LANL Sequestration Activities: Long-term Wellbore and Caprock Seal Integrity FWP LANL FE-890-18-FY19

U.S. Department of Energy National Energy Technology Laboratory
Mastering the Subsurface Through Technology Innovation,
Partnerships and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting

Experimental Study of Self-Sealing in Portland Cement

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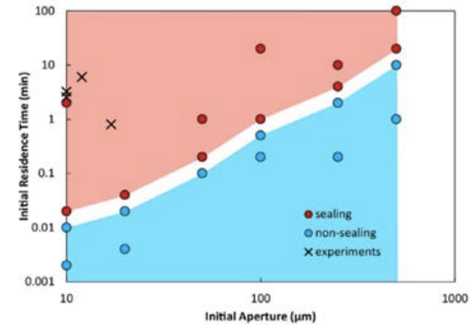
NNSA National Nuclear Security Administration

Outline/Motivation

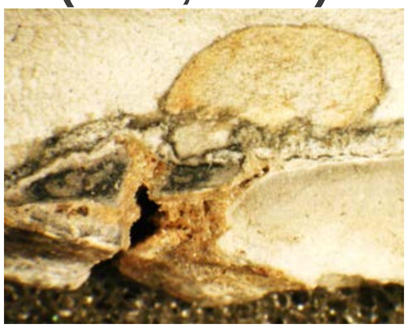
- **Project goal: Quantify potential leakage processes of CO_2 through wellbore and caprock seals**
- **Self-sealing phenomena in wellbore systems**
  - Experimental and numerical study of mechanisms, dynamics, and implications
  - How much cement is needed to ensure self-sealing?
  - What is a CO_2-compatible cement?
- **Geomechanical behavior of wellbore systems**
  - Stability and permeability of the cement-steel interface (experiments)
  - Reservoir expansion/contraction driven damage to wells (models)
- **Geomechanical experiments on fracture-permeability behavior of caprock**
  - Shale, dolomite and anhydrite shear fracture permeability as a function of confining stress and displacement

Why is Self-Sealing in Cement Important?

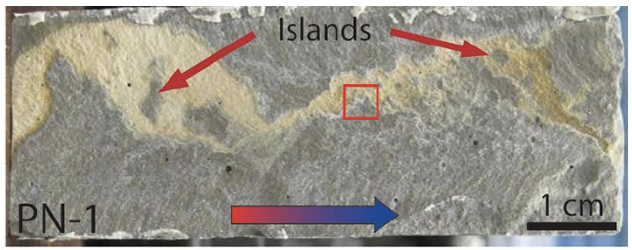
- Leakage of CO_2 from wells is a consistent "high-risk" factor in performance assessment
- Small leaks are difficult to detect and to remediate
- Field, experimental and numerical observations *indicate* that self-sealing occurs in Portland cement systems: Carey (MSA, 2013) and Carroll et al. (IJGGC 2016)



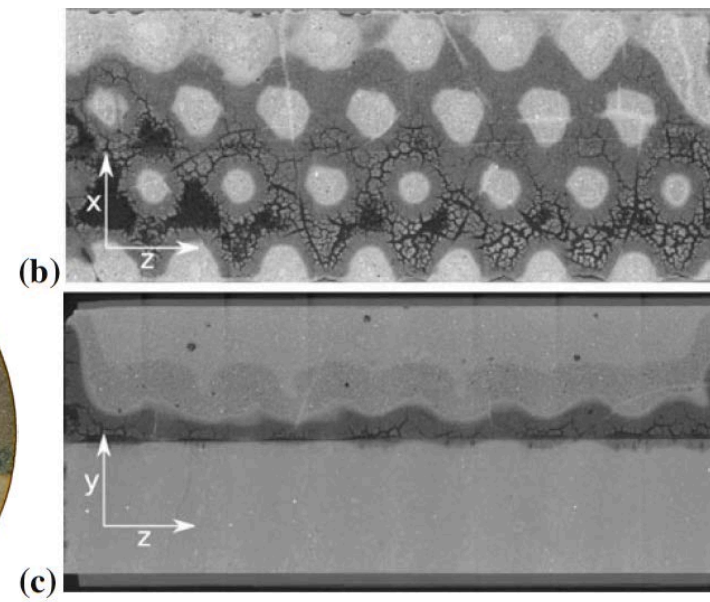
Iyer et al. (IJGGC 2017)

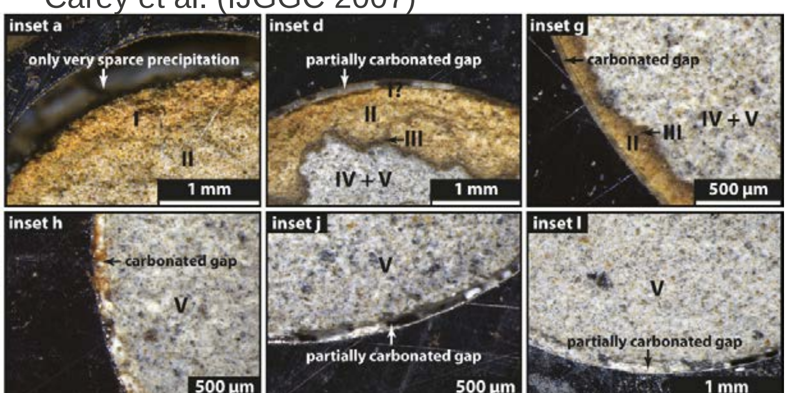


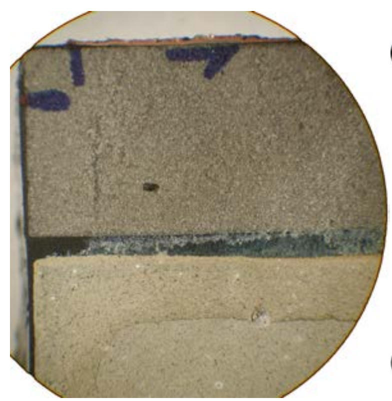
Cement from SACROC
Carey et al. (IJGGC 2007)



Huerta et al. (ES&T 2013)







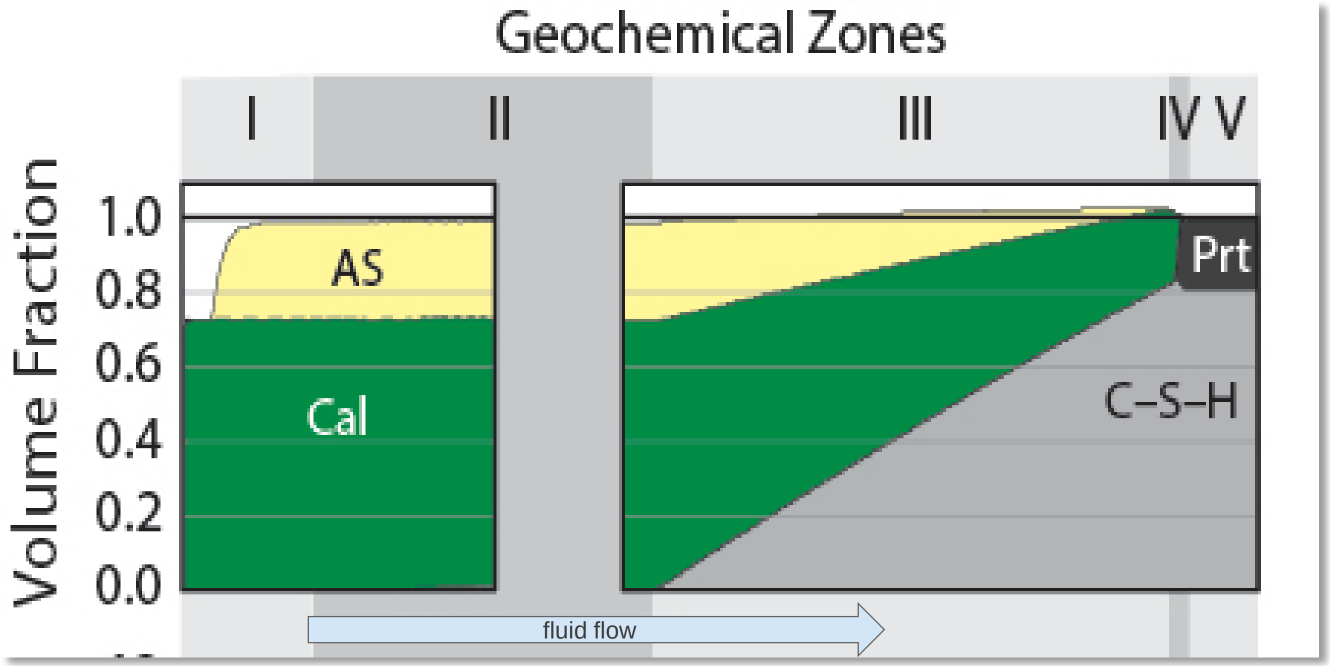
Wolterbeek et al. (IJGGC 2016)

