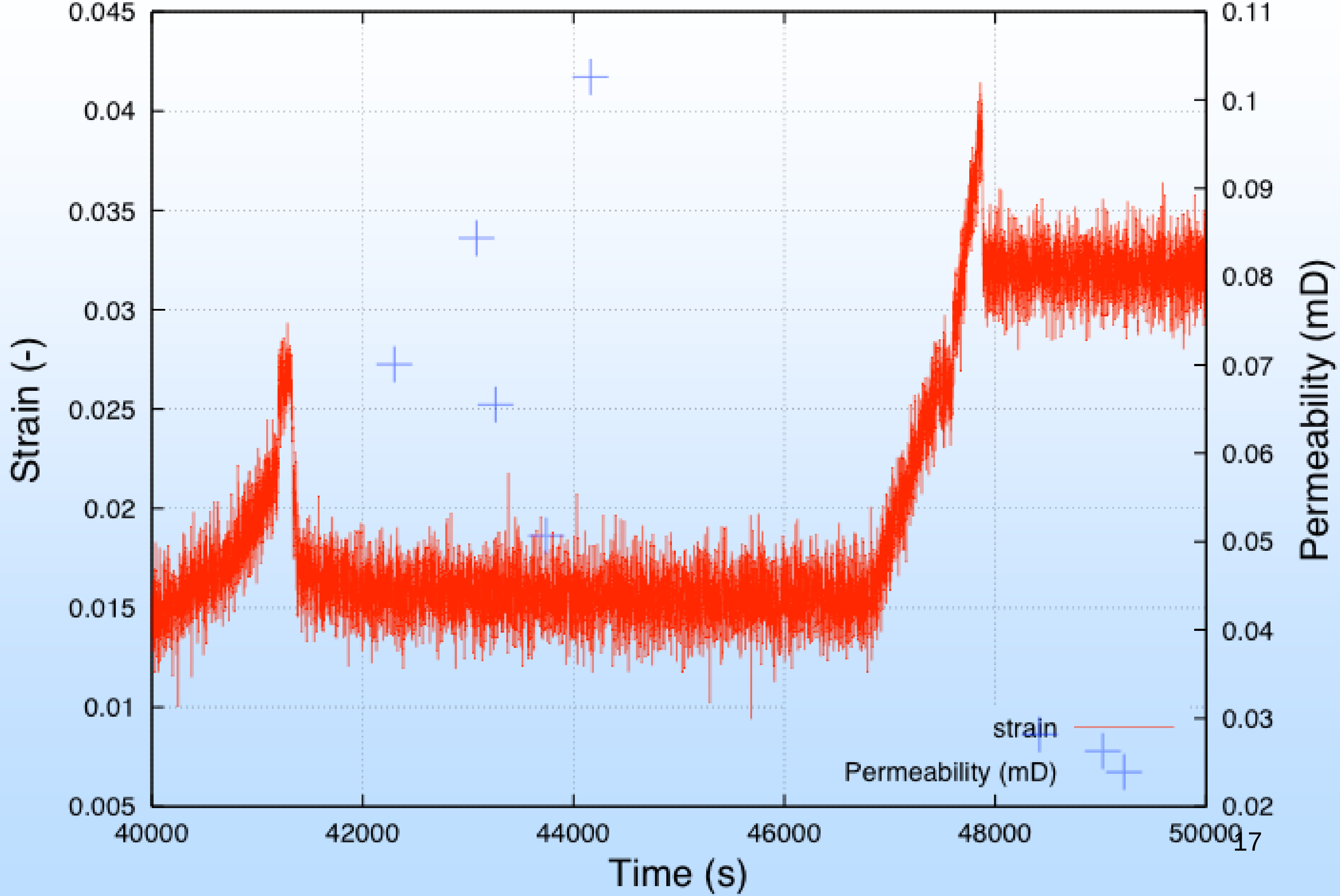


Differential Stress-strain: Utica 3
Strain (-)
Differential Stress, Axial, Confing (psi)
Time (s)
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
12000
10000
8000
6000
4000
2000
0
-2000
25000
30000
35000
40000
45000
50000
55000
60000
strain
differential stress
axial pressure
Confining pressure

