Etude expérimentale de la localisation des déformations dans les roches en utilisant des méthodes de mesure de champs

an experimental insight into the mechanisms of localized deformation in rocks

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+ Steve Hall, Nicolas Lenoir, Pierre Bésuelle, Jacques Desrues, Michel Bornert,
Elma Charalampidou, Sergei Stanchits, Erika Tudisco, Philippe Roux, …

- how can we model localized deformation ?
- how can we investigate it in the lab ?

two examples: (1) clay rock and (2) sandstone

Neutron Radiograhy to look inside an italian coffee maker

(there is plenty of fun things that one can do with full-field methods)

to fully understand the mechanisms at play
it is important to

- see inside test specimens (when possible)
- characterize the “full-field” behavior
- employ techniques sensitive to the phenomena of interest

→ full-field methods

full-field measurements: what and how

the fields that can be measured concern a range of physical variables, which may be scalars (*e.g.*, temperature), vectors (*e.g.*, displacement) or even tensors (*e.g.*, strain)

for each of such variables, many different techniques exist (each of them having its advantages and its limitations)

- Optical Methods for Kinematics (speckle, speckle interferometry, geometric moiré, moiré interferometry, holographic interferometry, image correlation, grid method, …)
- Ultrasonic Tomography
- Magnetic Resonance Imaging (MRI)
- Electrical Resistivity Tomography
- Neutron Tomography
- X-ray Tomography
- …

→ see review paper by Viggiani & Hall (2008)

full-field measurements - why?

qualitative and quantitative characterization of **heterogeneities** in both **material properties** and **processes**

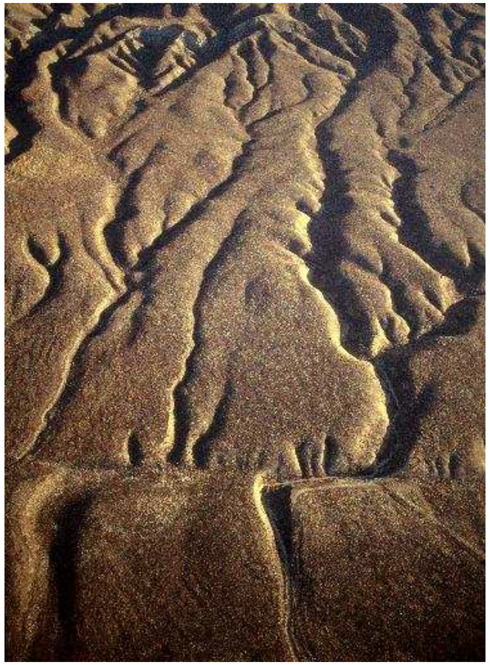
↓

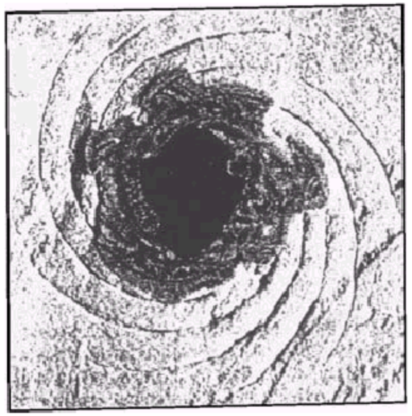
particularly attractive for geomechanics, because heterogeneity (at different scales) is the rule rather than the exception

useful in a number of ways:

- material characterization and specimen inspection
- assessment of actual test boundary conditions
- → tracking of heterogeneous response during a test
- validation and identification of models

this is ideal for studying mechanisms of **localized deformation** in rocks (shear/compaction bands, tensile/shear cracks or fractures





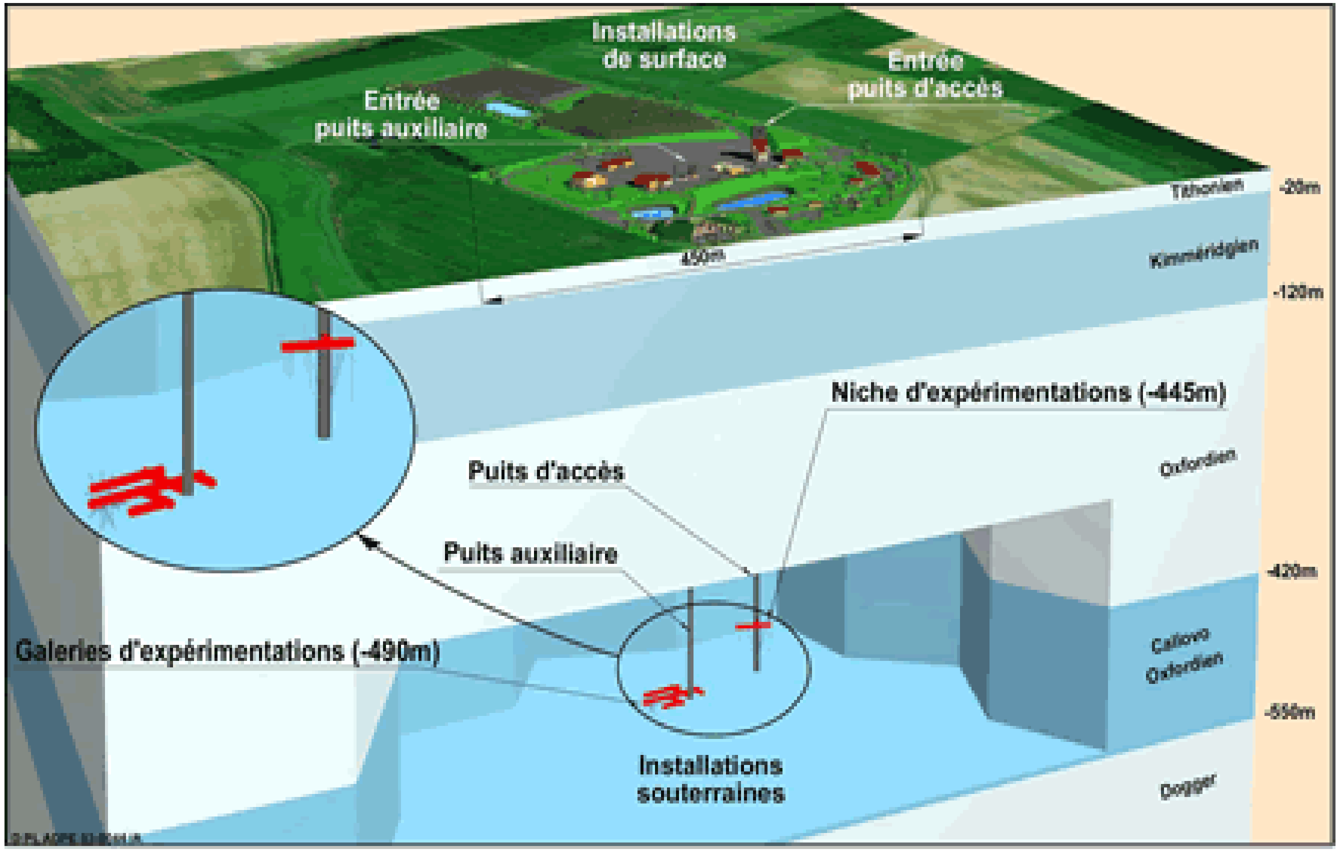
example 1

localization in clay rock

(the invisible localization)

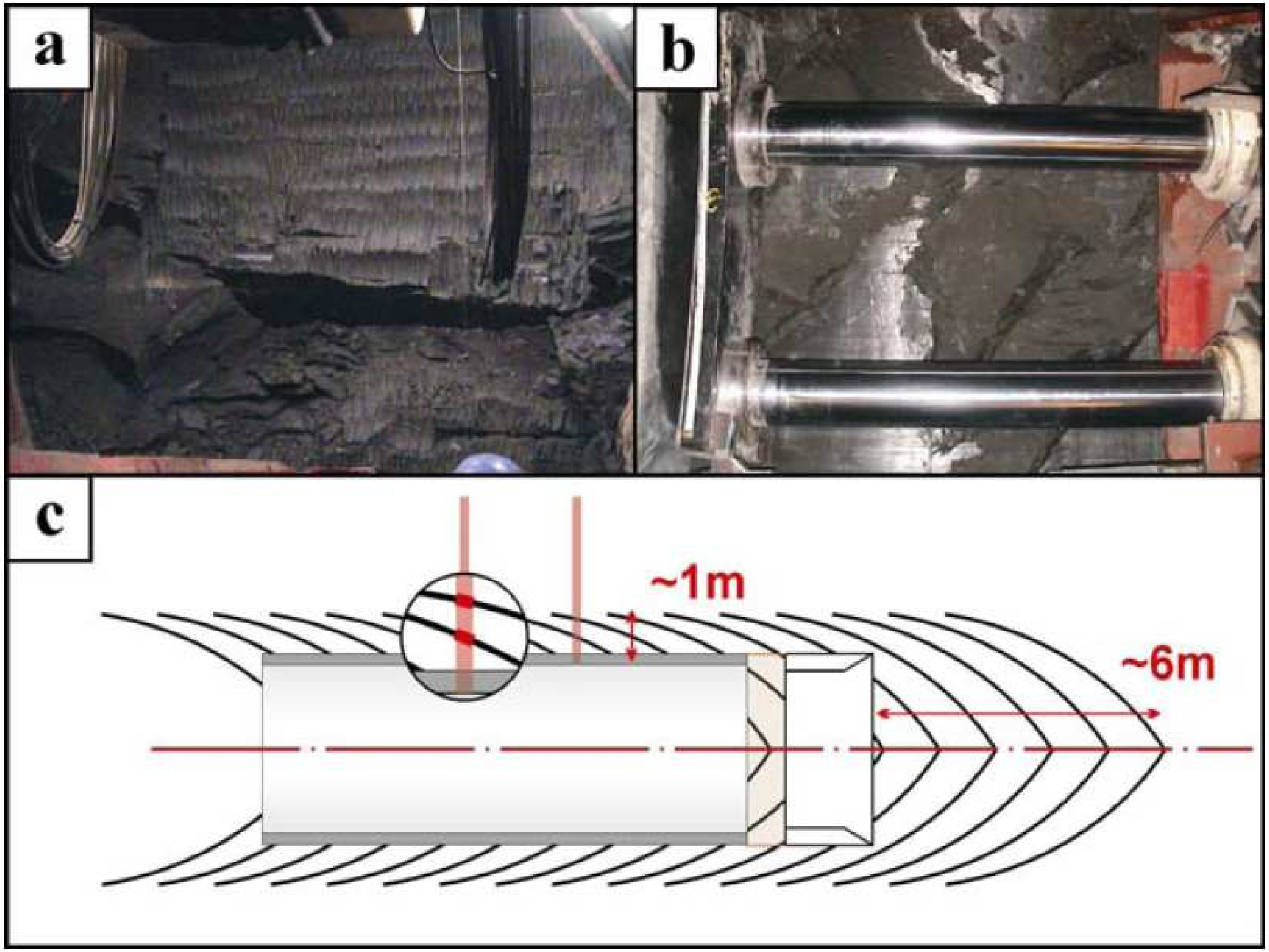
in-situ x-ray micro tomography + 3D DIC

radioactive waste disposal in deep underground galleries



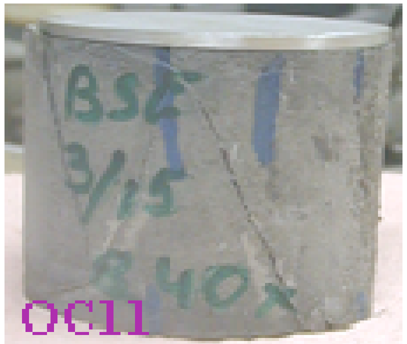
URL in Bure (France) , depth: – 490m

EDZ around radioactive waste underground storage galleries



DAMAGE/DEFORMATION around deep excavations in clays IS LOCALIZED !

patterns of localization observed in lab tests



BC14

BC15

BC12

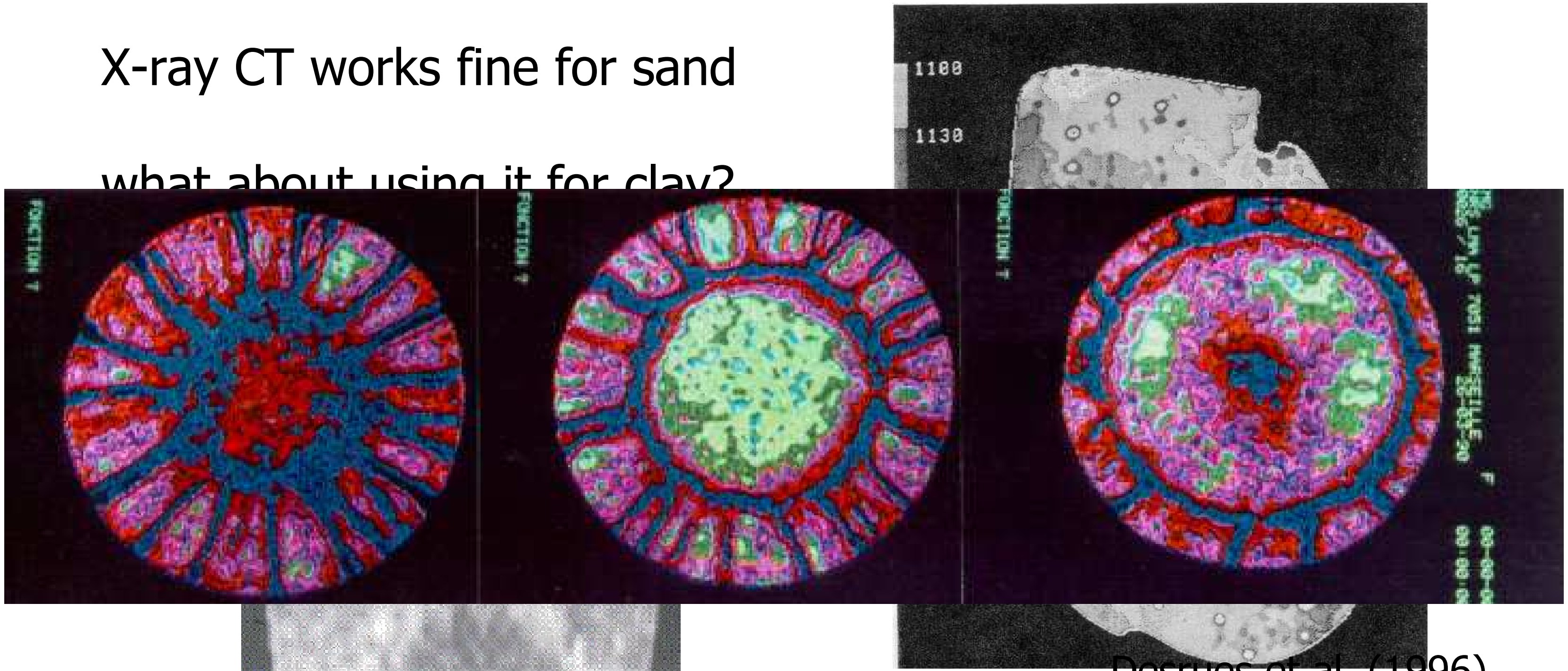
Opalinus Clay and Boom Clay tested in triaxial compression (Coll 2005 - SELFRAC)

x-rays to study strain localization

non destructive 3D imaging techniques → X-ray tomography

X-ray CT works fine for sand

what about using it for clay?