Newell and Carey (ES&T 2013)

Walsh et al. (Rock Mech. Rock Eng. 2013)

Numerical Simulation of Self-Sealing in Cement: Presented Last Year

1-D numerical model predicts a sequence of geochemical zones during CO_2 leakage through cement. A competition between flow-rate, channel geometry, and length of cement dictates sealing behavior



I — **Dissolution—porosity increase**

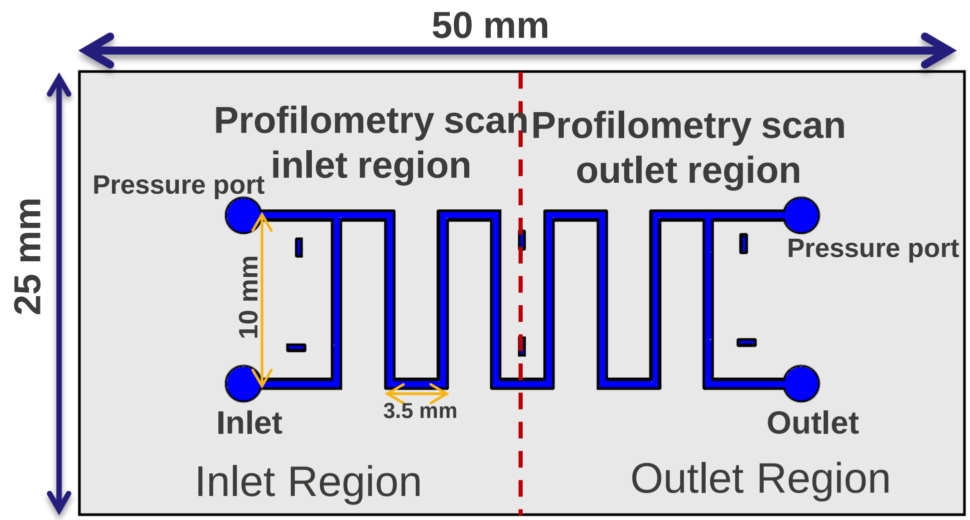
II — **Equilibrium of carbonated cement**

III — Loss of C-S-H with calcite precipitation—porosity decrease

IV — Loss of portlandite and precipitation of C-S-H and calcite—porosity decrease

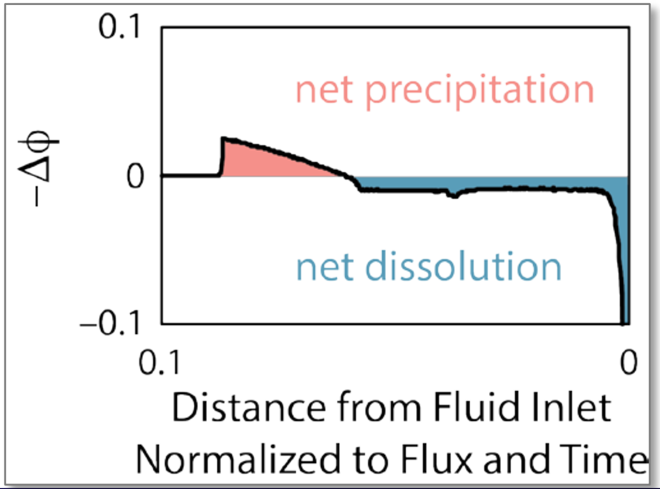
V — **Equilibrium of original cement**

Experimental Study of Self-Sealing: Microfluidics in Portland Cement



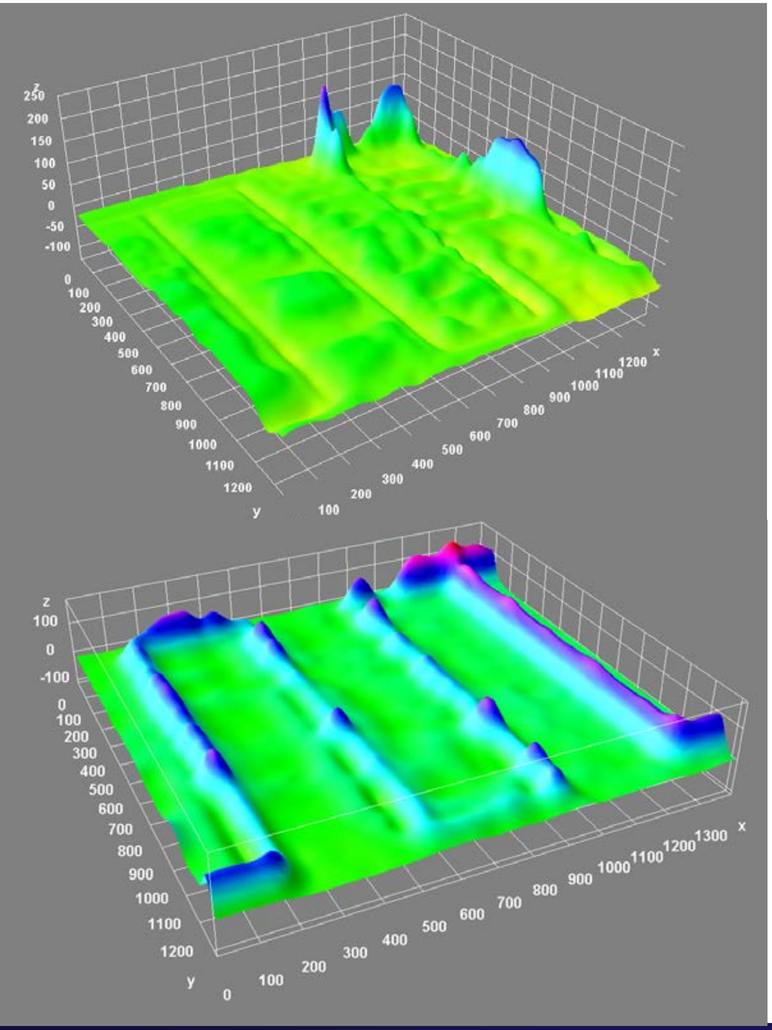
- Type G Portland Cement with etched channel system
- Inject CO_2-saturated deionized water
- P = 8 MPa, T = 25 ^{o}C
- Experiments as function of
  - Flow rate: 1-20 µL/min
  - Channel dimensions: 200, 500, 1000 µm width
- Duration about 2 days

