Rock Physics of Geologic Carbon Sequestration/Storage

DE-FE0002190

Jack Dvorkin

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

- Benefits to the Program
- Goals and Objectives
- Technical Status
- Accomplishments to Date
- Key Findings
- Future Plans

Benefit to the Program

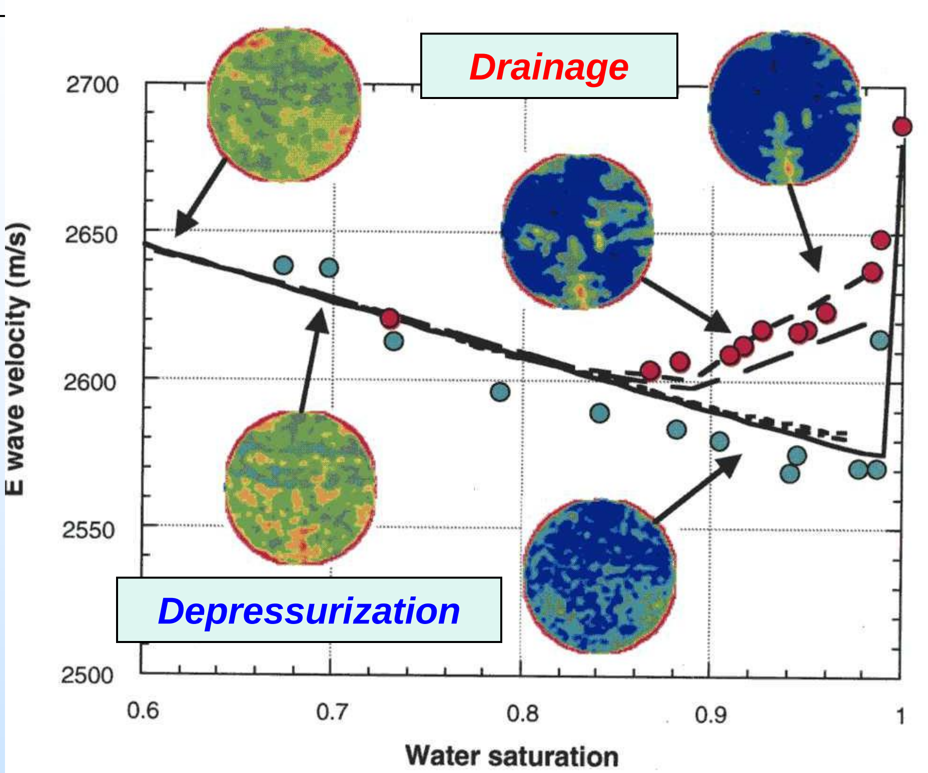
- Program Goals
  - Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
  - Develop technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zones.
  - Conduct field tests through 2030 to support the development of BPMs for site selection, characterization, site operations, and closure practices.
- Project Benefits
  - The interpretation of seismic data should be based on robust rock physics theory. To this end, we explore (a) the effects of saturation and (b) effects of alteration of the rock frame on the elastic properties of rock host to sequestration.

Project Overview:
Goals and Objectives

- Objective 1: Effects of transient flow during injection on saturation patterns and the resulting elastic response of the rock.
- Objective 2: Combine the effects of saturation with those of the mineral frame alterations.
- Objective 3: Assess the combined effects of fluid and frame changes on the seismic-scale response.
- Objective 4: Train Ph.D. students to become experts in rock physics of CO_2 sequestration.

- These objectives directly cater to the Program goals of estimating the storage capacity as well as monitoring of reservoirs hosts to CO_2 sequestration.

Technical Status: Fluid Substitution



Experimental data by Cadoret (1995) is supported by X-ray images of distinctive gas patches (yellow) in the sample that correspond to higher velocity at the same saturation.

The data are from a resonant bar experiment at approximately logging frequency.

Such velocity-saturation behavior was first discovered by Domenico (1976). Qualitatively similar experimental results were published later by, e.g., Lebedev et al. (2009); numerical analysis is in, e.g., Sengupta (2000); pore-scale computational analysis is in, e.g., Tolke (2010).

Message:

Harmonic mixing rule for the bulk modulus of fluid mix may not work at patchy saturation.

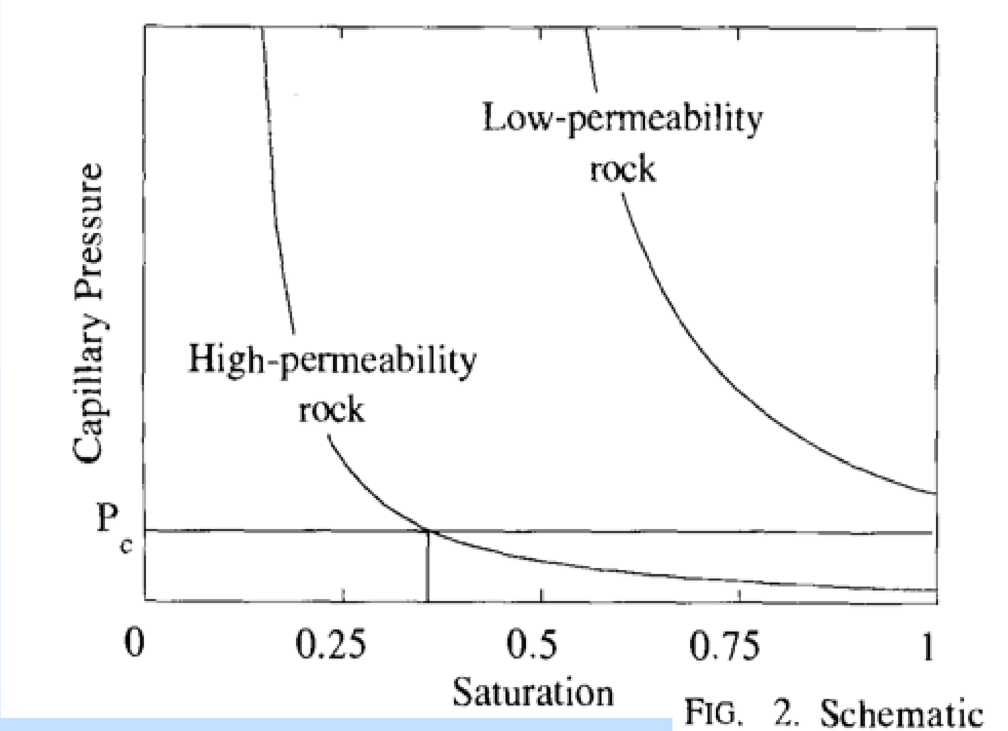
Task:

Adopt and develop a theory to quantify the saturation patterns as well as the resulting elastic properties of rock with fluids.

