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Subsurface Storage Security: Understanding and Mitigating Injection Hazards

Thomas Dewers

Geomechanics Department
Sandia National Laboratories

With:

Steve Bryant, UT Austin
Jason Heath, Sean McKenna, Joe Bishop, Peter Kobos, SNL

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CCUS Storage Security Issues

- Reservoir Injectivity
- Caprock Integrity
- Pressure Management Strategies

Acknowledgements

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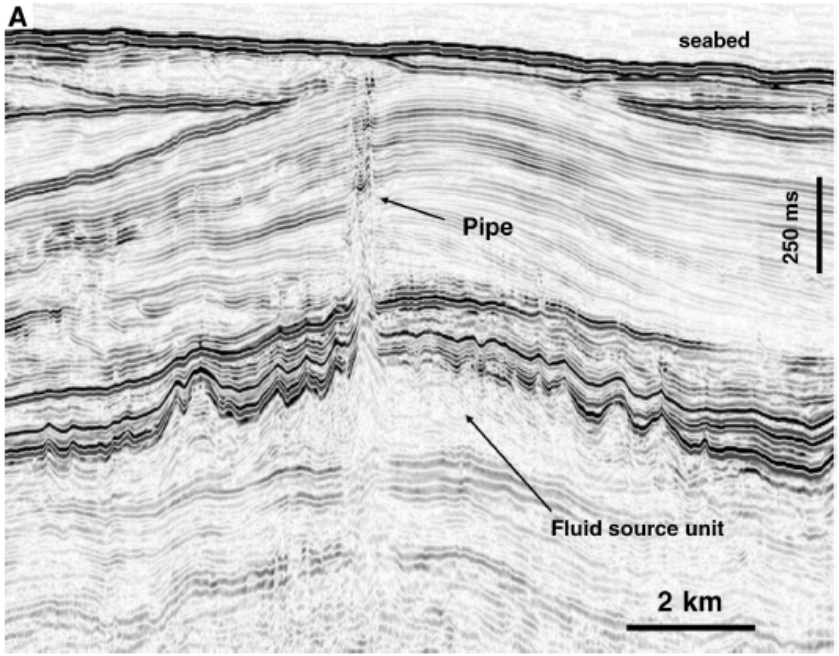
Subsurface Fluid Injection

- **Changes stress path by increasing fluid pressure (overpressure)**
- **Introduces reactive fluids**
- **Creates far-from-equilibrium conditions**

What is the geomechanical response to fluid injection and increased pore pressure during waste disposal?

Can we engineer solutions to mitigate pore pressure hazards?

Are there time-dependent coupled processes that can lead to emergent leakage?



Leakage pathway imaged in seismic cross-section
From Cartwright et al., 2007

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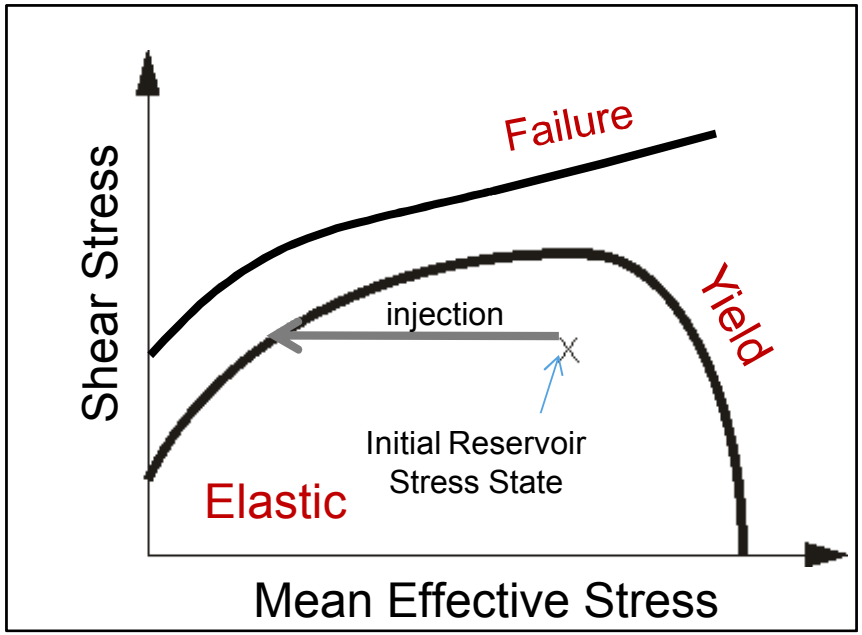
Fluid Overpressure Can Induce:

- Slip/extension along suitably oriented fractures
- Deformation in porous matrix
- Seismicity

Fracture Slip

Matrix Deformation



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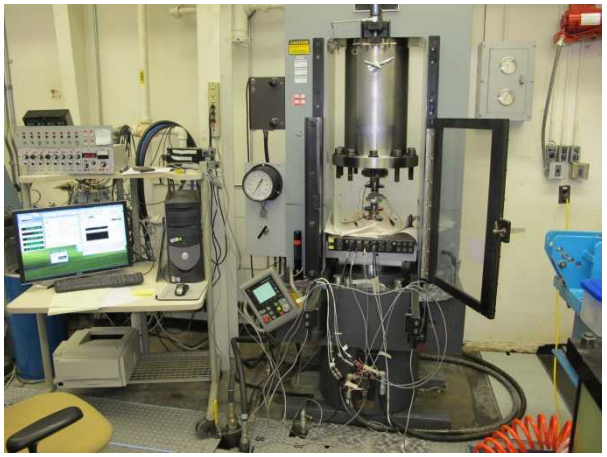
Approach

