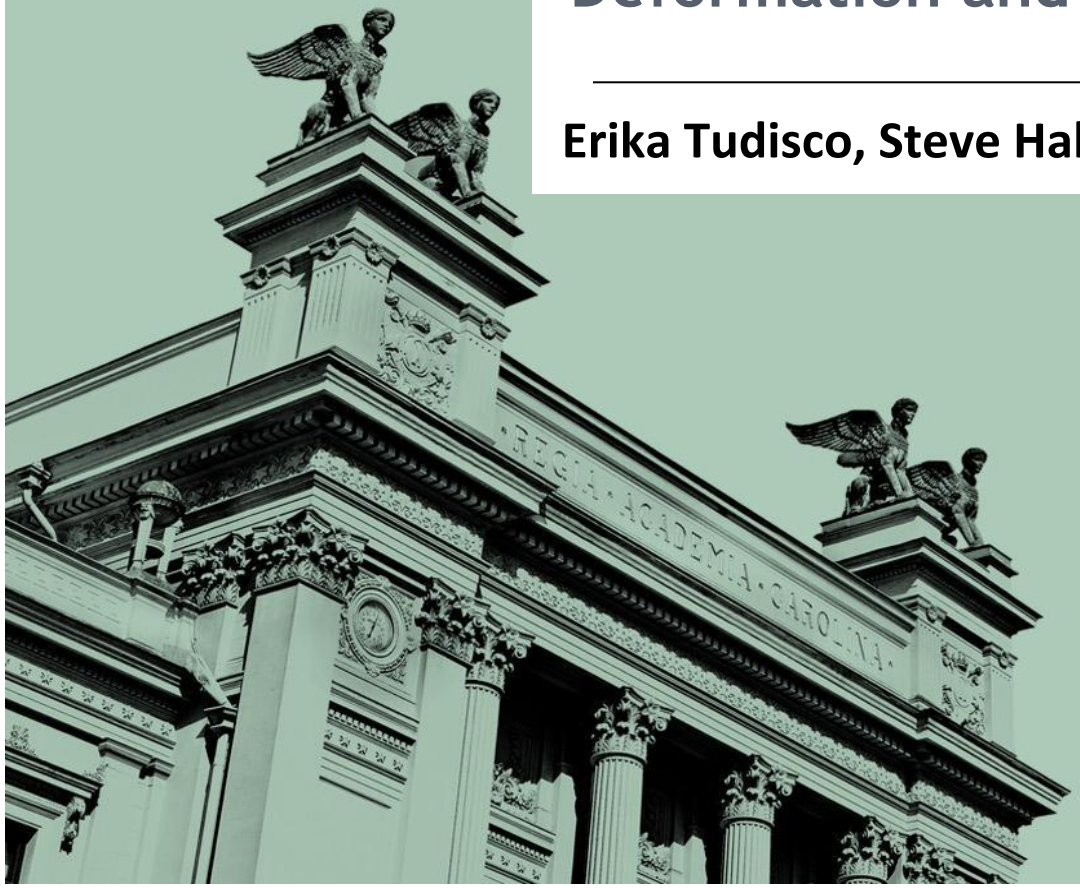
LUND UNIVERSITY

Neutron imaging in (geo)mechanics

Deformation and fluid flow in rocks

Erika Tudisco, Steve Hall, Maddi Etxegarai, Gary Couples ...



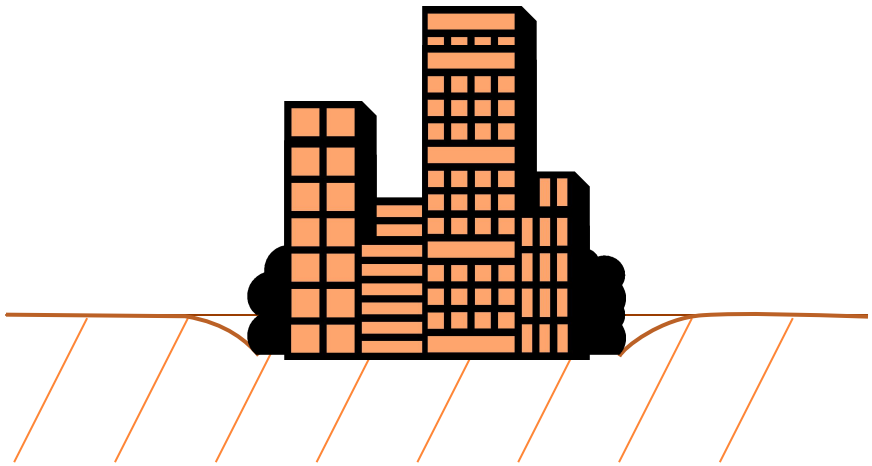
General context

What is the geomechanics?

Study of soil and rock behaviour

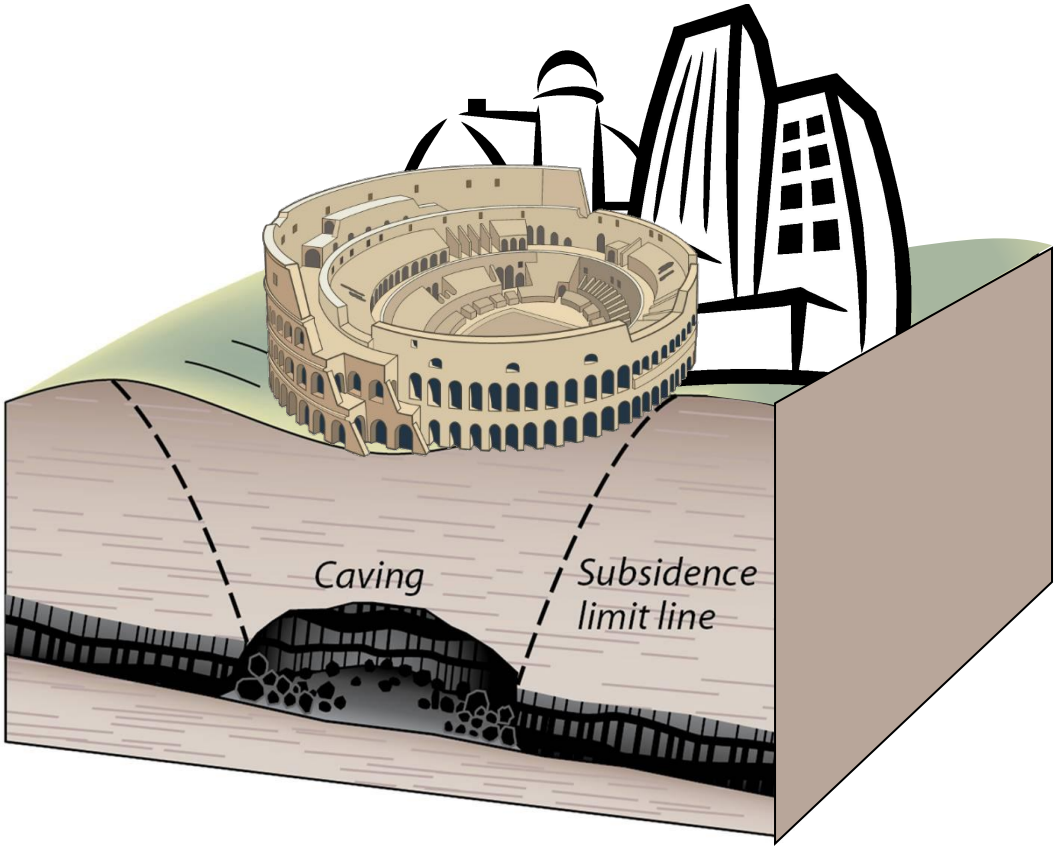
Why?

- Construction



General context

Why the geomechanics?



Taken from
http://geosurvey.state.co.us/

General context

Why the geomechanics?

The
USA

11/08/20
USA

1994 Tymfristos tunnel - Greece

General context

Why the geomechanics?

November 2007 – Yallourn, Australia

13/01/2011 - Nova Friburgo, Brazil

General context

What is the geomechanics?

Study of soil and rock behaviour

Why?

- Construction
- Excavation
- Landslide
- Gas/Oil extraction
- CO_2 sequestration

General context

Why the geomechanics?

General context

What is the geomechanics?

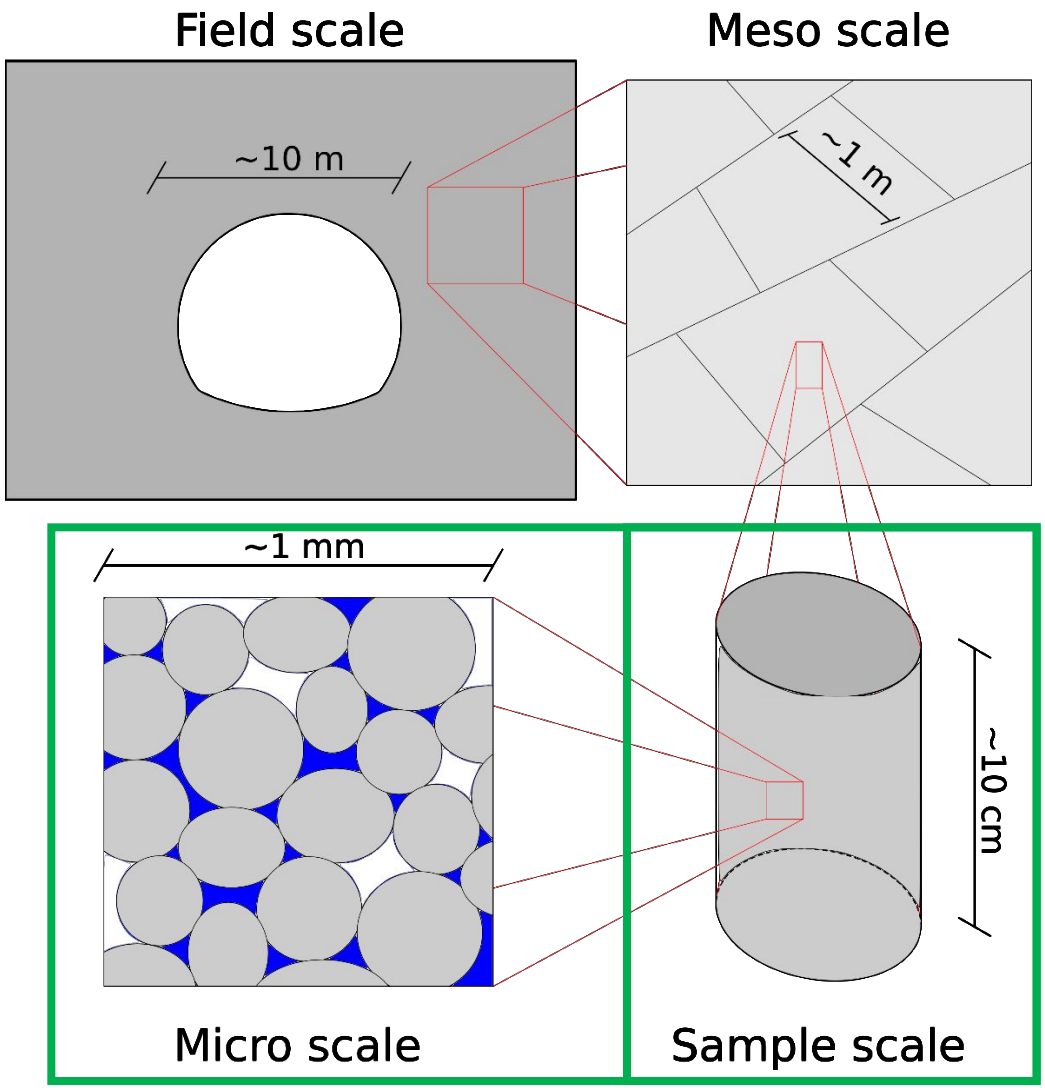
Study of soil and rock behaviour

Why?

- Construction
- Excavation
- Landslide
- Gas/Oil extraction
- CO_2 sequestration
- Nuclear waste storage

