LANL Sequestration Activities: Long-term Wellbore and Caprock Seal Integrity

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Poland and Davis (1969) “Land Subsidence Due to Withdrawal of Fluids

Outline/Motivation

- Project goal: Quantify possible leakage processes of CO_2 through wellbore and caprock seals
- Geomechanical model of injection-induced damage in wellbore systems
  - Injection/production results in expansion/contraction of the reservoir
  - Shear stress results that has the potential to damage the well-formation interface
- Geomechanical experiments on fracture-permeability behavior of caprock
- Numerical study and summary of geochemical self-sealing processes in wellbore systems

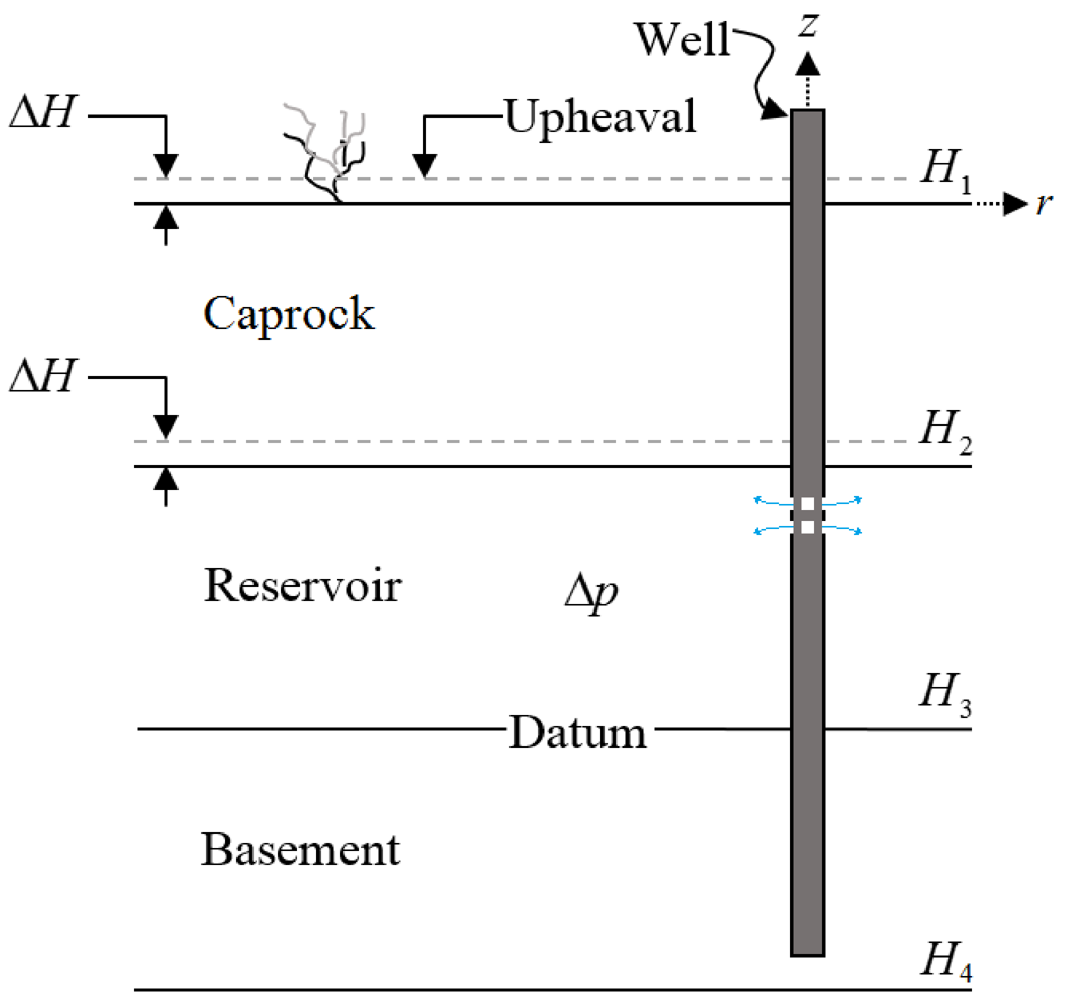
Technical Status

- Completed: “Engineering Prediction of Axial Wellbore Shear Failure due to Reservoir Uplift”
- Modified and enhanced a triaxial direct-shear coreflood system with simultaneous x-ray radiography/tomography
- Completed: experimental study of potential fracture leakage processes in shale as caprock
- Completed: “Hydrated Portland Cement as a Carbonic Cement: The Mechanisms, Dynamics, and Implications of Self-Sealing and CO_2 Resistance in Wellbore Cements”

Geomechanical Model of Injection-Induced Damage to Wellbores

- Analytical model that evaluates wellbore integrity in response to reservoir uplift
- Shear and tensile failure at cement interfaces in response to coupled casing-cement-rock poro-mechanics
- Initial state of stress of cement a key component of analysis
- Verified with Abaqus numerical model

