September 1, 2014
“Kraftwerk 2020”

Geomechanical investigation of CO_2 sequestration

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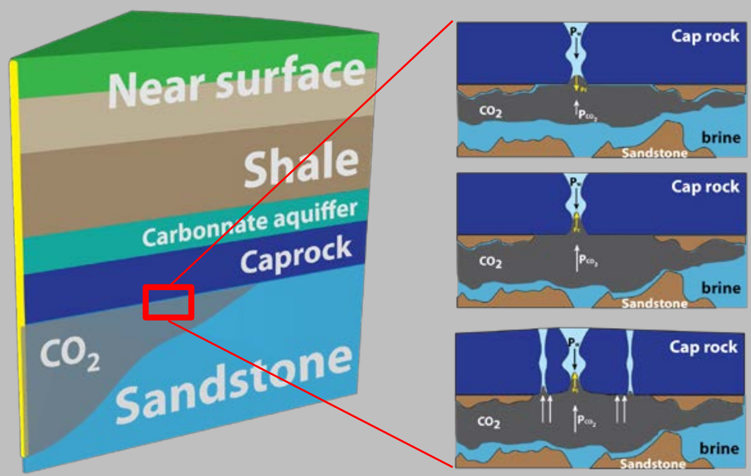
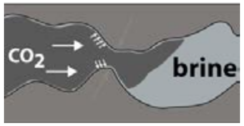
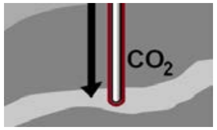
(LMS EPFL)





CO_2 storage, no thank you



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Wirtschaft

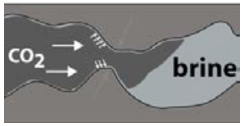
CO_2-Endlager, nein danke

Von Silvio Borner **— Um Atomstrom zu ersetzen, muss die Schweiz Gaskraftwerke bauen – und freiwerdendes CO_2 unterirdisch entsorgen. Die Technologie ist kaum erprobt und hoch riskant.**

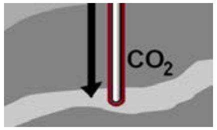
Die ökonomische Kritik an der Förderung kostendeckender Einspeisevergütung (KEV) für Sonne, Wind und Kleinwasserwerke wächst. Aber die Politik erhöht die Obergrenzen für diese falschen KEV laufend und plant deren Ausdehnung auch auf Grosswasserwerke. In Deutschland kostet diese Verschwendung bereits 20 Milliarden pro Jahr.

In der Schweiz wird der geplante Ausbau von Sonne und Wind von heute 0,9 Prozent der jährlichen Stromerzeugung auf 12,3 Prozent im Jahre 2035 wegen technologischer Mängel, ökologischer Bedenken und politi- grund nicht gefährlicher ist als in der Atmosphäre. Zudem ist ebenfalls nicht erforscht, wie denn die CO_2-Verbannung in den Untergrund praktisch zu bewerkstelligen wäre. Dazu gibt es nun ein sicher teures Forschungsprojekt Carma der ETH Zürich (PSI) und Lausanne sowie der Uni Bern.

Klar ist vorderhand nur, dass das zu versenkende Volumen per Kohlenstoffeinheit knapp dreimal grösser ist als dasjenige des ursprünglichen Brennstoffs. Ab einem Druck von 7,4 MPa (ca. 700 Meter unter der Erdoberfläche) verwandelt sich das CO_2 in eine Flüssig-



Carbon capture and storage



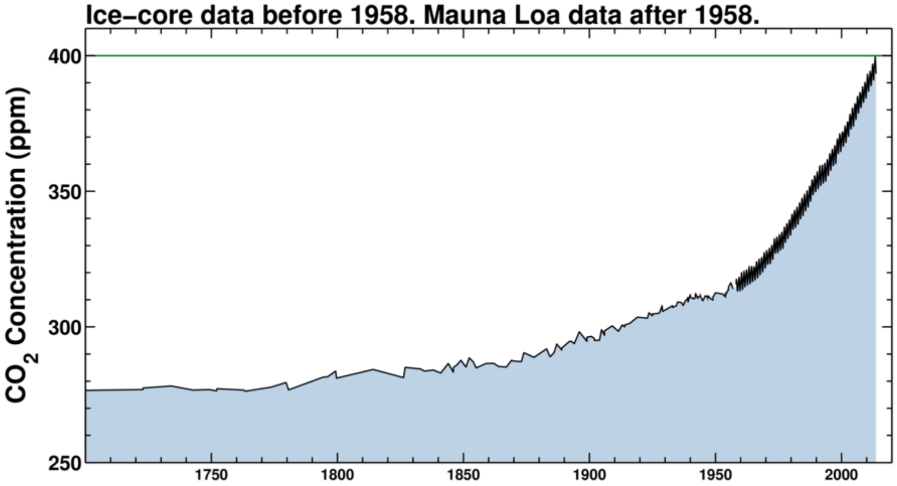
Problem:

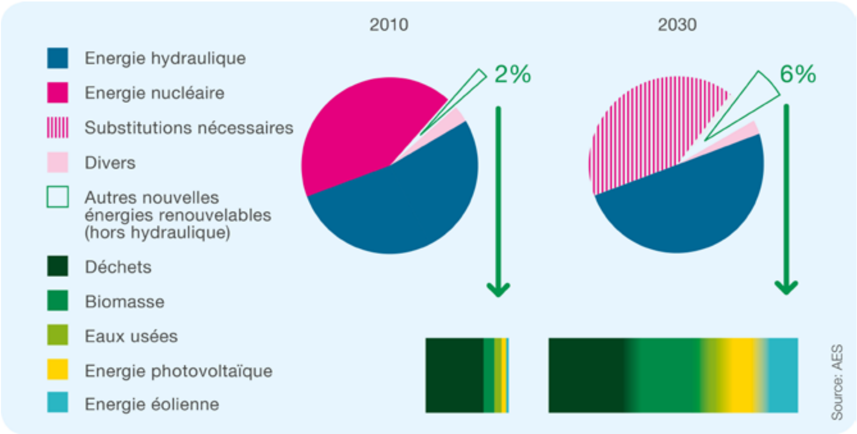
Concentrations of the greenhouse gas carbon dioxide in the global atmosphere are approaching 400 parts per million (ppm) for the first time in human history

- Temperature raise (anomaly: 0.56 ºC,
  2 ºC by 2100)
- Ocean level raise (+ 3 mm/year)
- Human health issues

cdiac.ornl.gov

The Keeling Curve (University of San Diego)





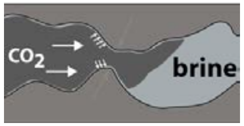
www.avenirelectricite.ch

Switzerland:

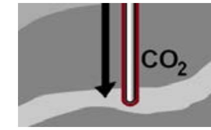
decommission of nuclear power plants

combined-cycle gas-fired power plants might be temporatily used (each produces 0.7 Mt CO_2/year)

Kyoto protocol (1997): reduction of CO_2 emissions

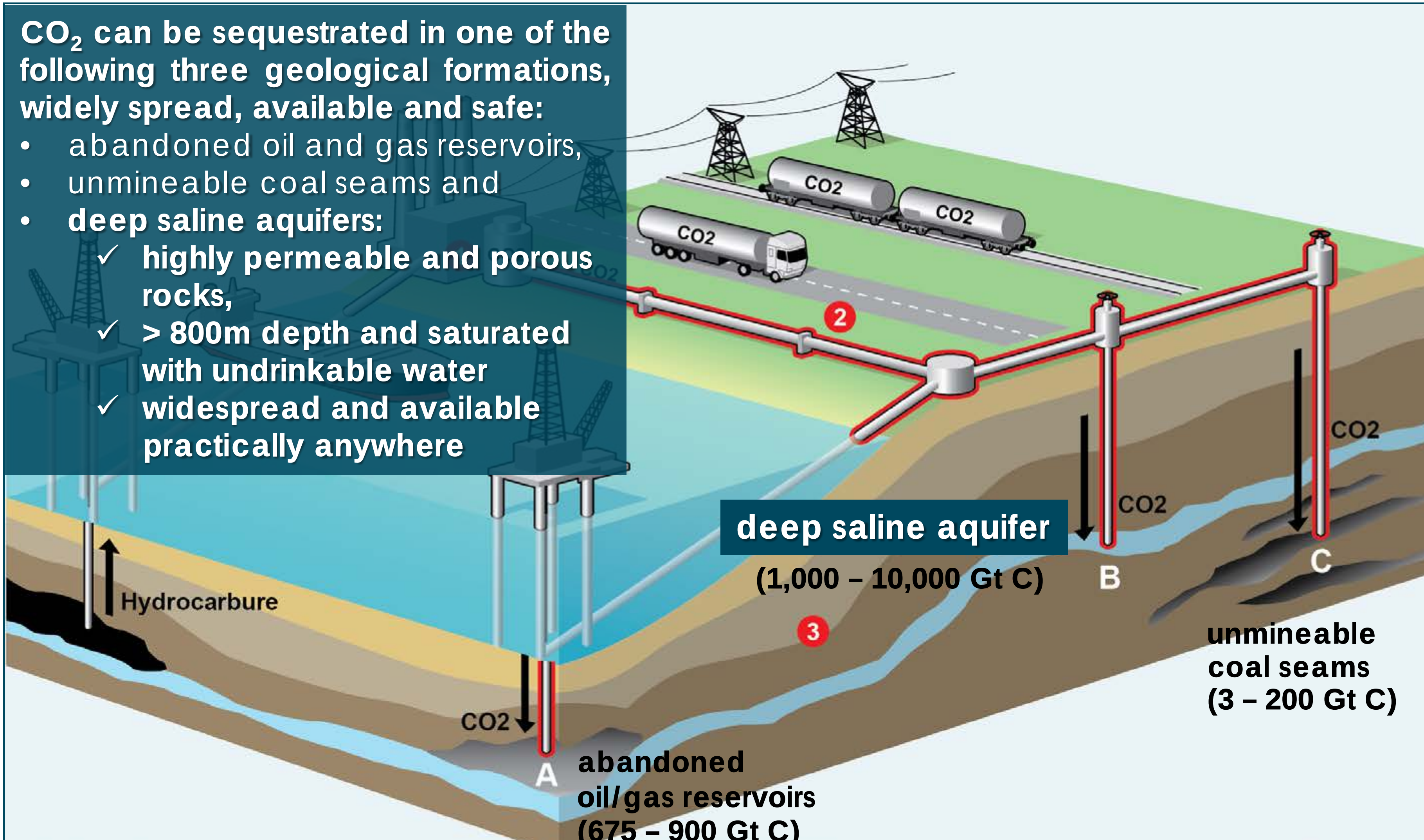


Geologic sequestration

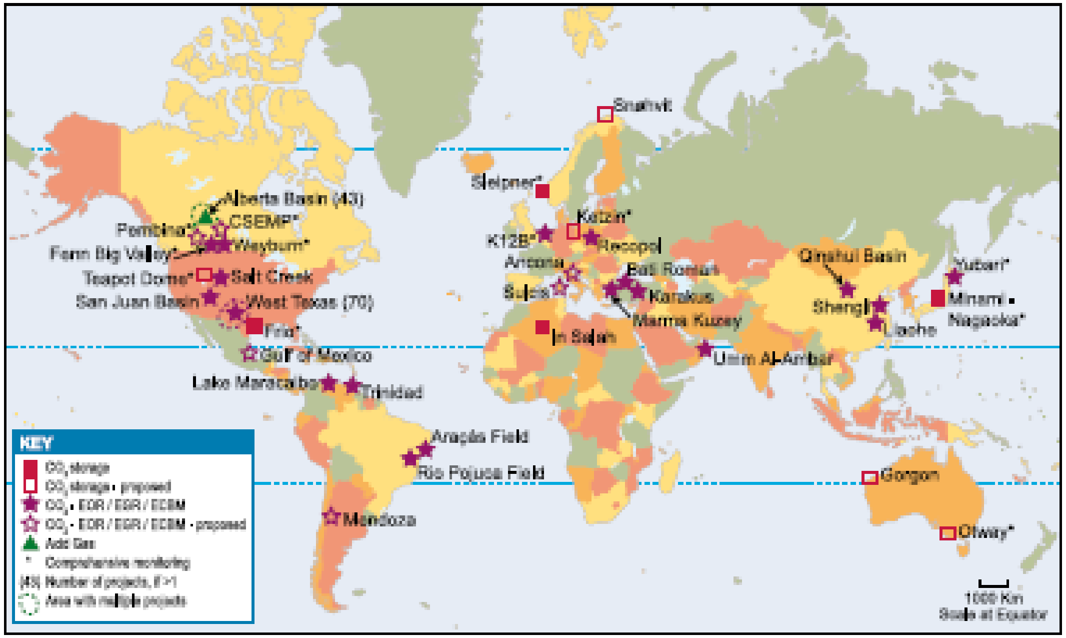


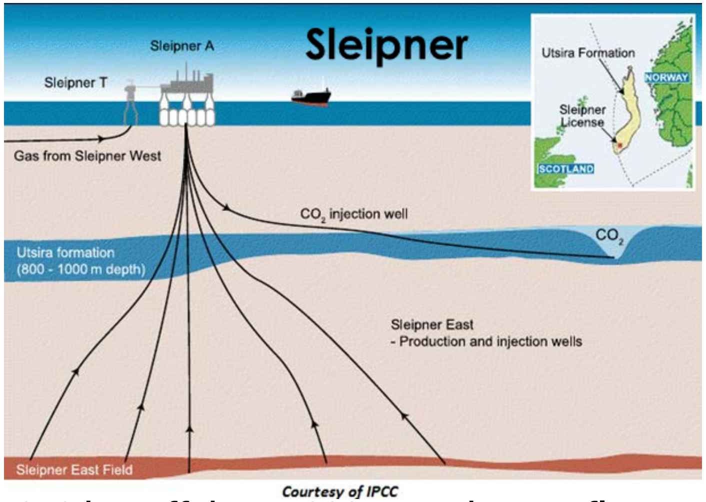
CO_2 can be sequestrated in one of the following three geological formations, widely spread, available and safe:

- abandoned oil and gas reservoirs,
- unmineable coal seams and
- **deep saline aquifers:**
  - ✓ **highly permeable and porous rocks,**
  - ✓ **> 800m depth and saturated with undrinkable water**
  - ✓ **widespread and available practically anywhere**



CO_2 sequestration – worldwide





Courtesy of IPCC

250 km offshore, 800 m under sea floor

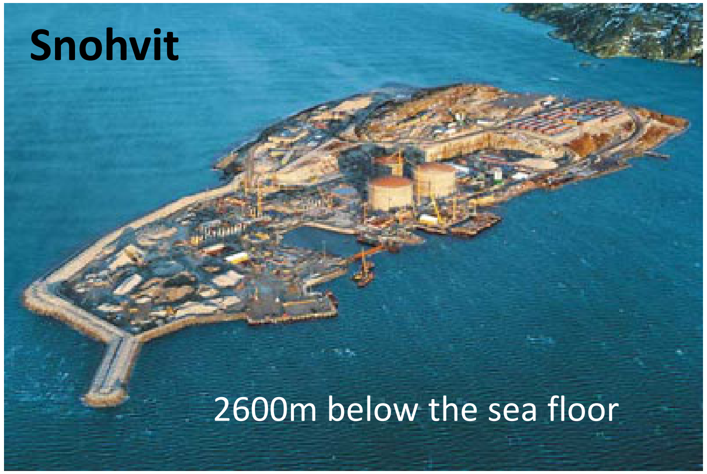
Injection: 2.5 kt CO_2/day (since 1996), 0.03 GT CO_2 have been sequestered so far

