Acoustic signature of fluid substitution in reservoir rocks

Christian David

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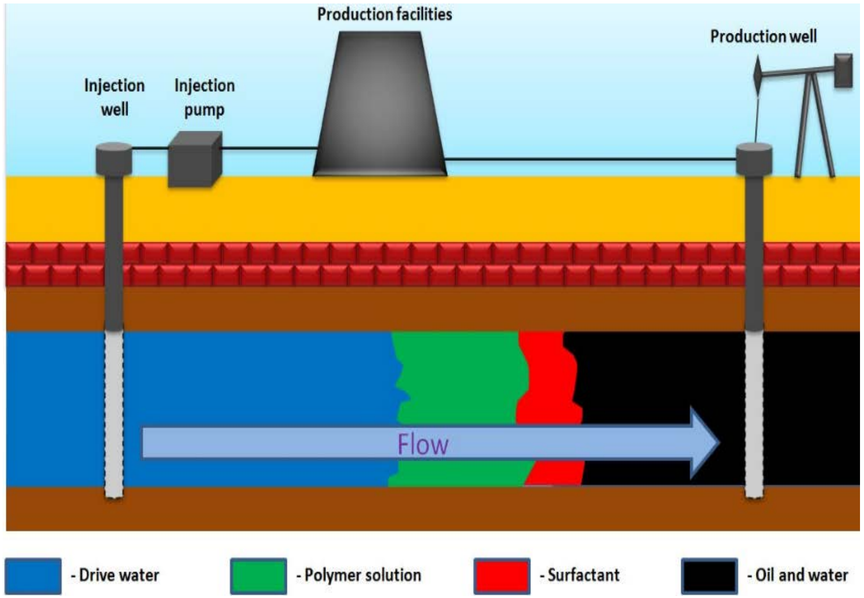
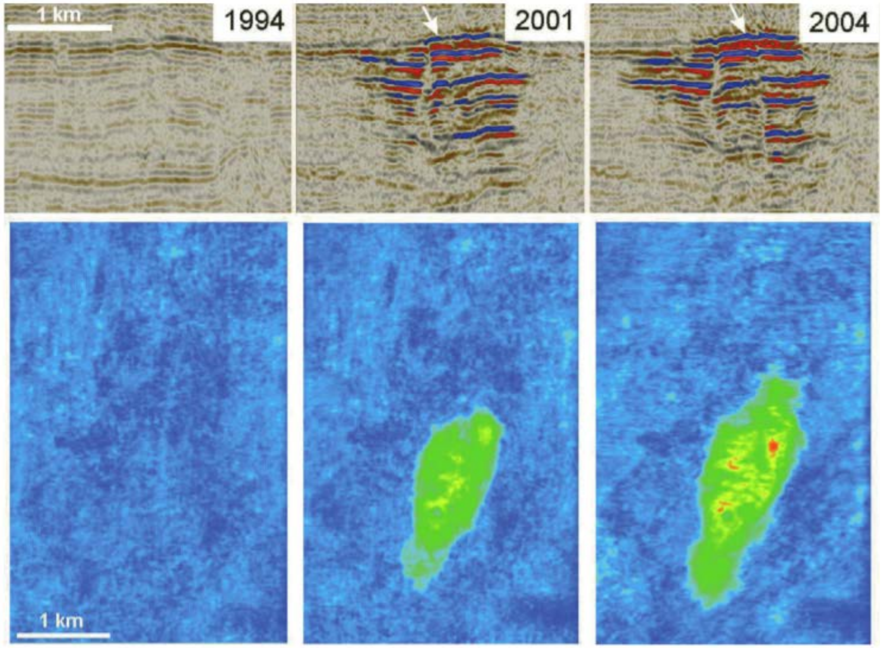
OBJECTIVE: MONITORING FLUID SUBSTITUTION





Enhanced oil recovery operations

CO_2 injection in a reservoir (Sleipner)

Question: What is the impact of fluid substitution on seismic and mechanical properties?

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OBJECTIVE: MONITORING FLUID SUBSTITUTION

Question: What is the impact of fluid substitution on seismic and mechanical properties?

→ 1) laboratory experiments mimicking oil-water substitution in reservoir rocks under stress

→ 2) spontaneous imbibition experiments with ultrasonic monitoring

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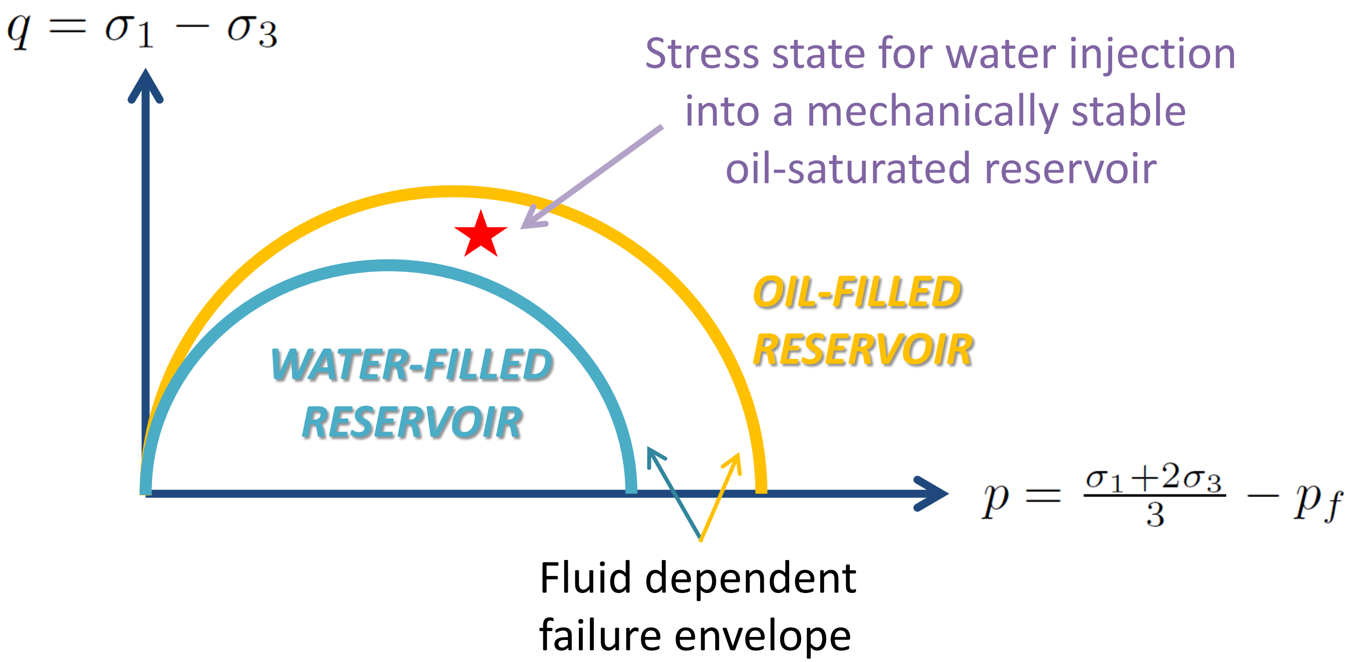
1) Oil-water substitution in reservoir rocks under stress

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



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CERGY PARIS UNIVERSITÉ

1) Oil-water substitution in reservoir rocks under stress

Selected rock: the **Sherwood sandstone (UK)**

Mineralogy

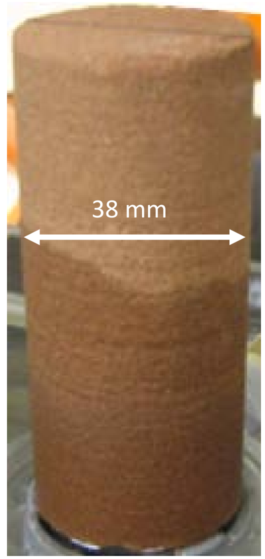
Quartz: 24-43% (Avg 30%)
Feldspar: 13-26% (Avg 18%)
Detrital clays (mainly Illite): 3-29% (Avg 12%)

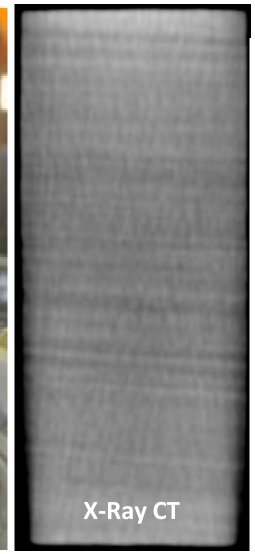
Petrophysics

Porosity: 30.2%
Peak pore diameter: 25 µm
Water permeability // bedding: 350 mD
Water permeability ✕ bedding: 200 mD

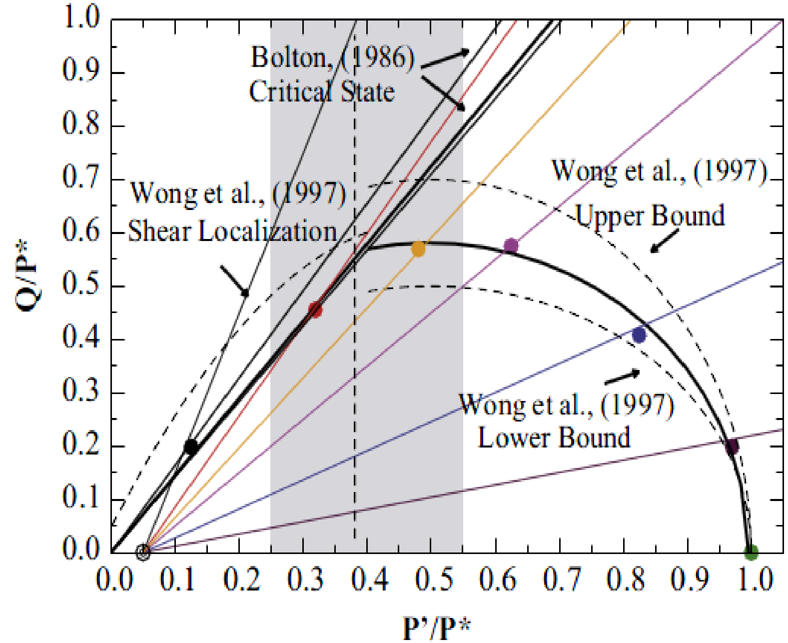
Geomechanics

Young modulus (dry) ✕ bedding: 4.6 GPa
Pore collapse pressure P*: 40 MPa

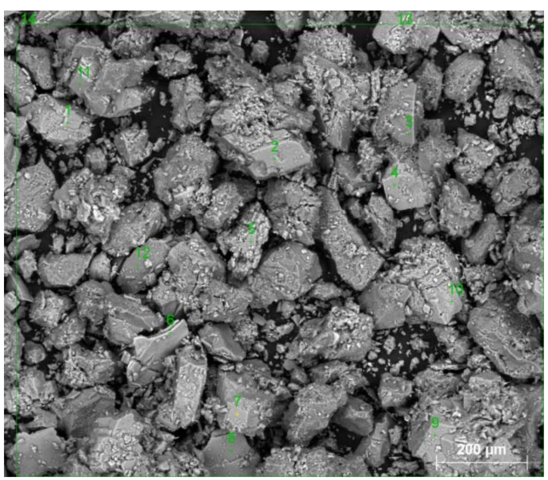


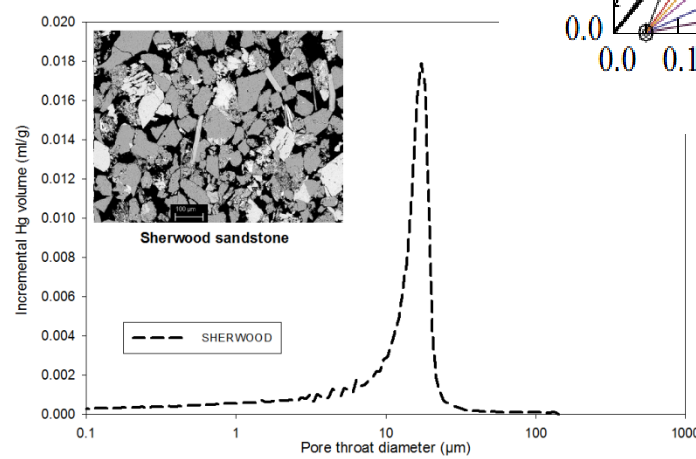


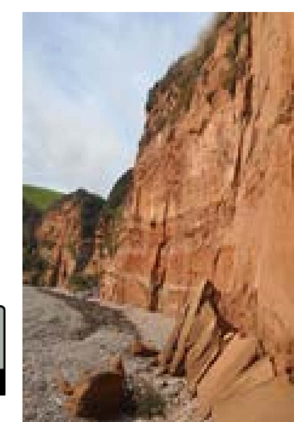
Failure envelope for water-saturated Sherwood sandstone