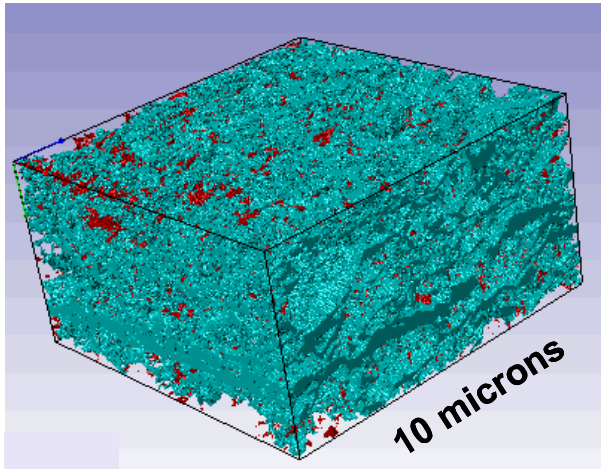
Experimental

- Poro-mechanical testing of reservoir & caprock lithologies
- Short-rod fracture propagation tests
- Acoustic/Ultrasonic measurement during fluid injection and fracturing (> 1 mm resolution)



Modeling

- Constitutive modeling of mechanical response
- Pore scale modeling of brine migration and residual trapping in “waste zone” lithologies as a pore-pressure mitigation strategy
- Pore fluid (brine) extraction for treatment and beneficial use



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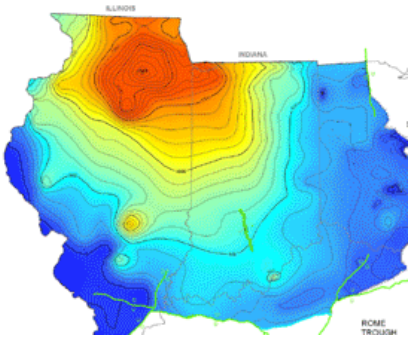
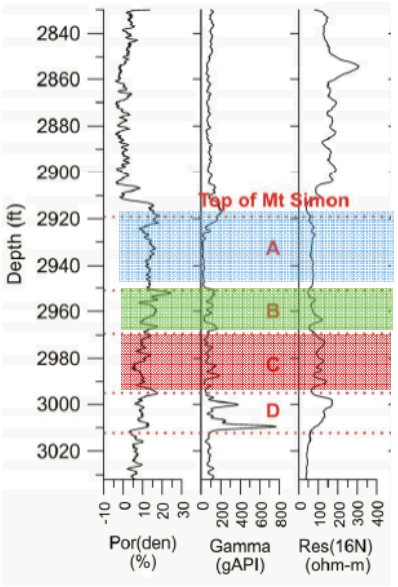
Deformational Behavior of Injection Targets

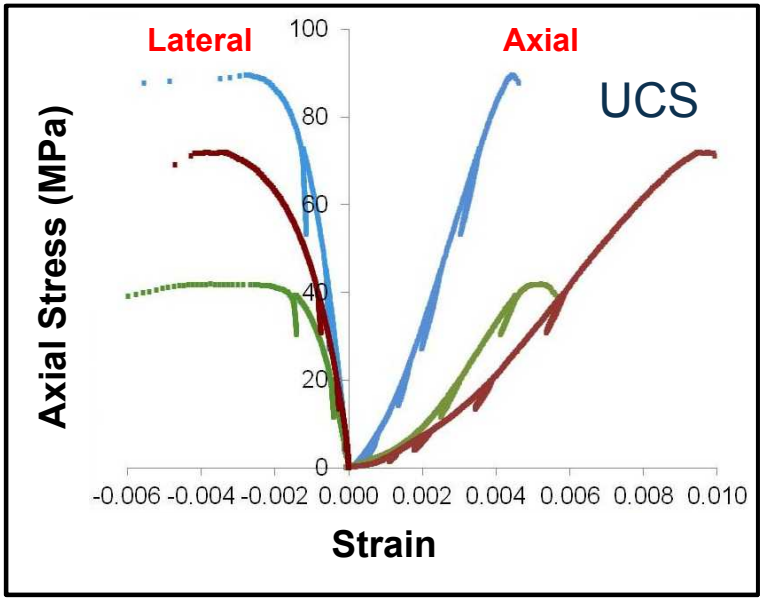
Research Finding:
Sandstone target reservoirs for CCS activities exhibit depositional heterogeneity, resulting in contrasting deformational styles.

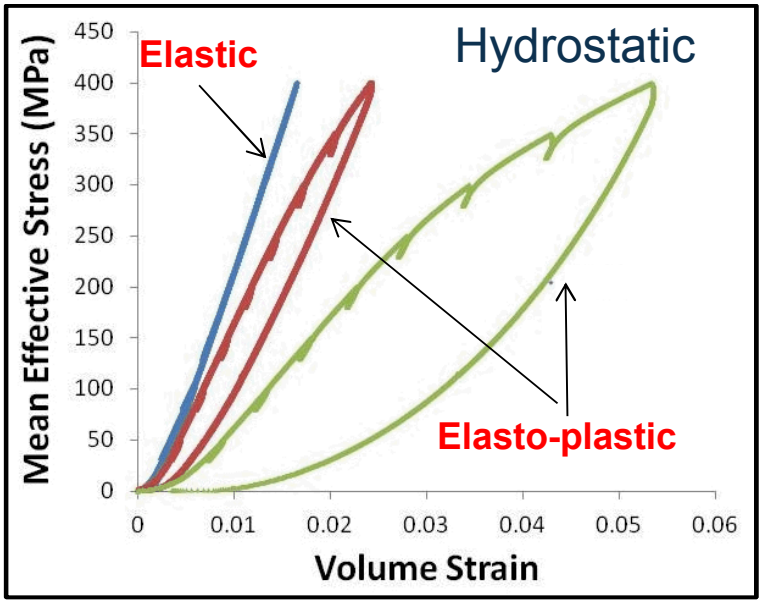
Impact:
Field-scale injection models need to account for both depositional heterogeneity and poro-elastic and poro-plastic deformation. Caution when applying 90% rule.