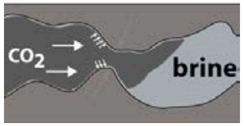
Depth: 800 - 2500 m

Overburden pressure: 20 – 100 MPa

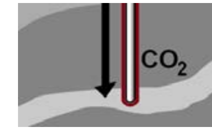
Water pressure: 7 – 40 MPa

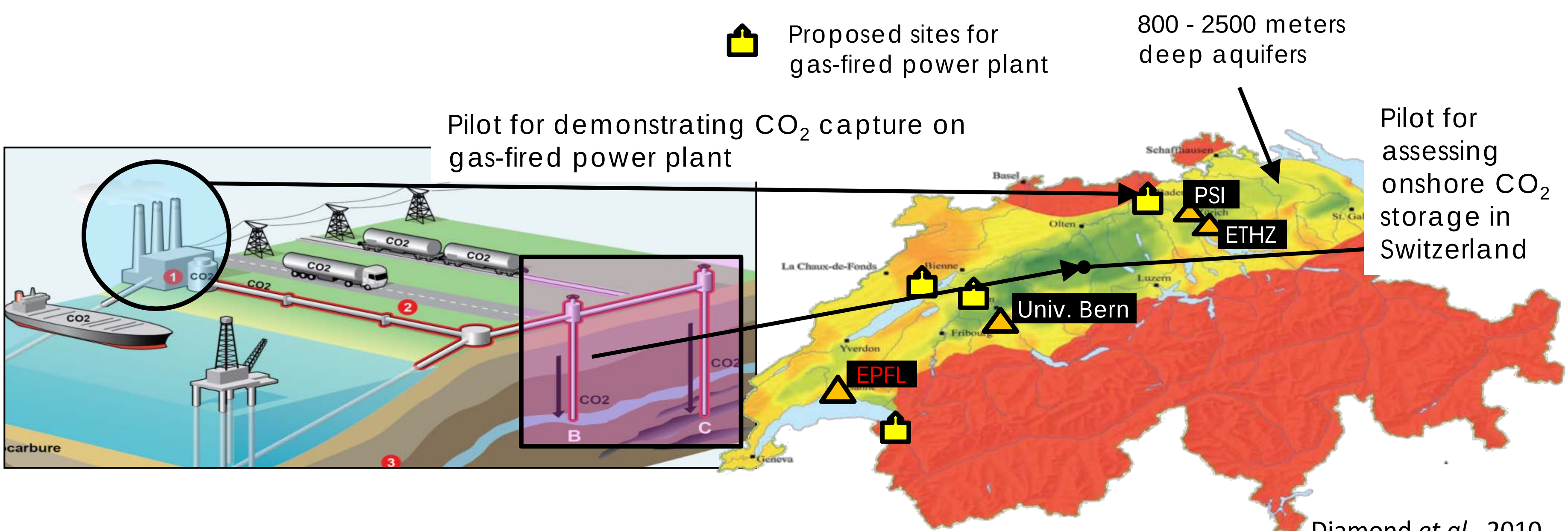
Temperature range: 25 – 125 ºC





CO_2 sequestration – Switzerland





Diamond *et al.*, 2010

<u>Switzerland (total):</u>

- 2.7 Gt of CO_2 can be stored
- current annual emission 11.3 Mt
- capacity of saline aquifers is sufficient for > 200 years

Aquifers:

<u>Upper Muschelkalk:</u>

65 m thickness, Dolomite

8.7 % of interconnected porosity

0.7 Gt CO_2 can be stored

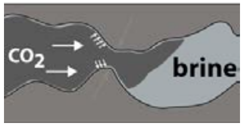
<u>Malm-Lower Cretaceous:</u>

50-1200 m thickness, Limestone

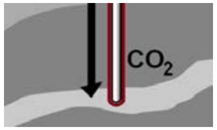
5 % of interconnected porosity

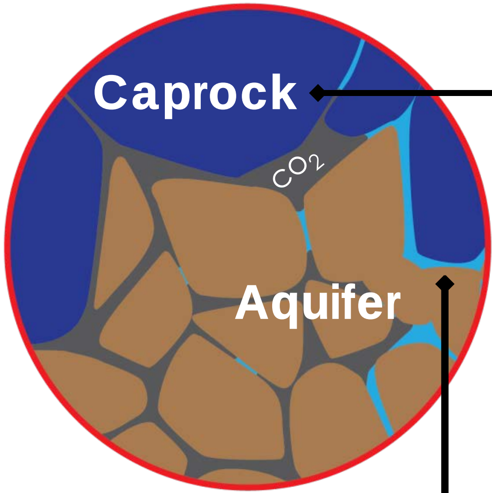
1.5 Gt CO_2 can be stored

Chevalier *et al.*, 2010

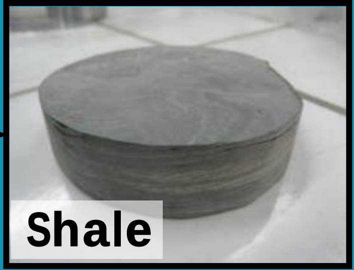


Reservoir materials





Candidate for sealing material



Mainly clay minerals and tiny fragments
Porosity: 5 - 30%
Intrinsic permeability: 10^{-10} – 10^{-7} cm/s
Stiffness: 1’000 – 70’000 MPa
Dominant pore size: dozens of nm

Candidates for host rock material

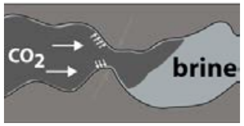
Mainly quartz and feldspar
Porosity: 3 - 30%
Intrinsic permeability: 10^{-7} – 10^{-2} cm/sec
Stiffness: 1’000 – 20’000 MPa
Dominant pore size: dozens of µm

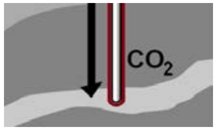
Mainly calcite
Porosity: 5 - 35%
Intrinsic permeability: 10^{-8} – 10^{-3} cm/sec
Stiffness: 1’500 – 55’000 MPa
Dominant pore size: dozens of µm

Under relevant CO_2 geological storage conditions, *limestone* suffers from potential alteration through chemical reactions with CO_2 saturated water.

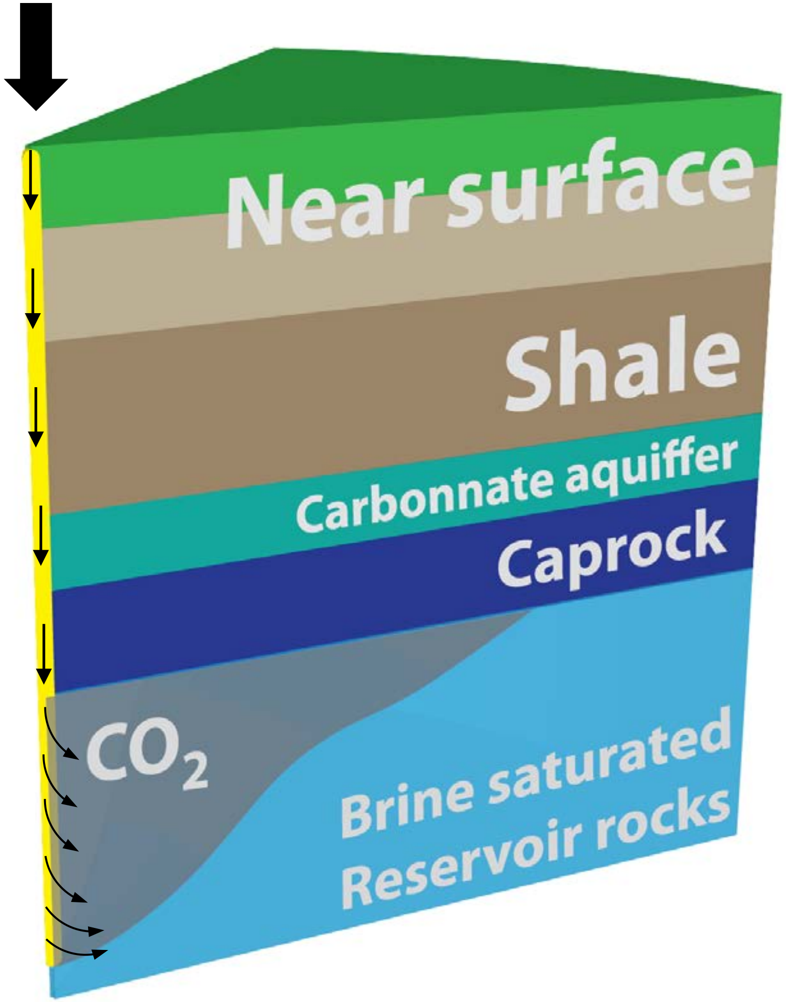
On the contrary, *sandstone* remains intact during the injection period.

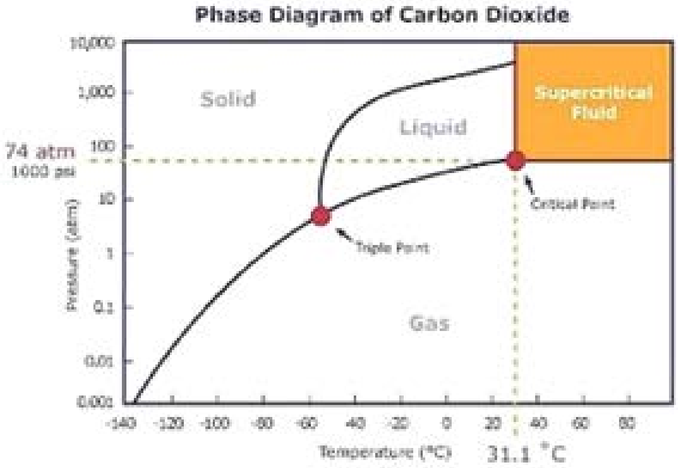
Injection of supercritical CO_2





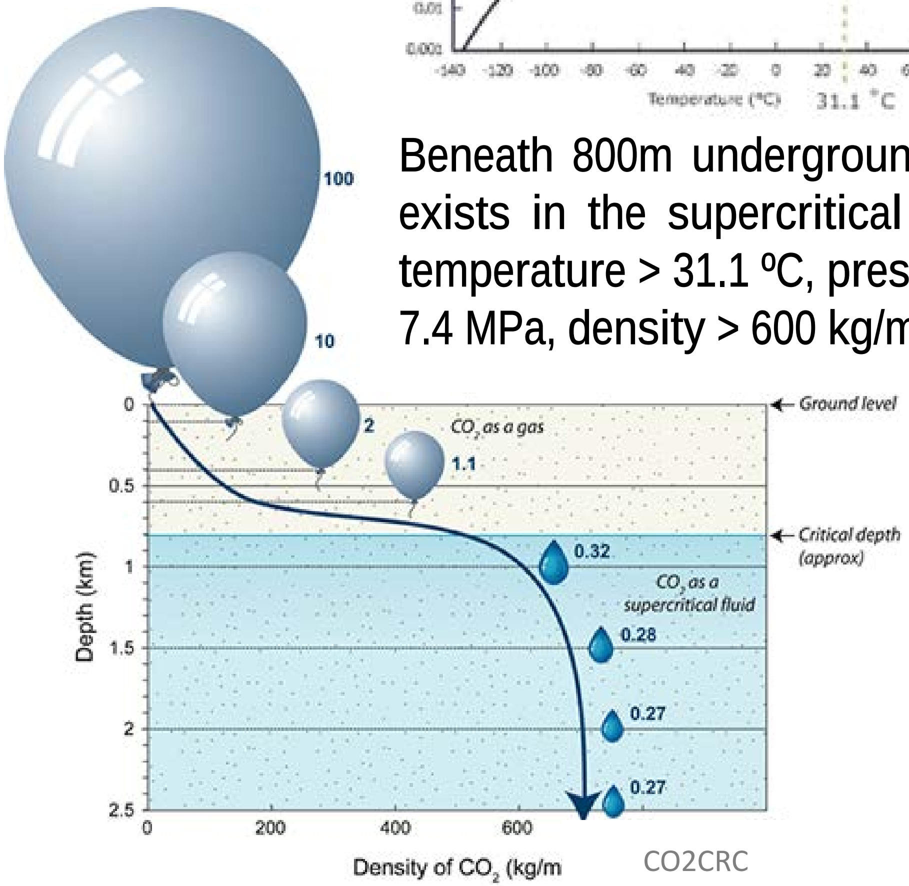
Injection of CO_2



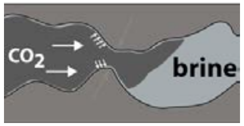


Nova Sterilis, 2014.

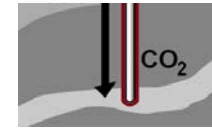
Beneath 800m underground CO_2 exists in the supercritical state: temperature > 31.1 ºC, pressure > 7.4 MPa, density > 600 kg/m^3



CO2CRC

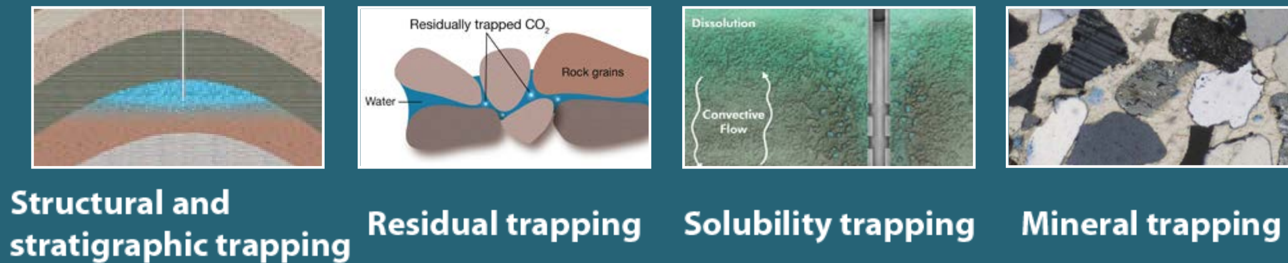


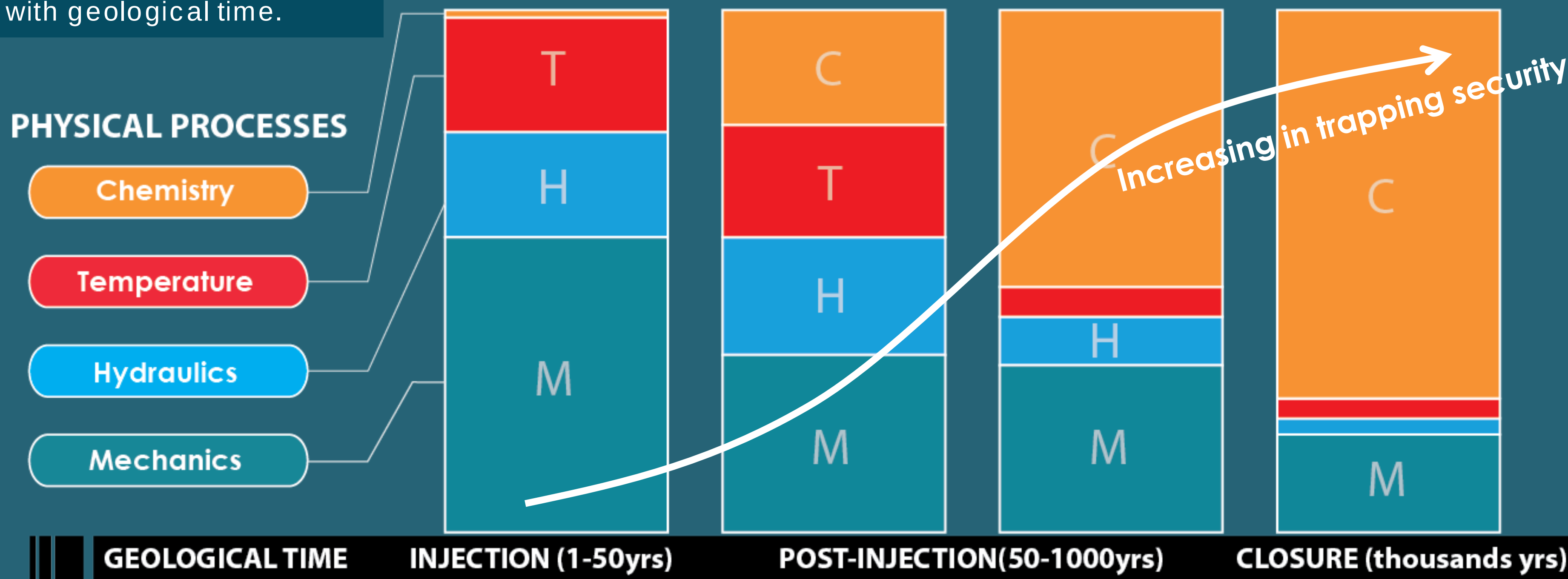
Trapping mechanisms



Trapping processes take place over many years at different rates from days to thousands of years.

