Rock Physics Analysis and Time-Lapse Imaging of the Induced Chemo-Mechanical Processes upon CO_2 injection into Reservoir Rocks

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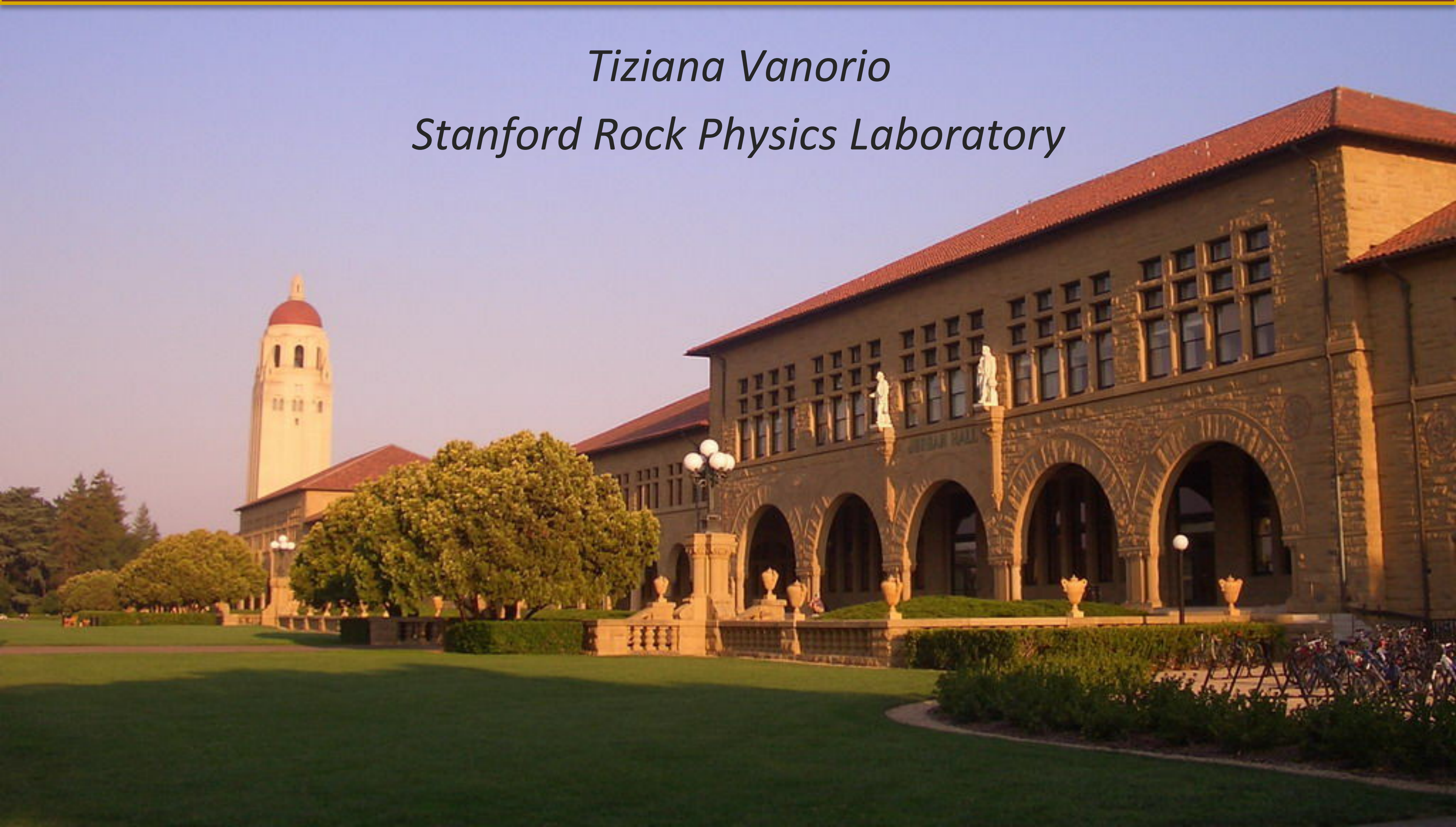
Stanford Rock Physics Laboratory



4D Seismic: Traditional Concept

- time-lapse geophysical monitoring is based on the assumption that the **time-variant changes** in the images of seismic velocity **depend** on the **variation of the properties of the rock frame and the fluid** permeating it **in response to changes in** **physical parameters** such saturation, pore fluid pressure, temperature, and stress.

Fluid Substitution: Gassmann Model

Changes in rock seismic velocity and impedance are caused by a **purely mechanical interaction between the fluid and the rock frame.**

Water Satur
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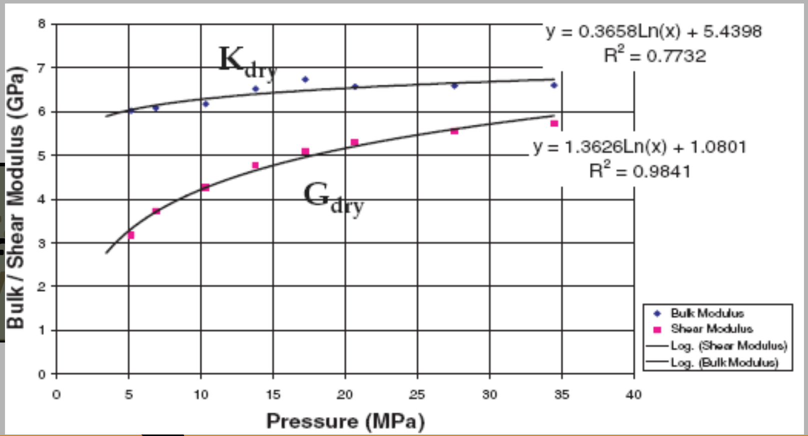
Rock Seismic V



ρ_{fl} ; K_{fl}

Fluid Properties (Water Properties)

saturation
free and dissolved gas
pore fluid pressure
temperature

Solid/Frame Properties

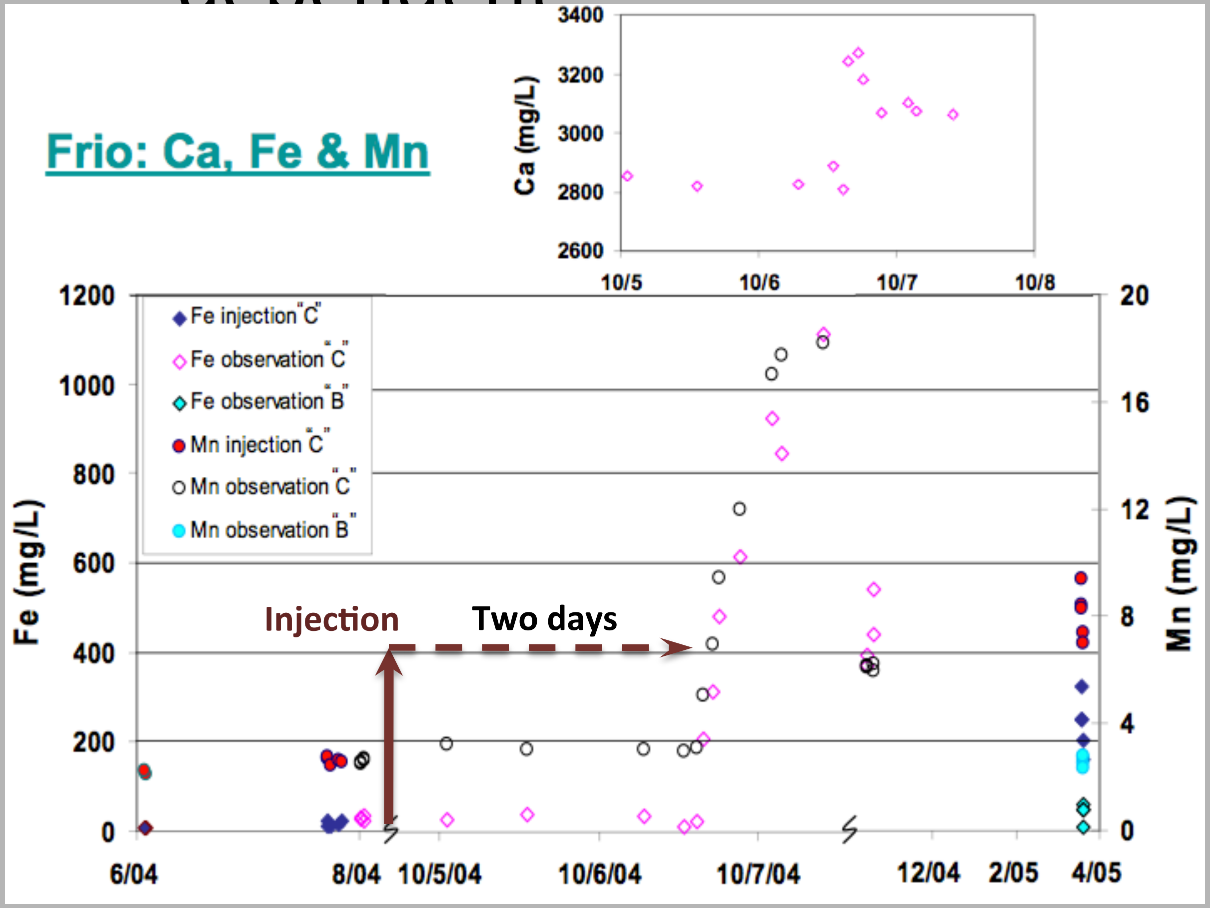
K_o K_{dry} μ_{dry}

ρ_0 ρ_{dry} Φ

mineral composition
properties of the frame
porosity

CO_2 Injection

- Chemical Disequilibria: Fast and Time-dependent



After <u>two days</u> from the beginning of the injection an increased concentration of cations such as **Calcium**, **Iron**, and **Manganese** are measured at the observation well.