General context

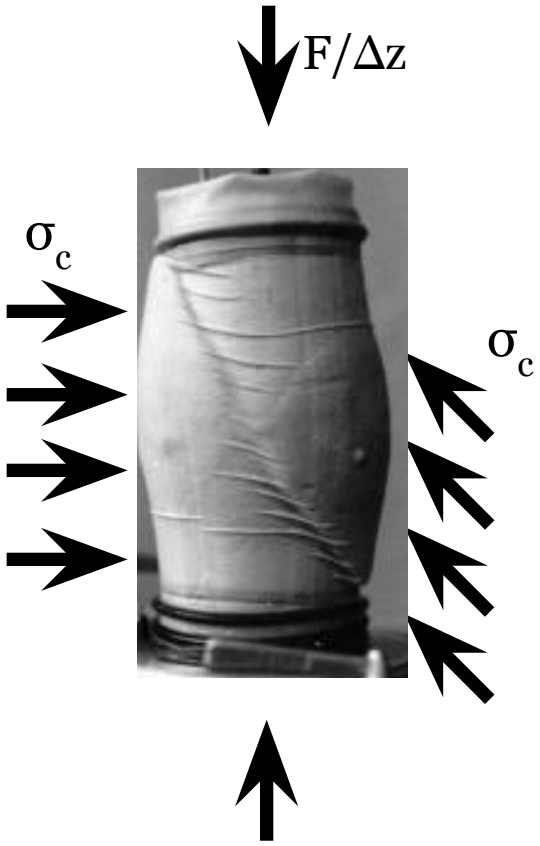
Multiscale challenge

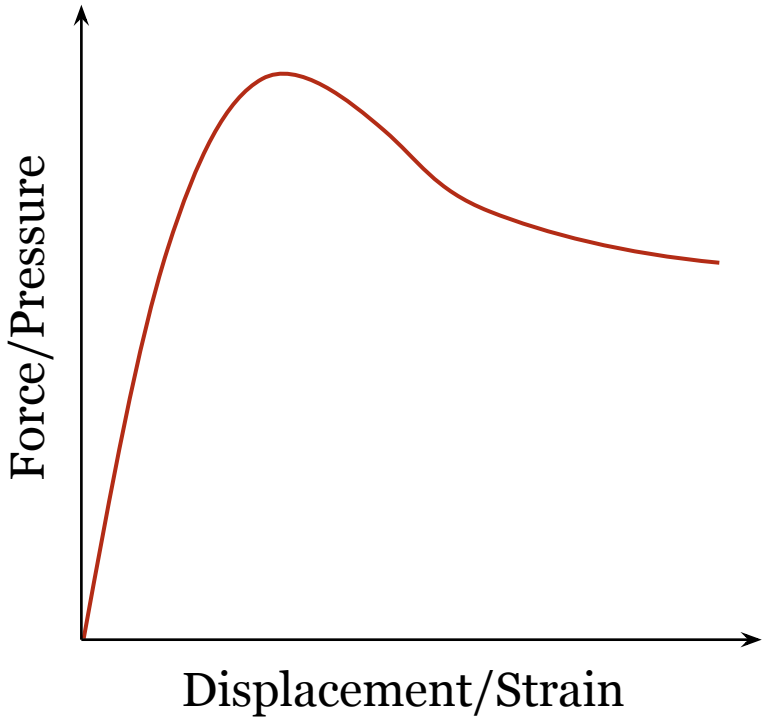


Motivations

Mechanical characterisation tests

Triaxial compression test



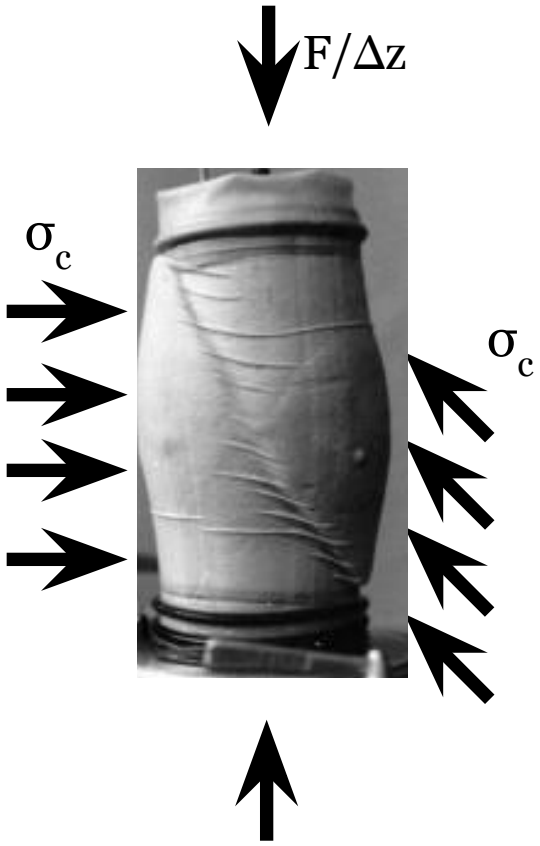


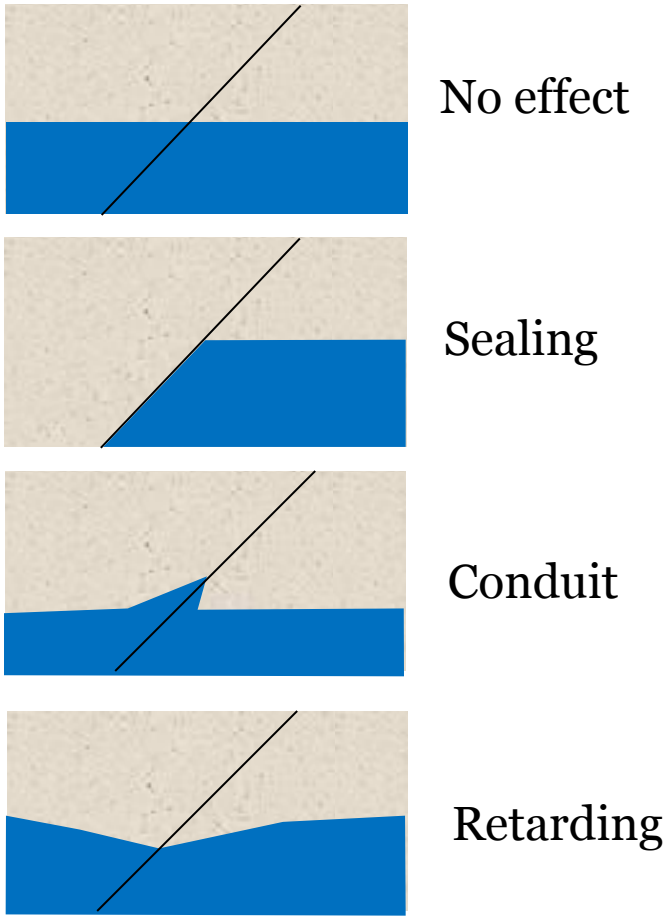
$$\sigma = \underline{C}\,\varepsilon$$

Motivations

Mechanical characterisation tests

Triaxial compression test





Motivations

The Challenge:

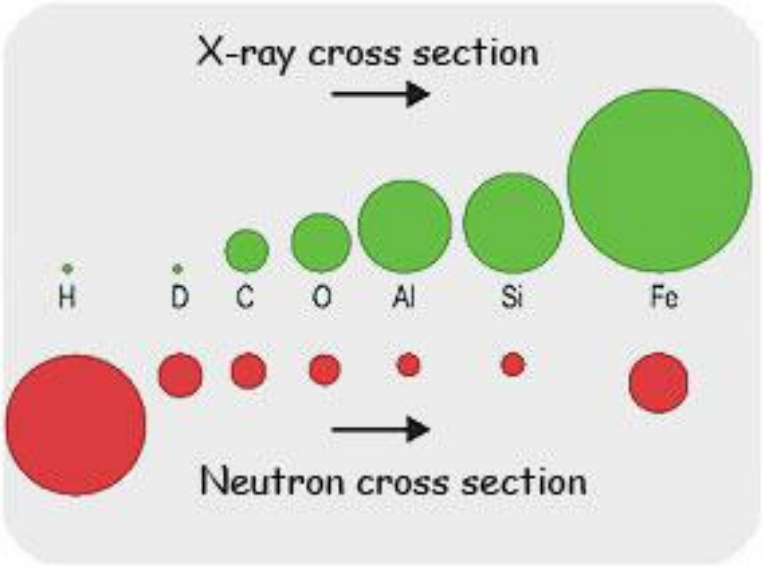
To develop appropriate tools for full-field quantification of **localised deformation** and its effect on **fluid-flow** in rocks under pressure

- Requires a technique that can

1 - see inside a test specimen of “reasonable” dimensions
2 - see the fluid distinctly from the solid part
3 - penetrate the walls of a (high) pressure cell

Motivations

X-ray “vs” neutron imaging



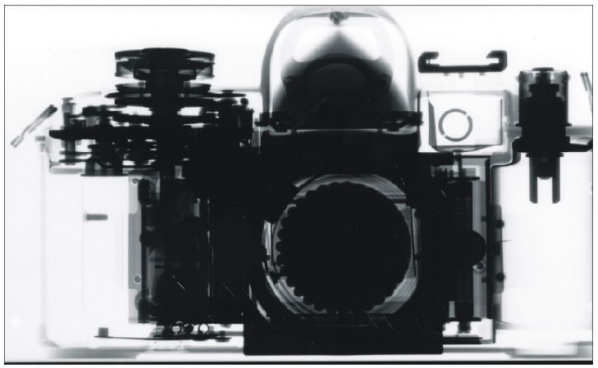


Fig. b: Radiographic image of a camera made X-rays

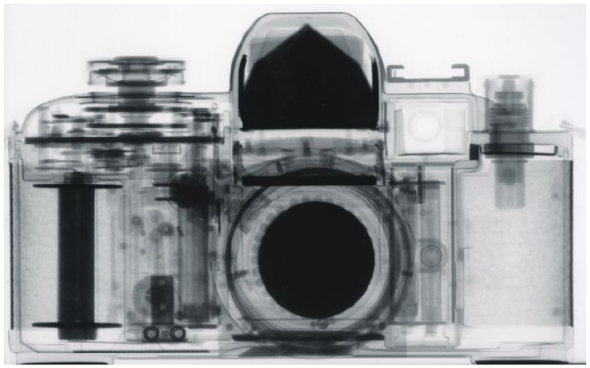


Fig. a: Neutron radiography of a camera

X-ray

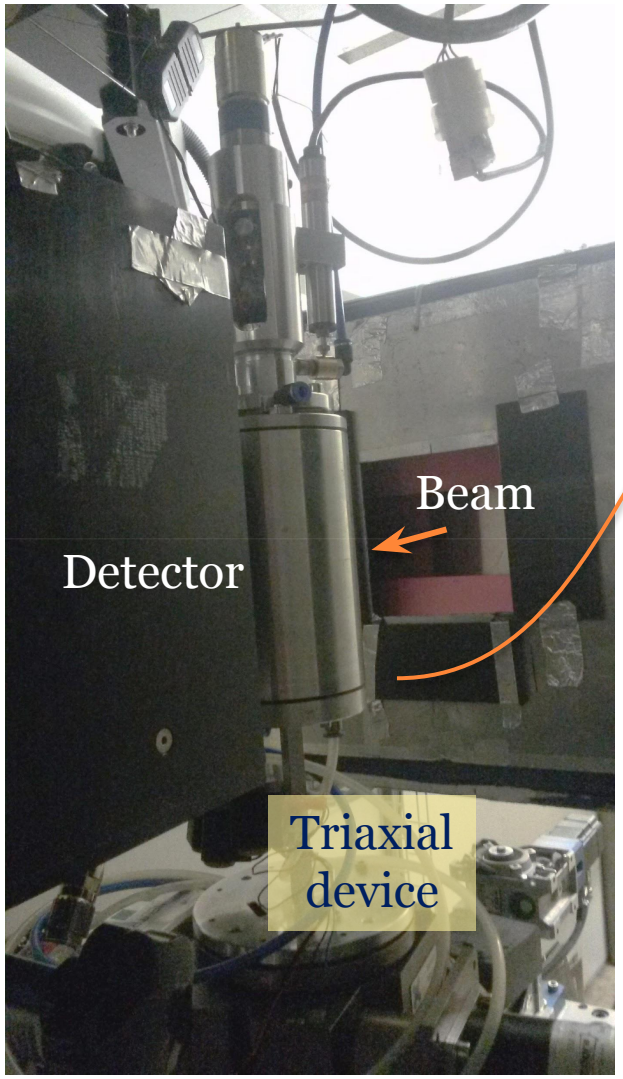
Bronze Buddha

Neutrons

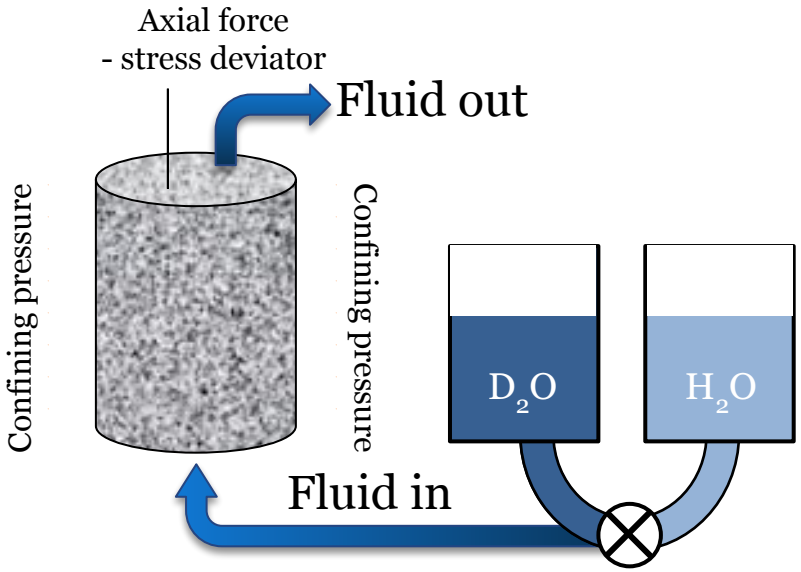
Neutrons advantages:

- Better penetration through metals
- Higher contrast for Hydrogens
- Isotopes can be distinguished

Deformation + Flow



In-situ 4D Imaging (NEUTRA@PSI)

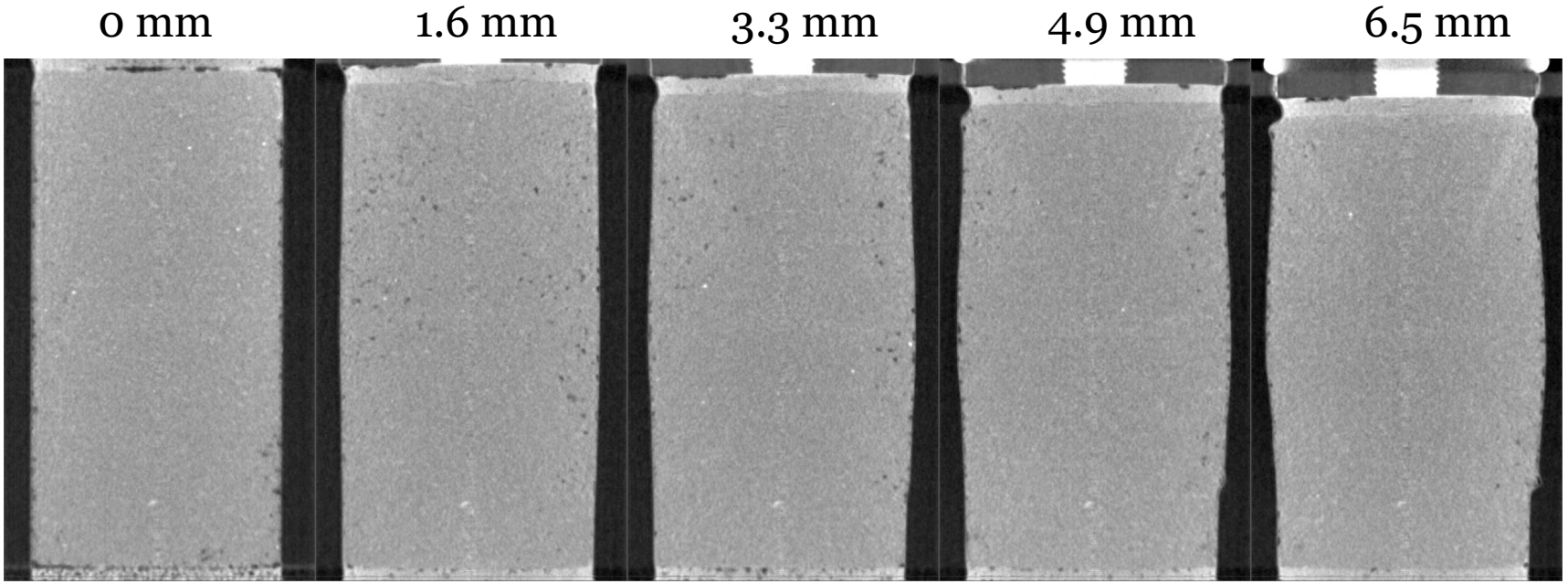


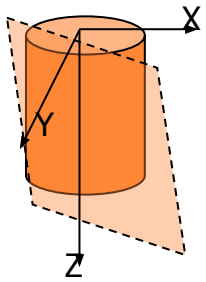
- Ottawa sand cemented with Ordinary Portland Cement
- In-situ triaxial loading
  - loading stopped for imaging
  - P_c < 1 Mpa (aiming for higher)
- Pressure control on fluid-in and -out
- Sample saturated with D_2O during loading
- Flooding with H_2O at each load step

Deformation + Flow

In-situ 4D Imaging (NEUTRA@PSI): deformation evolution

Slices through 3D tomographic images after each load step



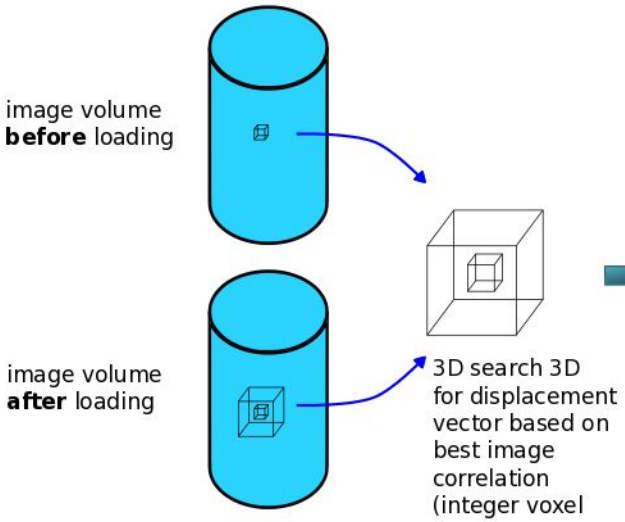


(Vertical slices through middle of volume perpendicular to main localisation)