Mount Simon Fm









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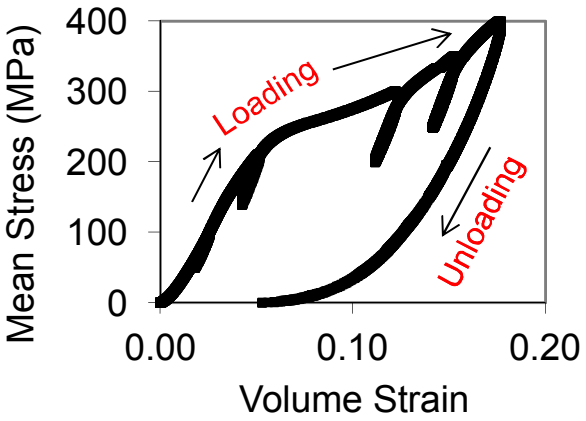
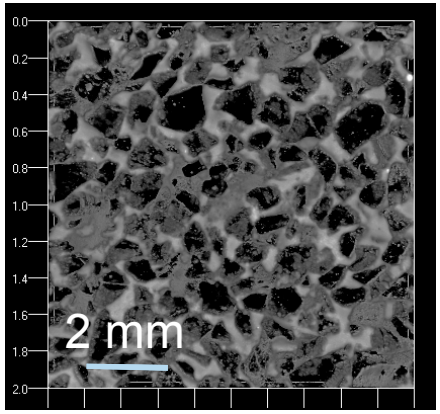
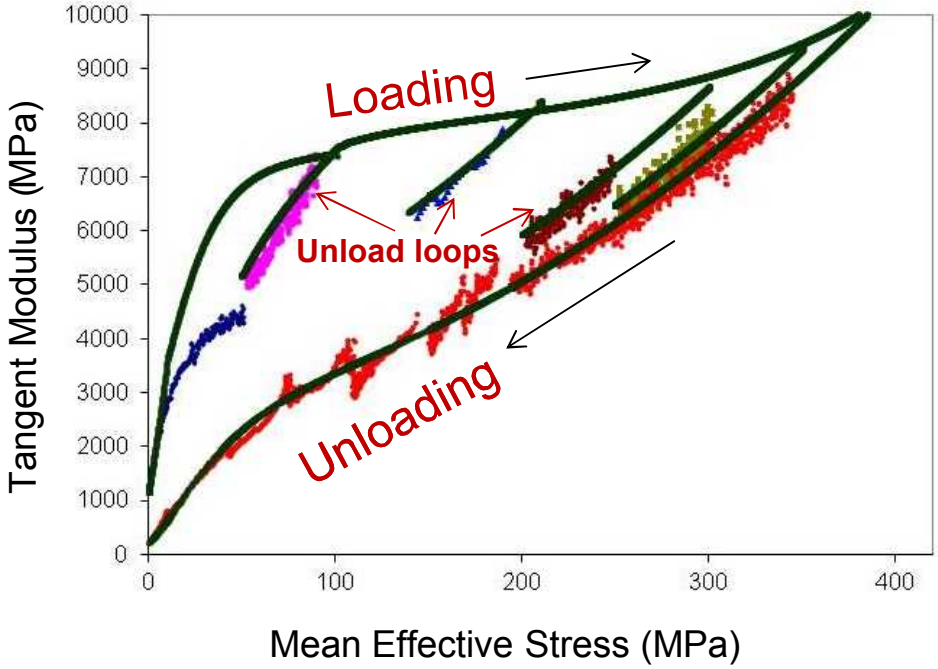
Damage in Reservoir Sandstones

Research Finding:
Weak porous sandstones exhibit evolving damage during deformation. New shear fractures form when shear modulus degrades by 50%.





Impact:
This has a big effect on injection-induced changes in elastic moduli, Biot's coefficient, and seismic velocities in continuum-scale geomechanics and inversion models.



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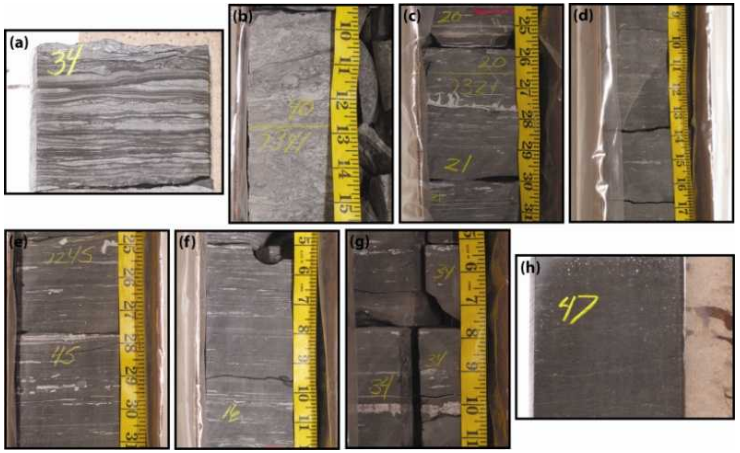
Caprock Ultrasonic/Acoustic Monitoring

Research Finding:
Preliminary velocity testing and CT imaging finds large variability in Mancos Formation properties.



Views of Mancos mudstone microfacies

Impact:
Unique capability for rock testing (near simultaneous active and passive scanning). Tracks evolution of damage and multiphase fluid flow & provide benchtop validation for seismic inversion models.


SNL Ultrasonic system for on-the-fly velocity tracking

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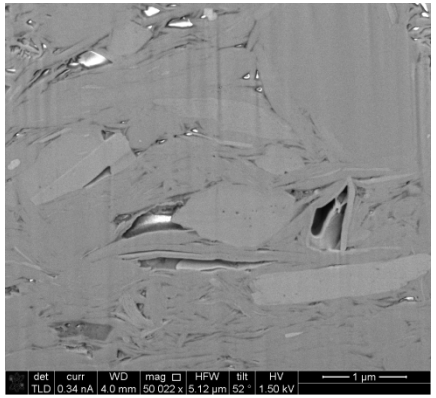
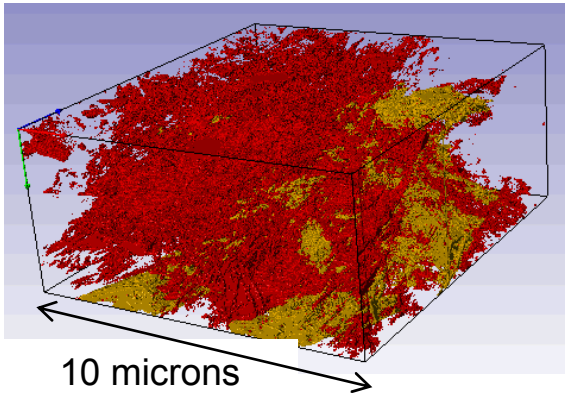
Pore-Scale Interrogation of Mudstone Multiphysics

