

Characterization of fracture anisotropy in clayey rocks by Digital Image Correlation

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Outline

- 1. Introduction / Context
- 2. Aims and Experimental approach
- 3. 2D Experimental approach and results
- 4. 3D Experimental approach and results
- 5. Conclusions / perspectives

1. Introduction / Context



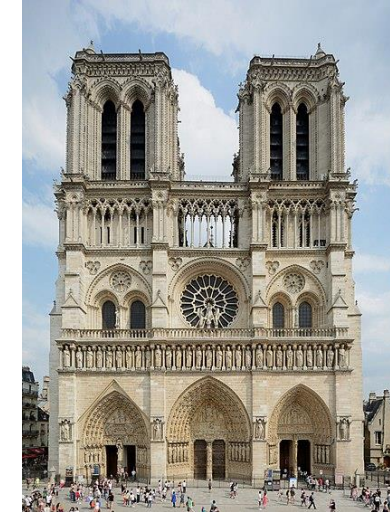
The Problem:

France depends to 80% on nuclear Energy. Total volume of nuclear wastes: 1 540 000 m³ in 2016 (Andra), including 3650 m³ of **Long-lived high-level waste (LLHL)**.

Previsions (after dismantling power plants): 4 400 000 – 5 050 000 m³
10 000 – 32 000 m³ LLHL.

For comparison: Internal volume of Notre Dame de Paris 100 000 m³.

For now: All wastes reside temporarily in surface storage facilities of Andra.



One solution:

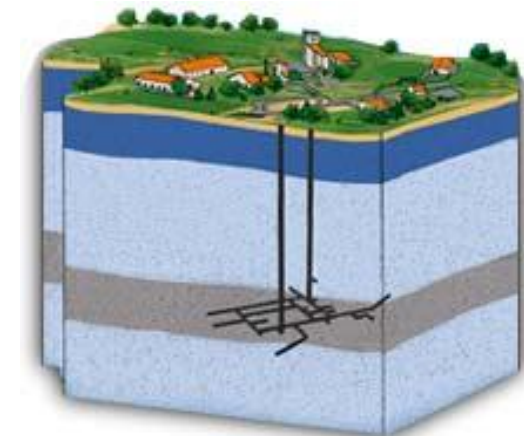
Long term storage (>100 k years) in deep underground repositories

2 possible geological formations:

impermeable evaporites or sedimentary rocks

Salt rock formation: USA, Germany

Clayey rock formation: France, Belgium, Switzerland

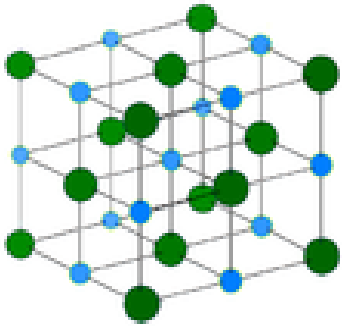


1. Introduction / Context

To remain impermeable the rocks must be able to:
1) accommodate deformation mostly by ductile flow; 2) self heal microfractures

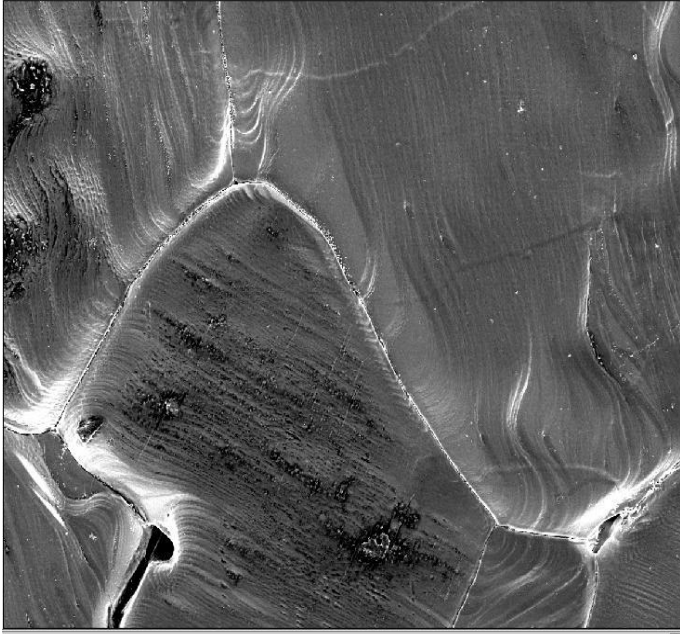
Rock Salt

Cubic crystal structure (FCC)



A few % porosity

SEM-in situ uniaxial compression



*Anisotropic Crystal Plasticity:
grain to grain incompatibilities
triggering Grain Sliding and
microdamage...*

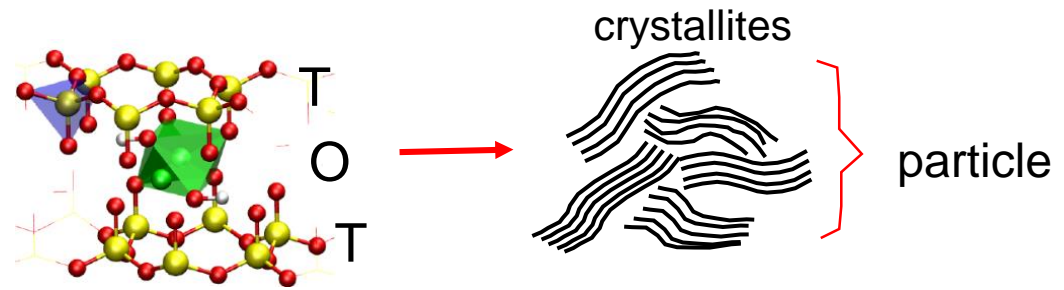


1. Introduction / Context

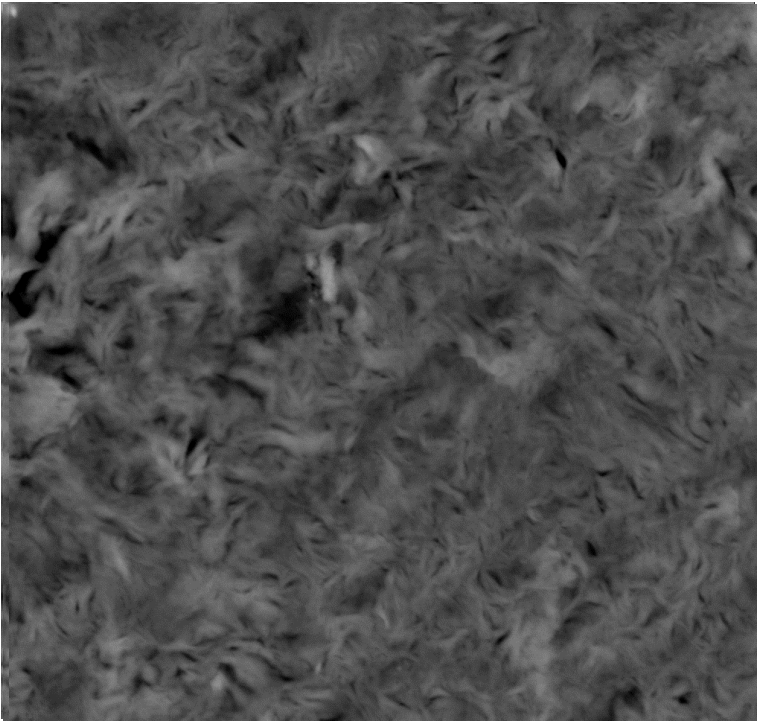
To remain impermeable the rocks must be able to
1) accommodate deformation mostly by ductile flow; 2) self heal microfractures

Clayey Rock TOT sheet minerals → μm sized crystallites

- nano-porous clay particles
- micro-porous clay aggregates



Ca-Smectite (Arizona)
Environmental SEM, hydration



“Bone Dry”
↓
25 % RH
↓
45 % RH
↓
65 % RH
↓
85 % RH

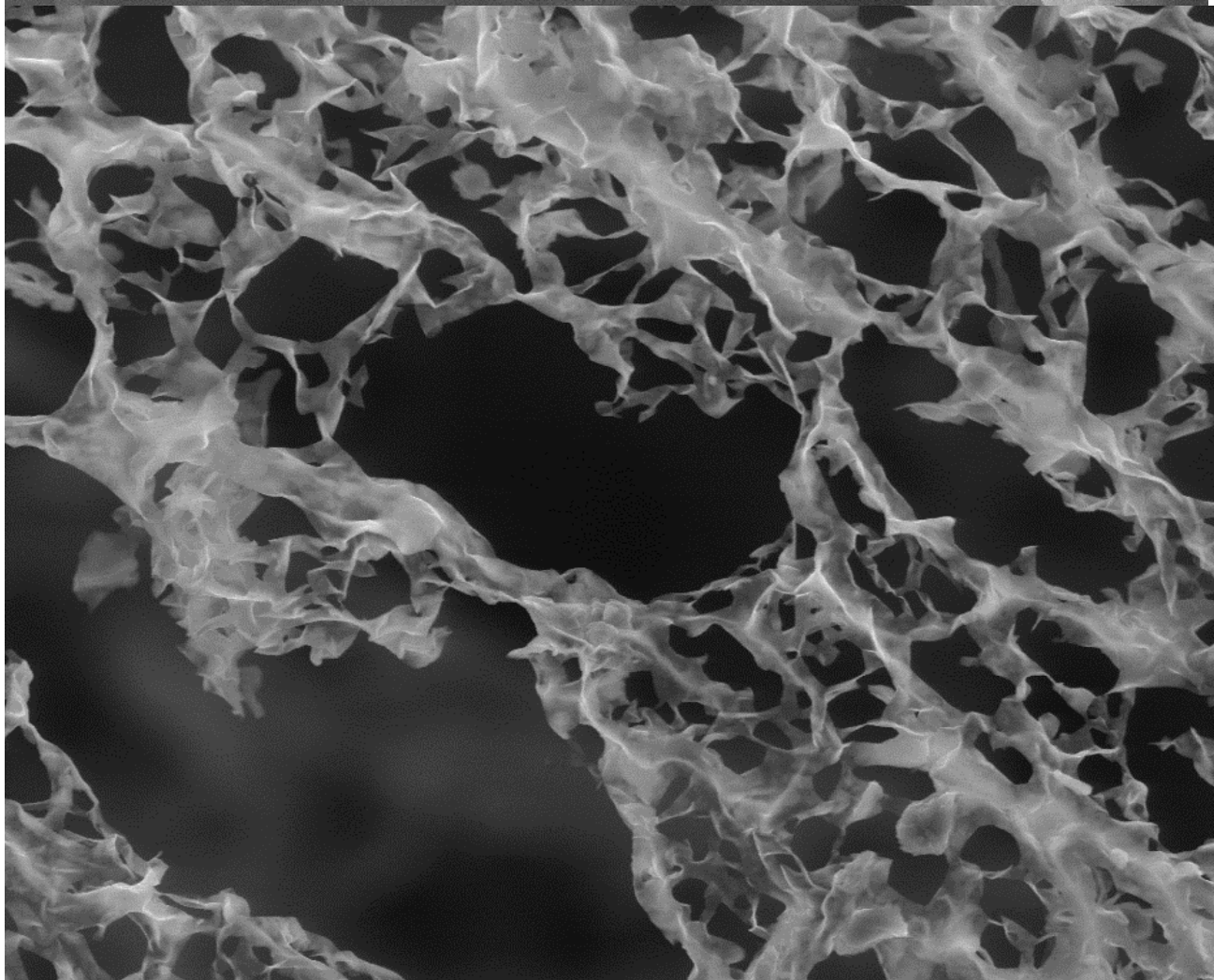
← 5 μm →

Brine → swelling → **self healing.**

1. Introduction / Context

Na-smectite (Wyoming)
Environmental SEM, dessication

10 μm



19,9 % RH

swelling & **gelling**

1. Introduction / Context

Nuclear waste repositories in Cox argillites

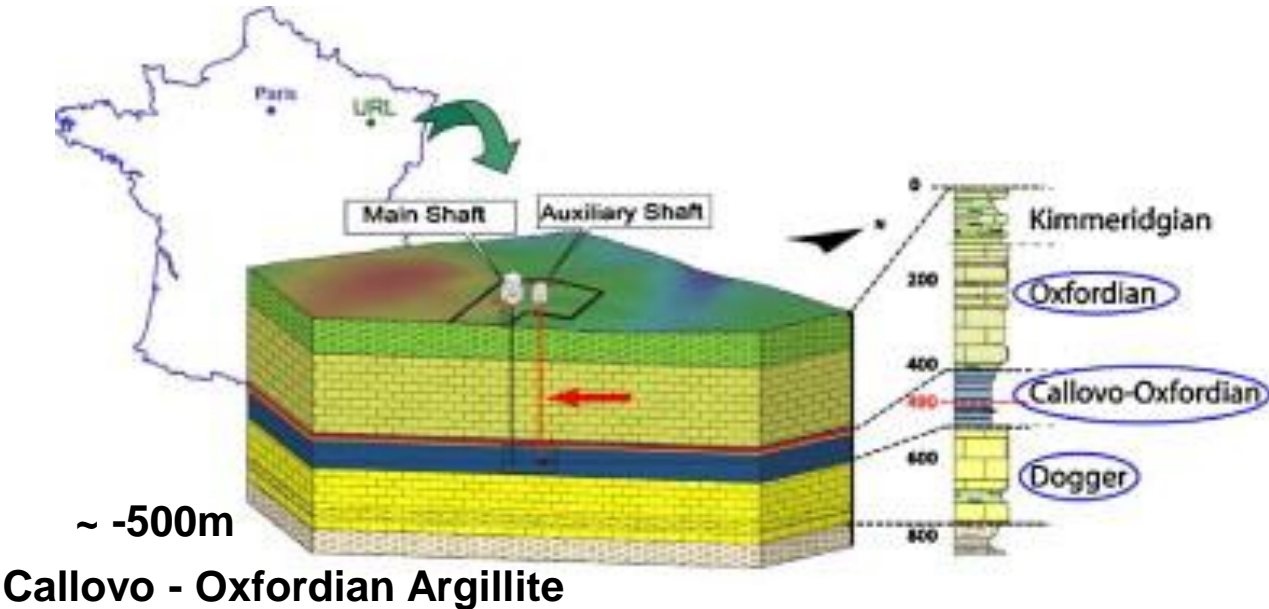
Short/mean term stability:

Desaturation/saturation of rocks in EDZ
Mechanical & transport properties.
-Development of *phenomenological Thermo-Hydro-Mechanical models*.

Long term stability:

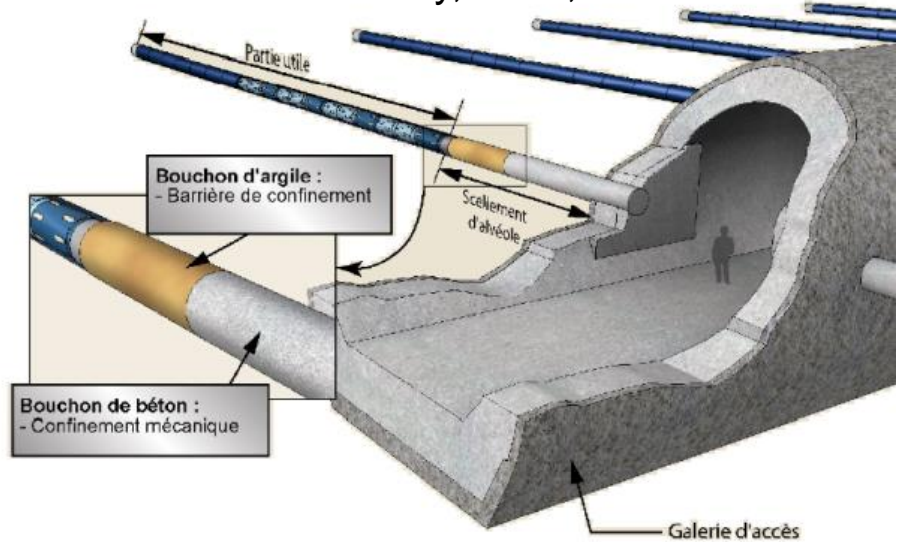
Development of predictive Thermo-Hydro-Mechanical models based on *physically sound micro-mechanisms*.

