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

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Developing the Technologies and
Infrastructure for CCS

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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.

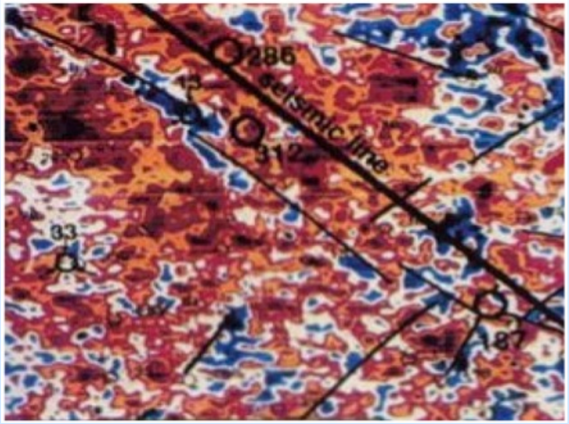
Project Overview:
Goals and Objectives

- 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.
  - Improved theoretical models that predict the seismic velocity changes associated with injection, including changes in pore pressure, saturation, and dissolution or precipitation of minerals in the rock frame.

Technical Challenge: Seismic Monitoring of CO_2

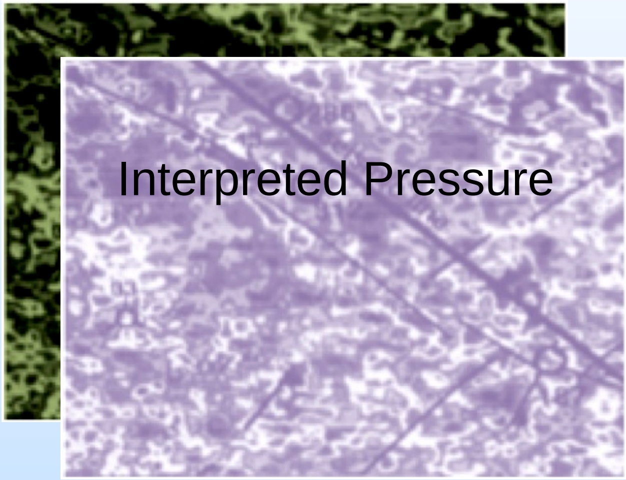
Workflow for monitoring changes in the subsurface

Map of Seismic Reflectivity
or *Changes* of Reflectivity



→ Rock/Fluid Model →

Interpreted Saturation



Interpreted Pressure

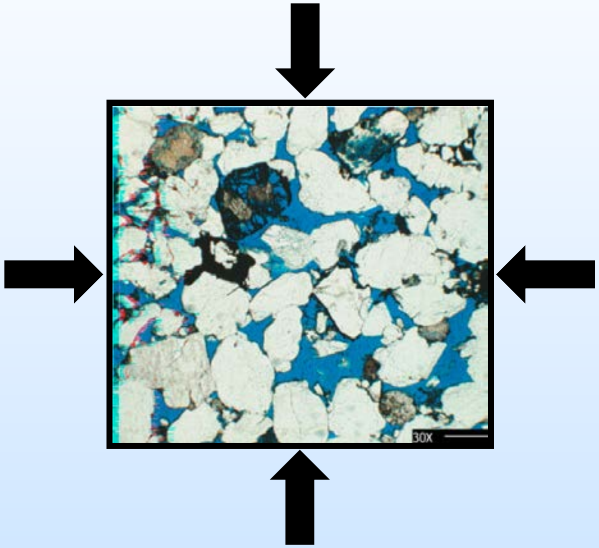
Changes in:
- Seismic Vp
- Seismic Vs
- Density
- Attenuation ?

⟺ model

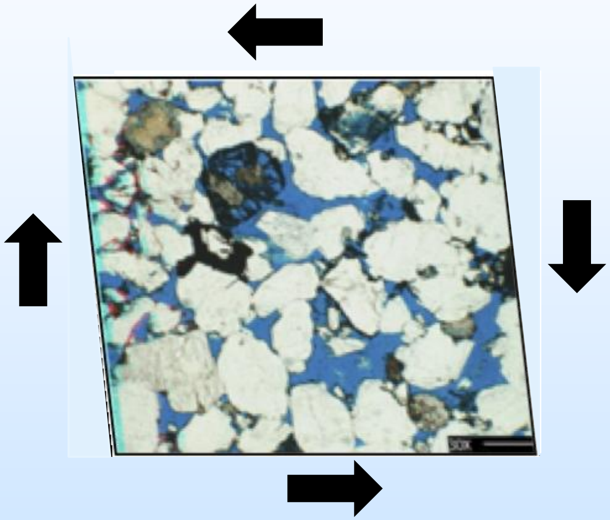
Changes in:
- Saturation
- Stress/pressure
- Rock mineral frame

