Laboratory testing for monitoring of reservoir properties during water injection

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Supported INEX Project

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Objectives :

Seismic survey is an effective and widely used tool in monitoring reservoir exploitation, whether linked to hydrocarbon production or any kind of operation which requires the injection of a foreign fluid with respect the in-situ one.

Ultrasonic monitoring at lab scale provides the best way to detect and understand any kind of problem related to these operations.

The goal of this study is to combine ultrasonic monitoring with mechanical data, like axial strain or applied load, as well as injection rate, in order to characterize and monitor the rock properties during water injection.

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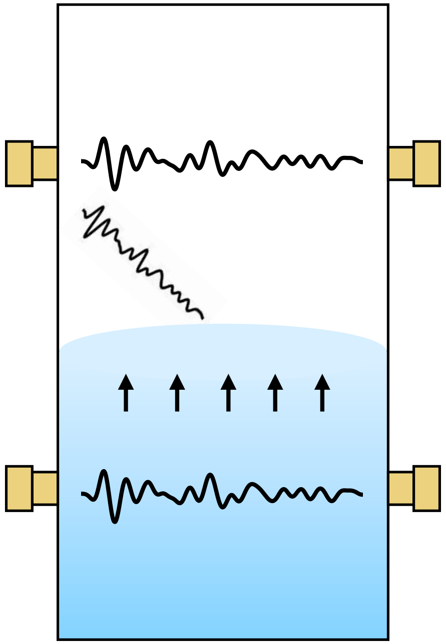
Objectives :

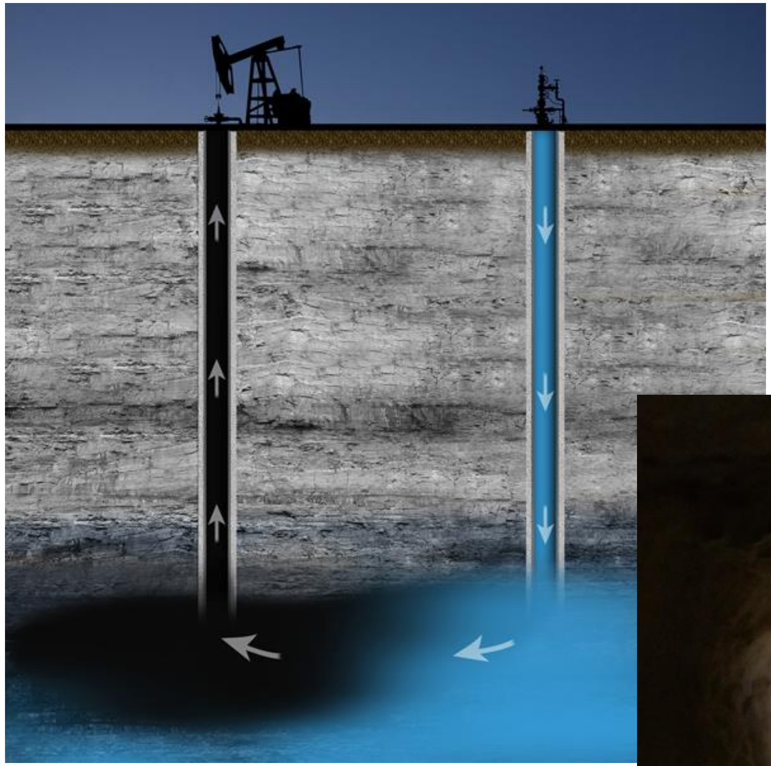
In particular, in this presentation, we are going to investigate the following fields:

- *Water saturation effect on P-wave velocity*
- *The effect of mechanical instability on P-wave velocity and amplitude;*
- *Water saturation effect on P-wave amplitude;*
- *Water – induced damage which impacts reservoir properties.*

Area in Scope:

- Hydrocarbon production (EOR)
- Enhanced Geothermal systems
- Risk related to flooded underground cavities

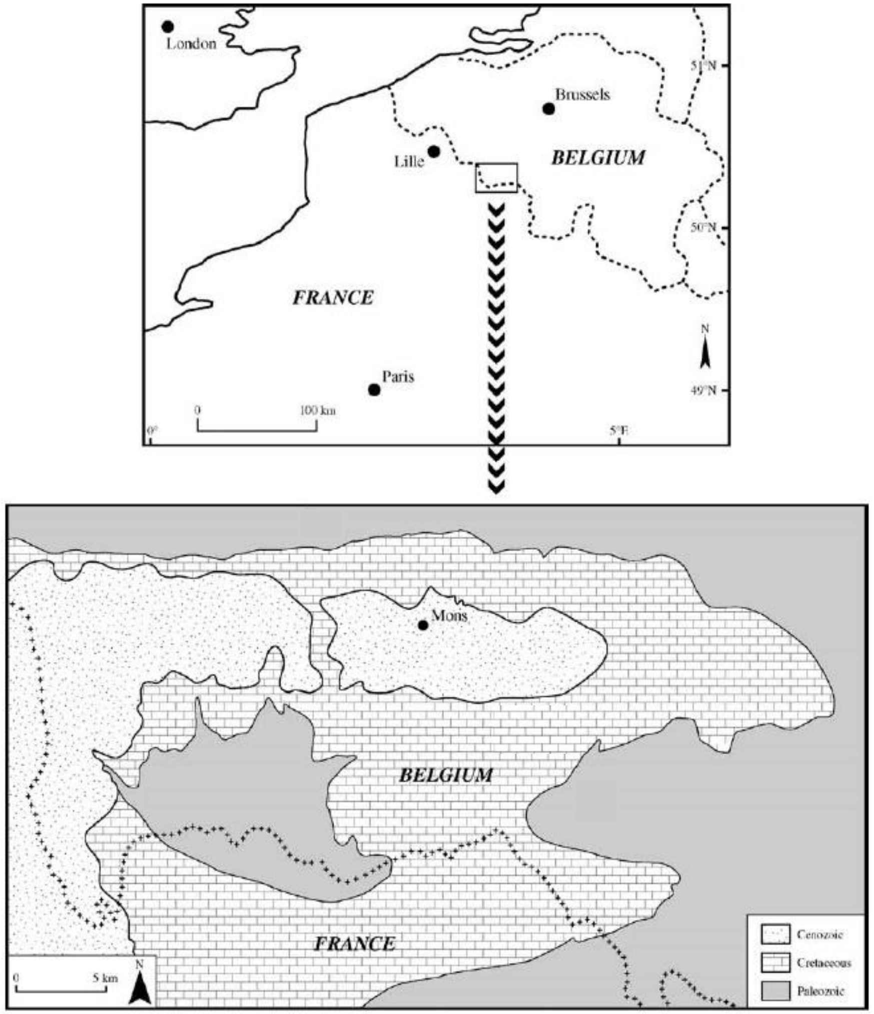




Summary

1. *Material*
2. *Methods*
3. *Results and Discussion: Ultrasonic Monitoring*
4. *Results and Discussion: P-wave amplitude and velocity*
5. *Results and Discussion: Water-induced damage*
6. *Conclusions*

Material – Obourg Chalk



Richard et al. 2005

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: 0.20 – 6 mD

Peak pore throat Radius (Mercury injection) = 0.291 μm

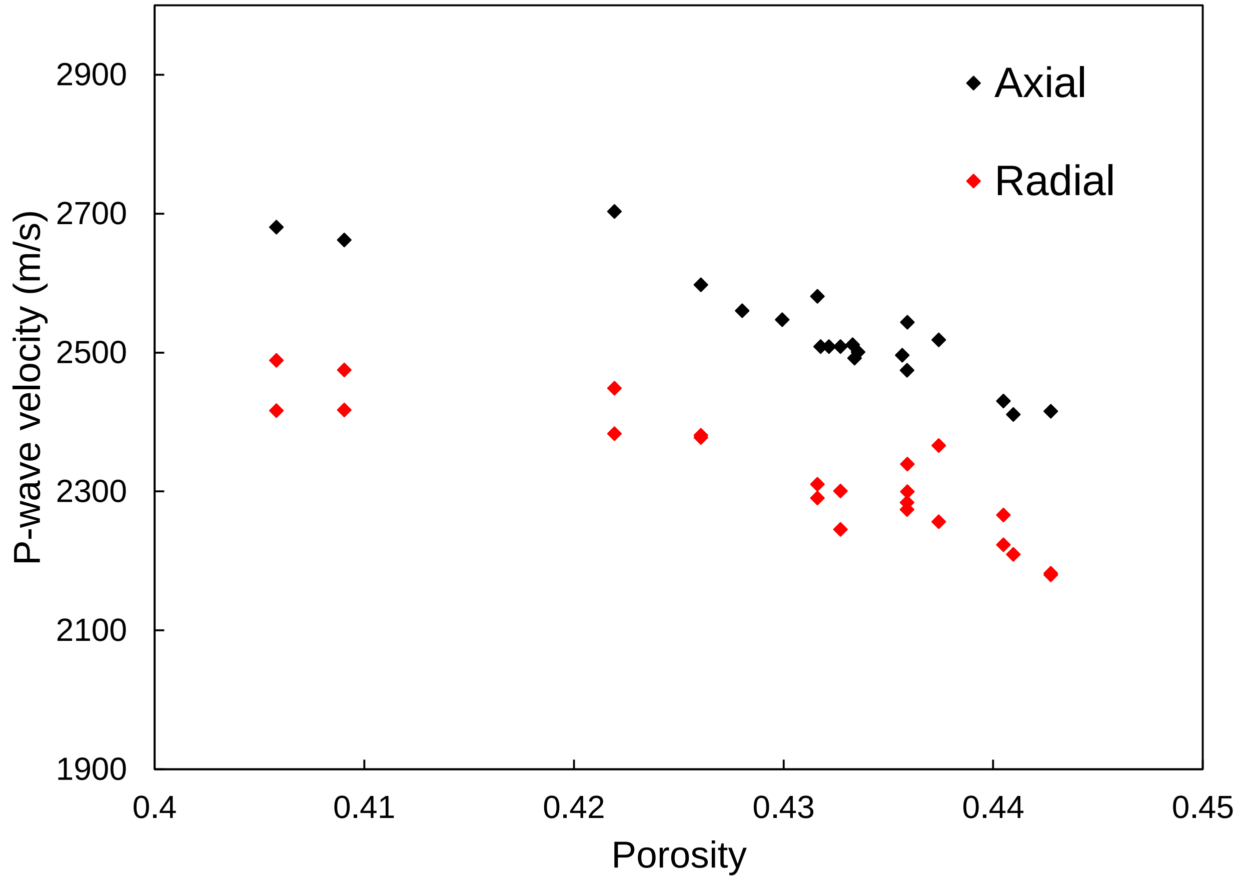
Peak grain size (statistical): 0.4 – 1.3 μm

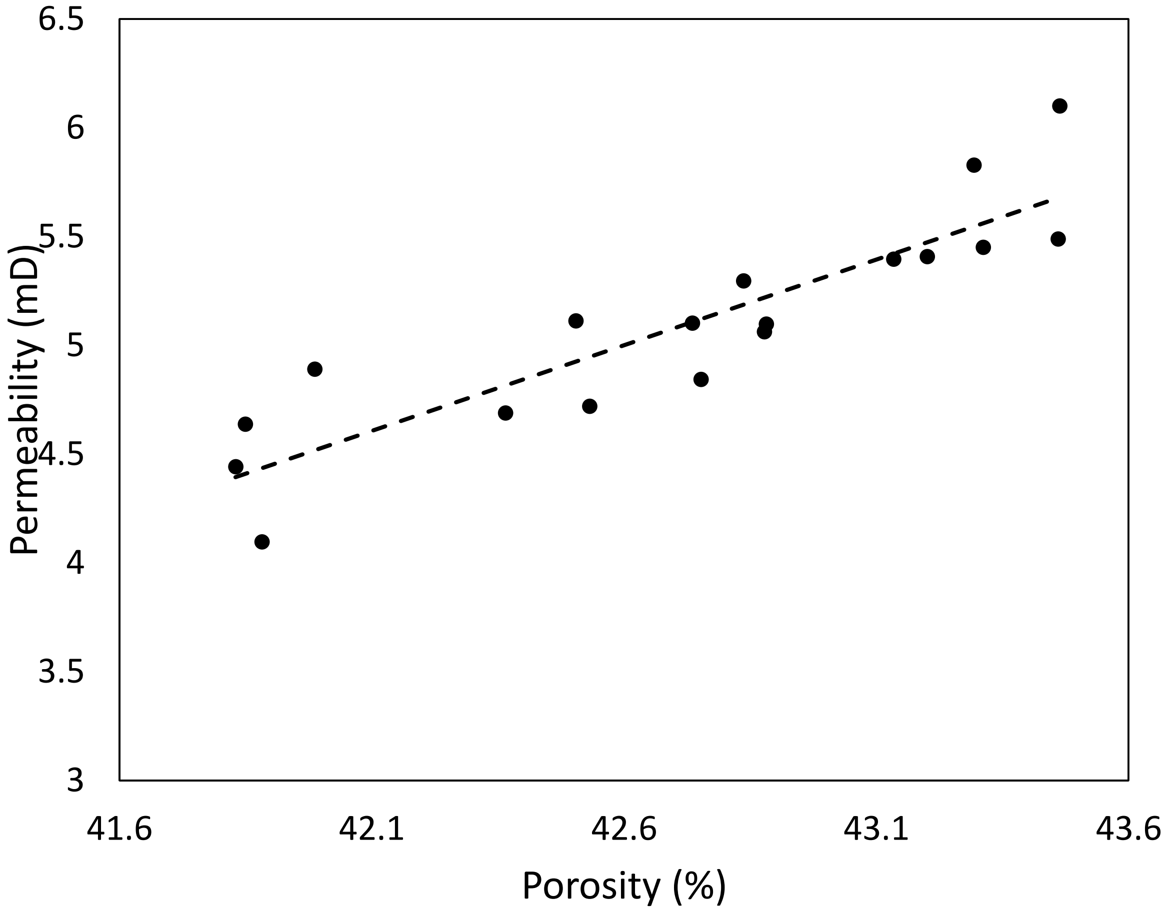
Collected from Hermignes Quarry (Mons Basin, Belgium)

Material – Petrophysical Properties

Obourg Chalk displays good relationship of P-wave velocity and Permeability with respect the porosity.

Axial velocity is higher than radial.





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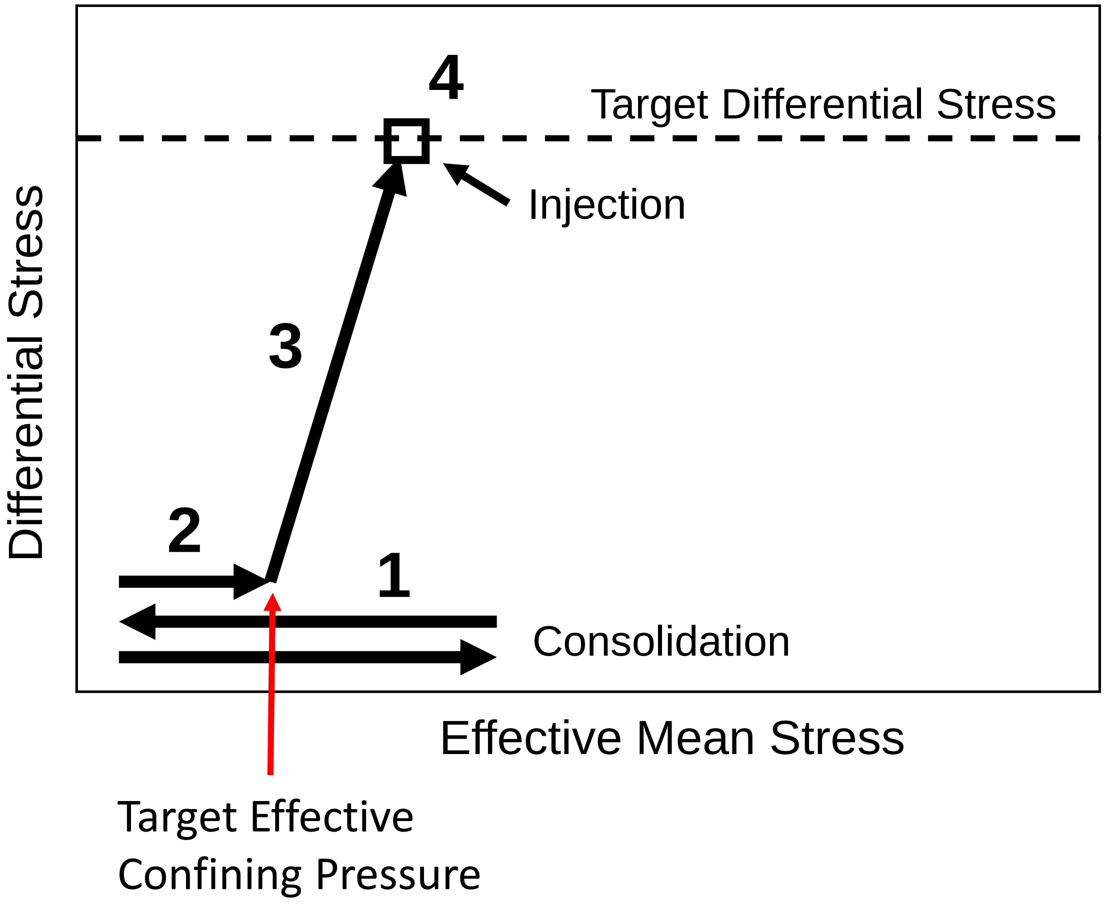
Method - Injection test



Rock sample is installed in a conventional triaxial cell.

The injection test proceeds as follow:

1. Consolidation stage: hydrostatic loading and unloading in order to homogenize the different samples and reduce dispersion in the results.
2. Hydrostatic loading: to the target confining pressure
3. Increase in differential stress: constant load rate to the target differential stress
4. Stabilization and Water injection