Desrues et al. (1996)

Tillard (1992) Hicher et al. (1994)

→ spatial resolution was not enough

micro x-ray CT at ESRF: a significant step forward

… let's go high tech: synchrotron radiation micro tomography!

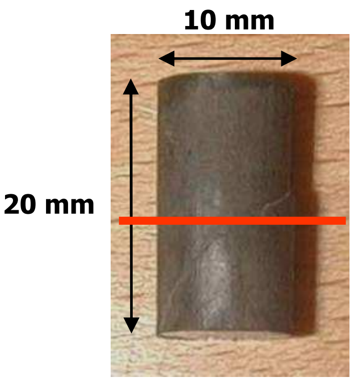
high-energy beamline ID15A at the ESRF in Grenoble (European Synchrotron Radiation Facility – collaboration w/ M. di Michiel)

key advantages:

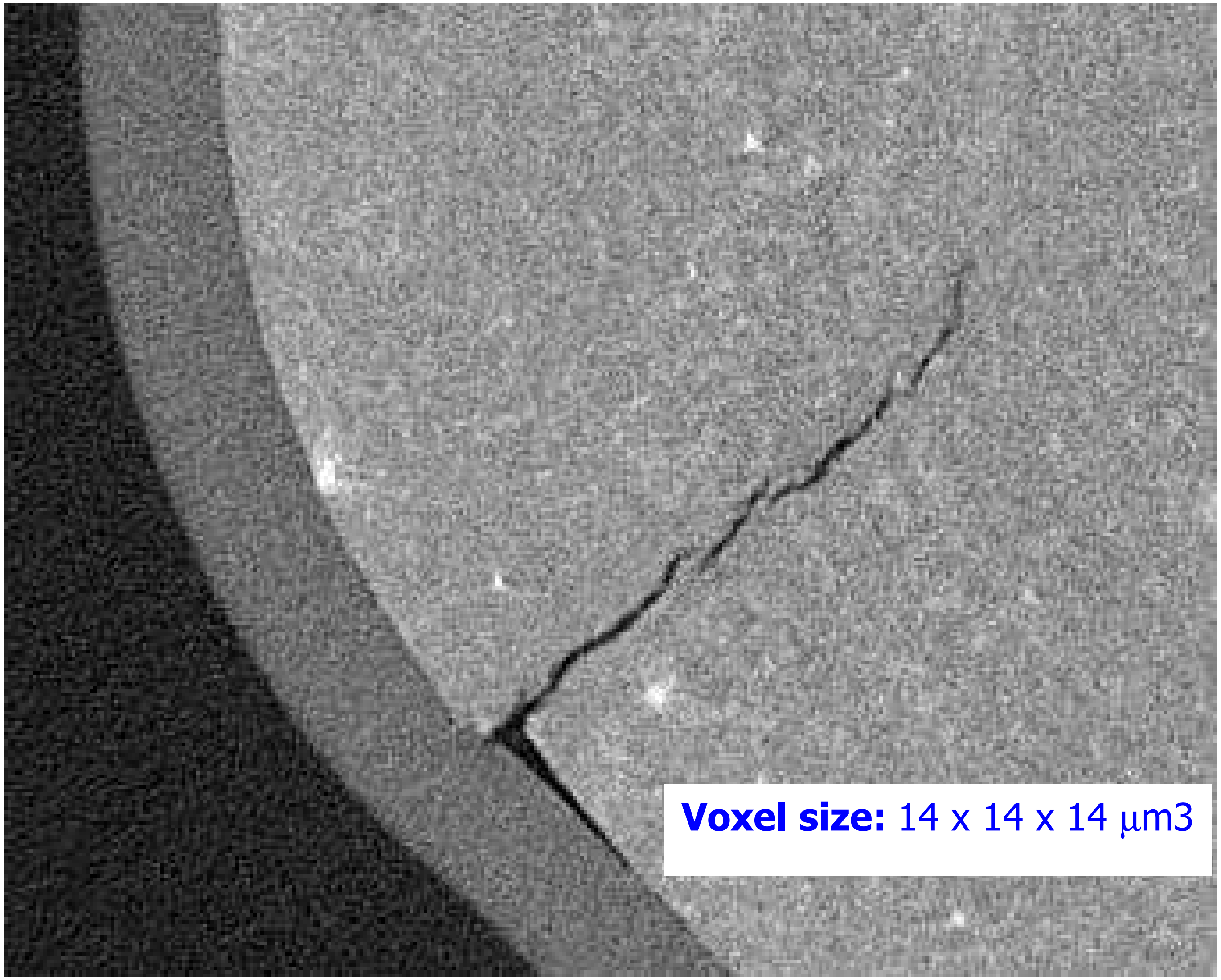
- ⇨ short scanning time
- ⇨ high resolution

acquisition of the entire specimen takes about 12 mins (4 scans of overlapping vertical sections)

voxel size in the reconstructed volume is $14 \times 14 \times 14\ \mu m^3$



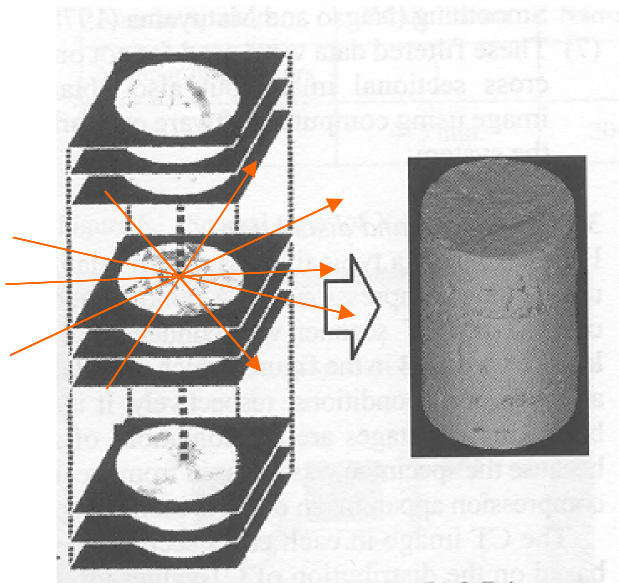
specimen after test



micro x-ray CT at ESRF

basic principle

- recording attenuation profiles through a specimen slice, under different angular positions
- reconstructing a radiograph of the slice
- repeating to get a complete set of slices over the specimen
- reconstructing a 3D image of the internal structure of the specimen from the spatial distribution of the linear attenuation coefficient

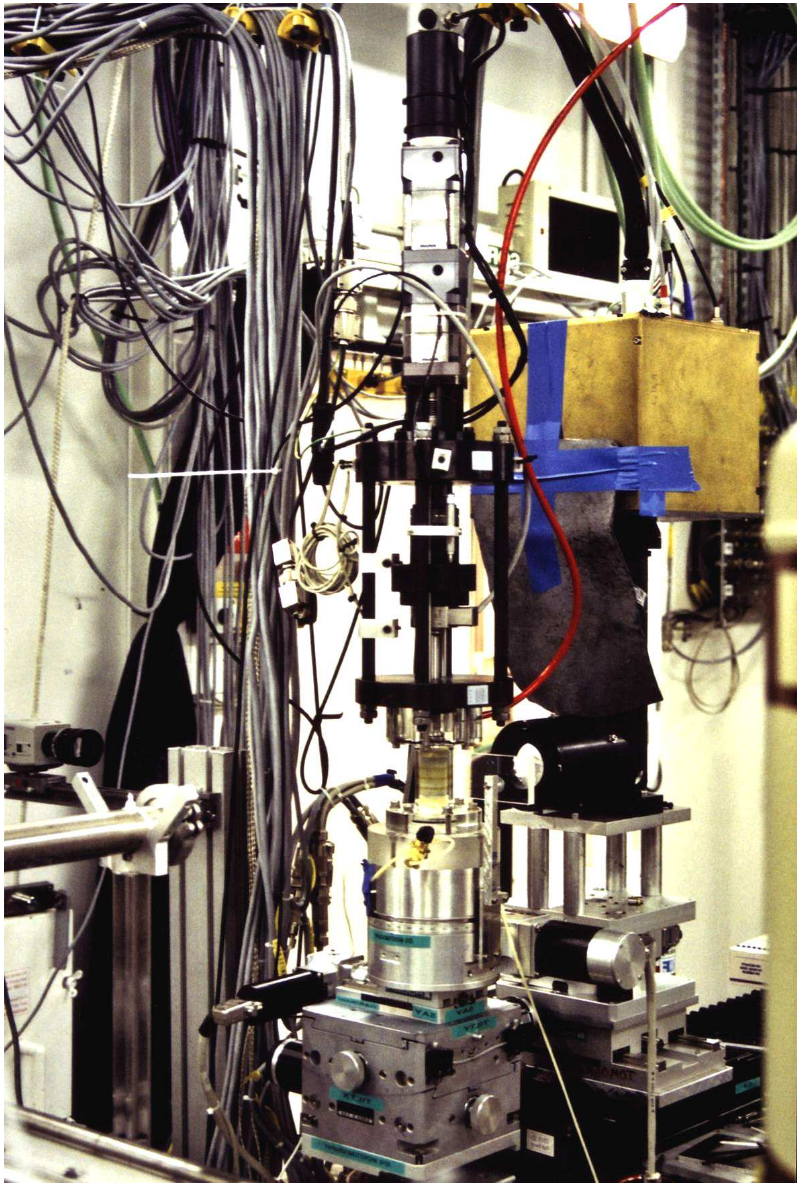


ESRF, Grenoble (France)

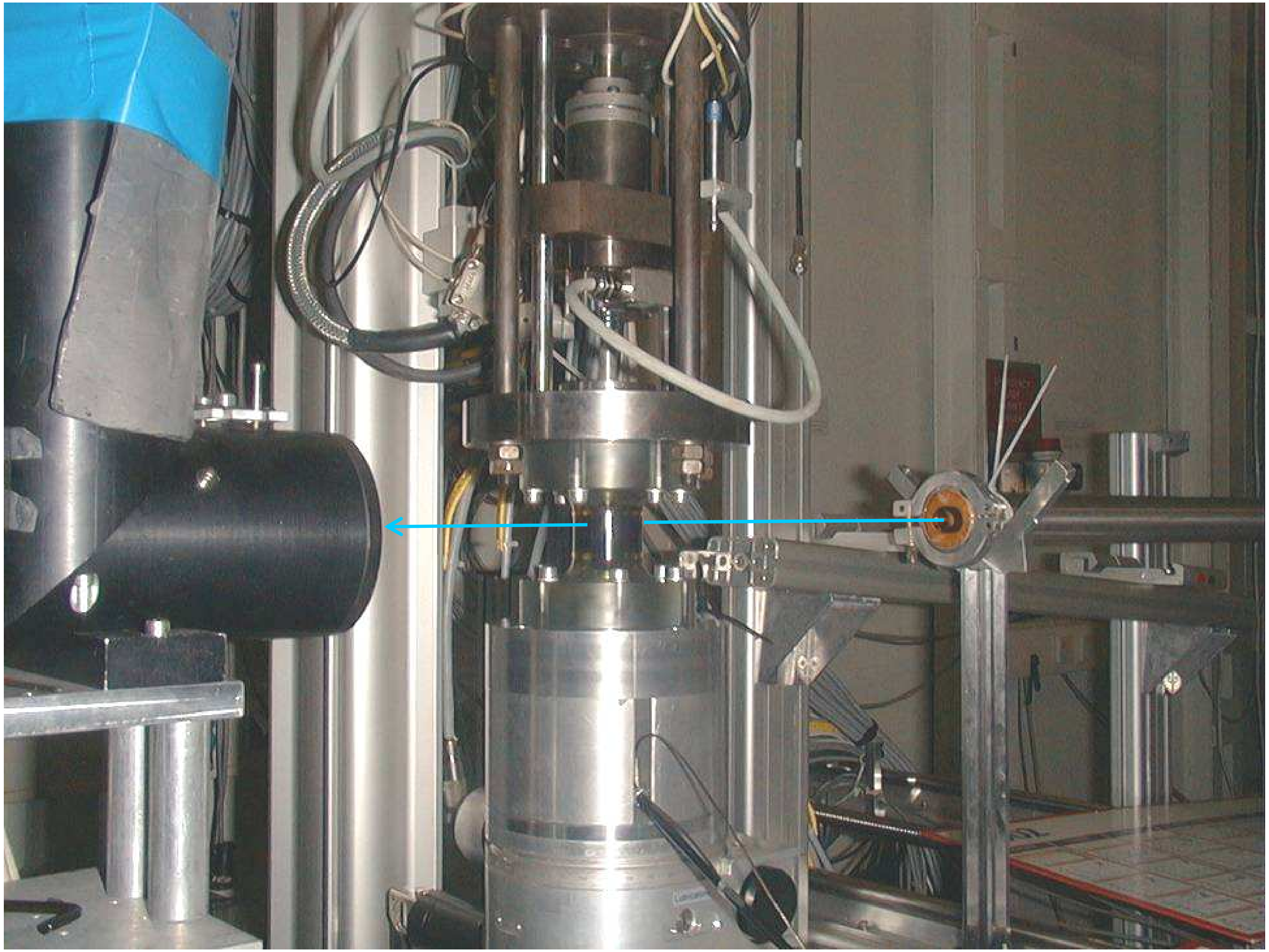
x-ray characteristics

- x-ray white beam to have a high photon flux
- x-ray energy: 50 to 70 keV
- spatial resolution: 14 µm (voxel size)
- time for scanning: 12 to 15 minutes