Need for **local scale experimental input**



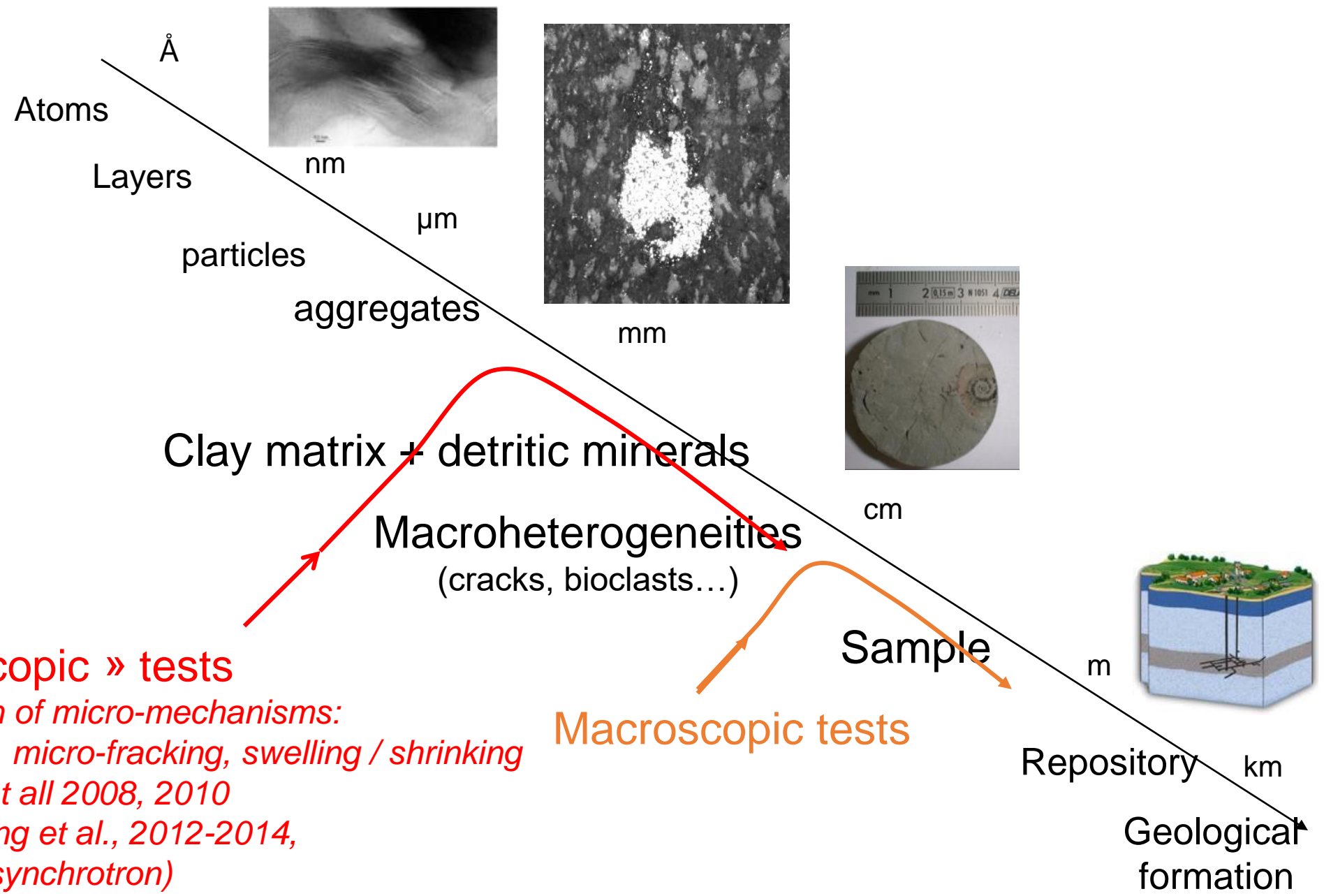
~ -500m
Callovo - Oxfordian Argillite

ANDRA Laboratory, Bure, France



1. Introduction / Context

Cox Argilites: Multiple scales of heterogeneity



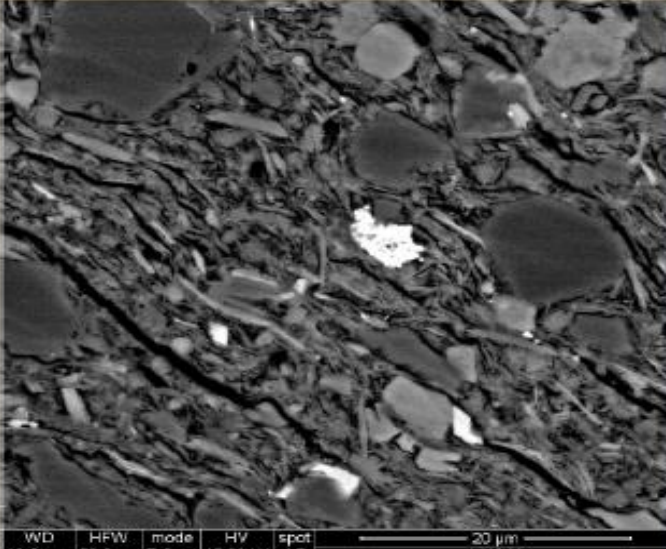
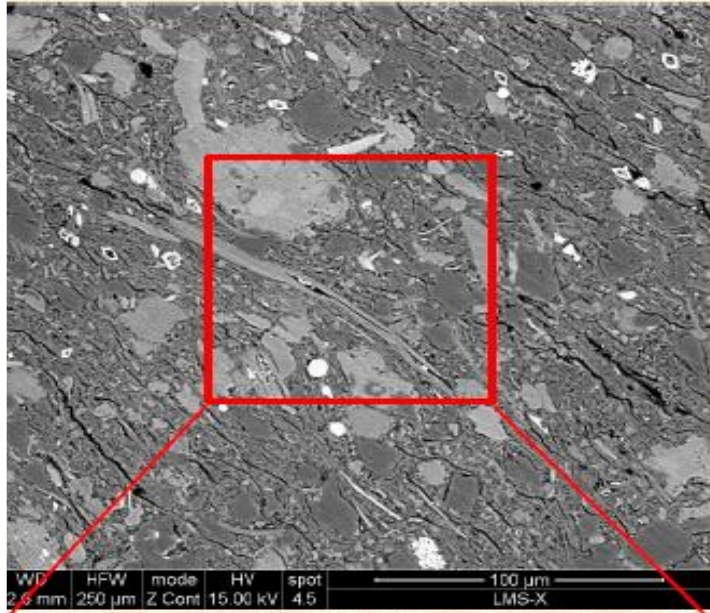
« Microscopic » tests
*Identification of micro-mechanisms:
deformation, micro-fracking, swelling / shrinking
OM: Valès et al 2008, 2010
E-SEM: Wang et al., 2012-2014,
μCT (lab & synchrotron)*

Macroscopic tests

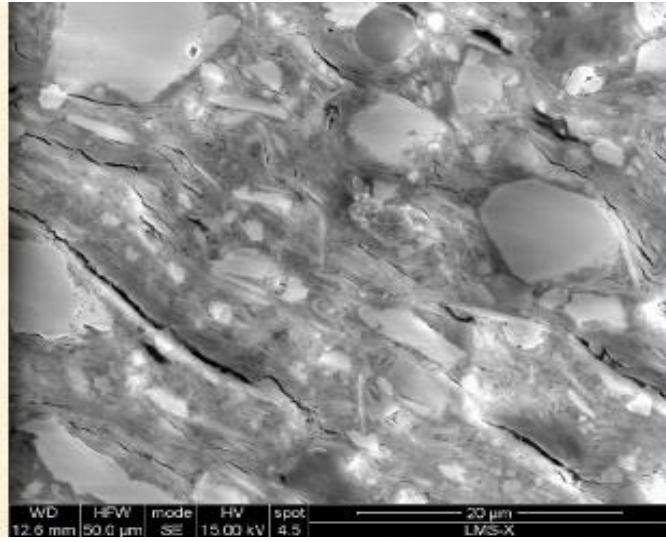
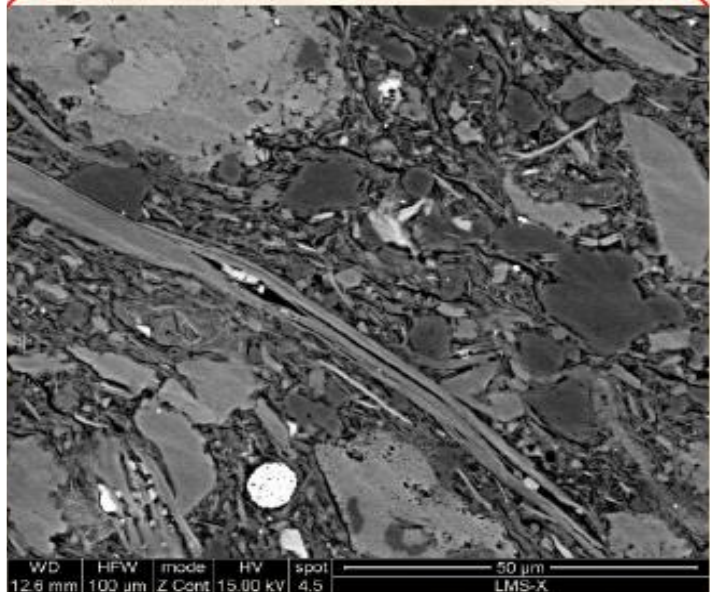
1. Introduction / Context

Cox Argilite: composite heterogeneous structure at microscale

Broad Ion beam cross section (vacuum)



Back-scattered electrons (Z and density)



Secondary electrons (topography)

clay matrix (I/S) 25-55 wt% (swelling)

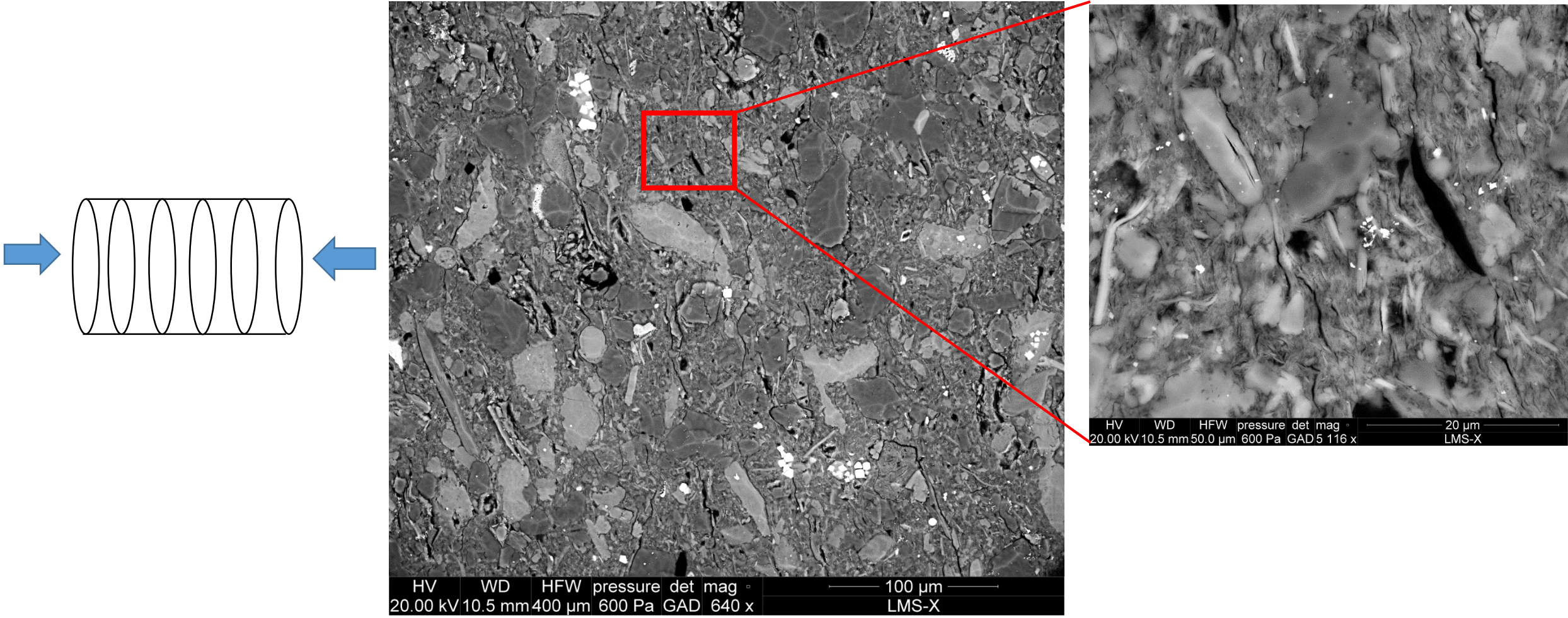
- + Calcite (23-42 wt%)
- + Quartz (20-31 wt%)
- + minor Pyrite...

Noticeable natural variability

Structural Anisotropy:
sedimentary bedding

2. Aims & experimental approach

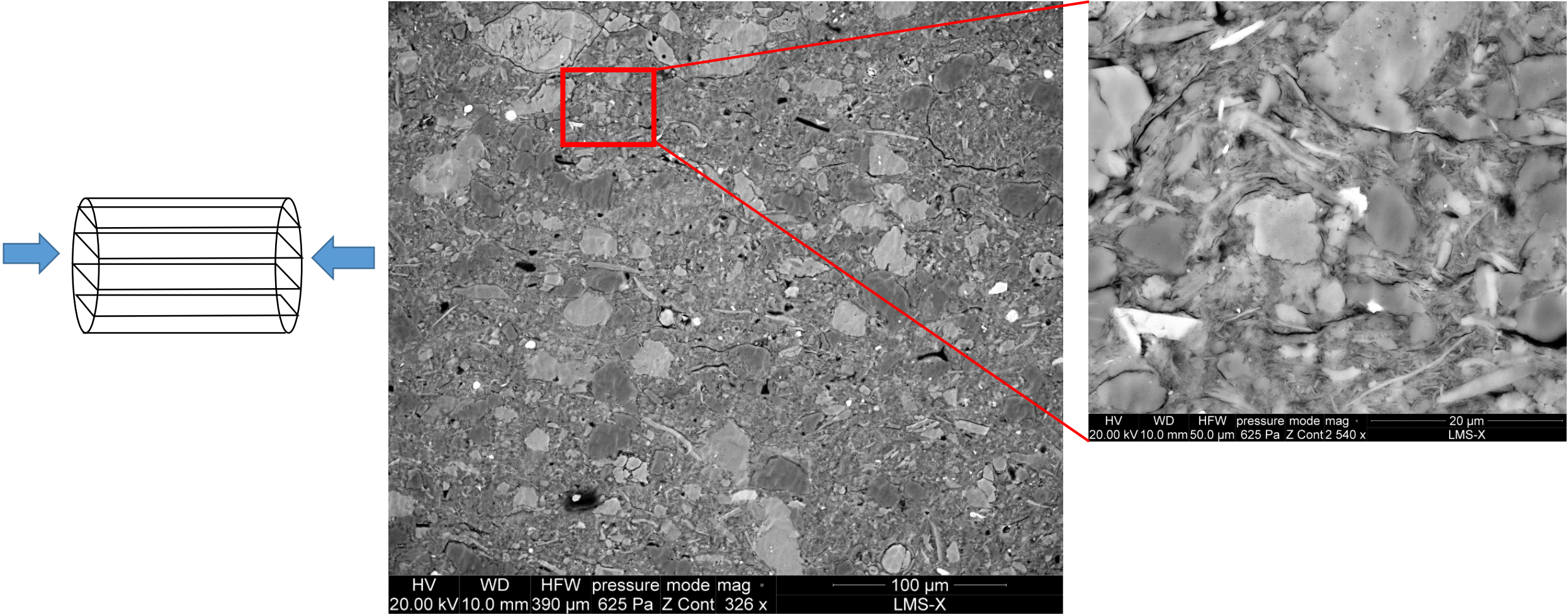
Aims: investigate the anisotropy of crack propagation under uniaxial loading with respect to the bedding



Plane Broad Ion beam polished (cryogeny)

2. Aims & experimental approach

Aims: investigate the anisotropy of crack propagation under uniaxial loading with respect to the bedding



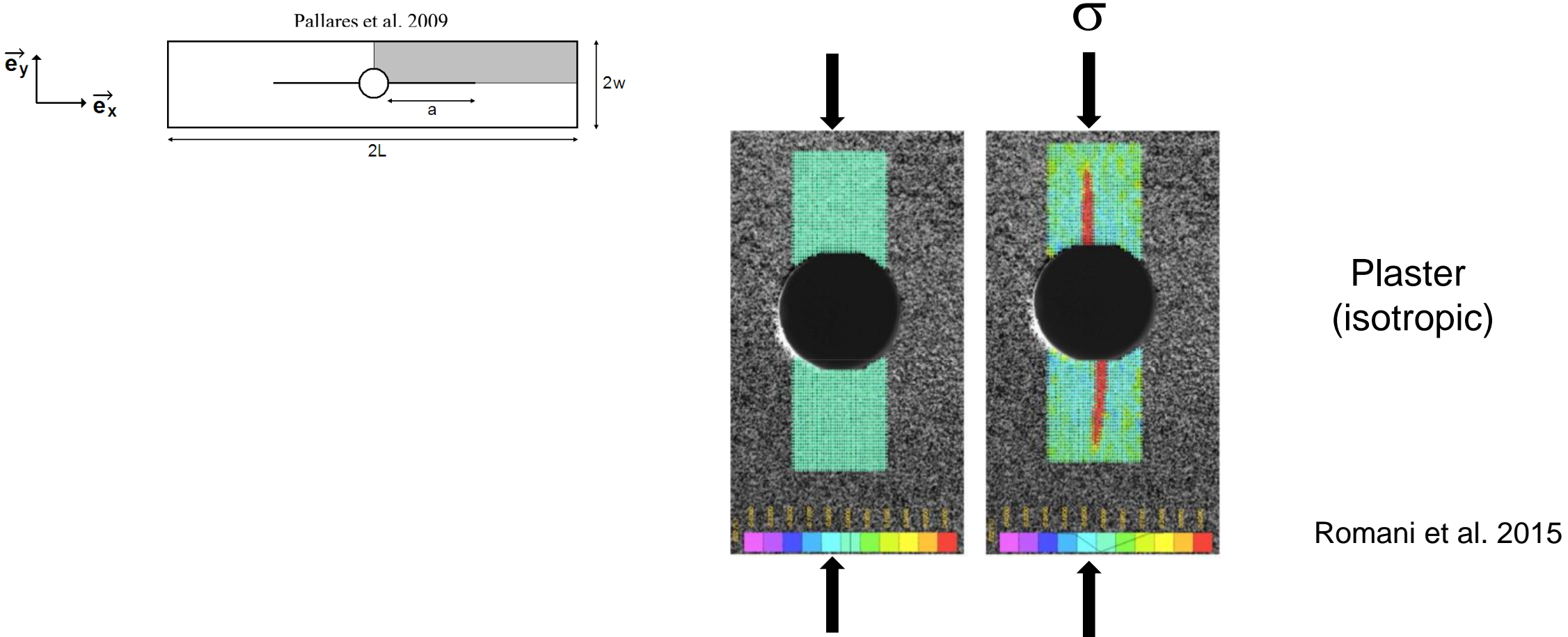
Plane Broad Ion beam polished (cryogeny)

2. Aims & experimental approach

Experimental approach: Double Cleavage Drilled Compression (DCDC)

Compression of rectangular column with a central through-thickness hole

Follow nucleation and stable crack propagation by Digital Image Correlation (DIC)



3. 2D experimental approach

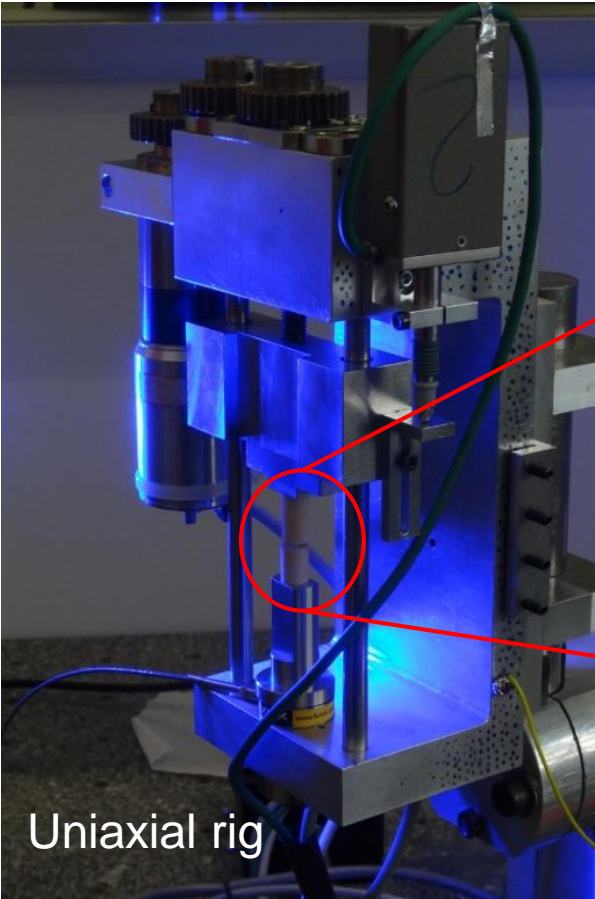
2D investigation by Optical Microscopy and 2D DIC