Nguyen et al., IJRM, 2014







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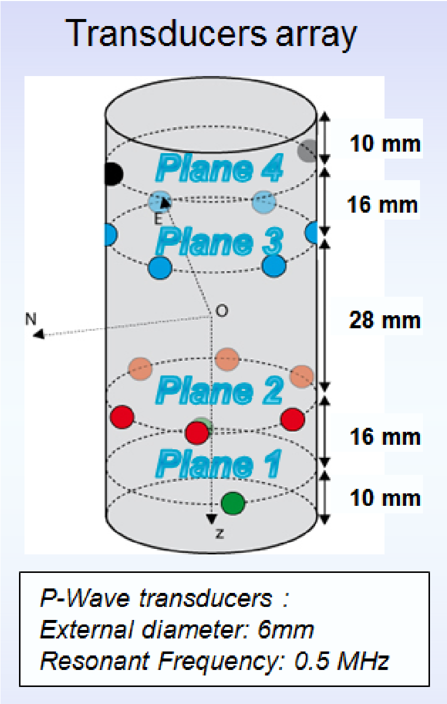
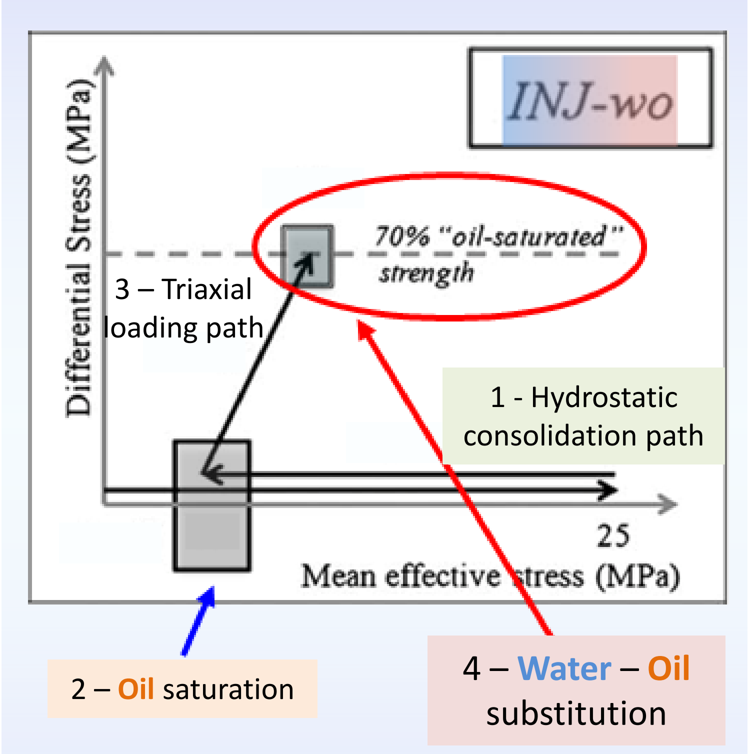
1) Oil-water substitution in reservoir rocks under stress

→ Lab experiments on the Sherwood sandstone (UK)





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

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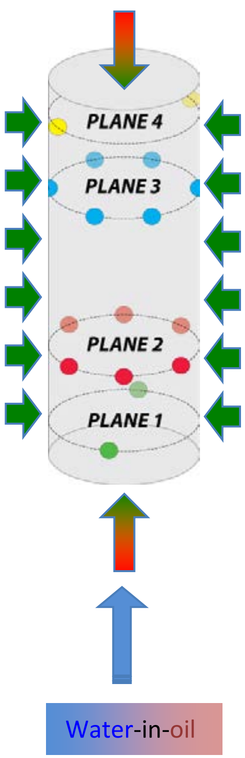
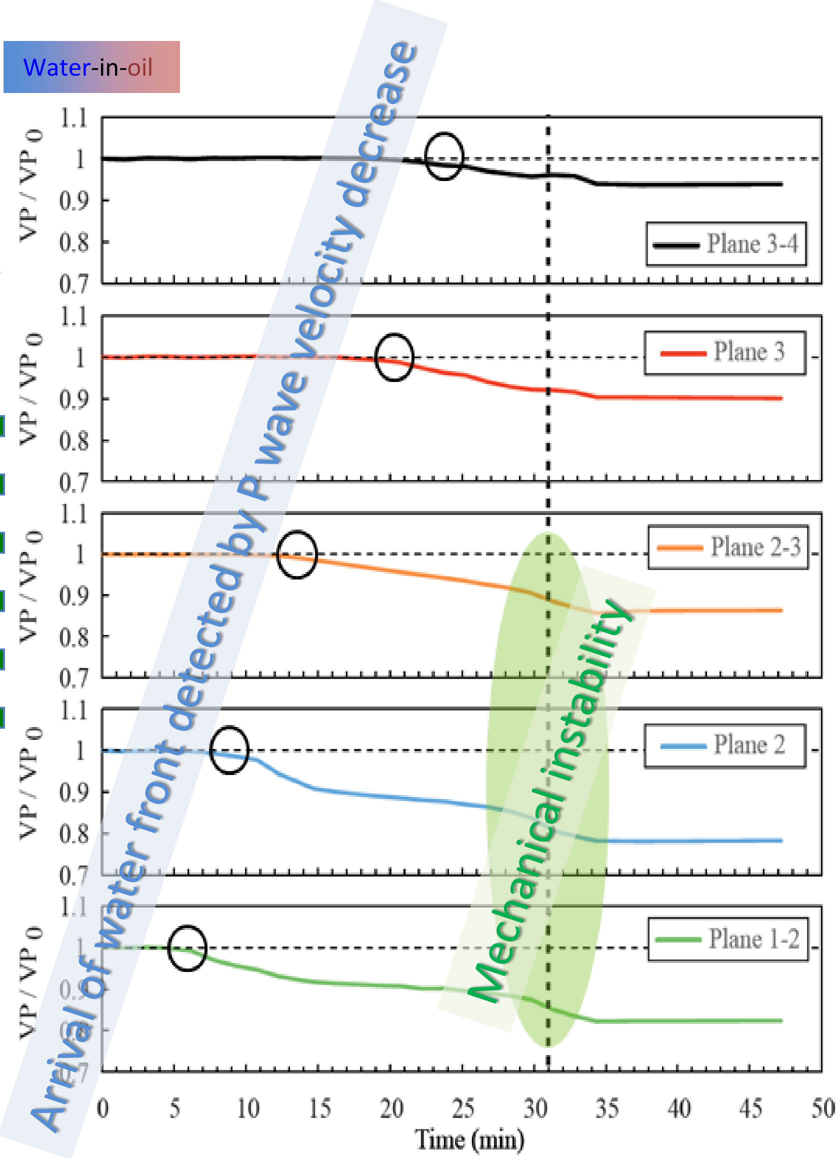
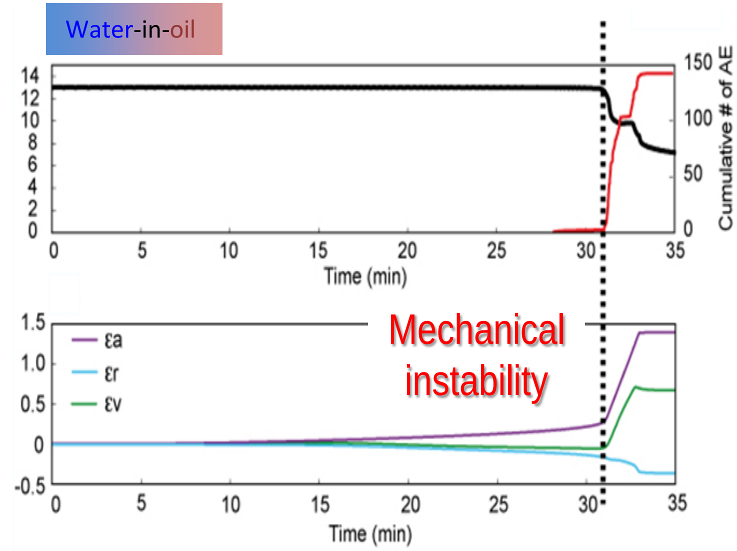
1) Oil-water substitution in reservoir rocks under stress

CRITICAL
diff stress q
70% of strength







Water – oil substitution under constant stress state triggered a **mechanical instability** (failure) in the lower part of the sample where **water weakening processes** took place

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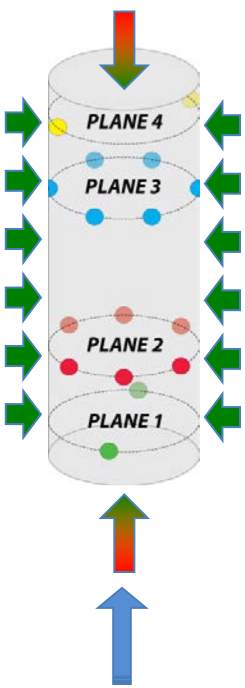
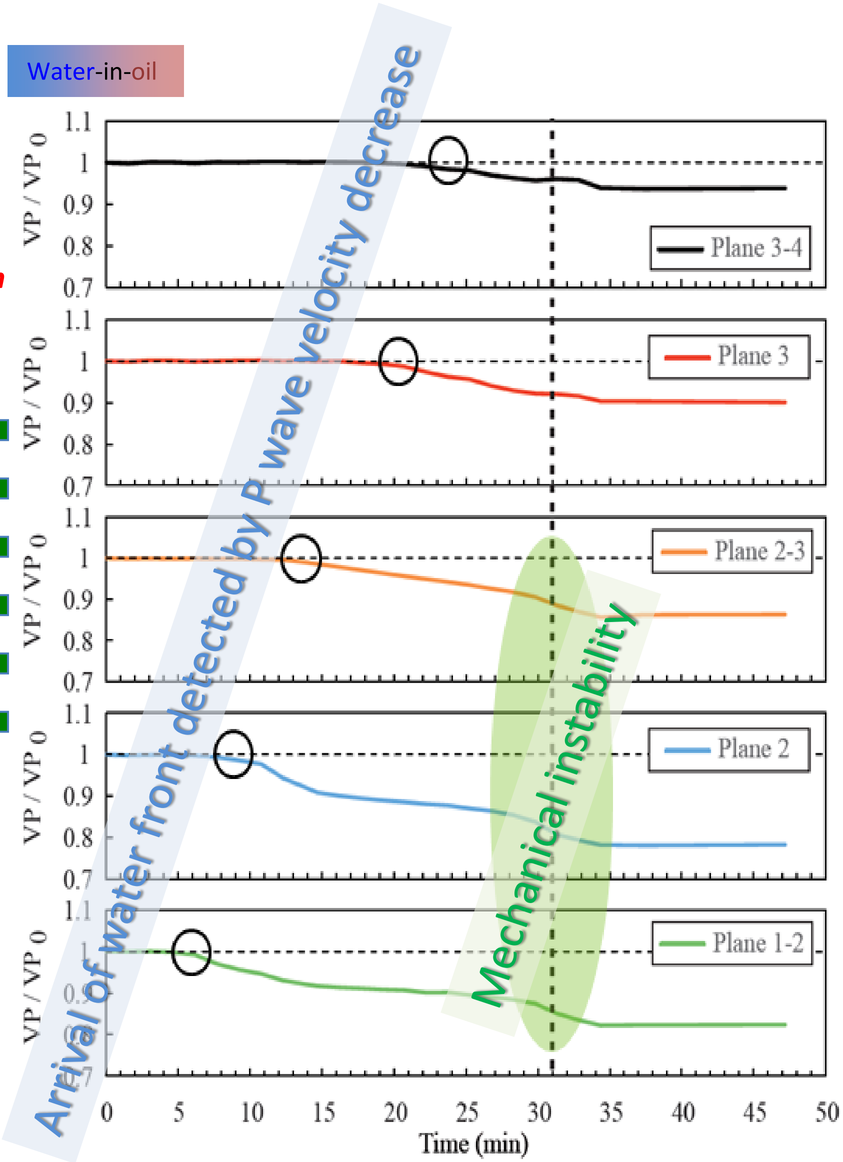
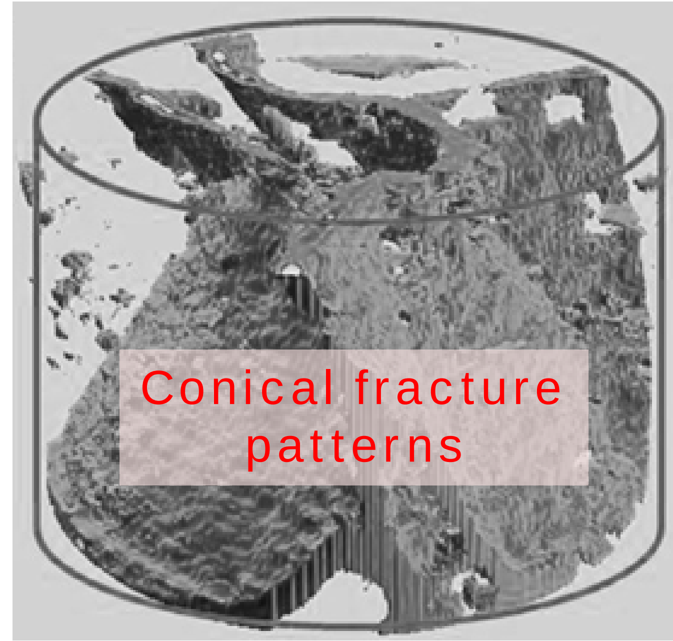
1) Oil-water substitution in reservoir rocks under stress