experimental setup



experimental setup



Callovo-Oxfordian argillite

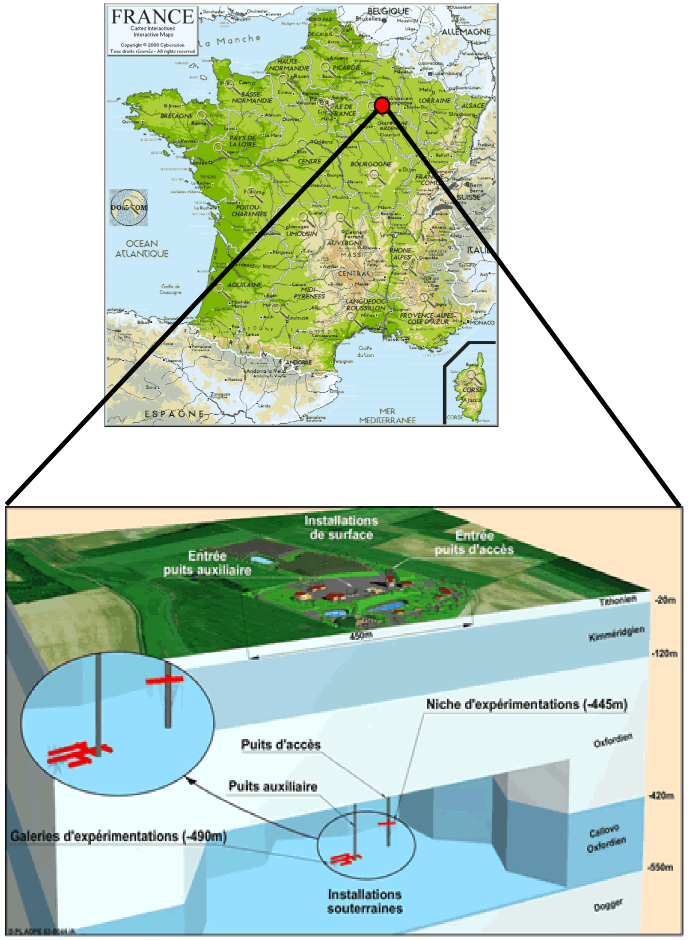
from the Borehole EST261 (depth 476m) of the Underground Research Laboratory of Bure (ANDRA)

a few characteristics

clay content : 40 %

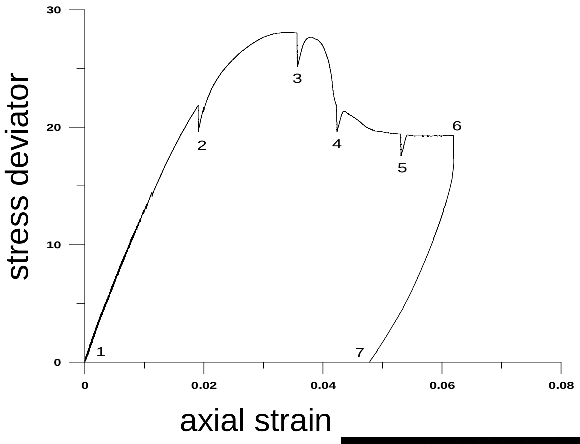
water content : 6 %

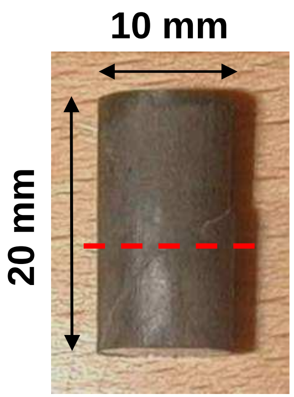
permeability : 10^{-20} to 10^{-22} m^2

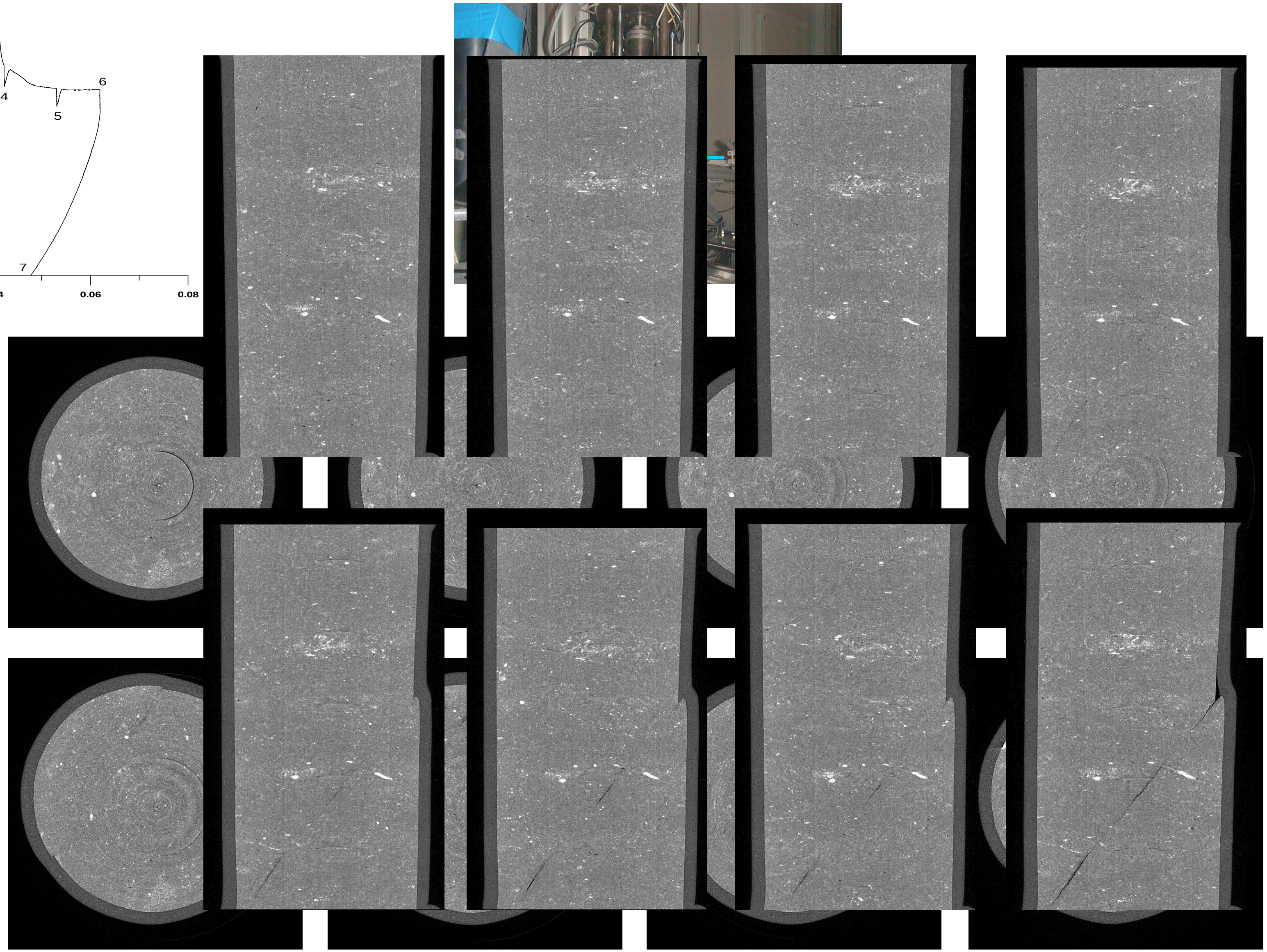


URL in Bure (France) , depth: – 490m

X-ray images from a test (σ_c = 10 MPa)



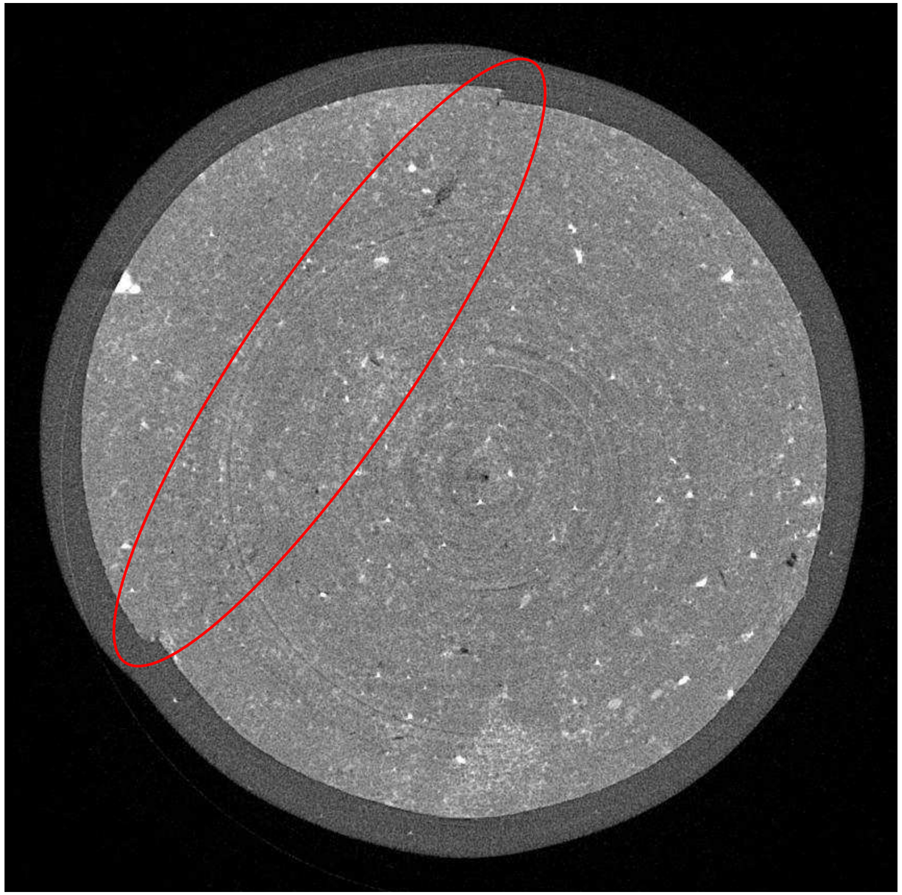




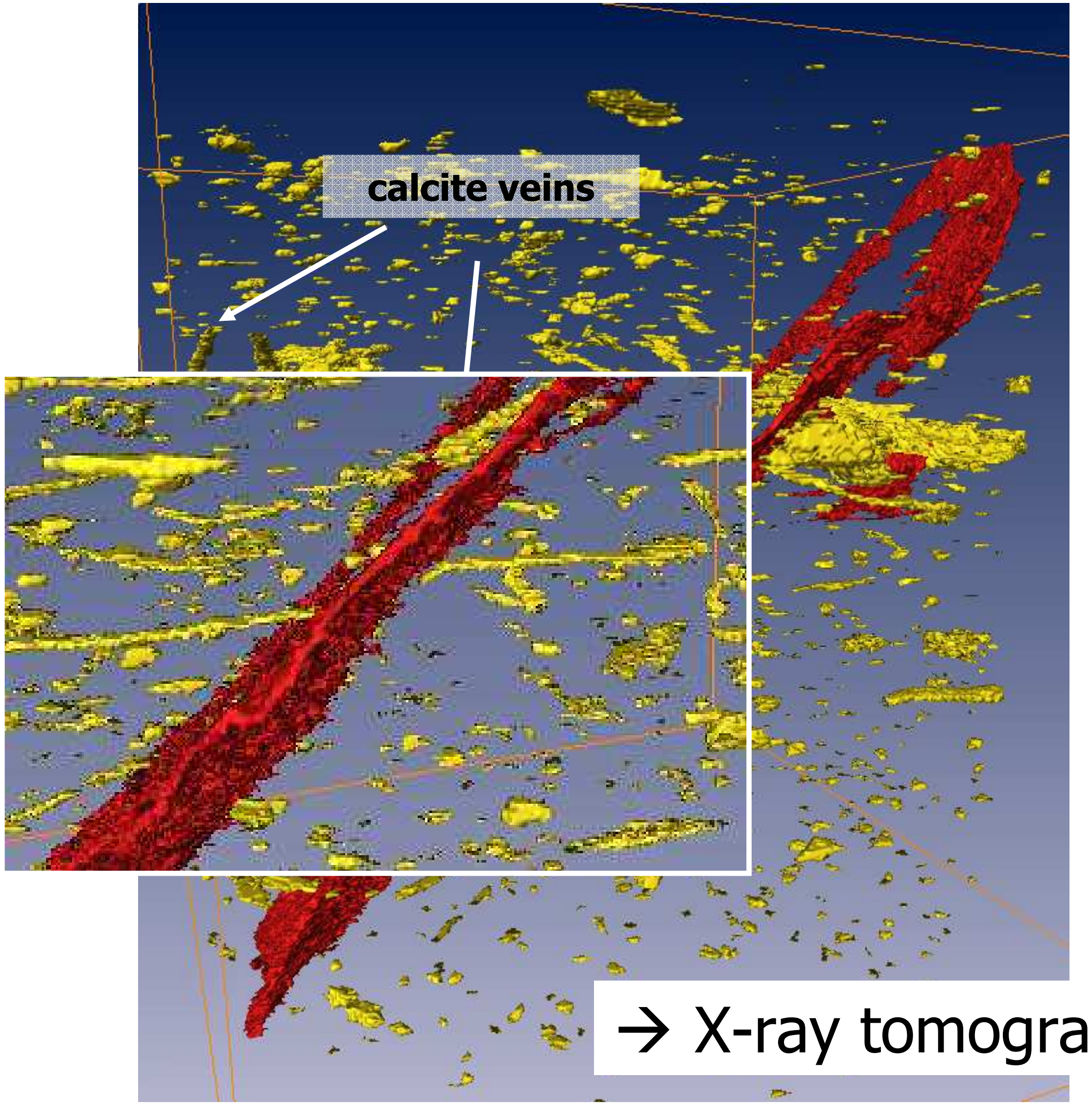
X-ray provides **3D** images

… and if density does not change ?