Laboratory Program on CO_2 Injection

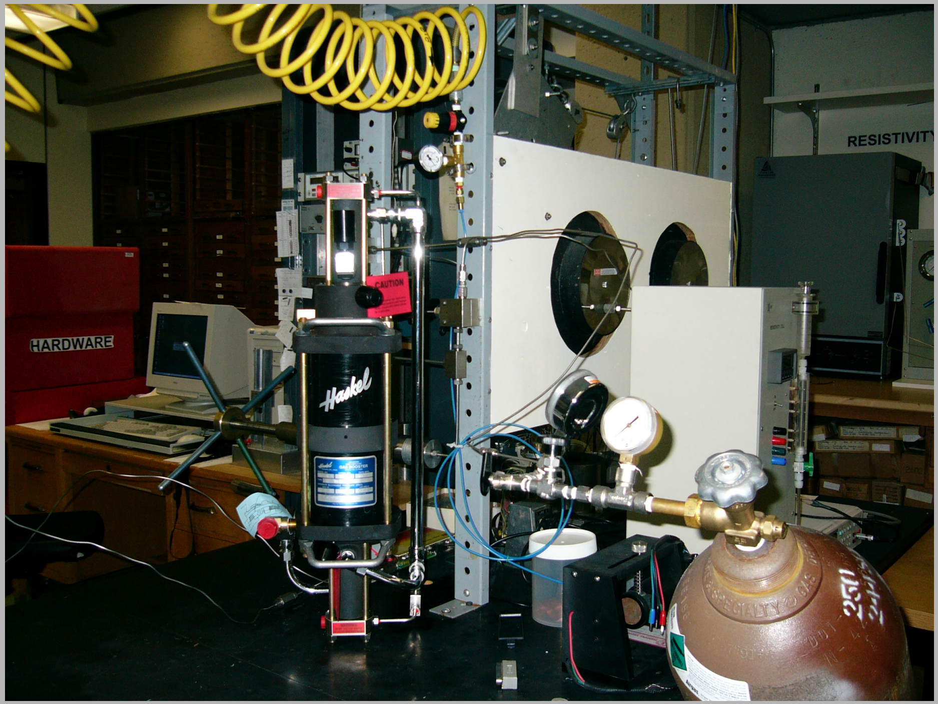
- Comprehensive Time-Lapse monitoring of:

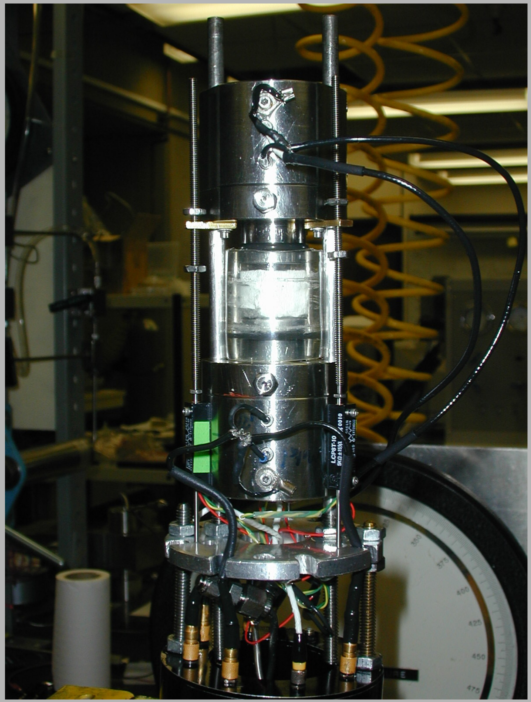
- **changes in transport, elastic, and geochemical properties** resulting from chemo-mechanical processes induced upon CO_2 injection
  - precipitation
  - dissolution

- **changes in the rock microstructure:** Time-Lapse high resolution imaging to quantify pore network modifications
  - SEM images
  - Ct-scan images

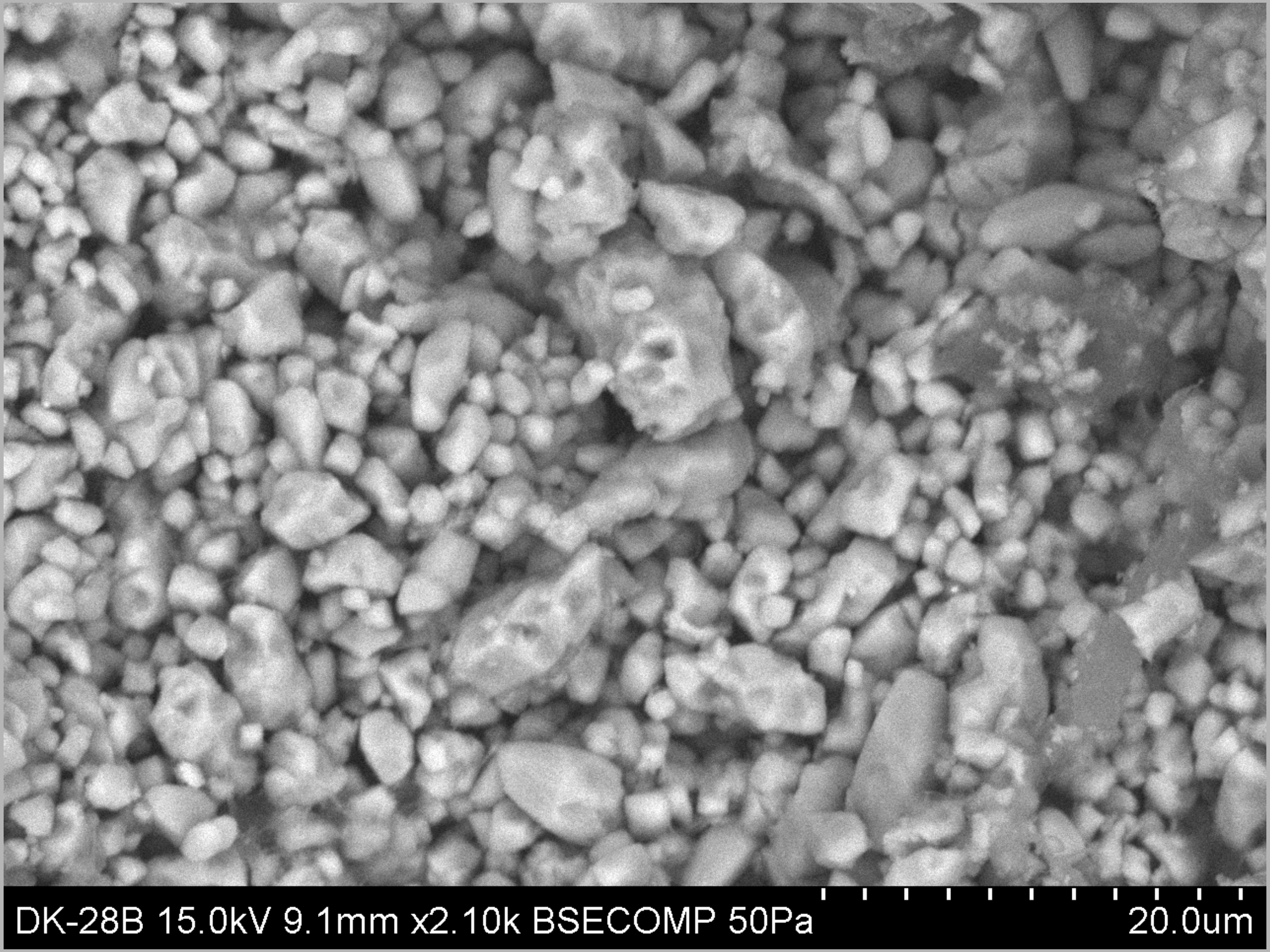
Experimental Design

- Injections are performed under reservoir pressure conditions : P_c up to 15-55 MPa and P_f up to 15-28MPa
  - Magnitude and location of changes