Test geometry: **3 orientations**
Test duration: **≈ 1h30 mn**
(sample ~ as received)

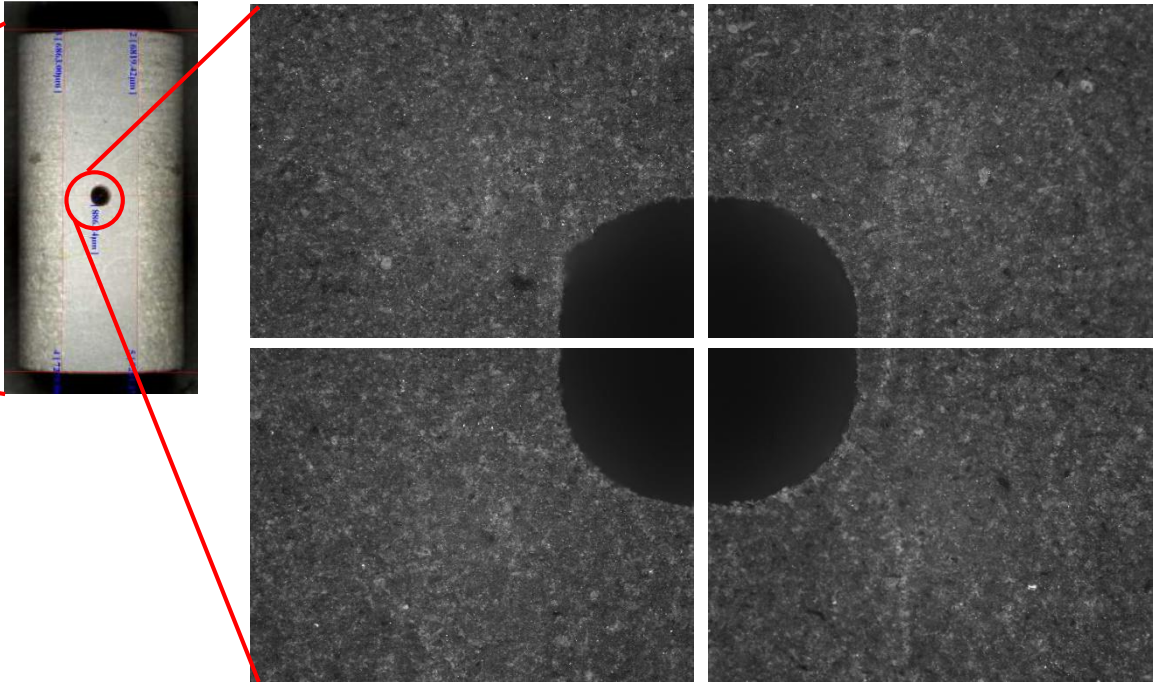
Region of Interest (ROI):
3,46 mm x 2,53 mm
Optical microscope (X10)
4 x 8MPixel images
Pixel size: **0,55 μm**

Correlation window: **25 pixels**
Local Strain Gage: **13,75 μm**

DIC software: **CMV**



Cox argillite sample
 $\Phi = 8 \text{ mm}$, $L = 16 \text{ mm}$
 $\Phi = \text{hole } 1 \text{ mm}$

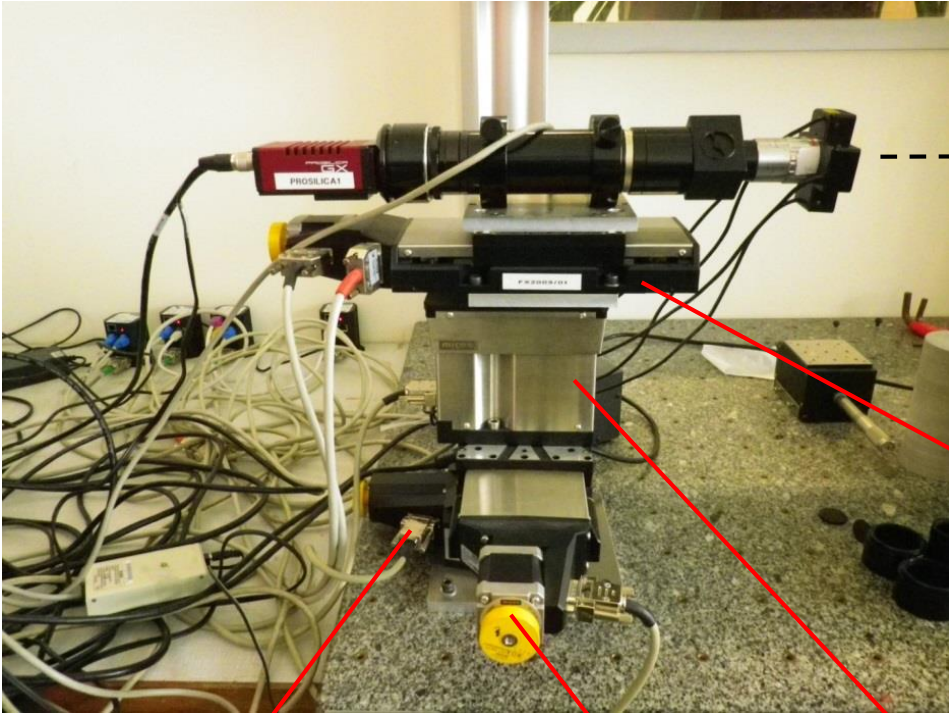


←→ 1 mm

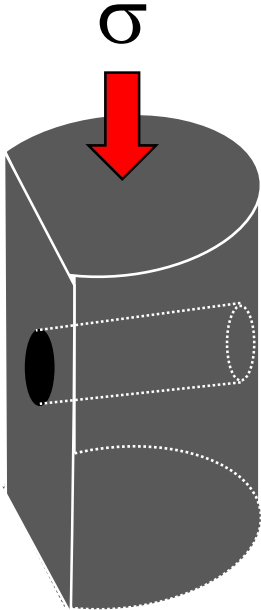
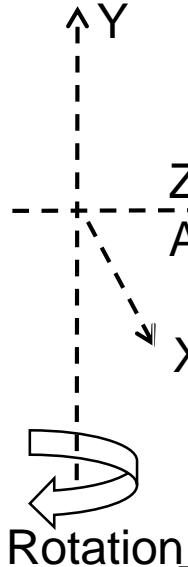
3. 2D experimental approach

2D investigation by Optical microscopy

microscope & stages automated control (SYLVIA, H. Gharbi, 2015)



Yang et al. 2012



depth of field $\approx \frac{0.61\lambda}{\alpha^2} \approx 3.7 \mu\text{m}$
(G = x10)



Rotation : Repetability +/- 0.01°



Axe X : Repetability +/- 1 μm

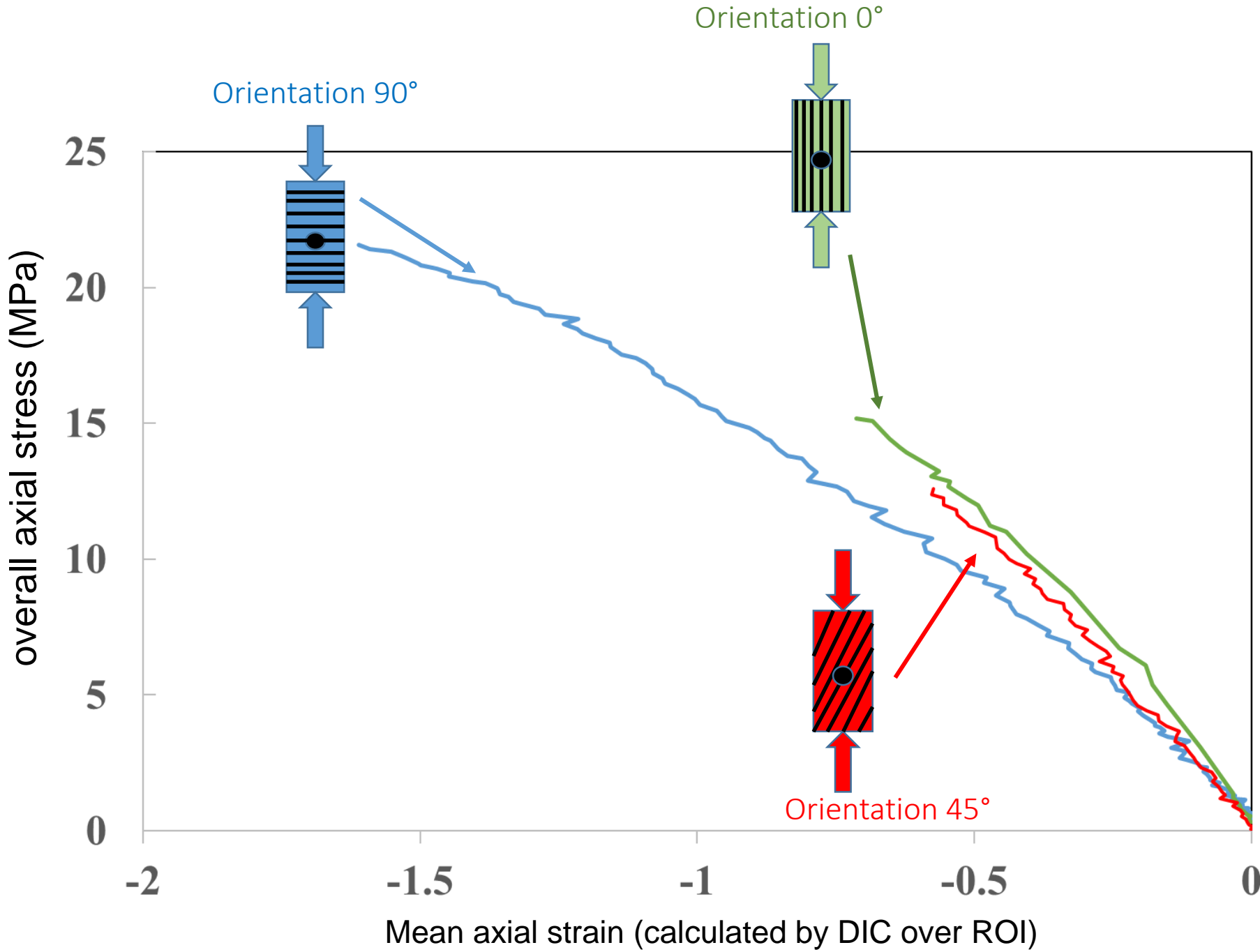


Axe Y : Repetability +/- 1.5 μm

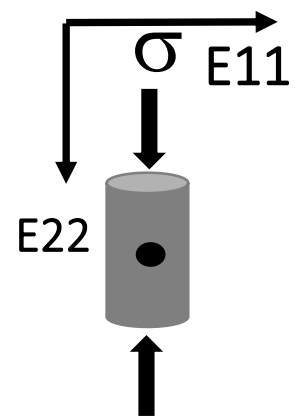


Axe Z : Repetability +/- 0.2 μm

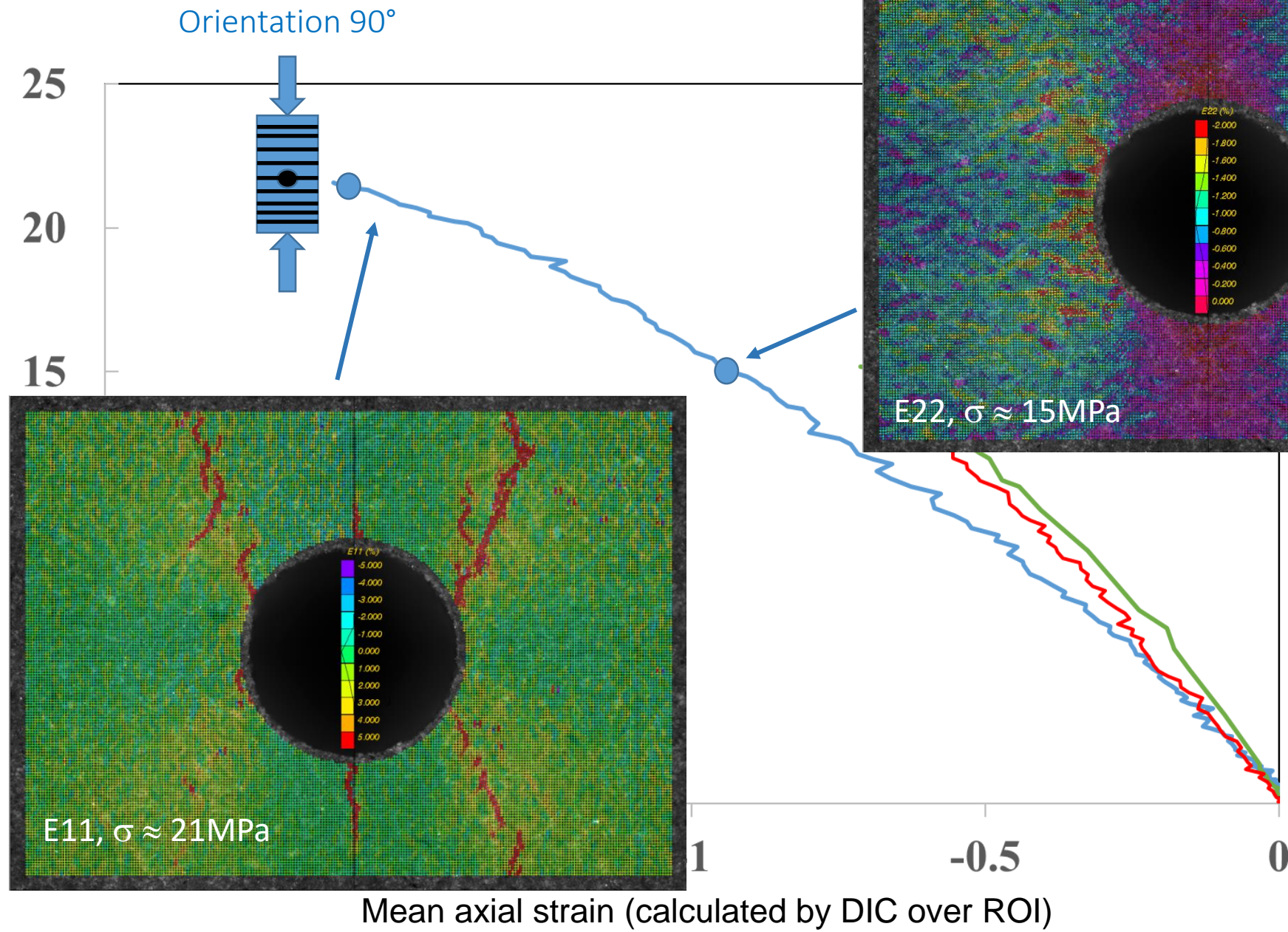
3. Results



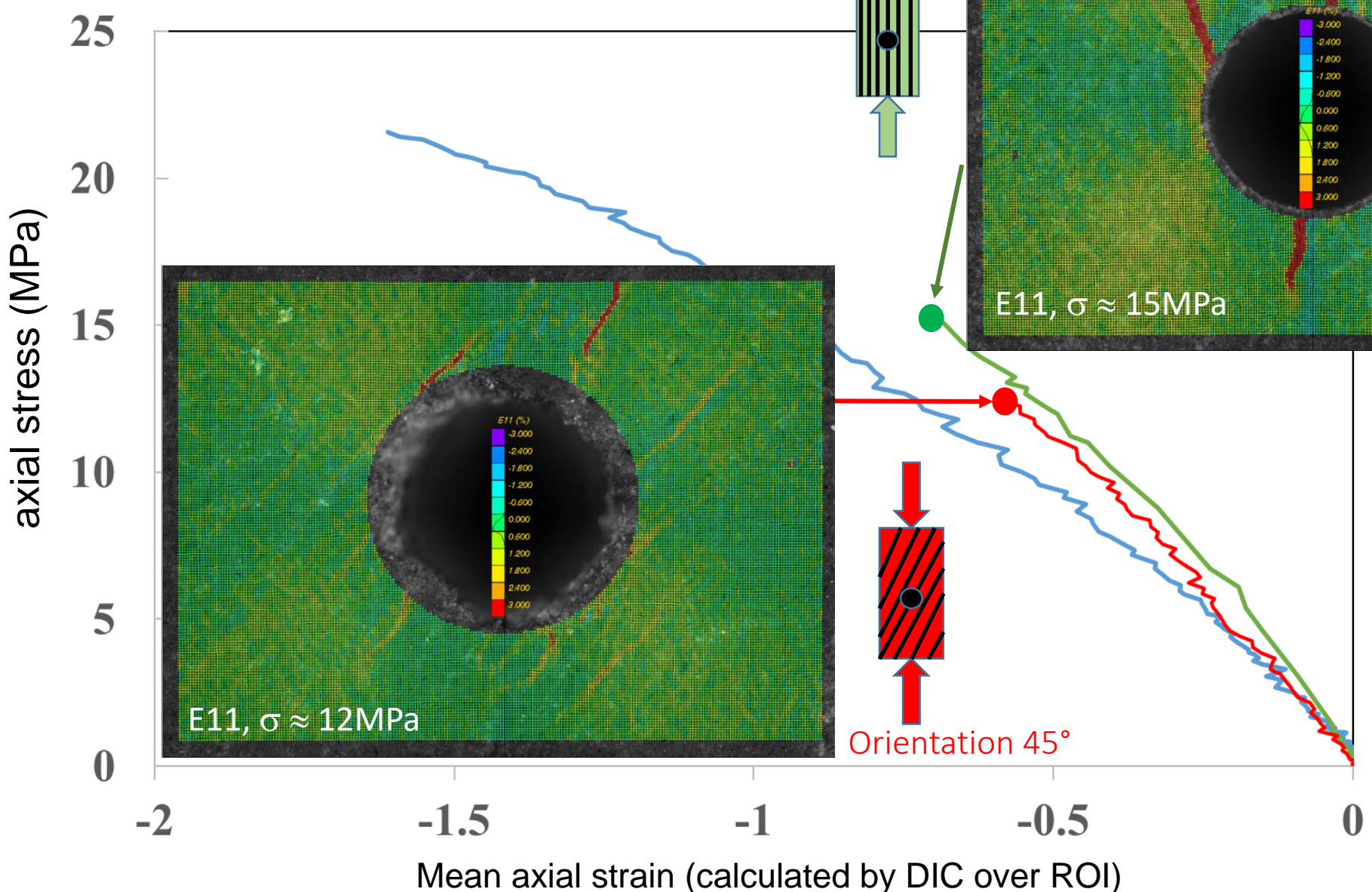
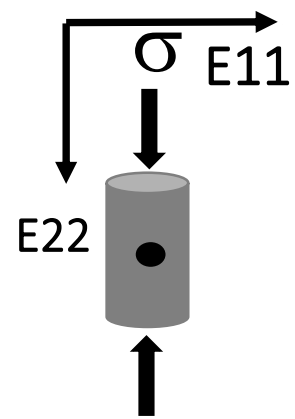
3. Results