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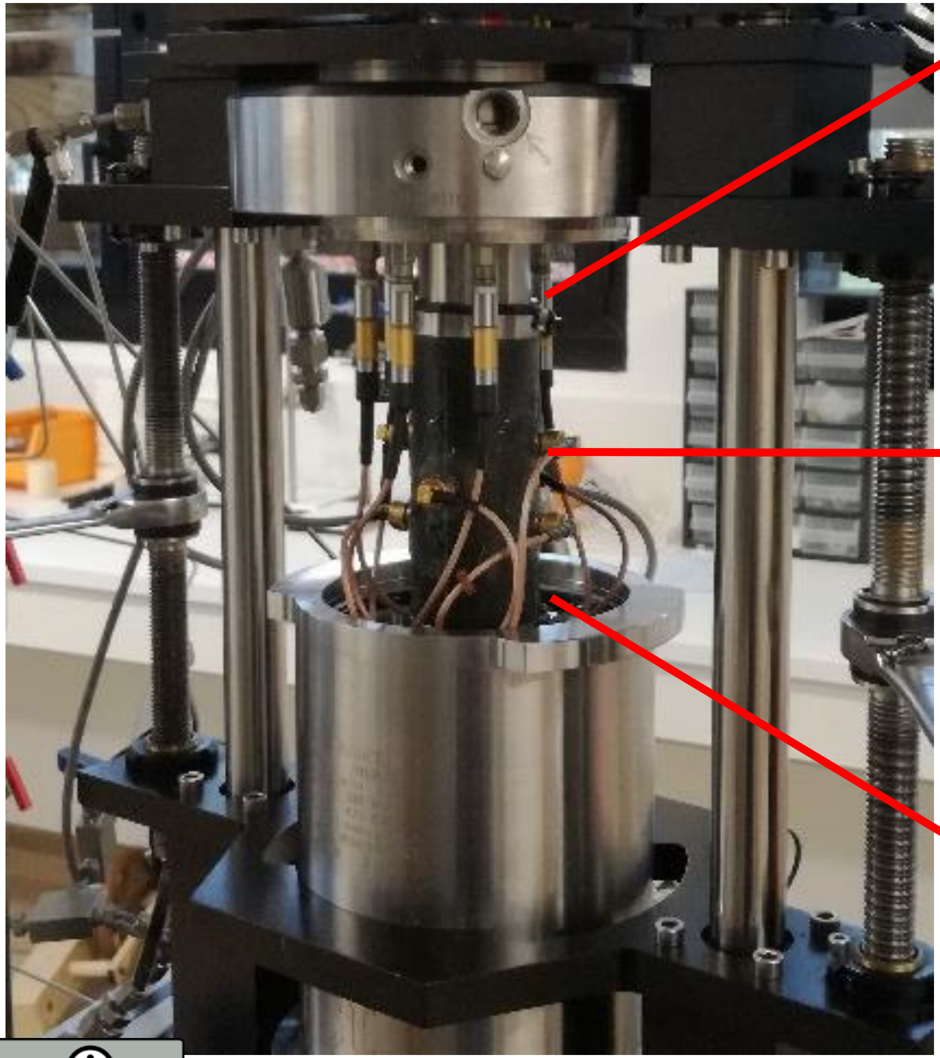
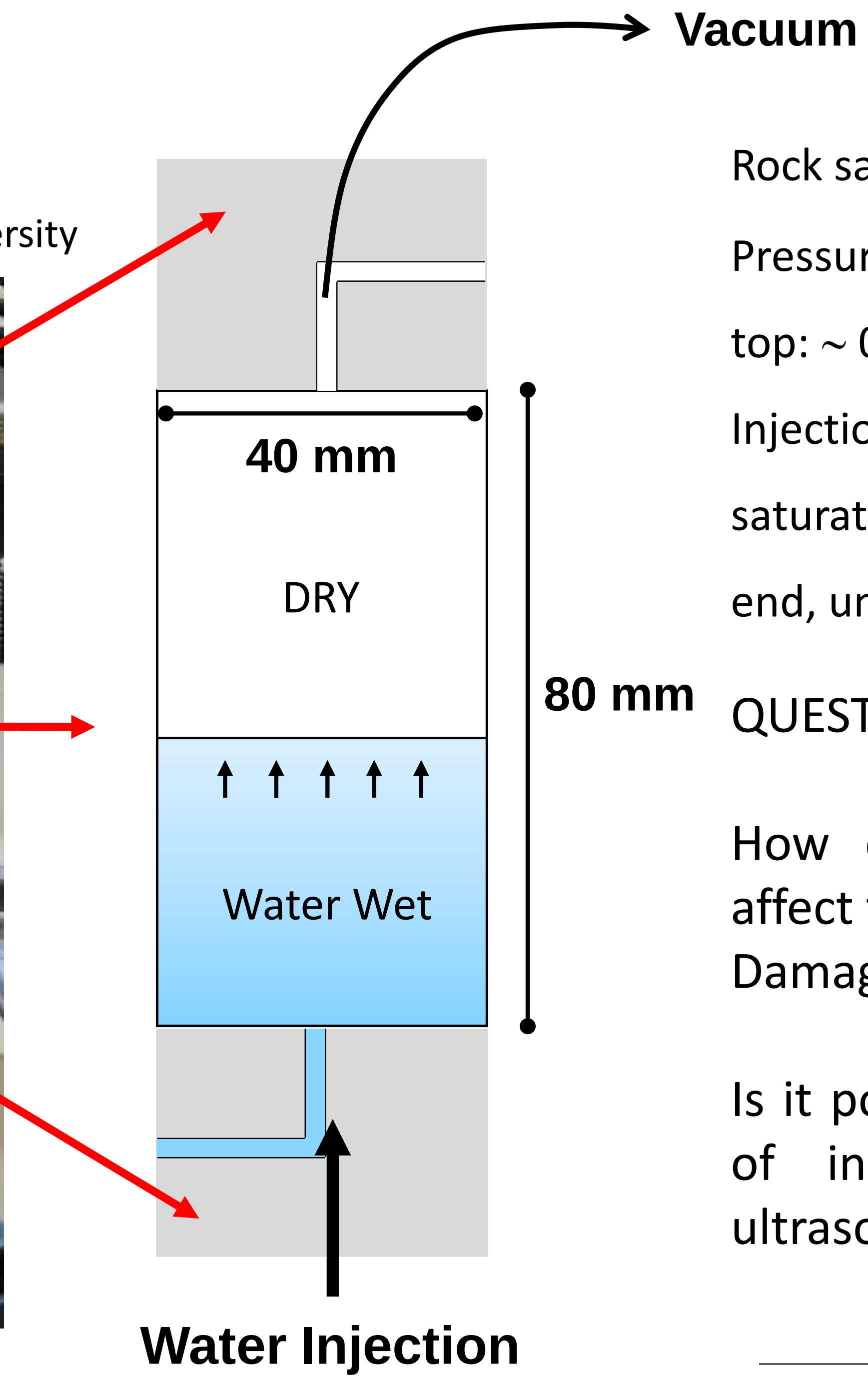
Method - Injection test

Triaxial Cell installed in the Geomechanics lab at CY University





Rock sample in initial dry condition.

Pressure difference from bottom to top: ~ 0.2 MPa.

Injection proceeds gradually, by saturating the rock from the lower end, until failure takes place.

QUESTIONS:

How does injection of water affect the rock? Damage?

Is it possible to detect any kind of induced change through ultrasonic monitoring?

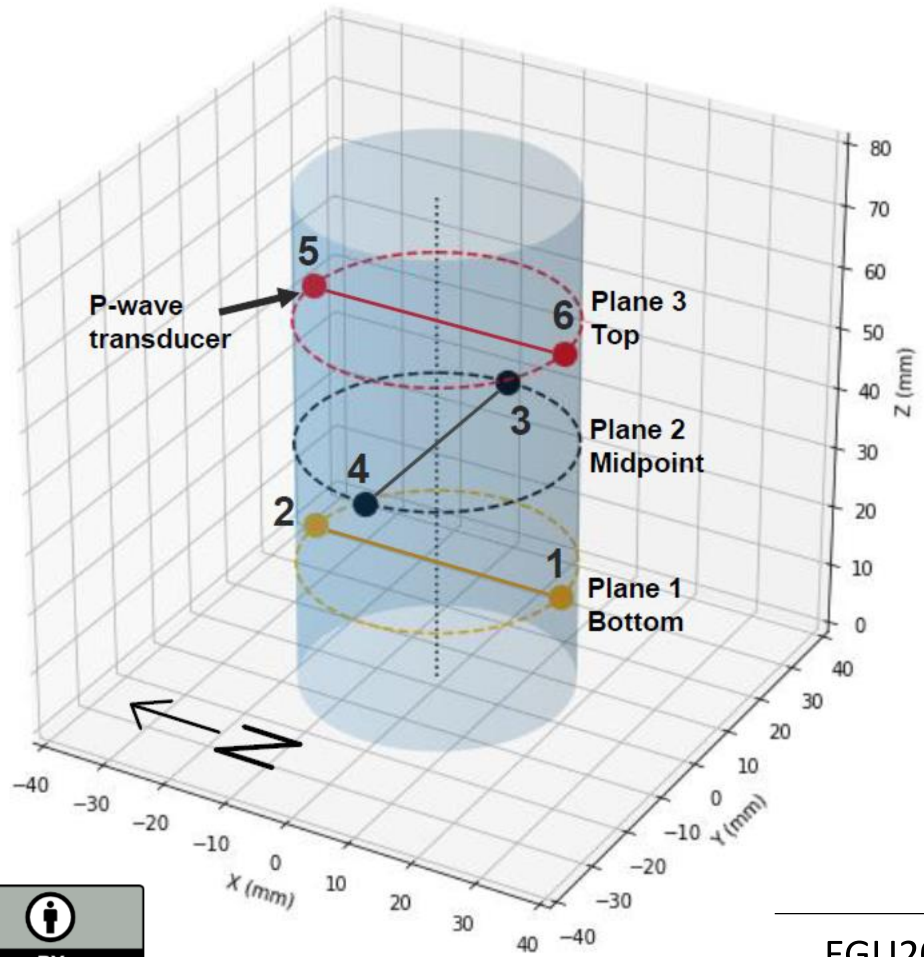
Methods – Ultrasonic monitoring

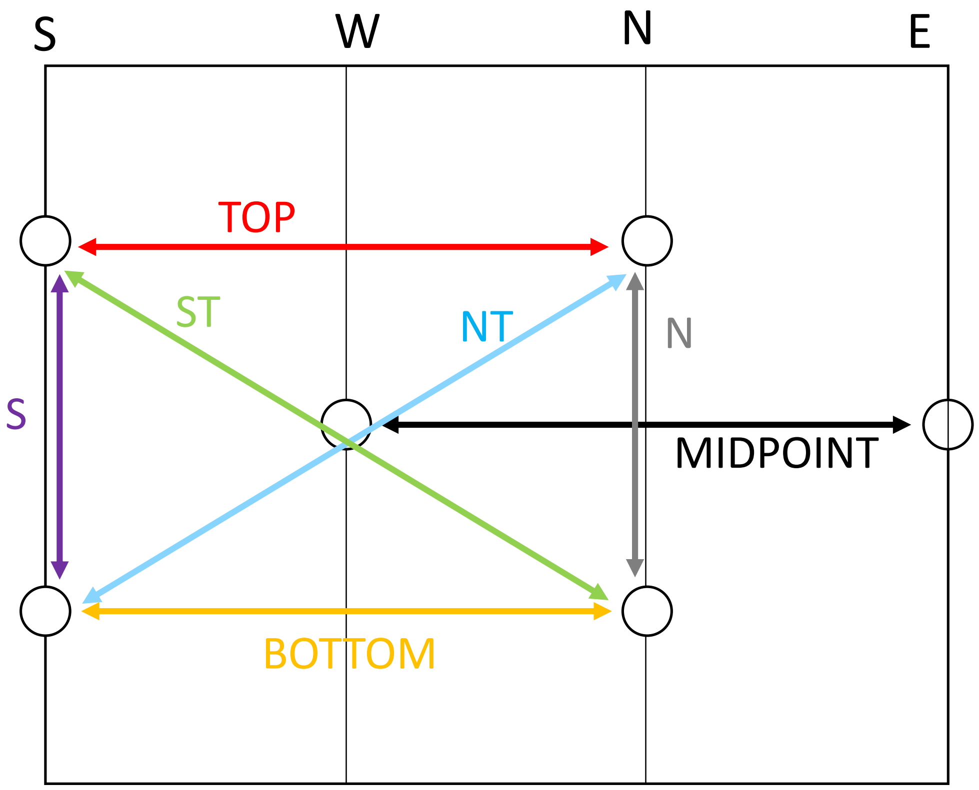
Rock sample is instrumented with six P-wave piezoelectric transducers.

(Resonance frequency 0.5 MHz)

They are distributed in three horizontal planes perpendicular to the sample axis, named Bottom, Midpoint and Top.

Allowing to measure P-wave velocity in 15 different pathways. (Here represented only 7)





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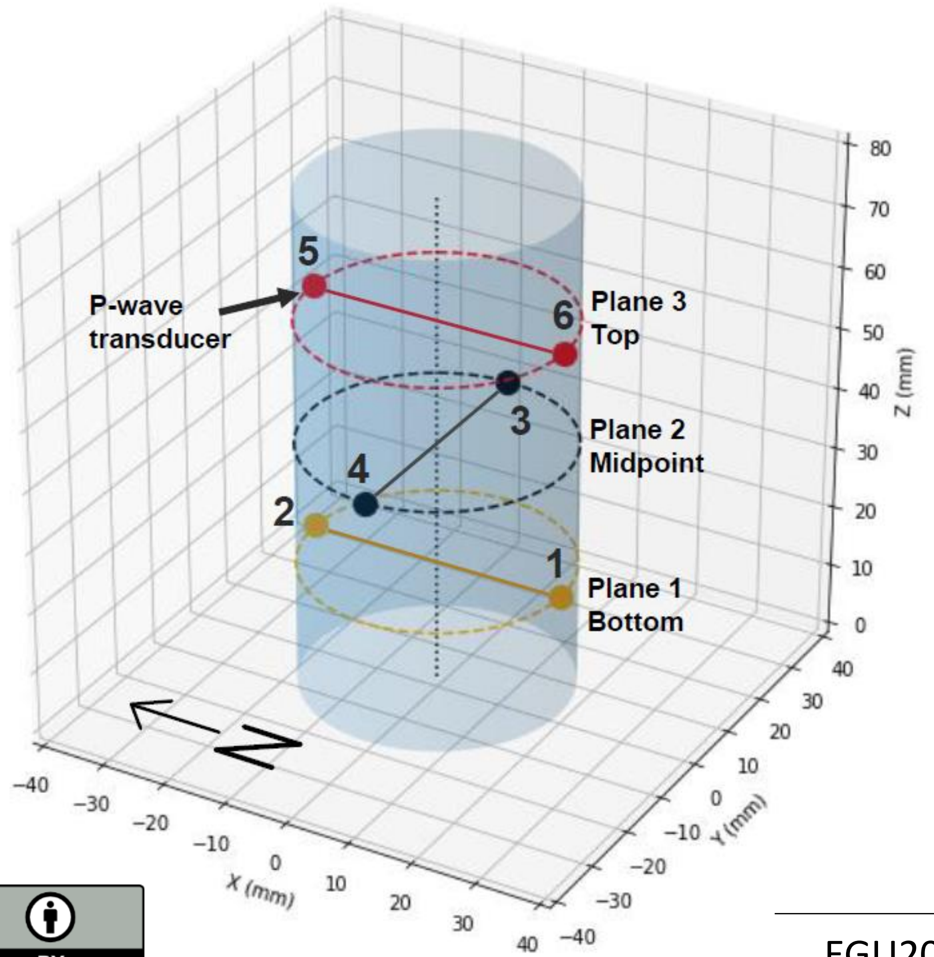
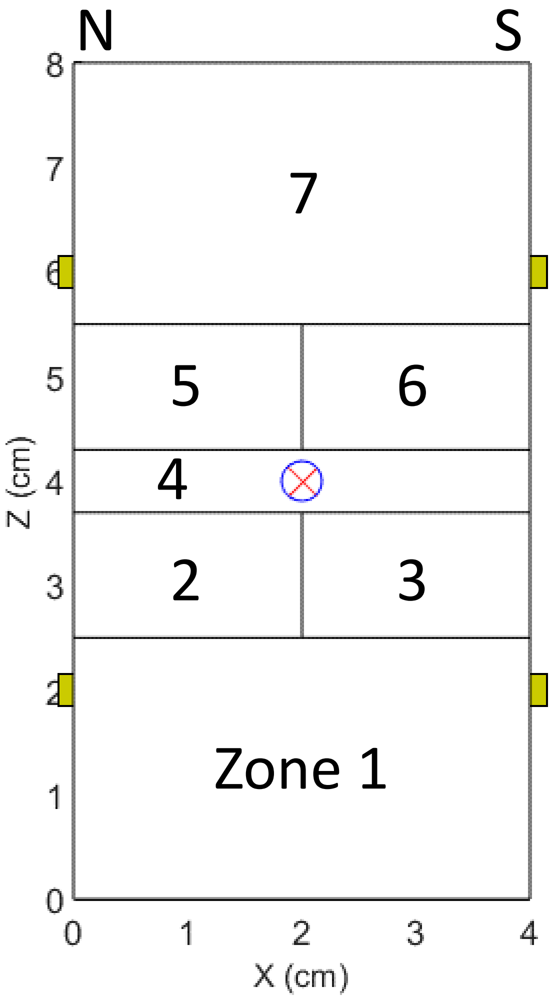
Methods – Ultrasonic monitoring

In order to show the P-wave velocity variations across the sample, we built a N-S slice across the sample divided in 7 areas, producing a pseudo-tomography.





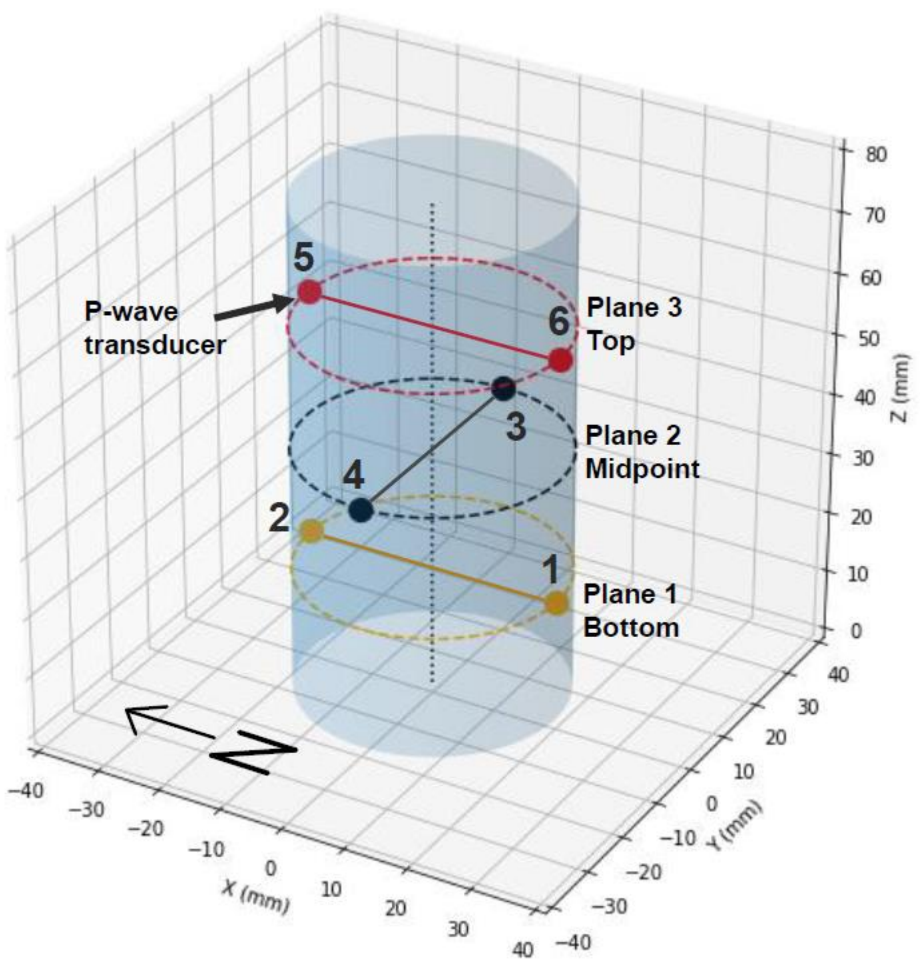
At each of these area has been assigned a velocity representing a particular path.

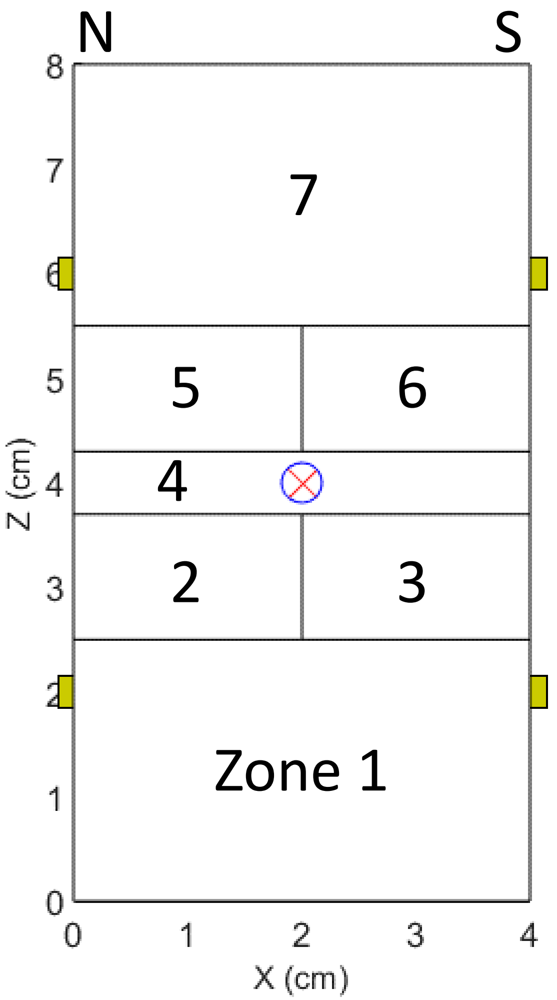
The zones 1, 4 and 7 represent the three horizontal directions.

The middle path (4) is directed perpendicular to the screen where the sensors are represented by the red cross and blue circle.

P-wave velocities will be represented by a color scale.