Problem Set-up



Effective Stress Changes

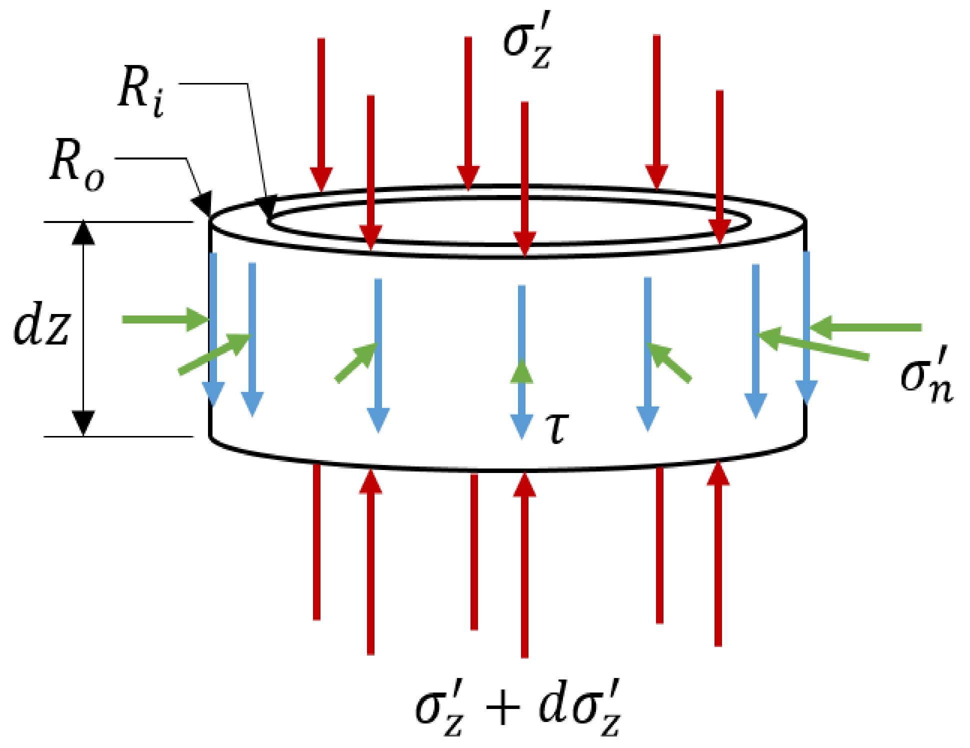
$$\sigma' = \sigma - \alpha p$$

Uplift function of elastic properties

$$\Delta\varepsilon_z = \frac{\Delta\sigma_z'}{E}\left(1 - \frac{2v^2}{1-v}\right)$$

Shear Criteria at Well Interface

Stress Diagram of Well



Shear Criteria

$$0 = \left(R_o^2 - R_i^2\right) d\sigma_z' - 2dzR_o\tau$$

$$\tau_{\max} = \sigma_n' \tan\phi + c_c$$

$$L = \frac{\left(R_o^2 - R_i^2\right)\Delta\sigma_z'}{2R_o\left(\sigma_n' \tan\phi + C\right)}$$

Tensile Criteria (Percolation)