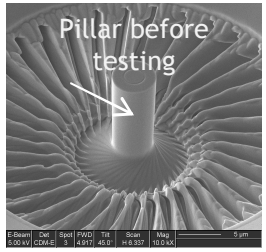
3D Pore Networks and Topology

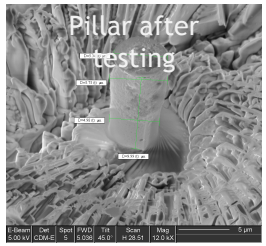


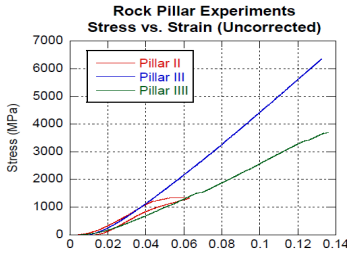


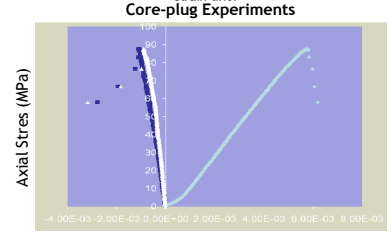
Focused Ion Beam slice (scale bar = 1 micron; left) and reconstructed 3D nano-pore network (right) in Haynesville gas shale. Gold pores are single connected network.

Micro and Macro Mechanics





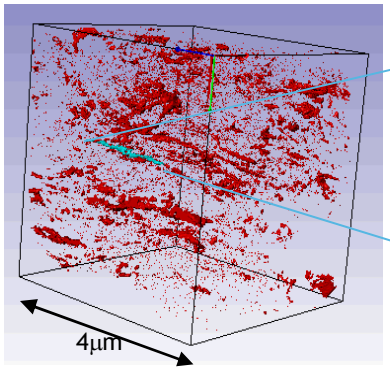


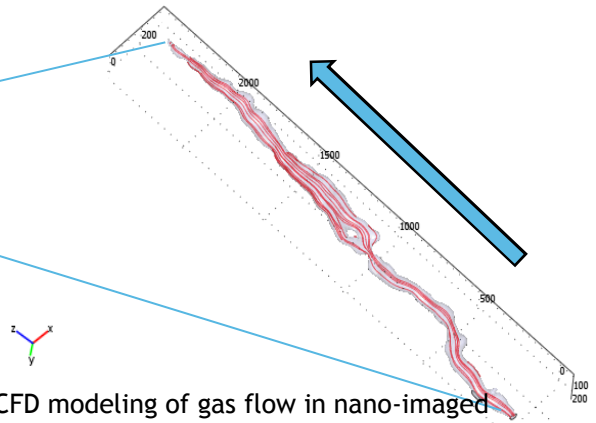


Radial (left) and Axial (right) Strain

Micropillar compression of clay packets (scale bar = 5 µm) compared to 1" core-plug testing. Microcracks in core plug result in order of magnitude loss in unconfined strength and factor of 3 degradation in elastic modulus, compared to micro-properties

Hydrological Characterization and Modeling





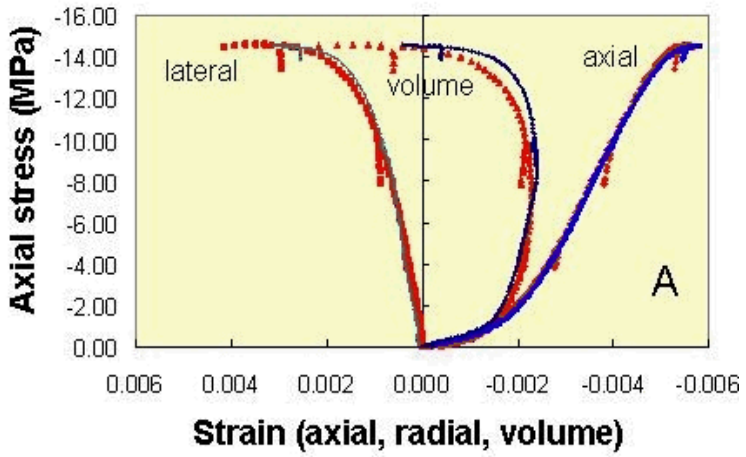
Streamlines (right) from CFD modeling of gas flow in nano-imaged kerogen pore network, shown in red at left (Gulf Coast Tuscaloosa Mudstone)

Impact:

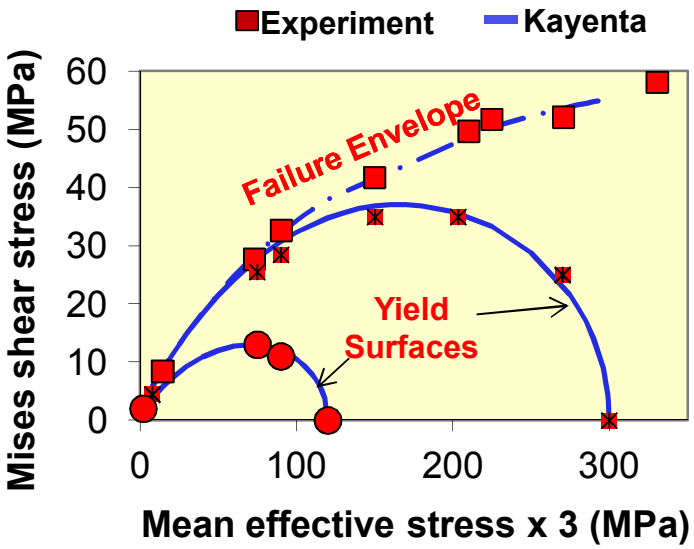
Mudstone caprock contain "water-wet" and "oil-wet" pore networks. Some mudstone-scCO2 interactions could have adverse influence on leakage.

Constitutive Modeling

Research Finding:
Kayenta (SNL Elasto-Plastic Model) yields excellent description for weak porous sandstone deformation.



Impact:
Provides parameterized constitutive model for almost any FEM. Is being applied to experimental behavior of sandstone lithologies associated with NETL partnership activities.



