# Advanced Technologies for Monitoring $CO_2$ Saturation and Pore Pressure in Geologic Formations

DE-FE0001159


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Rock Physics Project/Stanford University



U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for $CO_2$ Storage

August 21-23, 2012

# Presentation Outline

- Benefit to the Program
- Project Overview
- Motivating technical challenge
- Approach
- Technical Status
  - Laboratory results
  - Theoretical modeling
- Summary

# Benefit to the Program

- Program goals being addressed.
  - Develop technologies that will support industries' ability to predict $CO_2$ storage capacity in geologic formations.
  - Develop technologies to demonstrate that 99% of injected $CO_2$ remains in injection zones.
- Project benefits statement.
  - The project is developing $CO_2$-optimized rock-fluid models that will incorporate the seismic signatures of (1) saturation scales and free vs. dissolved $CO_2$, (2) pore pressure changes, and (3) $CO_2$-induced chemical changes to the host rock. These models will be an integral part of interpretation of seismic images of the subsurface at injection sites. They address the program's needs to predict storage capacity and to ensure 99% containment of $CO_2$.

# **Project Overview**:
## Goals and Objectives

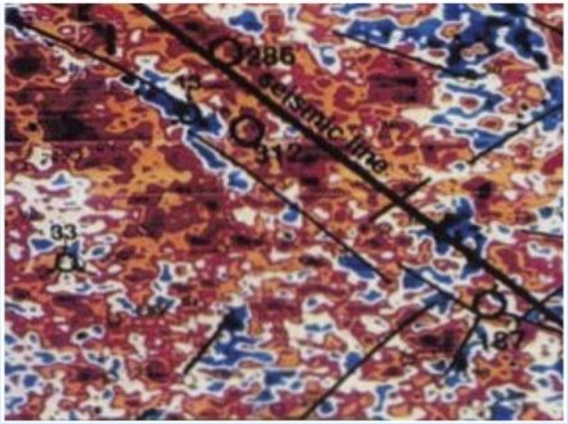
- The goal of this project is to provide robust quantitative schemes to reduce uncertainties in seismic interpretation for saturation state and pore pressure in reservoirs saturated with $CO_2$-brine mixtures.
- Success criteria include
  - Creation of laboratory dataset on changes in porosity, permeability, and elastic properties associated with injection of $CO_2$-brine mixtures in four different lithologies.
  - Improved theoretical models that predict the frequency-dependent seismic velocity changes associated with injection, including changes in pore pressure, saturation, and dissolution or precipitation of minerals in the rock frame.

# Technical Status

# The Challenge: Seismic Monitoring of $CO_2$

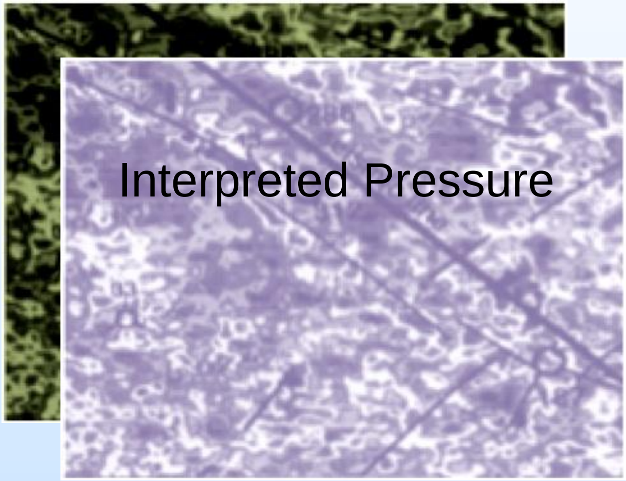
## Workflow for monitoring changes in the subsurface

Map of Seismic Reflectivity
or *Changes* of Reflectivity




→ Rock/Fluid Model →

Interpreted Saturation



Interpreted Pressure

**Changes in:**

- Seismic Vp
- Seismic Vs
- Density
- Attenuation ?

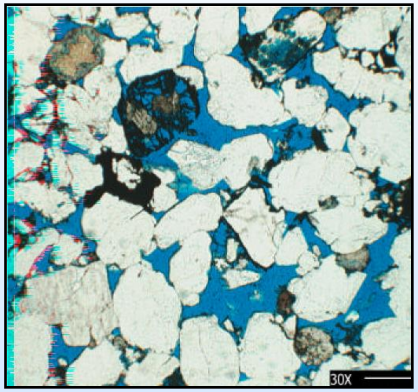
⟺ model

**Changes in:**

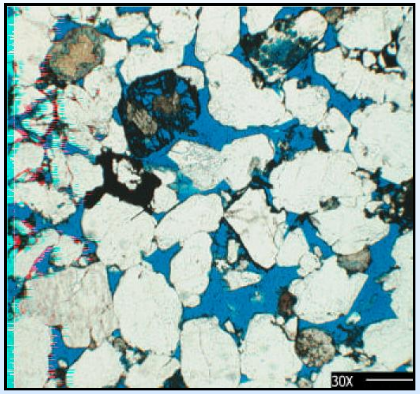
- Saturation
- Stress/pressure
- Rock mineral frame

# Rock's Seismic (Elastic) Response

Bulk modulus:




Shear modulus:




Affected by:

| | Bulk modulus | Shear modulus |
|---|---|---|
| Mineralogy | ✓ | ✓ |
| Porosity | ✓ | ✓ |
| Microgeometry | ✓ | ✓ |
| Stress/Pressure | ✓ | ✓ |
| Fluids | ✓ | |

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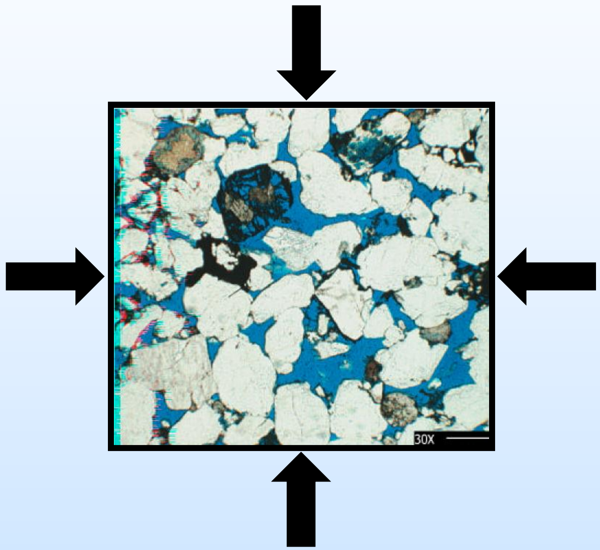
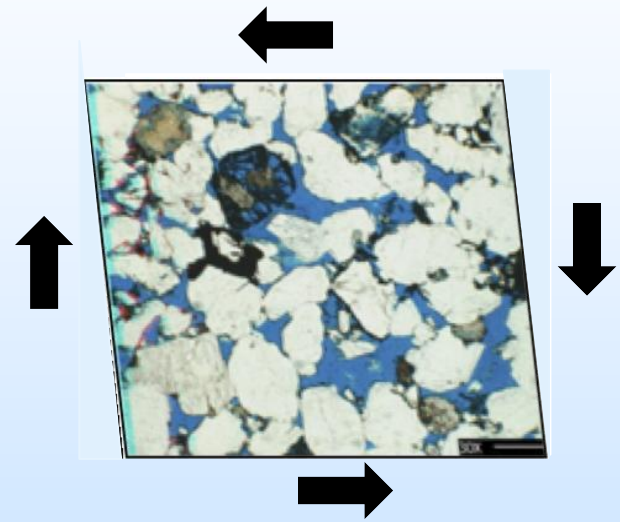
# Rock's Seismic (Elastic) Response

Bulk modulus:



Shear modulus:



Affected by:

| | | |
|---|---|---|
| Mineralogy | ✓ | ✓ |
| Porosity | ✓ | ✓ |
| Microgeometry | ✓ | ✓ |
| Stress/Pressure | ✓ | ✓ |
| Fluids | ✓ | |

# Conventional Seismic-Fluid Model

Current technology for seismic monitoring of injected $CO_2$ *saturation* is based on the equations of Gassmann (1951):

$$\Delta K^{-1} = \phi \, \Delta\left(K_{fluid} + K_{\phi}\right)^{-1}$$ bulk modulus

$$\Delta \mu = 0$$ shear modulus

$$\Delta \rho = \phi \, \Delta \rho_{fluid}$$ bulk density

These assume chemically inert processes; ie. ***constant microgeometry, porosity, mineralogy, and frame stiffness***.

They also require knowledge of the compressibility and density of $CO_2$-brine mixtures as a function of T, P, and salinity.

# The Problem

Multiphase $CO_2$-rich fluid-rock systems can be ***chemically reactive***, altering the rock frame via dissolution, precipitation, and mineral replacement.

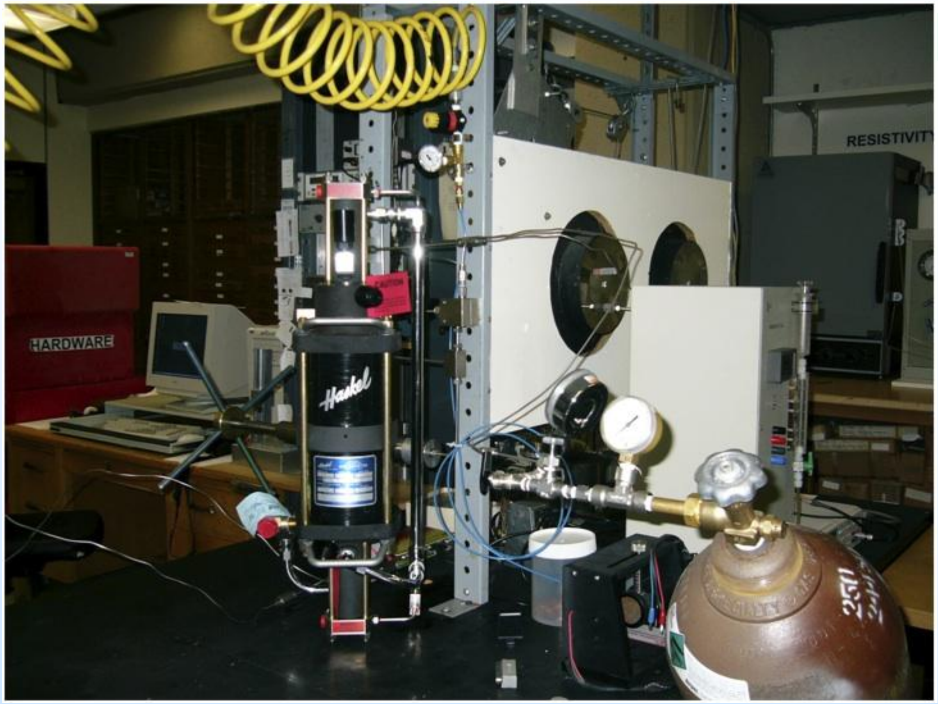
Errors from ignoring the physicochemical factors during $CO_2$ injection can affect not only the magnitude, but also the sign, of predicted seismic velocity changes, resulting in seriously compromised estimates of saturation and pressure of $CO_2$-rich fluids

# Approach: Tasks

1. Project Management, Planning, Reporting
2. Laboratory Measurements
   - Sample selection (MVA working groups, ExxonMobil, Stanford)
   - Rock characterization (porosity, perm, elastic velocities, microstructure)
   - Exposure to $CO_2$-brine, while monitoring Vp, Vs
   - Repeat characterization
   - $CO_2$-brine mixture characterization vs. T and P
3. Theoretical Modeling
   - Empirical/theoretical expressions for $CO_2$-brine properties
   - Quantification of changes to pore microstructure
   - Derive equations to describe velocity-vs.-saturation, accounting for chemical changes to rock microstructure.
4. Validation
5. Collaboration with MVA Working Groups

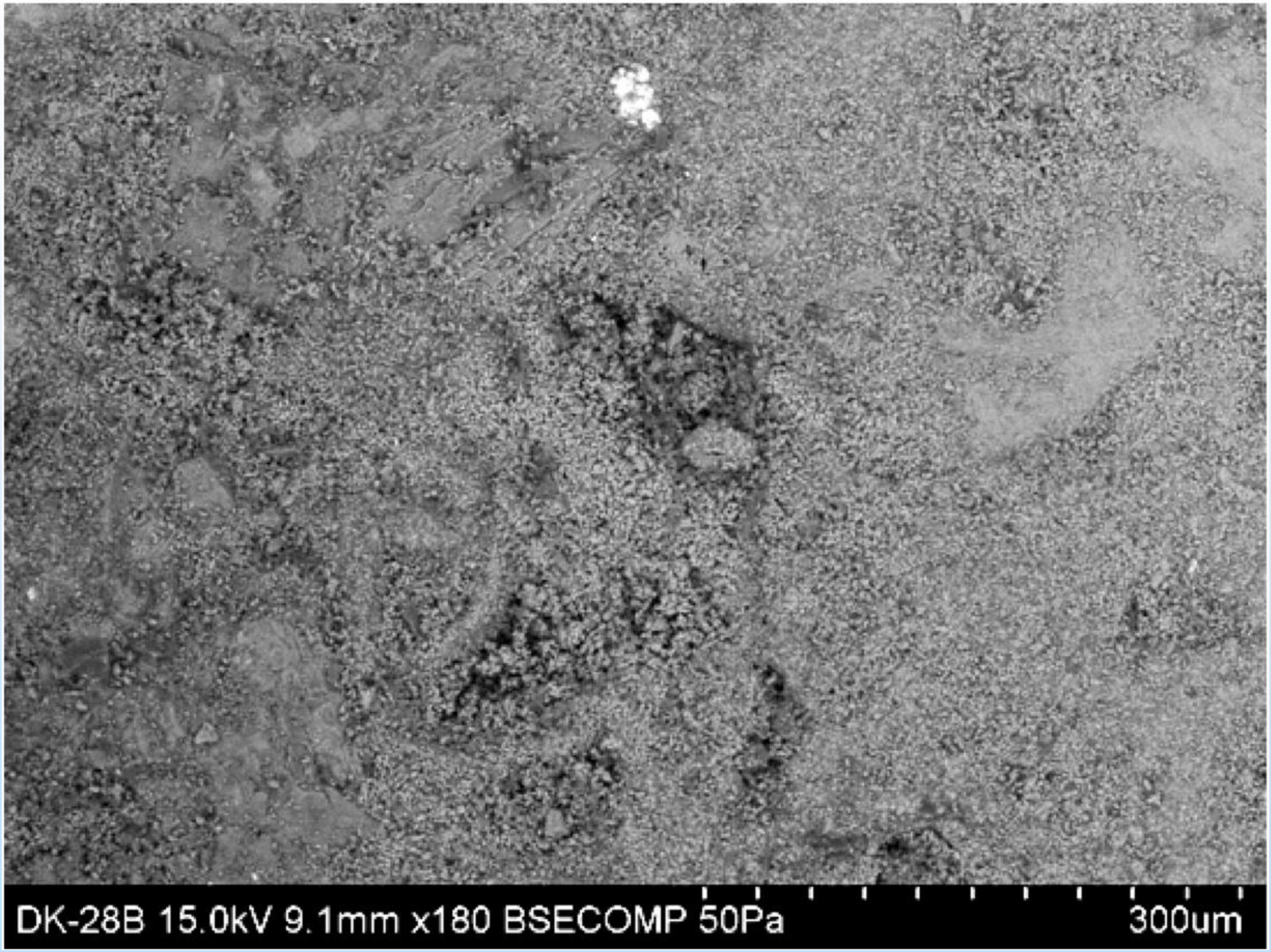
# Laboratory Work

# Experimental Design




- Injection of $CO_2$-rich brine into carbonates/sandstones ➔ dissolution of Calcite and Chamosite
- Injections are performed under reservoir pressure conditions $P_c$ up to 15-55 MPa and $P_f$ up to 15-28MPa