$$T \leq \sigma_n' - \left(p_W - \alpha p_P\right)$$

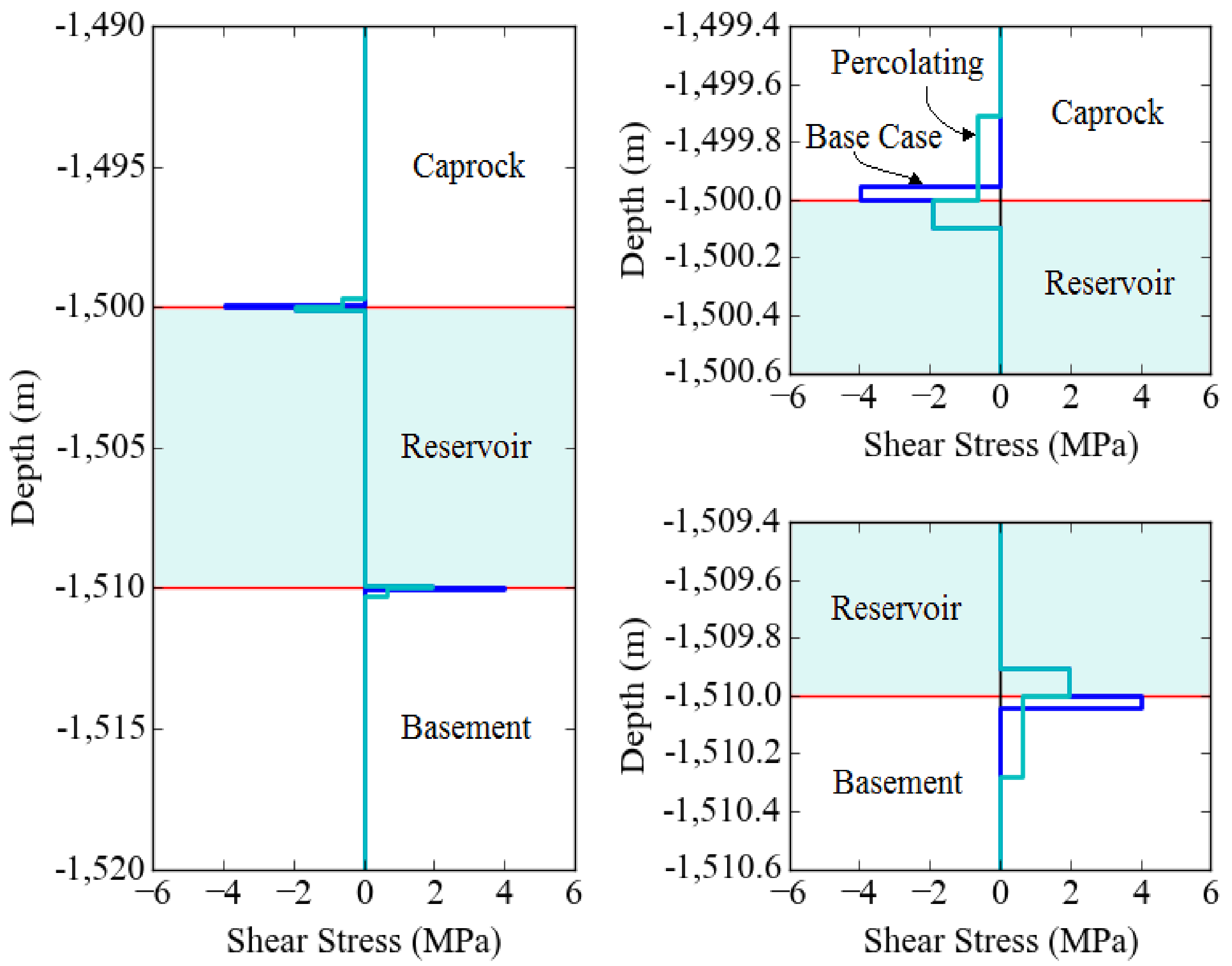
Parameters for Base Case

Parameter				
Injection overpressure, MPa (Δp)				6.000*

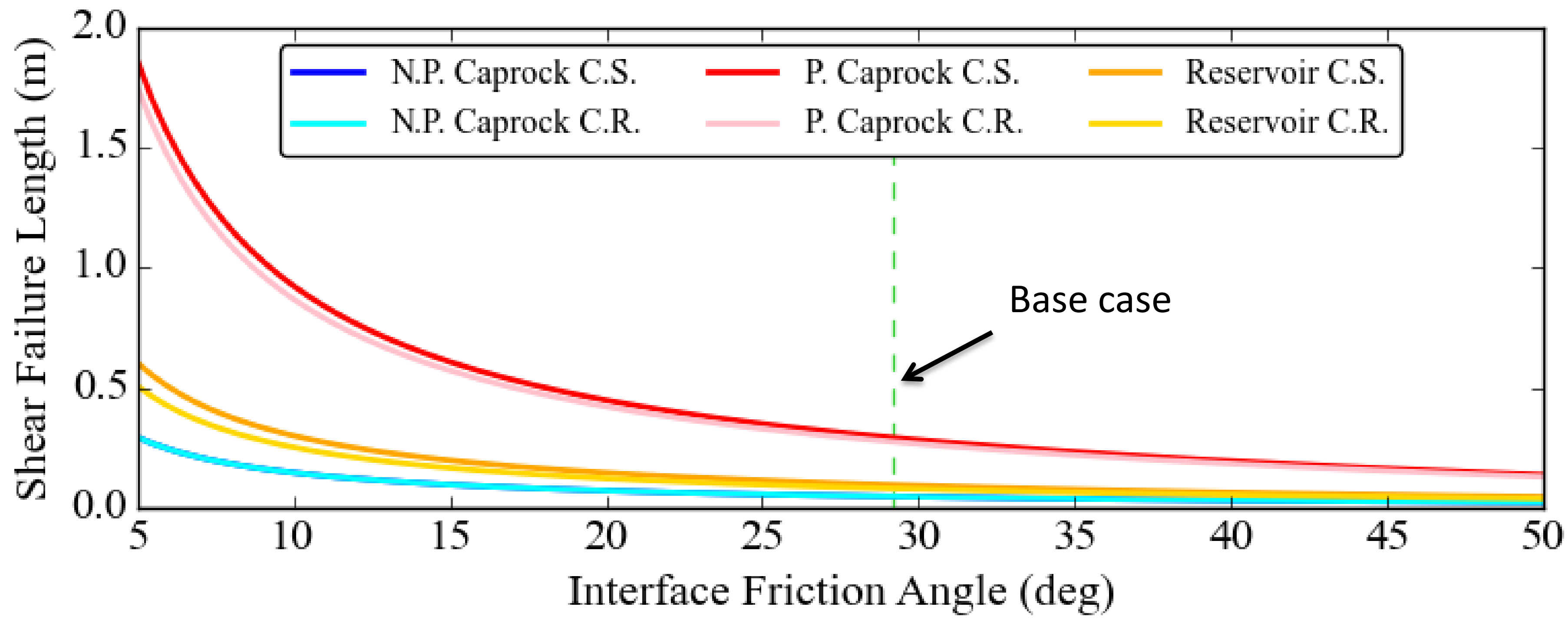
Non-percolating: Injection fluids do not enter damaged annulus
Percolating: Injection fluids enter damaged annulus