Methods – Ultrasonic monitoring





Zone 1 : path 1 → 2 (Bottom)

Zone 2 : average between path 2 → 4 and 2 → 3

Zone 3 : average between path 1 → 4 and 1 → 3

Zone 4 : path 3 → 4 (Midpoint)

Zone 5: average between path 4 → 5 and 3 → 5

Zone 6 : average between path 4 → 6 and 3 → 6

Zone 7 : path 5 → 6 (Top)

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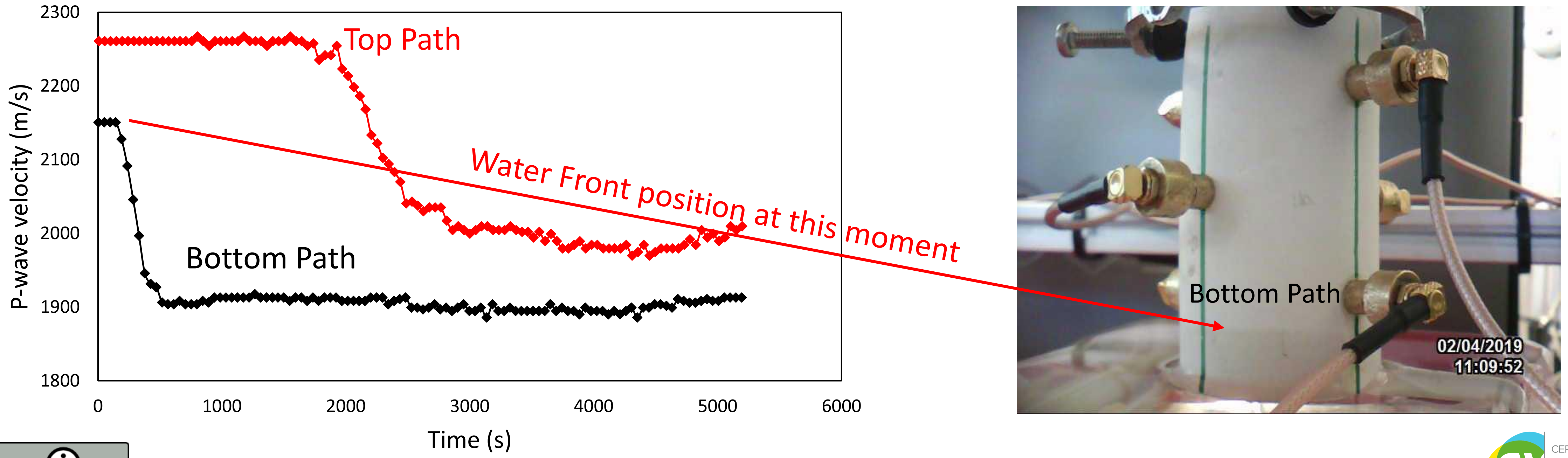
Methods – Imbibition test

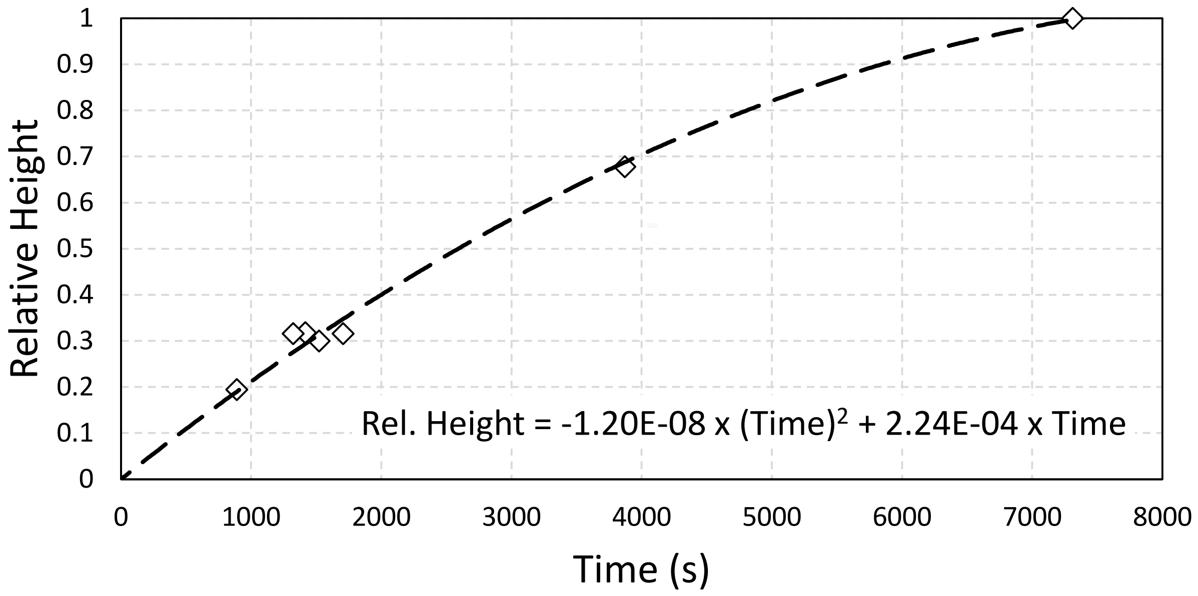
The imbibition test is performed prior the injection tests in order to infer the water front position where a direct observation of the water diffusion inside the rock sample is not possible.

To pursue that, we used the influence of water in decreasing the P-wave velocity when it is invading the Fresnel zone between the PZTs.

P-wave velocity starts decreasing when the water front has a distance from the middle point of the bottom PZTs of about 5 mm (in agreement with what has been found by David et al, 2017 on Sherwood sandstone)

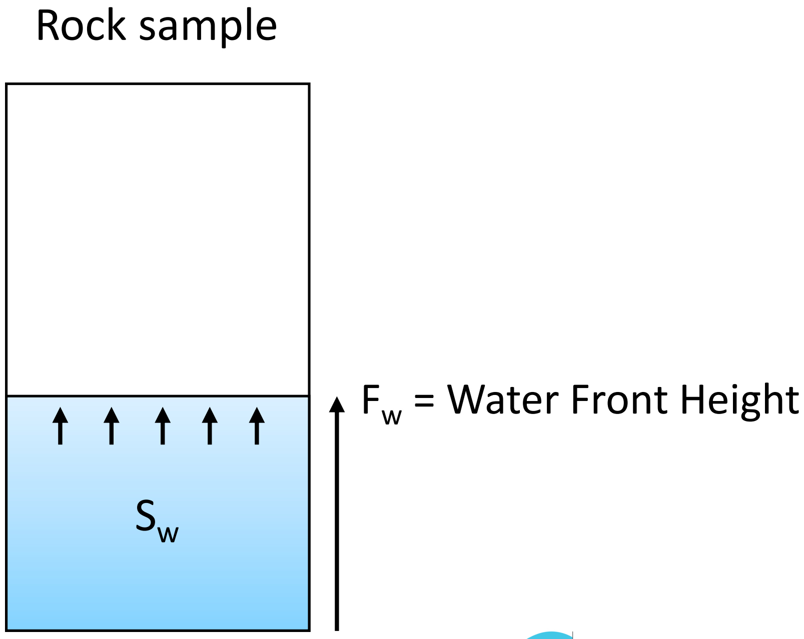


Methods – Water Saturation S_w



This figure displays an example of water front height calibrated for an injection test.

These results are introduced into the equation below in order to compute the Saturation versus Time during injection, assuming a flat water front.



$$S_w = V_{inj}/(\pi r^2 F_w \phi)$$

- S_w → Water saturation
- V_{inj} → Injected Volume
- r → Radius
- F_w → Height Water Front
- ϕ → Porosity

With the formula here shown we are assuming an average water saturation. However, there should be a saturation gradient from the bottom to the water front position.

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Injection tests – Q-P Plot – Stress State of Injection tests

Through conventional triaxial tests and hydrostatic tests we collected the critical stresses in a Q (Differential Stress) – P (Effective Mean Stress) plot.

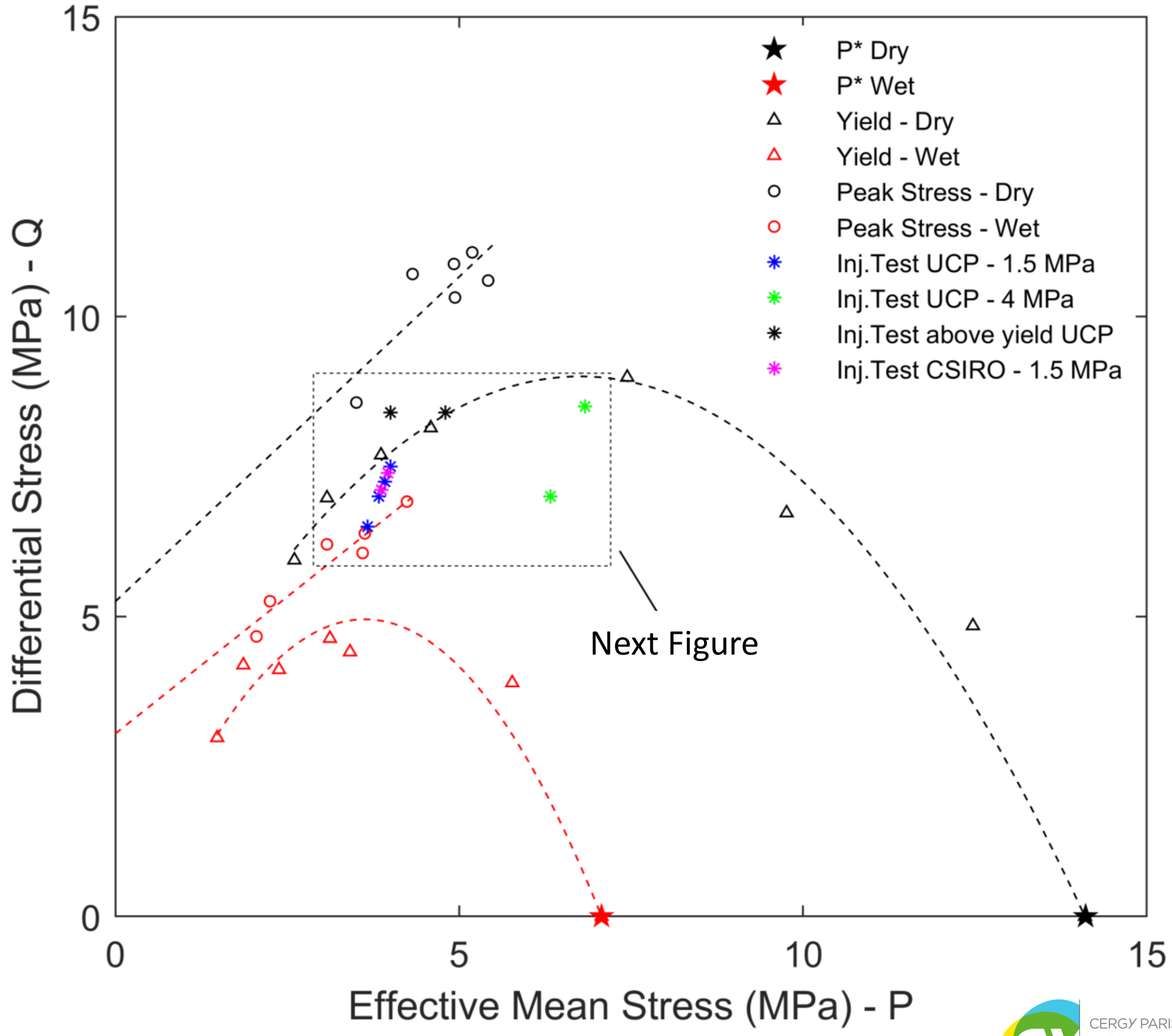
Critical stresses from triaxial tests are represented here with circles (peak stress) and triangles (yield stress).

Tests conducted in water – saturated condition are represented in red.

Tests conducted in dry condition are represented in black.

The two stars depict the onset of pore collapse obtained through hydrostatic tests.

The stress state for several Injection tests is shown here. The next slide highlights some of them.



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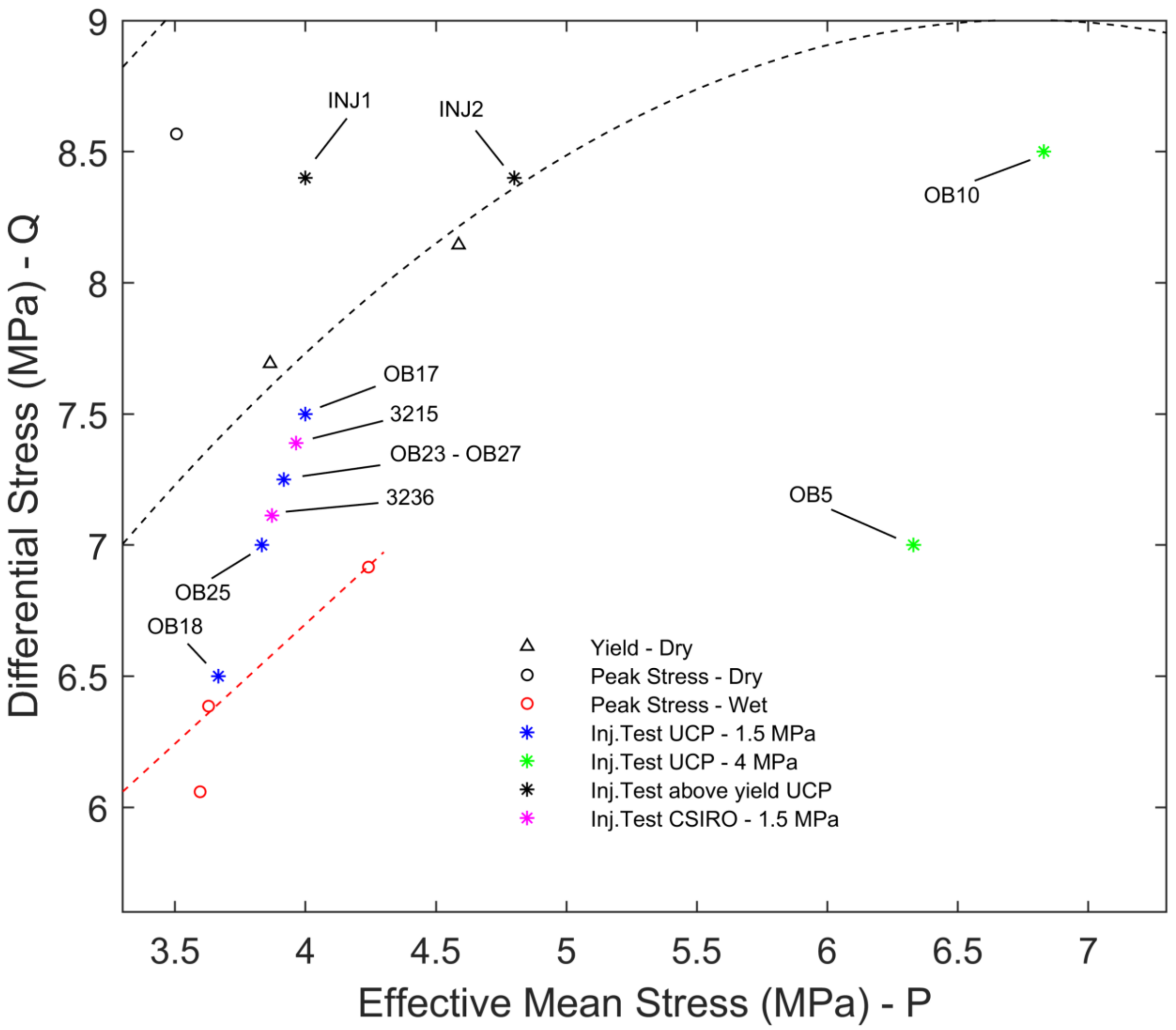
Injection tests – Q-P Plot



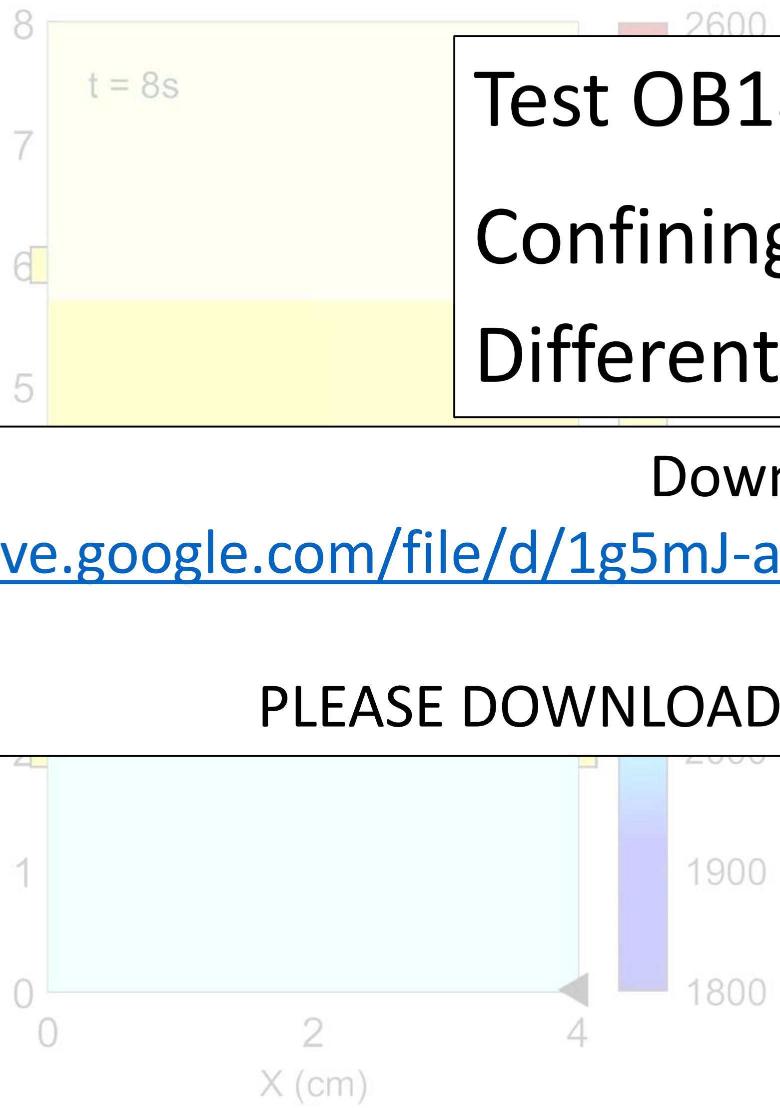
For the purpose of this study, only the injection tests named OB17, OB18 and OB25 will be shown.

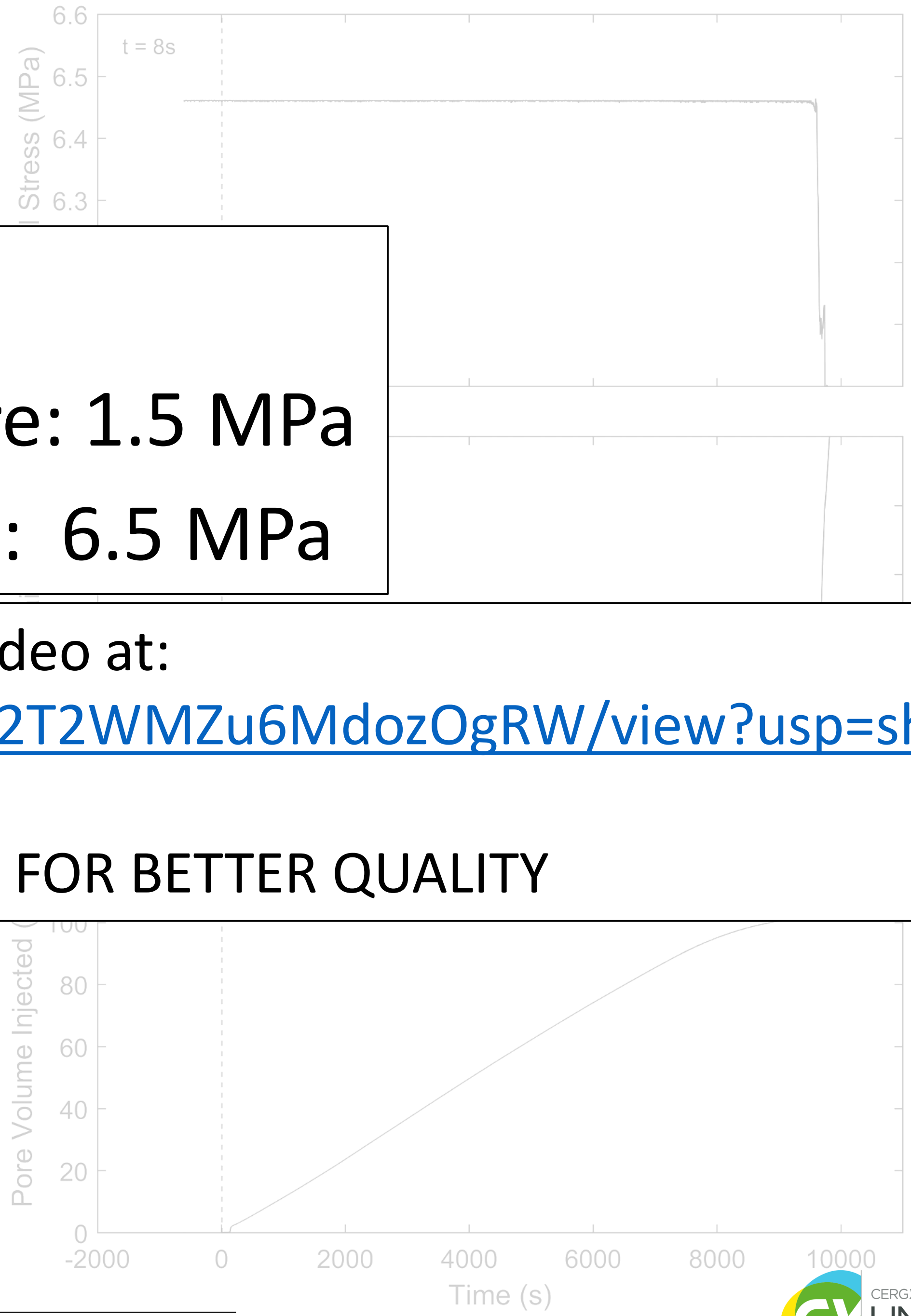
OB18 and OB17 might be considered as two end members, since the their stress state is located close to the peak stresses in wet condition (OB18) and close to the yields stresses in dry condition (OB17).

