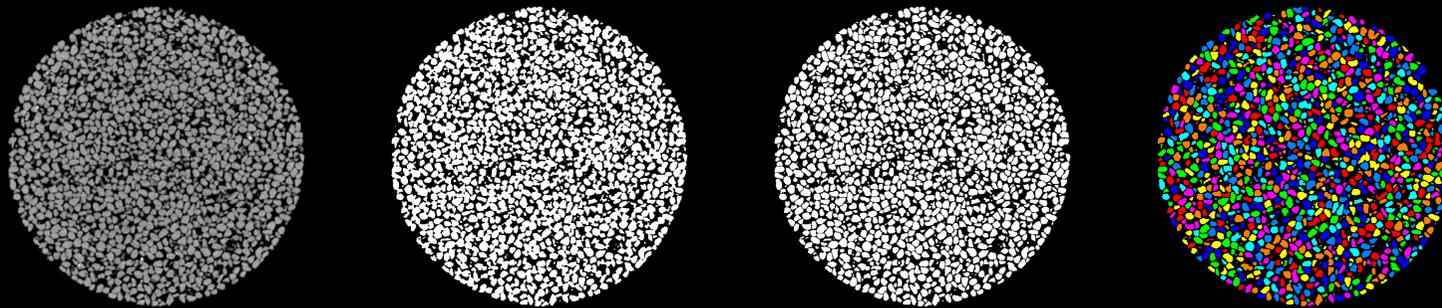# 3D AND 4D IMAGE ANALYSIS FOR STRUCTURES AND PROCESSES

**Stephen Hall**

*Division of Solid Mechanics, Lund University, Sweden*
*& Vice-Director Lund Institute for Advanced Neutron and X-ray Science (LINXS)*
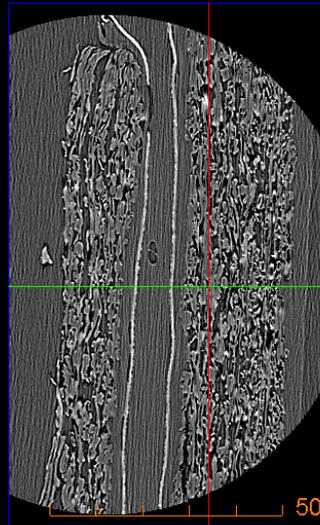
# Not just pretty images...


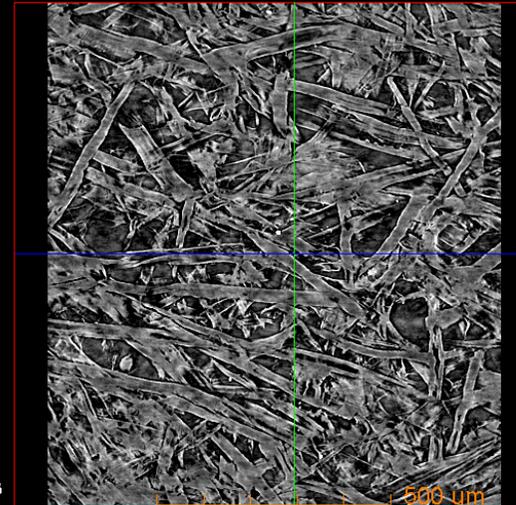
… very pretty… but so what!
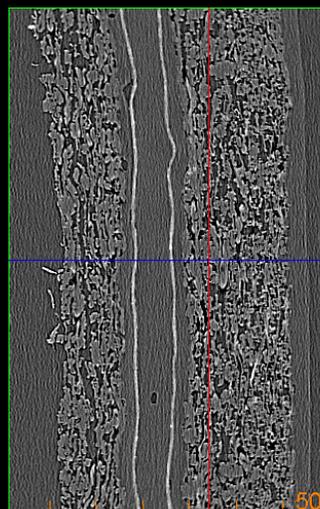  Challenge: *to extract pertinent, quantified information to elucidate properties*
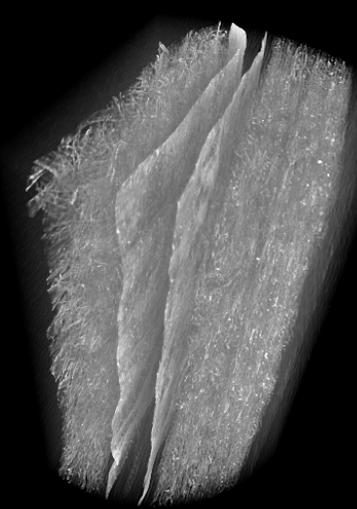
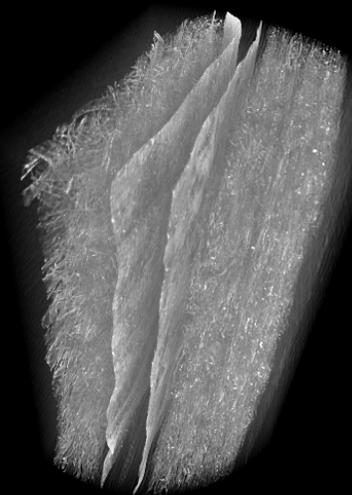TetraPak recart - chopped tomato carton

XY
# 488 / 975
C 22475 W 13023
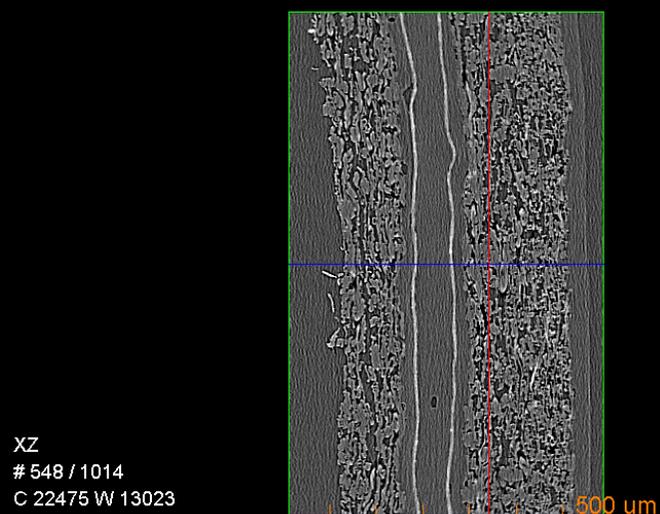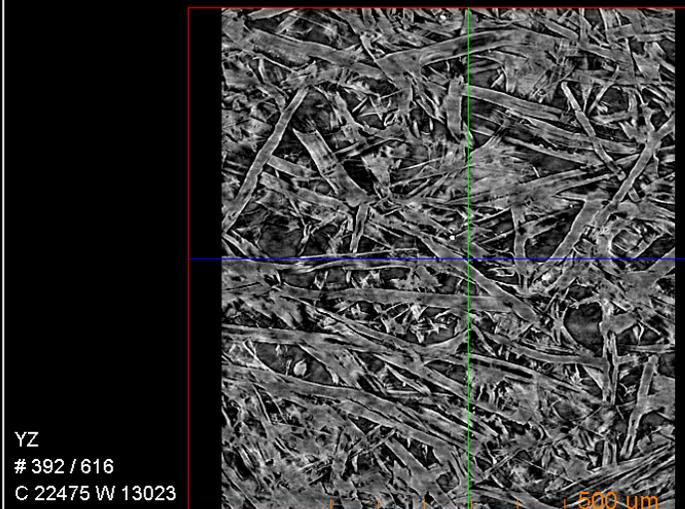500 um

YZ
# 392 / 616
C 22475 W 13023
500 um

XZ
# 548 / 1014
C 22475 W 13023
500 um

# TetraPak recart - chopped tomato carton
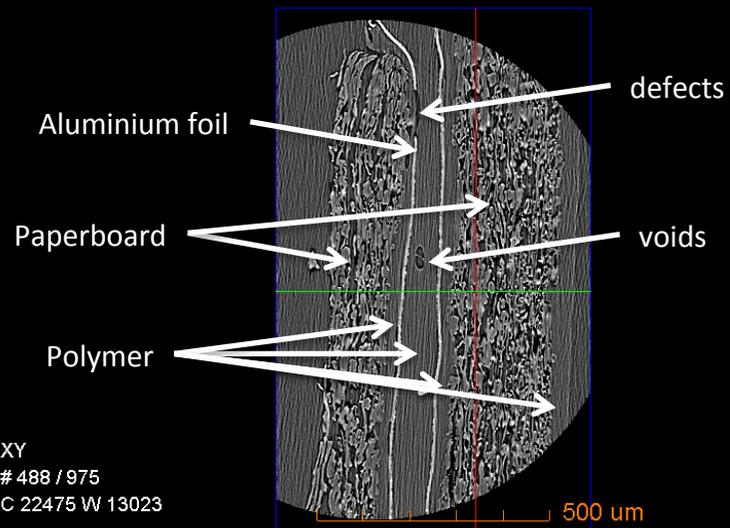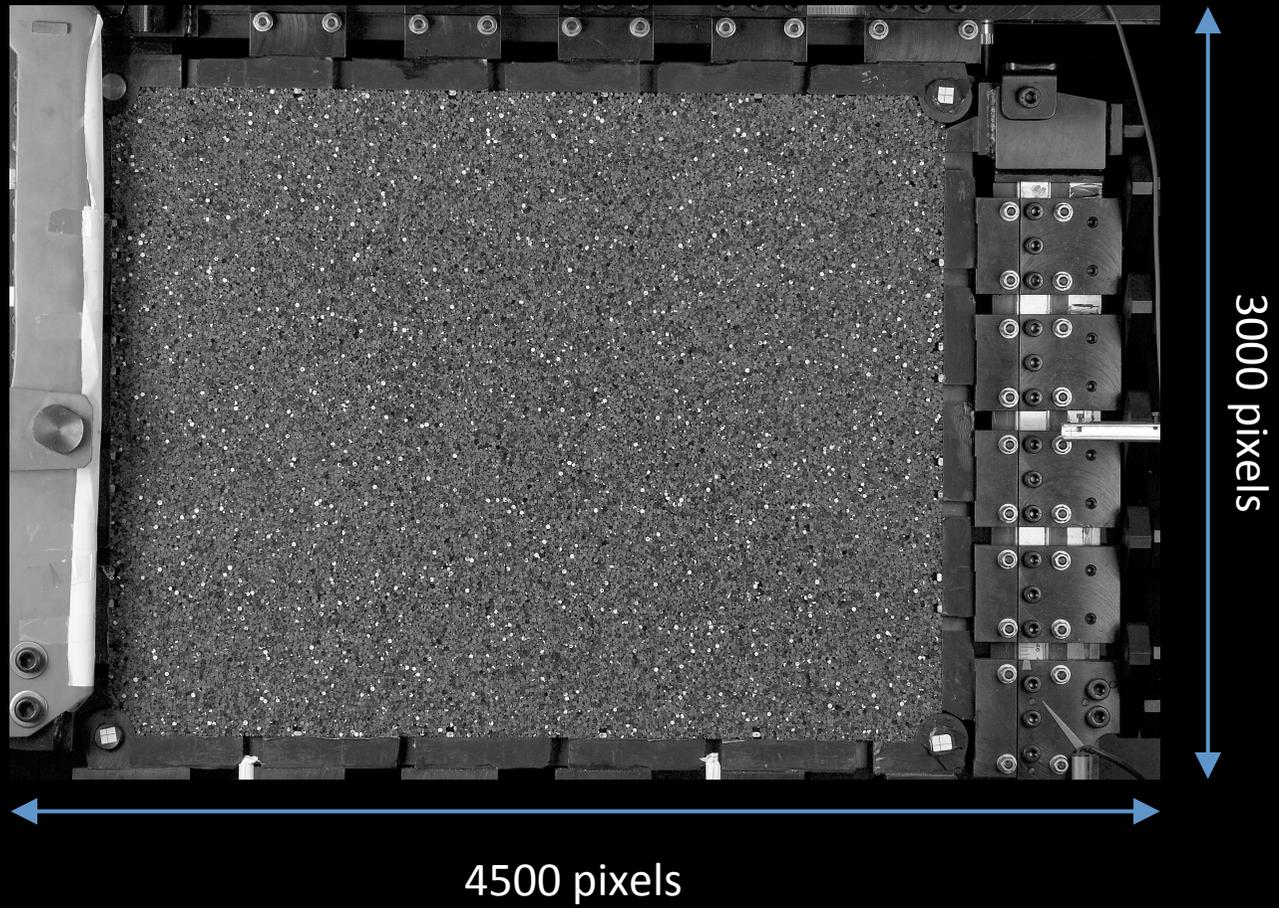
# A word of warning…



"La Trahison des Images" ("The Treachery of Images") by René Magritte, 1928

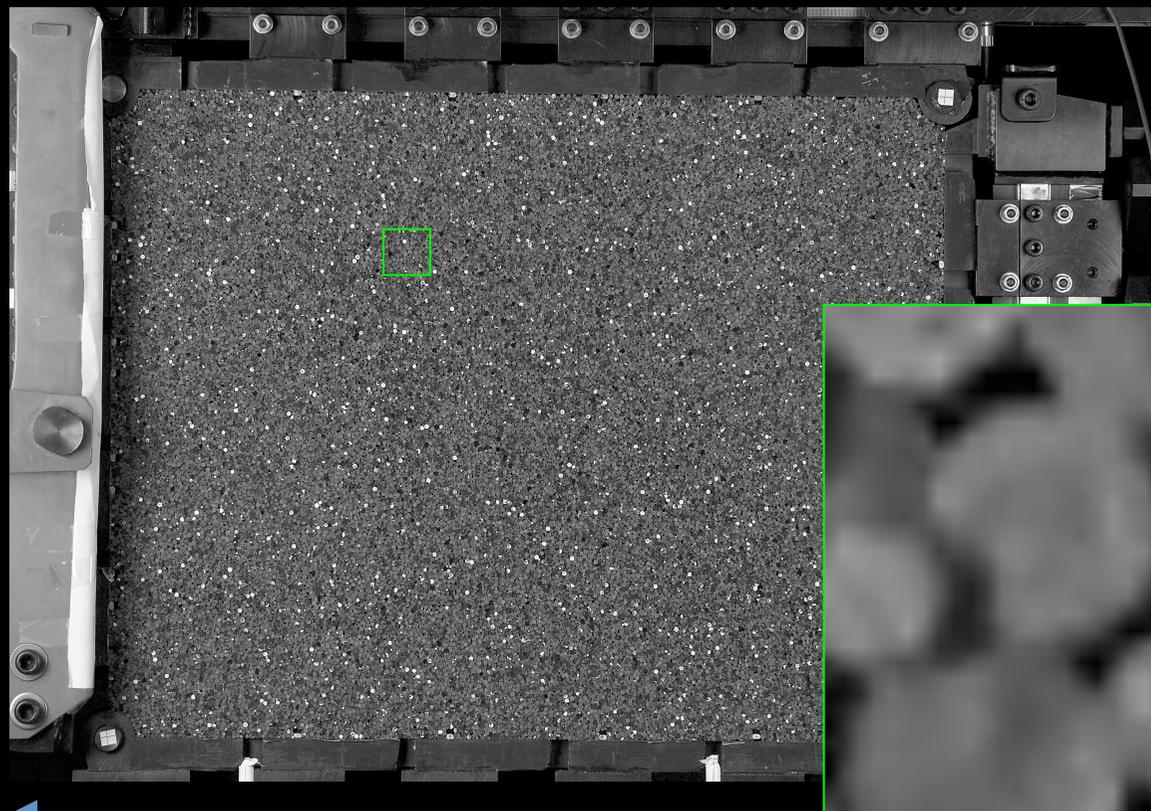…Images are just representations of reality…
    …what you see depends on what you are using to "look at " the object (i.e,
    the physics of the interaction between the radiation and the material)

2D digital data

4500 pixels

3000 pixels
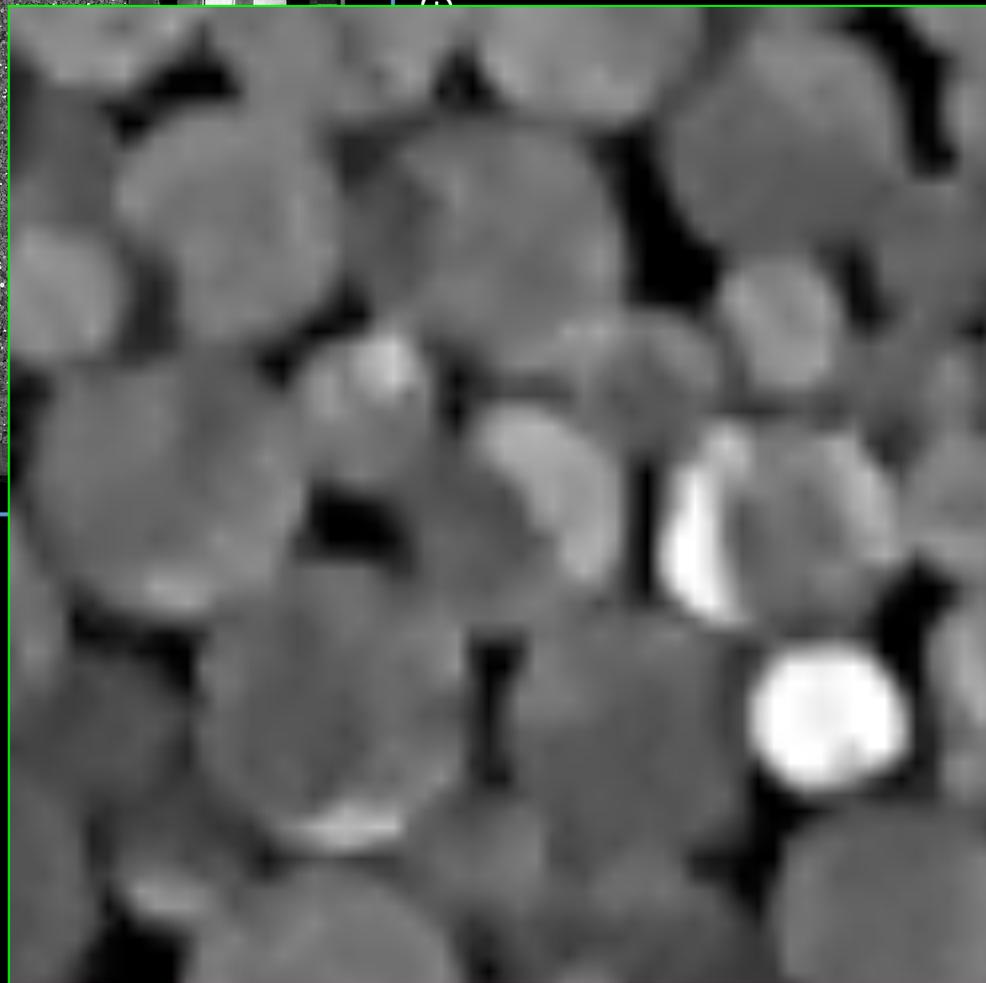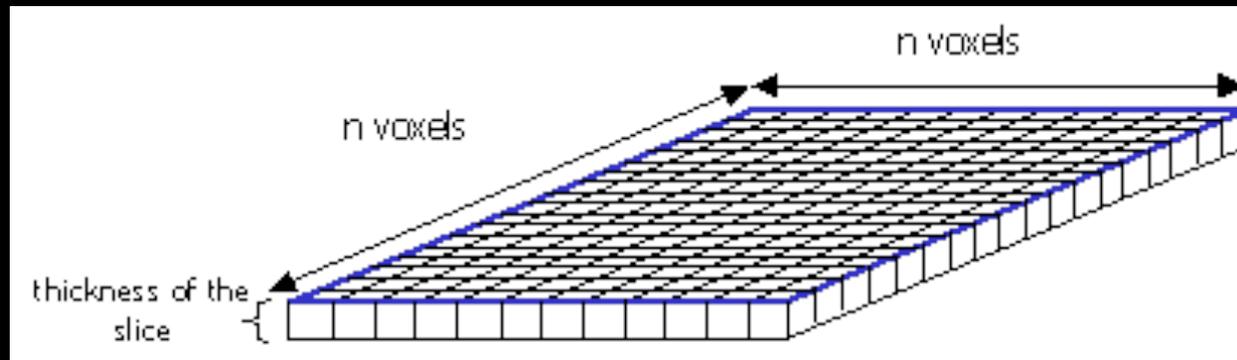
# 2D digital data



4500 pixels

# 2D digital data

Voxels - 3D equivalent of a pixel

In x-ray tomography images, for example, the image "reconstruction" is carried out at different heights, the thickness of which is defined by the detector pixel size to produce a set of slices that can be assembled to give a 3D image volume



*Schematic of a slice (composed of n x n voxels)*

## Data/Image resolution

The value of each sample/pixel/voxel will be the result of the measurement of a given quantity, integrated over the sampling time / sensor pixel area (or larger depending on the quality of the sensor)

- In the case of tomographic reconstruction the voxel value is also dependent on the blur/smoothing in the reconstruction

- Image format can effect the value - binary and tiff images should preserve pixel values, but jpeg, for example, uses an image compression function involving mathematical functions and thus the images are smoothed
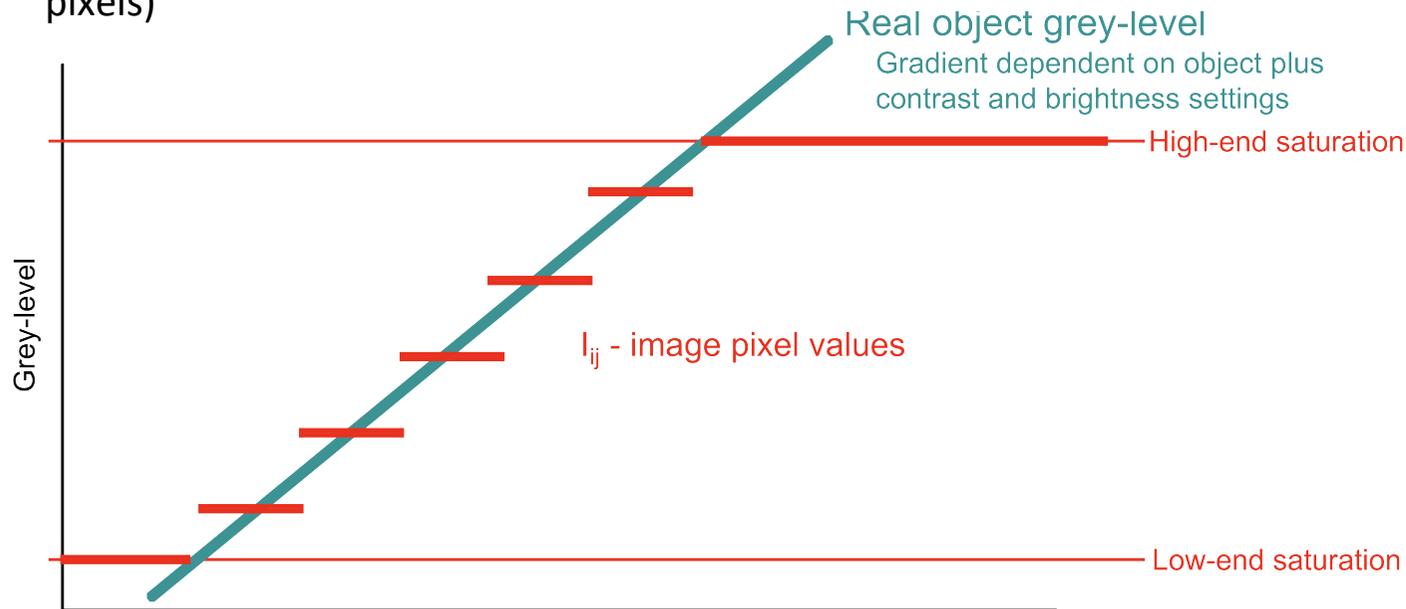
The size of the pixel/voxel is the **image "discretisation"**...