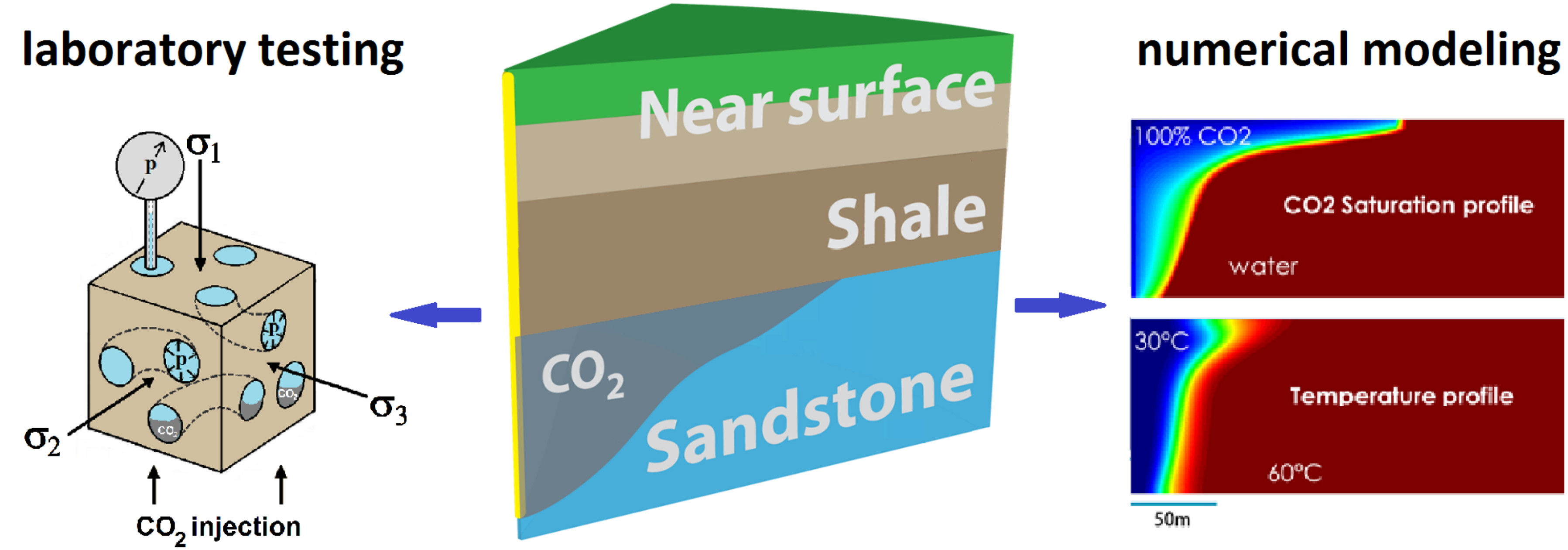
In general, CO_2 becomes ***more securely*** trapped with geological time.



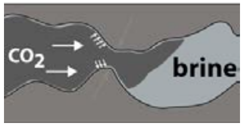


THM coupling behaviour during the injection phase is crucial to secure the CO_2 storage.

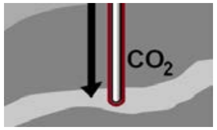
Chair « Gaz Naturel »



- understanding and prediction of the effects of surrounding environment, of mechanical and chemical changes as well as heat effect during CO_2 injection and storage
- experimental and numerical interdisciplinary research on the interplay between transport, reaction and mechanics
- advance scientific knowledge and provide reliable solutions to the industry.



Objectives of laboratory research

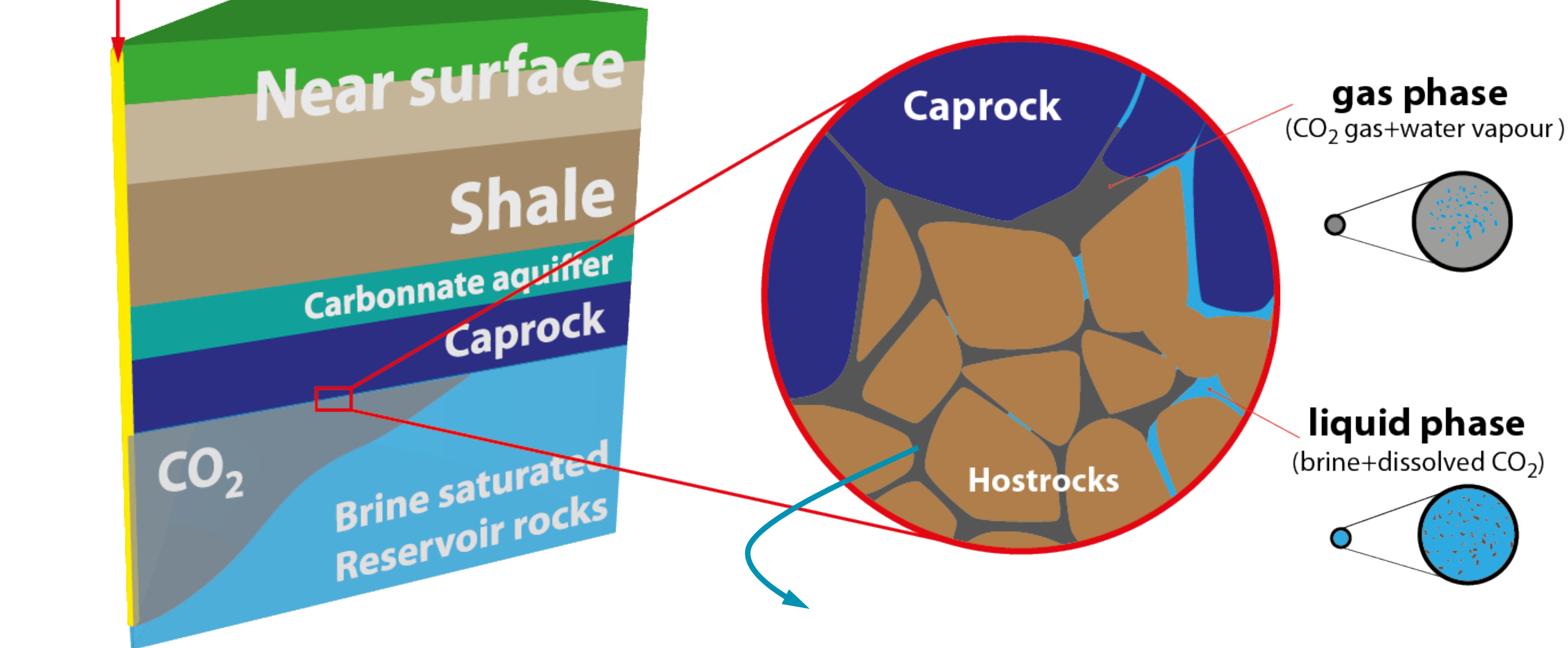


Characterization of thermo-hydro-mechanical behavior of possible host and cap rocks in contact with water, brine, supercritical and liquid CO_2

shale

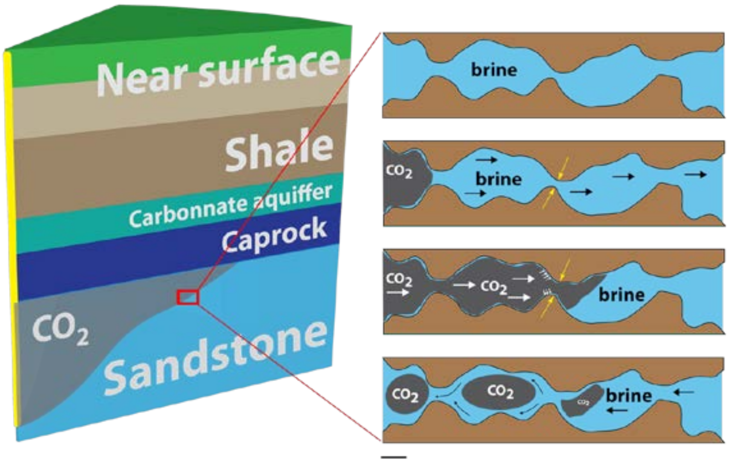
sandstone

limestone

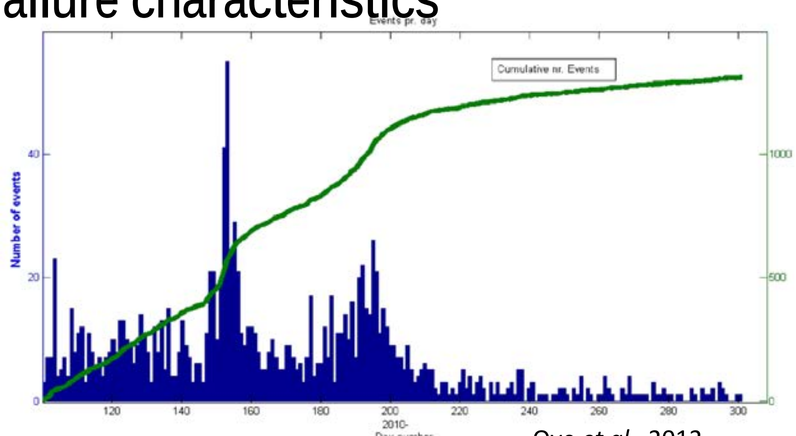


precipitation, cooling effect, chemical degradation, suction effect, permeability ↔ mechanical integrity

Host rocks: issues



- Change in poroelastic response due to chemical effect caused by CO_2 injection
- Change in inelastic parameters and failure characteristics



Oye *et al.*, 2012

Chemical reactions

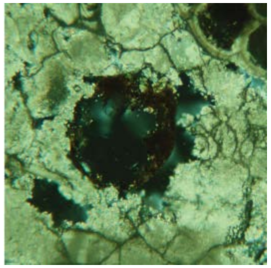
Dissolution

$$CO_{2\,(g)} \leftrightarrow CO_{2\,(aq)}$$
$$CO_{2\,(aq)} + H_2O_{(l)} \leftrightarrow H^+ + H_2CO^-_{3\,(aq)}$$
$$H_2CO^-_{3\,(aq)} \leftrightarrow H^+ + CO_{2\,(aq)}^{2-}$$

Reaction with carbonates (days/weeks)

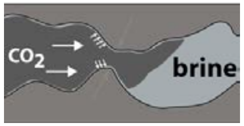
$$CaCO_{3(s)} + H^+ \leftrightarrow Ca^{2+} + HCO^-_3$$
$$CaCO_{3(s)} + CO_2 + H_2O \leftrightarrow Ca^{2+} + 2HCO^-_3$$
$$CaCO_{3(s)} + H_2O \leftrightarrow Ca^{2+} + HCO^-_3 + OH^-$$

Reaction with silicates (years)

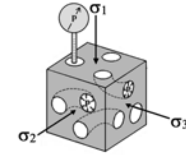


Ciantia & Hueckel, 2013

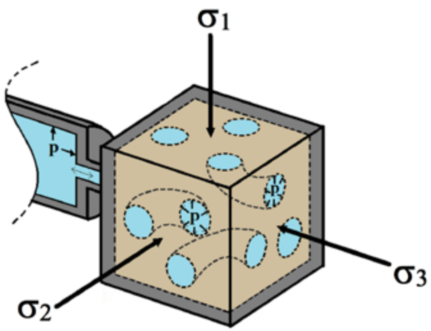
$$SiO_2 + 2H_2O \leftrightarrow H_4SiO_4$$
$$H_4SiO_4 \leftrightarrow H^+ + H_3SiO^-_4$$
$$H_3SiO^-_4 \leftrightarrow H^+ + H_2SiO^-_4$$



Poroelastic regimes



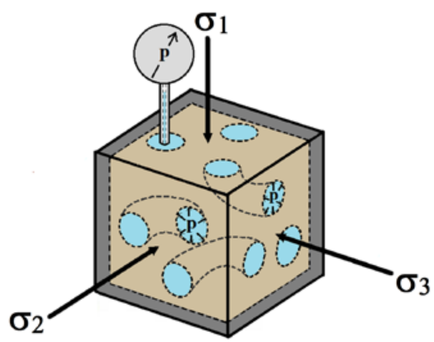
Drained



"drained" $\boldsymbol{\Delta p = 0}$

$$K = V \frac{\Delta P}{\Delta V}\bigg|_{\Delta p=0}$$

Undrained



"undrained" $\boldsymbol{\Delta m_f = 0}$

$$K_u = V \frac{\Delta P}{\Delta V}\bigg|_{\Delta m_f=0}$$

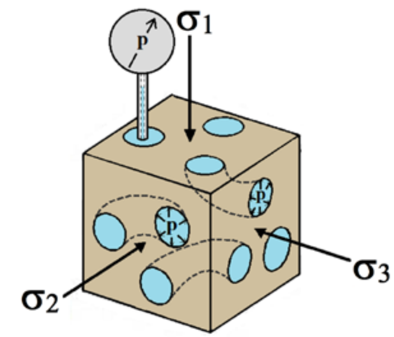
Skempton's coefficient:

$$B = \frac{\Delta p}{\Delta P}\bigg|_{\Delta m_f=0}$$

bulk modulus of pore fluid:

$$K_f = V_f \frac{\Delta p}{\Delta V_f}\bigg|_{\Delta m_f=0}$$

Unjacketed

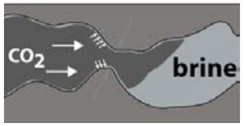


"unjacketed" $\boldsymbol{\Delta P = \Delta p}$

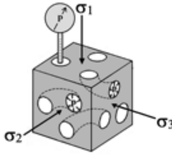
$$K_s' = V \frac{\Delta p}{\Delta V}\bigg|_{\Delta p=\Delta P}$$

unjacketed pore bulk modulus:

$$K_s'' = V_\phi \frac{\Delta p}{\Delta V_\phi}\bigg|_{\Delta p=\Delta P}$$



Host rock: sandstone



Berea sandstone (Ohio):

Slightly anisotropic (5% difference for ultrasonic velocities and 7-8% in UCS)

Porosity = 23%, density = 2100 kg/m^3 ,
UCS= 41-43 MPa, *E* = 13-15 GPa, and $\nu = 0.31$

Permeability *k* = 40 mD (at 5 MPa mean stress)

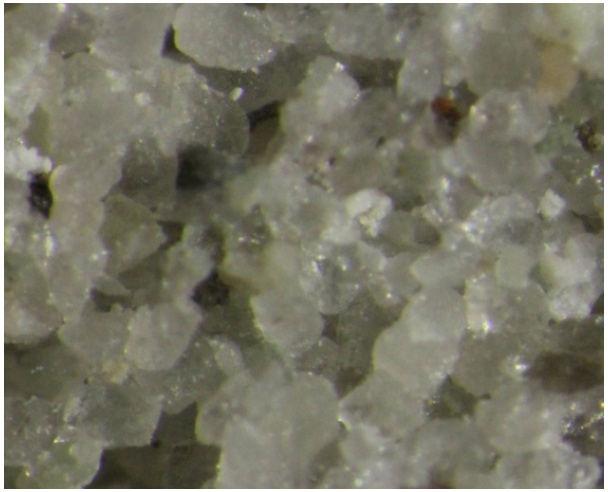
Diffusivity

$$c = \frac{2kG(1-\nu)(\nu_u - \nu)}{\mu\alpha^2(1-2\nu)^2(1-\nu_u)} = 0.2\,\frac{\text{m}^2}{\text{sec}}$$

$$t \approx \frac{L^2}{4c} = 0.01\,\text{sec}$$

- time to equilibrate Δp due to ΔP = 1 MPa

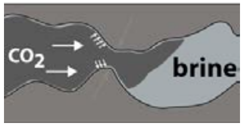
Berchenko *et al.*, 2004



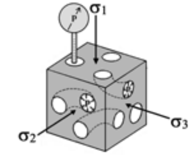
Mineralogical composition:
Quartz ~ 90%
Feldspar ~ 7%
Calcite ~ 1%
Clay – traces