Consequently, being initially in dry state, for OB18 it has been necessary to get a full saturation to induce failure. On the contrary, for OB17 only a small amount of water has been required to induce failure.

OB25 is located in the middle between the two.

Sample OB18 - VIDEO





Test OB18:

Confining pressure: 1.5 MPa

Differential stress: 6.5 MPa

Download the video at:

https://drive.google.com/file/d/1g5mJ-aapiVTVqgYI2T2WMZu6MdozOgRW/view?usp=sharing

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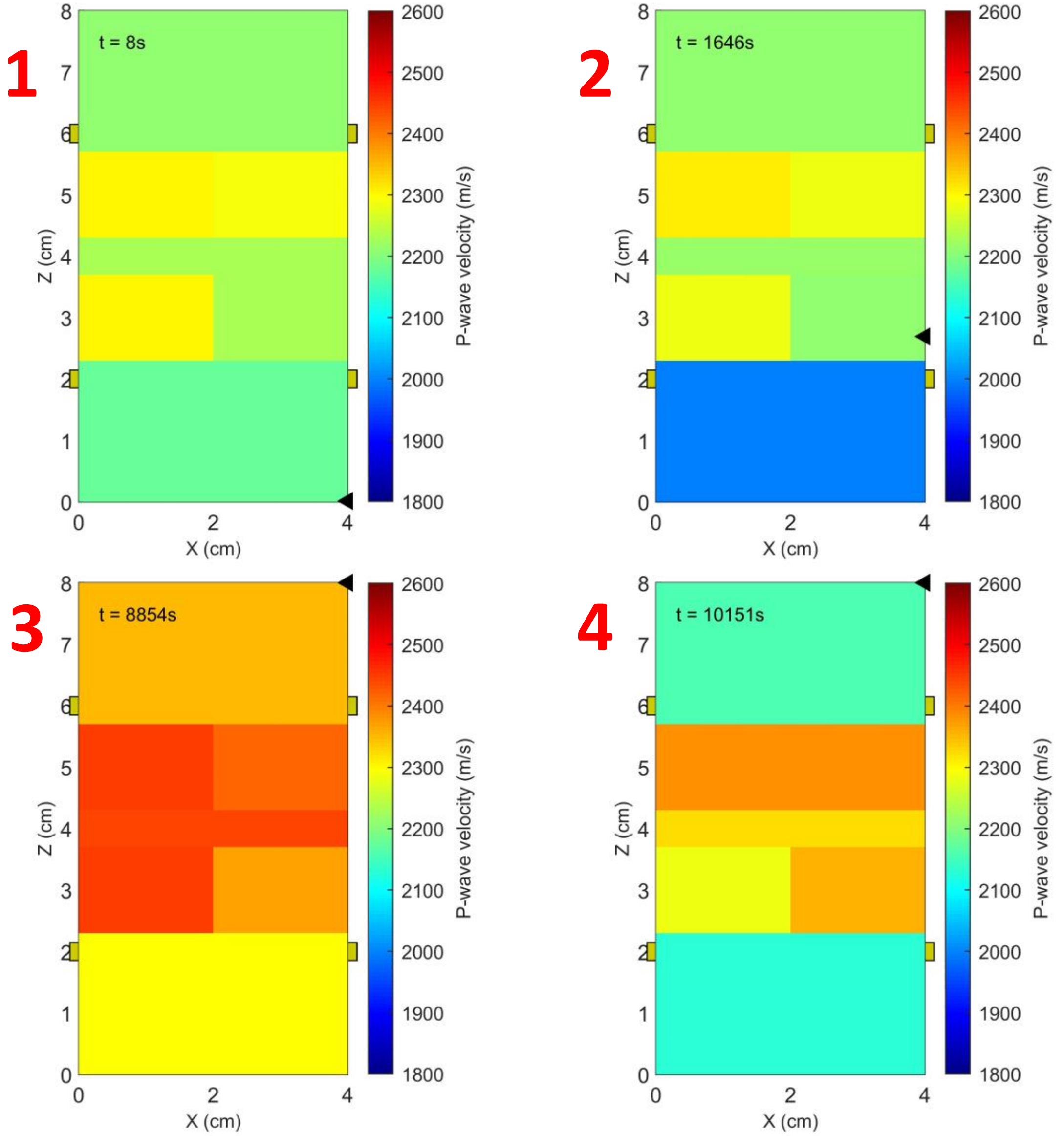
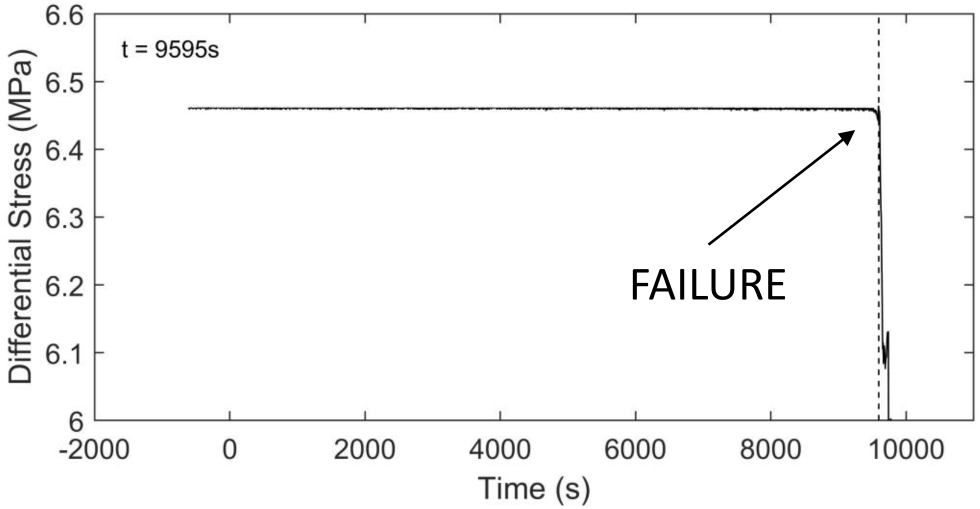
Sample OB18



- 1) Injection starts.
- 2) Water starts decreasing velocity from the bottom (when it enters the Fresnel Zone).
- 3) Water reaches the top of the sample and velocity increases.
- 4) Failure takes place lowering the velocity mostly at top and bottom.



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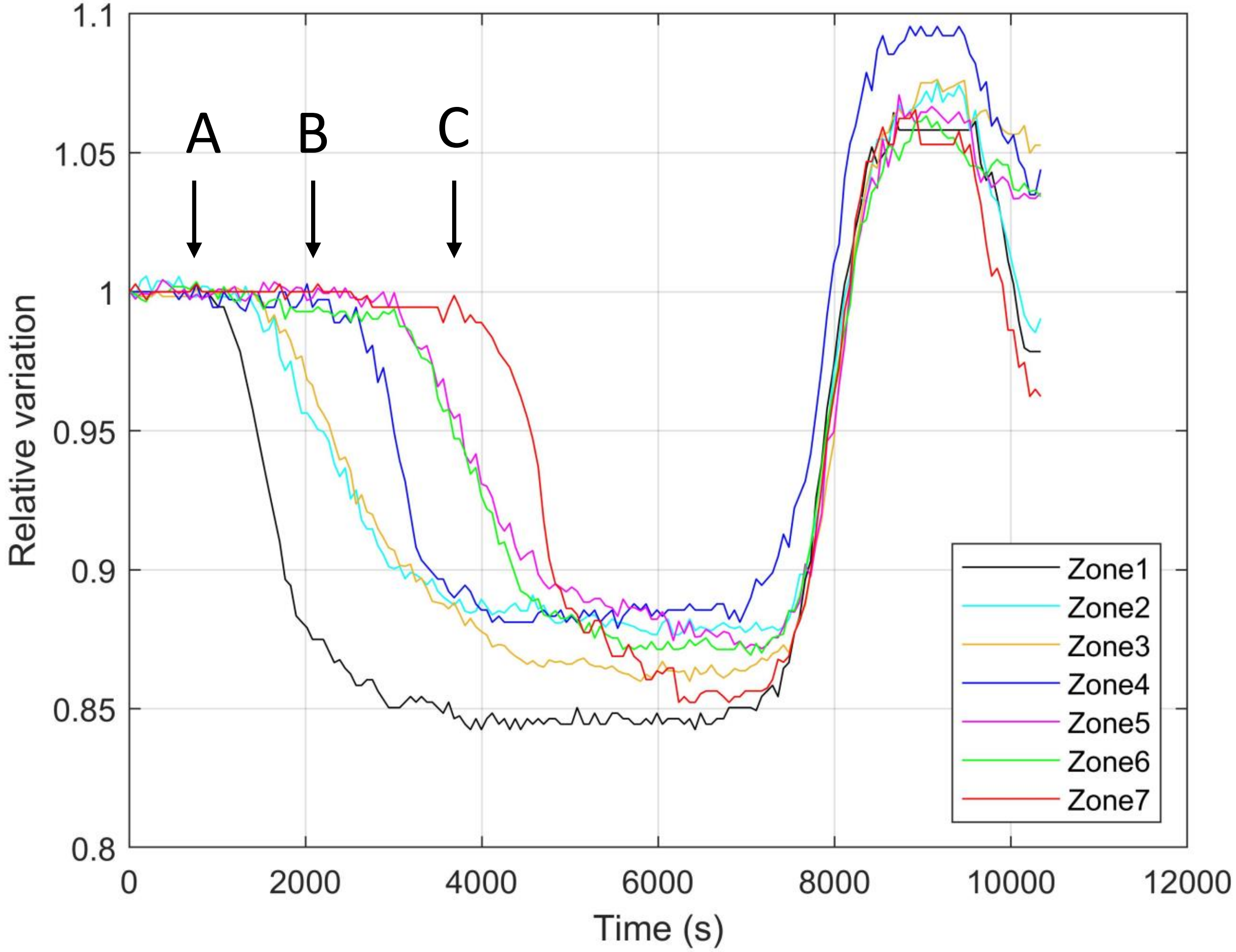
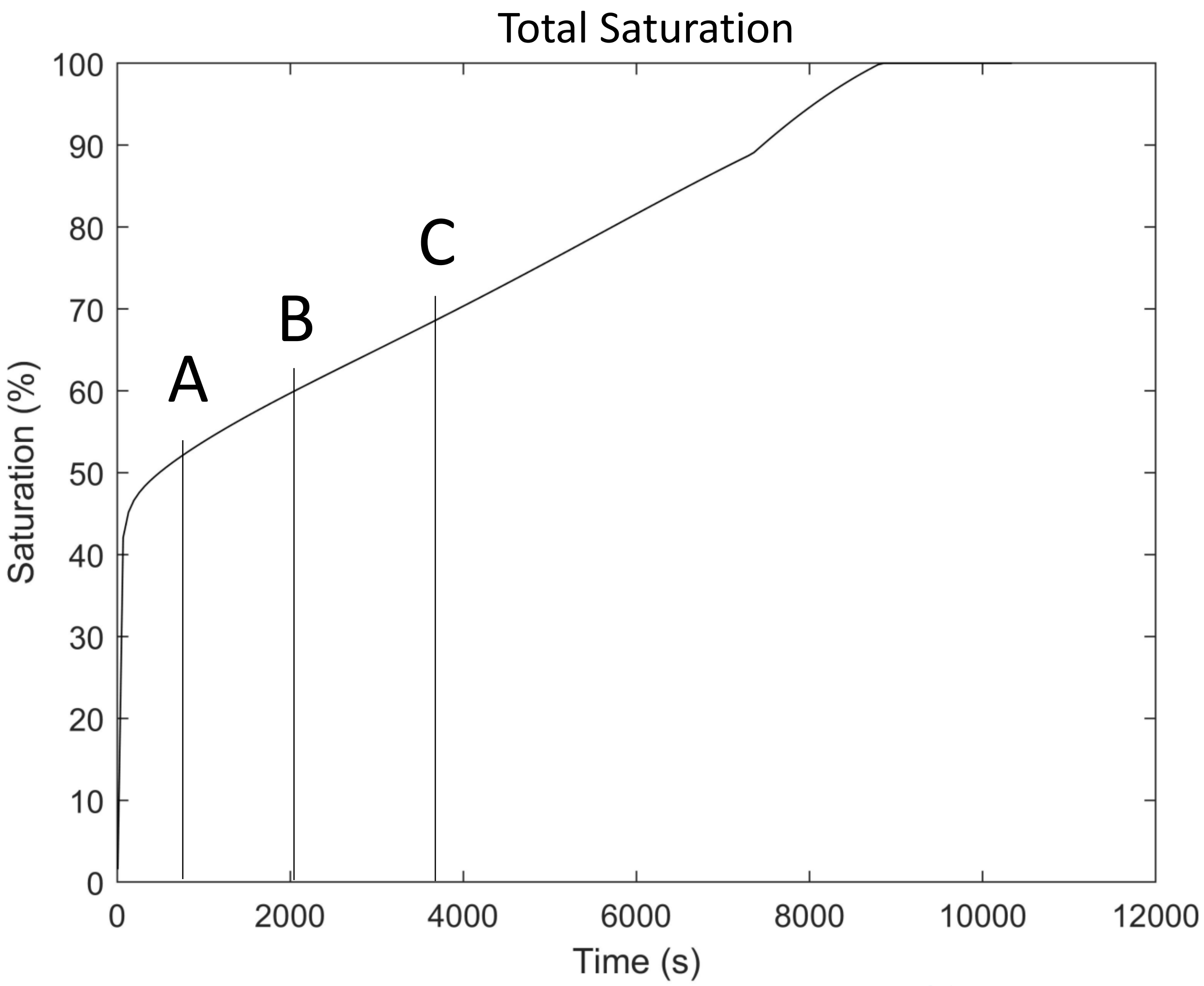
P-wave velocity variation - Summary

Velocity decreases first at the Bottom, then Middle and Top of the rock sample (points A, B and C).





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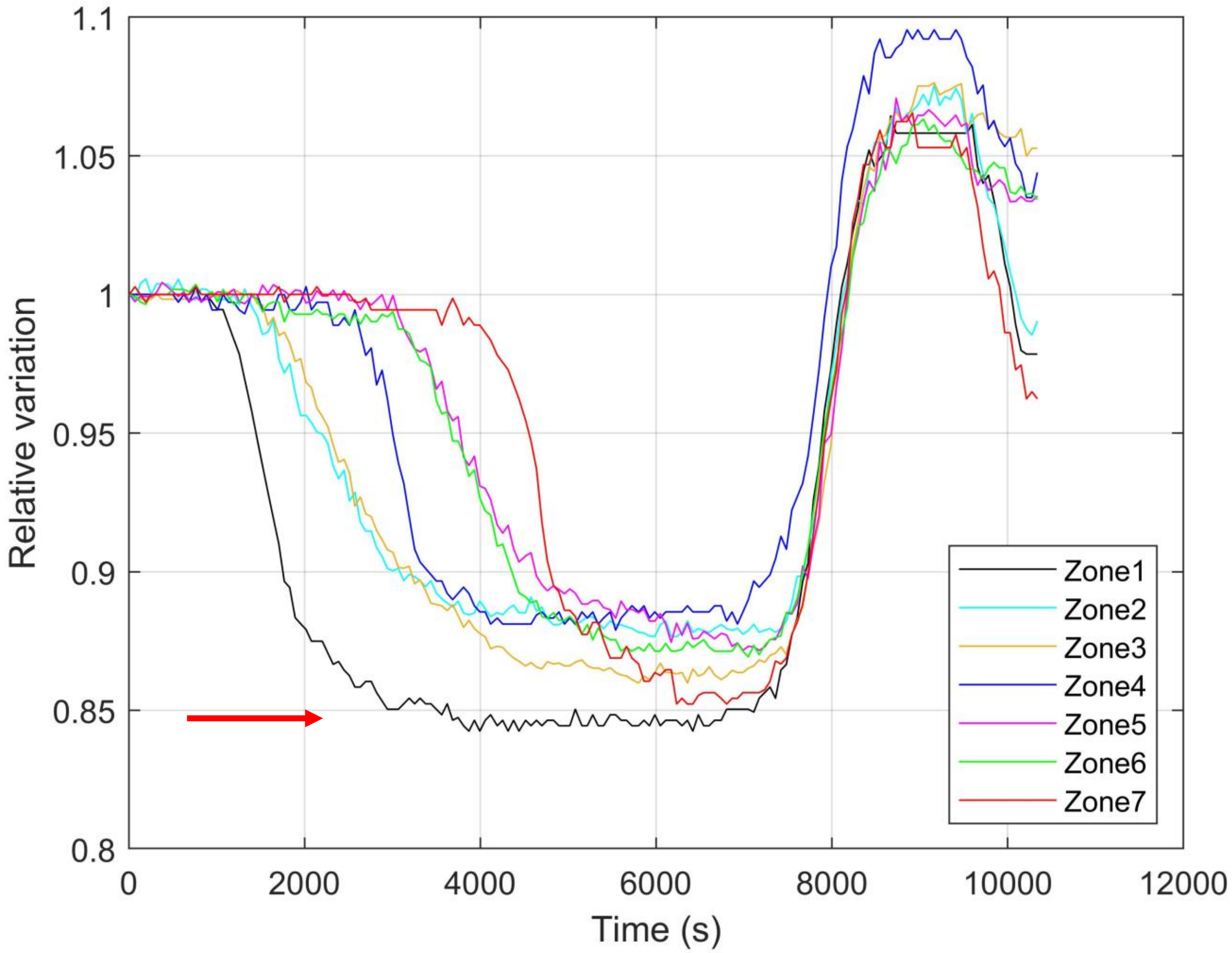
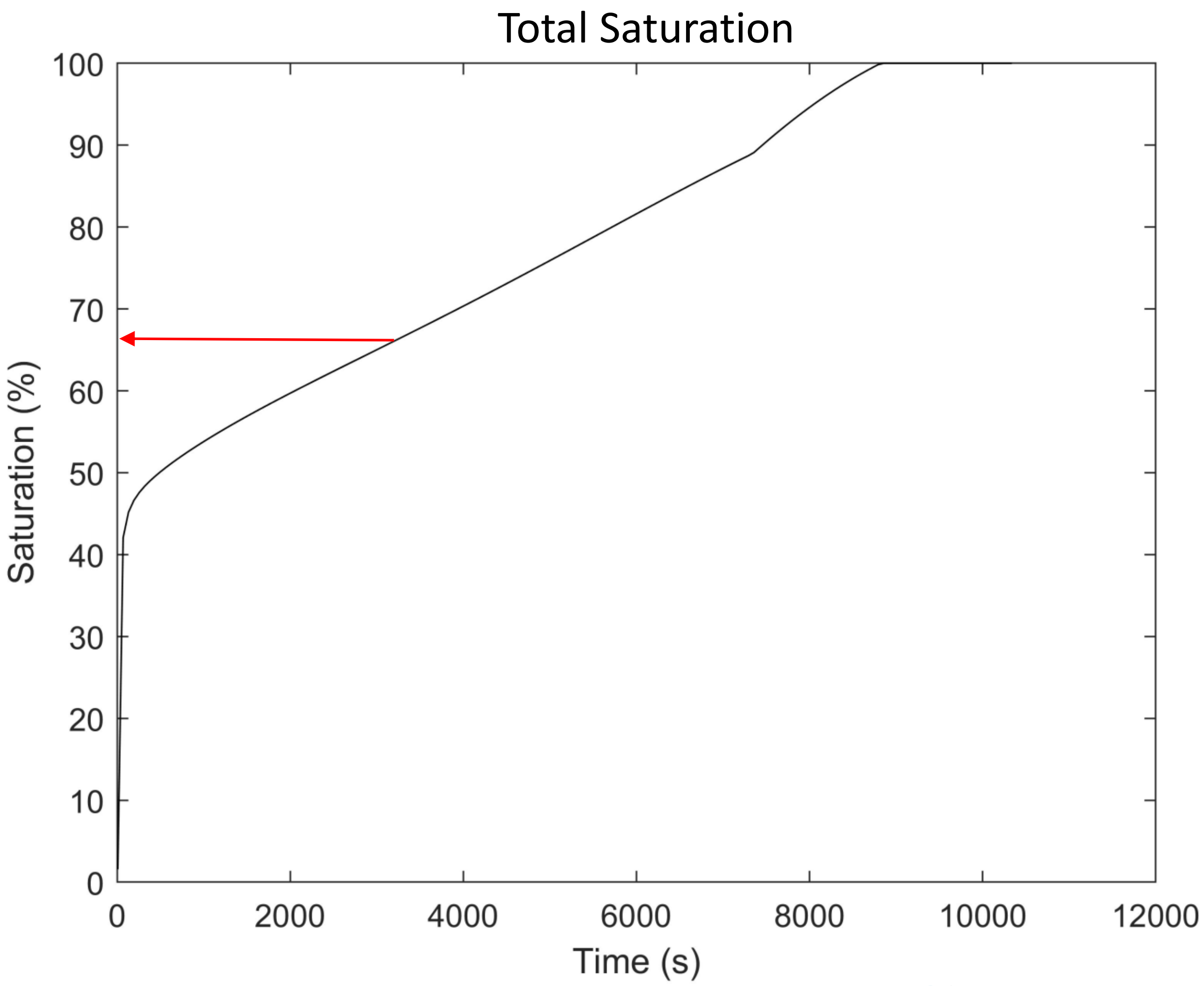
P-wave velocity variation - Summary