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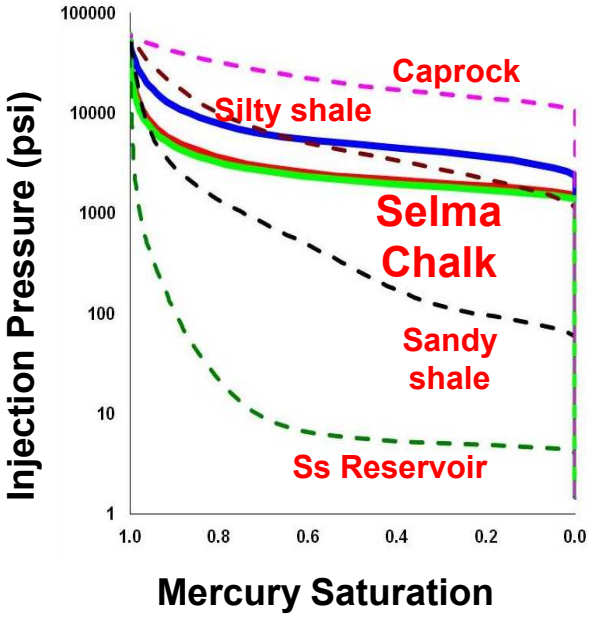
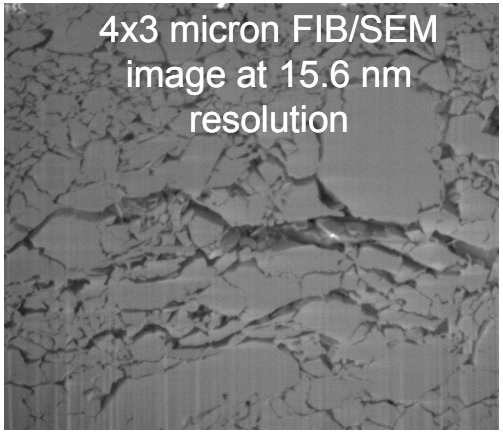
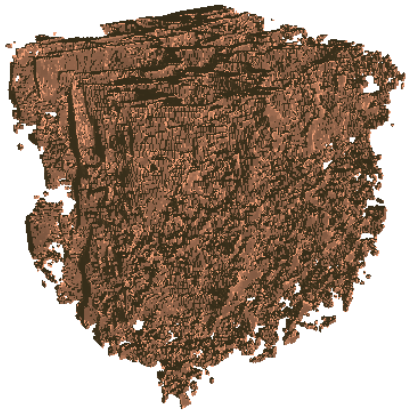
Pressure Management Strategies: Leaky Seals?

Research Finding:
Injection of bouyant $scCO_2$ beneath "waste-zone" lithologies allows brine migration and pressure dissipation but traps CO_2 as a residual phase.

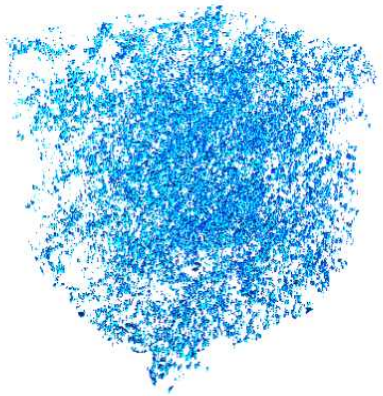
Impact:
Can predict small scale capillary pressure and relative permeability from FIB/SEM imaging (at better resolution than micro-CT). Effort on upscaling and comparison to experiments.







CO_2 Saturation



Residual Water Saturation

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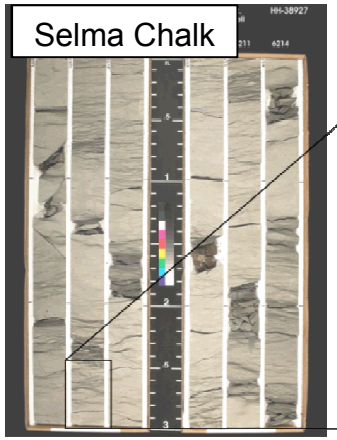
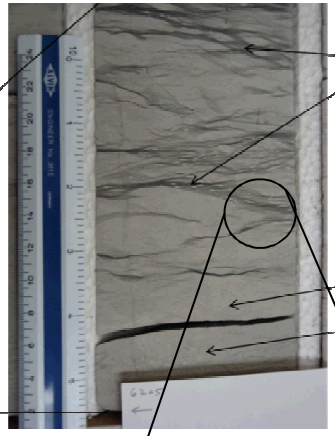
Pressure Management Strategies: Leaky Seals?

Upscaling pore-to-core capillary pressure and relative permeability



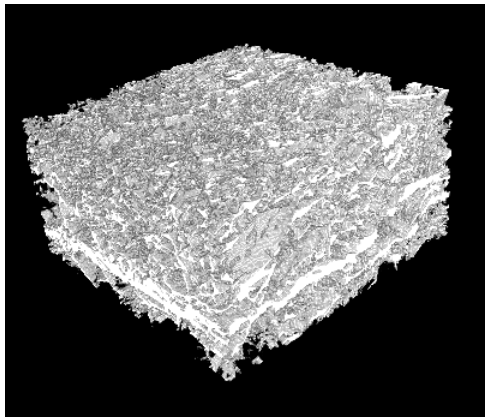


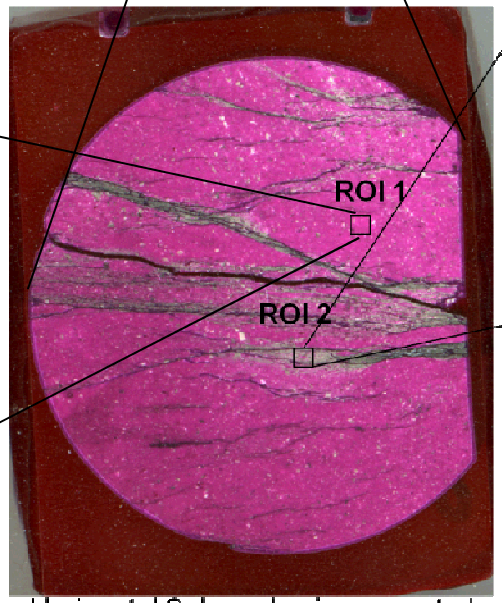
"Horsetail" structures (clay-rich)