# Rock Samples




Micritic Carbonates



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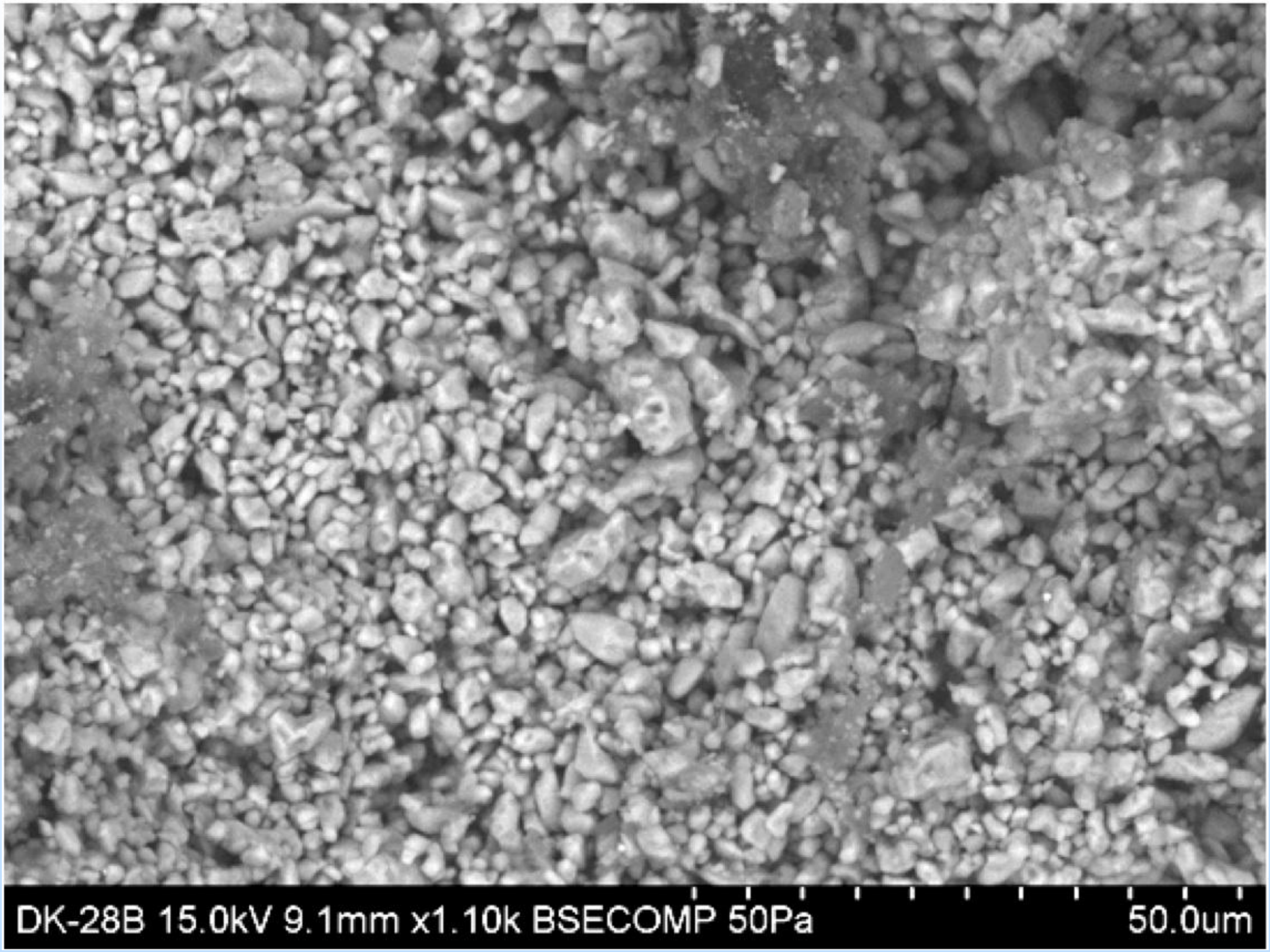
# Rock Samples




Micritic Carbonates



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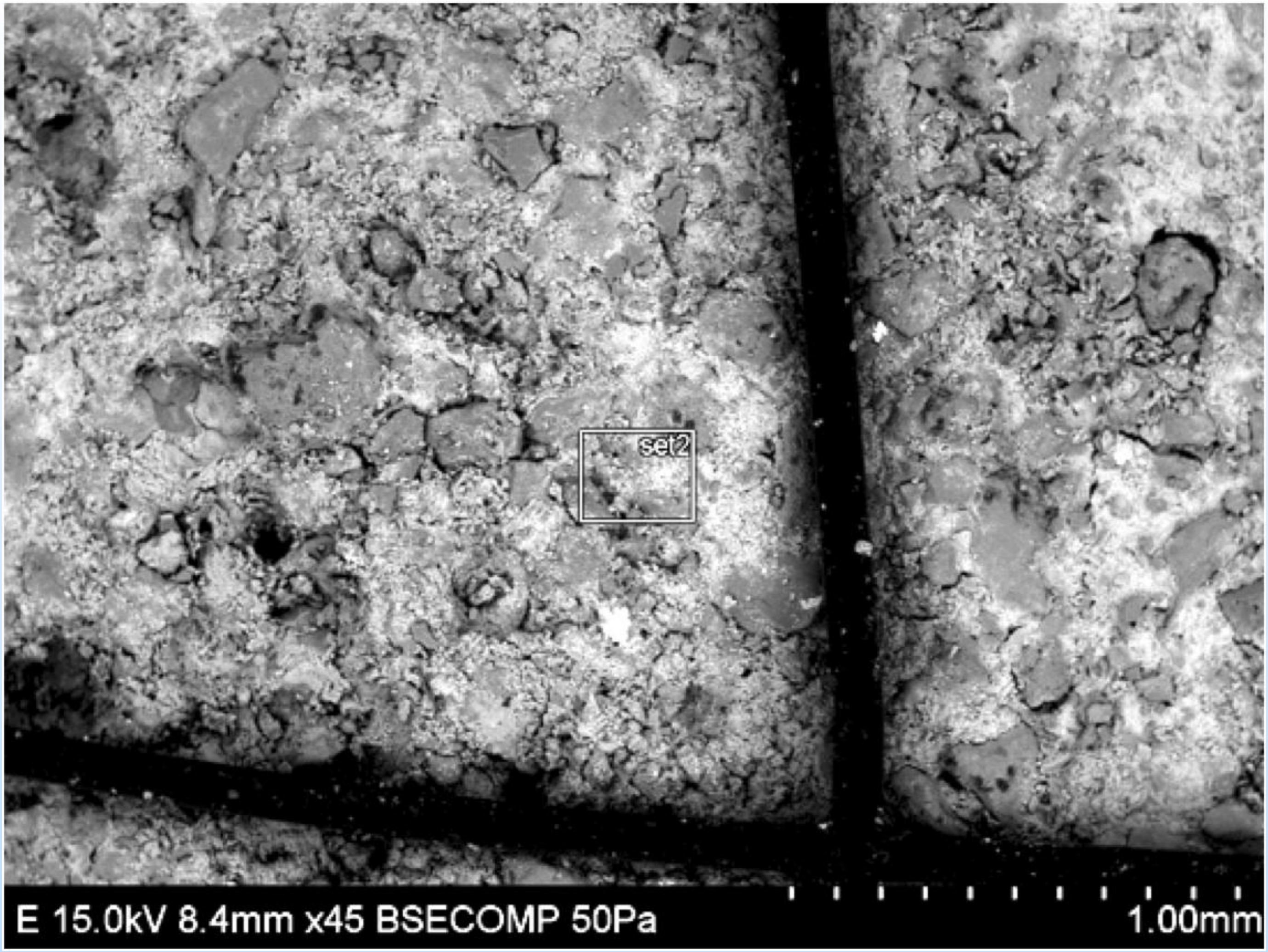
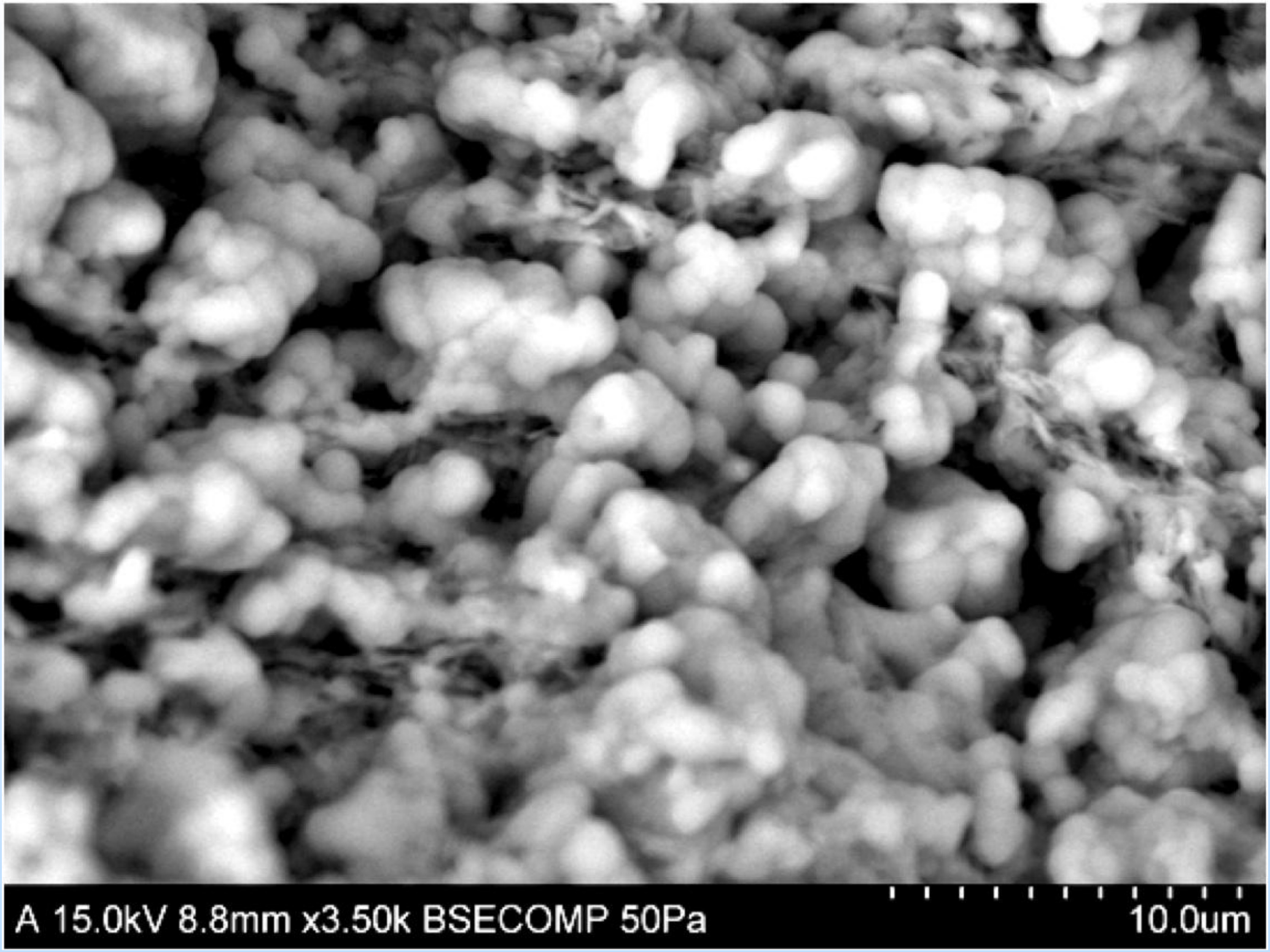
# Rock Samples




Fe-rich Chlorite (Chamosite) Sandstones from the Tuscaloosa Formation, Cranfield, MS