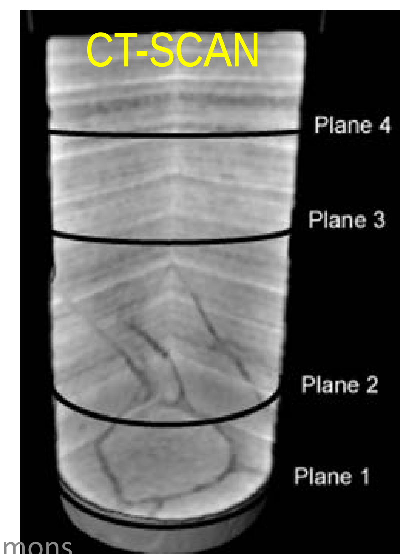
CRITICAL diff stress q 70% of strength

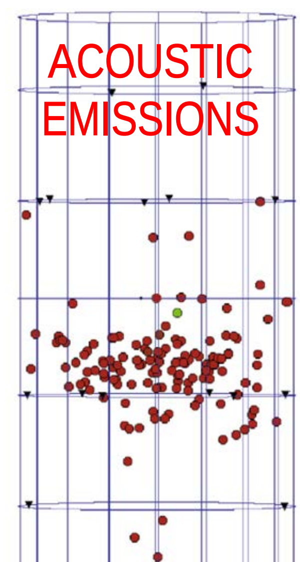


Water-in-oil









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Active and passive ultrasonic monitoring are able to monitor fluid substitution and induced damage

1) Oil-water substitution in reservoir rocks under stress

https://doi:10.1002/2015JB011894

AGU PUBLICATIONS
JGR
Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE
10.1002/2015JB011894

Key Points:
- We studied fluid injection effects on the mechanical behavior of a sandstone
- Water injection in a critically loaded sample leads to mechanical instability

Mechanical instability induced by water weakening in laboratory fluid injection tests

C. David[1], J. Dautriat[2], J. Sarout[2], C. Delle Piane[2], B. Menéndez[1], R. Macault[1,2], and D. Bertauld[1,2]

[1]Laboratoire Géosciences et Environnement Cergy, Université de Cergy-Pontoise, Cergy-Pontoise, France, [2]CSIRO Energy, Perth, Western Australia, Australia

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Remote monitoring of the mechanical instability induced by fluid substitution and water weakening in the laboratory

CrossMark

Jeremie Dautriat [a,*], Joel Sarout [a], Christian David [b], Delphine Bertauld [a,b], Romaric Macault [a,b]

[a] CSIRO Energy, Perth, Australia
[b] Université de Cergy-Pontoise, Laboratoire GEC, Cergy-Pontoise, France

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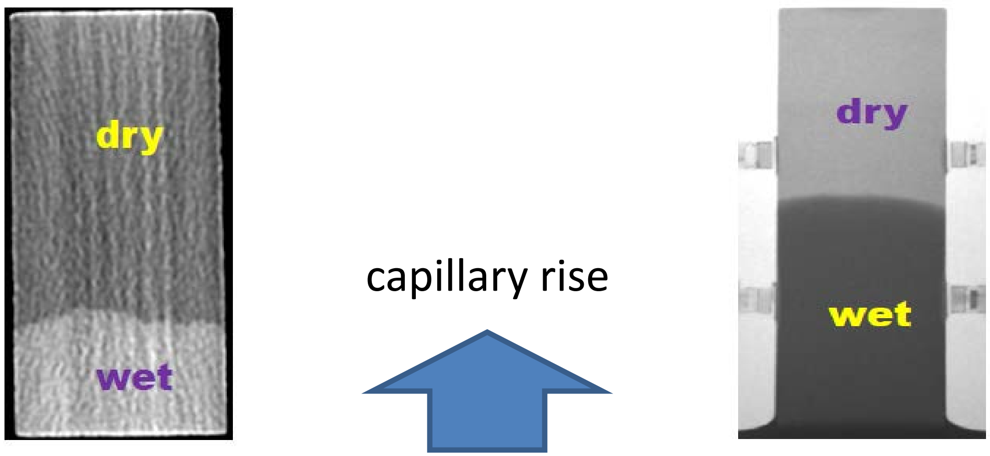
2) Air-water substitution in imbibition experiments

→ **with ultrasonic monitoring on 2 planes at different heights**

(2 pairs of P-wave transducers)

→ **with simultaneous imaging of the central cross-section using either X-ray CT-scan or neutron beam radiography**



X-ray CT scan imaging

Neutron radiography imaging

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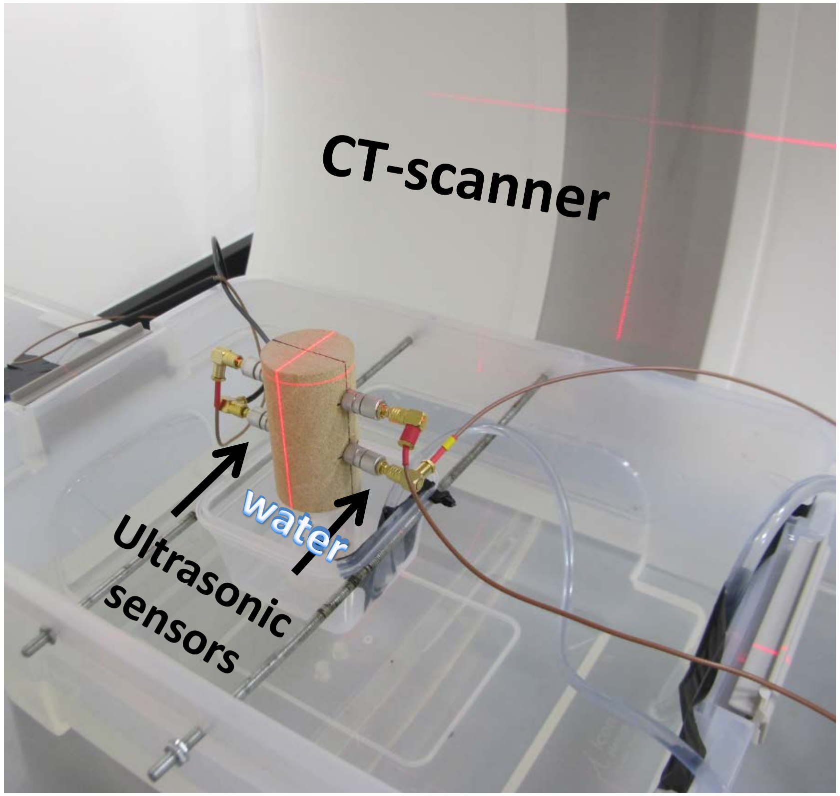
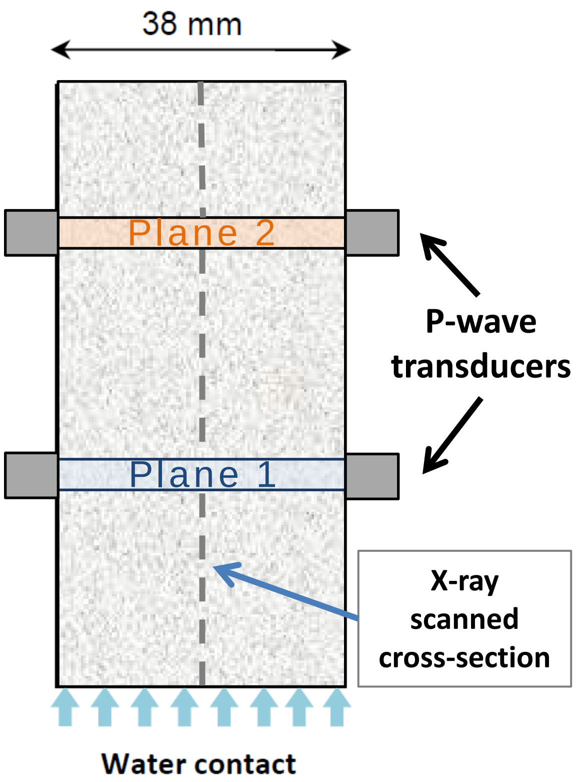
2) Air-water substitution in imbibition experiments

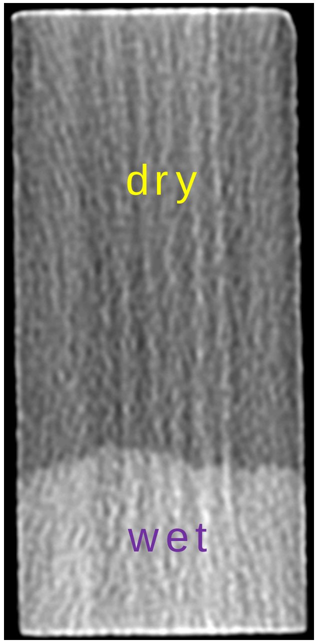
➢ Imaging using X ray CT scan (CSIRO)

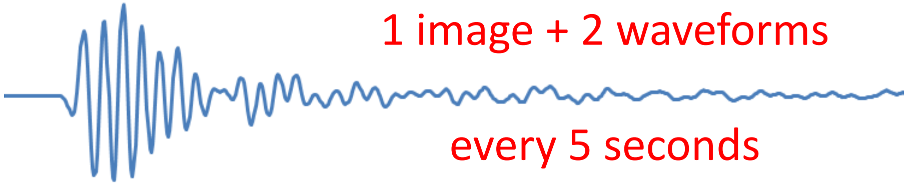
Experimental setup for X-ray CT scan





Enhanced image of cross-section





1 image + 2 waveforms

every 5 seconds

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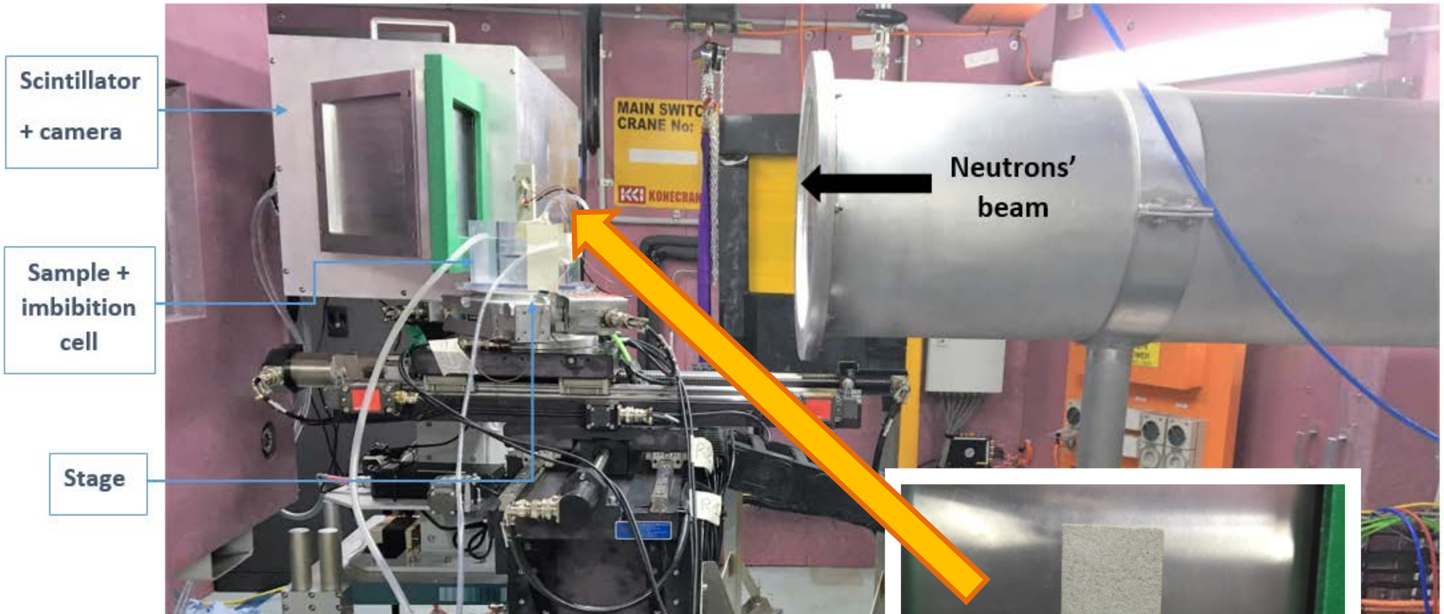
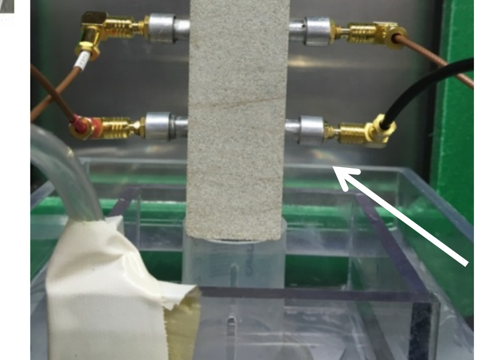
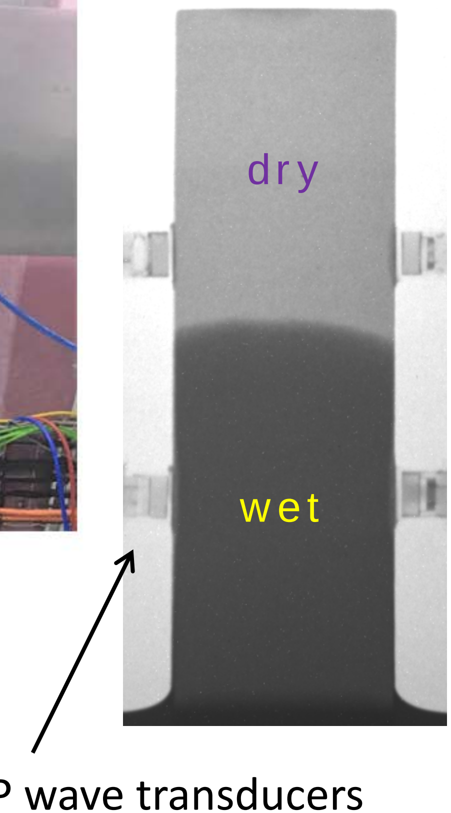
2) Air-water substitution in imbibition experiments