(mode II cracks, shear bands with no volume changes)



X-ray images do not show everything

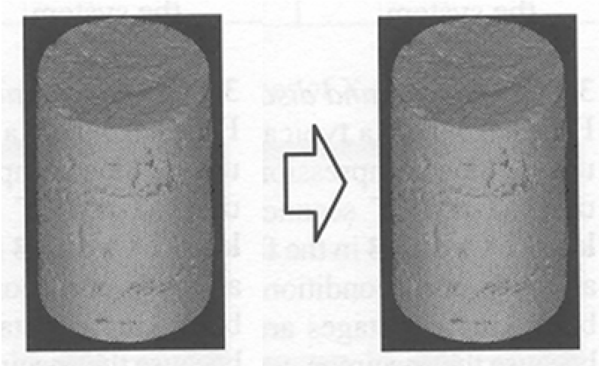


natural inclusions in yellow

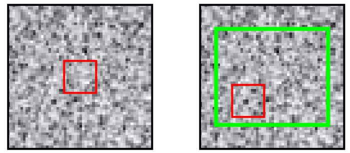
<u>open</u> cracks in red

→ X-ray tomography + 3D DIC

basic principles of 3D DIC: mapping one digital image onto another



two 3D images of specimen at different loading/deformation levels



search in 3D for best correlation displacement vector (integer - pixel)

sub-pixel refinement

interpolating correlation coefficient
fast, but can only assess rigid body motion

interpolating gray-level
slow, but more general transformations

displacement field with sub-pixel accuracy [dx, dy, dz])

definition of nodes distributed in the first image

definition of the "motif", or **correlation window** (region about each node)

calculation of a correlation coefficient for each displacement of this motif, within a region ("search" window) about the target node in the second image

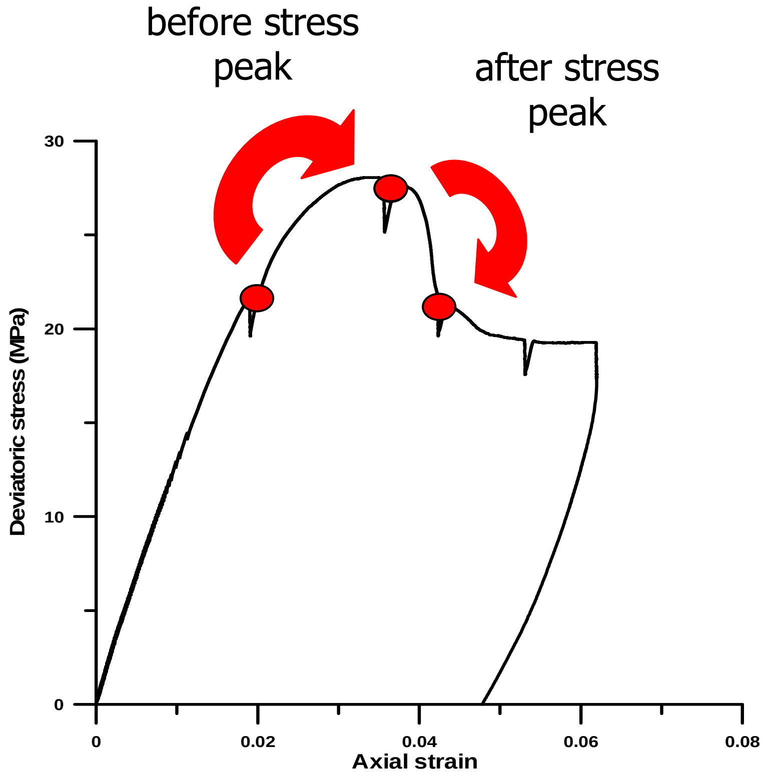
definition of the discrete displacement (integer number of pixels) i.e. that with the best correlation

sub-pixel refinement (because the displacements are rarely integers of pixels), which may also involve more complex transformations than simply rigidbody translation

calculation of strain from the displacements

3D DIC results from COX argillite

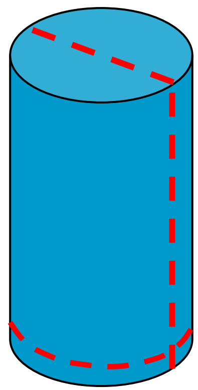
undrained compression, p_0 = 10 MPa



3D DIC using CorrelManu3D

86247 nodes

correlation window size = 20 voxels

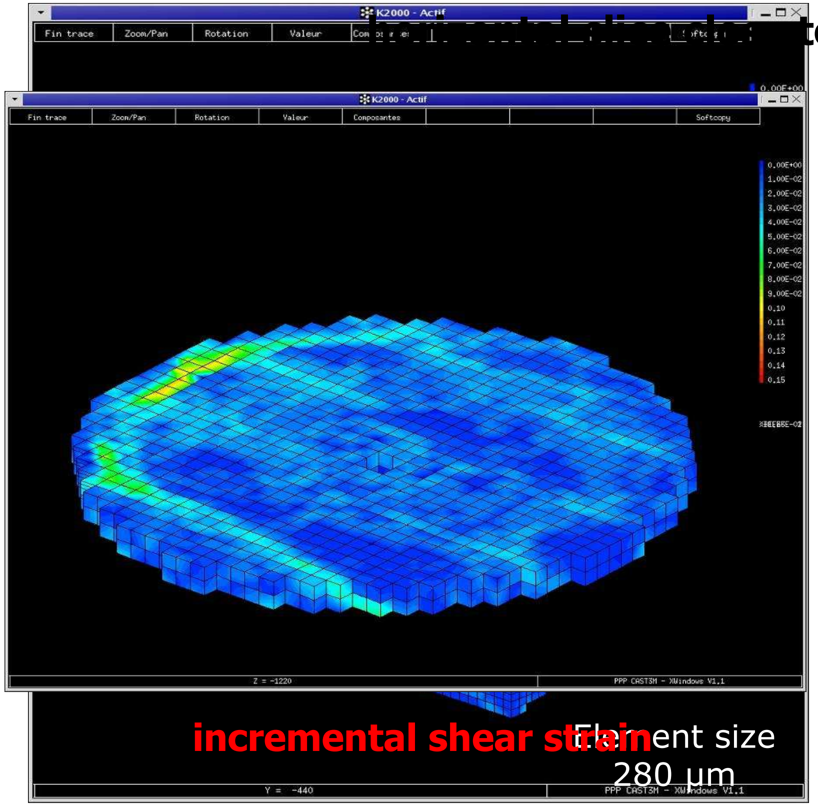


Lenoir et al. (2007) – Strain, International Journal for Experimental Mechanics, Vol. 43, No. 3, 193–205

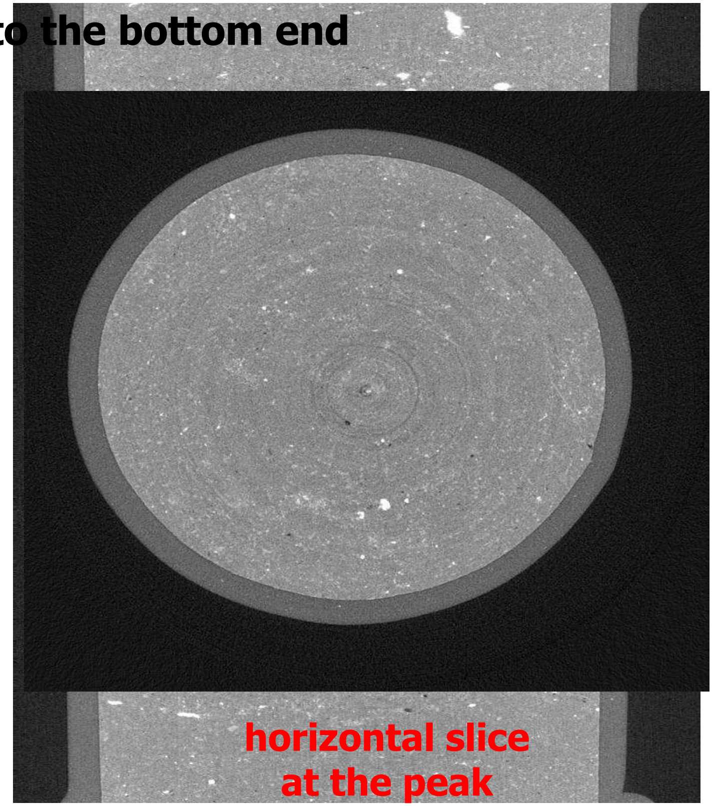
increment **before** stress peak

vertical slice along the axis

to the bottom end



incremental shear strain



horizontal slice at the peak

incremental shear strain

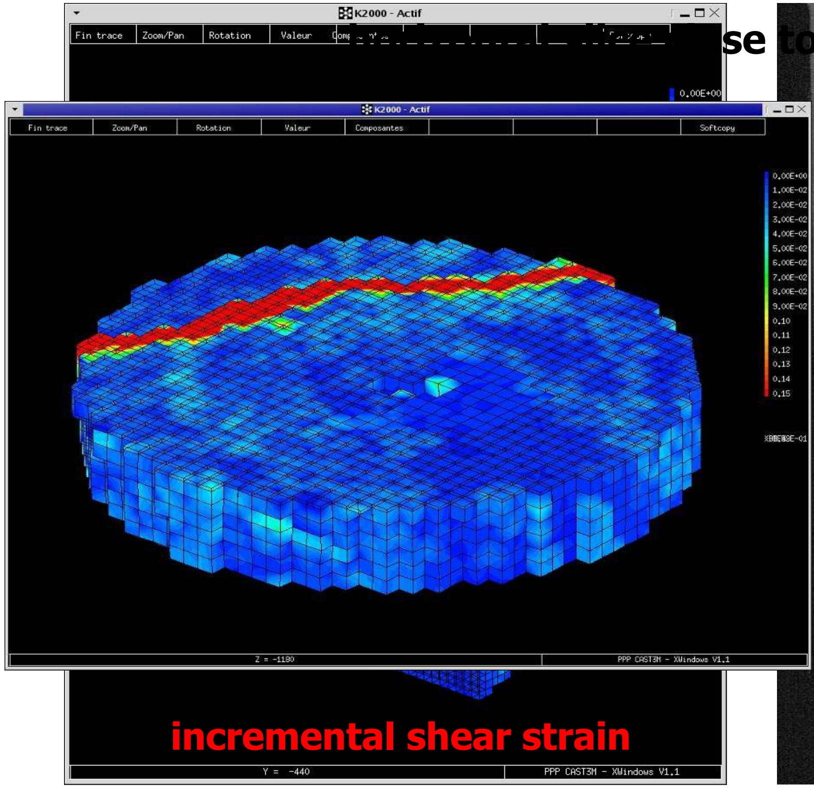
vertical slice at the peak

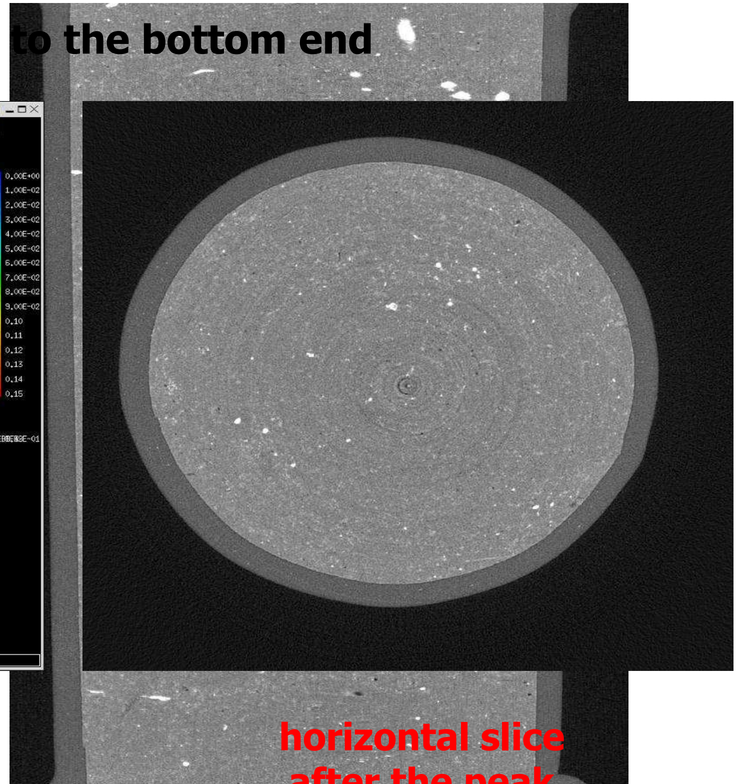
Lenoir et al. (2007) – Strain, International Journal for Experimental Mechanics, Vol. 43, No. 3, 193–205

increment **after** stress peak

vertical slice along the axis

se to the bottom end





incremental shear strain

vertical slice
after the peak

Lenoir et al. (2007) – Strain, International Journal for Experimental Mechanics, Vol. 43, No. 3, 193–205

example 2

localization in sandstone

(shear bands and compaction bands)

investigating **a range of full-field methods** with different **sensitivities** to different physical properties, to characterize different aspects of the **mechanical processes** investigating **a range of full-field methods** with different **sensitivities** to different physical properties, to characterize different aspects of the **mechanical processes**:

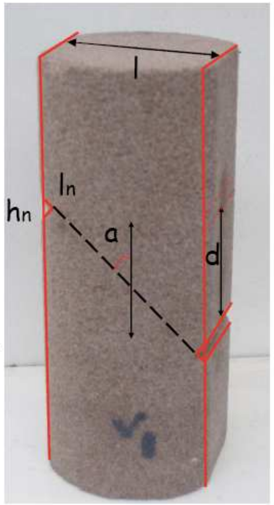
- pre- and post-mortem x-ray tomography
- 3D Digital image analysis
- 3D Digital Image Correlation (DIC)
- ultrasonic tomography
- neutron tomography
- acoustic emissions
- thin section analysis (microscopy and SEM)

specimens of Vosges sandstone – loaded in triaxial compression

Vosges sandstone
mean grain size = 0.3 mm

Notches → to enforce **distinct shear band** in the middle of the sample (expected)

Flattened faces→ contact surfaces for the barrettes

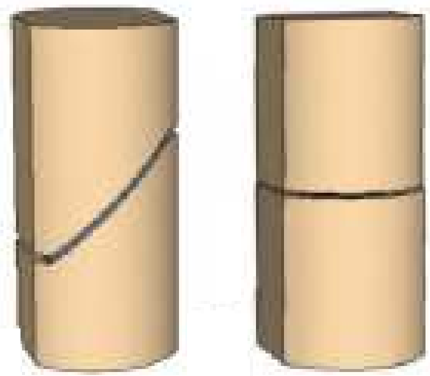


Vosges sandstone (see Bésuelle, 1999)

- ▣ Ve2 (50 MPa confining pressure):
  - shear bands
- ▣ Ve4/6 (130 MPa confining pressure):
  - compaction bands

→ "flattened cylinders"

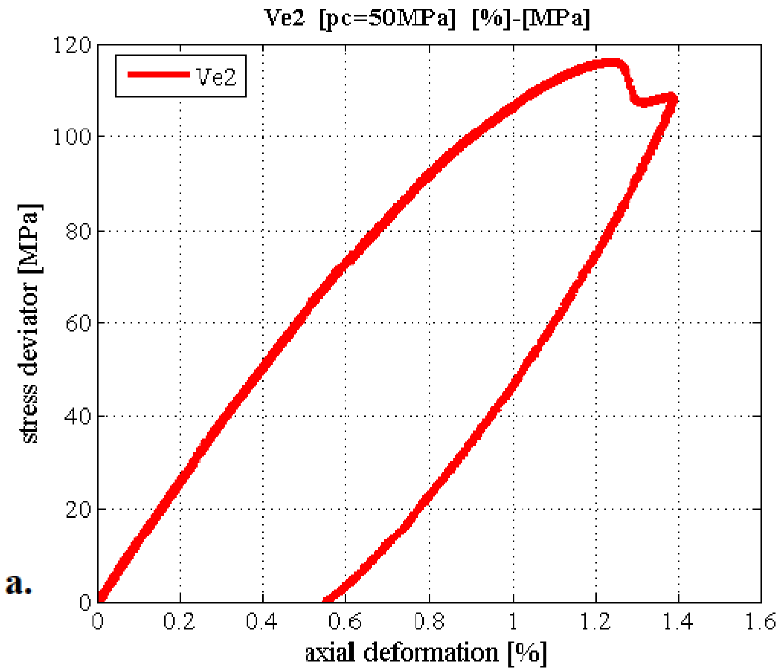
→ x-ray and ultrasonic scanning before and after tests

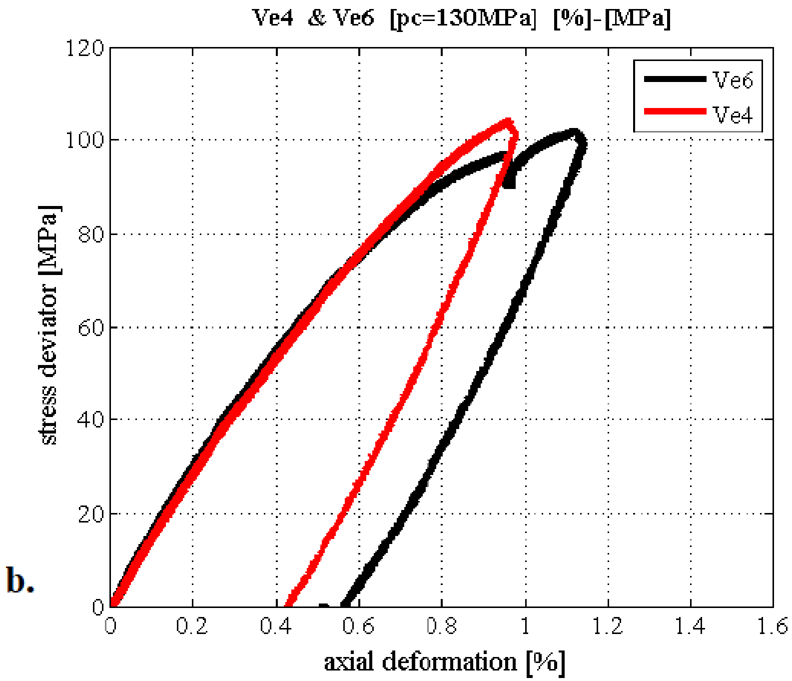


Vosges sandstone (see Bésuelle, 1999)

at GFZ, Potsdam

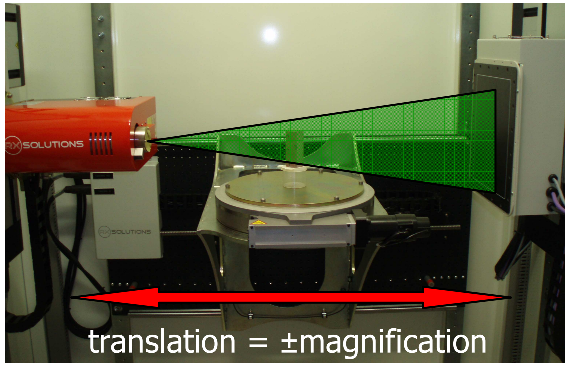
- Ve2 (50 MPa confining pressure)
  - shear bands
- Ve4/6 (130 MPa confining pressure)
  - compaction bands





→ tests stopped shortly after peak stress not to break the specimen in two pieces

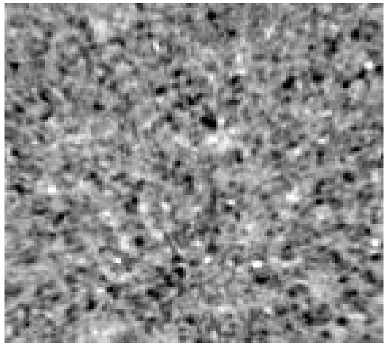
x-ray scanning performed at 3S-R (not at ESRF)

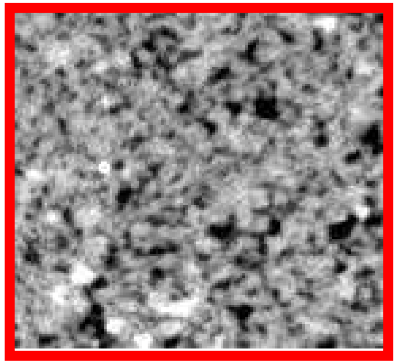


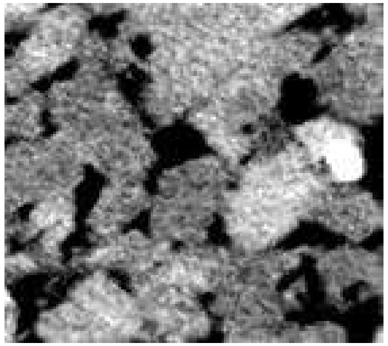
Cone Beam
Variable magnification:
ø4 mm ⇨ ≈ 5 µm voxel width
ø210 mm ⇨ ≈220 µm voxel width
Adaptability to access the physics of materials at the pertinent scale(s)

Grès de Vosges (grain diameter ≈300 µm)

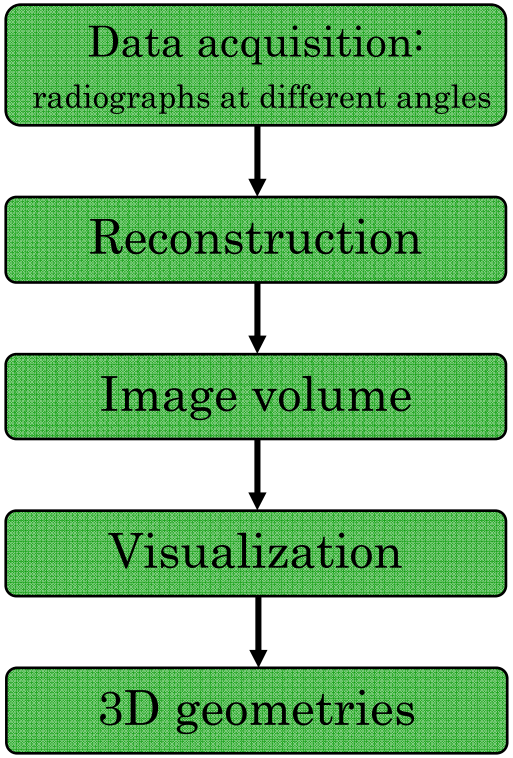
- Voxel width: 90 µm 30 µm 7 µm

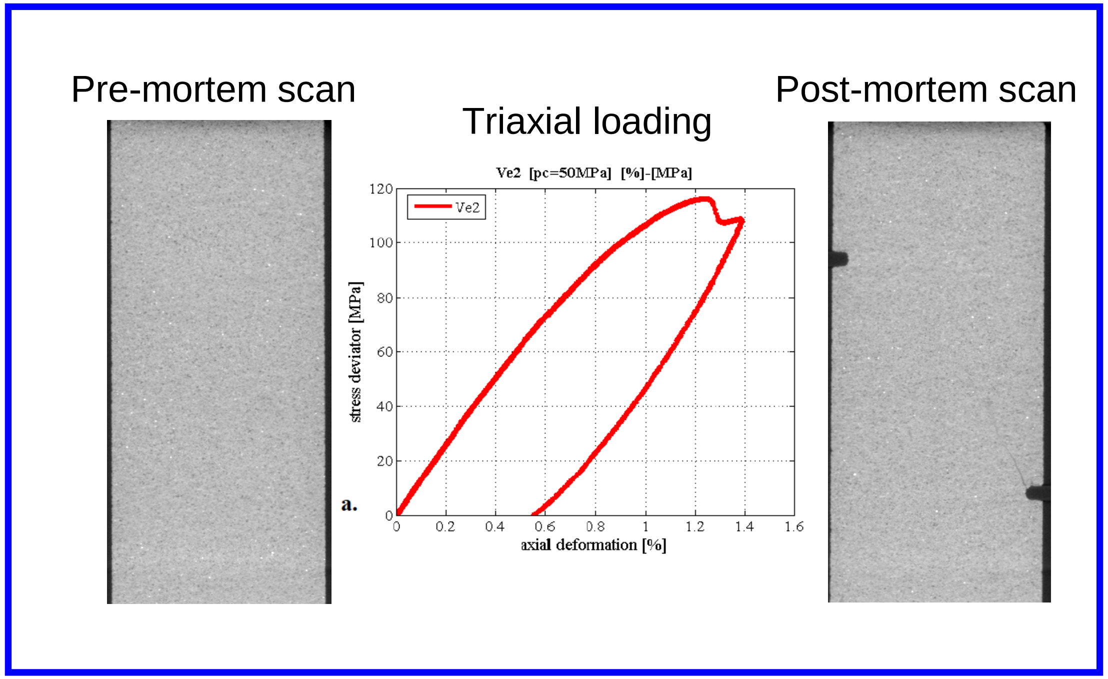




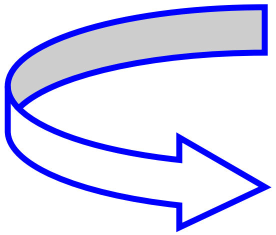


X-ray tomography at 3S-R





raw data (CT number)
- density information

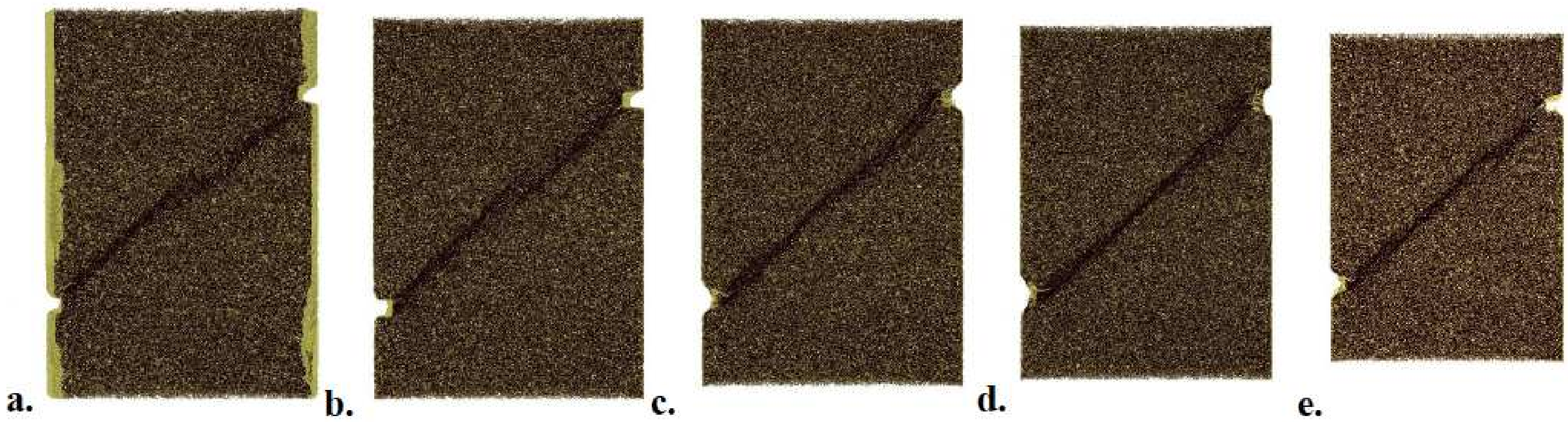


standard deviation
- heterogeneity

(Image voxel size ≈ 30µm)