Clay-poor calcite rich, with microfossils

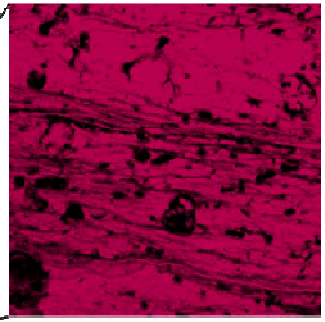
Core scale

FIB/SEM Imaged Pores: 14.7 x 7.9 x 15.0 micron



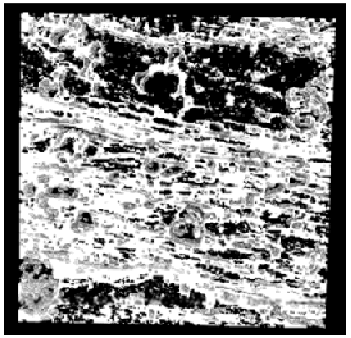


Horizontal Selma plug impregnated with rhodamine-dyed epoxy



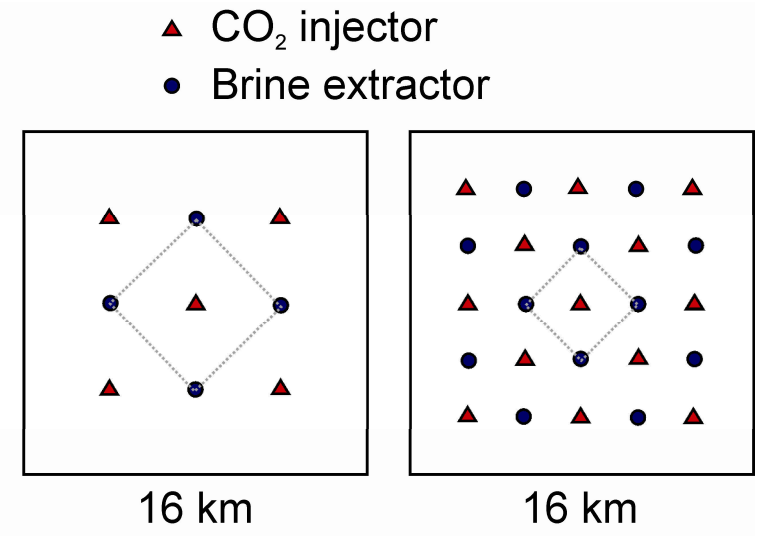
Laser scanning confocal microscope image of ROI 2 (1821x1821 microns at 1.77 µm/pixel)

3D Solid material (calcite + clay) in "horsetail" structures (1821x1821x 96 microns)



Pore scale

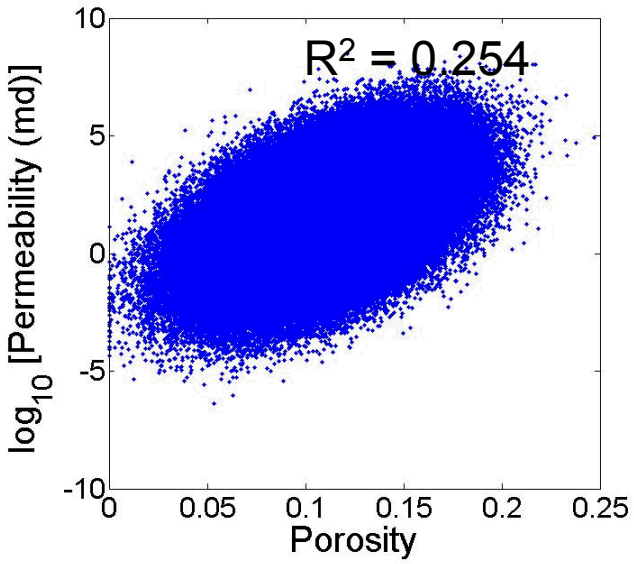
Pressure Management Strategies: CCS w/ Brine Extraction



How does correlation between permeability and porosity affect injectivity?

How different in terms of injection rates are the homogeneous versus heterogeneous cases?

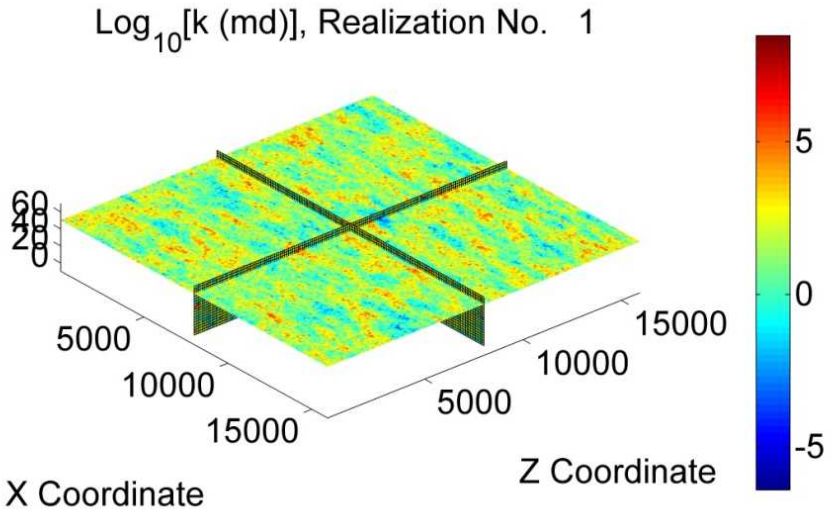
How does heterogeneity impact well numbers and associated costs? (see talk by Kobos this P.M)