➢ Imaging using neutron beam (ANSTO)







Australian Government

ansto

Australian cyclotron

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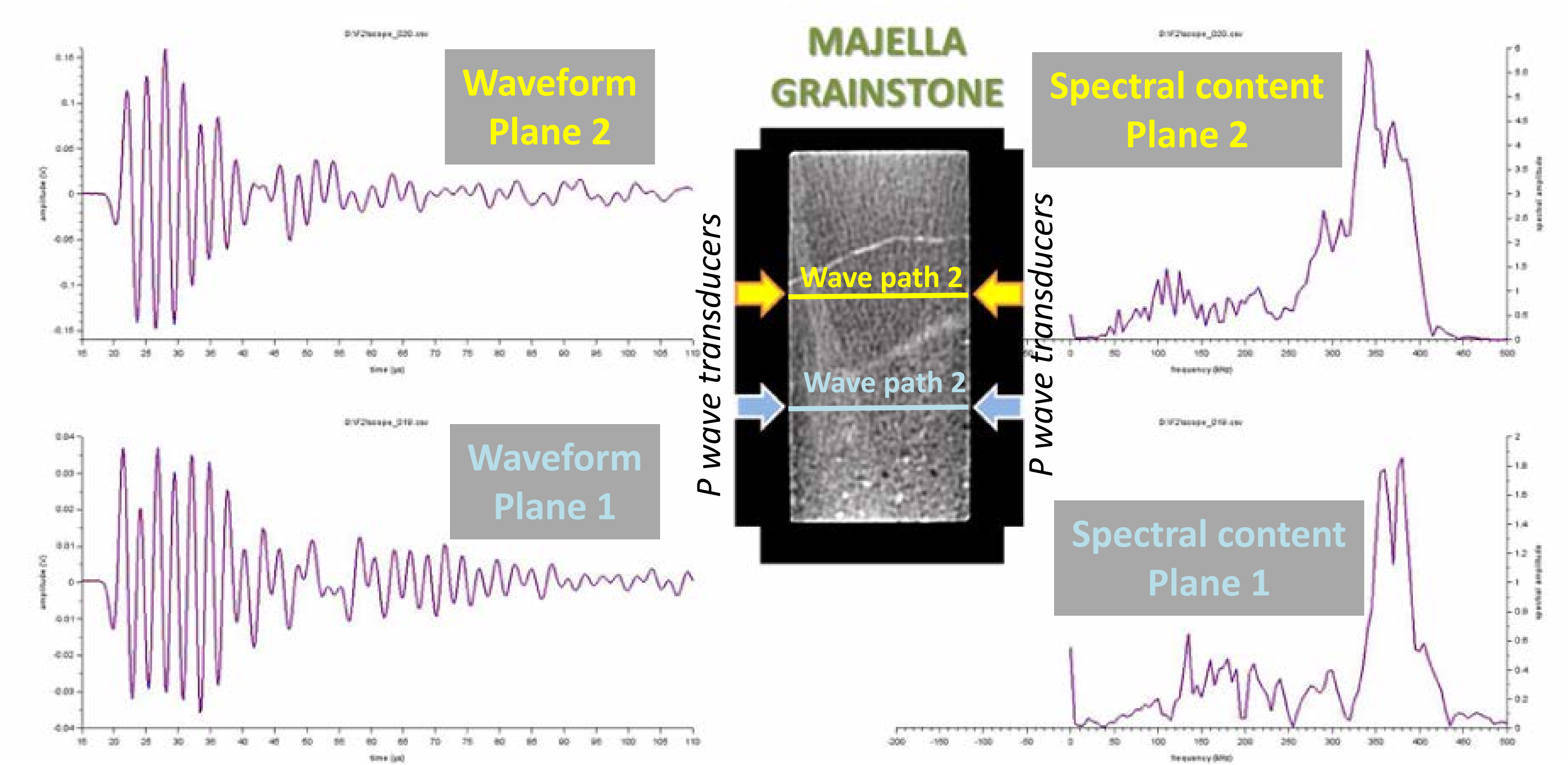
2) Air-water substitution in imbibition experiments

a) Waveform analysis



VIDEO ON NEXT SLIDE

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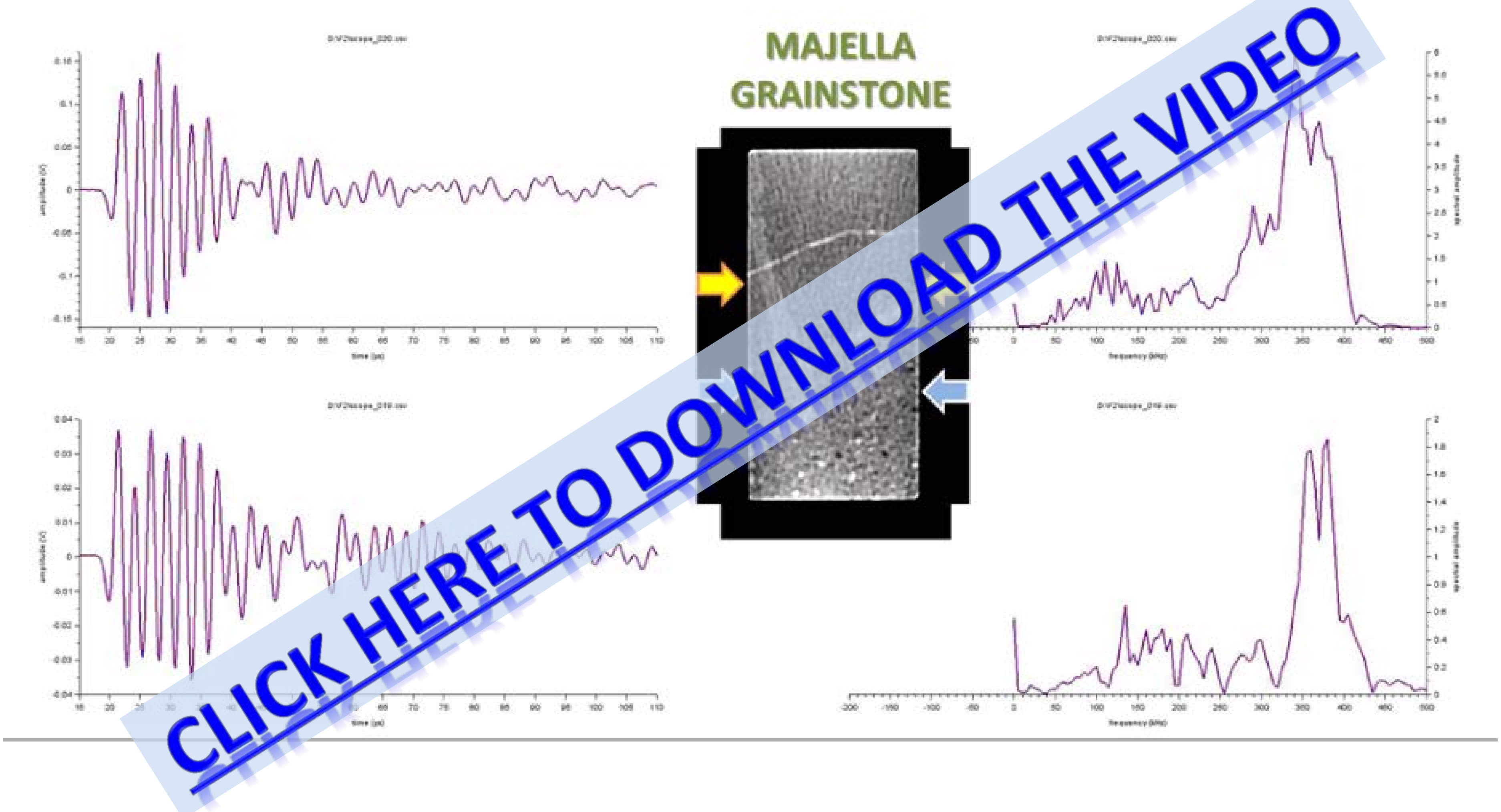
2) Air-water substitution in imbibition experiments

a) Waveform analysis



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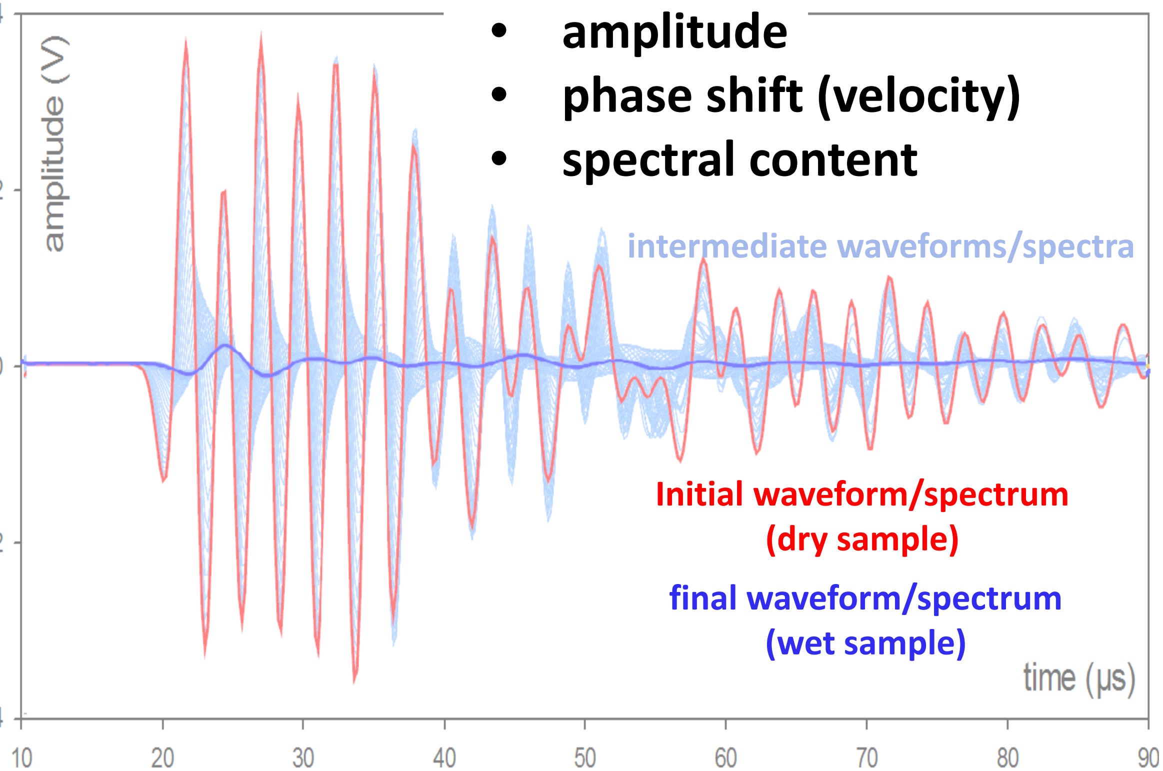
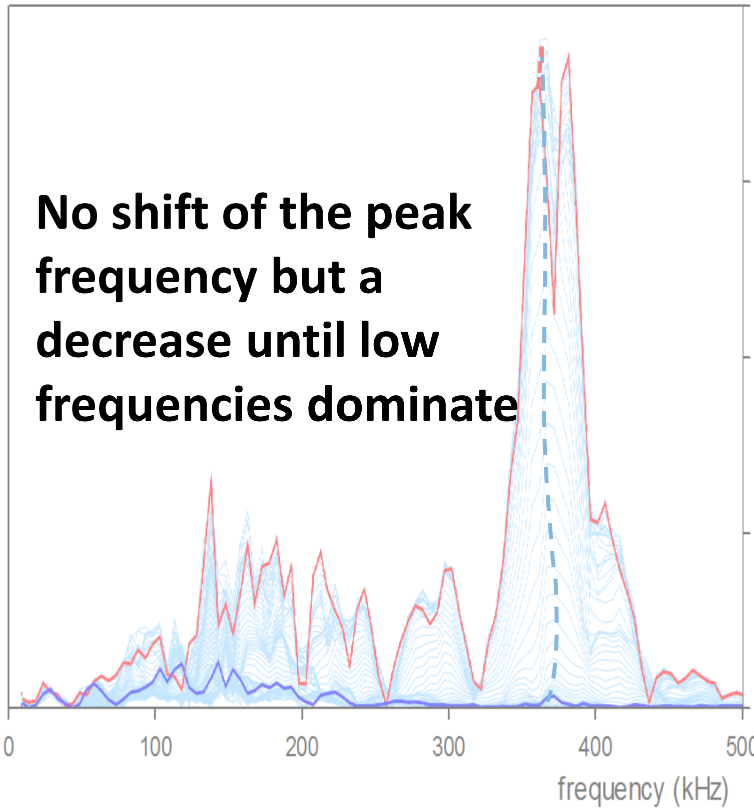
2) Air-water substitution in imbibition experiments

a) Waveform analysis

***Main conclusions from waveform analysis*:**

- **Imbibition has a strong impact on the waveforms**
  - **amplitude**
  - **phase shift (velocity)**
  - **spectral content**





No shift of the peak frequency but a decrease until low frequencies dominate

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2) Air-water substitution in imbibition experiments
a) Waveform analysis

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE

10.1002/2016JB013804

Special Section:
Seismic and micro-seismic signature of fluids in rocks: Bridging the scale gap

This article is a companion to *David et al.* [2017] doi:10.1002/2017JB014193.

