STANFORD UNIVERSITY

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

Linking the Chemical and Physical Effects to Elastic and Transport Properties

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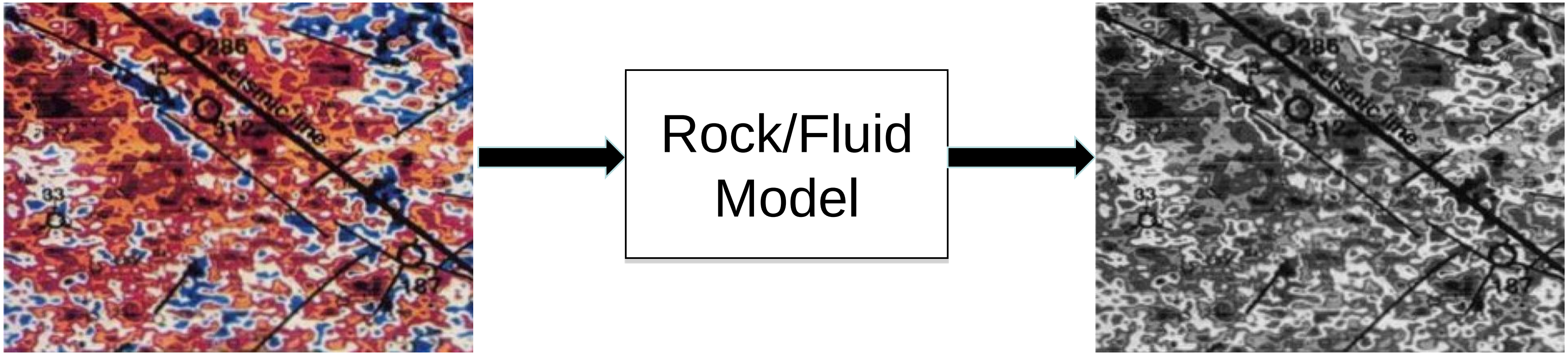
The Problem: Rock Models for Monitoring

Schematic Workflow for Monitoring Saturation in the Subsurface

Maps of Seismic Attributes

Interpreted Saturation



Results are only as good as the Rock/Fluid Model.

Current methods for interpreting in situ CO_2 saturation from seismic data are best suited for conditions of single-phase fluid saturation in relatively inert systems.

Conventional Fluid Substitution

Currently, seismic monitoring of CO_2 injection is modeled using the equations of Gassmann (1951):

bulk modulus

$$\frac{K_{after}}{K_{min} - K_{after}} = \frac{K_{before}}{K_{min} - K_{before}} + \frac{K_{fluid\,1}}{\phi\left(K_{min} - K_{fluid\,1}\right)} - \frac{K_{fluid\,2}}{\phi\left(K_{min} - K_{fluid\,2}\right)}$$

shear modulus

$$\mu_{after} = \mu_{before}$$

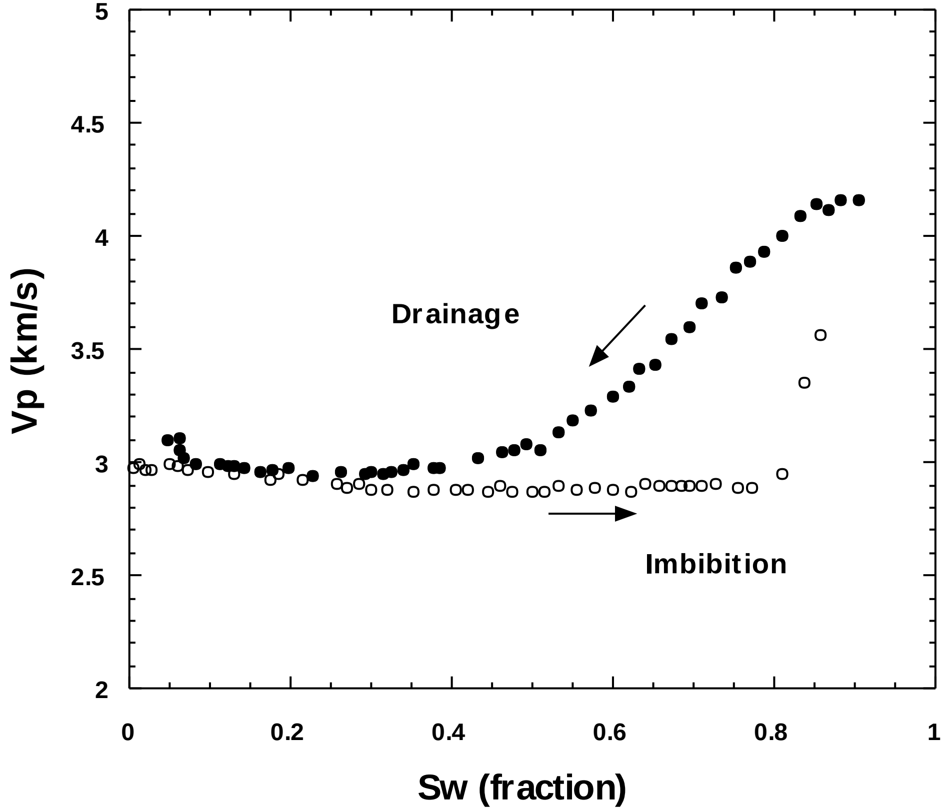
bulk density

$$\rho_{after} = \rho_{before} + \phi\left(\rho_{fluid\,2} - \rho_{fluid\,1}\right)$$

These assume 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.

