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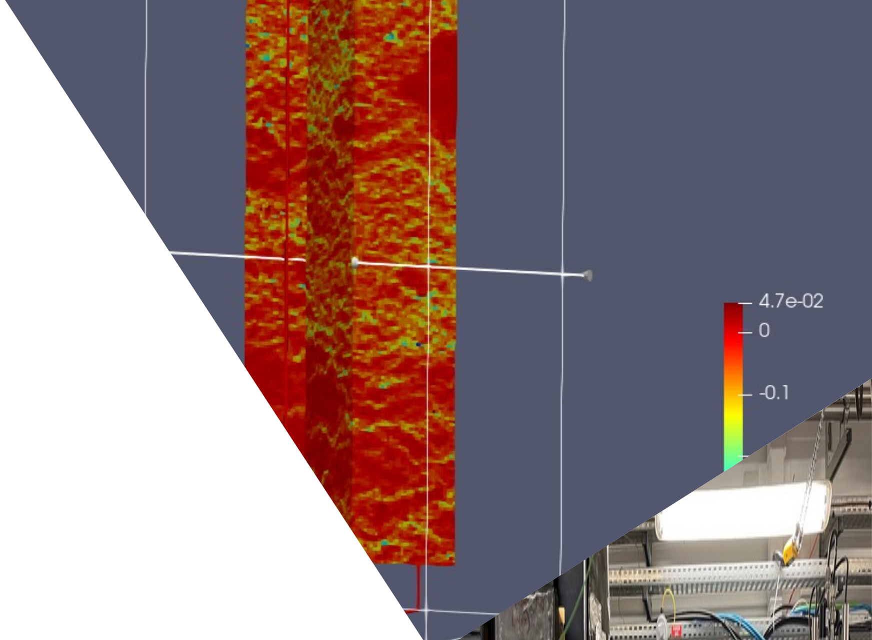

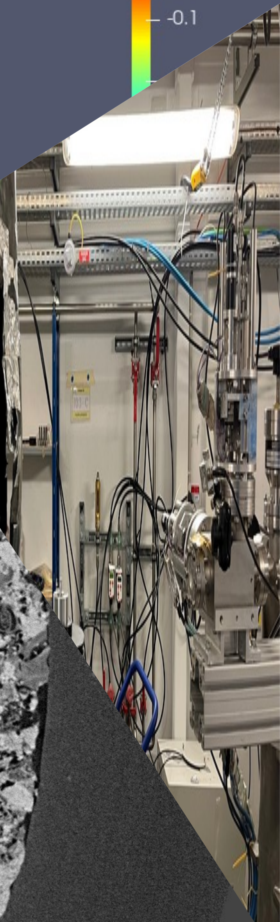

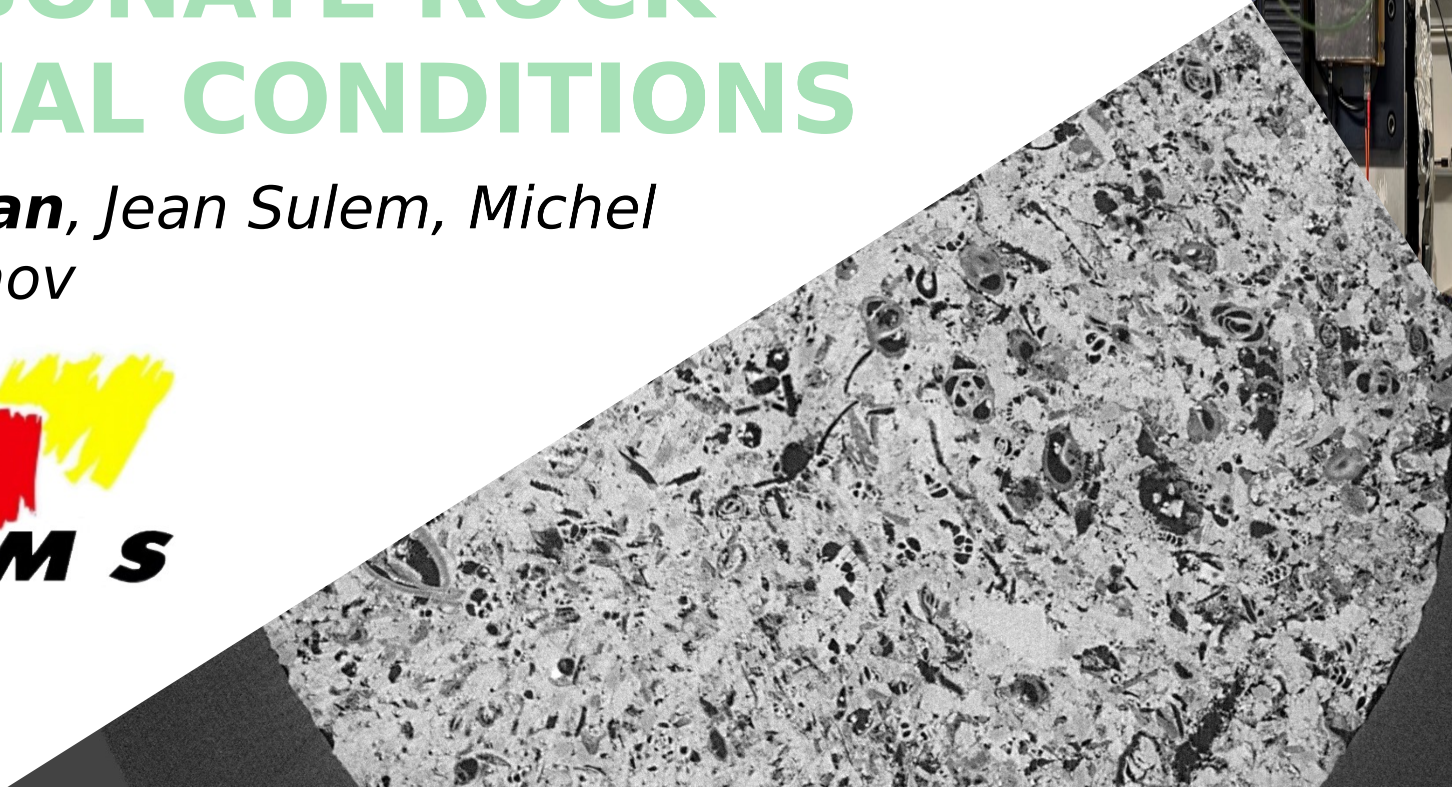

MULTI-SCALE ANALYSIS OF A POROUS CARBONATE ROCK UNDER TRIAXIAL CONDITIONS

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INSTITUT POLYTECHNIQUE DE PARIS

LMS

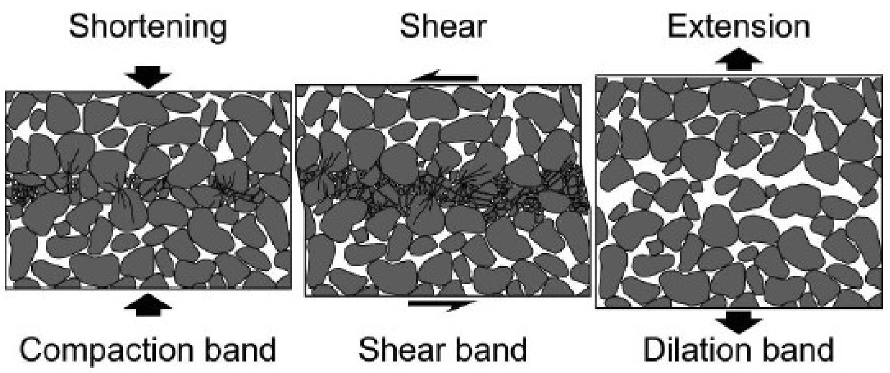
Université Gustave Eiffel

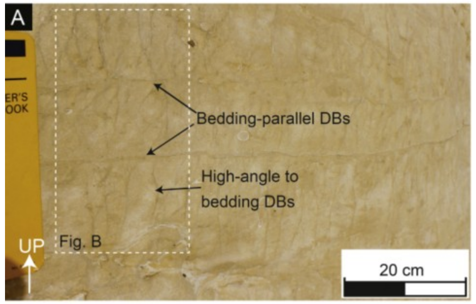
Introduction

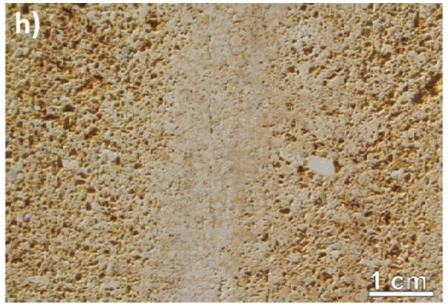
Sequestration of CO_2, energy storage (H_2), or geothermal energy in deep aquifers or depleted reservoirs : porous and permeable rocks

* *Sedimentary rocks: sandstones or limestones*

Deformation bands in porous rocks







- *Heterogeneous and/or localised deformation in triaxial conditions for carbonate rocks with porosities >20-25%;*
- *Deformation bands can reduce permeability up to several orders of magnitude ;*
- *Presence of fluids can reduce the resistance*

Post-localisation behavior? Geometry, number + spacing of deformation bands, relation to the microstructure at different scales?

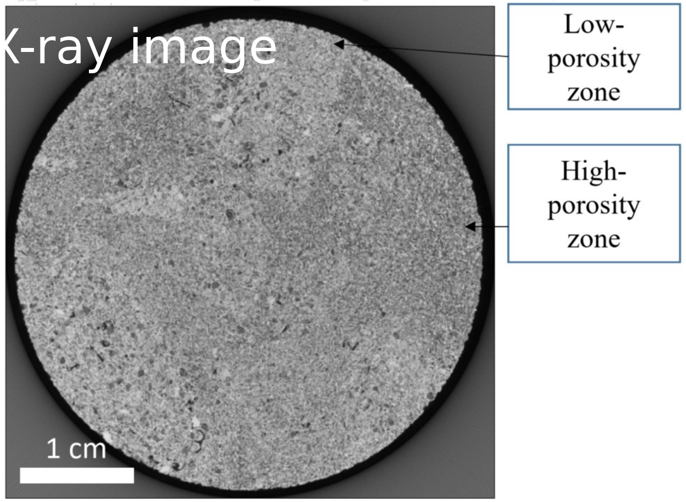
** *Experimental investigation***

Saint-Maximin Limestone

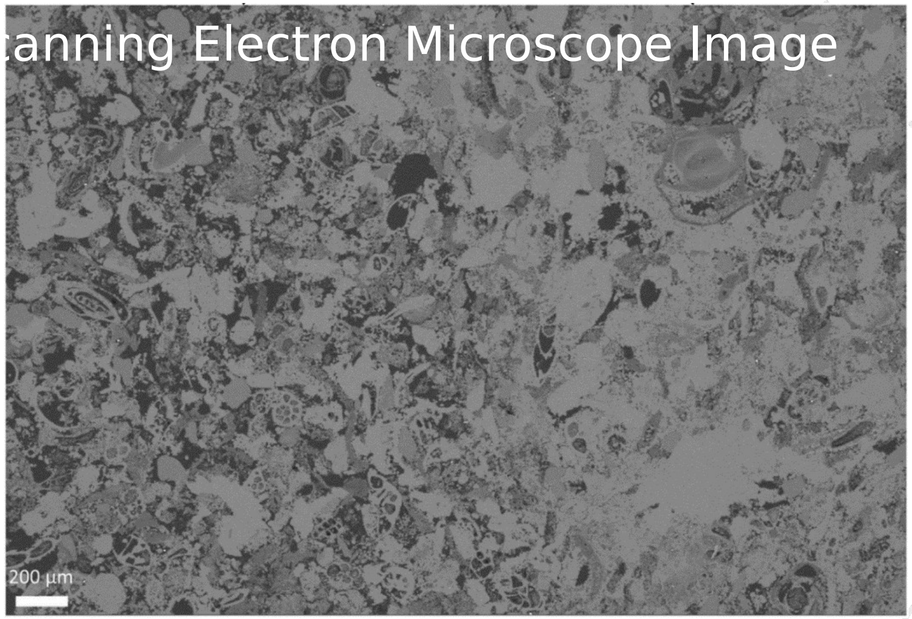
Saint-Maximin Limestone (SML) was extracted from Rocamat quarry, in Saint-Maximin-sur-Oise

- *Grainstone ;*
- *80% calcite and 20% quartz ;*
- *38% of connected porosity*
- *Isotropic*

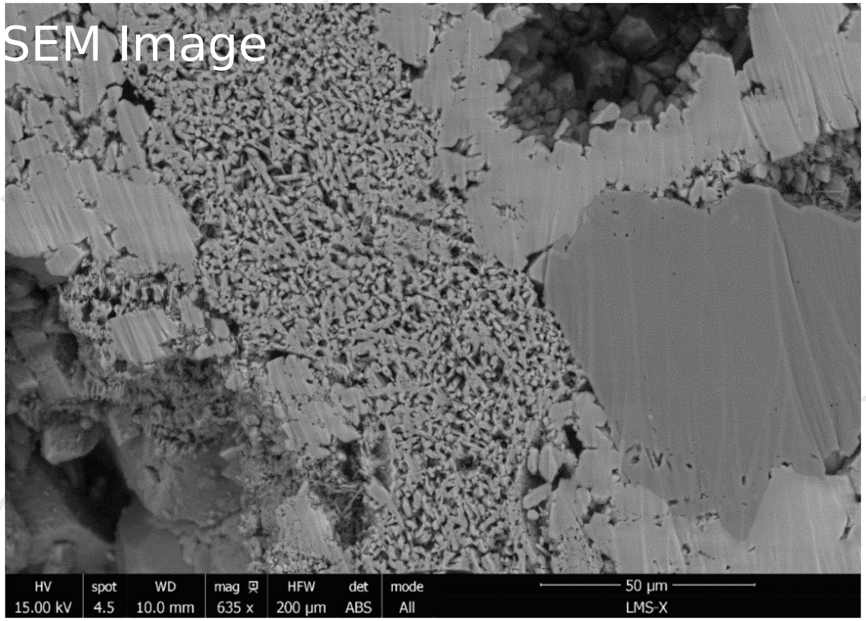
X-ray image



canning Electron Microscope Image



SEM Image



Previous results

[1] Abdallah, Y. (2019). *Compaction banding in high-porosity carbonate rocks: Experimental observations and modelling* (PhD dissertation).Marne-la-Vallée, France: Université Paris-Est.