Differential Stress-strain: Utica 3



Strain-Permeability Relations: Utica 3



Experimental Results

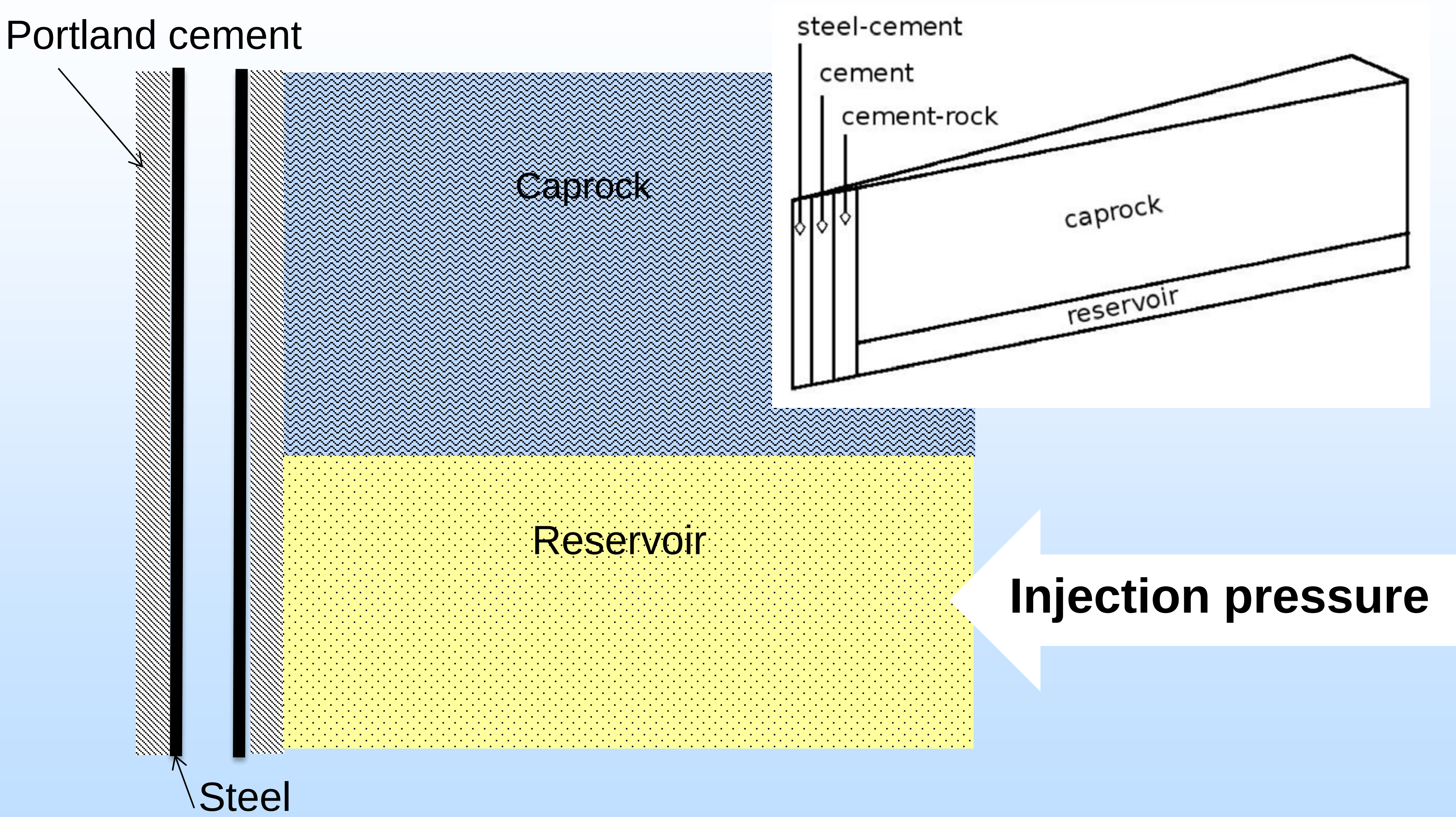
- Impermeable wellbore systems and shale fail under mechanical loads
- Permeability to supercritical CO_2 develops but is limited to < 1 mD
- Interfaces develop at the shale-cement interface but not at cement-steel
- Extensive fractures observed only in shale
- Limited permeability due in part to confining pressure and plasticity of system

What mechanical processes occur in wells?