Rock’s Seismic (Elastic) Response

Bulk modulus:



Shear modulus:



Affected by:

Mineralogy	✔	✔
Porosity	✔	✔
Microgeometry	✔	✔
Stress/Pressure	✔	✔
Fluids	✔	

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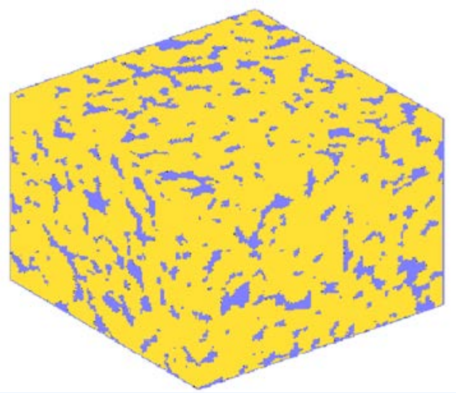
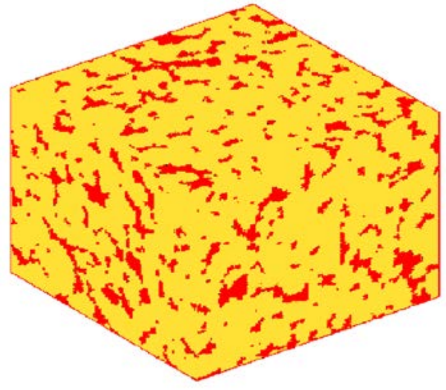
Conventional Seismic Rock-Fluid Model



Current technology for seismic monitoring of injected CO_2 saturation (or other fluids such as water, steam, oil, gas) is based on the equations of Gassmann (1951). The model predicts the change in effective elastic moduli of a porous medium upon exchange one pore fluid with another.



These treat the rock-fluid mechanical interaction, but assume that the system is chemically inert, i.e., constant rock/mineral frame stiffness.

The Problem

Multiphase CO_2-rich fluid-rock systems can deviate from assumptions of conventional seismic fluid modeling in several ways:

> The seismic response depends on the measurement frequency, controlled by rock permeability and scales of the saturation.
>
> Subresolution heterogeneity affects the fluid response.
>
> CO_2-rich fluid-rock systems can be chemically reactive, altering the rock frame via dissolution, precipitation, and mineral replacement.

Errors from ignoring spatial scales, frequency, and chemical changes to the rock frame can affect not only the magnitude, but also the sign, of predicted seismic velocity changes, resulting in seriously compromised estimates of saturation and press of CO2-rich fluids.

Approach: Tasks

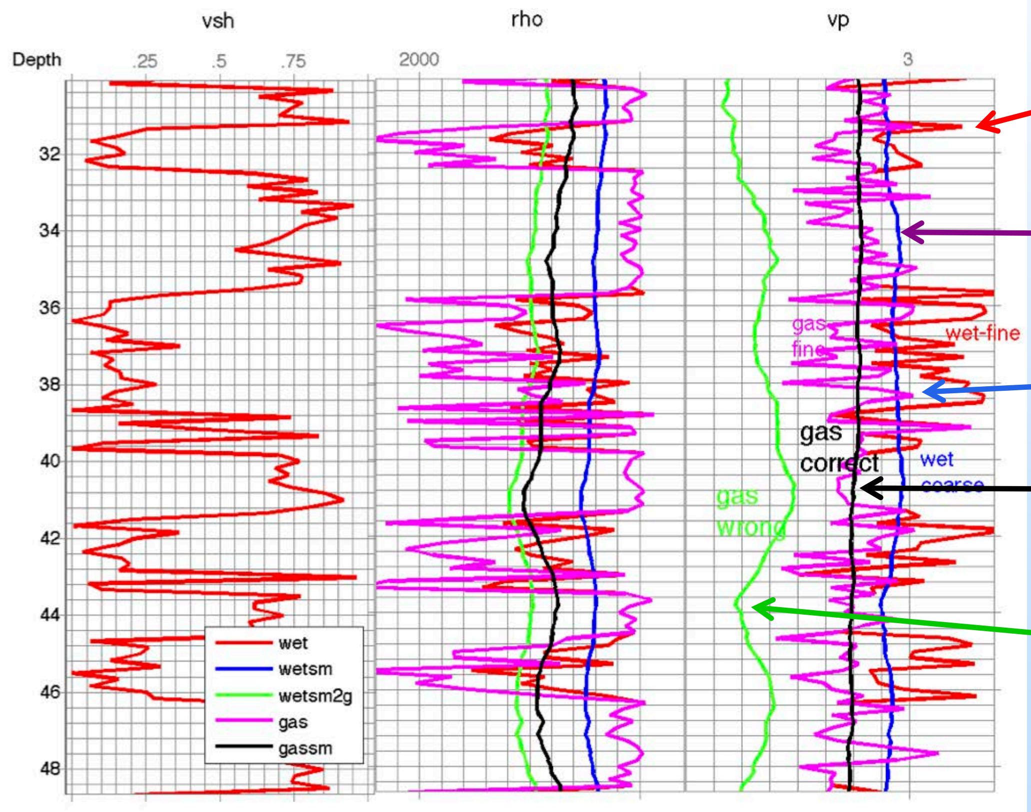
1. Laboratory Measurements
    - Rock characterization (porosity, perm, elastic velocities, microstructure)
    - Exposure to CO_2-brine, while monitoring Vp, Vs
    - Repeat characterization
    - CO_2-brine mixture characterization vs. T and P