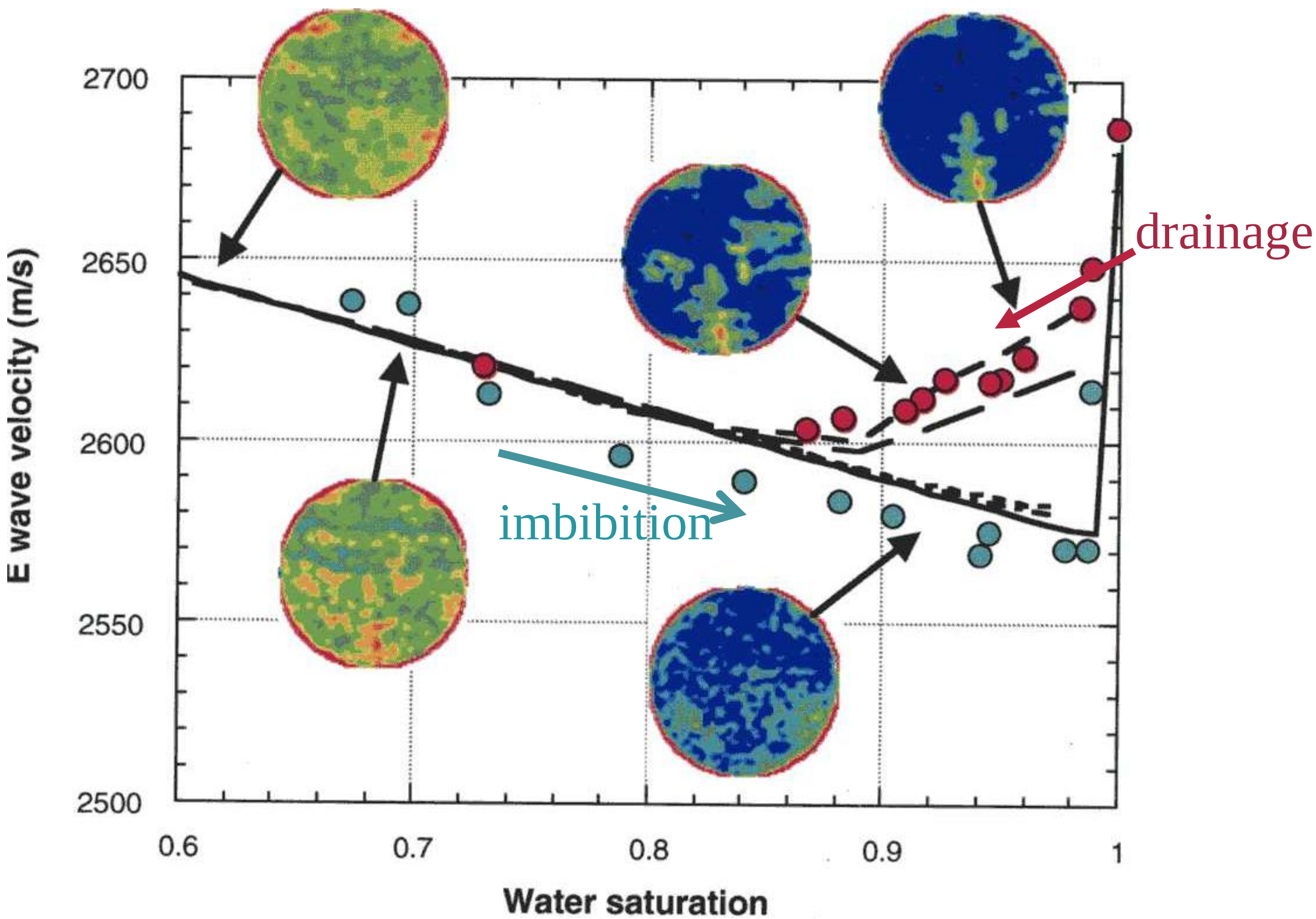
Complication: Partial Saturation



Knight and Nolen-Hoeksema (GRL, 1990) found saturation hysteresis at ultrasonic frequencies.

We know now that velocities depend, not just on saturation, but also on the scales at which the phases are mixed. The curve labeled “imbibition” is typical when phases are mixed at a fine scale. The curve labeled “drainage” is typical when the phases are mixed at a coarse scale -- which we call “patchy.”

Partial Saturation



Thierry Cadoret studied velocity vs. saturation using the resonant bar and found the coarse-scale and fine-scale behavior.

Complication: Elastic/Chemical Coupling

When a porous medium is saturated with a fluid, the minerals composing the formation may **no longer be in equilibrium** with the fluid.

Rocks saturated with **fluids**

Changes of the
Macroscopic Rock Properties
(k, σ and F, **P and S-waves velocities**…)

Fluid/rock interactions
Adsorption
Ionic exchanges
Dissolution/precipitation

Changes in the porous network

Chemical reactions, microstructure and macroscopic properties are thus strongly linked.

Project Objective

Provide CO_2-optimized rock-fluid models that incorporate the seismic signatures of

(1)Saturation scales and free vs. dissolved gas in a CO_2-water mix,

(2)Pore pressure changes, and

(3) CO_2-induced chemical changes to the host rock

… so that quantitative mapping of the movement, presence, and permanence of CO_2 relative to its intended storage location at injection sites can be made.

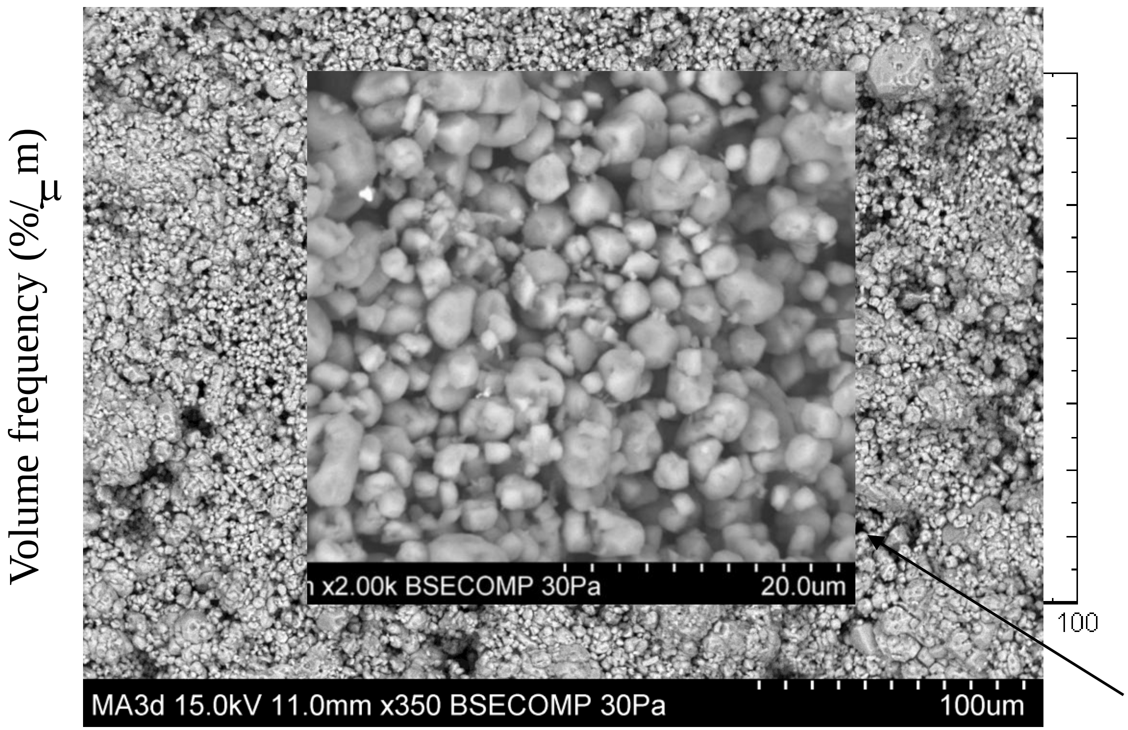
Laboratory Experiments

Monitor rock properties (elastic and transport) before, during, and after injection of CO_2-rich brine.

Materials and method

Example

- A micritic limestone from the Monte Acuto Formation (southern Italy) whose **microstructure** has been precisely analyzed. It is composed of pure calcite.



ϕ_{tot}	26.5%
ϕ_{micro}	25.2 %
$X_{micrite}$	48.0 %
k	75.3 mD
V_p	3500 m/s

Laboratory experiment: method

- We monitored :

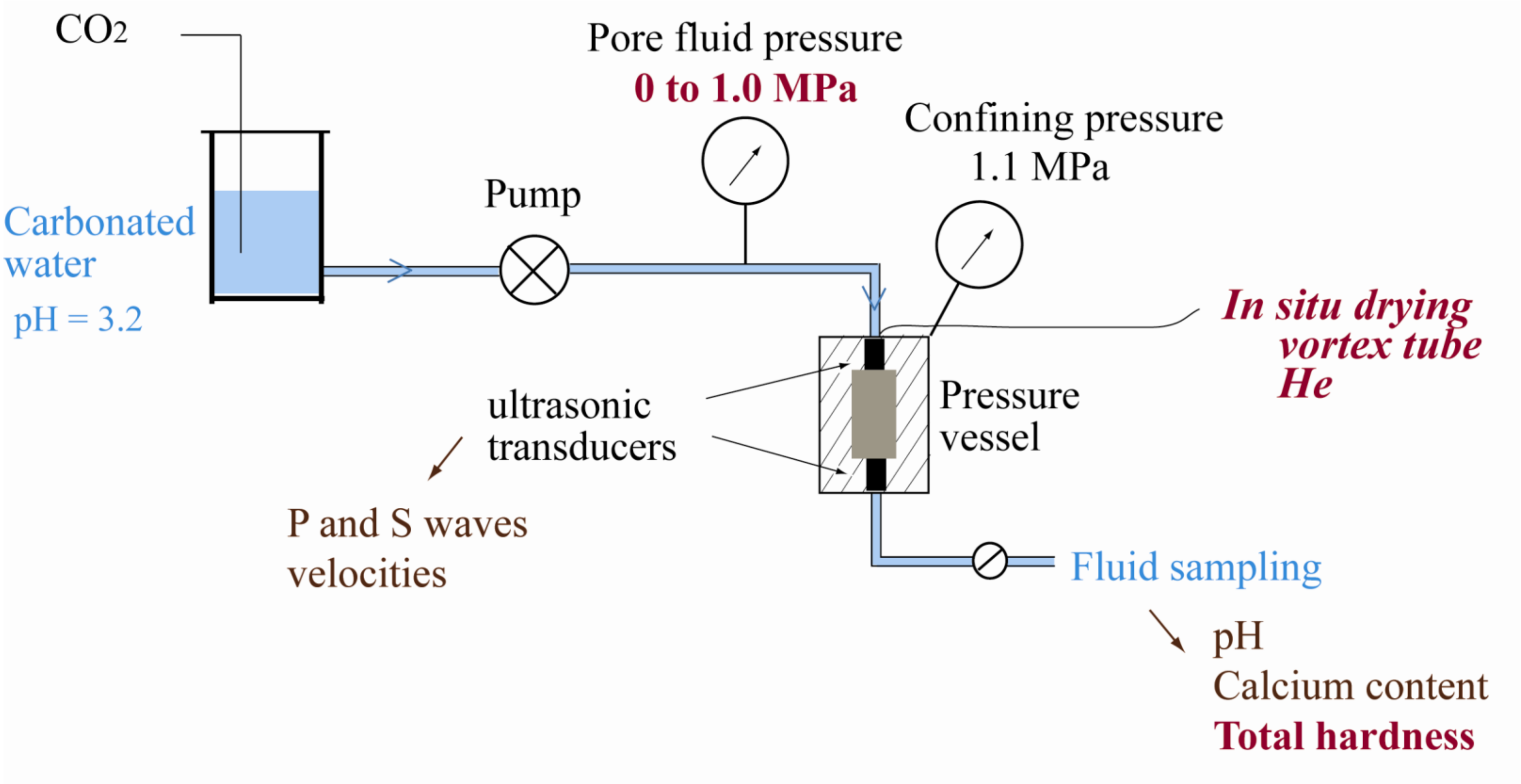
  ✓ the **velocities**, both under fluid-saturated- and dry conditions;