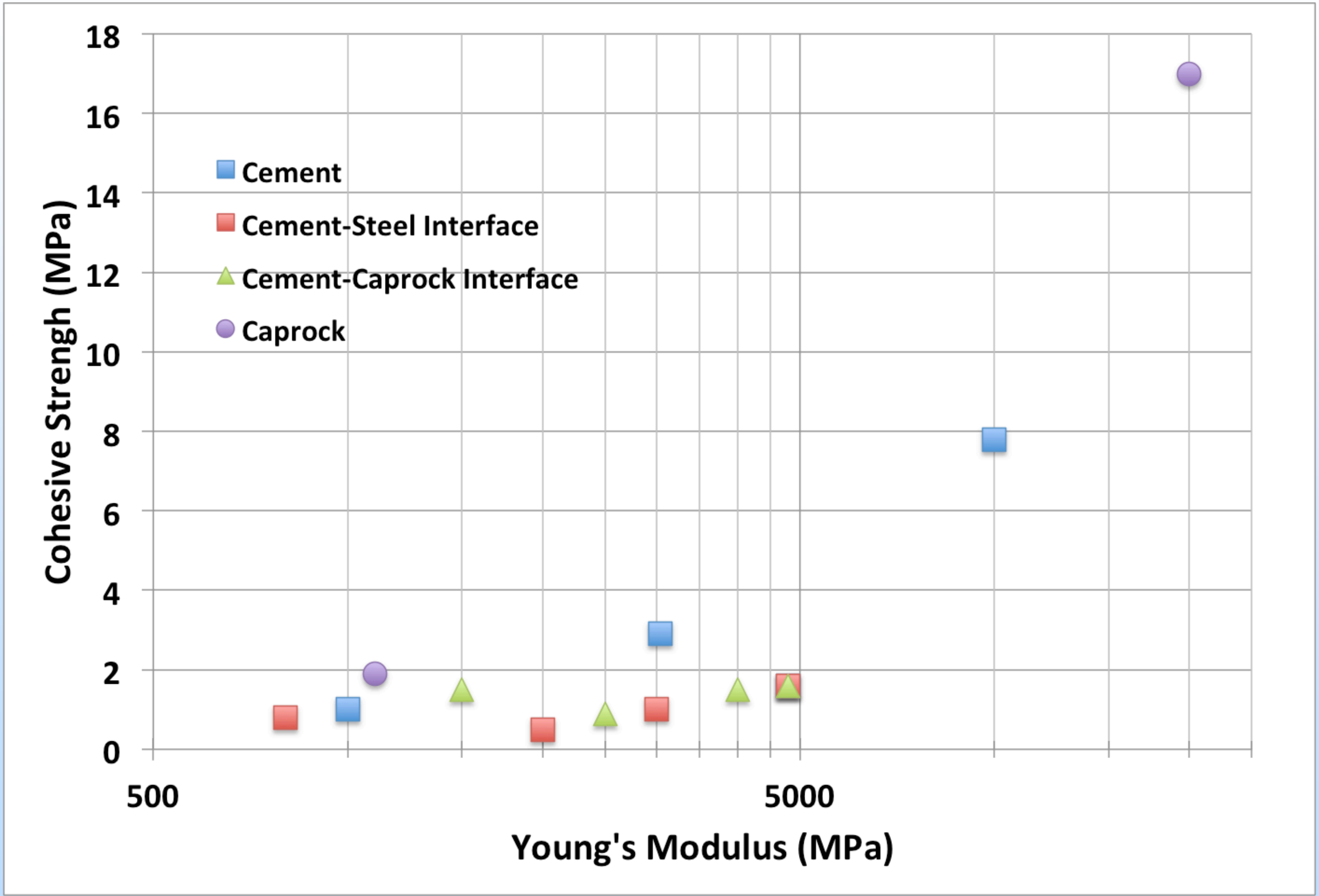
- **Internal to the well**
  - **Thermal**
    - **Injection or production of fluids**
  - **Pressure**
    - **Injection/production of fluids**
    - **Mechanical integrity tests**
    - **Wellbore operations**
- **External to the well**
  - **Thermal**
    - **Injection of cold/hot fluids**
  - **Pressure**
    - **Depletion of the reservoir**
    - **Injection into the reservoir**
    - **Tectonics and rock deformation**
- **Fluid flow in response to damaged wellbores not well quantified**