2. 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.

Technical Status

Seismic Modeling in Thinly Layered Aquifer

Conventional rock models deal with one facies at a time. Errors arise when layer thickness is below measurement resolution.



Brine-saturated sand/shale layers

Upscaled brine-saturated interval

CO_2 invades sandy layers but not shale

Upscaled with CO_2

Conventional fluid modeling approach

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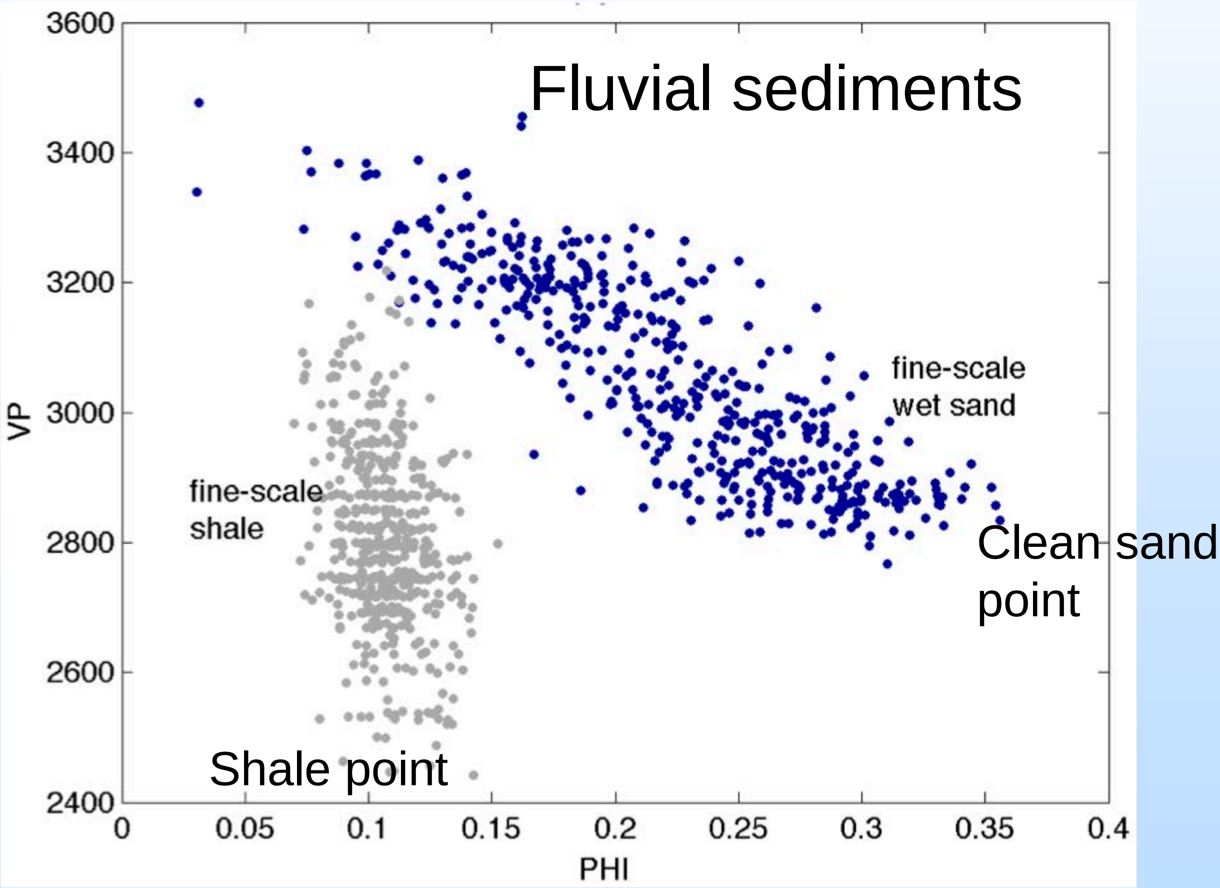
Seismic Modeling in Thinly Layered Aquifer

Fluvial sequence with two distinct facies: permeable sand and shale.