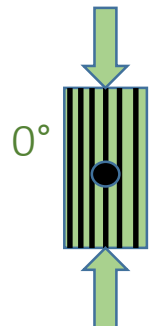
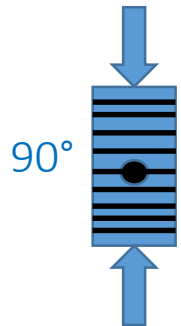
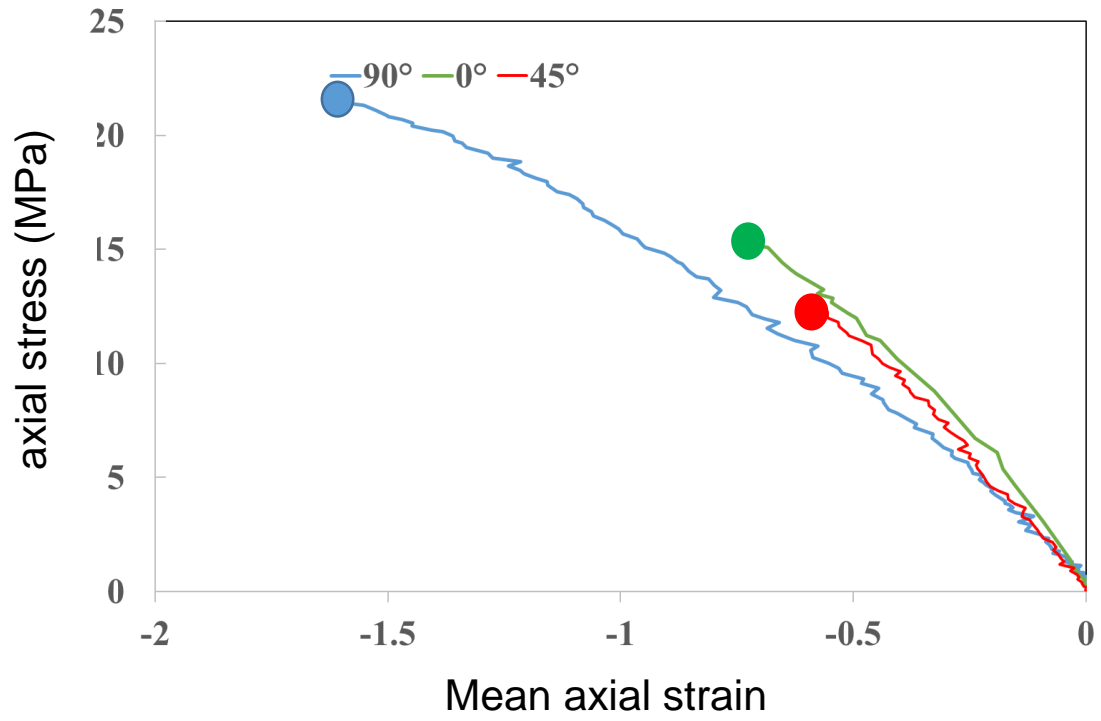
axial stress (MPa)



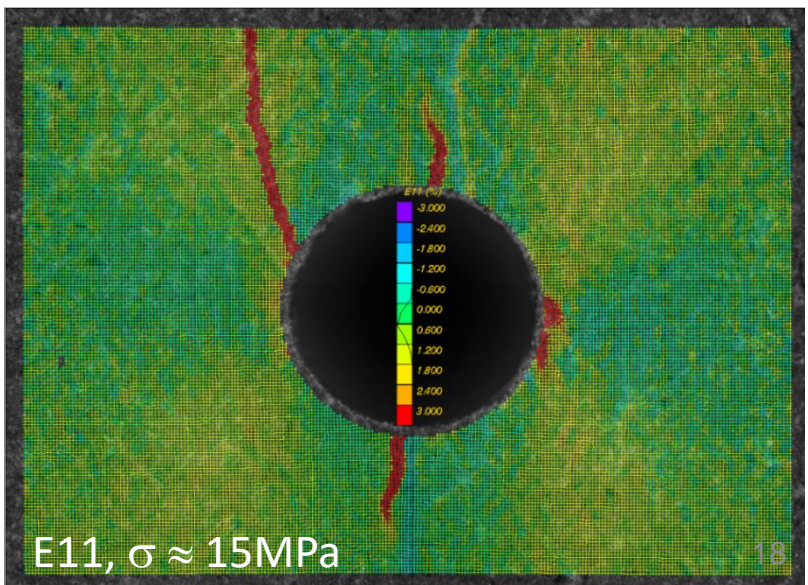
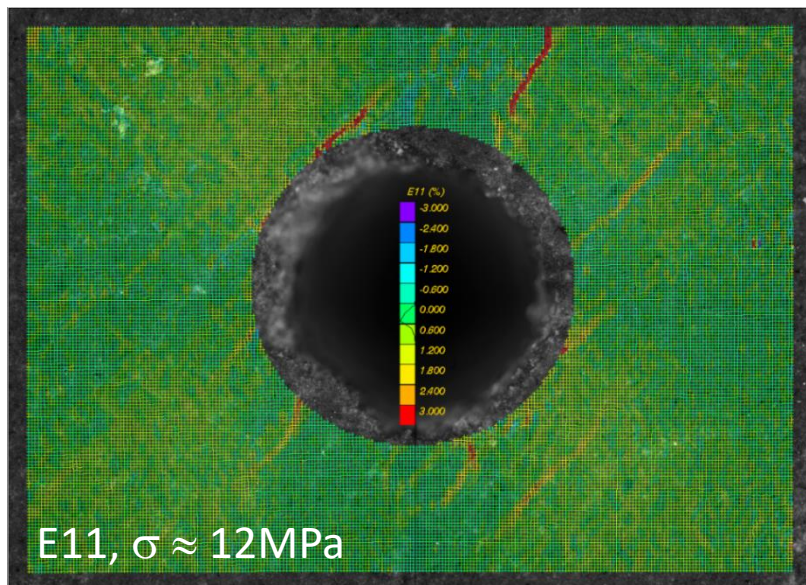
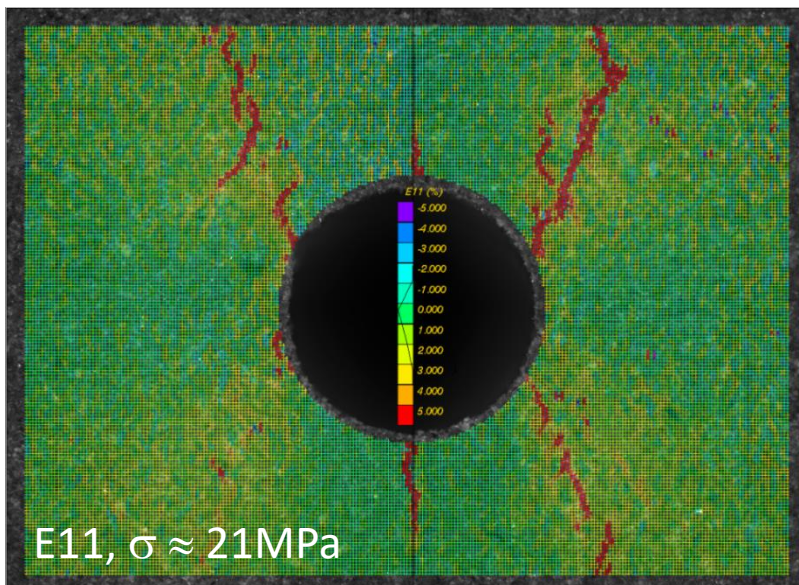
3. Results



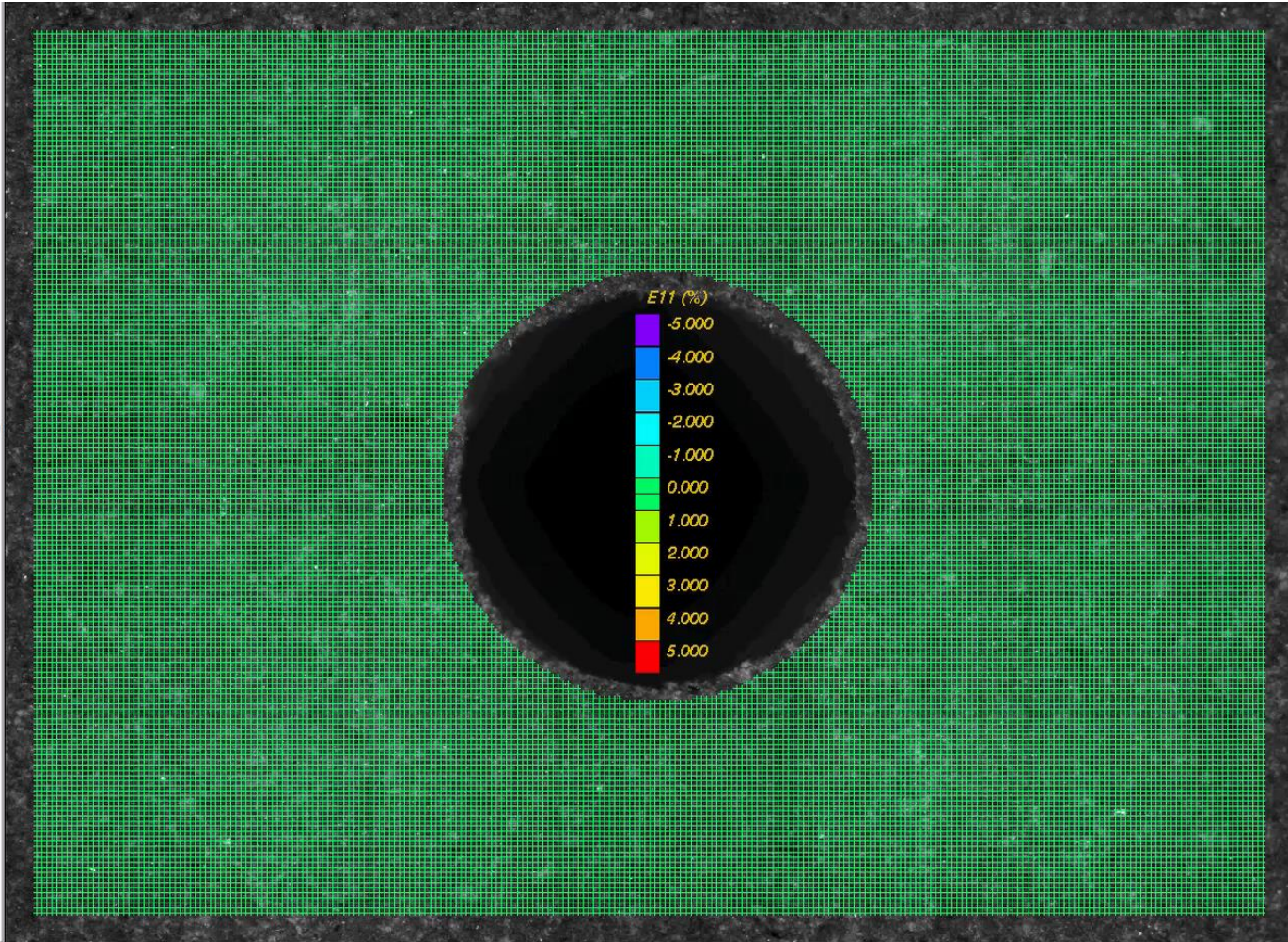
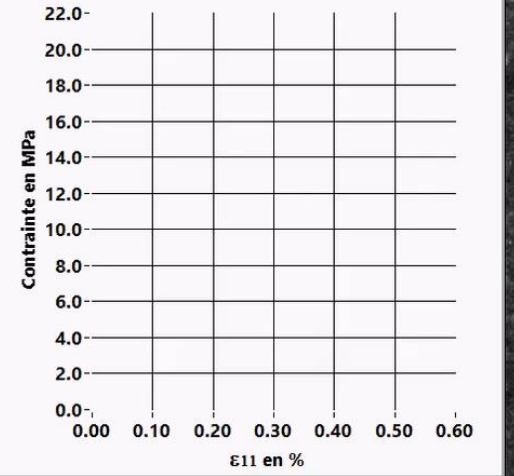
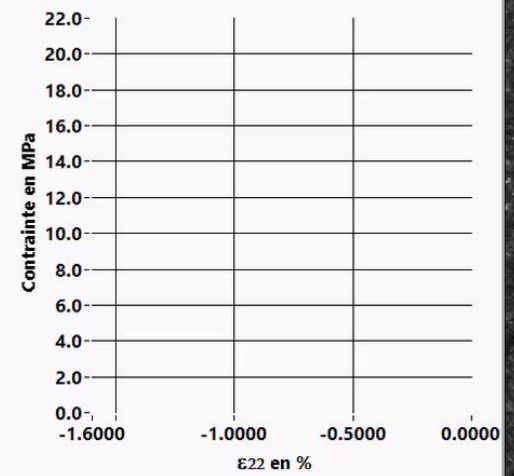
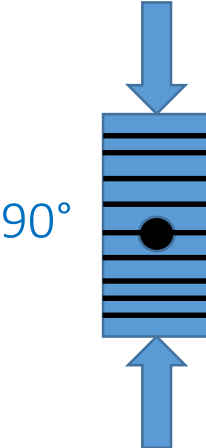
3. Results



At rupture



3. Results



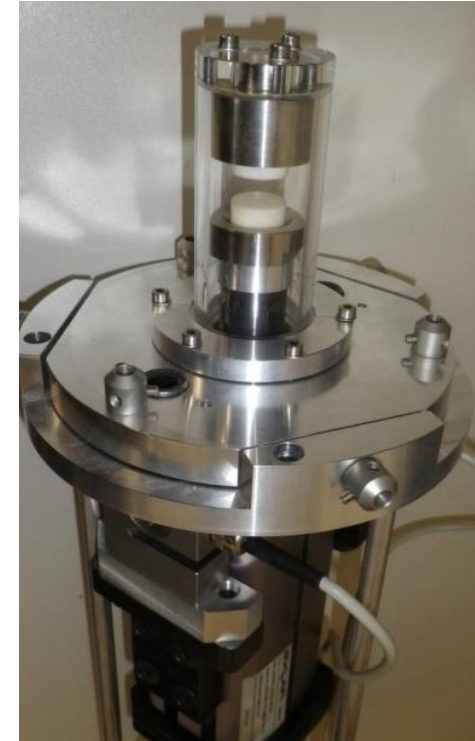
4. 3D experimental approach

3D investigation by X-ray tomography



synchrotron SOLEIL

XRCT, beamline PSICHÉ



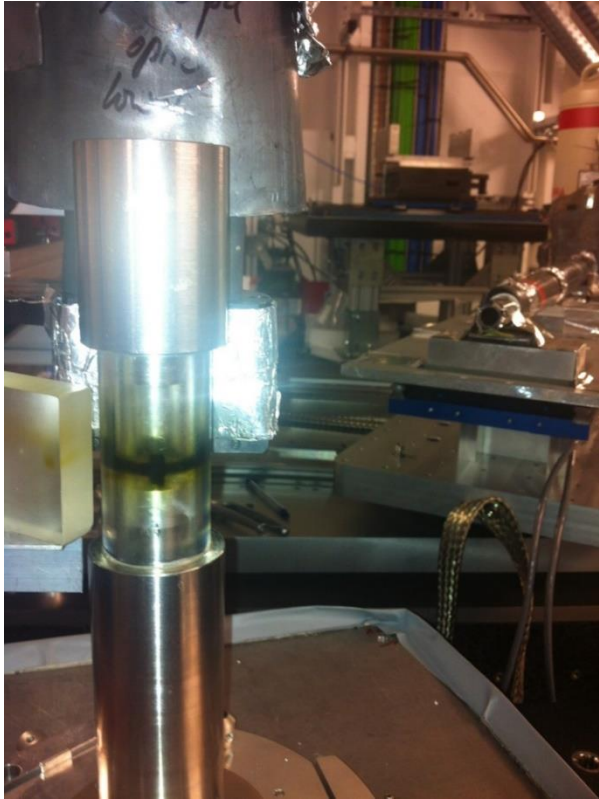
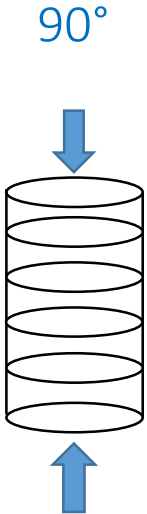
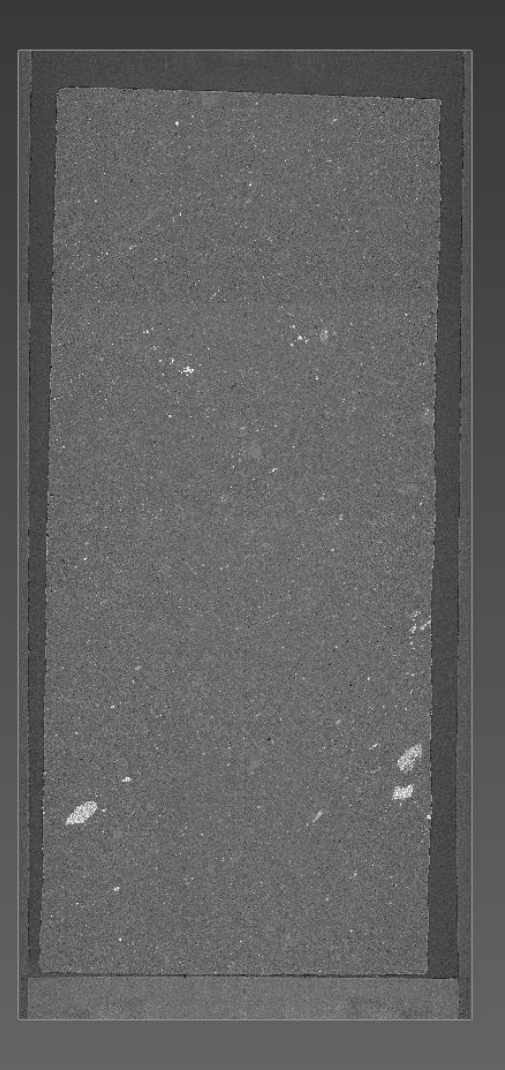
X-ray transparent uniaxial rig

V. De Greef

4. 3D experimental approach

3D investigation by X-ray tomography

Cox argilite samples
 $\phi = 3.6 \text{ mm}$, $L = 8 \text{ mm}$
 $\phi = \text{hole } 0.6 \text{ mm}$
Oriented 90°