... this is not the ***spatial resolution*** as is commonly said...
... spatial resolution will be a function of the detector quality and, for tomography, the reconstruction algorithm, and the beam divergence
... in reality the image is normally blurred between pixels/voxels
... and the pixel/voxel value is some mean value over a neighbourhood of dimensions ≥ pixel/voxel size

# Grey-scale images - dynamic range and discretisation

## Note that resolution will be also defined by the dynamic range of the images

- Relates to the reduction of the continuous (analogue) spectrum to the discretised (digital) sampling
- Determines how far apart in the grey-scale features are and therefore how well they can be separated
- Should be maximised during the image acquisition to capture all of the signal of interest but also to avoid saturating detector pixels (can cause leakage to adjacent pixels)



Real object grey-level
Gradient dependent on object plus contrast and brightness settings

High-end saturation

$I_{ij}$ - image pixel values

Low-end saturation

Grey-level

Analogue signal digitised such that $I_{ij}$ has integer values in range [0,N]:

8-bits: [0,255], 12-bits: [0,4095], 16-bits: [0,65535]

# Not just pretty images…

- Quantification of structures and processes (mathematical image analyses)

- Input to numerical simulation

  ➢ advanced material development
  ➢ optimised materials processing
  ➢ enhanced numerical simulation

- And sometimes, not even pretty images
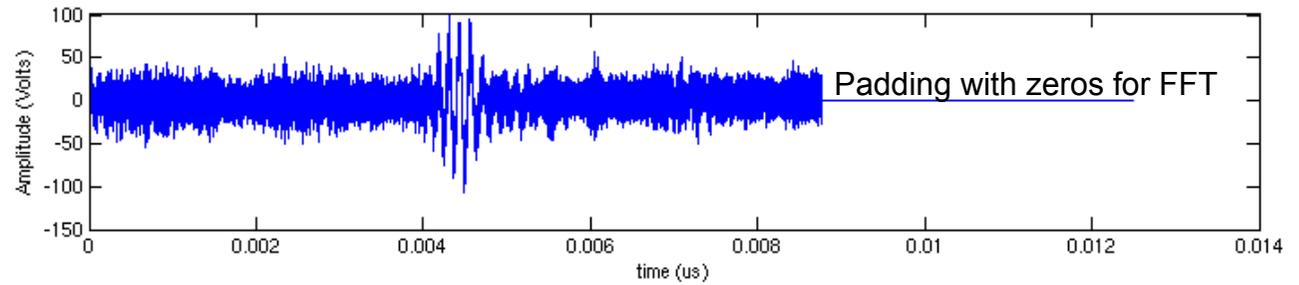  - Noise suppression
  - Artifact suppression

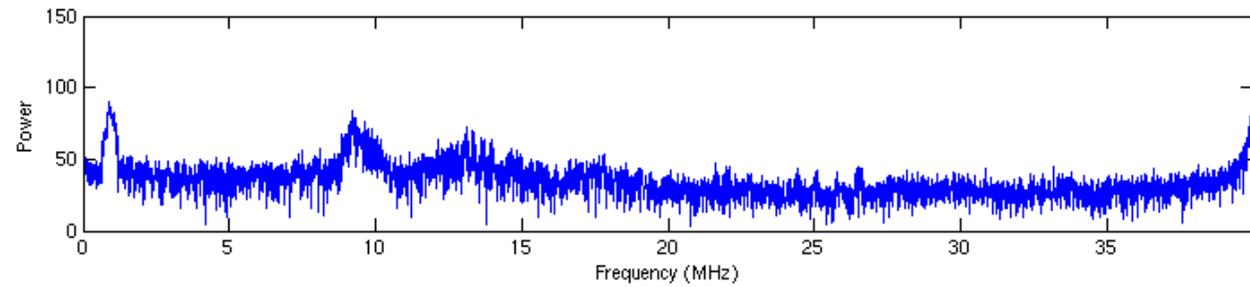# Filtering - example (ultrasonic data acquired across a sample of clay)
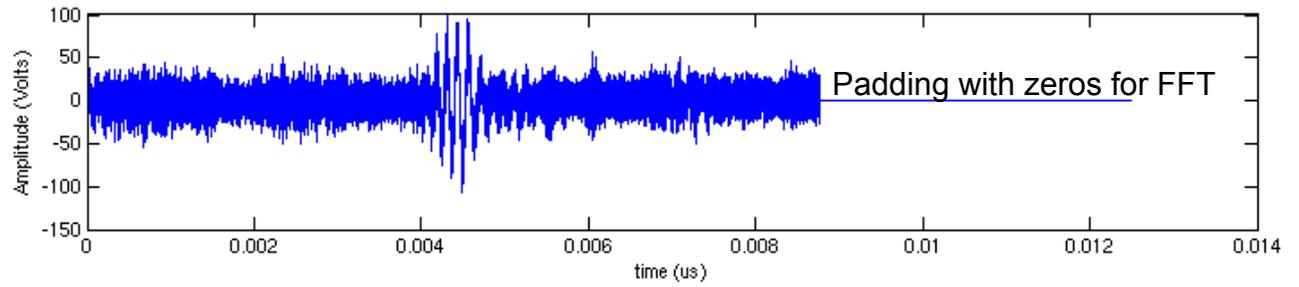
Original data



Padding with zeros for FFT

# Filtering - example (ultrasonic data acquired across a sample of clay)

Original data
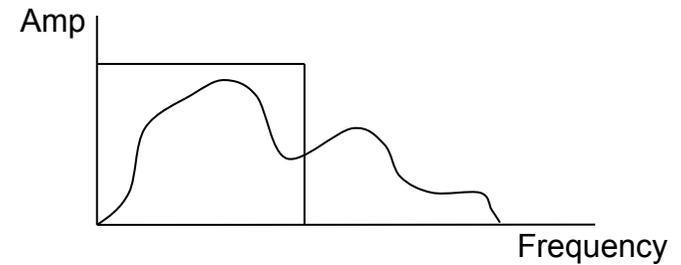


Padding with zeros for FFT

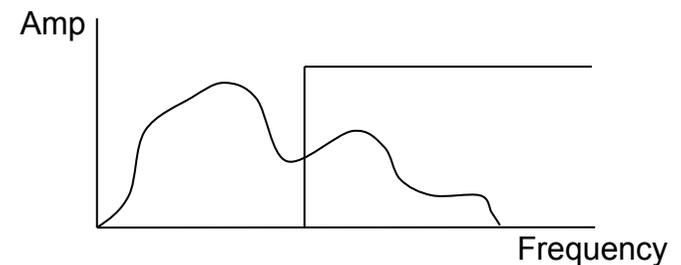Amplitude spectrum of original data determined by fast fourier transform (FFT)

# Filtering

Most common filters
represent some windowing
in the frequency domain
i.e., selection of a specific
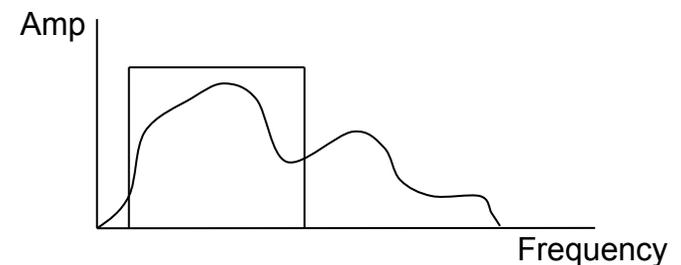range of frequencies
e.g., to isolate a signal from
low or high frequency noise
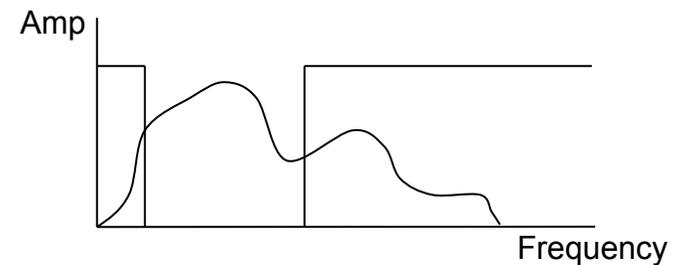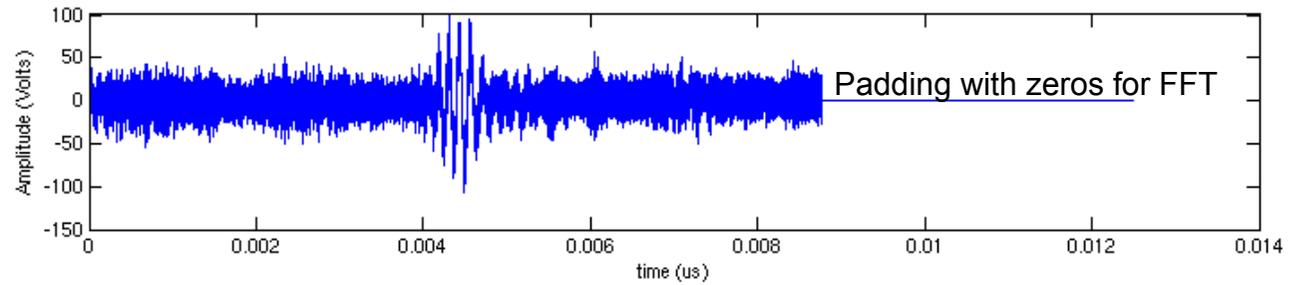
Low pass



High Pass



Band Pass



Notch Pass

# Filtering - example (ultrasonic data acquired across a sample of clay)

**Original data**

Padding with zeros for FFT

**Amplitude spectrum of original data**

**Filtered amplitude spectrum**

.75   1.25
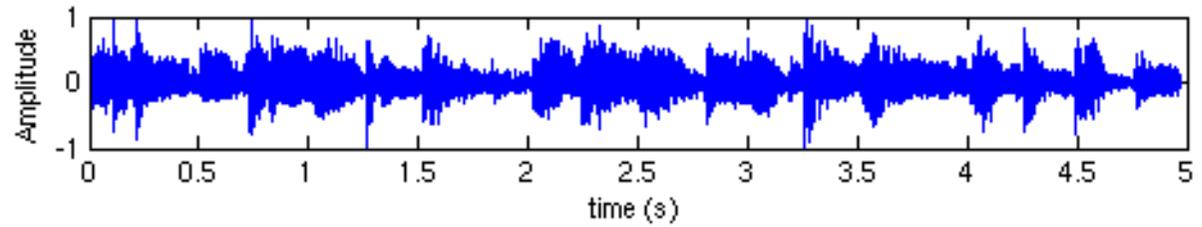
1

Filter

.25   2.0
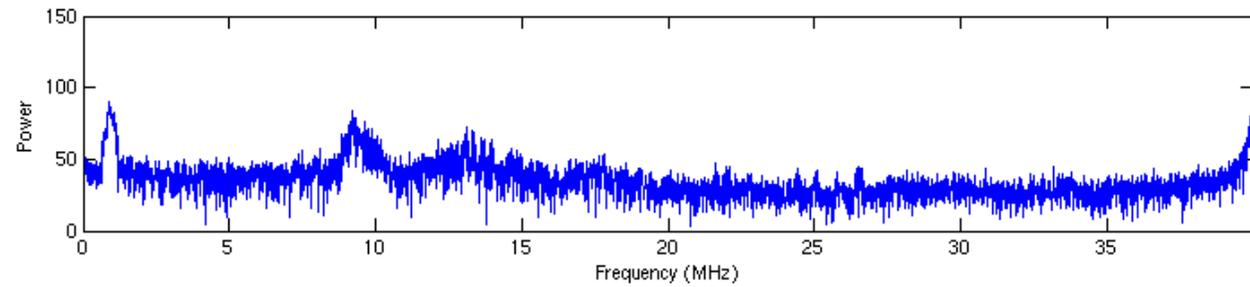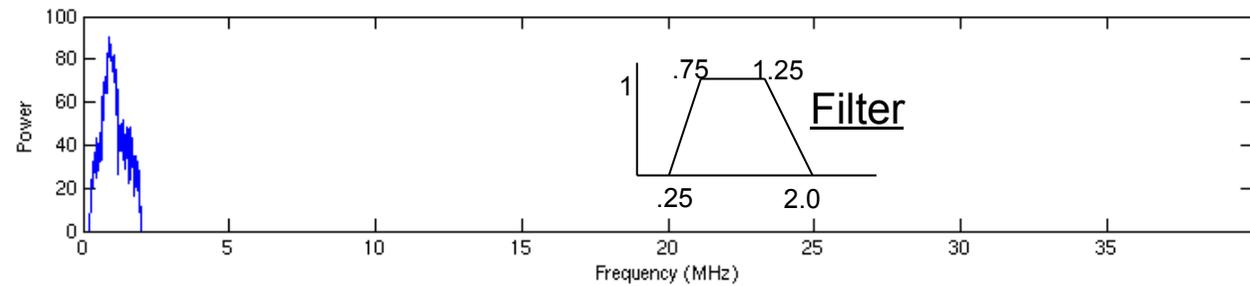
**Filtered data (inverse transformed)**
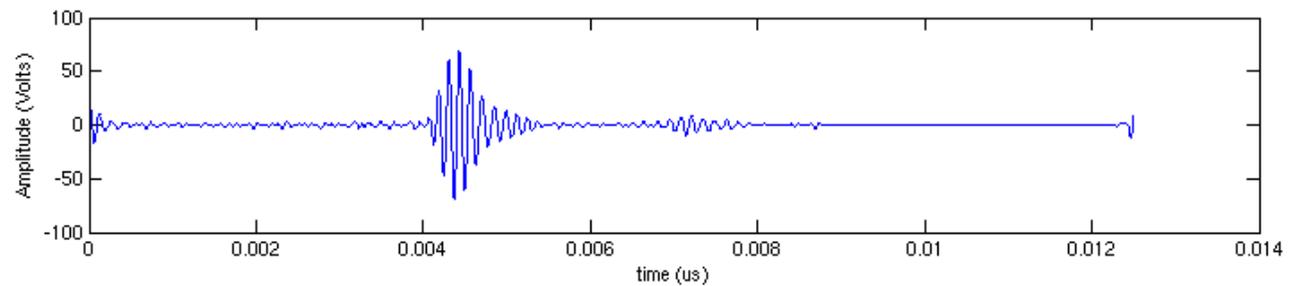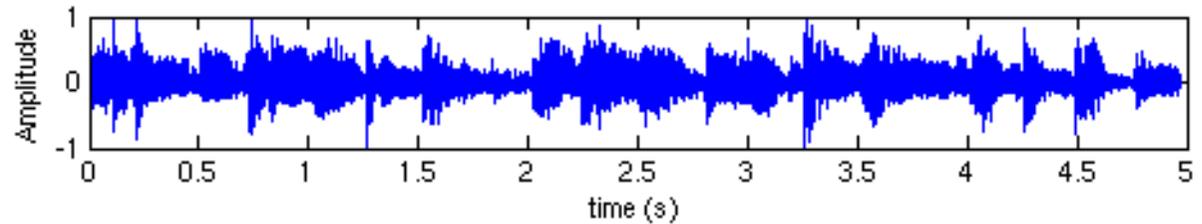
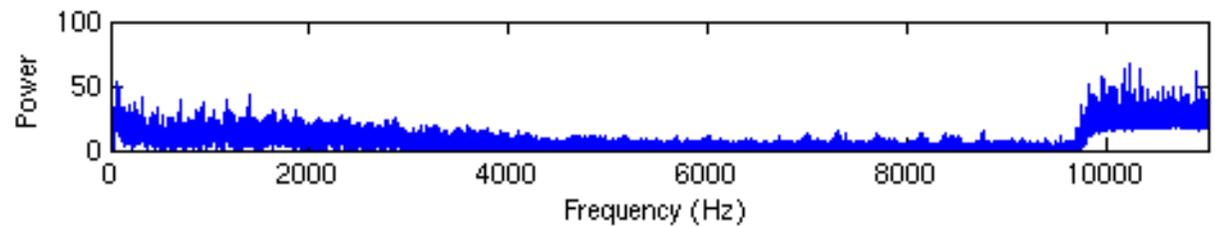# Filtering - example (Skatalites)

Original data

# Filtering - example (Skatalites)
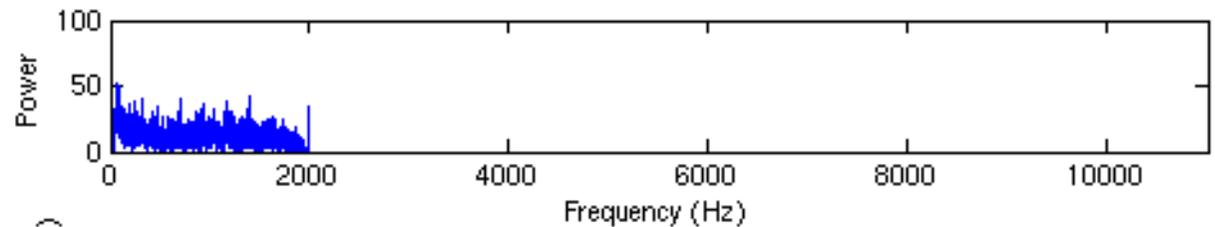
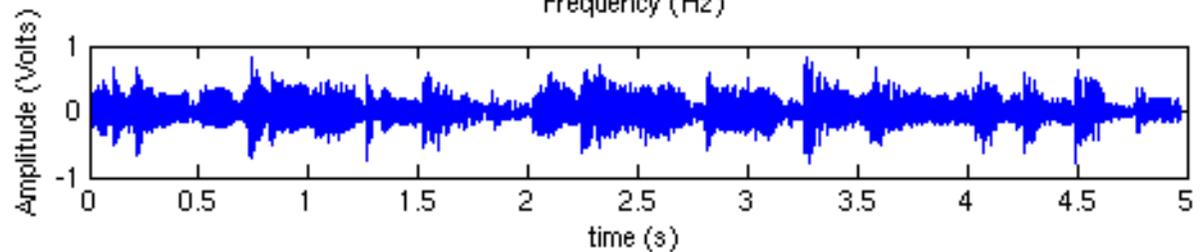Low pass filter

Original data

Amplitude spectrum
of original data
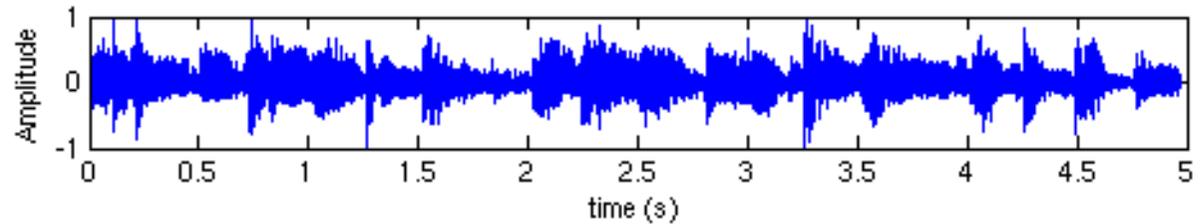
Filtered amplitude
spectrum

Filtered data
(inverse transformed)

# Filtering - example (Skatalites)

High pass filter

Original data

Amplitude spectrum of original data

Filtered amplitude spectrum

Filtered data
(inverse transformed)
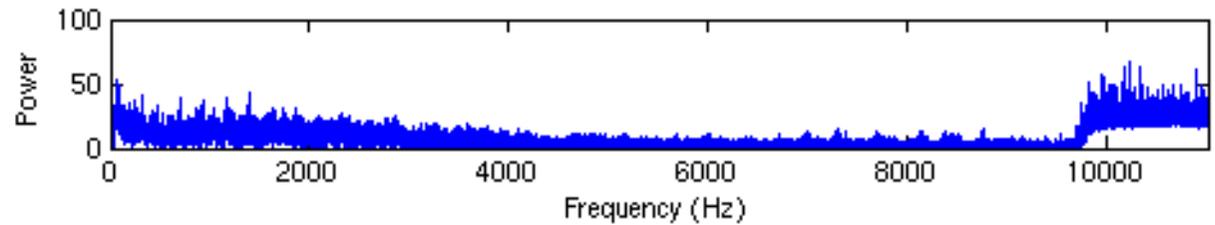
# Filtering - example (Skatalites)

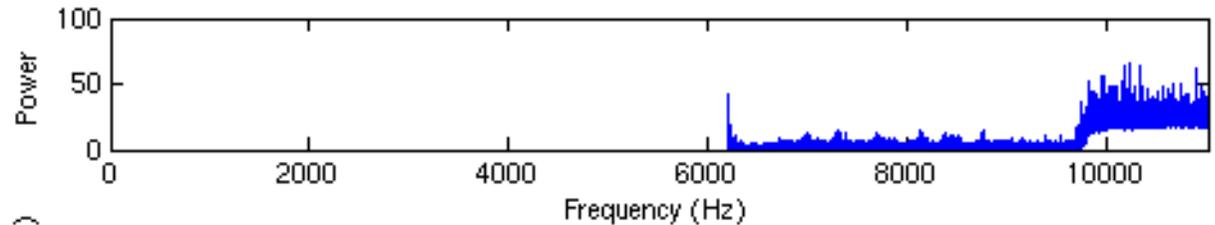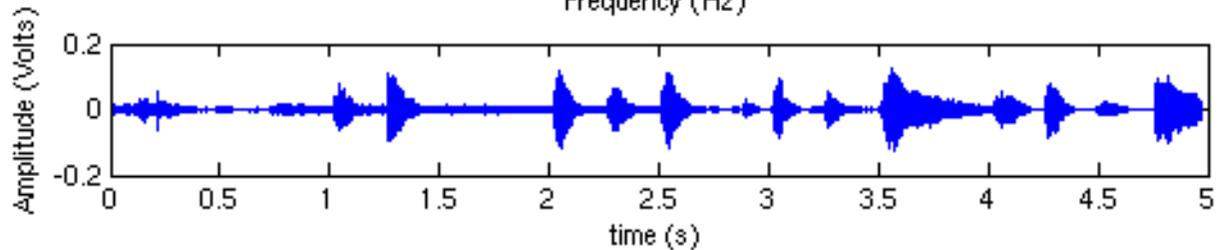Band pass filter

Original data

Amplitude spectrum
of original data

Filtered amplitude
spectrum

Filtered data
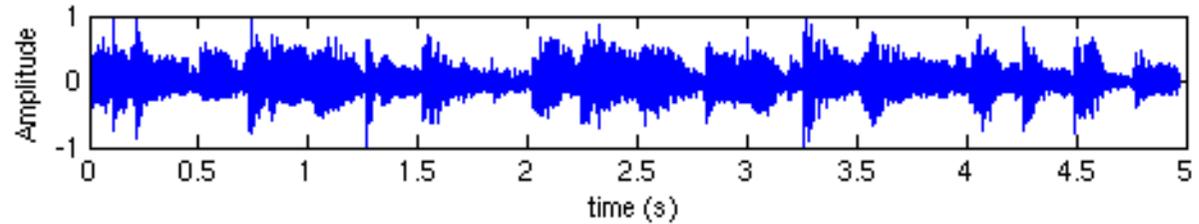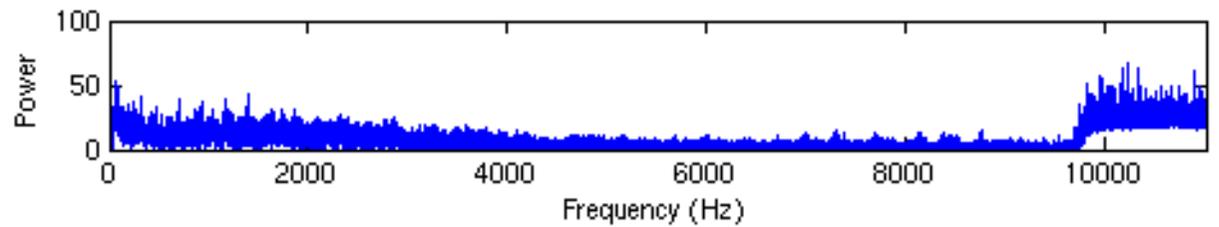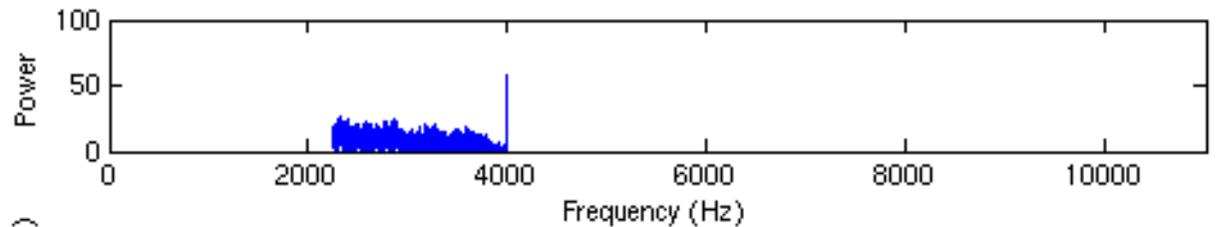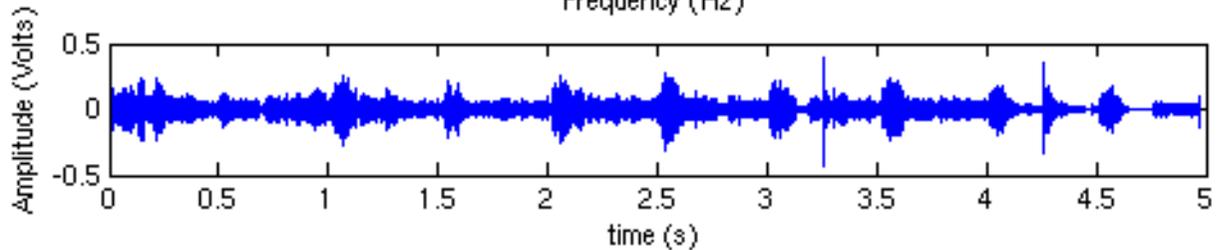(inverse transformed)