Predicted Change in Volume

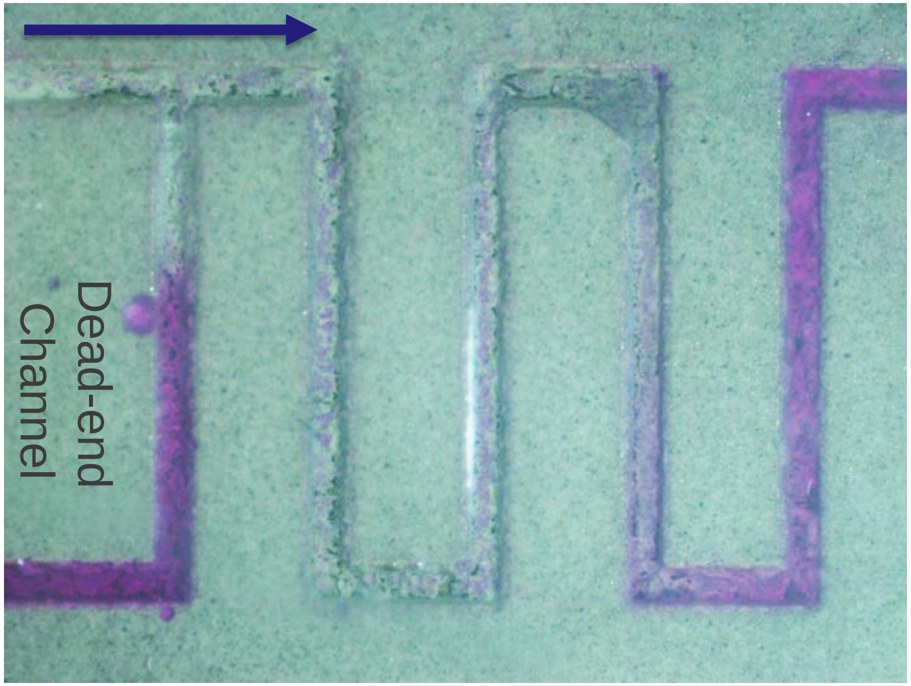


Experimental Analysis

Profilometry: Spatial Distribution of Dissolution and Precipitation

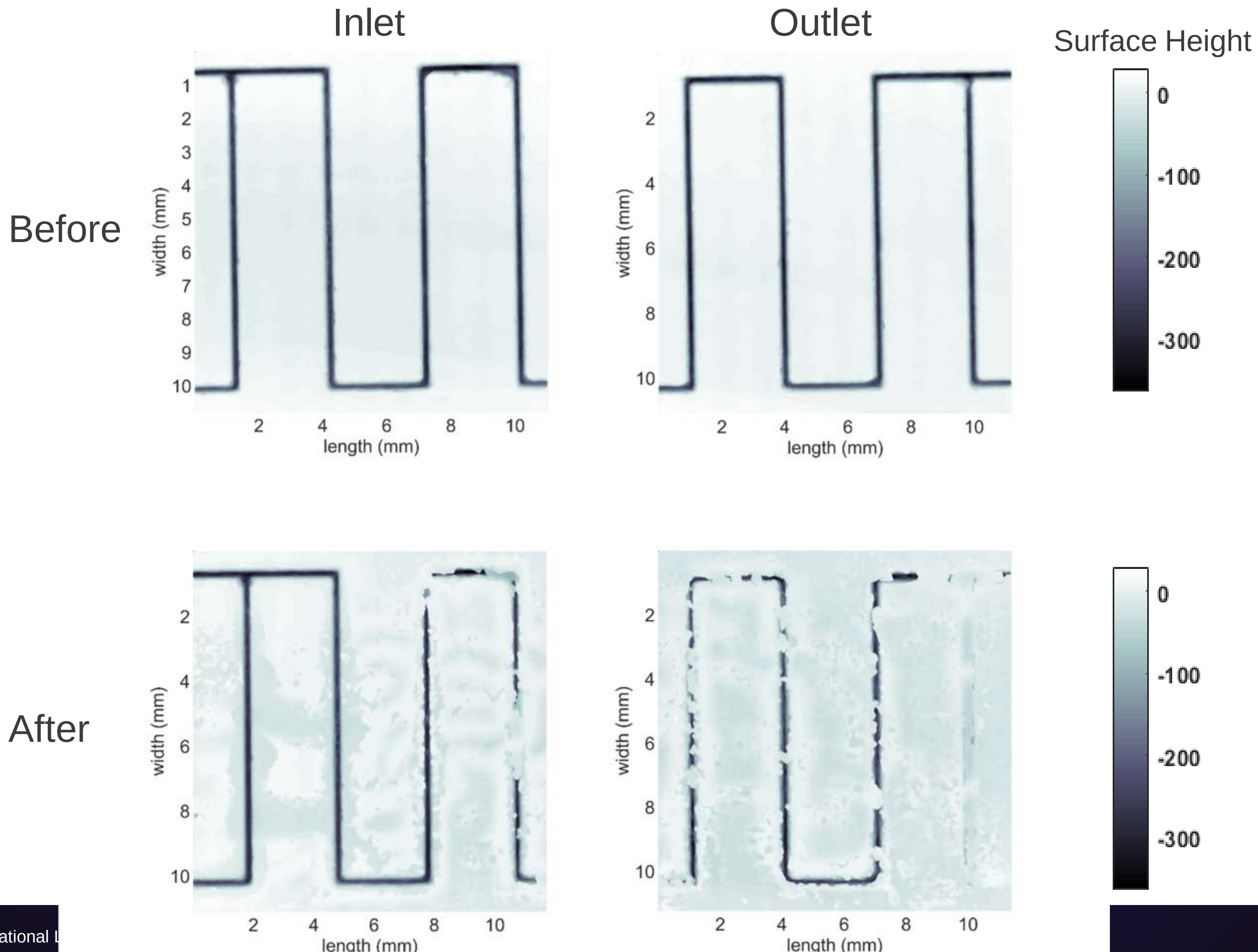


Optical Observations

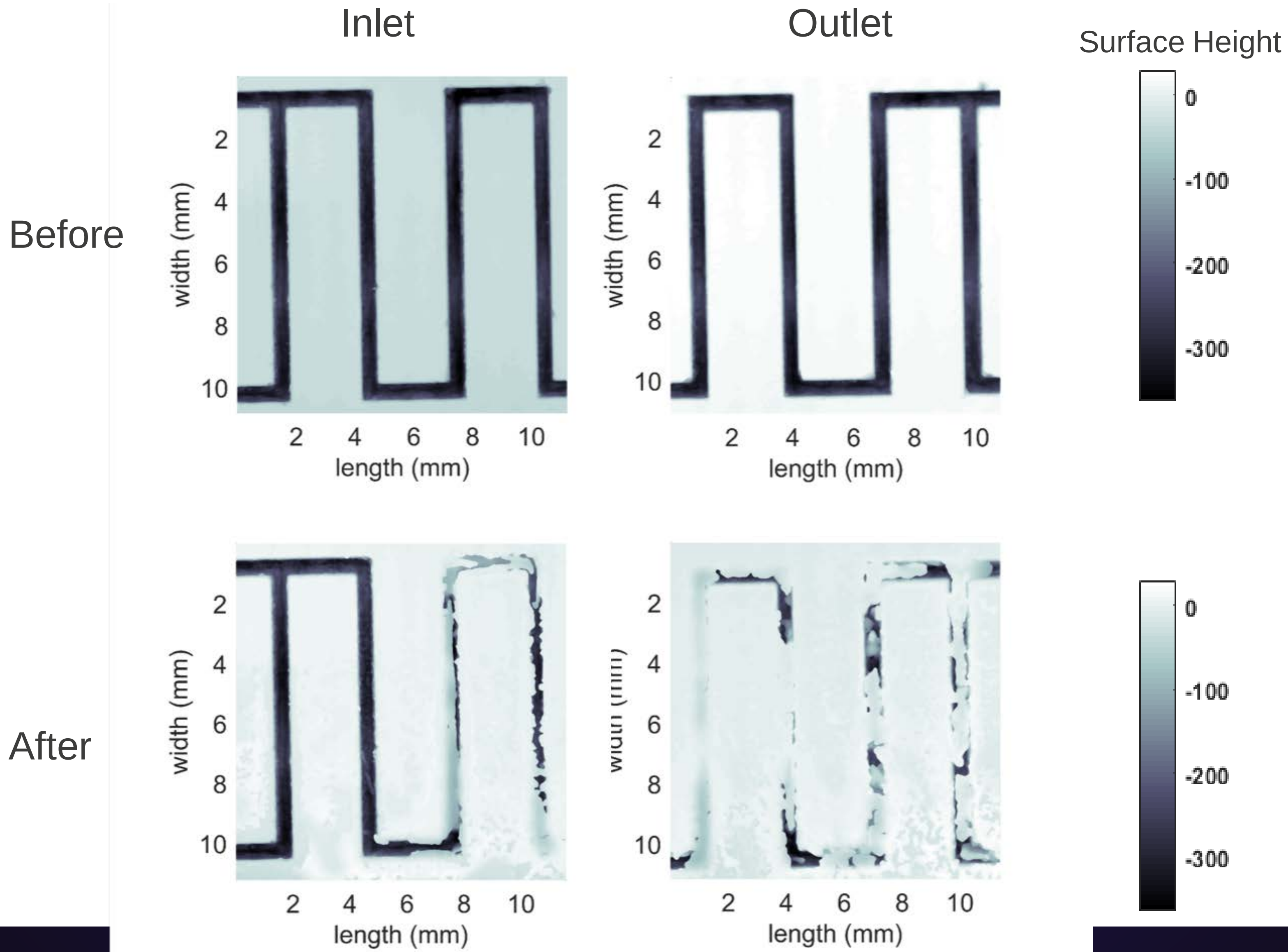


Phenolphthalein indication of pH front

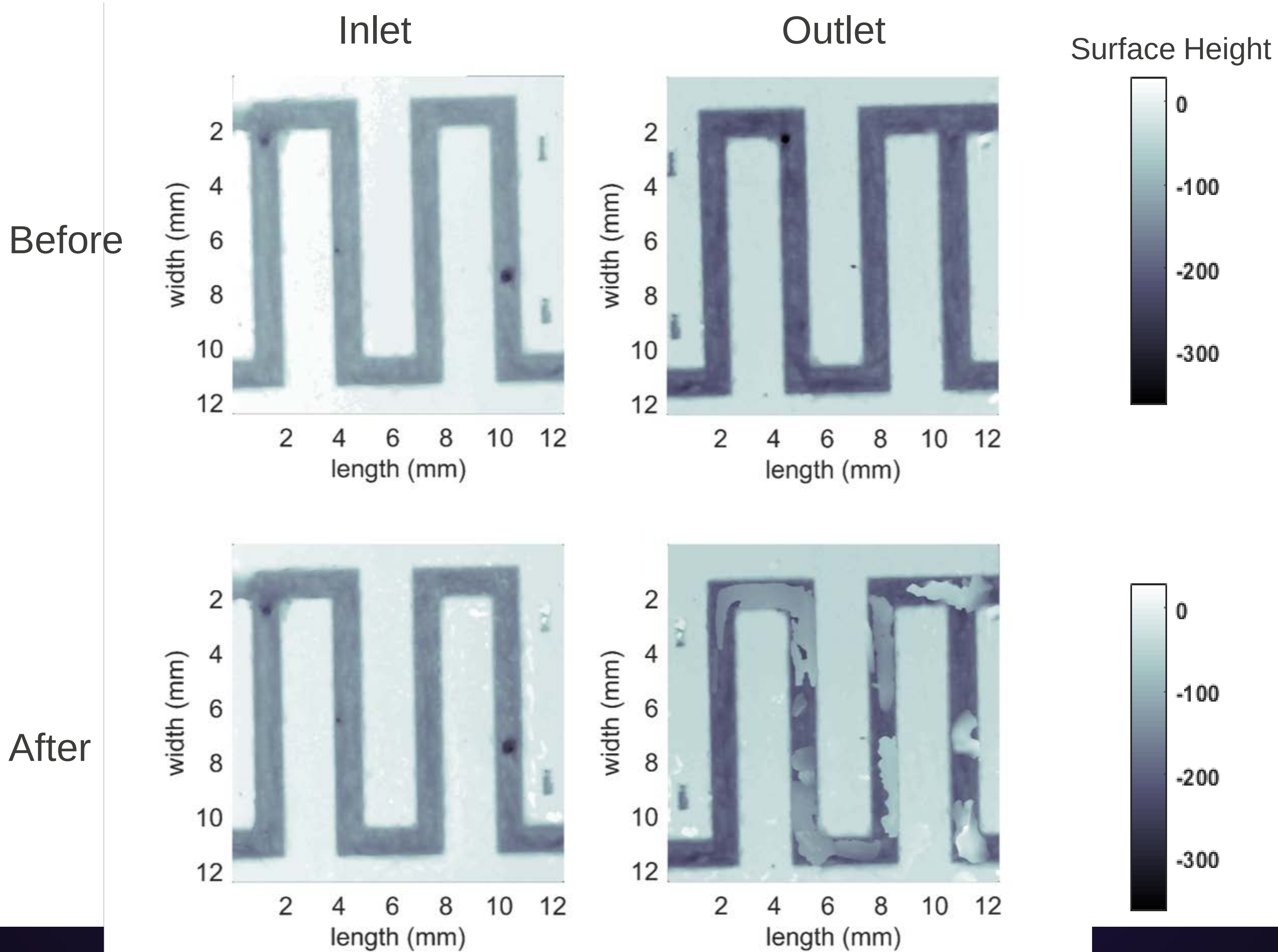
Results: 200 µm-Width Channel Profilometry