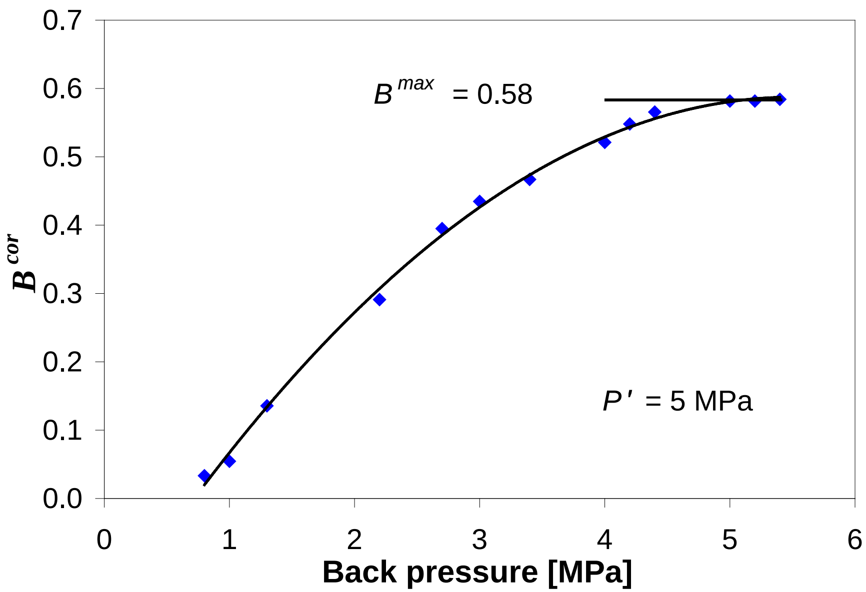
Quartz grain size ~ 0.2 mm

Makhnenko, 2013



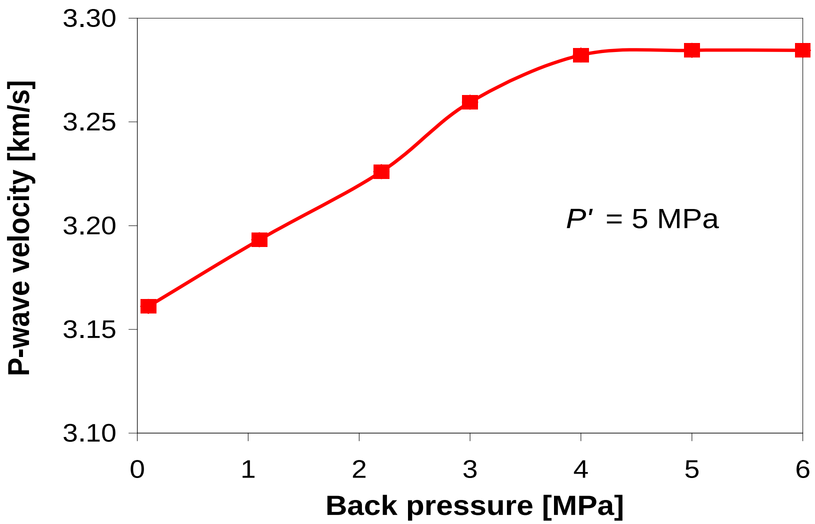
Poroelastic response: sandstone

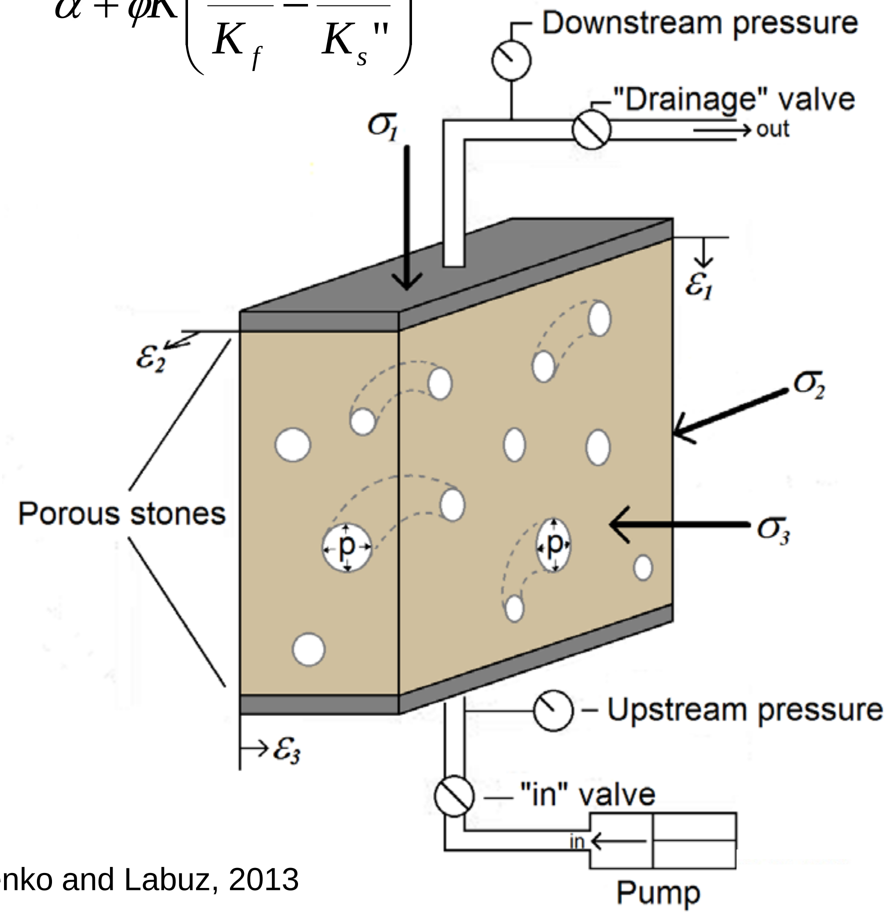




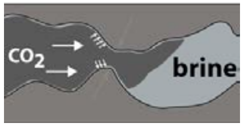
$$B^{cor} = \frac{1}{\left(\frac{(1+\nu_u)(\Delta\sigma_1+\Delta\sigma_3)}{3\Delta p}\right) - \frac{V_L}{V}\frac{K}{\alpha K_f}}$$

$$B = \frac{\alpha}{\alpha + \phi K\left(\frac{1}{K_f} - \frac{1}{K_s''}\right)}$$

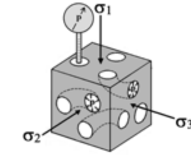




Makhnenko and Labuz, 2013



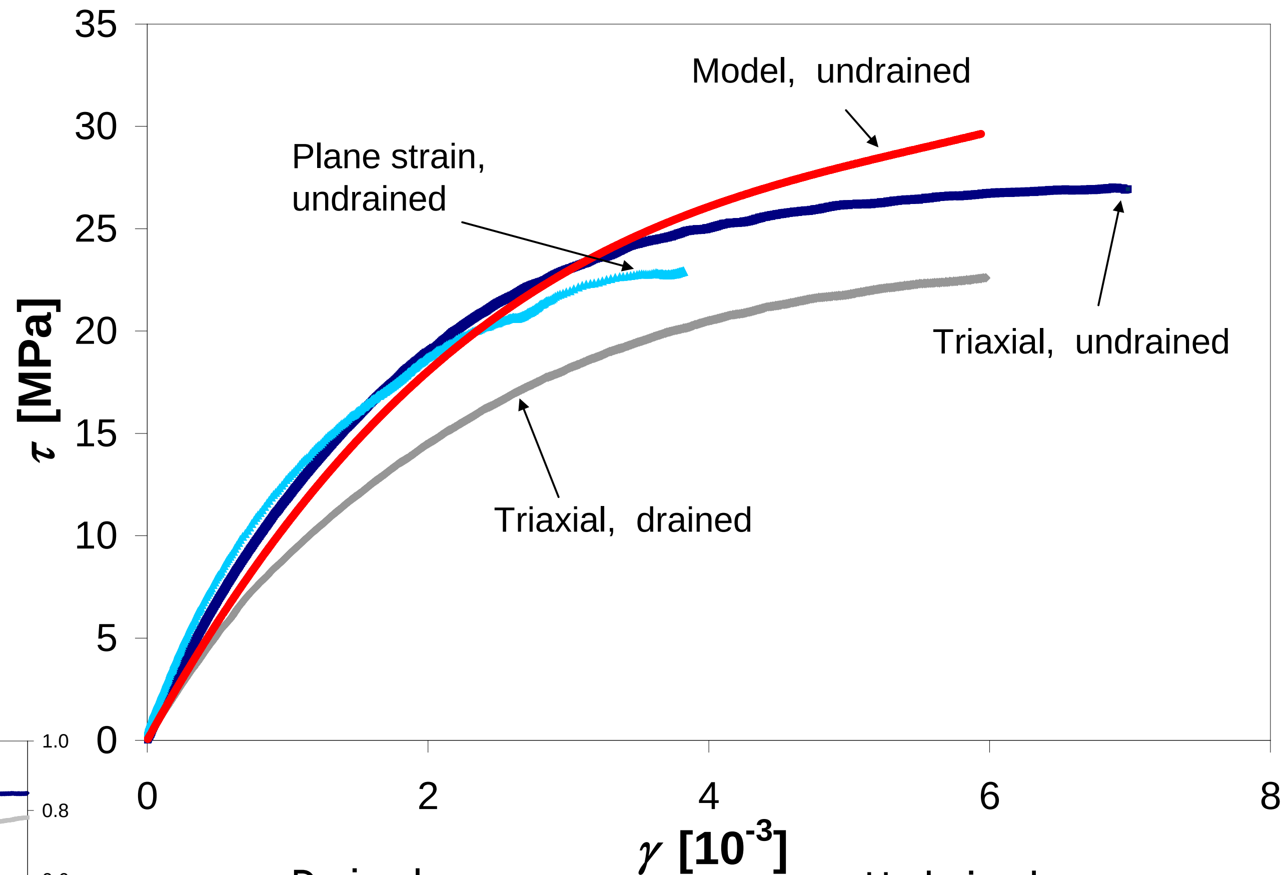
Constitutive response: sandstone

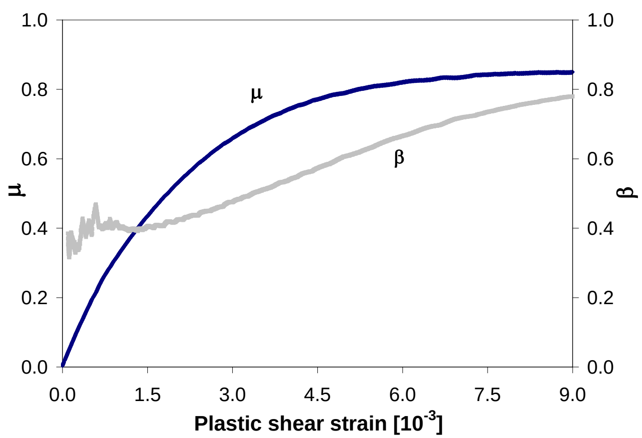


Initial conditions:
P = 20 MPa
p_o = 3 MPa

Drained:
$\Delta p = 0$

Undrained:
$\Delta m_f = 0$





Drained:

$$\frac{d\tau}{d\gamma} = \frac{H}{1 + H/G}$$

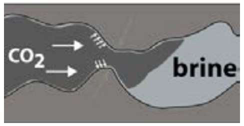
Rice 1975, Rudnicki 1985

Undrained:

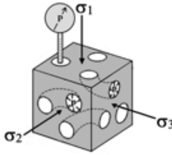
$$\frac{d\tau}{d\gamma} = \frac{H + \mu\beta K_{eff}}{1 + (H + \mu\beta K_{eff})/G}$$

$$1/K_{eff} = \upsilon\left(1/K_f - 1/K_s''\right) + \alpha/K$$

Makhnenko and Labuz, JGR-2014



Host rock: limestone

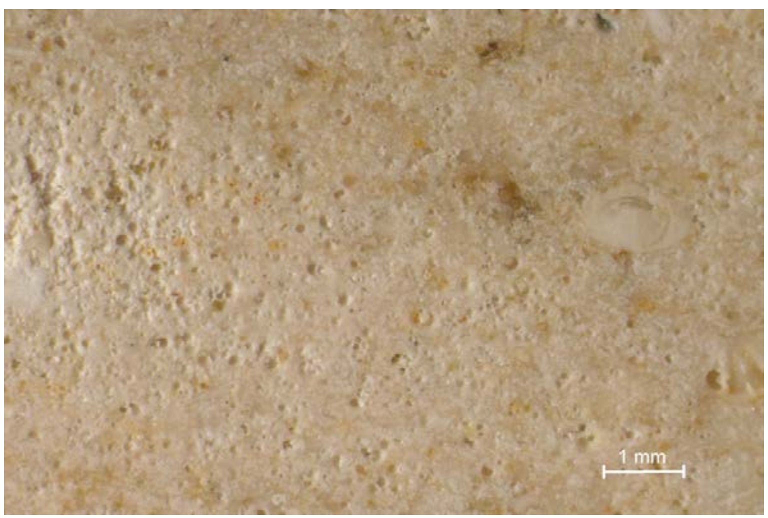


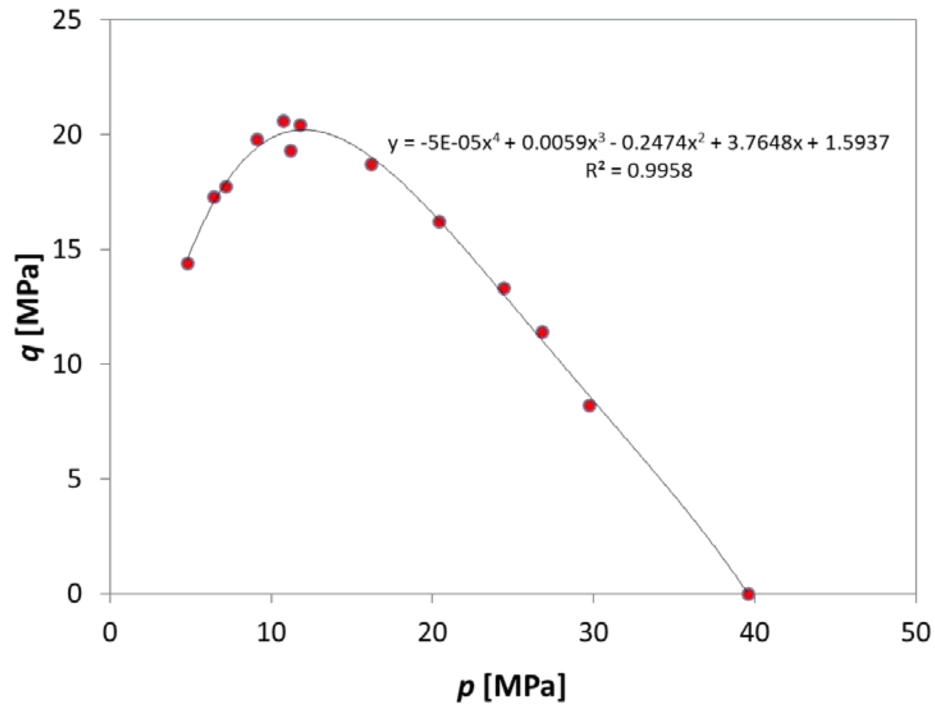
Calcarenite (Apulian limestone):

Close to be isotropic
(2% difference in ultrasonic velocities)

Porosity = 33%, density = 1400 kg/m^3 ,
UCS= 15 MPa, E = 7.3 GPa, and ν = 0.25

Permeability k = 3-5 mD (at P' = 5 MPa)





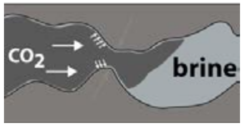
Mineralogical composition:

Calcite ~ 98%

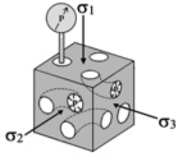
Traces of other minerals

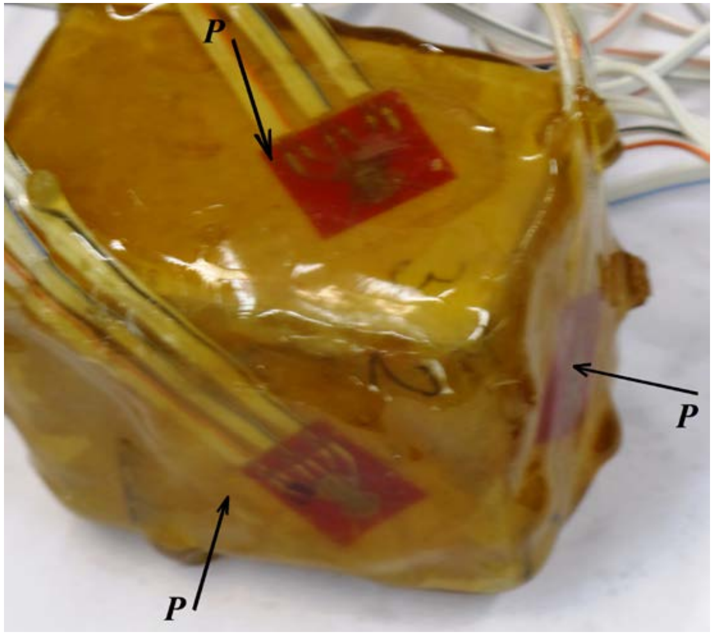
Grain size = 0.05 - 3 mm

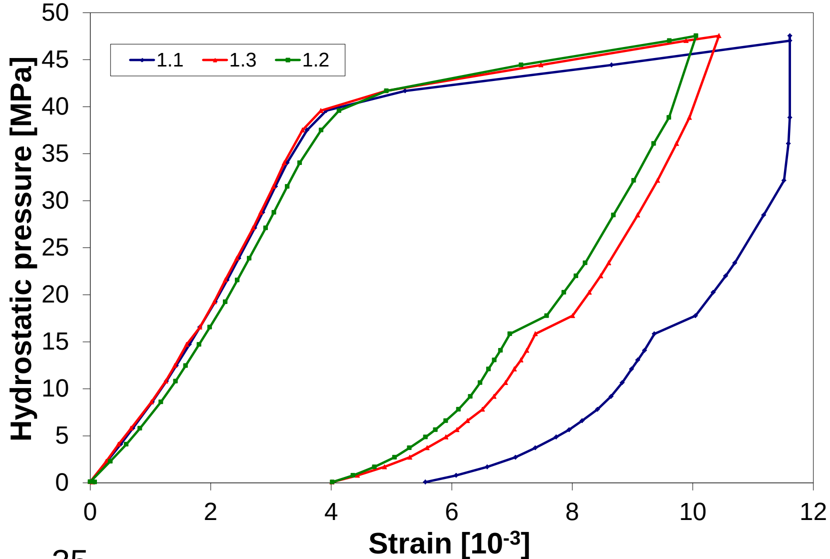
Makhnenko and Labuz, 2014



Poroelastic response: limestone





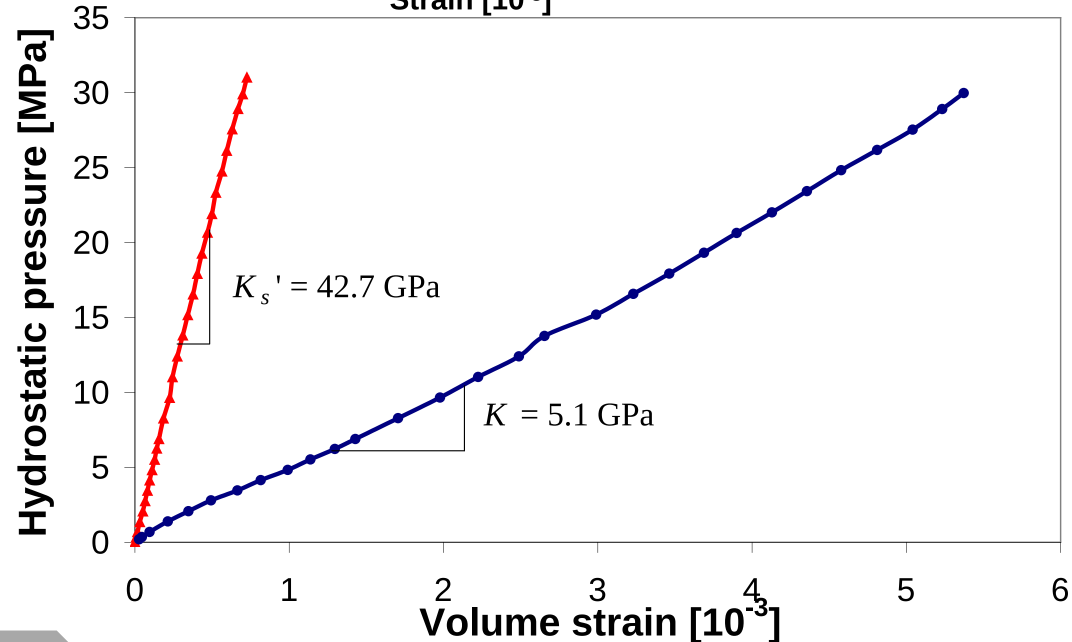


$$K = 5.1\,\text{GPa}$$

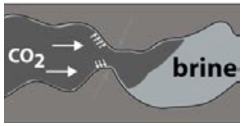
$$\alpha = 0.88$$

$$K_s' = 42.7\ \text{GPa}$$

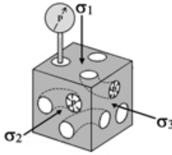
K_s' is significally smaller than $K_{calcite}$ – a lot of very small and non-connected pores