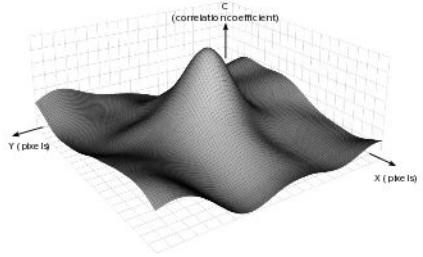
- Exposure time: 15 seconds
- 625 projections
- 3.5 hours acquisition time
- Voxel width : 48.5 microns

Deformation + Flow

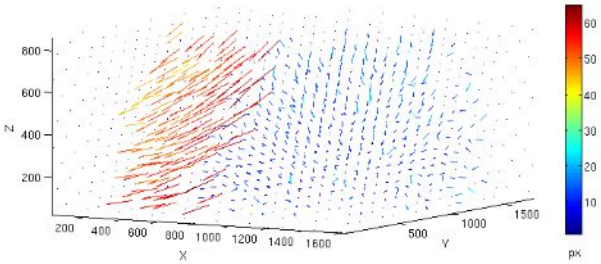
Digital Image Correlation (DIC)



Sub-voxel refinement of displacement vectors



Vector displacement field



continuum hypotersis

Full 3D strain tensor field

$$\varepsilon_{ij} = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{pmatrix}$$

(see Hall, 2006; Hall et al., 2009)

Strain invariants

- volumetric strains

$$\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$$

- shear strains

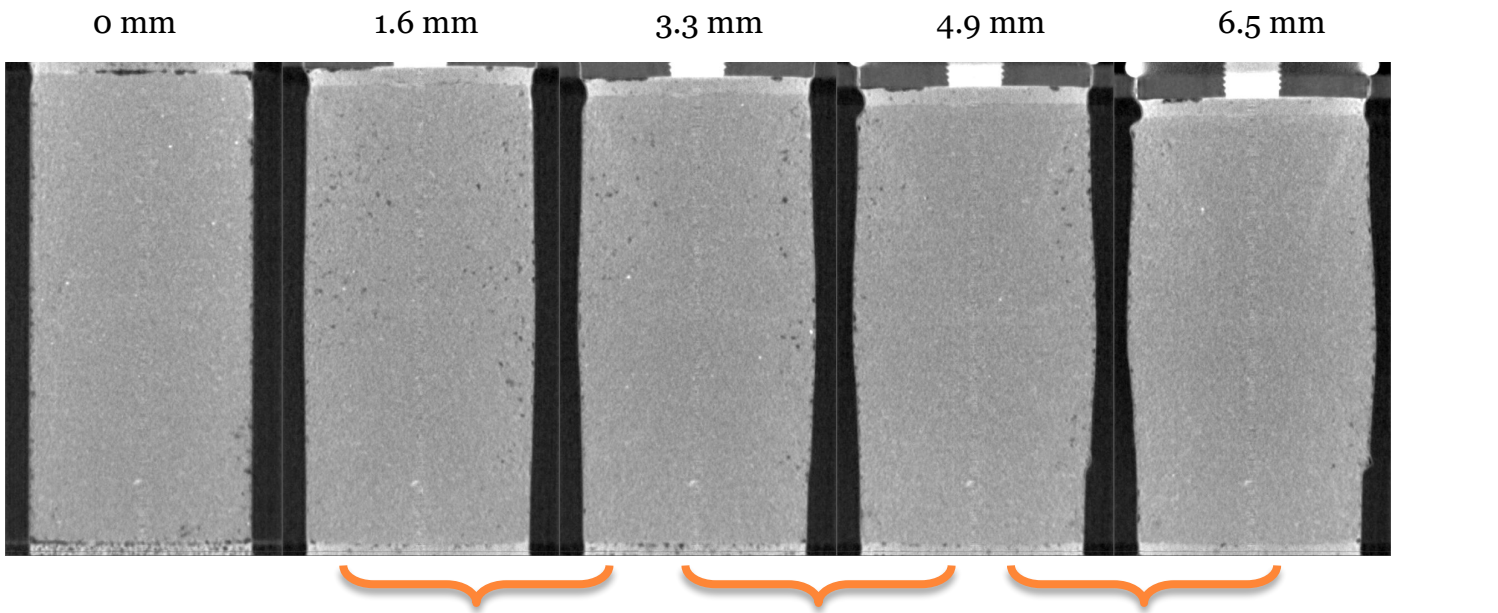
$$\varepsilon_s = \sqrt{\left(\frac{\varepsilon_1 - \varepsilon_2}{2}\right) + \left(\frac{\varepsilon_1 - \varepsilon_3}{2}\right) + \left(\frac{\varepsilon_2 - \varepsilon_3}{2}\right)}$$

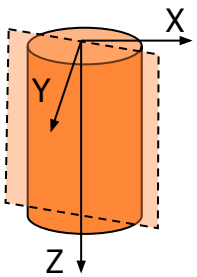
The analyses are perfomed using an in-house code **"TomoWarp2"**

Tudisco, Hall et al. (2017)

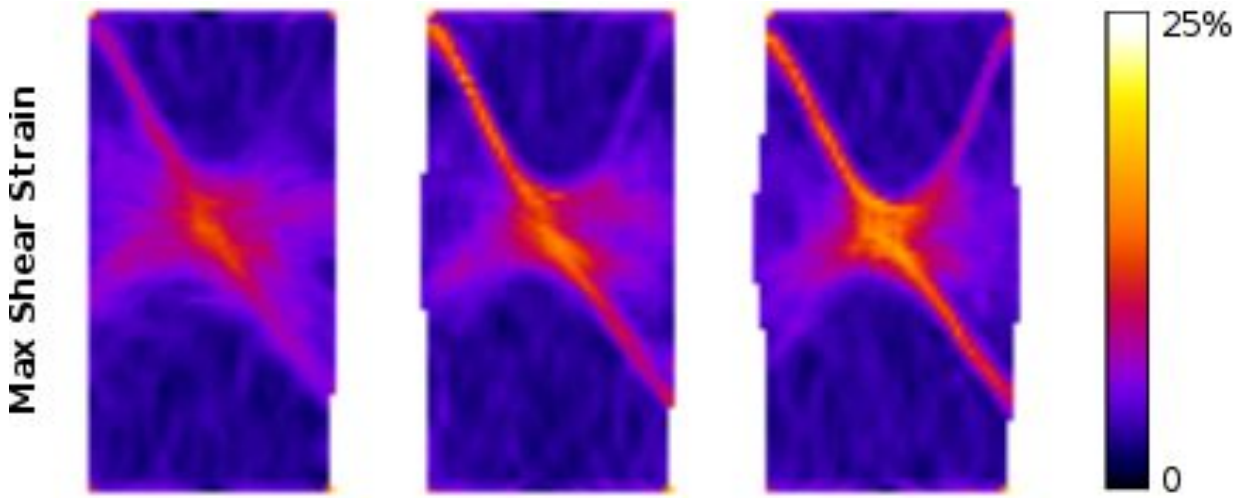
Deformation + Flow

In-situ 4D Imaging (NEUTRA@PSI): deformation evolution



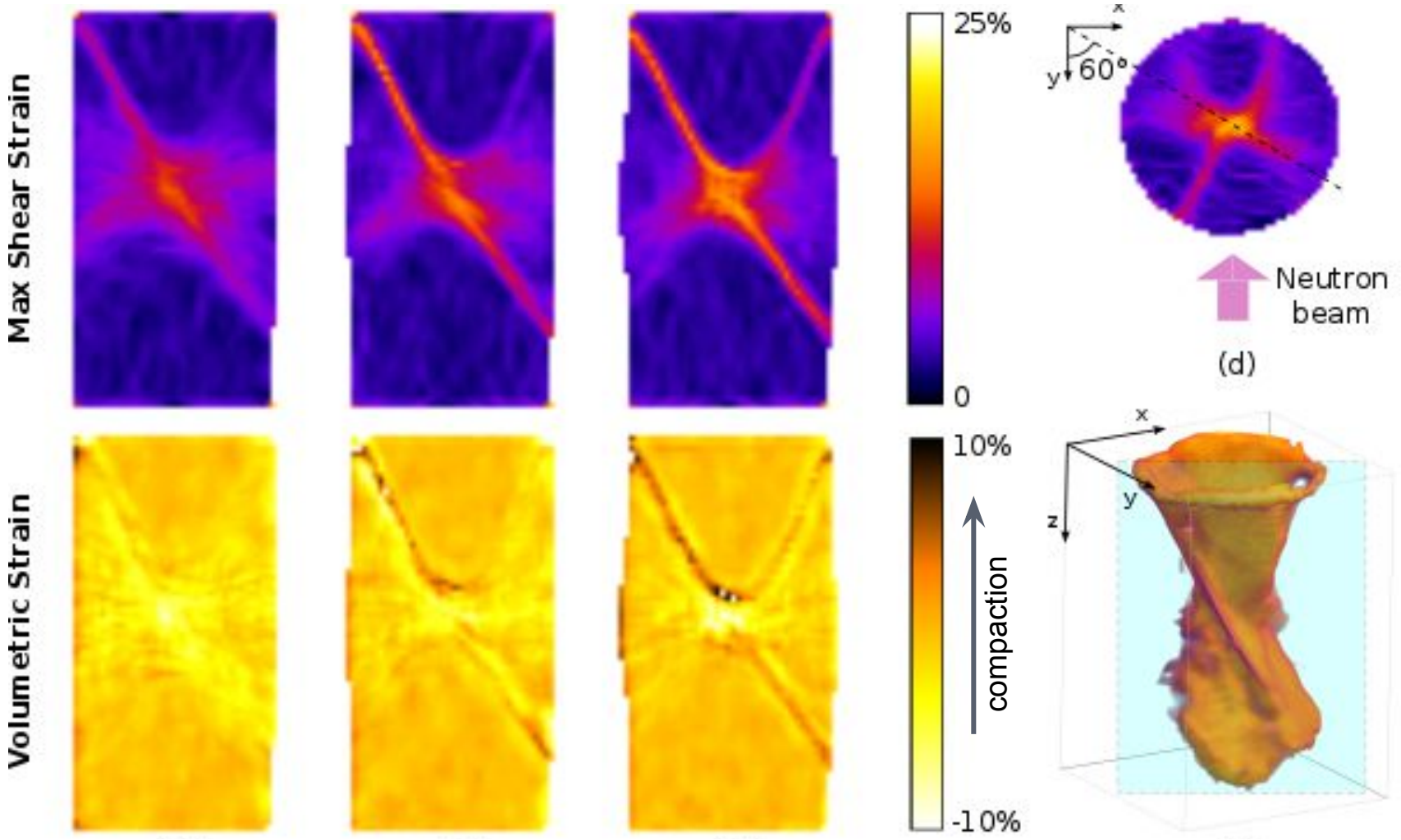


(Vertical slices through middle of volume perpendicular to main localisation)



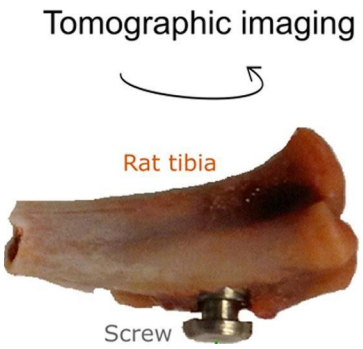
Deformation + Flow

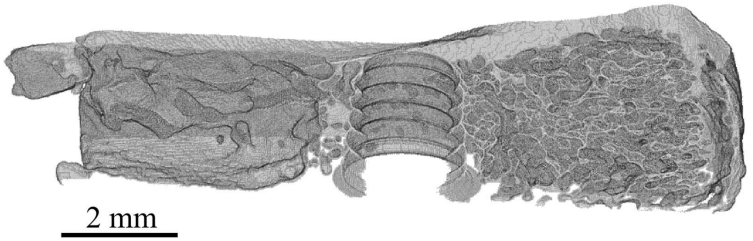
In-situ 4D Imaging (NEUTRA@PSI): deformation evolution

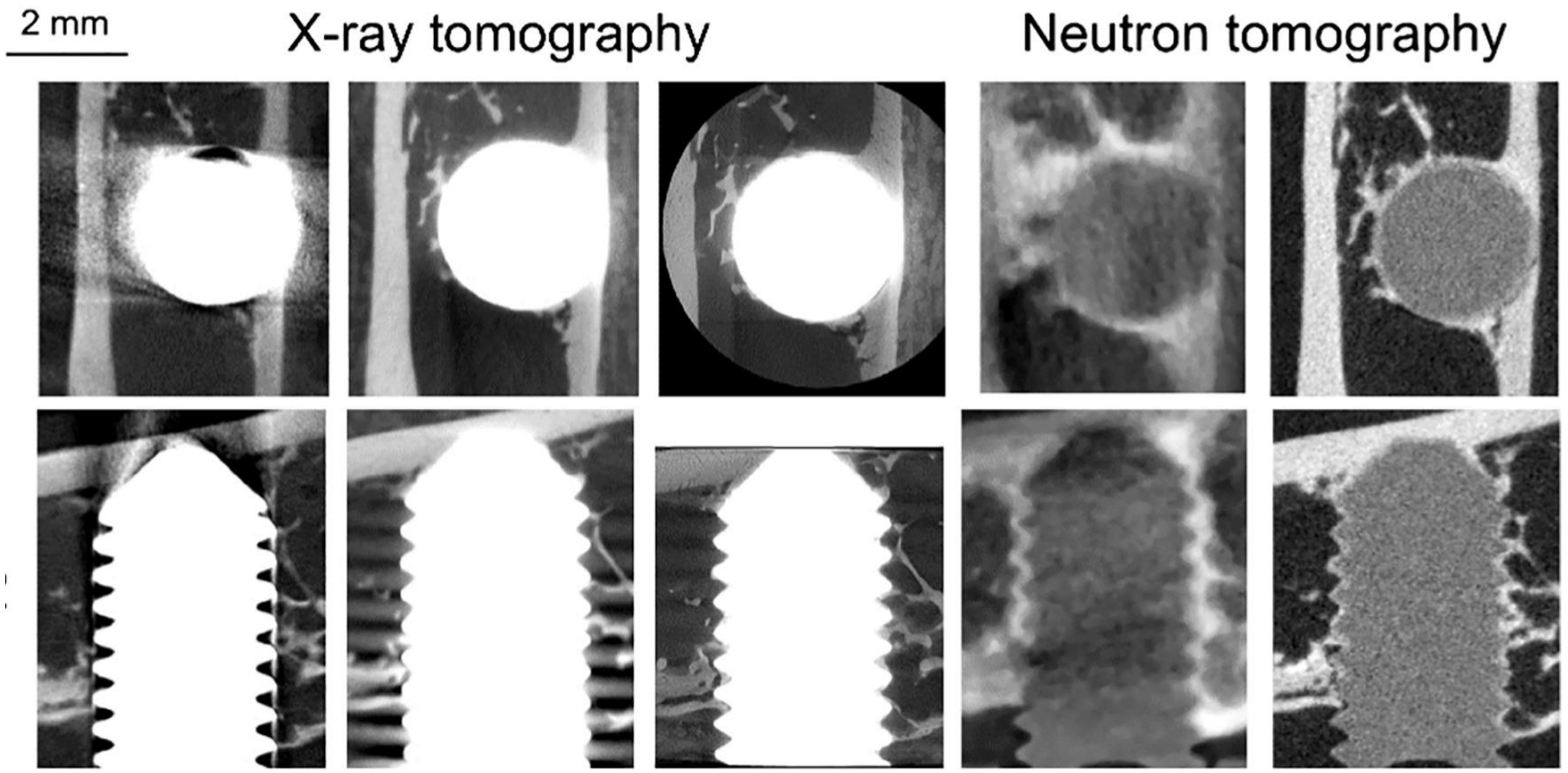


Tudisco, Hall et al. (2017)