**Brightness Image   Fourier Transform Inverse Transformed**
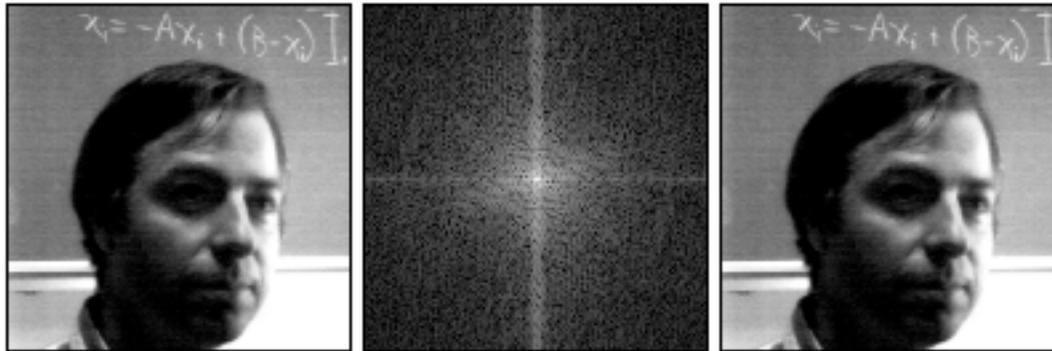


**Low-Pass Filtered   Inverse Transformed**
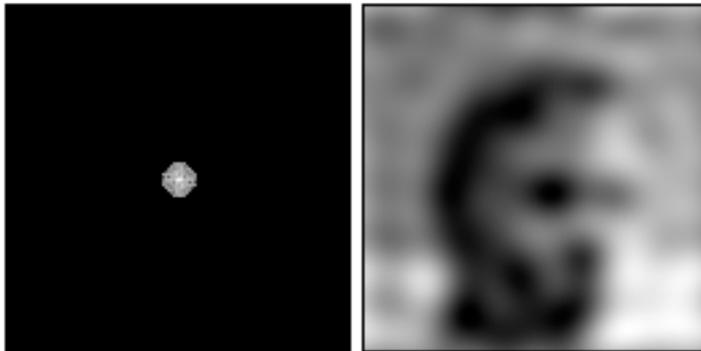


**High-Pass Filtered   Inverse Transformed**
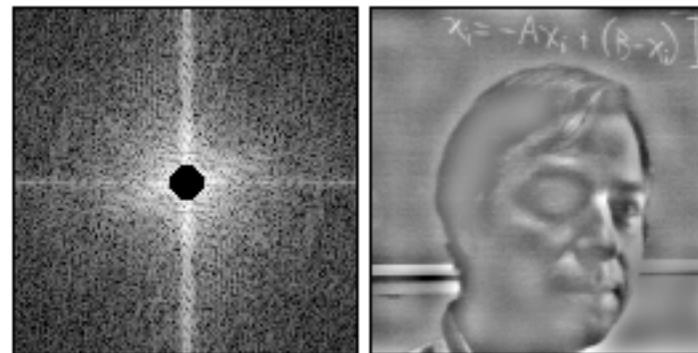


**Band-Pass Filtered Inverse Transformed**
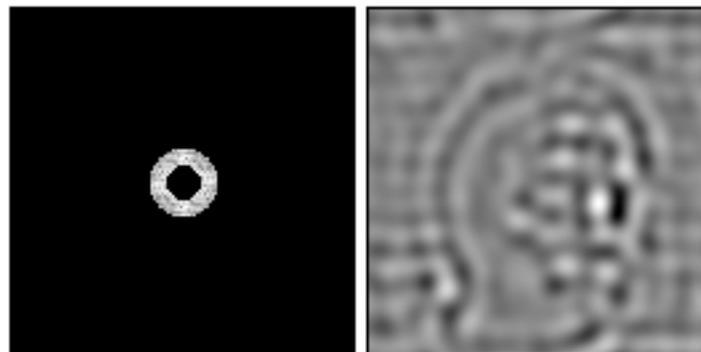
# Spatial domain operations

# Spatial domain operations

## Window operations

Differerent values/statistics can be determined over windows in the data

- windows can be randomly positioned and of any size, but usually the windows are placed on a regular grid and have a common (optimal) geometry for the whole image

- window analysis can be used for noise removal and smoothing as well as for analysis, data enhancement, visualisation and quantification

# e.g., noise removal and smoothing

- Noise can be "salt and pepper", Gaussian or structured
- The first two can be reduced by quite simple window operations
  - Classic operators are despike, mean, median



**FIGURE 3.37** (a) X-ray image of circuit board corrupted by salt-and-pepper noise. (b) Noise reduction with a 3 × 3 averaging mask. (c) Noise reduction with a 3 × 3 median filter. (Original image courtesy of Mr. Joseph E. Pascente, Lixi, Inc.)
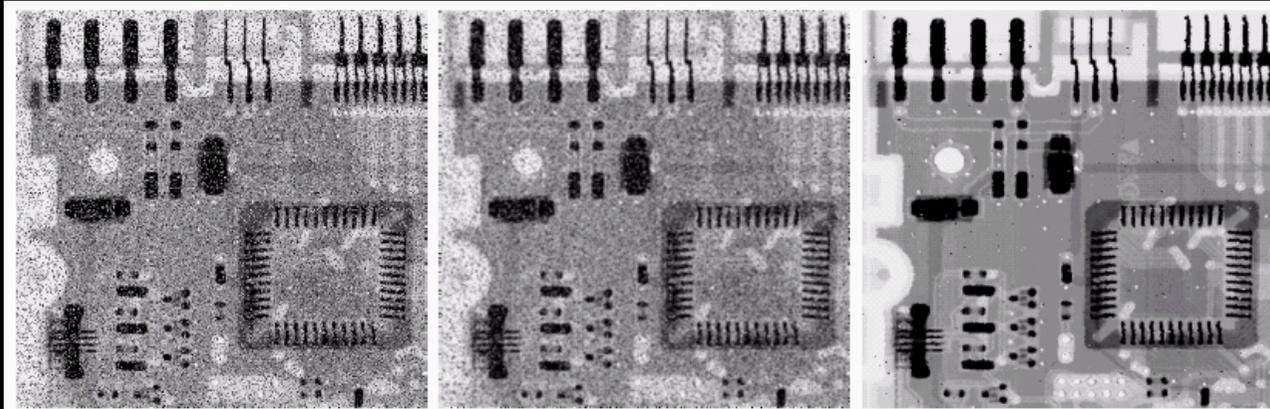
From Y. Wang - eeweb.poly.edu/~yao/EE3414/image_filtering.pdf

- Equivalent to low-pass filtering - may blur edges
- Also spatial domain operators also allow for more advanced methods e.g., adaptive, edge preserving, anisotropic diffusion..

# Example - enhancing contrast with standard deviation filter

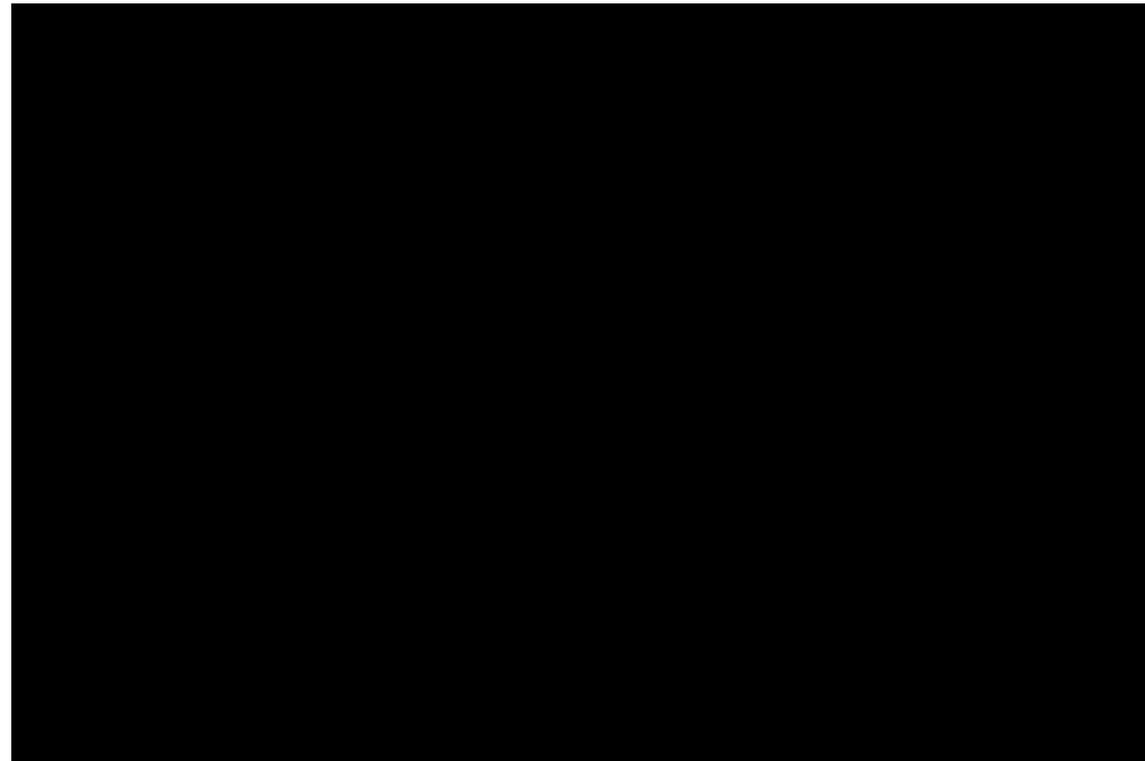## X-ray tomography results:

- **VE2** (50 MPa conf. pres.)

- High resolution scans ~30 µm voxel size



a.    b.    c.    d.    e.
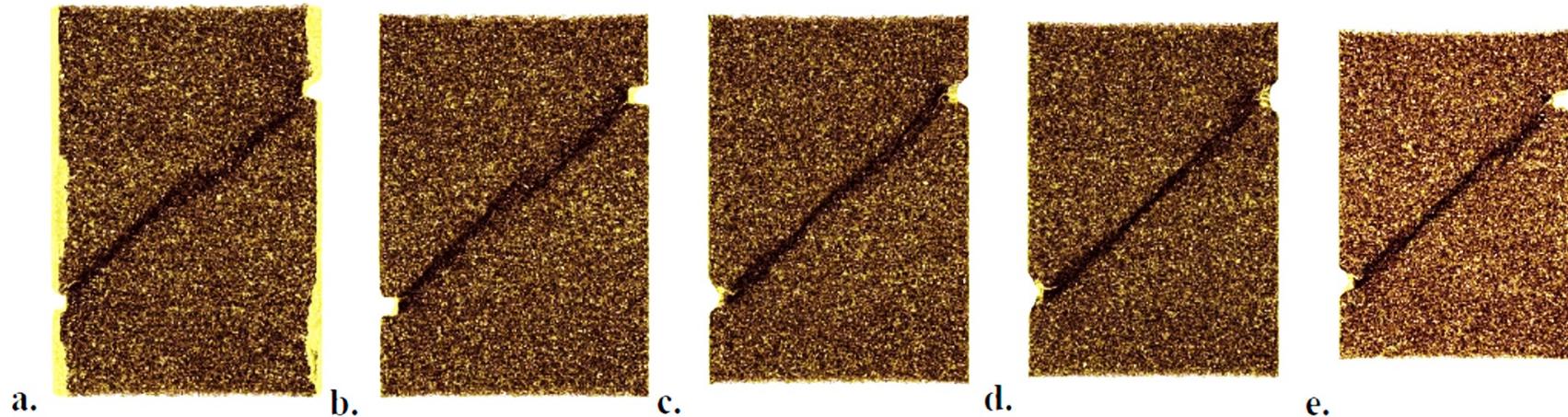
- Localised deformation appears as higher density zones
  (dark = higher density)
- Two bands meeting in middle of sample

E. Charalampidou, 2011, PhD Thesis, Heriot-Watt University and Université de Grenoble

## Local standard deviation analysis:

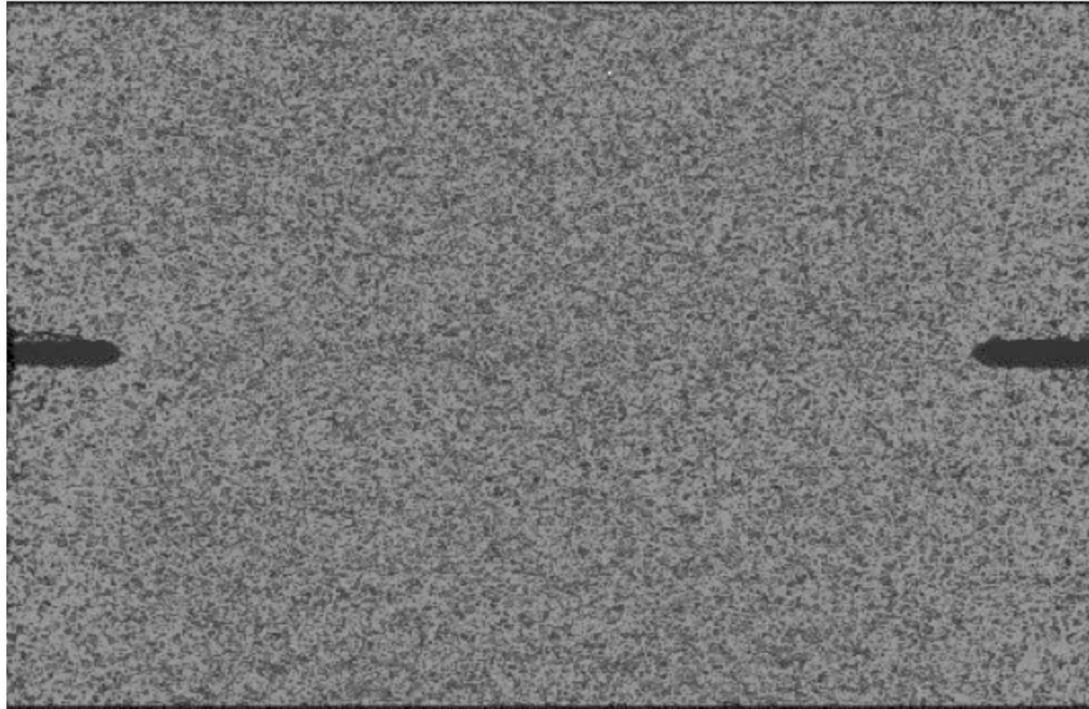- **VE2** (50 MPa conf. pres.)

- High resolution scans ~30 μm voxel size



Standard deviation

low          high

Localised deformation appears as lower standard deviation
- More homogeneous - reduced grain size?

E. Charalampidou, 2011, PhD Thesis, Heriot-Watt University and Université de Grenoble

## X-ray tomography results:
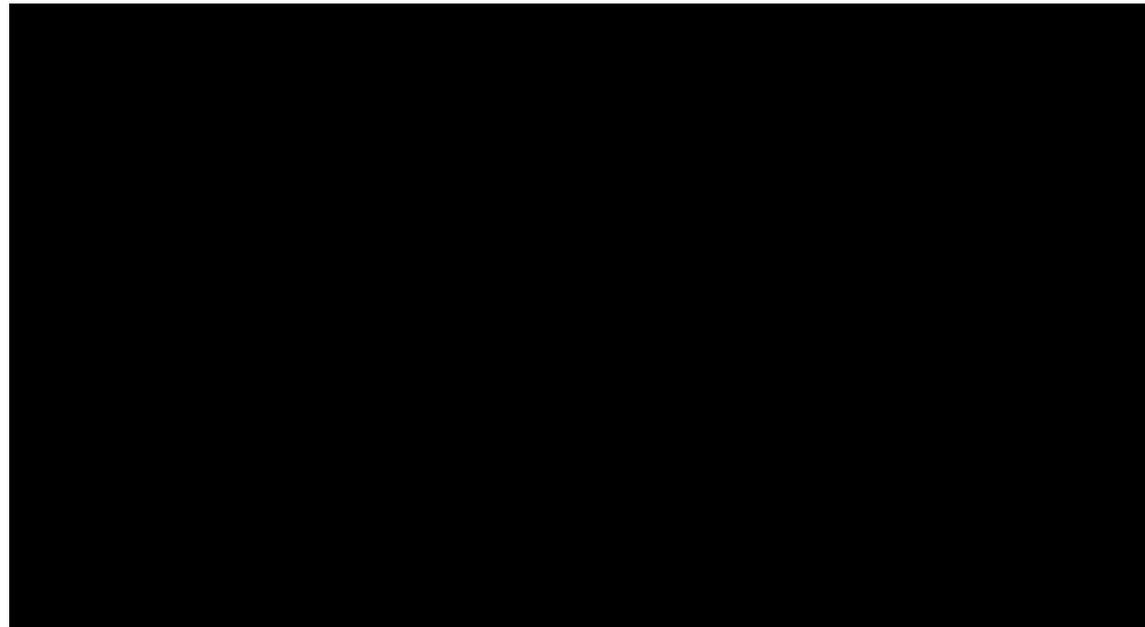
- **VE6** (130 MPa conf. pres.)

- High resolution scans ~30 μm voxel size



- No evidence (to the naked eye) of localised deformation

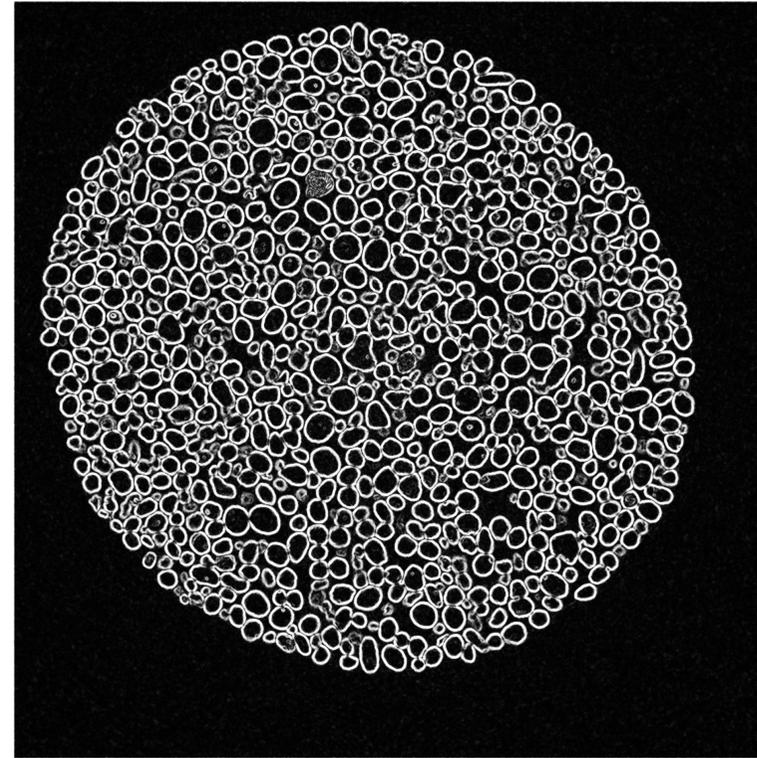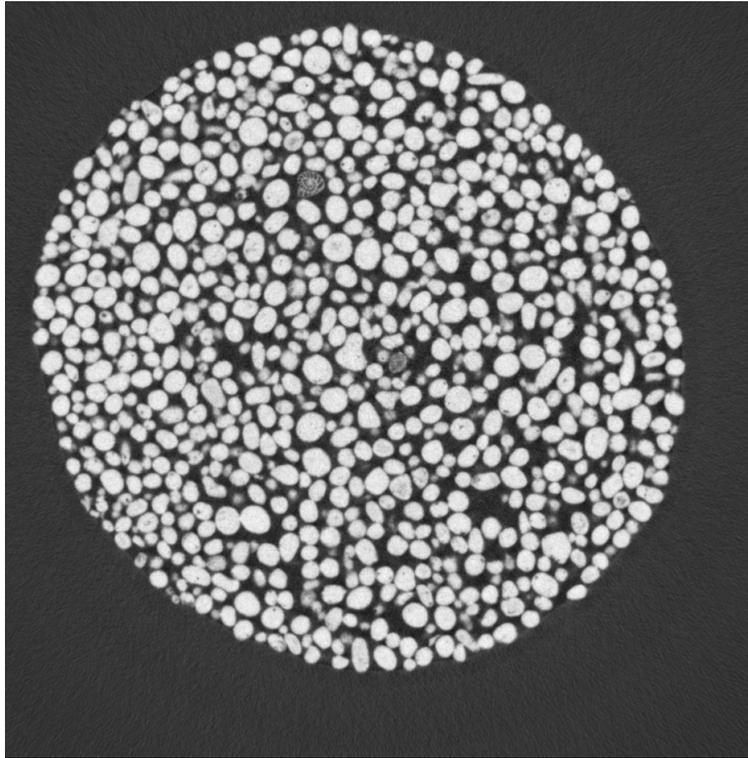# Local standard deviation analysis:

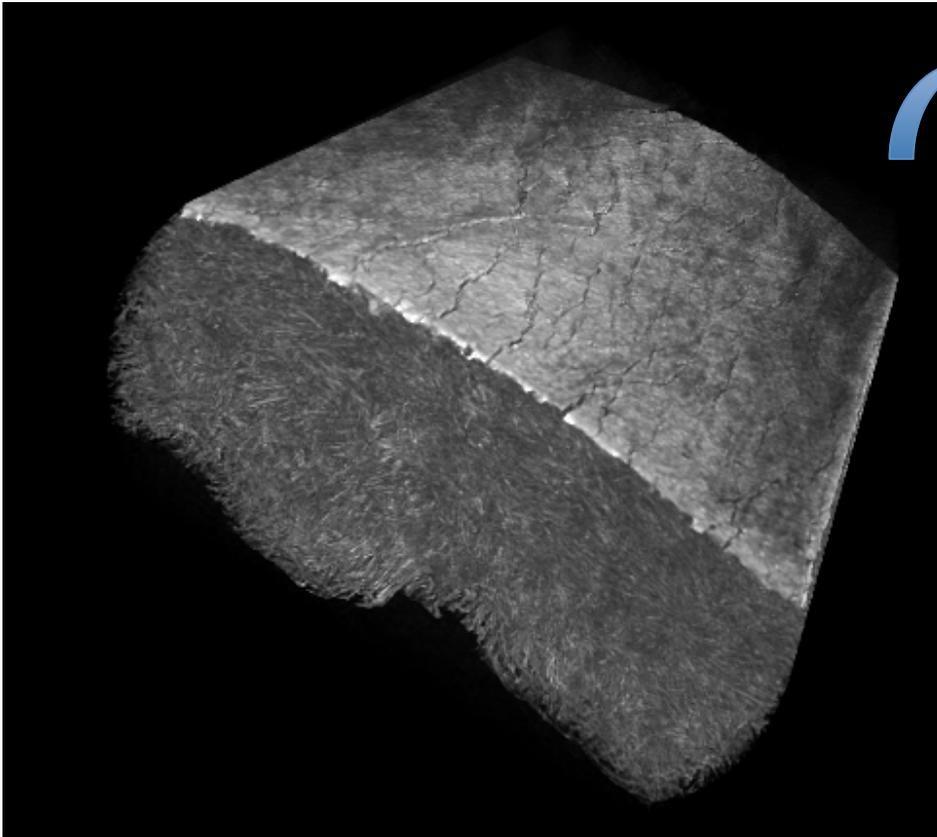- **VE6** (130 MPa conf. pres.)

