Water Weakening and Fluid Rock Interactions in Chalks from the Mons Basin

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CERGY PARIS UNIVERSITÉ

project
GEO^{2}FRI^{2}SK

UMONS
Université de Mons

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CSIRO

J. Sarout / J. Dautriat / L. Esteban

INVESTISSEMENTS D'AVENIR

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CY Initiative of excellence

GEO^{2}FRI^{2}SK

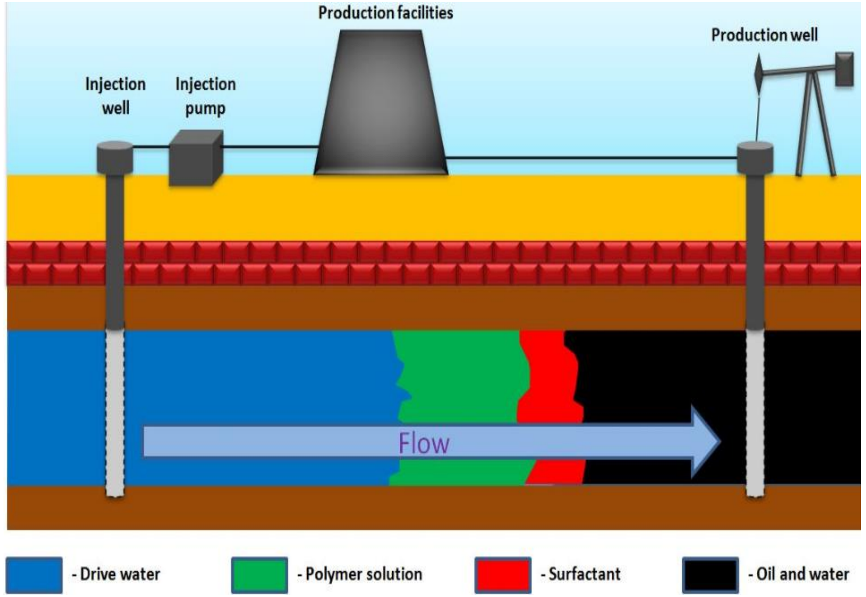
GEOphysical and GEOtechnical impact

of Fluid-Rock Interactions

For RISK assessment in chalk formations

Reservoir applications *Geotechnical applications*

Reservoir applications

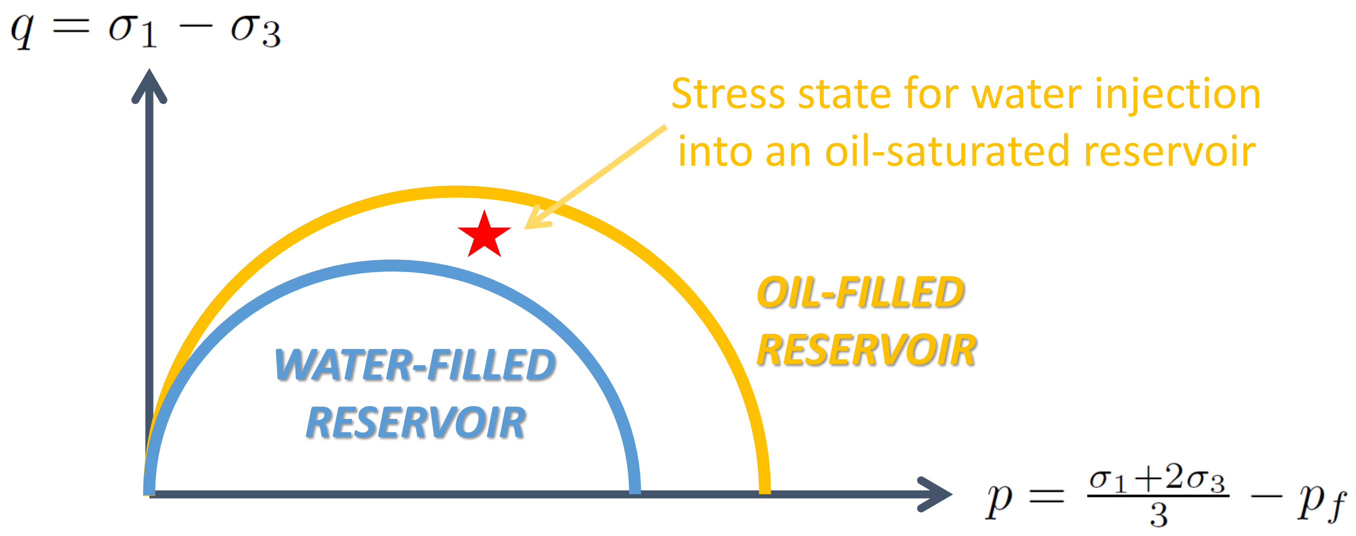


Enhanced oil recovery operations

What is the impact of fluid substitution
on the mechanical properties of a reservoir at depth?

Starting point of the project:

Design lab experiments mimicking oil-water substitution in reservoir rocks under stress

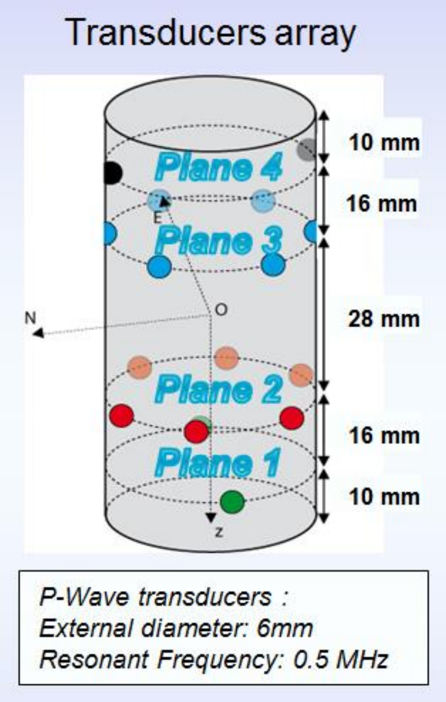


what happens in a reservoir at depth during the fluid substitution process ?

Oil-water substitution in reservoir rocks under stress

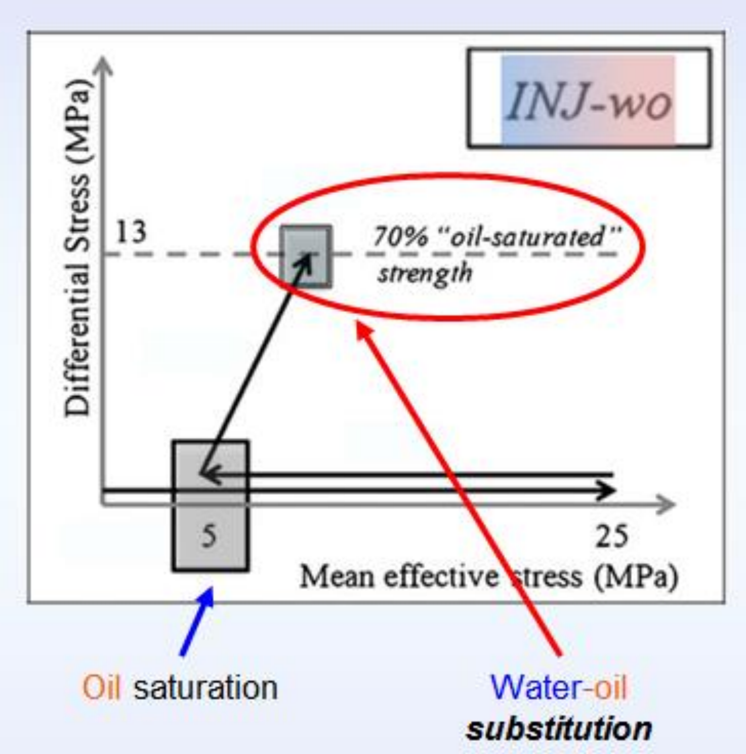
→ **Lab experiments on the Sherwood sandstone (UK)**

Rock specimen
D = 38mm - L = 80mm



Transducers array

P-Wave transducers :
External diameter: 6mm
Resonant Frequency: 0.5 MHz



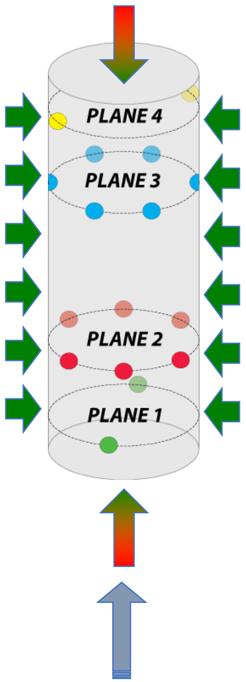
Oil saturation

Water-oil **substitution**

at **very low** injection pressure
< 1 MPa

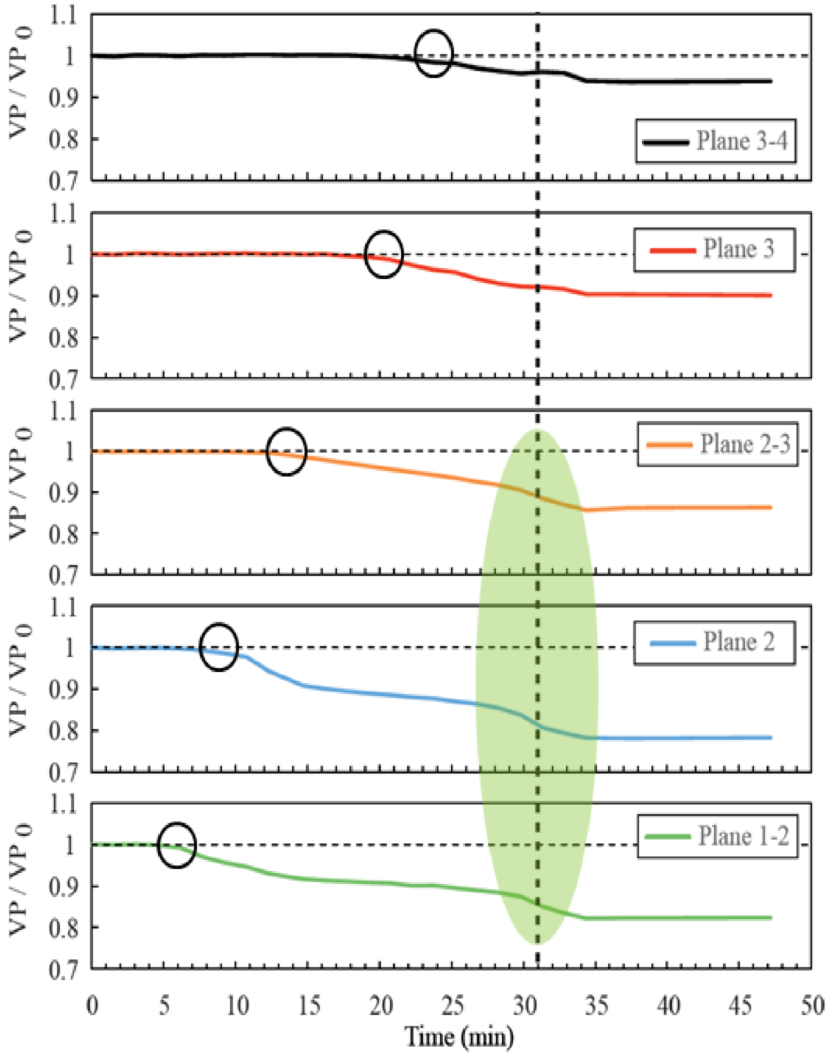
Oil-water substitution in reservoir rocks under stress

CRITICAL
diff stress q

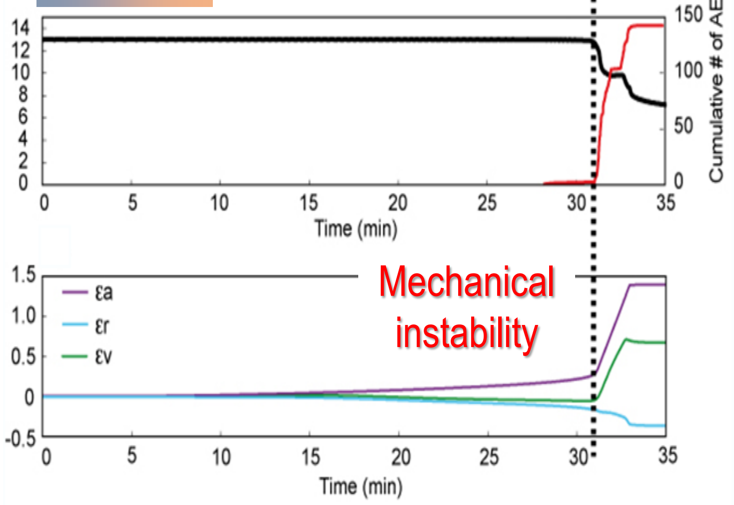


Water-in-oil

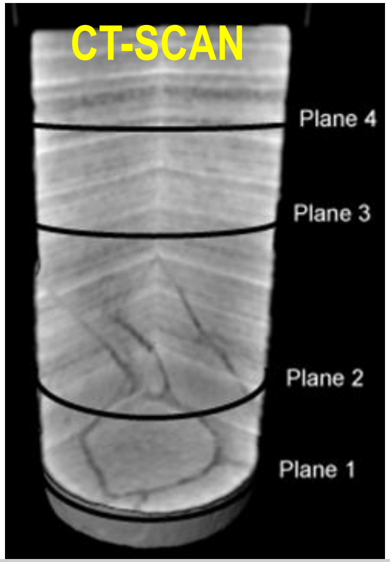
Water-in-oil

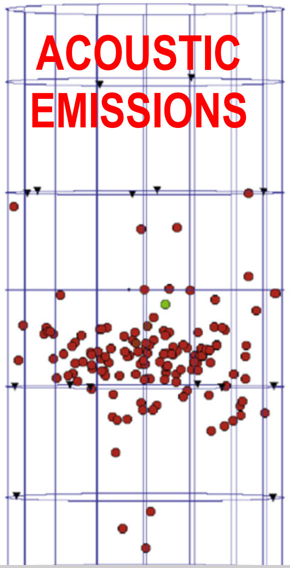


Water-in-oil



Mechanical instability





Water injection can result in mechanical instability which can be monitored through seismic survey

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GEOphysical and GEOtechnical impact

of Fluid-Rock Interactions

For RISK assessment in **CHALK FORMATIONS**

Reservoir applications

Geotechnical applications

Water-weakening and Fluid-Rock Interactions in Chalks from the Mons Basin

Presented by: Davide Geremia

Supervisors: Christian David, Beatriz Menéndez and Christophe Barnes

29.03.2022

GEO^{2}FRI^{2}SK project

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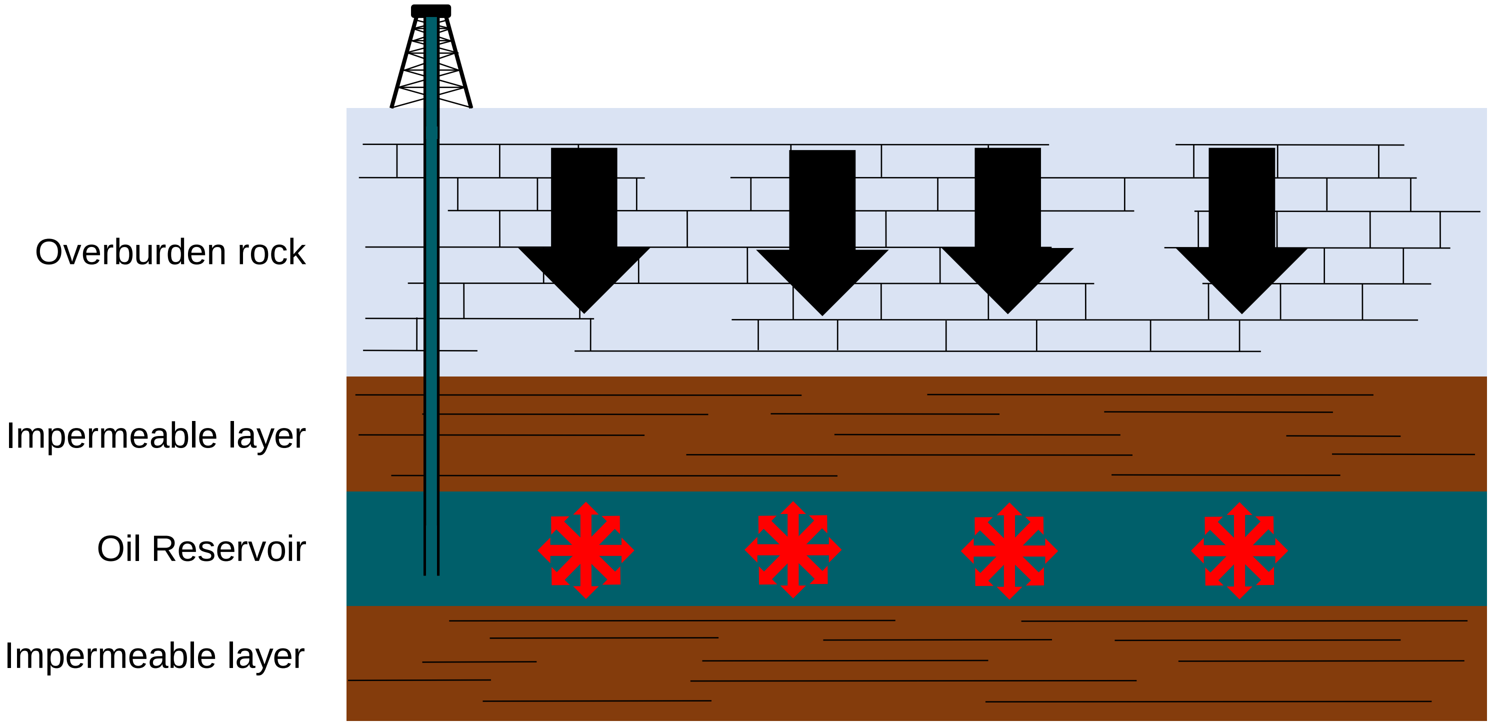
Initiative

of excellence

Outline

1. Water-Weakening: Underground geological reservoirs - secondary recovery of oil
2. Water-Weakening: Comparison in between Obourg and Ciply chalk
3. Theories of water-weakening
4. Application: Underground cavities stability in abandoned quarries