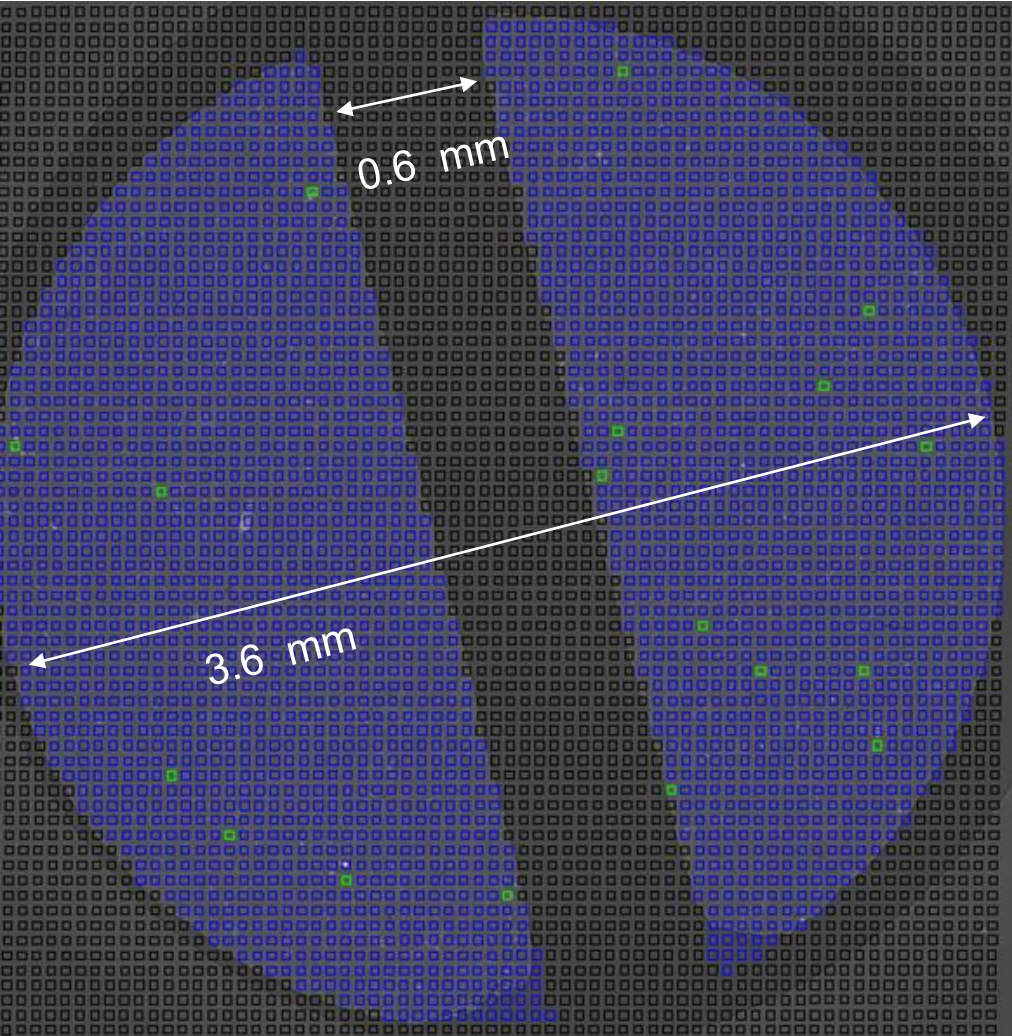
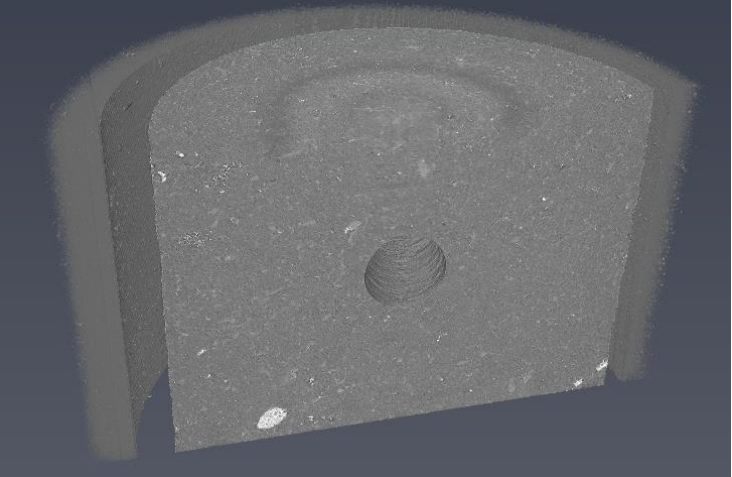


Sample mounting

4. 3D experimental approach

3D investigation by X-ray tomography

Cox argilite samples
 $\varphi = 3.6 \text{ mm}$, $L = 8 \text{ mm}$
 $\varphi = \text{hole } 0.6 \text{ mm}$



Step by step compression

Scan duration: $\approx 40 \text{ mn}$

voxel: $1.29 \mu\text{m}$

Correlation window: 40 voxels

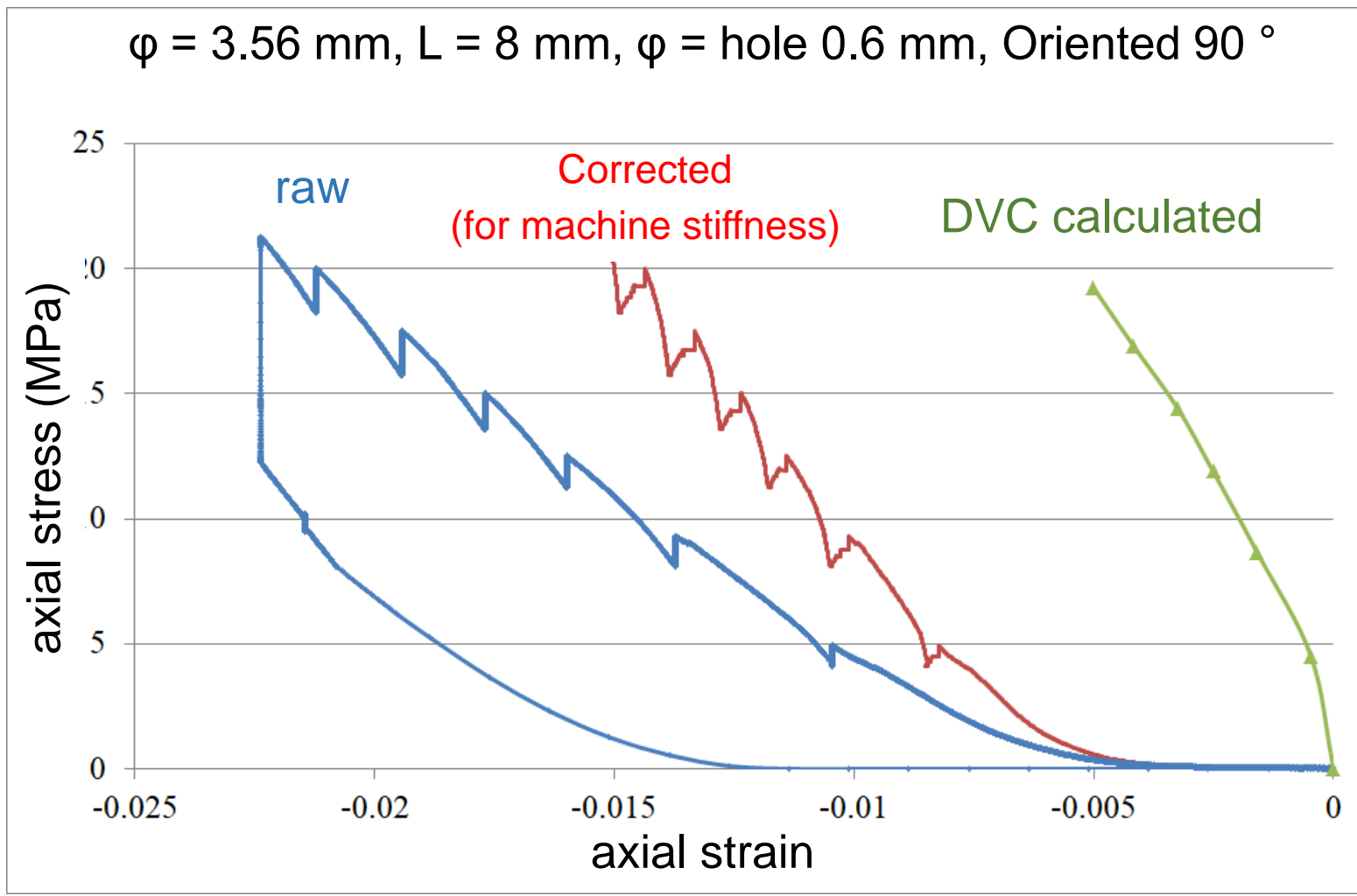
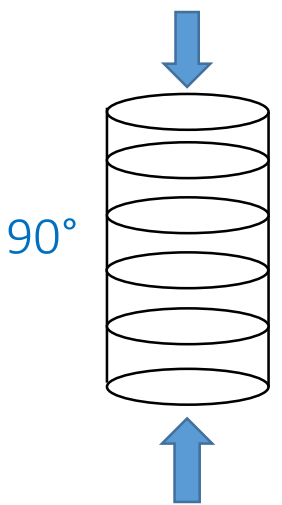
Gage length: $52 \mu\text{m}$

Volume of Interest:

$4,6\text{mm} \times 4,6\text{mm} \times 2,6\text{mm}$

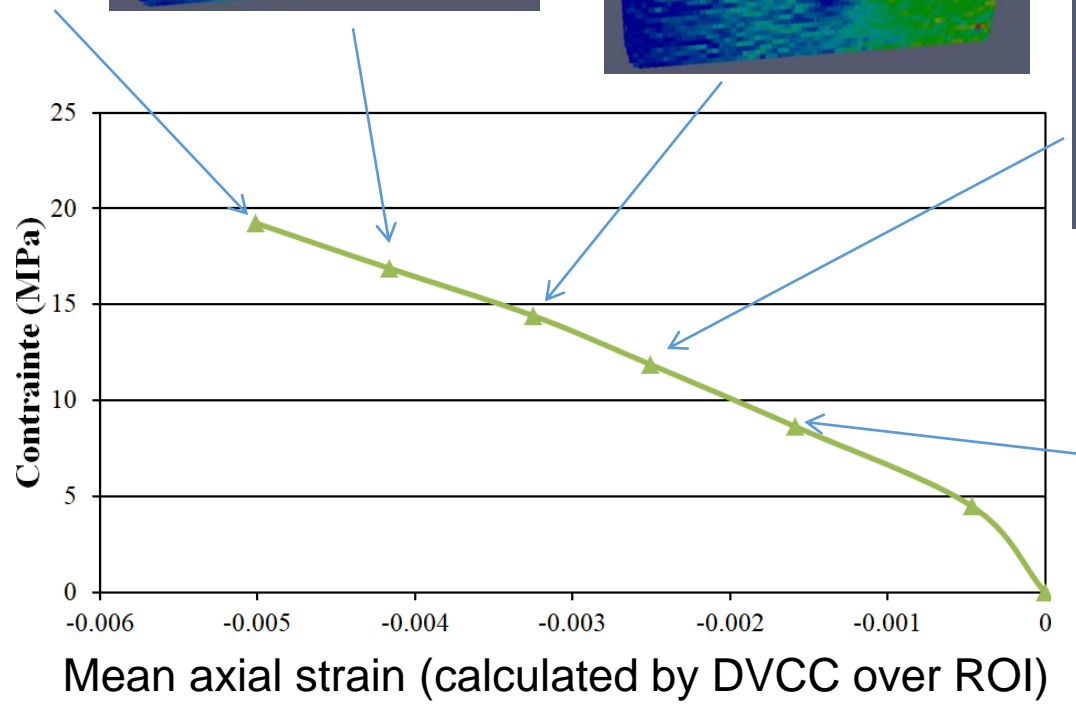
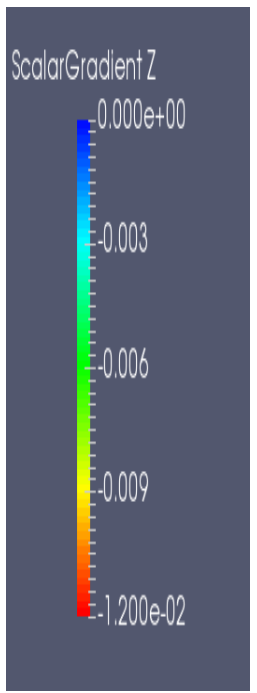
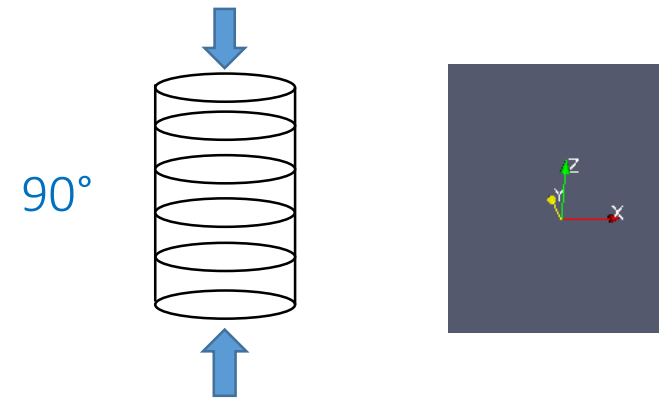
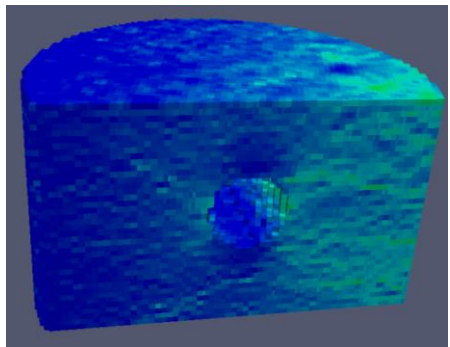
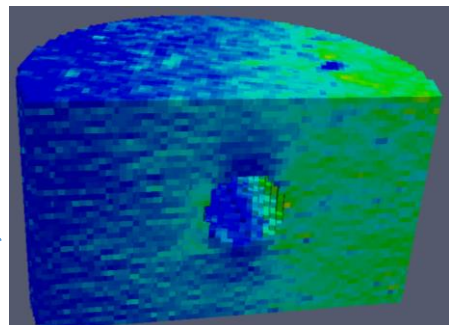
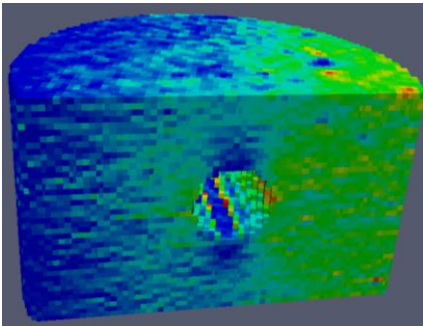
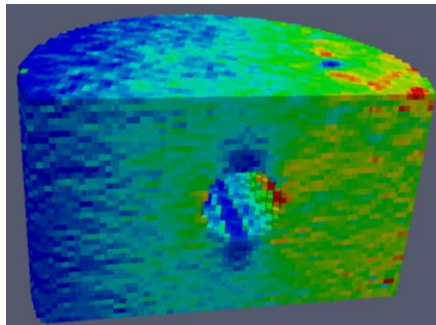
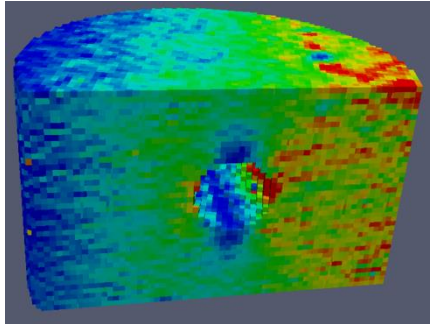
DVC soft: **CMV3D, Paraview**

4. Results



4. Results

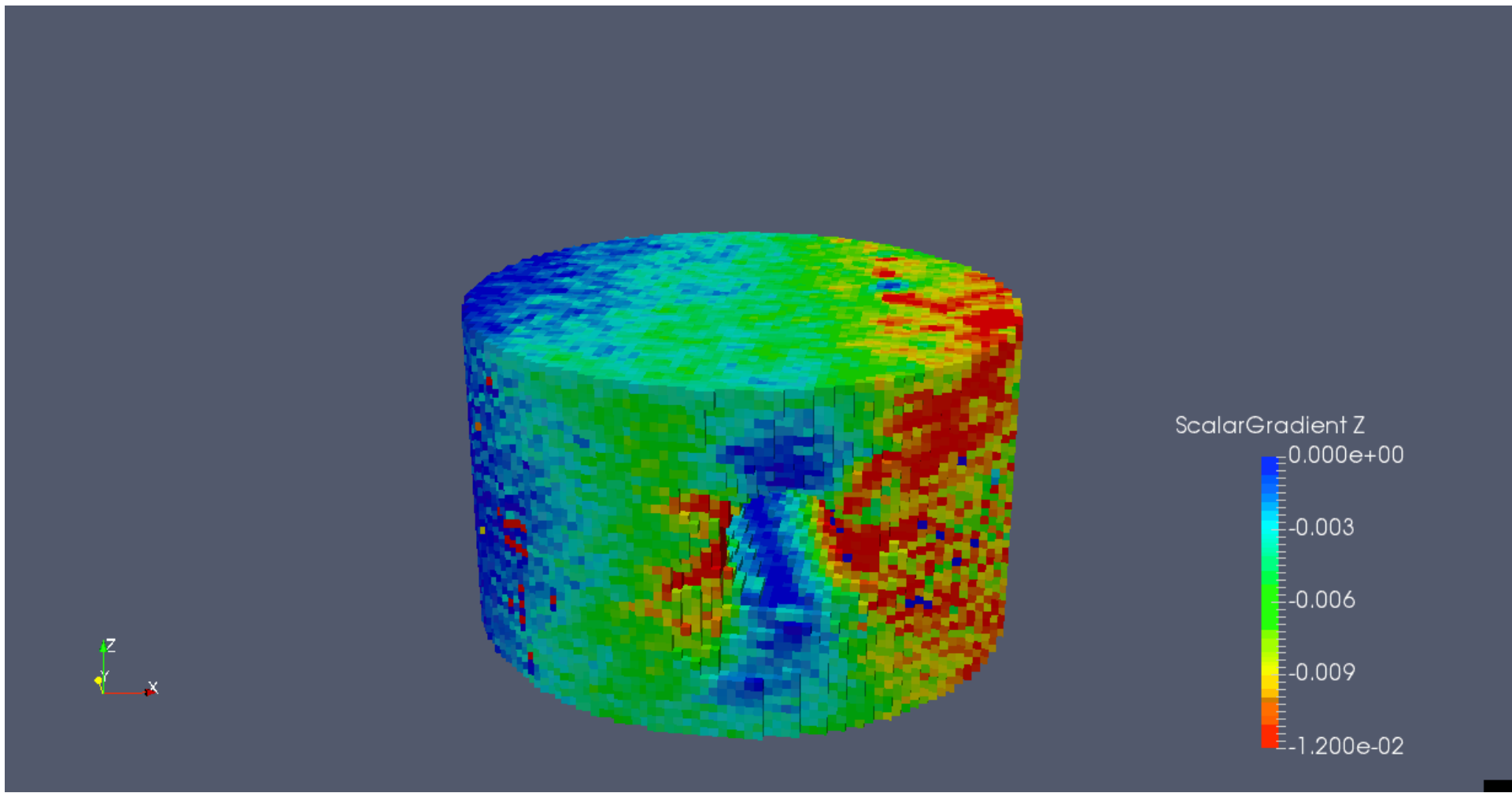
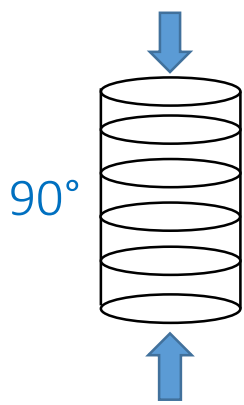
DVC calculated axial strain: step 2 to 6