Ultrasonic monitoring of spontaneous imbibition experiments: Acoustic signature of fluid migration

Christian David[1], Christophe Barnes[1], Mathilde Desrues[1,2], Lucas Pimienta[3], Joël Sarout[4], and Jérémie Dautriat[4]

[1]Laboratoire Géosciences et Environnement Cergy, Université de Cergy-Pontoise, Cergy-Pontoise, France, [2]EOST, Université de Strasbourg, Strasbourg, France, [3]Laboratoire de Géologie de l'ENS-PSL Research University-UMR8538 du CNRS, Paris, France, [4]CSIRO Energy, Perth, Western Australia, Australia

https://10.1002/2016JB013804

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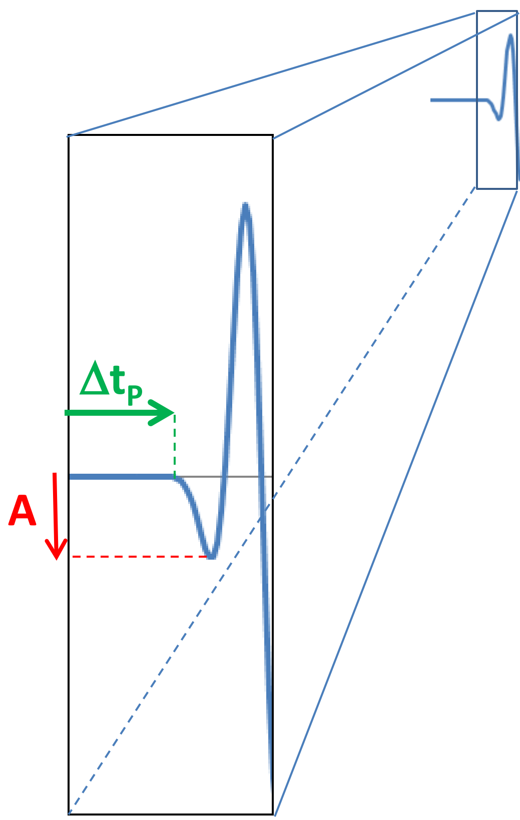
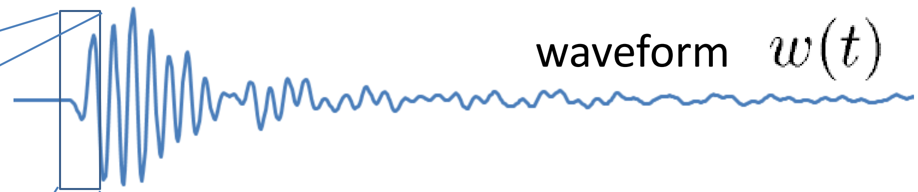
2) Air-water substitution in imbibition experiments

b) Evolution of P-wave attributes (velocity, amplitude)

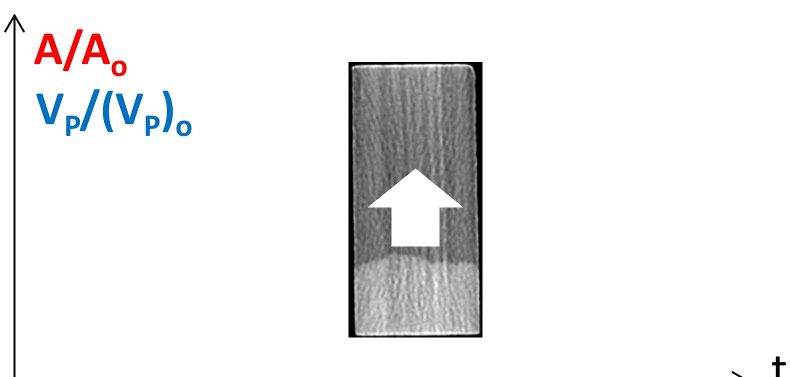




Automatic picking of

1) P-wave first arrival time Δt_P (AIC method)
   → velocity V_P

2) First peak amplitude **A**



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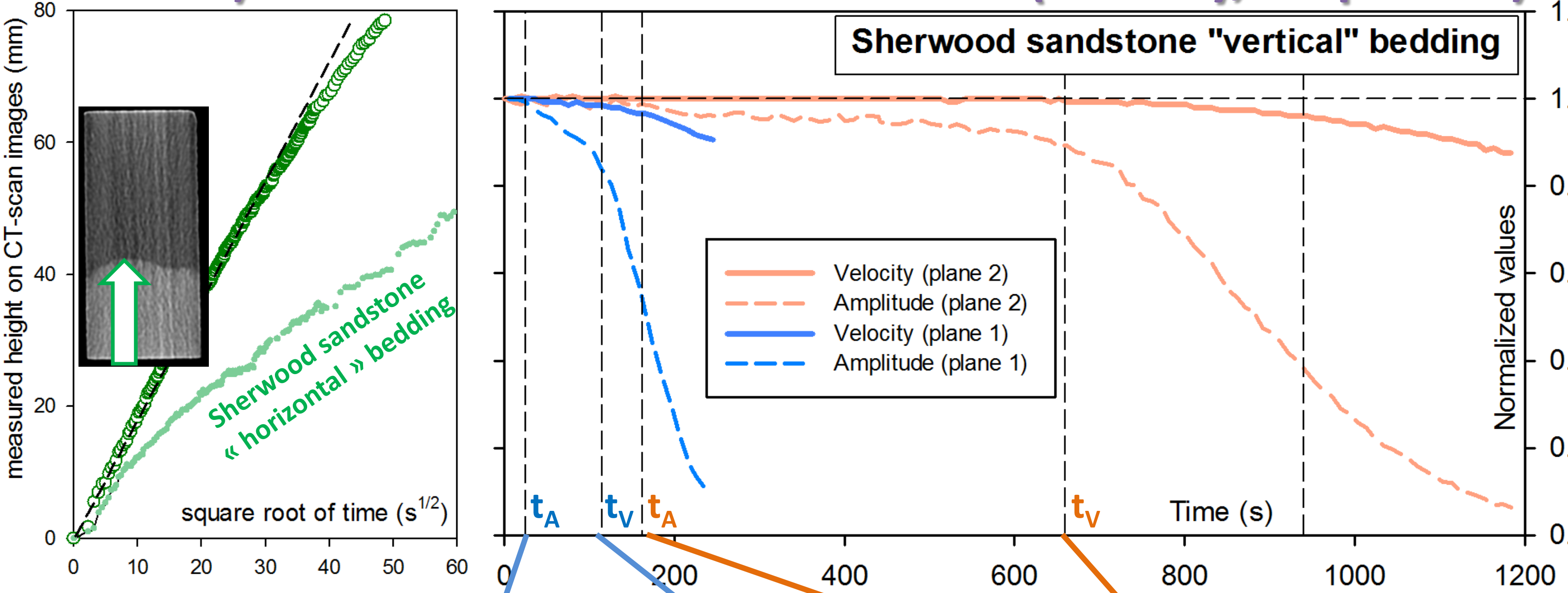
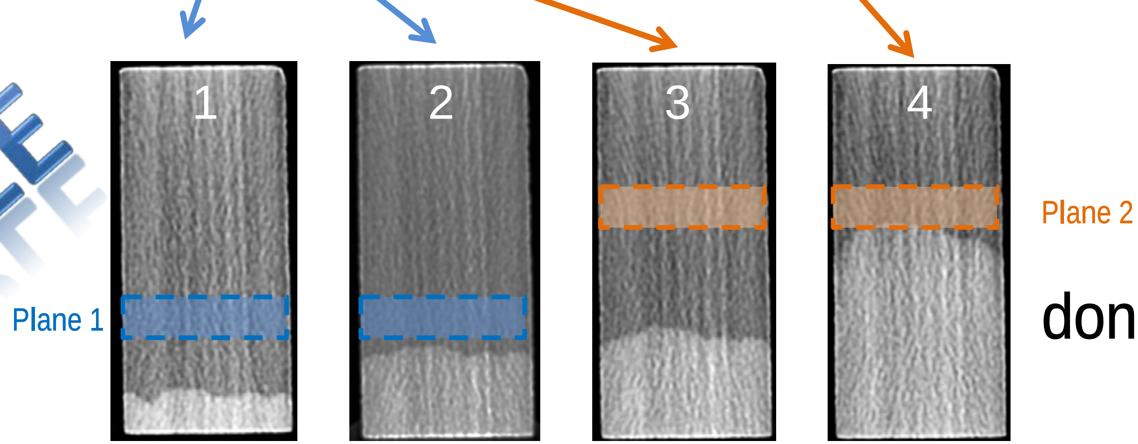
b) Evolution of P-wave attributes (velocity, amplitude)





AMPLITUDE VARIATION DETECTED

VELOCITY VARIATION DETECTED

AMPLITUDE VARIATION DETECTED

VELOCITY VARIATION DETECTED

EXAMPLE

done on 14 rock samples (carbonates + sandstones)

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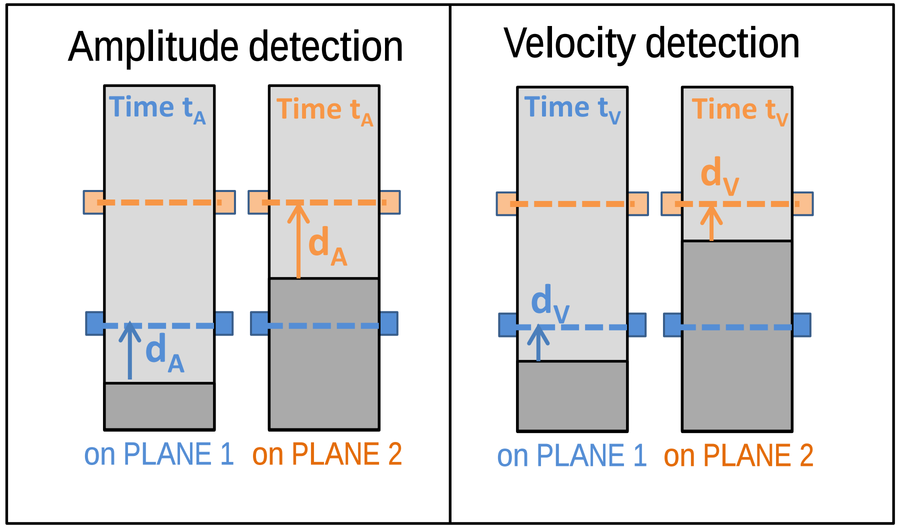

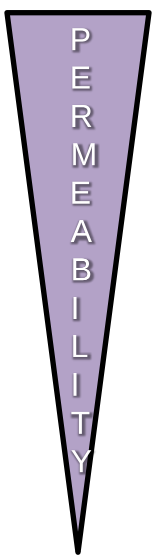

Sample	Amplitude variation (D)ecrease (I)ncrease	Time t_A at amplitude variation (s)	Distance d_A from sensors (mm)	Velocity variation (D)ecrease (I)ncrease	Time t_V at velocity variation (s)	Distance d_V from sensors (mm)
BOI	D / D	14 / 80	-4 / -7	I / I	29 / 96	+6 / -3
BEN	D / D	15 / 96	-7 / -5	I / I	16 / 95	-8 / -5
SMX	D / D	55 / 160	-11 / -6	D / D	75 / 180	-1 / -1
CSG	D / D	60 / 335	-6 / -13	D / D	89 / 499	-2 / -6
MAJ	D / D	65 / 380	-9 / -17	D / D	155 / 675	-3 / -3
SH-ver	D / D	25 / 160	-16 / -26	D / D	115 / 660	-6 / -5
LEO	D / D	178 / 2718	-10 / -17	D / D	614 / 4968	-3 / -6
SH-hor	D / D	225 / 1802	-5 / -15	D / D	345 / 3962	-6 / -6
SID	I,D / I,D	182 / 2051	-11 / -14	I / I	353 / 2582	-7 / -7
BER	D / D	1005 / 7015	-7 / -13	D,I / D,I	1411 / 11494	-3 / -3
CAT	D / D	984 / 4892	-5 / -7	I / I	1066 / 6233	-4 / -2
EDB	D / D	1660 / 13797	-8 / -13	D,I / D,I	2735 / 20822	-4 / -5
SAV	D,I / D	1452 / 9073	-6 / -6	D,I / D,I	2161 / 9812	-2 / -5
TUF	D / D	1085 / 5977	-6 / -8	D / D	1354 / 7589	-4 / -2

14 rock samples (carbonates + sandstones)

(plane 1 / plane 2)