Secondary Recovery

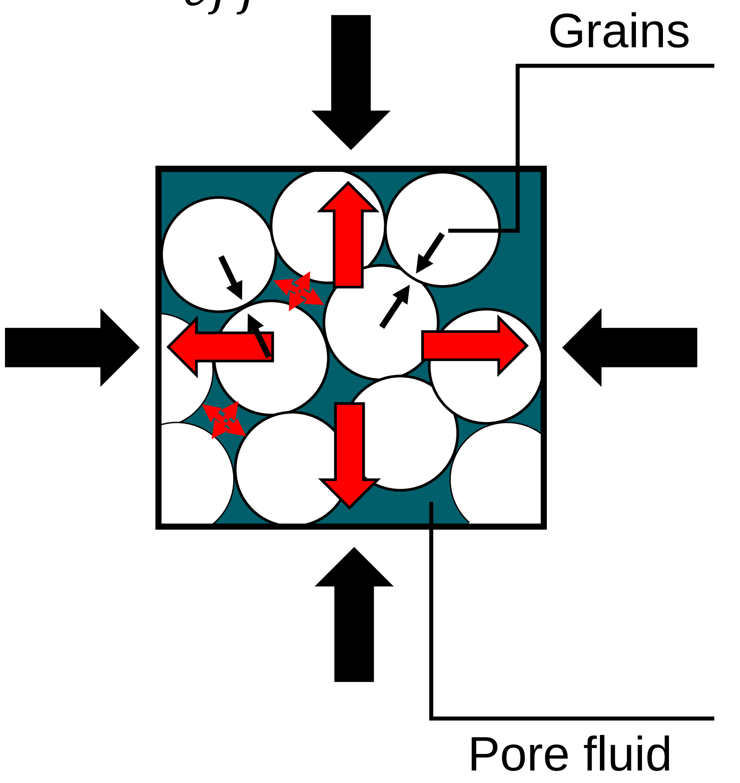


Effective pressure

Lithostatic pressure

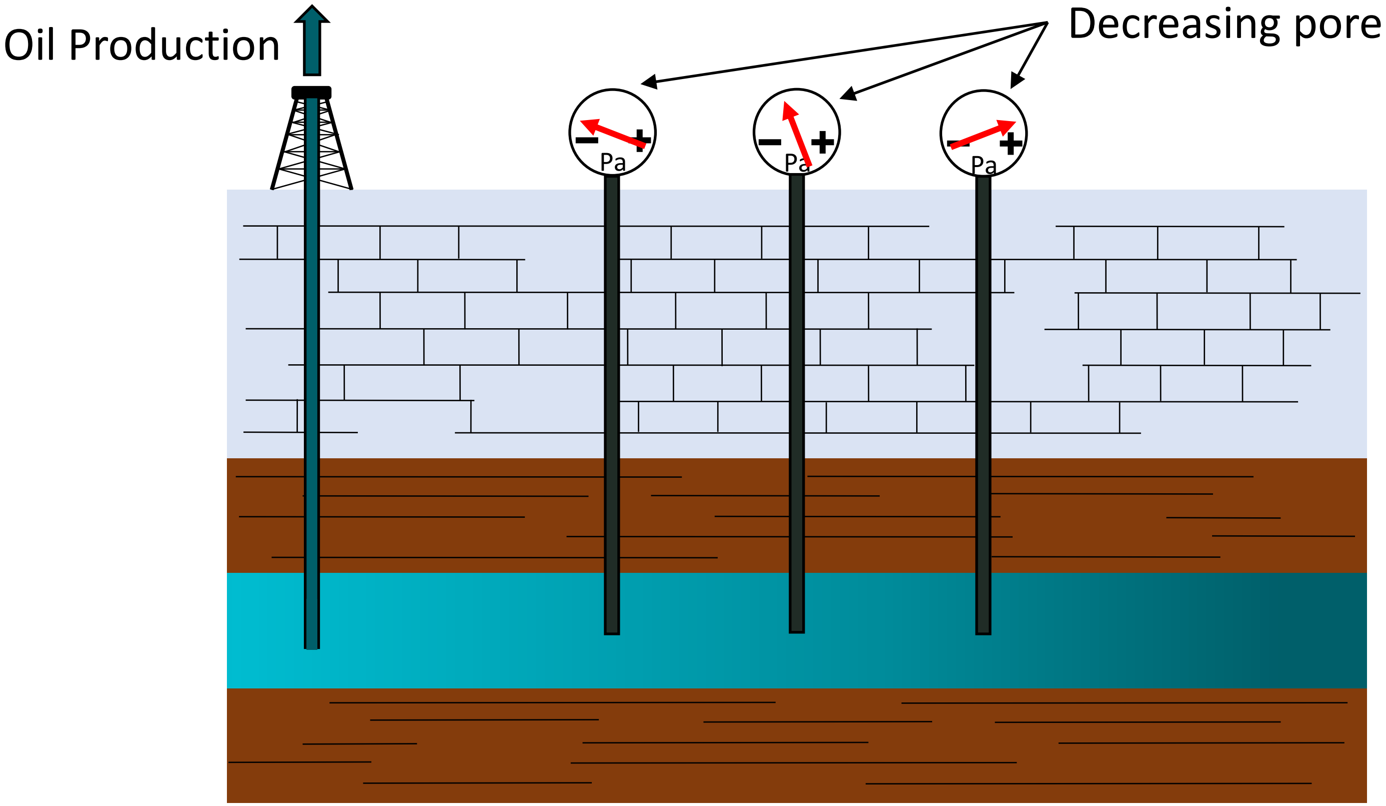
Pore pressure

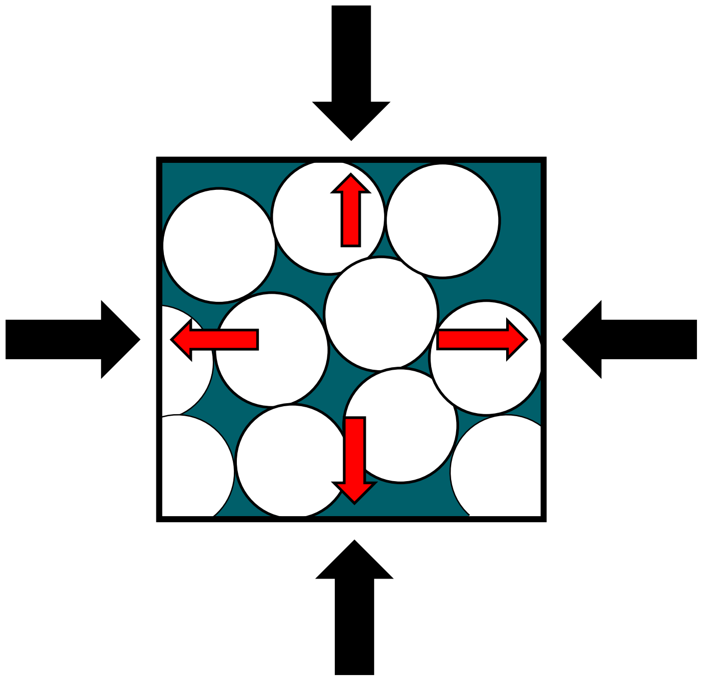
$$P_{eff} = P_l - P_f$$



Secondary Recovery

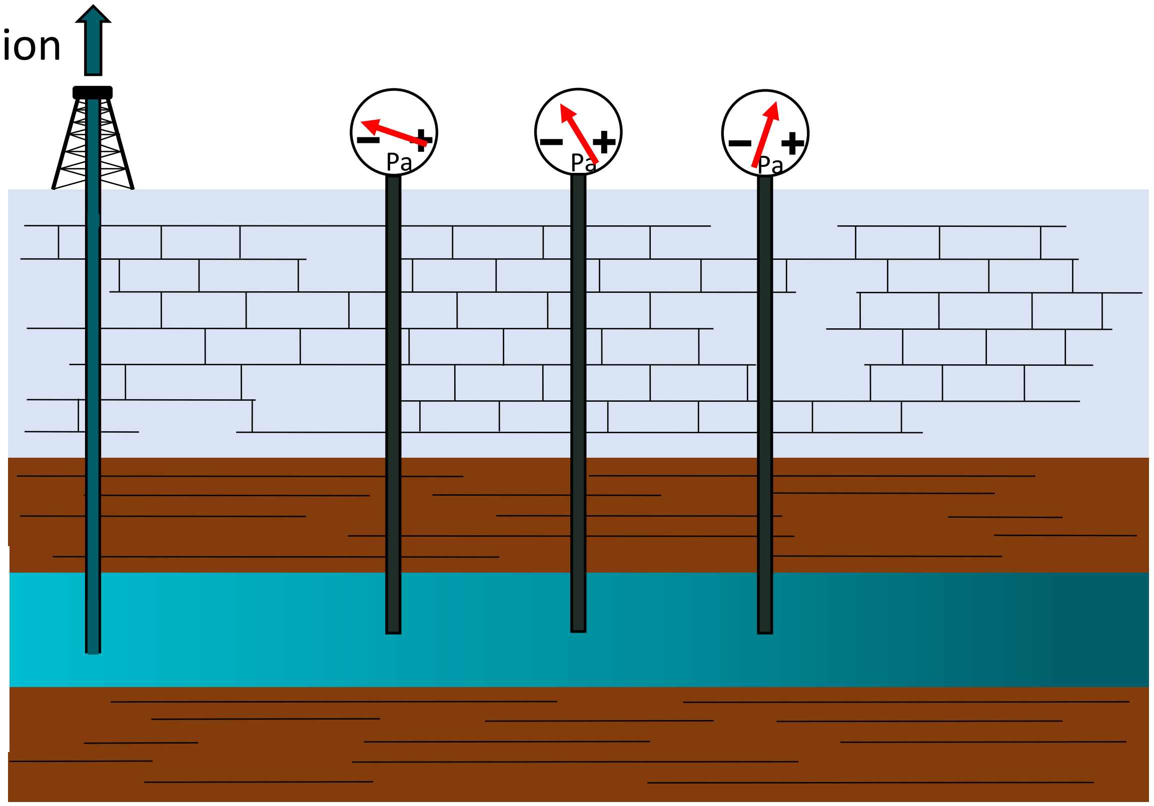
Phase 1: Oil production



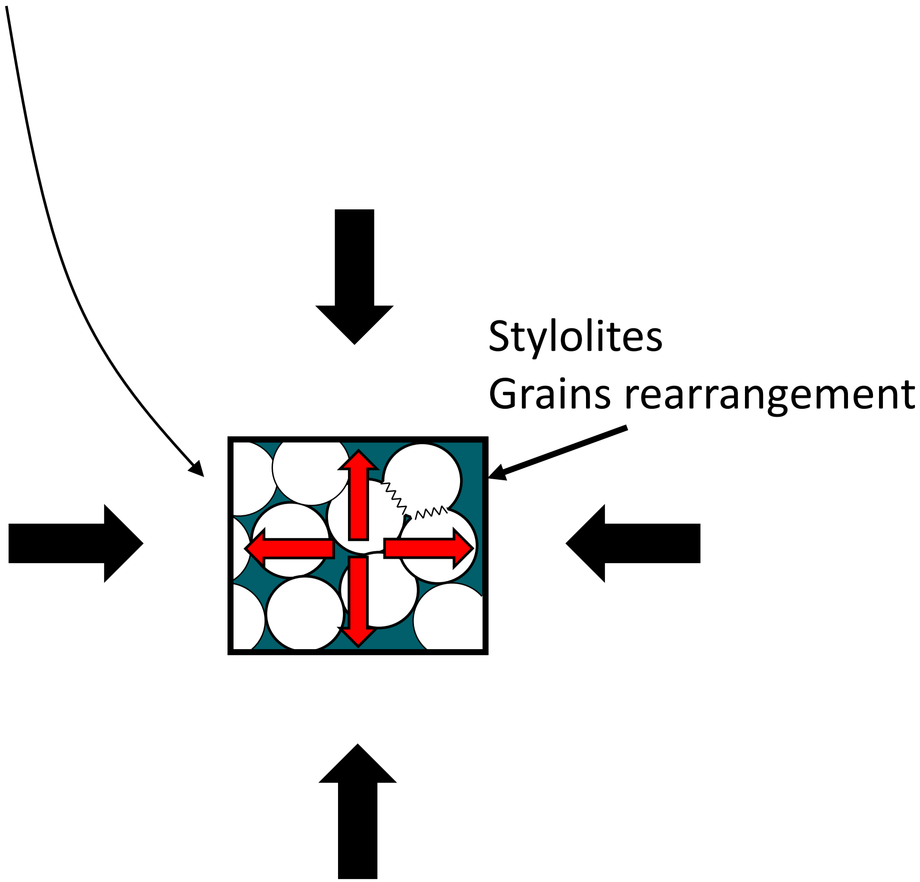


Secondary Recovery

Phase 1: Oil production

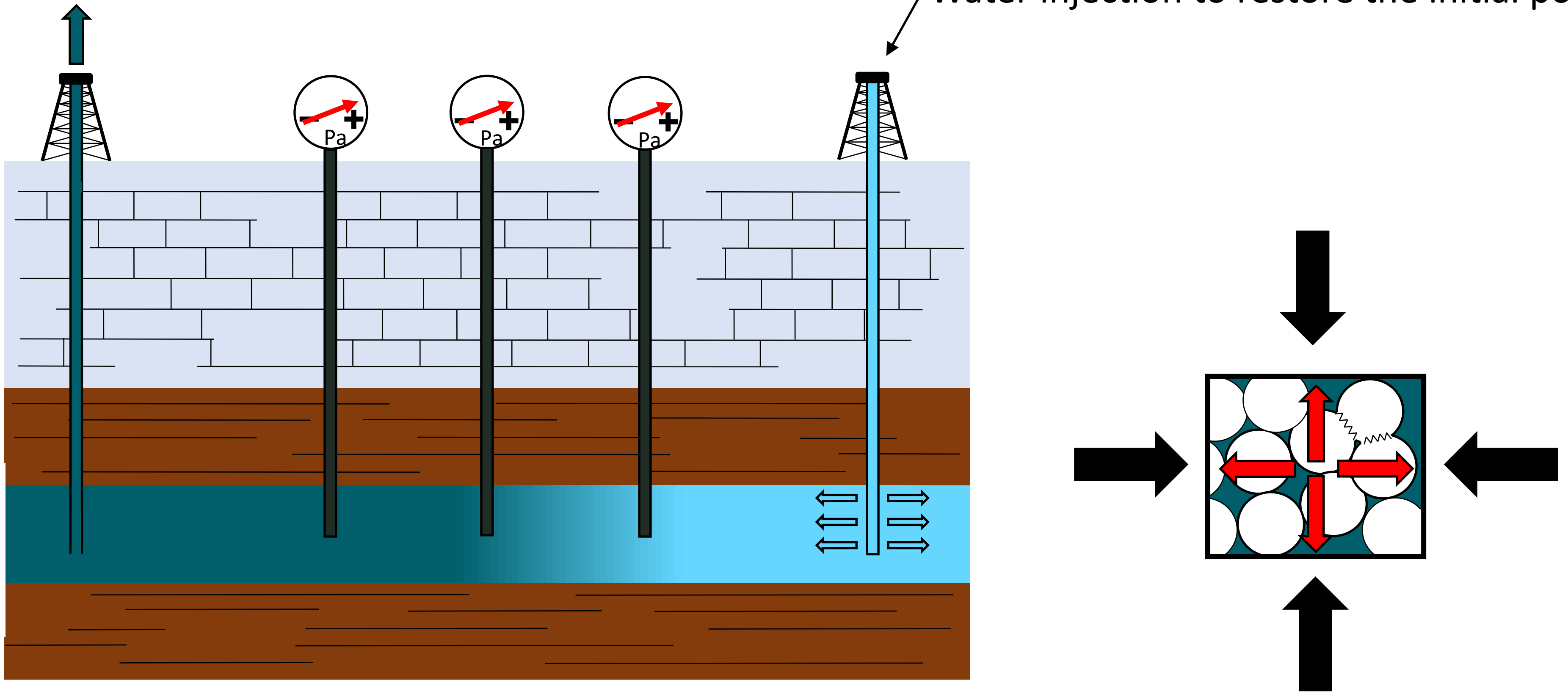


Compaction induced by increase in effective stresses



Secondary Rrecovery

Phase 2: Water injection

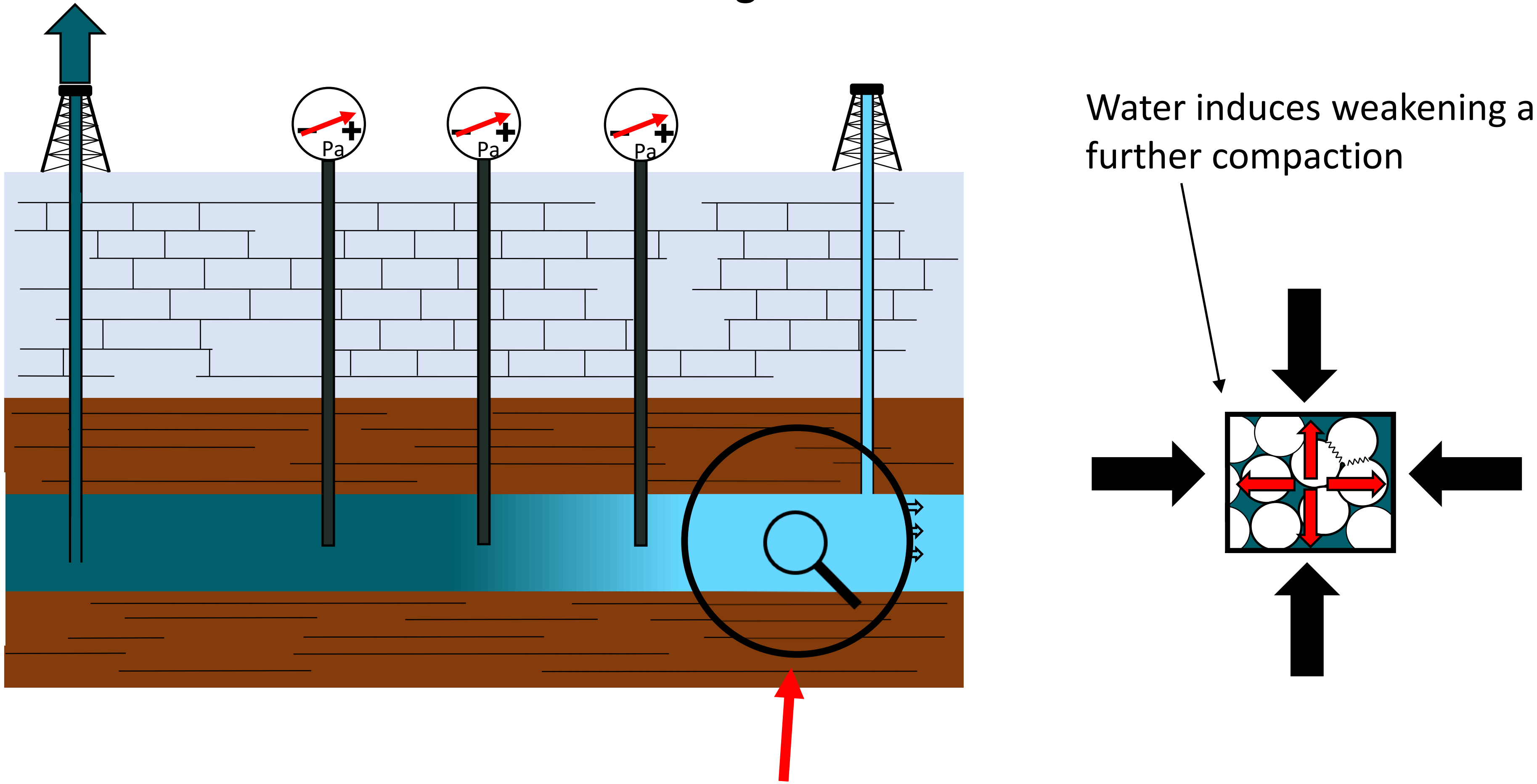


Water injection to restore the initial pore pressure

Secondary Rrecovery

Ekofisk Oil Field, North Sea

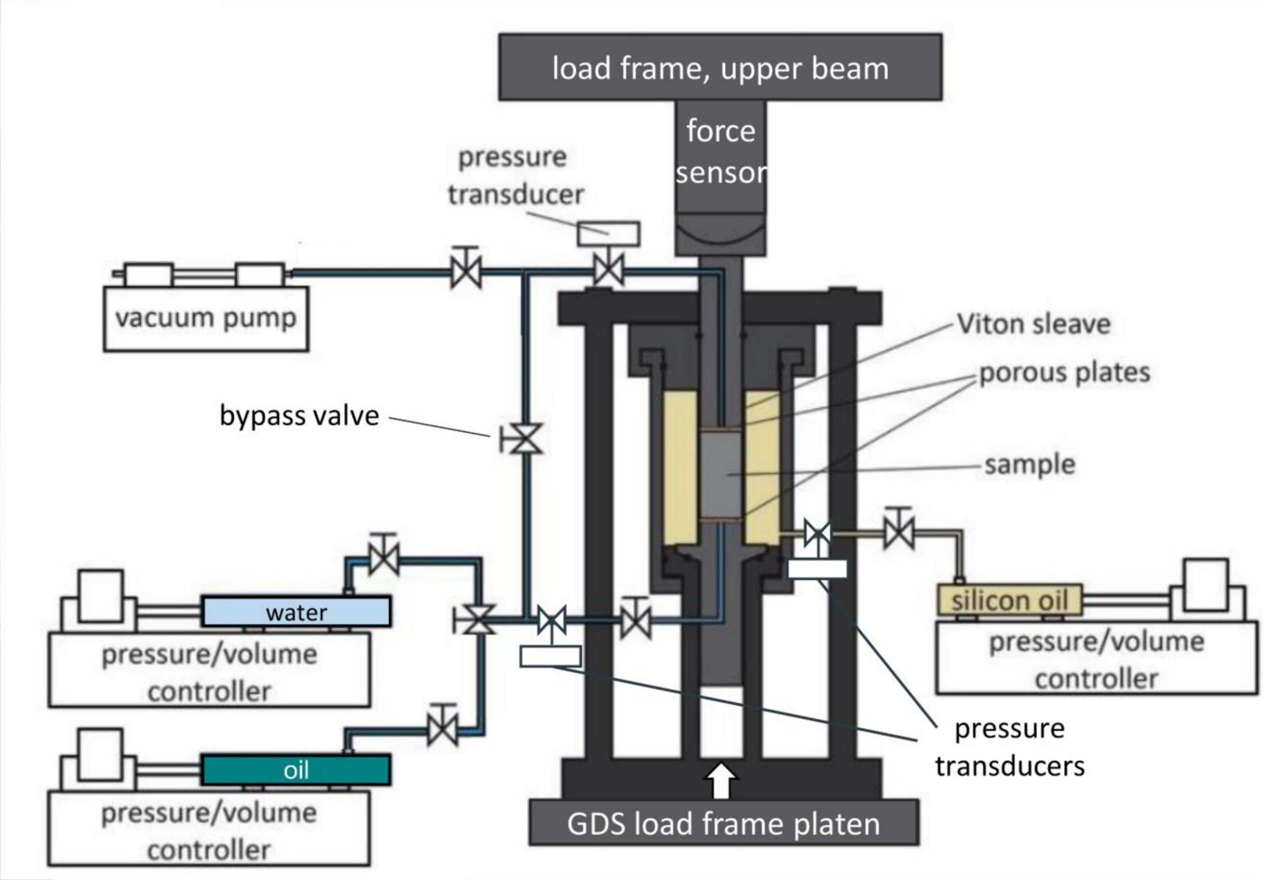
Phase 3: Chemical weakening and deformation



Water induces weakening and further compaction

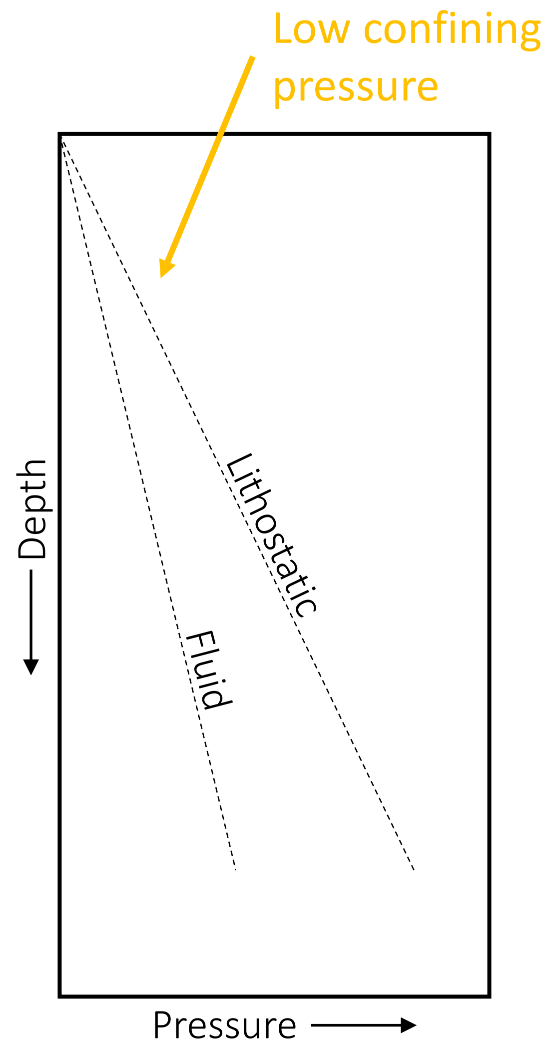
- What happens during oil replacement in this area?

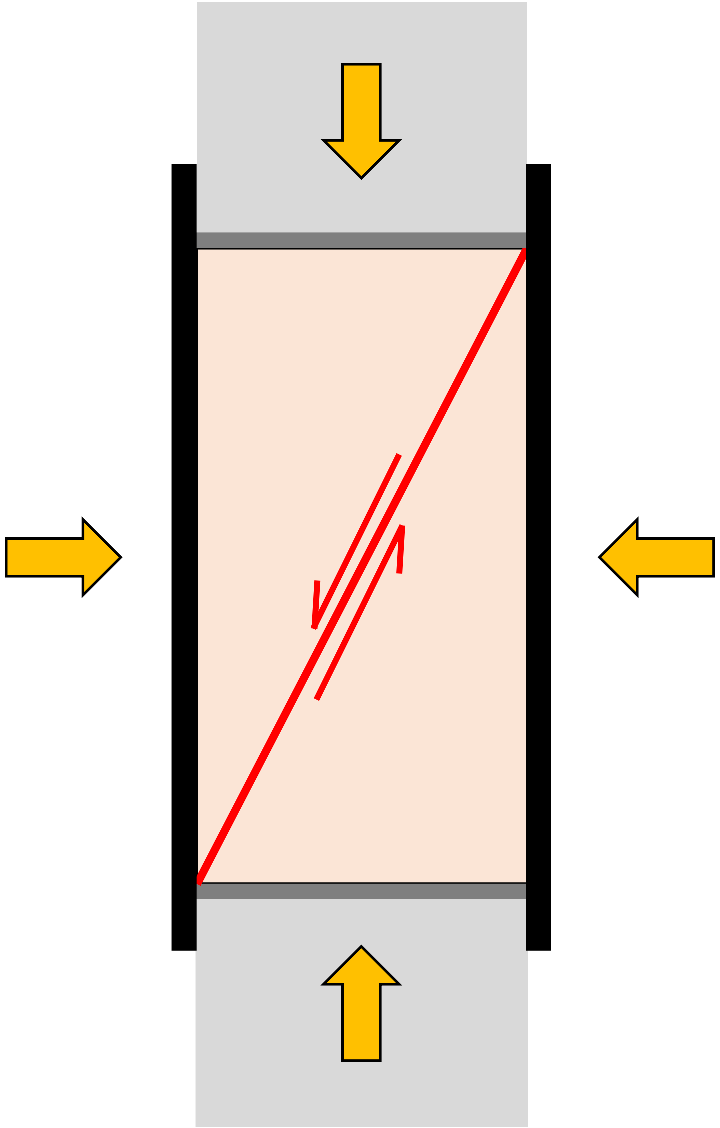
Experimental Approach - Secondary Recovery



Modified after Wild et al. 2015

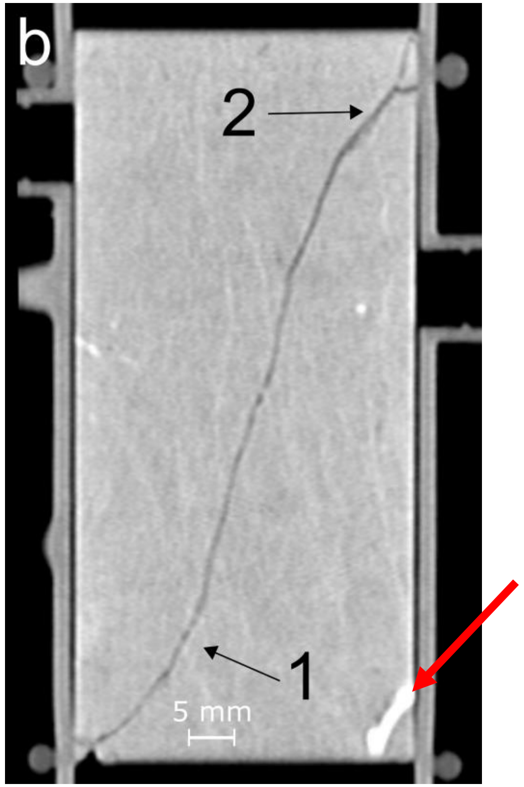
Experimental Approach – Conventional Triaxial Tests