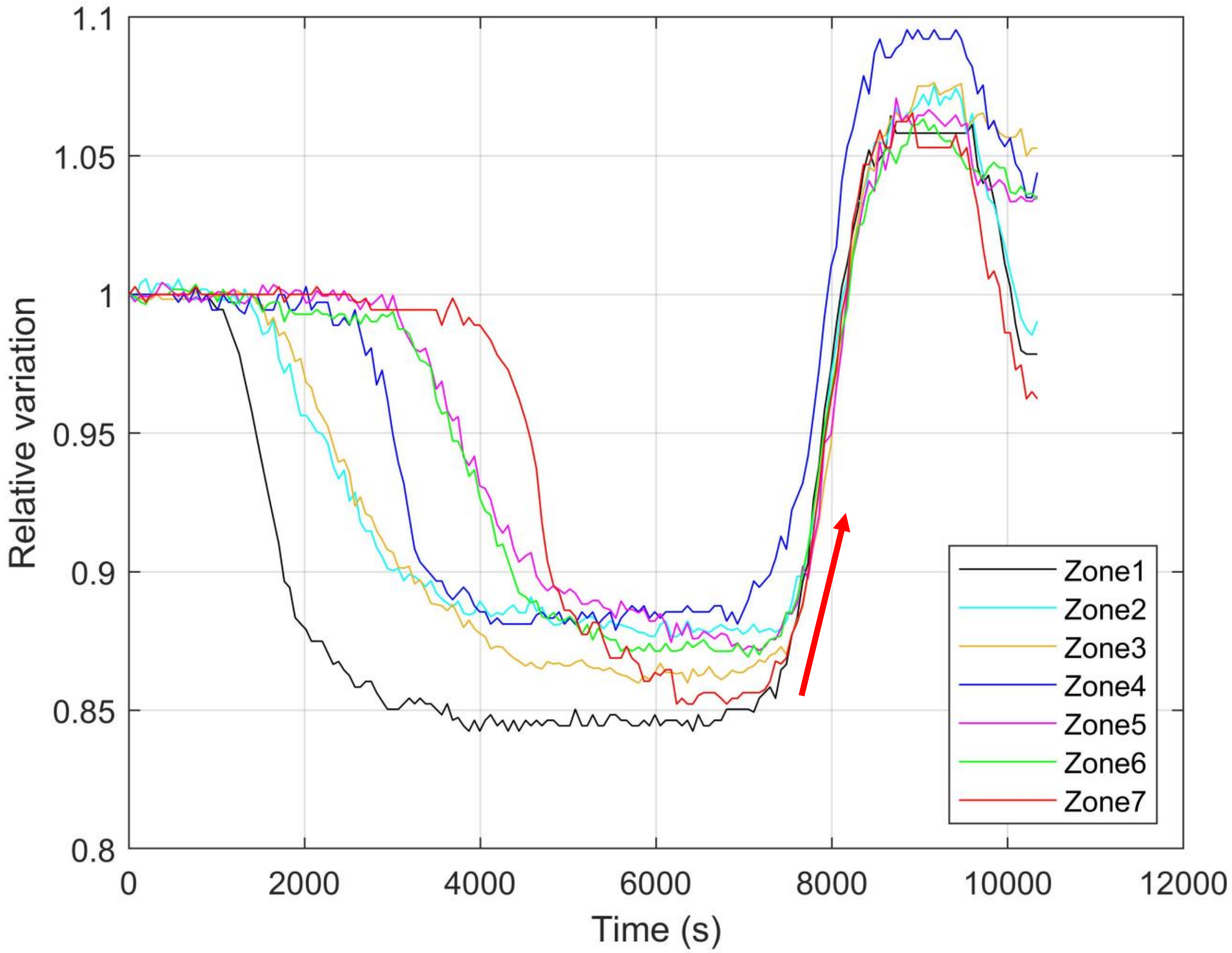
~ 66% of saturation at the bottom path to reach the first stabilization.

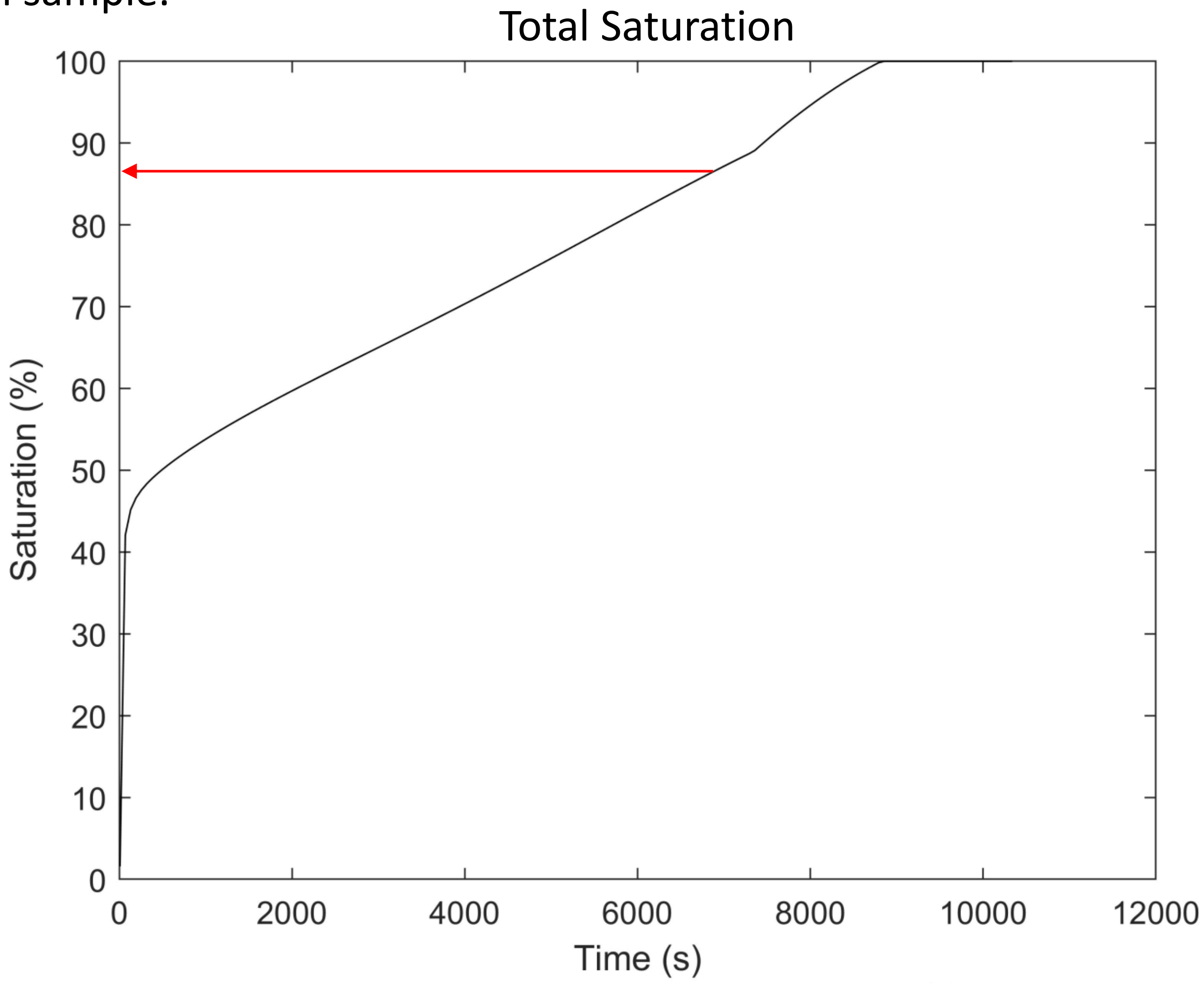




P-wave velocity variation - Summary

~ 87% of saturation to start increasing velocity. In this case, the increase is synchronized across the different zones, showing that at this moment saturation is similar in the overall sample.





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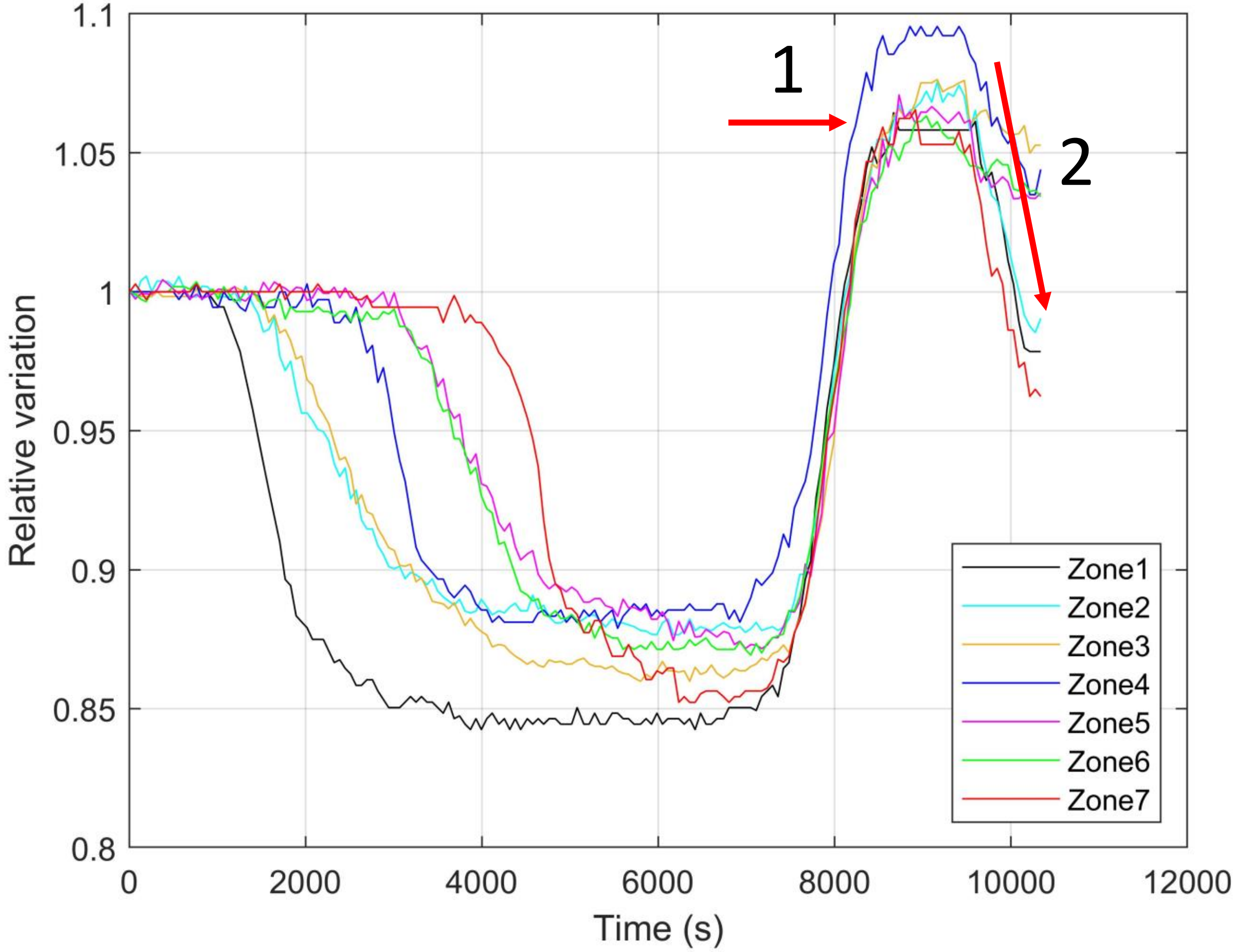
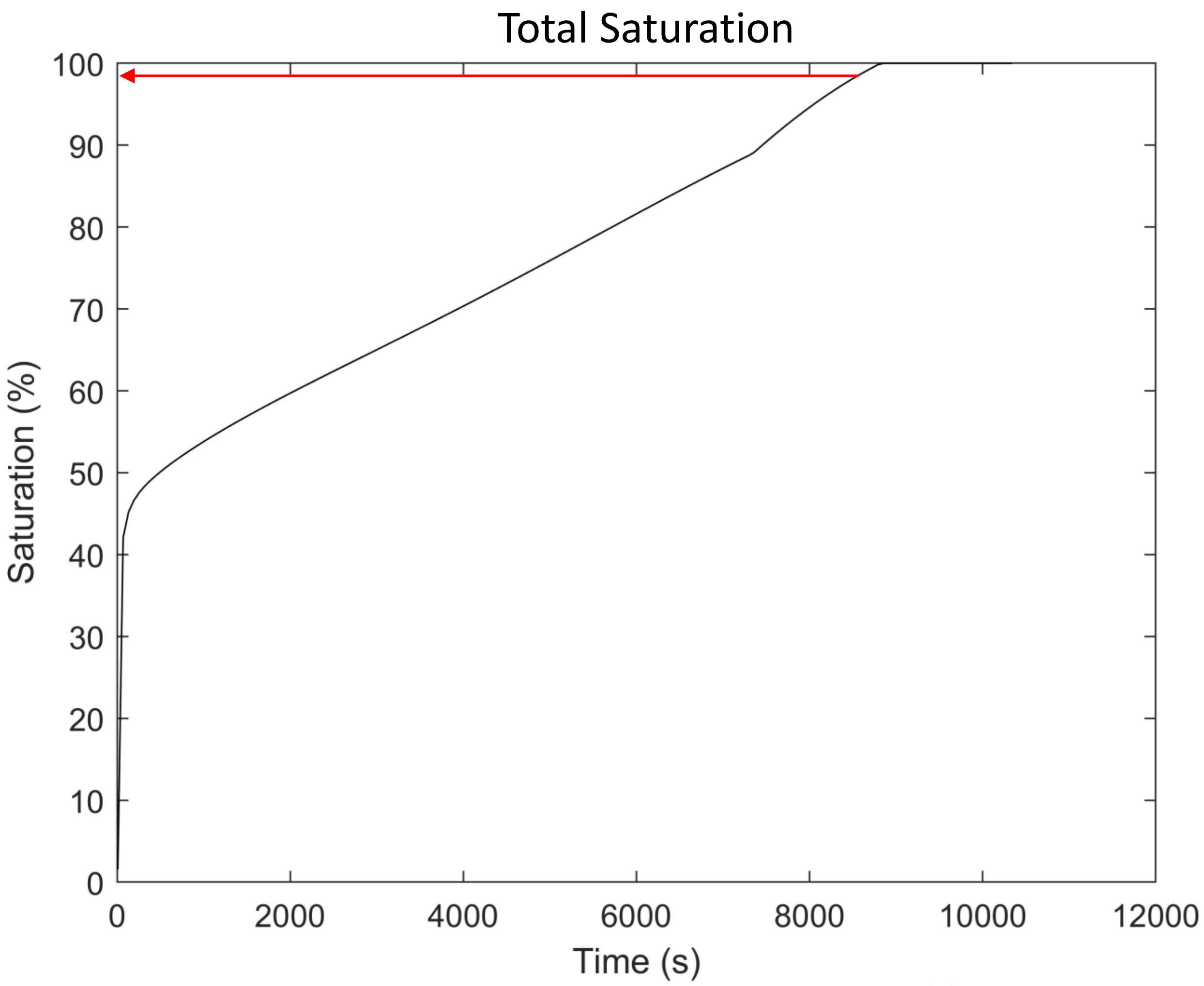
P-wave velocity variation - Summary

1) ~ 100% of saturation to stabilize at velocity higher than initial one.
2) Mechanical instability induces further decrease.





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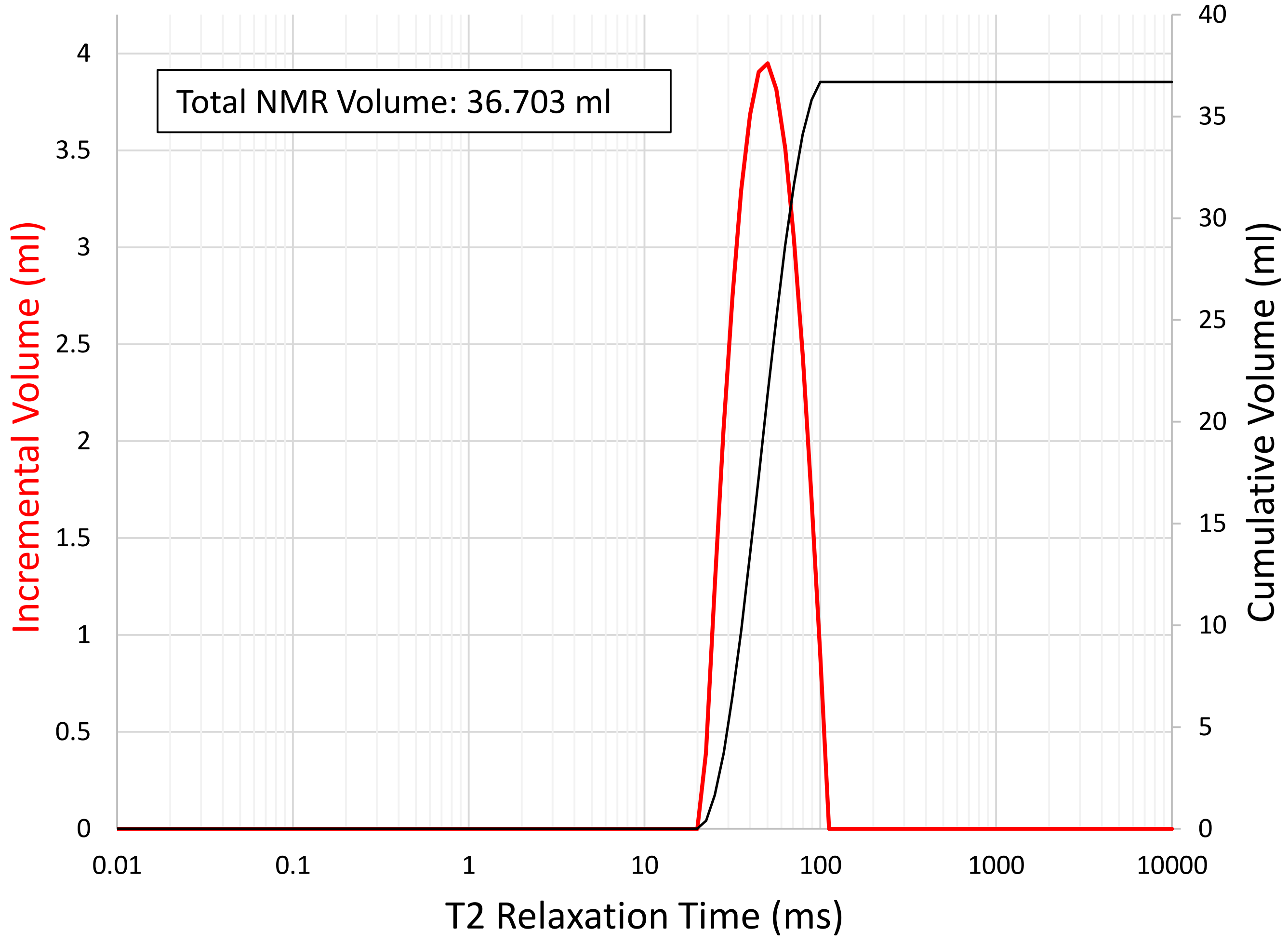
Water Saturation Post test - NMR



Low field NMR analysis on sample post test revealed full saturation of the sample after injection test.

Pore volume before injection test: 37.469 ml (Poroperm measurement with Nitrogen).

Water volume after injection test: 36.703 ml.