[2] Y. Abdallah, J. Sulem, M. Bornert, S. Ghabezloo, and I. Stefanou Compaction Banding in High-Porosity
Carbonate Rocks: 1. Experimental Observations, *Journal of Geophysical Research: Solid Earth*

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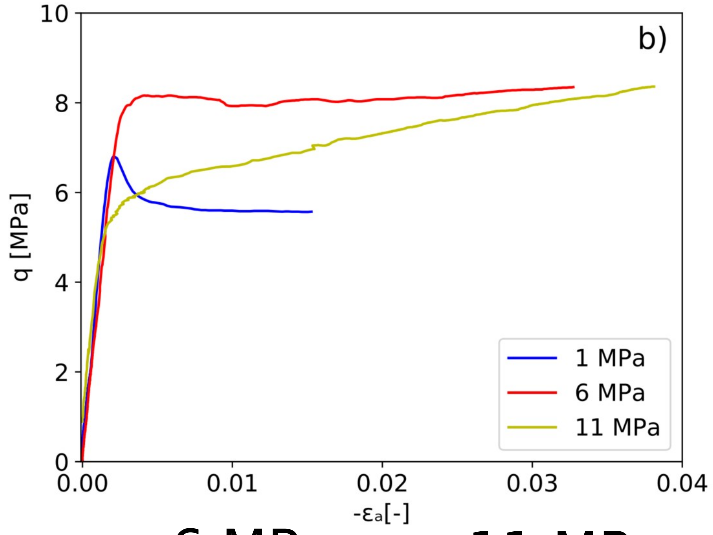
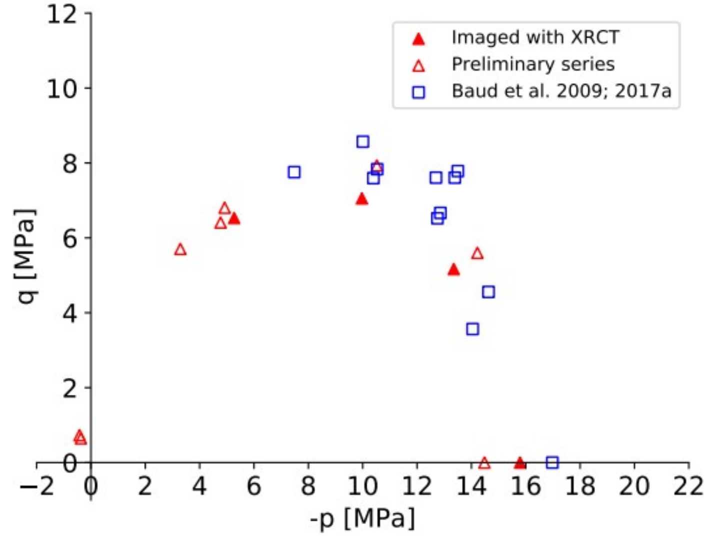
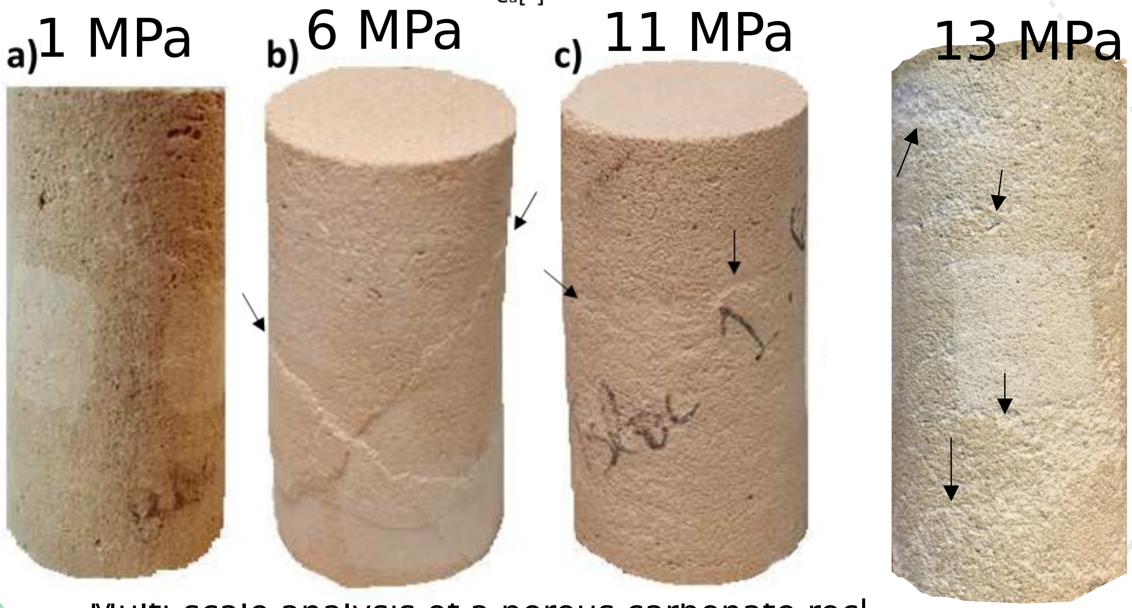
Strain Localisation in SML [1,2]







- *Deformation bands visible at all confining pressures*
- *Micromechanisms only visible post mortem on thin blades (SEM imaging)*

 How to access bands 3D geometry ?