Carey et al. (2007) IJGGC

Heterogeneous Mechanical System



Key Mechanical Properties in Model

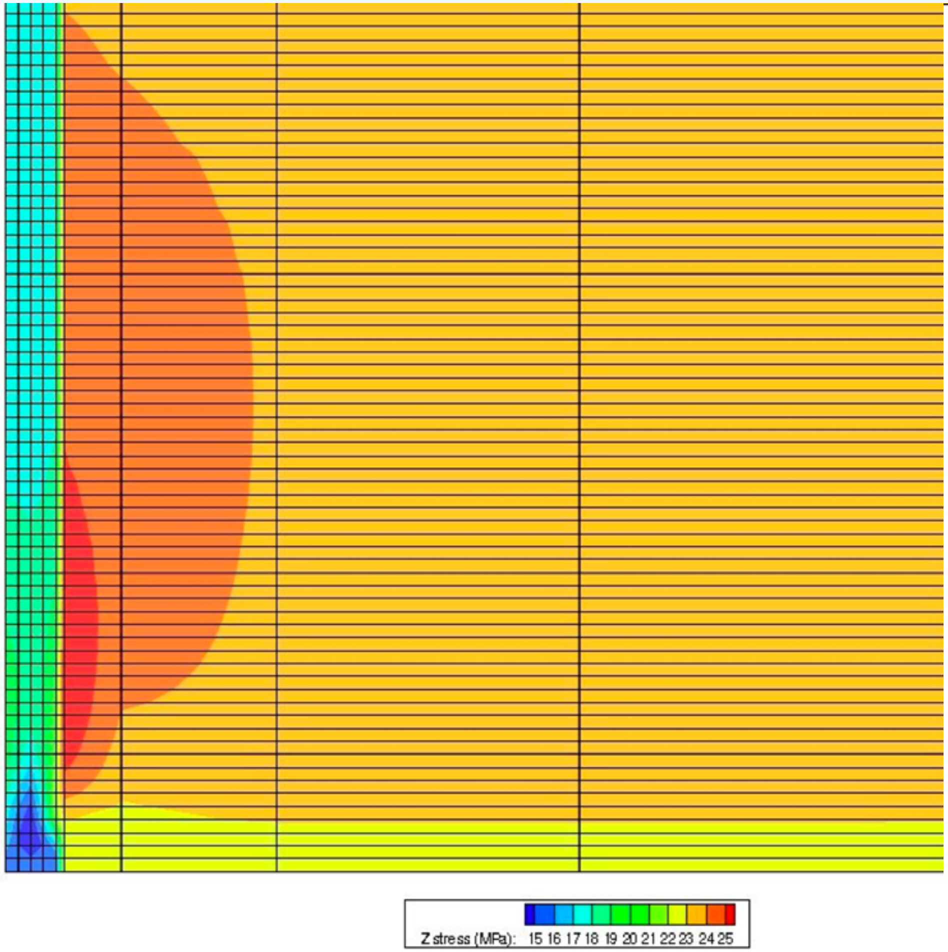


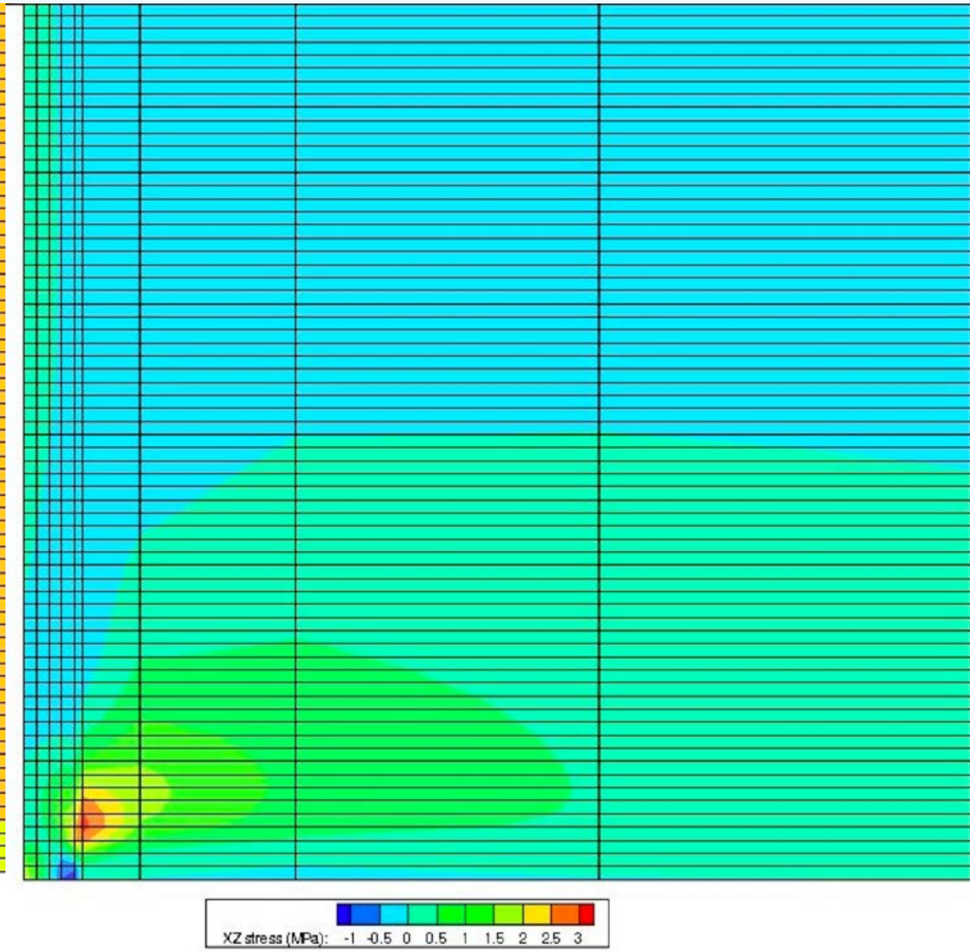
Stress distribution following injection of 10 MPa CO_2 in the basal reservoir

Mechanical failure within the cement and at interfaces

z-axis stress

xz stress





Accomplishments to Date

- Initiated *in situ* experimental studies of coupled fracture and permeability measurements of caprock and synthetic wellbore systems
- Determined role of plastic deformation in limiting permeability of damaged caprock and wellbore systems
- Developed a geomechanical model for investigating thermal and pressure impacts on wellbore integrity
- Experimental coreflood experiments show that Portland cement can survive relatively high flow-through rates of CO_2-brine mixtures and steel corrosion can be more significant than cement carbonation (Carey et al. 2010; Newell and Carey 2013).
- Self-healing of wellbore defects occurs, at least under some conditions, by precipitation of calcium and iron carbonates and migration of fines (Carey et al. 2007; Carey et al. 2010; Newell and Carey 2013).
- While bare-steel corrosion rates are high, Portland cement offers substantial protection for steel (Han et al. 2011, 2012).

Summary

– Plastic deformation limits the potential for high permeability pathways in both caprock and wellbore systems

– Self-healing observed in wellbore systems due to carbonate precipitation, residual cement phase migration and swelling