The ultimate goal, of course, is to predict saturation from seismic, cross-well, VSP, or well data.

Technical Status: Fluid Substitution
Capillary Pressure Equilibrium

In water-wet rock, as gas is injected, the larger pores will accept gas while smaller pores will remain 100% wet. The reason is high capillary forces in small conduits that resist the movement of the water.



From Knight, Dvorkin, and Nur (1998)

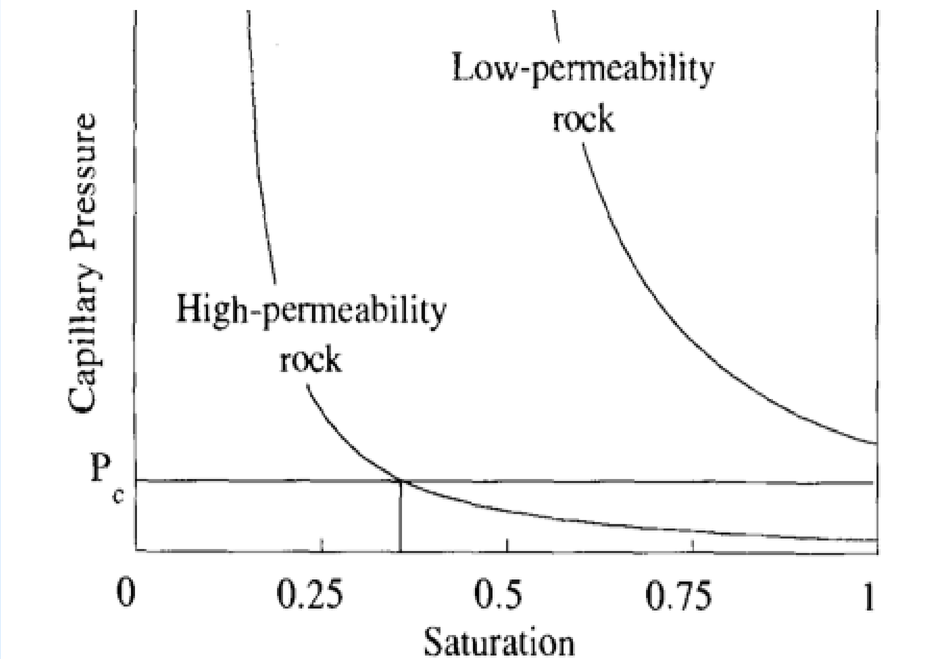
FIG. 2. Schematic capillary pressure curves for a low-permeability and a high-permeability rock. At the same capillary pressure P_c these two neighboring lithologies may have different saturations. The low-permeability rock is fully saturated, whereas the high-permeability rock has a saturation of about 0.35.

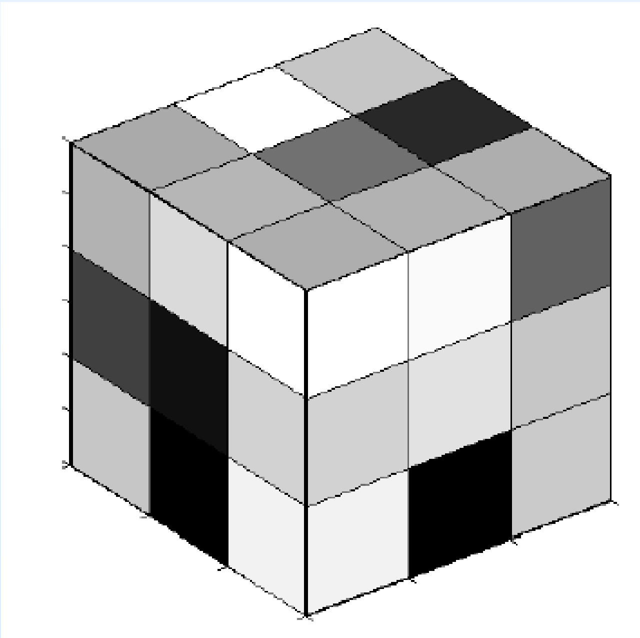
Technical Status: Fluid Substitution

Capillary Pressure Equilibrium

To implement this theory, we numerically construct a heterogeneous sample from subsamples selected from the same dataset. For example, depending on the reservoir type, we can use an unconsolidated-sand dataset (analog for Utsira formation); slightly-cemented high-porosity sand dataset; medium-to-low porosity dataset; or carbonate dataset. The capillary pressure varies – the saturation is computed for each subsample – the elastic properties are computed for each subsample using conventional fluid substitution – these elastic properties are averaged to arrive at the effective elastic properties of the sample versus global saturation. We conduct a large number of random realizations.

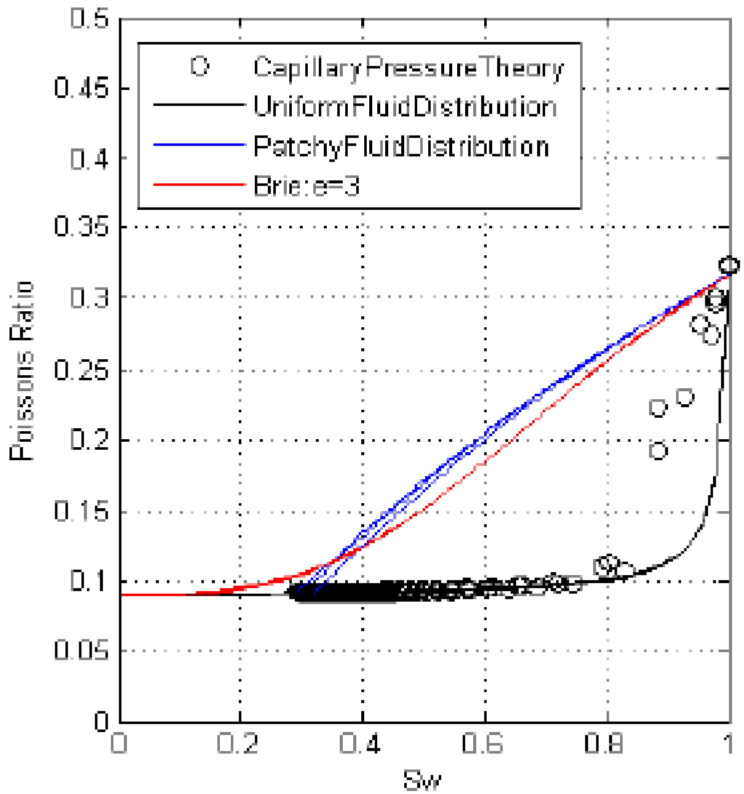
From Knight, Dvorkin, and Nur (1998)