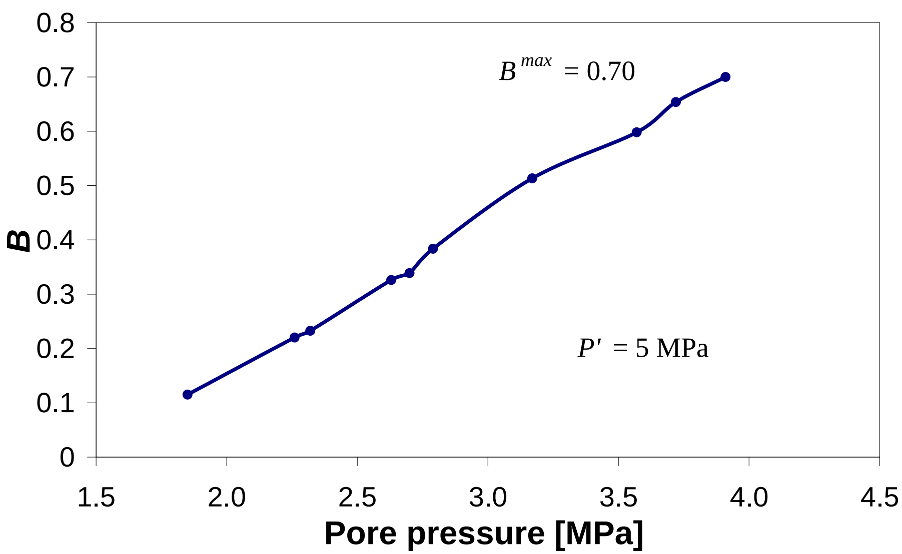


Makhnenko and Labuz, 2014



Characterization of dissolution





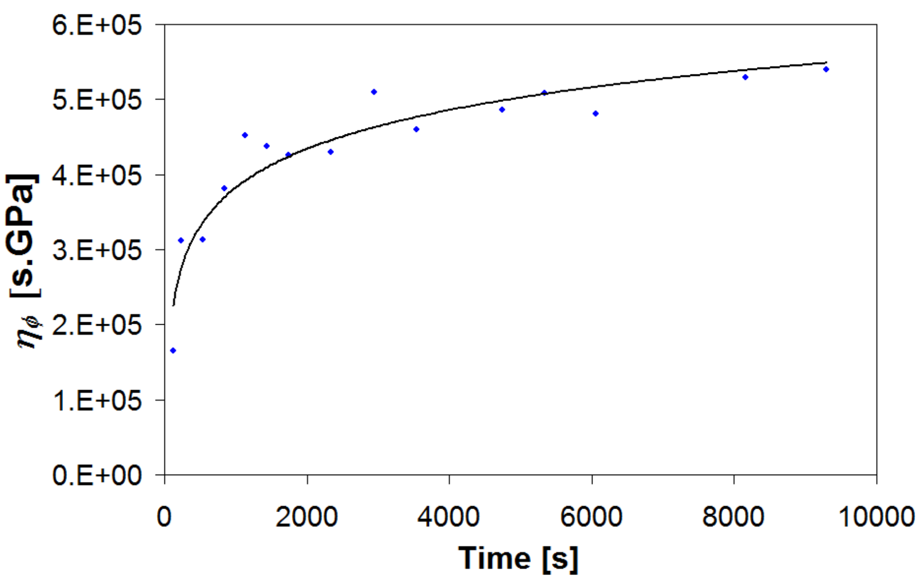
Viscoporoelastic formulation for undrained constant mean stress response:

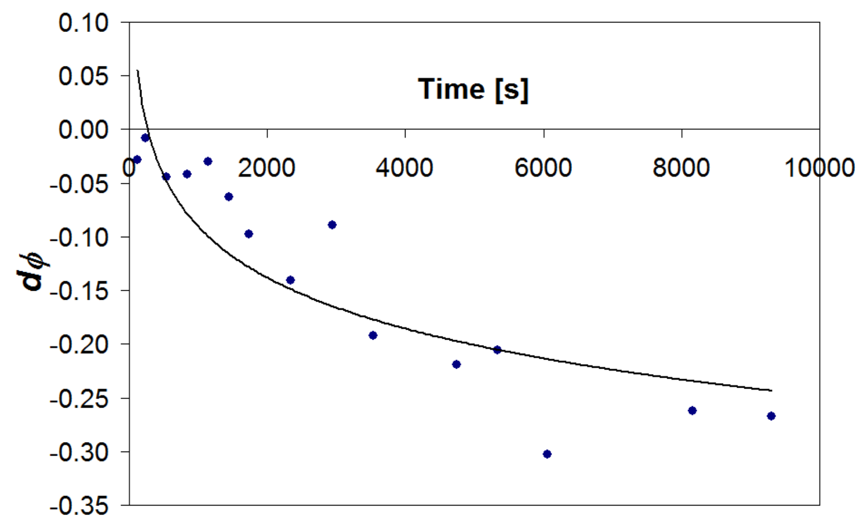
$$\frac{\alpha}{BK}\frac{dp}{dt} = \frac{1}{\eta_\phi(1-\phi)}(P-p)$$

$$\frac{d\phi}{dt} = \left(\frac{1}{K} - \frac{1}{(1-\phi)K_s'}\right)\frac{dp}{dt} - \frac{1}{\eta_\phi}(P-p)$$

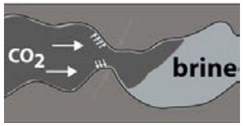
η_ϕ - matrix bulk viscosity

Connolly and Podladchikov 1998

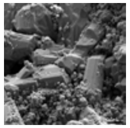




Makhnenko and Podladchikov, 2015



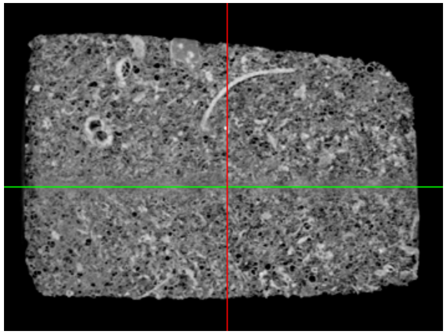
Characterization of chemical effect



X-ray CT scanning

8 µm/pixel

- microstructures
- pore space morphology and porosity
- fluid saturation
- mineralogical composition

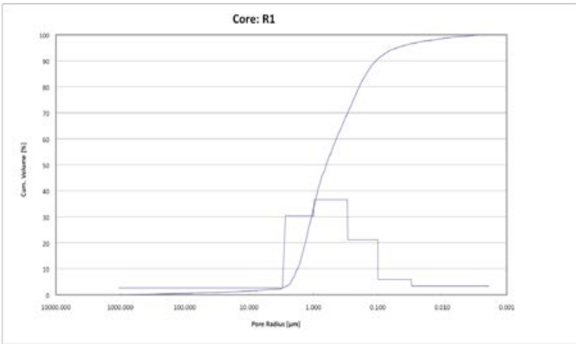


Non-destructive
Qualitative

Mercury Intrusion Porosimetry (MIP)

100-0.003 µm

- pore size ditribution
- relation between Hg pressure and volume of intruded pores.

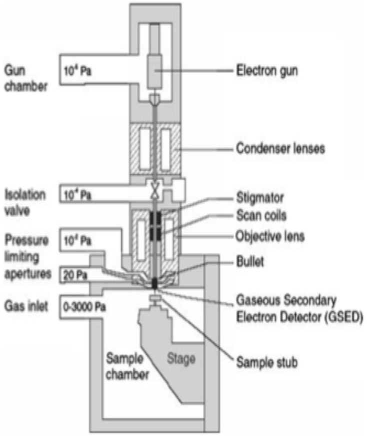


Destructive
Quantitative

Scanning Electron Microscopy (SEM)

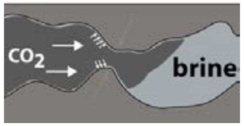
4 nm/pixel

- surface morphology and topography

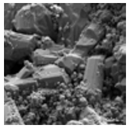


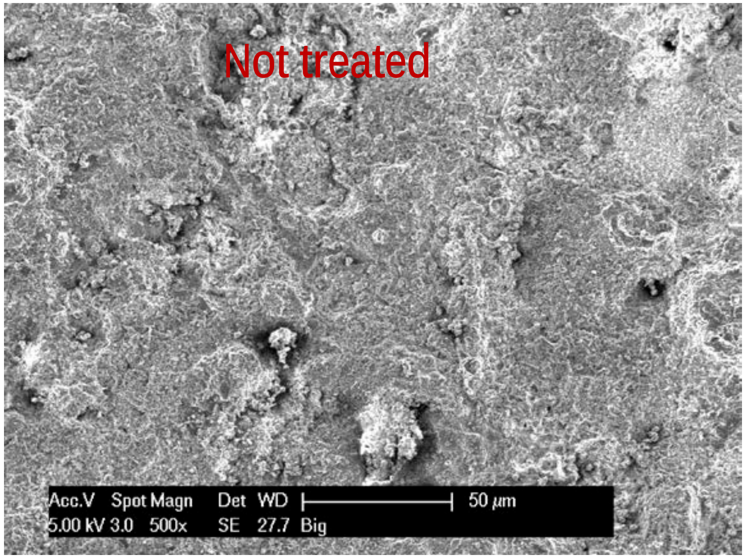
Destructive/non destructive
Qualitative

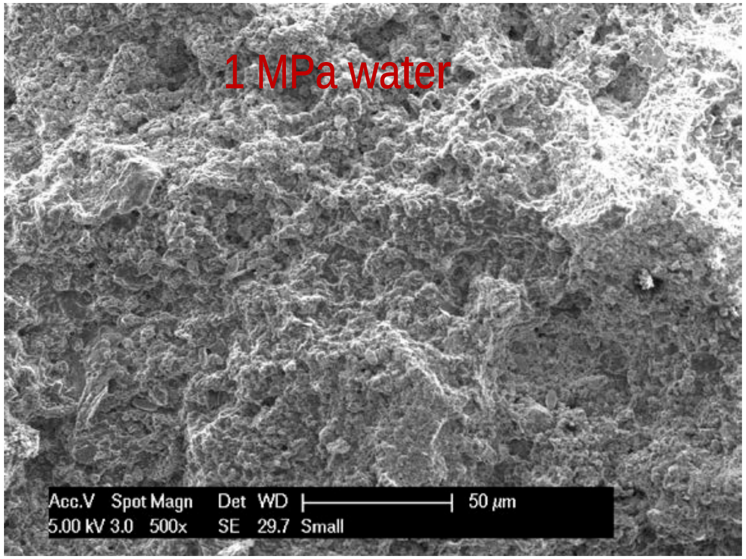
Romero et al, 2008



Scanning Electron Microscopy (SEM)

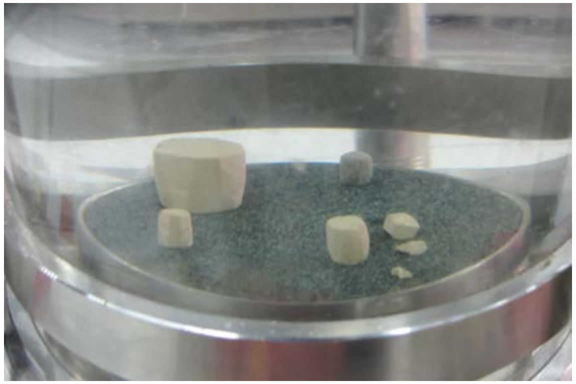


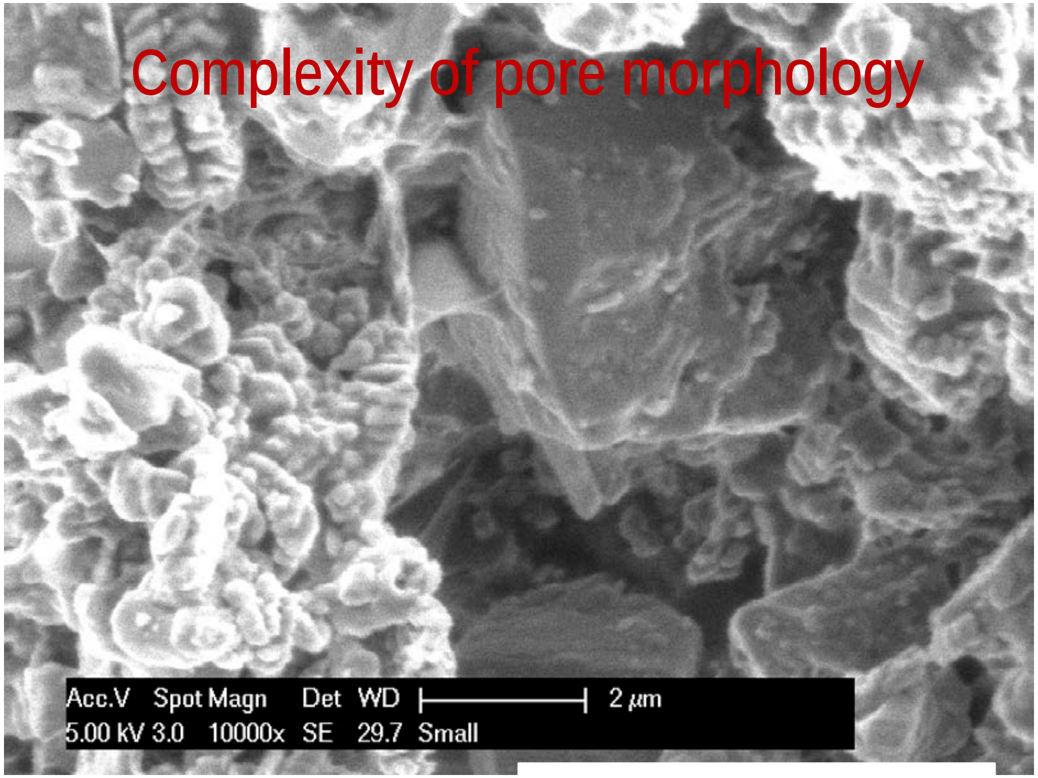


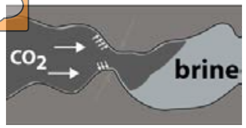


Water injection
(1 MPa for 4 days)