Other materials

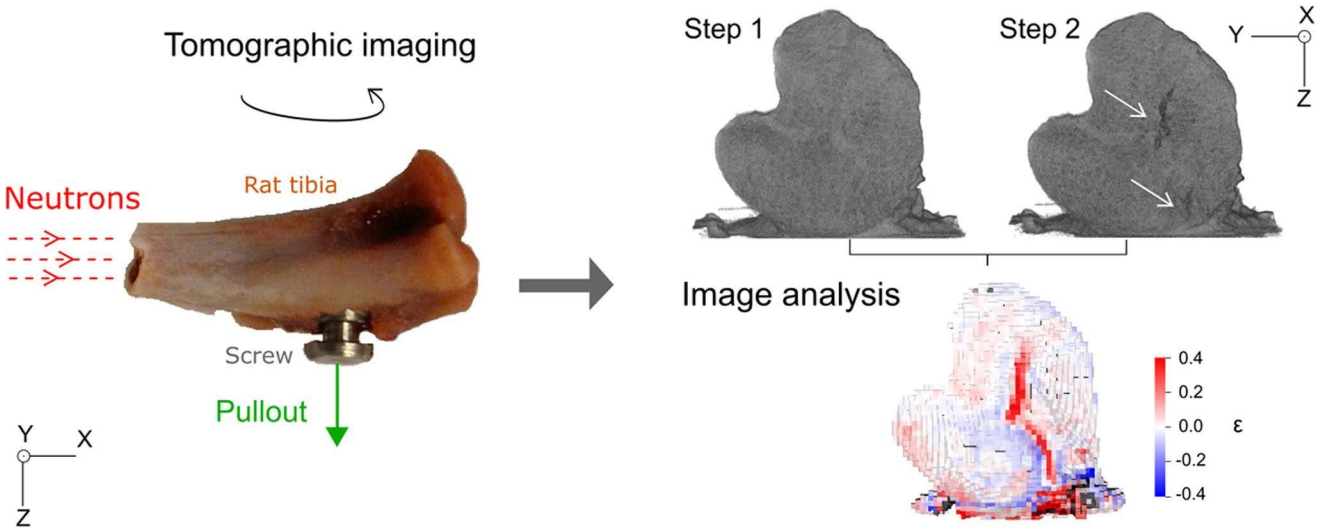


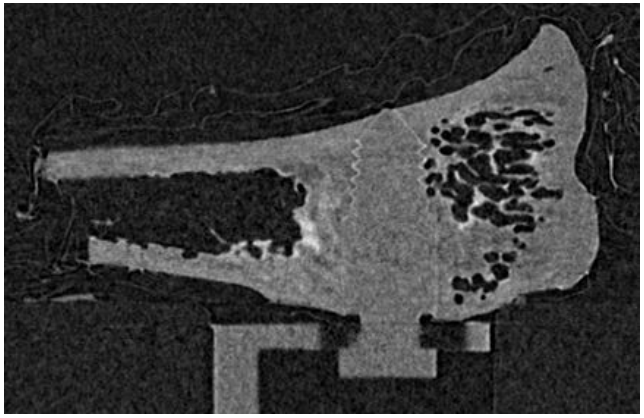


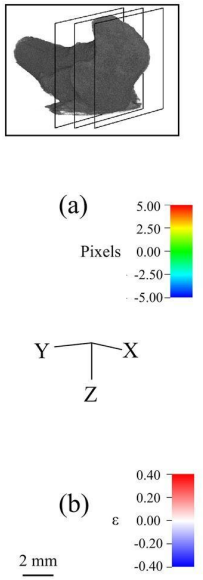


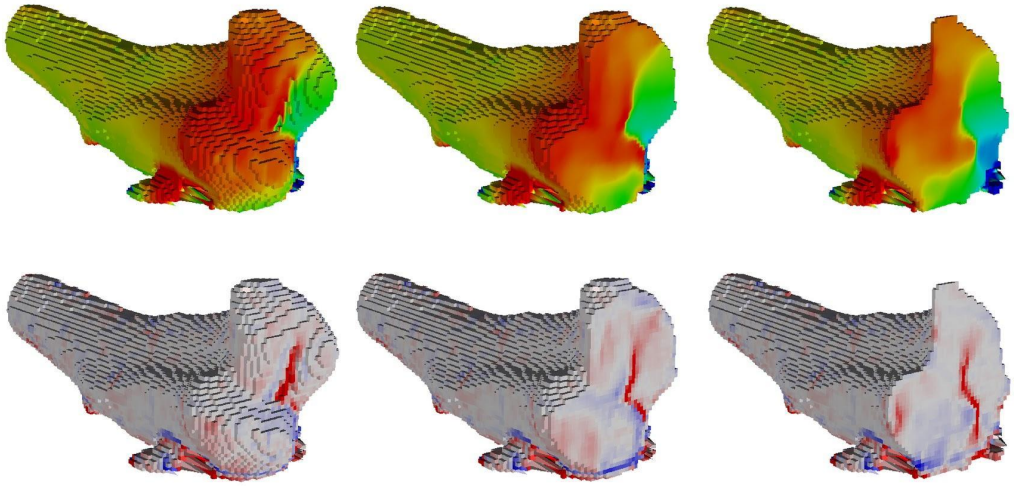
Isaksson et al. (2017) - Le Cann et al. (2017)

Other materials



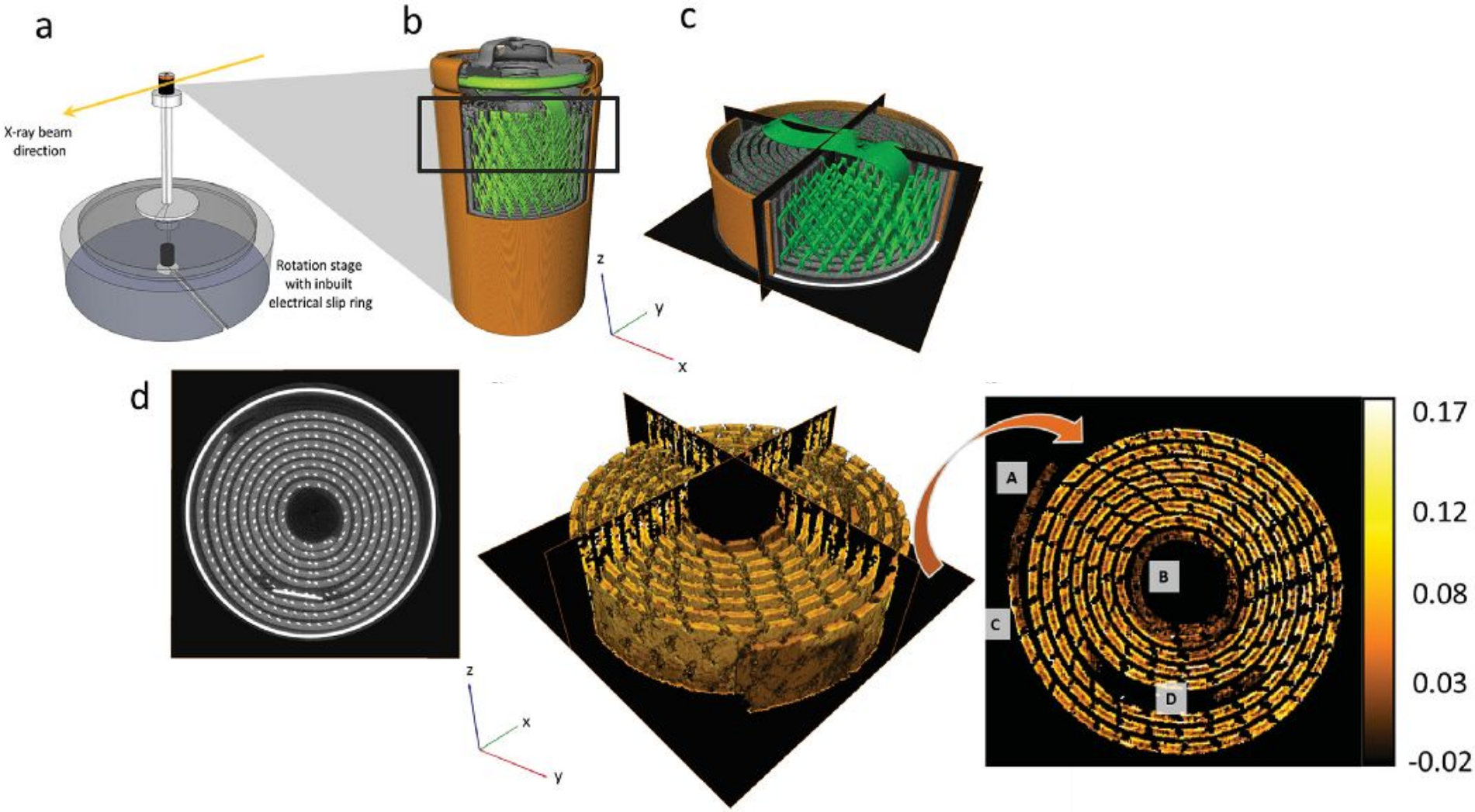






Isaksson et al. (2017) - Le Cann et al. (2017)

Other materials



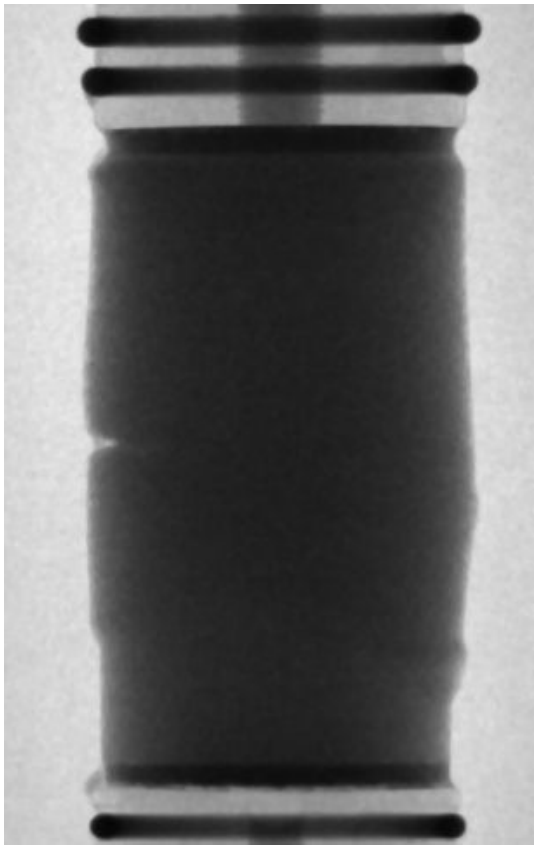
Finegan et al. (2015)

Deformation + Flow

Flow evolution: Pressure-driven H_2O / D_2O flooding

- 0.5 s exposure time
- 2Hz acquisition
- Pixel size: 194 microns

- Initially Saturated with D_2O
- H_2O flood
- Re flood with D_2O



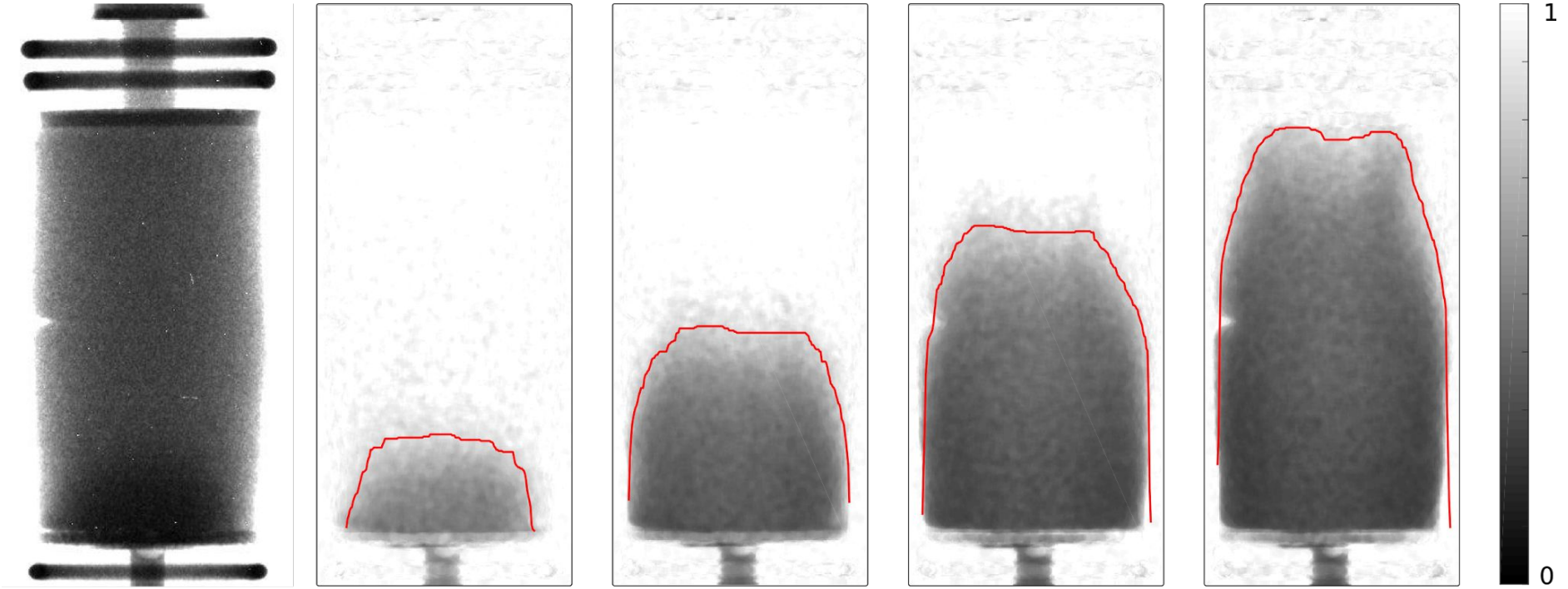
Pressure-driven H_2O / D_2O flooding after final load step

Vertical displacement = 6.5 mm

Tudisco, Hall et al. (2017)