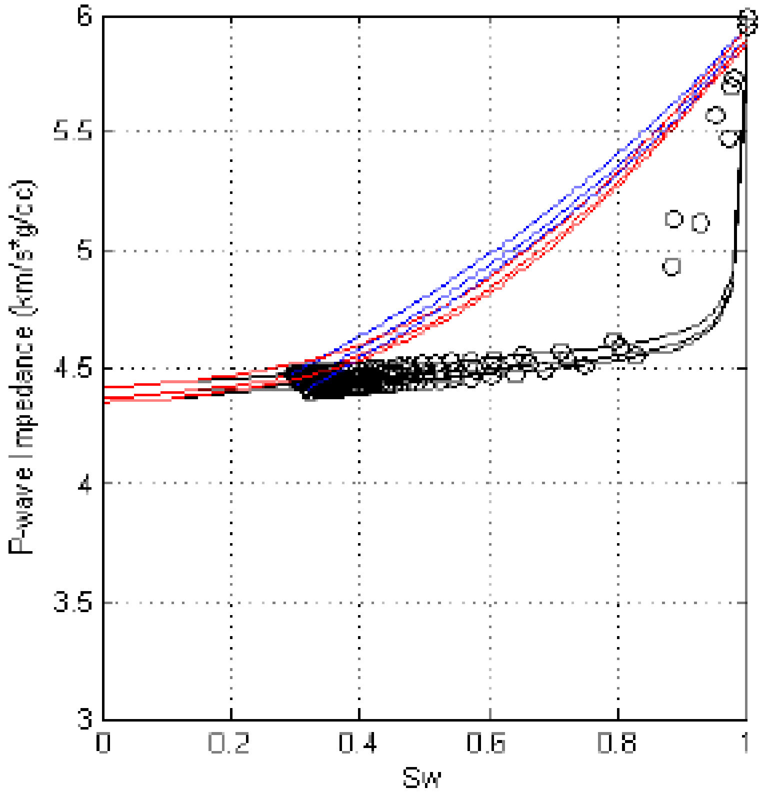




Technical Status: Fluid Substitution

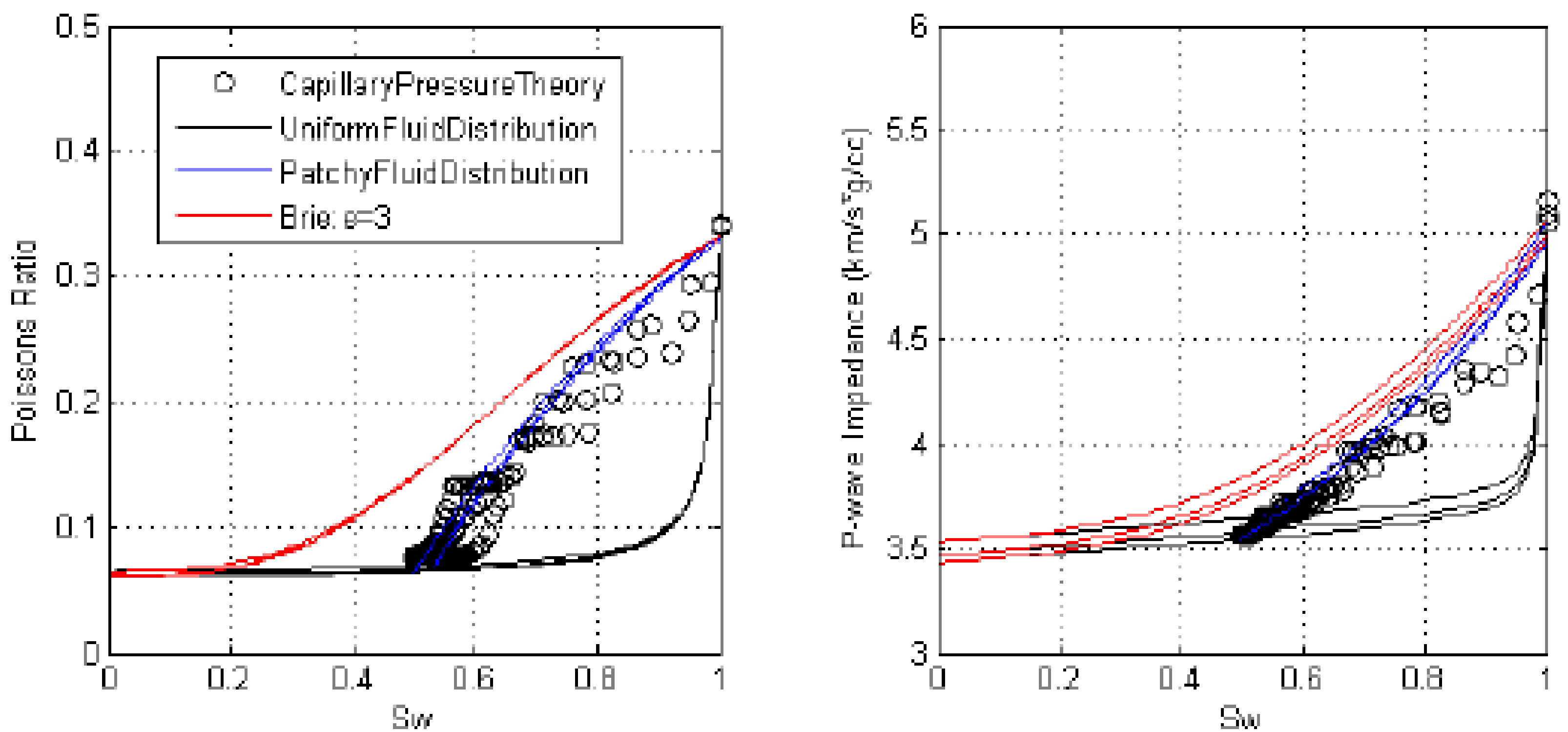
Capillary Pressure Equilibrium: Results





High-porosity slightly-cemented high-permeability sand (Oseberg field, the North Sea).