The small difference might be linked to pore volume change due to deformation.

The NMR also reveals the homogeneous pore size distribution of Obourg Chalk being composed by a single-mode.

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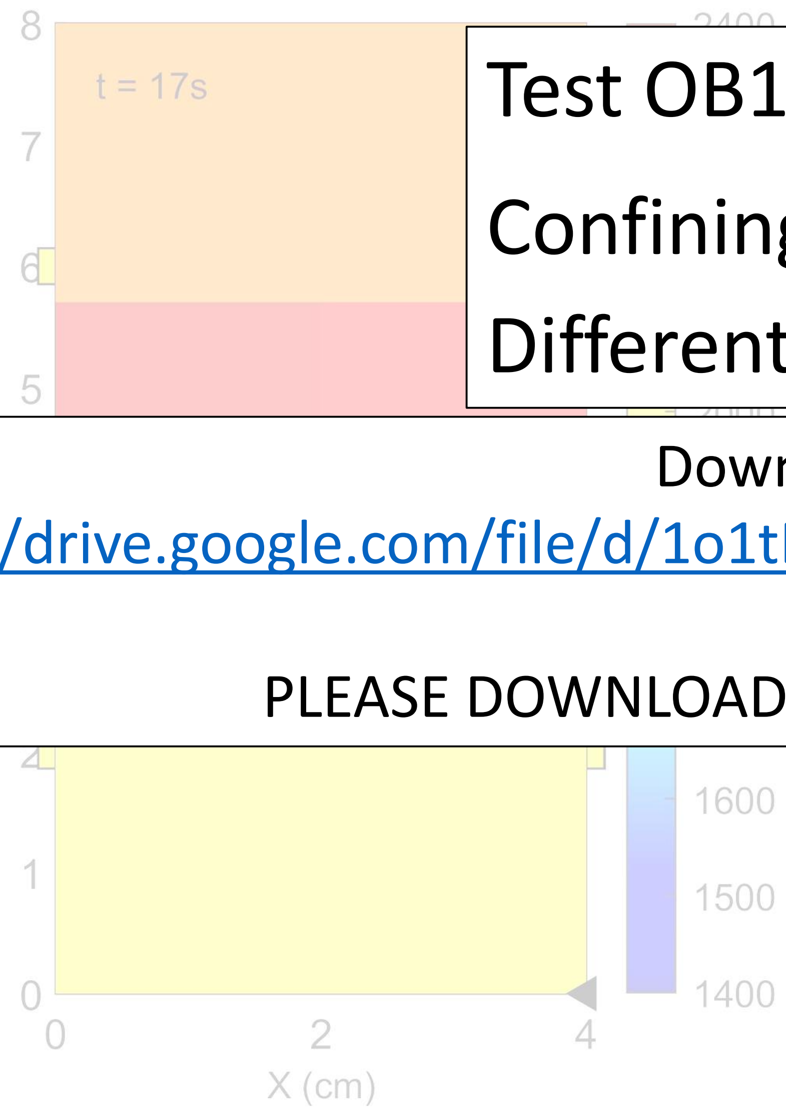
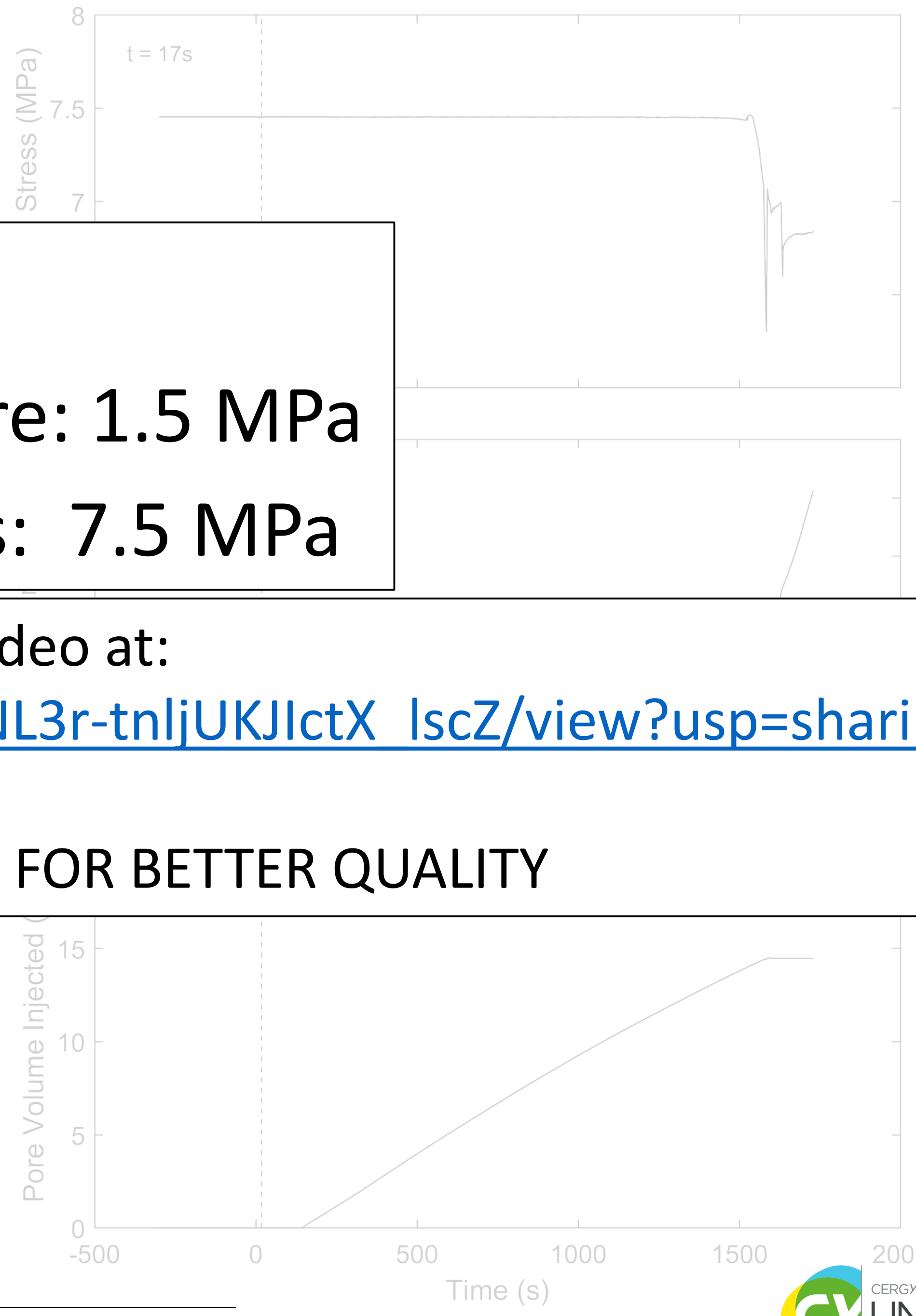
Sample OB17 - VIDEO





Test OB17:

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Differential stress: 7.5 MPa

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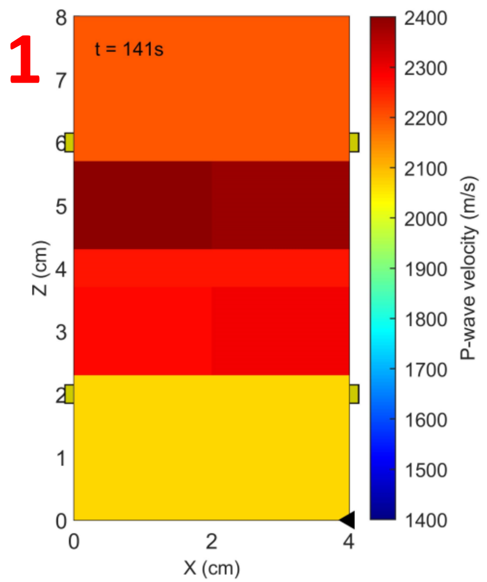
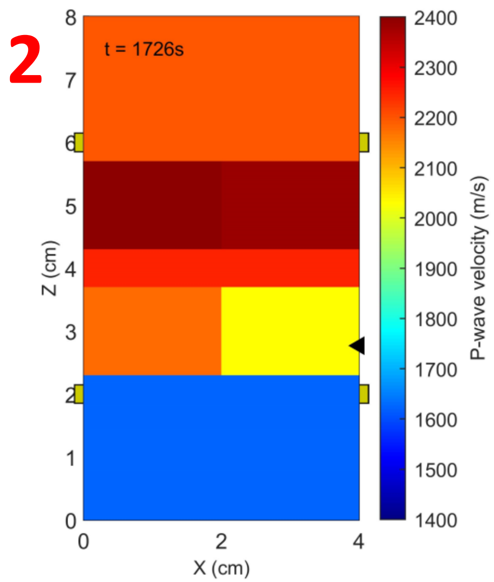
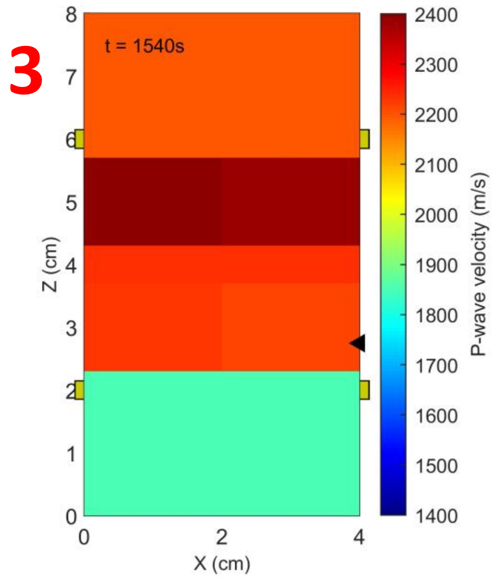
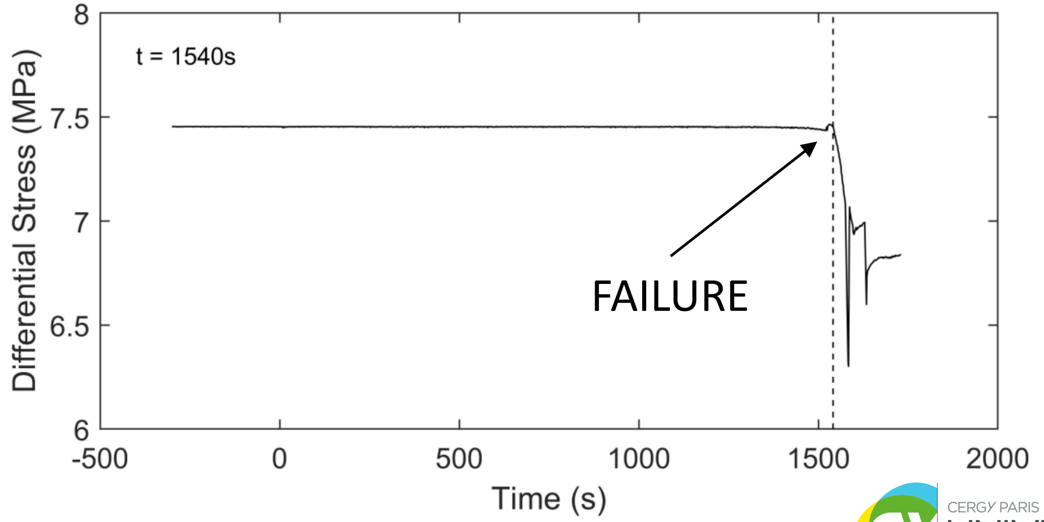
Sample OB17







- 1) 141 seconds: Injection starts
- 2) Water starts decreasing velocity from the bottom.
- 3) Failure takes place lowering the velocity mostly at bottom and zone 3.
- The velocity lowering at failure seems to start from the bottom to the middle. This might be generated by the deformation which starts at bottom and propagates upward.



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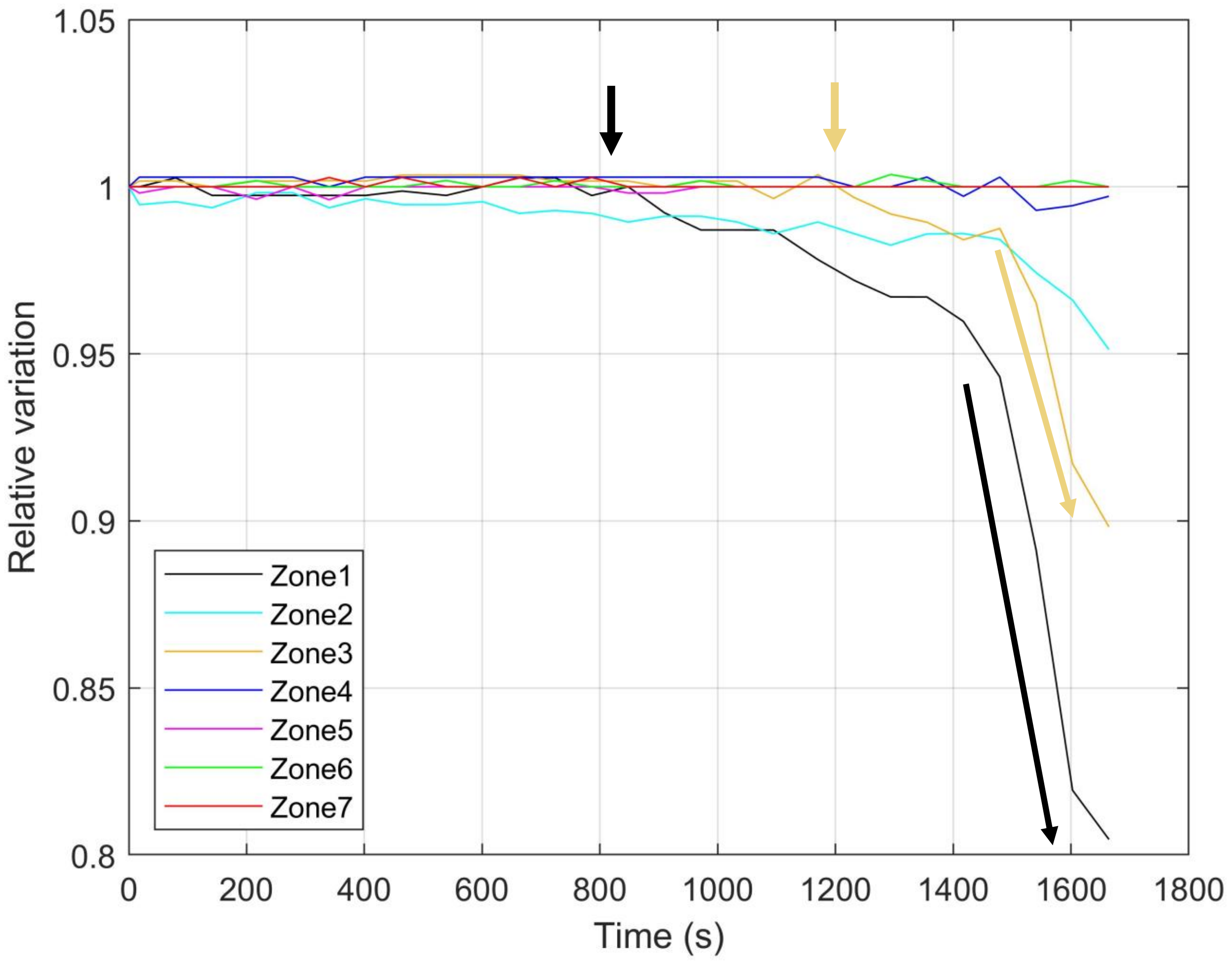
P-wave velocity variation - Summary

Sample OB17

Velocity decreases only at zone 1 (Bottom), 2 and 3.

Water doesn't reach the middle before failure takes place.

Rock failure induces further decrease in velocity. Mostly at Bottom and Zone 3.



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MicroCT Scans

Sample length : 80 mm

Sample diameter : 40 mm

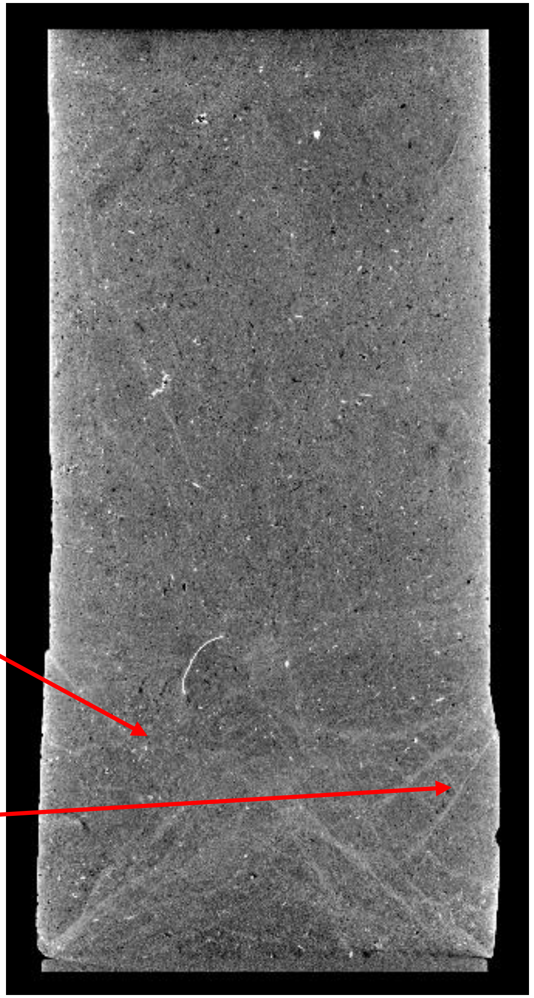
OB18

The wide diffuse band at the top and the open fractures at the bottom, might explain the stronger P-wave velocity decrease in these areas.

As expected, the sample shows deformation only in the lower half of the sample which is the water invaded area.

Deformation is widely diffused at the south bottom sensor respect to the north one. This might explain the stronger decrease observed in Zone 3, with respect to Zone 2

OB17



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Take home message

Water - air substitution causes two kinds of variation in the P-wave velocity when it invades the Fresnel zone near the transducers plane.

1. From 0 to about 65% of water saturation velocity decreases;
2. From 85 to 100% of water saturation velocity increases.

The final velocity (100% of saturation), is higher than in dry condition.

Velocity variation gives also indications of the rock failure and damage distribution.

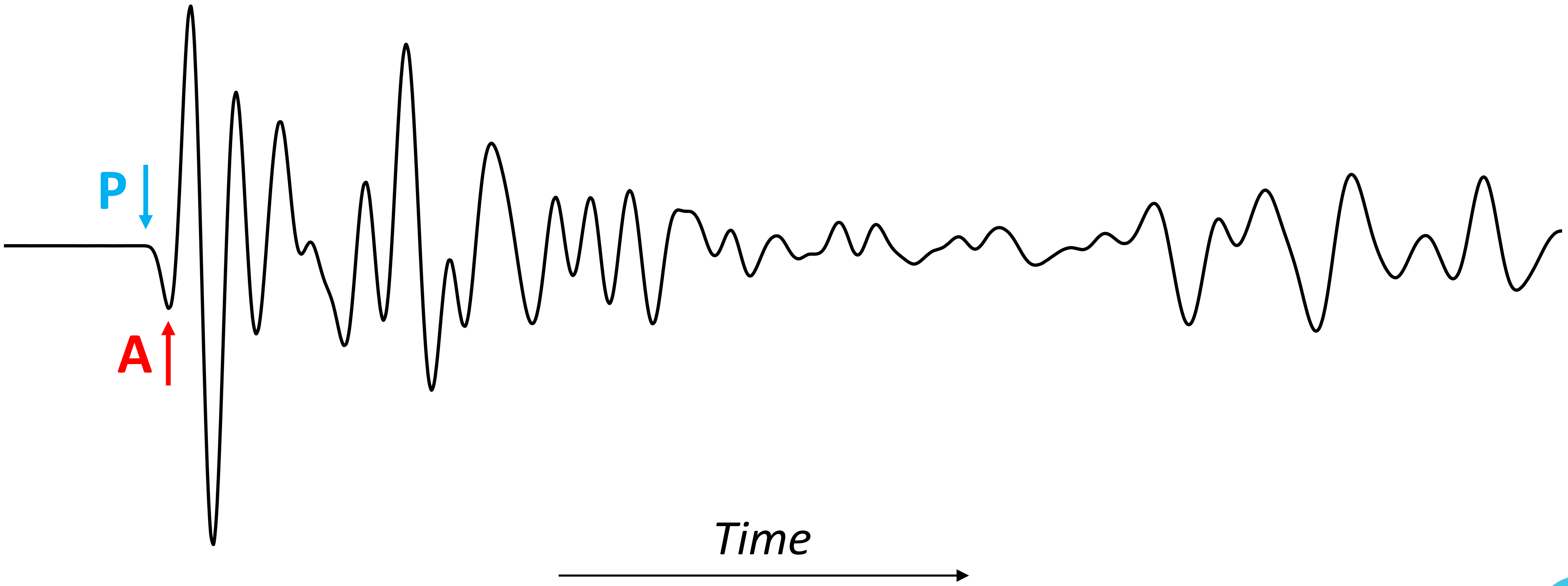
Correlation between P-wave velocity and amplitude

P-wave – First peak amplitude

We correlated the P-wave velocity with the wave amplitude.