# Rock Samples

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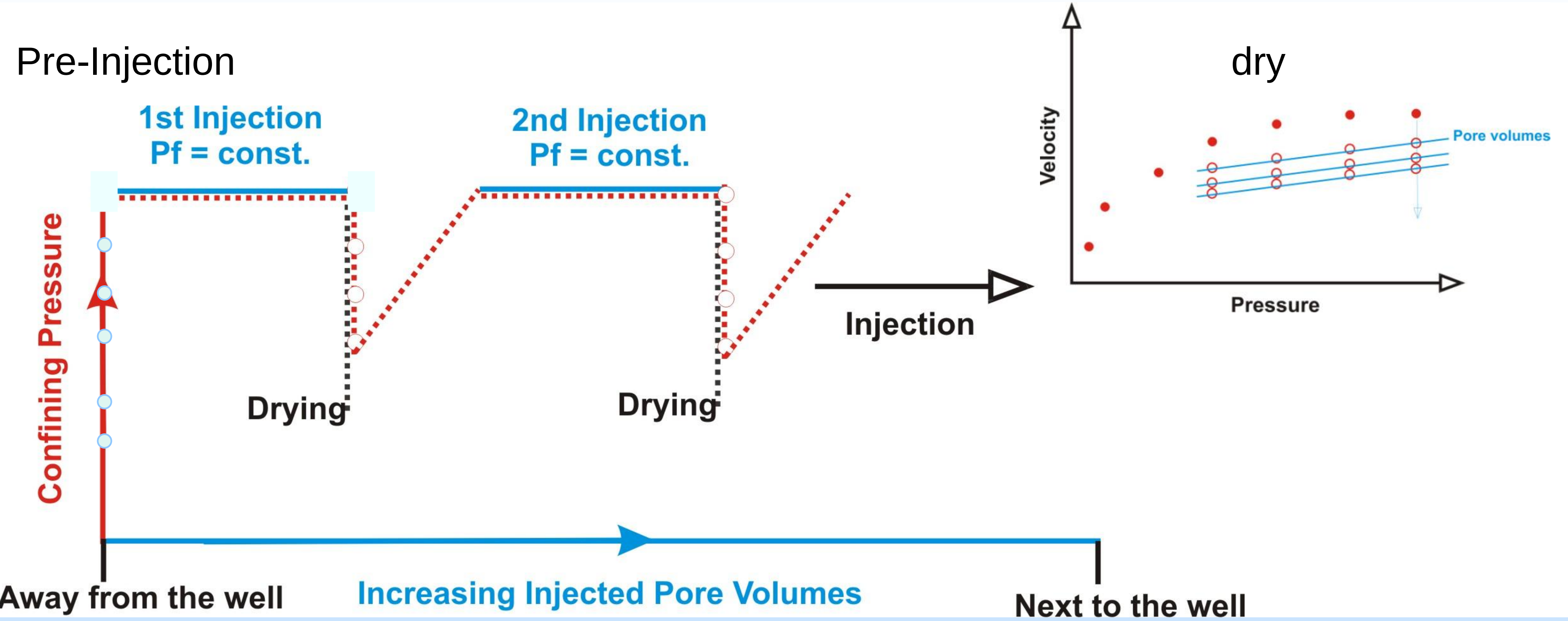
# Experimental Protocol



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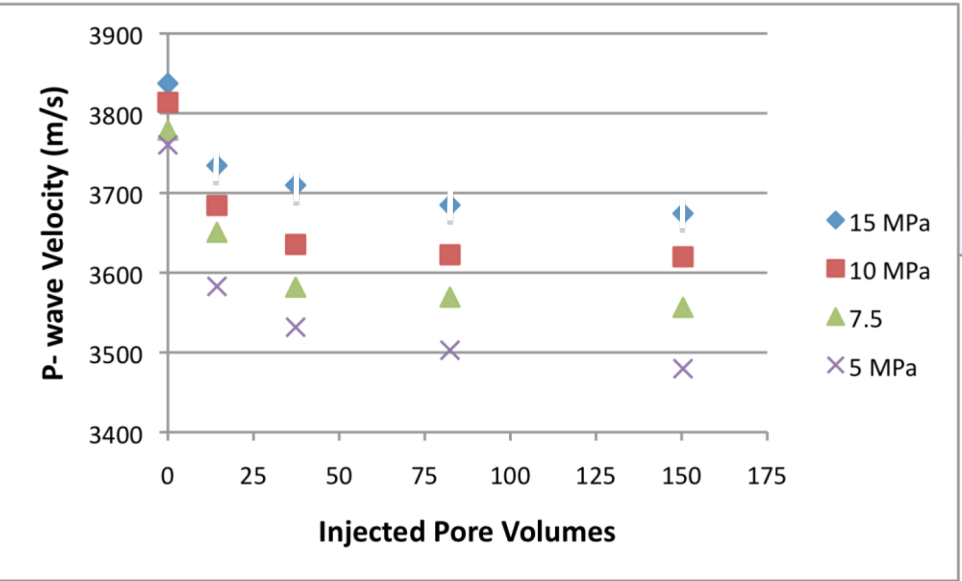
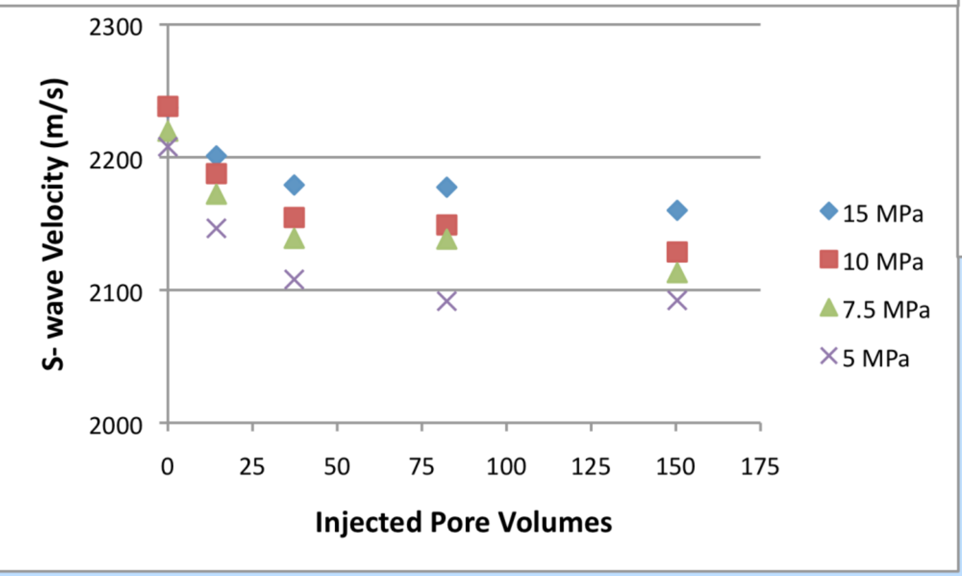
# Monitoring Properties

- **Chemical** composition (pH, Cation concentration) of the brine and the injected pore volumes
- **Porosity** and **permeability** as a result of dissolution and mechanical compaction
- **P-** and **S- wave velocities** of the saturated sample and of the dry frame