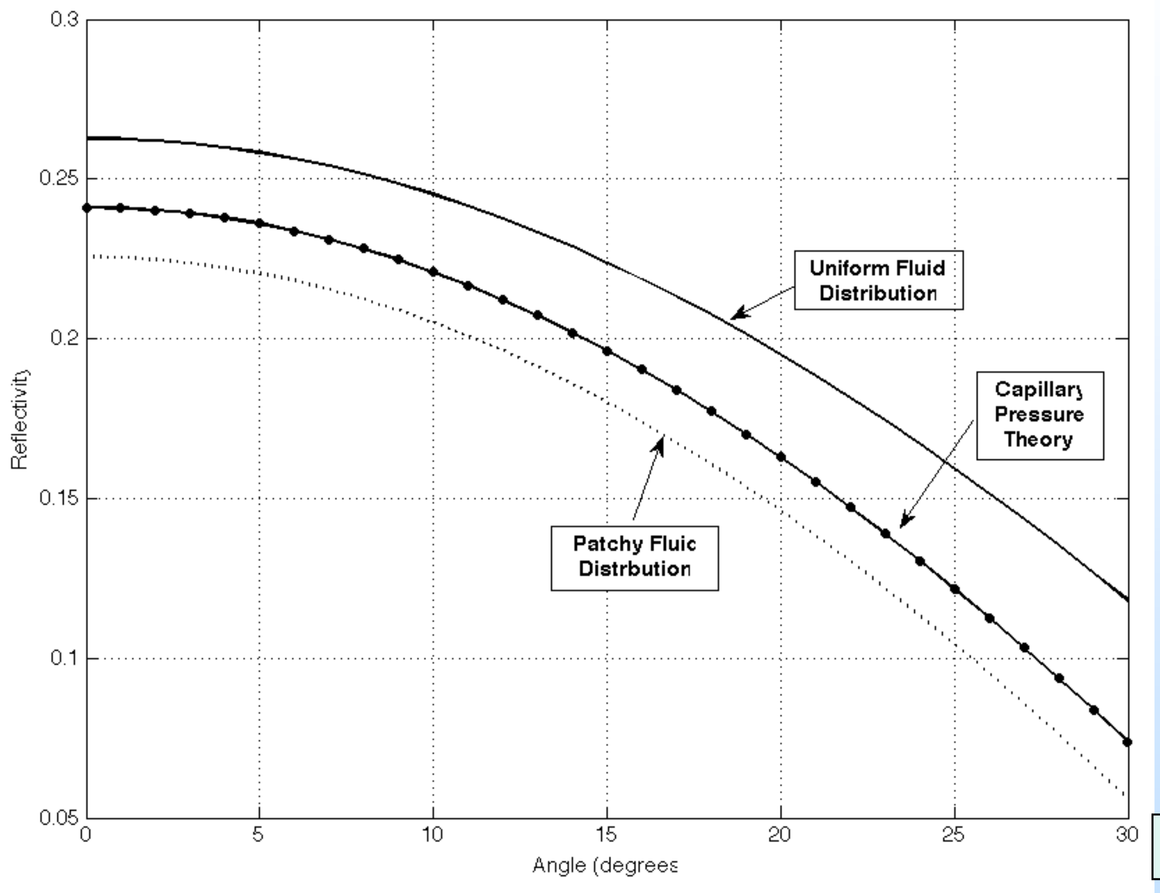
Technical Status: Fluid Substitution
Capillary Pressure Equilibrium: Results



High-porosity unconsolidated lower-permeability sand (Troll field, the North Sea).

Technical Status: Fluid Substitution

Capillary Pressure Equilibrium: Seismic Signatures



From Sen and Dvorkin (2012)

Figure 9. Reflectivity versus angle for an earth model where a shale layer caps a gas-CO_2/water saturated Oseberg sand layer. The top set of curves represents reflectivity for 100% water saturation while the bottom set of curves is for 50% water saturation. The gray curves are from the 25 realizations of the capillary pressure theory workflow. The uniform and patchy (solid) curves are from only one of the realizations. The dotted curve is the arithmetic average of the reflectivity from the capillary pressure theory at each angle of incidence.

Technical Status: Fluid Substitution

Challenge: Interpreting Seismic Data

There are two possible approaches:

(a) For a given target, create a number of forward modeling scenarios by varying, e.g., porosity and saturation. Compare synthetic seismic attributes to the recorded seismic attributes. The elastic properties that have to be used in this forward modeling will come from a rock physics model for the elastic properties of the dry frame and the capillary pressure theory.

(b) Conduct seismic acoustic and elastic impedance inversion and then interpret Ip and Poisson's ratio in terms of saturation.

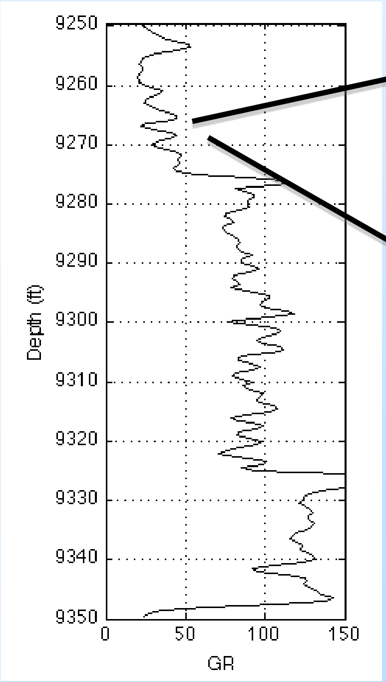
Both approaches require a rock physics analysis to establish a velocity-porosity-lithology model for the reservoir under examination.

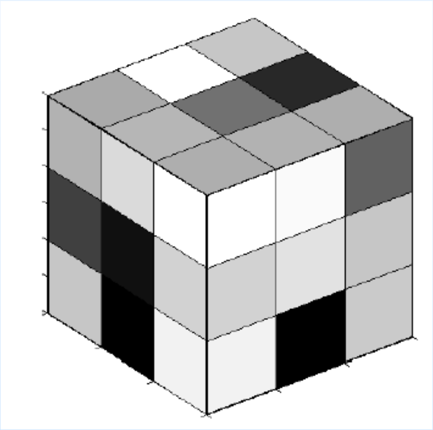
Technical Status: Fluid Substitution

Fluid Substitution Directly on Well Logs

We had to implement the capillary pressure fluid substitution theory for well data and at each data point. This is not straightforward as this theory requires heterogenization of a volume.

To accomplish this task, for each data point in the well, we randomly vary the porosity and lithology (clay content) within a selected range, create subvolumes, and then apply the capillary pressure theory as described.