- High resolution scans ~30 μm voxel size



Standard deviation

low      high

- localised deformation revealed

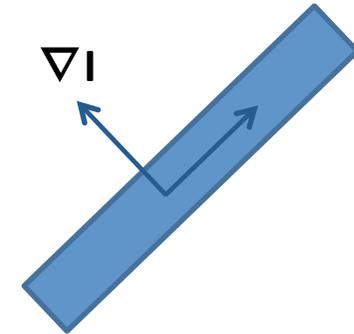# Example: Local image gradient



Images from E. Andò

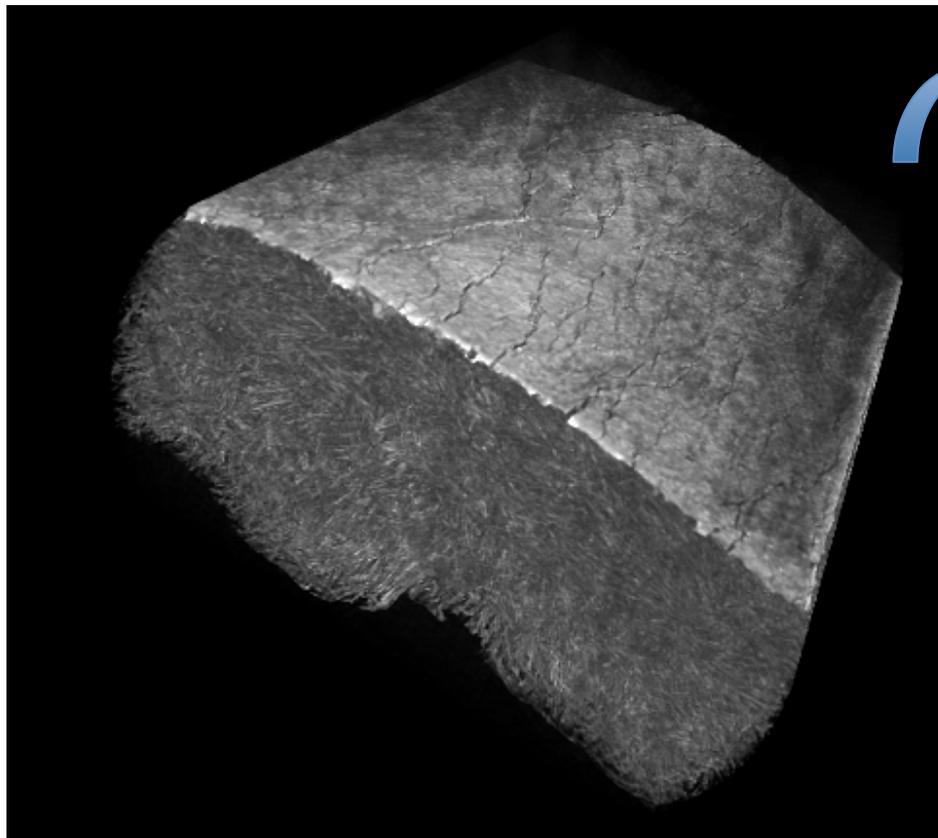# 3D imaging of folded paper board



Quantification of fabrics

$\nabla I$

- Least variation of intensity along fibers

- Direction of smallest directional derivative

- Perpendicular to the gradient in 2D

- Can be found with the structure tensor or Hessian in 3D
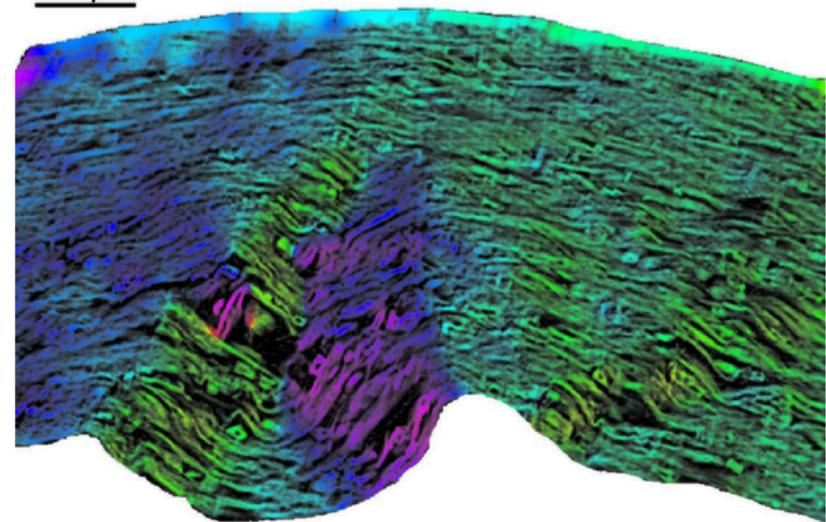
PhD project E. Borgqvist, Solid Mechanics, LTH
In collaboration with TetraPak

# 3D imaging of folded paper board



Quantification of fabrics
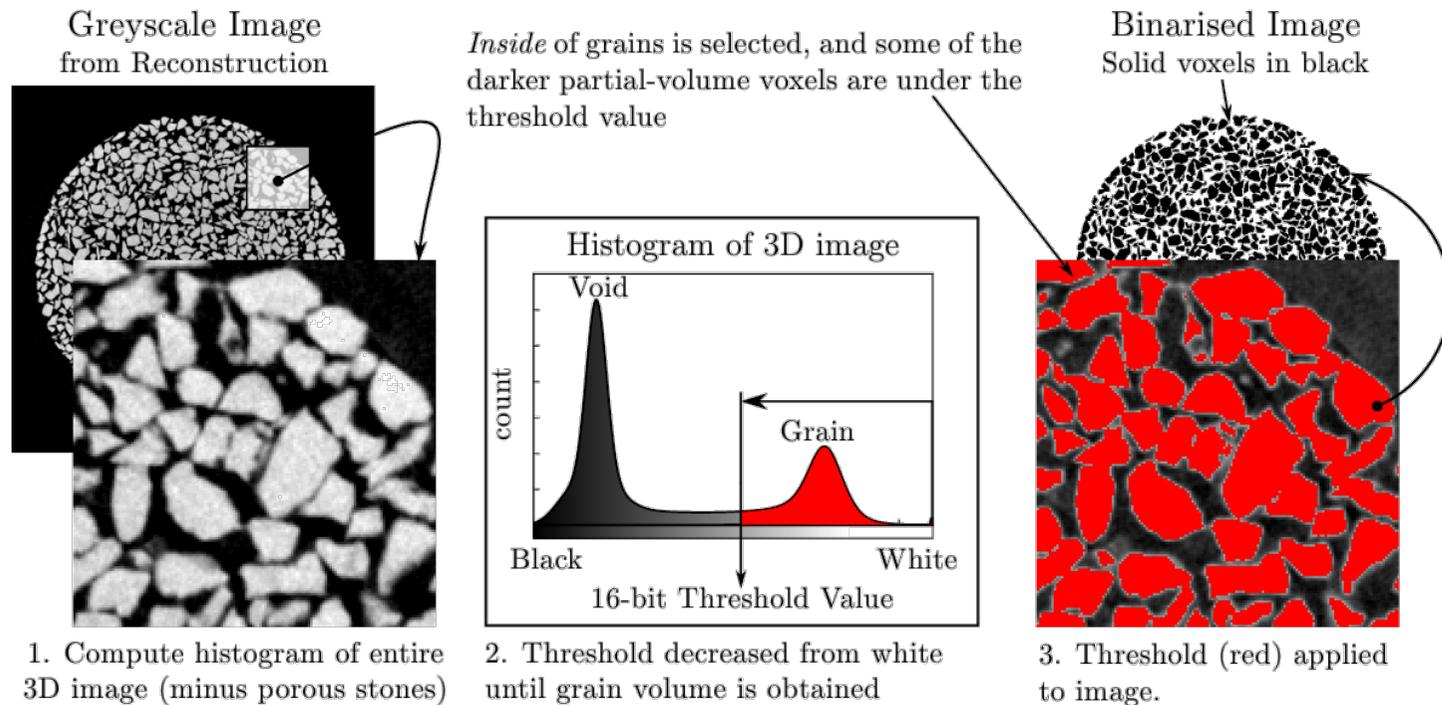


100 μm



Orientation of fibres
due to deformation

PhD project E. Borgqvist, Solid Mechanics, LTH
In collaboration with TetraPak

Binarisation and thresholding

# Many image processing operations are carried out on "binary" images

- Binary images are images where pixel values can take one of two values, usually 0 and 1

- Binary images can be made from grey-scale ones by **binarisation** - **thresholding** of grey-scale values such that all pixel values less than the threshold are set to 0 and all greater than the threshold are set to 1

- Threshold can be set manually or by some automatic means, e.g., Otsu's method

- Calibration might be possible, e.g., if the total volume of one/both phase is known (e.g., by weighing the grains in a sand sample

# Binarisation and thresholding



**Greyscale Image** from Reconstruction

*Inside* of grains is selected, and some of the darker partial-volume voxels are under the threshold value

**Binarised Image** Solid voxels in black

Histogram of 3D image

Void

count

Grain

Black — White

16-bit Threshold Value

1. Compute histogram of entire 3D image (minus porous stones)

2. Threshold decreased from white until grain volume is obtained

3. Threshold (red) applied to image.

**Figure 4.2:** Illustration of the application and calculation of a threshold value to a slice from test HNEA03. The voxels selected by the threshold (in red) show that the darker partial volume voxels on the outsides of the grains lie below the threshold and are thus not selected.

Image from PhD E. Andò (Grenoble, 2013)

Can be extended to multiple phases, e.g., trinarisation of grain, water and air in images of partially saturated sand
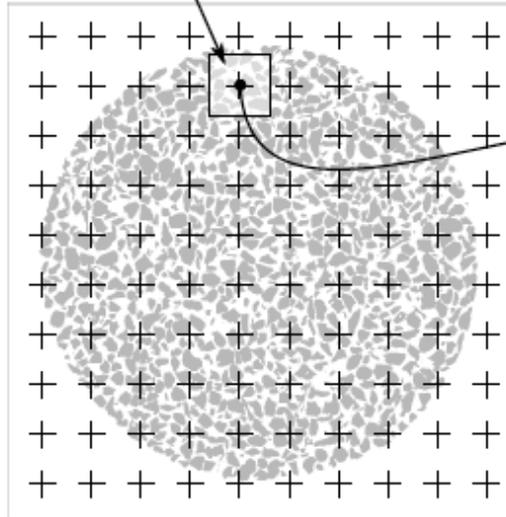
# Porosity



Binarised Slice
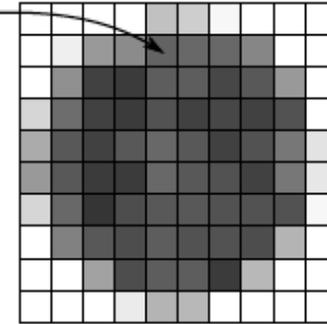(pixels not visible at this scale:
image  1000x1000 pixels)
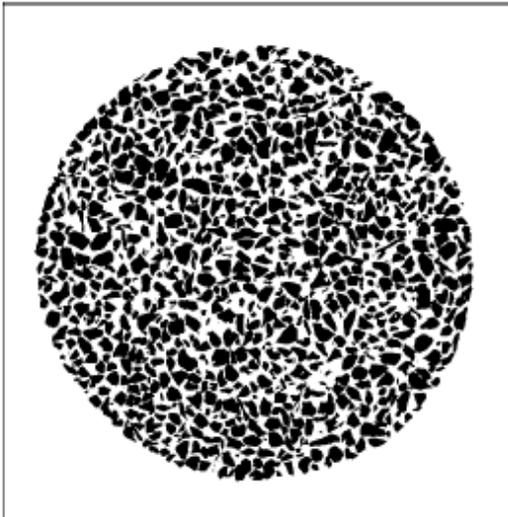
Binarised Slice
(with 10x10 nodes (+) for analysis)

Resulting Porosity Image
(pixels explicitly shown:
10x10 nodes gives 10x10 pixels)

Volume of calculation of porosity

Each node's porosity value gives
one pixel in the porosity image

Images from PhD E. Andò (Grenoble, 2013)

# Porosity



**Binarised Slice**
(pixels not visible at this scale:
image 1000x1000 pixels)

**Binarised Slice**
(with 10x10 nodes (+) for analysis)

**Resulting Porosity Image**
(pixels explicitly shown:
10x10 nodes gives 10x10 pixels)

Volume of calculation of porosity

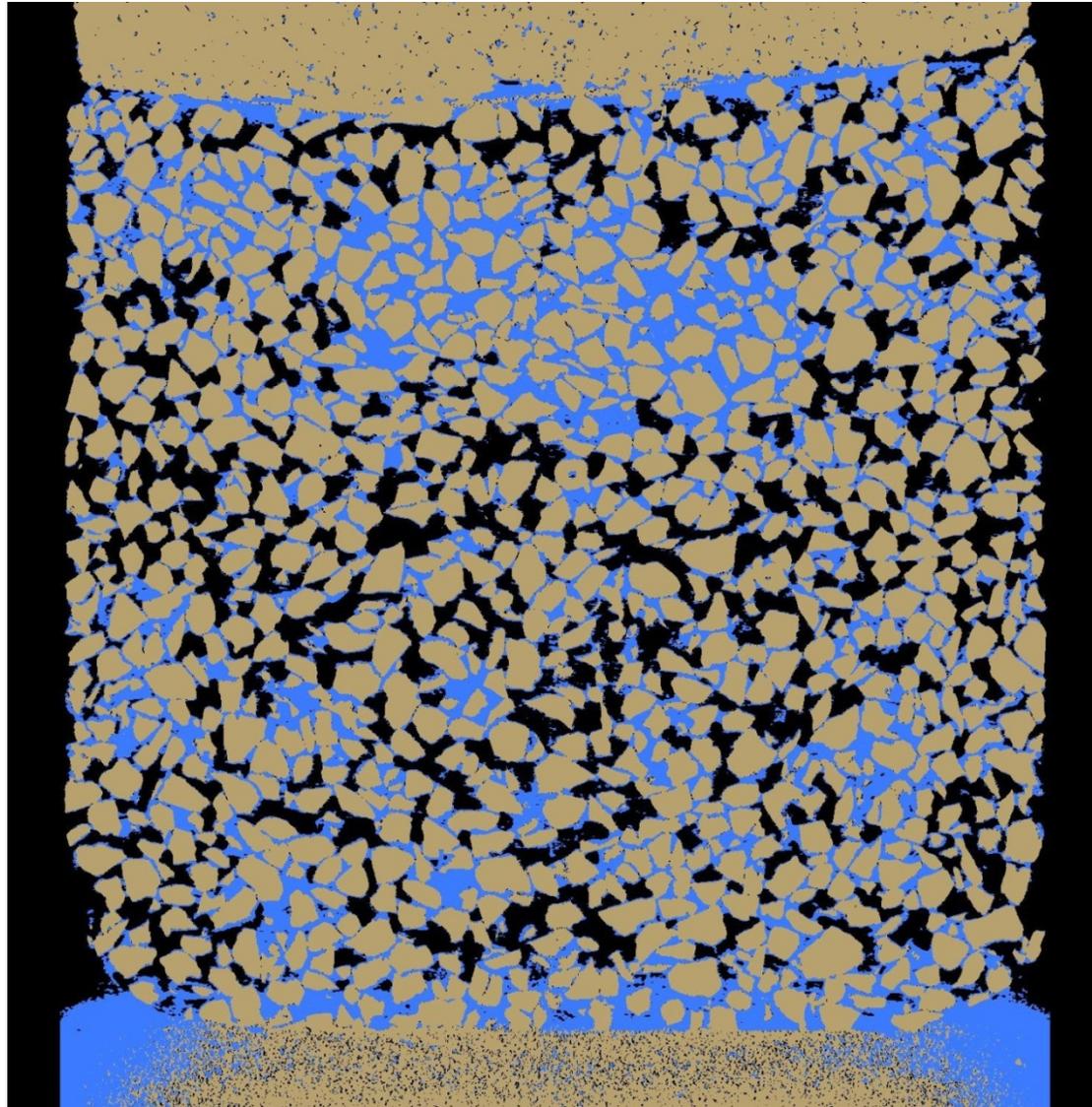Each node's porosity value gives
one pixel in the porosity image
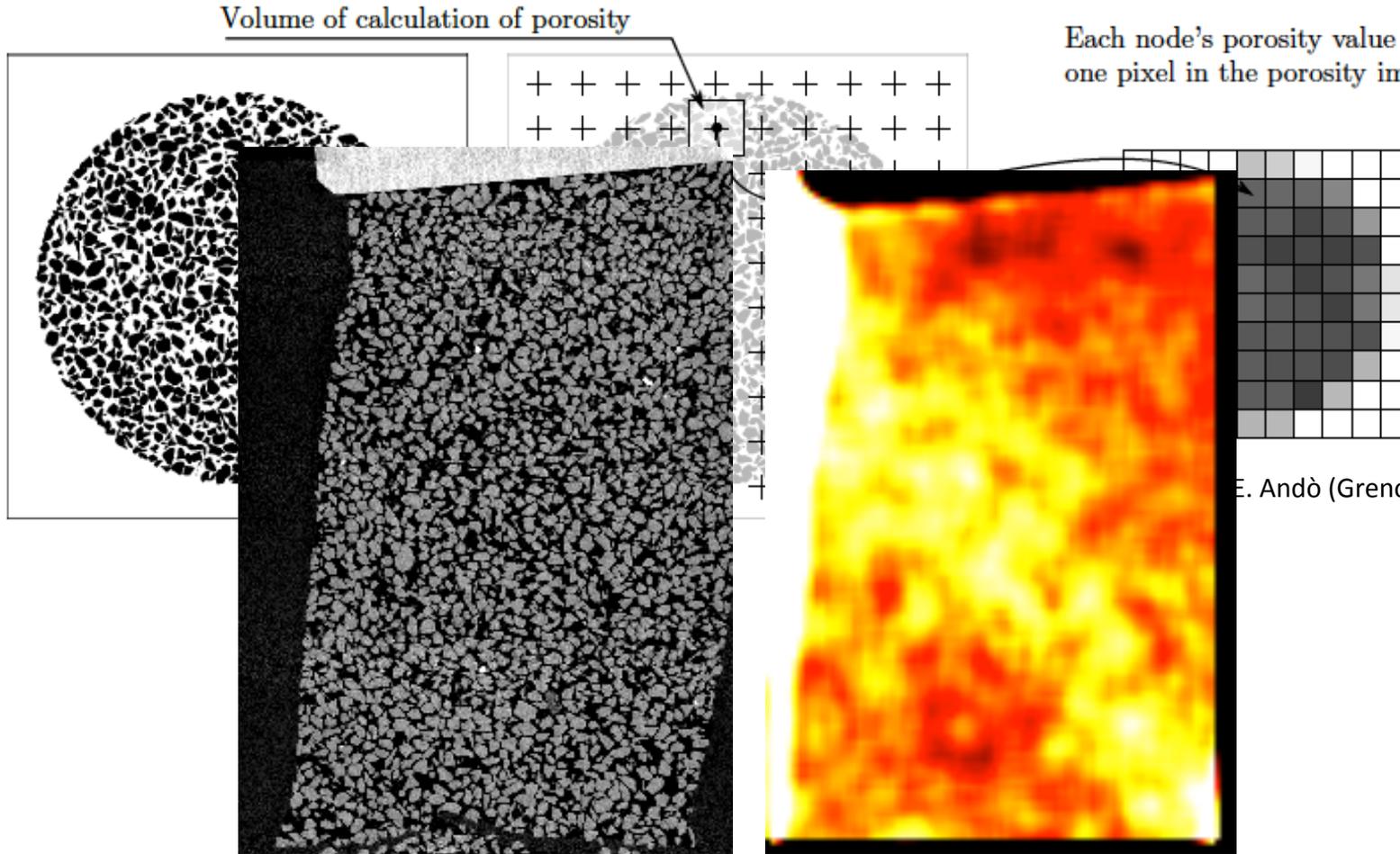
E. Andò (Grenoble, 2013)

<u>Tomo</u>        <u>Porosity</u>

# Trinarisation: patchy water saturation in a granular material

## Porosity - grey-scale

Not always possible to binarise images due to multiple phases or the image resolution relative to the porosity present

For the second case, if there are just two phases we can make a "look-up table" for porosity:grey-scale calibrated by "known" points



02_02

02_09

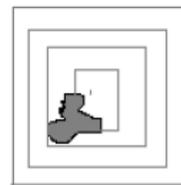Tuffeau de Maastricht

Porosity - grey-scale

Tuffeau de Maastricht



50% porosity

0% porosity

100% porosity

Fig.4.19 Concept of porosity determination



y = -437x + 50063

4..3.2 Porosity analysis



Image from MSc A. Moldovan (Grenoble, 2010)

## Porosity - grey-scale

## Tuffeau de Maastricht



Deviatoric stress versus axial strain for the triaxil test TX_05, made at a confining pressure of 4 MPa.
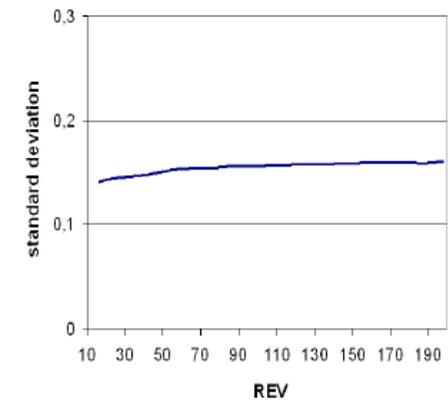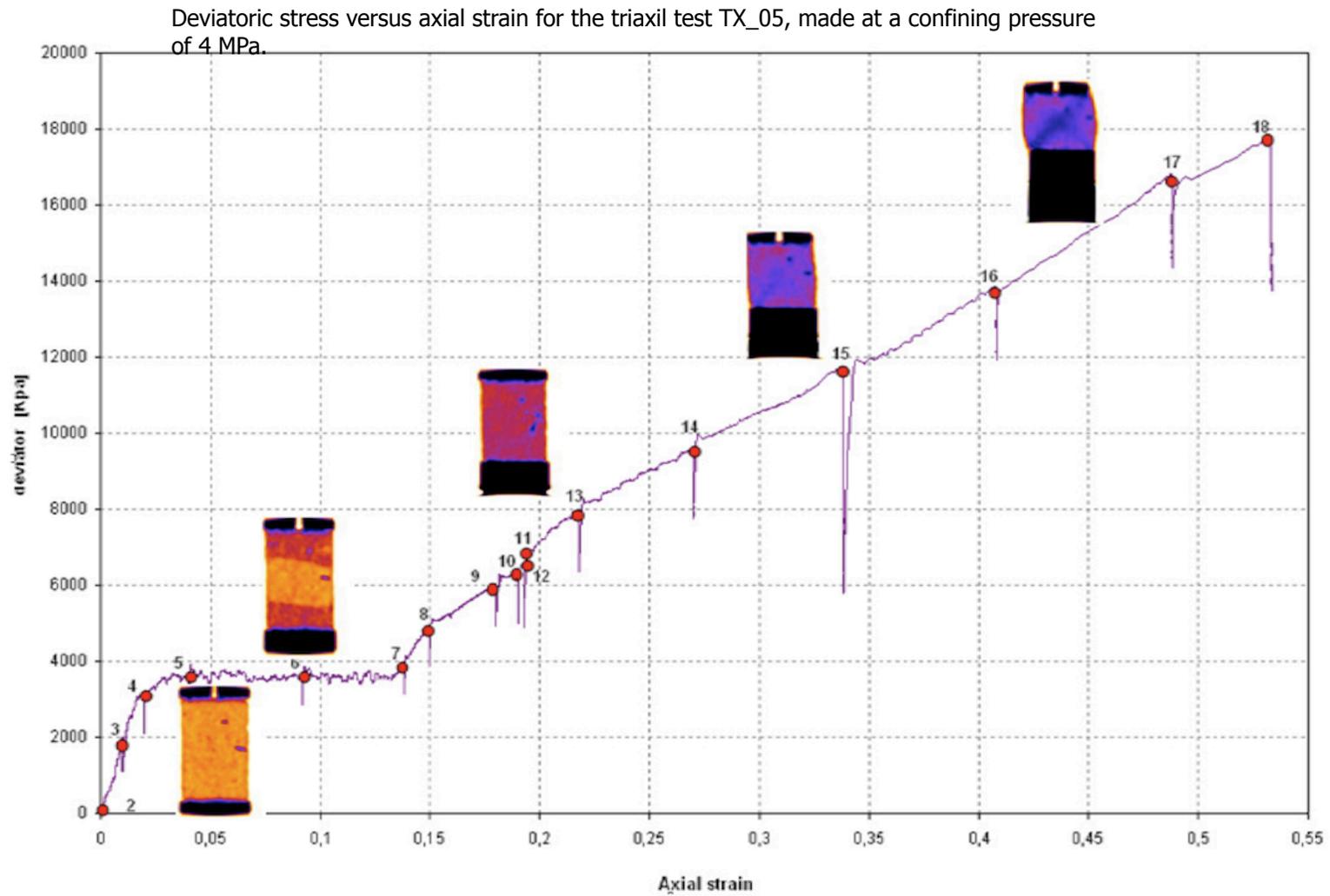
Morphological operations

**Mathematical morphology** (MM) is a theory and technique for the analysis and processing of geometrical structures

Mathematical Morphology was born in 1964 from the collaborative work of Georges Matheron and Jean Serra, at the École des Mines de Paris, France…

…for the quantification of mineral characteristics from thin sections

Includes operations such as dilation, erosion, opening, closing, granulometry, skeletonization, ultimate erosion, segmentation…

(after wikipedia)

A shape (in blue) and its morphological dilation (in green) and erosion (in yellow) by a diamond-shape structuring element.

http://en.wikipedia.org/wiki/Mathematical_morphology
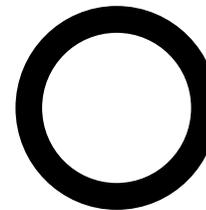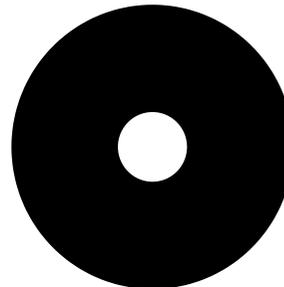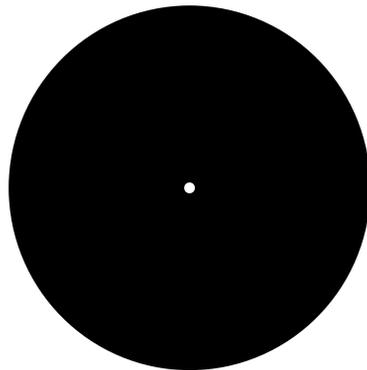
# Dilation and erosion

The **<u>dilation</u>** of the dark-blue square by a disk, resulting in the light-blue square with rounded corners.
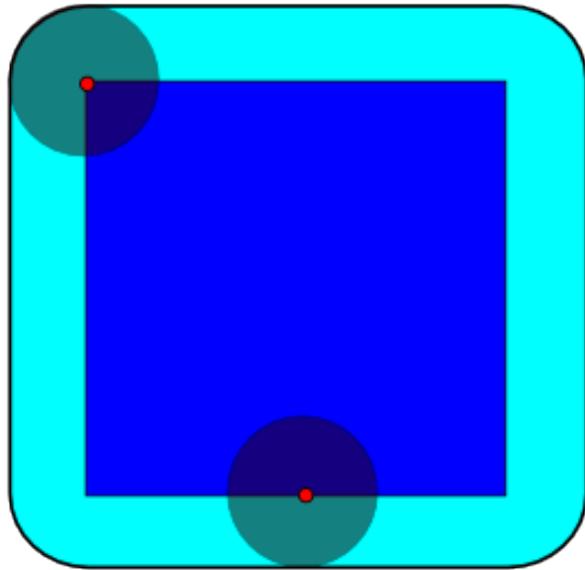
The **<u>erosion</u>** of the dark-blue square by a disk, resulting in the light-blue square.
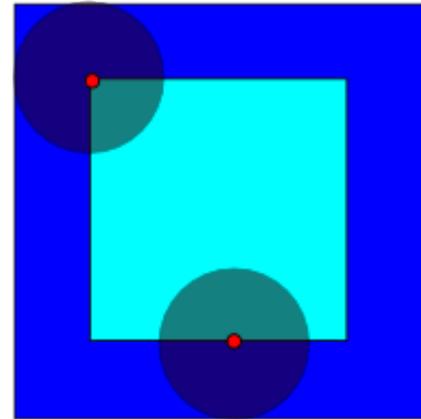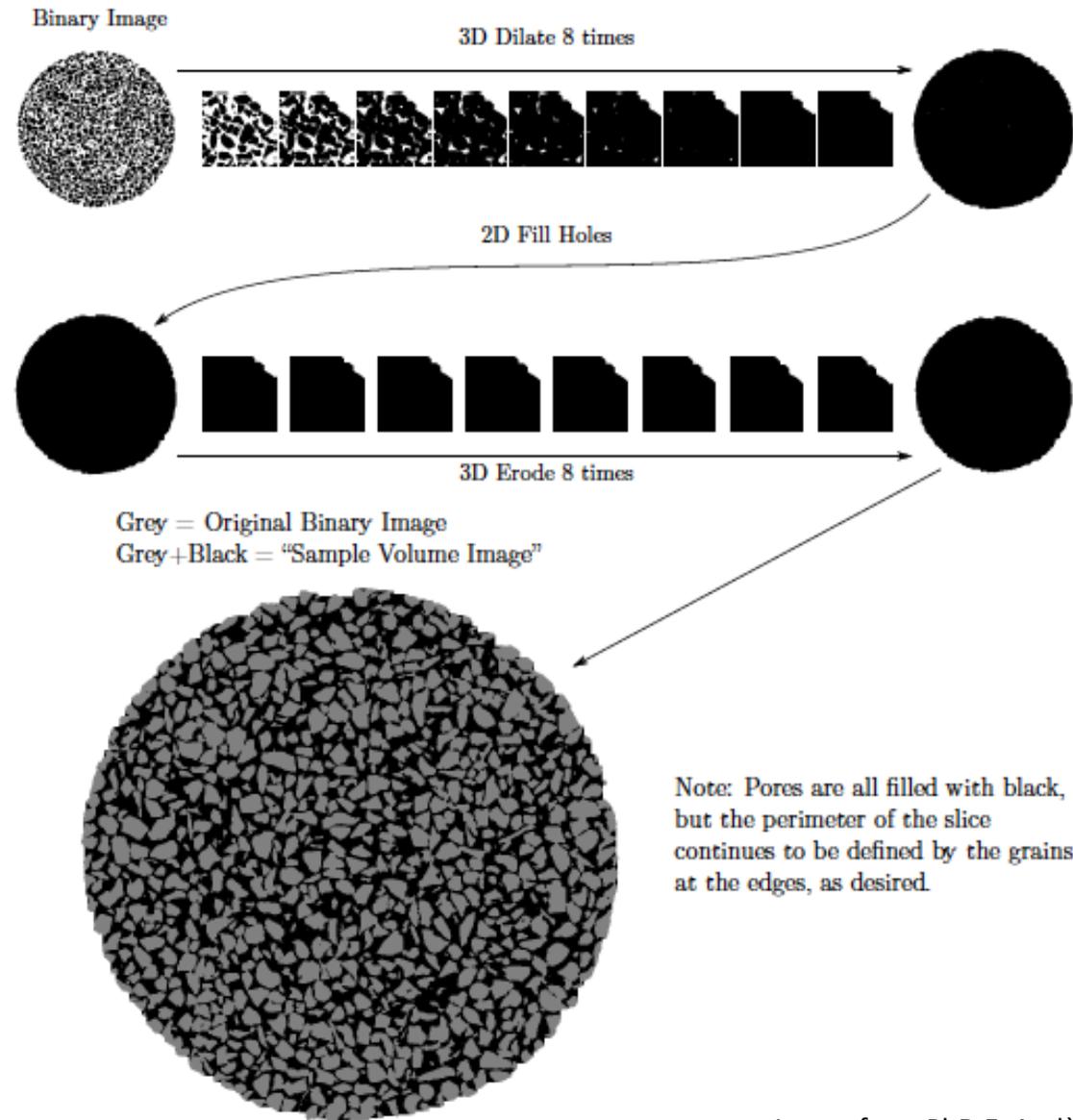


http://en.wikipedia.org/wiki/Mathematical_morphology

# Dilation and erosion - example of use

## Calculation of sample volume from tomography image



Grey = Original Binary Image
Grey+Black = "Sample Volume Image"

Note: Pores are all filled with black, but the perimeter of the slice continues to be defined by the grains at the edges, as desired.