Local strain gage = 52 μm

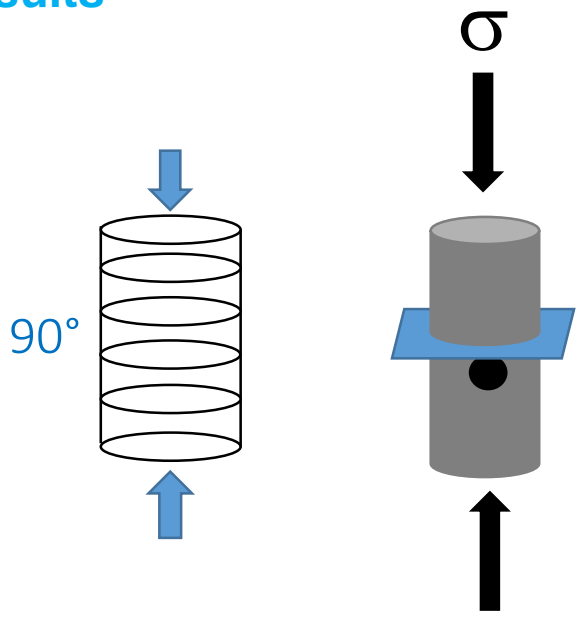
4. Results

axial strain E_{zz} : step 1 to 6

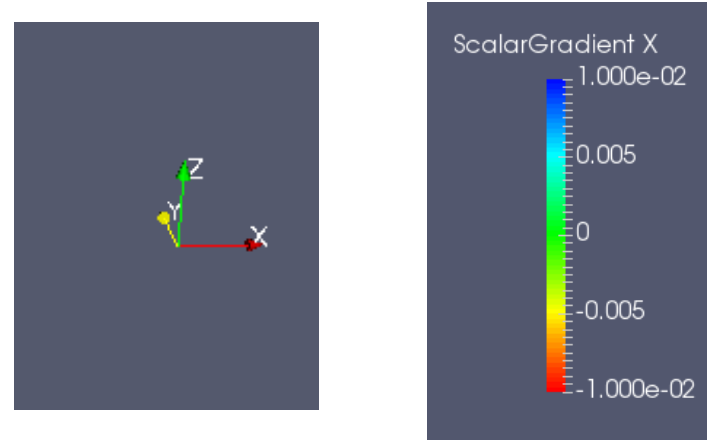


Step1 to 6

4. Results



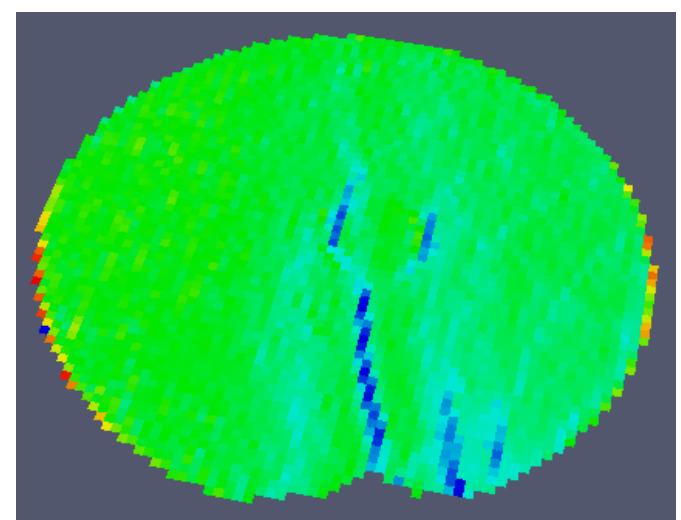
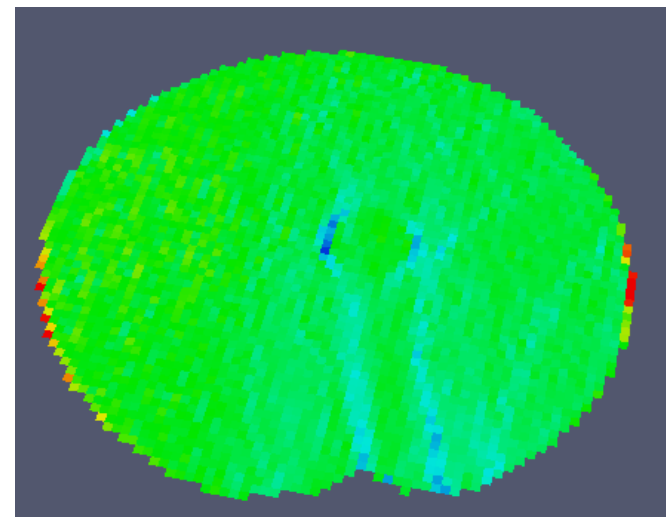
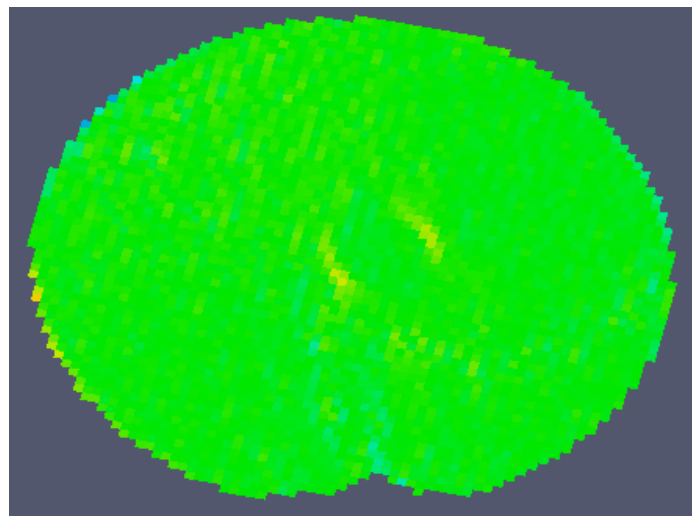
Transverse strain E_{xx}
just above hole



Step2

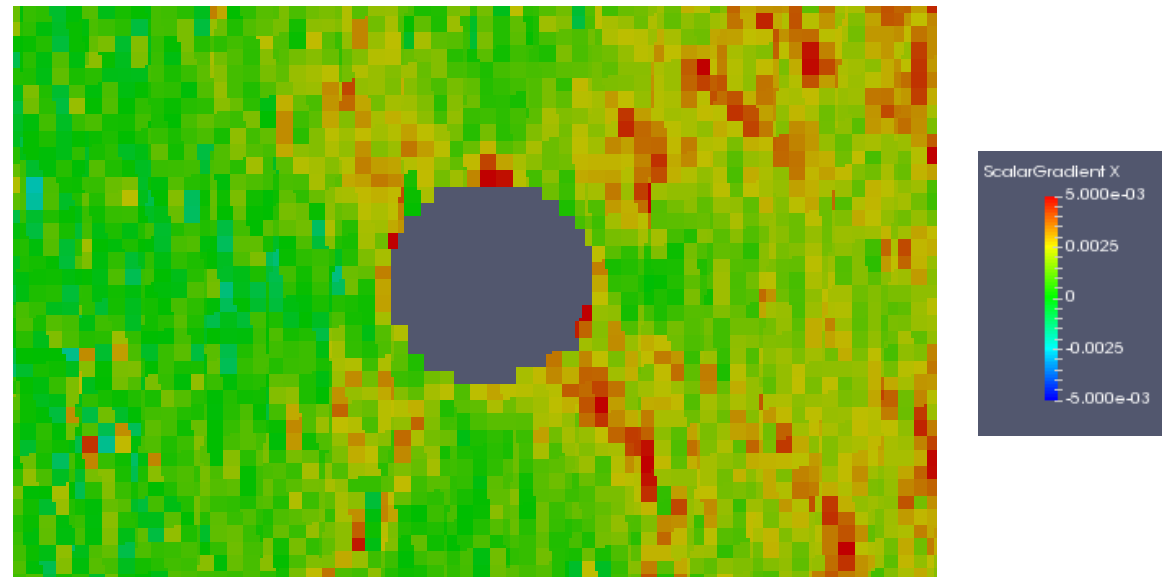
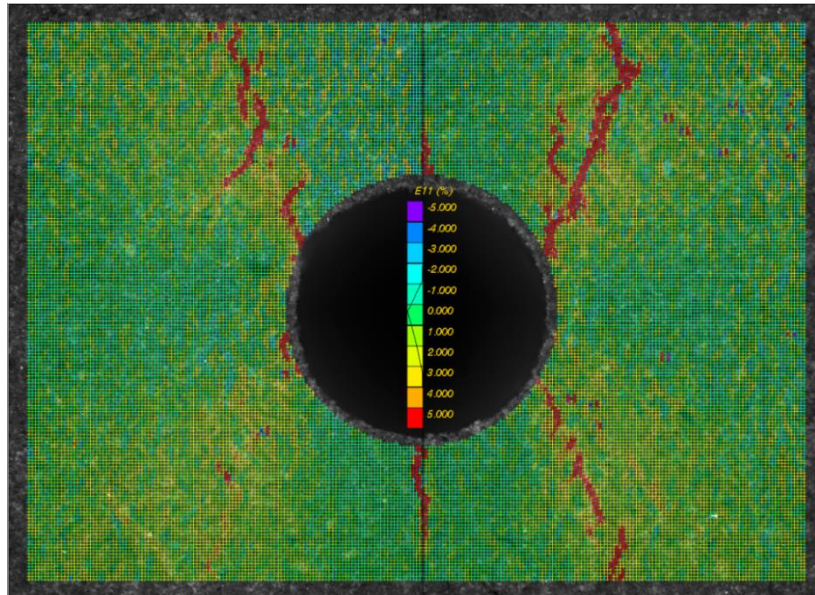
Step5

Step6



5. Conclusions

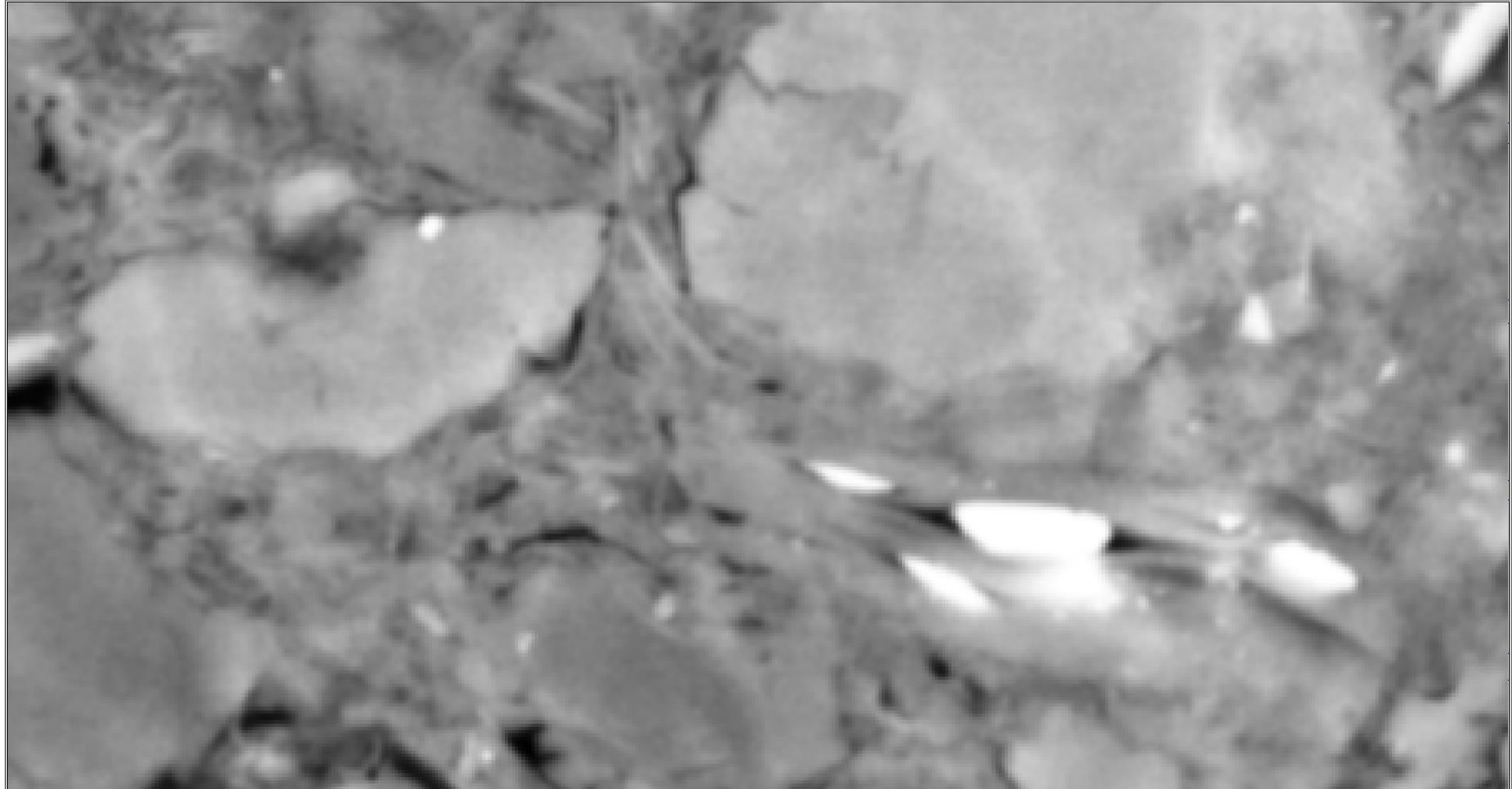
1. 2D DIC evidenced the « classical DCDC » strain field
+ the **influence of clayey rock anisotropy** on the fracture propagation pattern
2. 3D DVC qualitatively confirms the 2D observations (orientation 90°)



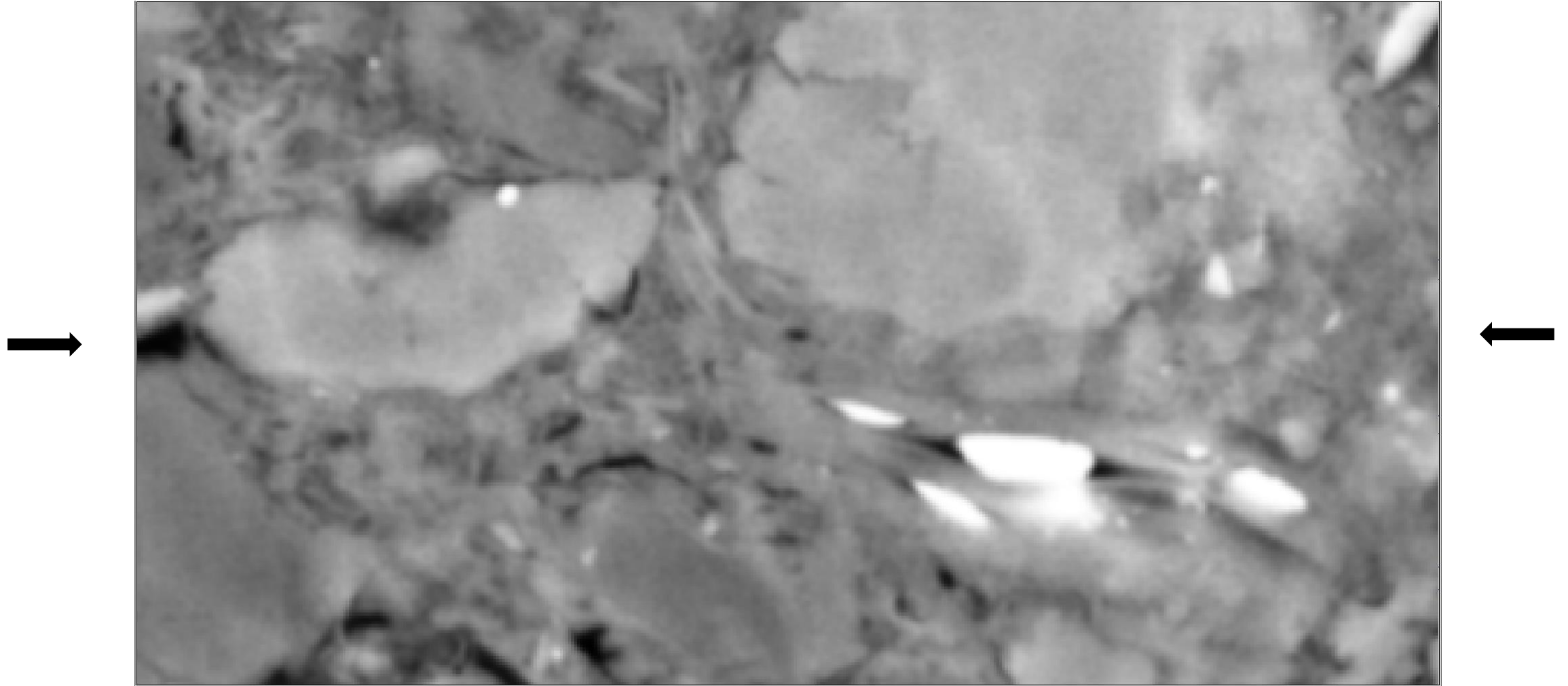
5. Conclusions & Perspectives

1. 3D investigations for other orientations
more detailed quantification of local discontinuities (improved DVC)
2. (More) Local scale investigations in E-SEM