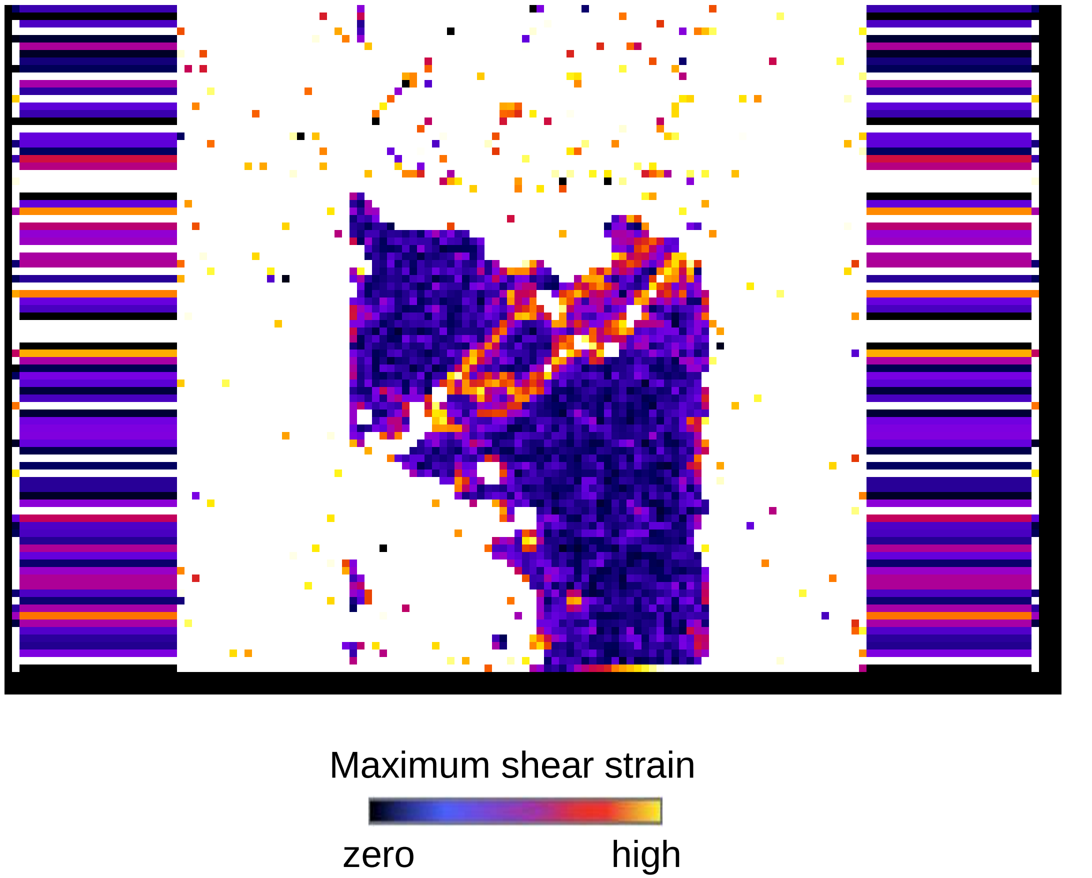
specimen VE2 (50 MPa confining stress)

high resolution scans ~30 μm voxel size



- Localised deformation appears as higher density zones
  (dark = higher density)
- Two bands meeting in middle of sample

specimen VE2 (50 MPa confining stress)

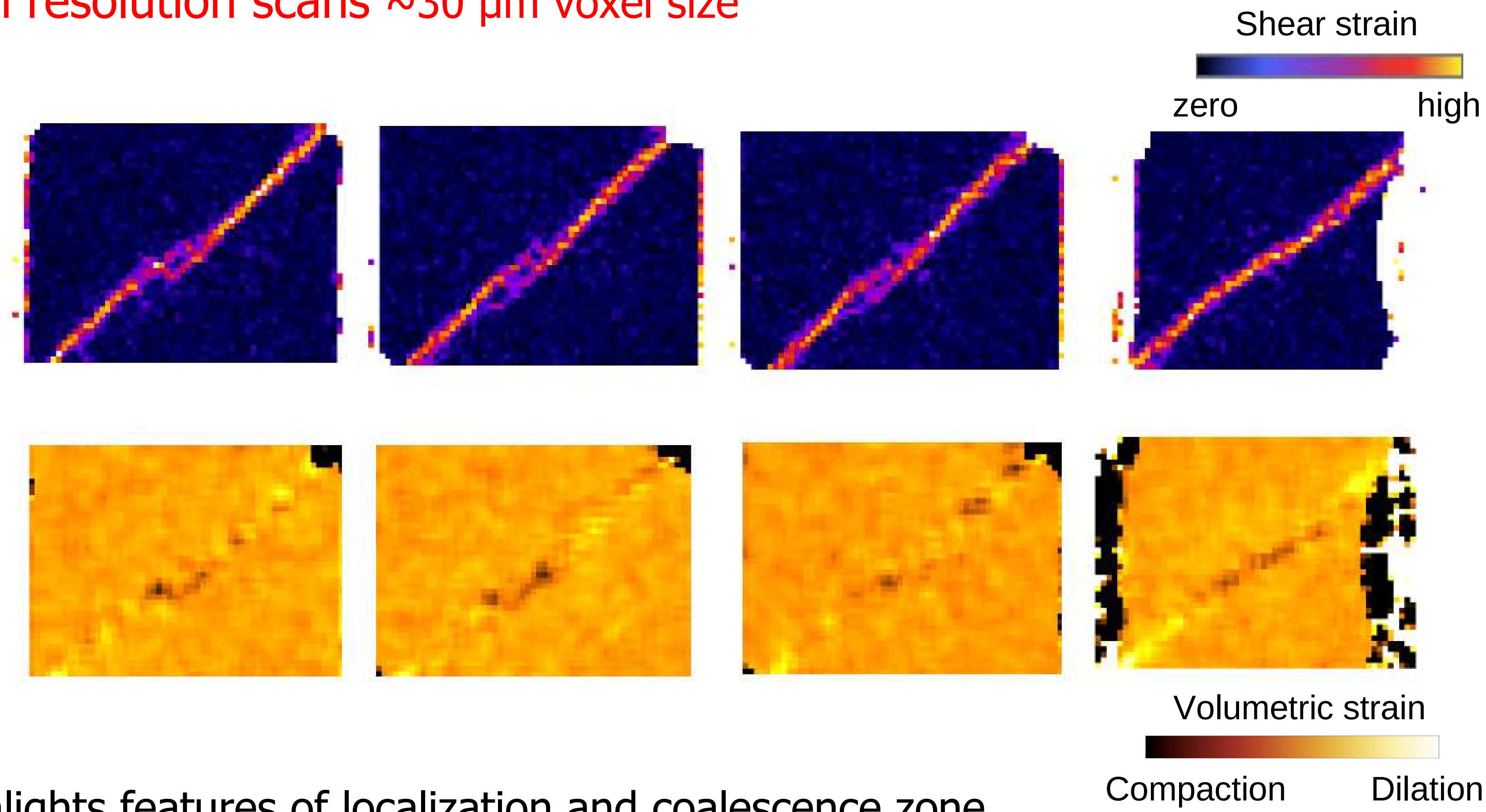


DIC grid spacing = 10 voxels
Correlation window = 5 voxels (voxel side = 30 μm)

3D DIC results (using in-house 3SR code *TomoWarp*)

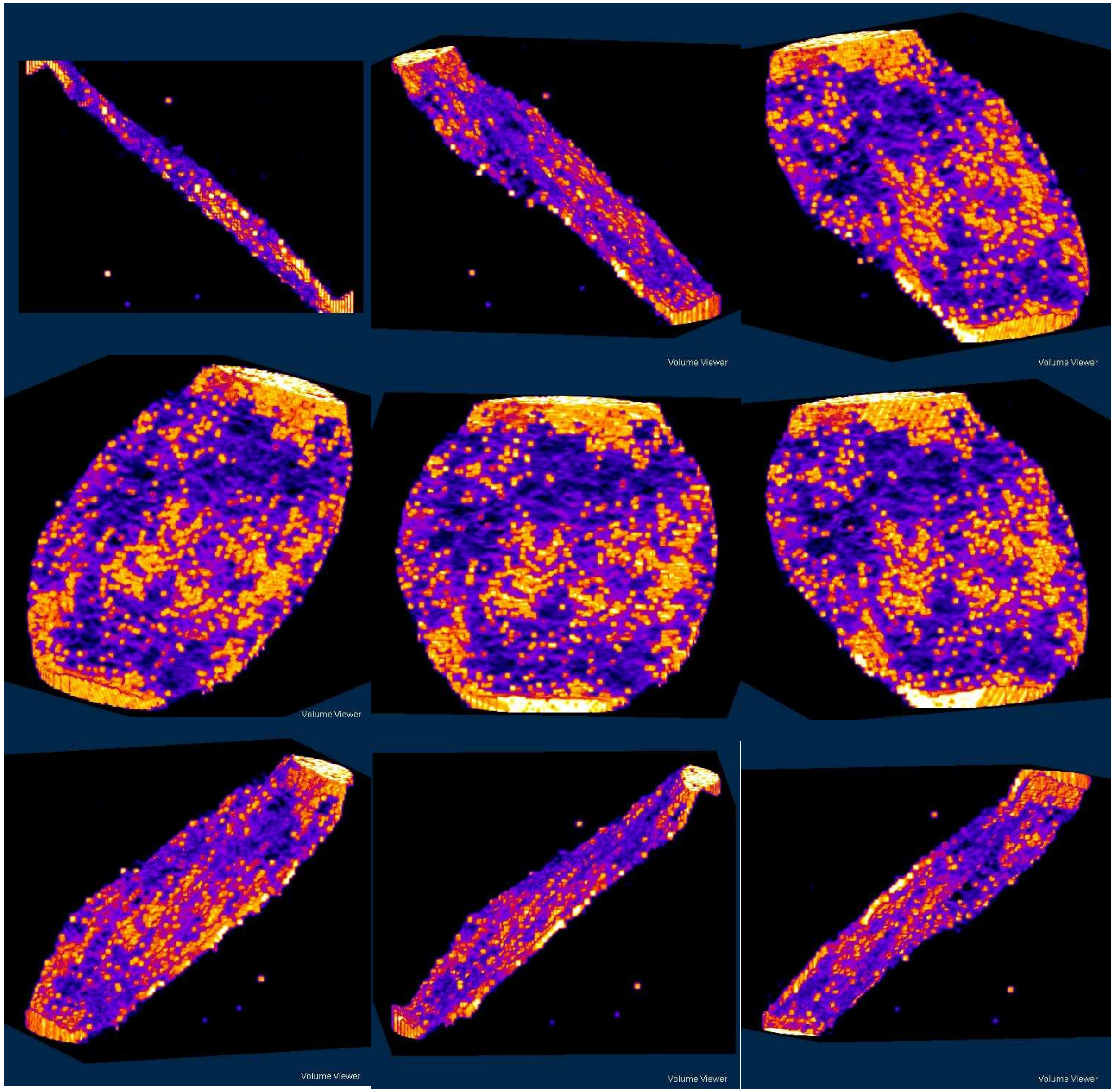
specimen VE2 (50 MPa confining stress)

high resolution scans ~30 μm voxel size

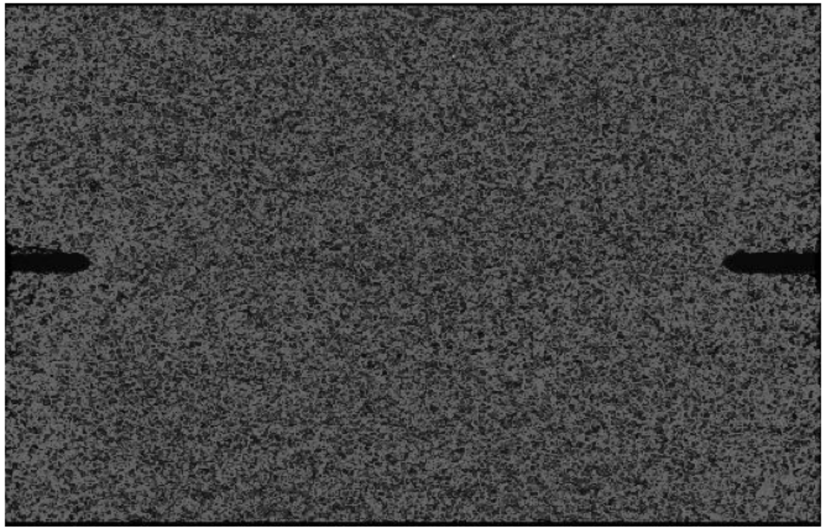


- highlights features of localization and coalescence zone
  - greater shear strain than volumetric
  - volumetric strain varies between compression and dilation