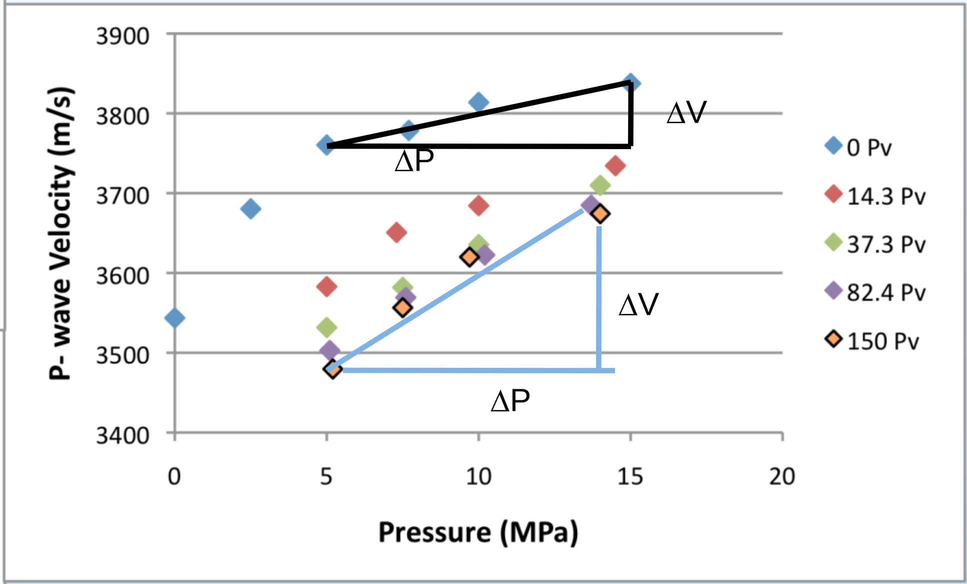
# Carbonate Rocks

# Velocity vs. Injected Volume and Pressure

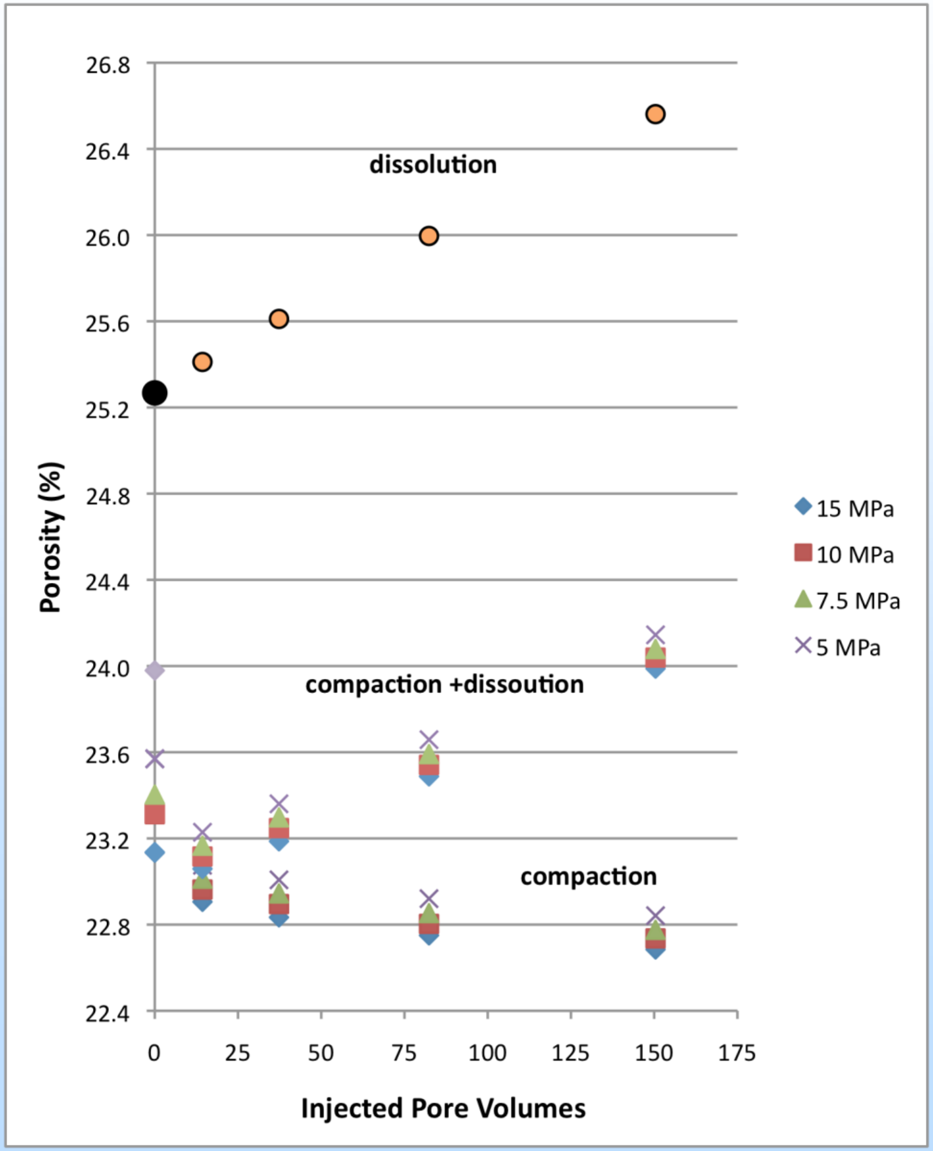


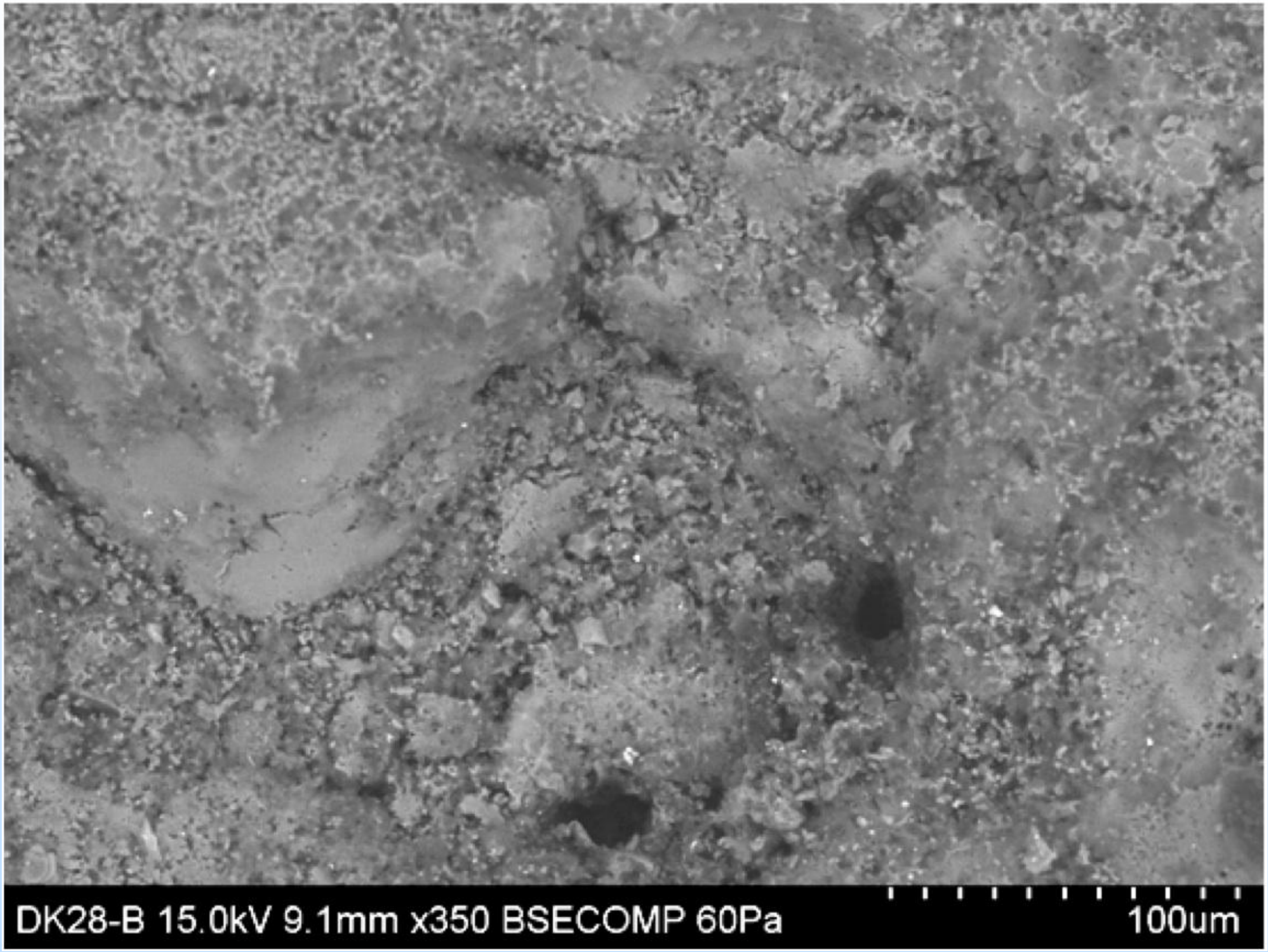

Velocities of the dry rock frame after injection



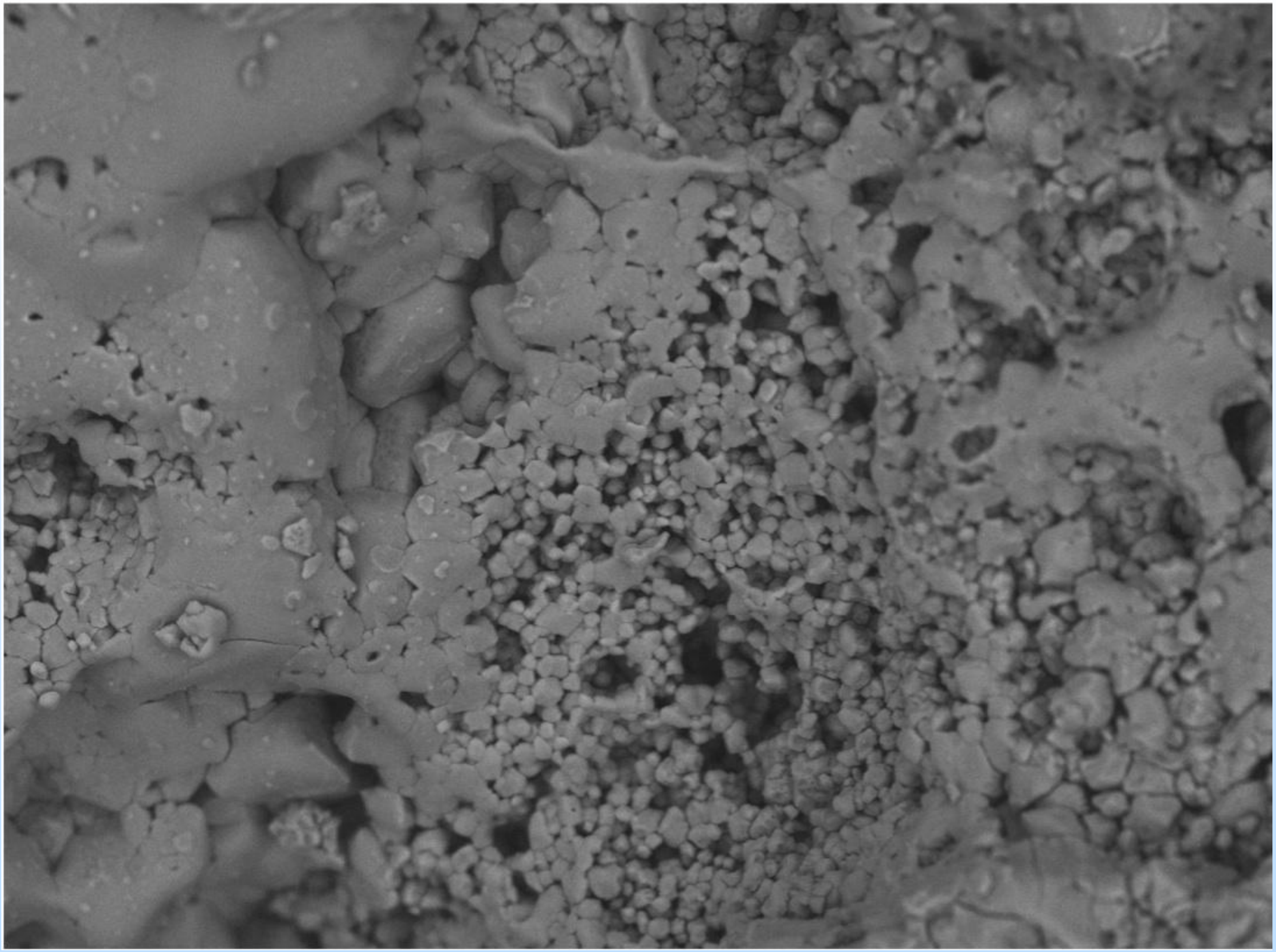
# Velocity vs. Injected Volume and Pressure