Experimental Method - *Ex situ/post mortem* Testing

Y. Abdallah, 2019

XRCT image of reference state Voxel size = 24 µm

Triaxial test conducted at a confinement on 40x80 mm samples

Unloading after beginning of yielding

XRCT image at Stage 1

Loading at confinement + ‘‘continuation’’ of deviatoric loading

Unloading

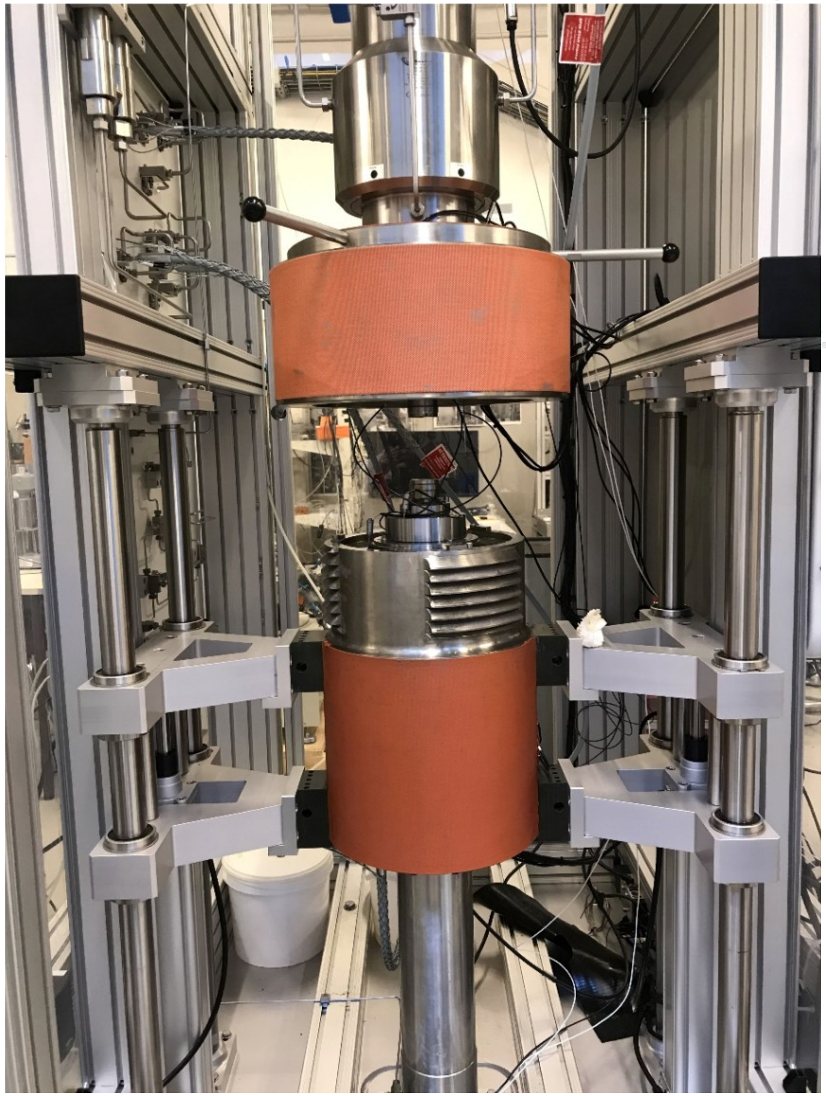
XRCT of sample at Stage 2

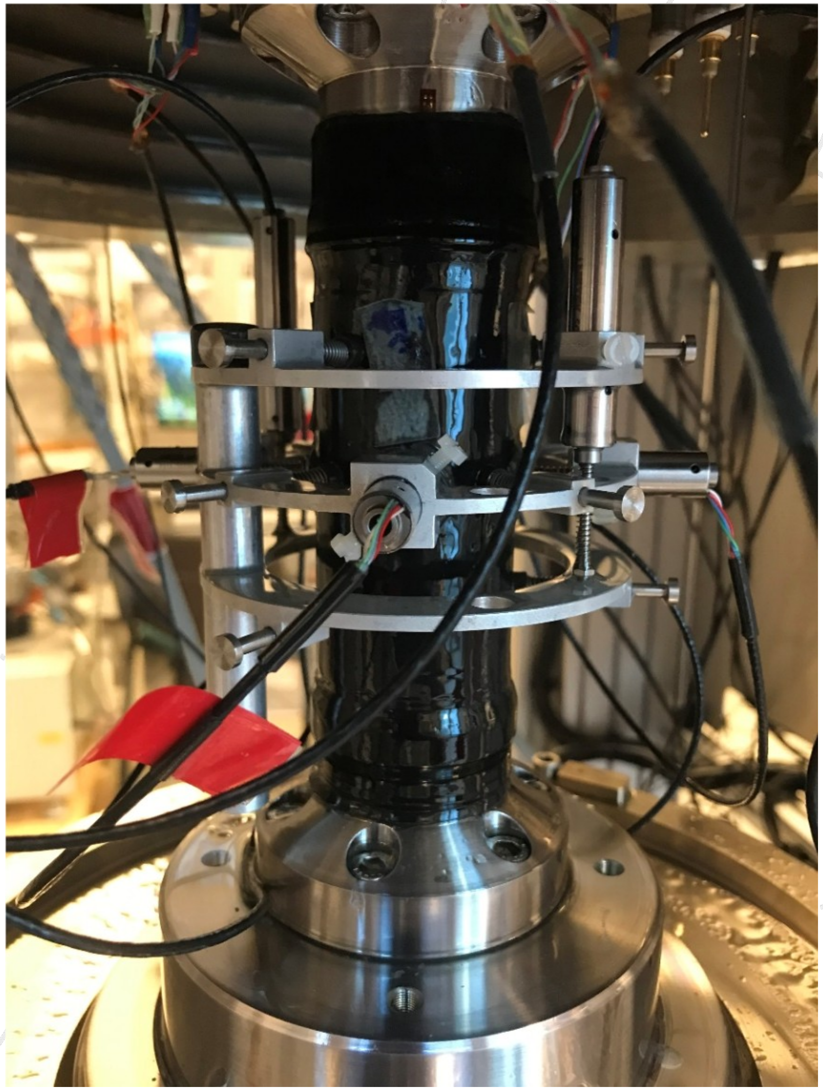
Strain Maps

Porosity maps

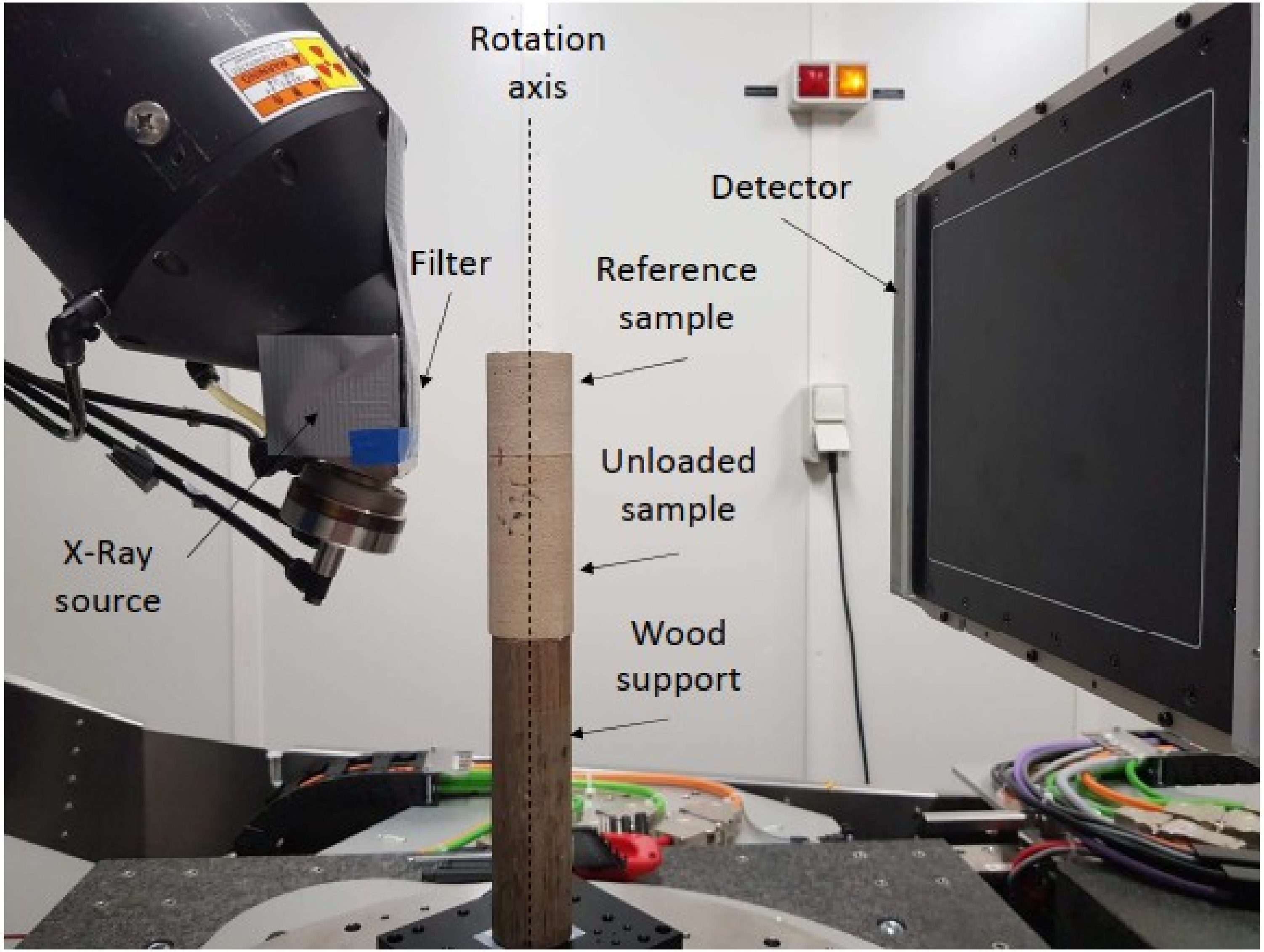
1 step = 1.5 day
1 scan = 24 hours
+ frequent leaking

Triaxial press for 40 mm in diameter samples





Experimental Setup



Local Porosity Map Calculation

→ ***Explore relationship between bands and microstructure by calculating local porosity from X-ray images***

<u>On the whole sample:</u> Mean Grey Level () is known with corresponding porosity , GL of a pore is manually evaluated from a large pore in XRCT image GL of solid phase is calculated (calcite and quartz attenuation coefficients are similar).

$$¿GL>¿<\phi>\cdot g_{pore}+¿$$

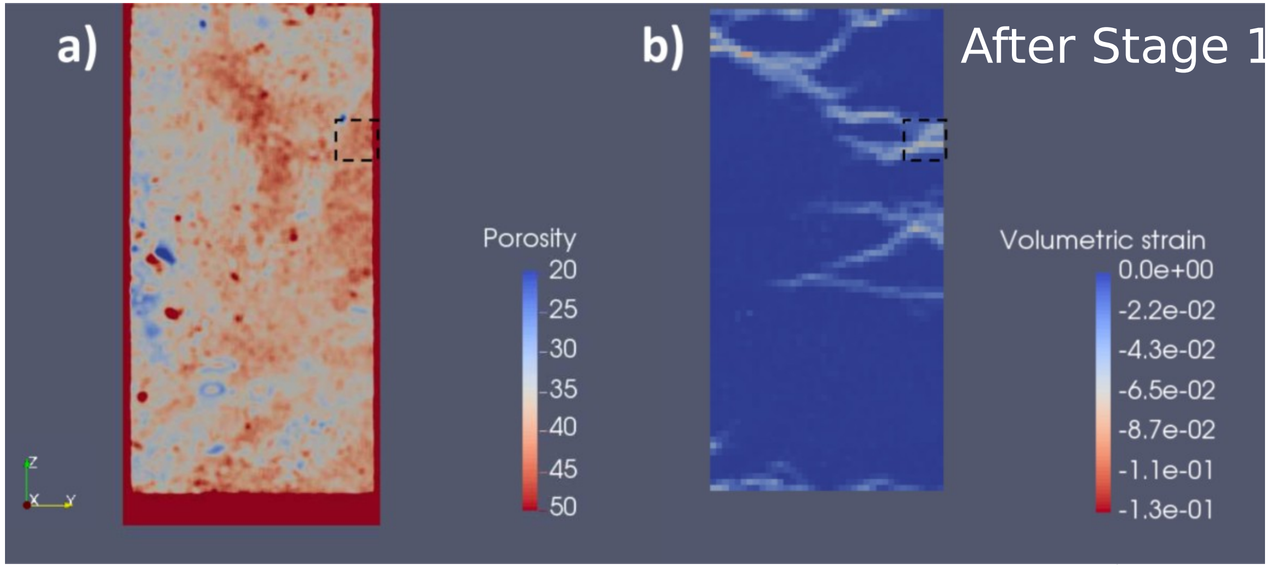
<u>Locally</u>: The unknown is the local porosity deduced from local mean GL

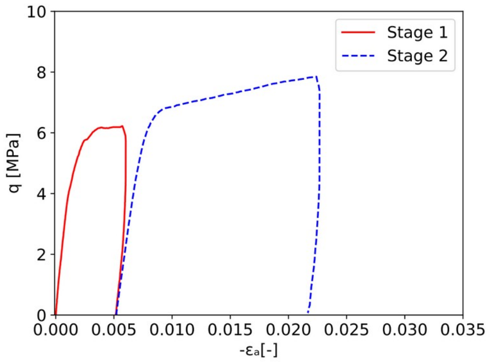
→ ***Explore relationship between bands and microstructure by calculating local porosity from X-ray images***

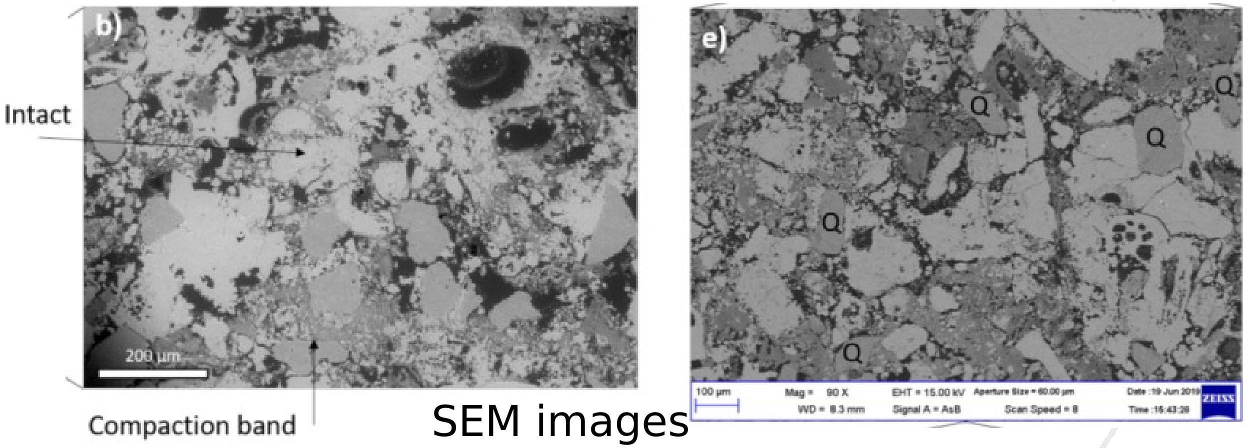
<u>On the whole sample:</u> Mean Grey Level ($< GL >$) is known with corresponding porosity $< \phi >$, GL of a pore g_{pore} is manually evaluated from a large pore in XRCT image → GL of solid phase $g_{solid\ phase}$ is calculated (calcite and quartz attenuation coefficients are similar).

<u>Locally</u>: The unknown is the local porosity ϕ_{local} → deduced from local mean GL

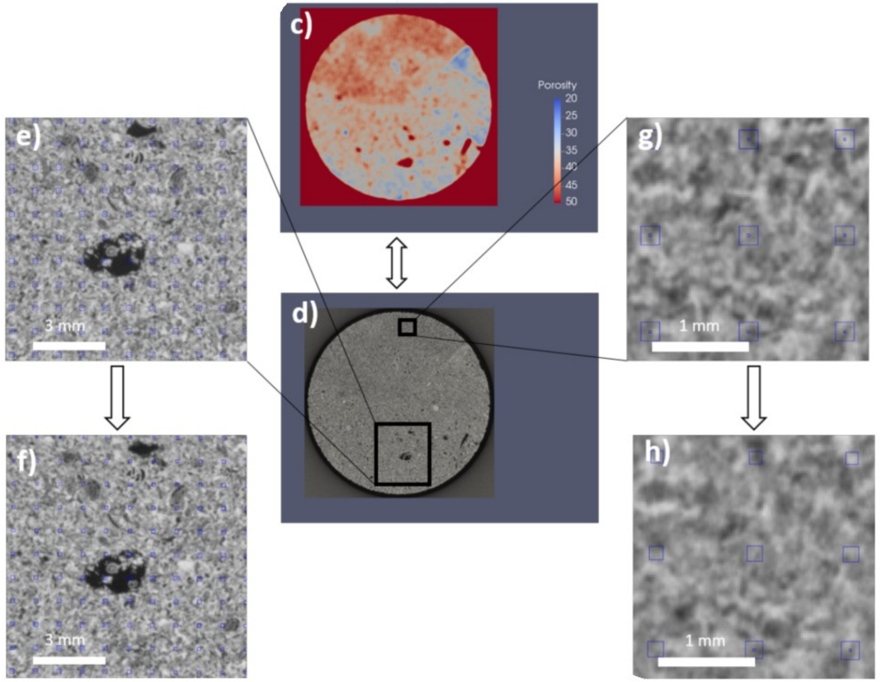
Results for Sample Tested Under High Confinement (11 MPa)





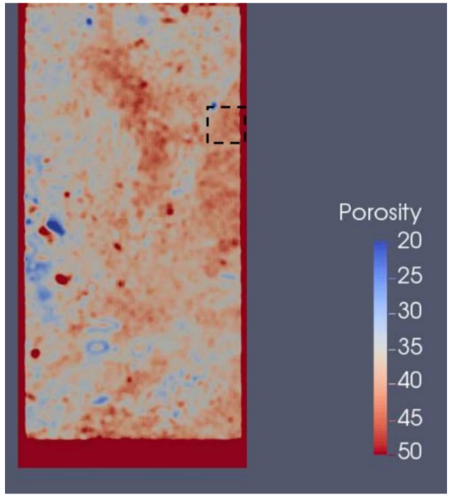


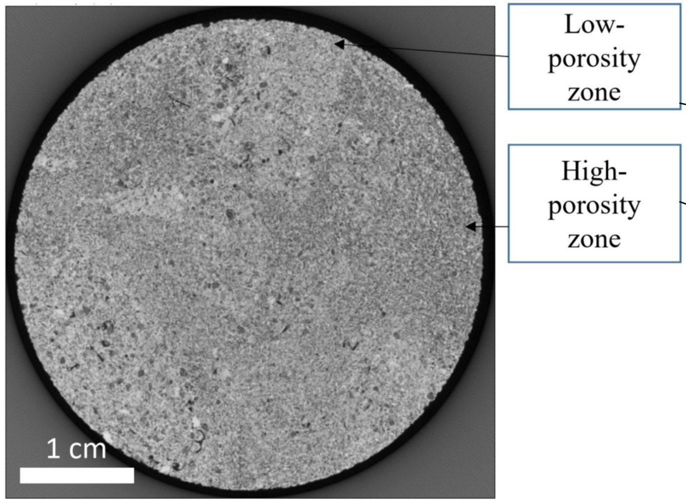
SEM images



XRCT images with a 24 µm resolution

How Would Strain Be Accommodated In Single Dense/Porous Zones?