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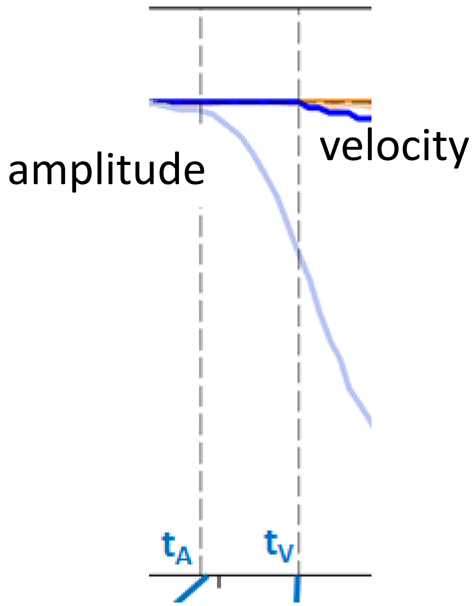
b) Evolution of P-wave attributes (velocity, amplitude)

GENERAL CONCLUSIONS FROM ALL EXPERIMENTS

1. The P-wave amplitude is systematically impacted by the approaching fluid front **before** the velocity is;



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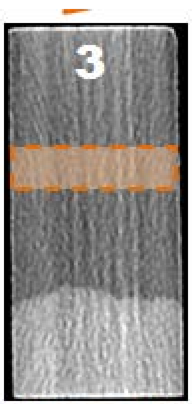
2) Air-water substitution in imbibition experiments

b) Evolution of P-wave attributes (velocity, amplitude)

GENERAL CONCLUSIONS FROM ALL EXPERIMENTS

1. The P-wave amplitude is systematically impacted by the approaching fluid front **before** the velocity is;

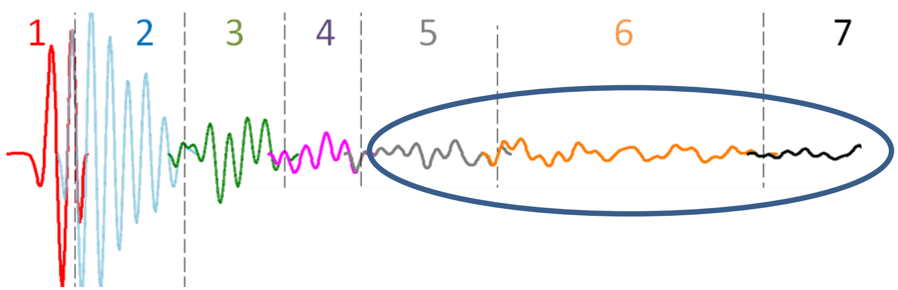
2. When the P-wave amplitude drops, the water front is always located **well below** the corresponding ultrasonic transducers' plane;

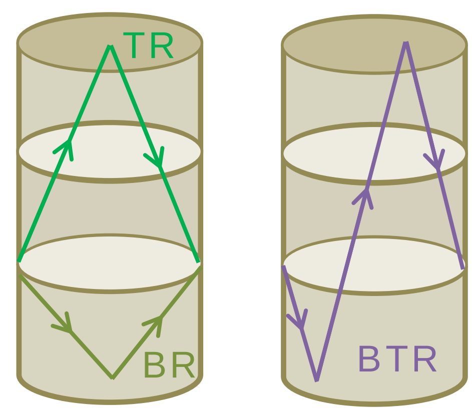


AMPLITUDE VARIATION DETECTED

→ P-wave amplitude variation is a **precursory signal** for fluid substitution

→ also true for the waveform CODA energy variation





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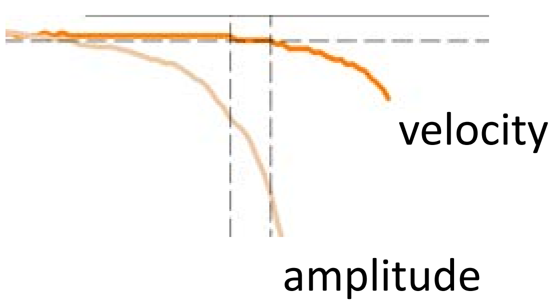
2) Air-water substitution in imbibition experiments
b) Evolution of P-wave attributes (velocity, amplitude)

GENERAL CONCLUSIONS FROM ALL EXPERIMENTS

1. The P-wave amplitude is systematically impacted by the approaching fluid front **before** the velocity is;

2. When the P-wave amplitude drops, the water front is always located **well below** the corresponding ultrasonic transducers' plane;

3. The relative variation of the P-wave amplitude is systematically and significantly **greater** than that of the P-wave velocity.



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2) Air-water substitution in imbibition experiments
b) Evolution of P-wave attributes (velocity, amplitude)

GENERAL CONCLUSIONS FROM ALL EXPERIMENTS

1. The P-wave amplitude is systematically impacted by the approaching fluid front **before** the velocity is;

2. When the P-wave amplitude drops, the water front is always located **well below** the corresponding ultrasonic transducers' plane;

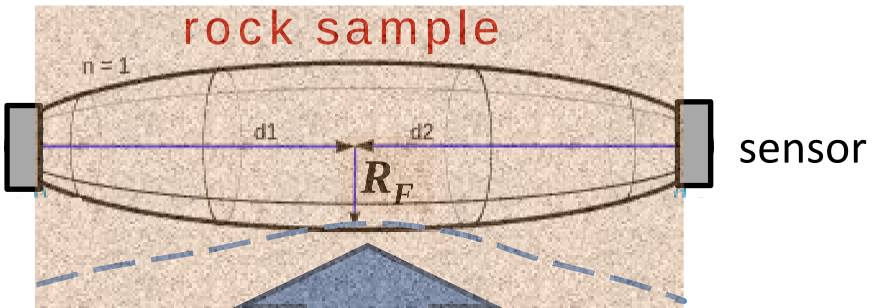
3. The relative variation of the P-wave amplitude is systematically and significantly **greater** than that of the P-wave velocity.

4. The P-wave velocity is impacted when the water front appears to be located **within the Fresnel clearance zone** of the corresponding ultrasonic transducers' plane.

$$R_F = 0.5\sqrt{\lambda D + \frac{\lambda^2}{4}}$$

λ = wavelength

D=d1+d2



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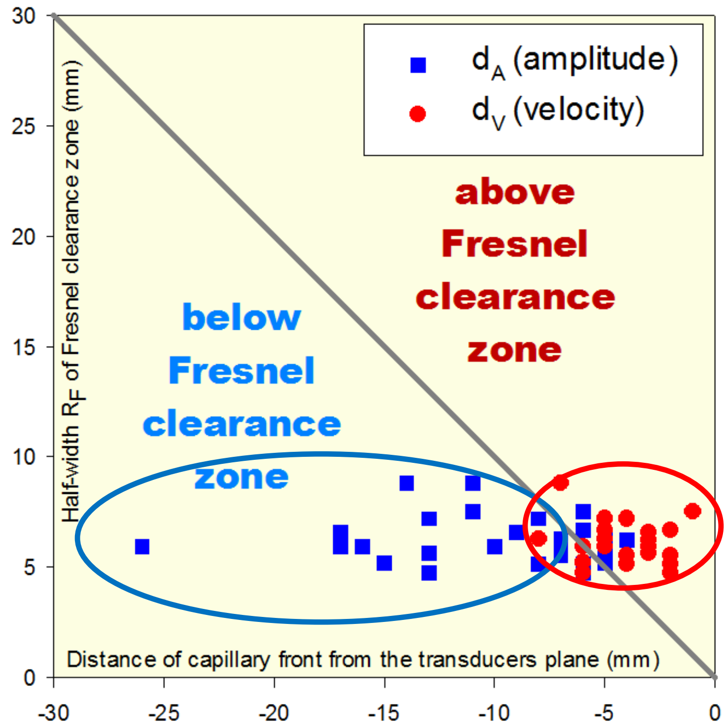
2) Air-water substitution in imbibition experiments

c) Scenarios for explaining the amplitude/velocity variations

Our study highlights **two puzzling observations**:

1. The P-wave amplitude is systematically impacted by the approaching fluid front **before** the velocity is;

2. When the P-wave amplitude drops, the water front is always located **well below** the corresponding ultrasonic transducers' plane;



Amplitude decreases first

WHY?

Velocity decreases later

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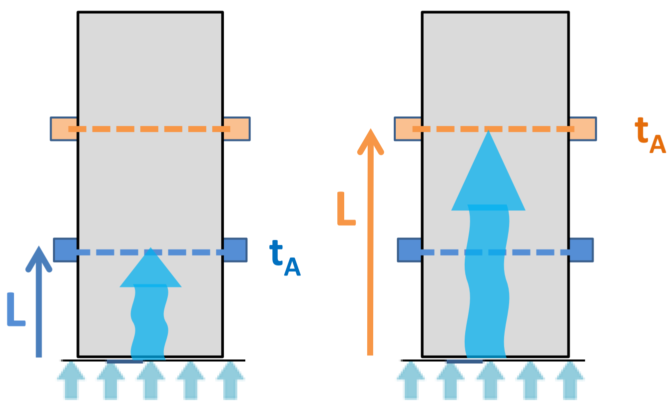
2) Air-water substitution in imbibition experiments

c) Scenarios for explaining the amplitude/velocity variations

SCENARIO #1

the amplitude drop is due to **diffusion of moisture (water vapor)** in the pores from the bottom that weakens the rock (decrease of surface energy), not affecting the P wave velocity, only the amplitude



$$D_{eff}^{(meas)} = \frac{L^2}{t_A}$$

effective diffusion coefficient

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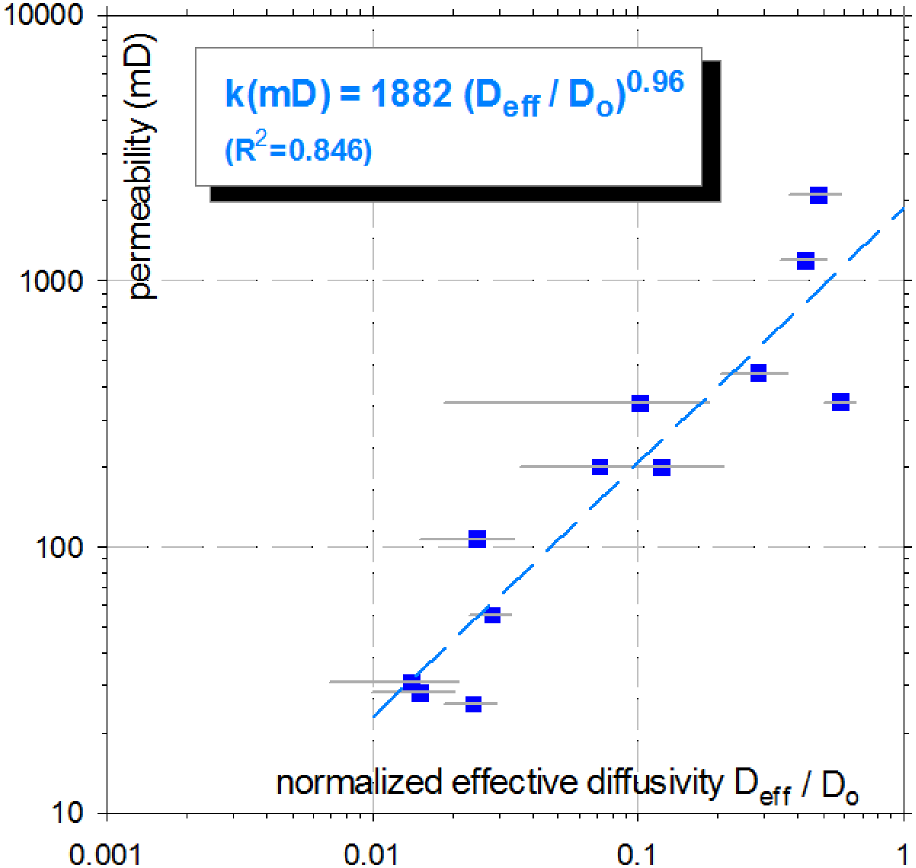
2) Air-water substitution in imbibition experiments

c) Scenarios for explaining the amplitude/velocity variations

SCENARIO #1



With this scenario it is possible to estimate the effective diffusivity of water vapor in the pore space from the time t_A corresponding to the first amplitude drop.
We show here that the effective diffusivity correlates reasonably well with the rock permeability.