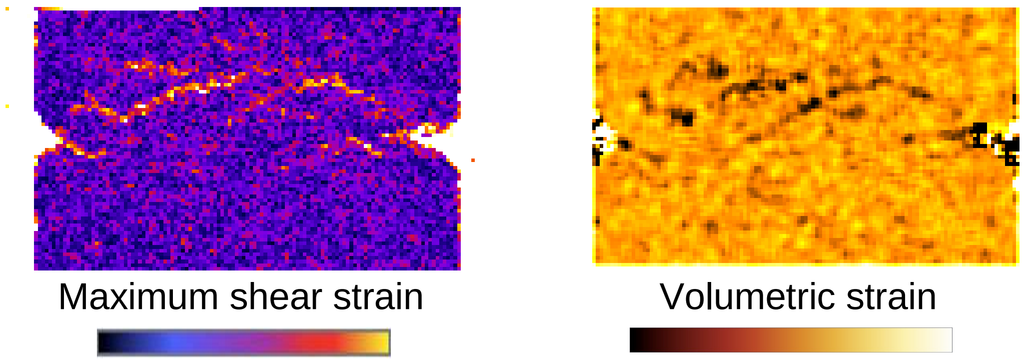
3D DIC results (same test, 3D views of the shear band)



specimen VE6 (130 MPa confining stress)



- no evidence (to the naked eye) of localized deformation



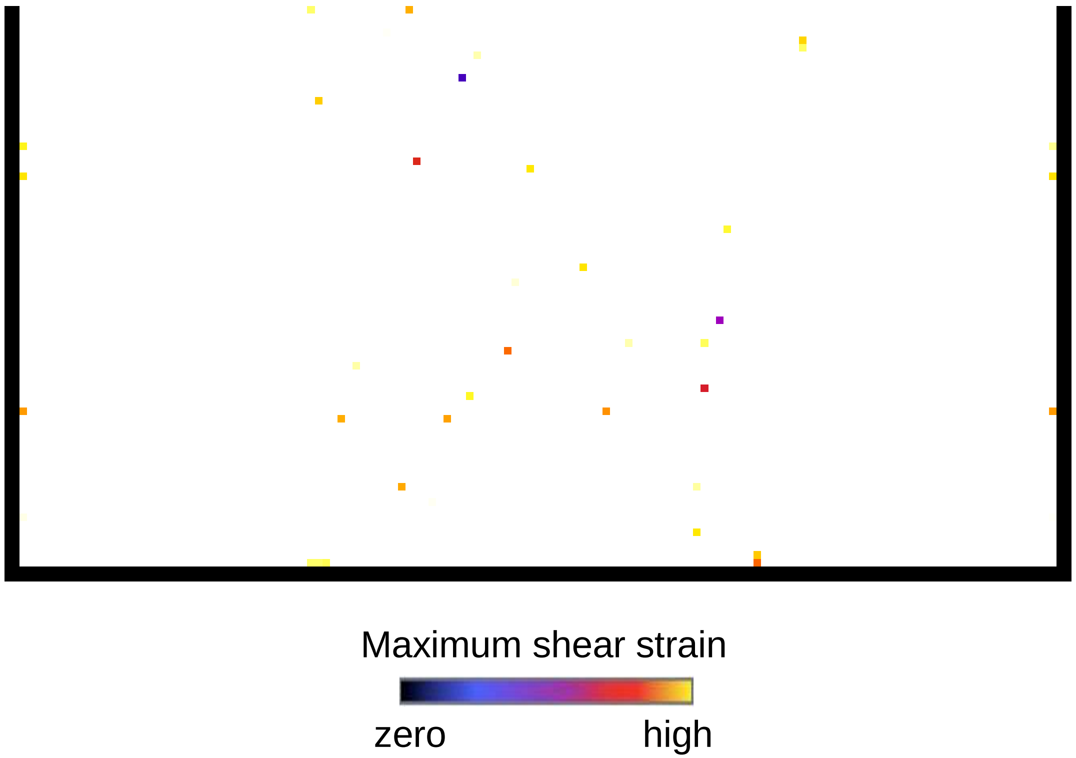
Maximum shear strain — zero … high

Volumetric strain — Compaction … Dilation

DIC grid spacing = 10 voxels, correlation window = 5 voxels

specimen VE6 (130 MPa confining stress)

- DIC results clearly show localized deformation



DIC grid spacing = 10 voxels, correlation window = 5 voxels

VE2 (50 MPa) / ~30 µm voxel size

when direct observation of x-ray tomography images does not allow compaction band features to be resolved, local statistical measures of the gray-level values such as skewness and standard deviation may help (Louis et al. 2006)

Standard deviation

low high

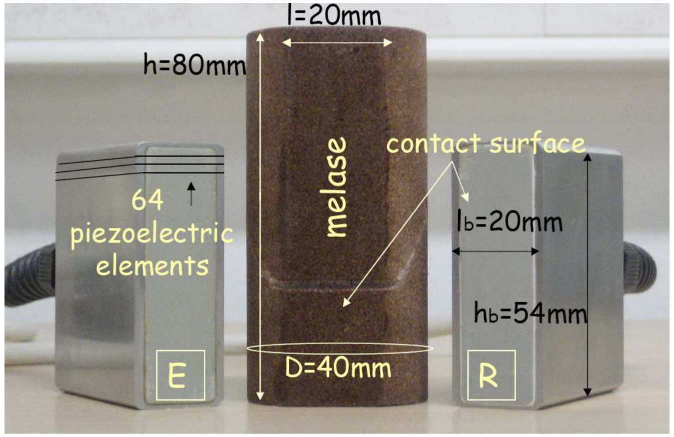
calculation made throughout the image volume over sub-volumes of 20x20x20 voxels^3 at a spacing of 5 voxels in each direction

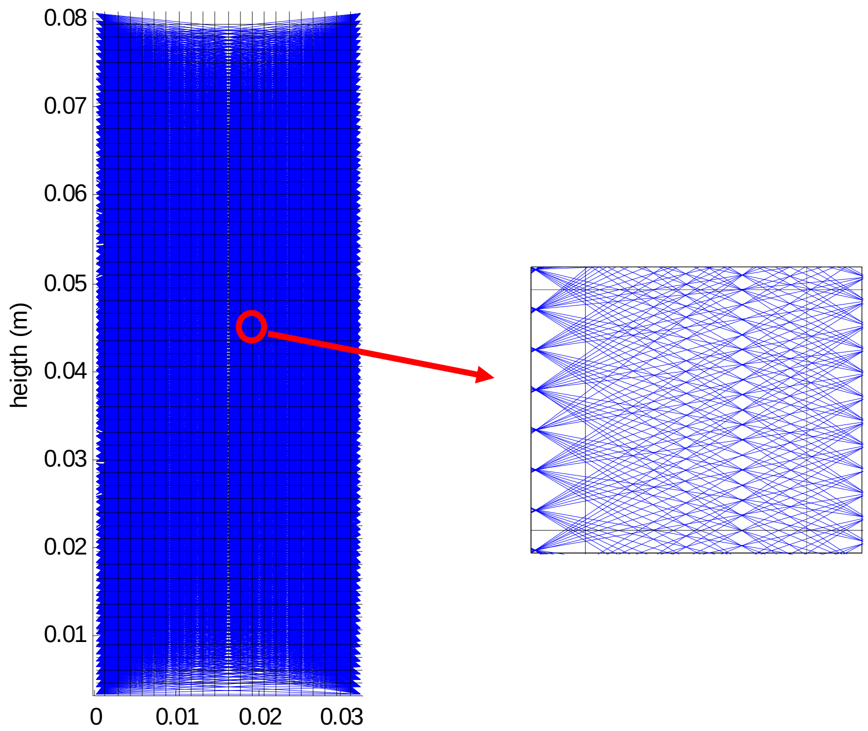
shear and compaction bands appear as zones of decreased standard deviation

VE6 (130 MPa) / ~30 µm voxel size

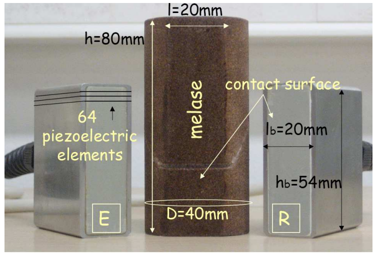
- Ultrasonic data acquisition:
  - two arrays of **64 piezoelectric transducer elements** (Vermon)
    - elements size: about 20 x 0.75 mm
    - main frequency : 1 MHz
  - **64 source/receiver channel recording system** (Lecoeur Electroniques)
  - LGIT, Grenoble

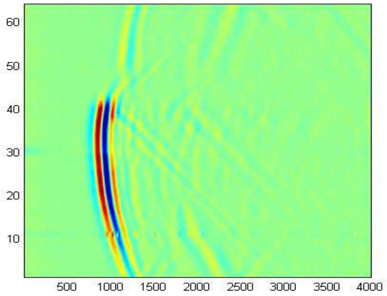
- Data acquired over 64x64 intersecting raypaths in a few seconds
  - unprecedented (for geomaterials) spatial coverage

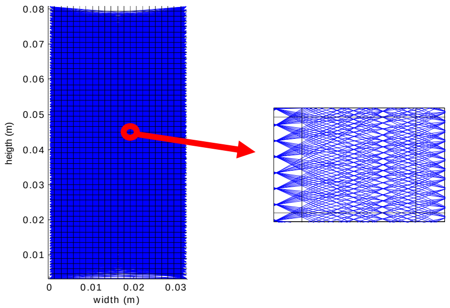


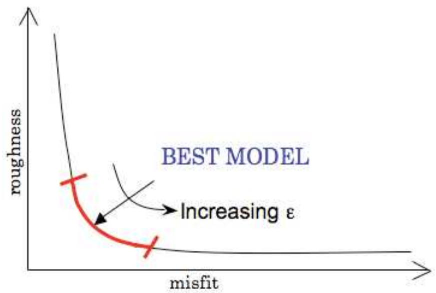


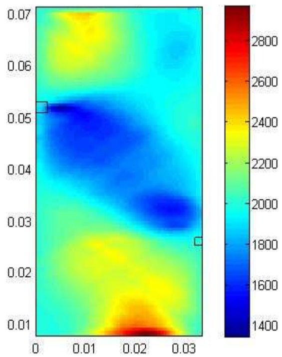
ultrasonic tomography – method: discretization











Pick travel-times

⇩

Discretise model space (grid)

⇩

$$t_i = \sum_j l_j p_j$$

$$d_i = (t_1, t_2, t_3, \ldots t_N)$$

$$\mathbf{d} = \mathbf{Am} \quad A_{ij} = \{l_1, l_2, l_3, \ldots l_N\}_i$$

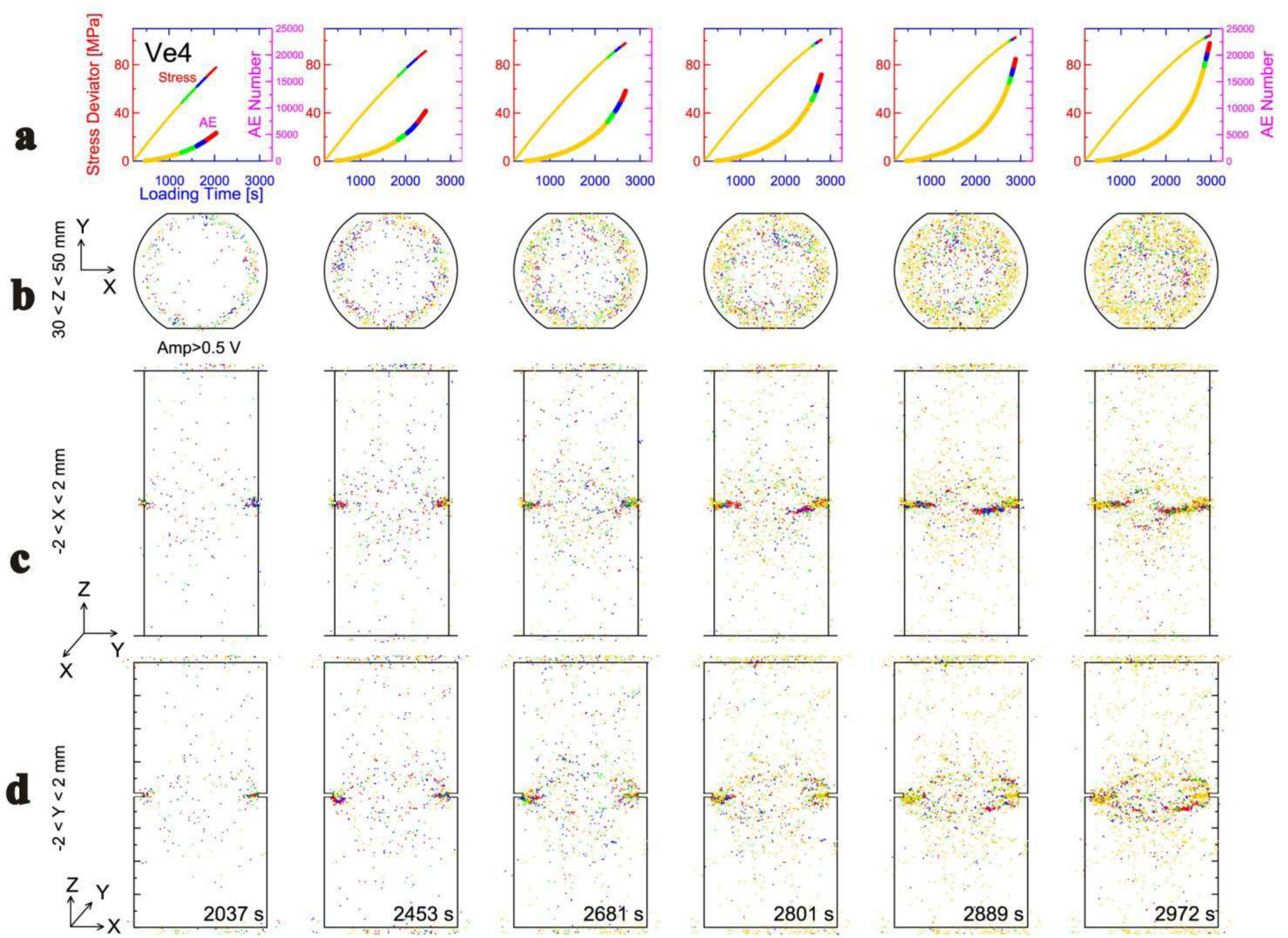
$$m_j = (p_1, p_2, p_3, \ldots p_M)^T$$

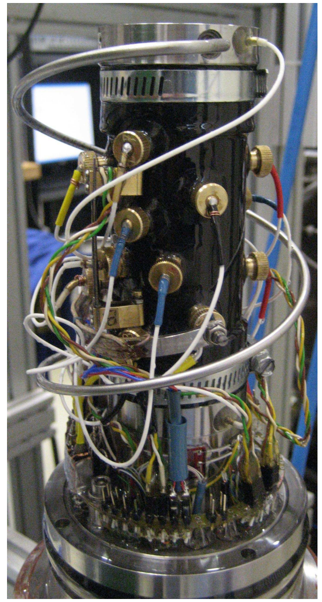
solve $\mathbf{m}=(\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{d}$
(with constraints)

t_i = travel time of *ith* ray
l_j = path length of *ith* ray in *jth* cell
p_j = slowness = velocity^{-1} in *jth* cell