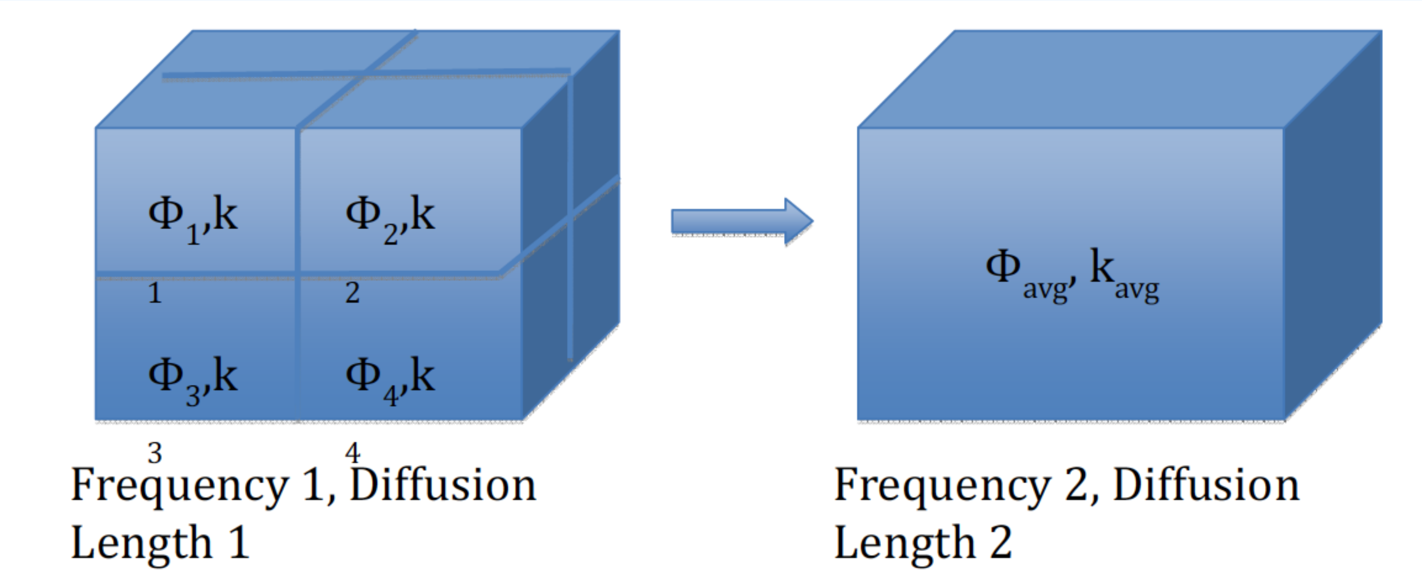




Technical Status: Fluid Substitution

Effects of Frequency

Because the "visible" patch size depends on the effective size sampled by the elastic wave, the response is frequency dependent: what is patchy at the log scale may not be patchy at the seismic scale. Hence, we developed a workflow to estimate the velocity-frequency dispersion.



Technical Status: Fluid Substitution

Effects of Frequency

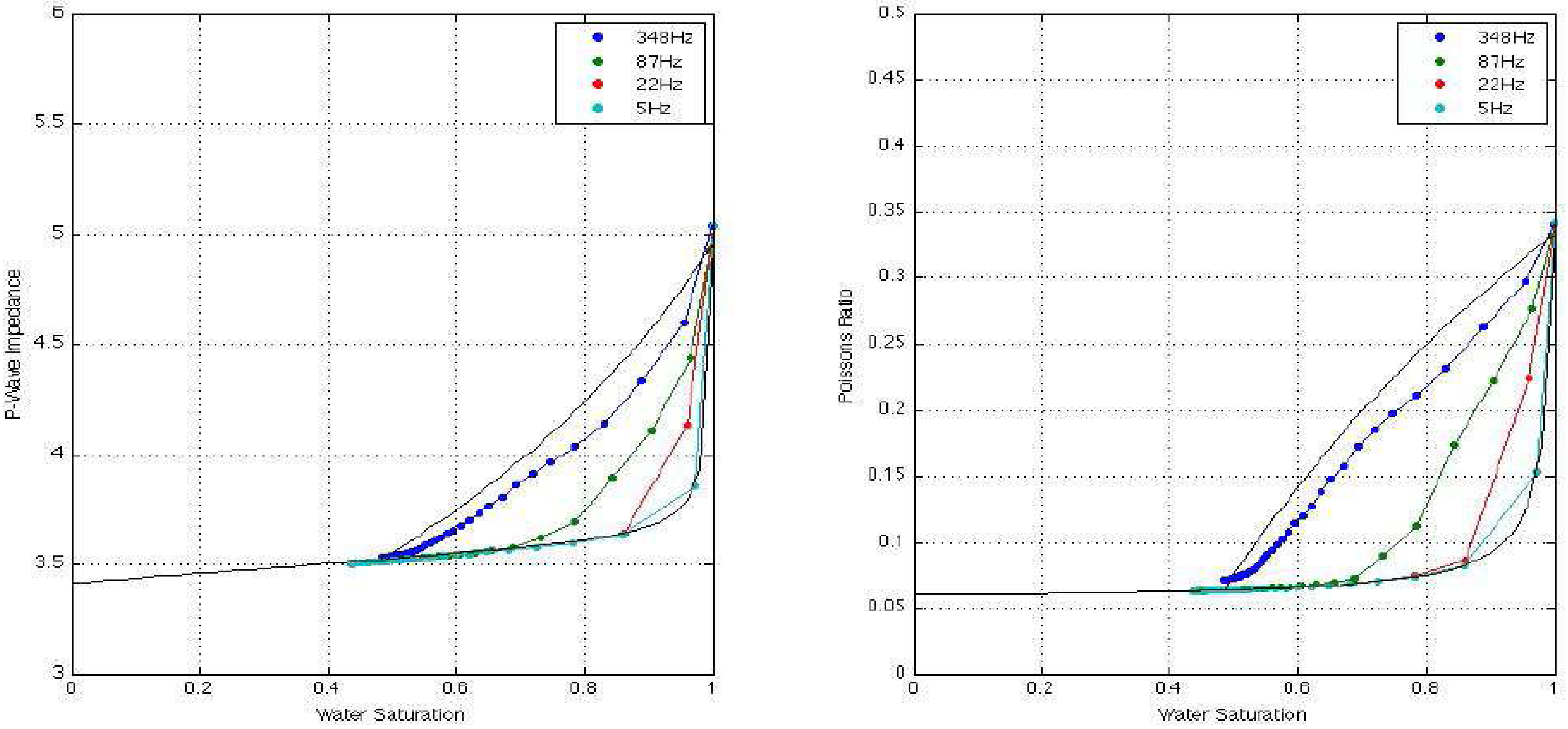


Figure 2. P-wave impedance and Poisson's ratio versus water saturation as a function of frequency for the Troll sands.