- Low confining pressure
- Brittle failure
- Damage localization

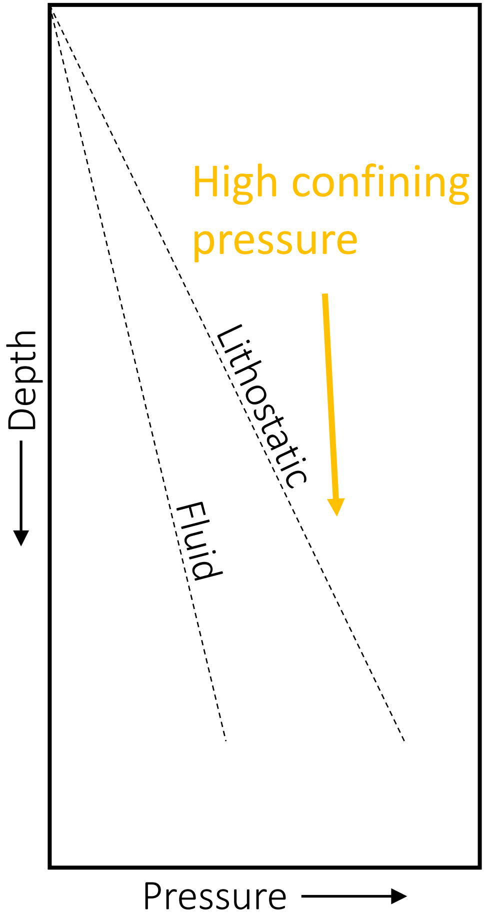
X-Ray Tomography

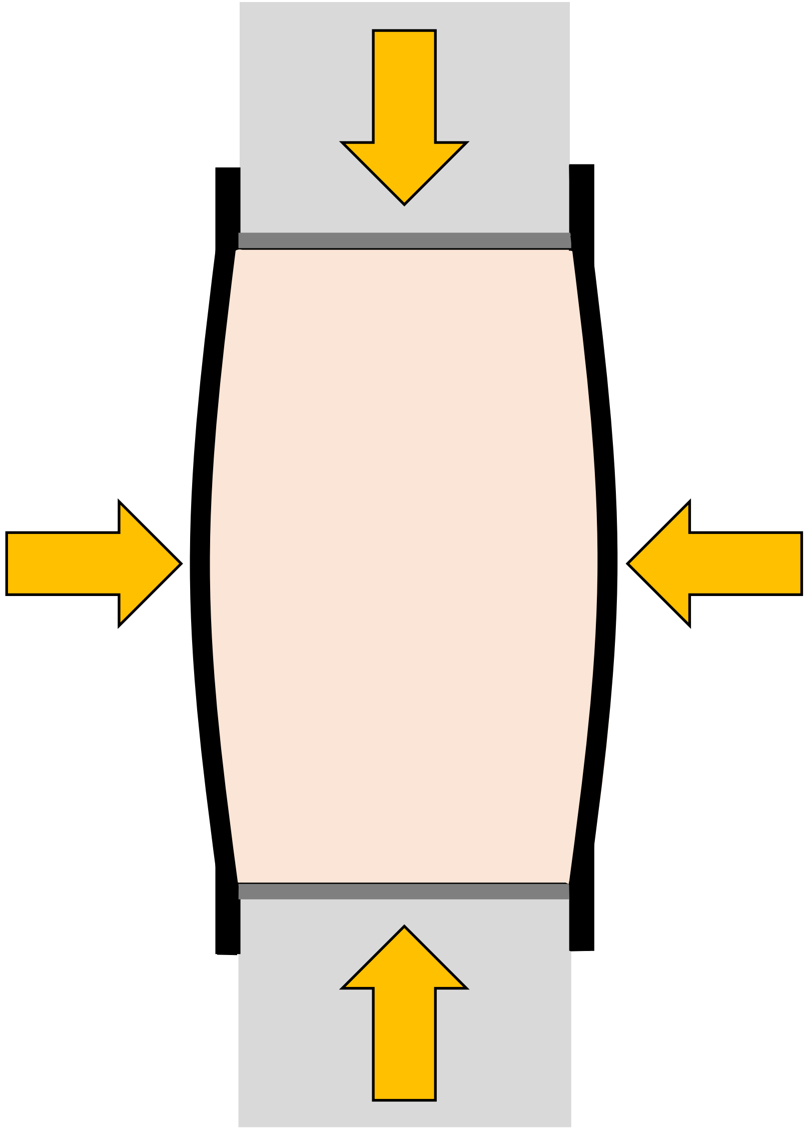


Lighter = Denser

Geremia et al. 2021a

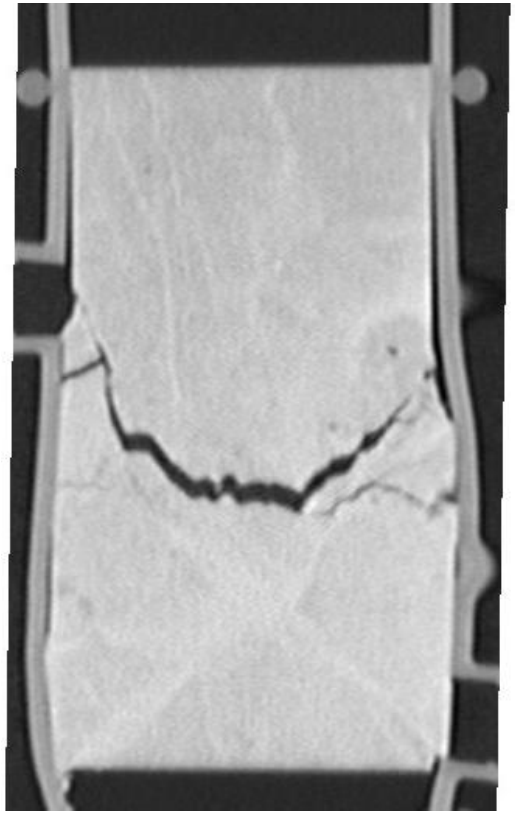
Experimental Approach – Conventional Triaxial Tests





- High confining pressure
- Ductile failure
- Diffuse damage

X-Ray Tomography



Materials

Composition: ~ 100% Calcite (Voake et al., 2019)

Grain density: 2.72 g/cm^3

Bulk Density: 1.55 g/cm^3

Mean Porosity: 43%

Permeability: 0.2 – 6 mD

Peak pore throat Radius (Mercury injection) = 0.3 μm

Peak grain size (statistical): 0.4 – 1.3 μm

Obourg chalk

Ciply chalk

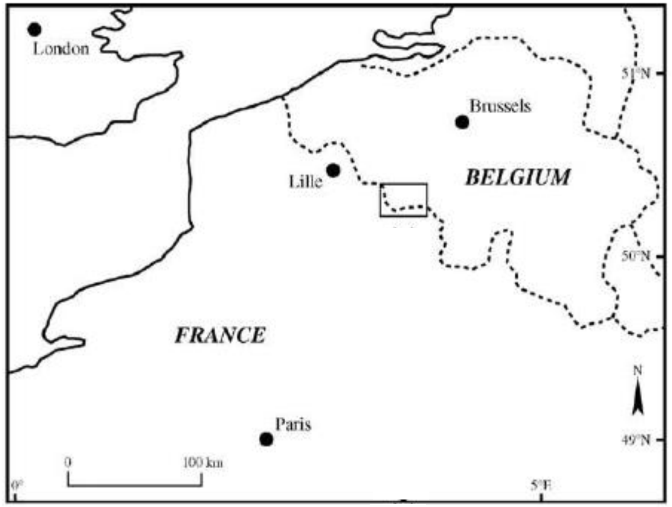
Composition: Calcite, Fluoroapatite

Grain density: 2.73 g/cm^3

Bulk density: 1.68 g/cm^3

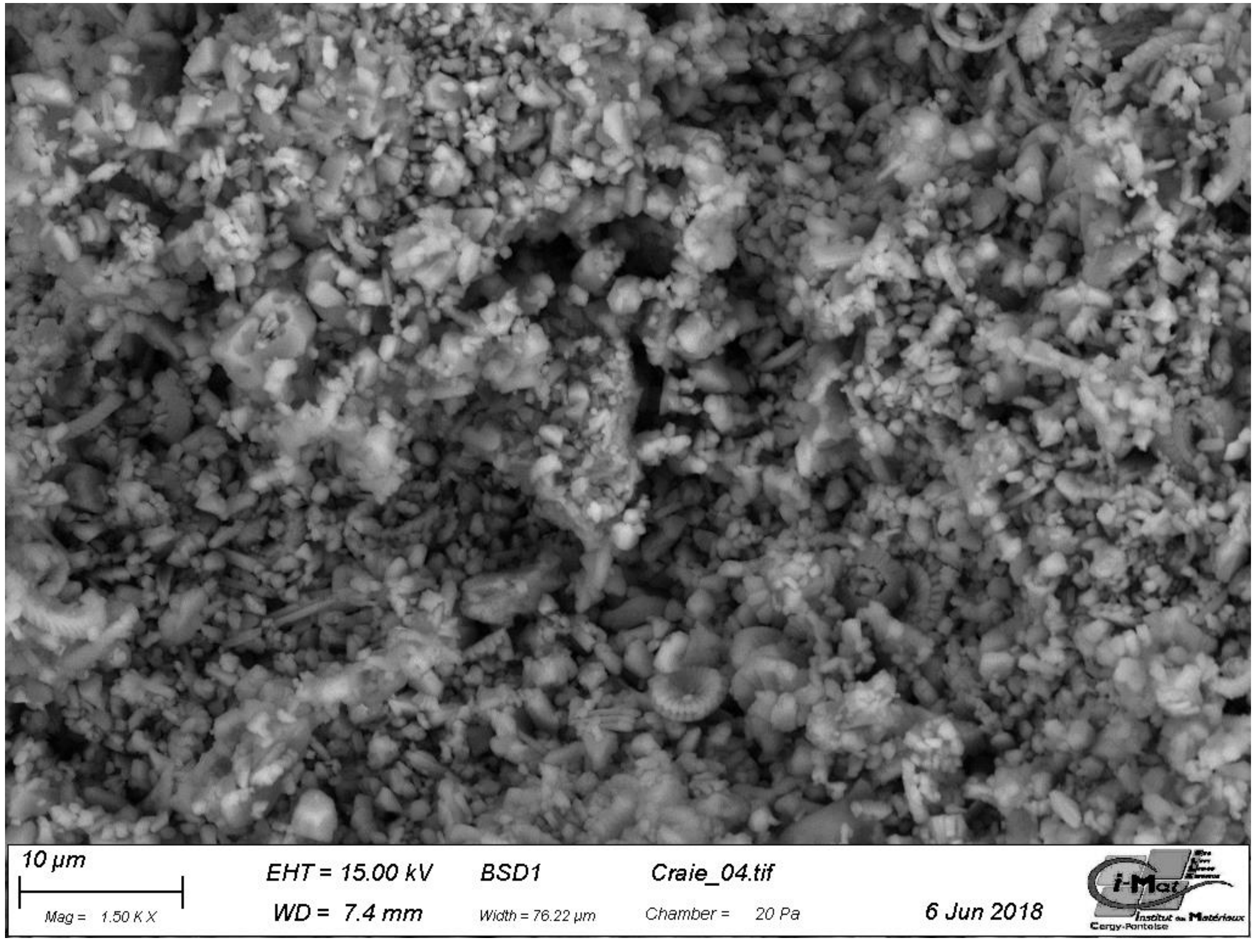
Mean Porosity: 39%

Permeability: 40 mD



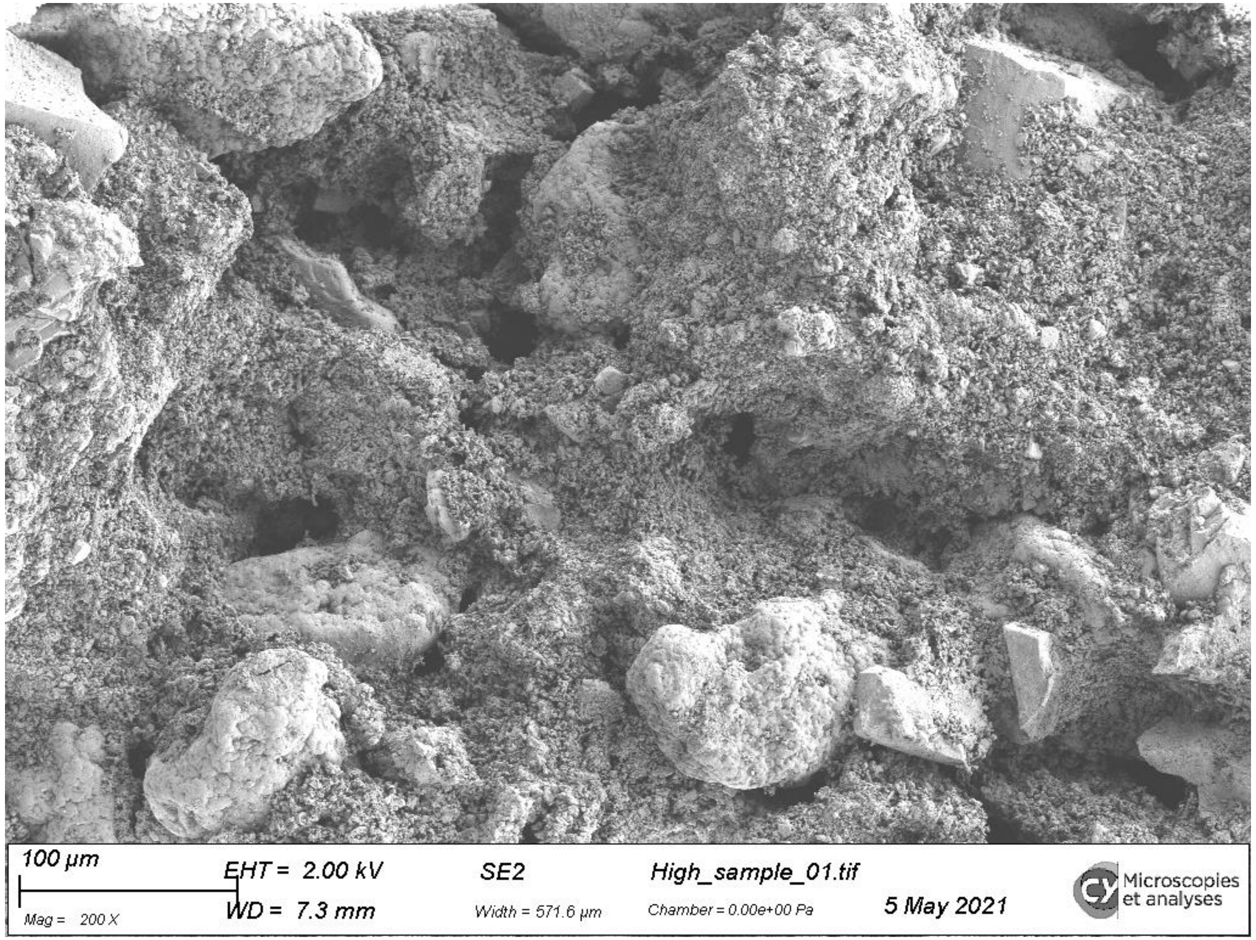
Materials

Obourg chalk



Geremia et al. 2021a

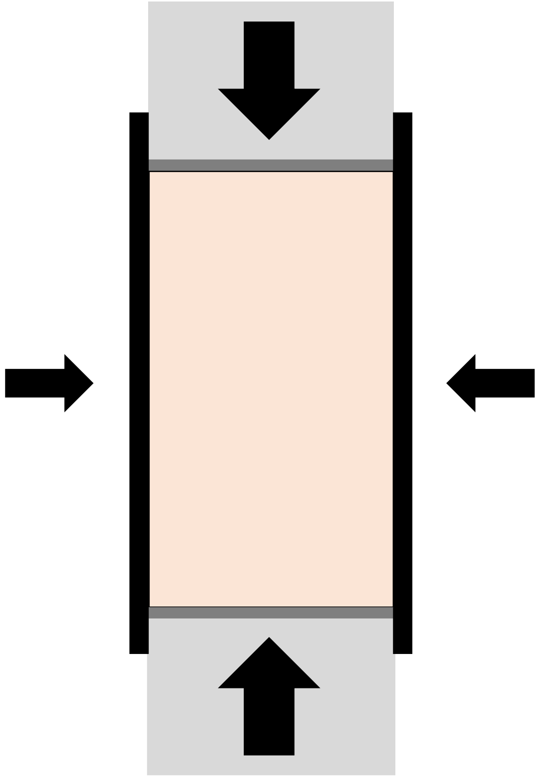
Ciply chalk

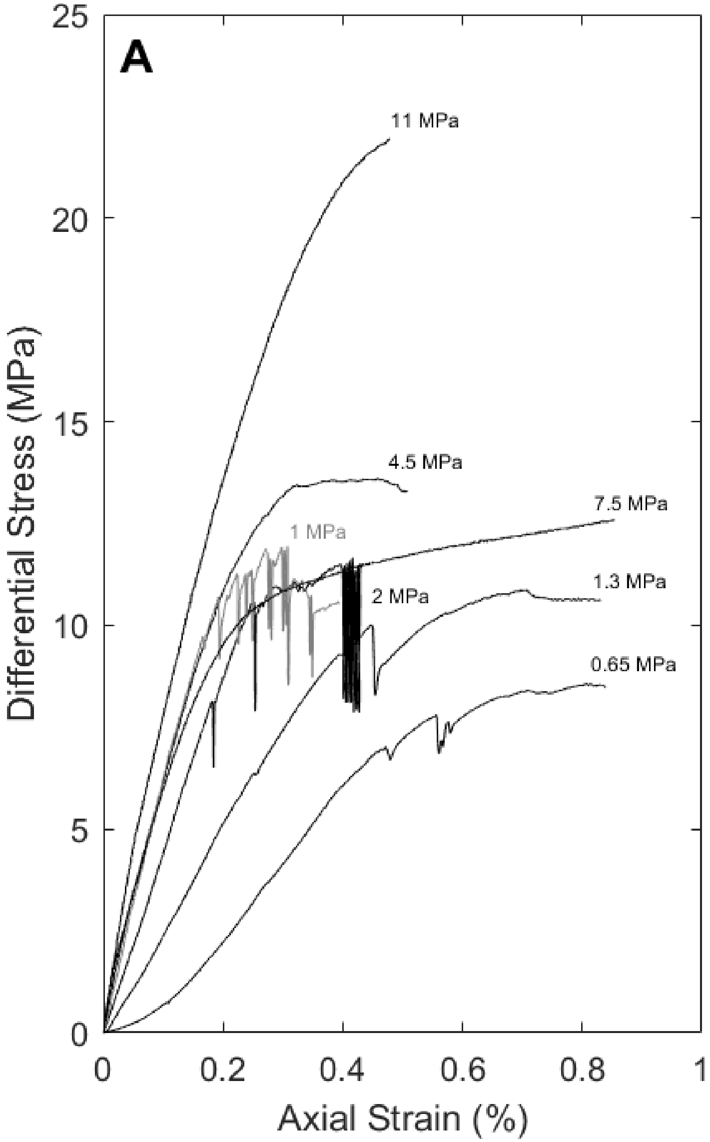


Geremia et al. 2021b

Results - Triaxial Tests

Axially increased stress until failure

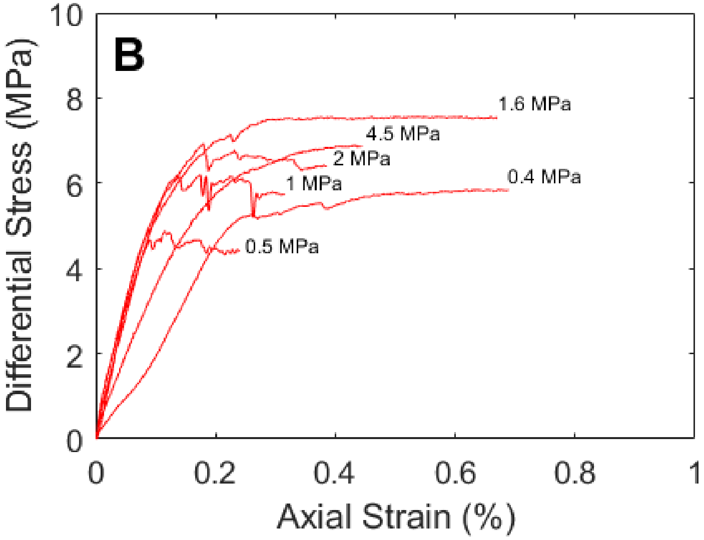




Geremia et al. 2021a

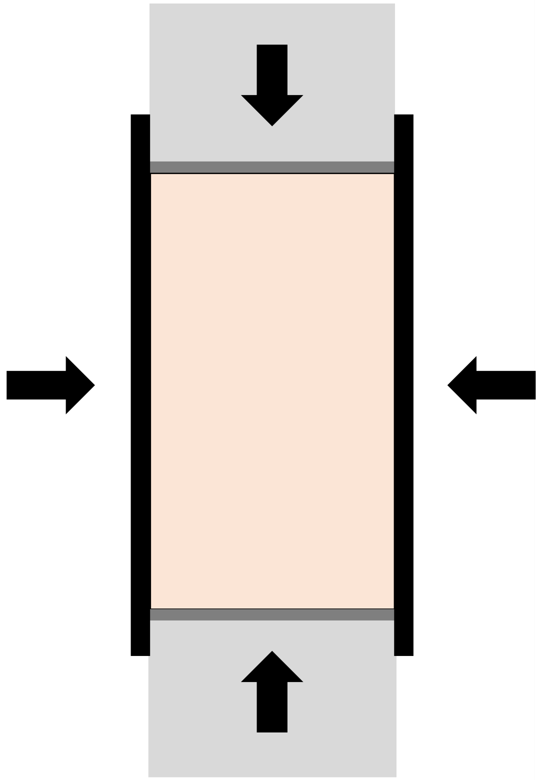
Observation
- Strength weakening in water saturated conditions

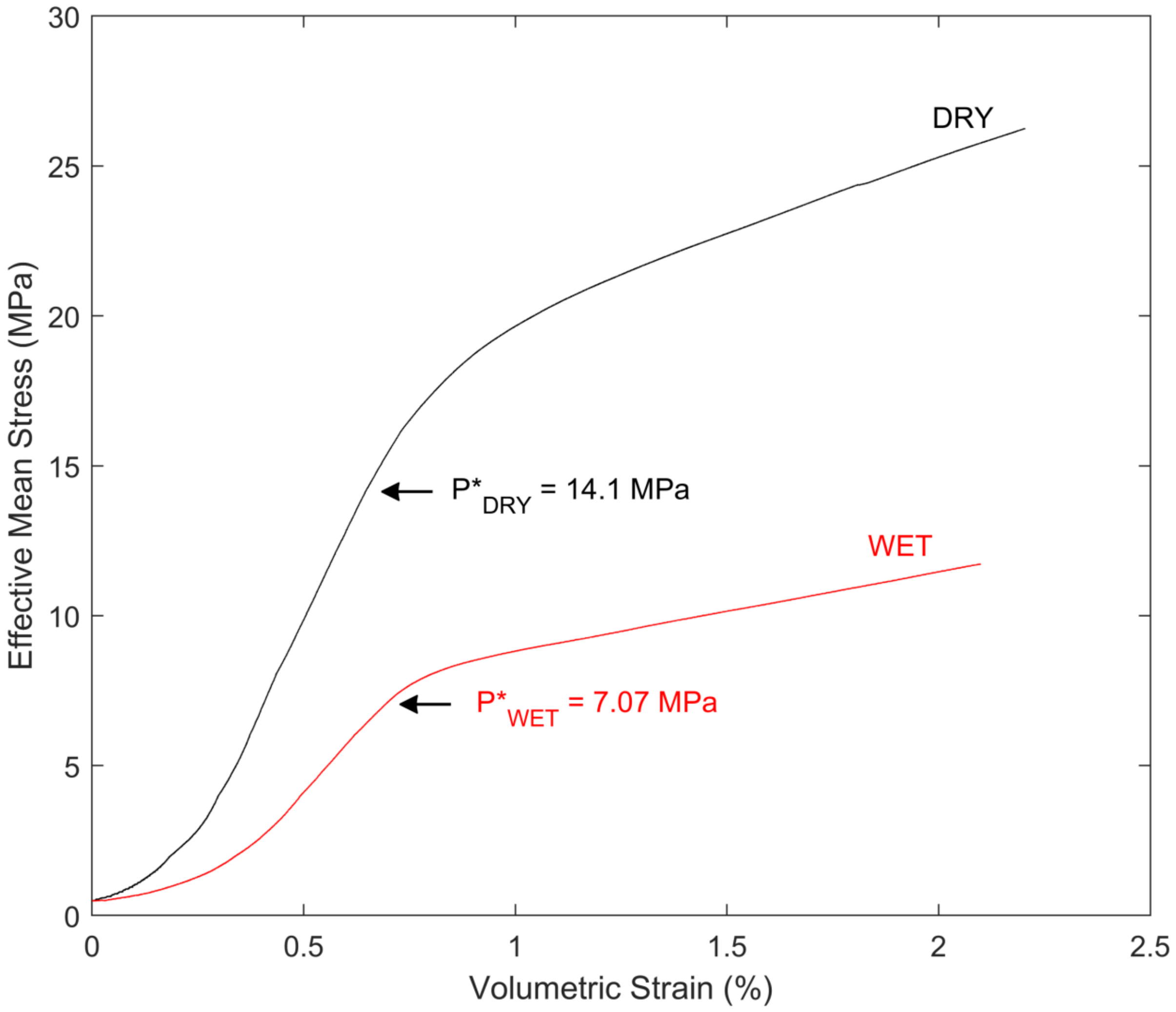
Parameters:
- Peak stress
- Yield (Elastic-Plastic transition)
- Young’s Modulus