Results: 500 µm-Width Channel Profilometry

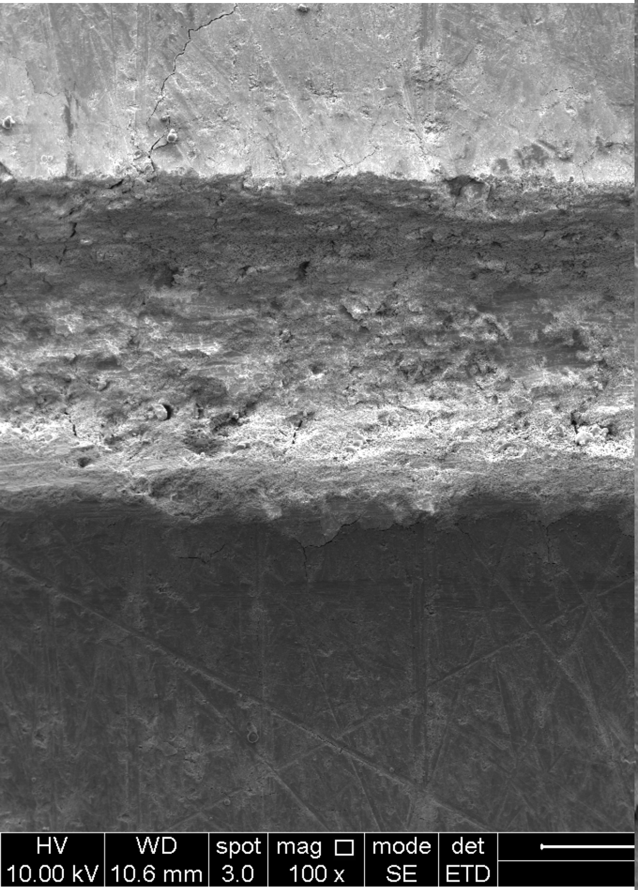


Results: 1000 µm-Width Channel Profilometry

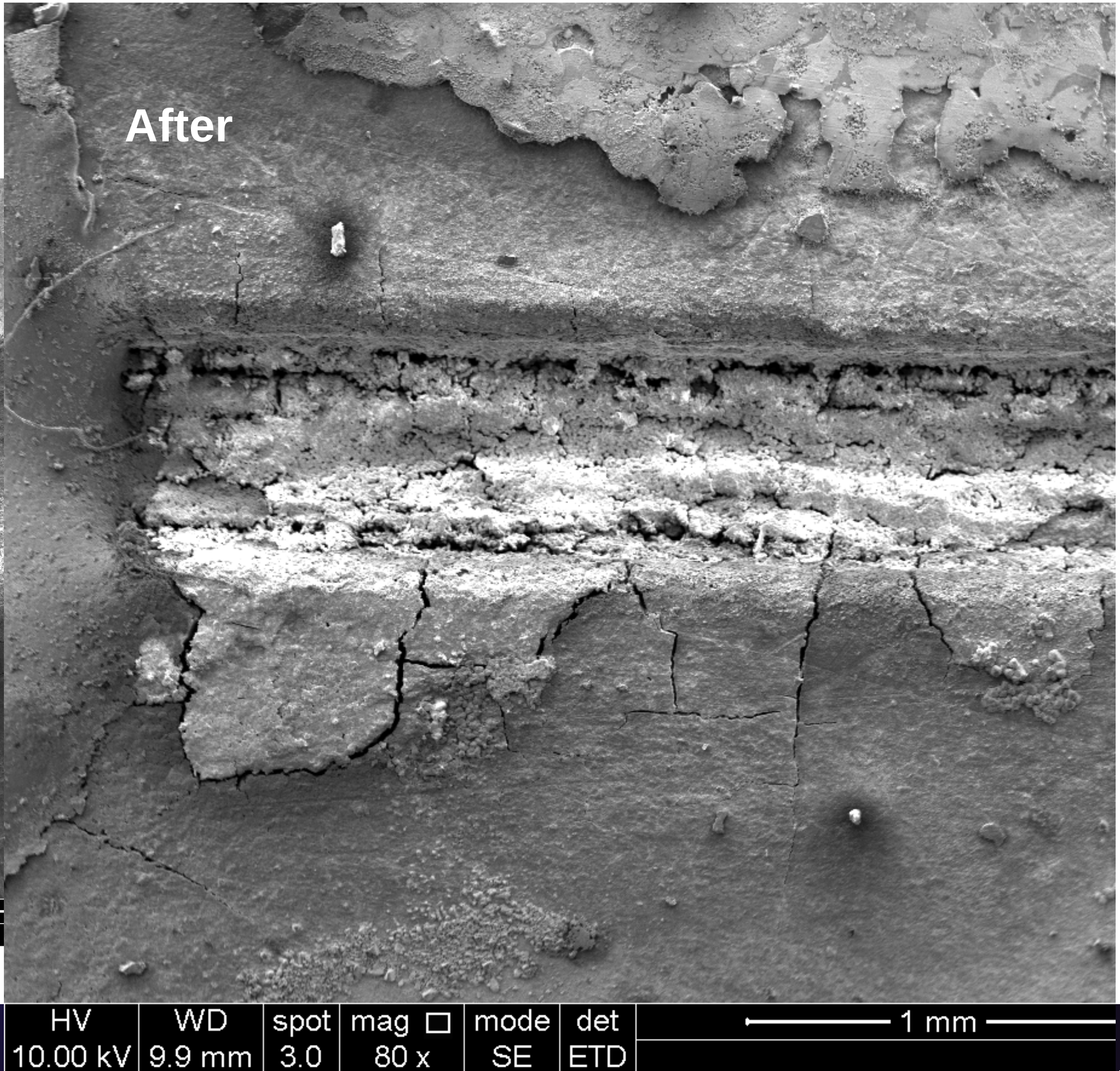


Inlet Region 500 µm-channel: Dissolution Textures

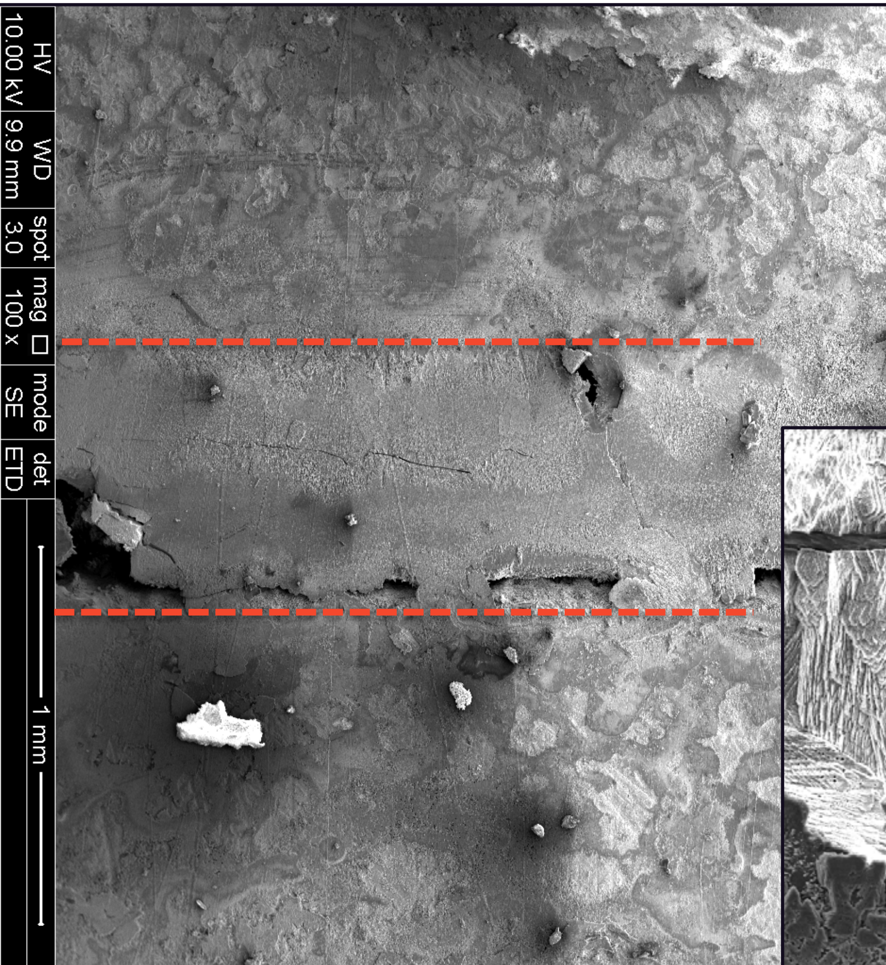
Before

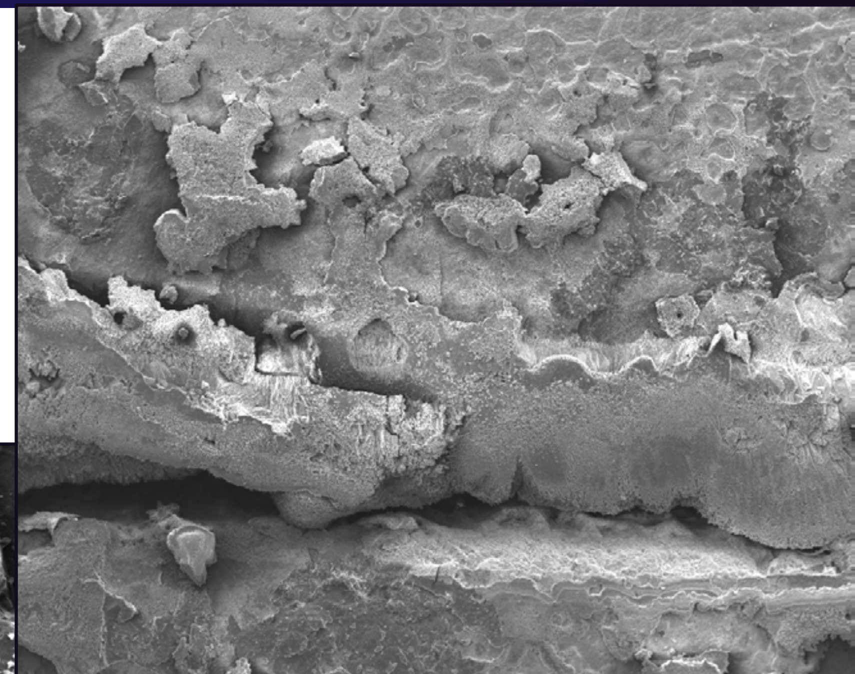