Image from PhD E. Andò (Grenoble, 2013)

# Skeletonisation

In shape analysis, skeleton (or topological skeleton) of a shape is a thin version of that shape that is equidistant to its boundaries. The skeleton usually emphasizes geometrical and topological properties of the shape, such as its connectivity, topology, length, direction, and width. Together with the distance of its points to the shape boundary, the skeleton can also serve as a representation of the shape (they contain all the information necessary to reconstruct the shape).

(Wikipedia)



http://www.inf.u-szeged.hu/~palagyi/skel/skel.html
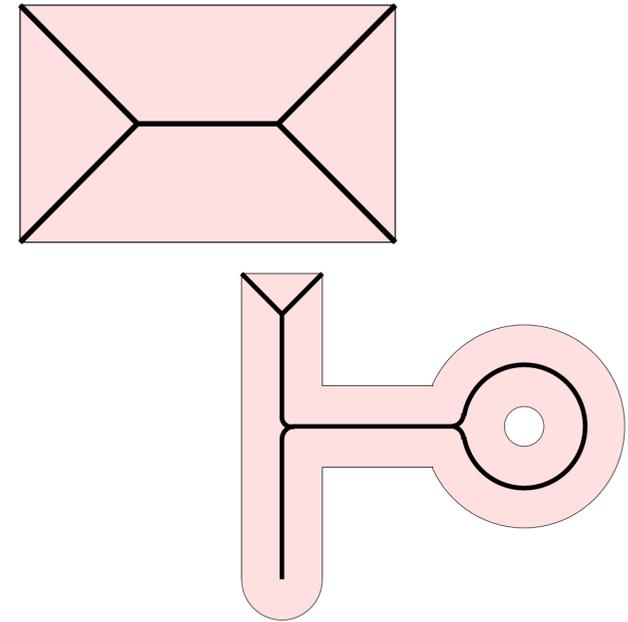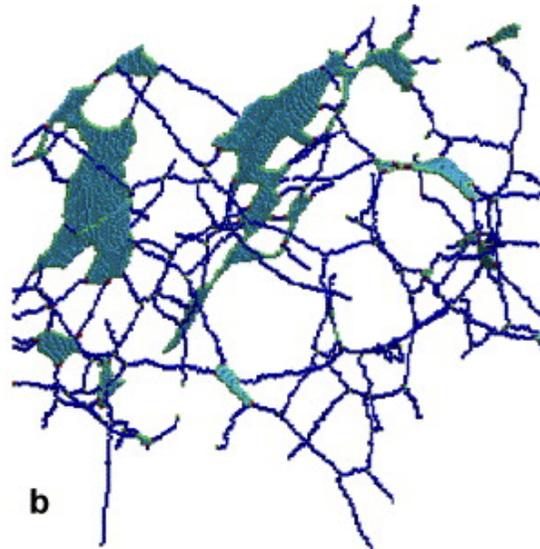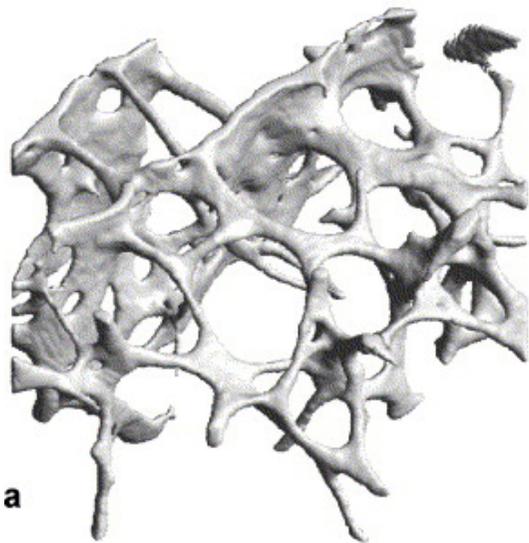


Lenthe & Müller, 2006, Bone

Structural imaging and characterisation:
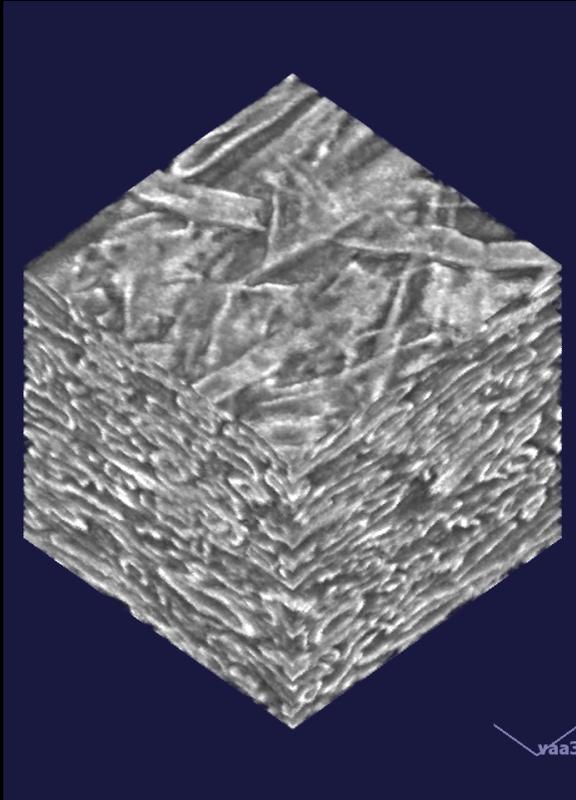


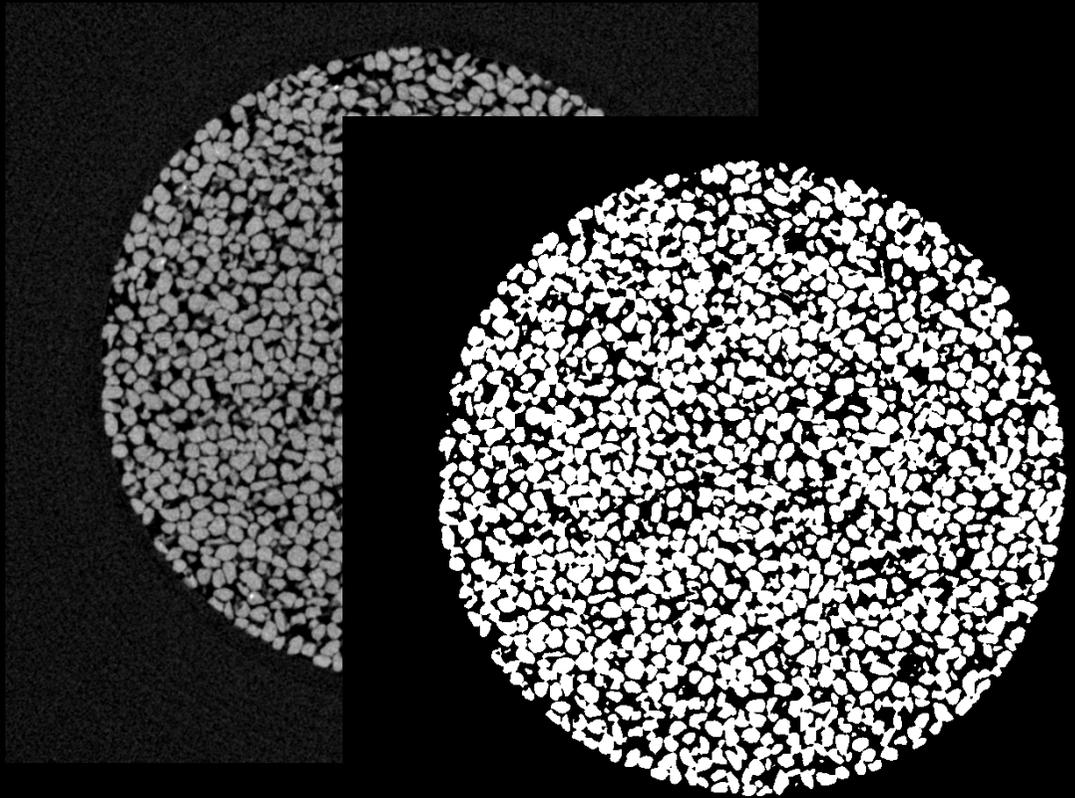Paperboard
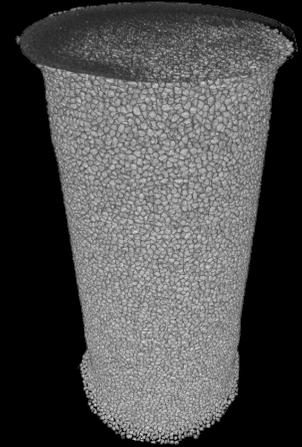(1.5 micron voxel size)
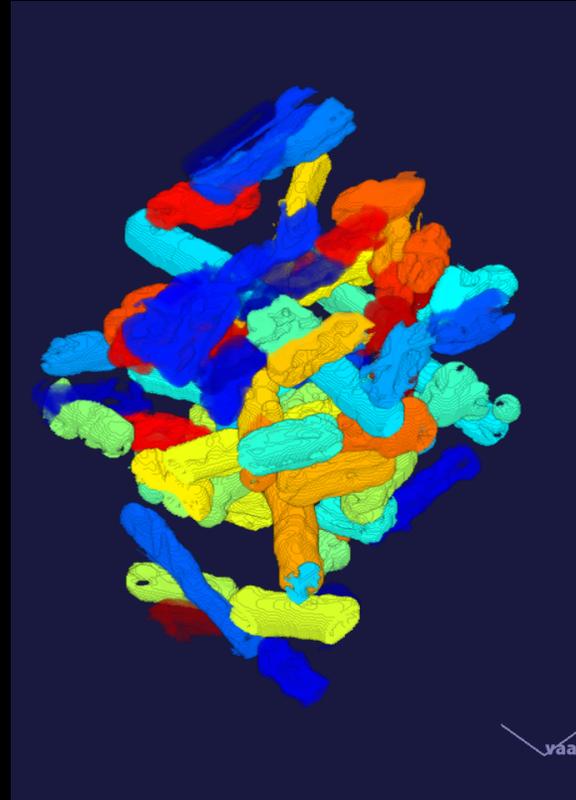
Segmented & Labelled fibres
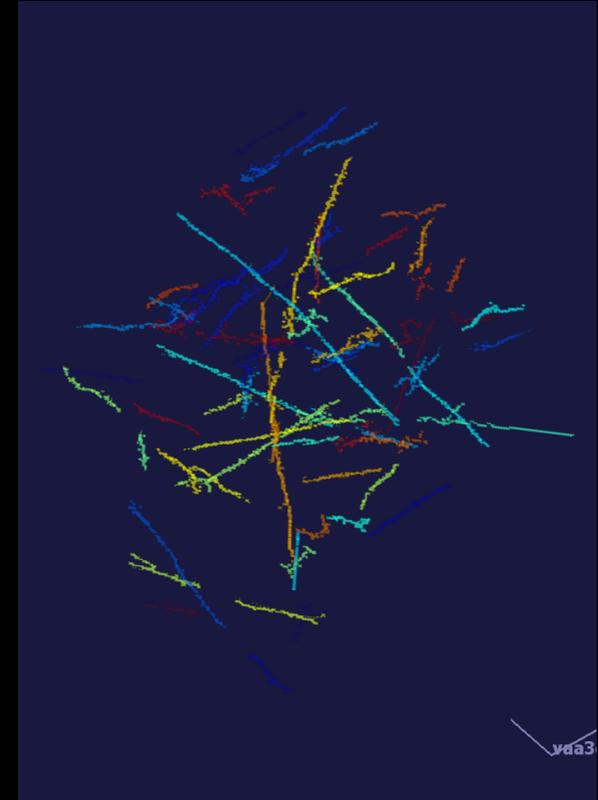
Fibre central axes

PhD Project, M. Al-Ibadi, Solid Mechanics, LTH, collab. TetraPak

4D IMAGING LAB@LTH

**Structural imaging and characterisation: 3D image analysis, e.g.,**
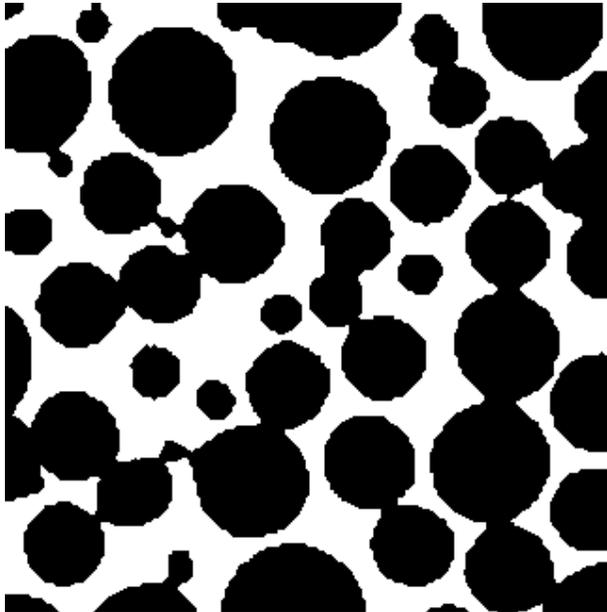
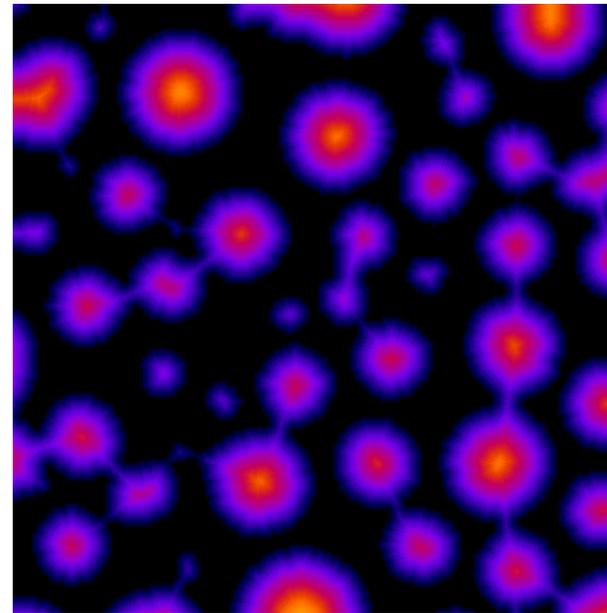How do we see/identify and characterise microstructure?



"Raw" image

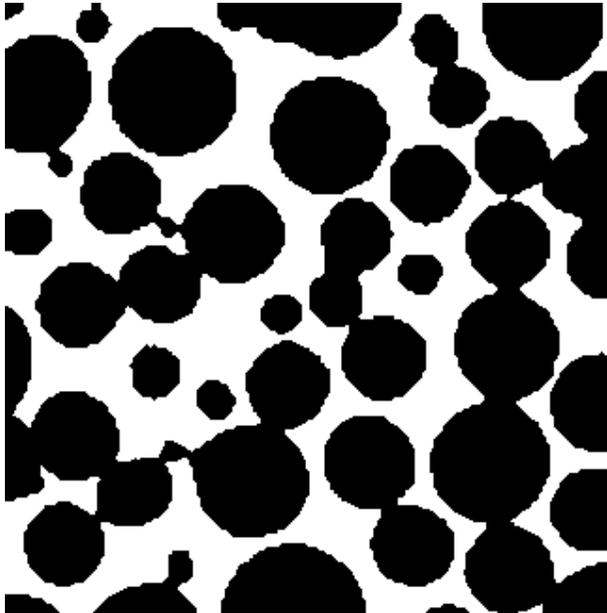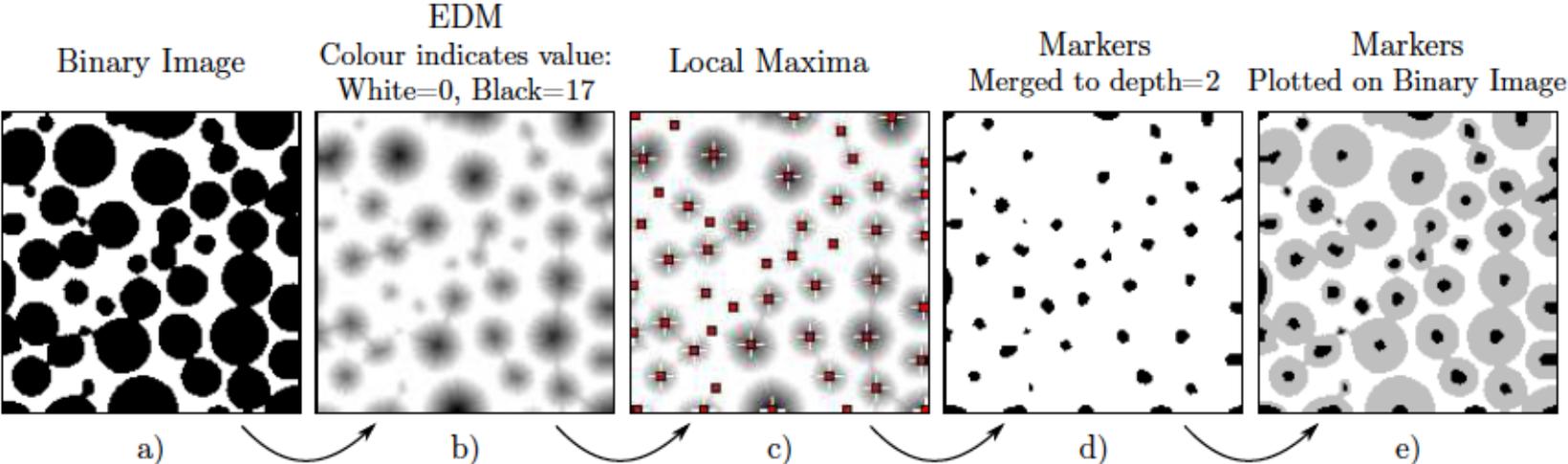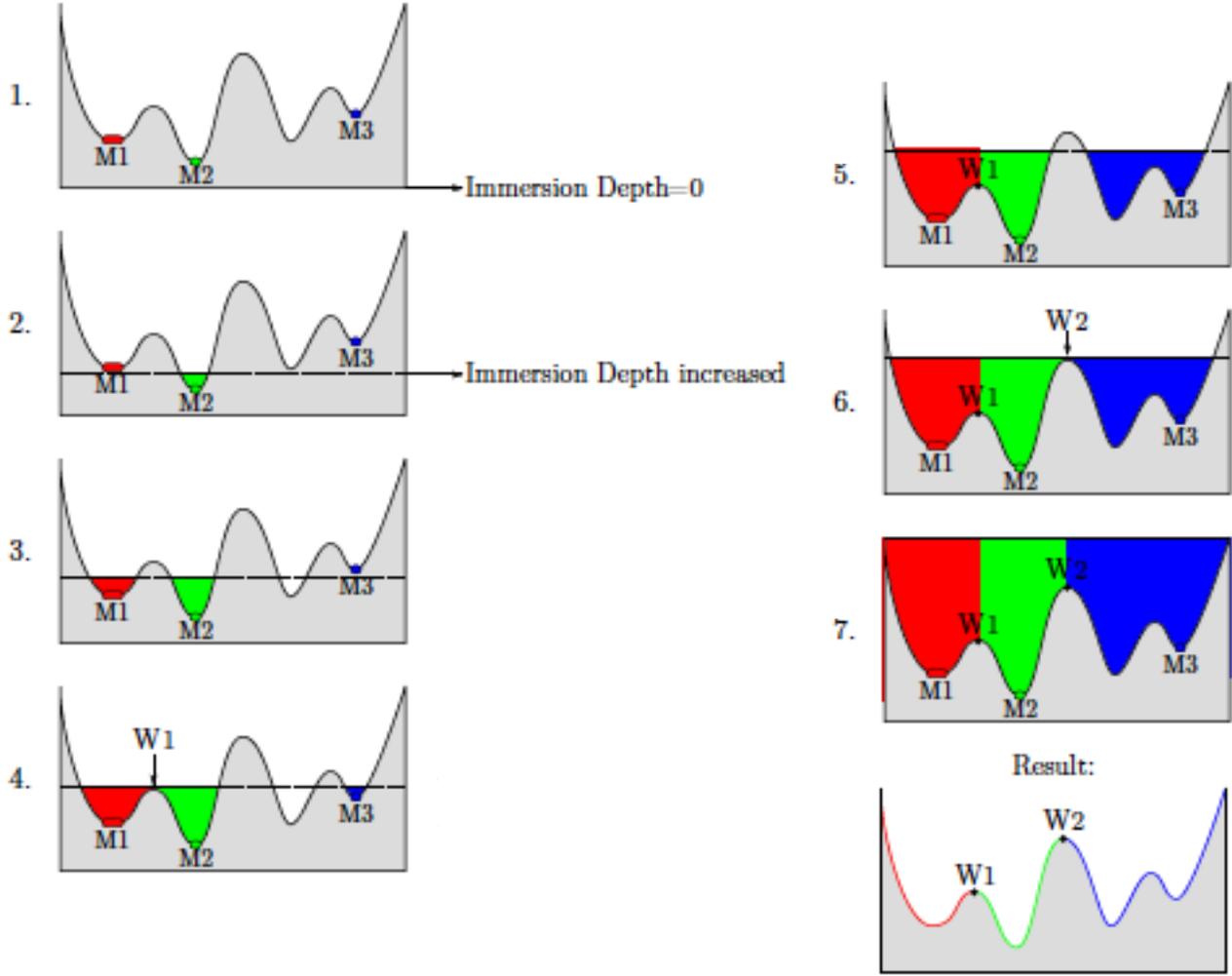Binarise
(grains and voids)