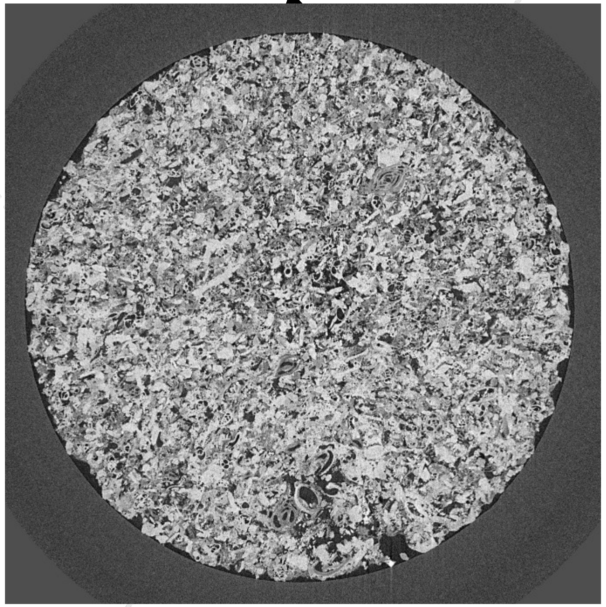




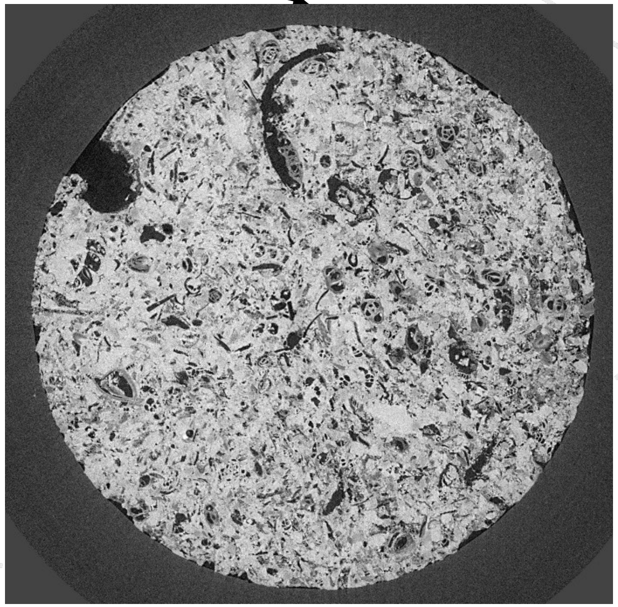
 Standard size sample (40 mm in diameter and 80 mm in height) and porosity map with a 40 voxels window

*8mm in diameter samples cored in dense *
and porous zones

Before tests, cored samples are imaged to visualize their microstructure and evaluate the porosity field



Porous microstructure

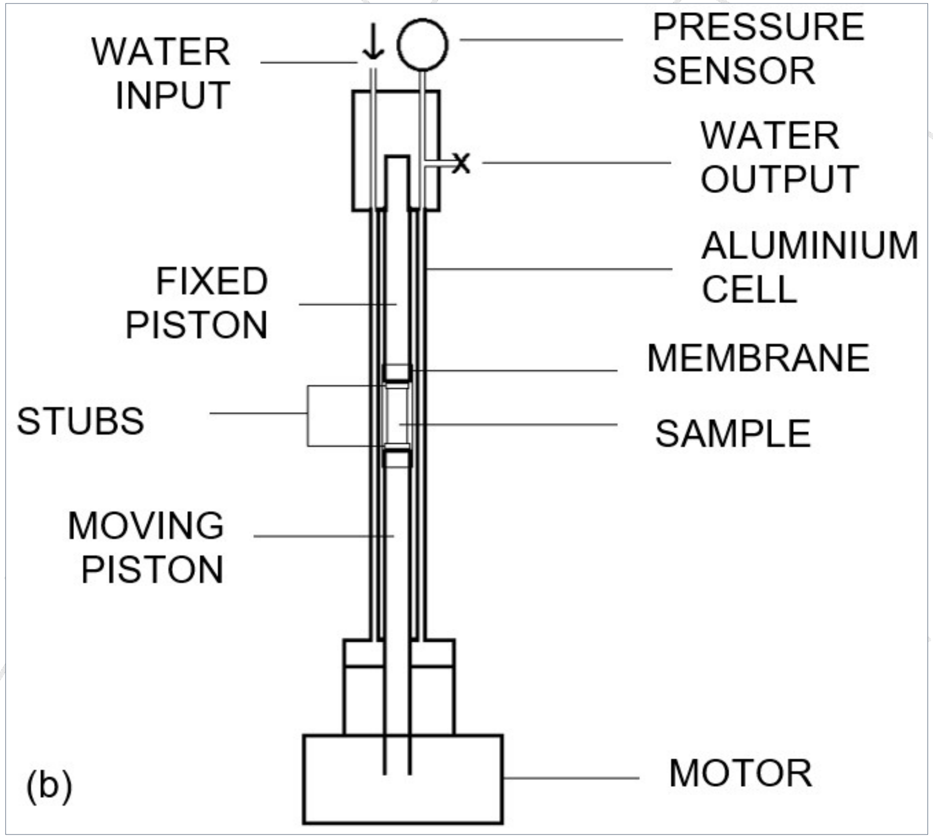


Dense microstructure

Experimental Method

New testing device

A new testing device for micro tests on samples with diameter smaller than 15 mm, developed at LMS for in situ (4D-imaging) tests.