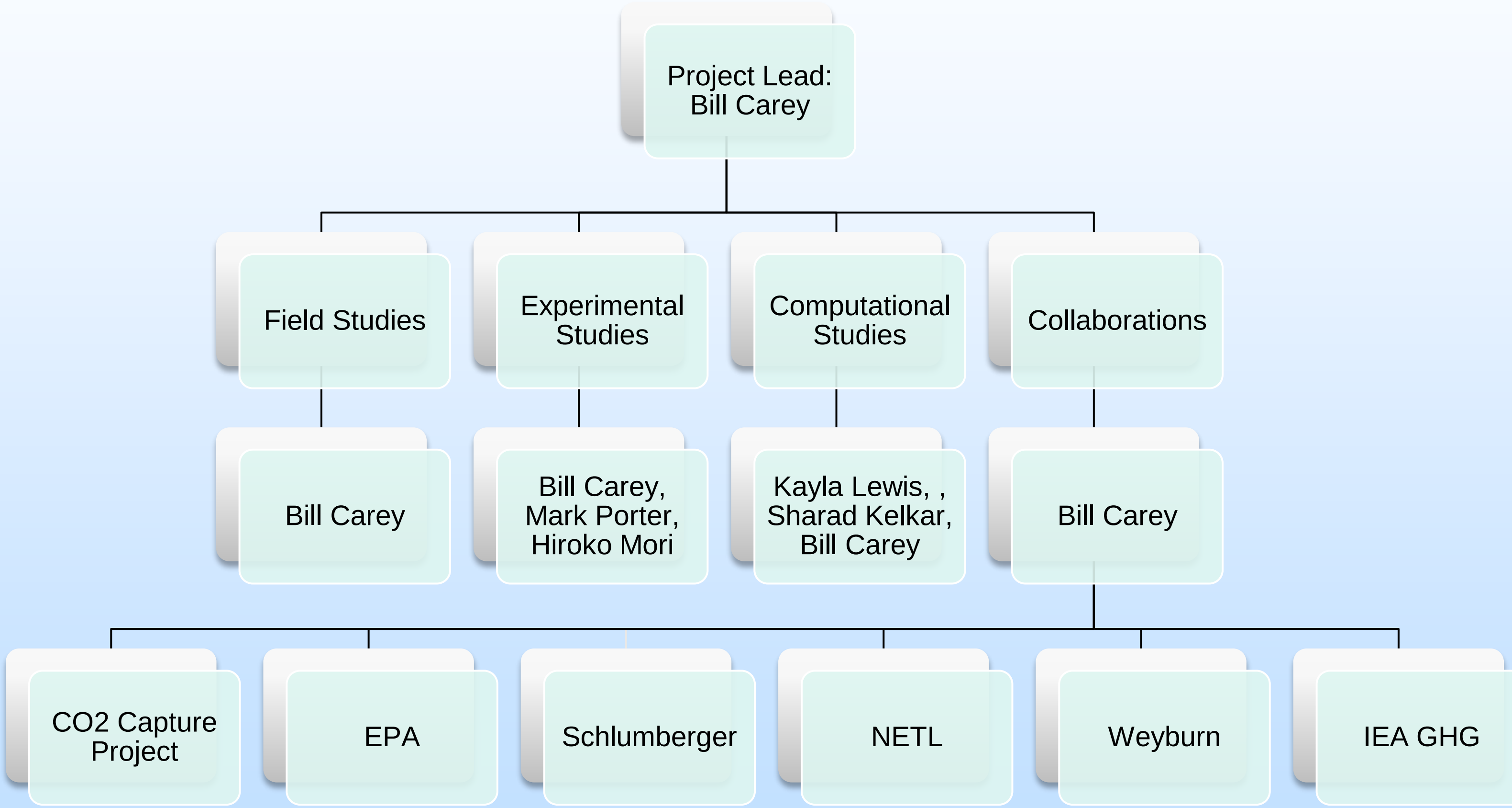
– Future Plans

  • Continued development of triaxial experiment protocol and investigation of coupled deformation and flow

  • Continued development of geomechanical model with benchmarking against experiments

Appendix

Organization Chart



Gantt Chart

Task	FY10				FY11				FY12				FY13			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1.1 Project Management and Planning																
Task 1.2 Field Studies of Wellbore Integrity																
Task 1.2.1 Interpretation of Wellbore Samples obtained from the CO_2 Capture Project																
Task 1.2.2 Develop and Conduct Analyses of Wellbore Samples from New Analog Sites																
Task 1.3 Experimental Studies of Wellbore Integrity																
Task 1.3.1 Cement-cement interface studies																
Task 1.3.2 Cement-casing interface studies																
Task 1.3.3 Cement-caprock interface studies																
Task 1.4 Numerical Modeling Studies of Wellbore Integrity																
Task 1.4.1 Numerical model of 2-phase cement-rock reactions																
Task 1.4.2 Numerical model of reactive transport of CO_2-brine in 2-dimensions in a																
Task 1.4.3 Numerical model of cement-interface evolution																
Task 1.5 Collaborative Studies of Wellbore Integrity																
Task 1.5.1 Provide organizational leadership for the Wellbore Integrity Network																
Task 1.5.2 Develop collaboration with IFE and/or CCP on wellbore and/or caprock																
Task 1.5.3. Develop study with NETL's Pittsburgh Lab on cement integrity																