# Watershed Segmentation - introduction of distance map

# Watershed Segmentation - introduction of distance map

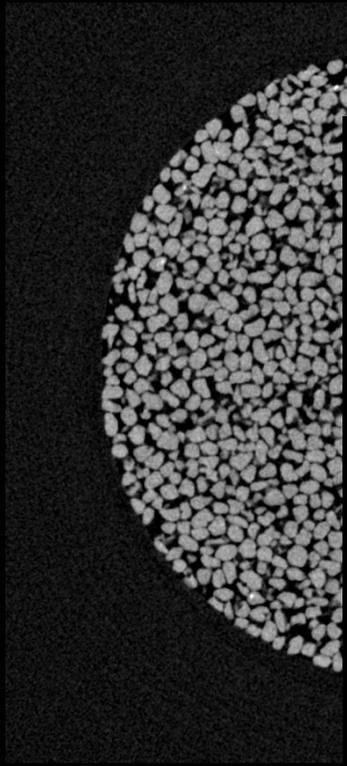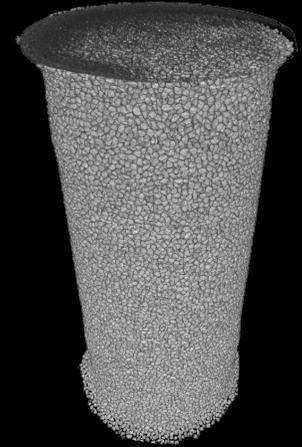# Watershed Segmentation - introduction of distance map



| Binary Image | EDM<br>Colour indicates value:<br>White=0, Black=17 | Local Maxima | Markers<br>Merged to depth=2 | Markers<br>Plotted on Binary Image |

a)   b)   c)   d)   e)

Image from PhD E. Andò (Grenoble, 2013)

# Watershed Segmentation



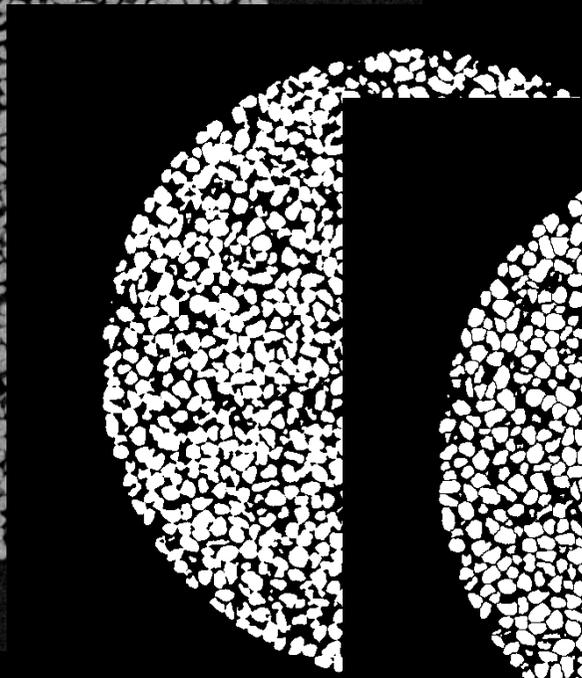Image from PhD E. Andò (Grenoble, 2013)

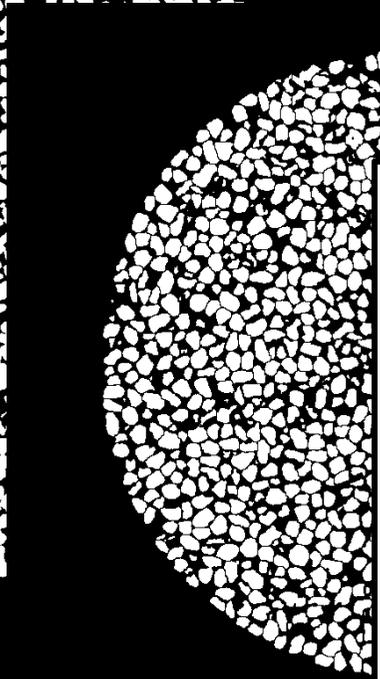**Structural imaging and characterisation: 3D image analysis, e.g.,**

How do we see/identify and characterise microstructure?
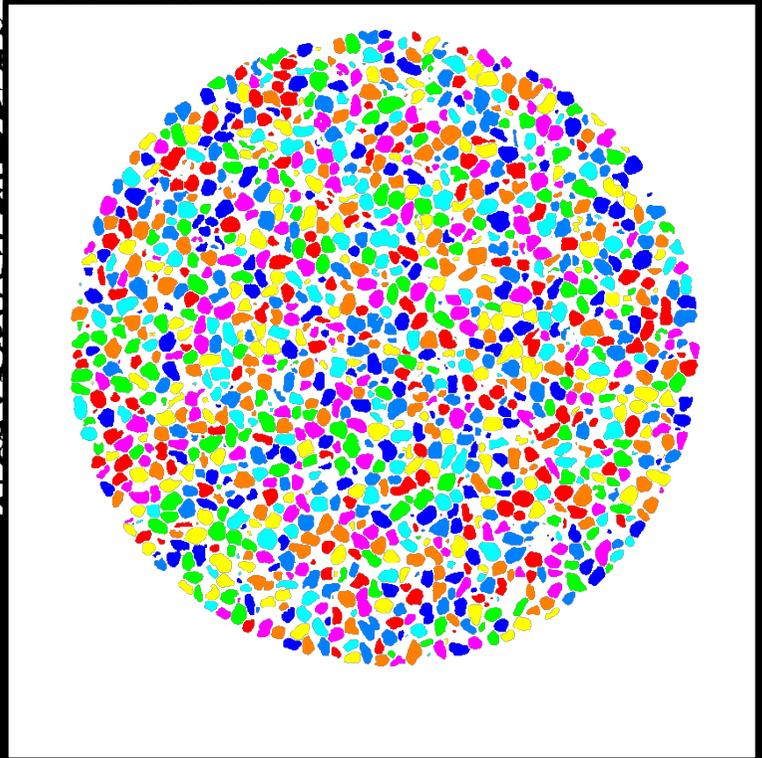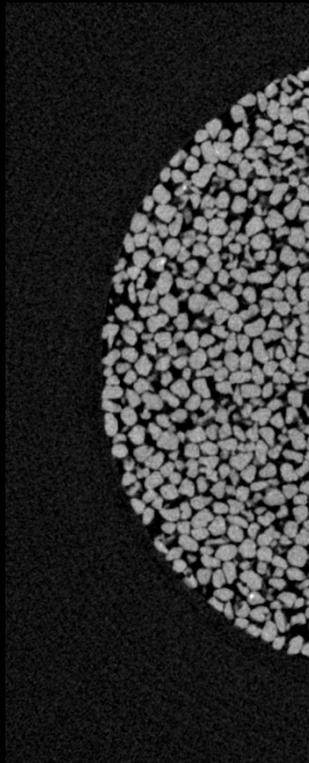
"Raw" image

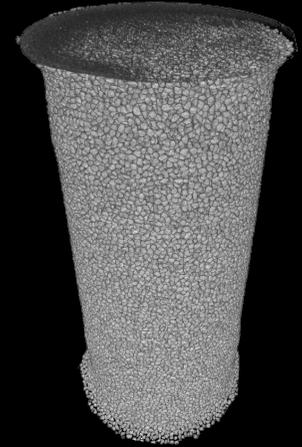Binarise
(grains and voids)

Watershed
Segmentation
(split grains apart)

Label Individual Grains

**Structural imaging and characterisation: 3D image analysis, e.g.,**

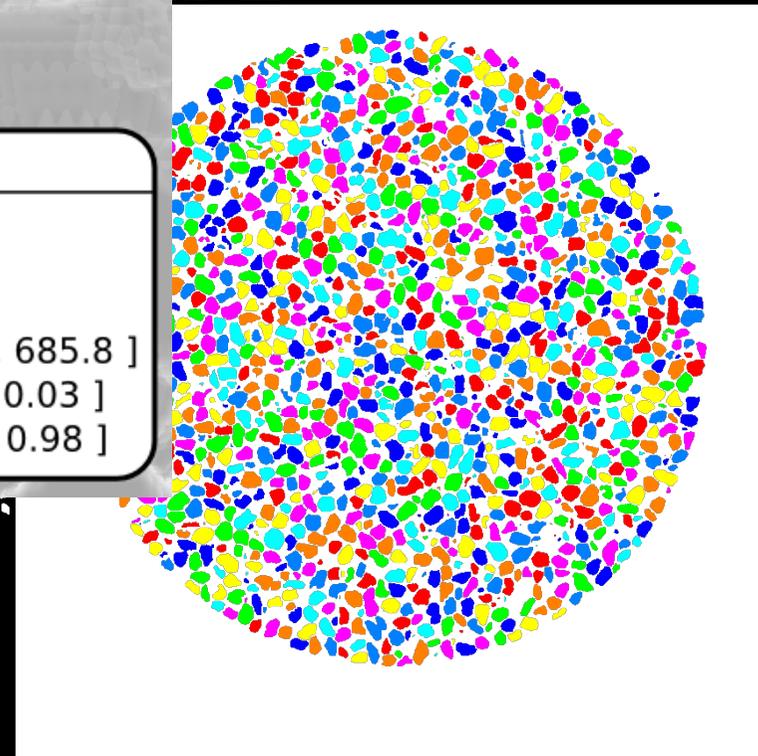How do we see/identify and characterise microstructure?

"ID Card" of each object

**Ottawa 50/70**

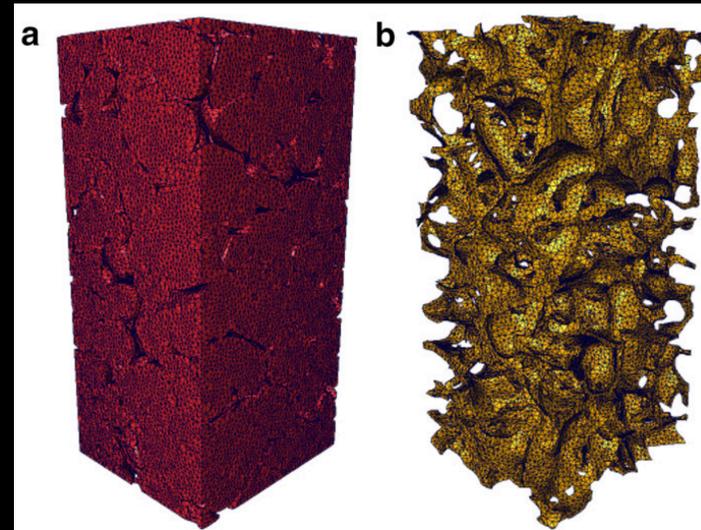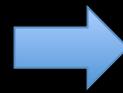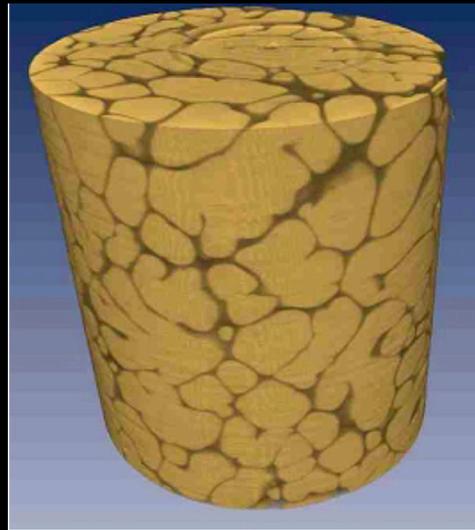| | |
|---|---|
| **Grain ID** | = 46808 |
| 3D Surface Area | = 1354.4 px² |
| 3D Volume | = 4066 vx |
| Centre of Mass | = [ 448.3, 371.8, 685.8 ] |
| Orientation Vector 1 | = [ 0.40, 0.92, 0.03 ] |
| Orientation Vector 2 | = [ -0.07, -0.19, 0.98 ] |

"Raw" image

Binarise
(grains and voids)

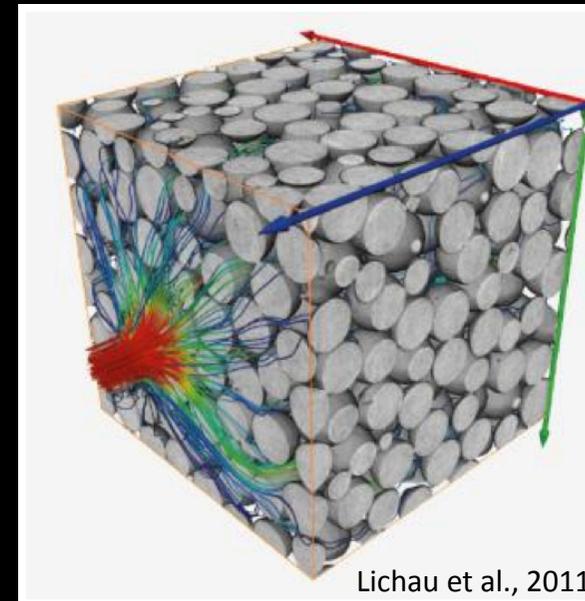Watershed
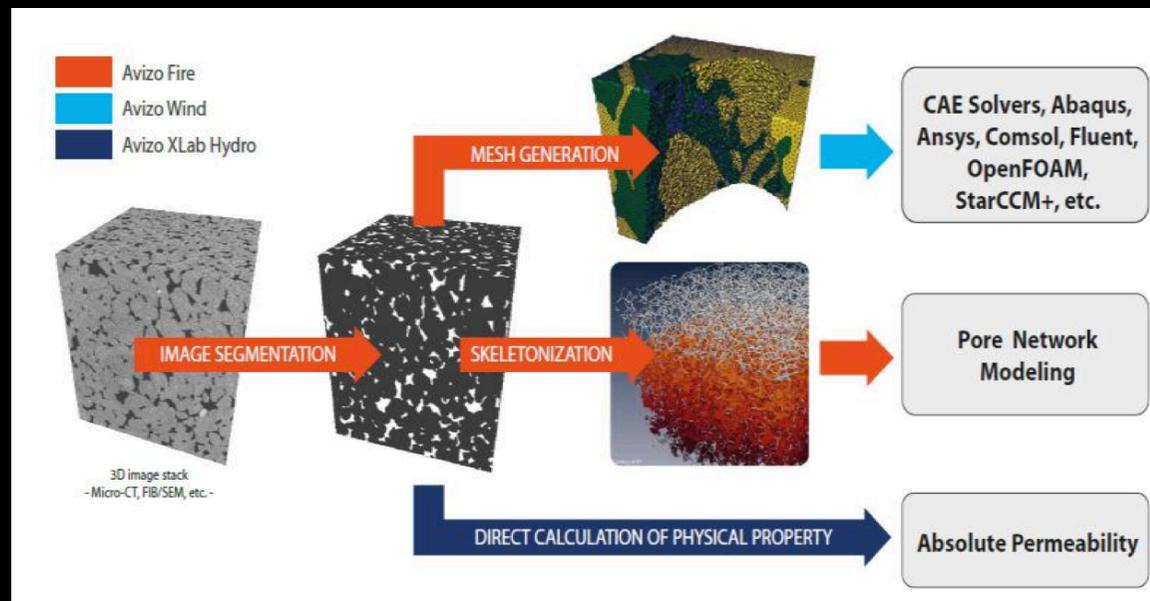
Segmentation
(split grains apart)

Label Individual Grains

# Structural imaging and characterisation → models



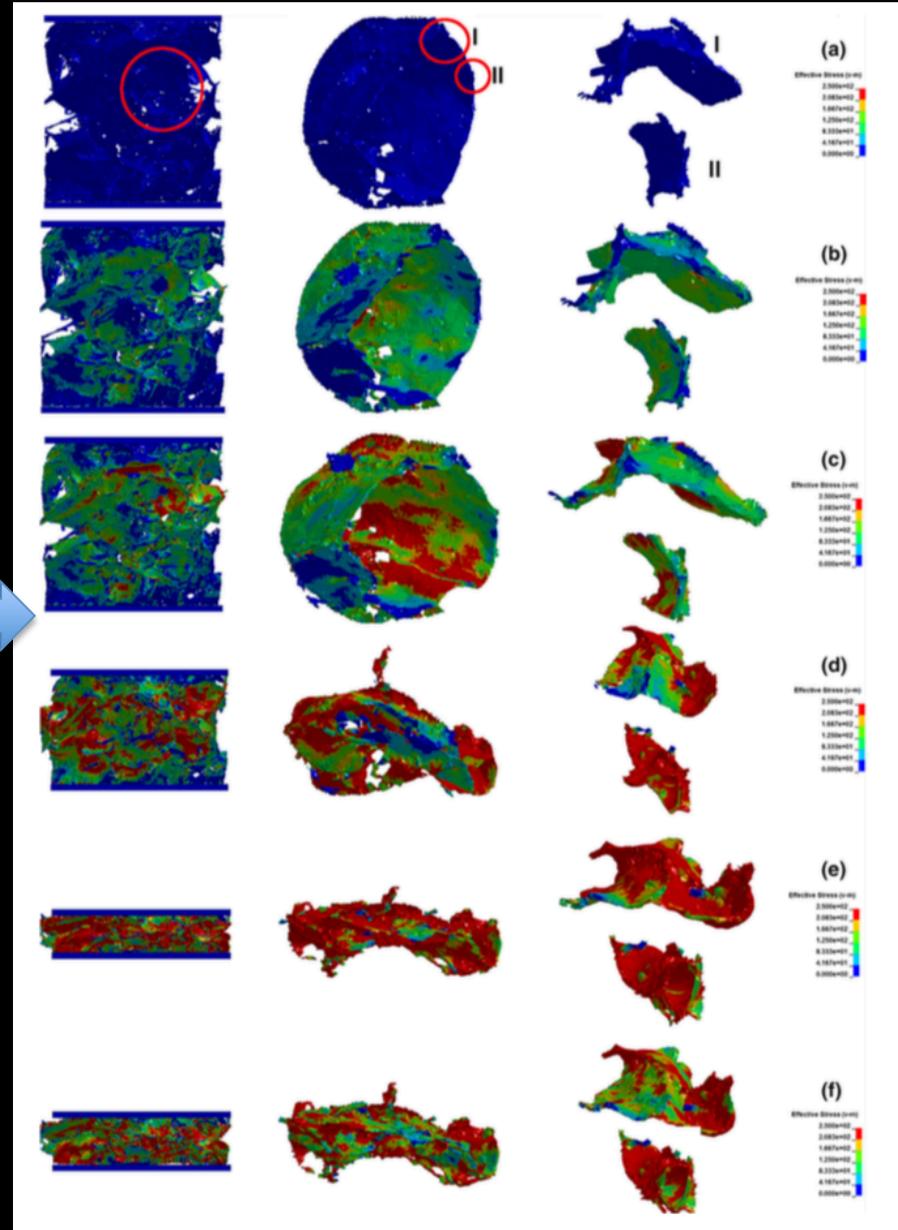Madi et al., 2006



Lichau et al., 2011

# Structural imaging and characterisation → models
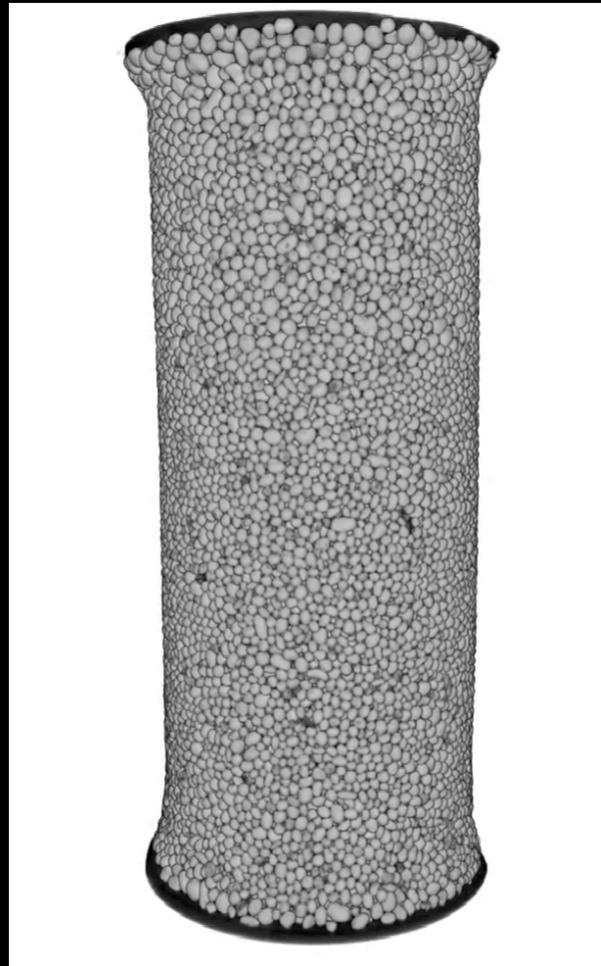


(Images from 4D Imaging Lab)

Srinivasa, Kulachenko , Karlberg, 2017, Cellulose

# 4D imaging and in-situ experiments
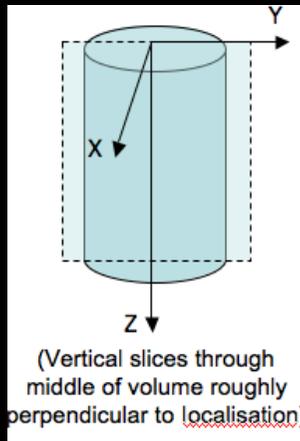


E Andò, CNRS,
Grenoble, France
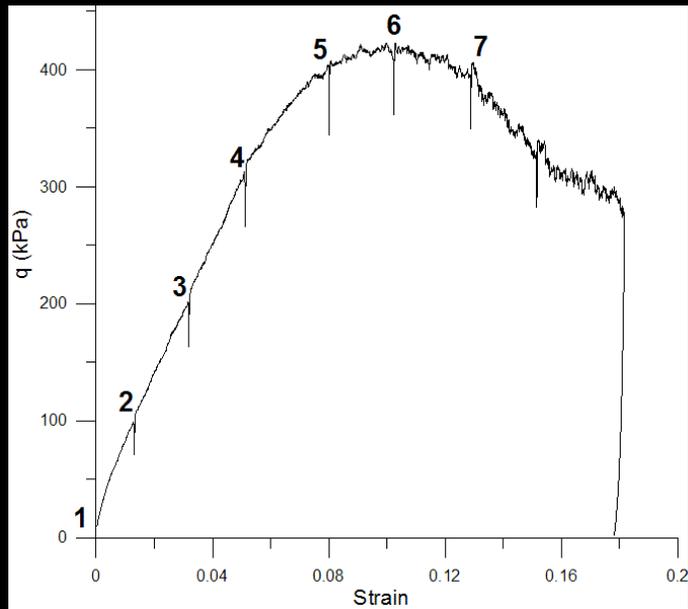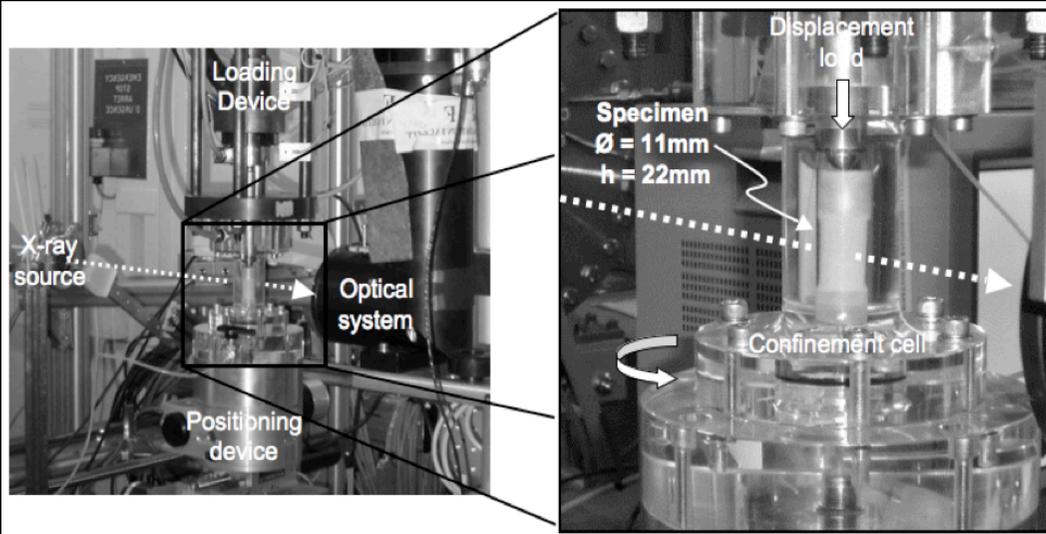
# 4D imaging and in-situ experiments

4D = 3 dimensions in space plus time

In-situ = performing an experiment within the measurement set-up, in this case within an x-ray tomograph (lab or synchrotron)