  ✓ the chemical composition of the output fluid by measuring **calcium content** and **total hardness.**

Total hardness TH = concentration of dissolved calcium, magnesium and other polyvalent ions which can be substituted in the calcite crystal lattice (Mn, Fe, Co, Zn)

$(Ca,\underline{Fe,Mg,Mn,Zn,Co})CO_3$

Laboratory experiment: method



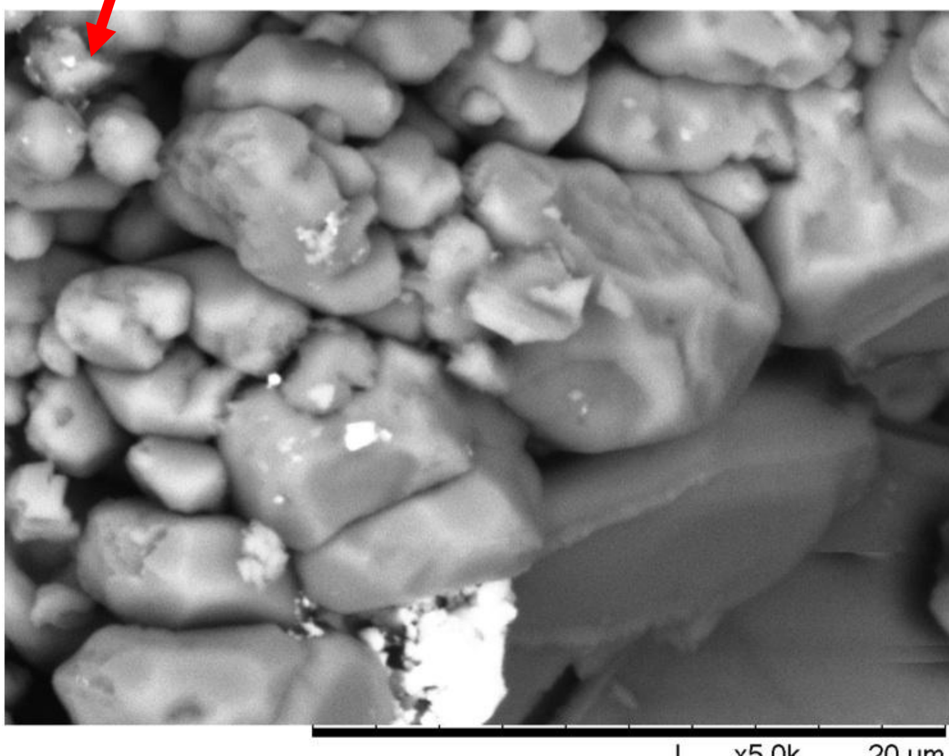
- The fluid is injected with a flow rate of about 8 mL/min and under Pc = 1.1 MPa.
- Saturated velocities are taken under a pore fluid pressure Pf = 1 MPa (no flow).
- Sample can be dried *in situ*.

Characterization of Rock Microstructure

We can quantitatively determine the textural parameters describing the microstructure of carbonates such as **micrite content and/or grain-micrite matrix ratio** via CT-scan imaging (Vanorio et al., 2010 – in submis. Geophysics)