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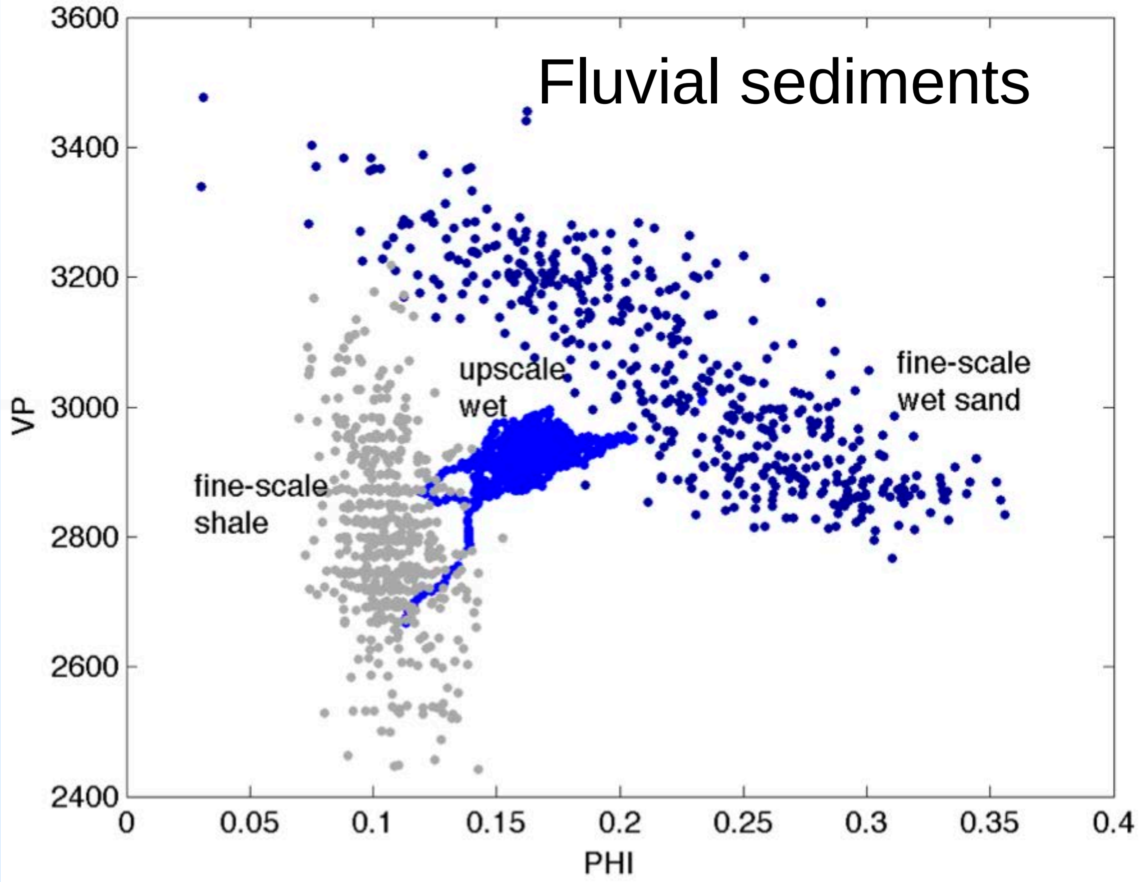
Fluid Modeling in Thinly Layered Aquifer

Upscaled measurements never reveal the aquifer properties -- always averaged with shale