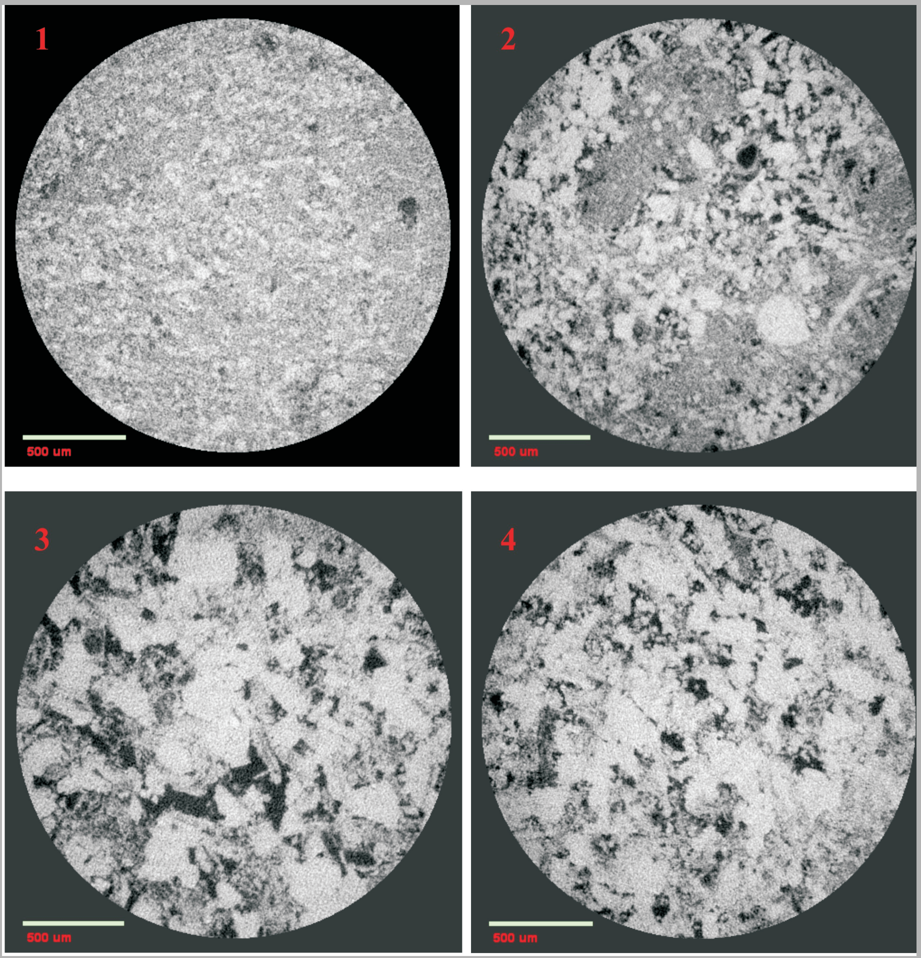


Rock Samples

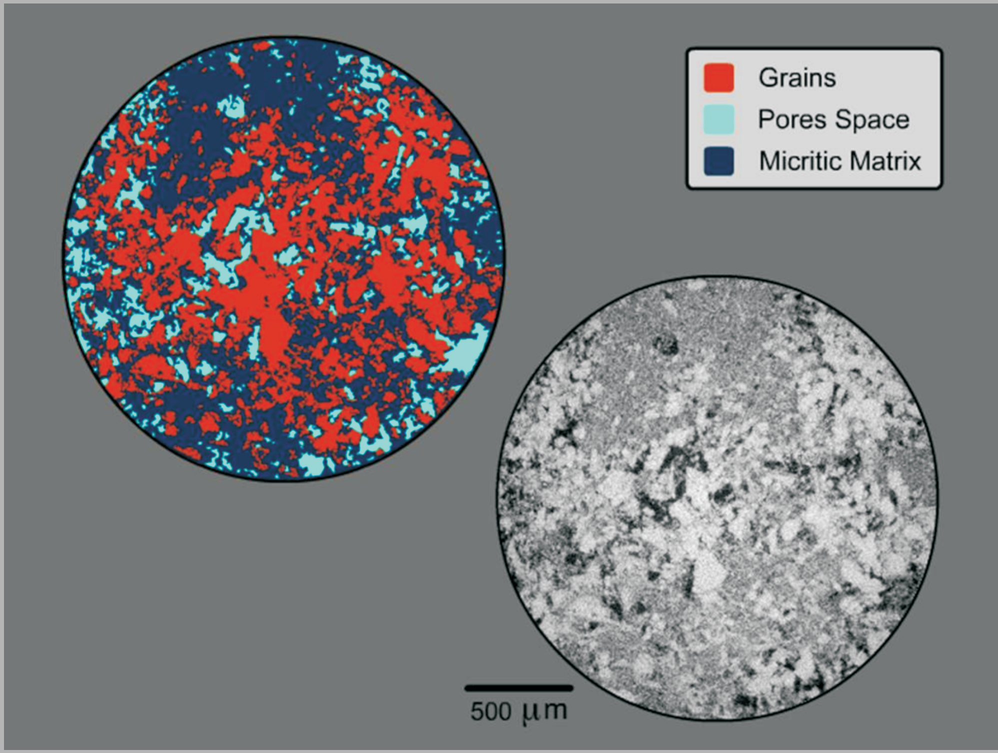


Micritic Carbonates

Pre-Injection Characterization

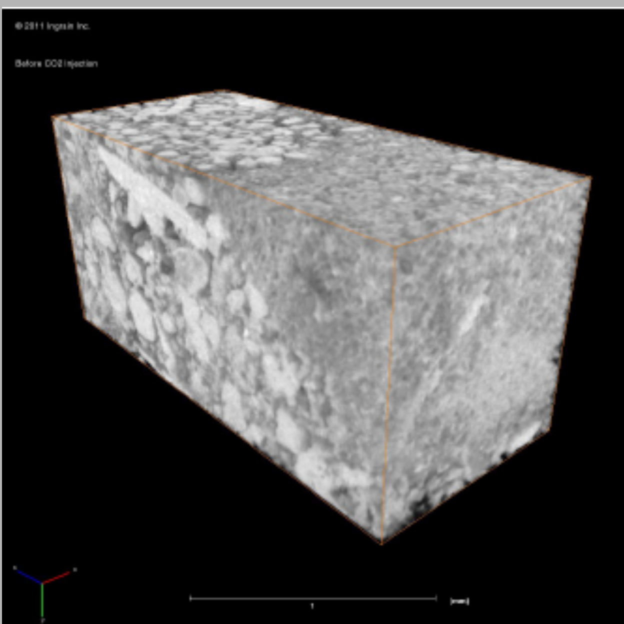


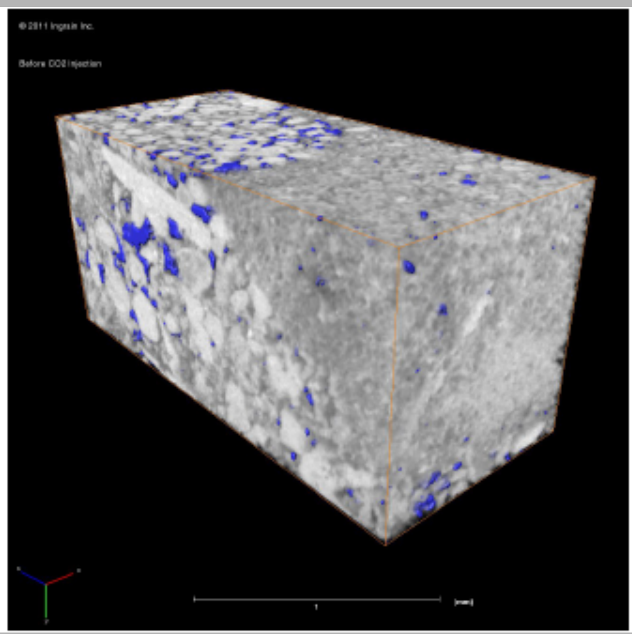
Mictrite Content



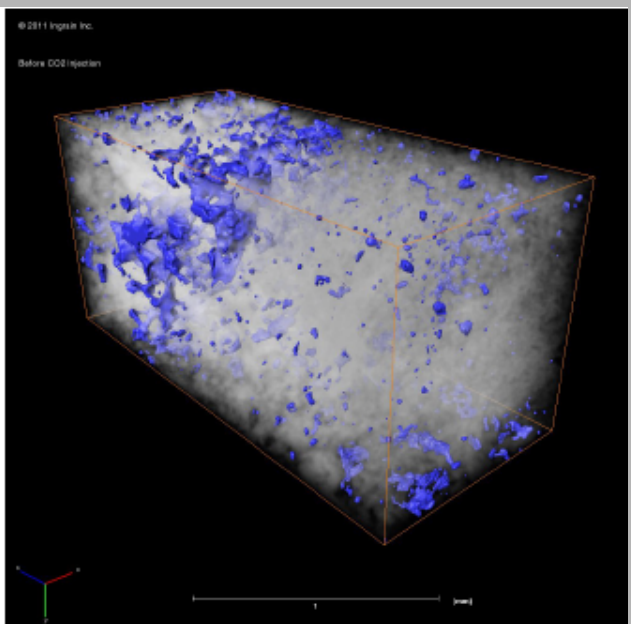
Pre-Injection Characterization

Pore Space and Its Connectivity





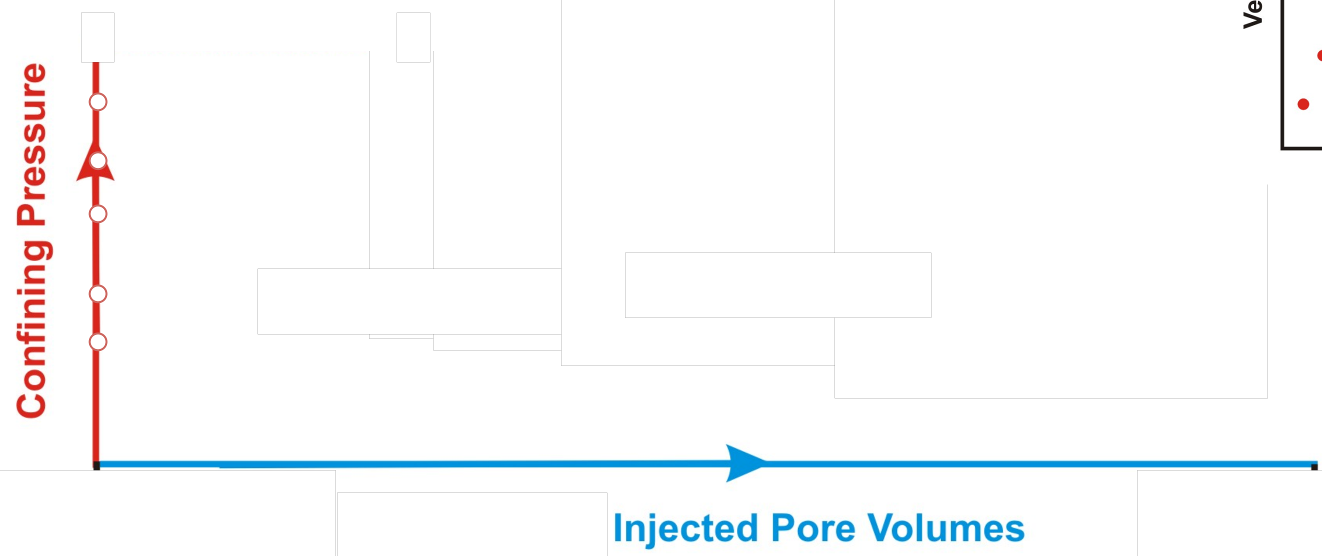
Pore space in blue

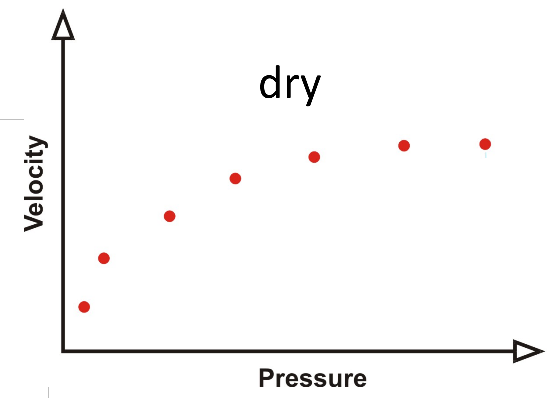


Grayscale opacity
Reduced to show
Pore space

Experimental Protocol

Pre-Injection





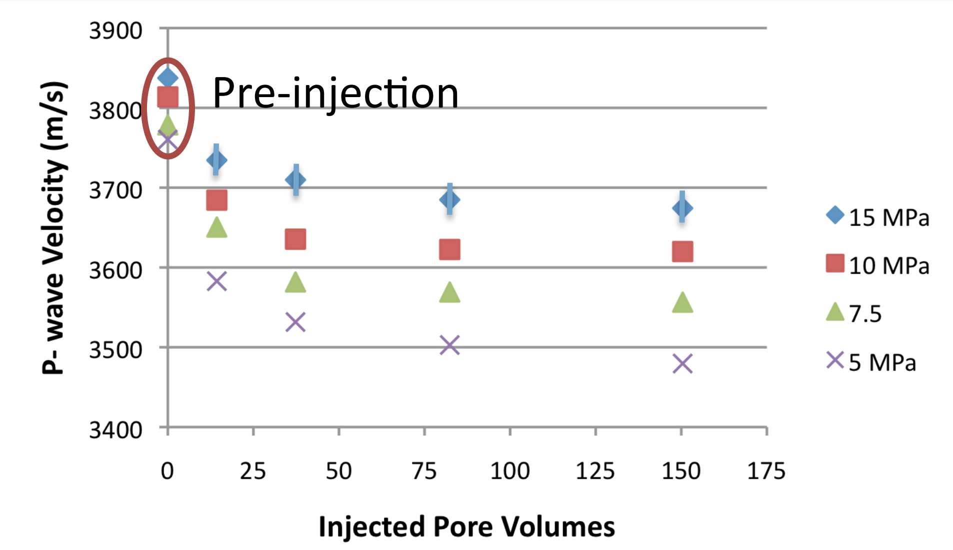
Monitored Properties

- Chemical composition (pH, Cation Concentration) of the outlet brine (dissolution)

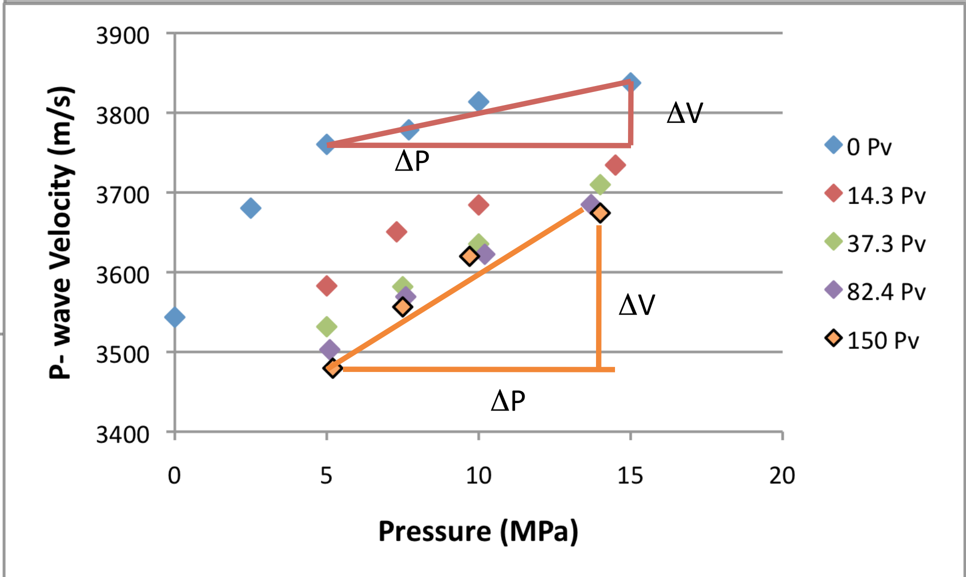
$$\left[t_{i-1}, t_i\right]$$

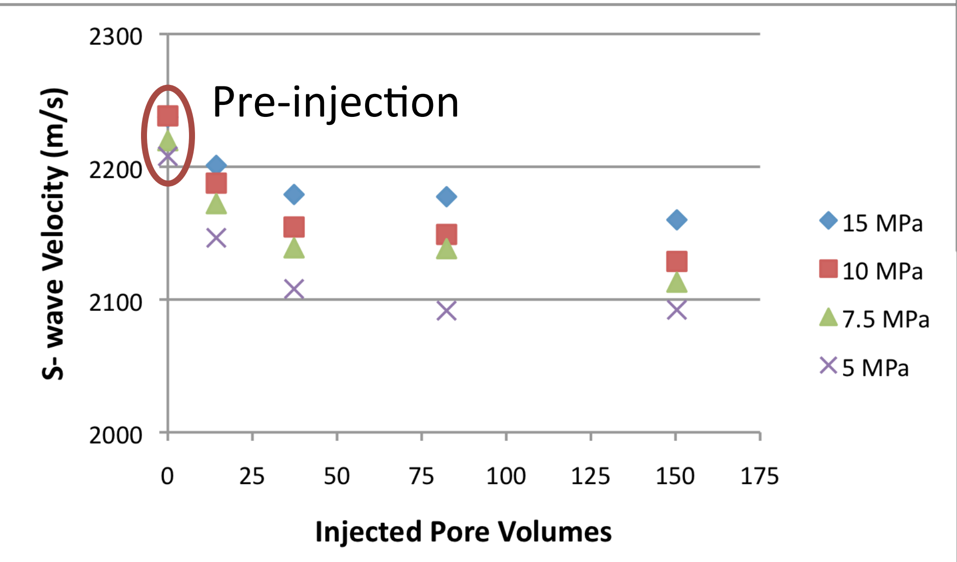
$$\Delta\Phi_c(t_i) = \frac{\sum_1^n \Delta m_n}{V_{bulk} * \rho_{\min}} = \frac{V_{inj}{}^f \; {}_{(t_i)}\sum_1^n C_n{}^{Cation} * M_{w\,\min}}{V_{bulk} * \rho_{\min}}$$