Goal: observe change in porosity and pore morphology



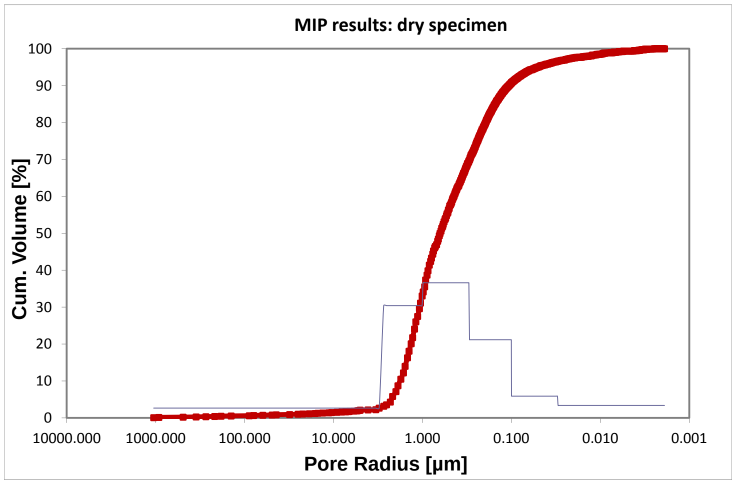


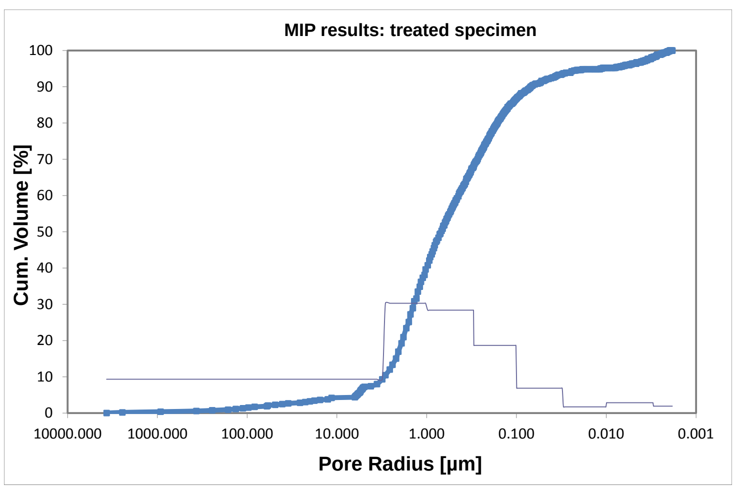


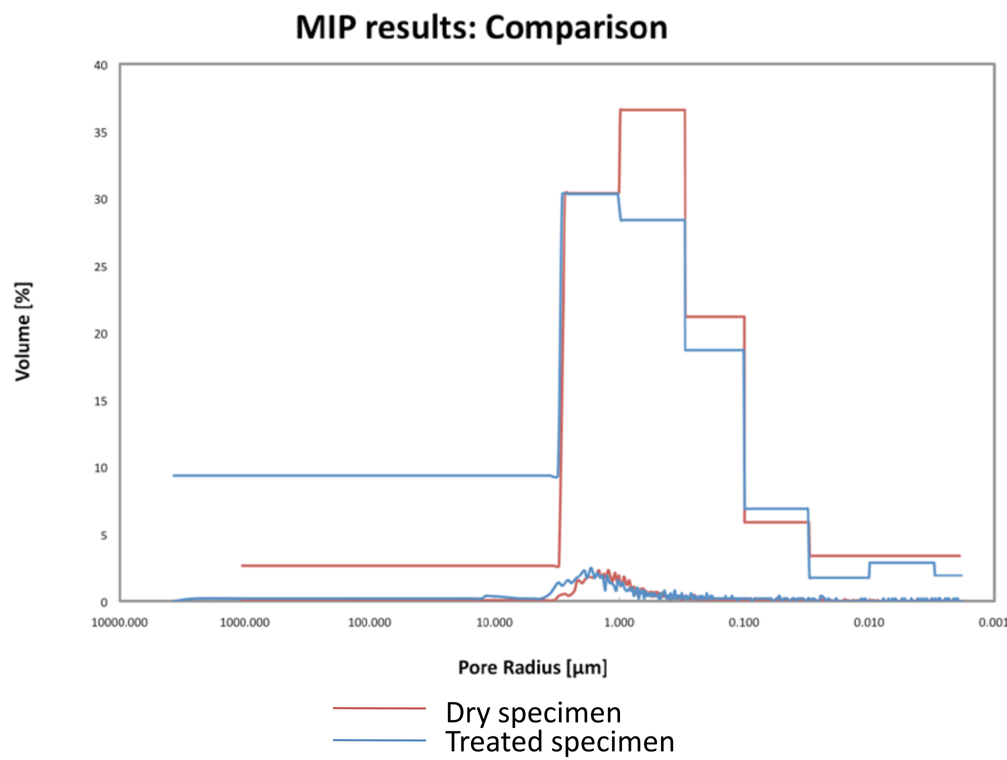
Mercury Intrusion Porosimetry (MIP)

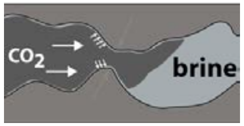
Treated and dry specimens of similar size were tested with MIP

- Cumulative volume of pores with radius larger than 5 μm increases from 3 to 10%
- Increase in total porosity is about 2-3%

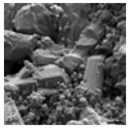


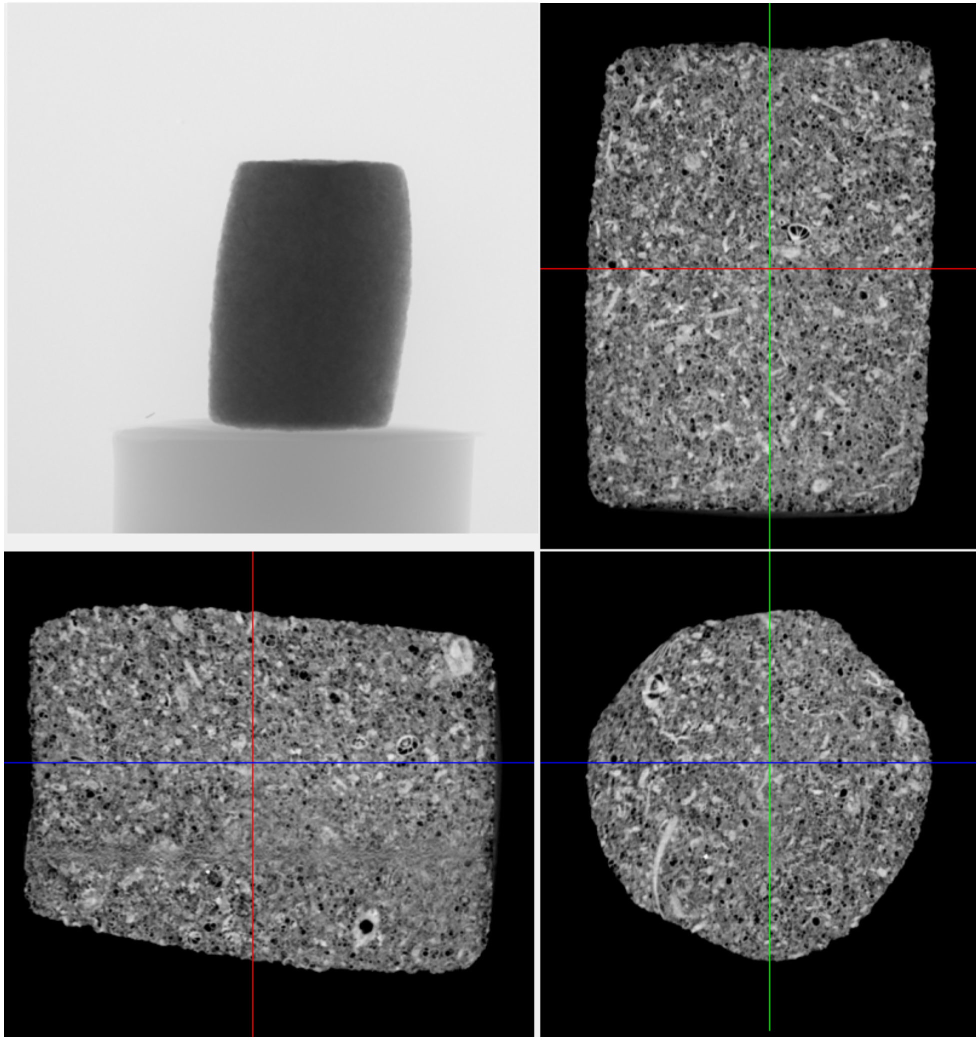


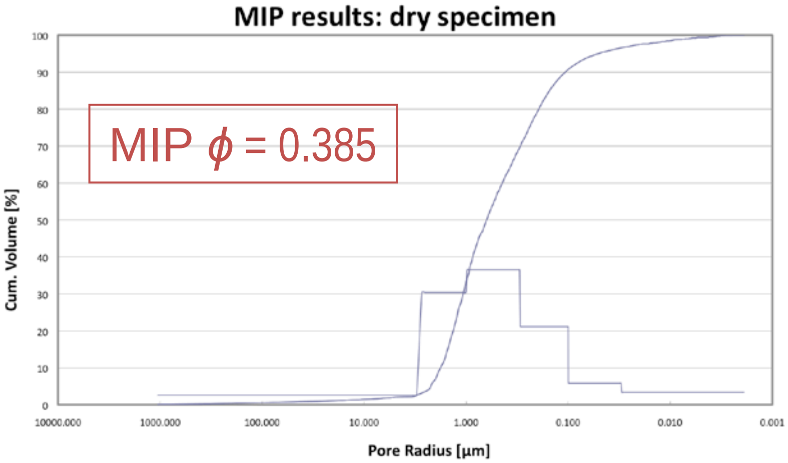




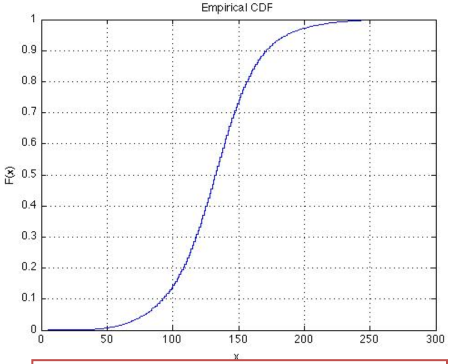
X-ray CT scanning







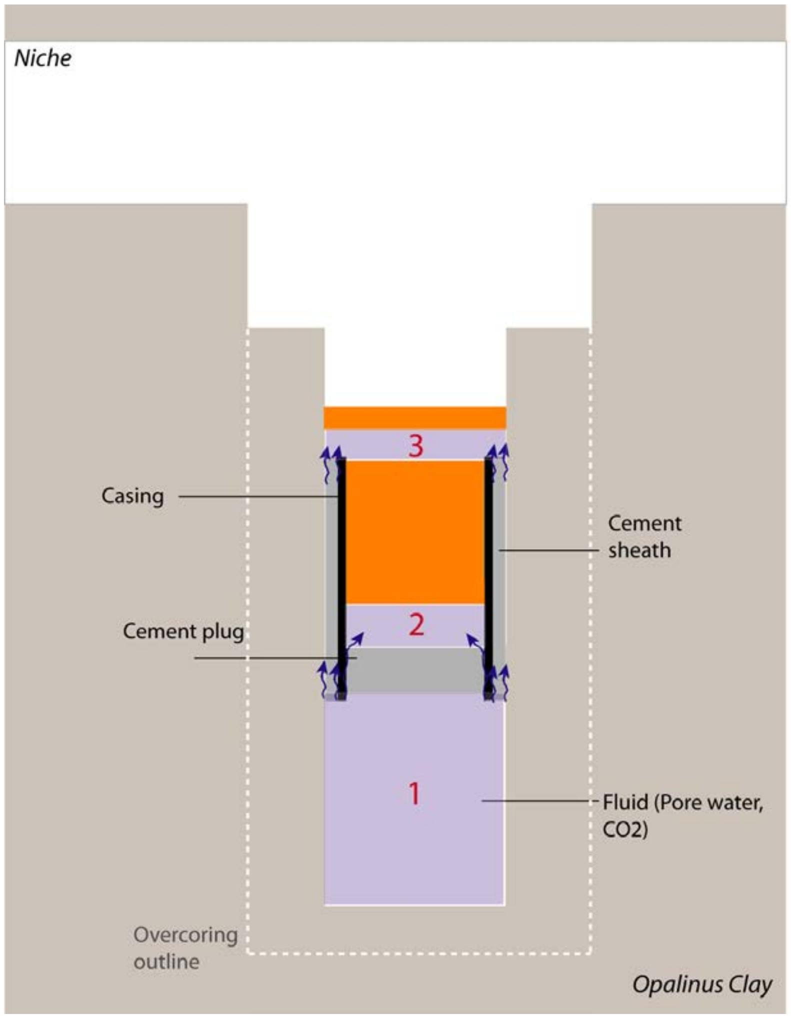
MatLab©
- Pixel size 8.41 μm
- Grey-scale 0-255

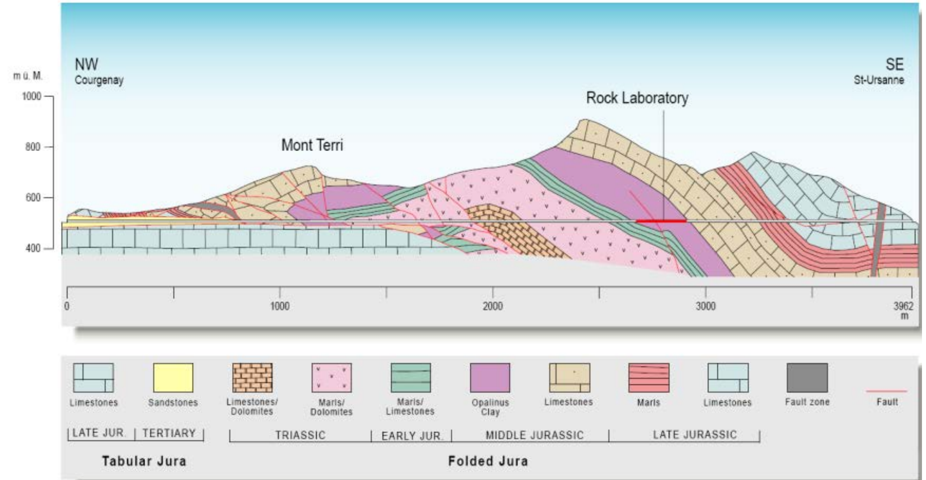


MatLab© ϕ = 0.375

- Each mineral has the same density
- Grey intensity is in proportion to pore size
- Normal distribution

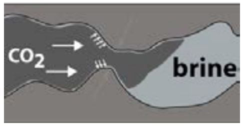
CO_2 injection project at Mont Terri



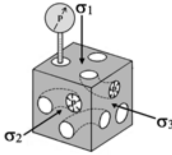


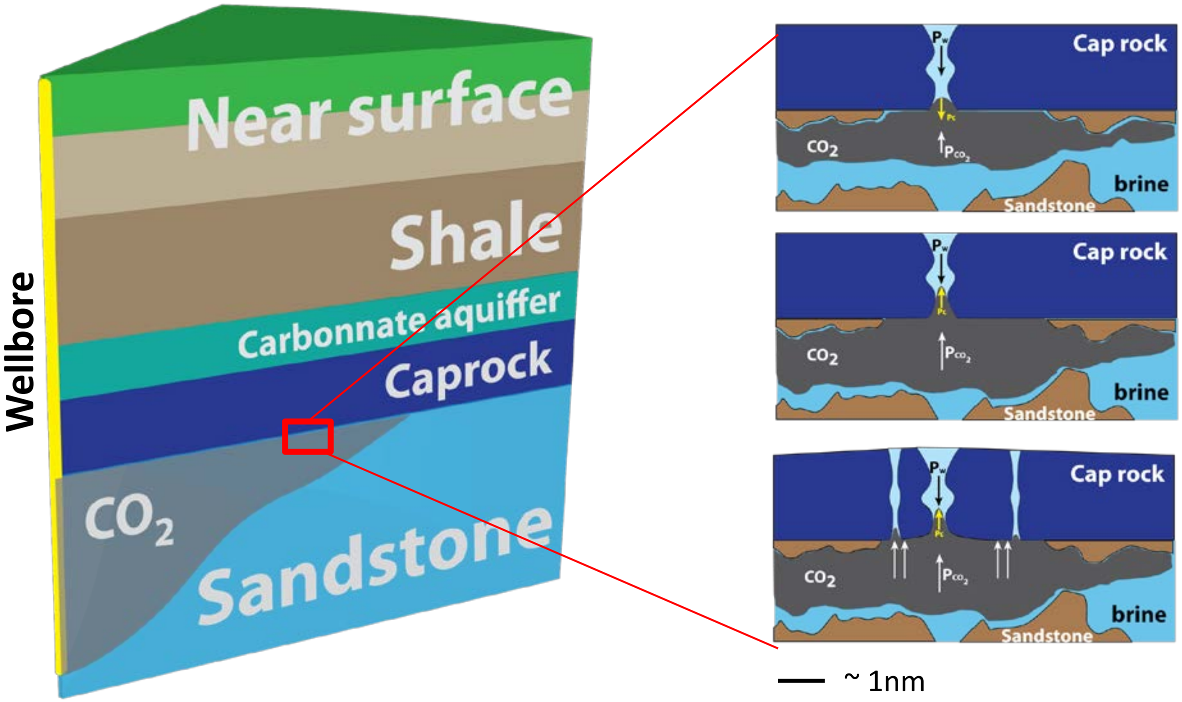
- Main Objectives
  - Build well elements
  - Measure of the flow inside and outside the casing
    -> *sealing changes*
  - Sample fluid across time
    -> *fluid changes*
  - Take samples of the different elements (overcoring)
    -> *mineralog. changes*