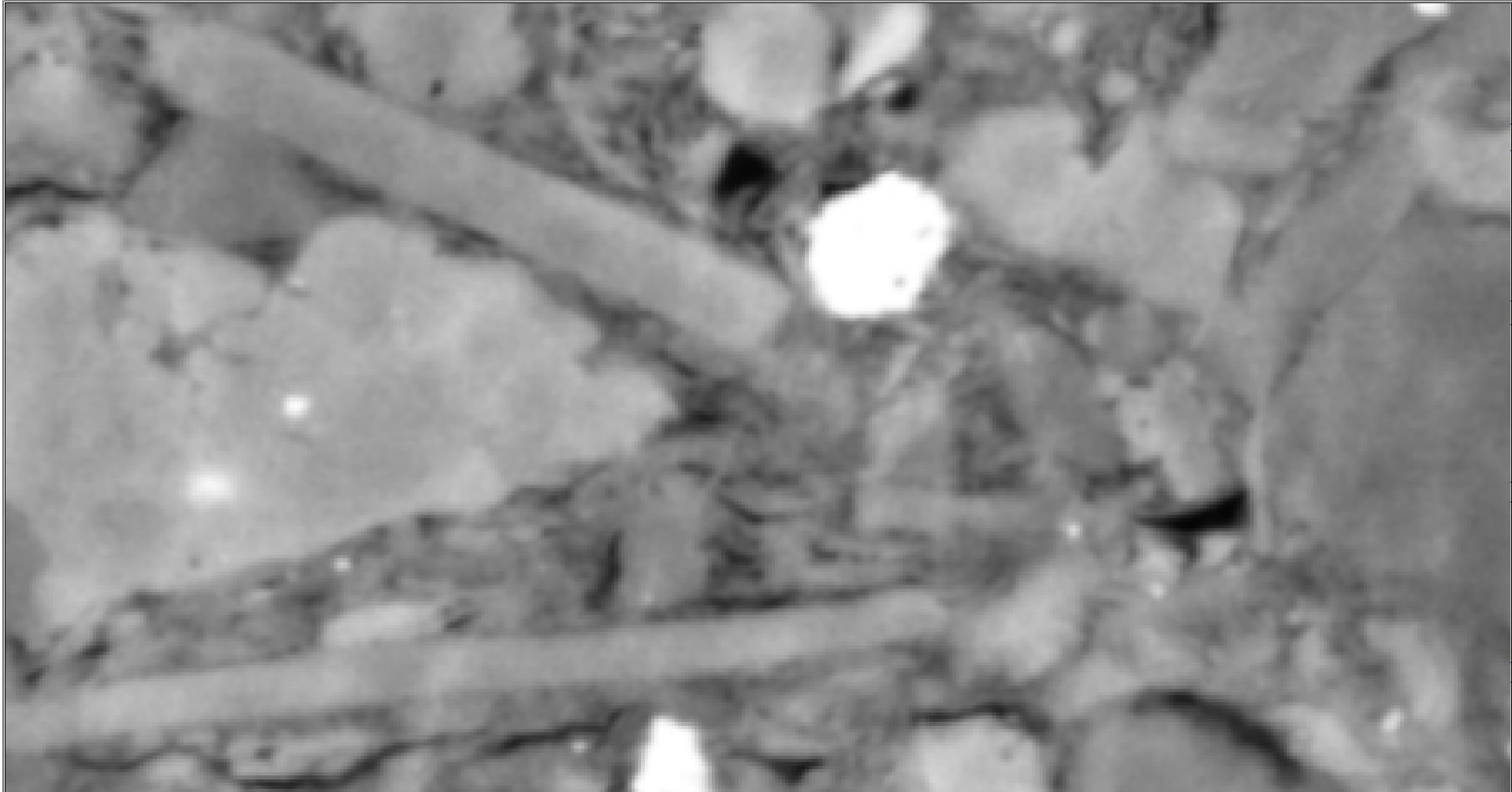
Example: ESEM uniaxial Compaction



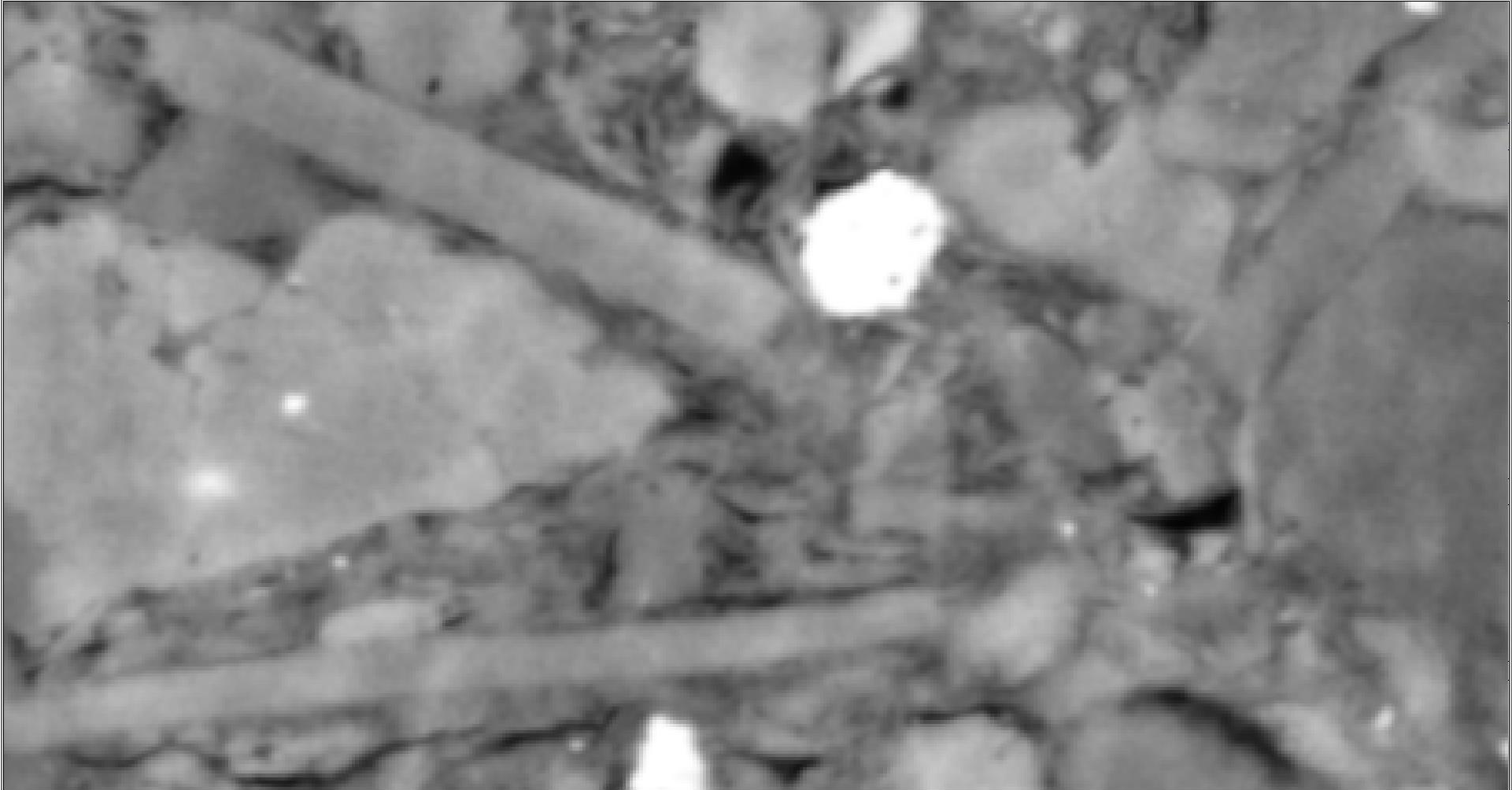
Example: ESEM uniaxial Compaction



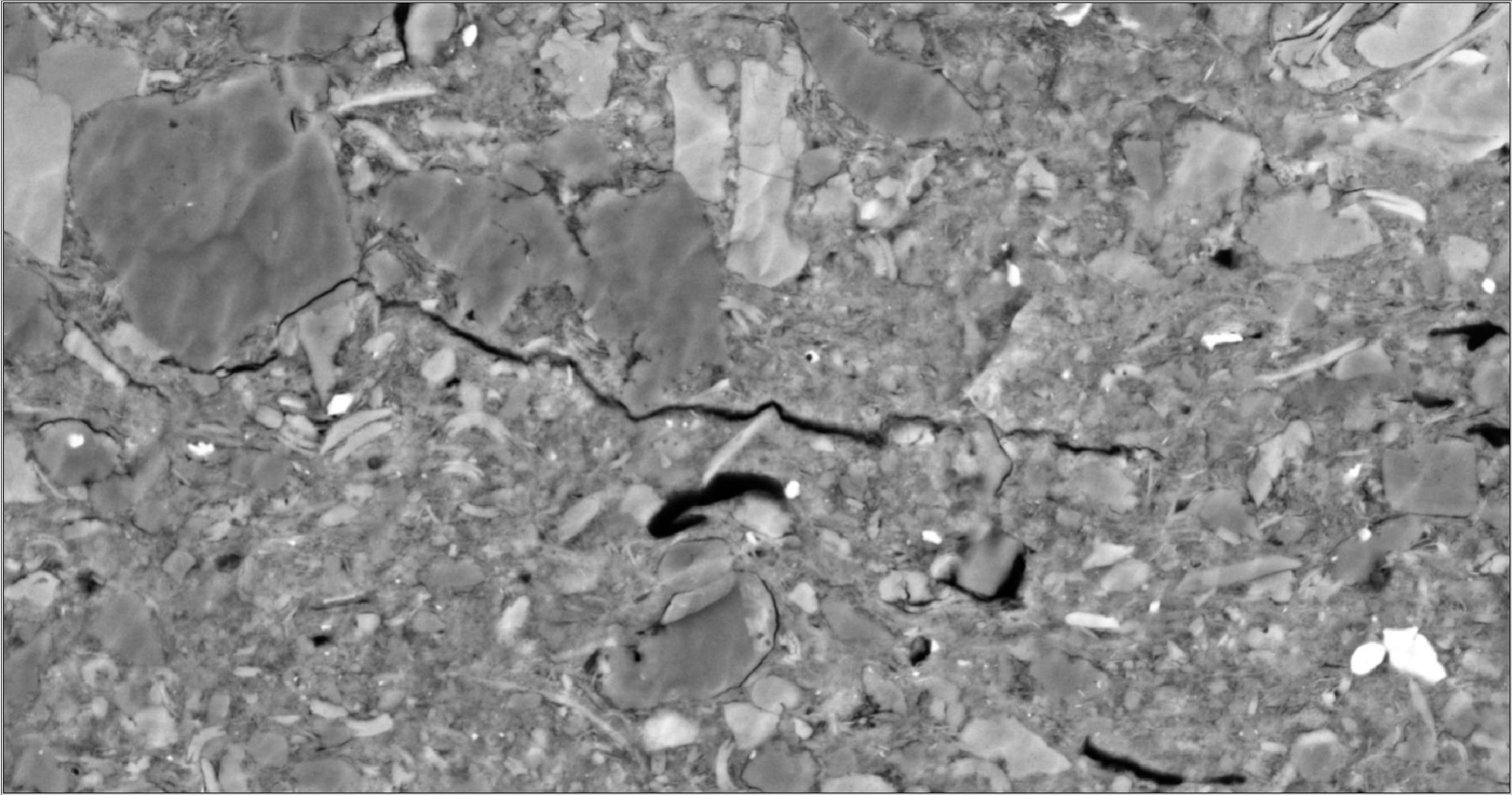
Compaction/shear



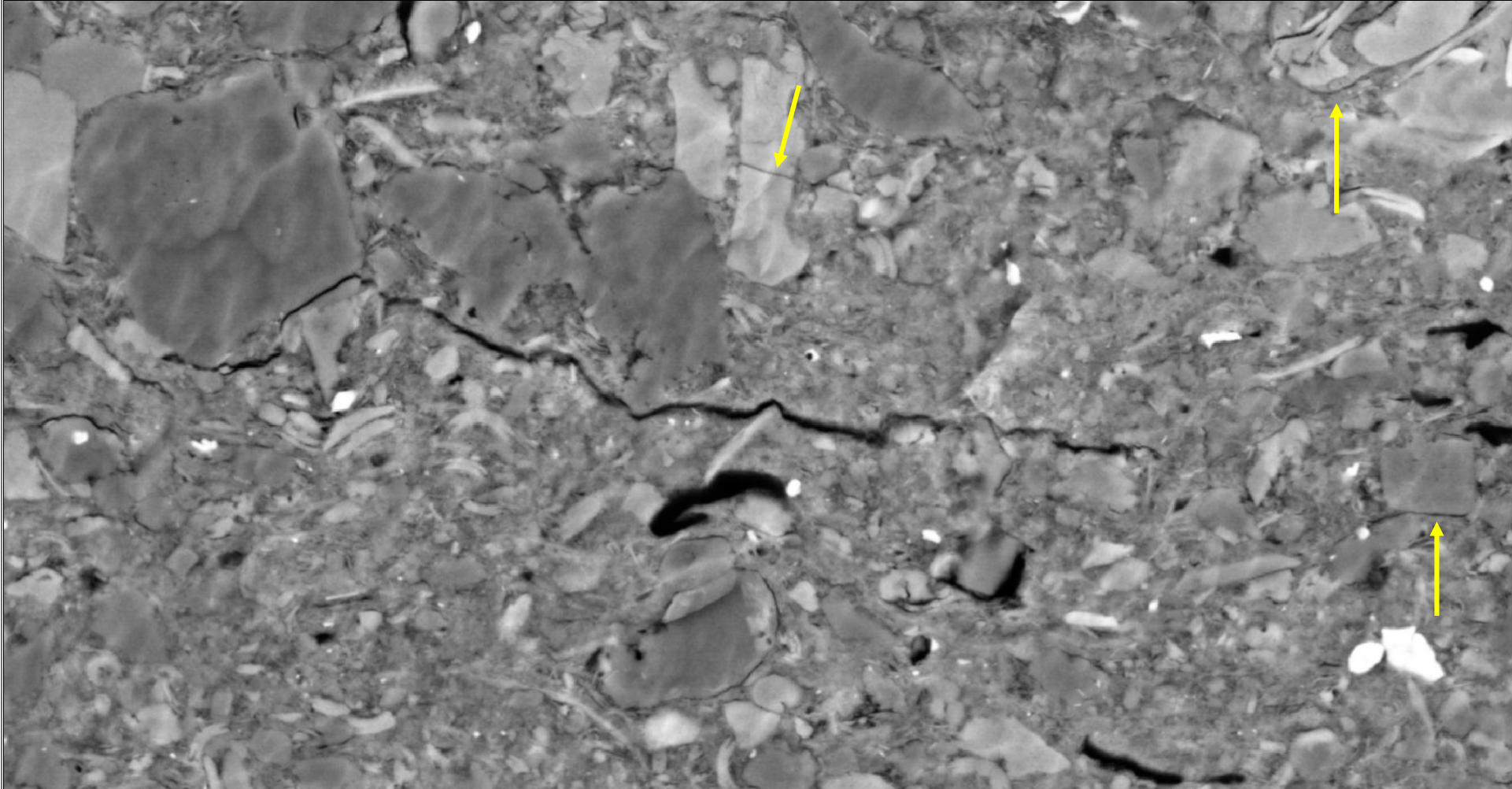
Compaction/flexion/shear



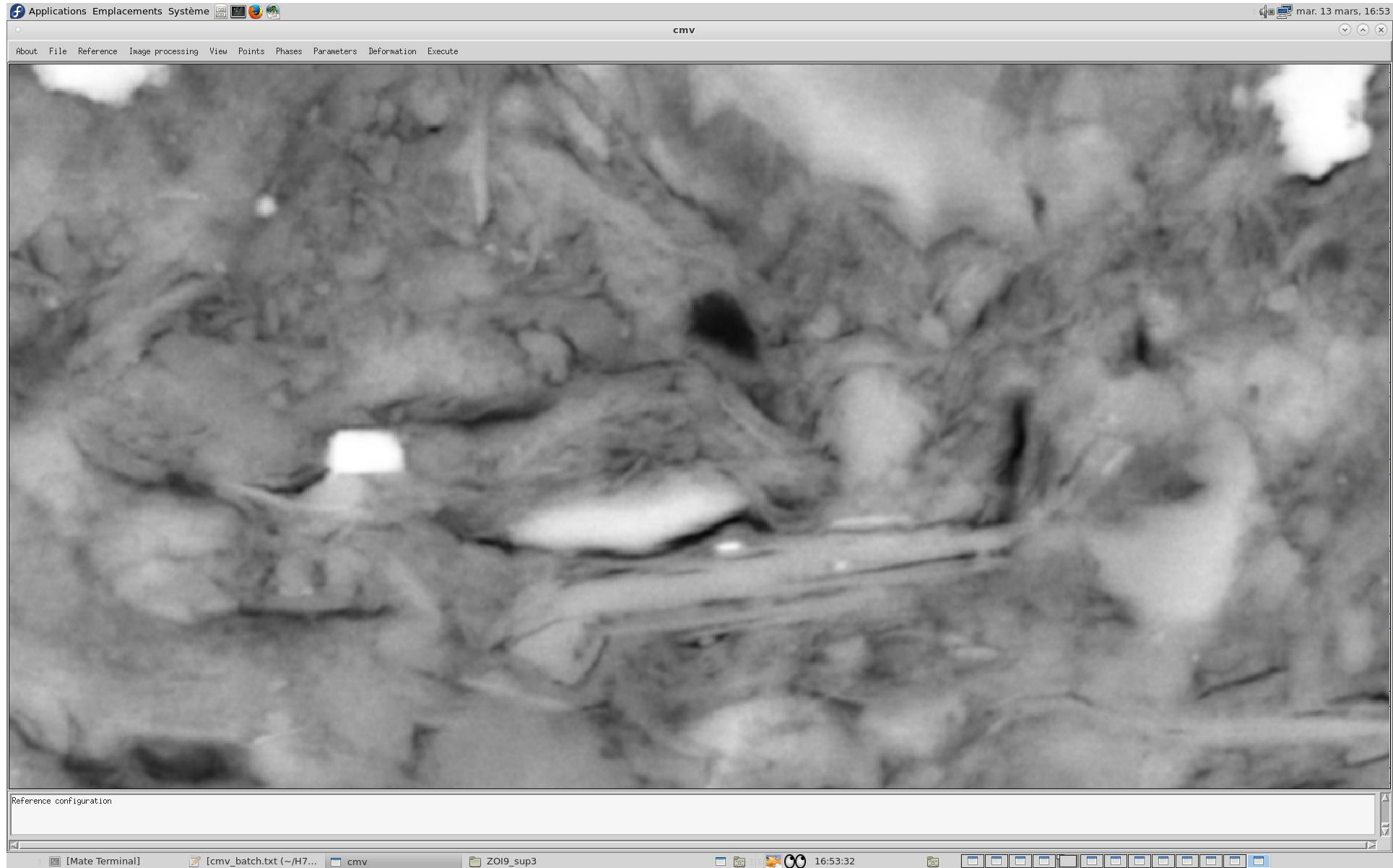
shear/compaction/opening