Microporosity
~ 2 microns

Micrite aggregates



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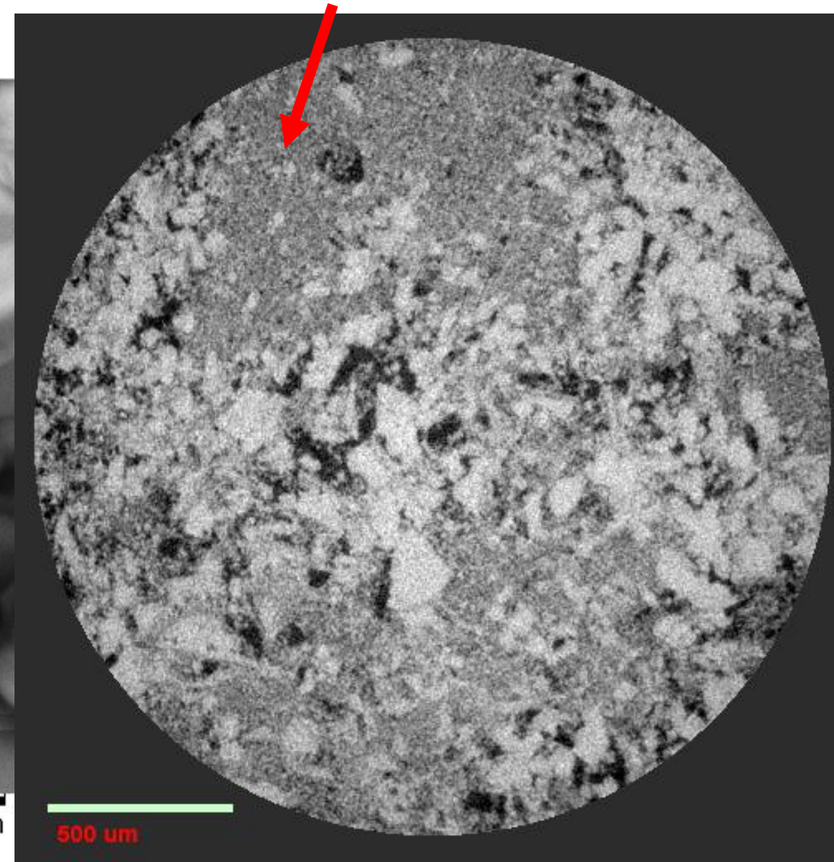
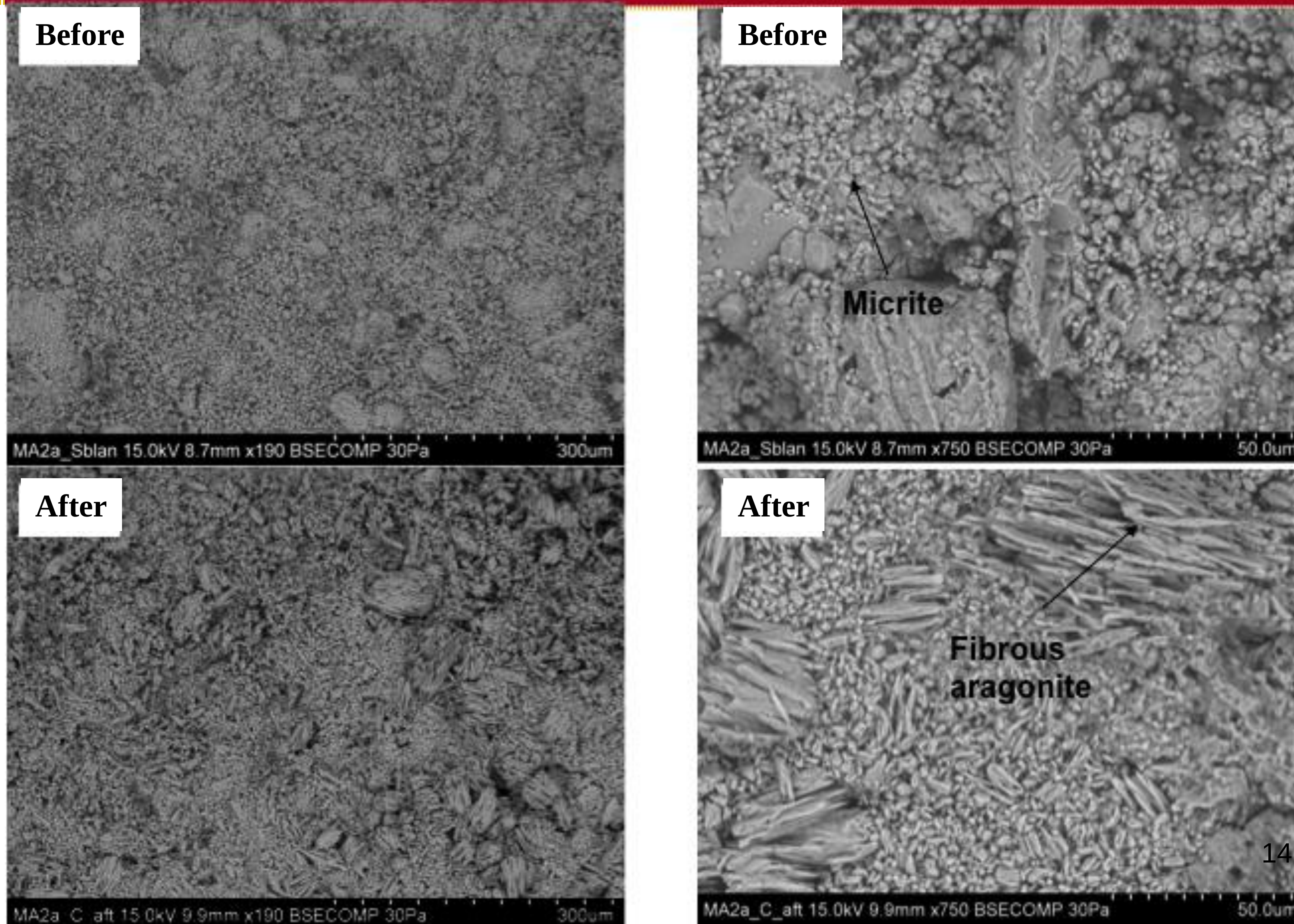
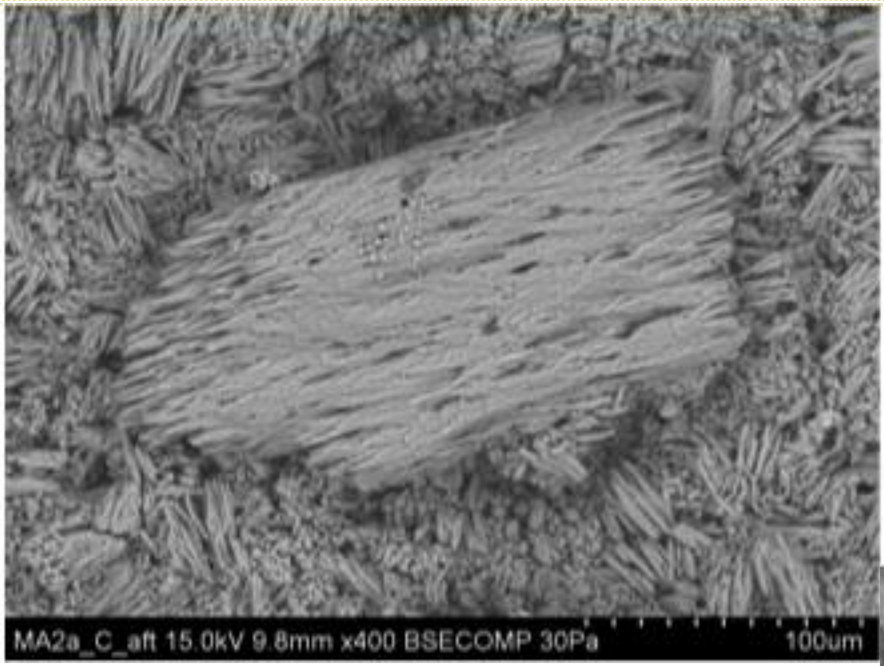


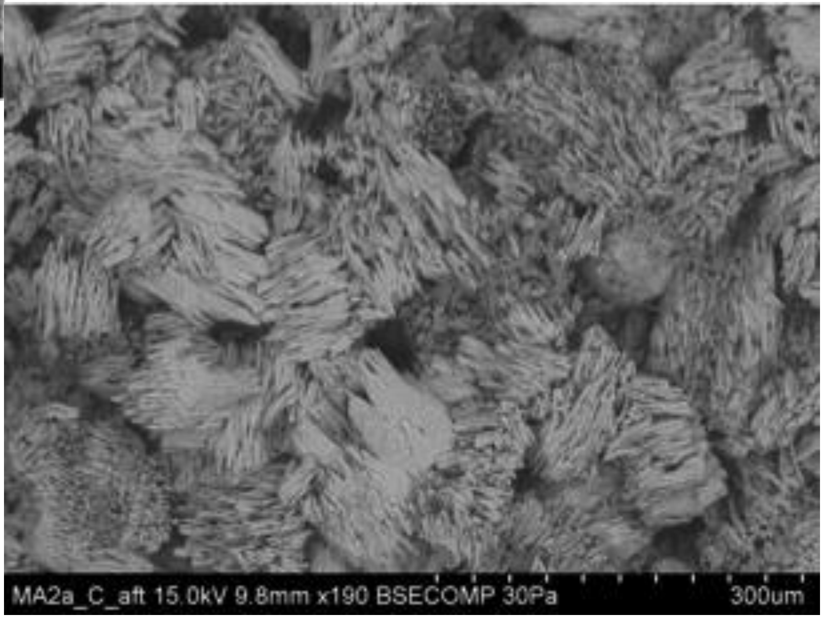
CO_2-rich water in Micritic Carbonates



CO_2-rich water in Micritic Carbonates



Zoom on newly formed aragonite crystals filling and coating the initial microstructure