Deformation + Flow

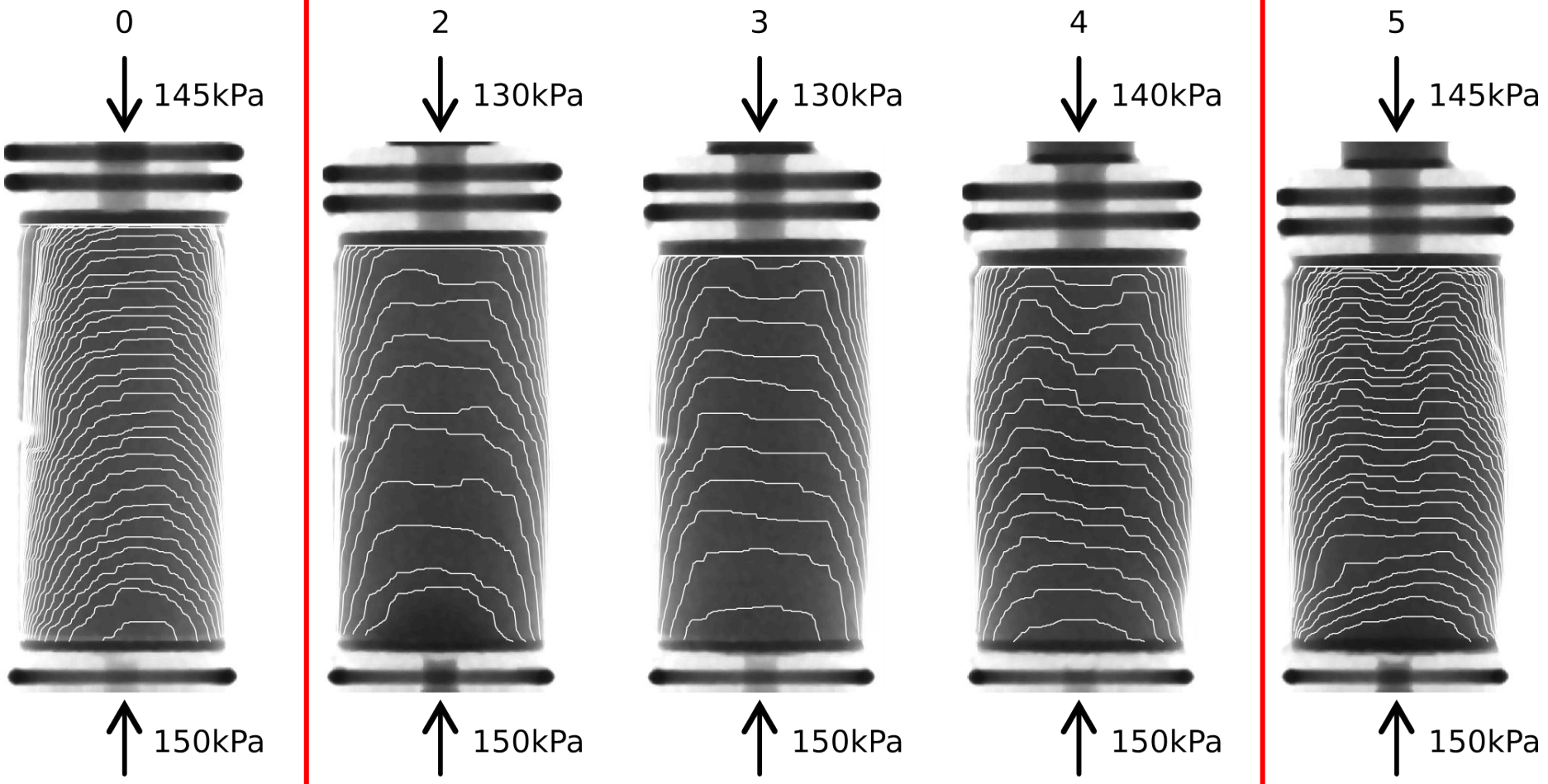
Flow evolution: Pressure-driven H_2O / D_2O flooding



Tudisco, Hall et al. (2017)

Deformation + Flow

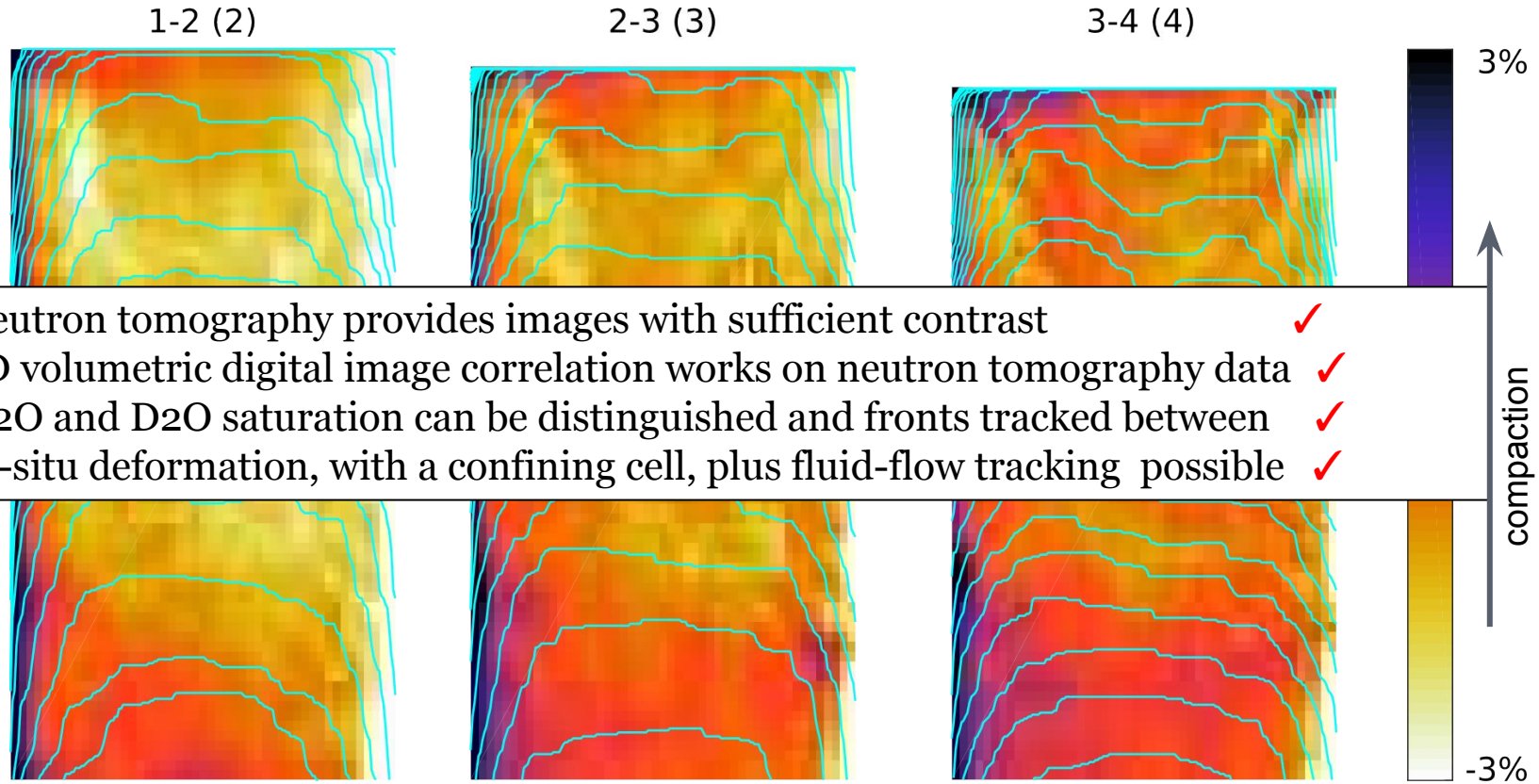
Flow evolution: Pressure-driven H_2O / D_2O flooding



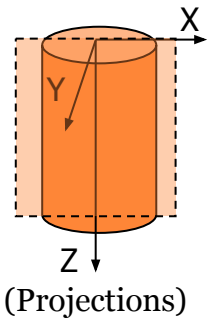
Tudisco, Hall et al. (2017)

Deformation + Flow

Coupling between deformation and flow evolution

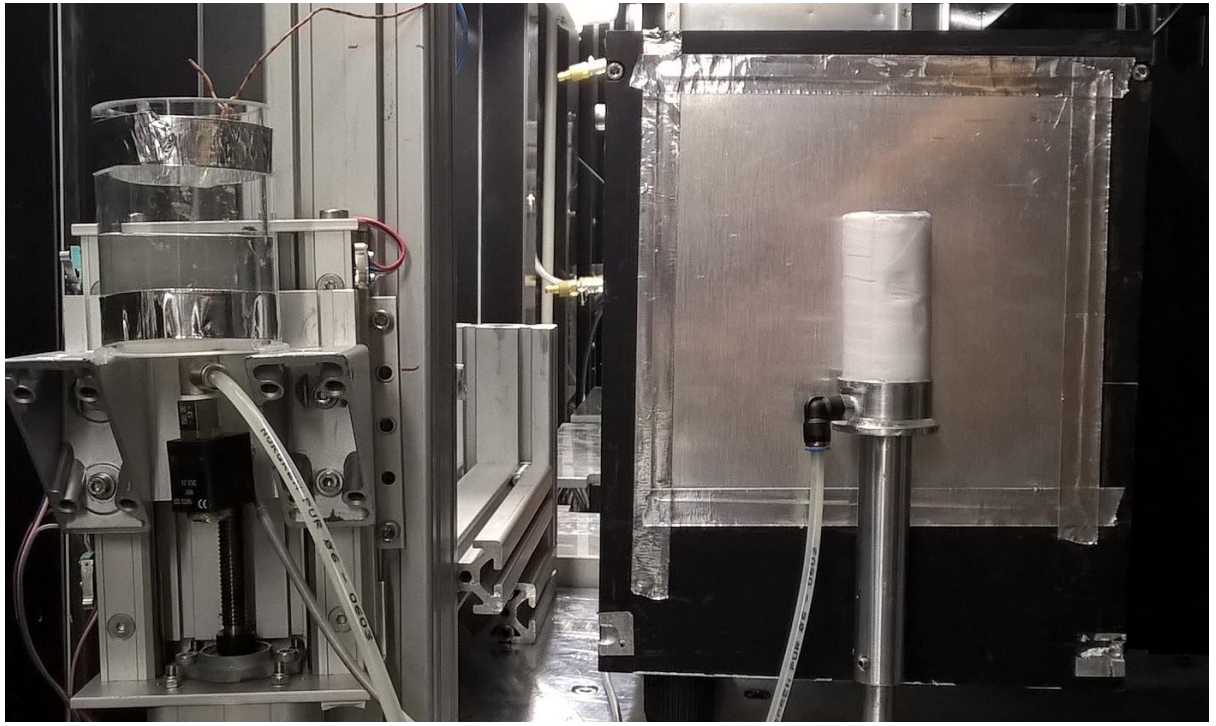


- Neutron tomography provides images with sufficient contrast ✓
- 3D volumetric digital image correlation works on neutron tomography data ✓
- H2O and D2O saturation can be distinguished and fronts tracked between ✓
- In-situ deformation, with a confining cell, plus fluid-flow tracking possible ✓



Tudisco, Hall et al. (2017)

Towards full 3D...



- Vosges sandstone
- Intact and “ex-situ” defomed samples
- Pressure control on fluid-in
- Sample initially dry
- Flooding with H_2O

1 minute tomography!!

180° / 2 images per seceond

Towards full 3D...

3D Flow evolution: H_2O imbibition into deformed sample

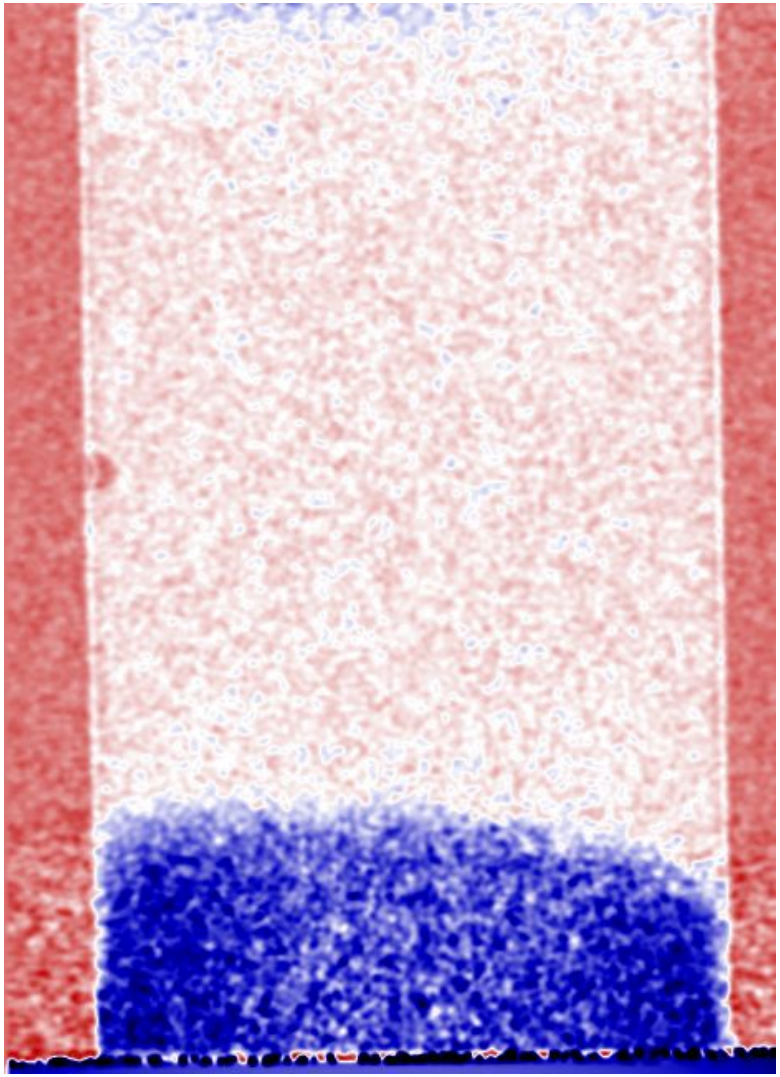
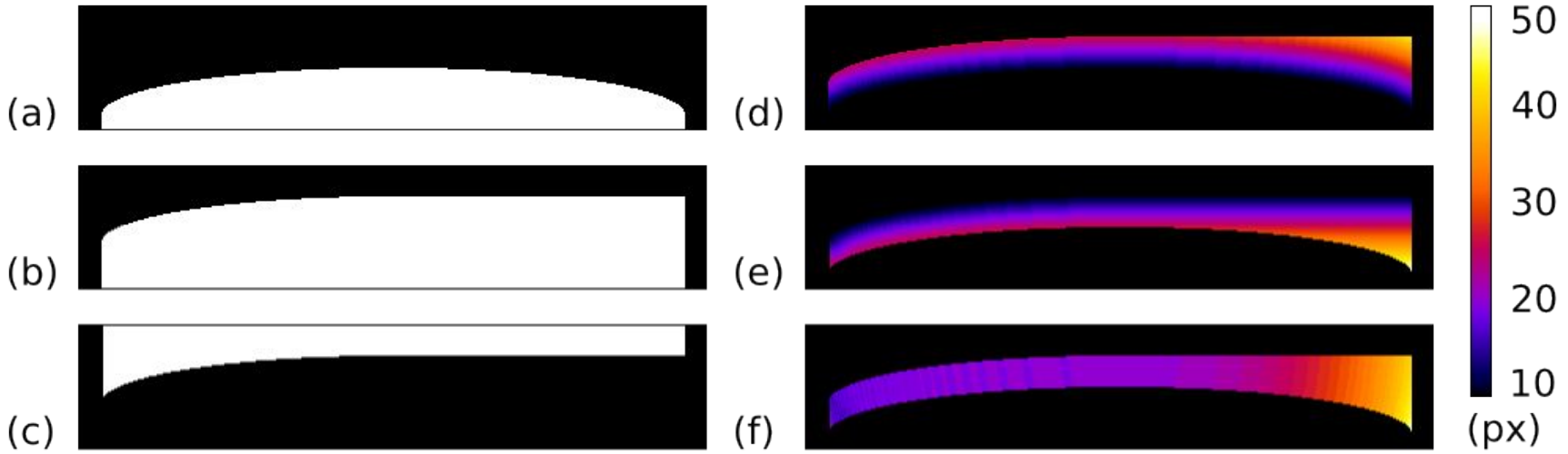