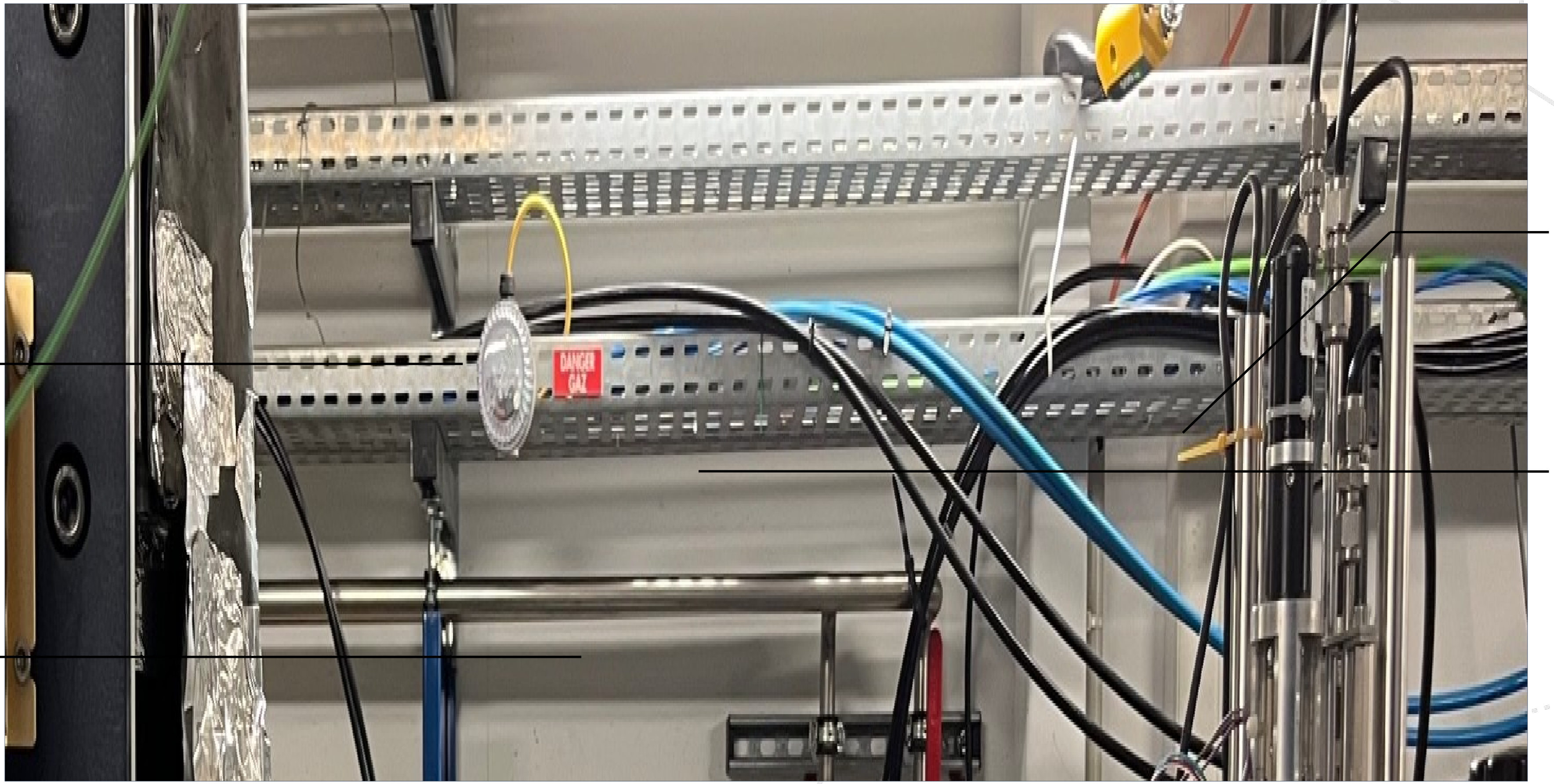


Projet CNRS PEPS 2018, Aquifair

Experimental Setup

Detector

Rotatin
g stage

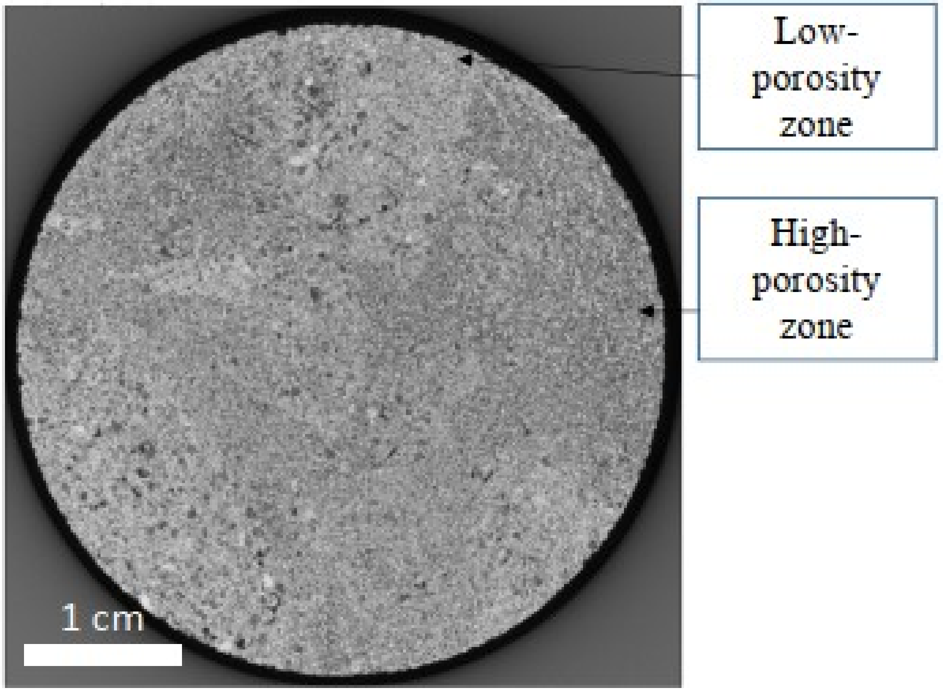


X-ray
beam

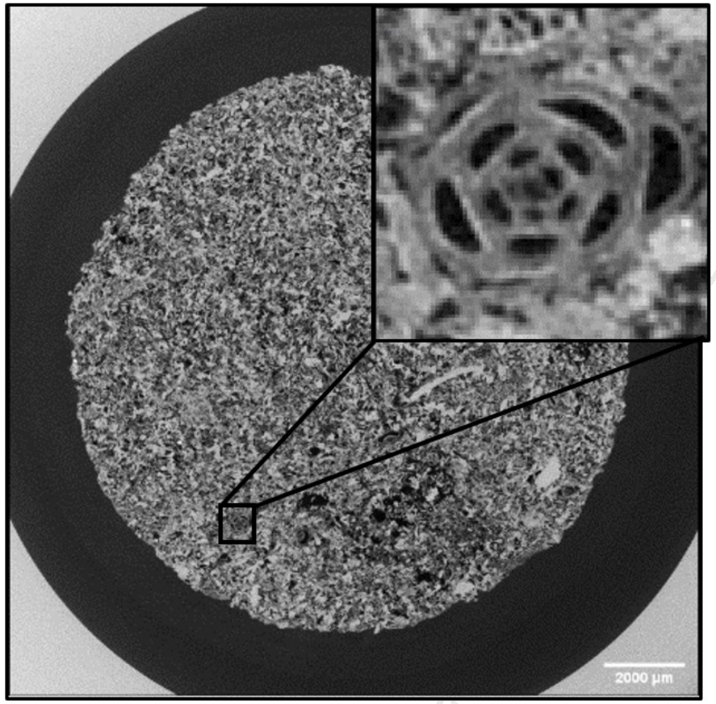
Triaxial
rig
for 8 mm
samples

Beamline Psiché @ Synchrotron Soleil, A. King, proposal 20220588, September 2022

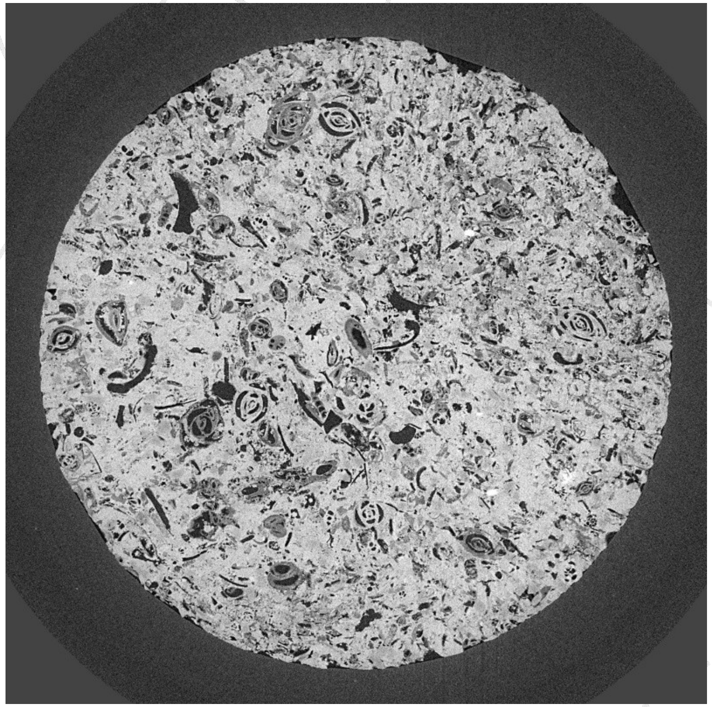
Synchrotron Imaging Advantages



40 mm sample with 24 µm voxel size



15 mm sample with 8.5 µm voxel size

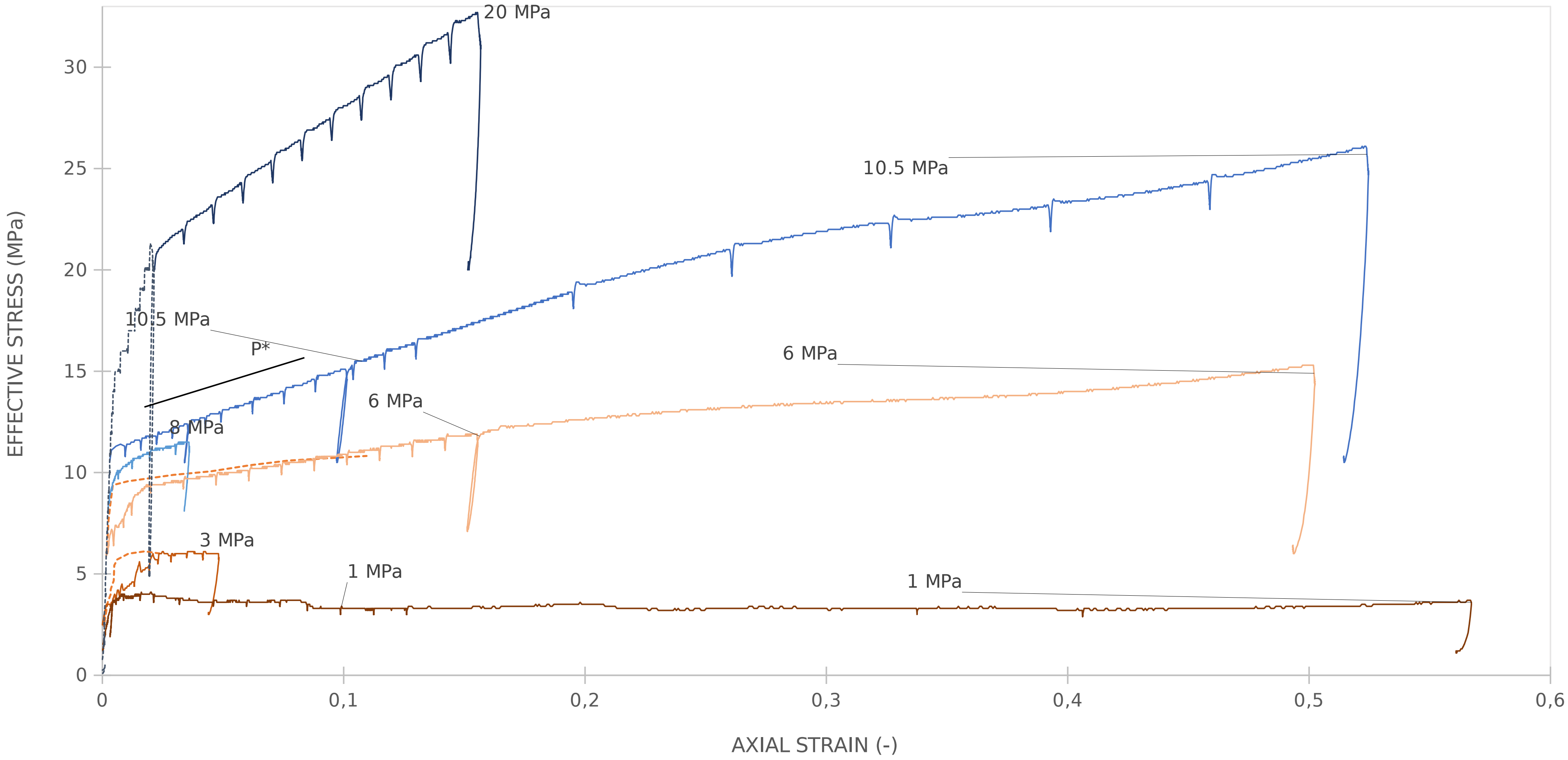


8 mm sample with 3.25 µm voxel size

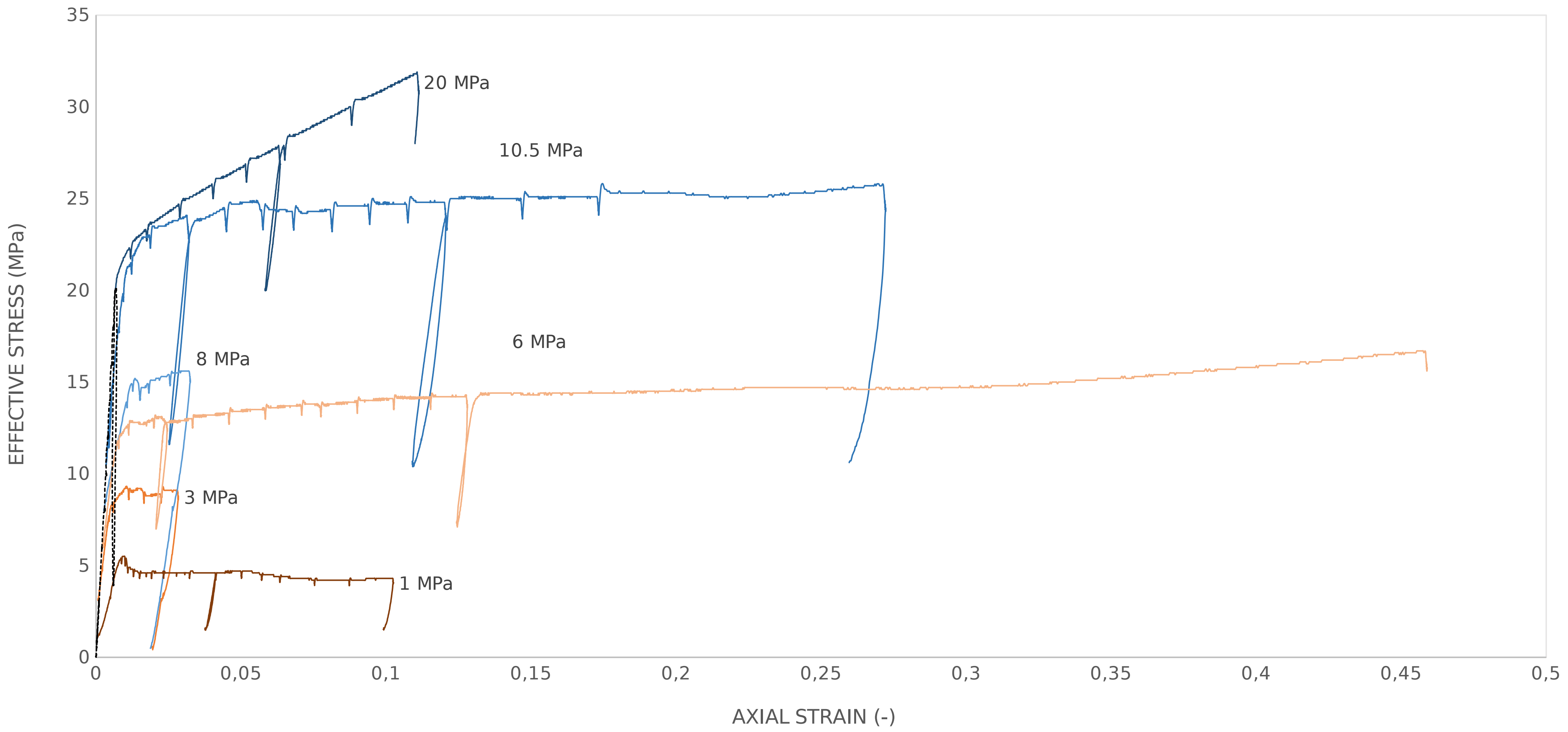
+ duration of a scan = 10 min (vs 16h at Navier)