Velocity-Injected Pv-Pressure

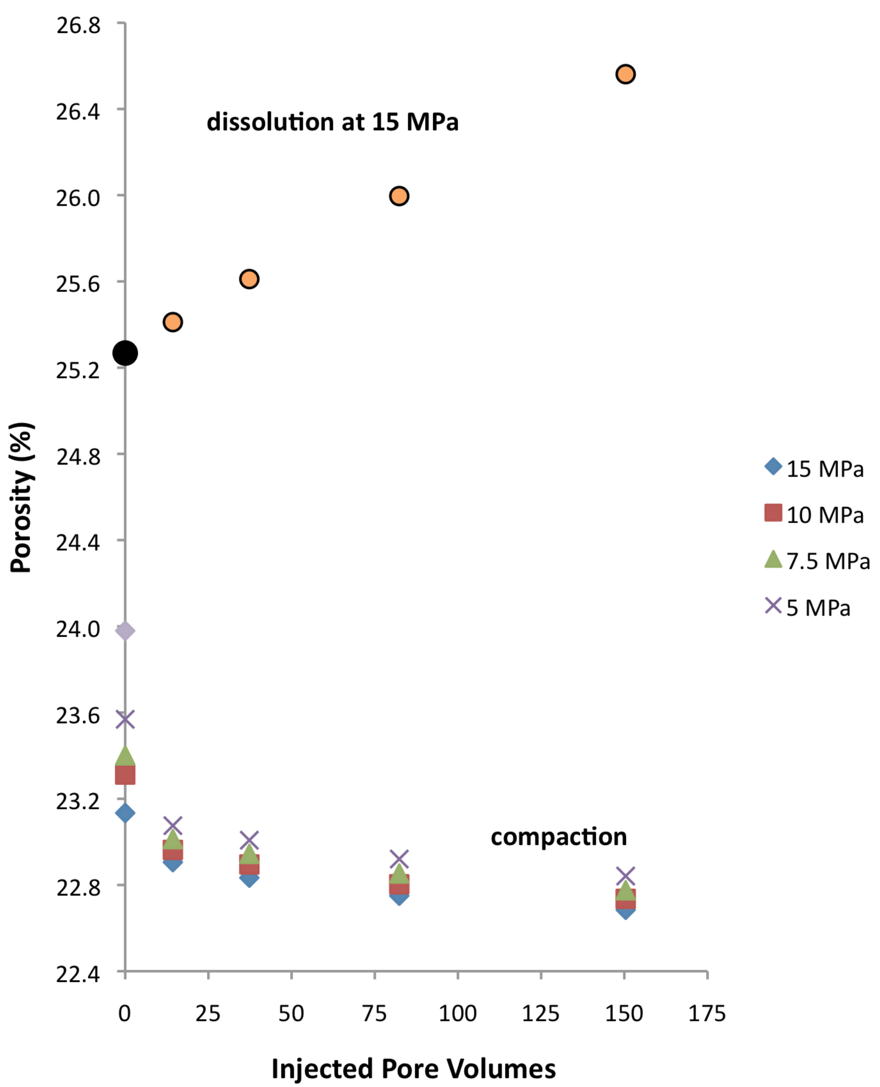


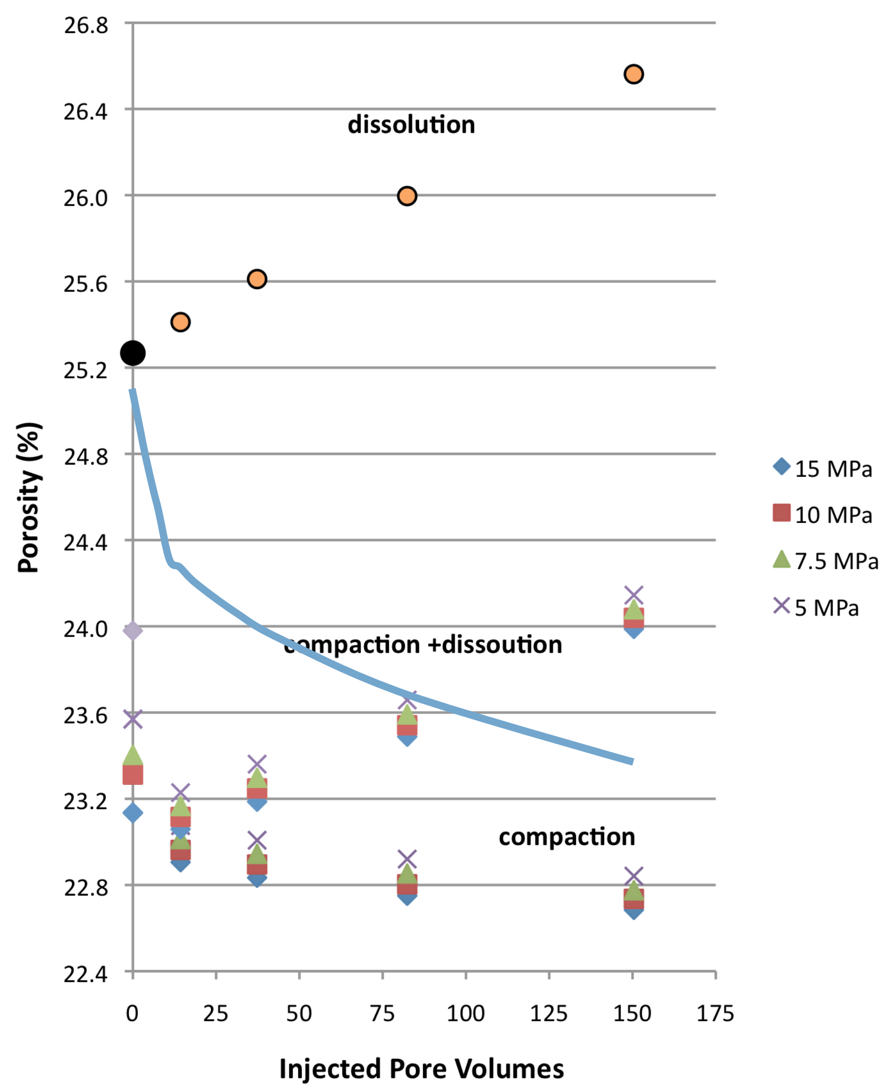
Velocities of the dry rock frame after injection