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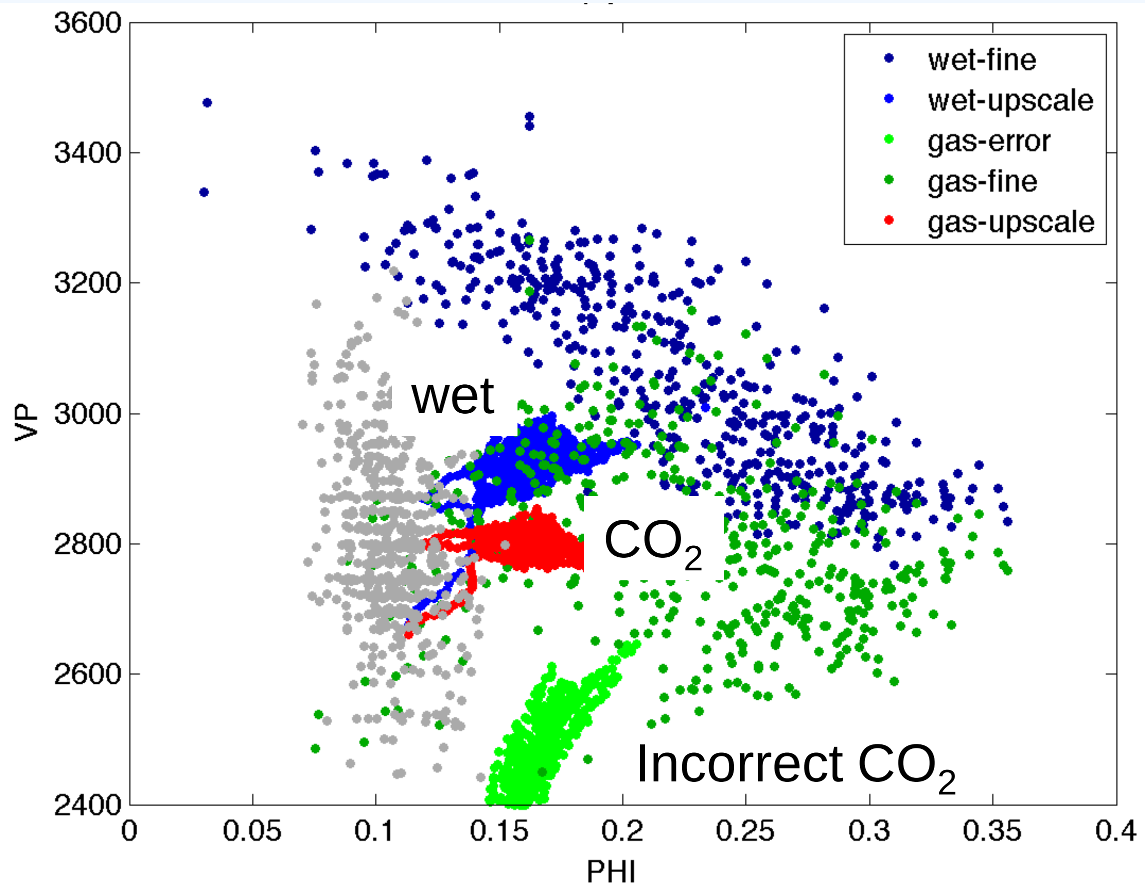
Fluid Modeling in Thinly Layered Aquifer

Correct scale-appropriate fluid substitution versus conventional approach.



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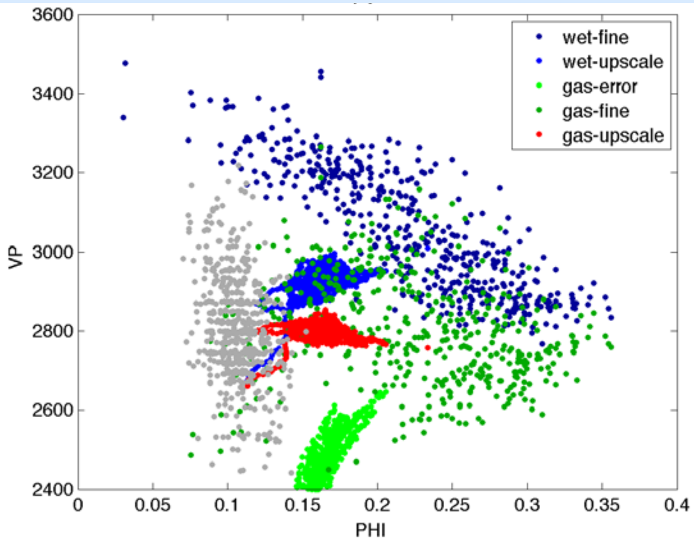
Fluid Modeling in Thinly Layered Aquifer

New fluid substitution algorithm automatically detects subresolution layering and performs scale-appropriate correction.

$$C_{sat2} = C_{sat1} - \left(\frac{\varphi_{eff}}{\varphi_{sand}}\right)\left(C_{Sandfluid1} - C_{Sandfluid2}\right)$$



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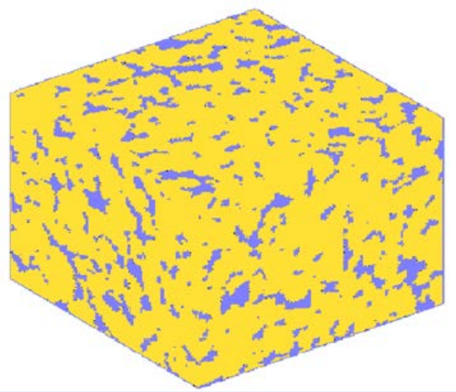
Seismic modeling of Fluid-Solid Substitution

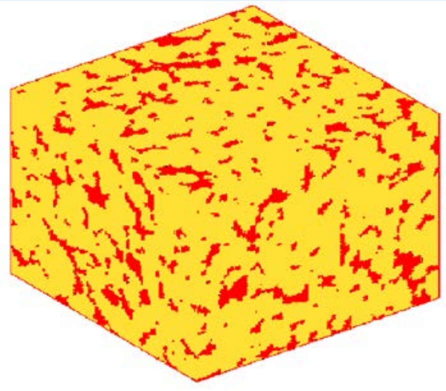
Classic Scenario: Rock with some initial pore fill.