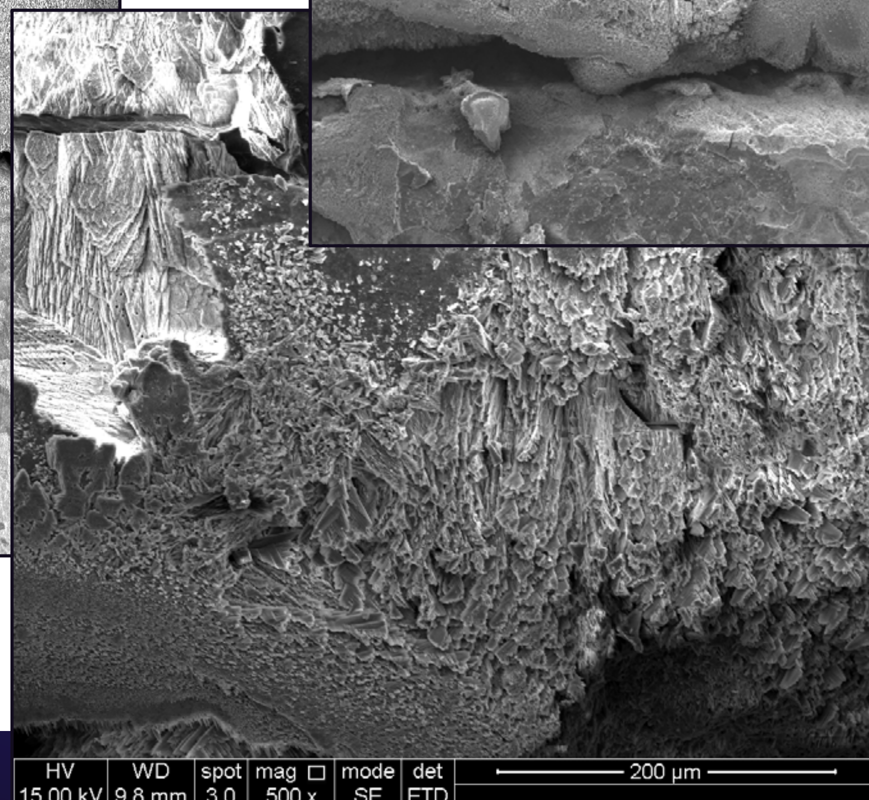
After



Outlet Region 500 µm-channel: Precipitation textures

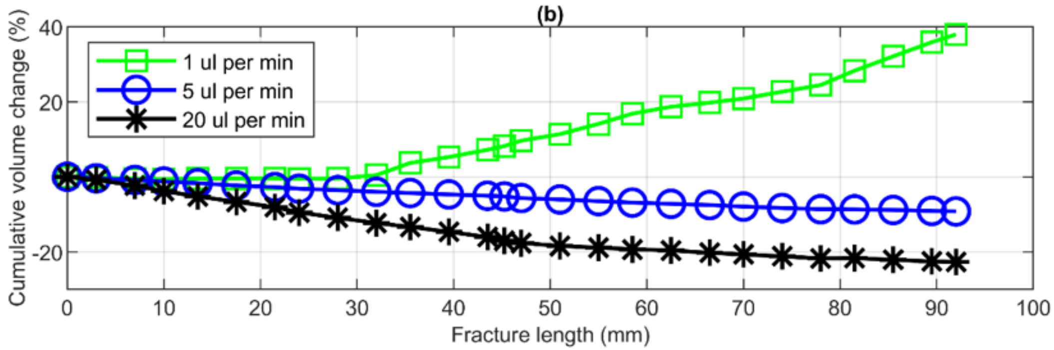




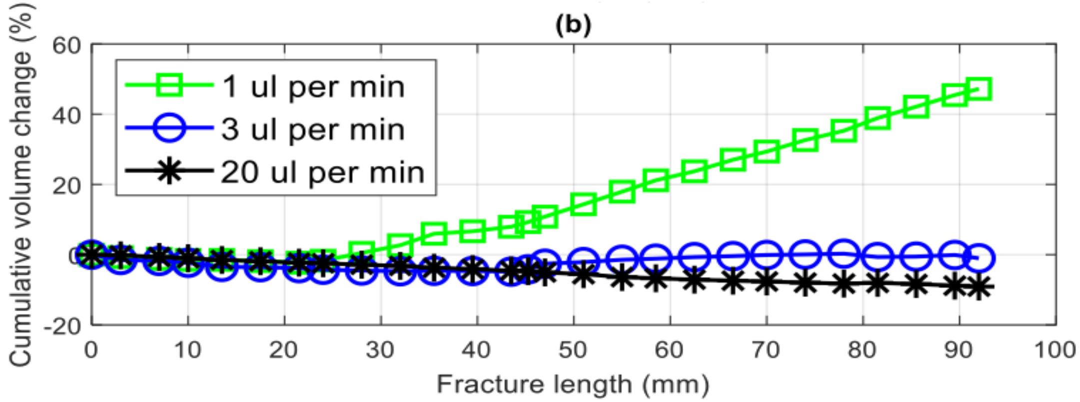


Summary of Self-Sealing Experiments: Cumulative Volumetric Change Due to Dissolution/Precipitation