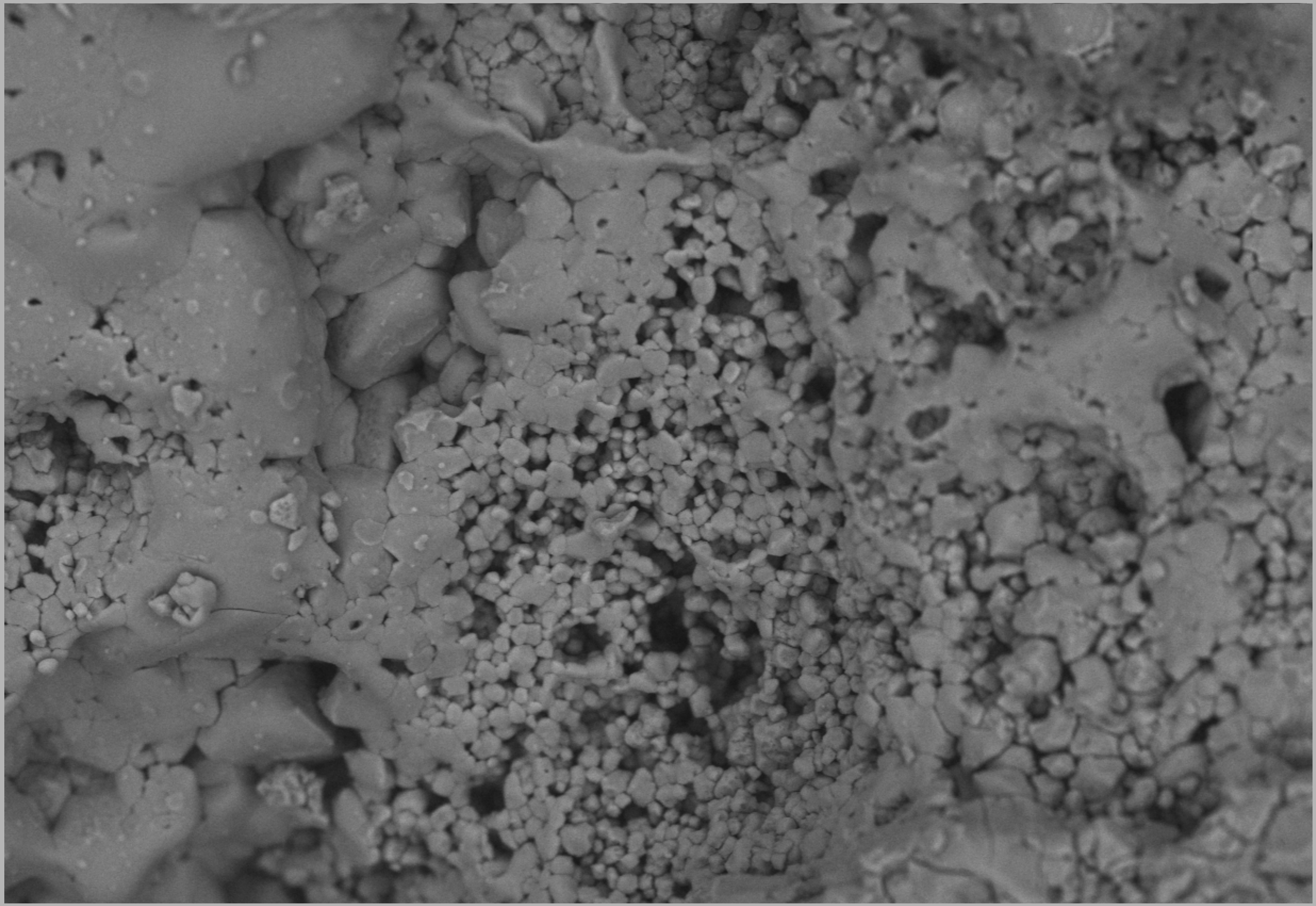


Porosity-Injected Pv-Pressure

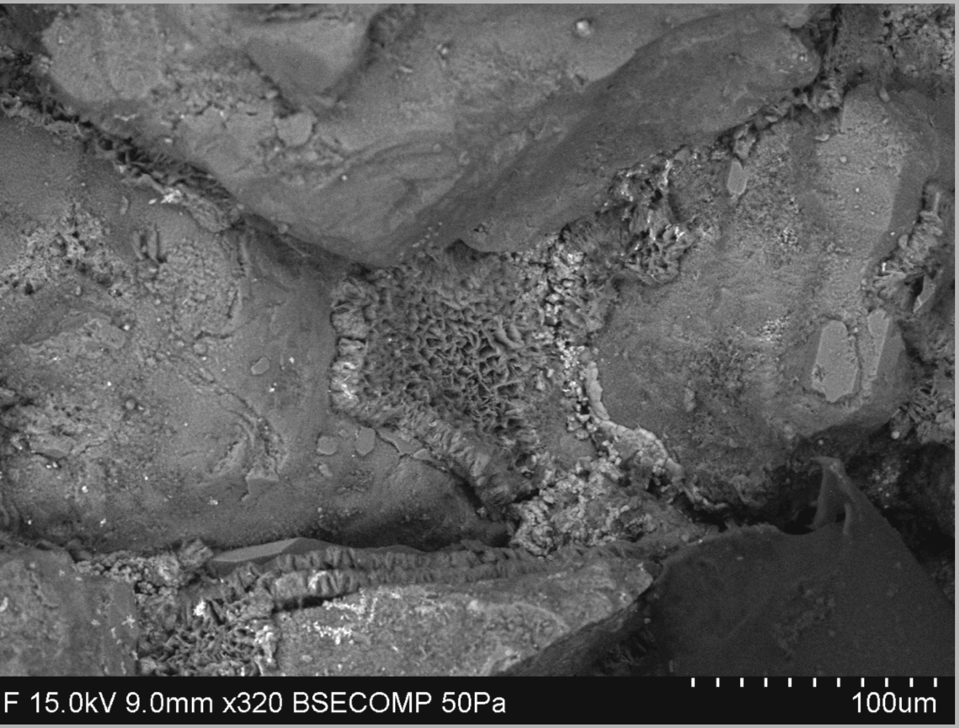


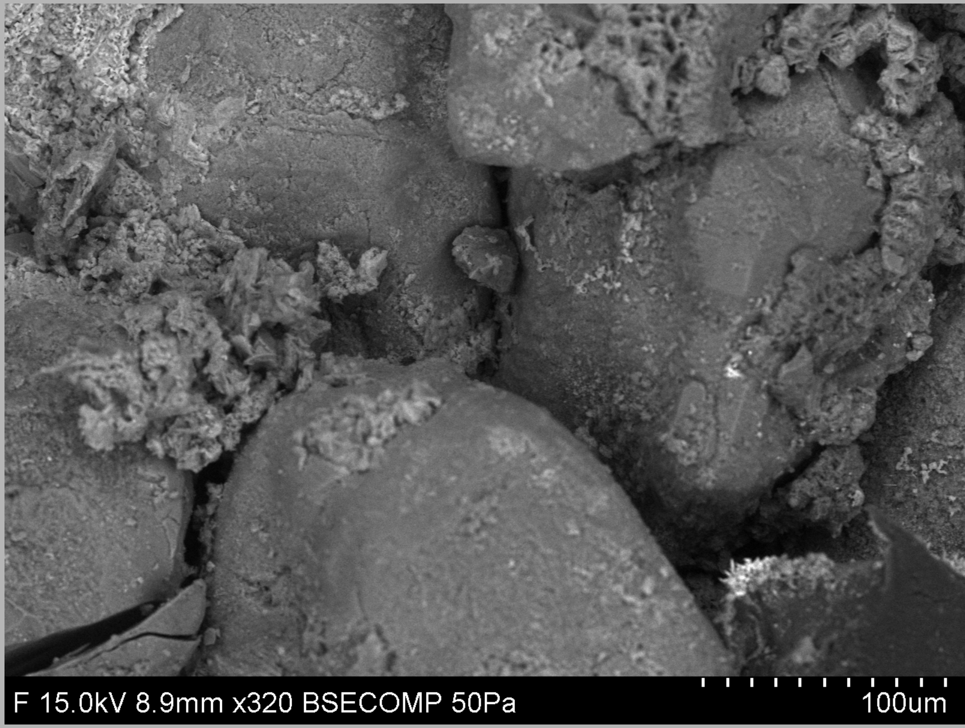


Time-Lapse SEM



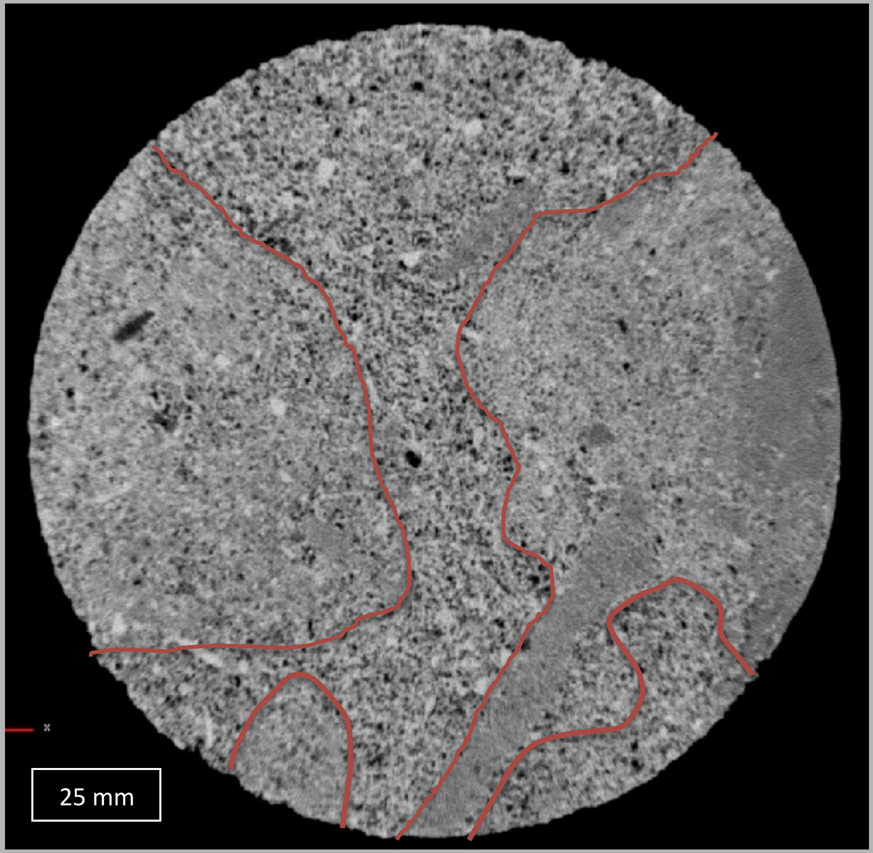
Time-Lapse SEM



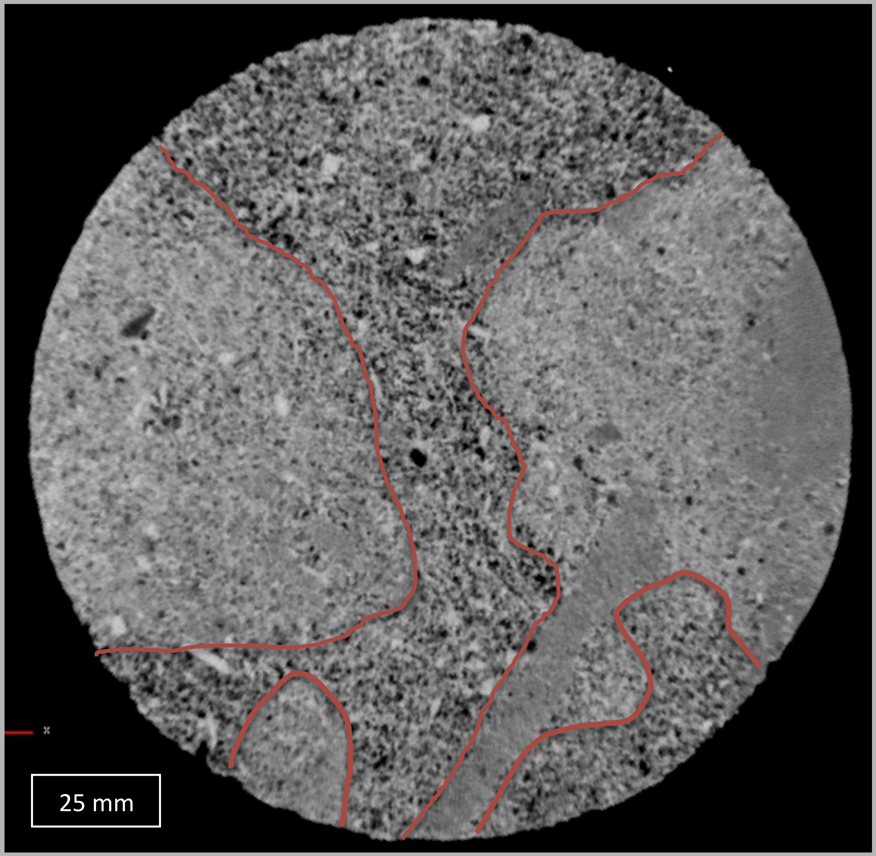


Selective Dissolution

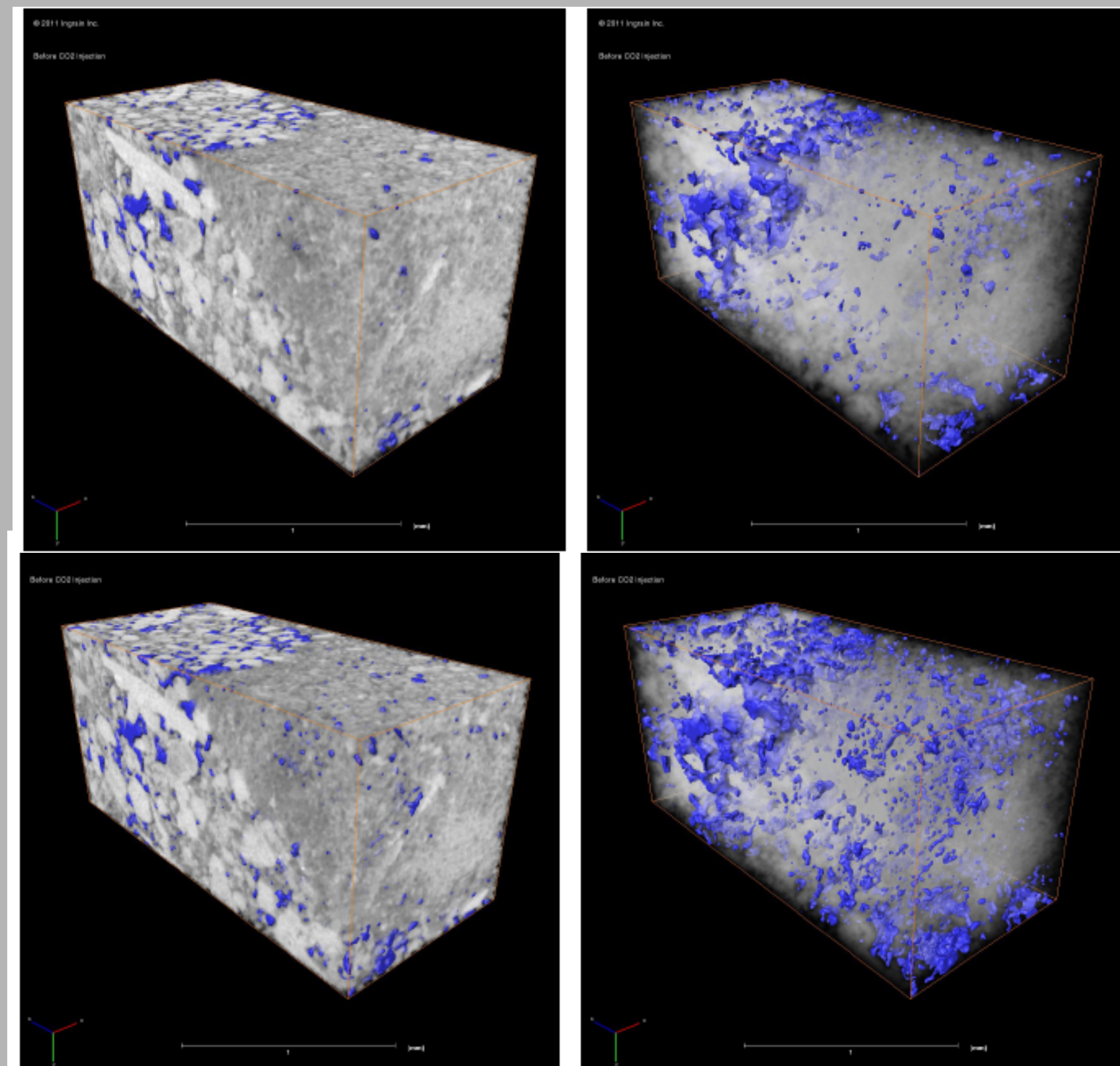
Before CO_2 injection



After CO_2 injection



Post-Injection Characterization



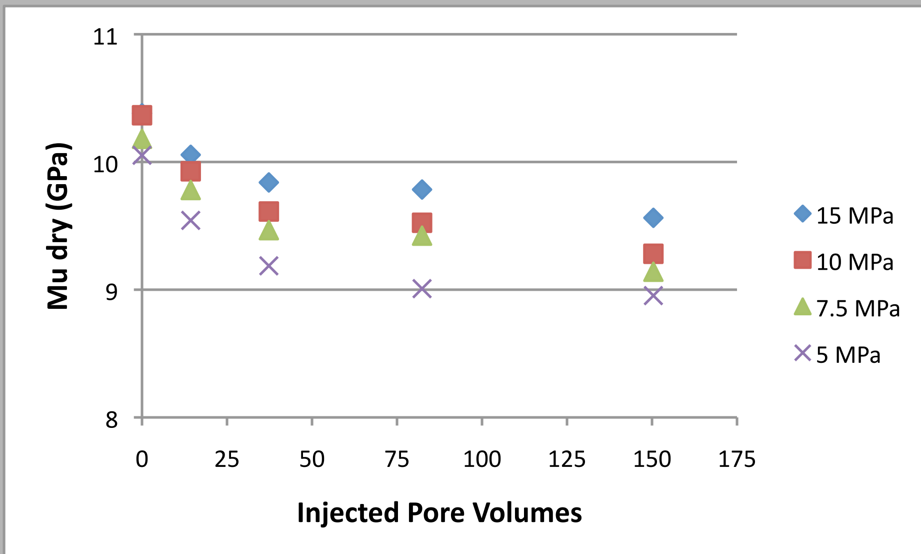
Conclusions

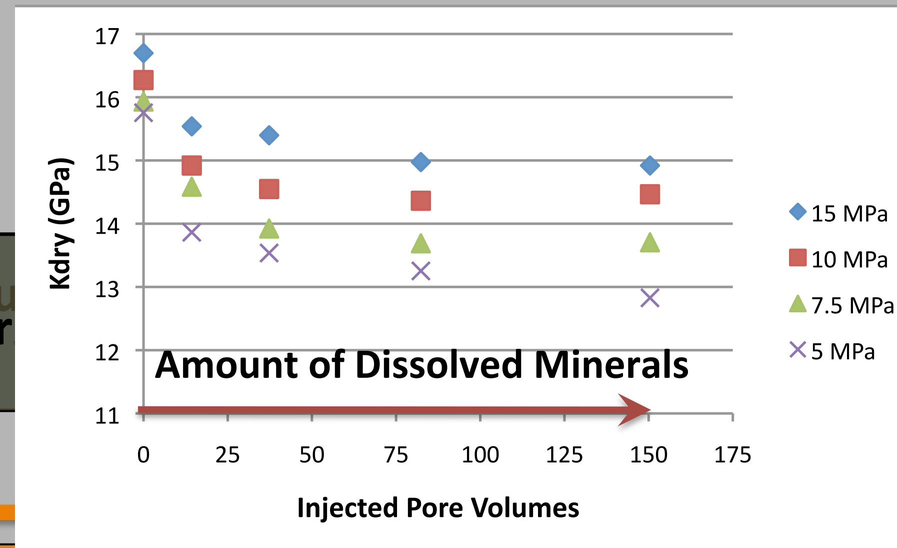
- Experimental data and pore scale images show that the seismic response of CO_2 injection in brine-rock systems is far from being a pure fluid-substitution problem.