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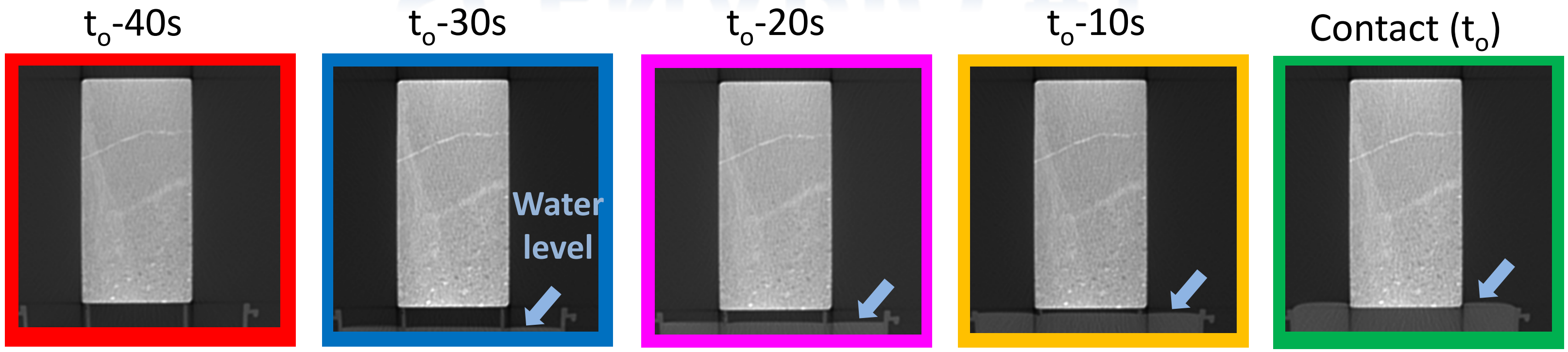
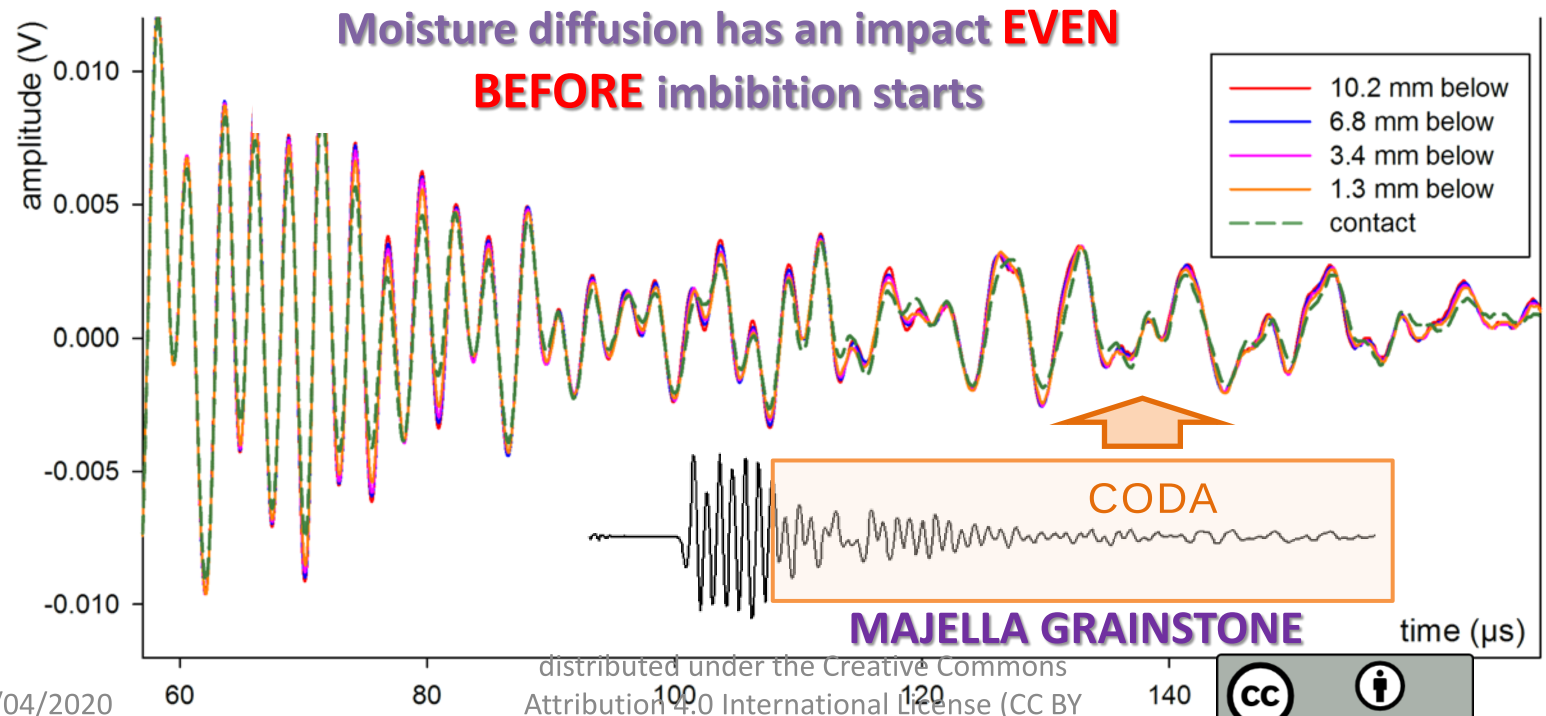
c) Scenarios for explaining the amplitude/velocity variations

SCENARIO #1





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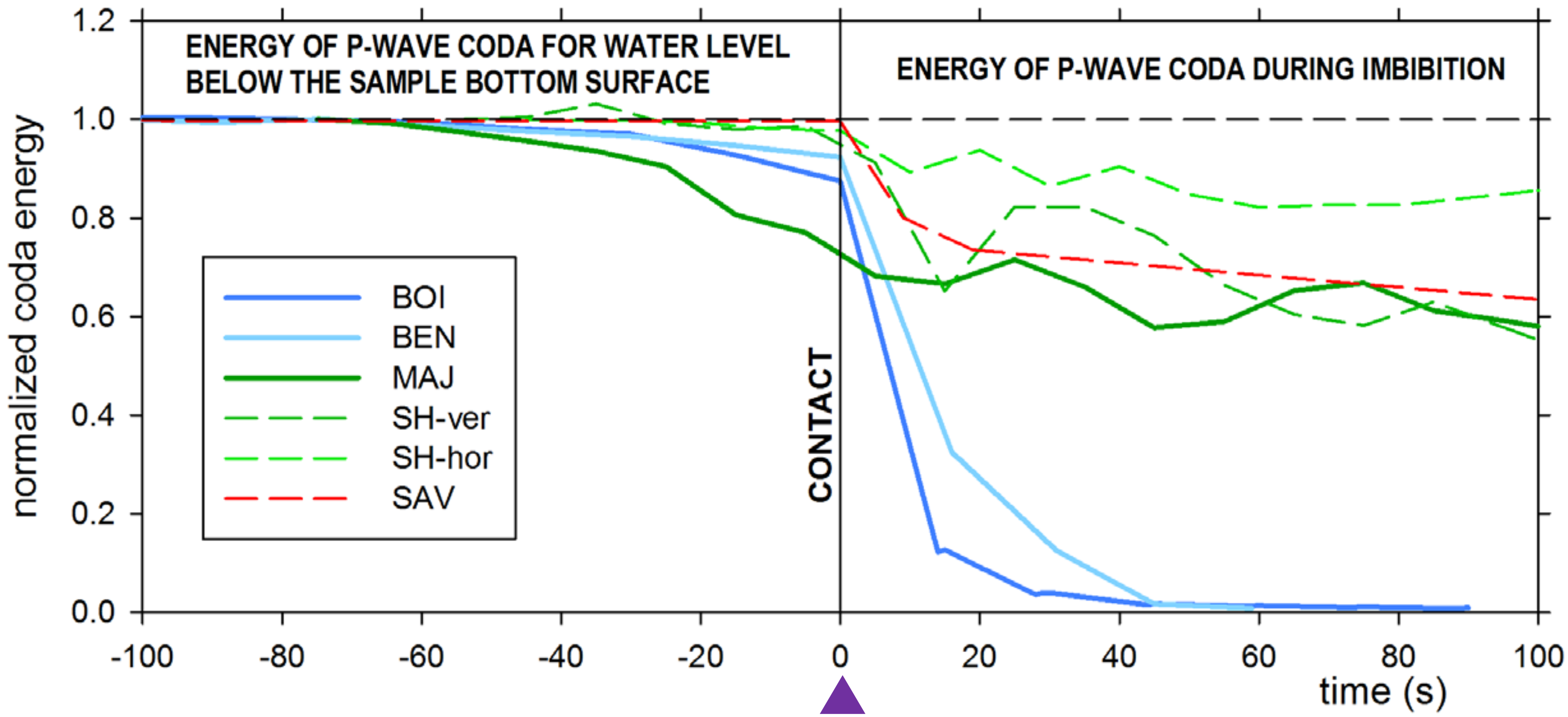
c) Scenarios for explaining the amplitude/velocity variations

SCENARIO #1

Moisture diffusion has an impact **EVEN BEFORE** imbibition

→ confirmed by **coda energy analysis**



CAPILLARY RISE
IN THE ROCK SAMPLE
STARTS HERE

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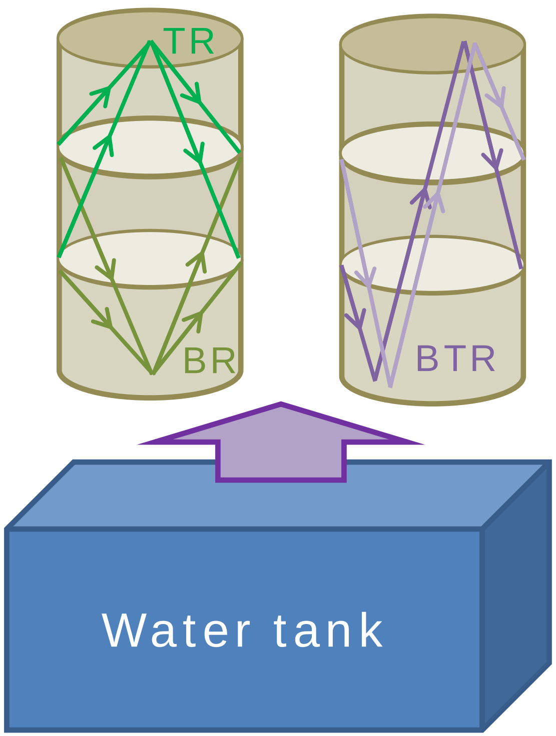
c) Scenarios for explaining the amplitude/velocity variations

SCENARIO #1

Moisture diffusion has an impact EVEN BEFORE imbibition



Water vapor diffusion
1) in the air gap
2) in the sample

impacts bottom P-wave reflections

impacts the Coda before water contact

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SCENARIO #1

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE

10.1002/2017JB014193

Special Section:
Seismic and micro-seismic signature of fluids in rocks: Bridging the scale gap

This article is a companion to *David et al.* [2017] doi:10.1002/2016JB013804.

Ultrasonic monitoring of spontaneous imbibition experiments: Precursory moisture diffusion effects ahead of water front

Christian David[1], Joël Sarout[2], Jérémie Dautriat[2], Lucas Pimienta[3], Marie Michée[2], Mathilde Desrues[1,4], and Christophe Barnes[1]

[1]Laboratoire Géosciences et Environnement Cergy, Université de Cergy-Pontoise, Cergy-Pontoise, France, [2]CSIRO Energy, Perth, Western Australia, Australia, [3]Laboratoire de Géologie de l'ENS, PSL Research University UMR 8538 du CNRS, Paris, France, [4]EOST, Université de Strasbourg, Strasbourg, France

https://10.1002/2017JB014193

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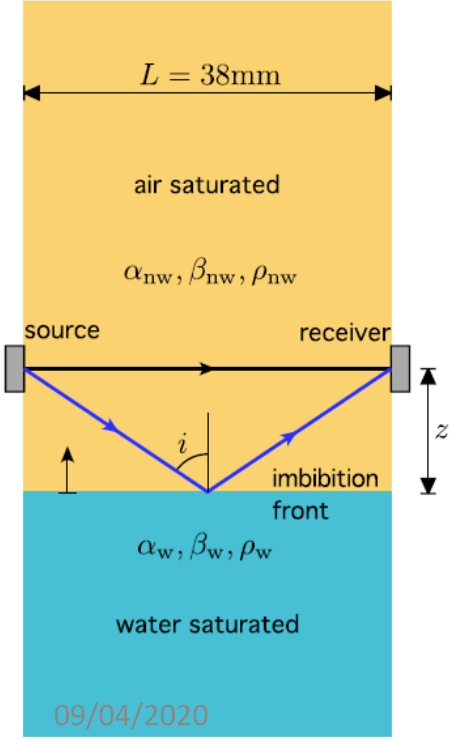
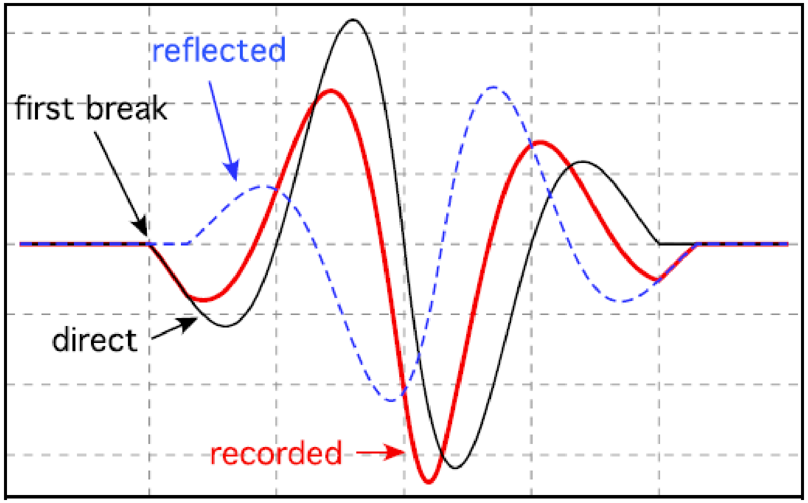
2) Air-water substitution in imbibition experiments

c) Scenarios for explaining the amplitude/velocity variations

SCENARIO #2

the amplitude drop is due to **composition of direct and reflected P waves** , which does not affect the P wave velocity