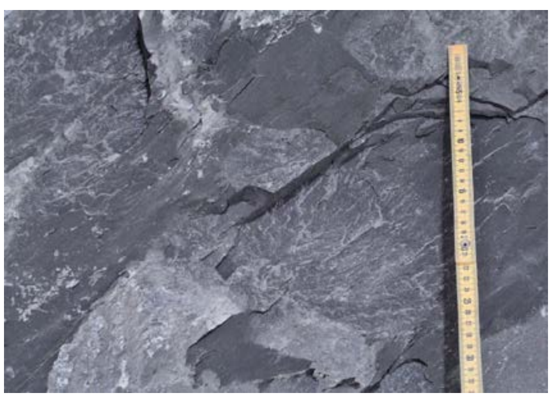
swisstopo



Caprock - issues

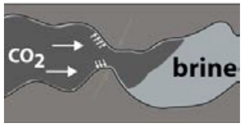




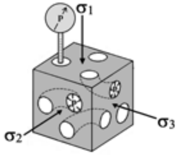


mont-terri.ch

- Seal permeability (w/ respect to H_2O and CO_2)
- Seal capacity (CO_2 retention properties)
- Seal integrity (propensity for brittle or ductile behavior)
- Pressure build-up due to injection of CO_2
- Geomechanical/failure characteristics (effect of in-situ stress variations)
- Change in mineralogy/ porosity/ permeability due to the chemical effect



Geomechanical testing of shales

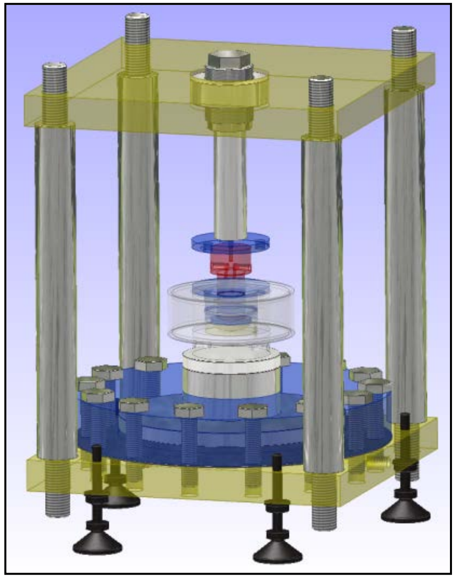


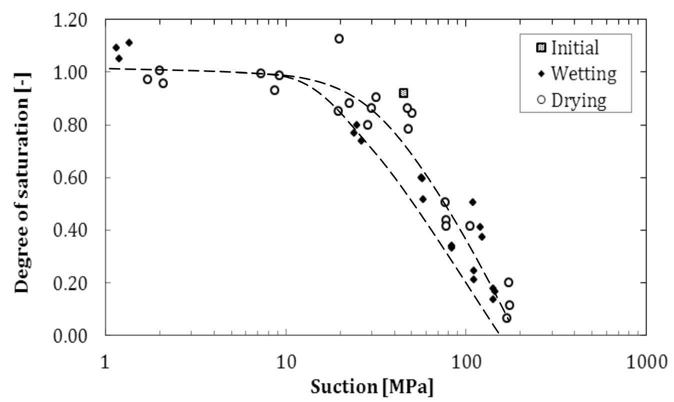
Opalinus clay behavior at different mean stresses and temperatures:

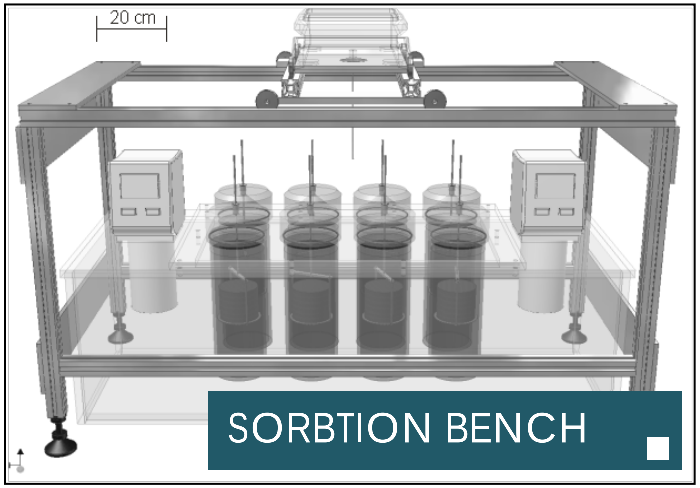
Water retention curve of Swiss shale

[Ferrari, Manca, Laloui]

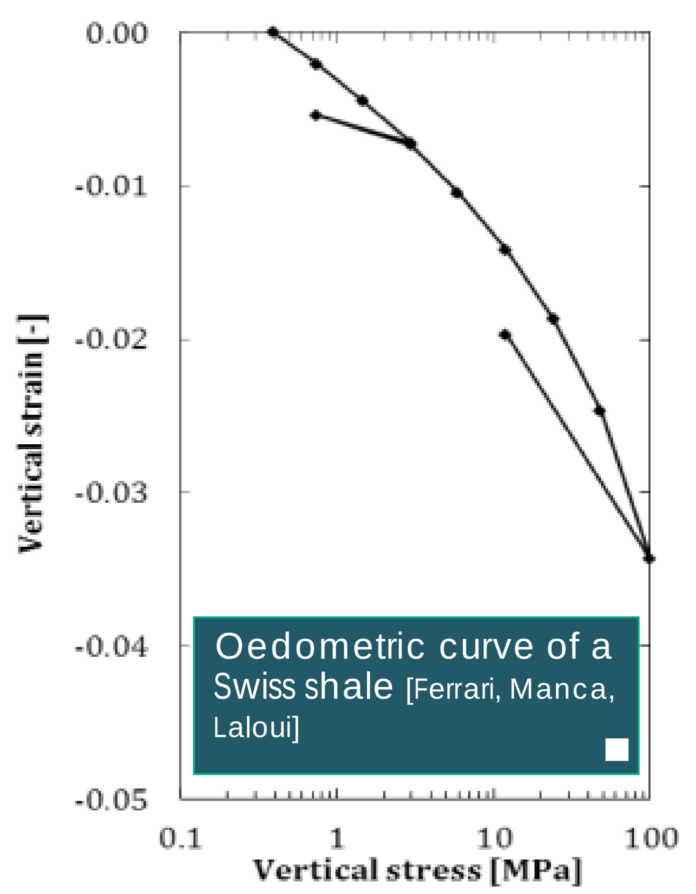
HIGH-PRESSURE OEDOMETER



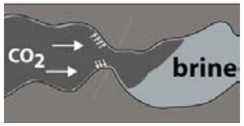




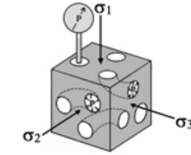
SORBTION BENCH

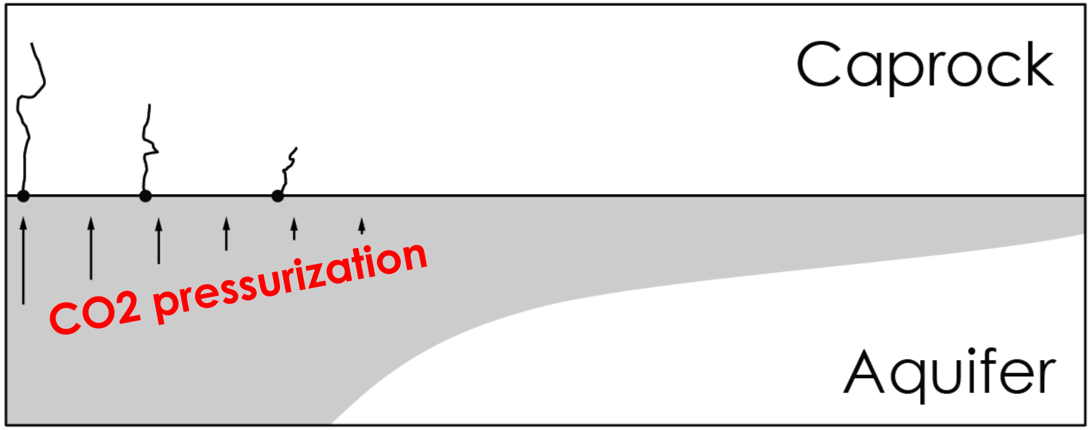


Oedometric curve of a Swiss shale [Ferrari, Manca, Laloui]



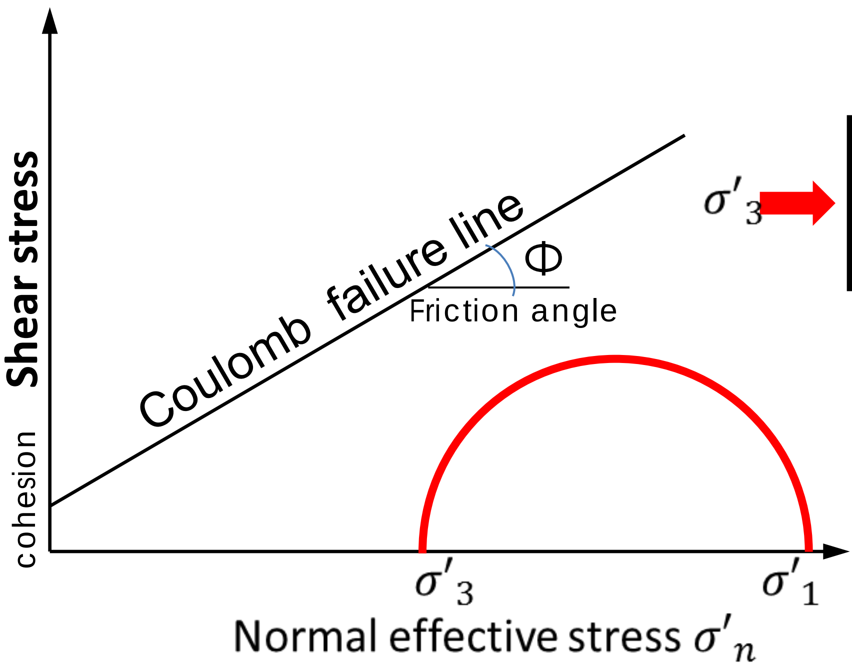
Caprock: failure

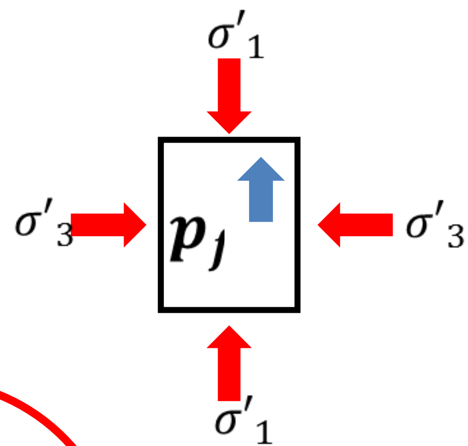


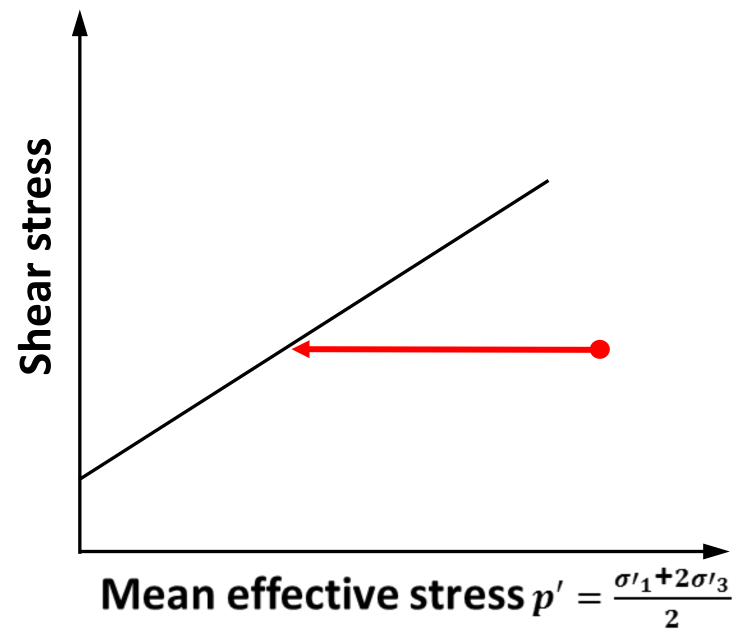


Mechanical weakness:
the interface between the caprock and the aquifer:

- Primary barrier to prevent CO_2 from leakage
- Failure potentials to be evaluated



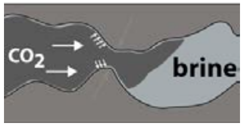




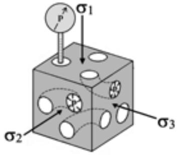
$$p_f = S_c p_c + S_w p_w$$

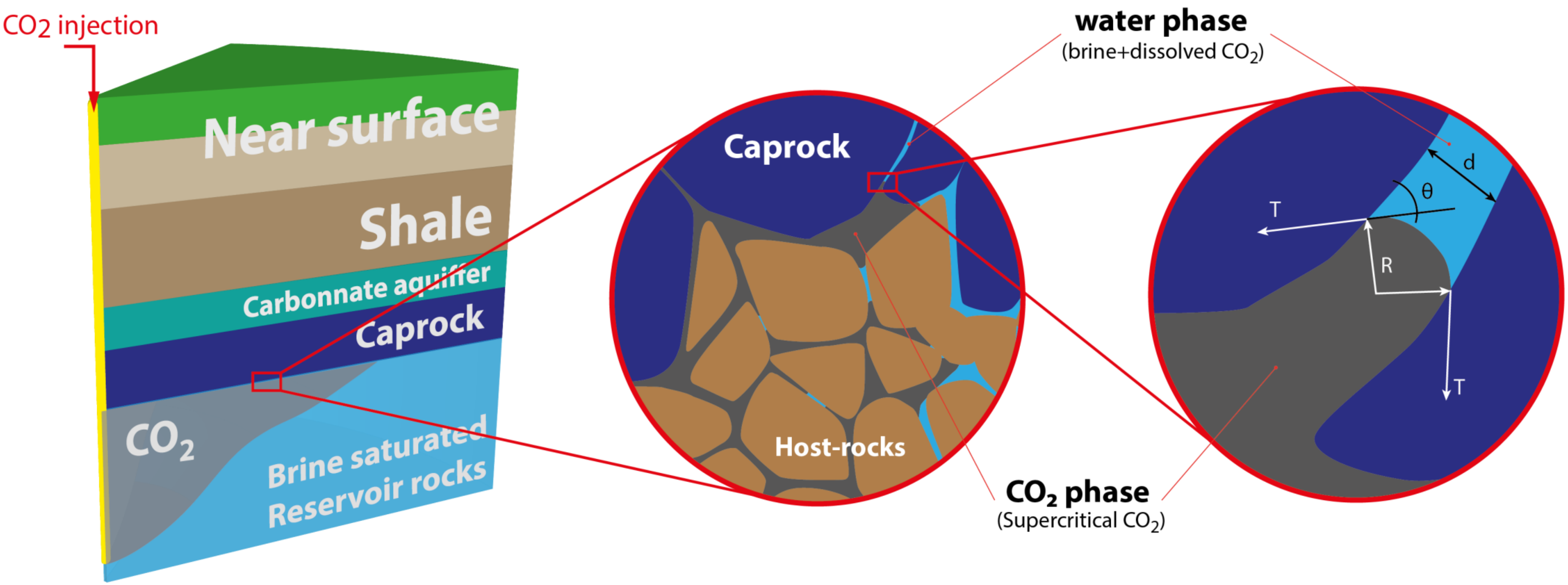
$$\sigma' = \sigma - p_f$$

Laloui and Li, 2014



Capillary effects

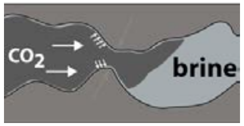




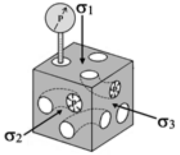
Wetting phase : water

Non-wetting phase : CO_2

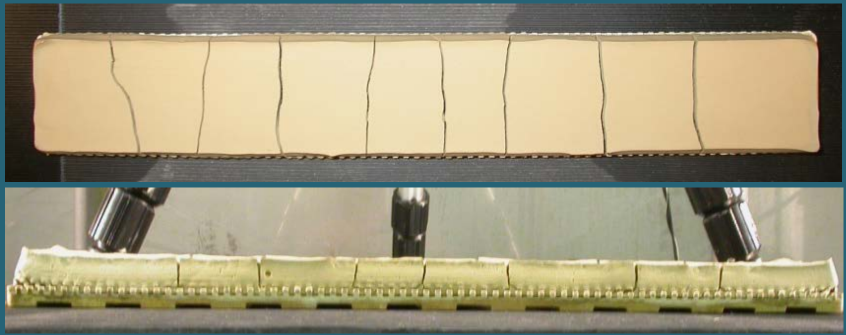
Capillary stress : $p_w - p_{CO_2} = -\dfrac{4T\cos\theta}{d} = -\dfrac{2T}{R}$



«Capillary» failure



- CO_2 pressure increase / capillary stress increase / effective stress increase ➡ mass shrinkage (*free* shrinkage)



- If shrinkage is constrained, reaction forces arise.