Numerical Experiments of CO_2 Injection w/ Brine Extraction

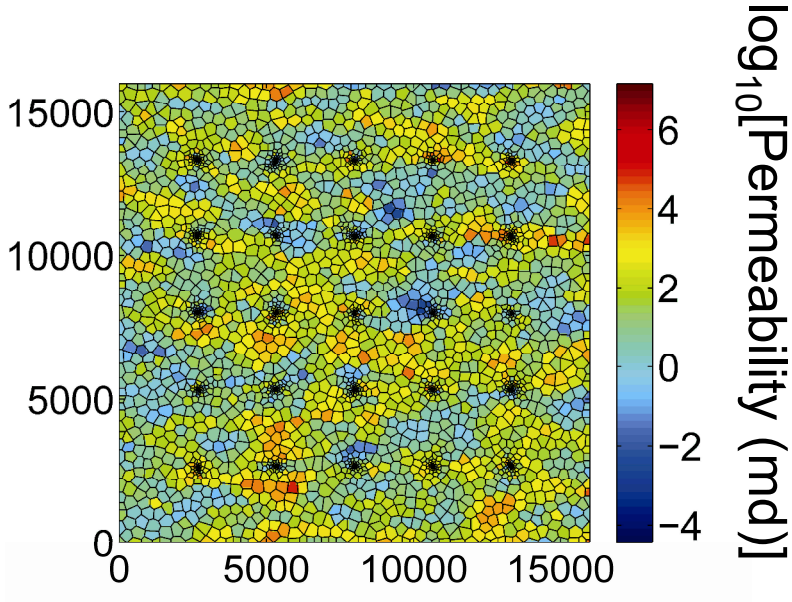
Geostatistics:

Coregionalization and SGSIM (Rautman and McKenna, 1997; Deutsch and Journel 1992)



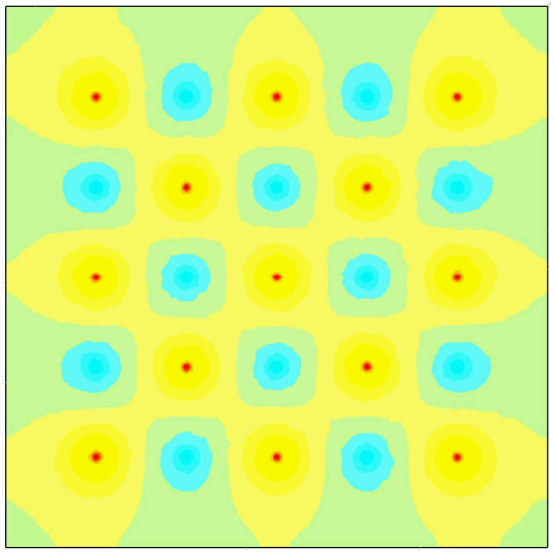
Multiphase Flow:

TOUGH2-ECO2N (Pruess et al., 1999; Pruess 2005



Pressure Management Strategies: CCS w/ Brine Extraction

Injection and Extraction

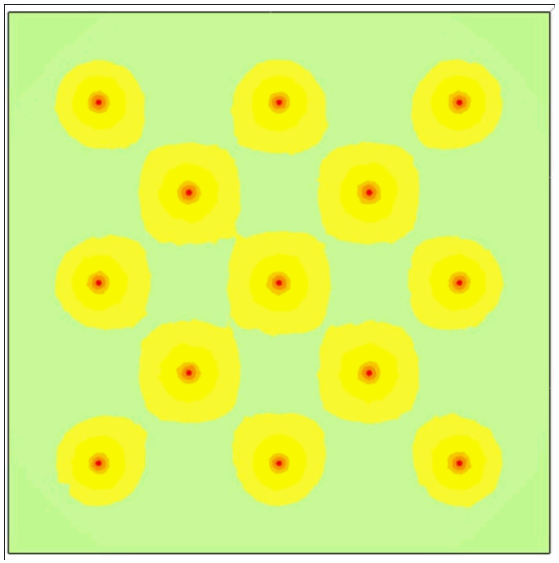


P (MPa)

28

14

Injection only



Time = 36 days

- Permeability = 29.7 md; porosity = 11.1 % (modeled after Mt. Simon Fm from Finley, 2005)
- CO_2 injection with or without brine extraction
- Constant bottomhole pressure for injection
- Closed reservoir
- Homogenous and heterogeneous cases

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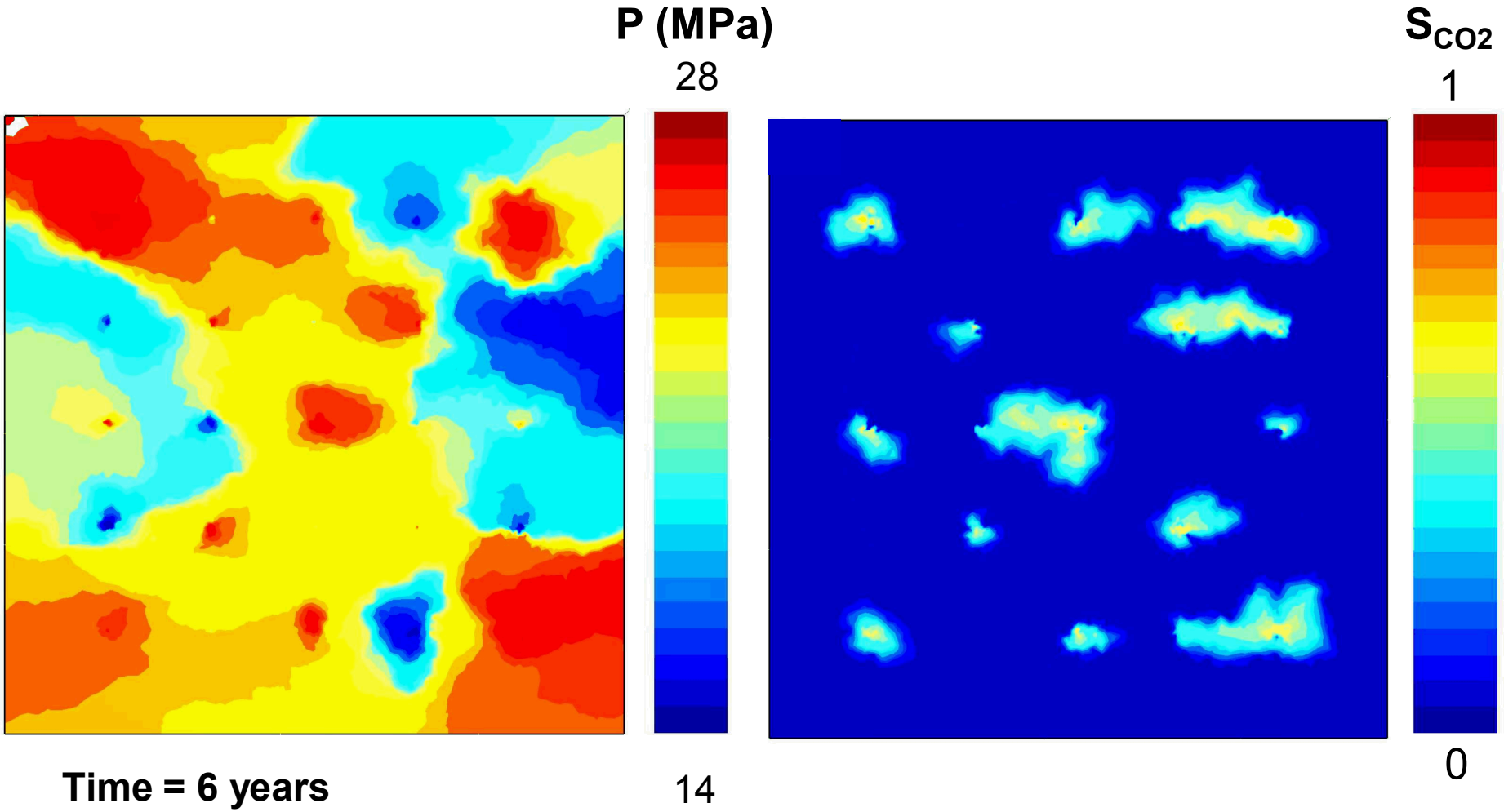
Heterogeneity Matters!