Technical Status: Fluid Substitution

Effects of Frequency

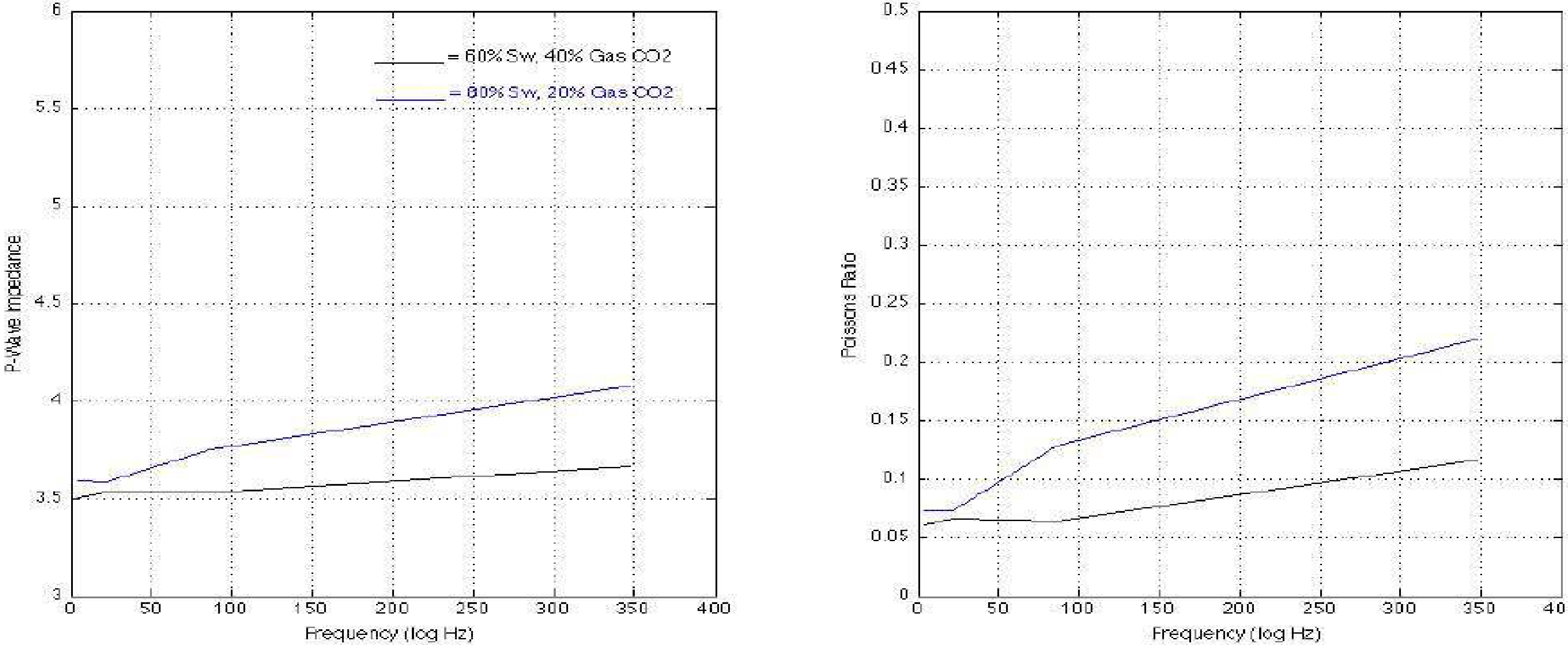


Figure 3. P-Wave impedance and Poisson's ratio versus frequency for constant water and gas saturations.