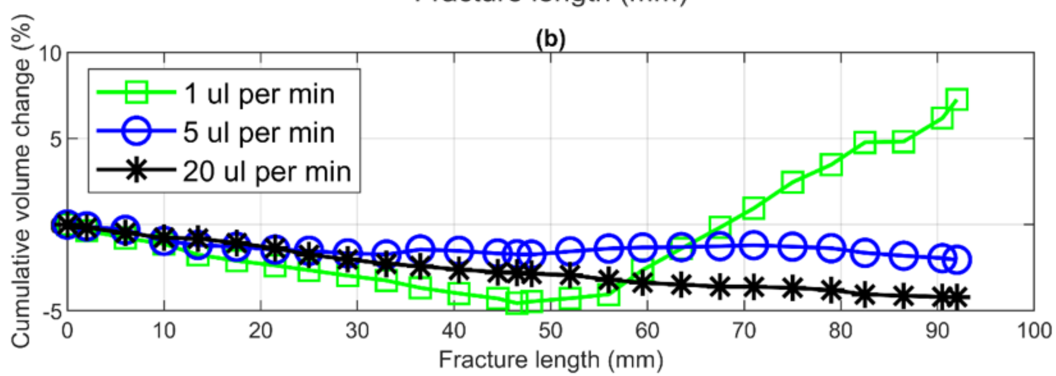
200 µm-Channel



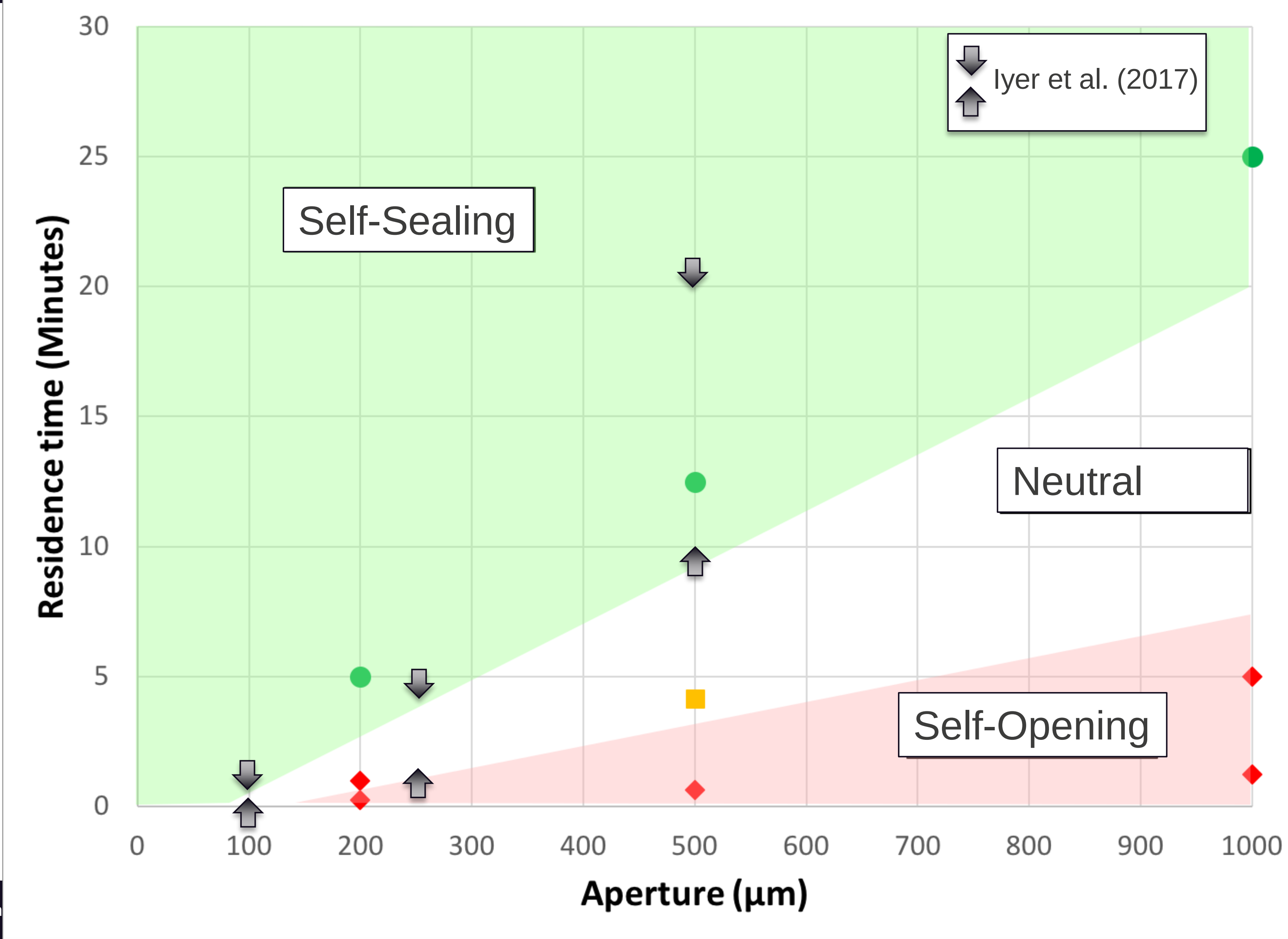
500 µm-Channel



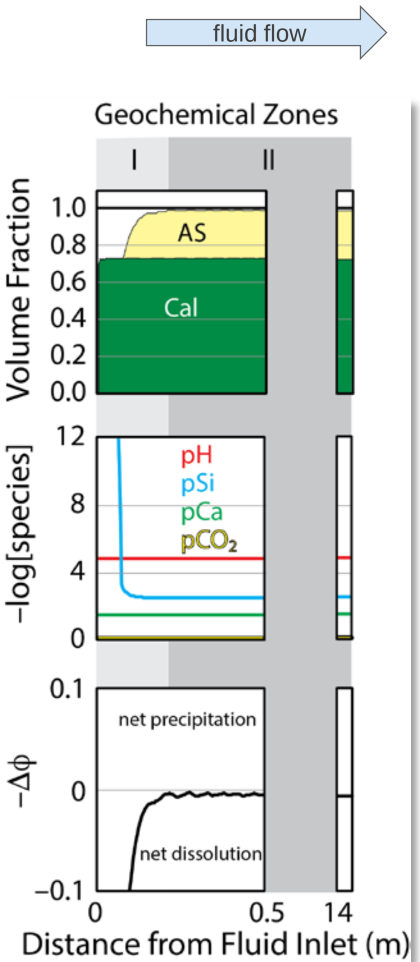
1000 µm-Channel



Summary of Results: Residence Time versus Aperture



Zone I: Dissolution; Zone II: Static (Equilibrium)



Zone I

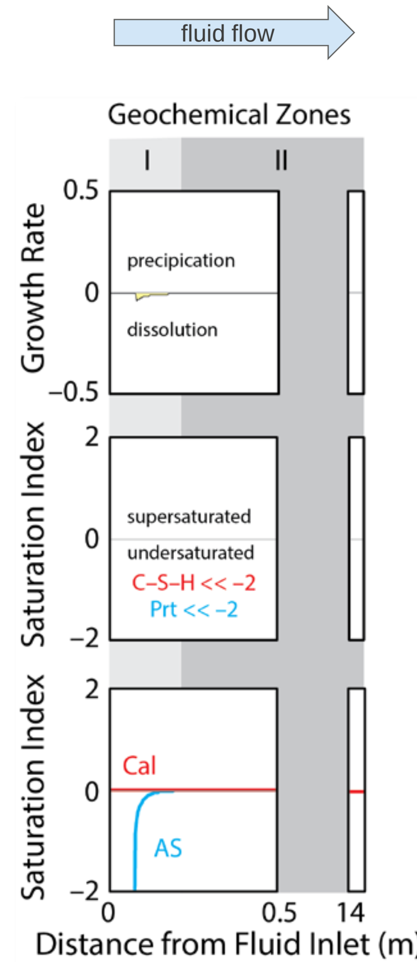
$SiO_{2\,(am)}$ (+ $CaCO_{3\,(s)}$ + H^+) → $SiO_{2\,(aq)}$ (+ Ca^{2+} + HCO_3^-)