Image analysis

WATER FRONT SPEED



(a) (b) Binarized reconstructed volume to get consecutive fronts

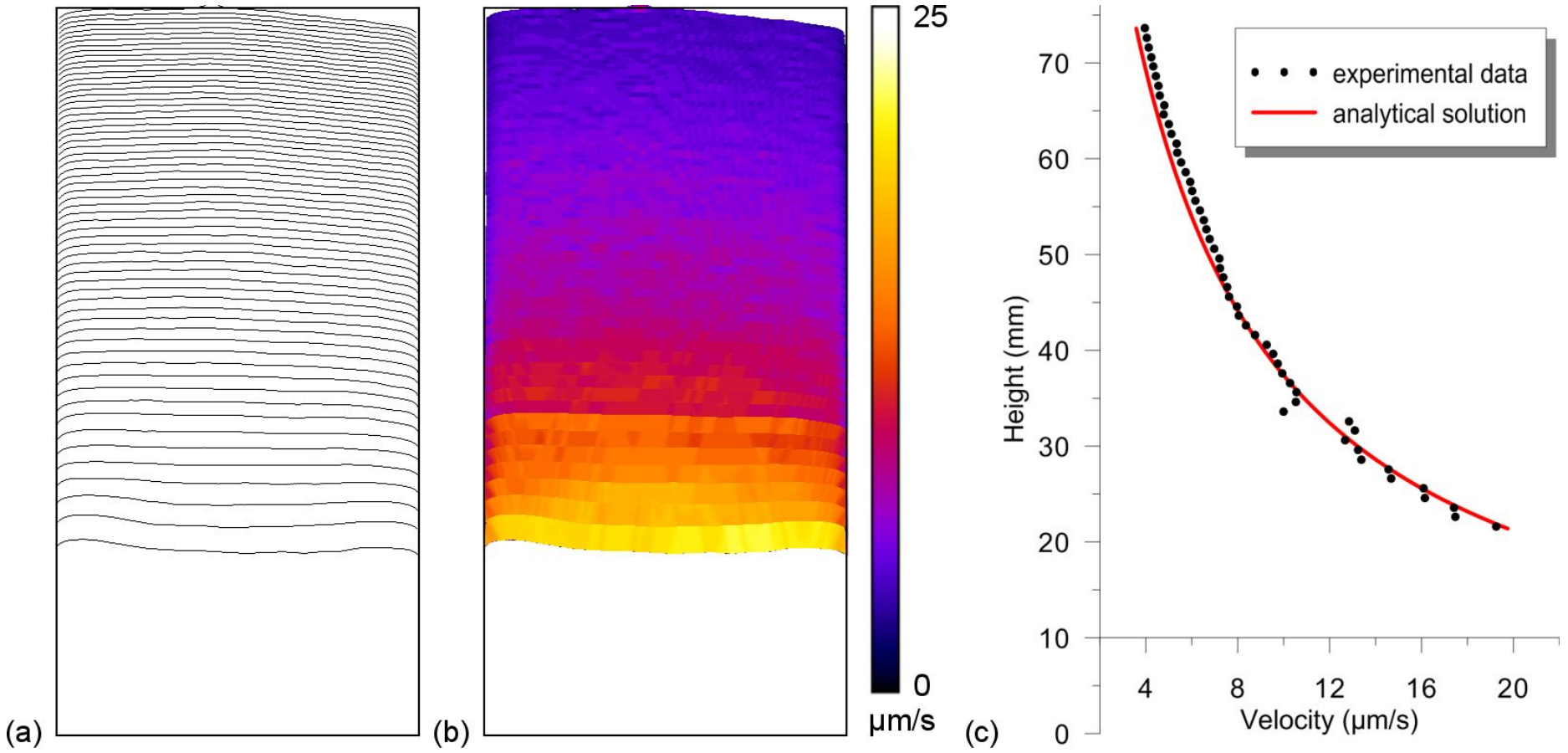
(c) Invert the second front

(d) (e) Distance maps calculated in the space between the fronts

(f) Sum of distance maps

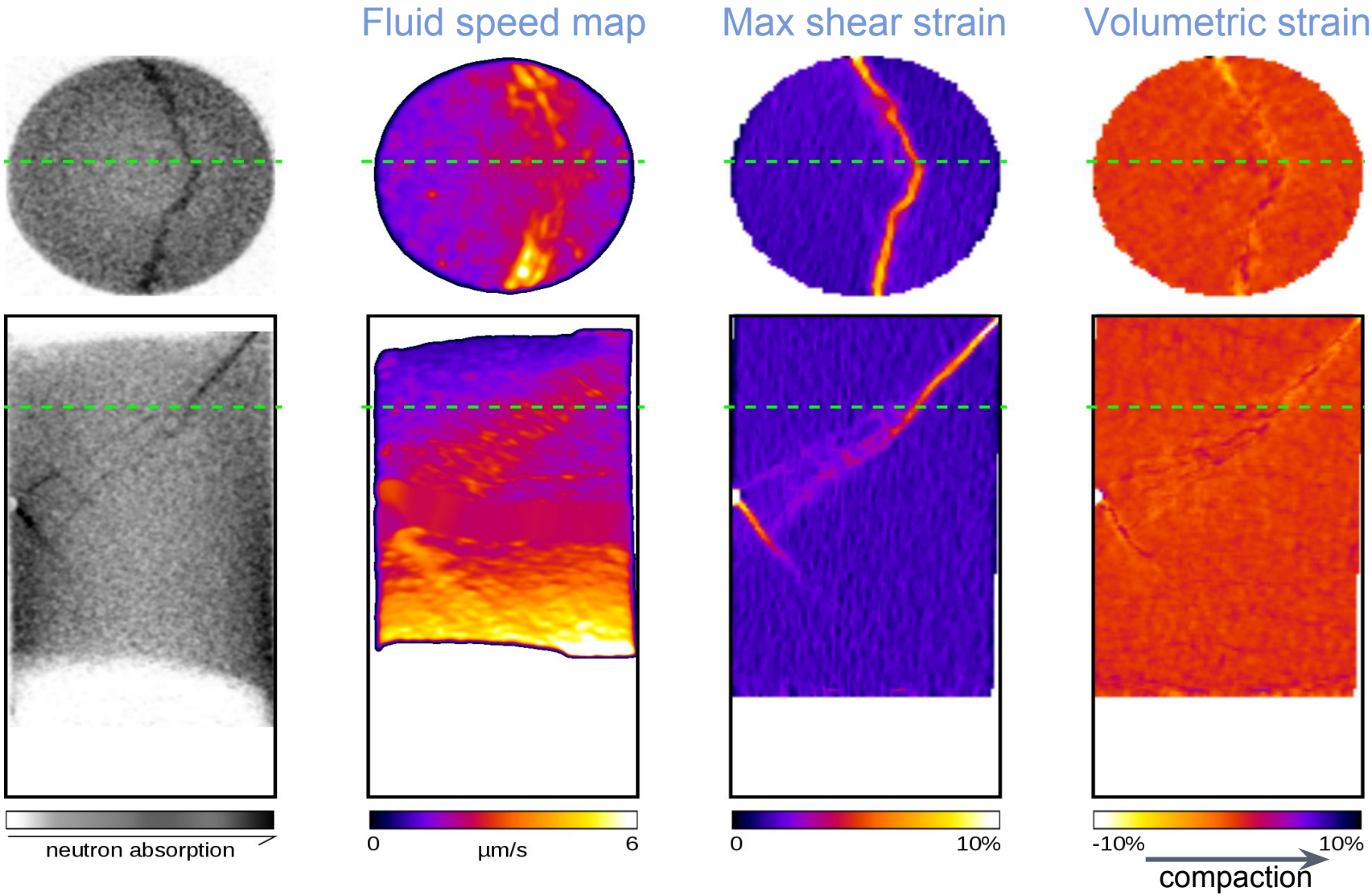
Analytical solution

Intact sample - pressure driven flow (constant pressure at the bottom)

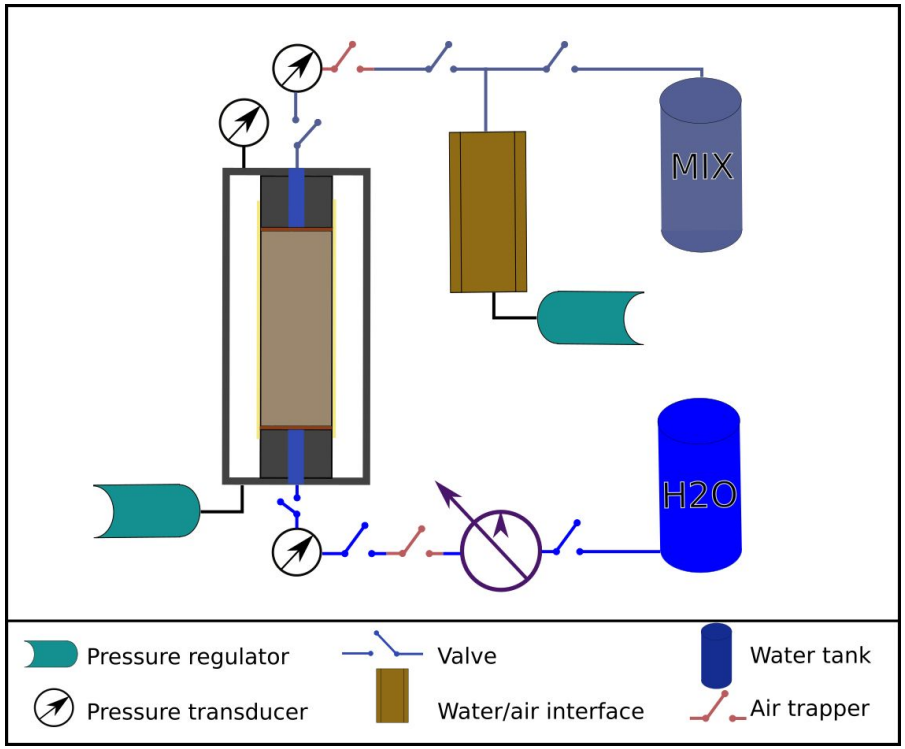


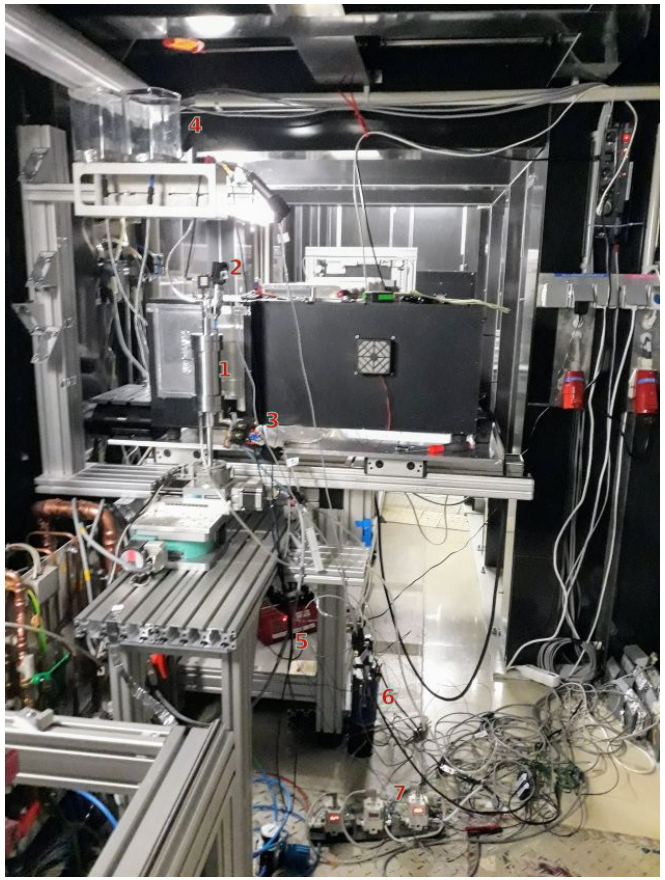
Results

3D Flow evolution: H_2O imbibition into deformed sample



Controlling flow





- Vosges sandstone
- Intact and “ex-situ” defomed samples
- Flow rate control on fluid in Pressure control on fluid-out
- Sample initially Saturated in D_2O
- Flooding with H_2O

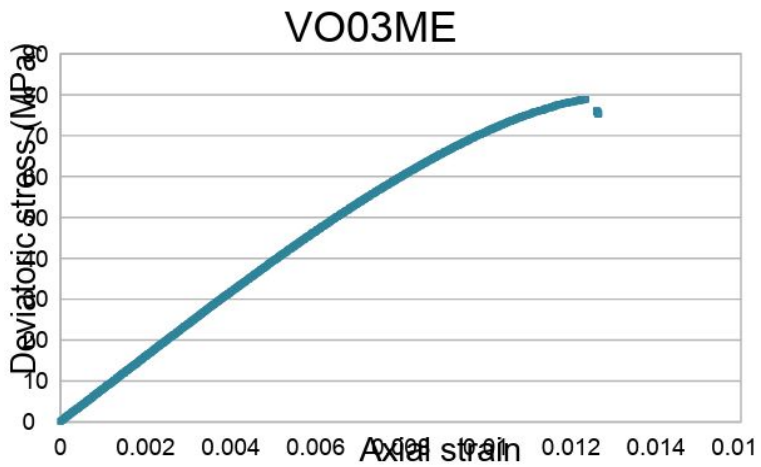
1 minute tomography!!