We have measured (e.g., from well logs):

- Initial elastic constants ($K^{(1)}, \mu^{(1)}$)
- Porosity
- Mineral moduli

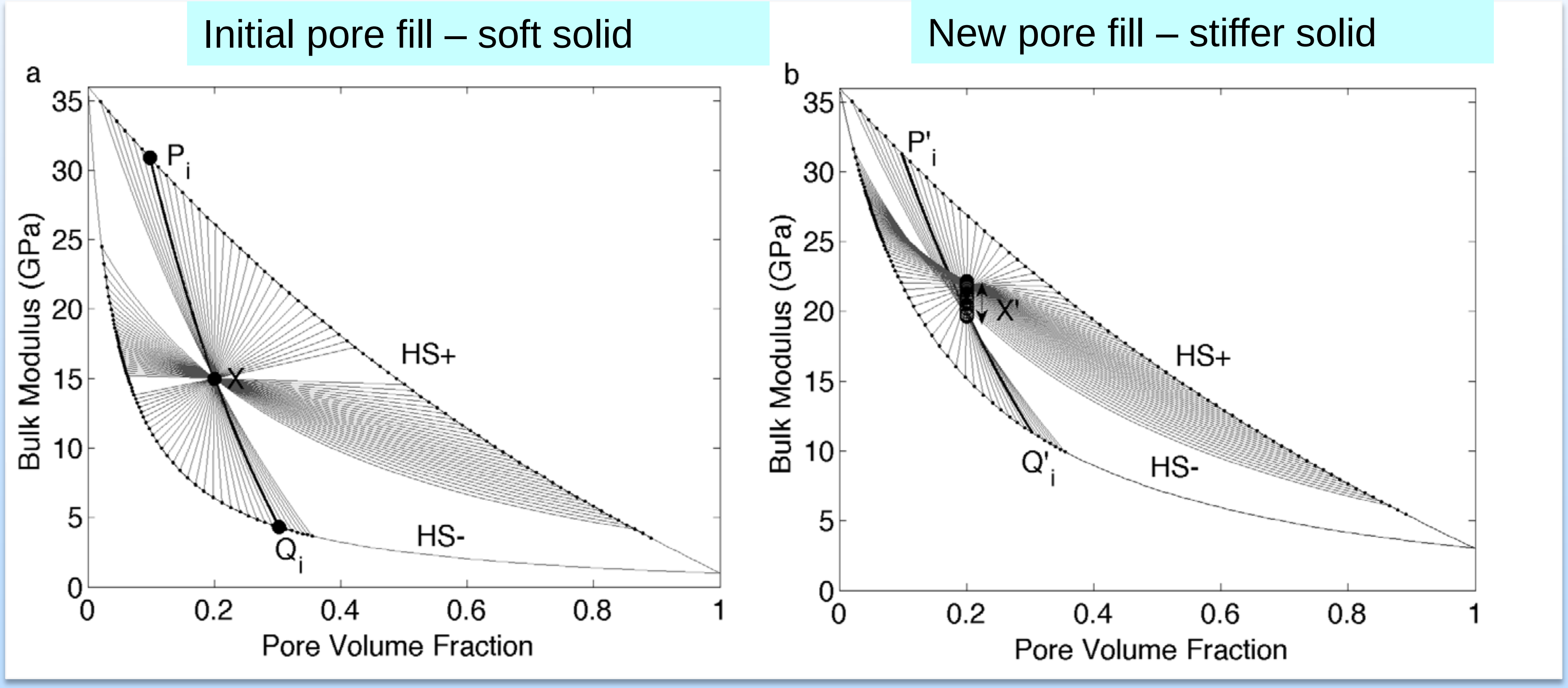
We want to predict the new elastic moduli of the same rock, $K^{(2)}, \mu^{(2)}$ when the pore space is filled with something else.



“Porosity” is the volume where *changes* are occurring.

Embedded bound solid substitution

We can construct a set of Hashin-Shtrikman bounds through data point X. Each transforms to a different modulus at X’ after substitution.