Base Case Results

Shear Failure Length

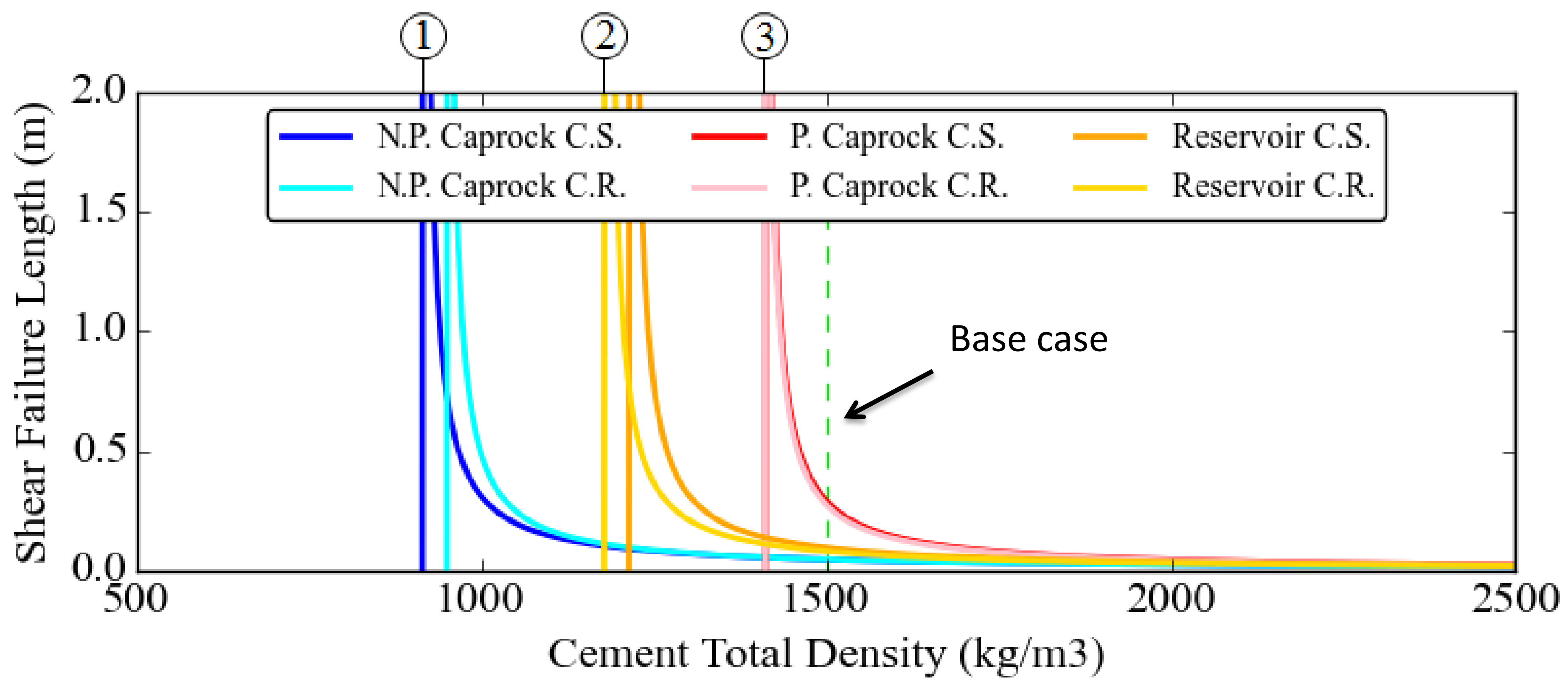


Sensitivity to Friction Angle



N.P. = Non-percolating
P. = Percolating
C.S. = Cement-steel
C.R. = Cement-reservoir

Sensitivity to Cement Density



N.P. = Non-percolating
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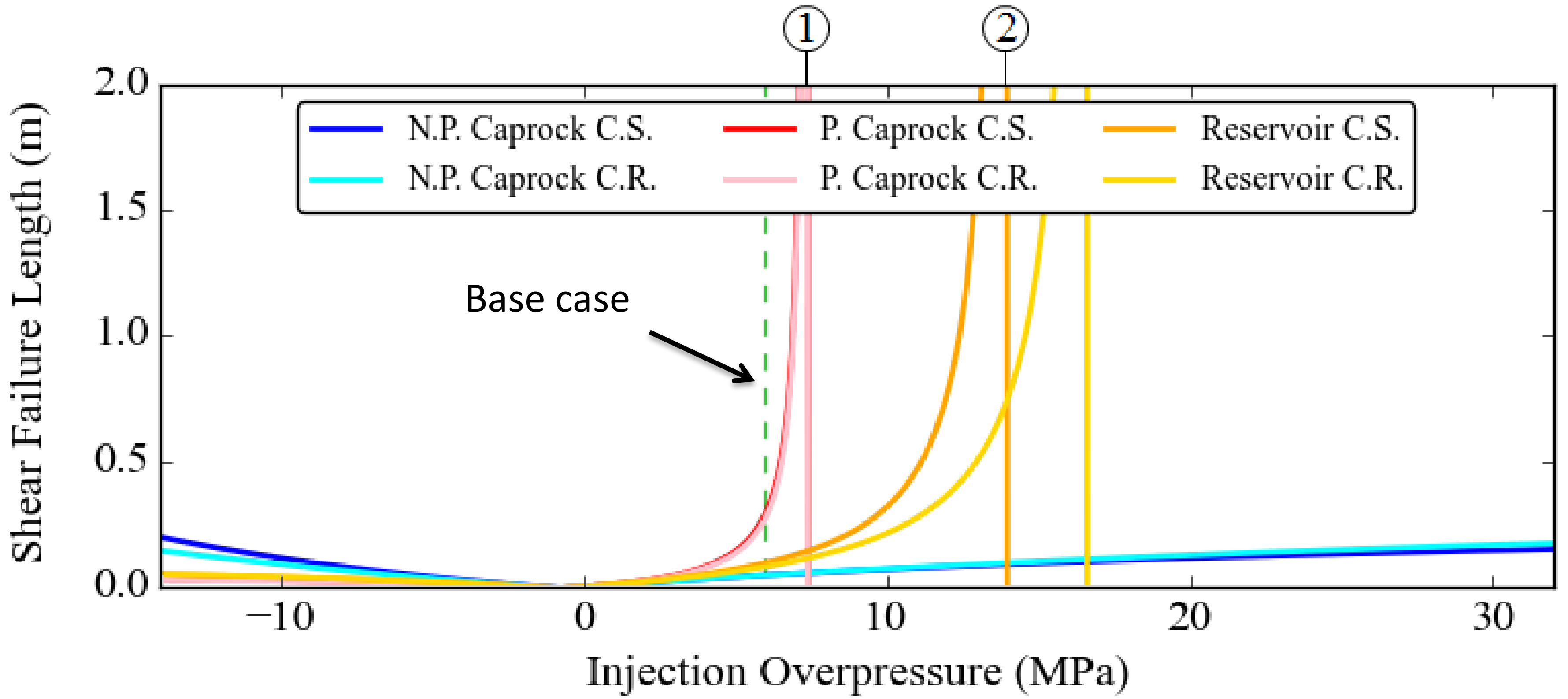
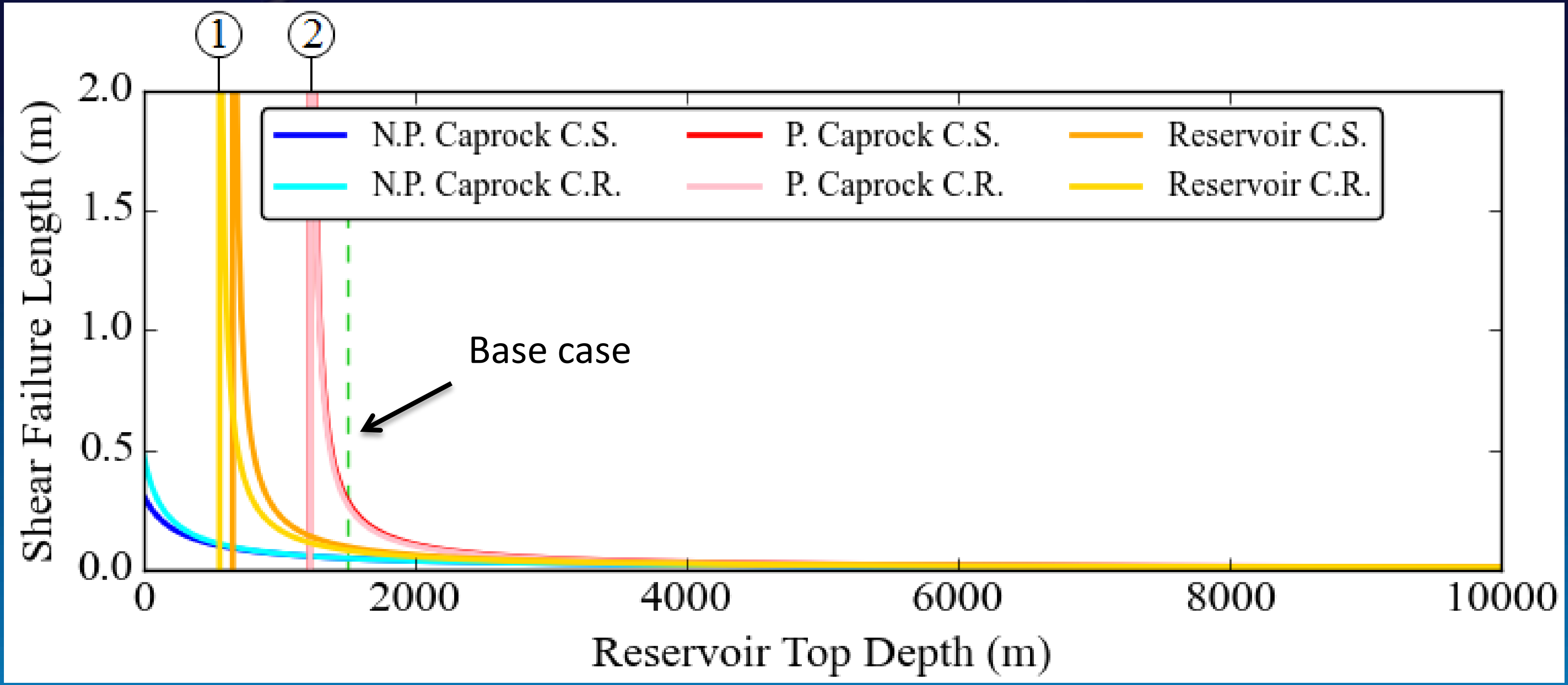
Sensitivity to Injection Pressure