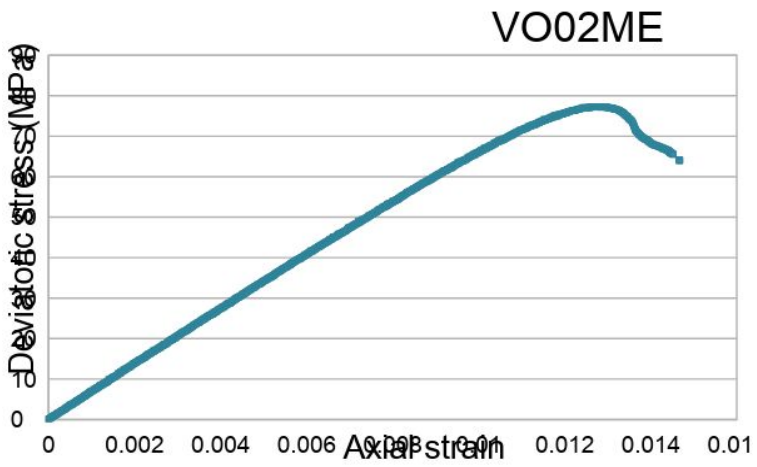
180° / 2 images per seceond

Test: Triaxial loading

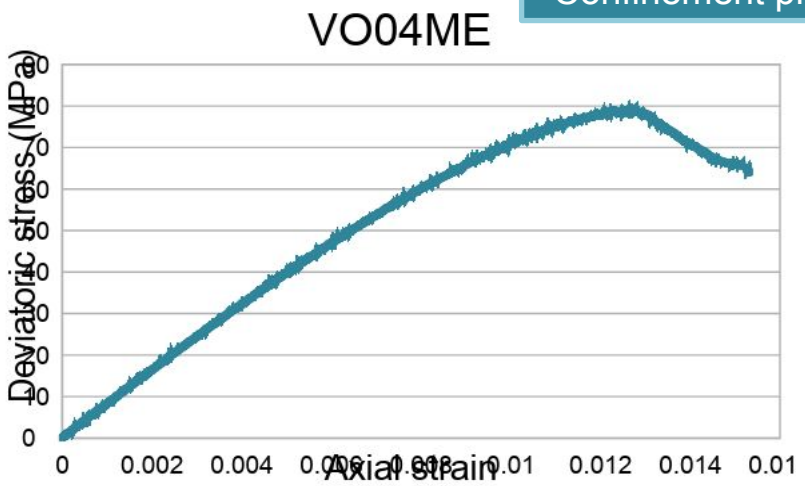
5 Vosges samples with different deformation levels were tested

Confinement pressure: 30 MPa





Confinement pressure: 40 MPa



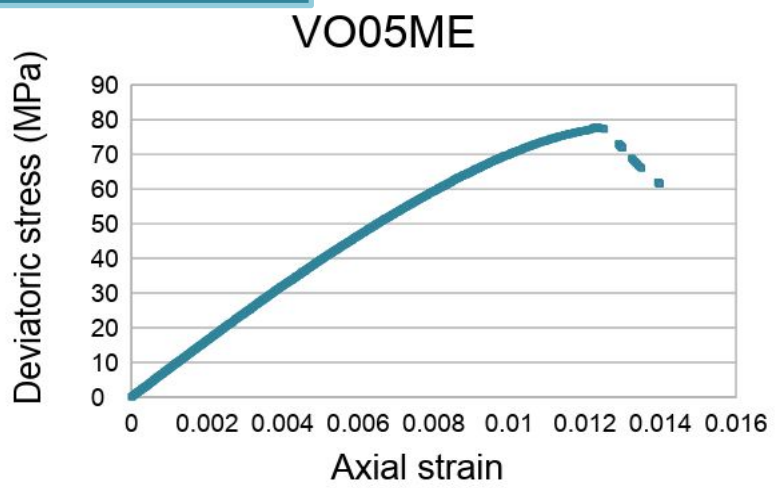
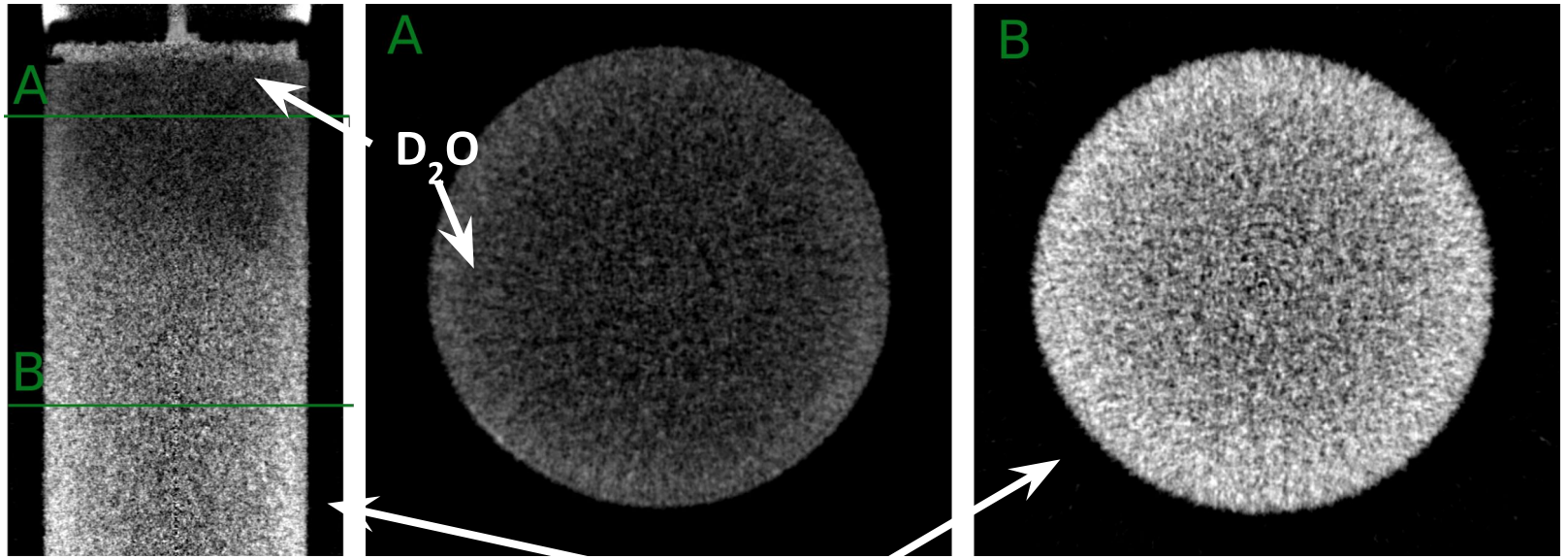


Image analysis

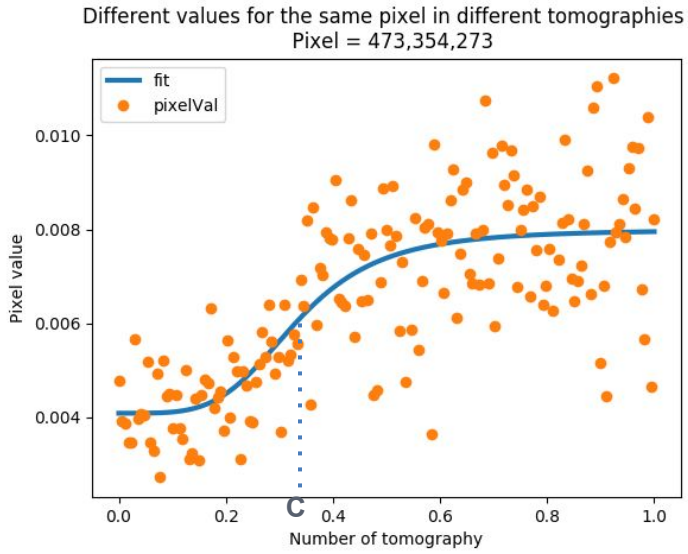


- One minute fast tomography
- Beam hardening effect
- Not a strong contrast between the gray scale of both waters.

Image analysis

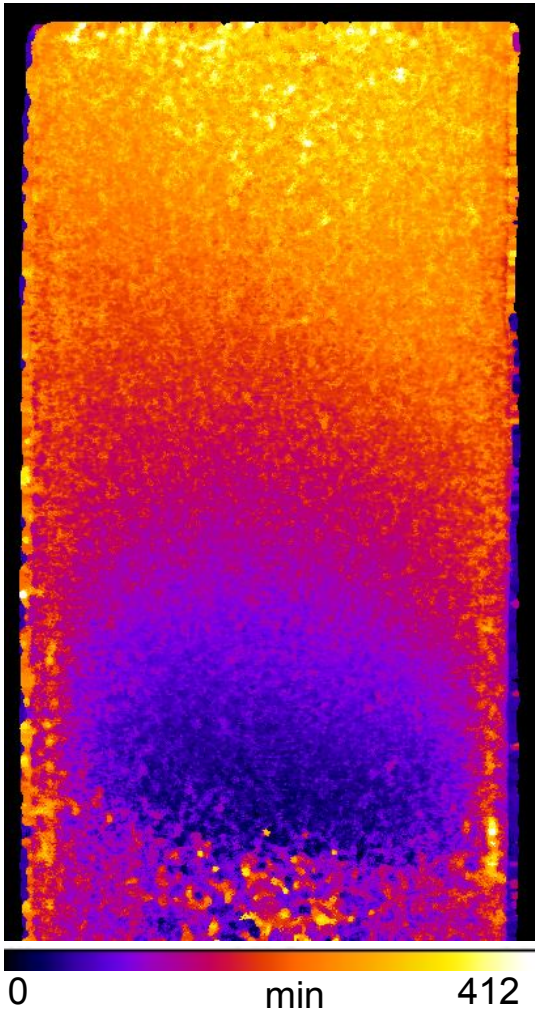
SIGMOIDAL FITTING

- The gray scale of a pixel is plot for all the tomographies and **fit** in a sigmoidal function
- The C parameter gives the **arrival time**



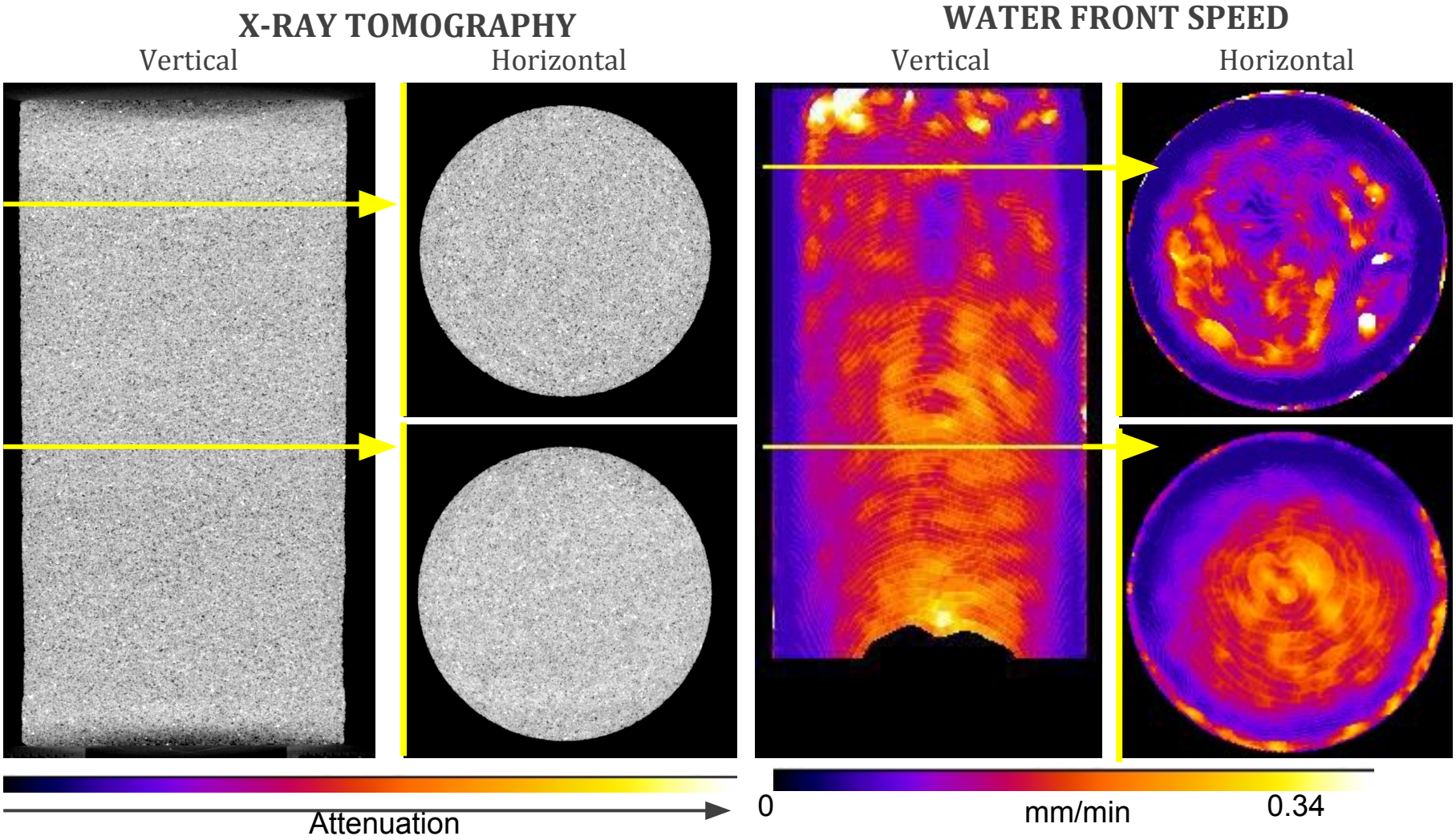
$$Gray\ Scale = A + \frac{(B-A)}{1+\left(\frac{C}{t}\right)^{D}}$$

WATER FRONT TIME MAP



Results: VO01ME

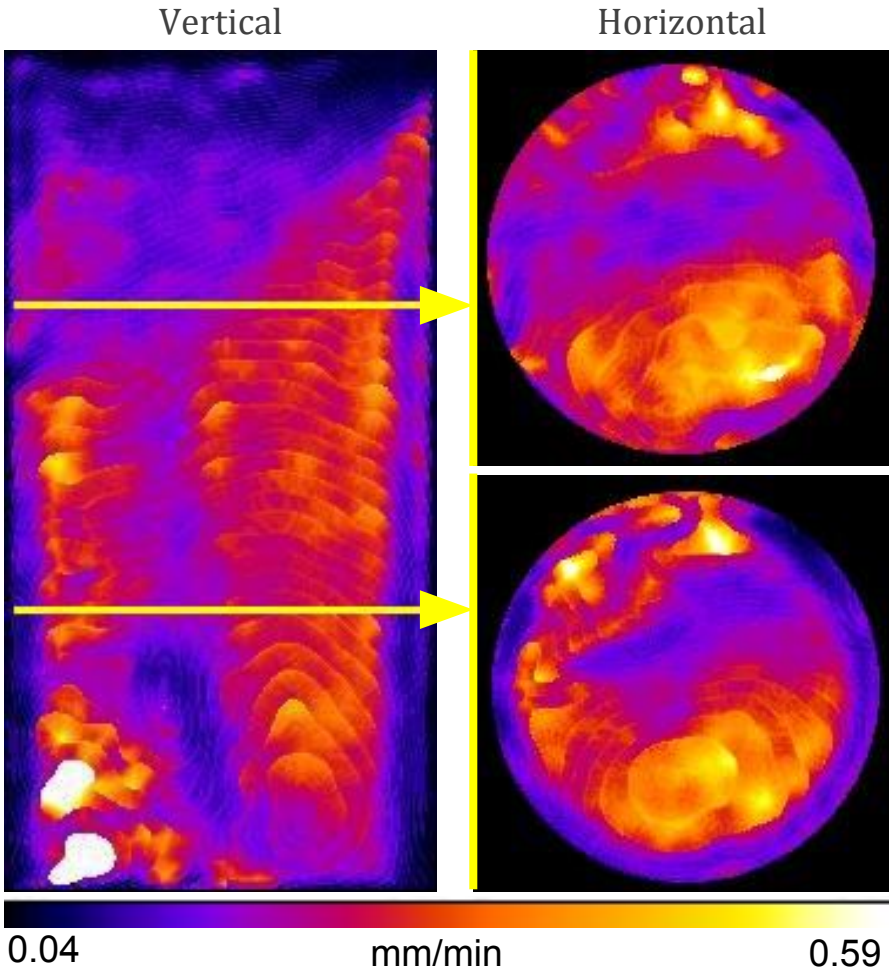
- Intact sample
- The water was flushed at 4 ml/h: Front speed of 0.253 mm/min



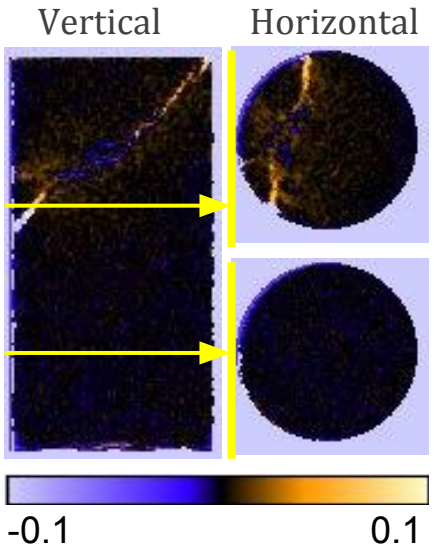
Results: VO02ME

- Sample deformed at 30 MPa confinement, in the beginning of the plateau in the stress/strain response
- The water was flushed 8 ml/h:
- Front speed of 0.506 mm/min