Initial pore fill – soft solid

New pore fill – stiffer solid

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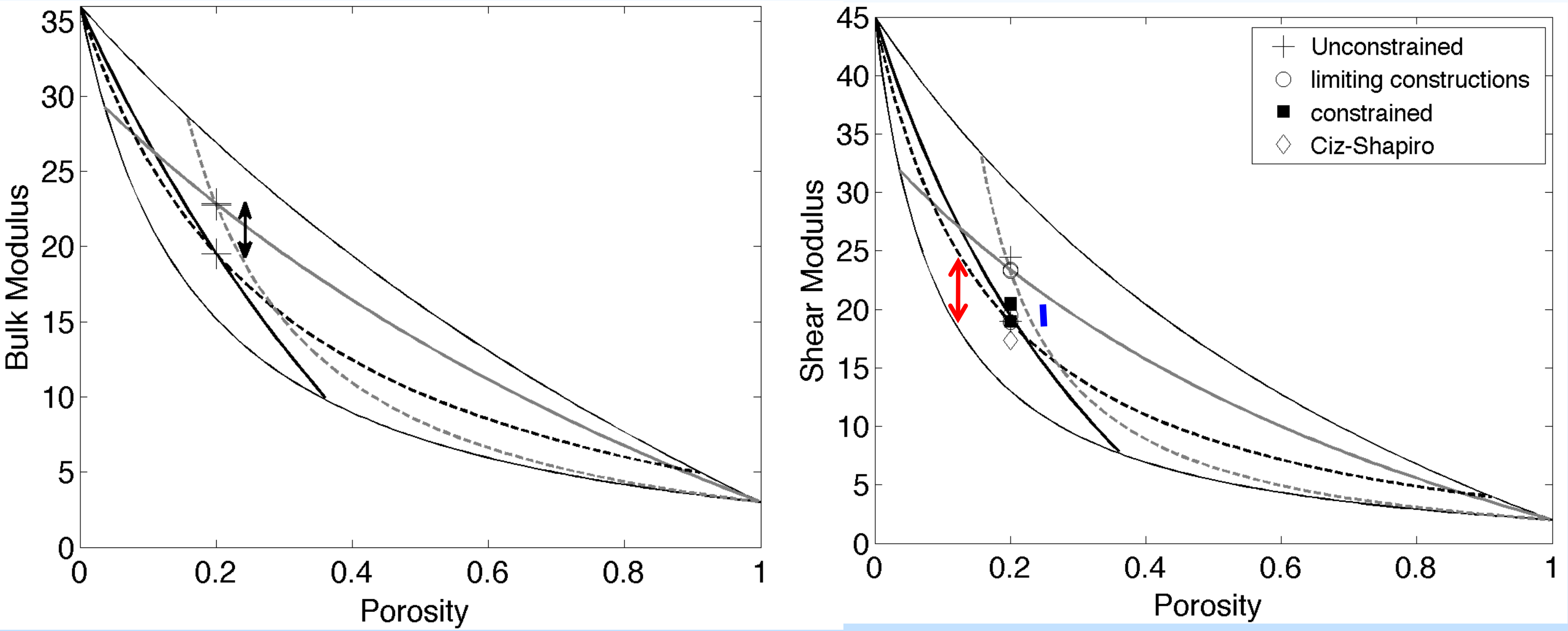
Embedded bound solid substitution

Substitution to a stiffer solid in the pore space.



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Solid Substitution

- All fluid or solid substitution is nonunique but improves when calibration allows pore space microgeometry to be constrained.
- Gassmann fluid sub is unique, … only because we make the assumption that the pore space is connected. In fact, Gassmann is only a lower bound on the modulus change.
- Previous models are tightly linked to an assumption of homogeneous pore stiffness. They underestimate change, and sometimes the predictions are unphysical.
- The Embedded-bound method provides an accurate range on the substituted moduli. Pore information can narrow it.

Accomplishments to Date

- Laboratory measurements completed on four lithologies (clean sandstone, clay-bearing sandstone, calcite-cemented sandstone, carbonates)
- Currently 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.
- Model developed for “solid-substitution.”
- Model developed for fluid substitution modeling in thinly layered formations.