# Time-Lapse SEM

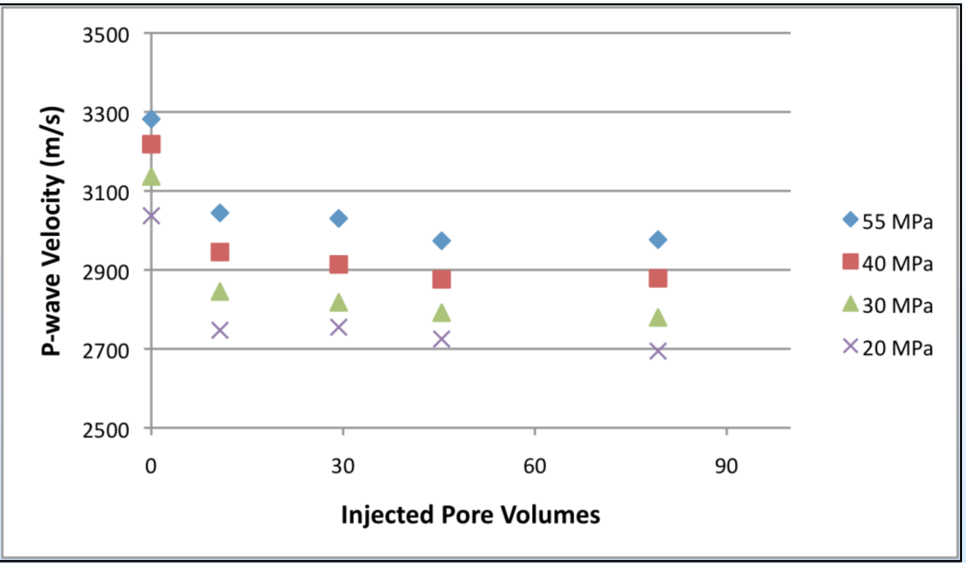


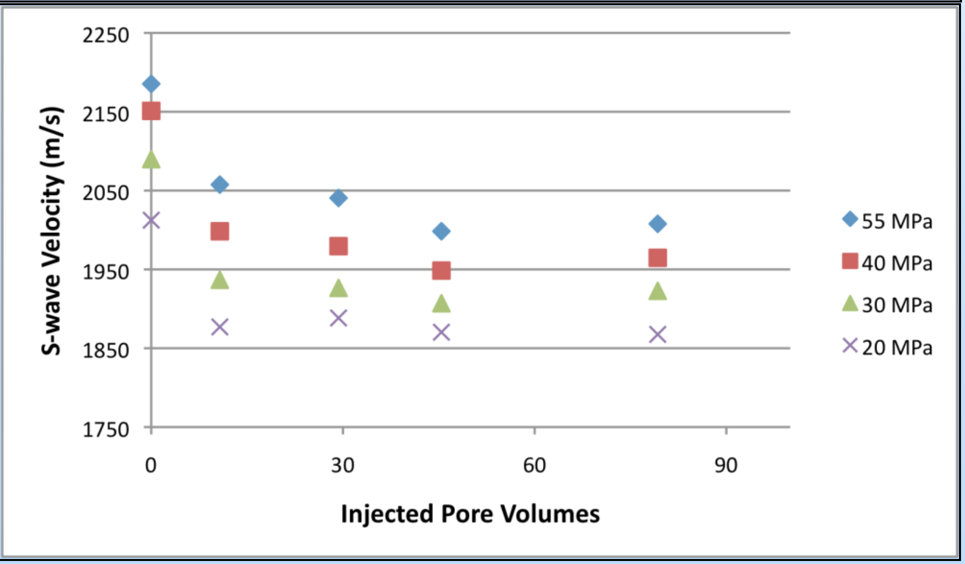
# Time-Lapse SEM



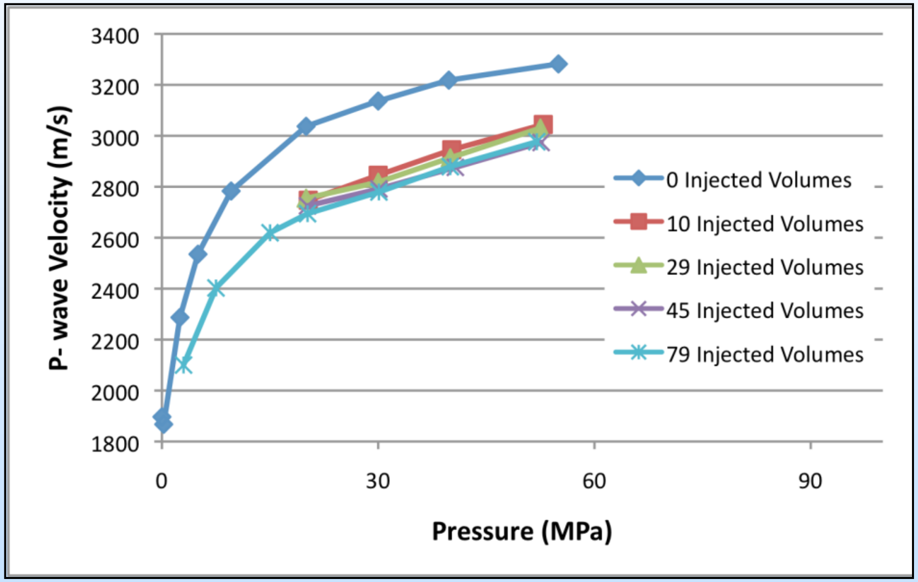
# Chamosite-Rich Sandstones

# Velocity vs. Injected Volume and Pressure

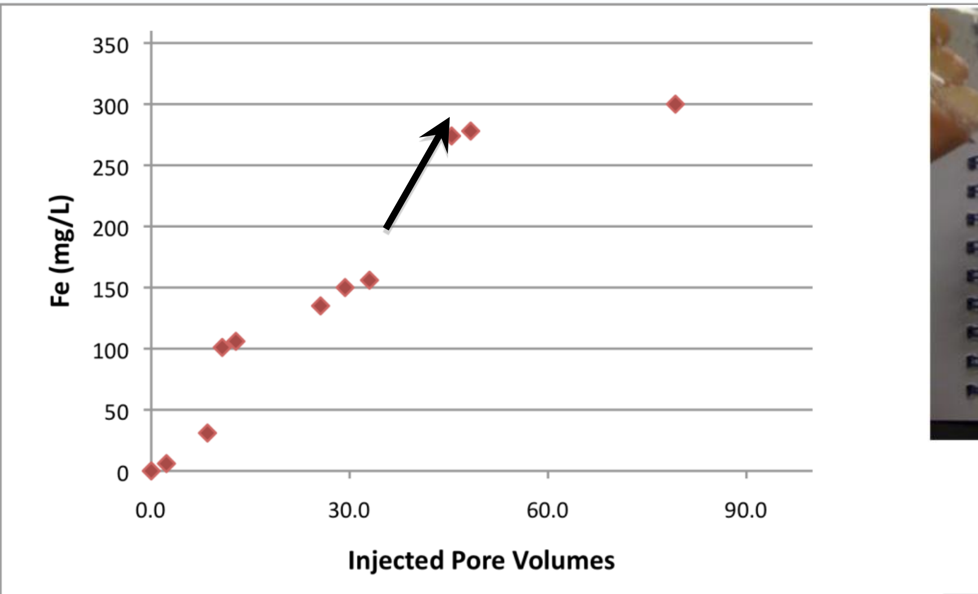


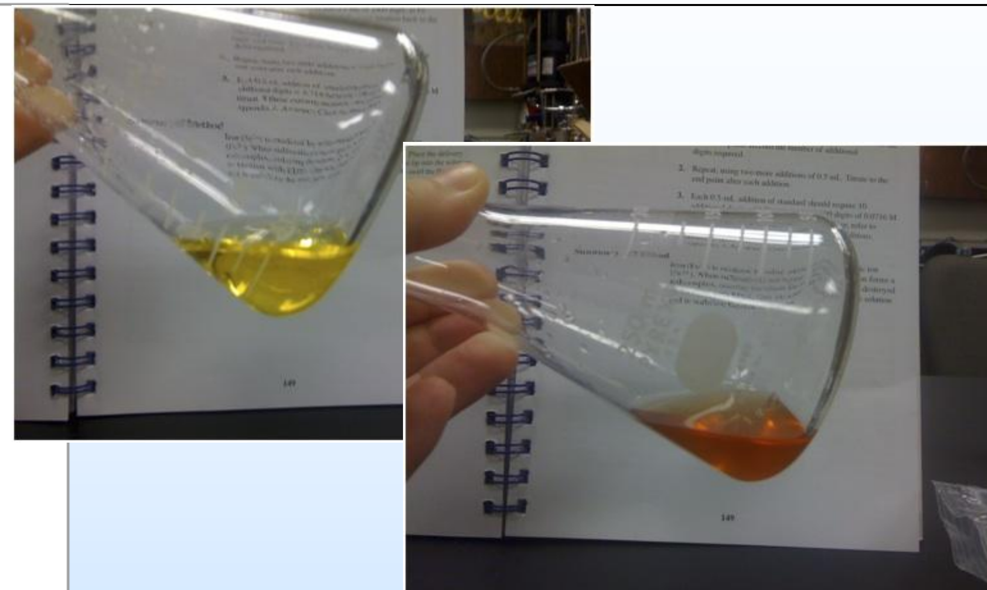



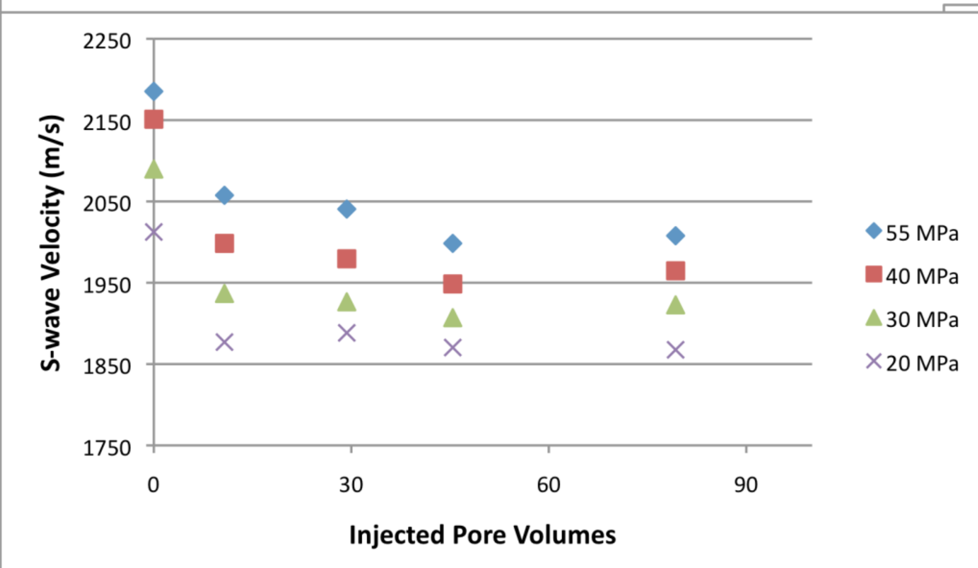

Velocities of the dry rock frame after injection

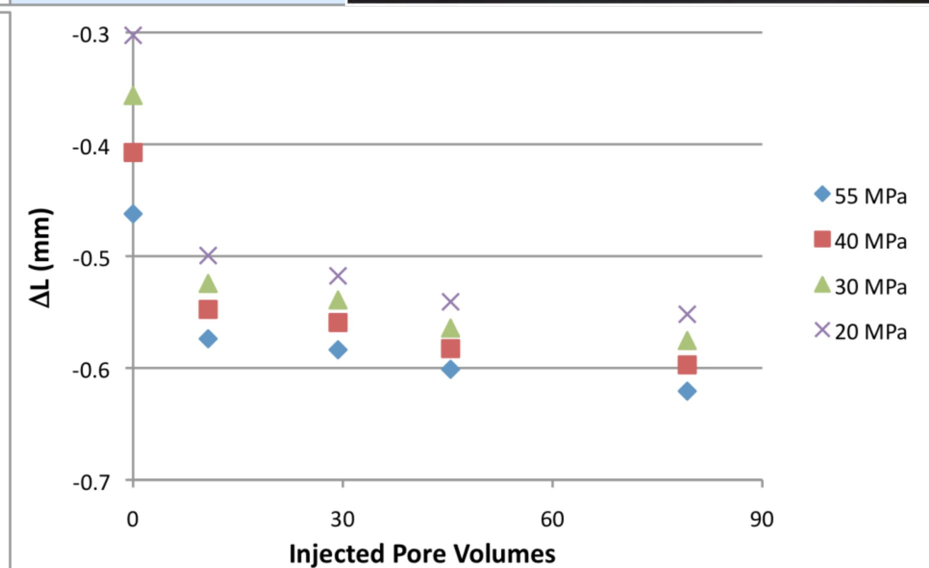


# Velocity & Fe Conc. vs. Inject. Volume and Pressure





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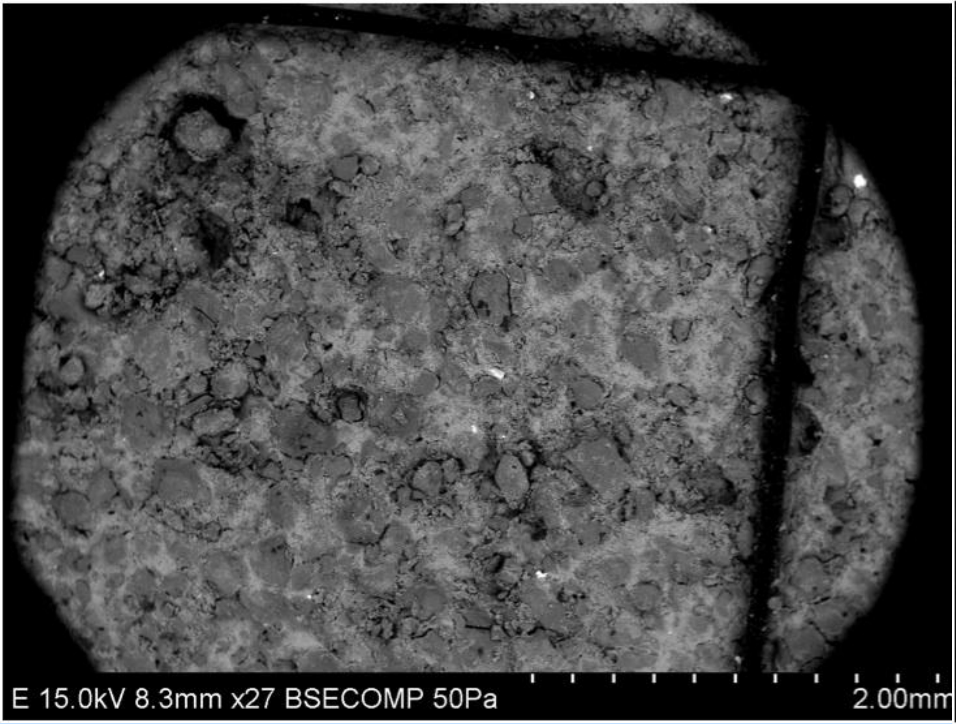


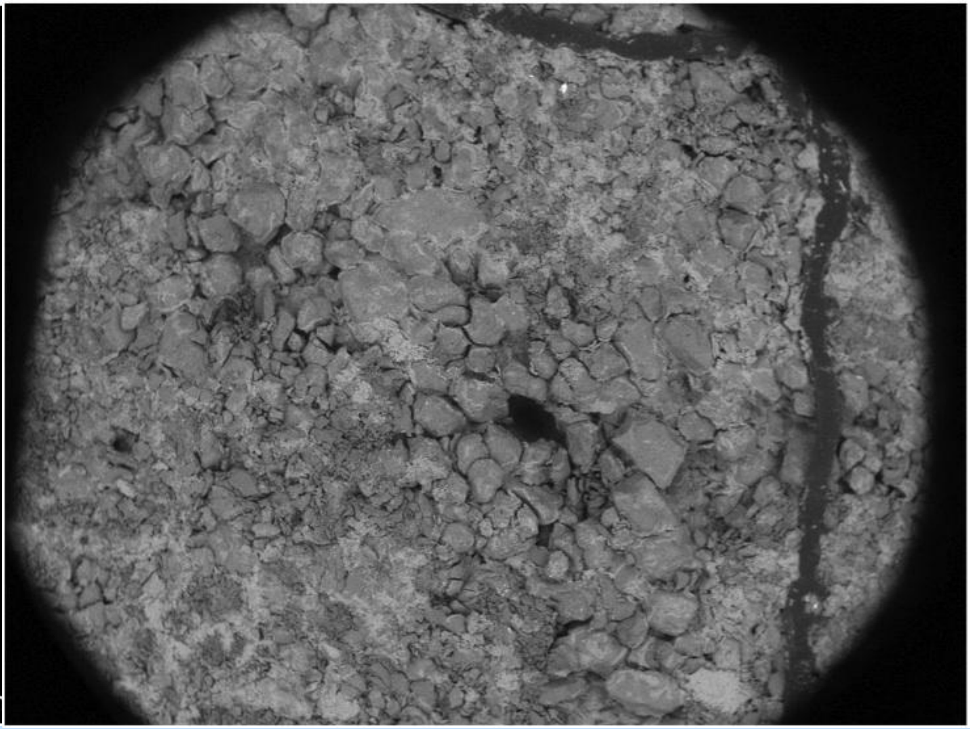

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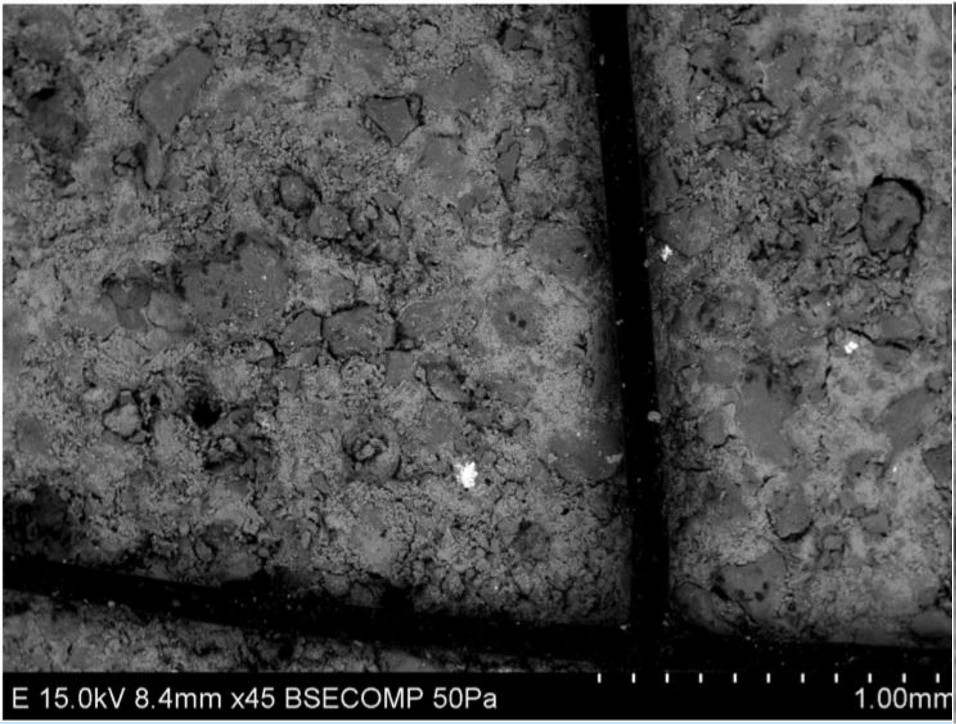