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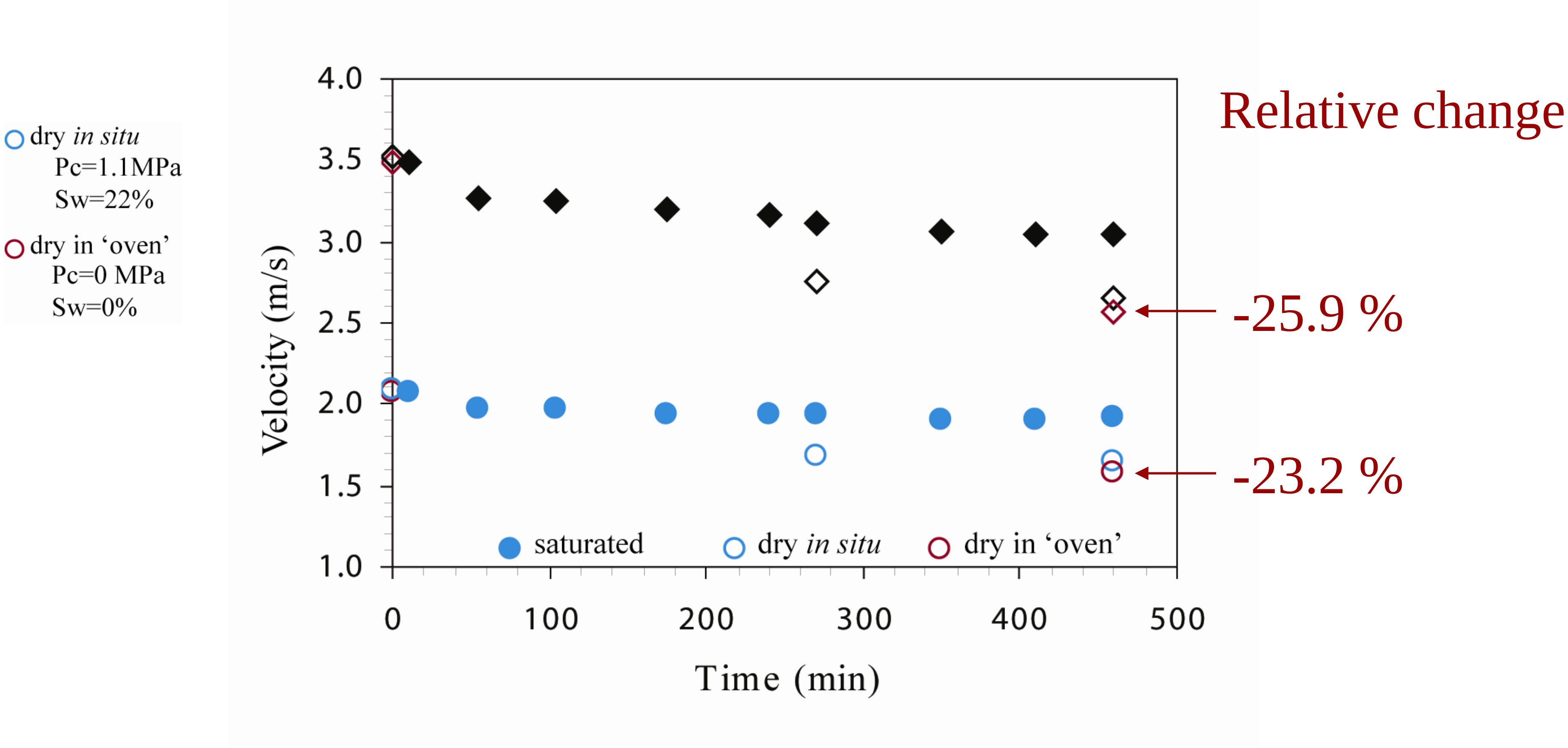
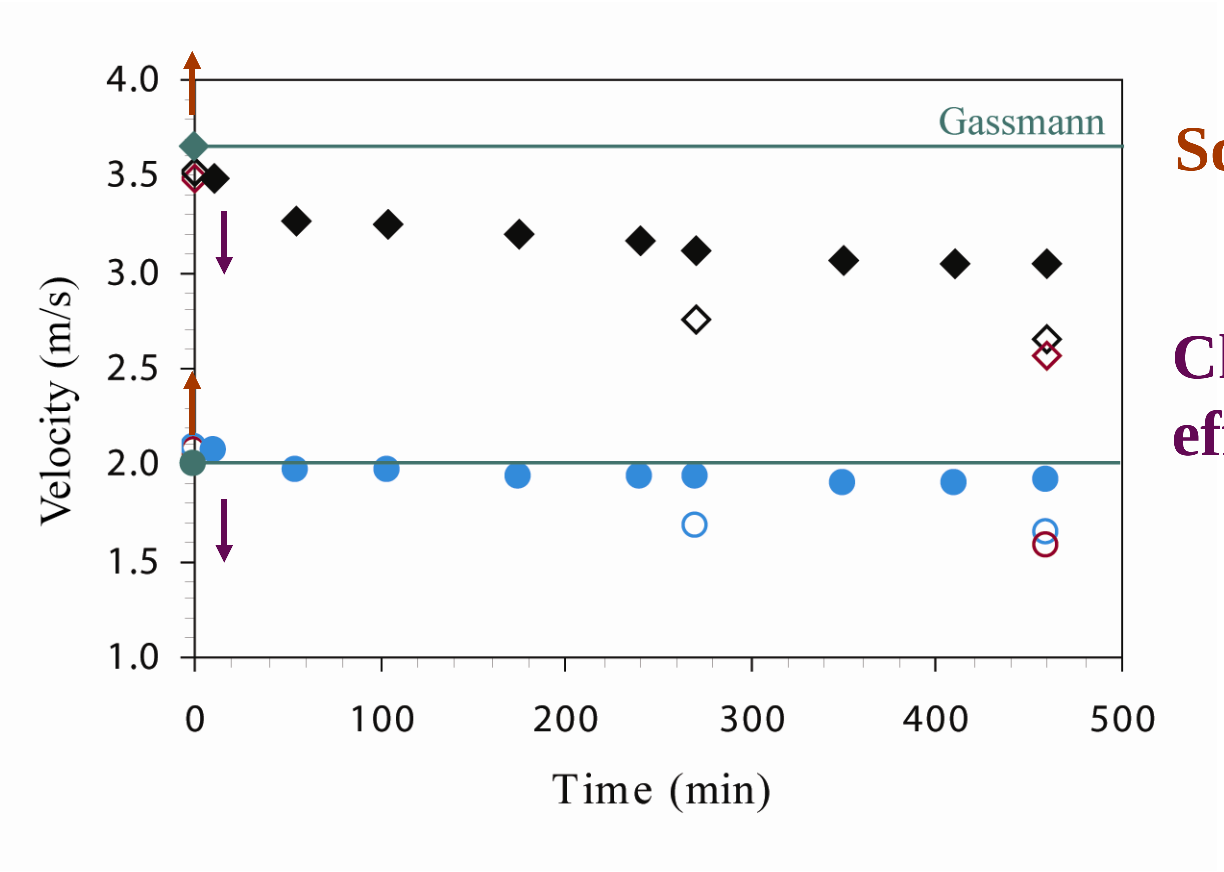
Results

Velocity monitoring



- **V_P and V_S decrease** in both dry and fluid saturated sample.