Summary

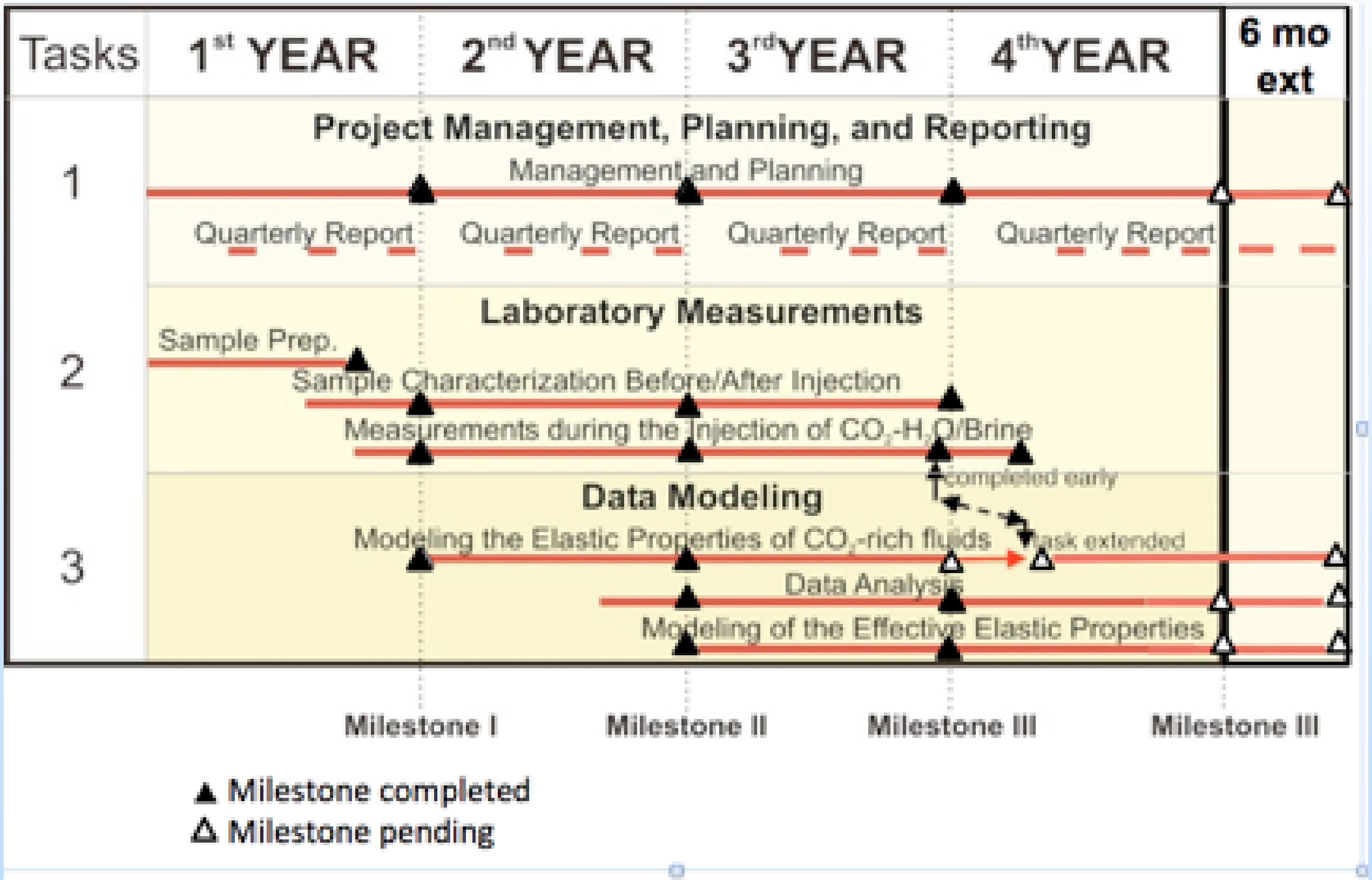
- We have observed irreversible changes in porosity, permeability, and elastic properties in carbonate and clay-bearing rocks when injected with CO_2-brine mixtures.
- These changes to the solid rock frame are not included in conventional interpretation of seismic data.
- We have developed a strategy 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, though useful bounds can be found.
- We have developed new efficient algorithms for describing corrections for frequency and spatial scales of saturation.

Appendix

Organization Chart

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

Gantt Chart


Tasks
1st YEAR
2nd YEAR
3rd YEAR
4th YEAR
6 mo ext
1
Project Management, Planning, and Reporting
Management and Planning
Quarterly Report
Quarterly Report
Quarterly Report
Quarterly Report
2
Laboratory Measurements
Sample Prep.
Sample Characterization Before/After Injection
Measurements during the Injection of CO2-H2O/Brine
completed early
3
Data Modeling
Modeling the Elastic Properties of CO2-rich fluids
task extended
Data Analysis
Modeling of the Effective Elastic Properties
Milestone I
Milestone II
Milestone III
Milestone III
▲ Milestone completed
△ Milestone pending

Bibliography

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- Mavko, G., 2013, Relaxation shift in rocks containing viscoelastic pore fluid: Geophysics, v. 78, p. M19-M28.
- Mavko, G., and Saxena, 2013, Change in effective bulk modulus upon fluid or solid substitution: Geophysics, v 78, p. L45-L56.