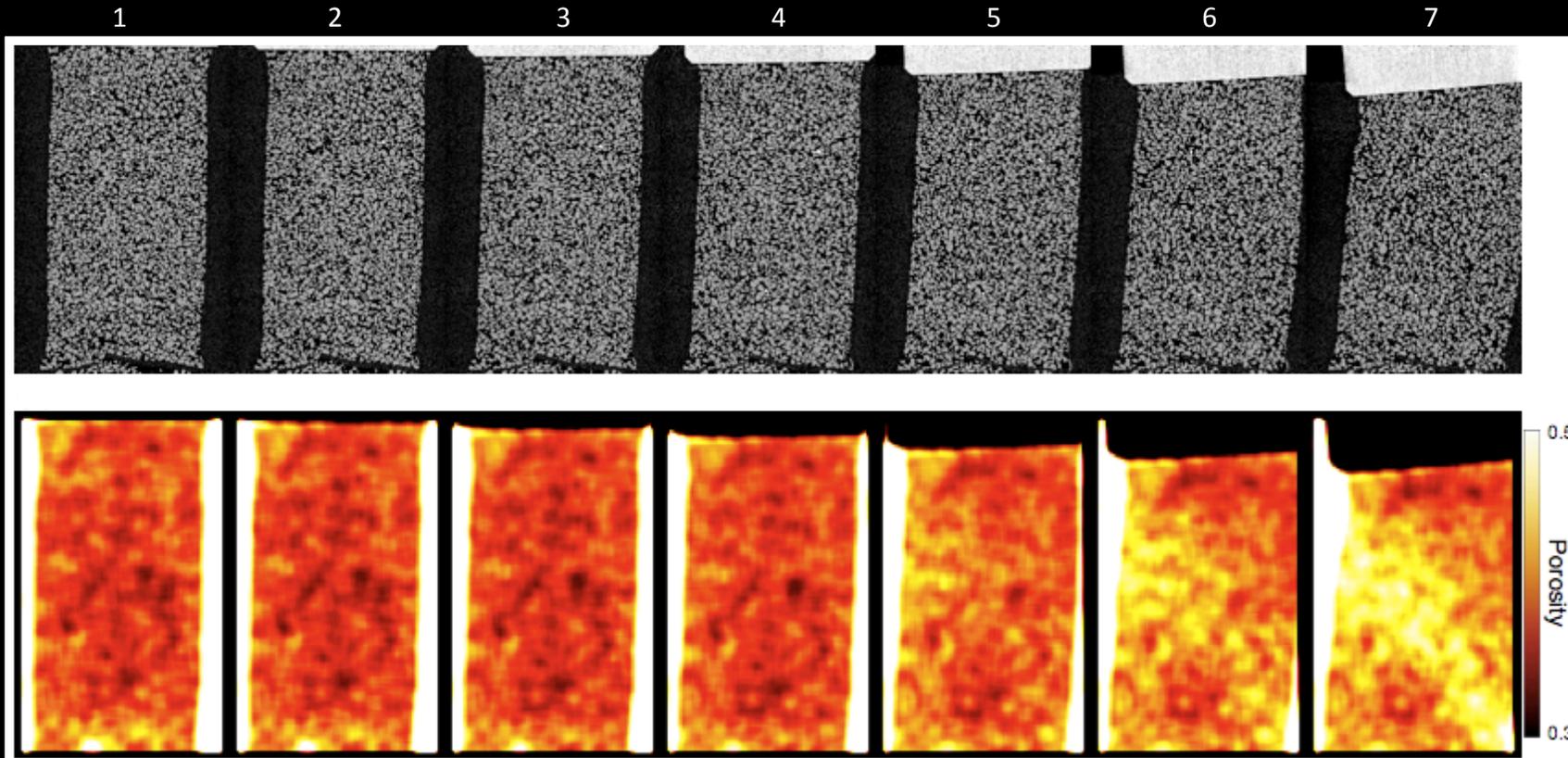# e.g., in-situ deformation of sand under pressure
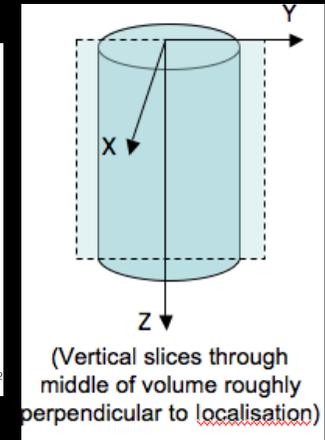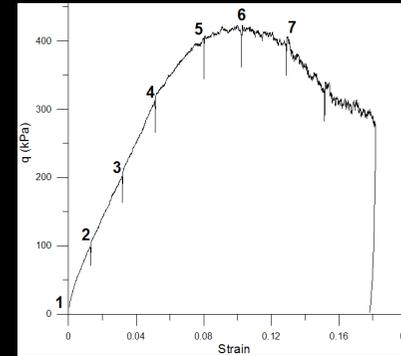
(See Hall et al., 2010, Géotechnique)
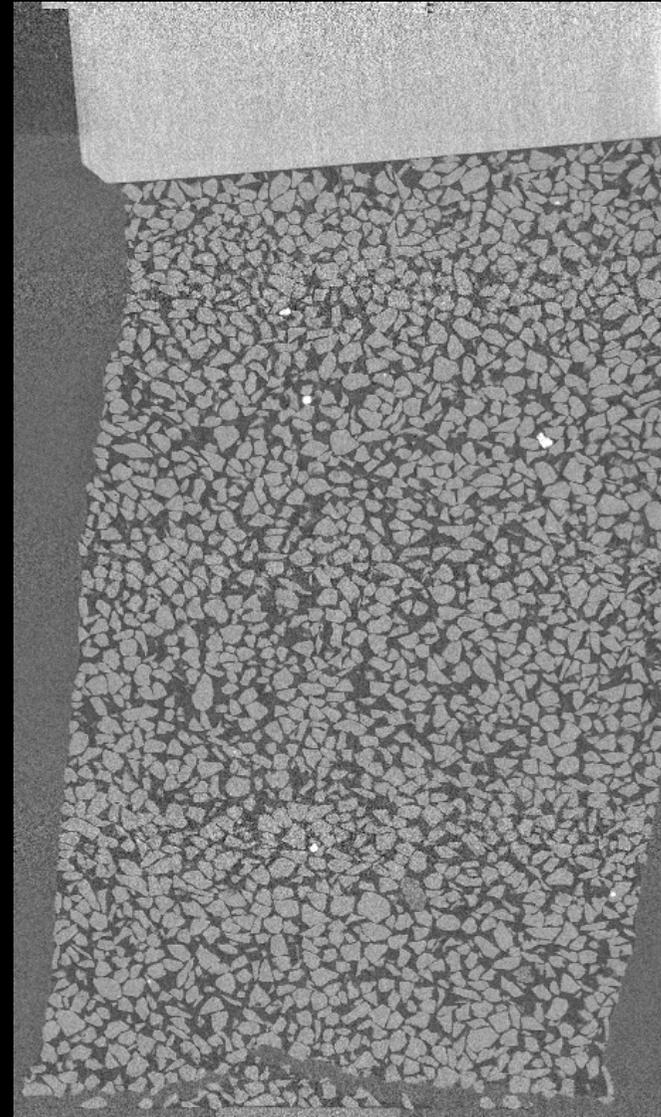
# 4D Image analysis

- N x 3D

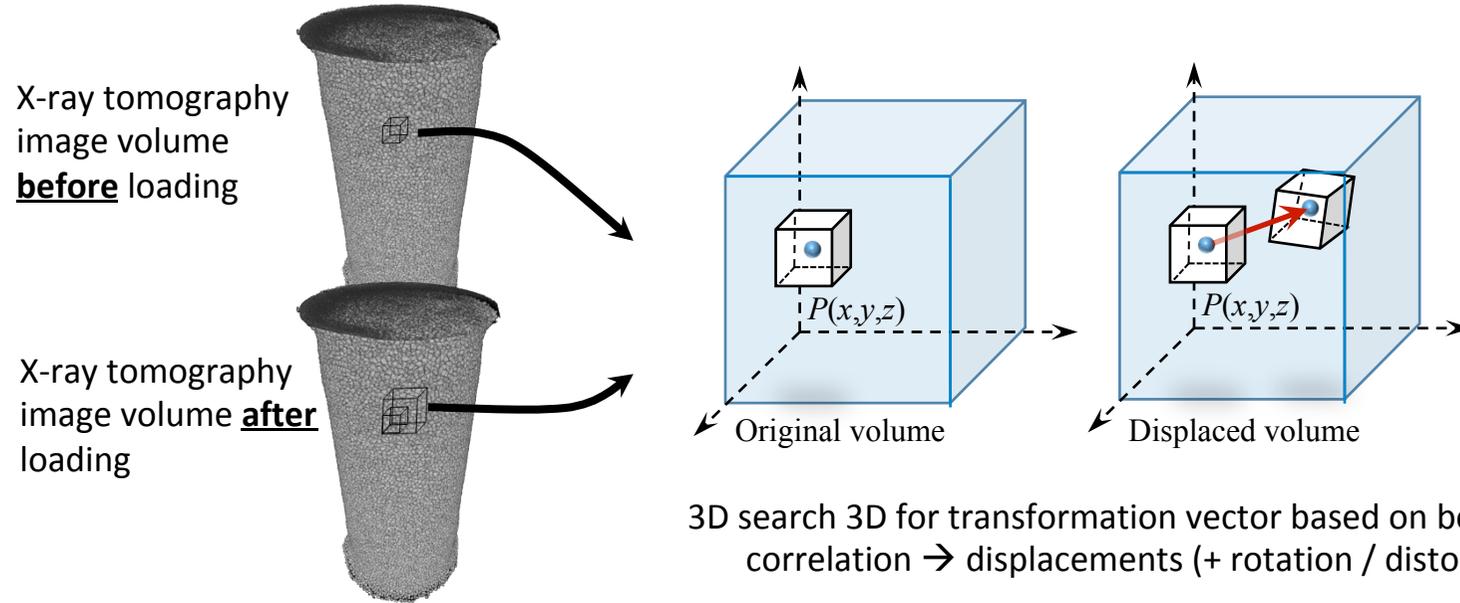e.g., Porosity - evolution



(See Hall et al., 2010, Géotechnique)

# Digital Volume Correlation (DVC)

e.g., "TomoWarp2": Tudisco et al., 2017

(See Hall (2005, Geophysics) and Hall et al., (2009, ComGeo), Tudisco et al., 2017)



X-ray tomography image volume **before** loading

X-ray tomography image volume **after** loading

$P(x,y,z)$

Original volume

$P(x,y,z)$

Displaced volume

3D search 3D for transformation vector based on best image correlation → displacements (+ rotation / distortion)

## Vector displacement field



Continuum hypothesis
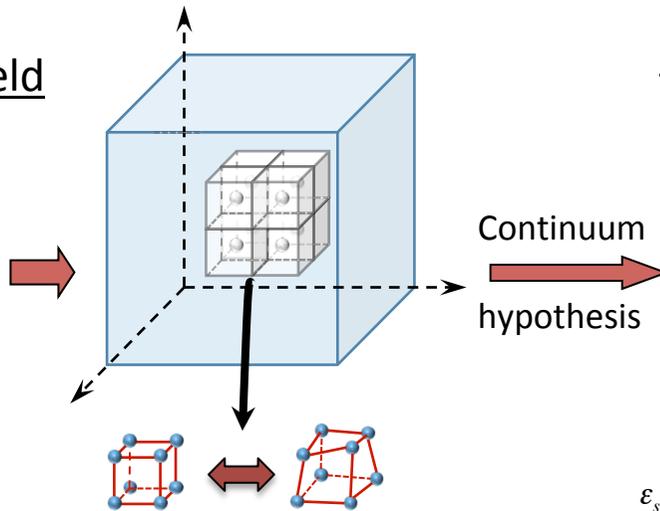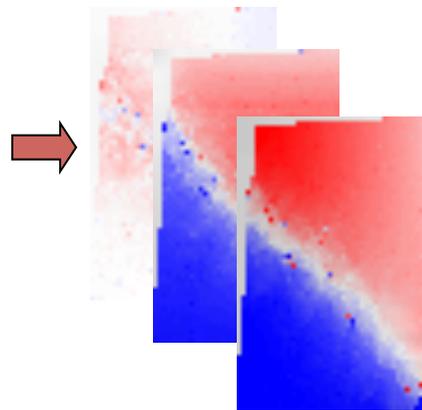
## Full 3D strain tensor field

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

Strain invariants
- volumetric and shear strains

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

$$\varepsilon_s = \sqrt{\left(\frac{\varepsilon_1 - \varepsilon_2}{2}\right)^2 + \left(\frac{\varepsilon_1 - \varepsilon_3}{2}\right)^2 + \left(\frac{\varepsilon_2 - \varepsilon_3}{2}\right)^2}$$
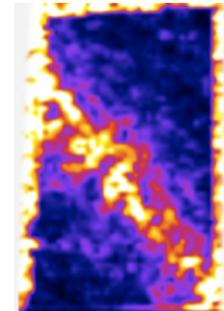
# 4D Image analysis - DVC



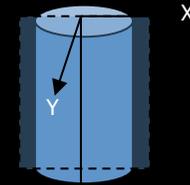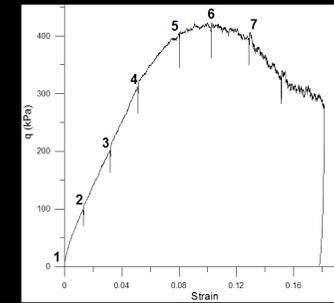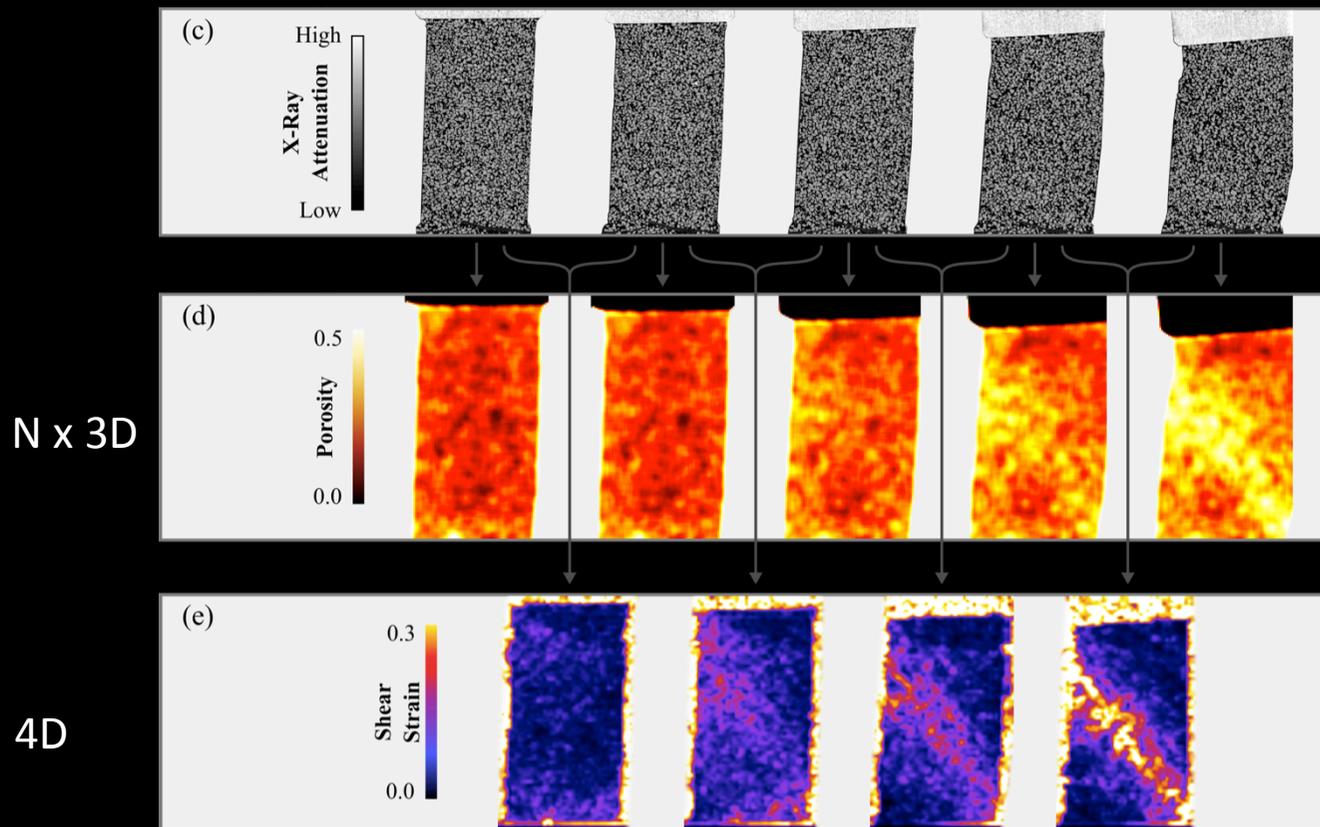N x 3D

4D

DVC

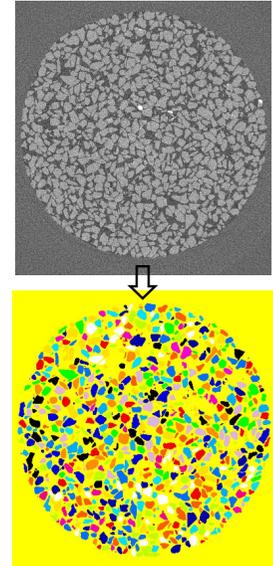What about the grains?

(See Hall et al., 2010, Géotechnique)

# "Discrete" DVC



❶ "Classic" DIC
⇨ initial estimate of
*[dx,dy,dz]* for each grain

❷ Image segmentation
→ grain-mask to define
grain-shape correlation
domains (3 voxels expansion
to capture grain boundary)

## Discrete DIC

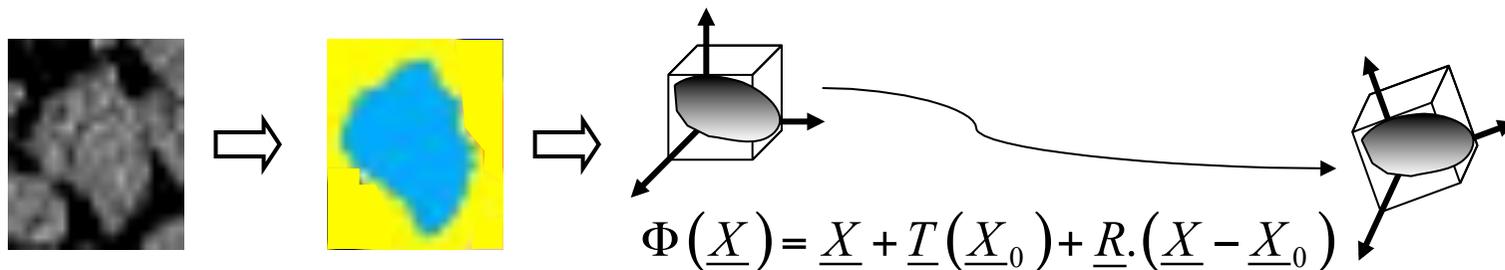- "Grain shape" correlation domain centred on each grain (from ❷)
- Initial estimate of displacements from classic DIC results (from ❶)

⇩

sub-voxel refinement
(6 parameters: 3 displ. + 3 rotations)

⇩

full grain kinematics for each grain



$$\Phi(\underline{X}) = \underline{X} + \underline{T}(\underline{X}_0) + \underline{\underline{R}} \cdot (\underline{X} - \underline{X}_0)$$

(See Hall et al., [2010])

# Quantified granular mechanics



(c) High — X-Ray Attenuation — Low

(d) Porosity 0.5 / 0.0

N x 3D

(e) Shear Strain 0.3 / 0.0 — DVC

(f) Rotation 30° / 0° — "Discrete" DVC

4D

X, Y, Z
(Vertical slices through volume)
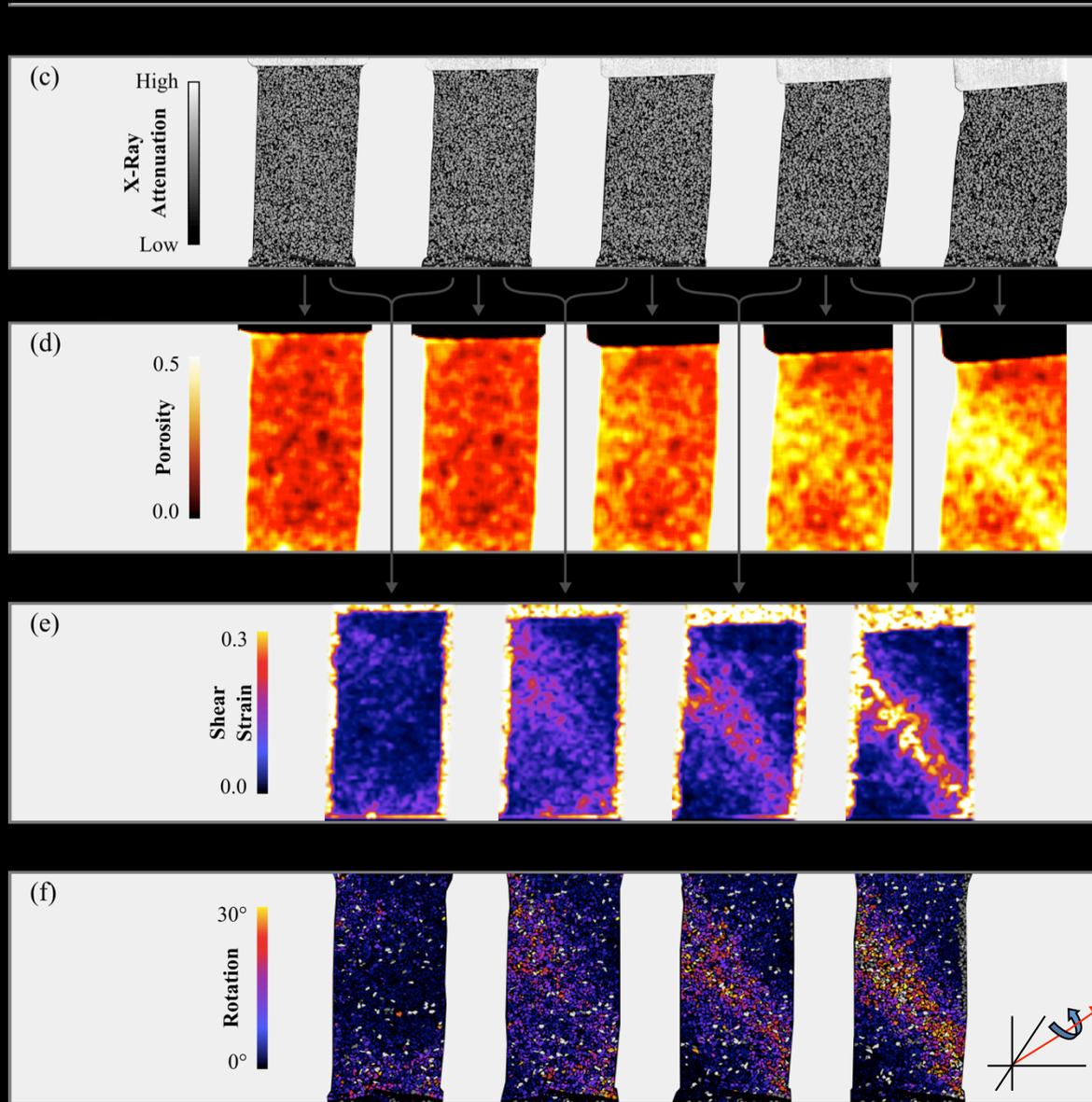
(See Hall et al., 2010, Géotechnique)