N.P. = Non-percolating
P. = Percolating
C.S. = Cement-steel
C.R. = Cement-reservoir

Sensitivity to Depth



N.P. = Non-percolating
P. = Percolating
C.S. = Cement-steel
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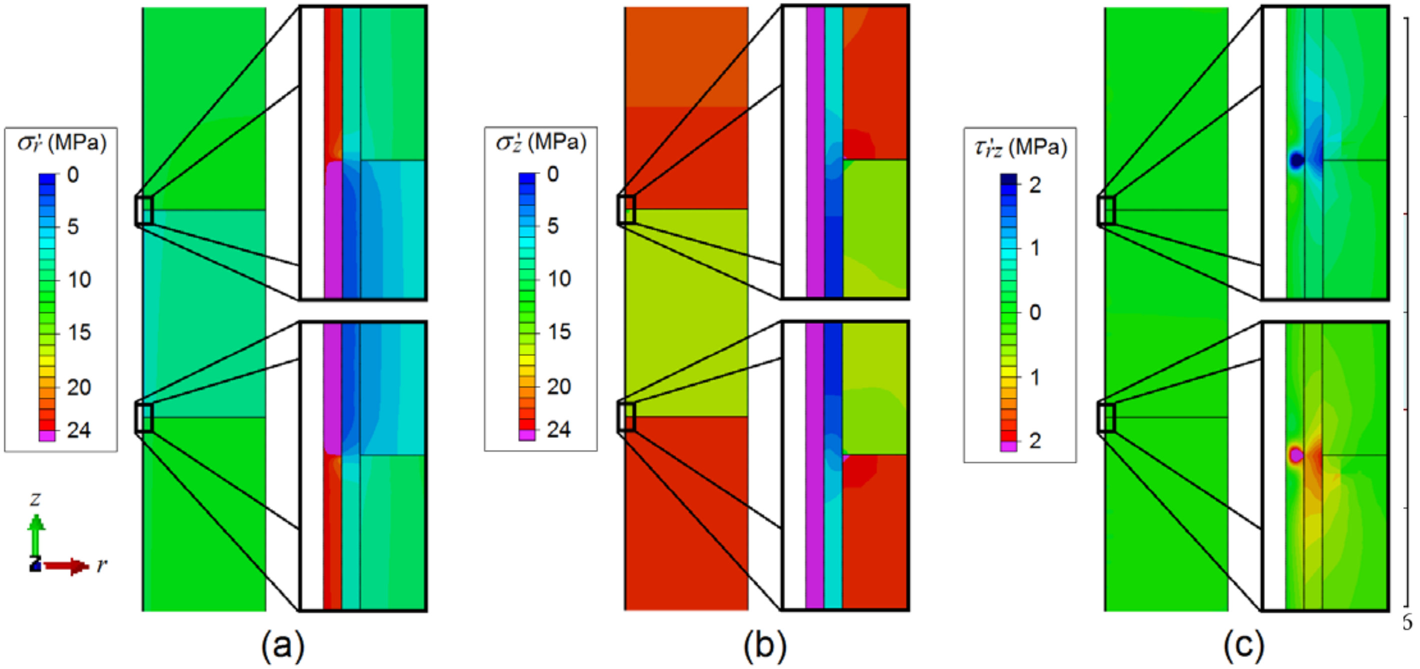
Numerical Validation