- Fluid - rock chemical interactions affect the acoustic and transport properties of rock frame. This interaction implies a time-dependence of the properties of the rock frame in addition to those of the fluid permeating the rock (saturation, pressure…).

Conclusions

- Experiments shows where changes are likely to occur:
  - cement dissolution at the grain contact → elastic modui
  - porosity/density → elastic moduli
  - the fraction of complaint pores seems to increase with injection as carbonates become more sensitive to pressure upon injection

Where Are We Going?





$\rho_{fl}; K_{fl}$

Fluid Properties

Solid/Frame Properties

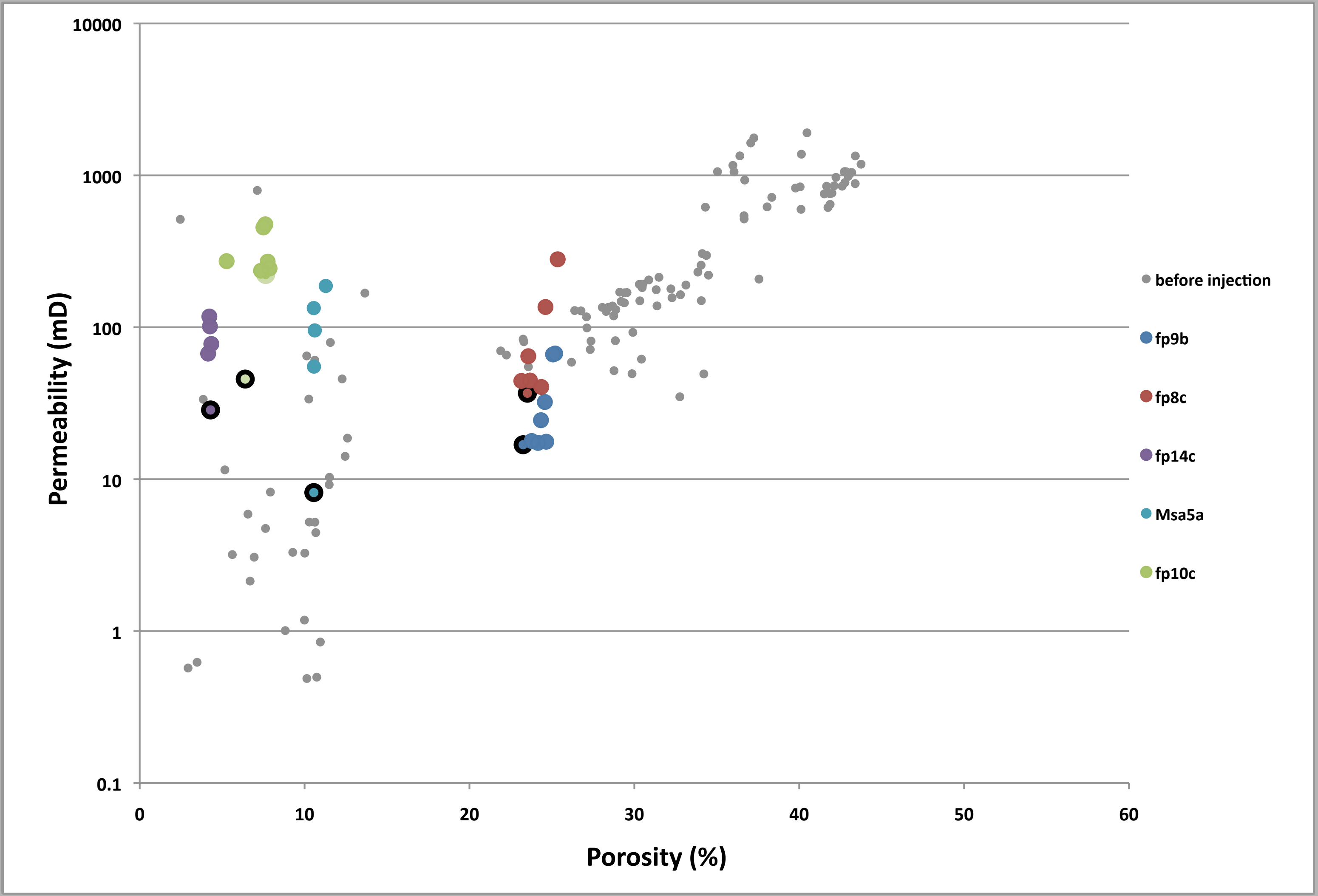
K_o K_{dry} μ_{dry}

ρ_0 ρ_{dry} Φ

saturation
free and dissolved gas
pore fluid pressure
temperature

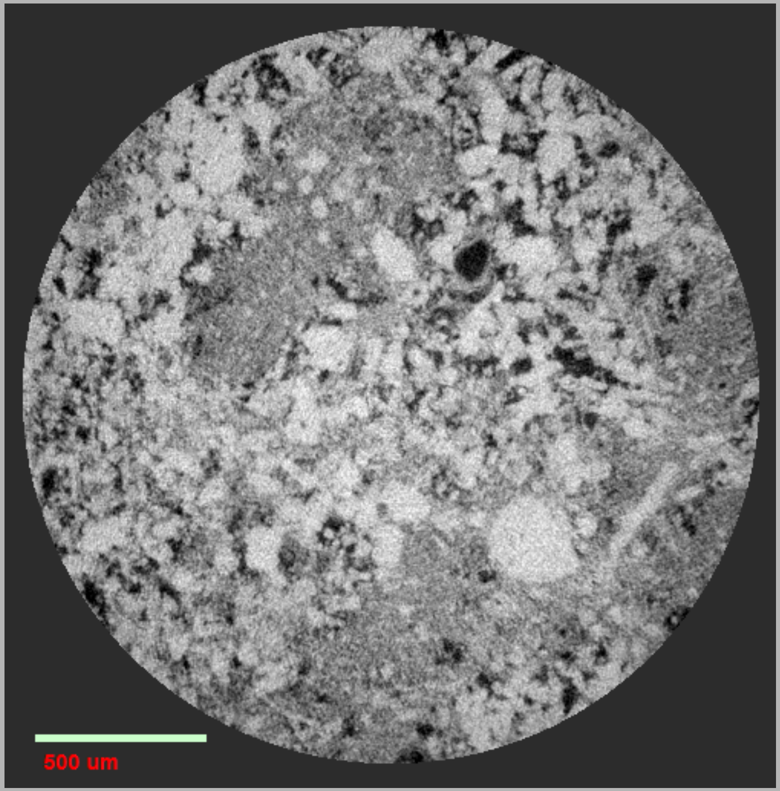
mineral composition
properties of the frame
porosity