Experimental and theoretical velocities

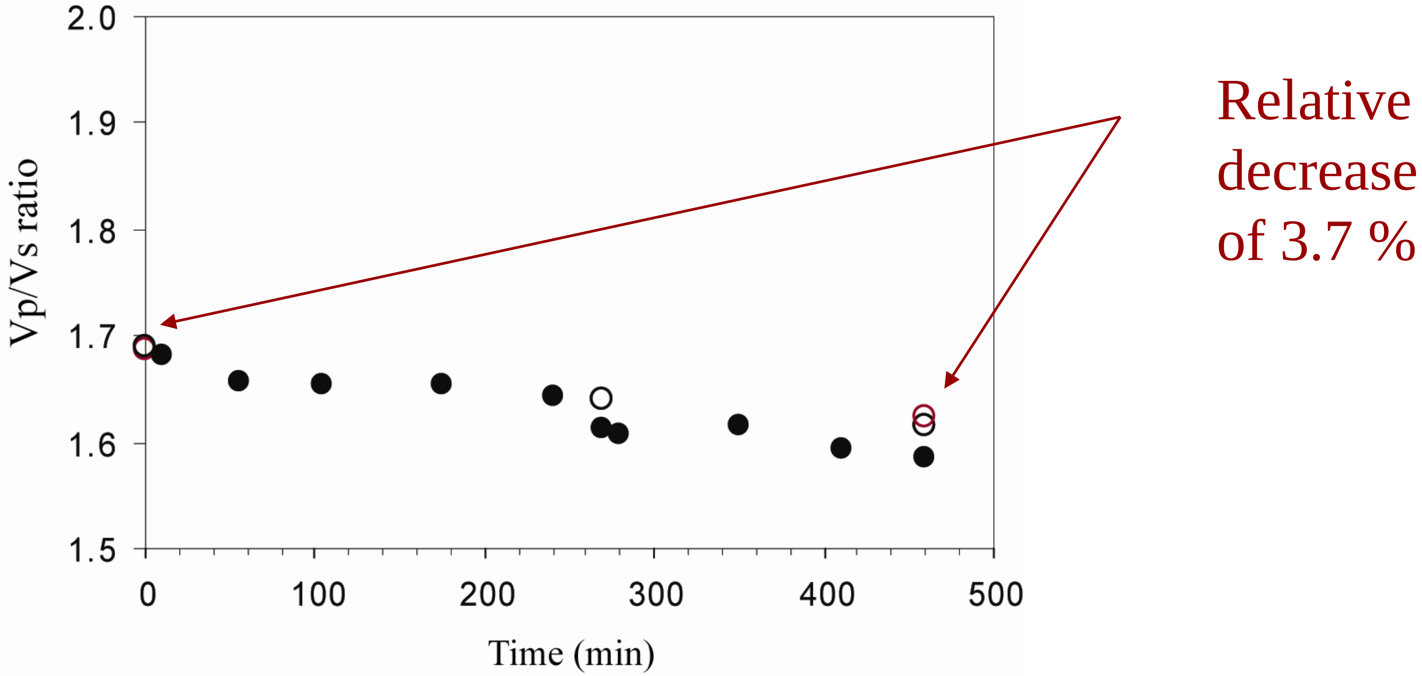


Squirt flow

Chemical effects

- ❑ Several mechanisms are present, leading to lower velocities than the ones predicted by purely mechanical models.

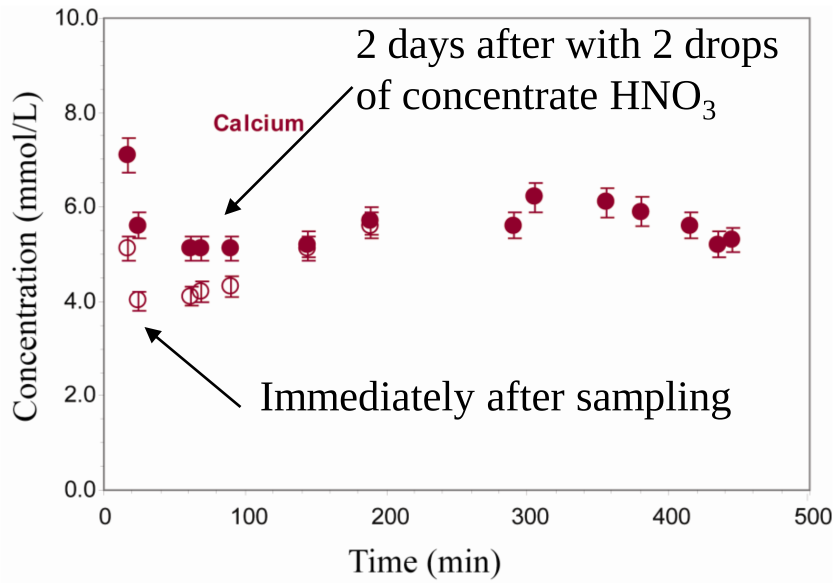
Evolution of Vp/Vs ratio

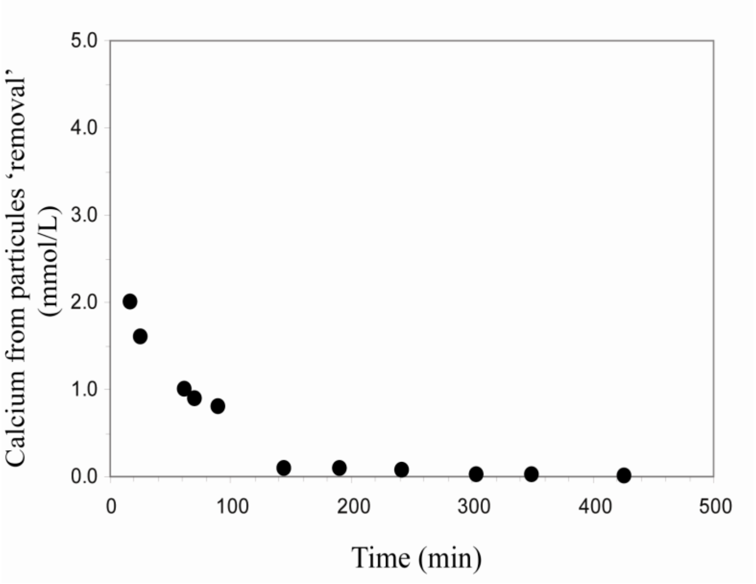


- Vp/Vs ratio decreased, both for dry and saturated conditions.

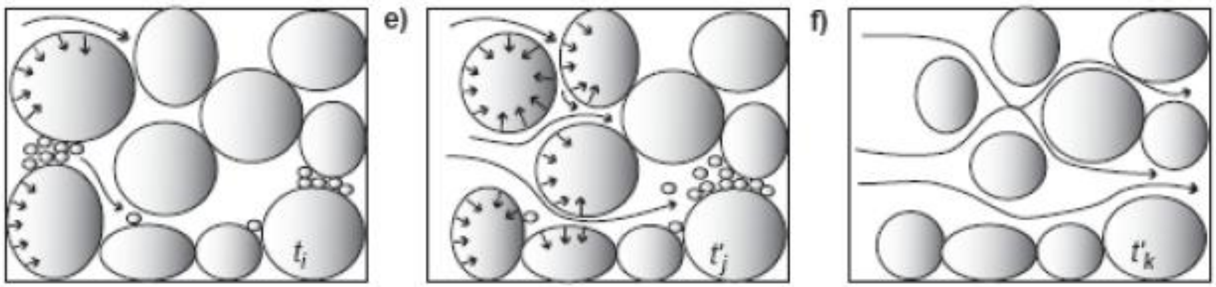
  Relative decrease of 3.7 % between the first and the last dry measurements

Results of the chemical monitoring



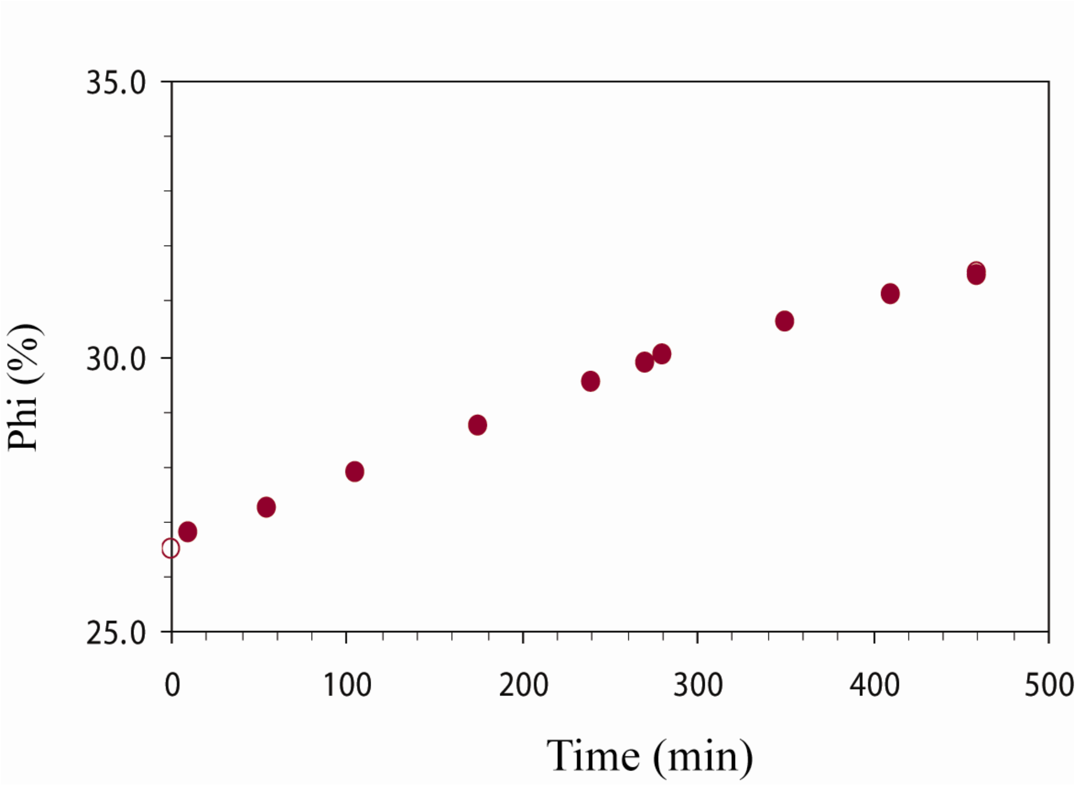


❑ At the beginning of the experiment, the processes of dissolution are supplemented by particle removal.