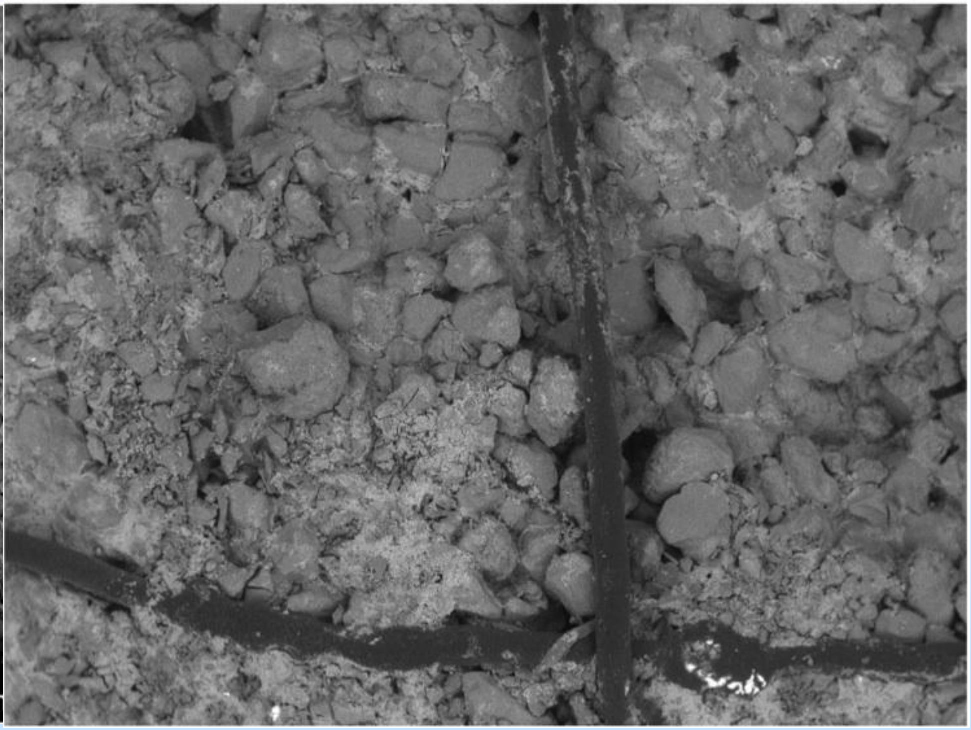

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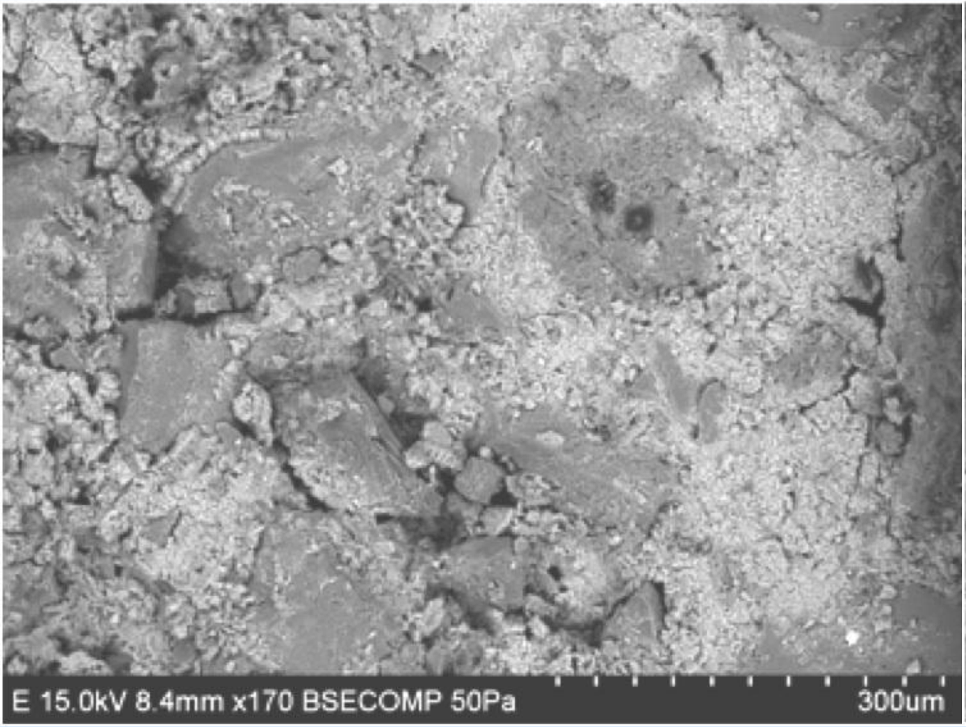
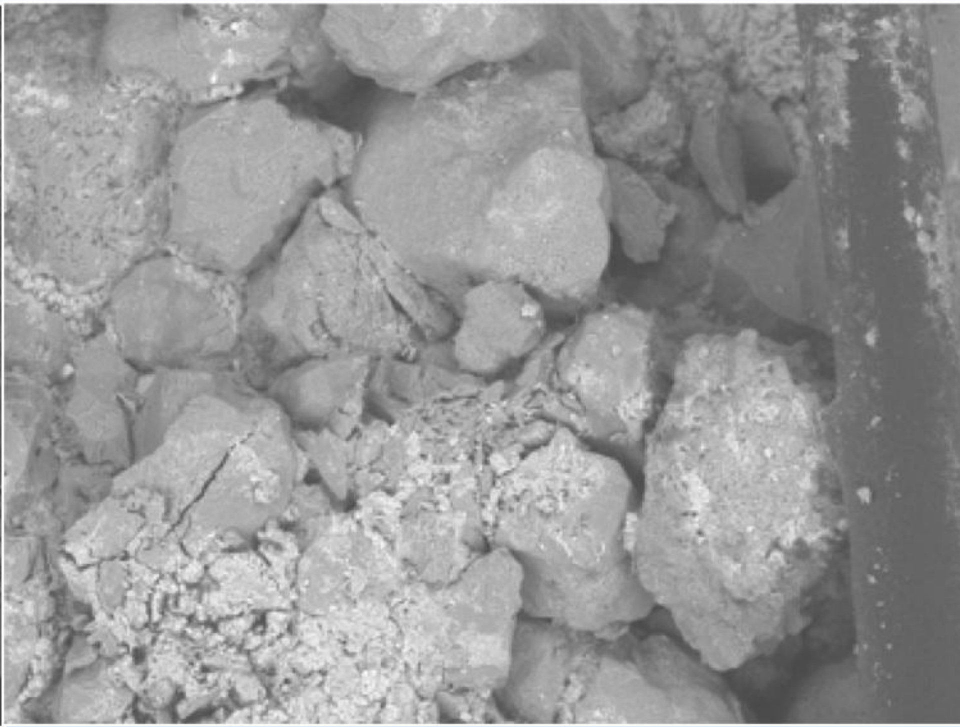
# Time-Lapse SEM



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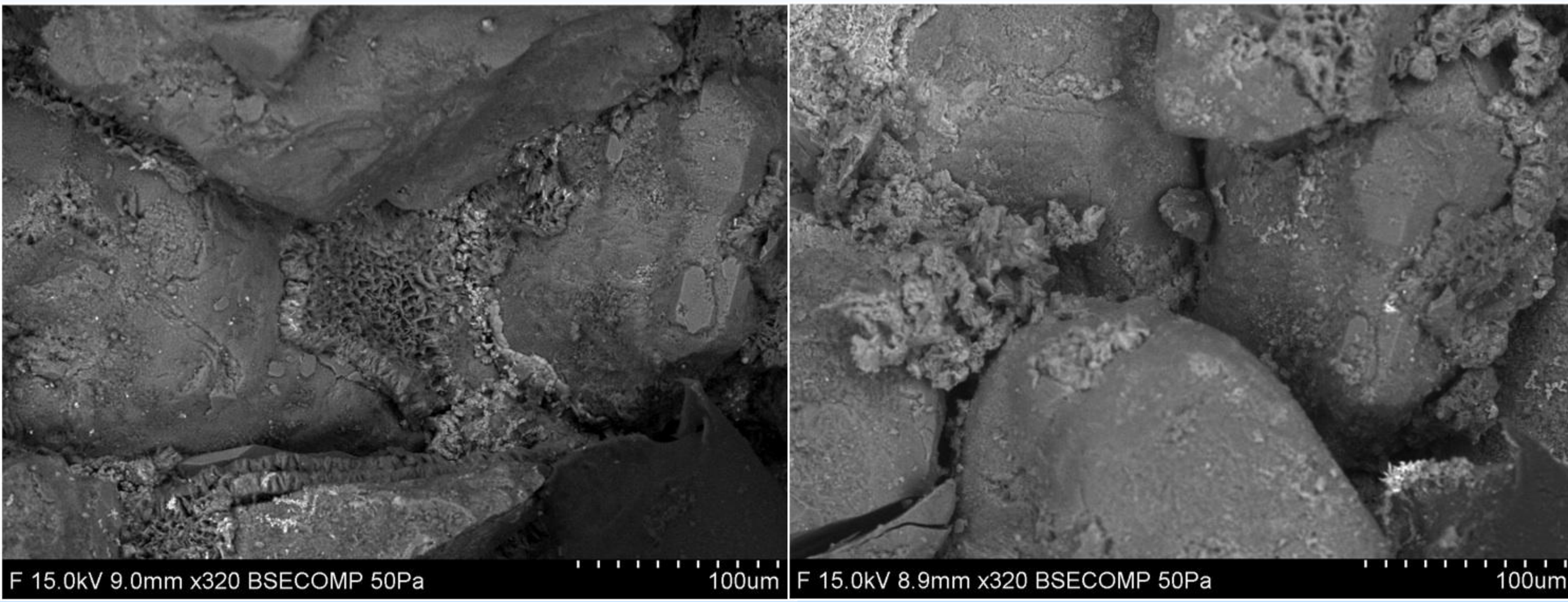


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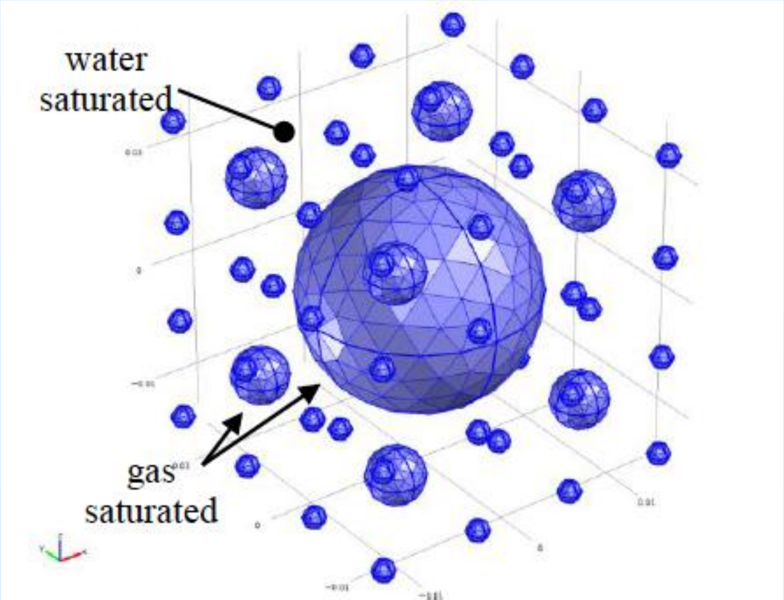
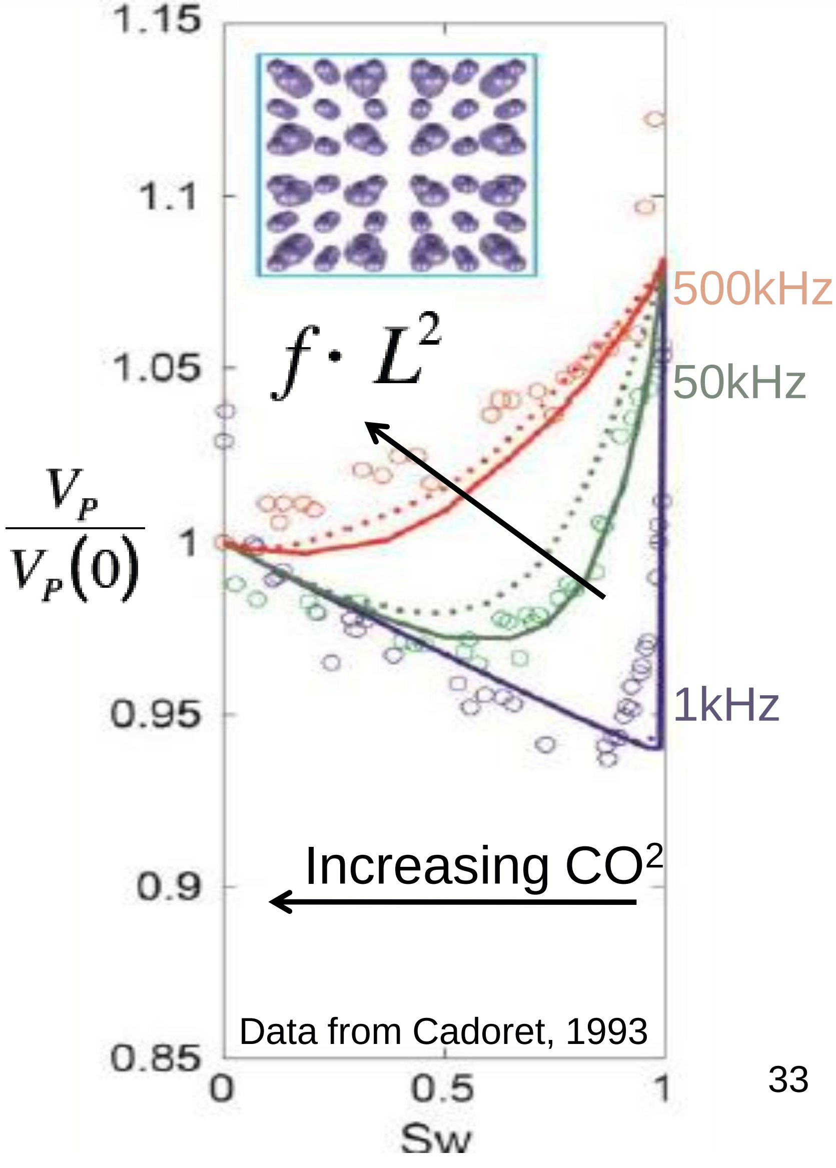
# Rock Physics Models

# Modeling: Elastic Response to Saturation

Finite element and analytical methods to simulate velocity vs. frequency response of $CO_2$ saturation. In the field, we expect Sw heterogeneities to depend on lithologic scales