- Dissolution of silica+calcite, depending on incoming brine (shown in "Volume Fraction" and "–Δφ" and "Growth Rate")
- Undersaturated in all phases except reservoir mineralogy (shown in "Saturation Index")
- Aqueous chemistry initially reflects reservoir equilibrium (shown in "–log[species]")

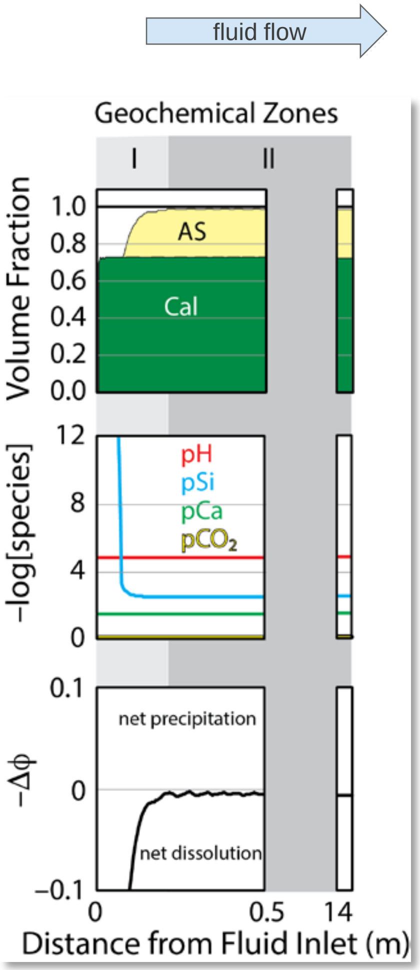
Zone II

$SiO_{2\,(am)}$ + $CaCO_{3\,(s)}$ + H^+ □ $SiO_{2\,(aq)}$ + Ca^{2+} + HCO_3^-

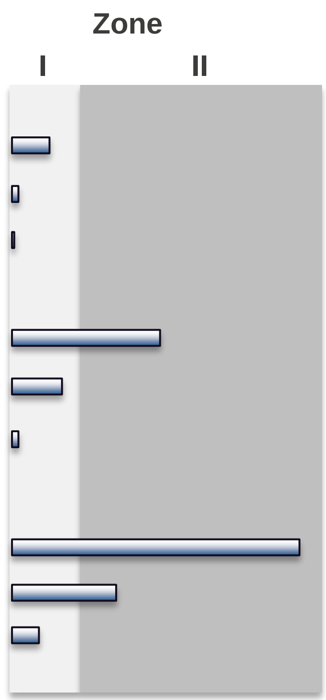
- No net dissolution or precipitation (shown in "Volume Fraction" and "–



Predicted Zones for Microfluidic Experiments at Termination of Runs

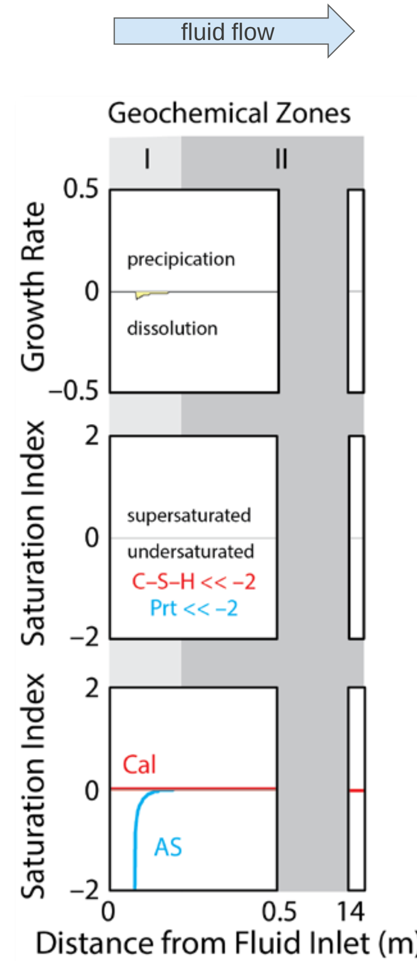


Zone Predictions



Microfluidic Experiments

Fracture Width (µm)	Fracture Depth (µm)	Flow Rate (µl/min)	Total Time (hours)
200	250	1	72
200	250	5	24
200	250	20	24
500	415	1	72
500	415	20	72
500	415	1	24
1000	400	1	72
1000	400	5	48
1000	400	20	24



Self-Sealing in Cemented Wellbores: Major Conclusions

Self-Sealing Mechanism

- Results from a net increase in volume of solids from two reactions tied to carbonation of hydrated cement
- Occurs in a reaction zone between unaltered and carbonated cement, ultimately producing silica + carbonate

Experimental validation

- Self-sealing observed over a range of flow conditions and fracture sizes
- Persistent and widespread precipitation of calcite observe in downstream regions
- Experimental results provide quantitative validation of simulations (Guthrie et al. 2018; Iyer et al. 2017) predicting self-sealing conditions
- Experimental results are conservative since they do not include stress-induced fracture sealing

Impact

- Small leakage paths (difficult to detect and difficult to remediate) are self-sealing in the presence of CO_2 and brine
- Significant reduction in risk and uncertainty of successful CO_2 disposal

Lessons Learned

- **Self-sealing is a reproducible phenomena that obeys theoretical and numerical analysis**
  – Confidence in self-sealing processes is high
- **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
- **Challenges**
  – Coupled processes are technically challenging both experimentally and computationally—proving resilience of well or caprock systems requires a coupled stress and chemistry approach
  – Field observations of well and caprock failure processes are extremely limited

Synergy Opportunities

- **Excellent opportunities to collaborate on well integrity problems**
  - NETL studies of well integrity (collaborations already exist with N. Huerta/B. Kutchko)
  - Norway's SINTEF group studies of well integrity (collaborations already exist with M. Torsæter and N. Opedal)
  - Clemson study of strain/stress measurement in wells (L. Murchoch)
  - LLNL study of thermal stresses in wells (J. Morris/P. Roy)
  - LLNL studies of cement deformation and sealing (collaboration initiated with Carroll, Iyer)
- **Excellent opportunities to collaborate on geomechanics and induced seismicity of storage reservoir systems**
  - Mechanical and hydrologic behavior of fractured shale at NETL (collaboration already exists with D. Crandall)
  - Penn State study of rheology of fracture slip (D. Elsworth)
  - UT-Austin study of reservoir seal geomechanics (P. Eichhubl)
  - LBNL study of in situ fault slip (J. Birkholzer)
- **Many other projects are closely allied to work here (reservoir geomechanics, well integrity studies, etc.)**

Future Directions

- **Are other cement formulations self-sealing?**
  - Cement + fly ash
  - CO_2-resistant cements
  - Enhanced self-sealing cements
- **Development of a best-practices document**
  - Evaluation of self-sealing in site-specific cement formulations
- **Integration of chemical and mechanical self-sealing behavior**

Appendix

Project Summary

- **One key to reducing uncertainty of CO_2 leakage is through observation and measurement of self-healing properties of cement and caprock**
- **We have shown that leakage in cement is conditionally self-limiting**
  - We have developed a theoretical framework for demonstrating self-sealing
  - We have developed an experimental protocol and proven self-sealing behavior in cement
  - Wellbore integrity is better understood and mitigation appears to be bounded by the size and continuity of the defect
  - Understanding mitigation of caprock leakage is at an early stage
- **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
  - We have complete a study of cement-steel interface properties and shown that shear displacement of this interface has limited consequences for well integrity
- **Understanding fracture-permeability behavior of caprock is an effective means of addressing potential impact of induced-seismicity**