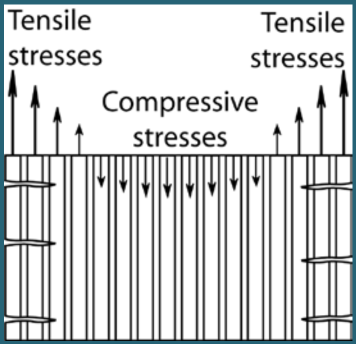
tensile stresses are built up, tensile strength is reached ➡ cracks appear and propagate.

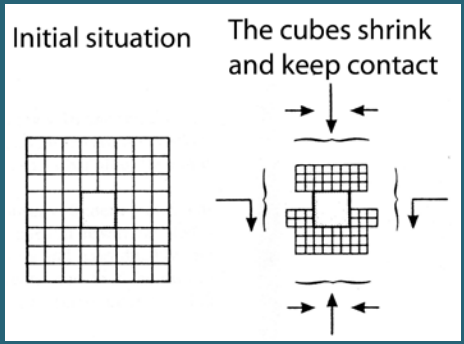
- Three main causes of shrinkage constraint:

(1) Boundary restraint

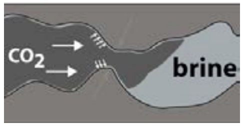
(2) Moisture gradients inside the body

(3) Internal structure

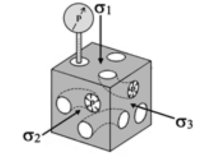


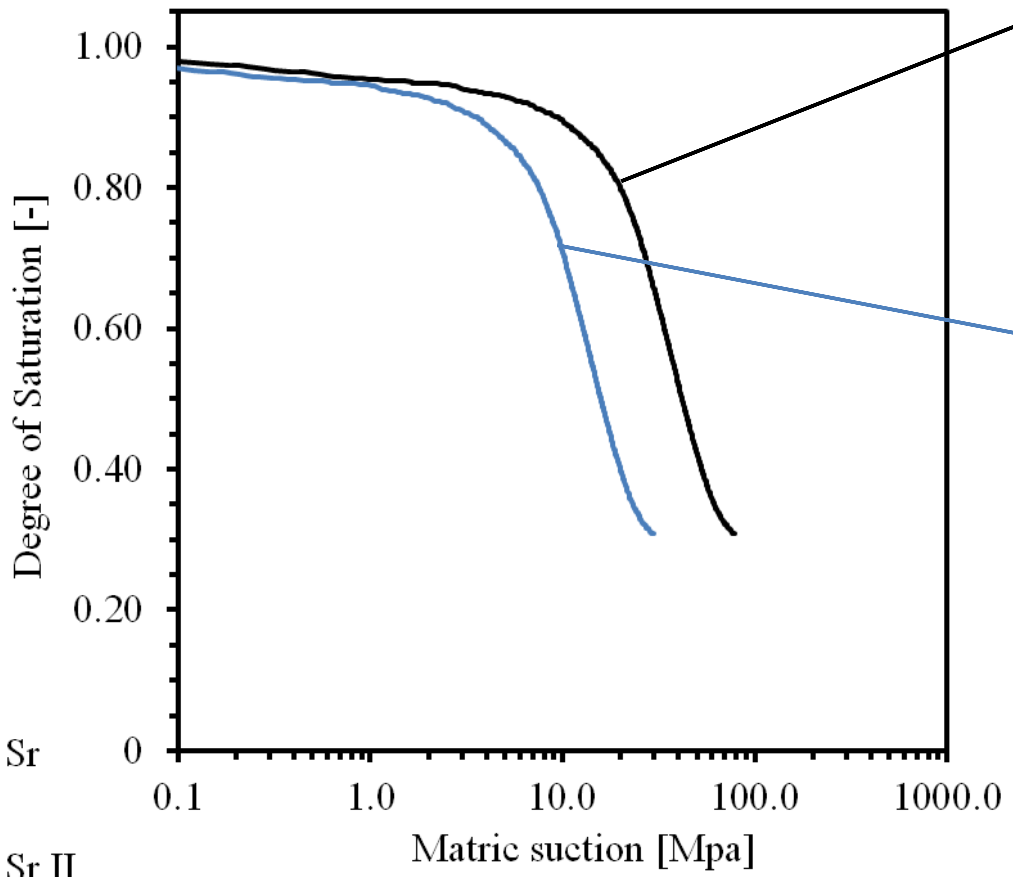


Laloui and Li, 2014



CO_2 retention behavior





Water retention curve of Opalinus Clay:
Ferrari et al., 2014

Water retention curve with **air** at room **temperature** and **atmospheric pressure** :

σ = 0.073 [N/m]

θ = 0 [˚]

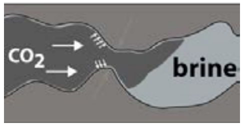
Water retention curve with CO_2 at 20 ˚**C** and **pressure** of 8 MPa :

σ = 0.030 [N/m]

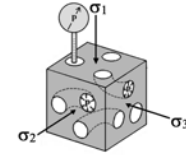
θ = **20** [˚]

(Espinoza and Santamarina, 2010)

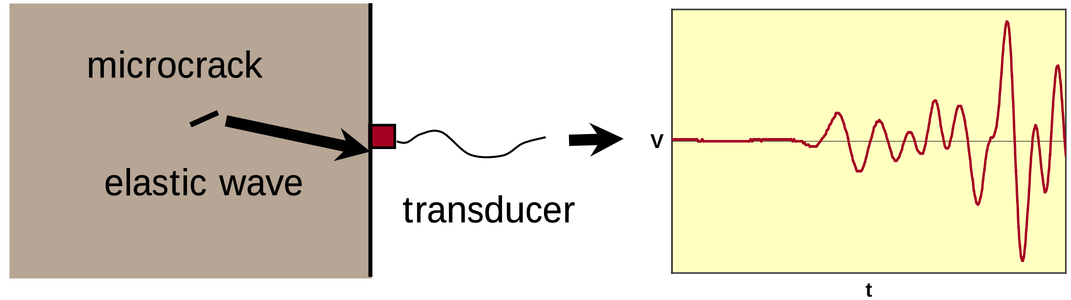
Reduction of gas entry value **from** 13 to 8 [MPa]

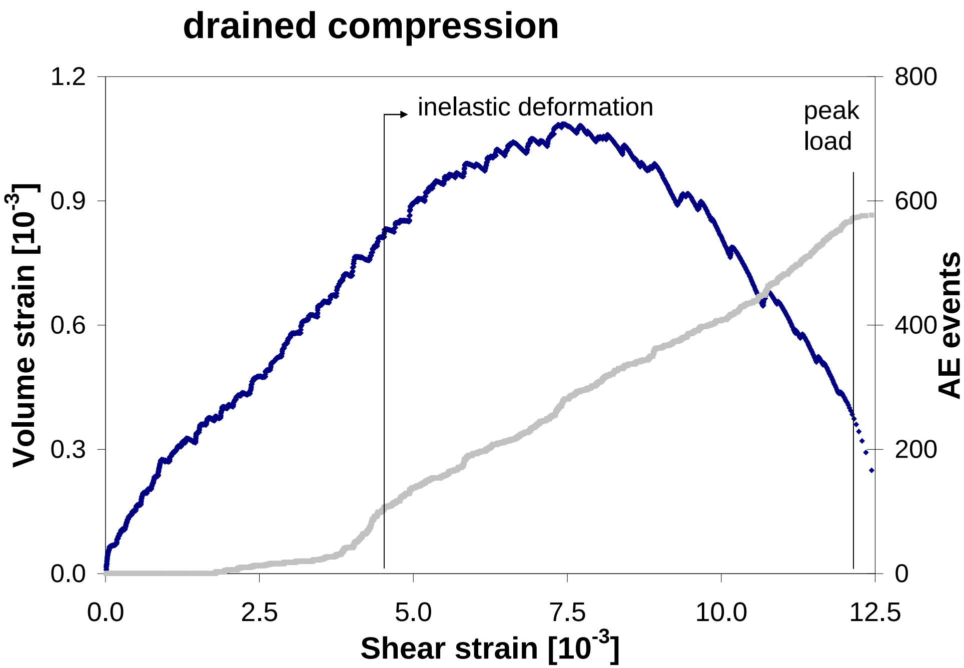


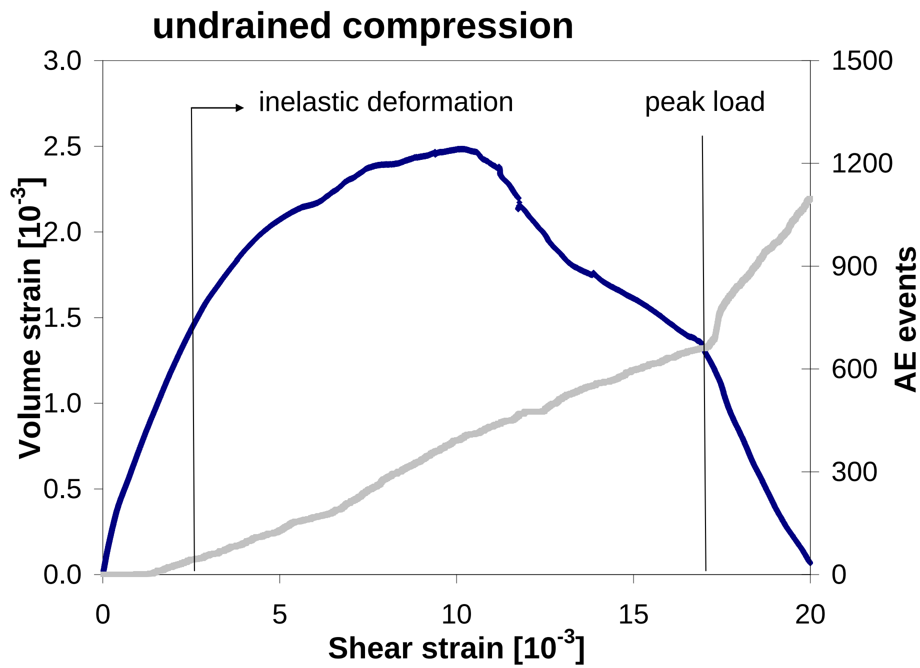
Host rock and caprock microcracking



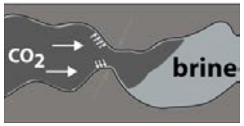
Inelastic response (yielding) of rock is associated with microcracks, which generate elastic waves called acoustic emission, AE.



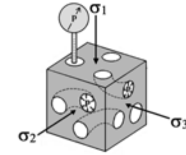


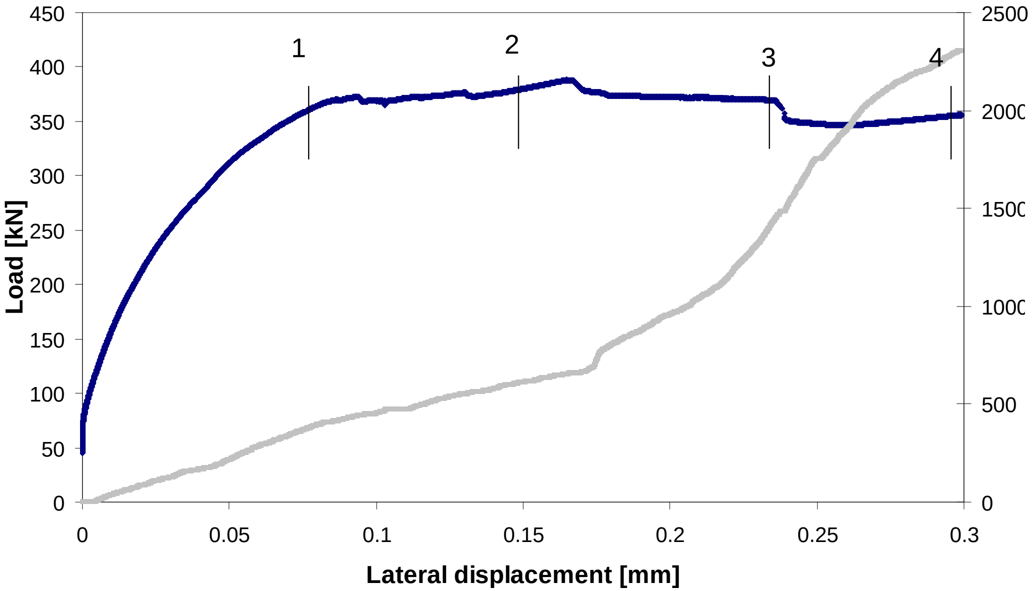


Makhnenko and Labuz, JGR-2014

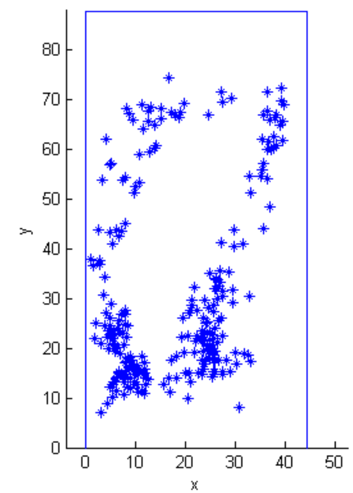


Host rock: AE events locations



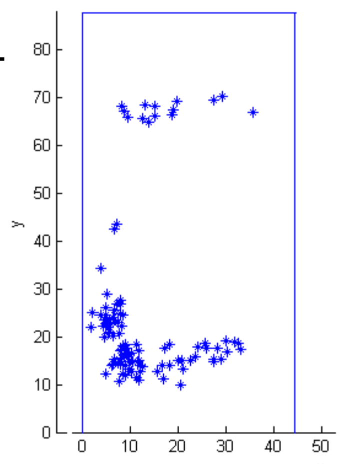


all events

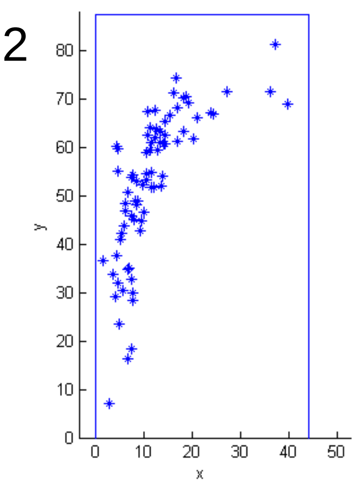


fractured specimen

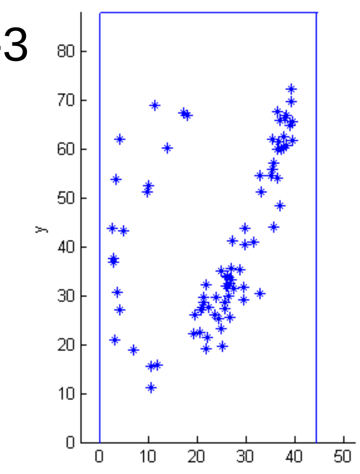
0-1



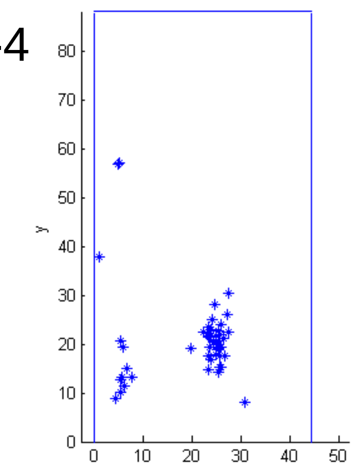
1-2



2-3



3-4



Makhnenko, Ge and Labuz, 2015

Summary

- Geologic sequestration of carbon dioxide is promising option for reducing greenhouse gas emissions

- Thermo-hydro-mechanical processes occur during CO_2 storage: deformation and failure potentials triggered by injection-induced overpressure and cooling are the key issues to be addressed

- Laboratory testing is needed to characterize different aspects of rock-water-CO_2 interactions and an advanced equipment has to be used to get accurate results and make reliable predictions

- Geomechanics will play a key role in seeking a balance between injectivity and integrity/safety of host and caprocks