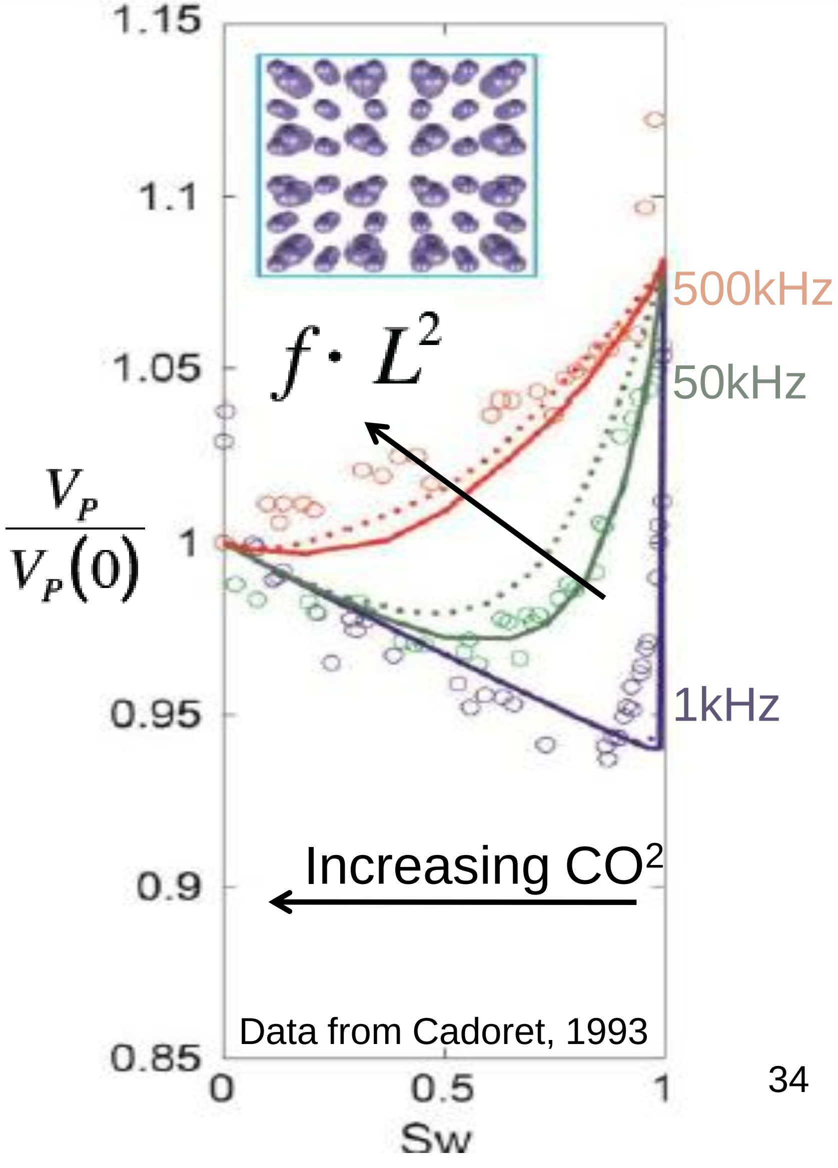
Different scales of saturation



# Modeling: Elastic Response to Saturation

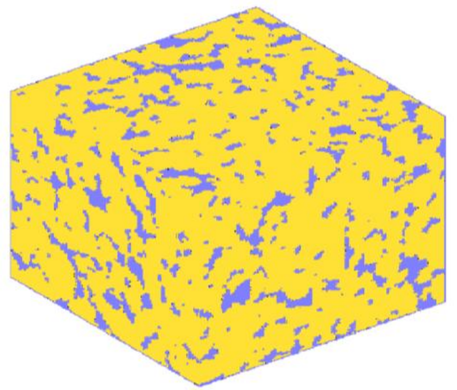
We have developed a simple, differential scheme that allows us to analytically superimpose distributions of saturation scales in the rock.



# Modeling:  Fluid-Solid Substitution

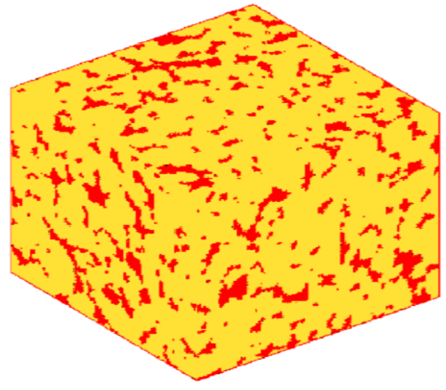
Classic Scenario:  Rock with some initial pore fill.  We have measured (e.g., from well logs):

- Initial elastic constants
- Porosity
- Mineral moduli



We want to predict the new elastic moduli of the same rock,  when the pore space is filled with something else.

In our case, this could be brine, $CO_2$, or solid mineral.



# Modeling: Fluid-Solid Substitution

Predicting the new moduli after substitution of the pore fill is (almost) never unique, without knowledge of the pore space geometry.

But … we can predict bounds on the substituted moduli.

# Modeling:  Fluid-Solid Substitution

Gassmann gives a unique prediction, only because we make a very strong assumption that the pore space is connected.

If we don't know much about the pore space, then Gassmann gives a lower bound.  It is well known that disconnected pores, squirt, etc yield a different result.

(Gibiansky and Torquato, 1998)

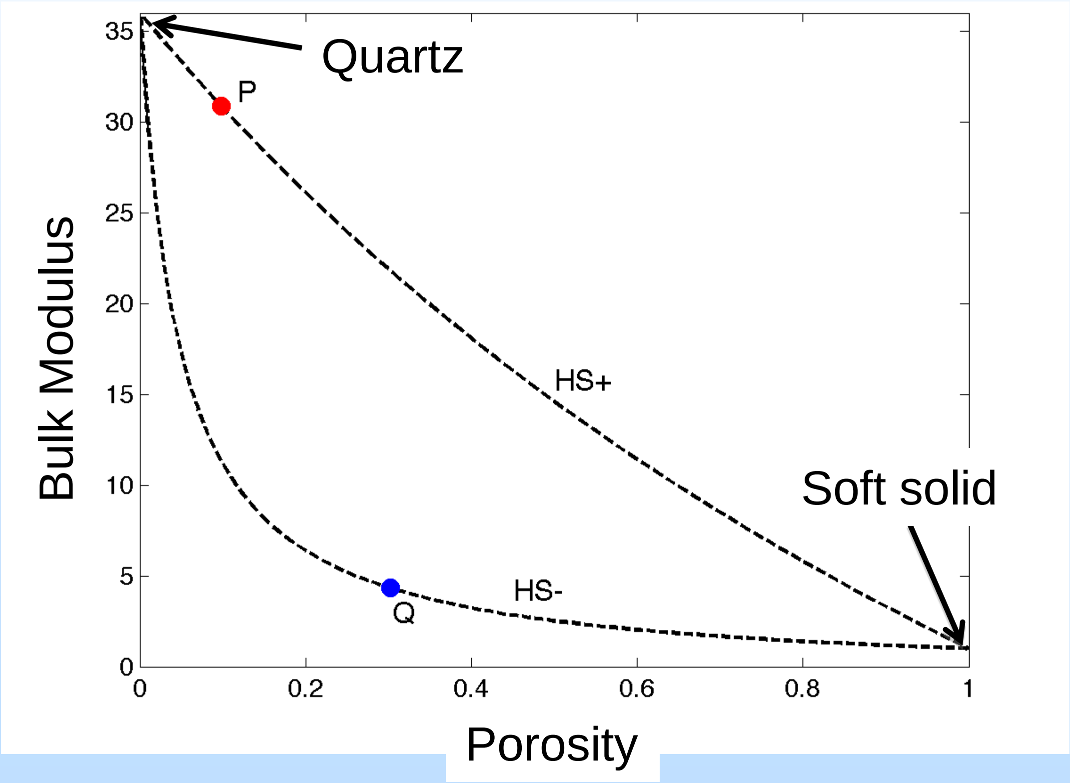
# Modeling: Fluid-Solid Substitution

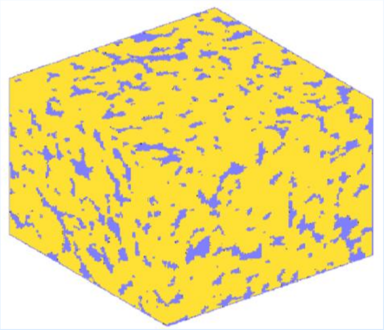
So how do we model solid substitution?

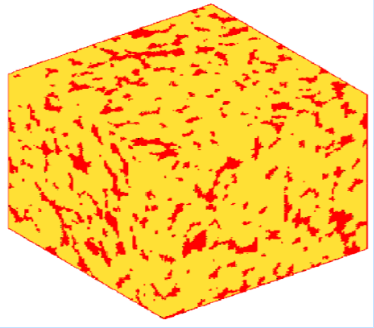
… we need an exact continuum mechanics equation for the rock elasticity.

# Modeling:  Fluid-Solid Substitution

Points on the HS bounds are *physically realizable* -- *the HS equations are the exact expressions for the effective moduli of those materials.*

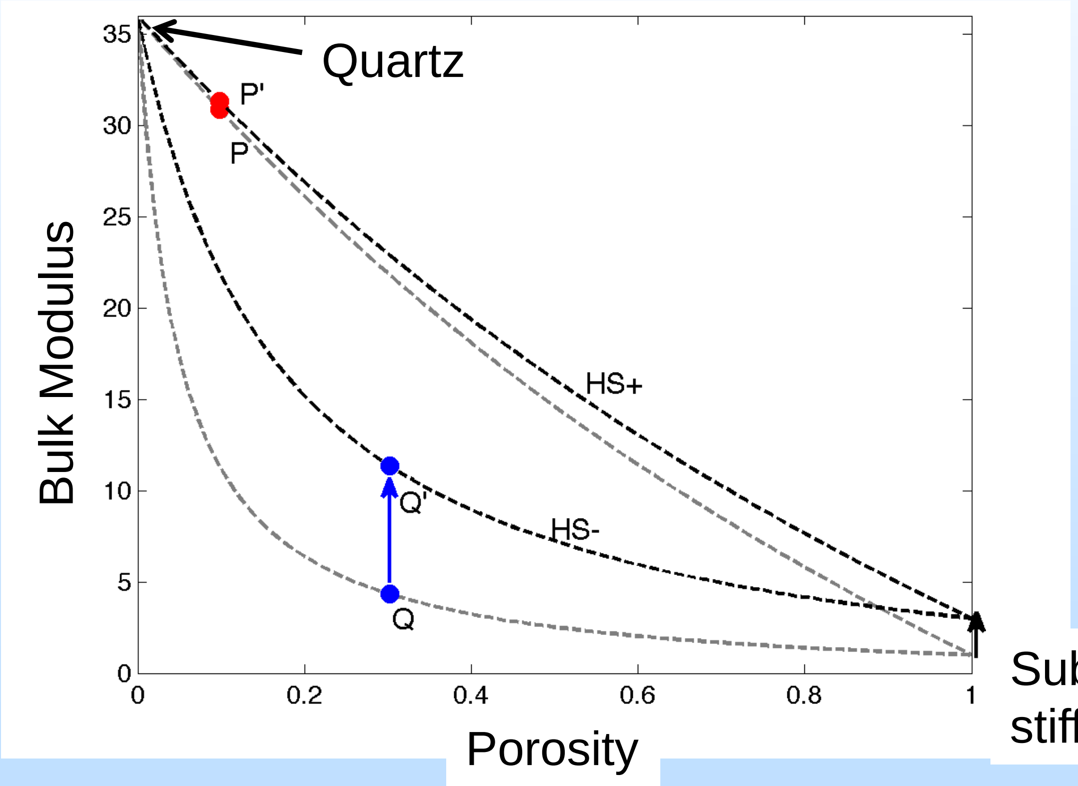


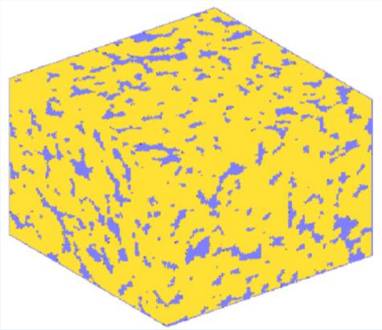



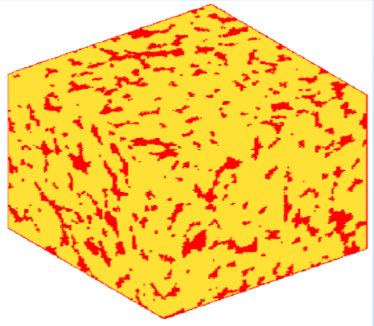


# Modeling: Fluid-Solid Substitution

Fluid or solid substitution for a point on the HS bounds is exact and unique.







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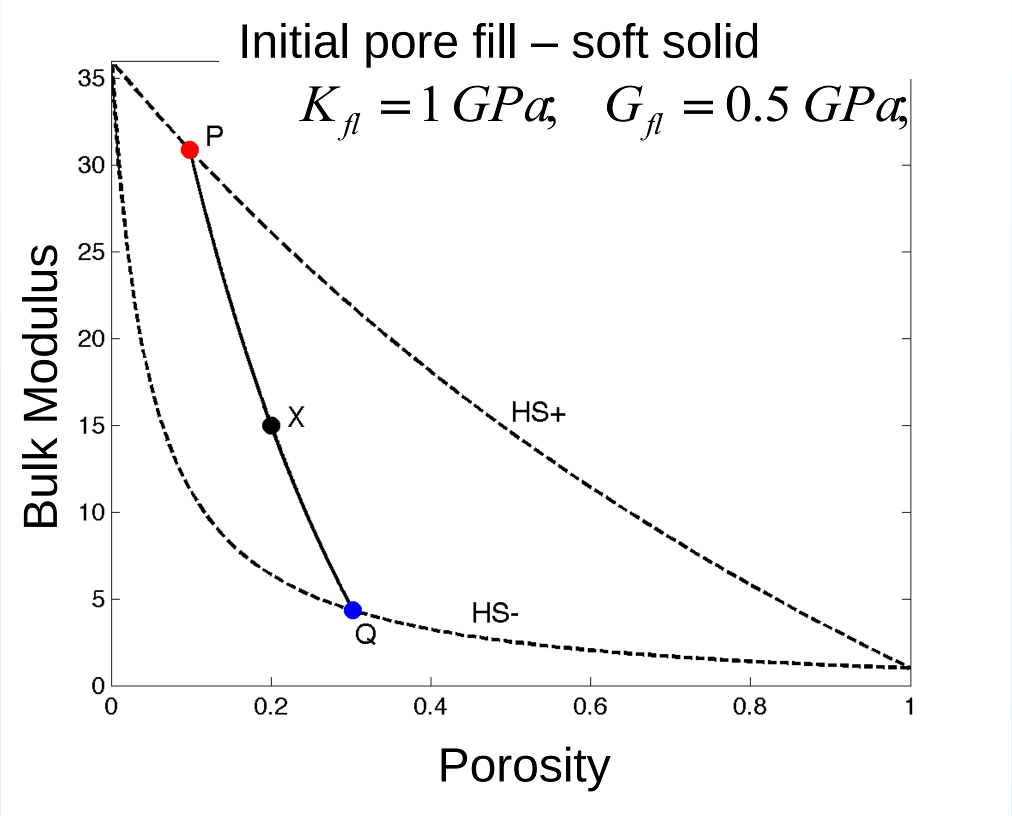
# Modeling: Fluid-Solid Substitution

Off the bounds? We construct modified upper HS bound through point X. Hence, MUHS is the exact expression for modulus of material at X, which can be constructed from points P and Q, which in turn are constructed from the end points.