Technical Status

- **Completed: Validation of theoretical model by comparison of simulations with microfluidics**
  – Reported in quarterly. Manuscript “Self-sealing in fractured wellbore cement” by P. Nguyen, J. W. Carey and G. D. Guthrie in final stages of preparation for submission to peer-reviewed journal.
- **Mechanical and hydrologic integrity of the cement-steel interface**
  – Completed experiments on mechanical-hydrologic behavior of cement-steel interfaces using a triaxial direct-shear coreflood system with simultaneous x-ray radiography/tomography. Manuscript exists in draft form to be submitted soon.
- **Completed: Thermodynamic and kinetic model for cement self-sealing**
  – “Hydrated Portland Cement as a Carbonic Cement: The Mechanisms, Dynamics, and Implications of Self-Sealing and CO_2 Resistance in Wellbore Cements” (Guthrie et al., 2018, Int. Journal Greenhouse Gas Control)
  – Initiated microfluidics experiments on self-sealing of cement
- **Completed: experimental study of potential fracture leakage processes in shale as caprock**
  – Completed complementary study of anhydrite and dolomite caprock
- **Completed: “Engineering Prediction of Axial Wellbore Shear Failure due to Reservoir Uplift” (**Frash and Carey, 2019, SPE Journal**)**

Accomplishments to Date

- Completed experimental validation of self-sealing in Portland cement systems (manuscript near submission)
- Completed experimental study of cement-steel interface strength and permeability (manuscript near submission)
- 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. 2018) 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, 2019; SPE Journal)

Benefit to Program

- Develop long-term predictive models of leakage processes through wells and caprock for use in risk-based analyses of carbon storage systems

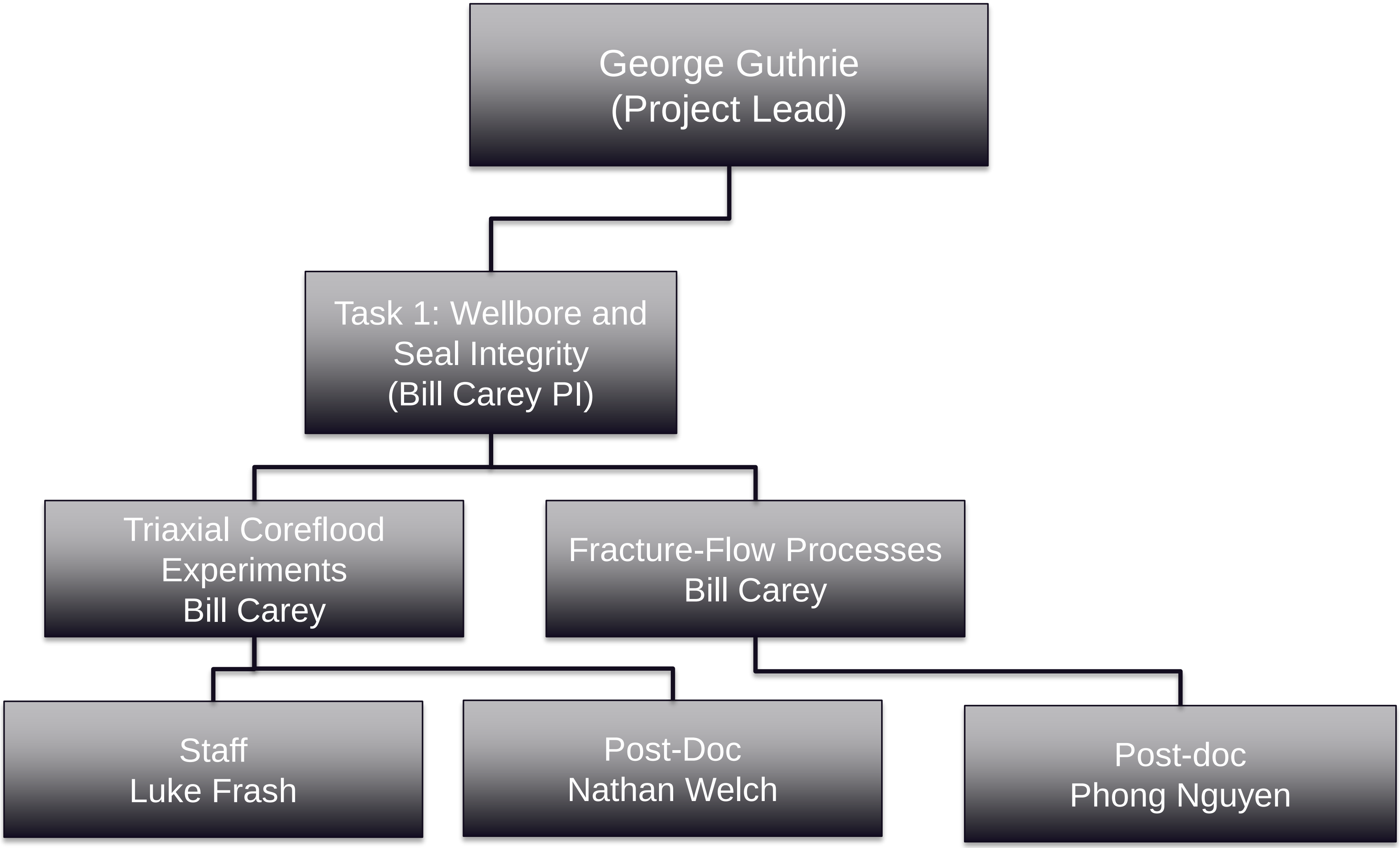
- Determine the consequences of stress-induced damage to wellbore and caprock seals

- Develop and validate technologies to ensure 99% storage permanence.

Project Goals

- 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

Organizational Chart

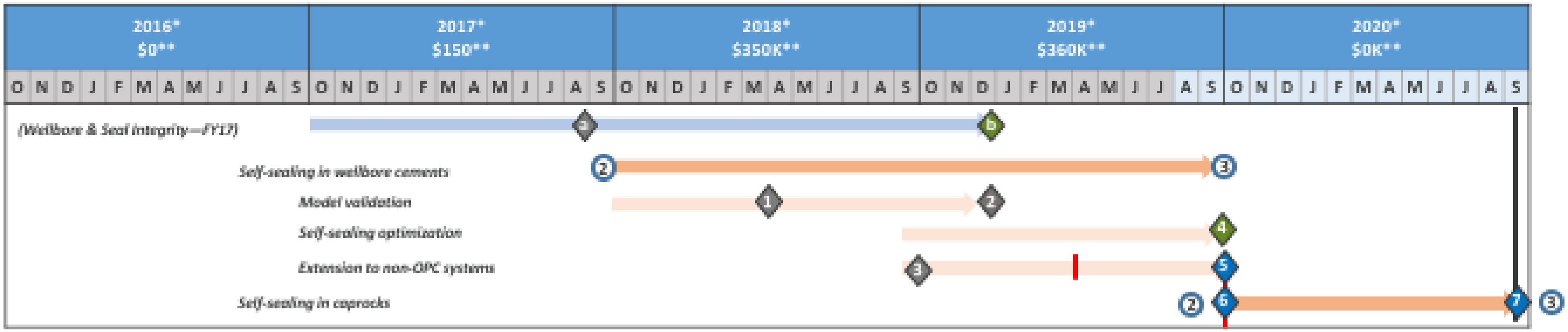


Gantt Chart

Task 1: Project Timeline Overview

NATIONAL ENERGY TECHNOLOGY LABORATORY

Predicting the Integrity of Seals and Wellbores during Injection and Post Injection



Milestones

a. Capstone report on self-sealing in wellbore cements.
b. Capstone report on geomechanics and seal integrity.
1. Experimental protocol for validating self-sealing using microfluidics.
2. Validation of theoretical model by comparison of simulations with microfluidics.
3. Extension of microfluidics protocol to CO_2 resistant cement-based systems.
4. Identification/demonstration of potential admixtures and other strategies to enhance self-sealing.
5. Best-practices document for operators to evaluate efficacy of self-sealing in normal Portland cement and CO_2-resistant cement under site-specific conditions.
6. Extension of self-sealing approach to caprock-based systems (go/no-go).
7. Identification of key self-sealing processes and characteristics in shales and/or other types of caprocks.

Chart Key

TRL Score | Go / No-Go Timeframe | Project Completion | Milestone
Complete | FY19 | FY20

Go / No-Go

1. Initiate tech transfer plan for self-sealing wellbore cements?
2. Initiate experimental work on self-sealing processes in caprocks?
Decision based on proof of concept that self-sealing (geochemical and/or geomechanical) may be significant and can be observed at lab scale.

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Publications (2015-2019) Supported by or in part by this project

- Carey, J. W. and Torsæter, M. (In Press). Shale and Well Integrity. In Shale Science. John Wiley & Sons.
- Frash, L. P., and J. W. Carey (2018) Engineering prediction of axial wellbore shear failure caused by reservoir uplift and subsidence, SPE Journal, 23: 1039-1066.
- Guthrie, G. D., Jr., R. J. Pawar, J. W. Carey, S. Karra, D. R. Harp, and H. S. Viswanathan. (2018) The mechanisms, dynamics, and implications of self-sealing and CO_2 resistance in wellbore cements. International Journal of Greenhouse Gas Control, 75:162–179, 2018.
- 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.

Publications (2015-2019) Supported by or in part by this project

- 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.
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- 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.