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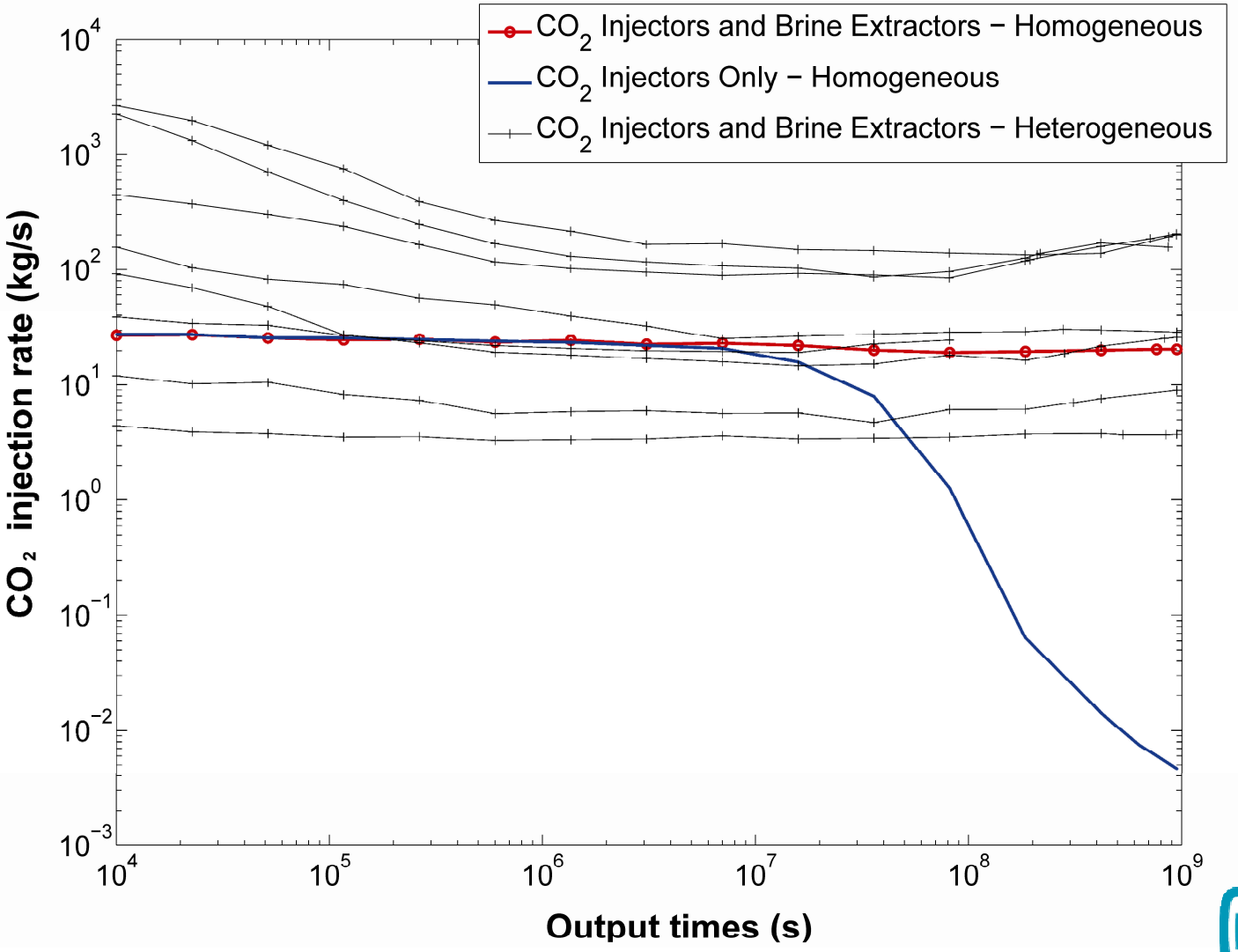
Pressure Management Strategies: Brine Extraction Extends High Injectivity



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Conclusions/Talking Points

- Sandstone saline formations exhibit poro-elastic and poro-plastic responses during injection-induced stress paths
- Induced damage may be an issue of concern (esp. in stress-sensitive EOR settings??)
- Mudstone heterogeneity at all scales can be a challenge for monitoring & prediction
- Maybe leaky seals are OK? Even better than “tight” ones?
- Brine extraction extends injectivity in compartmentalized (closed) reservoirs (limited by CO_2 breakthrough)
- Heterogeneity in saline formations represents a challenge for systems-level models and in application of simple analytical solutions for injectivity