"Embedded Bounds Method"

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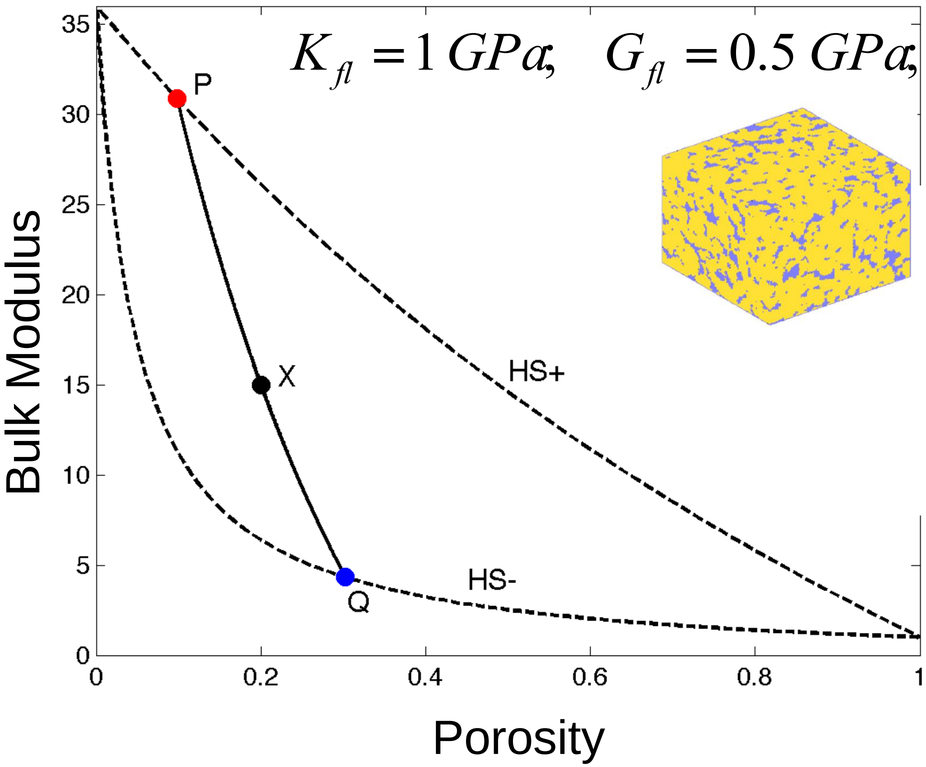
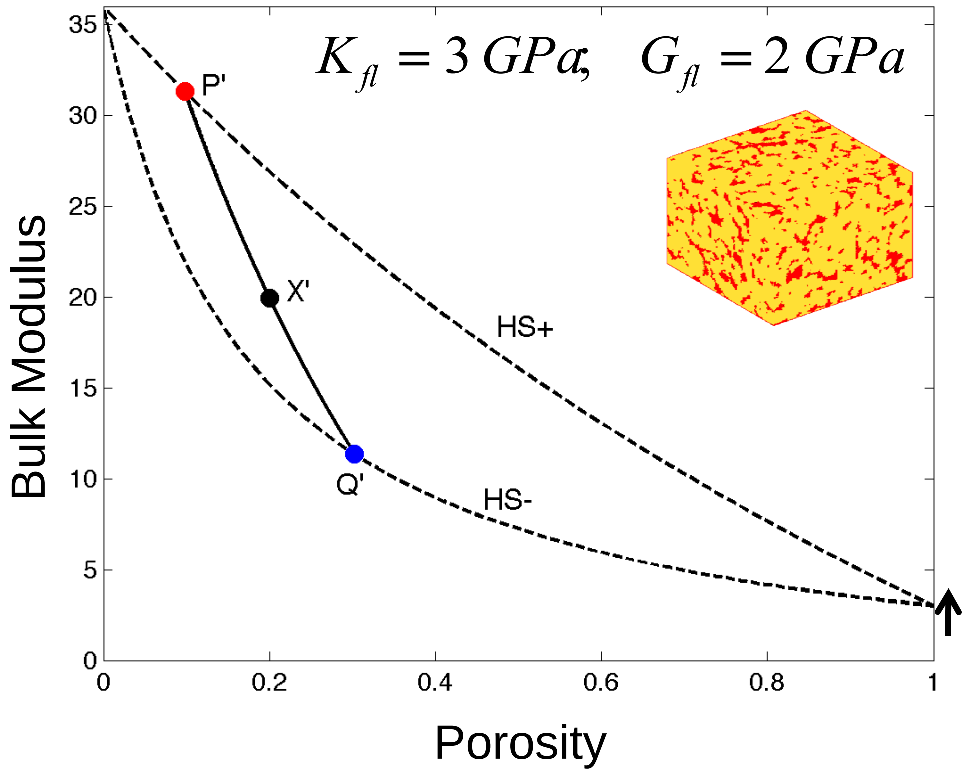
# Modeling: Fluid-Solid Substitution

Fluid or solid substitution for point X can be computed exactly...

Initial pore fill – soft solid

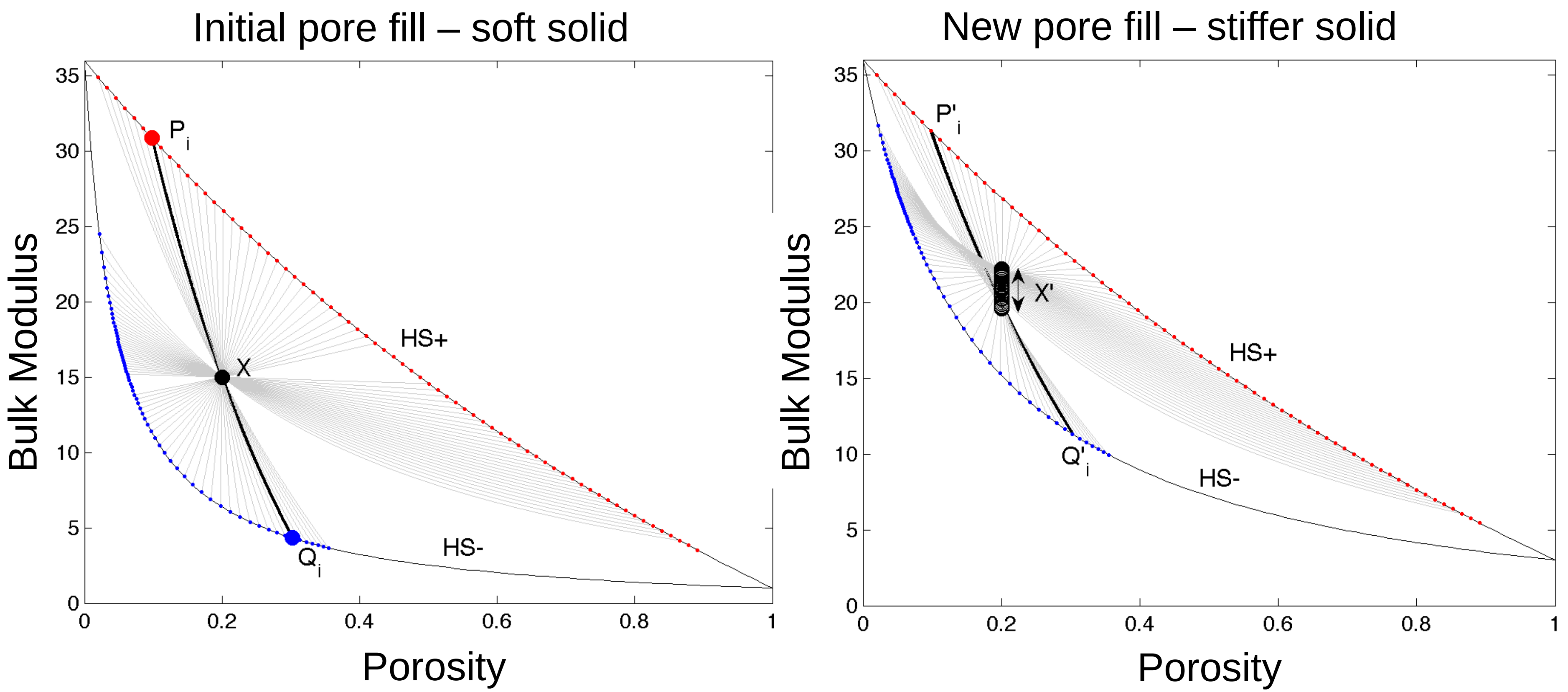



New pore fill – stiffer solid



# Modeling: Fluid-Solid Substitution

… but not uniquely. We can construct an infinite number of MUHS and an infinite number of MLHS bound through point X. Each transforms to a different modulus at X' after substitution.



# Accomplishments to Date

- Laboratory measurements completed on four lithologies (clean sandstone, clay-bearing sandstone, calcite-cemented sandstone, carbonates)
- Apparatus built and tested for measuring dynamic elastic moduli of $CO_2$-brine mixtures.
- Analytical method developed to model frequency- and saturation-dependent elastic properties of $CO_2$-bearing rock.
- Preliminary model developed for “solid-substitution.”

# Summary

- We have observed irreversible changes in porosity, permeability, and elastic properties in carbonate and clay-bearing rocks when injected with $CO_2$-brine mixtures.
- These changes to the solid rock frame are not included in conventional interpretation of seismic data.
- Preliminary observations suggest that dissolution moves elastic properties along normal diagenetic trends, which gives strategies for modeling the elastic response to dissolution or precipitation.
- We have developed a strategy for modeling “solid substitution in rocks, based on embedded Hashin-Shtrikman bounds.  We have shown that all fluid or solid substitution is nonunique unless information on pore microgeometry is available.
- Many rock models have an implicit geometry.  Be cautious with substitution.  Even though it fits the original data exactly, its substituted prediction might be wrong.

# Future Plans

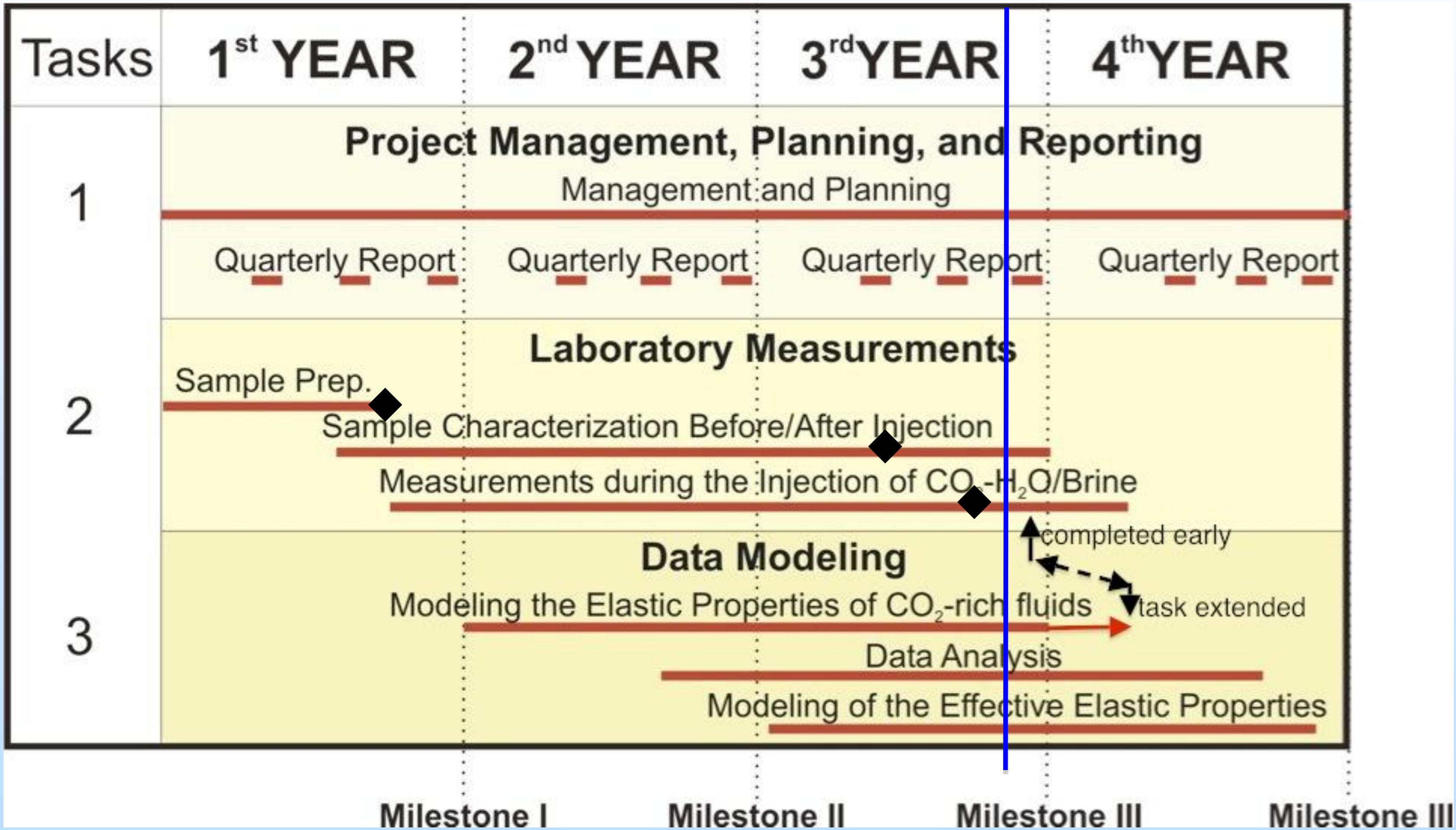
- Complete measurements on the compressibility of $CO_2$-brine mixtures.
- Complete theoretical modeling on effects of frequency, saturation, pressure, and permanent changes to the rock frame.

# Appendix

# Organization Chart

- Mavko PI
- Dr. Tiziana Vanorio – Laboratory lead
- 1 Postdoc
- 2 Graduate Students

# Gantt Chart




◆ = task completed