Results - Hydrostatic Tests

Stress increases hydrostatically up to failure



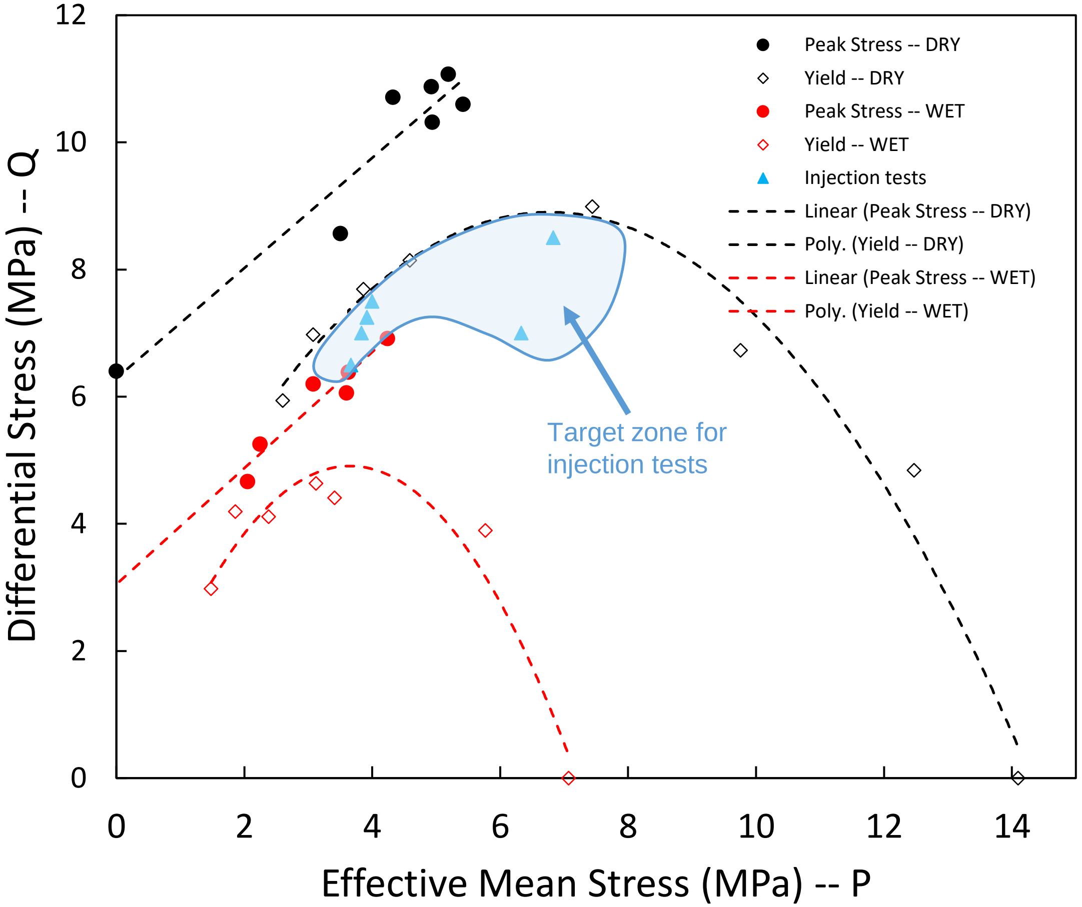


Geremia et al. 2021a

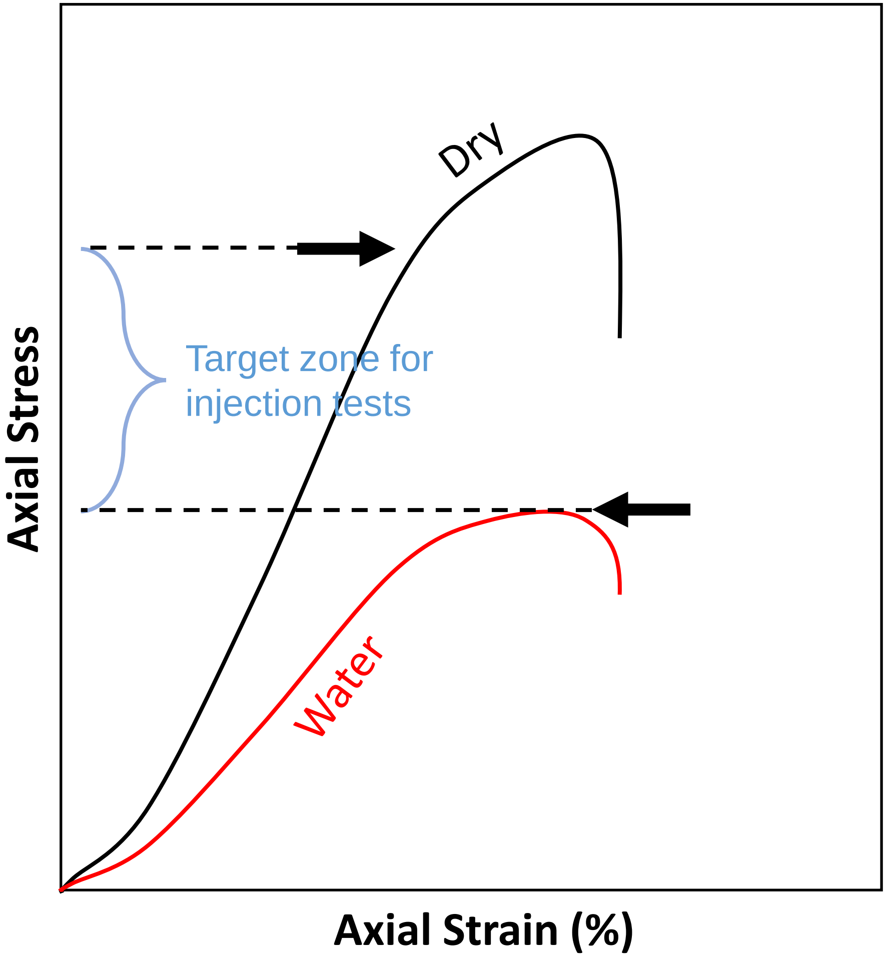
Observation
- Strength weakening in water saturated conditions

Parameters:
- P* (Pore collapse critical stress)
- Bulk Modulus

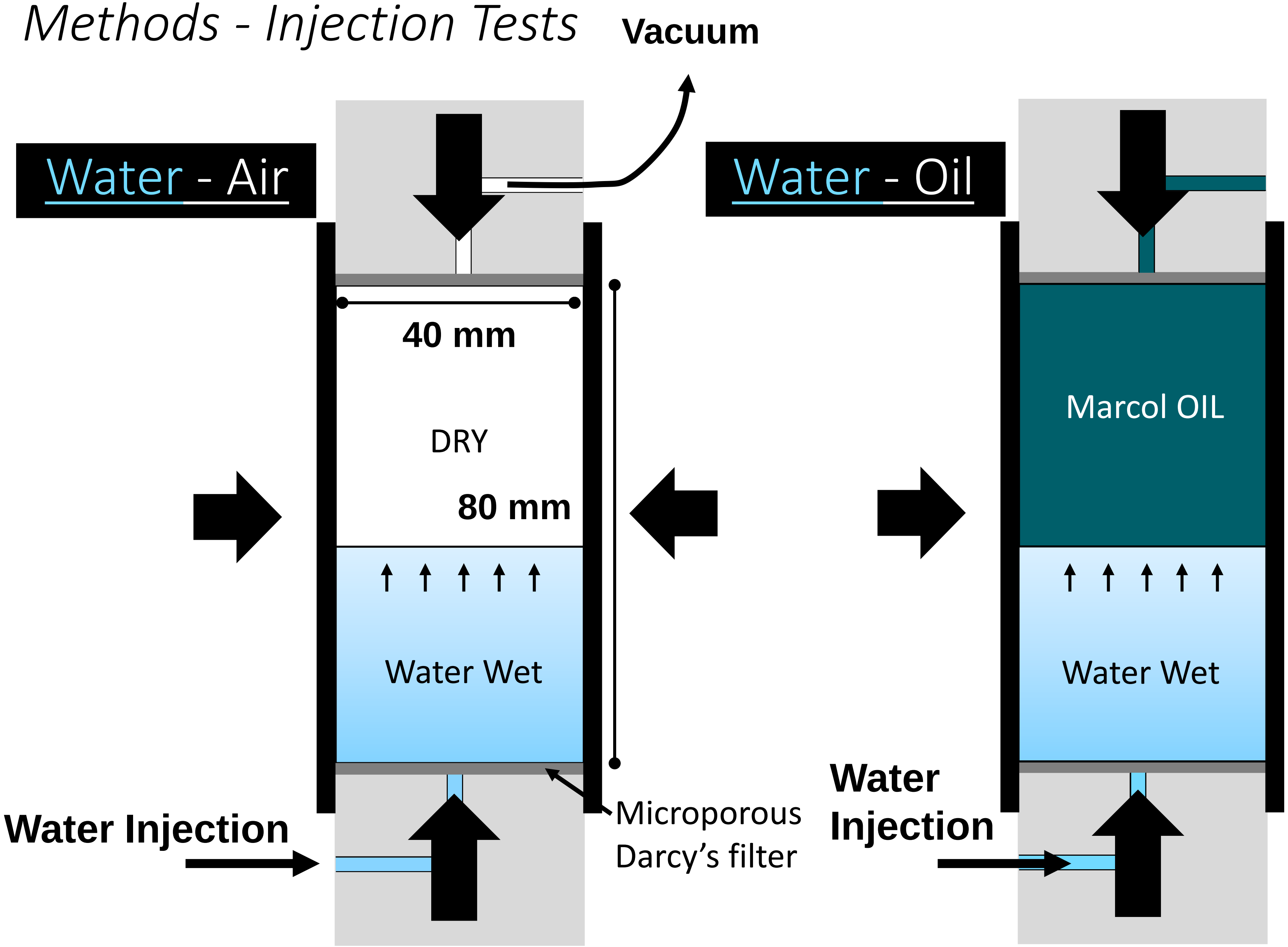
Planning Injection Tests



Geremia et al. 2021a



Methods - Injection Tests



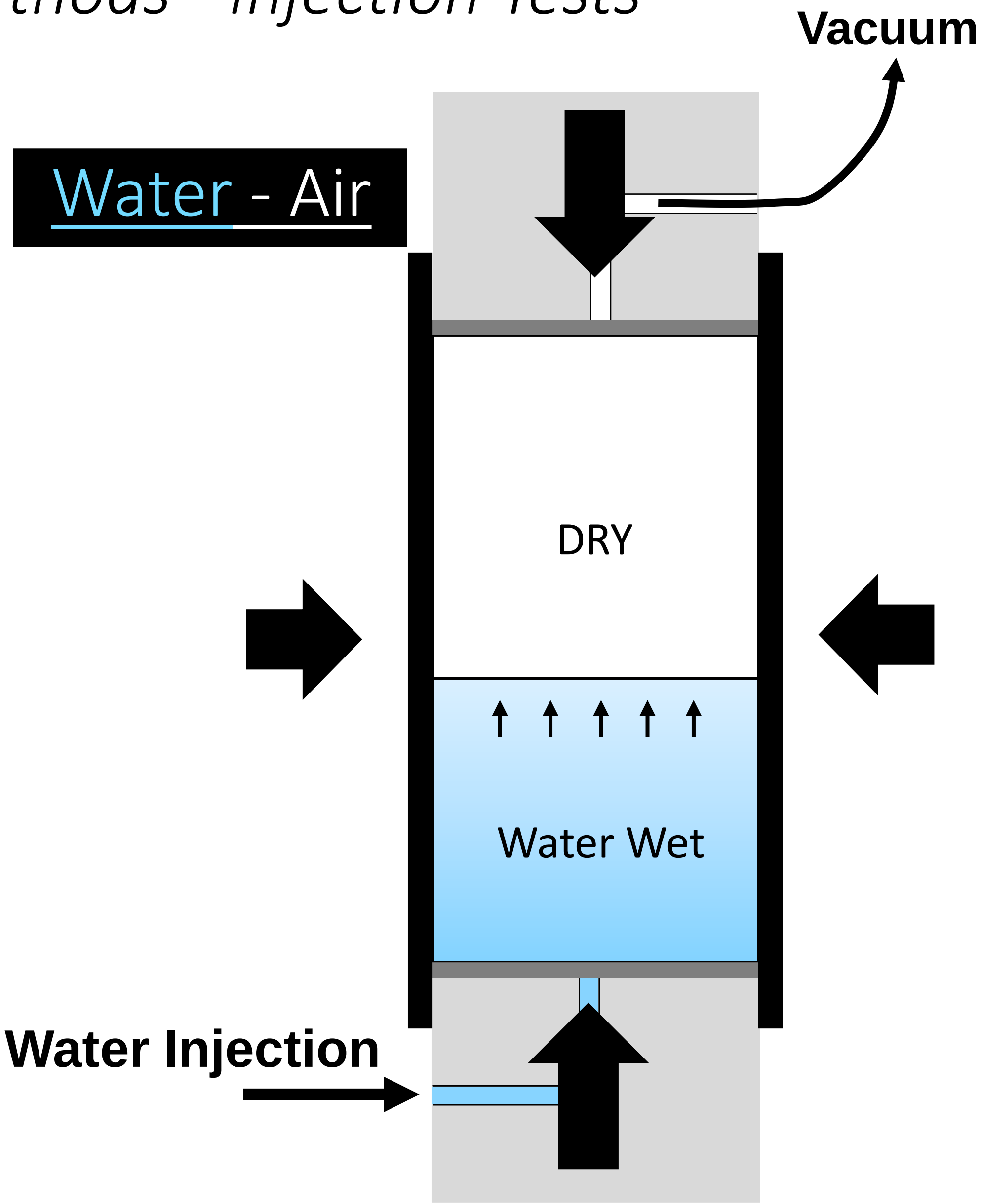
$$P_{eff} = P_l - P_f$$

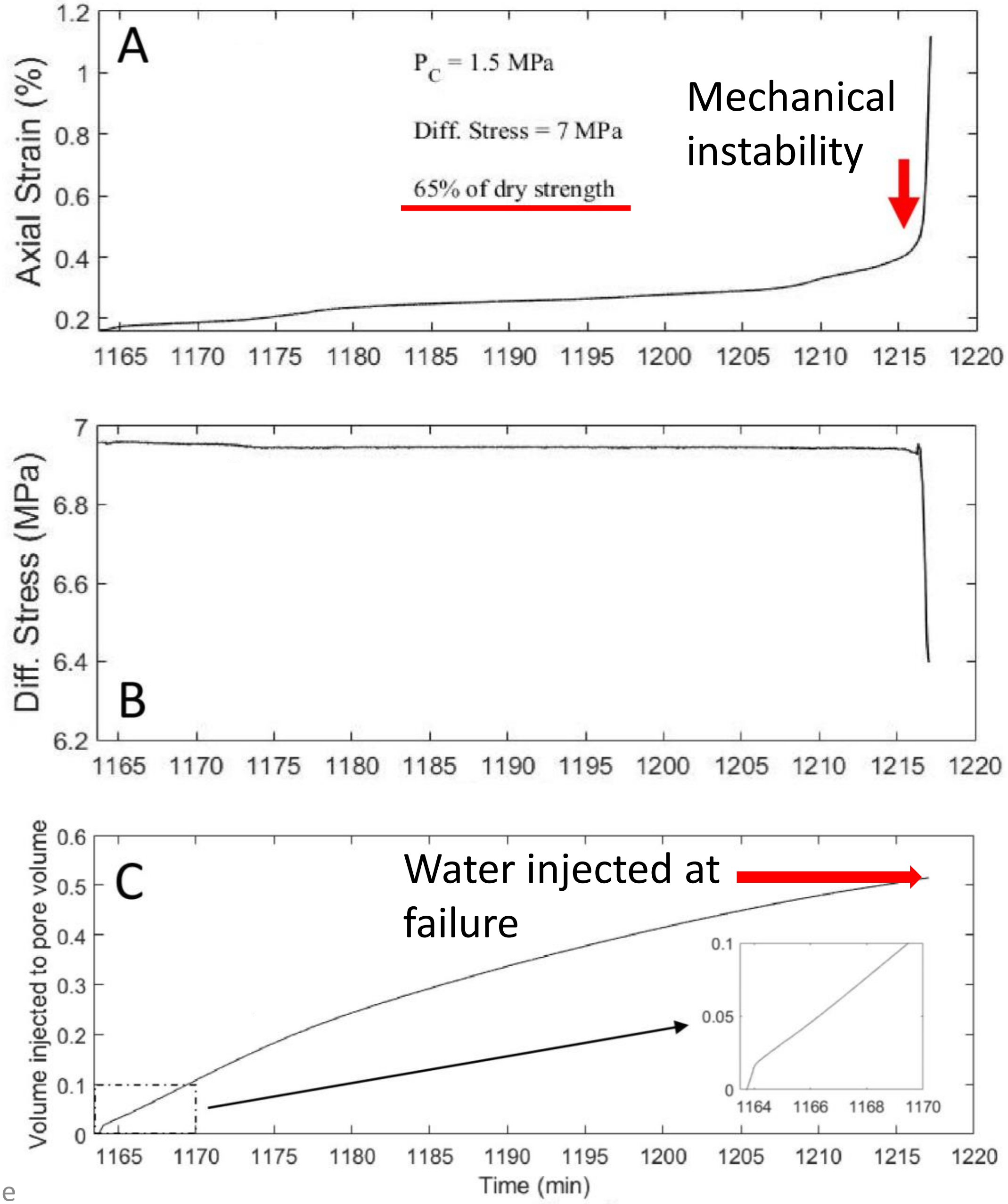
Samples critically loaded above the water-saturated failure envelope

Pressure difference from bottom to top: ~ <u>0.2 MPa</u>.