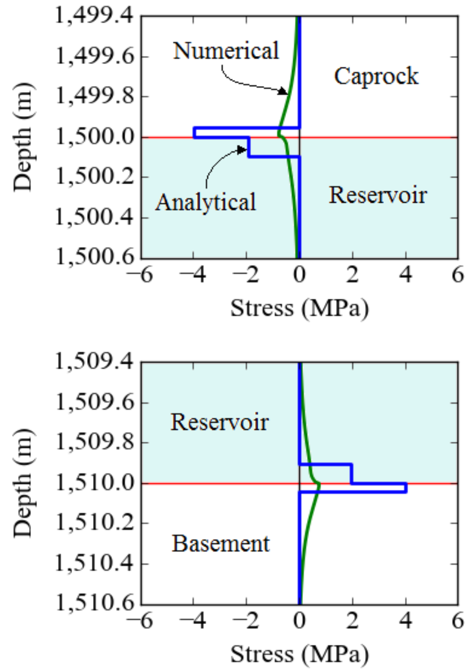
Stress Distributions

Radial Vertical Cross

Failure Length



(a) (b) (c)



Conclusions for Well Geomechanics

- We developed a system of analytical equations that allows calculation of stress and failure in wellbore systems subject to changing reservoir pressures
- Shear failure and fluid percolation are most sensitive to cement density, injection pressure, and depth of the reservoir
- The equations provide a rapid and effective way of designing wells for planned injection operations
- The equations provide a rapid and effective way of evaluating whether wells in the Region of Interest are subject to potential injection-induced shear failure and leakage

Frash and Carey (submitted) SPE Journal

Hydrated Portland Cement as a Carbonic Cement:

The Mechanisms, Dynamics, and Implications of Self-Sealing and CO_2 Resistance in Wellbore Cements

- Newly developed model of self-sealing behavior in cement associated with CO_2 and brine flow
- See poster by George Guthrie et al. for details
- Self-sealing conditions arise for large range in cement and reservoir properties
- For constant flow conditions, self-sealing conditions migrate at velocity proportional to fluid velocity and maintain precipitation-dominated for sealing-favorable periods of time
- CO_2-reacted Portland cement is a “carbonic cement” in the same sense that H_2O-reacted Portland cement is a hydraulic cement

Accomplishments to Date

- Published reviews of wellbore integrity (Carey 2013; Carroll, Carey et al. (2016)
- Developed field evidence (Carey et al. 2007), experimental evidence (Carey et al. 2010; Newell and Carey 2013) and computational models (Guthrie et al. 2017) of self-sealing behavior
- Developed and demonstrated a protocol for characterizing leakage behavior in caprock as a function of stress conditions (Carey et al. 2015; Frash et al. 2016, 2017)
- Determined a threshold change in leakage potential in caprock as effective stress increases (Frash et al. 2016, 2017)
- Developed an analytical geomechanical model for analysis of stress and failure in wellbore systems (Frash and Carey, submitted)

Lessons Learned

- Portland cement is a carbonic cement with self-sealing properties; it is far more resilient than originally thought
  - Coupled casing corrosion and cement carbonation is not yet understood
  - Experimental geomechanics of wellbore systems is just beginning
- Caprock integrity characterization involves more than determining low permeability; fracture-permeability behavior is key to understanding risk of leakage
  - Much work remains to understanding resilience and breakdown of caprock systems as function of lithology and subsurface conditions
- Difficulties
  - Coupled processes are technically challenging both experimentally and computationally
  - Field observations of well and caprock failure processes are extremely limited

Synergy Opportunities

- Excellent opportunities to collaborate on geomechanics and induced seismicity of storage reservoir systems
  - Penn State study of rheology of fracture slip (D. Elsworth)
  - UT-Austin study of reservoir seal geomechanics (P. Eichhubl)
  - LBL study of *in situ* fault slip (J. Birkholzer)
- Excellent opportunities to collaborate on well integrity problems
  - Clemson study of strain/stress measurement in wells (L. Murchoch)
  - LLNL study of thermal stresses in wells (J. Morris/P. Roy)
  - NETL studies of well integrity (N. Huerta/B. Kutchko)
  - LLNL studies of cement deformation and sealing (Carroll, Iyer, Walsh)
- Many other projects are closely allied to work here (reservoir geomechanics, well integrity studies, etc.)