Technical Status: Frame Alteration
Tuscaloosa Sandstone

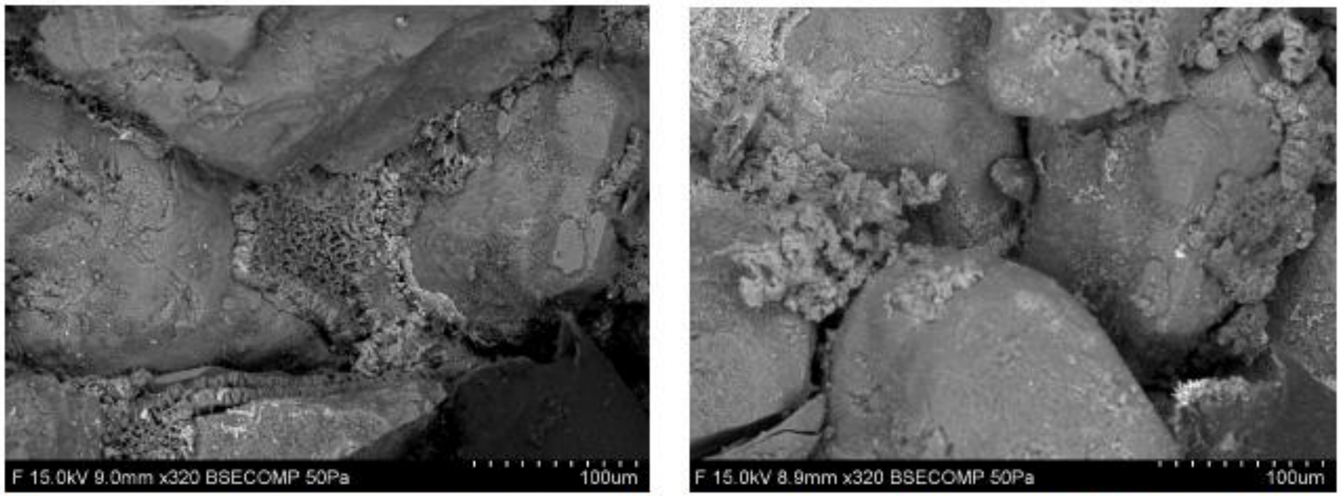
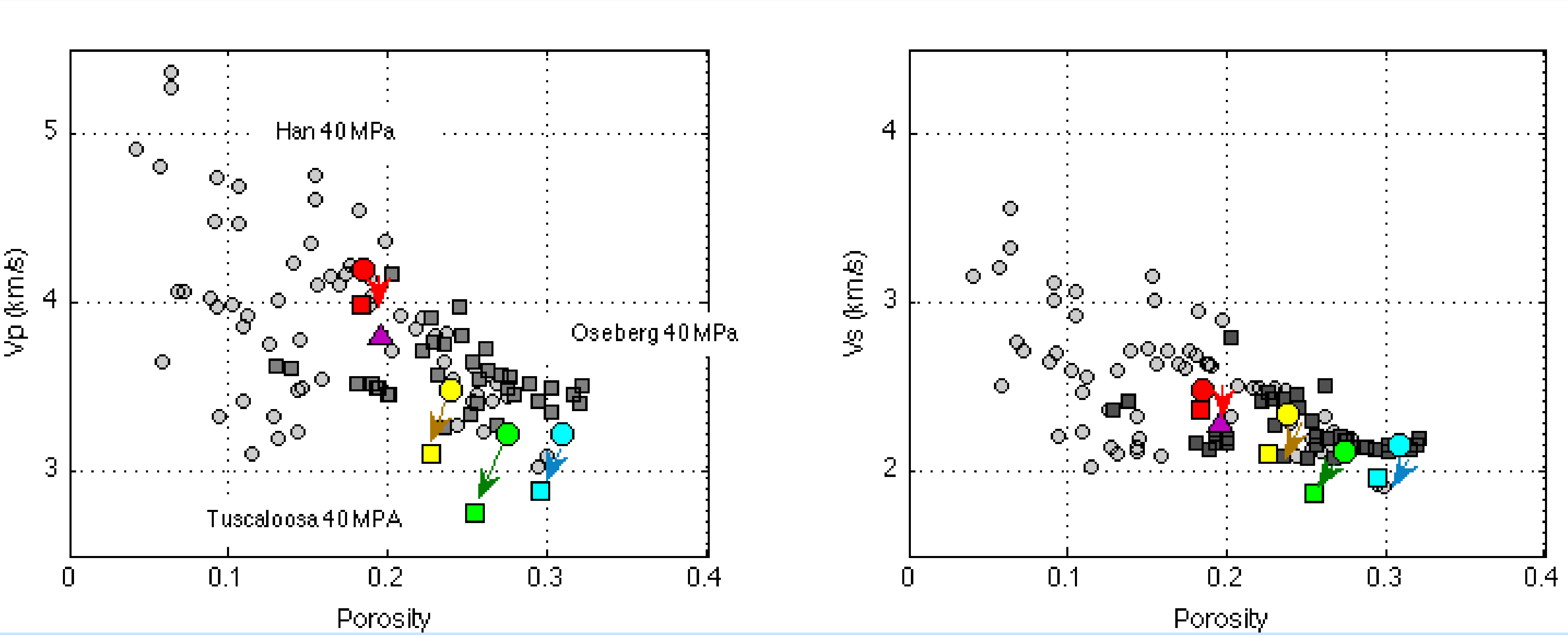


Figure 1. SEM images of the same portion of rock before (left) and after (right) injection. The intergranular cement visible on the left is partly removed and, arguably, redeposited away from the grain contacts or removed permanently. Although the location of the SEM image is the same in the original sample and the sample after the injection, it is difficult to identify the original grains as the grains moved during compaction in the loading cell.

Experiments: Vanorio et al. (2011). About 100 pore volumes of brine with CO_2 dissolved flushed through each sample.

Technical Status: Frame Alteration
Tuscaloosa Sandstone

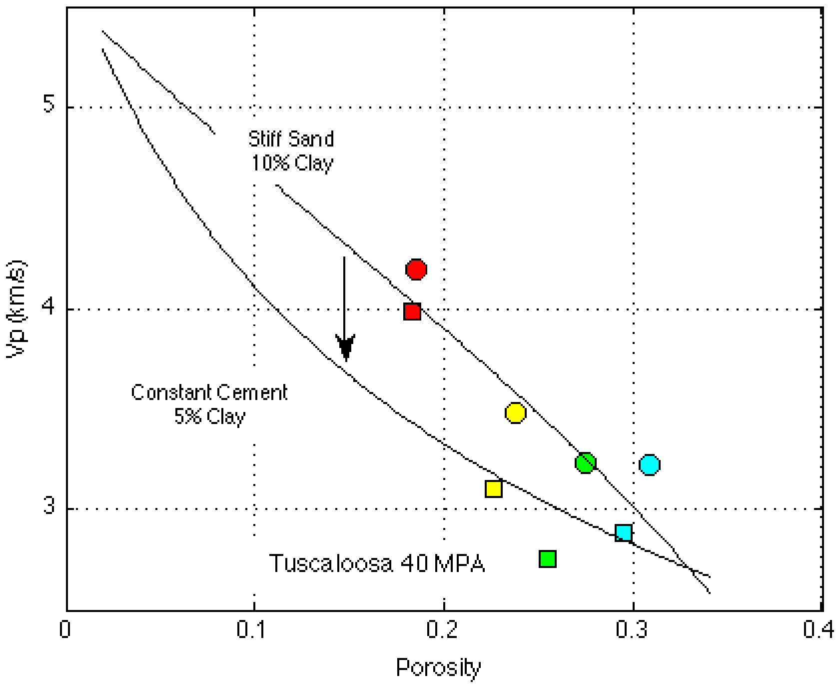


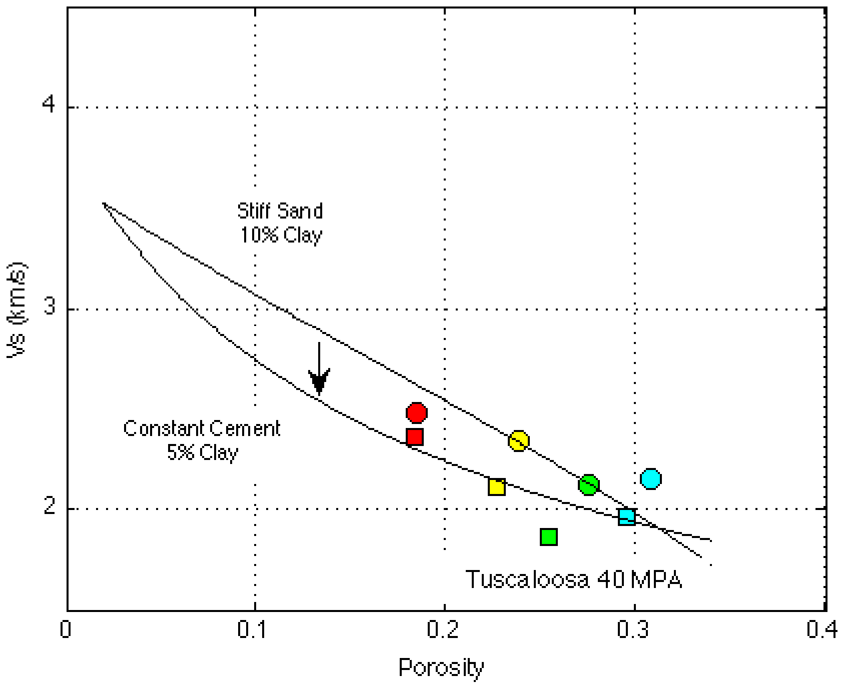
Experiments: Vanorio et al. (2011). About 100 pore volumes of brine with CO_2 dissolved flushed through each sample.