Injection proceeds gradually, by saturating the rock

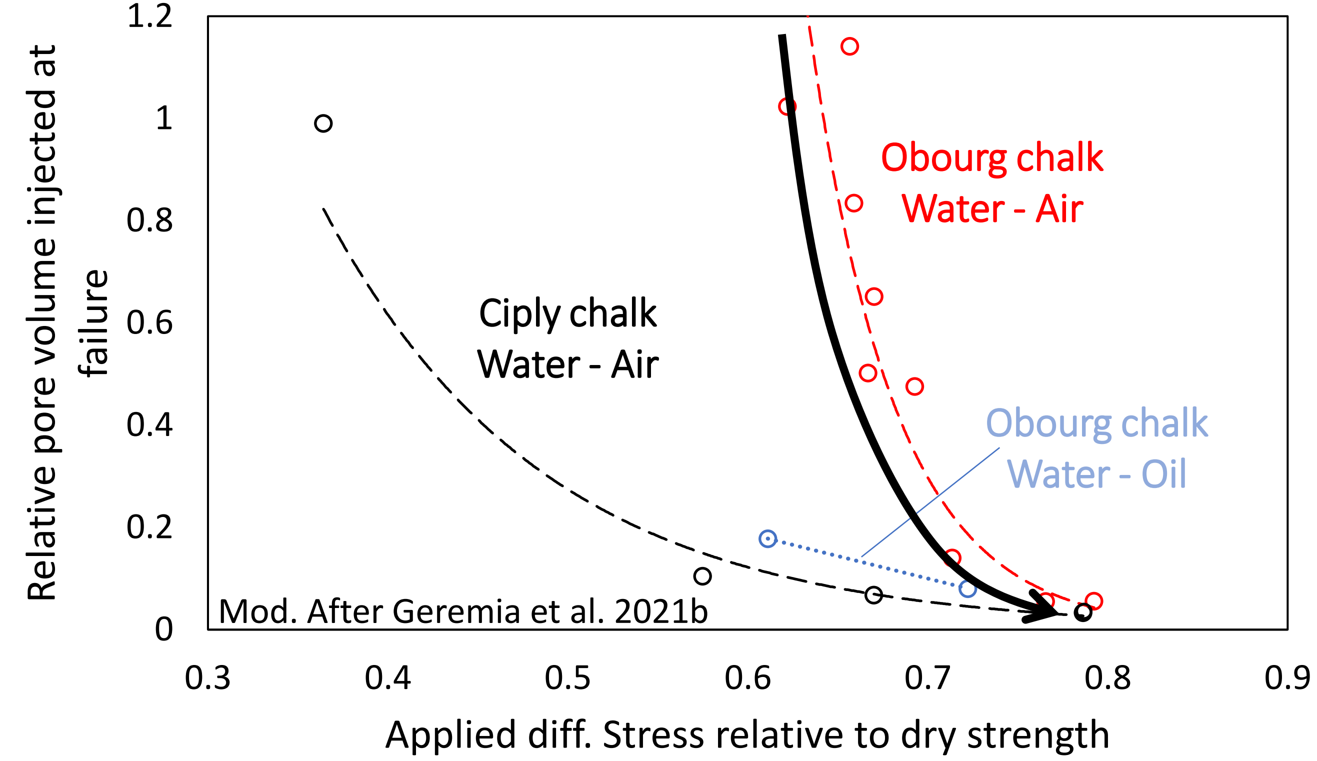
Methods - Injection Tests

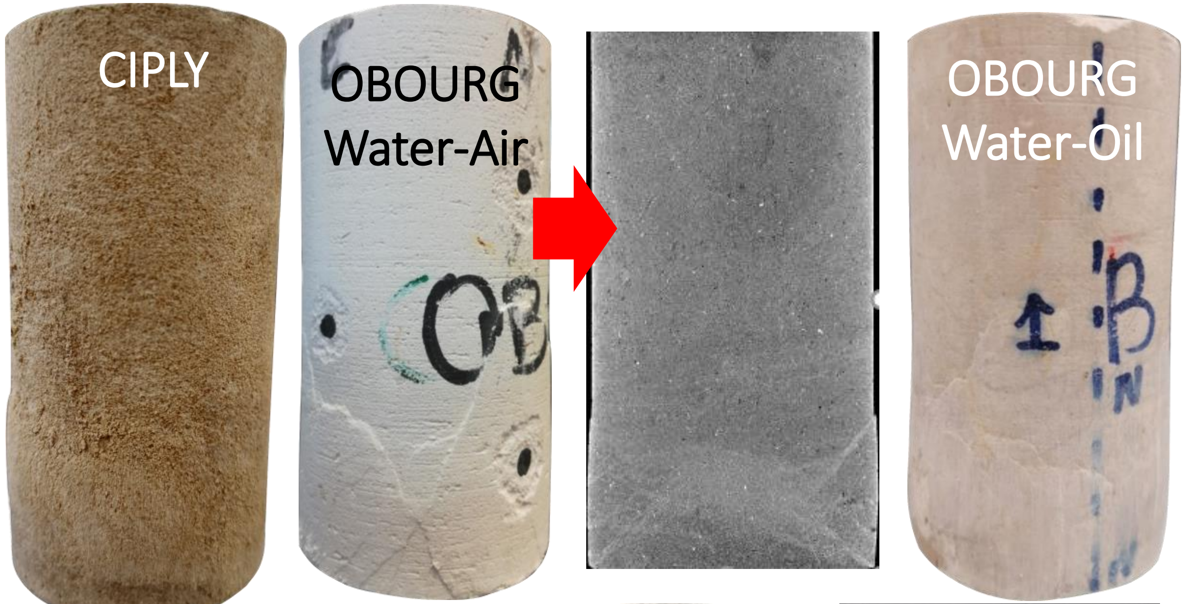


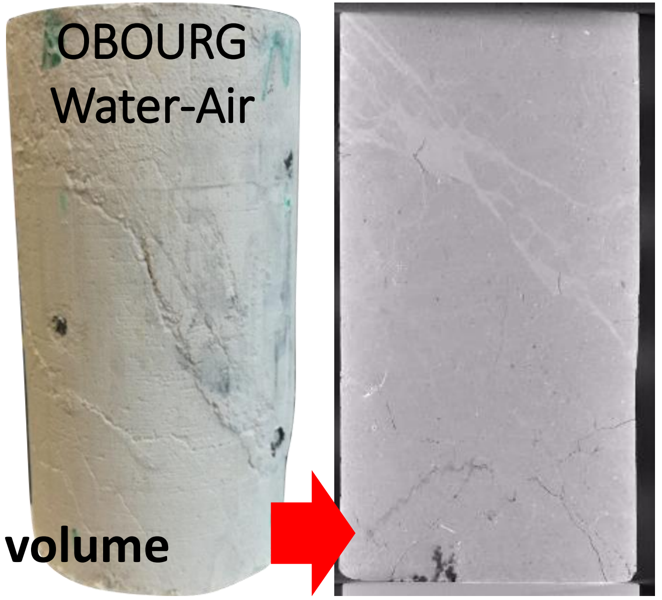


Geremia et al. 2021a

Results – Injection Tests







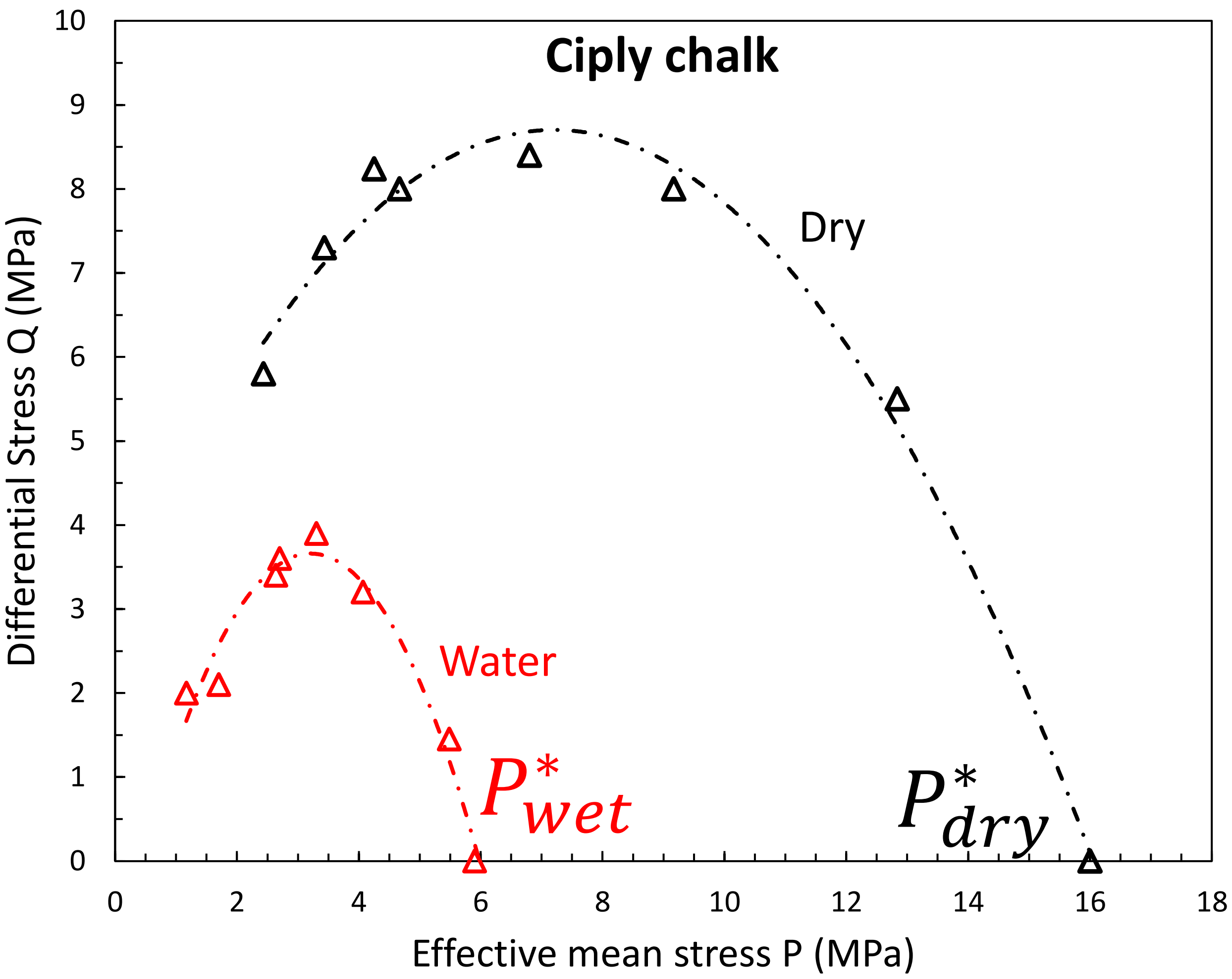
- **The injected amount needed to trigger failure depends on the applied load**
- **In other words, the rock strength decreases exponentially by increasing the wet volume**
- **The Ciply chalk is more sensitive to water**

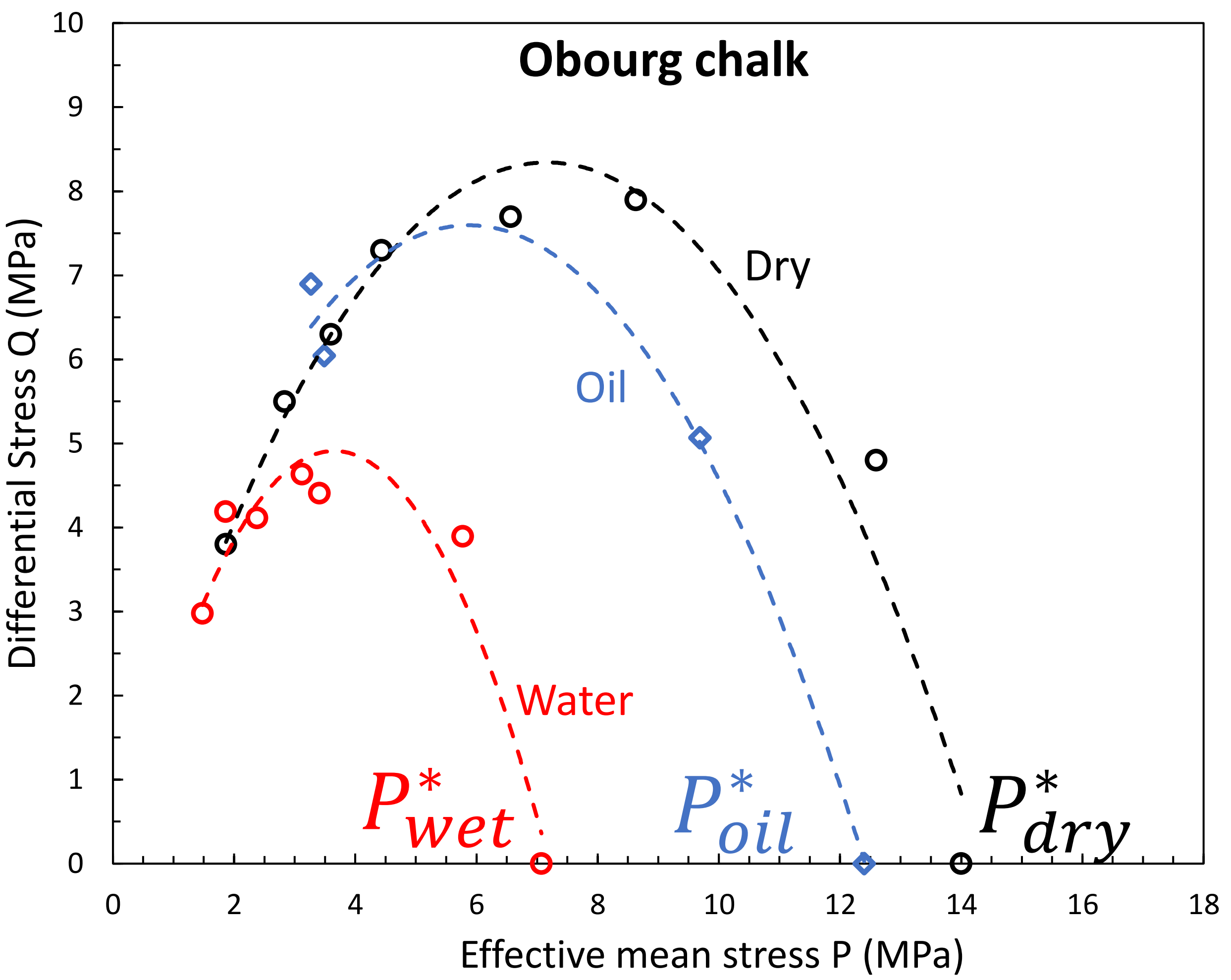
2nd Part

Comparing the two Chalks

Comparison Obourg and Ciply Chalk

Modified after Geremia et al. 2021b

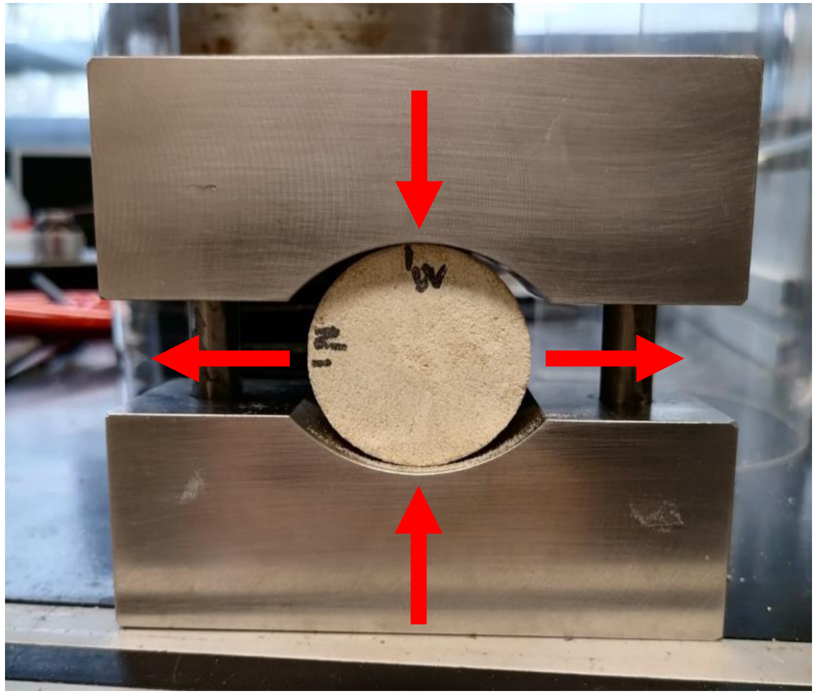




$$\frac{P^*_{Wet}}{P^*_{Dry}} = 0.37$$

$$\frac{P^*_{Wet}}{P^*_{Dry}} = 0.5 \qquad \frac{P^*_{Oil}}{P^*_{Dry}} = 0.89$$

Comparison Obourg and Ciply Chalk

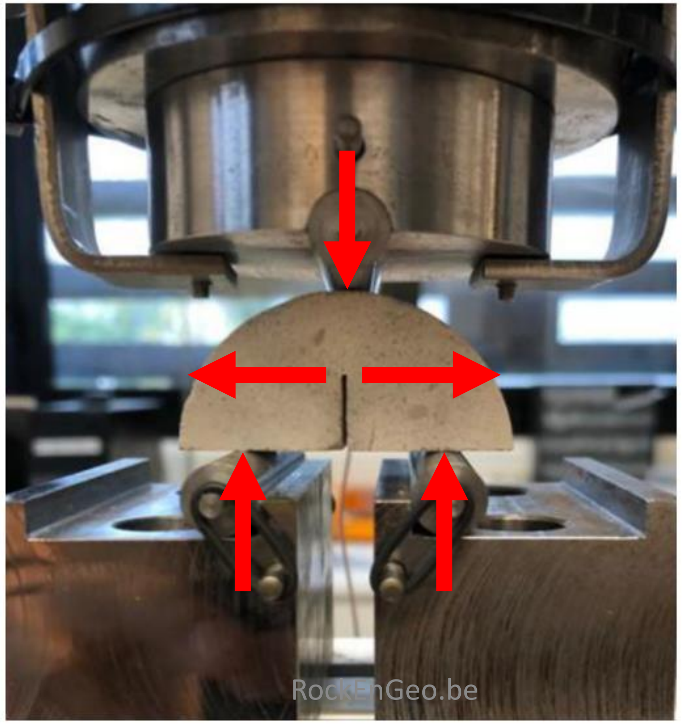


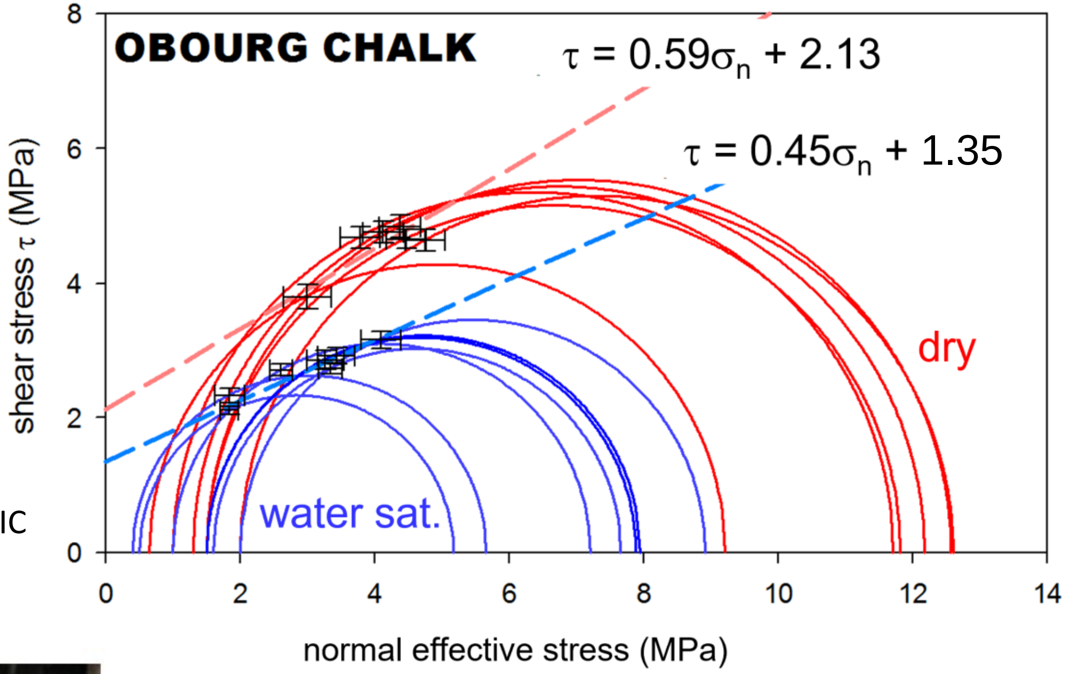
Brazilian test:

- Tensile strength

Triple point load test:

- Fracture toughness K_{IC}
- Surface Energy





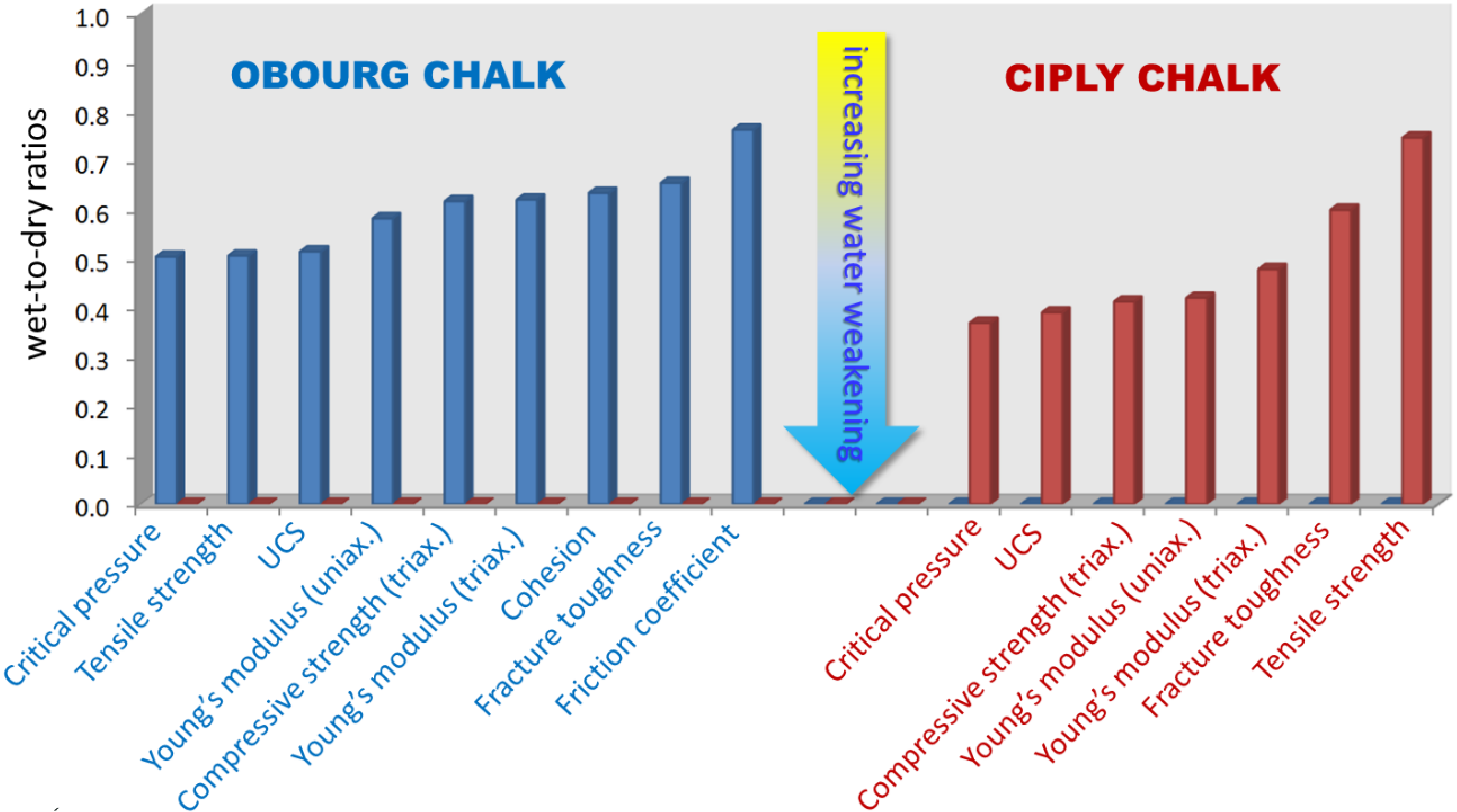
Geremia et al. 2021b

Through triaxial tests at low confining pressure:

- Cohesion
- Friction coefficient

Comparison Obourg and Ciply Chalk – Wet to Dry Ratios

Geremia et al. 2021b

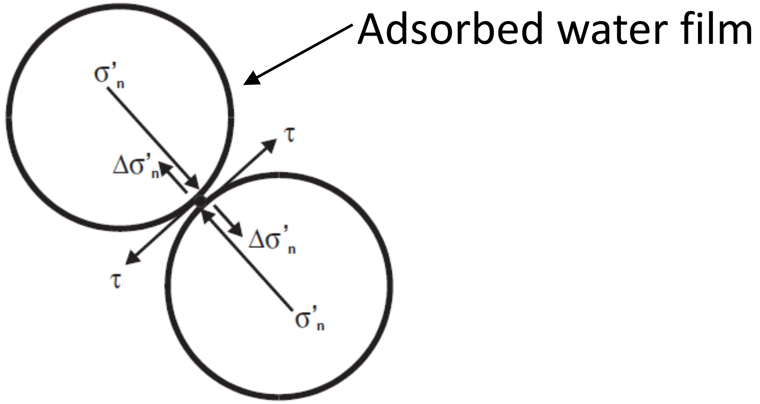


3rd Part

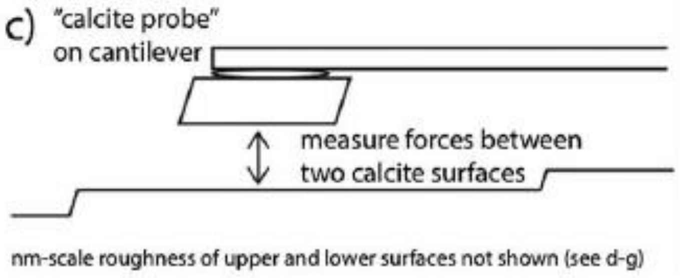
The Mechanisms of Water-Weakening

Short-Term Mechanisms

Repulsive Pressure



Risnes et al. 2005


c) "calcite probe" on cantilever

measure forces between two calcite surfaces

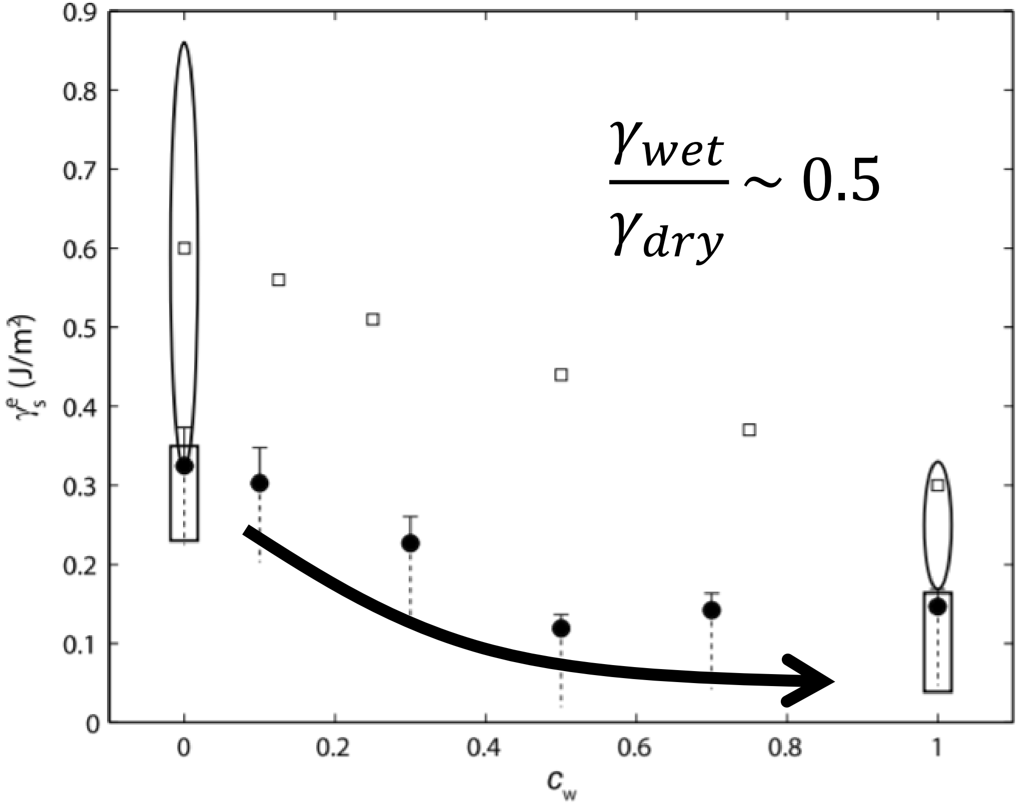
nm-scale roughness of upper and lower surfaces not shown (see d-g)