Project Summary

- One key to reducing risk of leakage is through observation and measurement of self-healing properties of cement and caprock
- We have shown that leakage is mitigated under *some* conditions
  - Wellbore integrity is better understood and mitigation appears to be bounded by the size and continuity of the defect
  - Understanding mitigation of caprock leakage has just started
- Understanding fracture-permeability behavior of caprock is an effective means of addressing potential impact of induced-seismicity
- A complete treatment of the geomechanics of wellbore systems is limited by lack of understanding of *in situ* stress conditions in cement
  - A framework for analysis has been established but awaits additional characterization of full implementation

Appendix

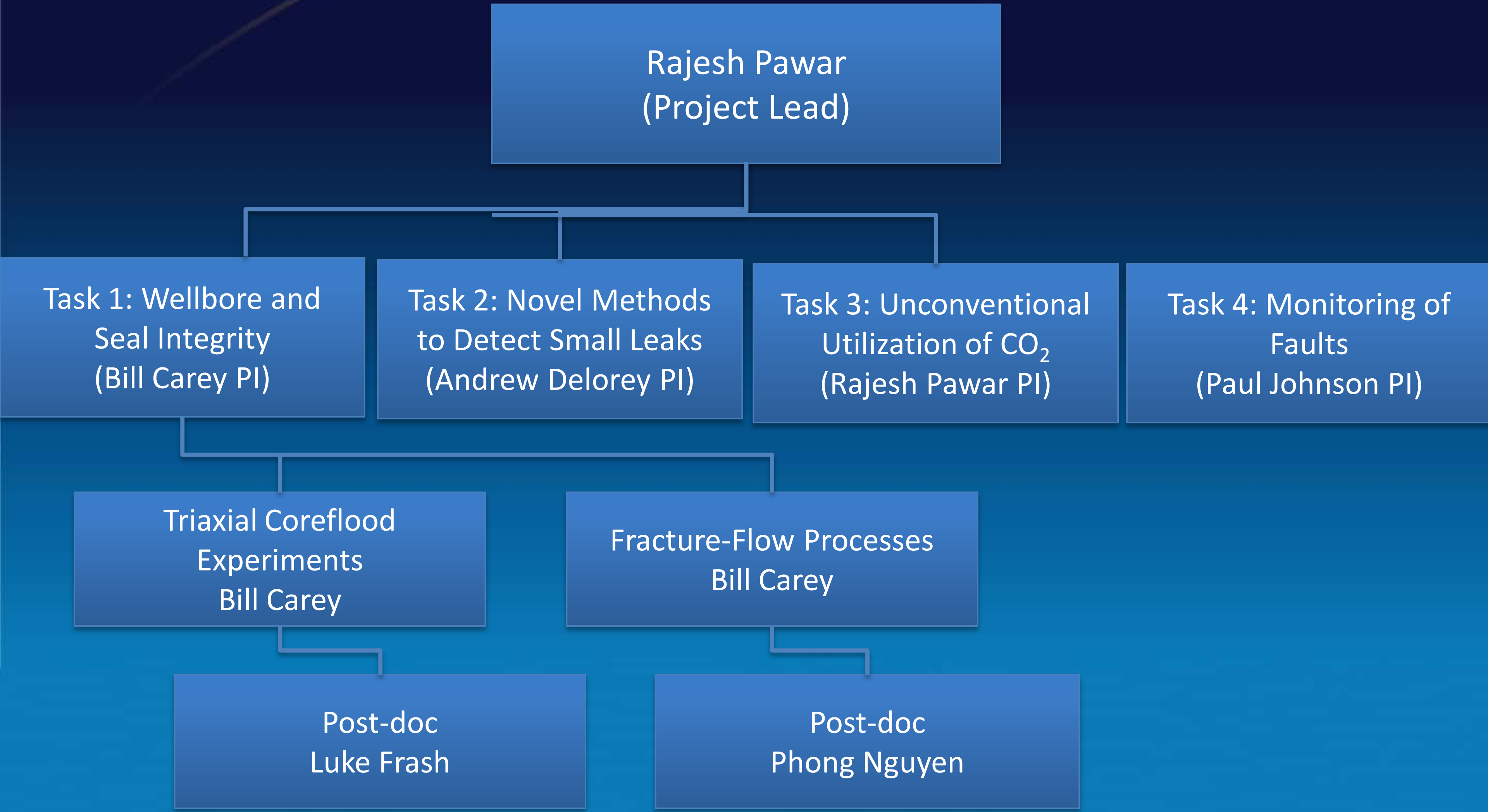
Benefit to the Program

- Develop long-term predictive models for use in risk-based analyses of carbon storage systems
- Determine the consequences of stress-induced damage to wellbore and caprock seals?
- Develop and validate technologies to ensure 99% storage permanence.

Project Overview
Goals and Objectives

- Impact of stress (mechanical and chemical) on wellbore and caprock integrity focused on role of CO_2-water
  - Experimental studies of the impact of mechanical stress on leakage processes
  - Experimental studies of the impact of CO_2 flow and geochemical reactions on leakage
  - Field studies of cement-steel-caprock samples obtained from CO_2-containing reservoirs
  - Numerical models to predict damage and leakage in wellbore and caprock seals

Organization Chart



Rajesh Pawar
(Project Lead)

Task 1: Wellbore and Seal Integrity
(Bill Carey PI)

Task 2: Novel Methods to Detect Small Leaks
(Andrew Delorey PI)

Task 3: Unconventional Utilization of CO_2
(Rajesh Pawar PI)

Task 4: Monitoring of Faults
(Paul Johnson PI)