Typical results

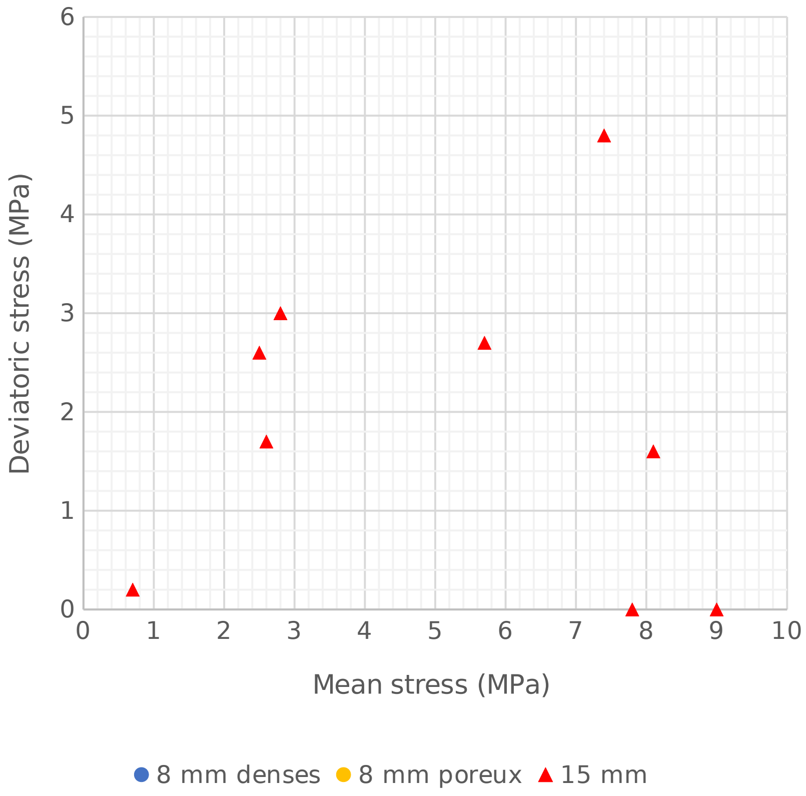
Overview – porous samples

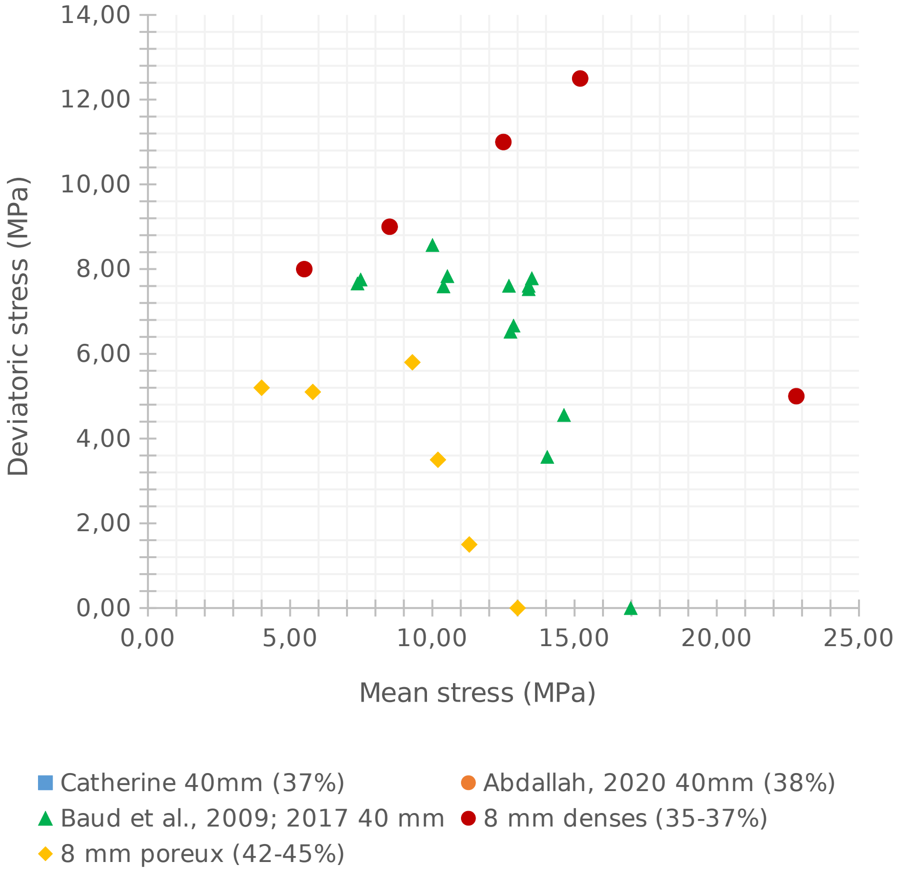


Overview – dense samples

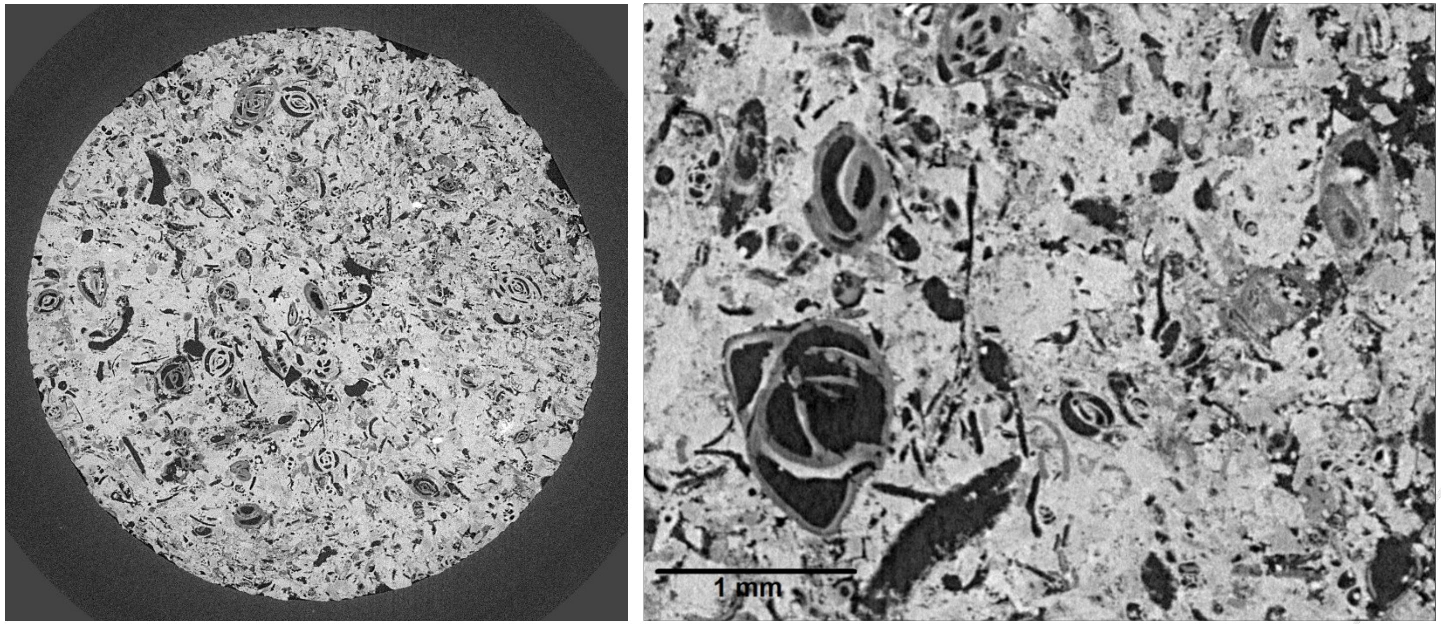


Overview – all triaxial tests on SML



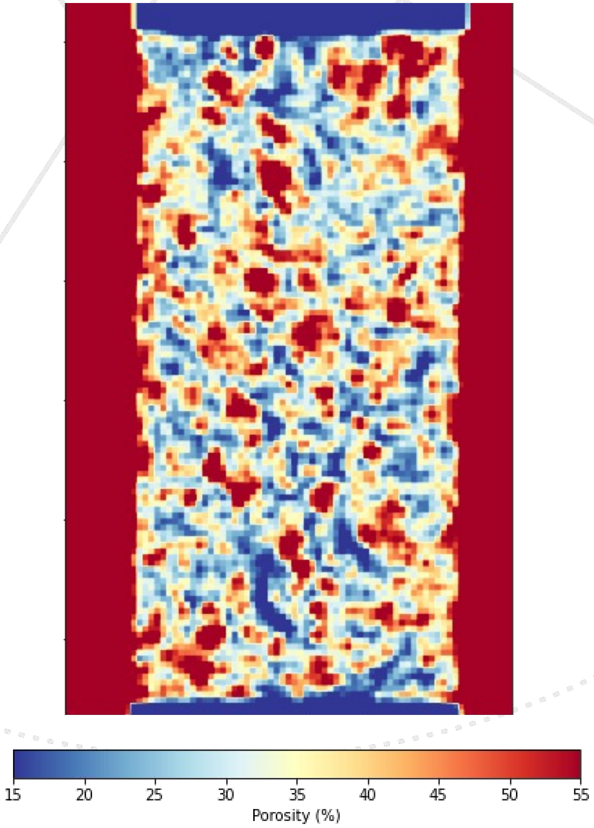


Triaxial Test on a Dry, Dense (= 35%) 8 mm Sample at a Confining Pressure of 6 MPa



Horizontal cross section of an 8 mm dense sample obtained by XRCT 3D imaging and zoom on microstructure

Local density map



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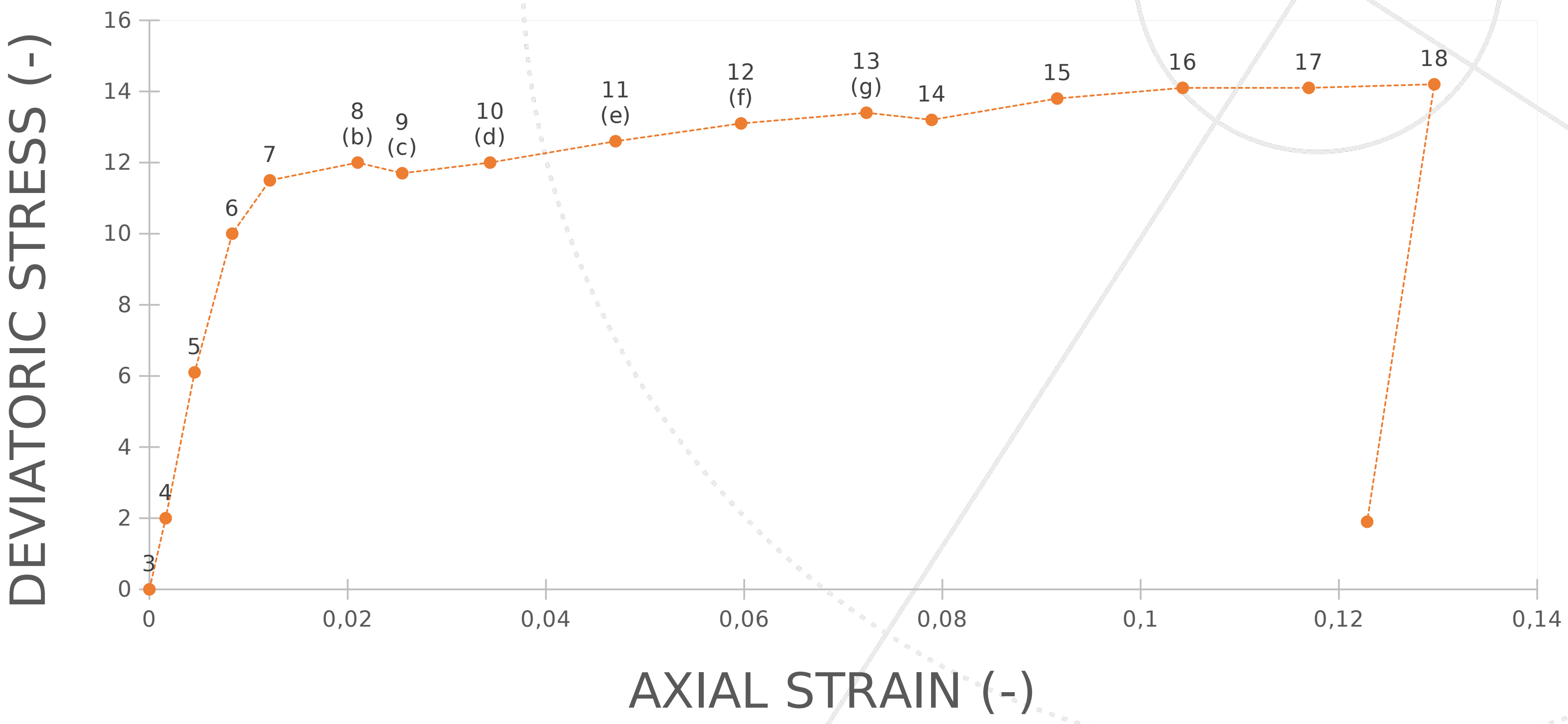

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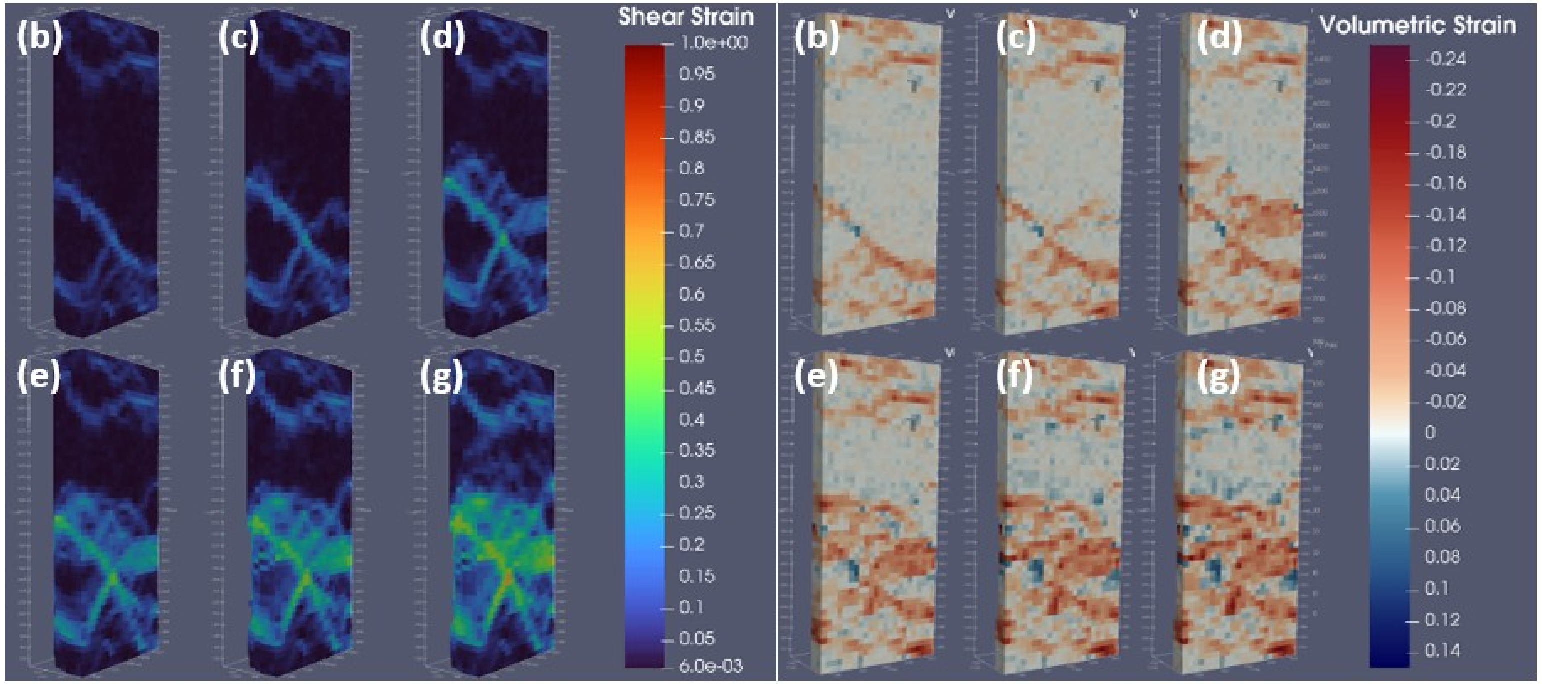
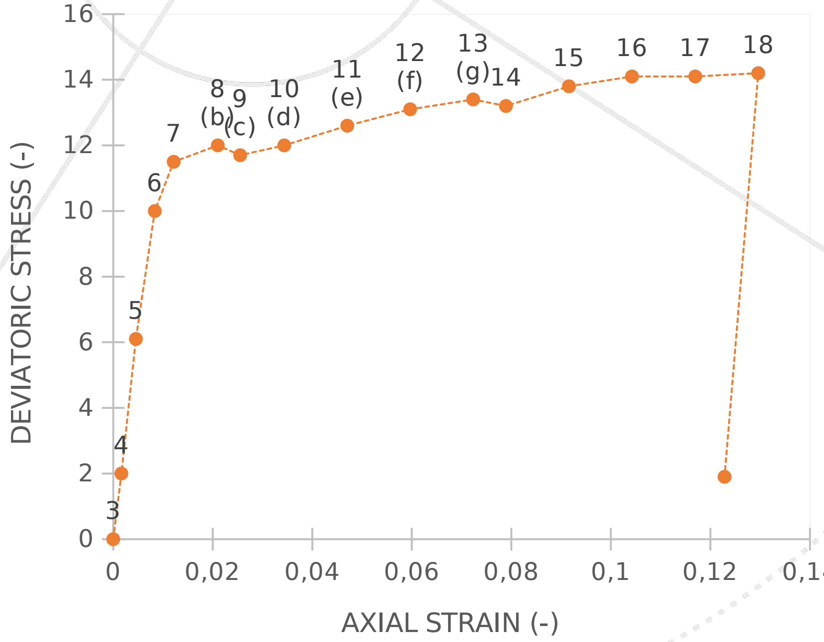
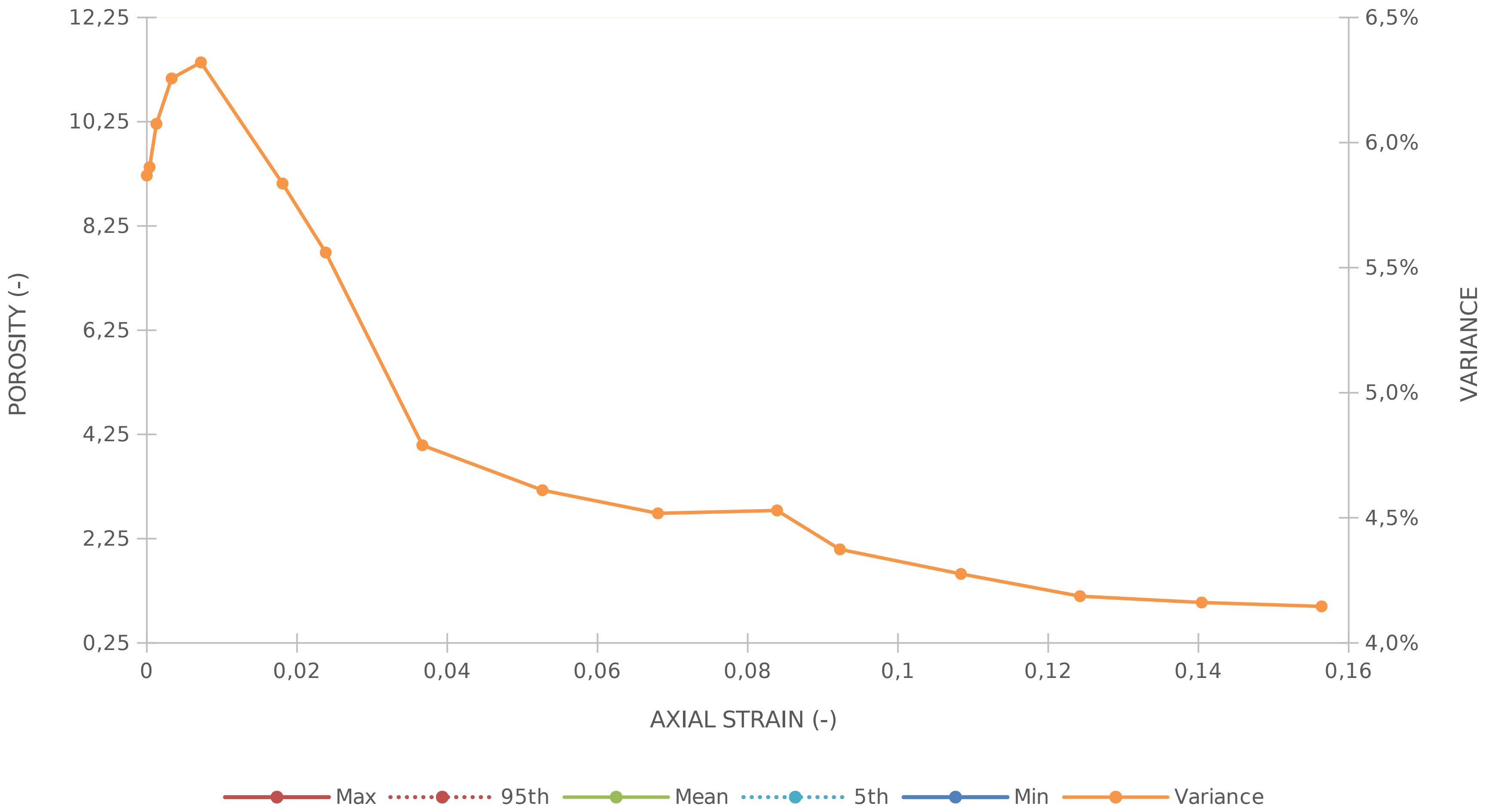
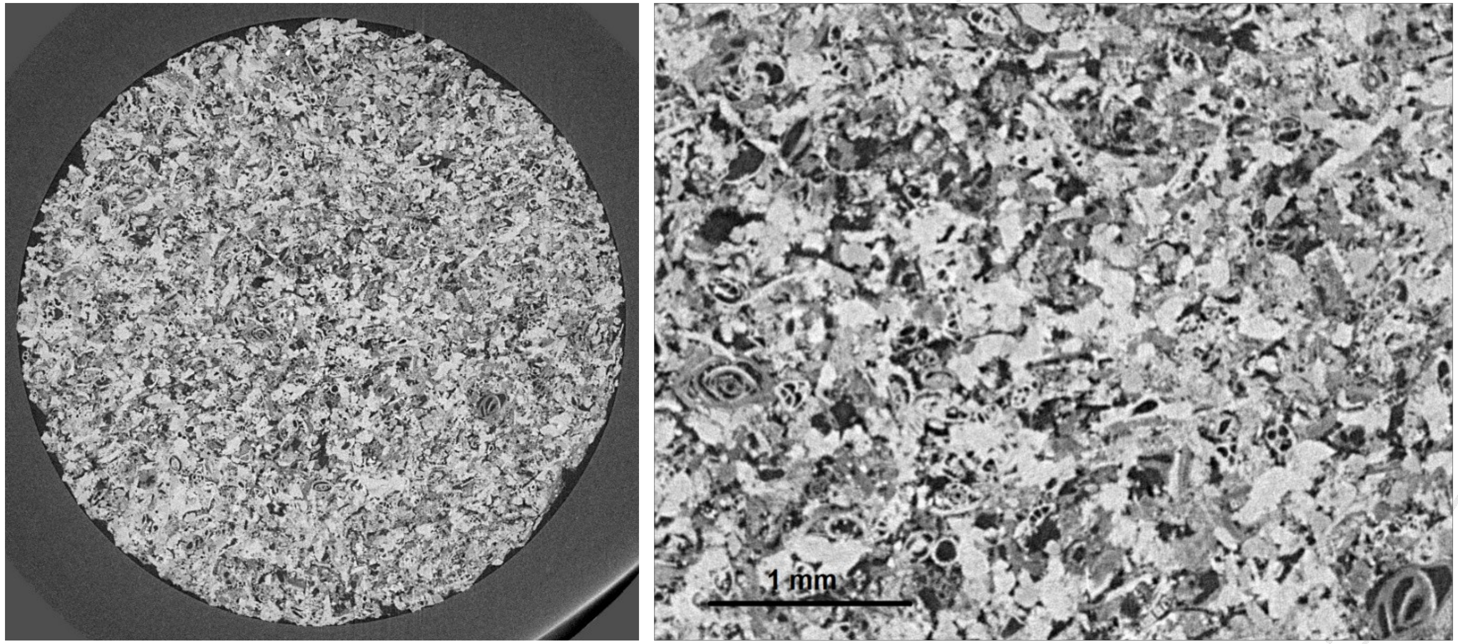