From Noirel, 2004

Change in porosity from chemical analyses

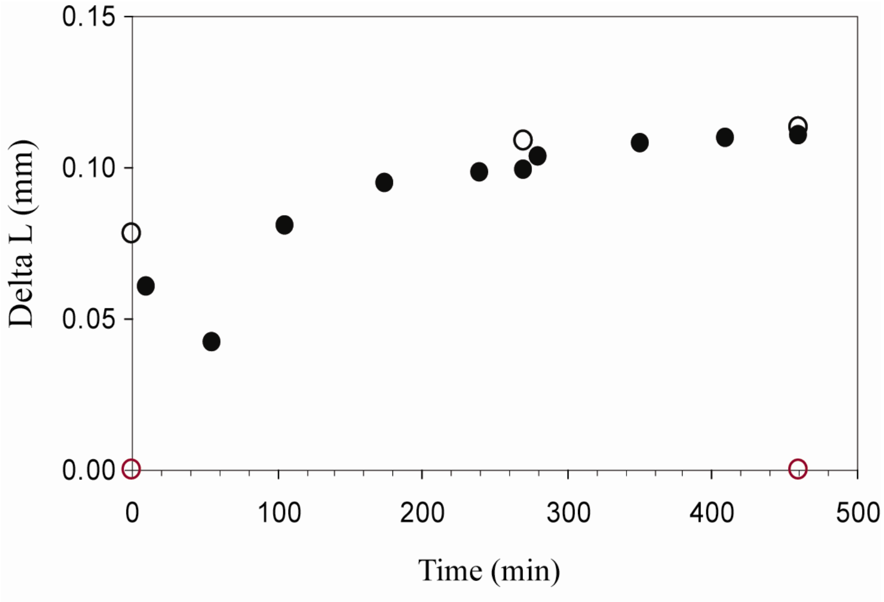


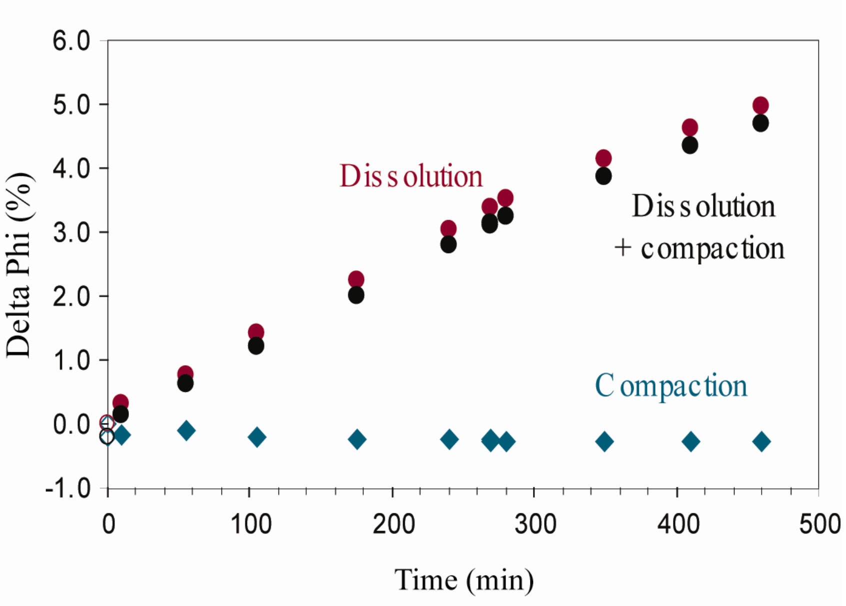
$$\Delta\phi = \frac{m_{dissolved}}{V_{total}\rho_{grain}}$$

$$m_{dissolved} = C_{TH} \cdot V_f \cdot M_{CaCO_3}$$

- Porosity increased from 26.49 % to 31.46 % (+ 5 %).
- He porosimetry gives a final porosity of 31.50 %.

Compaction and effect on porosity

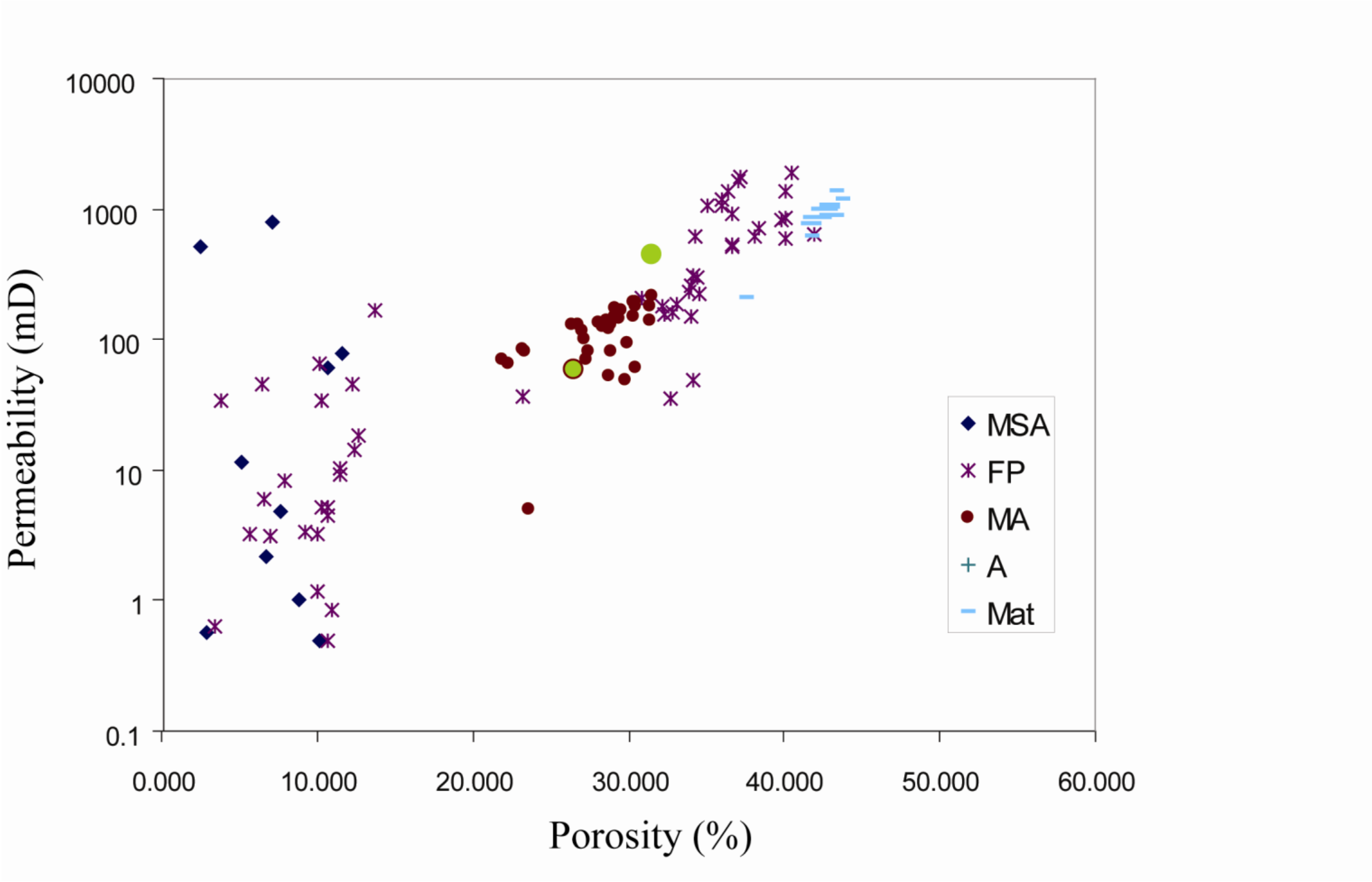




❑ The decrease of porosity due to compaction is smaller than the increase due to dissolution and particles removal.

porosity increased, even in the pressure vessel under confining pressure.