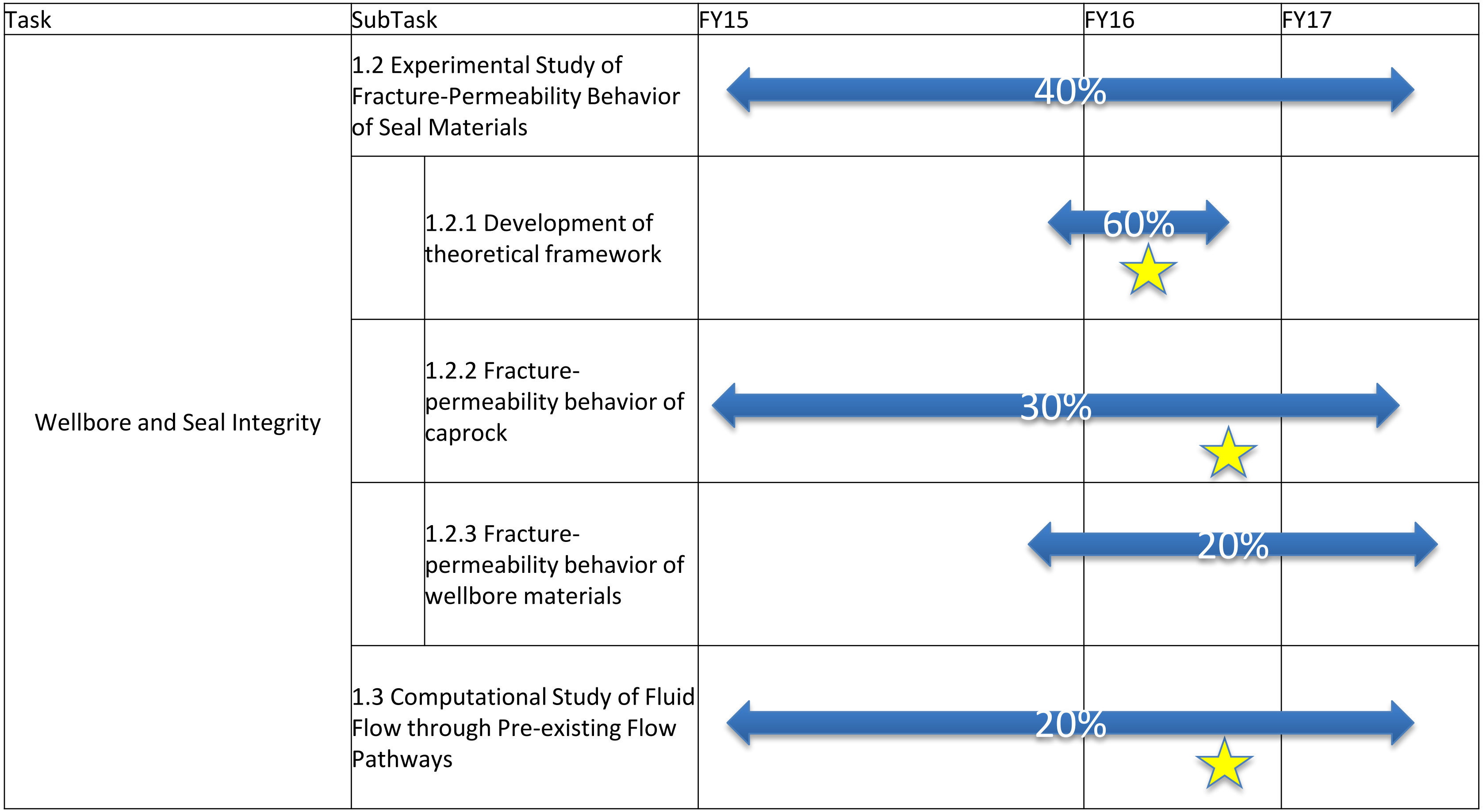
Triaxial Coreflood Experiments
Bill Carey

Fracture-Flow Processes
Bill Carey

Post-doc
Luke Frash

Post-doc
Phong Nguyen

Gantt Chart



Task	SubTask	FY15	FY16	FY17
Wellbore and Seal Integrity	1.2 Experimental Study of Fracture-Permeability Behavior of Seal Materials			
	1.2.1 Development of theoretical framework			
	1.2.2 Fracture-permeability behavior of caprock			
	1.2.3 Fracture-permeability behavior of wellbore materials			
	1.3 Computational Study of Fluid Flow through Pre-existing Flow Pathways			

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Appendix: Publications 2015/2017

Supported in total or in part by this project

- Frash, L. P., and J. W. Carey (submitted) Engineering prediction of axial wellbore shear failure due to reservoir uplift, SPE Journal.
- Carey, J. W. and Torsæter, M. (accepted). Shale and Well Integrity. In Shale Science. John Wiley & Sons.
- Carey, J. W., L. P. Frash, T. Ickes, and H. S. Viswanathan (2017) Stress cycling and fracture permeability of Utica shale using triaxial direct-shear with x-ray tomography, in 51th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA, USA, 26-28 June 2017, p. 6.
- Frash, L. P., J. W. Carey, T. Ickes, and H. S. Viswanathan (2017) Caprock integrity susceptibility to permeable fracture creation, International Journal of Greenhouse Gas Control, 64, 60 – 72.
- Frash, L. P., J. W. Carey, T. Ickes, and H. S. Viswanathan, High-stress triaxial direct-shear fracturing of Utica shale and in situ x-ray microtomography with permeability measurement, Journal of Geophysical Research, 121, 5493–5508, 2016.
- Carey, J. W., Frash, L. P., and Viswanathan, H. S. (2016). Dynamic Triaxial Study of Direct Shear Fracturing and Precipitation-Induced Transient Permeability Observed by In Situ X-Ray Radiography. In 50th US Rock Mechanics / Geomechanics Symposium held in Houston, Texas, USA, 26-29 June 2016.

Appendix: Publications 2015/2017 (cont.)

Supported in total or in part by this project

- Carroll, S., Carey, J. W., Dzombak, D., Huerta, N., Li, L., Richards, T., Um, W., Walsh, S., and Zhang, L. (2016). Review: Role of Chemistry, Mechanics, and Transport on Well Integrity in CO_2 Storage Environments. International Journal of Greenhouse Gas Control, 49:149-160.
- Carey, J. W., Lei, Z., Rougier, E., Mori, H., and Viswanathan, H. S. (2015). Fracture-permeability behavior of shale. Journal of Unconventional Oil and Gas Resources, 11:27–43. doi: 10.1016/j.juogr.2015.04.003.
- Carey, J. W., Rougier, E., Lei, Z., and Viswanathan, H. S. (2015). Experimental investigation of fracturing of shale with water. In 49th US Rock Mechanics/Geomechanics Symposium, 28 June-1 July 2015, San Francisco, CA USA.