Akaike Information Criterion (AIC) Method is used to pick automatically the P-wave first arrival P.

Then, the algorithm finds automatically the minimum which correspond to the First Peak Amplitude A



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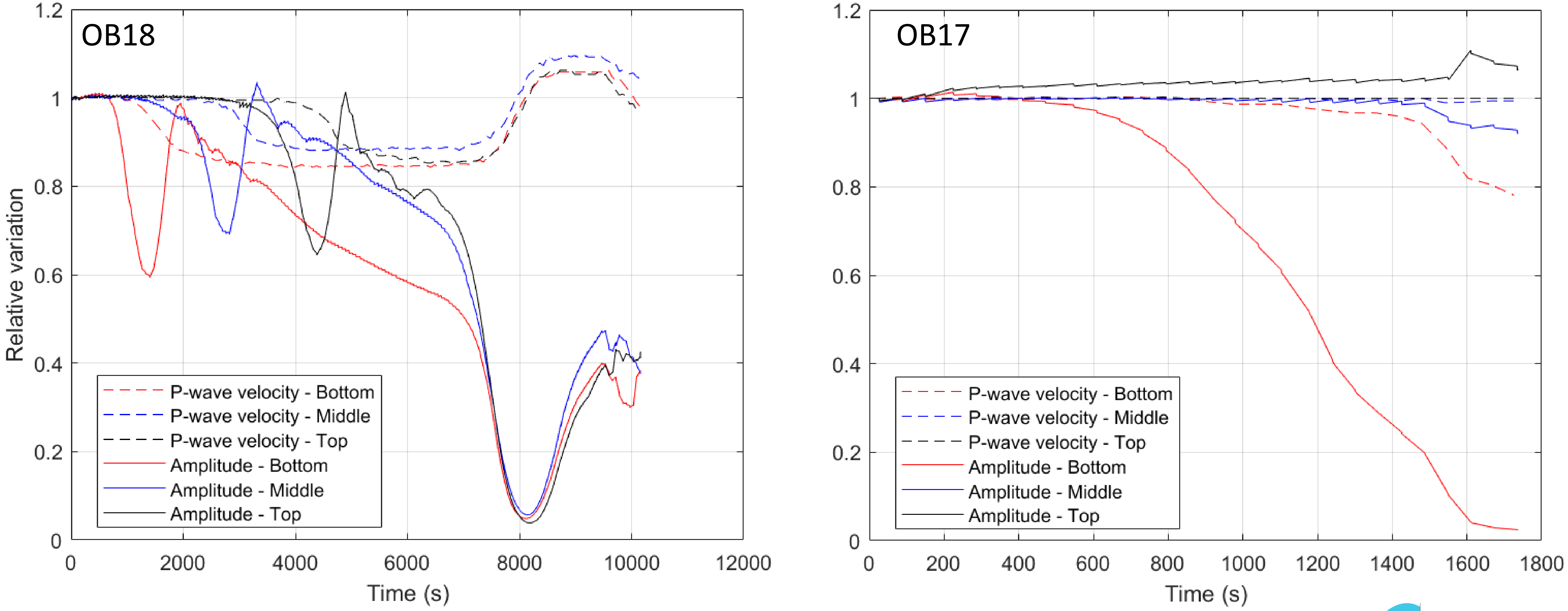
Seismic Attributes – V_P and Amplitude

In both test, P-wave Amplitude decreases systematically before velocity. Observed by David et al, 2015, 2017 on Sherwood Sandstone and other rocks and one explanation might be the diffusion of moisture diffusion above water front which impact the wave amplitude first.



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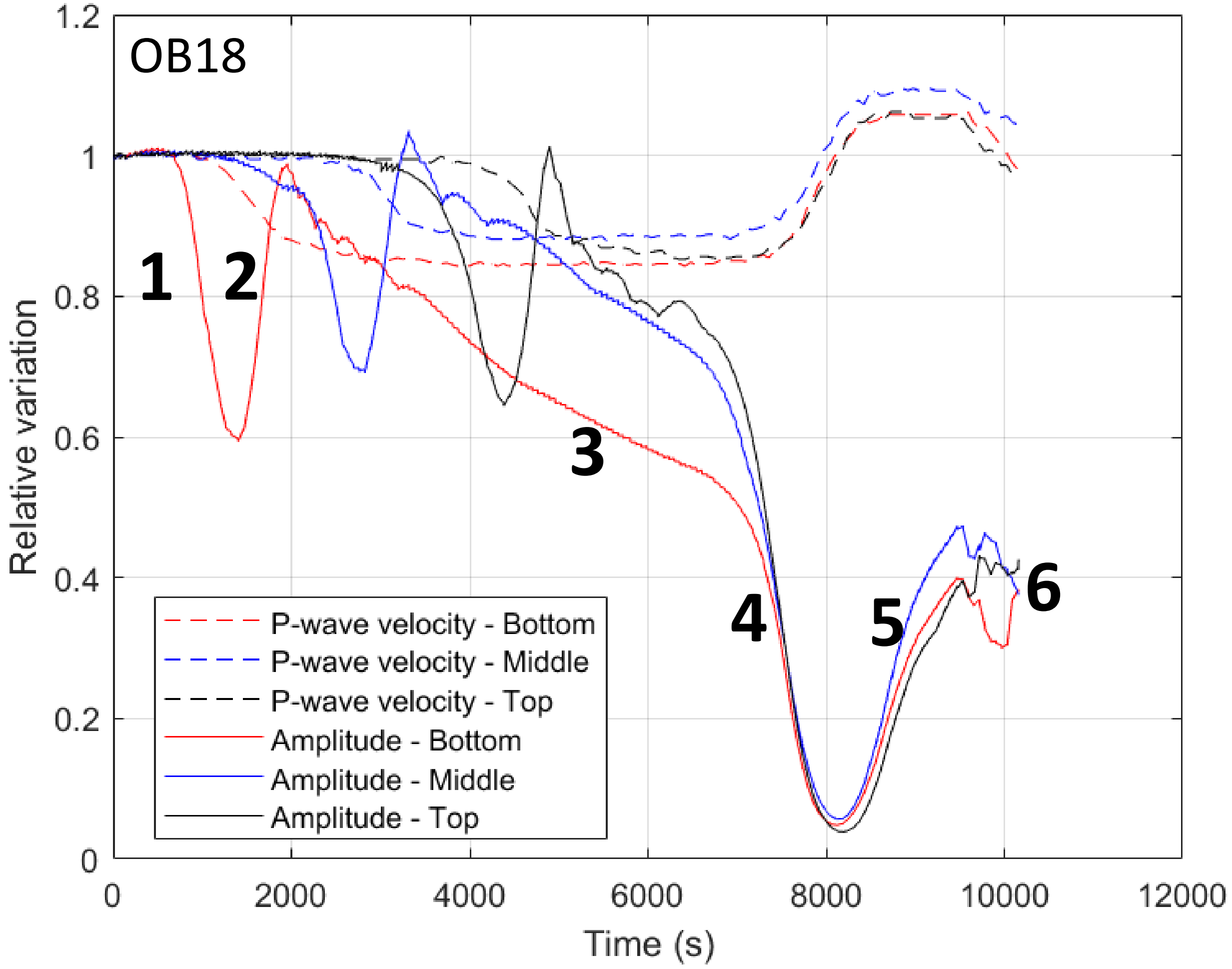
Seismic Attributes – V_P and Amplitude



Bottom Path:

1. Wave amplitude undergoes firstly a strong decrease.
2. It increases, going back to about the initial value.
3. It starts to decrease again in a slower manner.
4. Sample full saturation (above 90% of saturation) generates the opposite effect respect to the ultrasonic velocity.
5. Once the sample is saturated, amplitude undergoes a further rise up to the failure (6), where it becomes unstable while the velocity is decreasing

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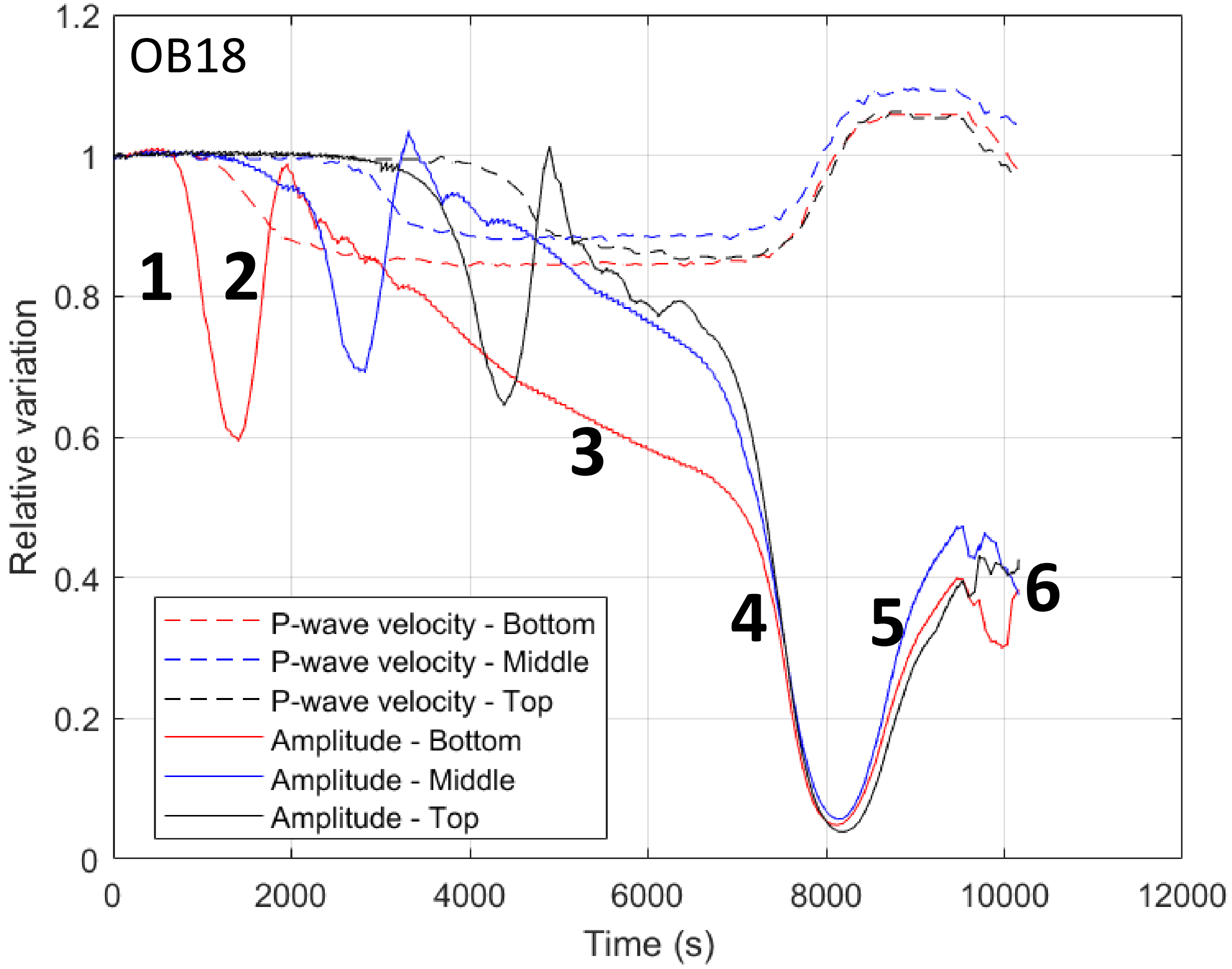
Seismic Attributes – V_P and Amplitude



Part 2: the amplitude increase might be explained by the invasion of water into the interference area between the transducers: the Fresnel zone. At this moment, P-wave velocity starts decreasing.

Part 3 seems to coincide with the moment where P-wave velocity starts stabilizing.

The nature of variation number 4 and 5 is still unclear and under investigation. However, they are linked with the complete saturation of the rock sample.

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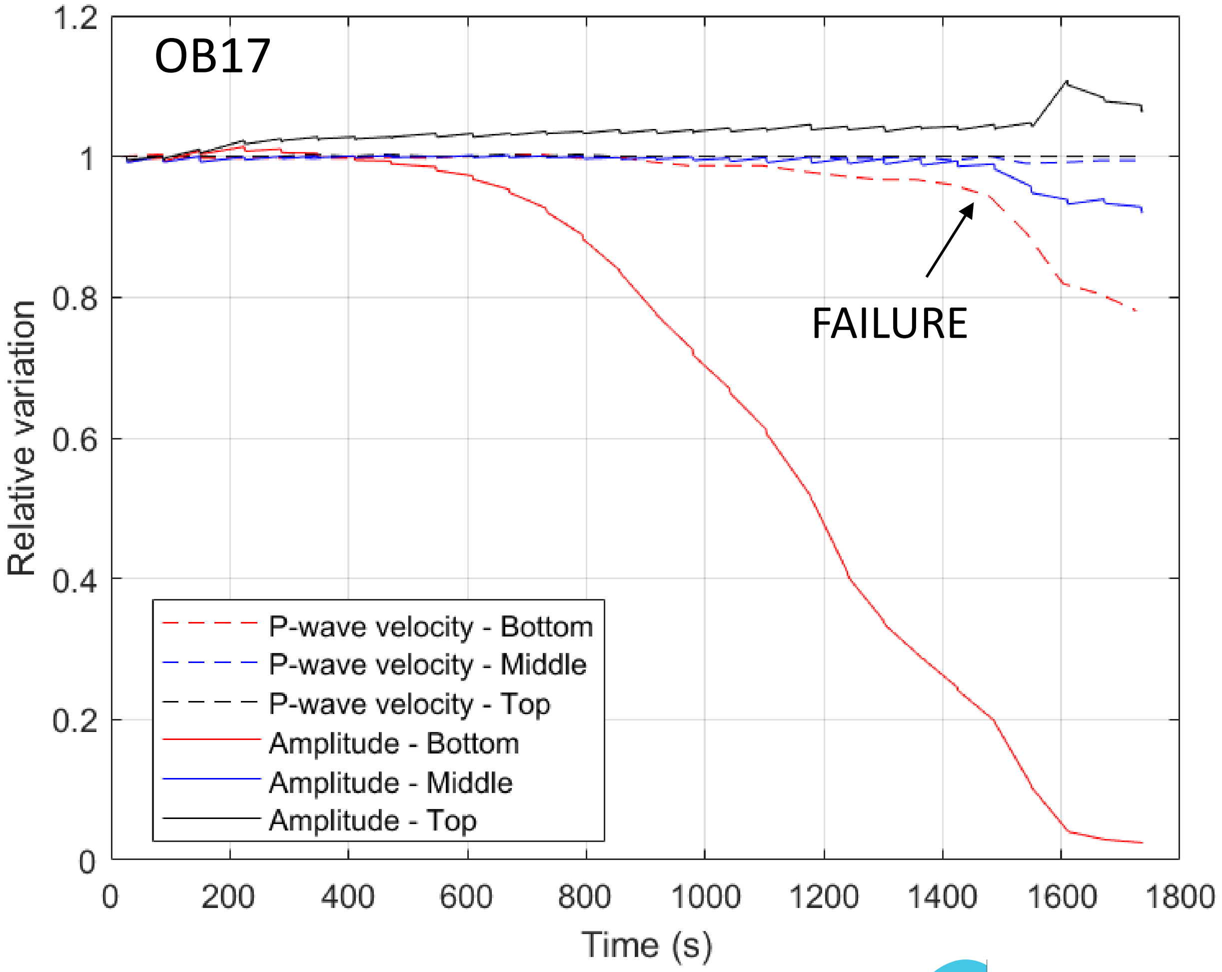
Seismic Attributes – V_P and Amplitude

For OB17:

P-wave amplitude is impacted before P-wave velocity by the water rise.

At the middle path, only amplitude starts decreasing since the test ended before reaching the Fresnel zone.

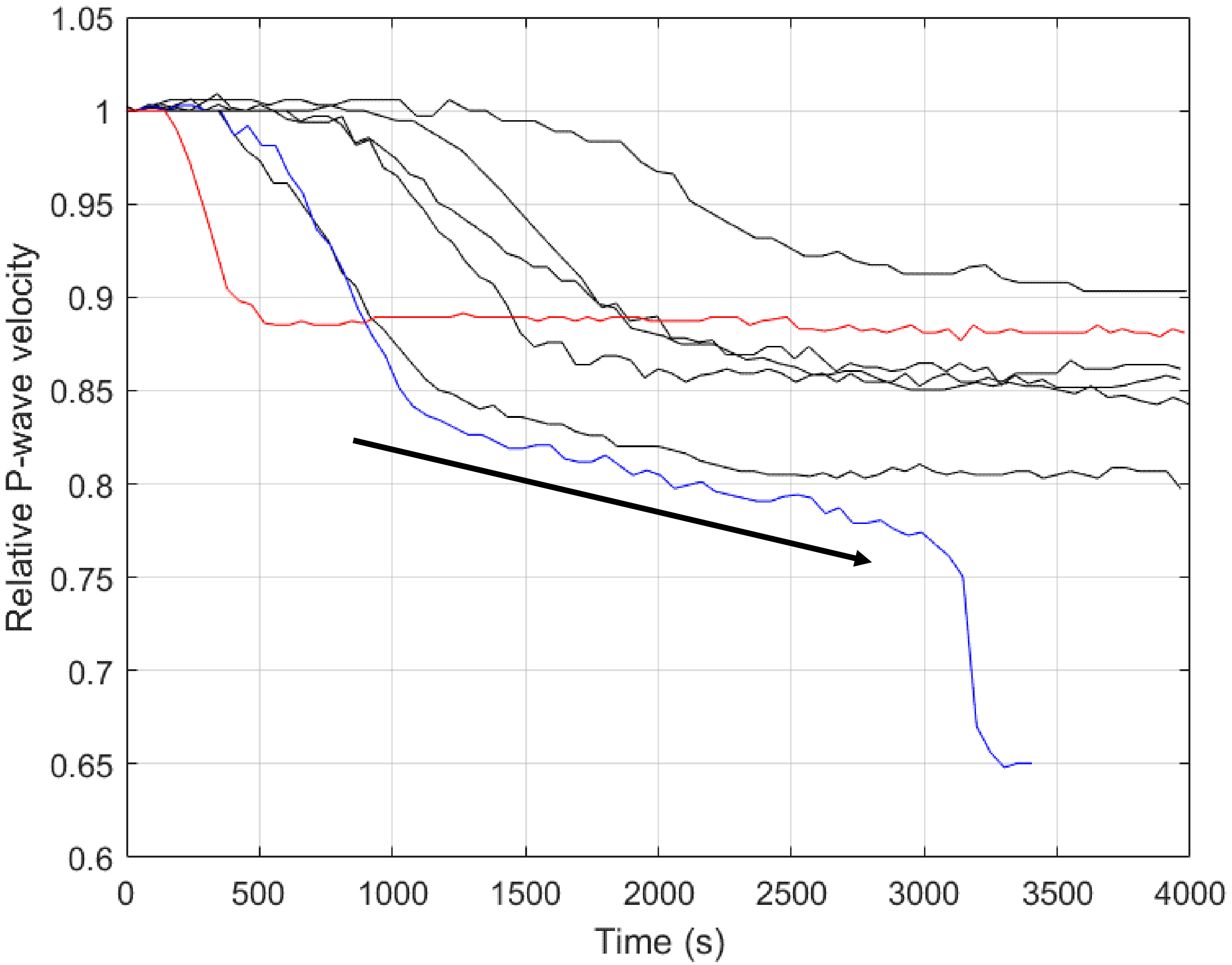
The amplitude at bottom doesn't show the same rise observed in OB18 in the part 2. This might be due to the approaching failure which would induce a further decreasing.



Water – induced damage while injection

Sample OB25 - Damaging

The same pattern of P-wave velocity variation is observed in different injection tests.