Triaxial Test on a Dry, Dense (= 35%) 8 mm Sample at a Confining Pressure of 6 MPa

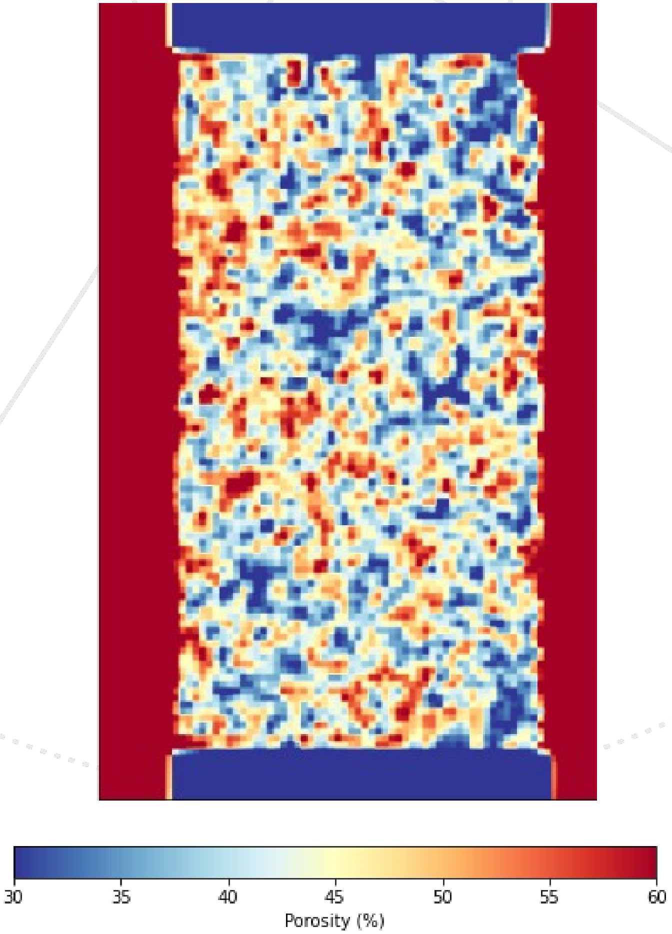


Triaxial Test on a Dry, Porous (= 41%) 8 mm Sample at a Confining Pressure of 6 MPa

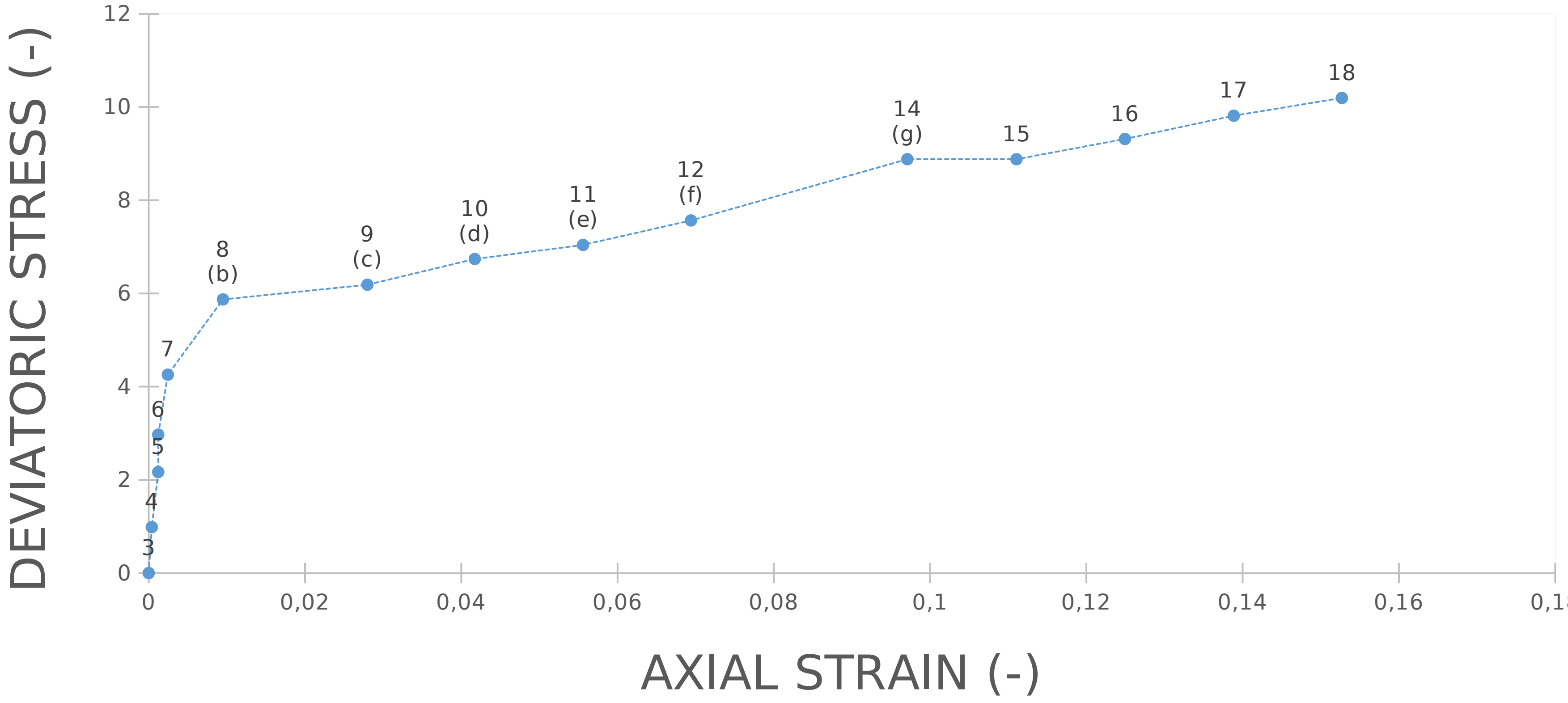


Horizontal cross section of an 8 mm porous sample obtained by XRCT 3D imaging and zoom on microstructure

Local density map



Triaxial Test on a Dry, Dense (≈ 35%) 8 mm Sample at a Confining Pressure of 6 MPa