Røyne et al. 2019

Surface Energy

Energy to cut a solid body in two parts

Røyne et al. 2011 through double torsion experiment

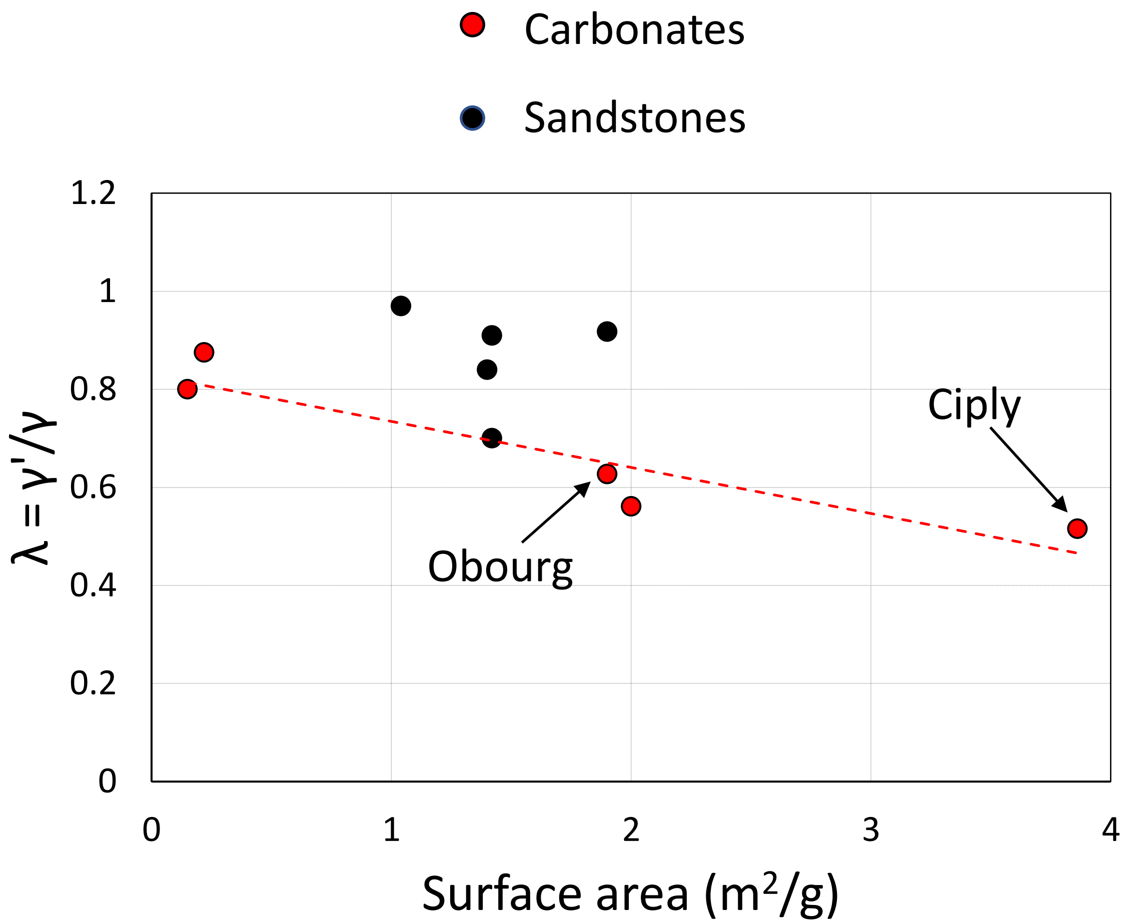


$$\frac{\gamma_{wet}}{\gamma_{dry}} \sim 0.5$$

*Surface Energy and P**

$$\frac{P^*_{wet}}{P^*_{dry}} = \left(\frac{\overset{\text{Water-saturated}}{\gamma'}}{\underset{\text{Dry}}{\gamma}}\right)^{3/2} = \lambda^{3/2}$$

Zhang et al. (1990a)
Baud et al, 2000



Modified after Geremia et al. 2021a

Obourg Chalk

$$\frac{P^*_{wet}}{P^*_{dry}} = 0.5$$

$\lambda = 0.63$

Ciply Chalk

$$\frac{P^*_{wet}}{P^*_{dry}} = 0.37$$

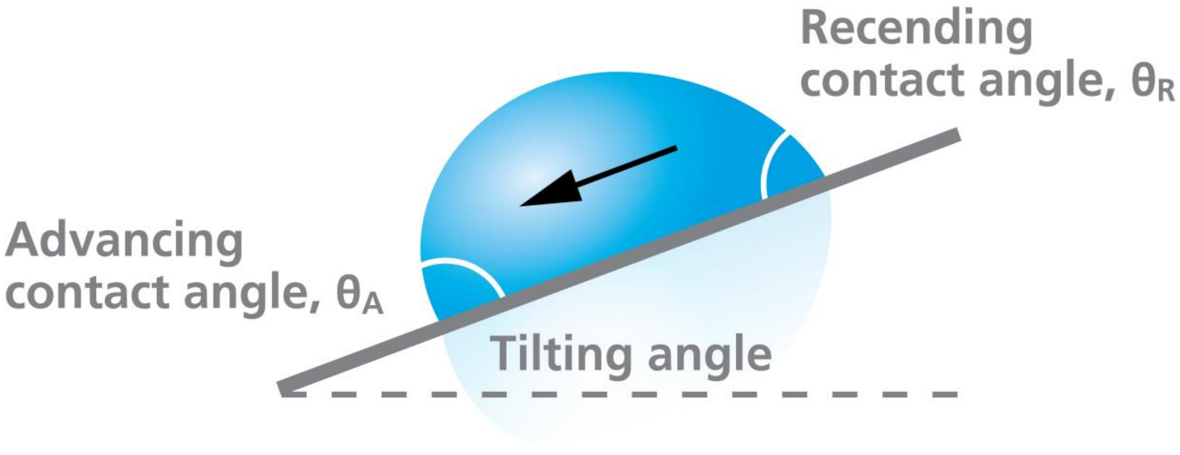
$\lambda = 0.52$

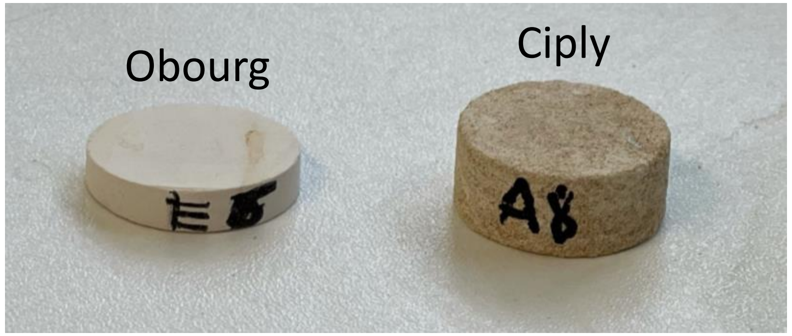
Two parameters:

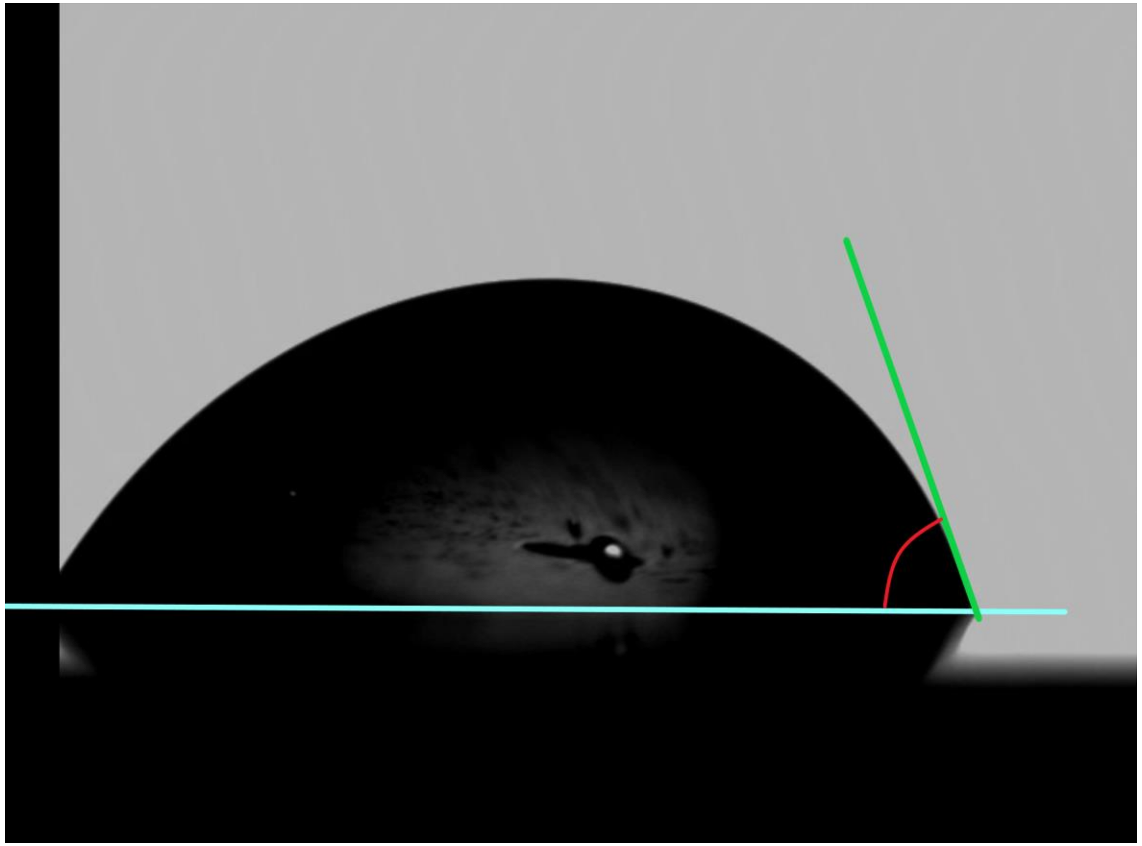
- Surface area
- Mineralogy

Surface Energy Estimation

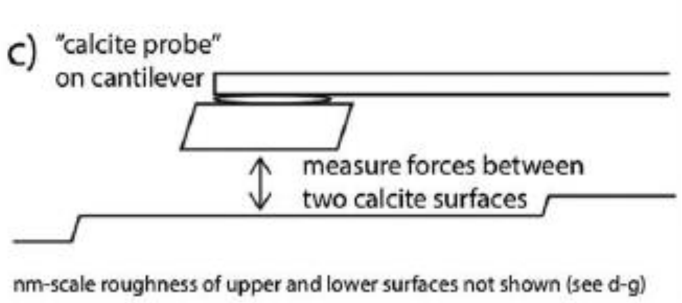
From Rachid Ismail's Internship



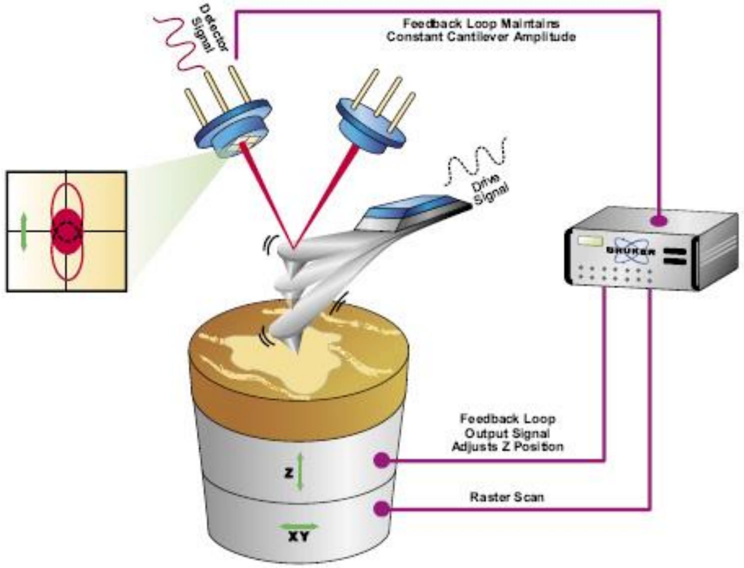


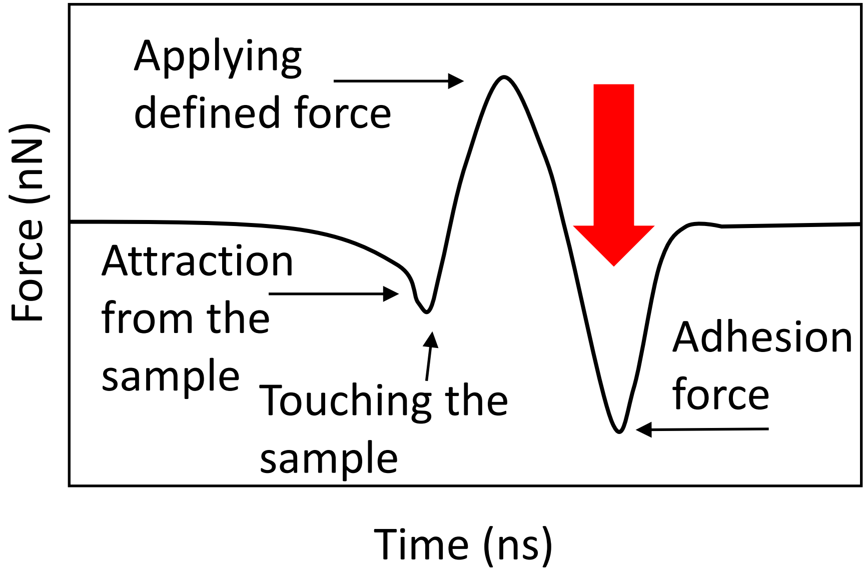


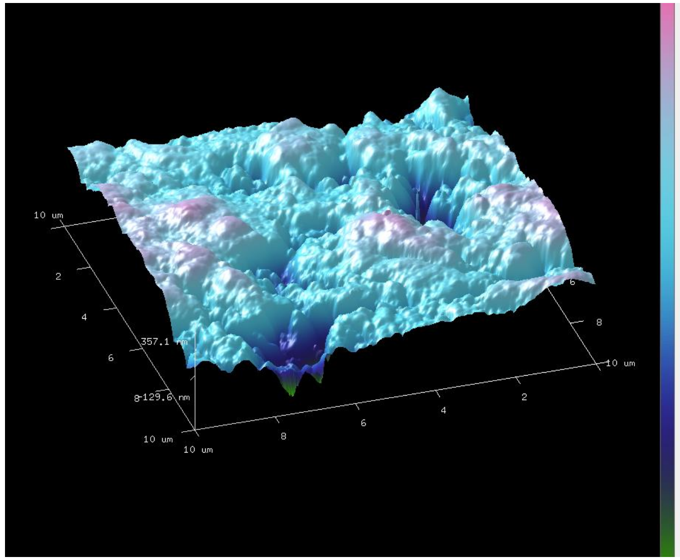
Surface Eenergy and Repulsive Pressure - AFM

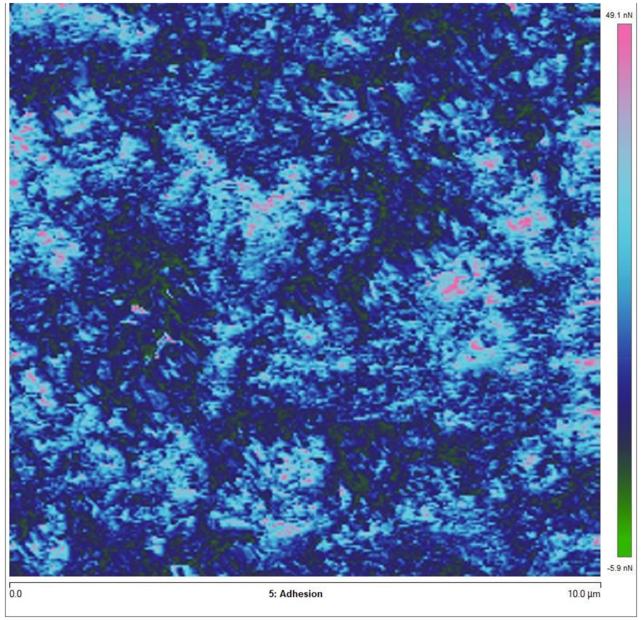


Røyne et al. 2019









Summary

	Obourg Chalk			Ciply Chalk		
Surface Energy (J/m²)	Dry Rock	Water-Saturated Rock	$\lambda = \frac{\gamma^{(sat)}}{\gamma^{(dry)}}$	Dry Rock	Water-Saturated Rock	$\lambda = \frac{\gamma^{(sat)}}{\gamma^{(dry)}}$
From contact angle measurements	0.0234	not measurable	X	0.0253	not measurable	X
From AFM	0.0207	0.0165	0.80	0.0196	0.0141	0.72
From K_{IC} measurements	0.5270	0.4150	0.79	1.01	0.84	0.83

Owens-Wendt model

$$\gamma = \frac{F_{adh}}{4\pi R}$$

$$\gamma = \frac{K_{IC}^2}{2E}$$

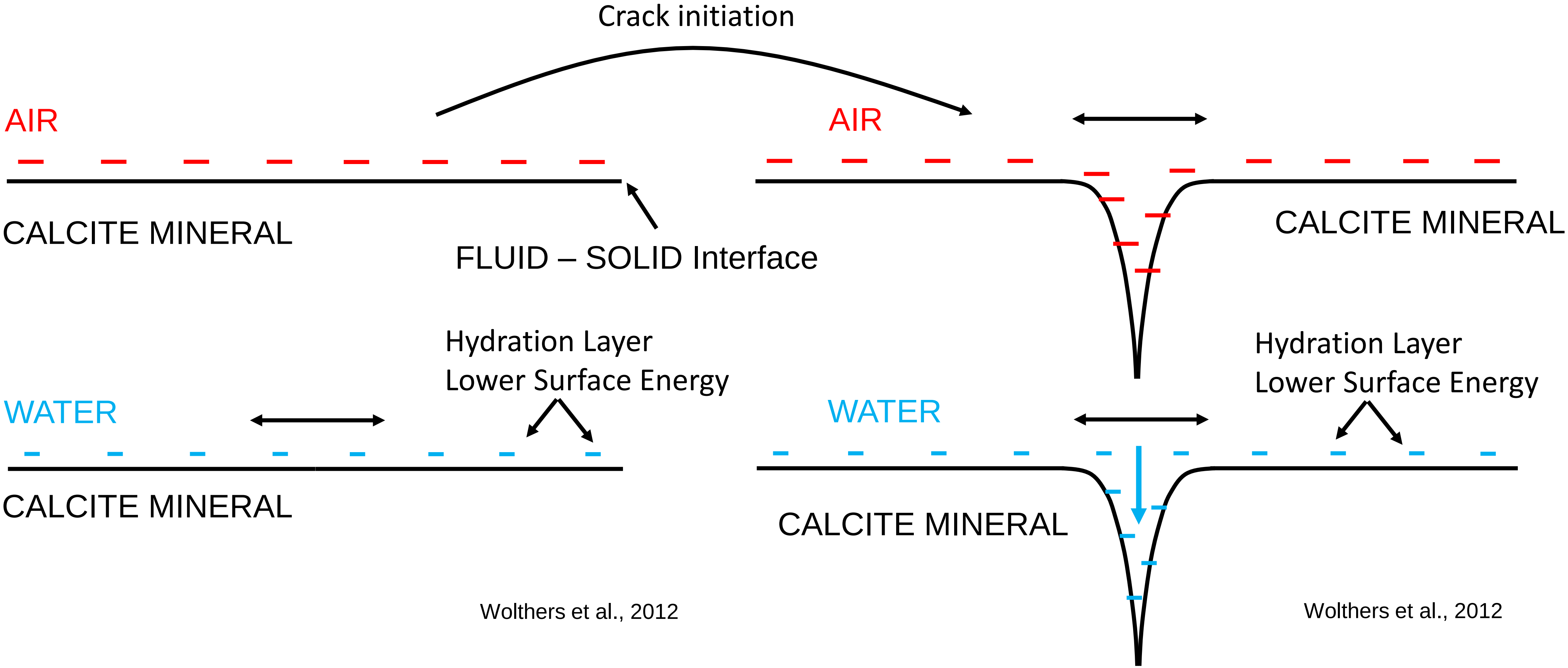
$$P_{adh}^{(Dry,Wet)} = \frac{F_{adh}^{(Dry,Wet)}}{2\pi R^2}$$

$$Repulsive\ pressure = P_{adh}^{(Dry)} - P_{adh}^{(Wet)}$$

	Obourg Chalk	Ciply Chalk
Dry	5.06 MPa	4.79 MPa
Wet	0.99 MPa	0.84 MPa
Rep. Pressure	4.1 MPa	3.9 MPa

$$C_{Dry} - C_{Wet} = 0.8\ MPa$$

Surface Energy mechanism



Wolthers et al., 2012

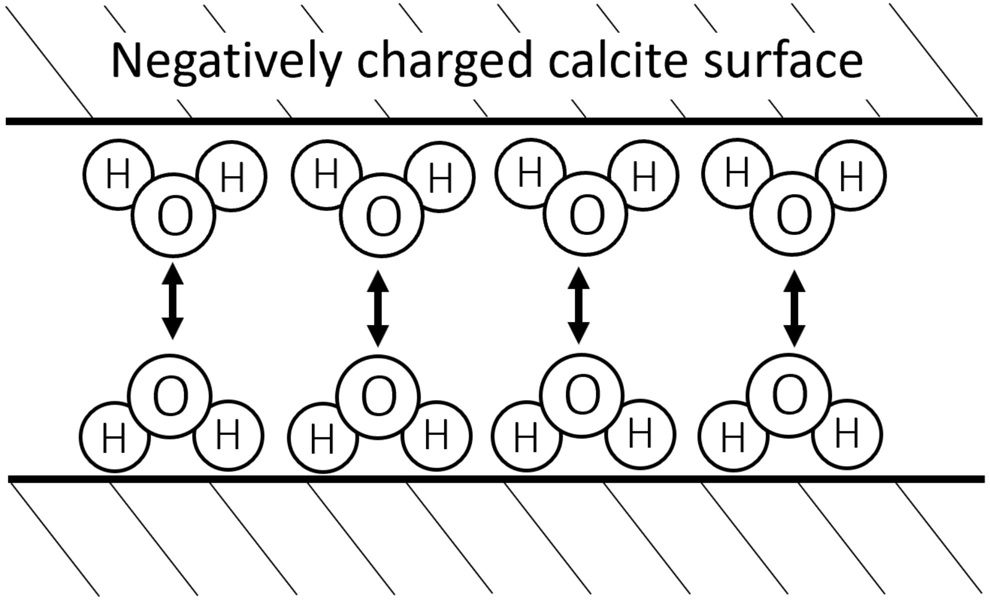
Wolthers et al., 2012

Take home message:

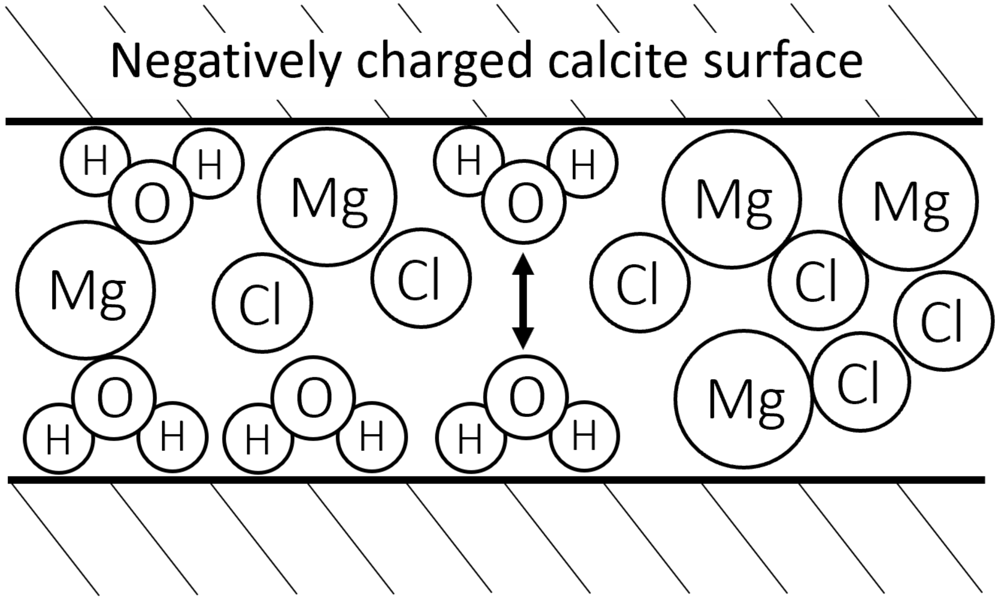
- Results indicate that a hydration layer can decrease the surface energy, hence the energy to induce cracking

Repulsive Pressure mechanism

Pure water, repulsive pressure



Water + ions, lower repulsive pressure



Geremia et al. 2021b

Take home message:

- Results indicate that a hydration layer can also set up a repulsive pressure
- The presence of adsorbed ions dismantles the repulsive pressure