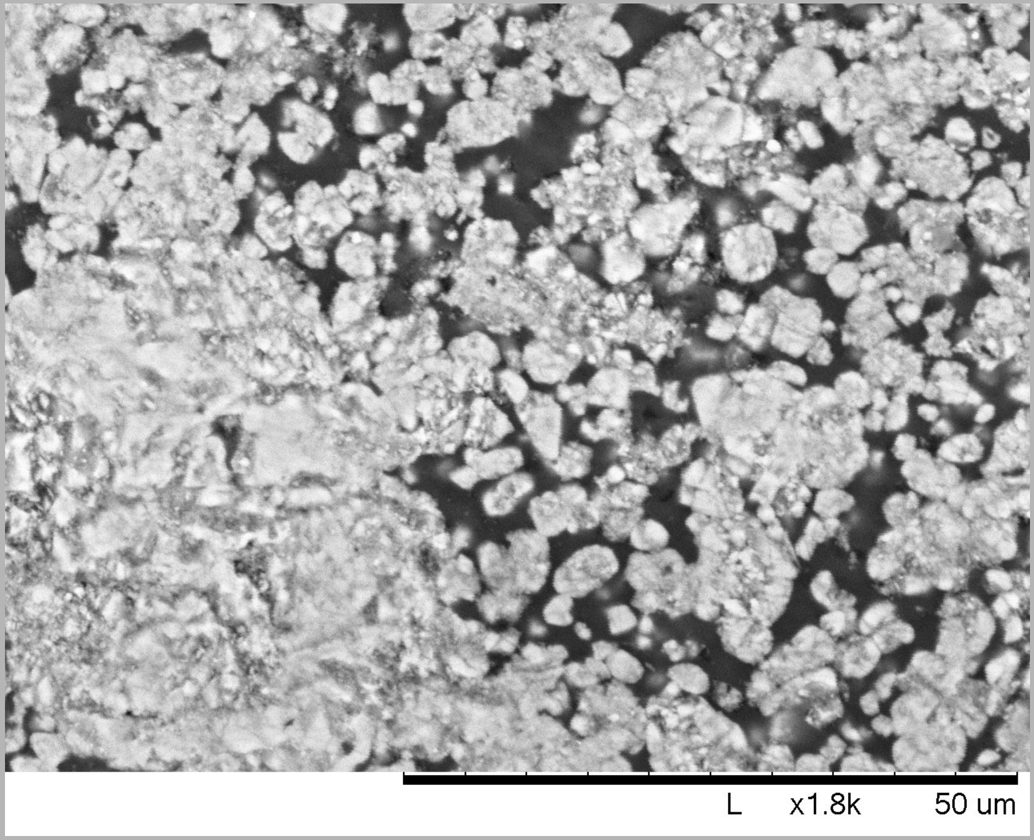
Where Are We Going?



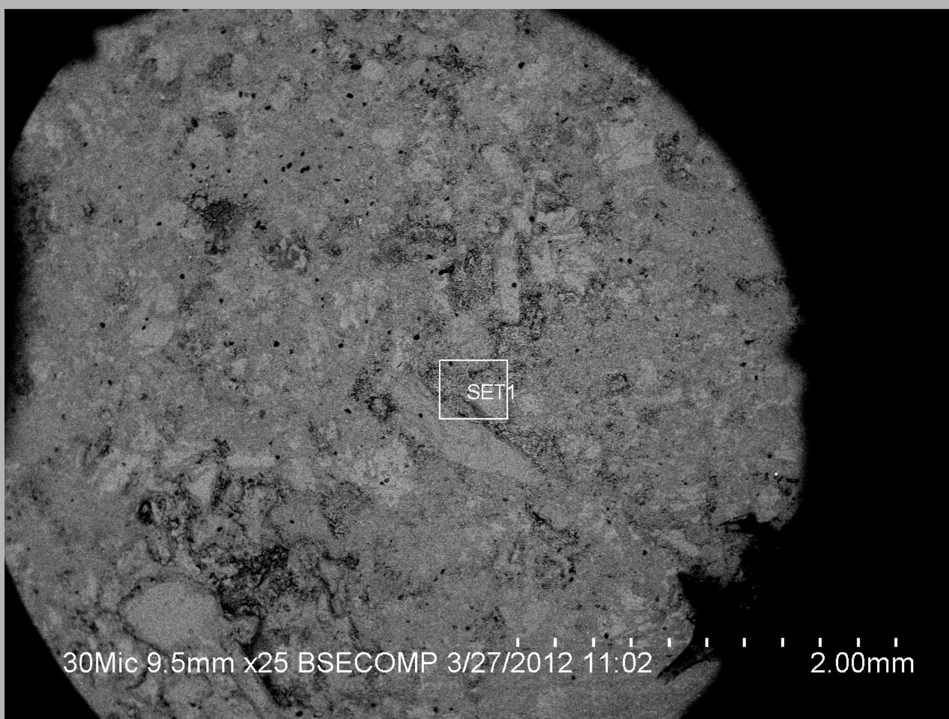
Carbonate Rock Physics

Heterogeneous Microstructure





Synthetic Samples



Acknowledgments

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- Petrobras, Brasil
- Stanford Rock Physics & Borehole Consortium

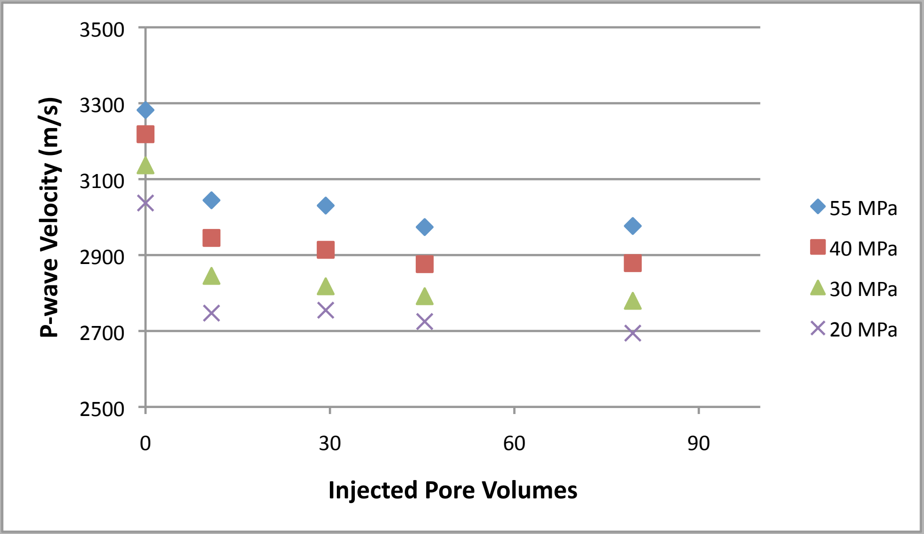
Conclusions

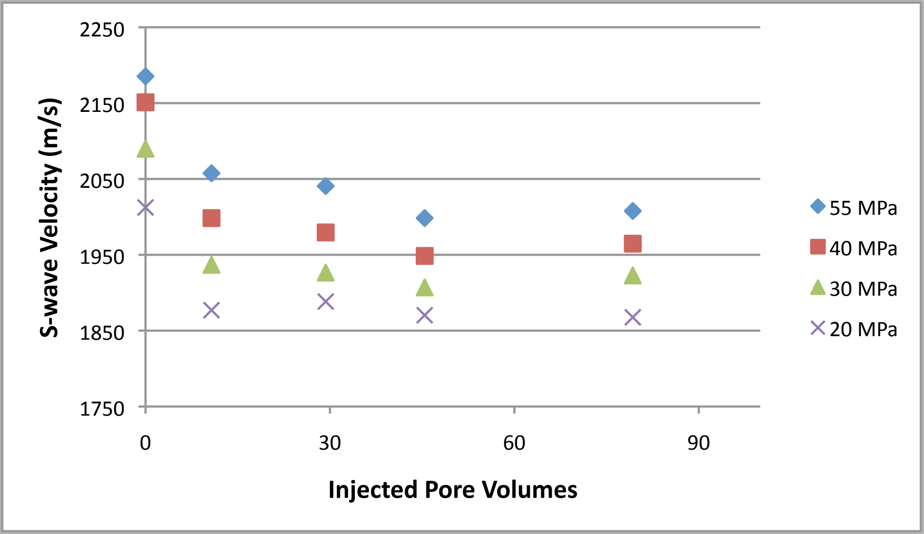
- In carbonate rocks, velocity decreases mainly because of the formation of new, more complaint pores. Carbonates become more sensitive to pressure upon injection; i.e., the fraction of complaint pores increases.

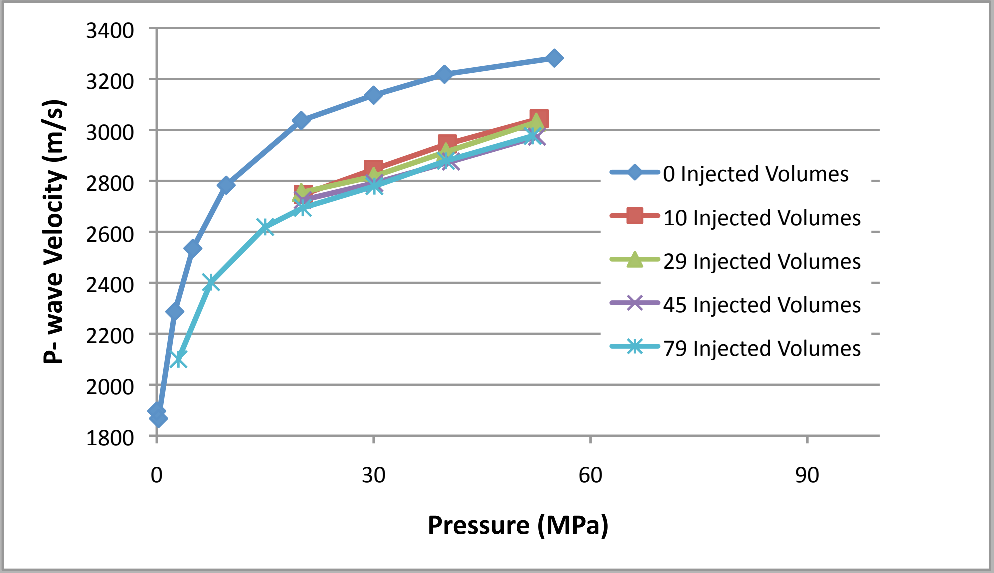
- Sandstones experience larger decrease in velocity as well as larger compaction than carbonates; velocity decreases because of dissolution of cement at the grain contacts.