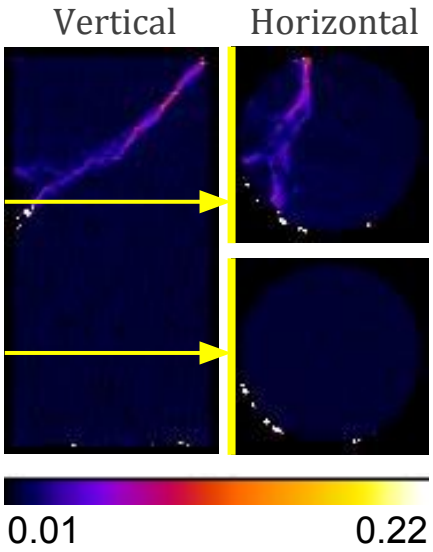
WATER FRONT SPEED



VOLUMETRIC STRAIN



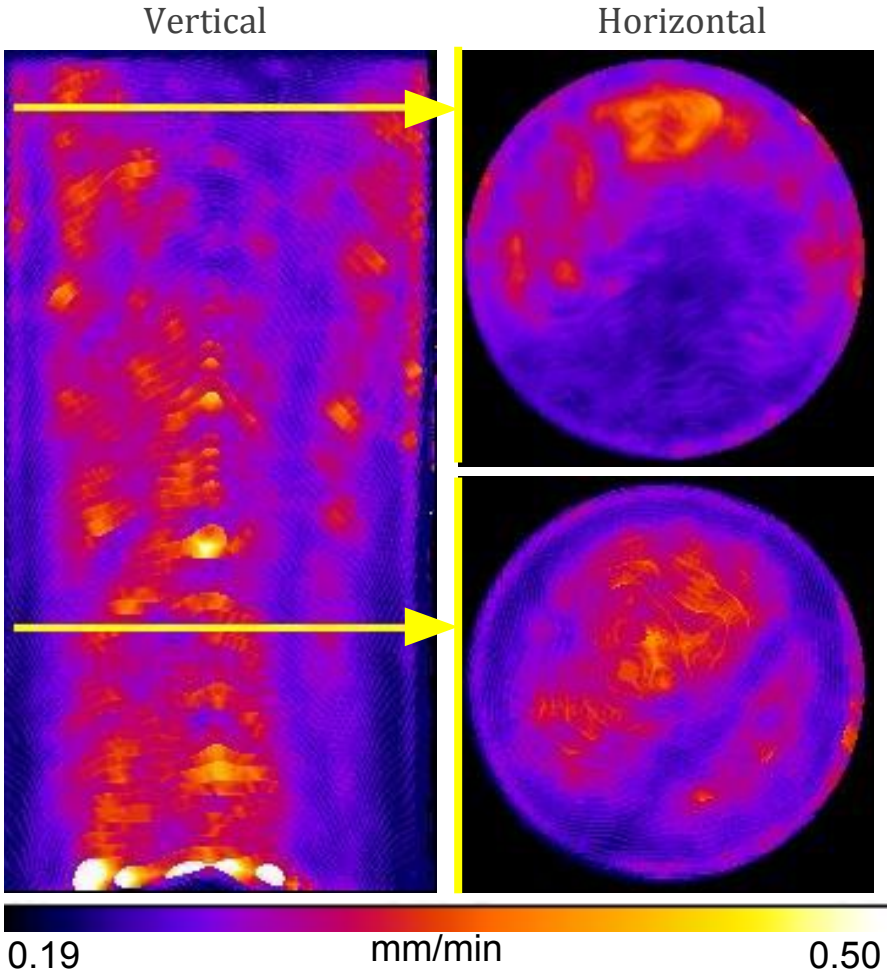
SHEAR STRAIN



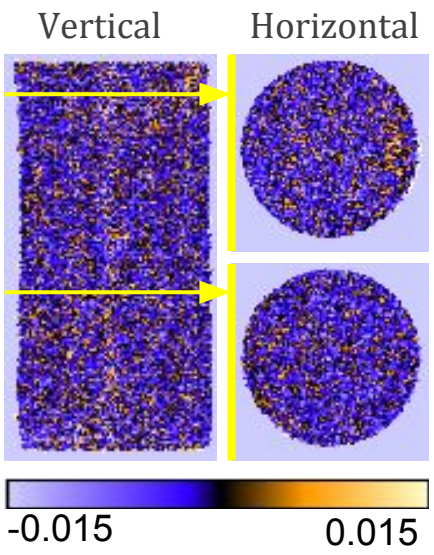
Results:VO03ME

- Sample deformed at 30 MPa confinement, close to the stress peak
- The water was flushed at 4 ml/h
- Front speed of 0.253 mm/min

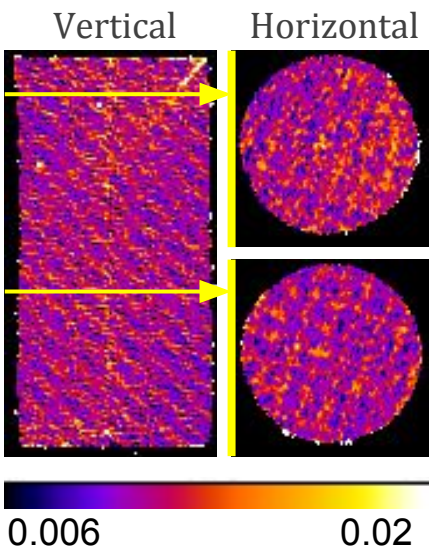
WATER FRONT SPEED



VOLUMETRIC STRAIN



SHEAR STRAIN

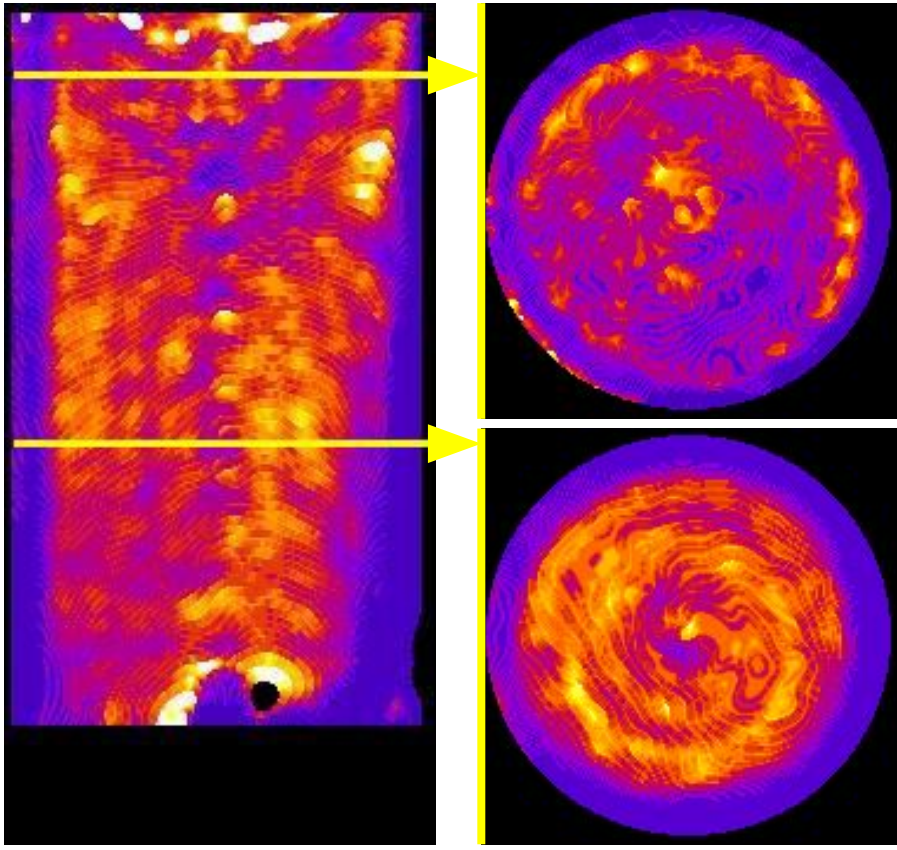


RESULTS: VO04ME

- Sample deformed at 40 MPa confinement, in the beginning of the plateau in the stress/strain response
- The water was flushed at 3 ml/h
- Front speed of 0.19 mm/min

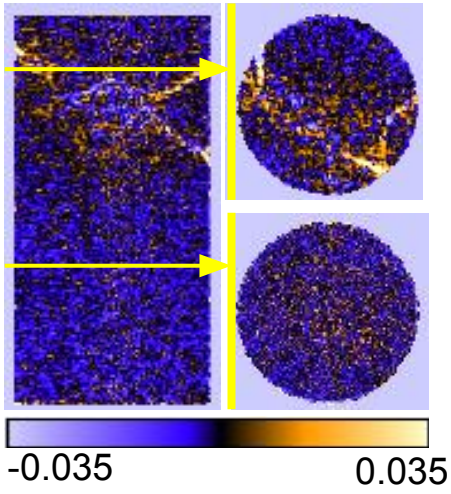
WATER FRONT SPEED

Vertical Horizontal



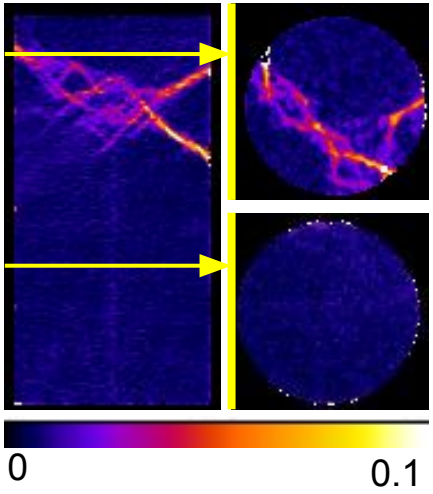
VOLUMETRIC STRAIN

Vertical Horizontal



SHEAR STRAIN

Vertical Horizontal

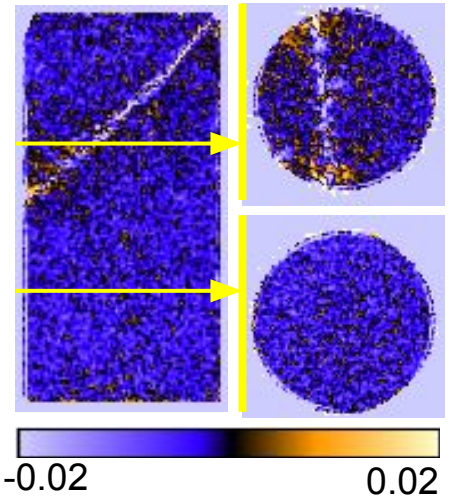


Results: VO05ME

- Confining pressure 40 MPa
- Close to the stress peak
- Flow rate 4 ml/h
- Average front speed 0.253 mm/min

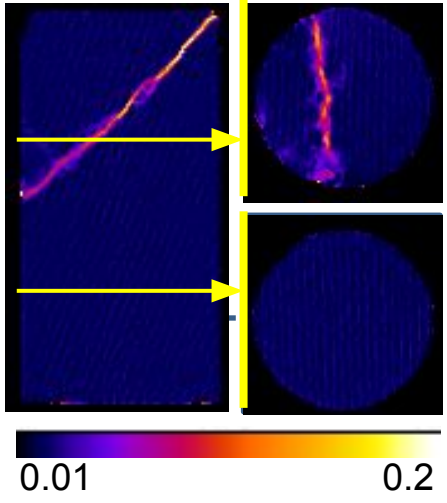
VOLUMETRIC STRAIN

Vertical Horizontal



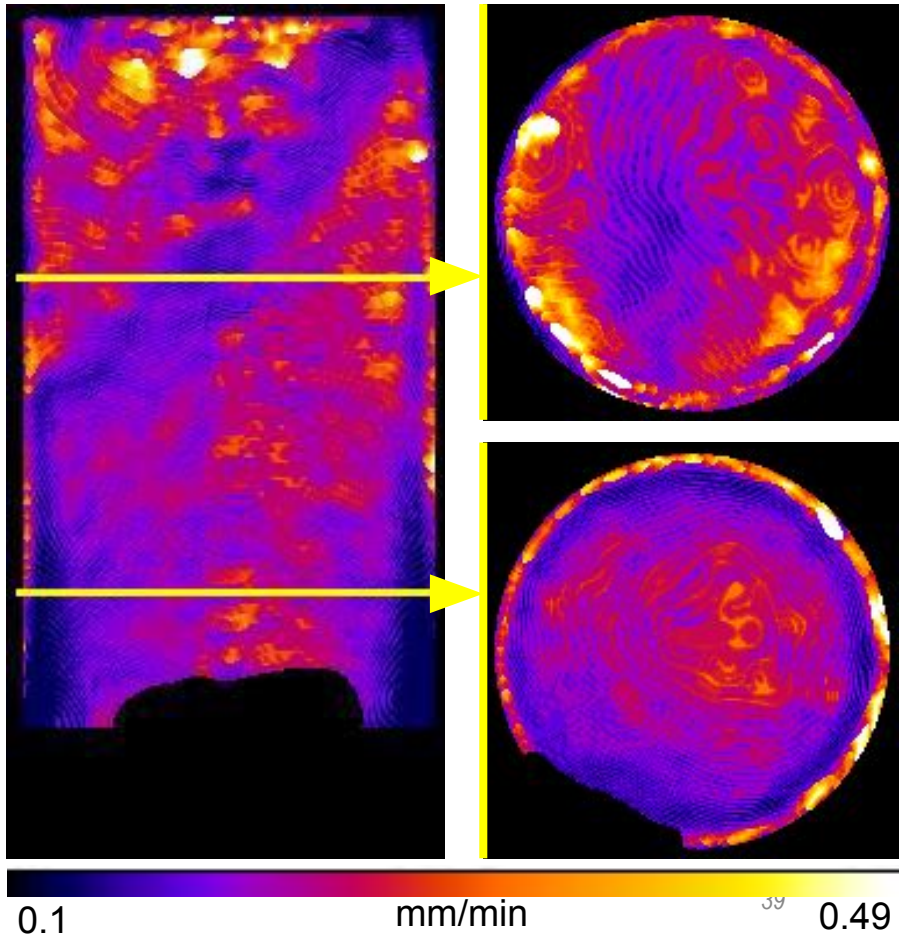
SHEAR STRAIN

Vertical Horizontal



WATER FRONT SPEED

Vertical Horizontal



Neutron imaging - Summary

- Concept for coupled fluid-flow and deformation monitoring in-situ with neutron imaging has been demonstrated
  - **Digital Volume Correlation** works on neutron tomography data
  - H2O and D2O saturation can be distinguished and **3D water front** can be track in dry and saturated samples.
  - **3D flow speed map** of a hydraulic process can be obtained
  - In-situ **deformation**, with a confining cell, **plus** H2O/D2O **fluid-flow** tracking possible
- Findings in rock behaviour
  - **Imbibition** in compactand shear band ⇨ **higher** flow speed
  - **Pressure driven** flow in compactand shear band ⇨ **lower** flow speed
- Future Work
  - **In-situ** hydro-mechanical test
  - Upgrade of the setup for **high confining pressure** tests
  - Measure **local permeability** ⇦ **Flow simulation** to get the pressure

The experimental world!