Bibliography

- Carey, J. W. (2013, in press). Geochemistry of Wellbore Integrity in CO2 Sequestration: Portland Cement-Steel-Brine-CO2 Interactions, volume 77 of Reviews in Mineralogy and Geochemistry, chapter 15. Mineralogical Society of America, Washington, DC.
- Newell, D. L. and Carey, J. W. (2013). Experimental evaluation of wellbore integrity along the cement-rock boundary. Environmental Science & Technology, 47: 276-2825.
- Carey, J. W., Lewis, K., Kelkar, S., and Zyvoloski, G. A. (2013). Geomechanical behavior of wells in geologic sequestration. Energy Procedia. 11th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan, November 18-22, 2012.
- Carey, J. W. and Lichtner, P. C. (2011). Computational studies of two-phase cement-CO2 -brine interaction in wellbore environments. SPE Journal, 16:940–948.

Bibliography

- Han, J. and Carey, J. W. (2011). Localized CO2 corrosion propagation at moderate FeCO3 supersaturation initiated by mechanical removal of corrosion scale. Journal of Applied Electro- chemistry, 41:1367–1371.
- Han, J., Carey, J. W., and Zhang, J. (2011). Effect of sodium chloride on corrosion of mild steel in CO2 -saturated brines. Journal Of Applied Electrochemistry, 41:741–749.
- Han, J., Carey, J. W., and Zhang, J. (2011). Effect of bicarbonate on corrosion of carbon steel in CO2 saturated brines. International Journal of Greenhouse Gas Control, 5:1680–1683.
- Han, J., Carey, J. W., and Zhang, J. (2011). A coupled electrochemical-geochemical model of corrosion for mild steel in high-pressure CO2 -saline environments. International Journal of Greenhouse Gas Control, 5:777–787.
- Carey, J. W., Svec, R., Grigg, R., Zhang, J., and Crow, W. (2010). Experimental investigation of wellbore integrity and CO2 –brine flow along the casing-cement microannulus. International Journal of Greenhouse Gas Control, 4:272–282.

Bibliography

- Crow, W., Carey, J. W., Gasda, S., Williams, D. B., and Celia, M. (2010). Wellbore integrity analysis of a natural CO_2 producer. International Journal of Greenhouse Gas Control, 4:186– 197.
- Wigand, M., Kaszuba, J. P., Carey, J. W., and Hollis, W. K. (2009). Geochemical effects of CO_2 sequestration on fractured wellbore cement at the cement/caprock interface. Chemical Geology, 265:122–133.
- Viswanathan, H. S., Pawar, R. J., Stauffer, P. H., Kaszuba, J. P., Carey, J. W., Olsen, S. C., Keating, G. N., Kavetski, D., and Guthrie, Jr., G. D. (2008). Development of a hybrid process and system model for the assessment of wellbore leakage at a geologic CO_2 sequestration site. Environmental Science & Technology, 42:7280–7286.
- Carey, J. W., Wigand, M., Chipera, S., WoldeGabriel, G., Pawar, R., Lichtner, P., Wehner, S., Raines, M., and Guthrie, Jr., G. D. (2007). Analysis and performance of oil well cement with 30 years of CO_2 exposure from the SACROC Unit, West Texas, USA. International Journal of Greenhouse Gas Control, 1:75–85.

Bibliography

- Carey, J. W. and Lichtner, P. C. (2007). Calcium silicate hydrate (C-S-H) solid solution model applied to cement degradation using the continuum reactive transport model FLOTRAN. In Mobasher, B. and Skalny, J., editors, Transport Properties and Concrete Quality: Materials Science of Concrete, Special Volume, pages 73–106. American Ceramic Society; John Wiley & Sons, Inc.