Color circles: before flushing. Color squares: after flushing.

Technical Status: Frame Alteration

Rock Physics Model





Transition from the stiff-sand model to constant-cement model explains the apparent velocity reduction as the porosity slightly increases.

Accomplishments to Date

- New fluid substitution theory implemented for CO_2 injection. The results are based on physics and help bypass *ad-hoc* selecting one of fluid substitution methods (uniform or patchy)
- The theory has been implemented as a workflow applied to well log data.
- The effect of frequency has been investigated and implemented as application of the theory.
- Rock physics model to explain the frame alteration in sandstone due to CO_2 injection.

Summary

– Key Findings: Theories for fluid substitution and frame alteration in a wet reservoir target for sequestration. Because rock is heterogeneous, physically simple theories takes some skills to consistently implement.

– Lessons Learned: Although the theories are physics-based and relatively straightforward, they require a number of inputs that have to be estimated prior to injection. Frame alterations are far from being simple and may strongly depend on the lithology and texture of rock.

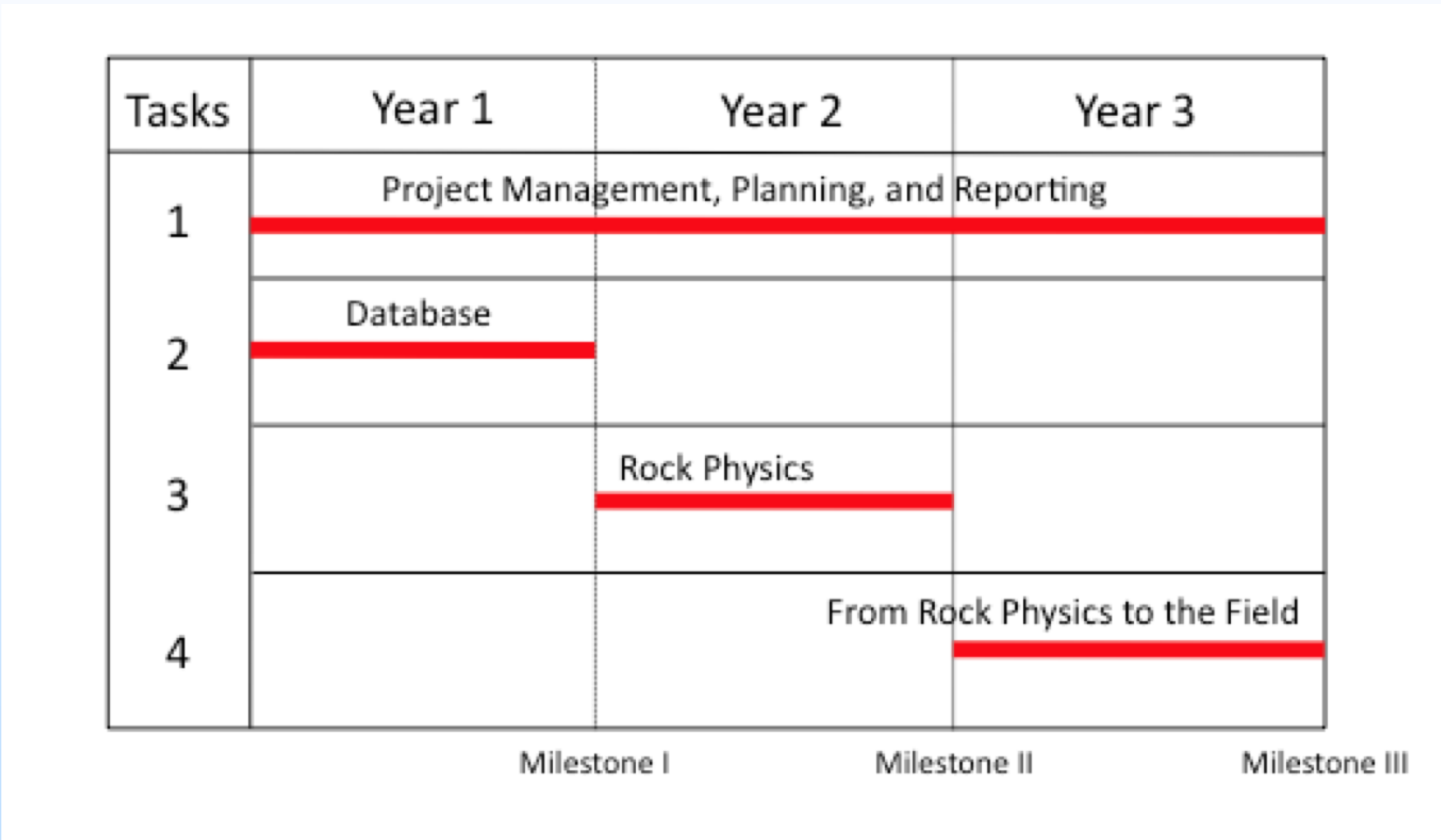
– Future Plans: Examples of combining frame alteration with fluid substitution. Attenuation in a reservoir where water co-exists with gas. Extended catalogue of seismic attributes (e.g., gradient versus intercept) for various reservoir types and conditions.

Appendix

Organization Chart

- PI: Gary Mavko
- Research Scientist: Jack Dvorkin
- Ph.D. Student: Amrita Sen (analytical theory and log/seismic implementation)
- Ph.D. Student: Nishank Saxena (analytical/computational theory)

Gantt Chart


Tasks
Year 1
Year 2
Year 3
1
Project Management, Planning, and Reporting
2
Database
3
Rock Physics
4
From Rock Physics to the Field
Milestone I
Milestone II
Milestone III

Bibliography

– Sen, A., and Dvorkin, J., 2012, Fluid substitution in gas/water systems: Revisiting patchy saturation, submitted to Geophysics.