CO_2 Injection in Sandstones

Velocities of the dry rock frame after injection







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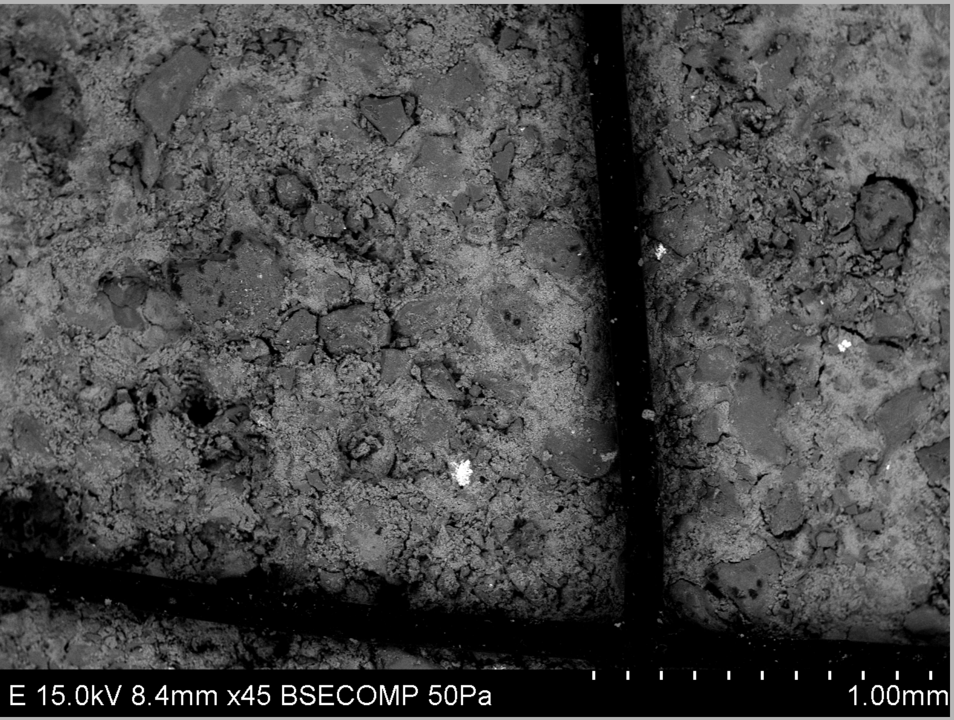

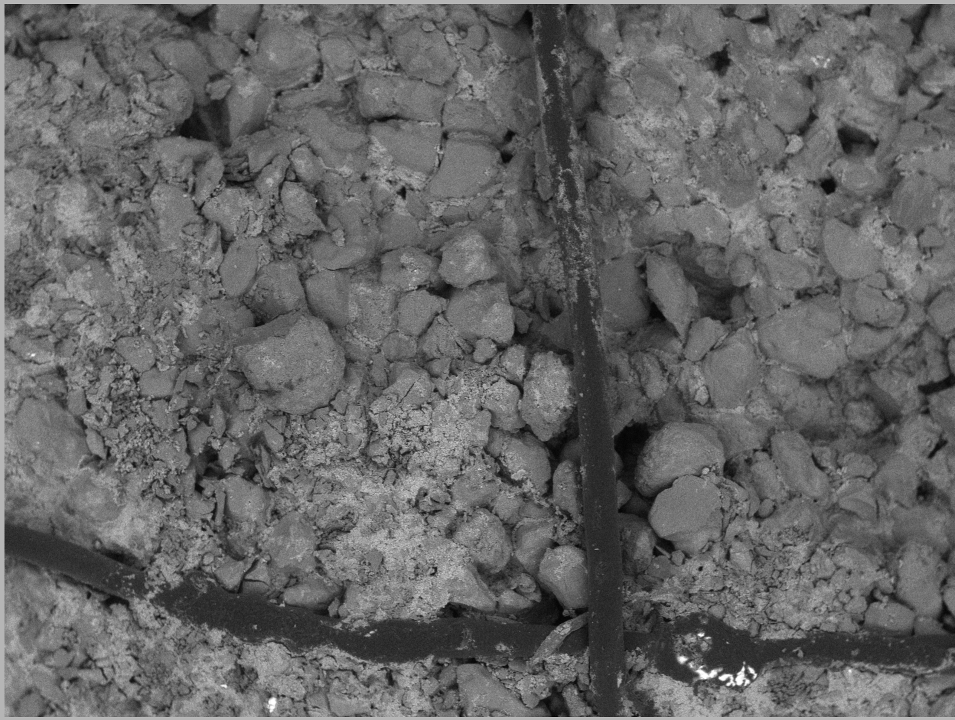

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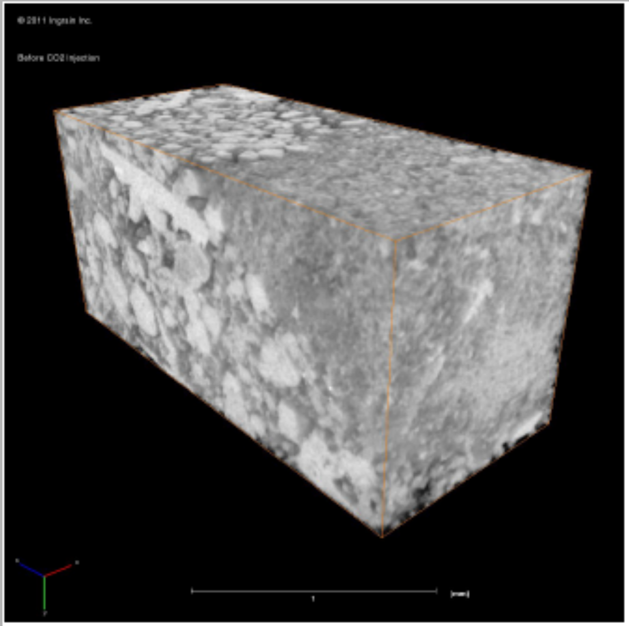
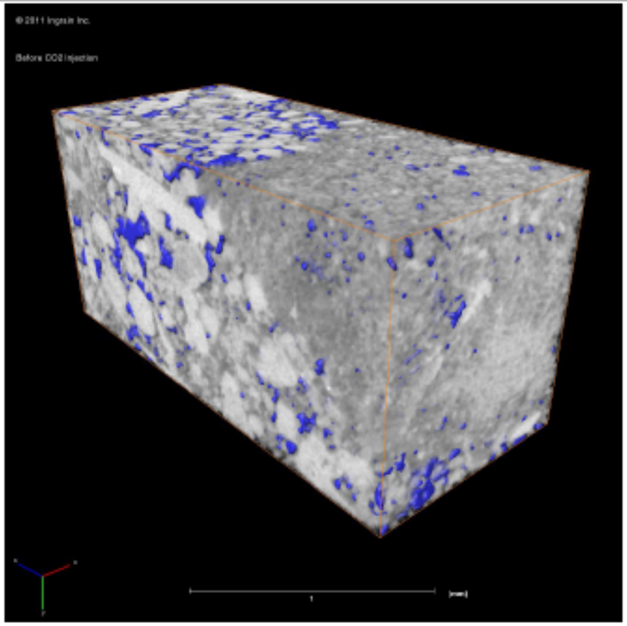
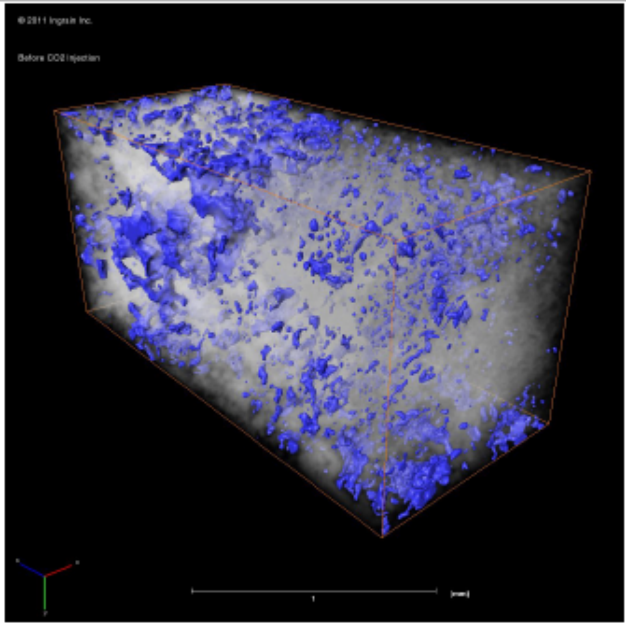
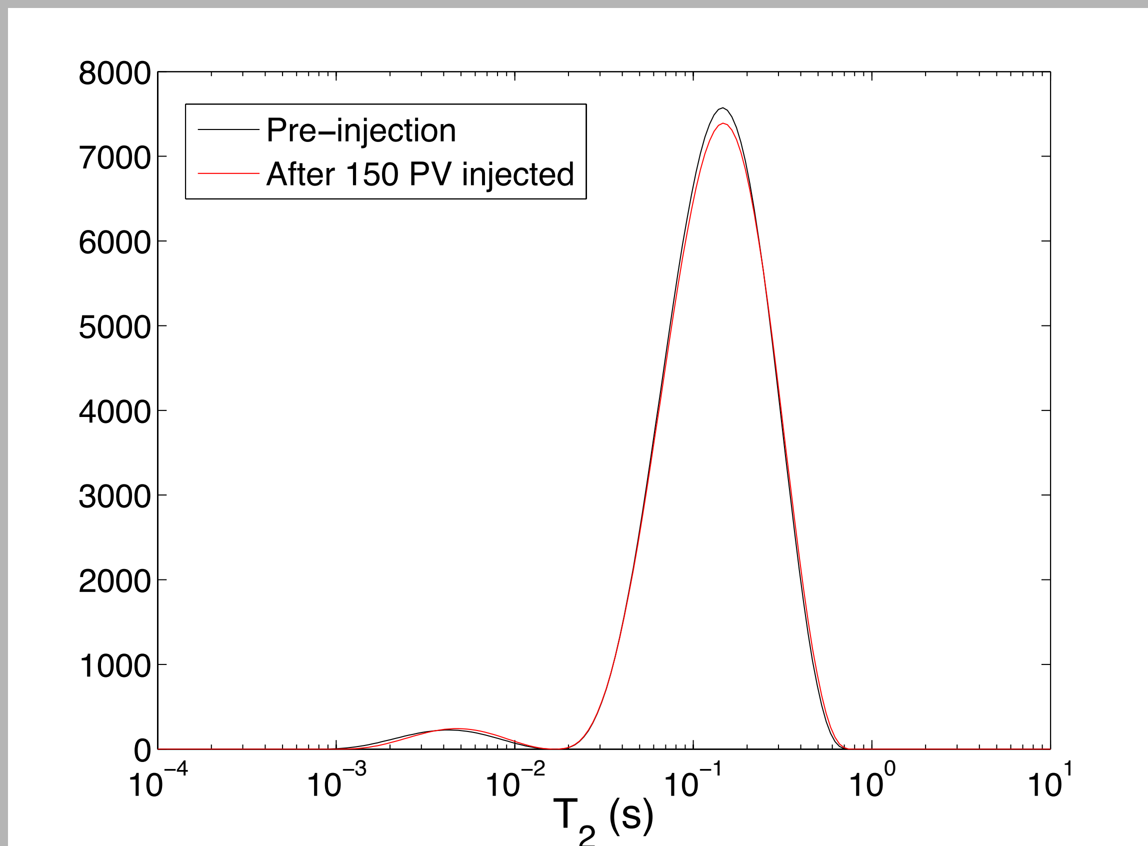






Time-Lapse NMR

T2 is inversely proportional to Surface/Volume ratio of the pore space



Tight Limestone
Micritic Carbonate

Smaller Pores

Larger Pores

Grombacher and Vanorio, 2011- Geophysics

Time-Lapse SEM