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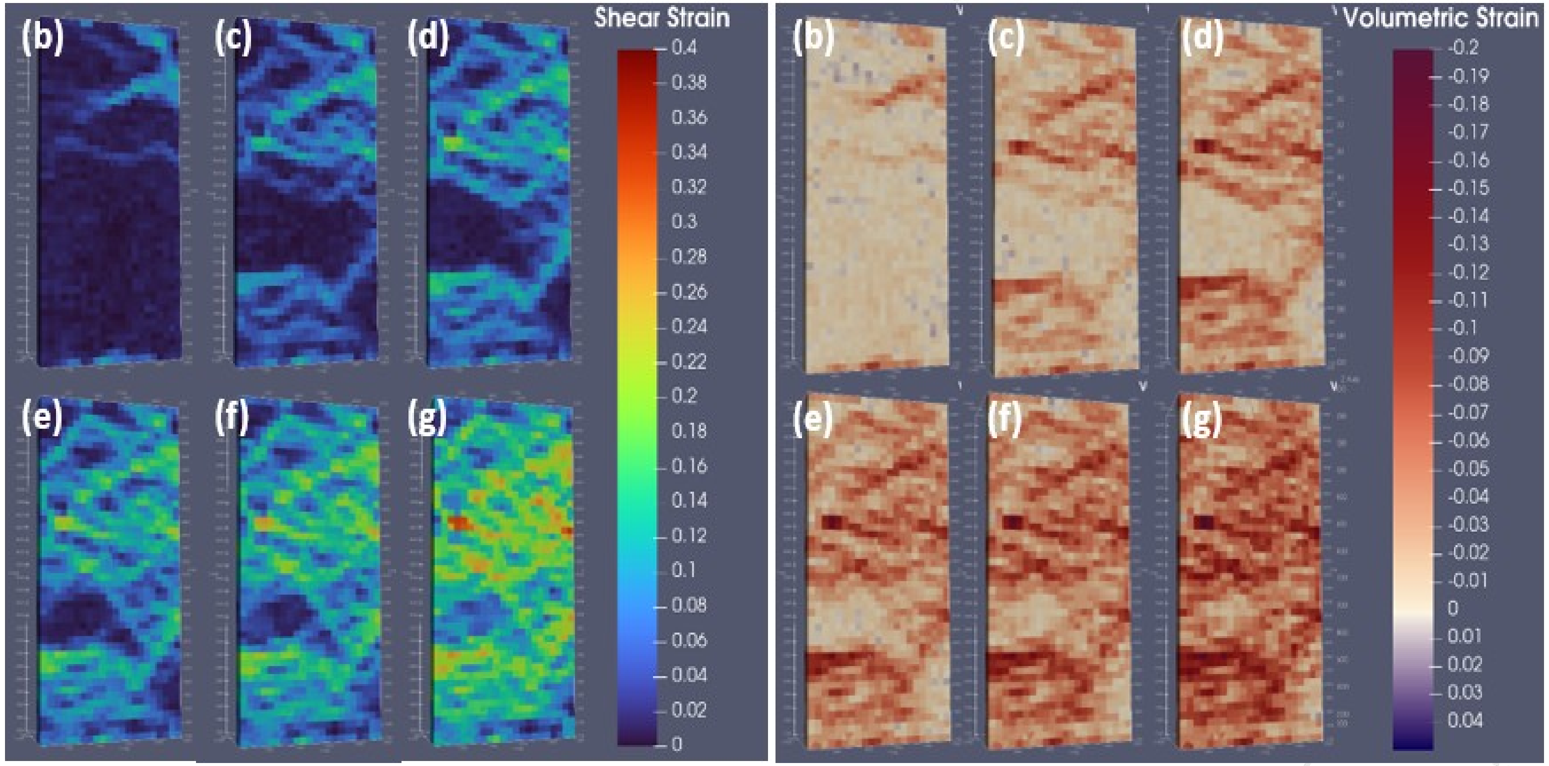
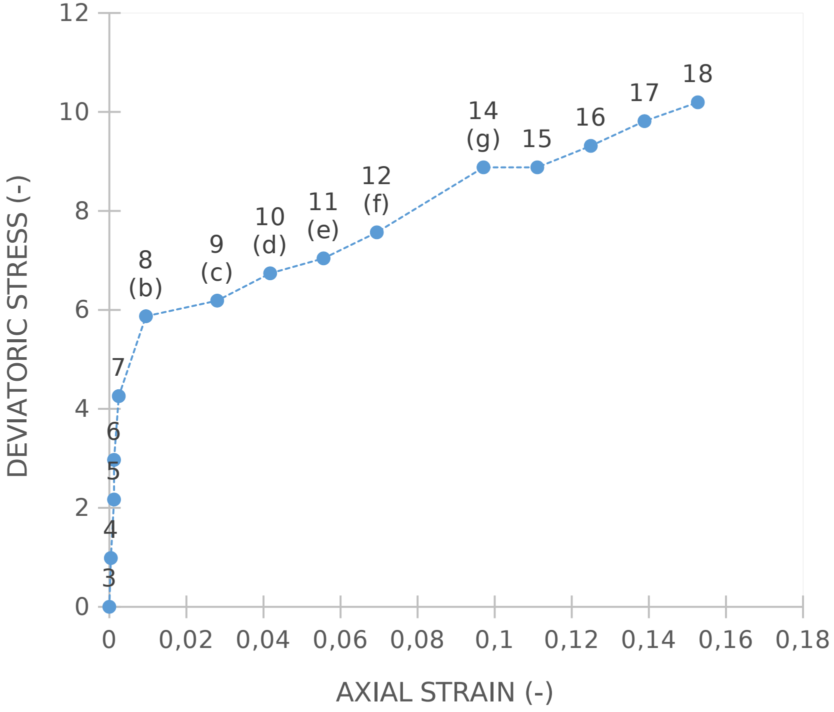
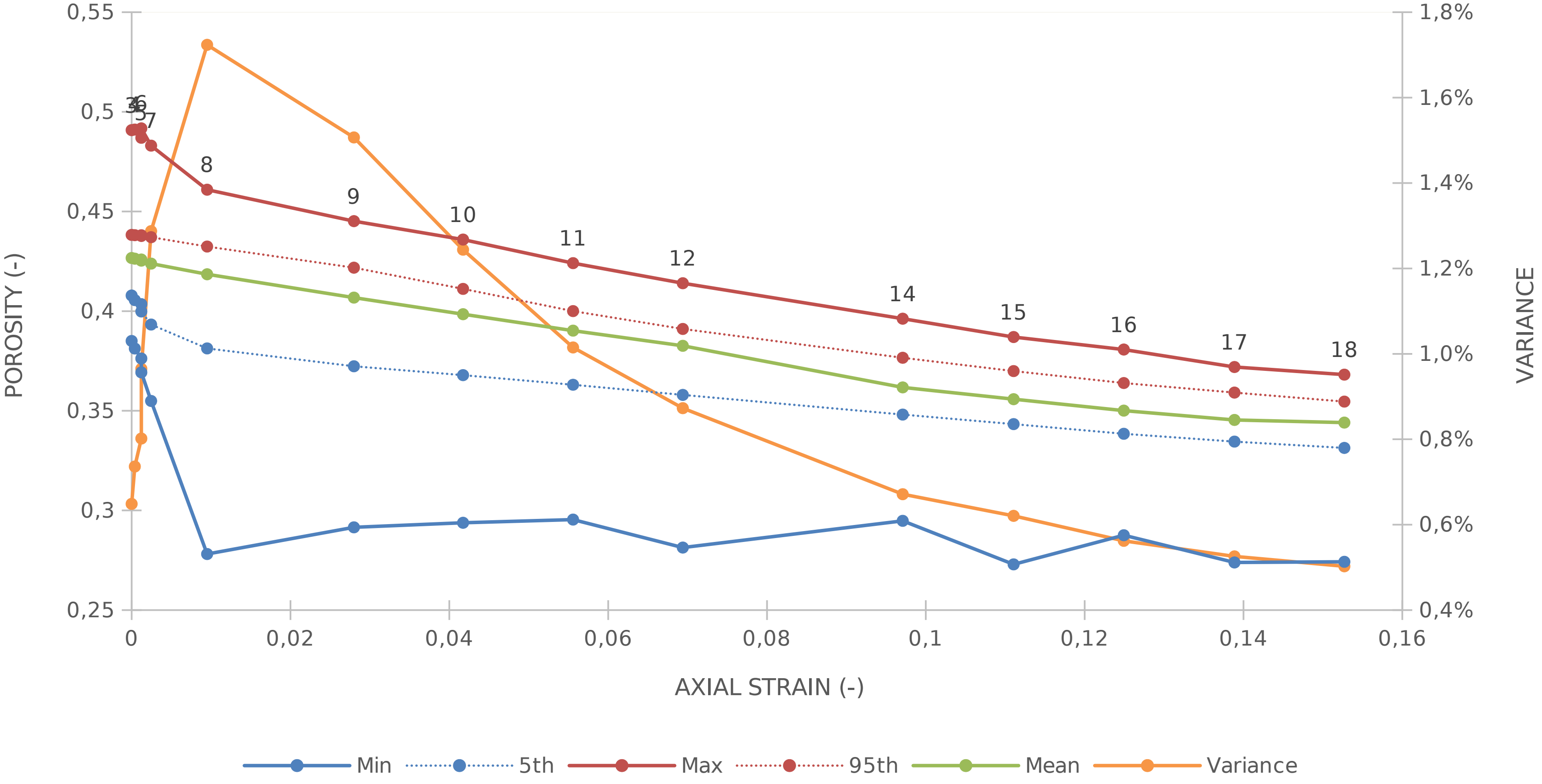
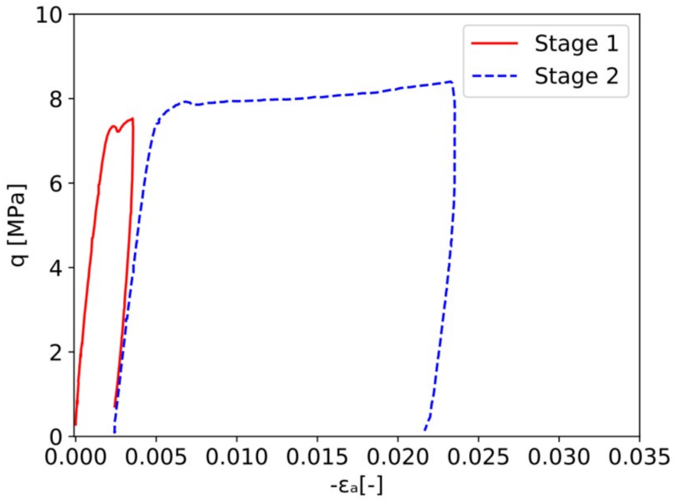


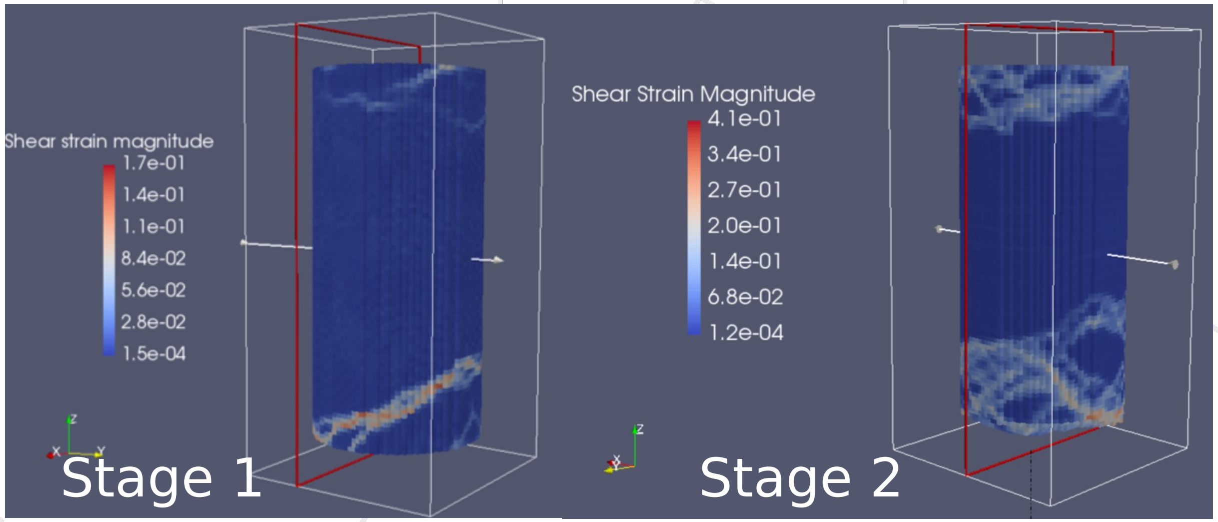


Triaxial Test on a Dry, Dense (= 35%) 8 mm Sample at a Confining Pressure of 6 MPa

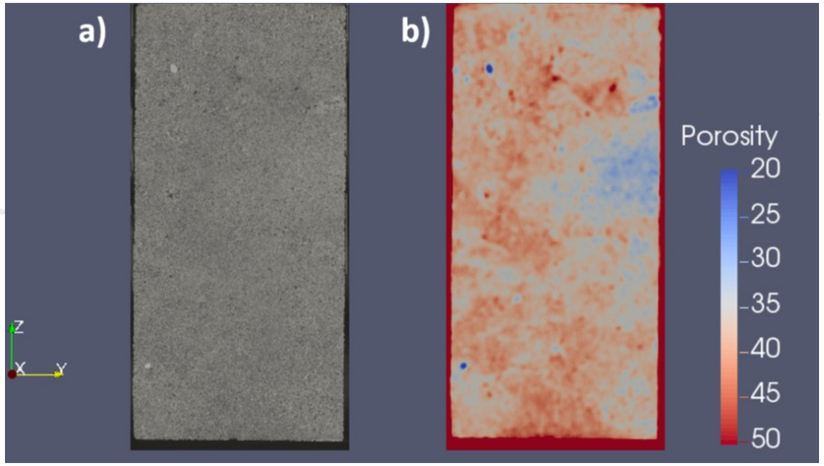


Triaxial Test on a Dry 40 mm Sample (= 38%) at a Confining Pressure of 6 MPa(Abdallah,





- *Porosity heterogeneity at centimeter scale ;*
- *Transition from brittle to ductile behaviour at 6 MPa, perfectly plastic behaviour ;*
- *Strain localisation is already visible on shear strain volumetric map right after plasticity onset at stage 1 ;*
- *New bands are formed at stage 2 ;*
- *The bands pass through high porosity zones, but cut sometimes through dense zones to connect high-porosity zones.*



Perspectives

Conclusions

- In situ triaxial tests on small samples permit to explore micromechanisms of deformation at small scale ;
- Porous and dense samples exhibit different behaviors. Dense samples have a larger elastic domain and the brittle/ductile transition occurs at a higher confinement (11 MPa as compared to 3-6 MPa for porous samples) ;
- Under hydrostatic loading, pore collapse is observed at 13-14 MPa in porous samples while it occurs above 20 MPa for dense ones. At macro-scale (40 mm in diameter samples), pore collapse is observed at 16 MPa ;
- Diffuse compaction has been observed in small porous samples, while a single deformation band is observed in dense ones and spreads progressively throughout the whole sample, while several deformation bands initiate and develop through mostly porous zones at macro-scale.

Future Tasks

- Confirm first observations by systematic DVC analyses to build 3D deformation maps and porosity maps ;
- Link local porosity evolutions with hardening of sample ;
- Identify the micro-mechanisms (pore collapse, grain rearrangement, inter or intra granular fracturing, etc.) involved deformation band formation + determine their sequence ;
- Define the key features of the microstructure (beyond porosity) that differentiate dense and porous sample;
- Complete data with ex situ testing in order to fully define the yield loci for porous and dense samples ;
- Link permeability at several scales to deformation history ;
- Upscaling from the small samples to standard-sized samples.