Final example - flow front tracking
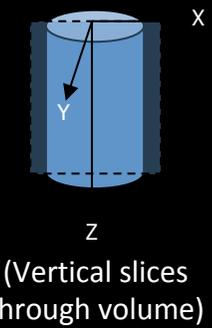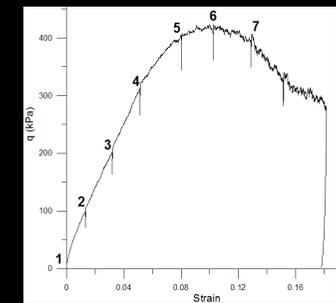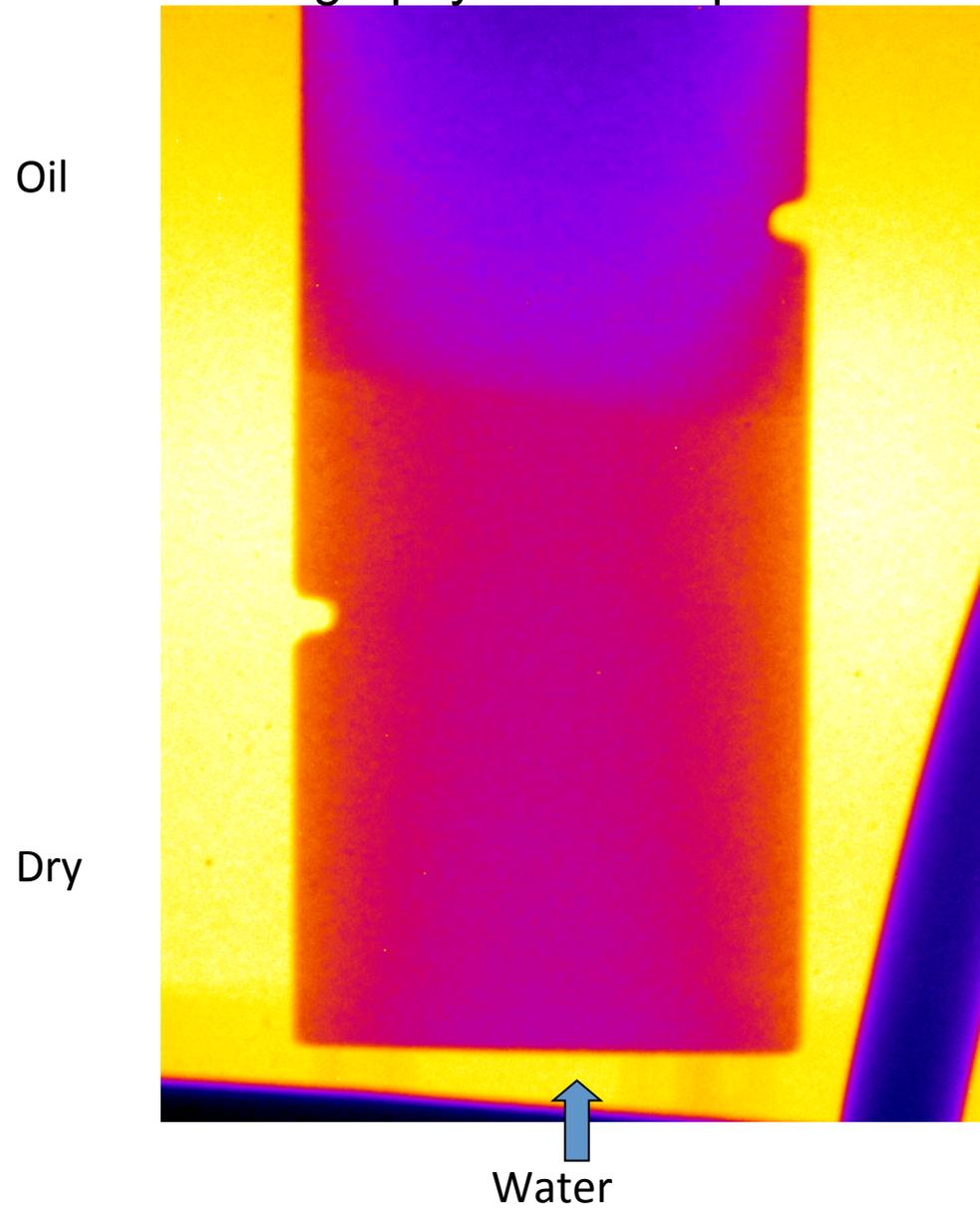
Timelapse neutron radiography of "2D" specimens and two fluid phases
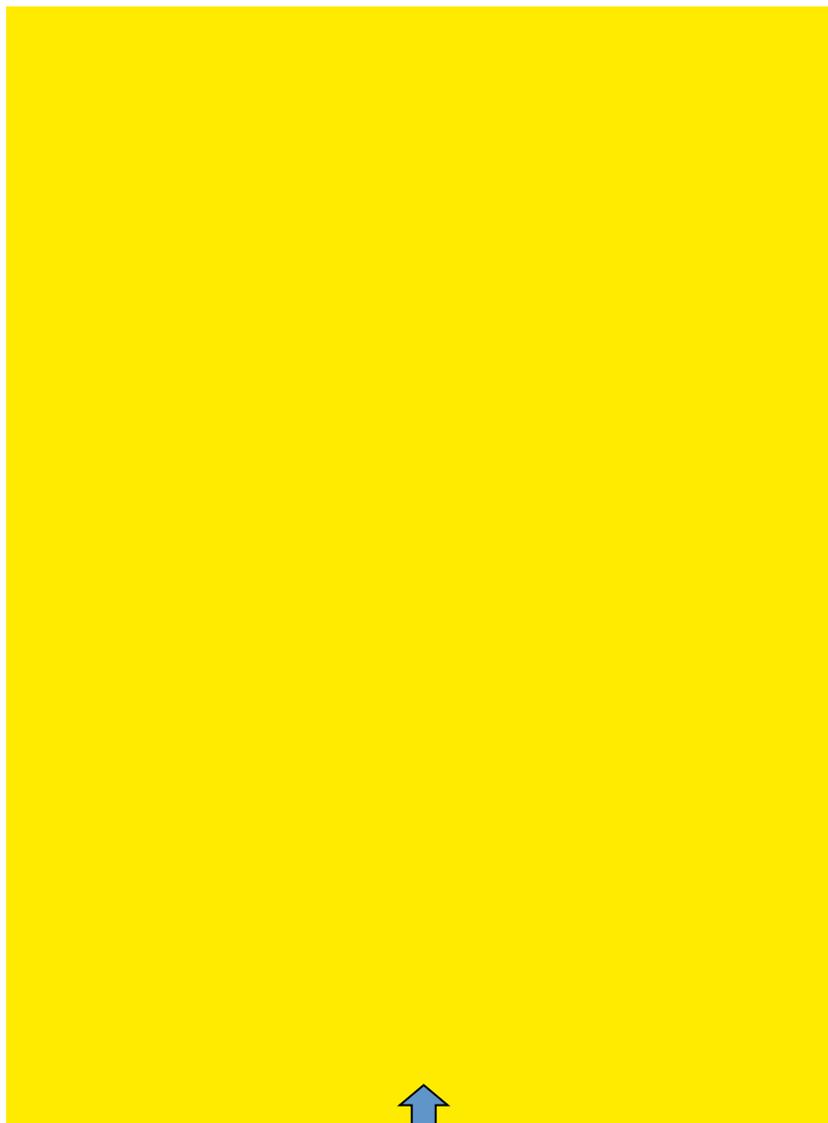


Oil

Dry

Water

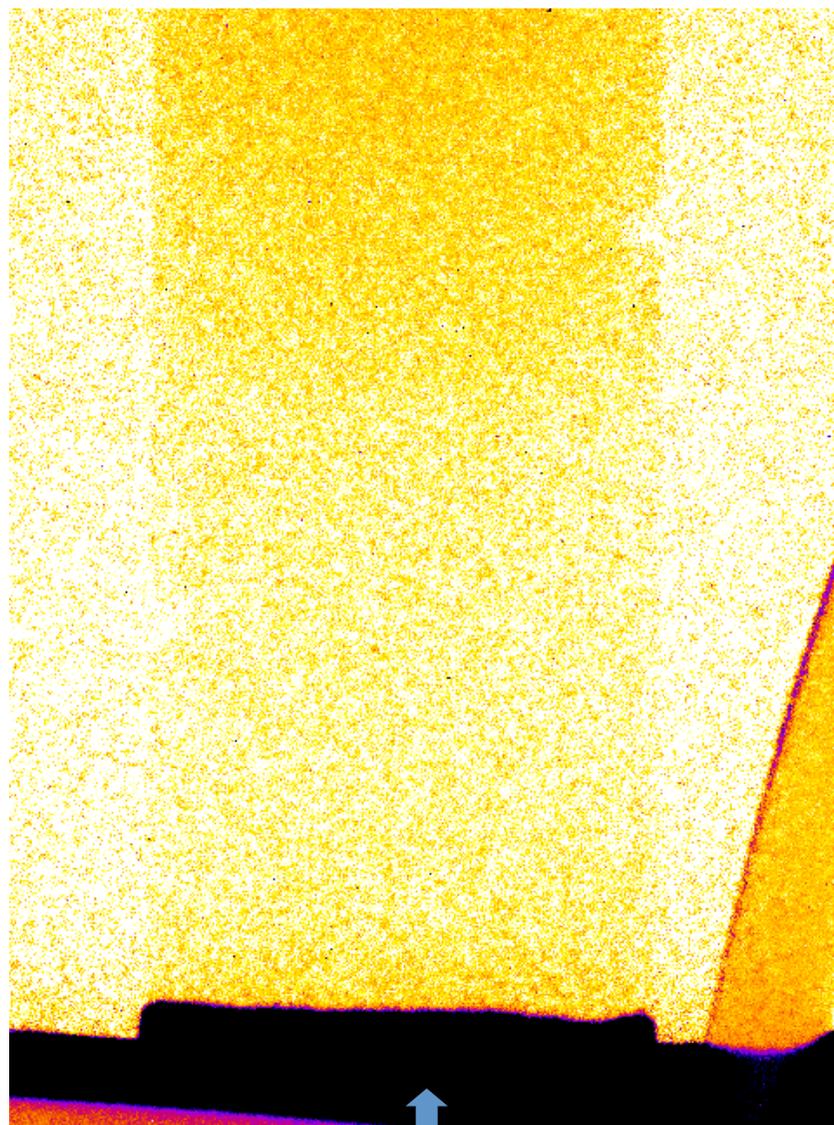# Difference image relative to first image

Oil

Dry

Water

# Incremental difference image



Oil

Dry

Water

# Quantification

•Automatically picked fluid fronts at time N

•Track each point on the front at time N through each image for all time steps

 •Challenging due to concavities and convexities of front and need to follow points on the front through time
 •Deformable contour tracking and front propagation
 •Flow fronts at each step
 •Flow lines from start to finish

•Flow velocities from distances along flow lines and image times
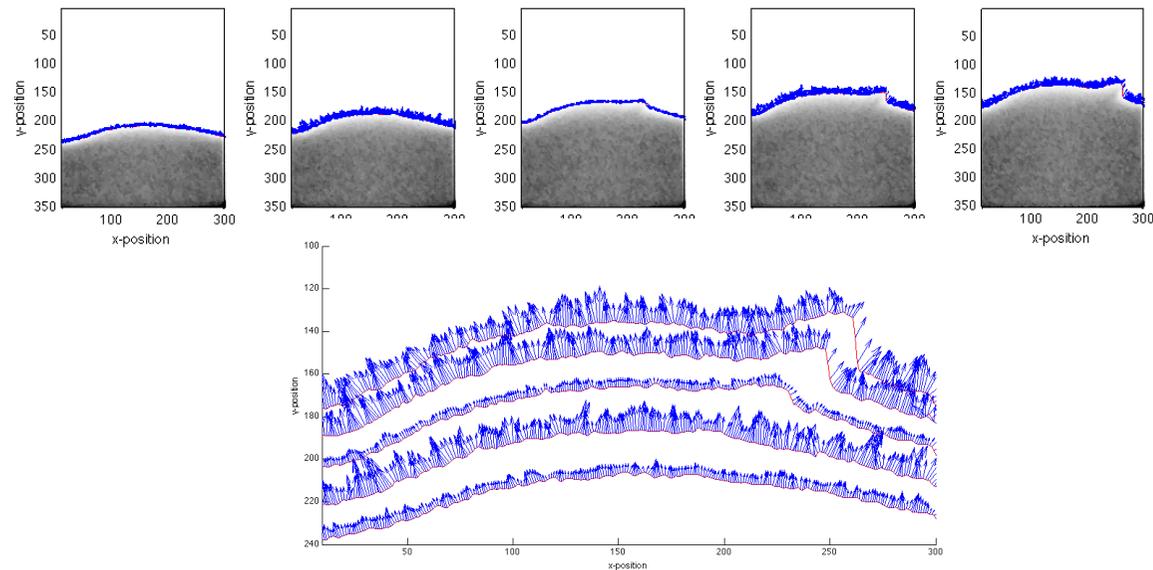
# Quantification
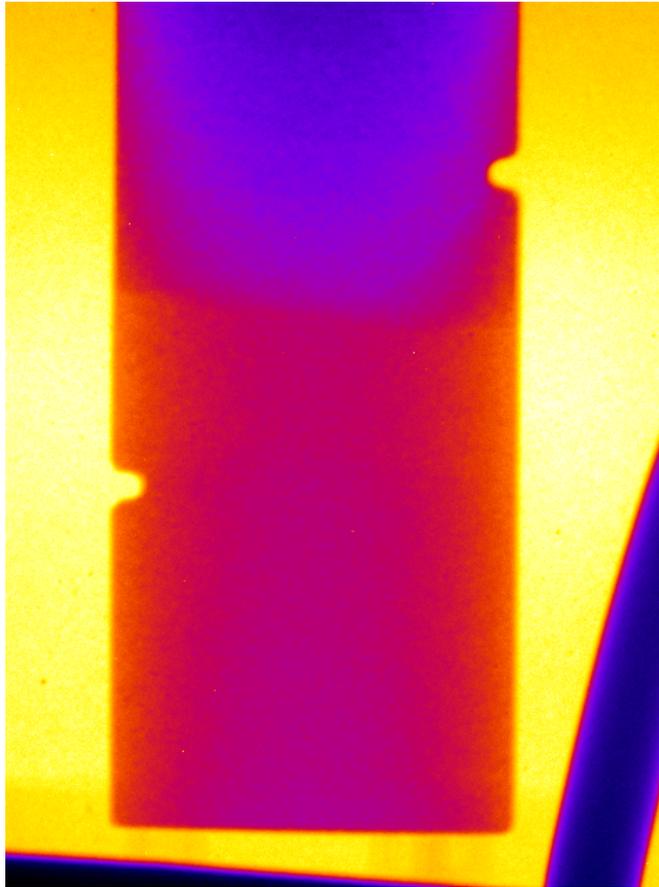
## Flow-fronts

## Flow-velocities

velocity (mm/s)

0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
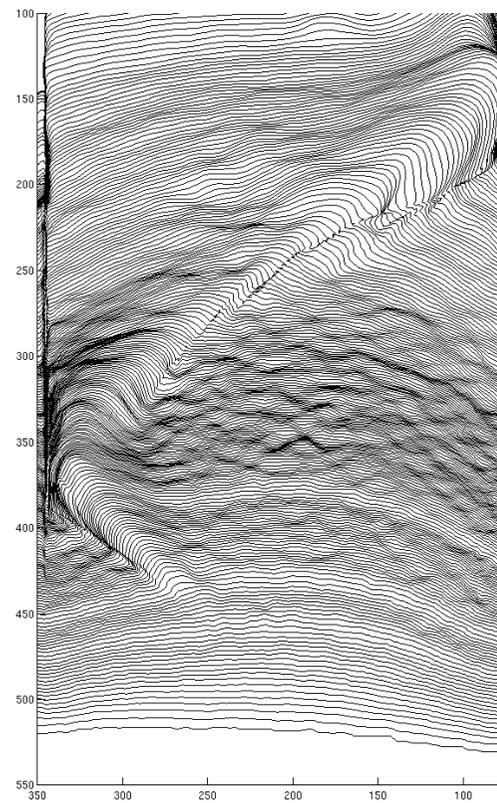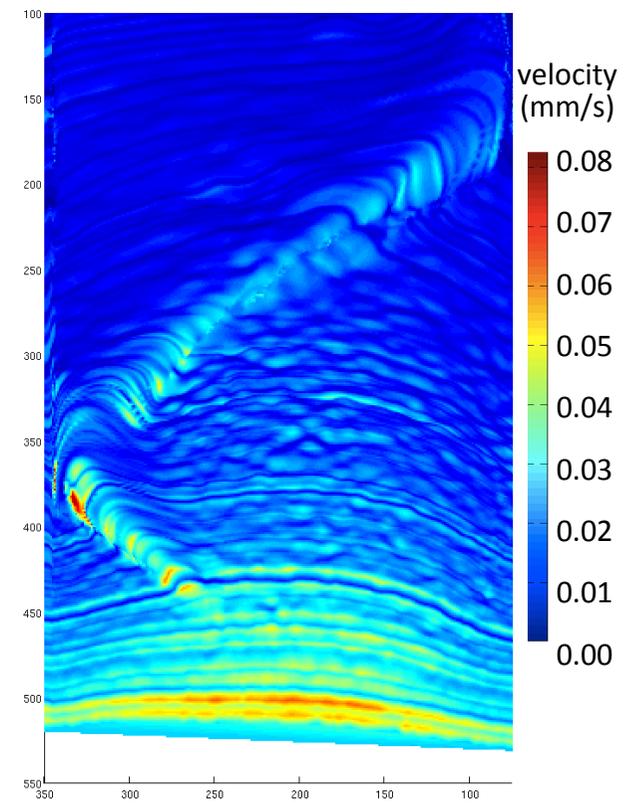
Pixel width = 0.124 mm

# Hydromechanics of geomaterials: neutron imaging (fluid flow)

Imbibition monitoring in 3D (high-speed neutron tomography)
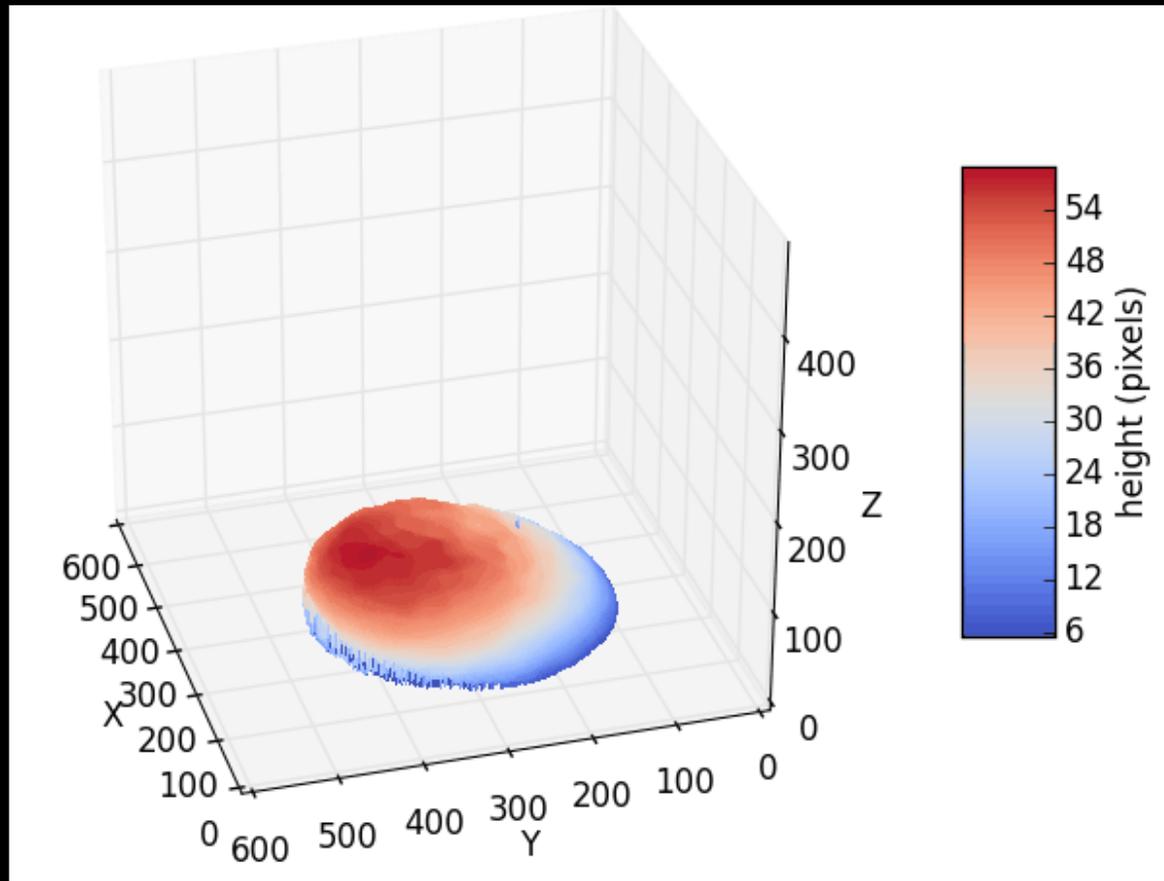


1 minute tomographies @ HZB

*PhD project of Maddi Etxegarai*
*(collaboration with Univ. Grenoble)*

# Dynamic imaging…?

Radiographies with evolution during rotation…



**Fig. 4** Projection of the 3D column of fluid at the first **a** and last **b** angle. The difference between the first and the (mirrored) last images in **c** shows the fluid advance during the scan

Jailin et al., 2018

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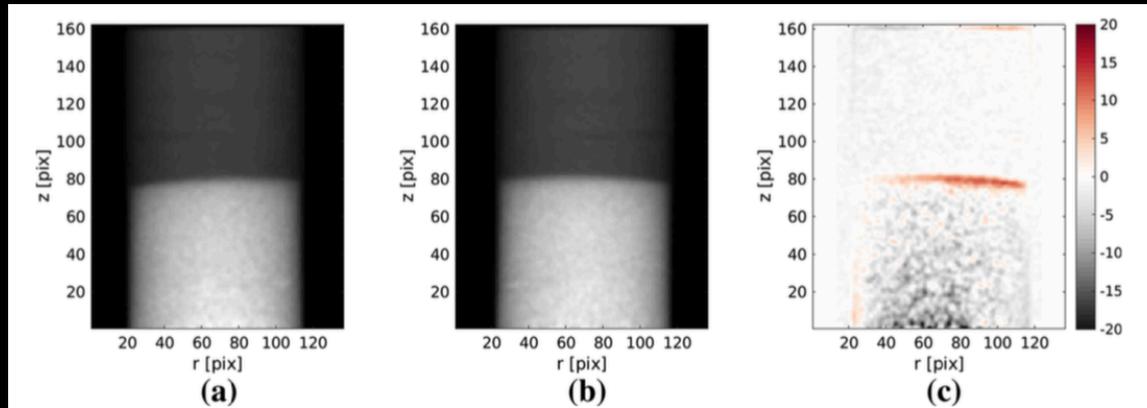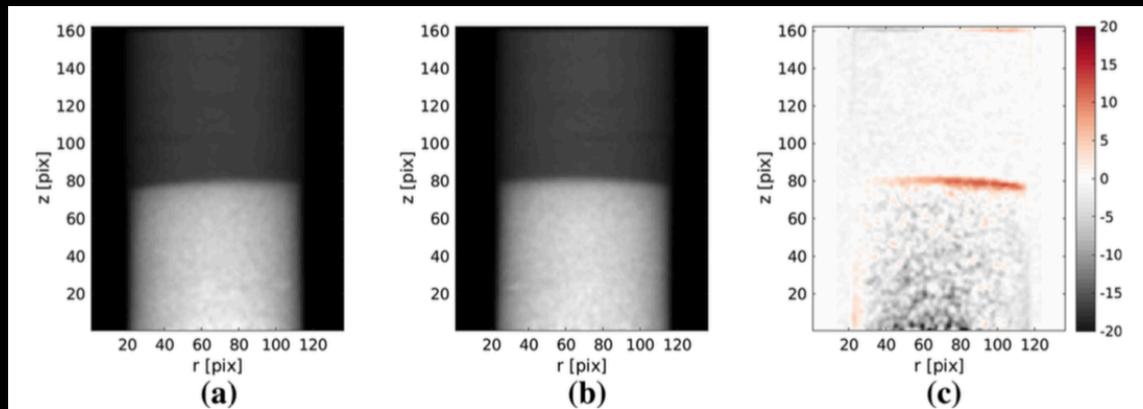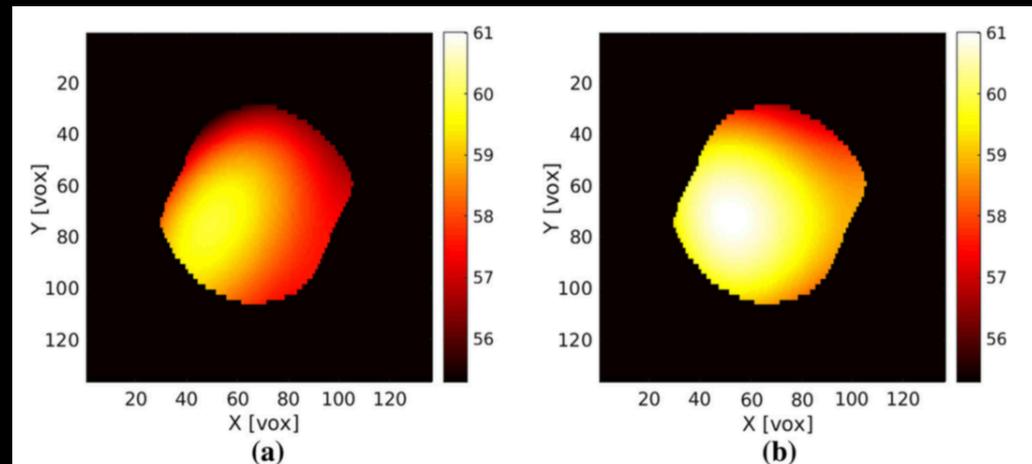
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- Directly to dynamic quantification (skipping reconstruction?)
- Blurring the interface with modelling
- model-based inversion
  - Forward model projection data based on a model of the sample
  - Update model and iterate to convergence



Fig. 9 Evolution of the front at different times of the scan acquisition, in voxels, reconstructed from the three modes for **a** $t = 0$ and **b** 60 s

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Radiographies with evolution during rotation…



Fig. 11 Projections of the sample during the pressure-driven flow test **a** step 7, $\beta = 240°$, **b** step 21, $\beta = 0°$ and **c** step 40, $\beta = 292°$
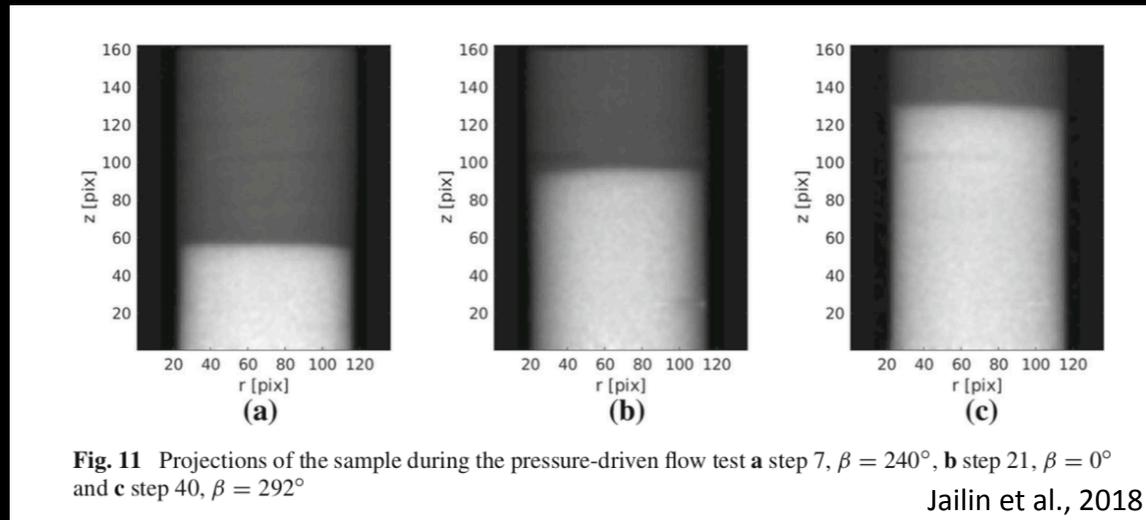
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Even possible with large jumps in position during rotation