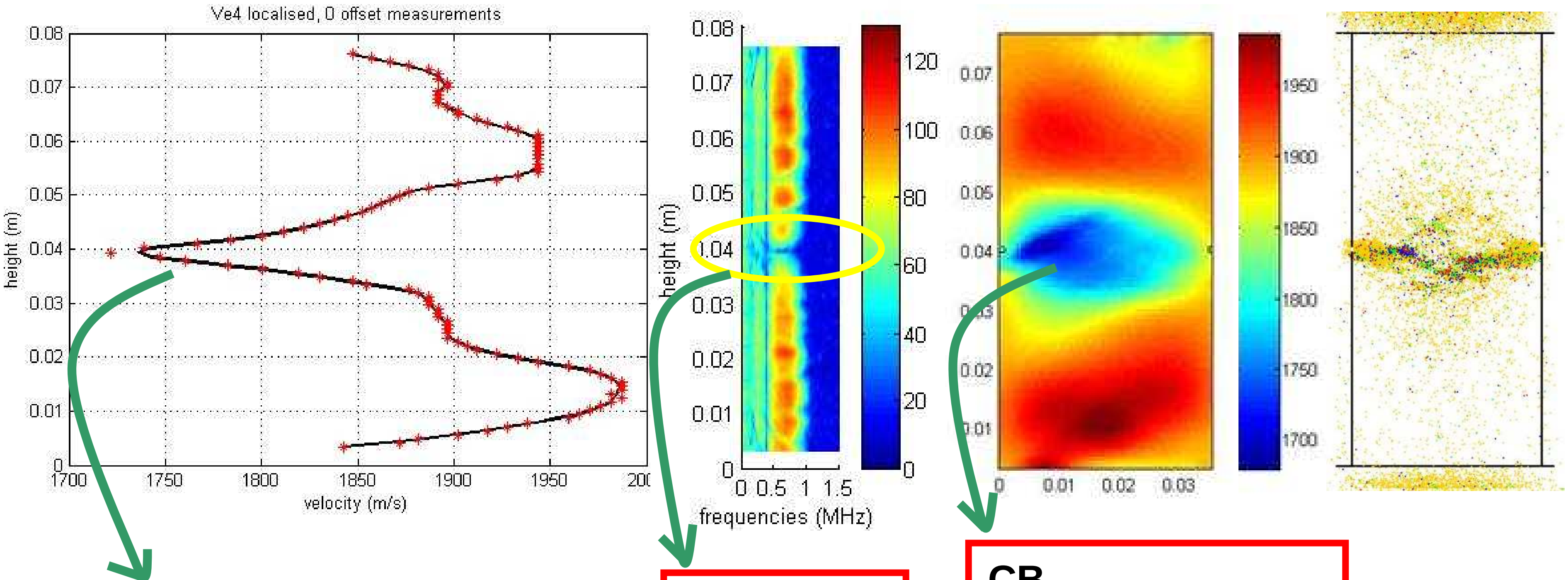
1

specimen VE4 (130 MPa confining stress)





specimen VE4 (130 MPa confining stress)



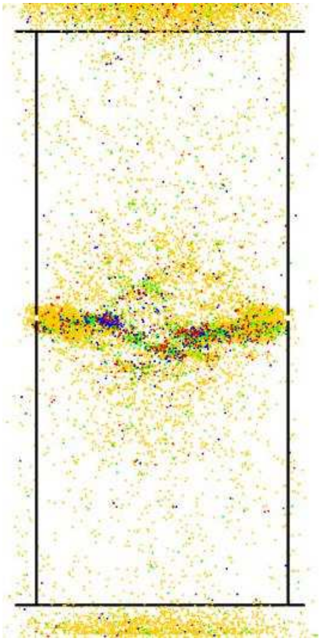
drop in velocities
→ cracking, damage

~ 70%
amplitude
reductions

CB
low velocity zone
but resolution?

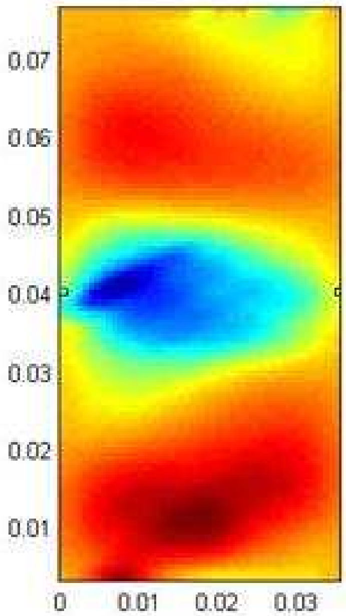
specimen VE4 (130 MPa)

AE



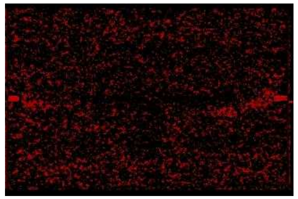
-10mm<x<10mm

traveltime tomography



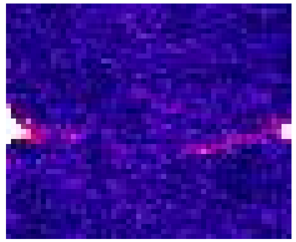
-10mm<x<10mm

high resolution X-ray scans (~30 µm)

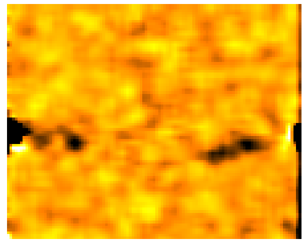


y=18.79 mm

Max shear strains



Volumetric strains

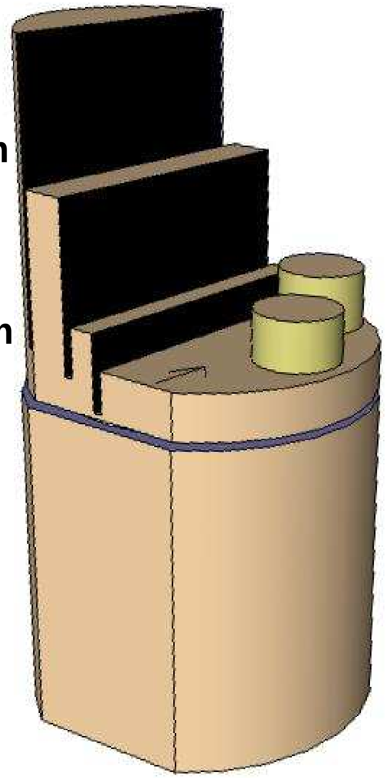


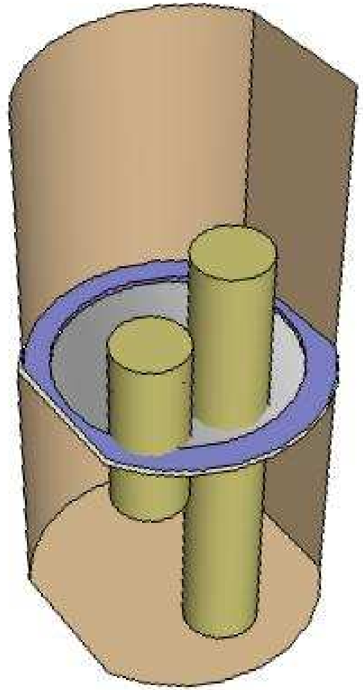
small density variations,
homogeneous regions in the band
compaction and localized shear in the band

acoustic emissions,
reduced velocities,
→ damage mechanisms

from specimen to grain scale

epoxy



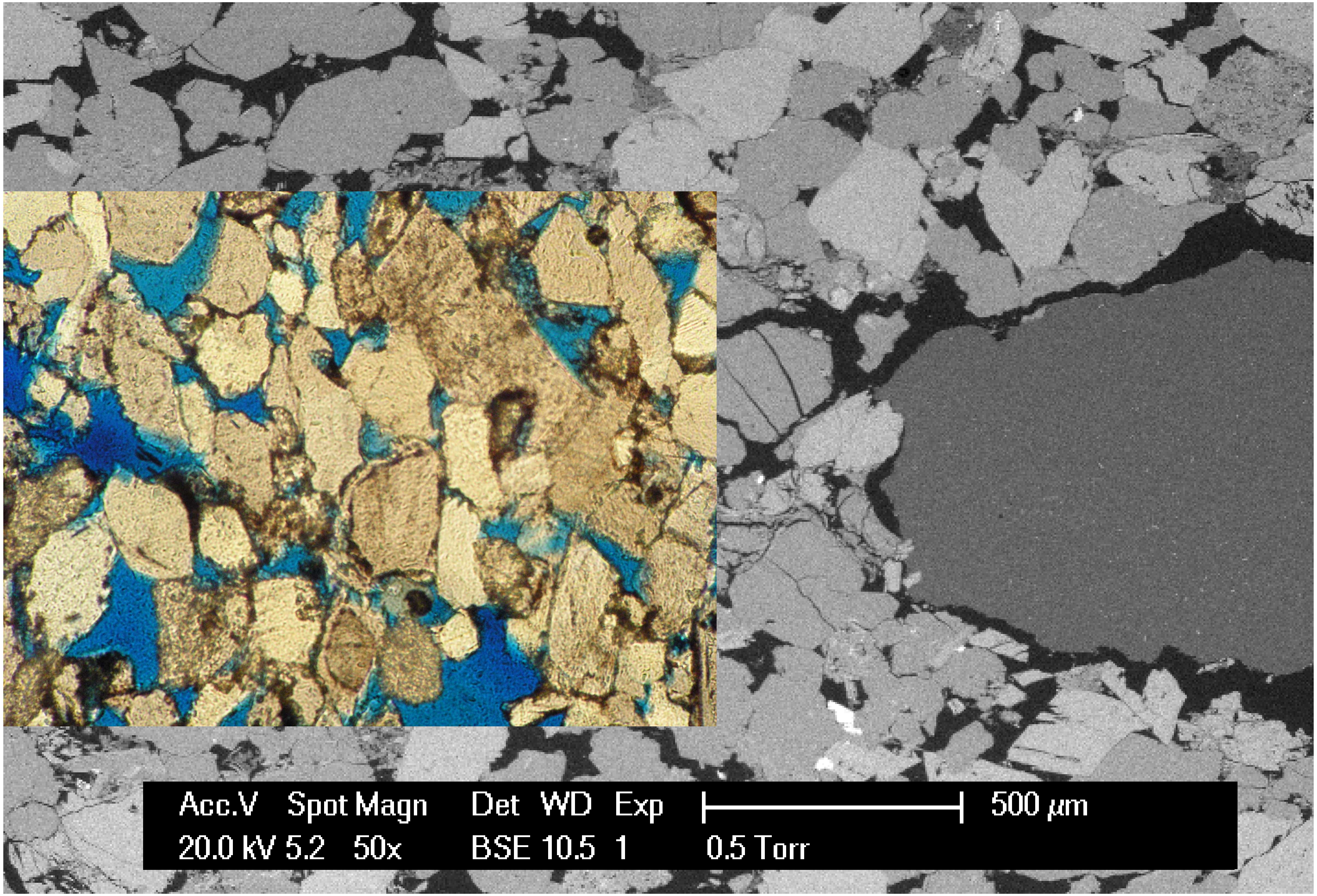


thin sections

optical & electron microscope

small cores (D=10mm)

very high resolution x-ray images ~ 7 μm


Acc.V Spot Magn Det WD Exp
500 µm
20.0 kV 5.2 50x BSE 10.5 1 0.5 Torr

the key idea: combining different methods!

- Full-field methods essential in the study of localization
  - capture heterogeneity of the processes
  - allow measurement of dimensions e.g., localization widths
- X-ray tomography provides insight into 3D density distributions
  - high spatial resolution - Geometrical features and dimensions
  - low sensitivity to damage (only sees larger density changes)
- 3D-DIC
  - clearer view of localization structures
  - quantification of strain and decomposition into shear and volumetric (compaction or dilation) components
- Ultrasonic tomography
  - damage mapping (full-field measurement of elastic properties)
- Next steps - in-situ experiments
  - during-loading x-ray tomography
  - plane strain apparatus for rocks
  - neutron tomography