Comparison with SRB carbonates data



- Permeability increased from 75.3 mD to 448.9 mD.

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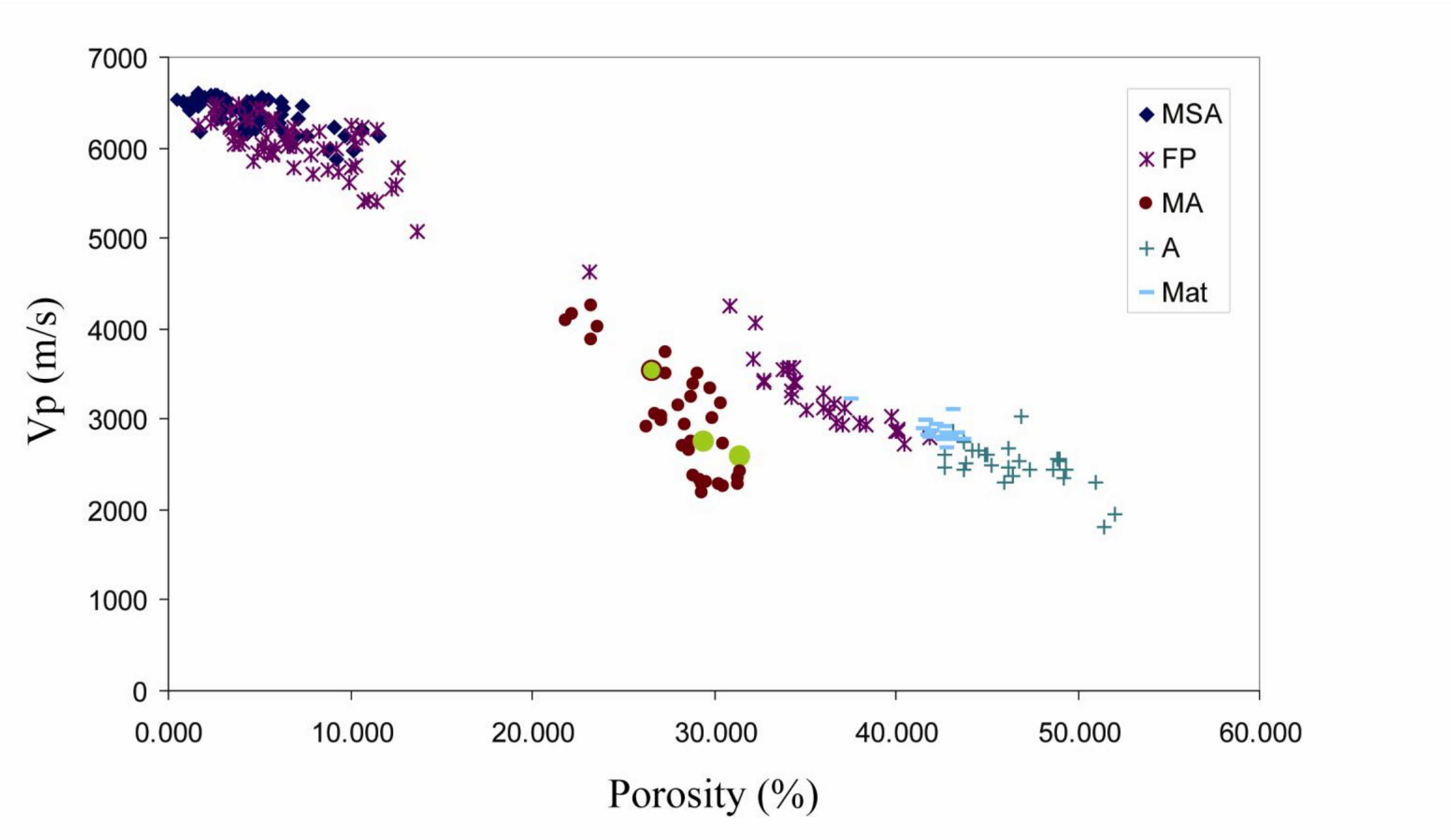
Comparison with SRB carbonates data

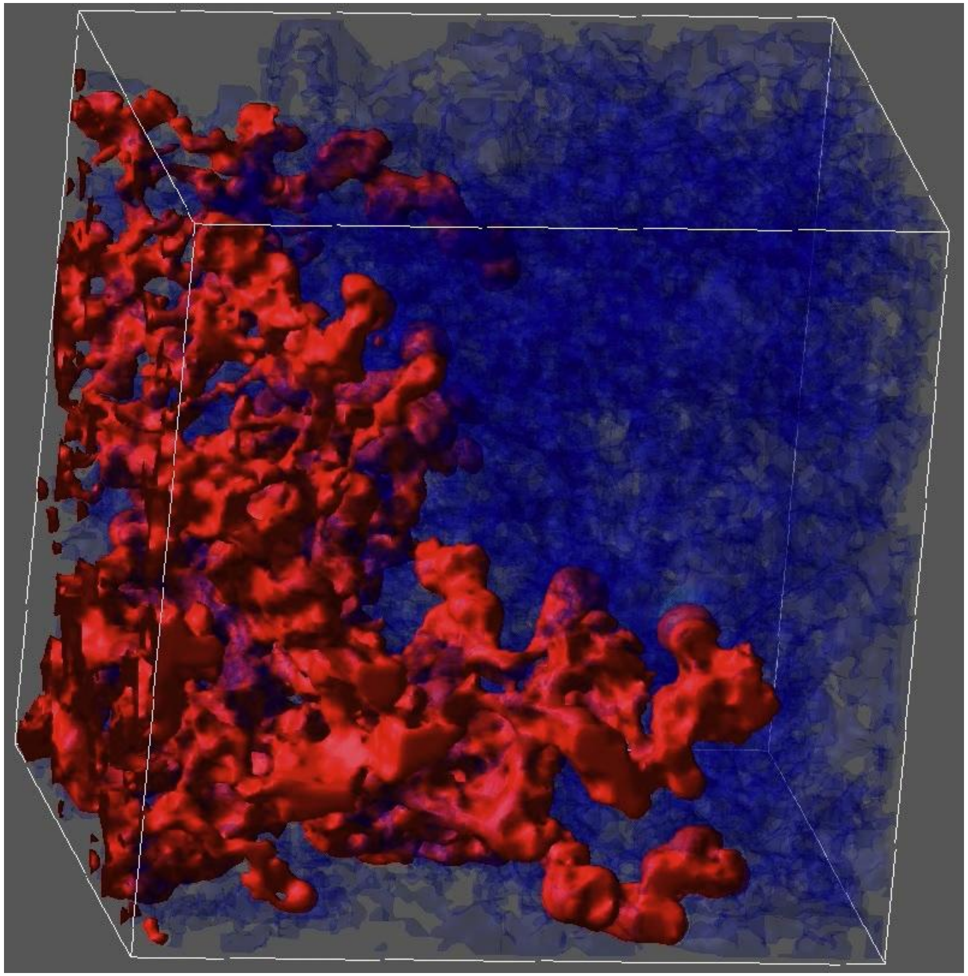


- The sharper slope characteristic of Ma samples is preserved.

Summary

- Quantitative seismic monitoring of CO_2 injection requires updated rock physics models.
- More data are needed on the compressibility of brine-CO_2 mixtures over a range of conditions.
- A more complete understanding is needed of chemical changes to elastic and transport properties associated with dissolution, precipitation, mineral replacement, and compaction.
- Our measurements show that fluid-mineral reactions cause substantial increase in porosity and permeability and decrease of seismic velocities in carbonate rocks.
- Elastic properties depend on the scales of fluid mixing.
- Future work will include sandstone and calcite-cemented sandstone.

Partial Saturation



Courtesy of InGrain, Inc