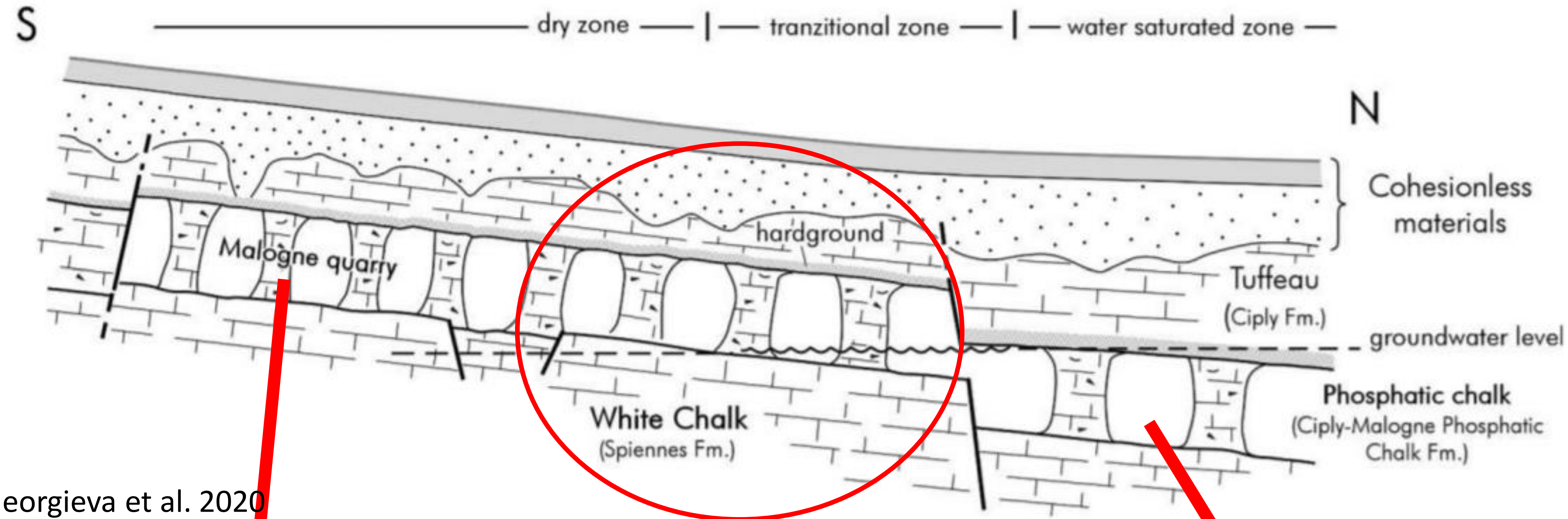
4th Part

Influence of Cyclic Imbibition of Water on the Mechanical Properties of Ciply Chalk

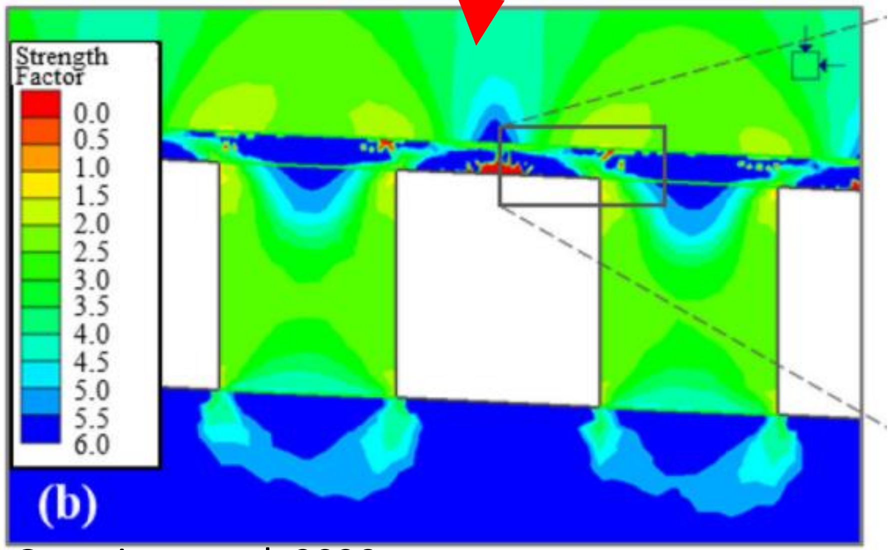
Ciclic Imbibition of Ciply Chalk – La Malogne Quarry

Georgieva et al. 2020

Ciclic Imbibition of Ciply Chalk – La Malogne Quarry

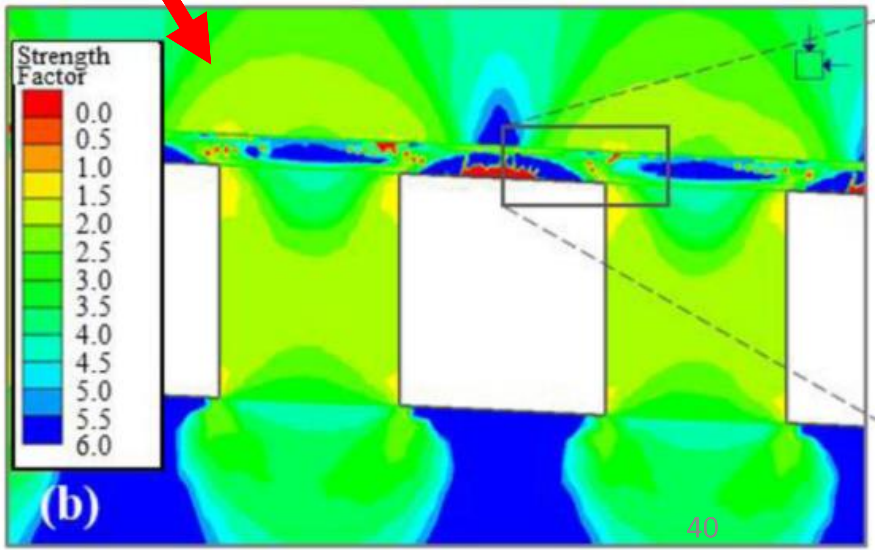


Georgieva et al. 2020



Georgieva et al. 2020

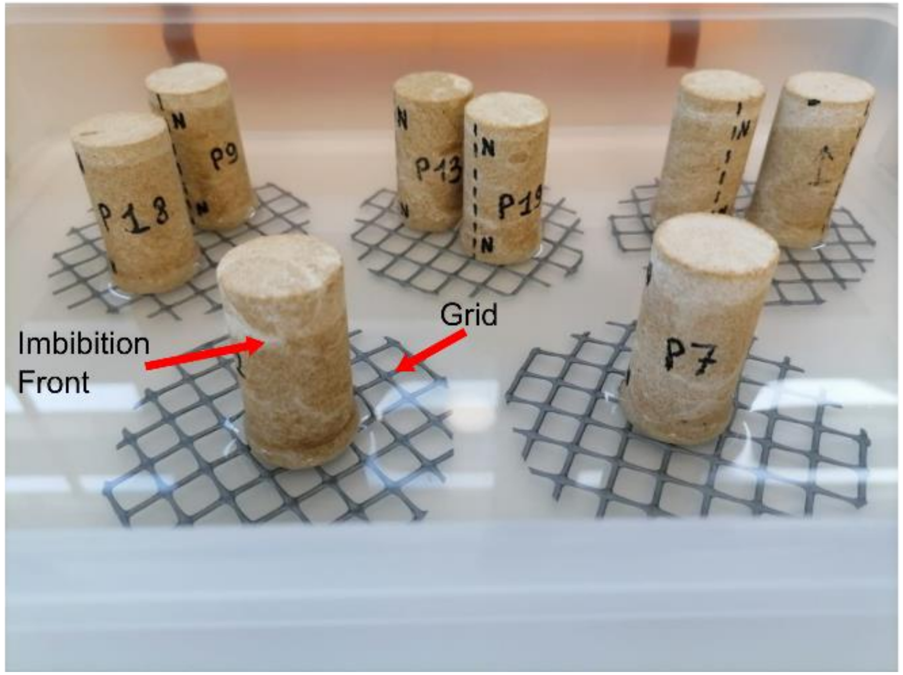
- Uniaxial Compressive strength
- Young's modulus

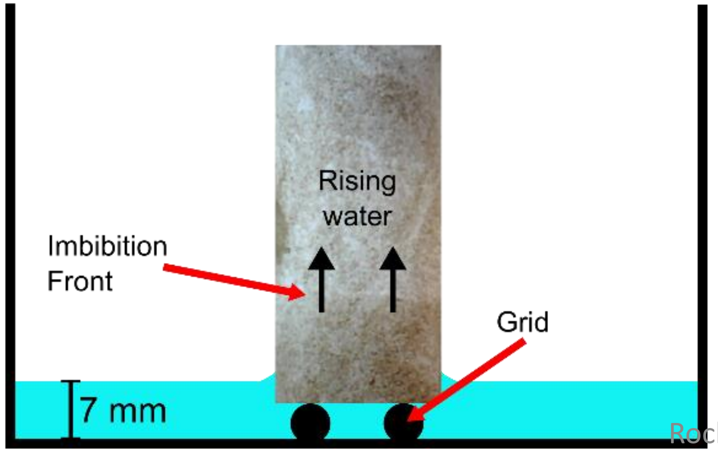


Georgieva et al. 2020

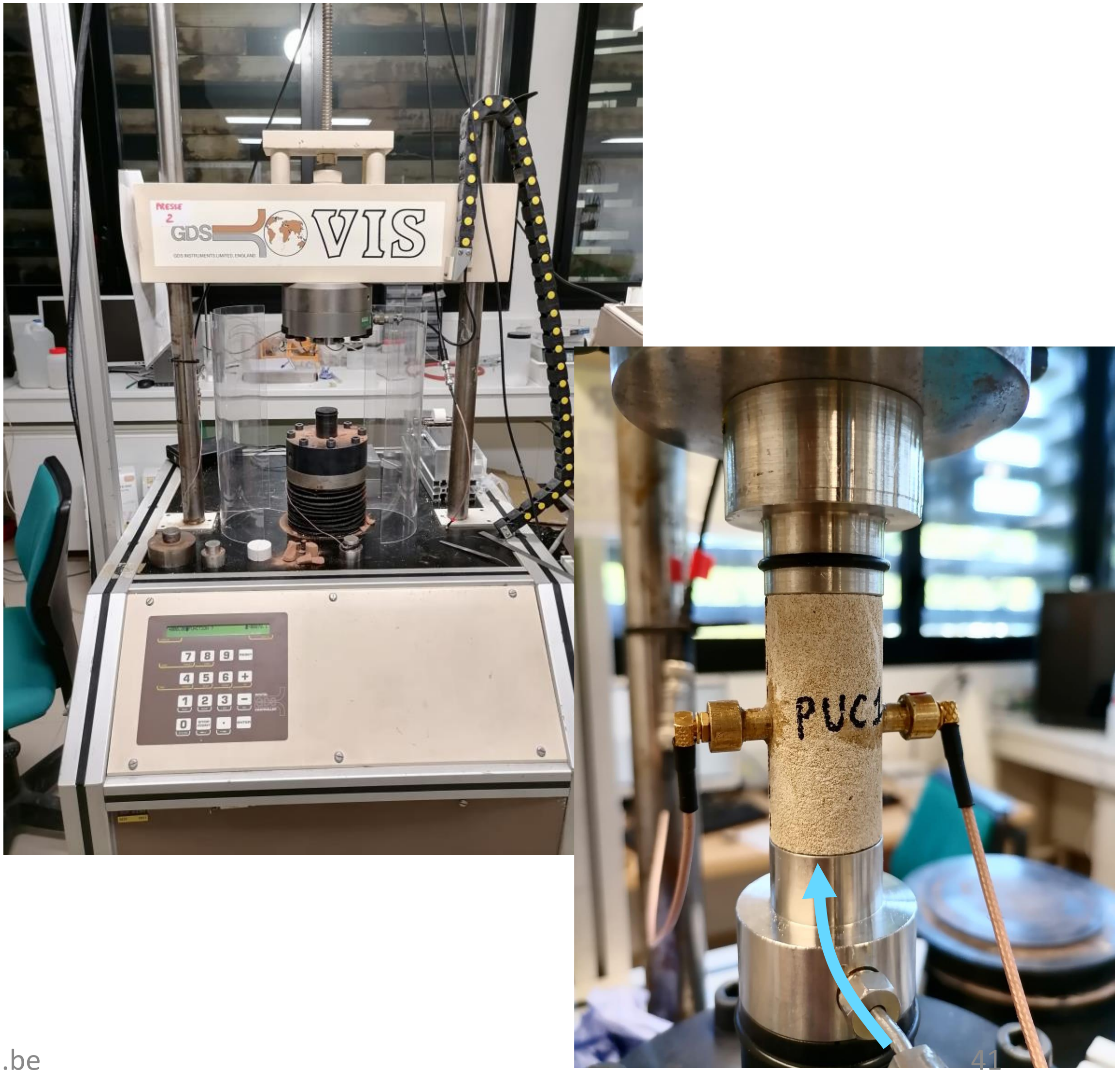
Experimental Approach – Imbibition/Drying Cycles

Ambient stress

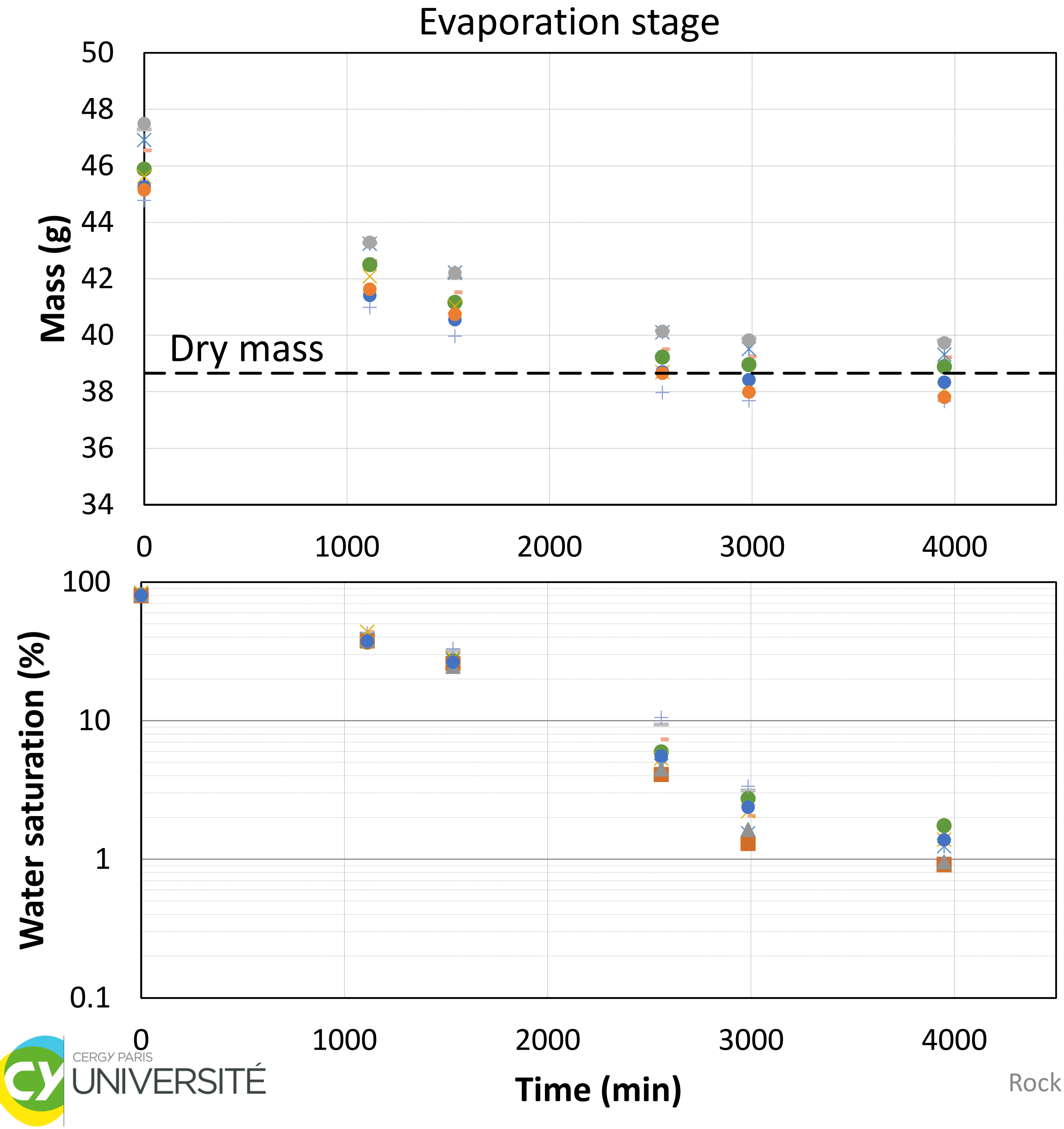




Constant, not critical, axial load



Ciclic Imbibition of Ciply Chalk – Ambient Stress

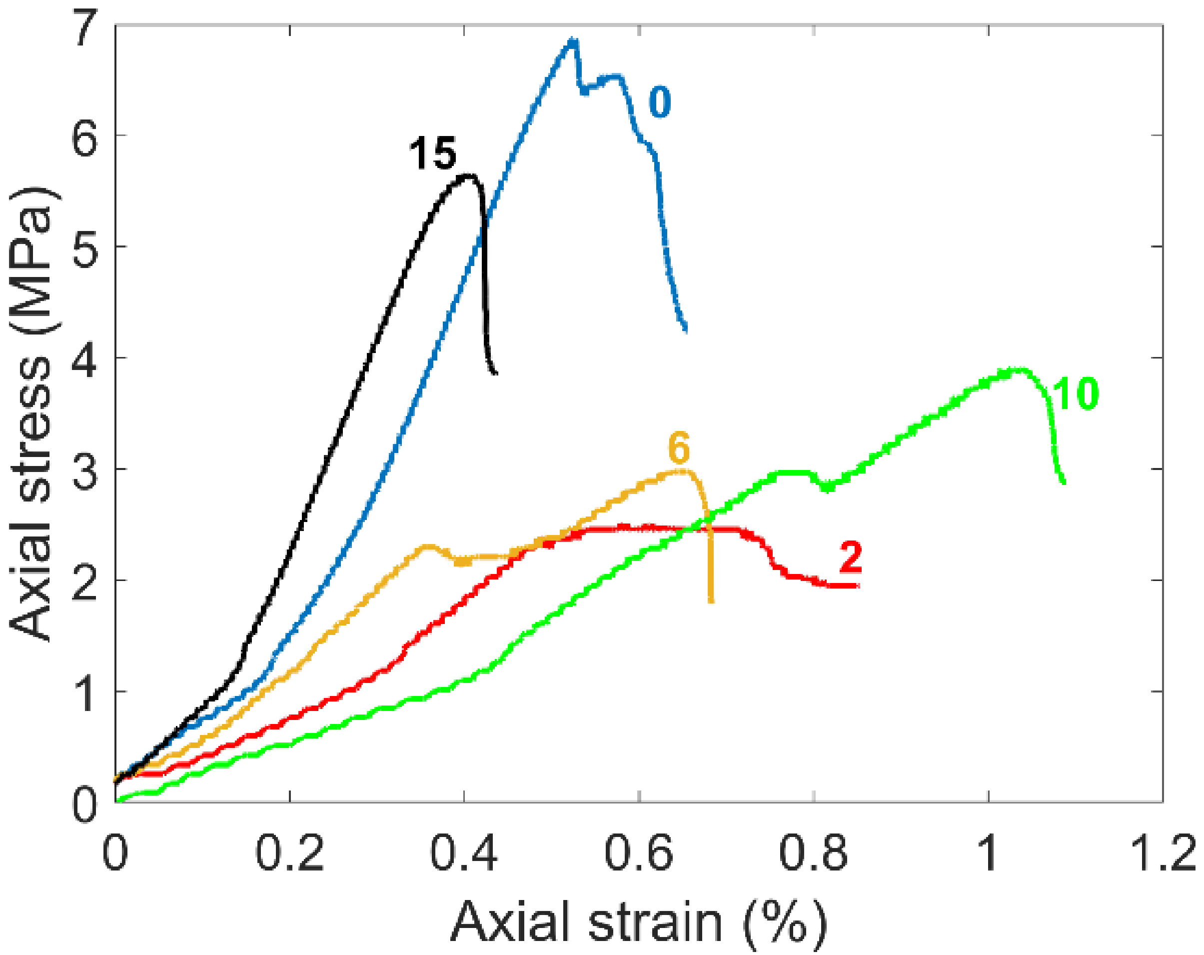


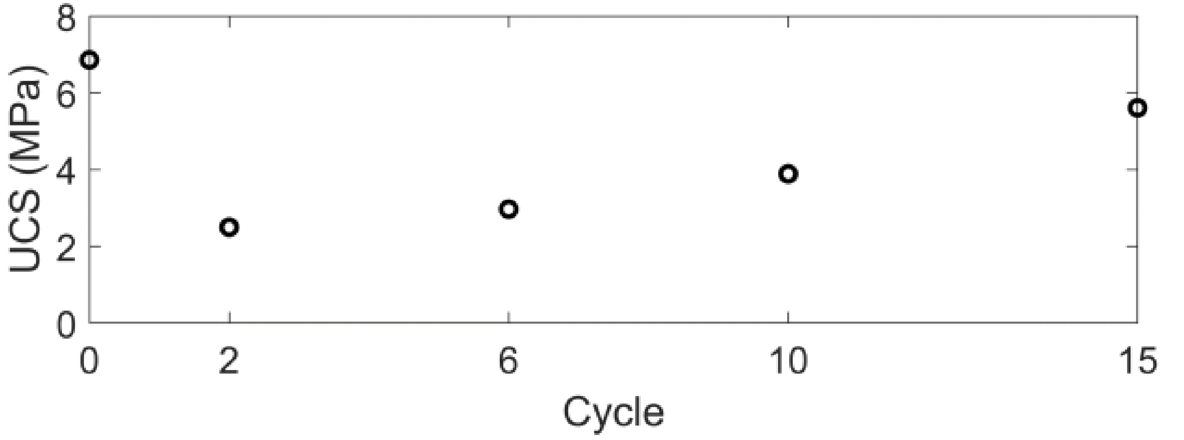
- 15 cycles of imbibition-evaporation with distilled water
- Imbibition: between 30 and 60 mins
- Evaporation: three days
- UCS and Young's modulus at cycle 0, 2, 6, 10, 15
- 5 samples for Young's modulus (load/unload cycle)
- 5 samples for UCS
- Environmental conditions:

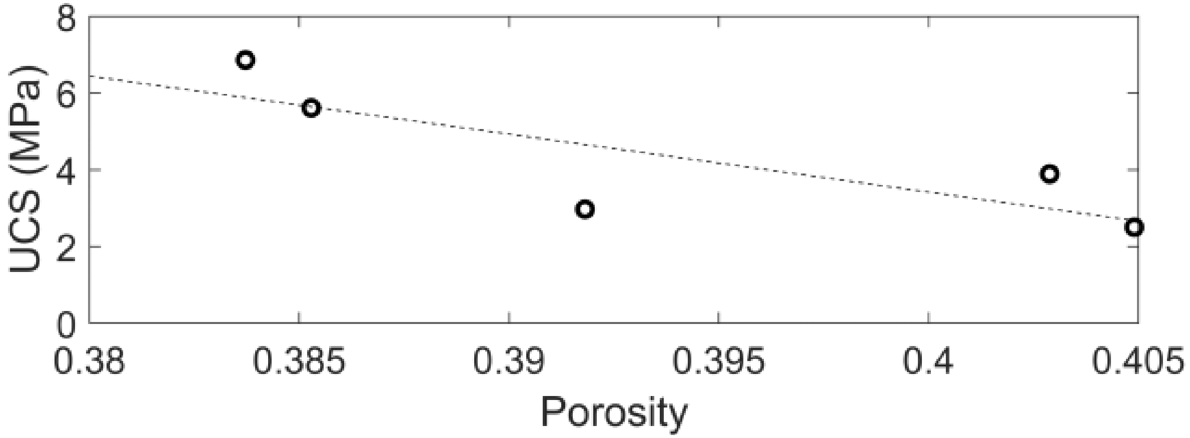
Temperature range: 23-25 °C

Humidity range: 46 – 64 %

Ciclic Imbibition of Ciply Chalk – Ambient Stress



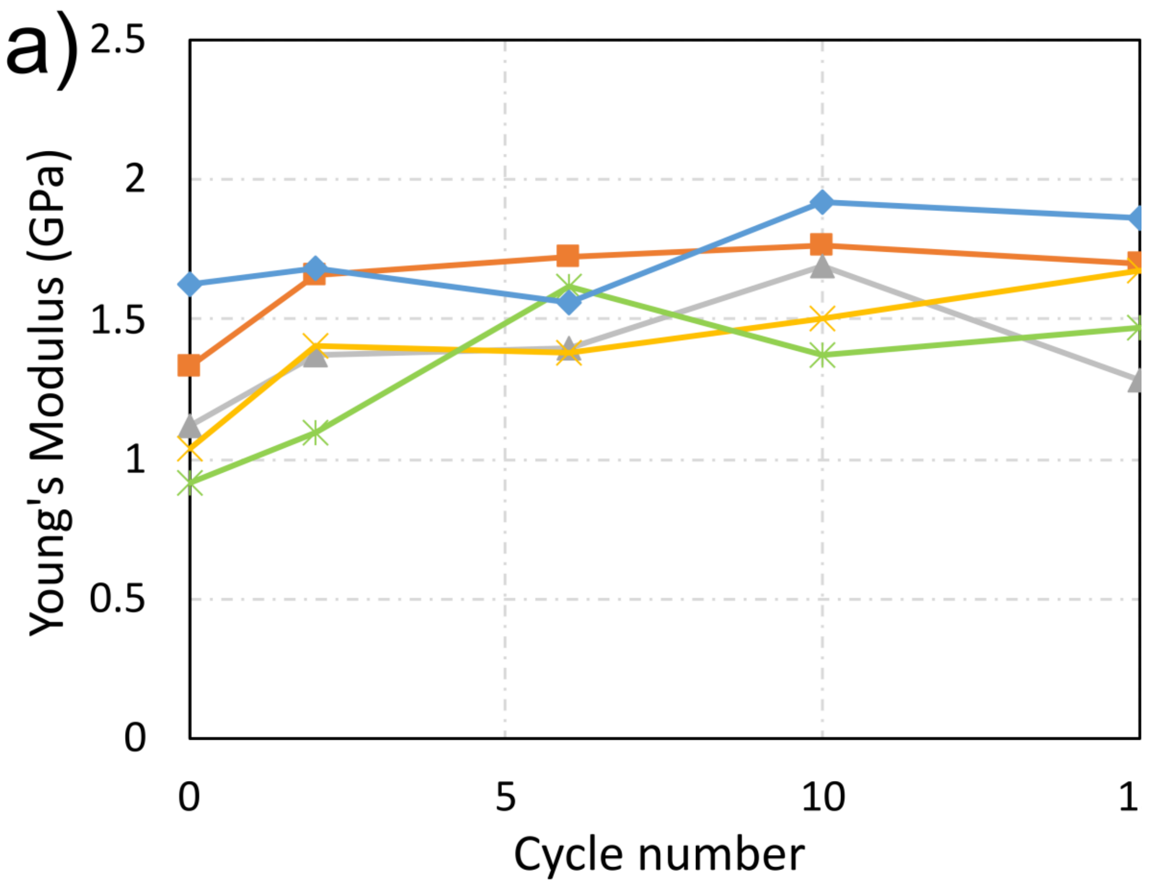


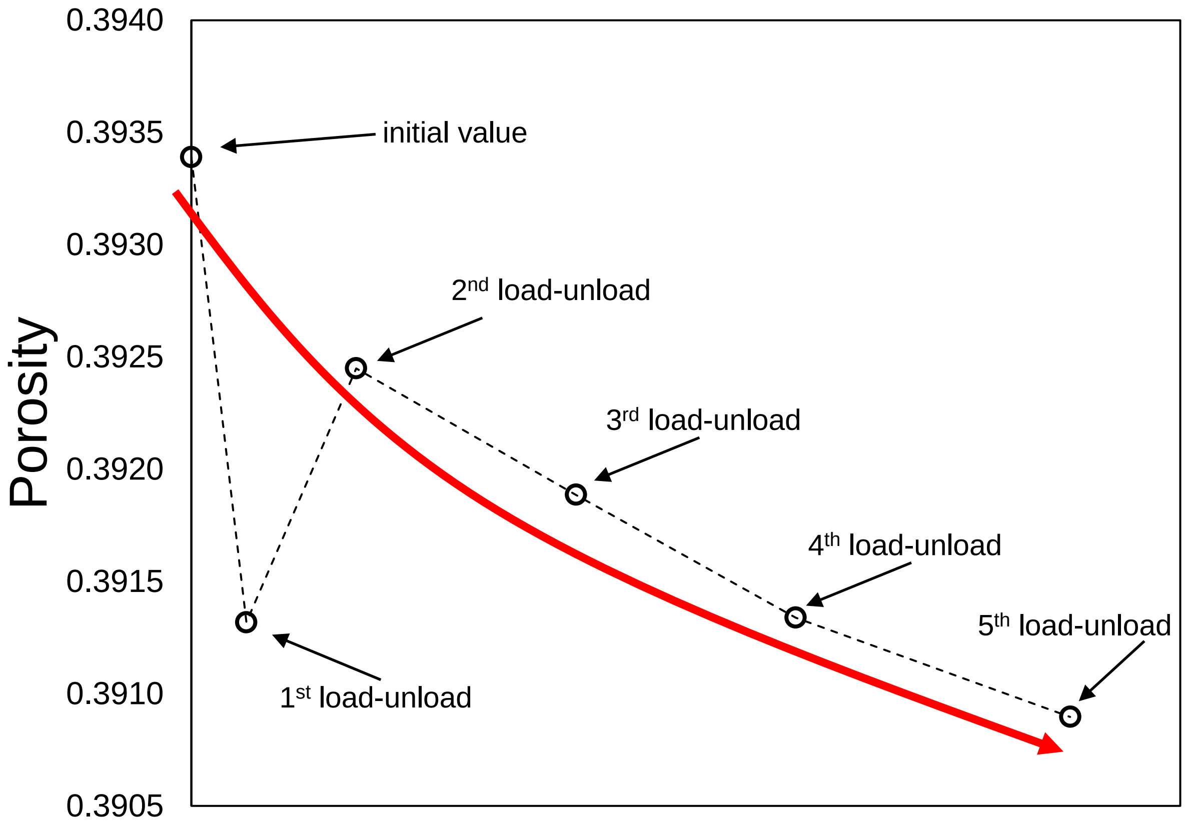


Take home message:

- The mechanical behavior indicates heterogeneity in the rock samples
- UCS seems to be more affected by the porosity rather than cyclic imbibition

Ciclic Imbibition of Ciply Chalk – Ambient Stress





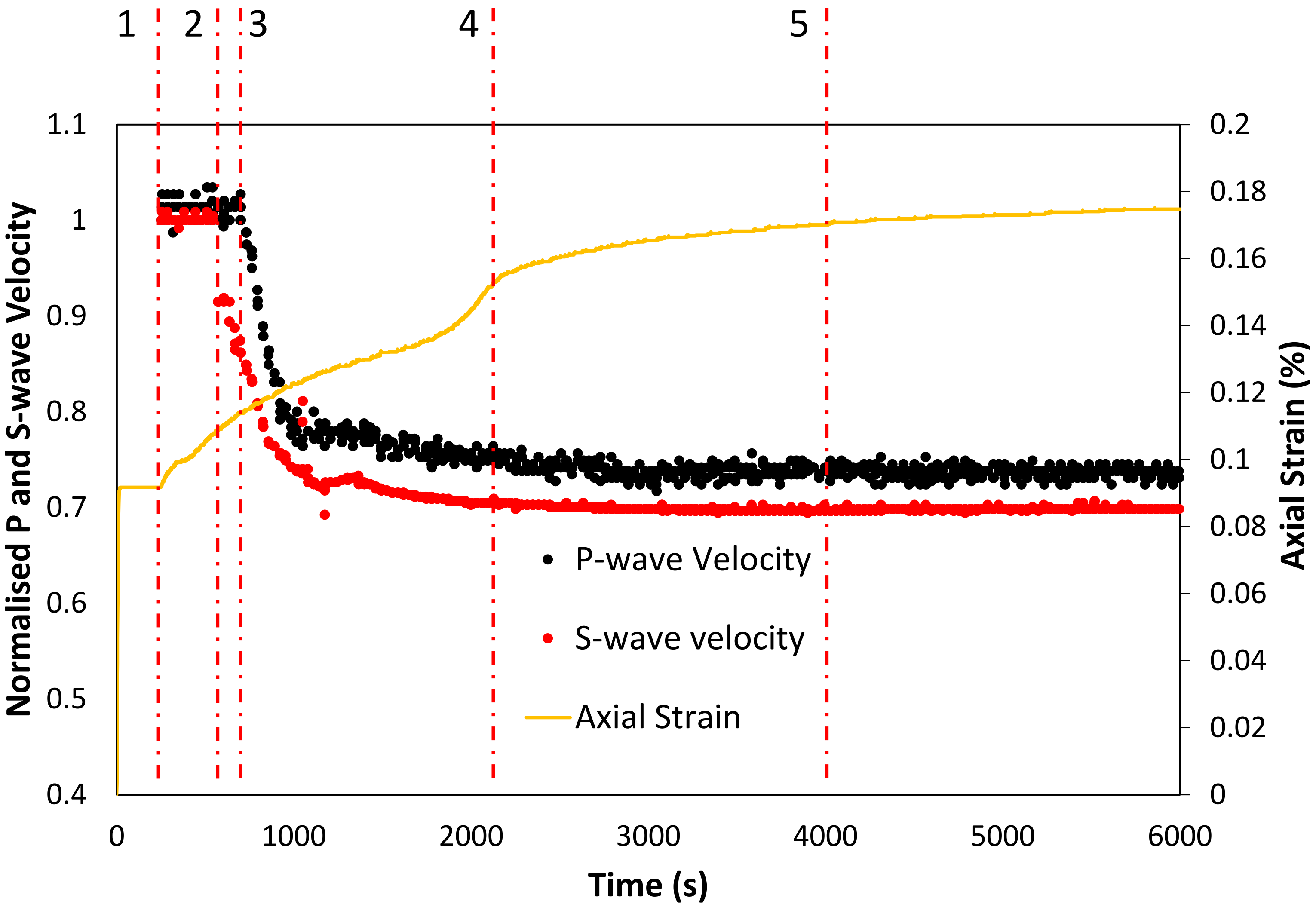
Take home message:

- Young’s Modulus does not appear to be affected by cyclic imbibition
- Young’s Modulus undergoes hardening

Ciclic Imbibition of Ciply Chalk – Constant Load

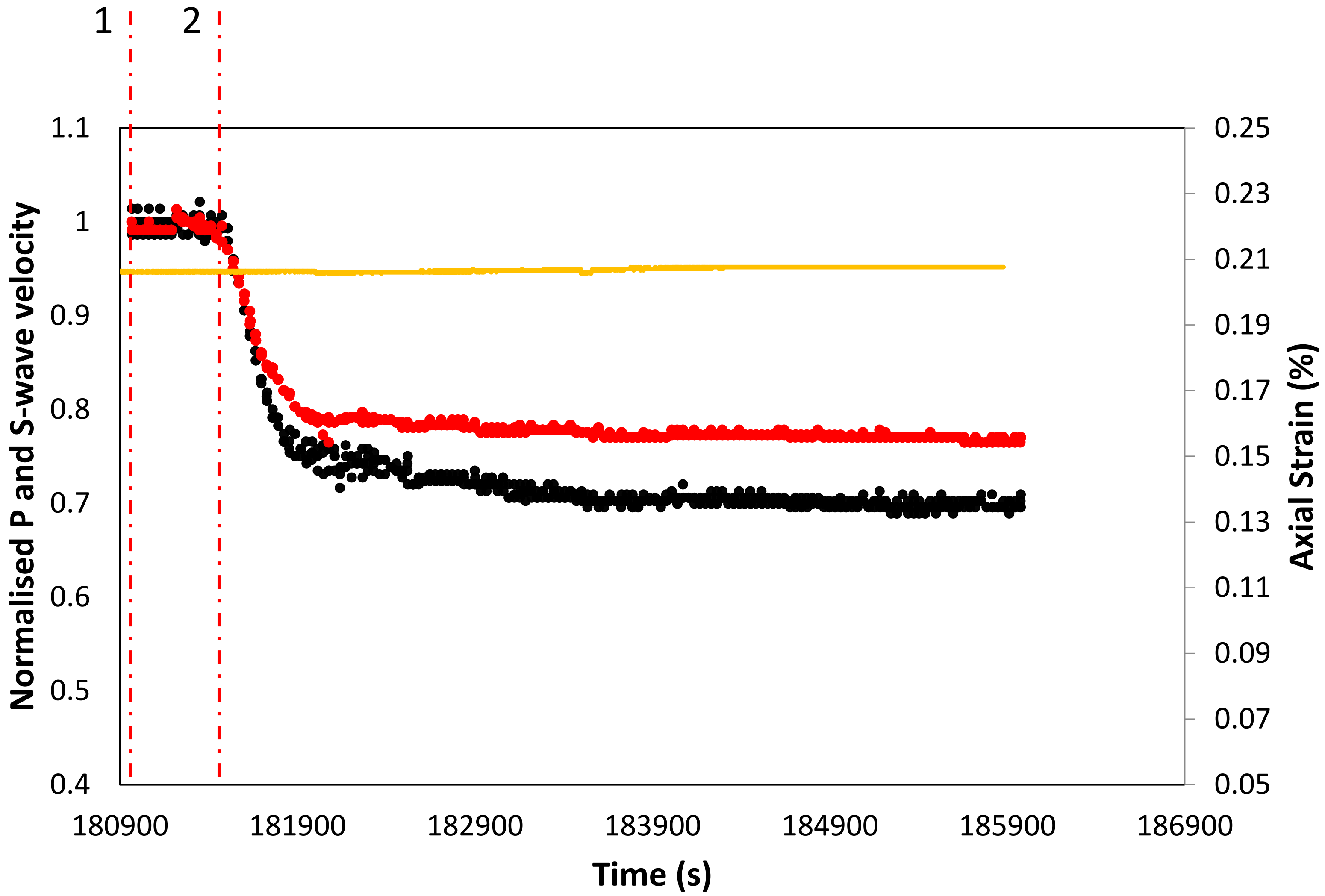
- Constant axial stress: 0.6 MPa
- 6 cycles of imbibition-evaporation with chemically equilibrated water
- Imbibition: around 60 mins
- Evaporation: two days

1° Imbibition – Constant Load



1. As soon as the water enters in contact with the sample the axial strain increases
2. S-wave velocity decreases
3. P-wave velocity decreases
4. Water reaches the top of the sample
5. Stop test

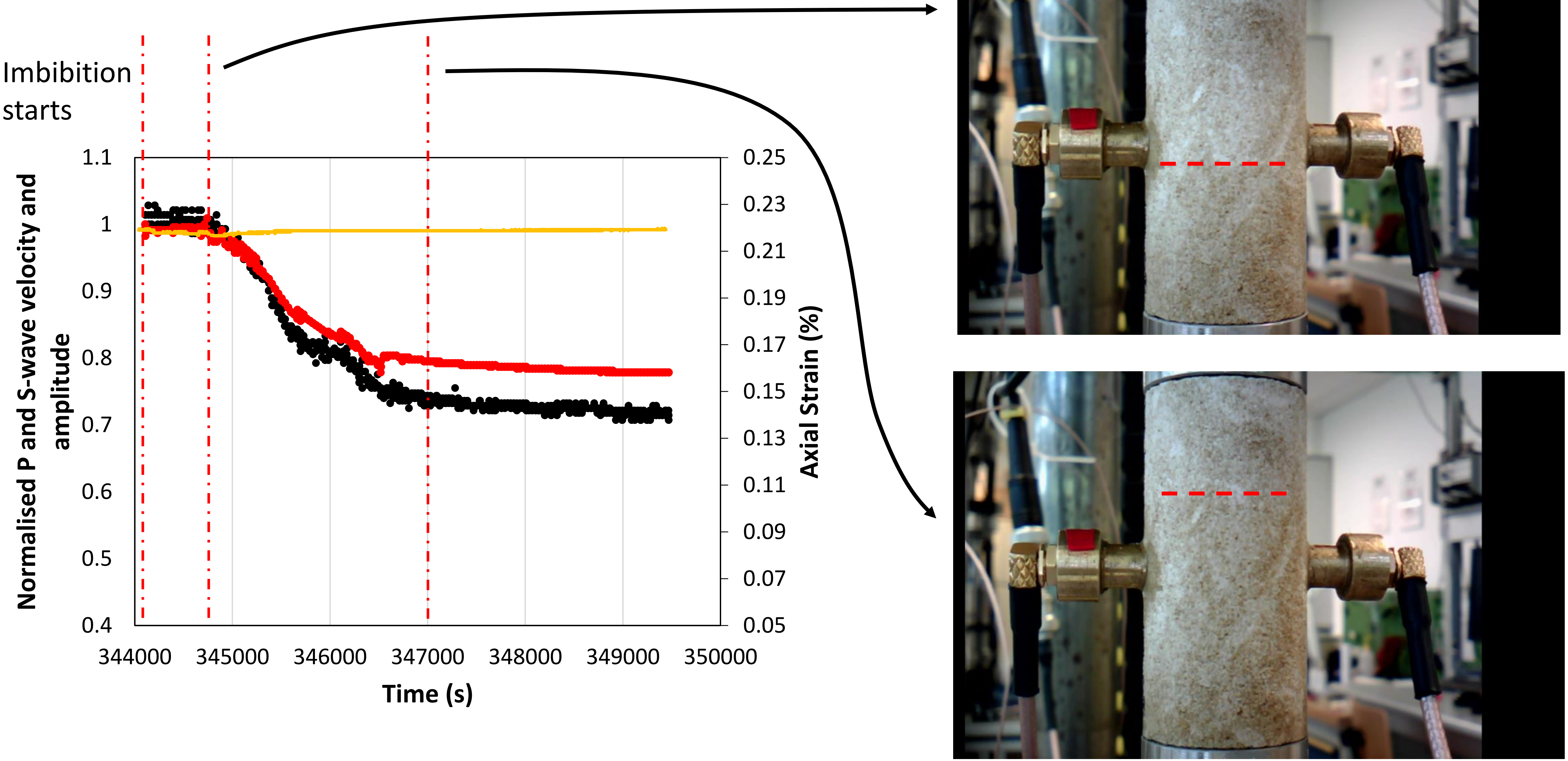
2° Imbibition – Constant Load



1. As soon as the water enters in contact no change in the axial strain

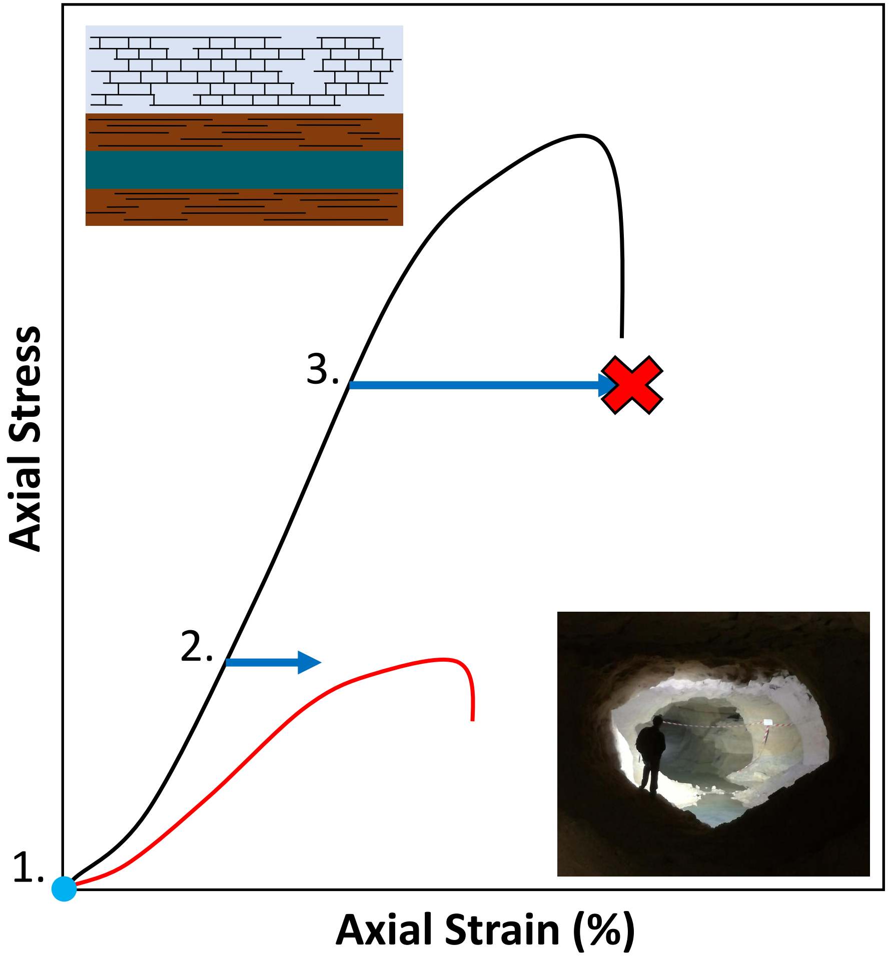
2. S-wave and P-wave velocity decreases

3° Imbibition – Constant Load



Imbibition starts

Take Home Message



1. Imbibition at ambient stress

Water saturation does not induce strain
When dried, the rock strength is recovered

2. Imbibition at constant **not-critical** load

Water saturation leads the rock sample from a dry state to a wet state producing irreversible strain
When drying, no strain is recovered
Hence, a new imbibition does not induce strain

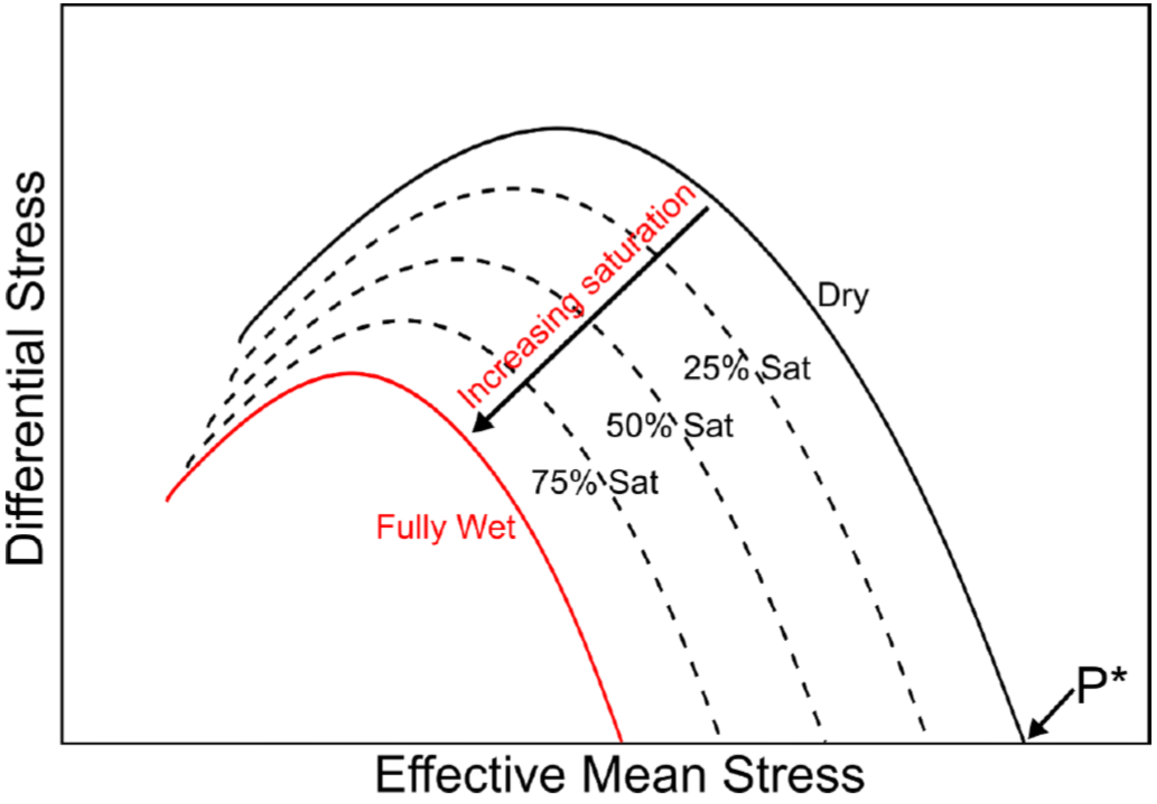
3. Injection test at constant **critical** load

Being the constant applied stress much higher than its water-saturated strength, it fails catastrophically

- Knowing the stress state we can predict the resulting deformation/compaction
- Open question: What then causes higher damage in the transitional zone?
  Frost weathering?

General Conclusions

- Results indicate that a hydration layer can both decrease the surface energy and set up a repulsive pressure
- Changing the saturating fluid means changing completely the mechanical properties; the new properties can be quantified through conventional mechanical tests
- The mechanical strength reduces exponentially and progressively with the water saturation or wet volume



Thanks for your attention!
Any questions?