From Y. Kovalyshen, JGR 2018, comment on our JGR paper promoting scenario #1

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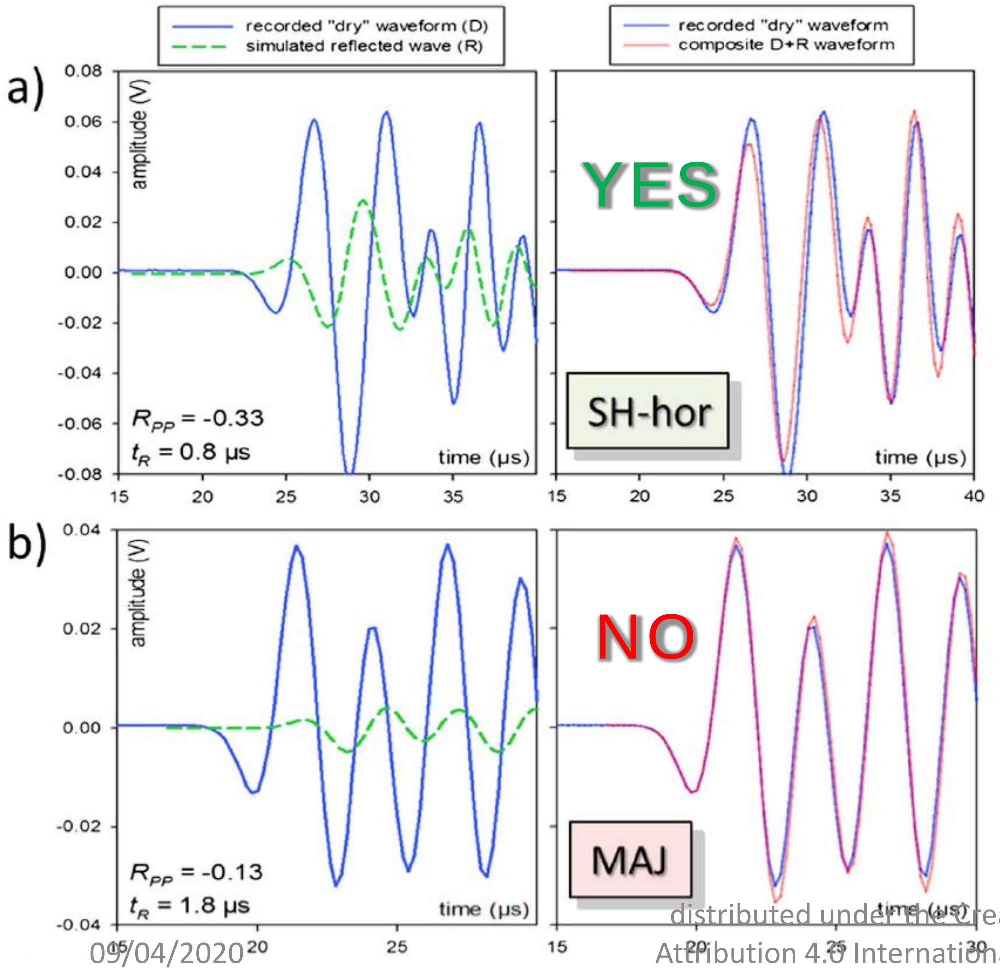
c) Scenarios for explaining the amplitude/velocity variations

SCENARIO #2



Simulation of composite waveforms knowing:

- The time delay t_R for reflected P wave arrival
- the estimation of the reflection coefficient R_{PP} (Knott-Zoeppritz equation)

It works in few cases

But in general it doesn't work

- Large time delays
- Small values for the reflection coefficients R_{PP}

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SCENARIO #2

AGU100 ADVANCING EARTH AND SPACE SCIENCE
JGR
Journal of Geophysical Research: Solid Earth

COMMENT
10.1029/2018JB016040

This article is a comment on David et al. (2017) https://doi.org/10.1002/2017JB014193.

Key Point:
- *P* wave reflection from imbibition front can explain amplitude change of recorded *P* waves

Comment on "Ultrasonic Monitoring of Spontaneous Imbibition Experiments: Precursory Moisture Diffusion Effects Ahead of Water Front" by David et al. (2017)

Yevhen Kovalyshen[1]

[1]Energy, CSIRO, Perth, Western Australia, Australia

https://10.1029/2018JB016040

AGU100 ADVANCING EARTH AND SPACE SCIENCE
JGR
Journal of Geophysical Research: Solid Earth

REPLY
10.1029/2018JB016133

Special Section:
Seismic and Micro-Seismic Signature of Fluids in Rocks: Bridging the Scale Gap

Reply to Comment by Y. Kovalyshen on "Ultrasonic Monitoring of Spontaneous Imbibition Experiments: Precursory Moisture Diffusion Effects Ahead of Water Front"

Christian David[1], **Christophe Barnes**[1], **Joël Sarout**[2], **Jérémie Dautriat**[2], **and Lucas Pimienta**[3]

[1]Laboratoire Géosciences et Environnement Cergy, Université de Cergy-Pontoise, Cergy-Pontoise, France, [2]CSIRO Energy, Perth, Australia, [3]Laboratory of Experimental Rock Mechanics (LEMR), ENAC, EPFL, Lausanne, Switzerland

https://10.1029/2018JB016133

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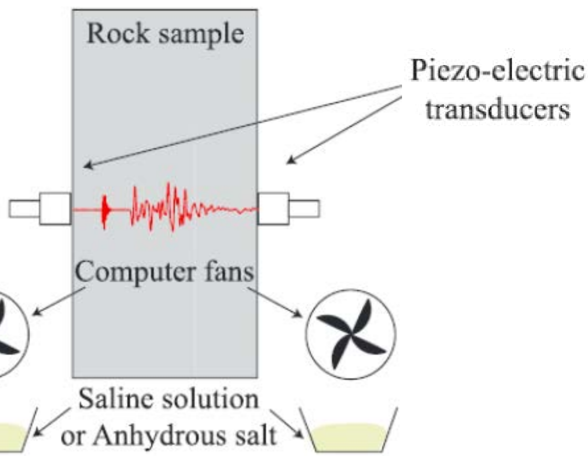
c) Scenarios for explaining the amplitude/velocity variations

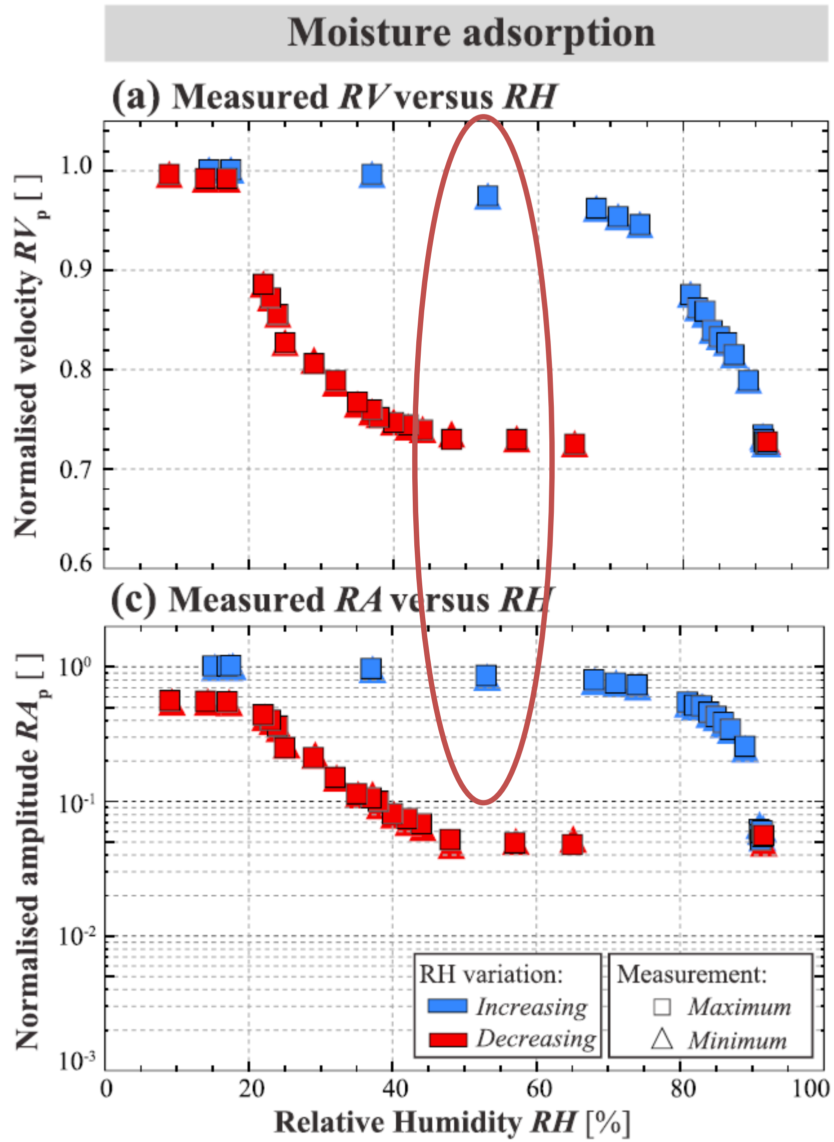
SCENARIO #3

When measuring P-wave attributes vs. relative humidity, it was shown that moisture adsoption leads to a decrease of **BOTH the amplitude AND the velocity**

→ *Disagrees with our results*



(e.g. Pimienta et al, GJI 2014)



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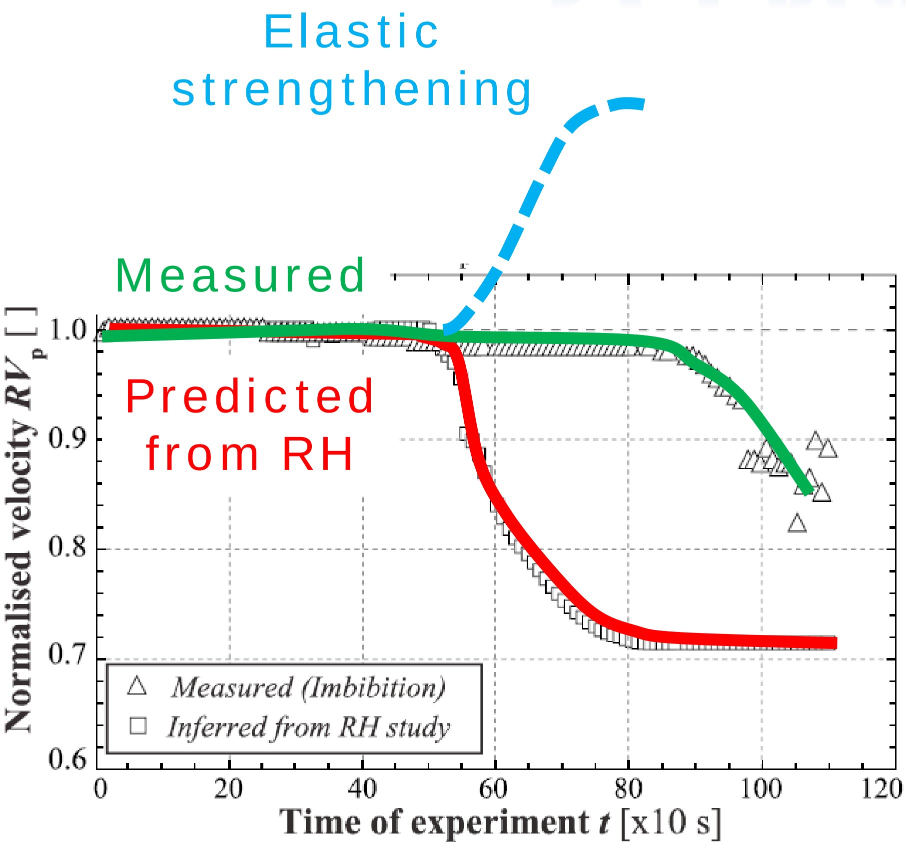
2) Air-water substitution in imbibition experiments

c) Scenarios for explaining the amplitude/velocity variations

SCENARIO #3



The measured delayed velocity drop is interpreted as the **combination of two opposite effects**:

(i) Softening from moisture adsorption

(i) Elastic strengthening affecting only ultrasonic velocities

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SCENARIO #3

Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL082419

Evolution in Seismic Properties During Low and Intermediate Water Saturation: Competing Mechanisms During Water Imbibition?

L. Pimienta[1], C. David[2], J. Sarout[3], X. Perrot[4], J. Dautriat[3], and C. Barnes[2]

[1]Laboratory of Experimental Rock Mechanics, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, [2]Laboratoire Géosciences et Environnement Cergy, Université de Cergy-Pontoise, Cergy-Pontoise, France, [3]CSIRO Energy, Perth, Western Australia, Australia, [4]Lab. de Météorologie Dynamique, Ecole Normale Supérieure, PSL University, Paris, France

Key Points:

- Comparative study of seismic monitoring of rock in low (moisture) and intermediate (imbibition) saturation range
- Strong amplitude loss, very similar to moisture adsorption, but little and uncoupled velocity variations during spontaneous water imbibition
- Evidence for two competing effects of adsorption-induced softening and frequency-dependent stiffening during water imbibition

https://10.1029/2019GL082419

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CONCLUSIONS

- At the sample scale, ultrasonic monitoring is able to detect fluid substitution processes and its consequences
    - under pressure in fluid injection tests
    - in spontaneous imbibition experiments

- P-wave velocity variation → fluid substitution is located within the **Fresnel clearance zone** near the sensors

- Amplitude drop and waveform coda energy decrease are both **precursory signals** of remote fluid substitution.

- If due to moisture diffusion, it provides a way to **predict rock permeability** from P wave amplitude variation

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