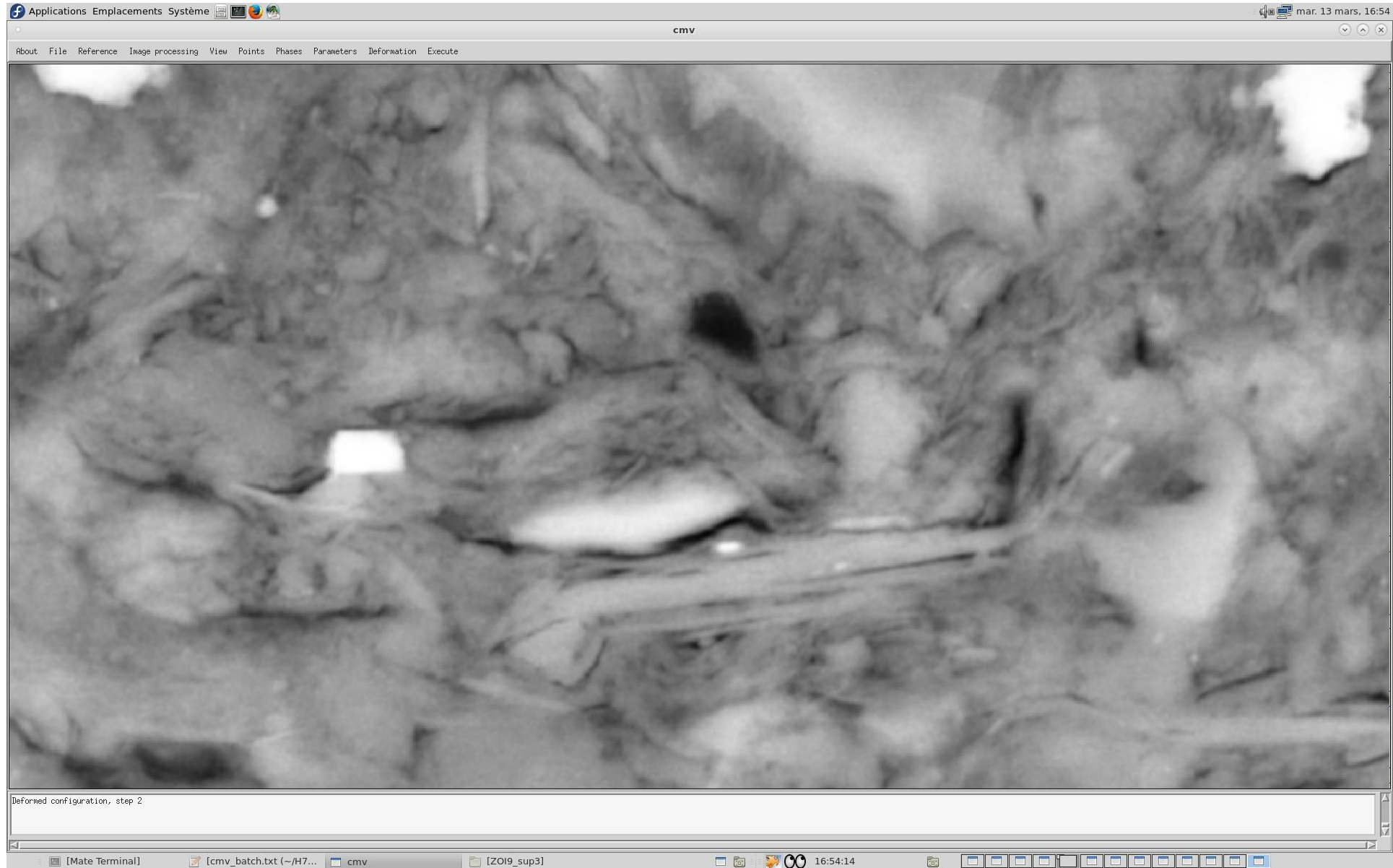
shear/compaction/opening



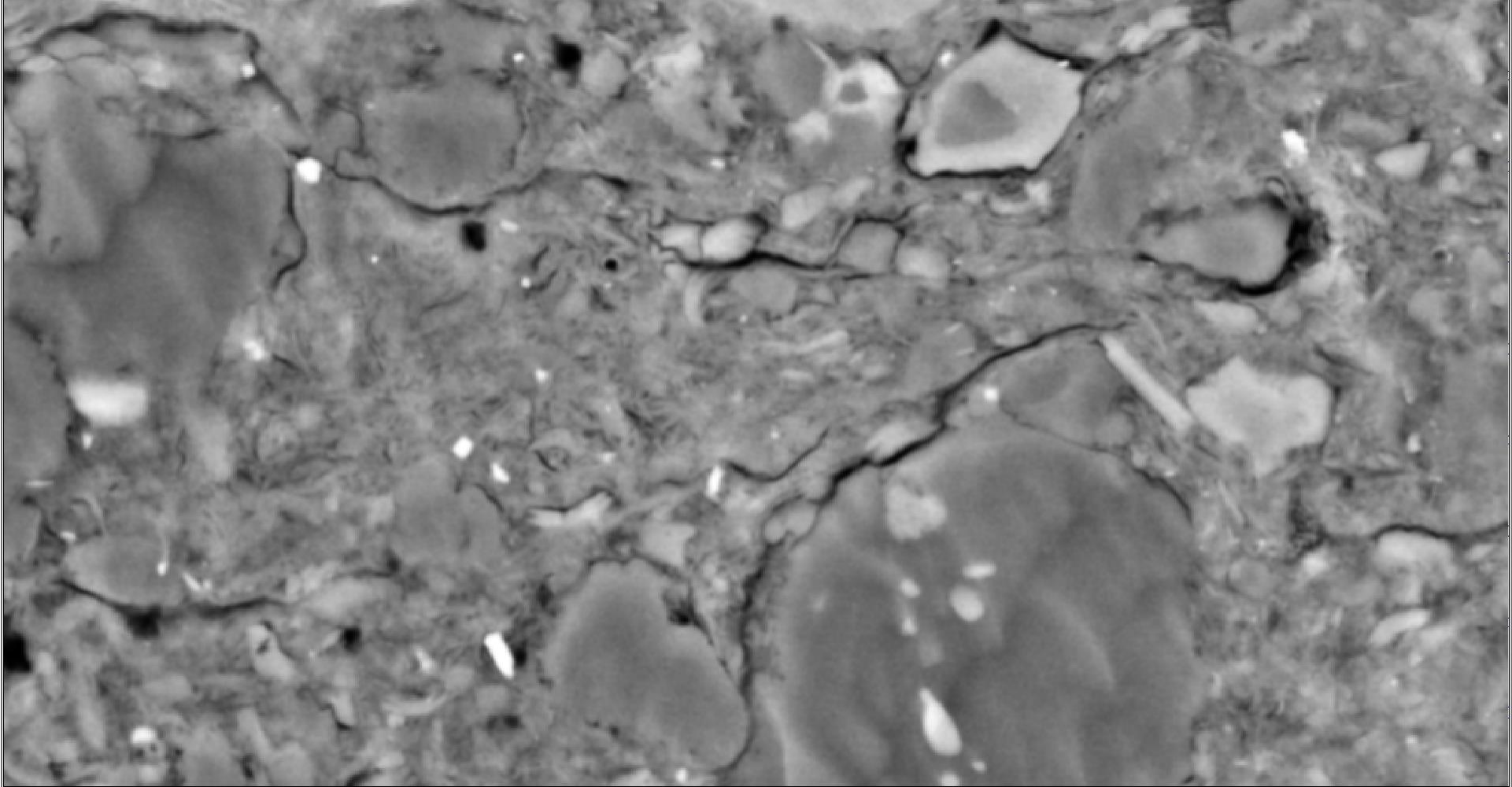
shear



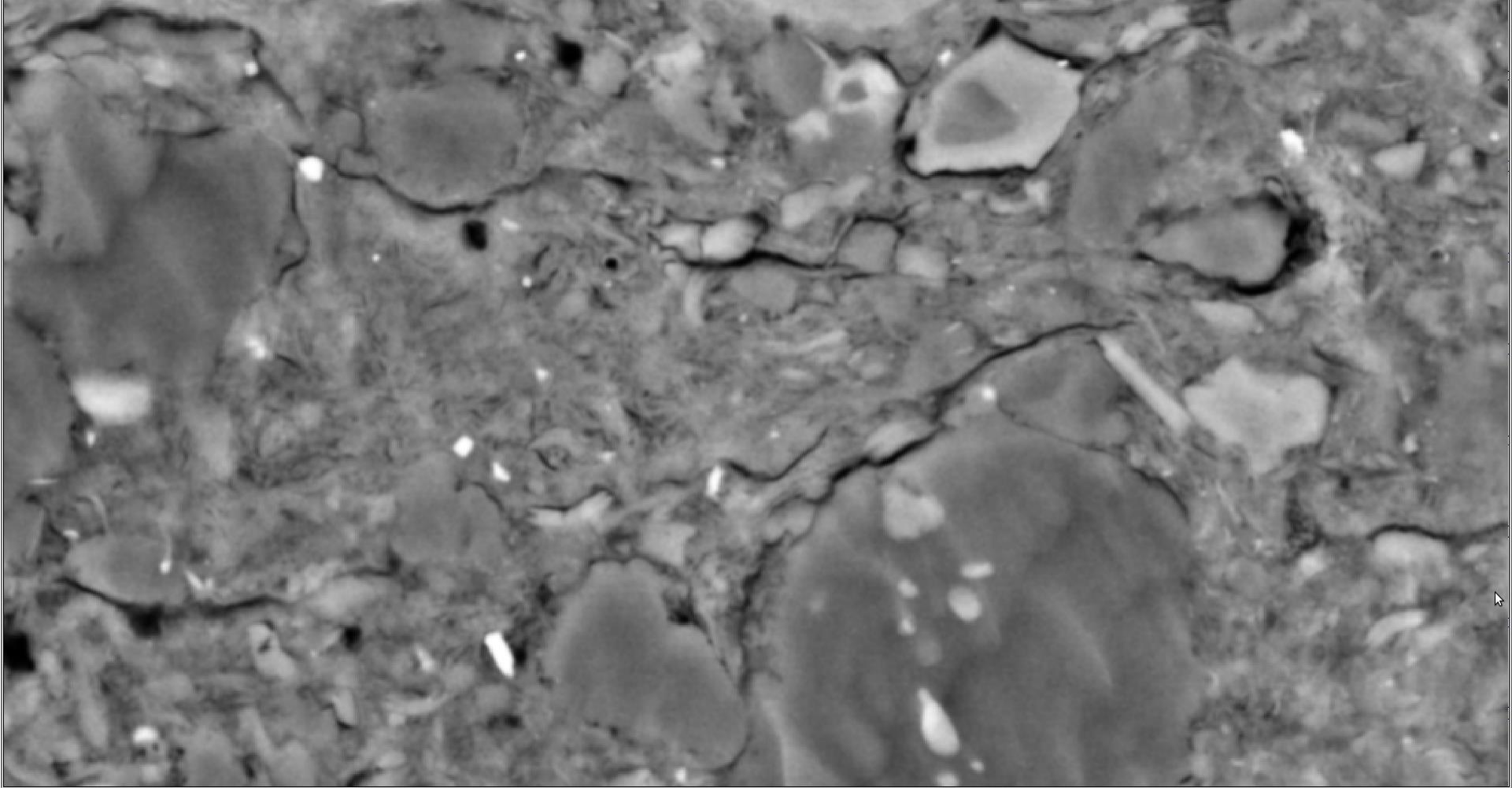
shear



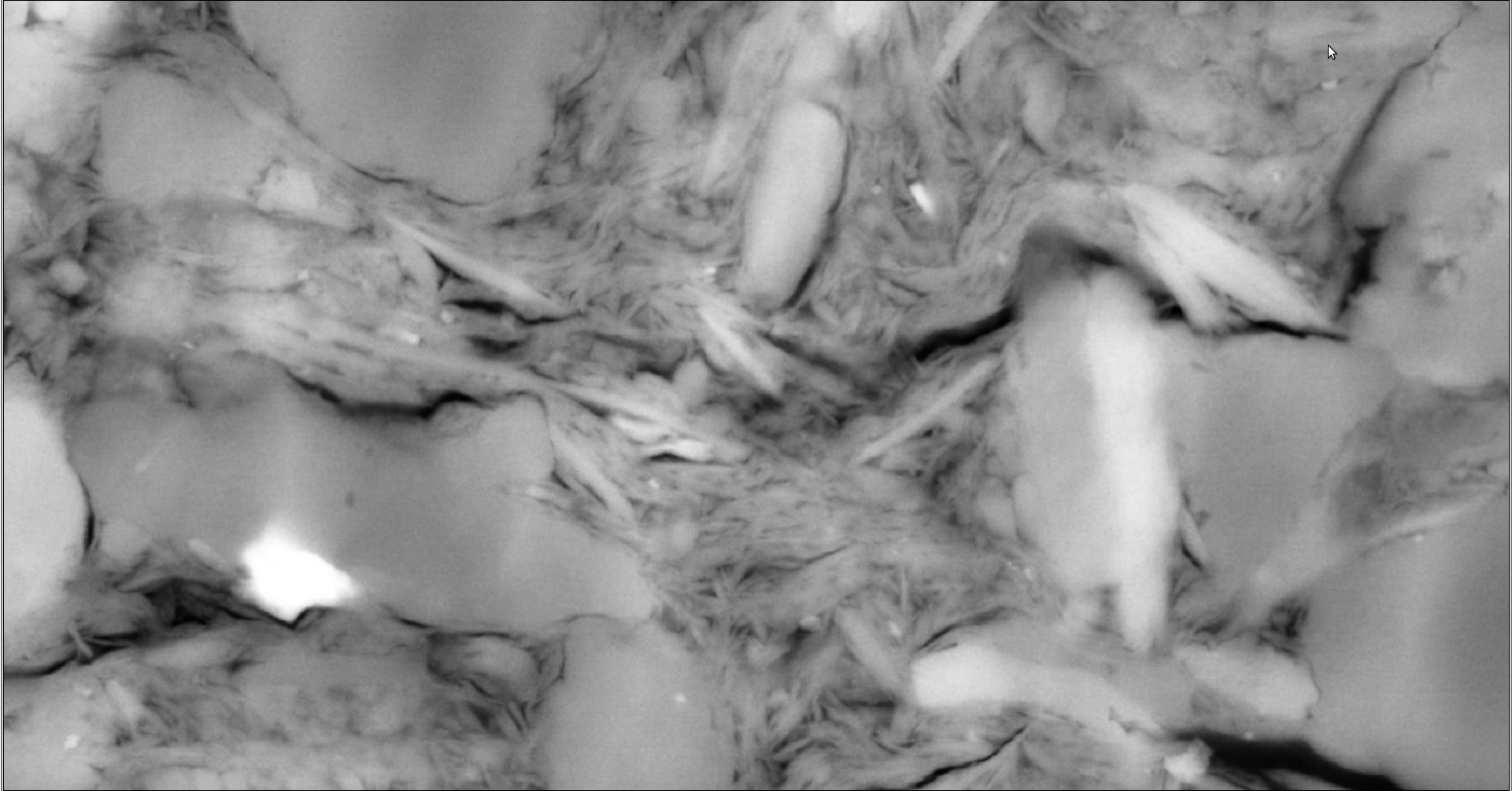
Opening/compaction



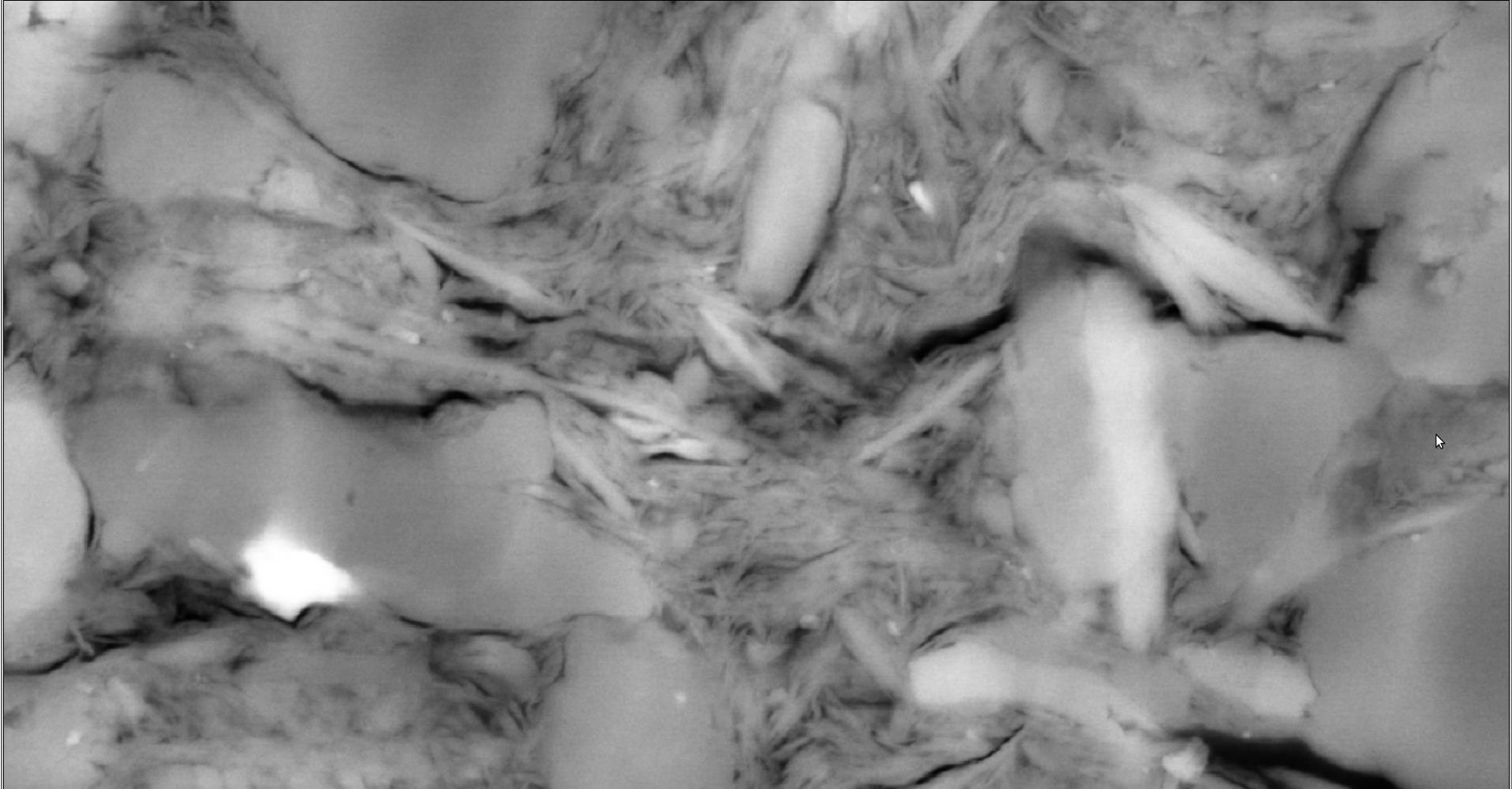
Opening/compaction



opening



opening



Essai H11 (90°)