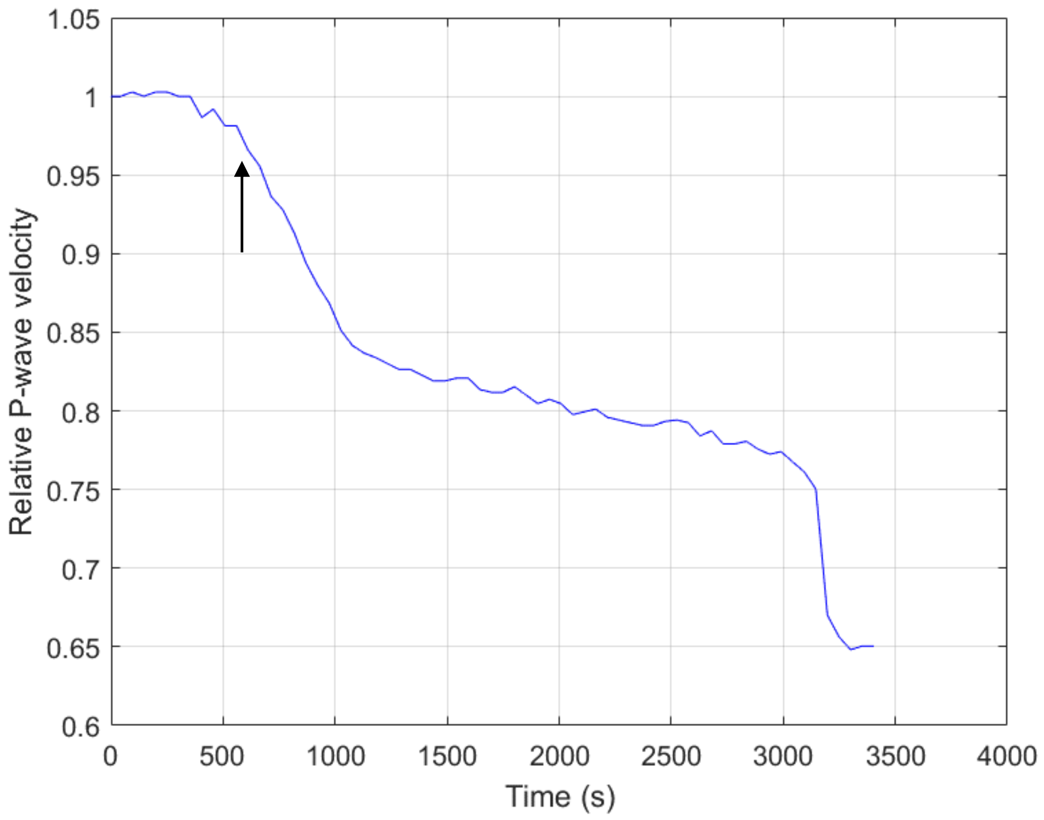
However, Some injection tests showed an important decrease in P-wave velocity respect to others.

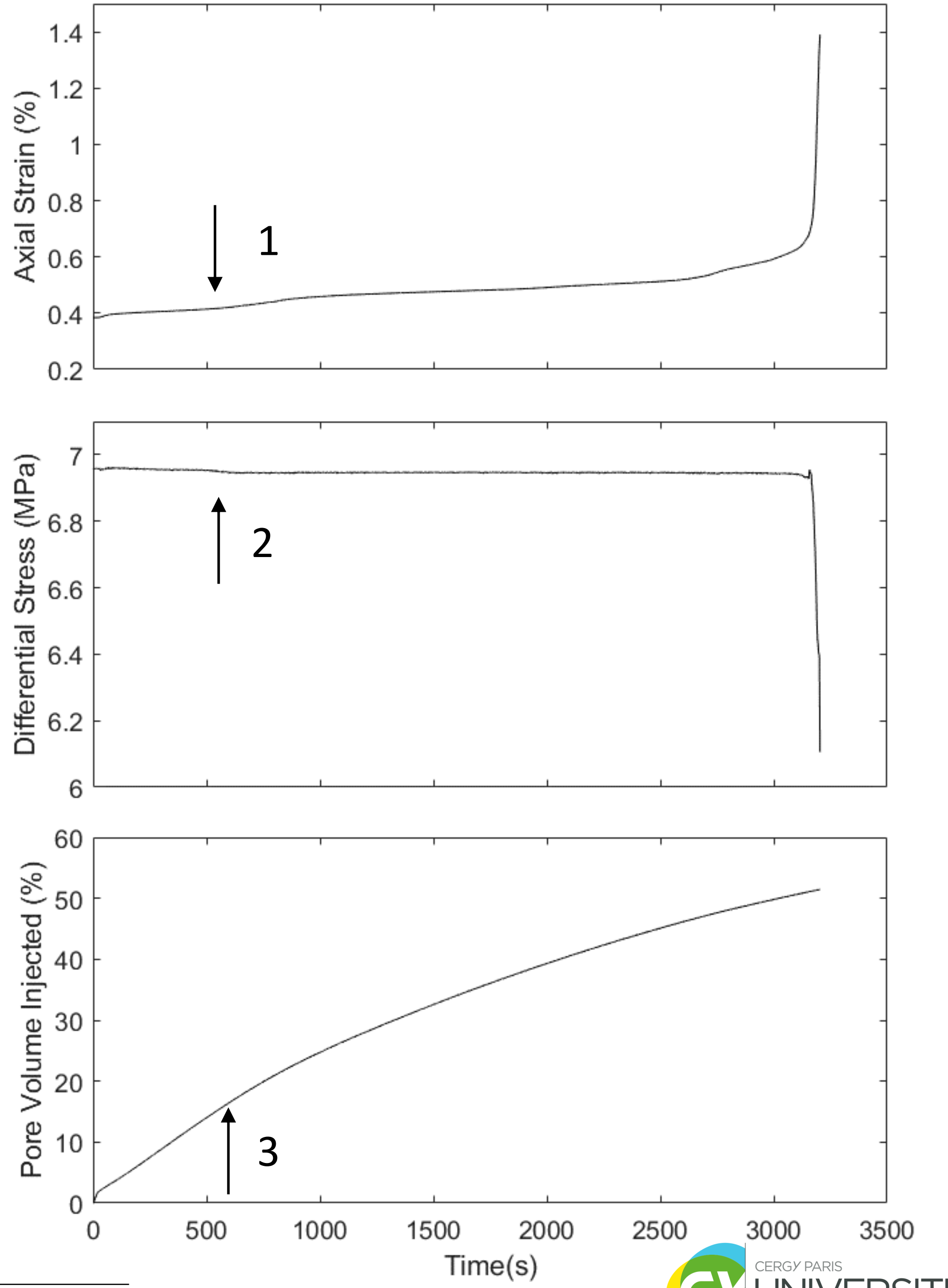
Most of them depict a stabilization after the strong decrease (black curves) similar to what is observed in imbibition test (red curve).

Sample OB25 (blue curve) shows a continuous decrease even after the variation induced by the water.

Sample OB25 - Damaging

At about 550 sec, the rock sample undergoes a small increase in the axial strain rate (1), followed by a small stress drop (2) and by a decrease of the injection rate (3) which switches from a linear to a non linear trend. Hence, the rock sample might have experienced water-induced damage.





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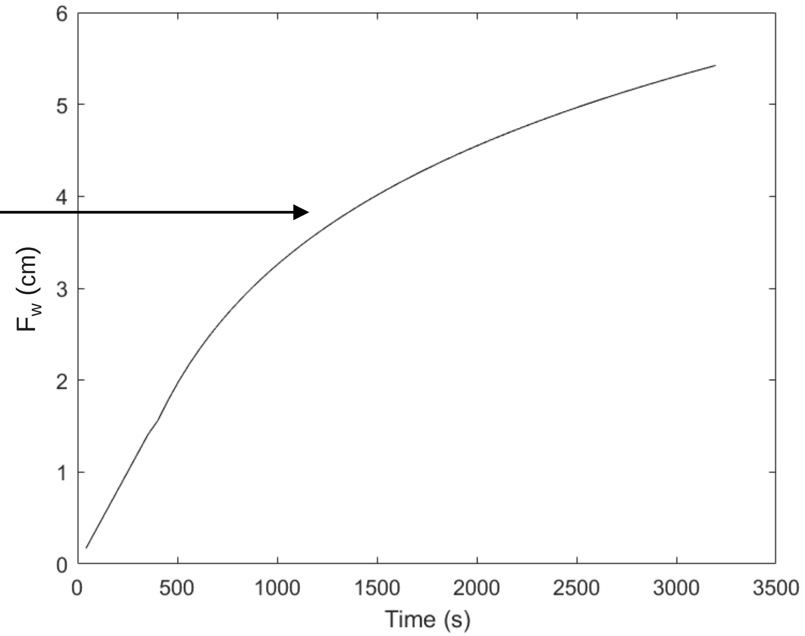
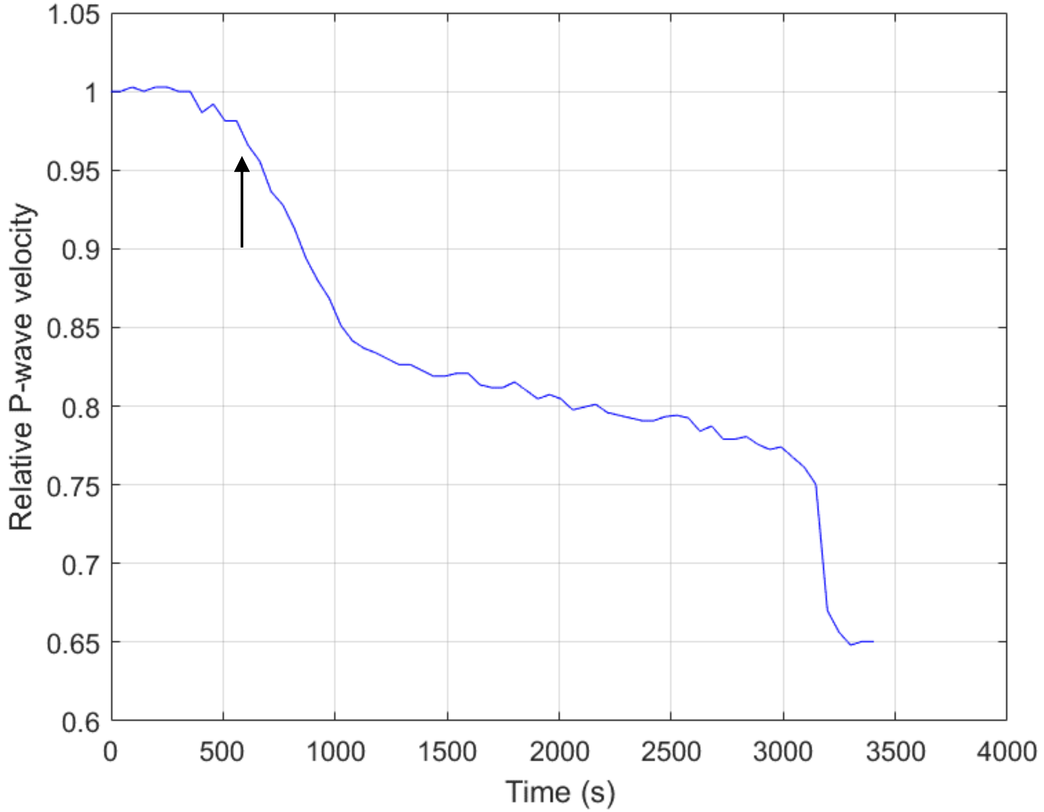
Sample OB25 - Damaging

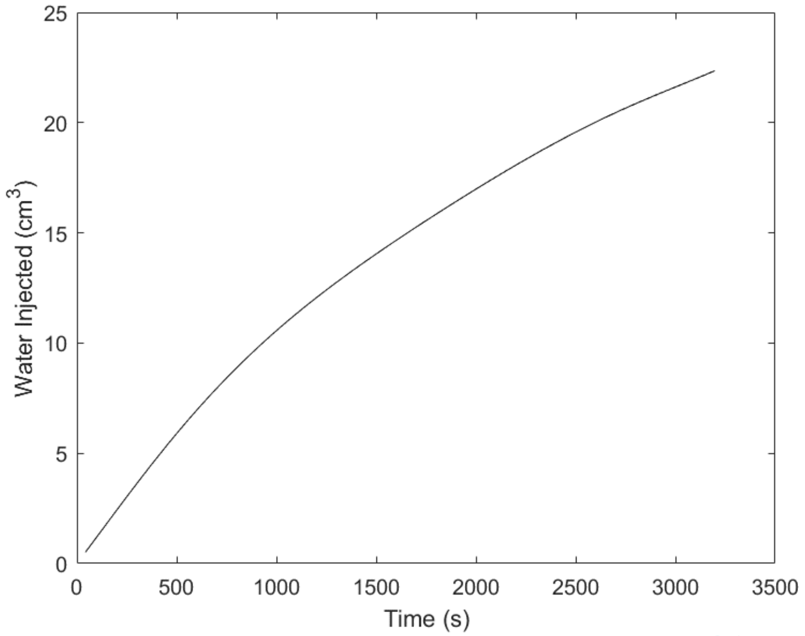
Water front height during injection test on Sample OB25, inferred from P-wave velocity variation.

Also the water rise slows down at about 550 seconds.

Furthermore, it is well correlated with the injection rate, hence showing the goodness of the calibration.







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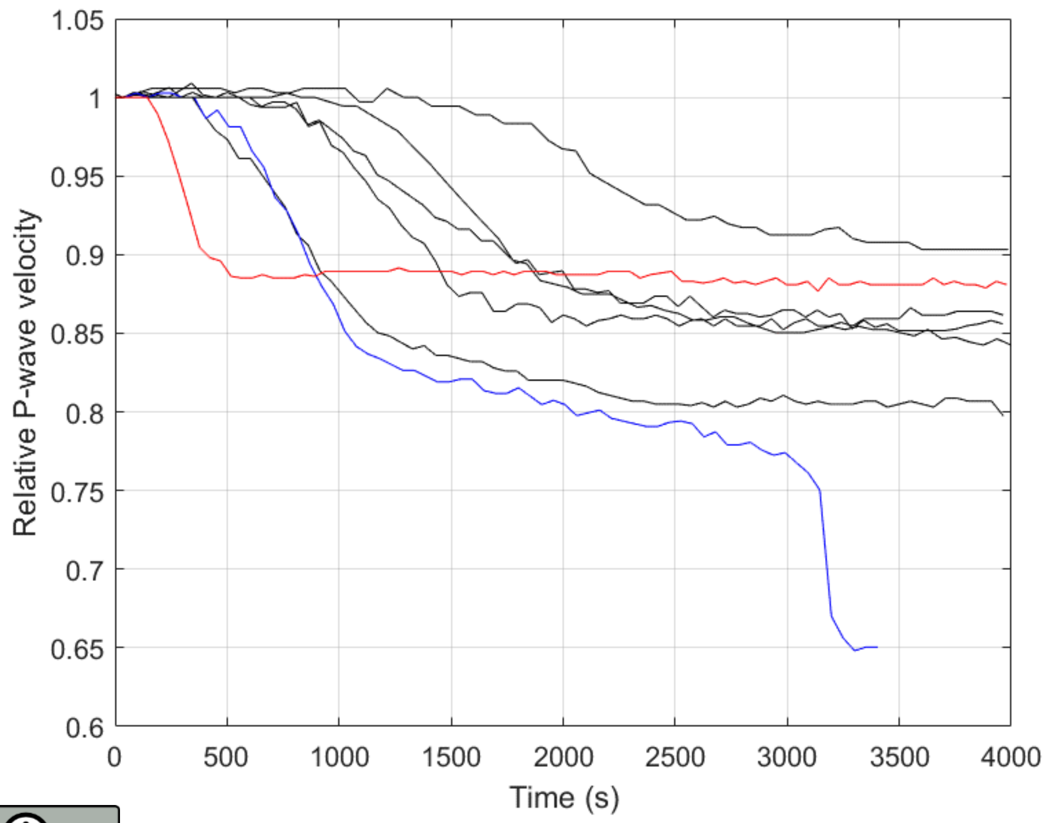
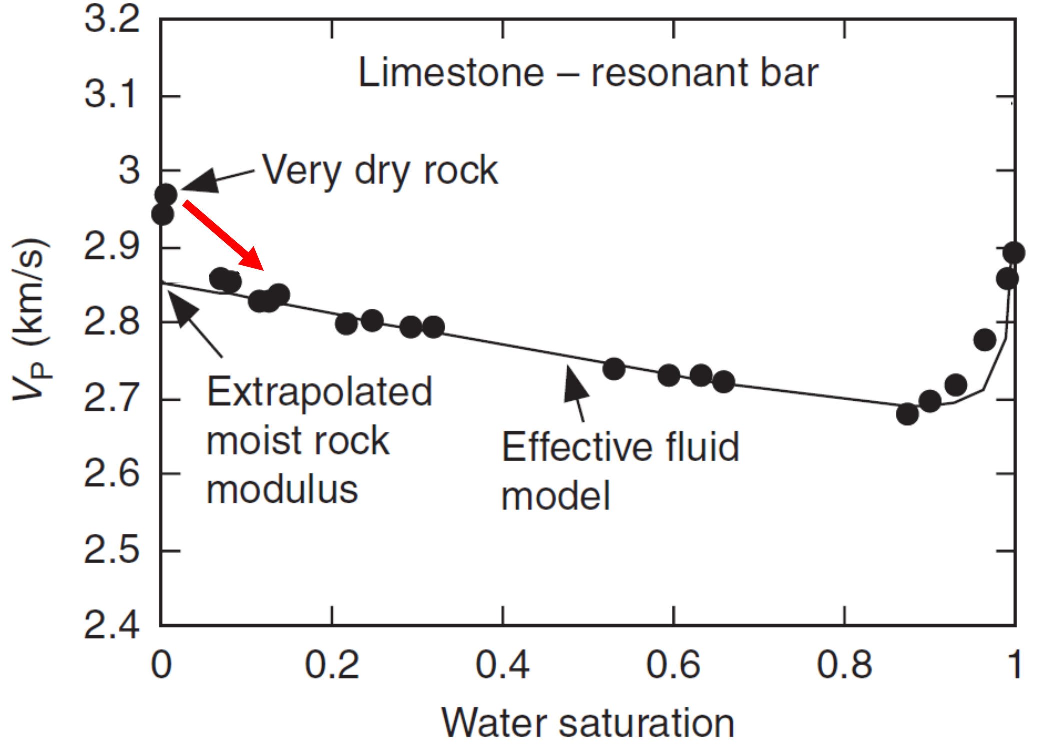
Damaging

The decrease in velocity observed in all the injection tests in the first degrees of saturation has been observed in literature (red arrow in figure) when passing from a very dry rock to a «moist rock», i.e. with moisture, and might be attributed to chemical softening of cements, or to surface effects acting at the grain-grain contact. This softening, coupled with the applied load might have induced deformation.



After Mavko et al, 2009



Data from Cadoret, 1993

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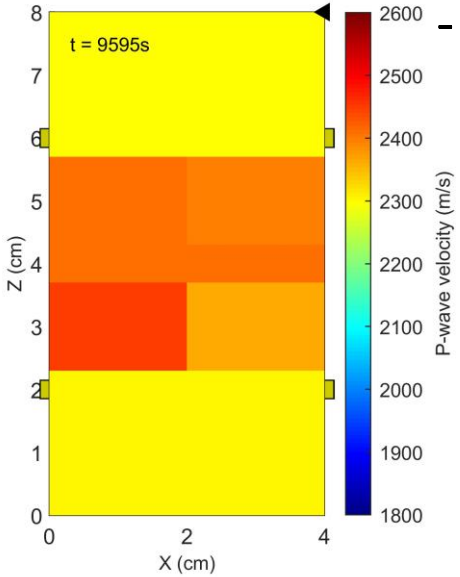
Concluding remarks

We showed how combining ultrasonic monitoring with multiple data source, is fundamental to catch up important information related to reservoir exploitation. In particular :

- *Provides a good indicator of water movement and distribution;*

- *Allows to detect mechanical instability and damage distribution;*

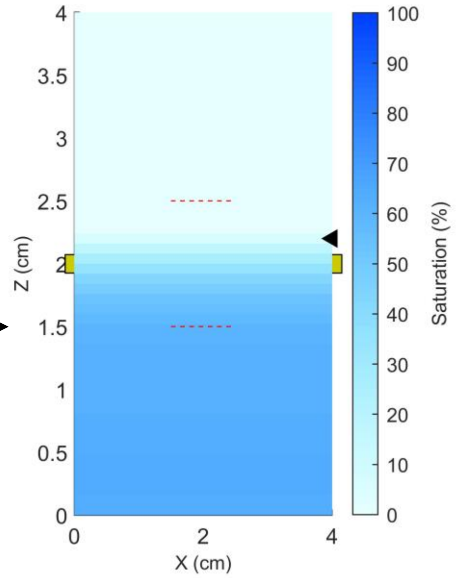


- *Provides indication of change in reservoir properties.*

Furthermore:

Oil/Water substitution experiments would contribute to more realistic scenarios;

Further studies will conduct to a better modelling of water movement inside porous rocks during injection.



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THANKS FOR YOUR ATTENTION!!

Chalk Quarry, Mons (Belgium)

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