SWEDNESS/LINXS Doctoral Course on Neutron Imaging

3D/4D Image analysis

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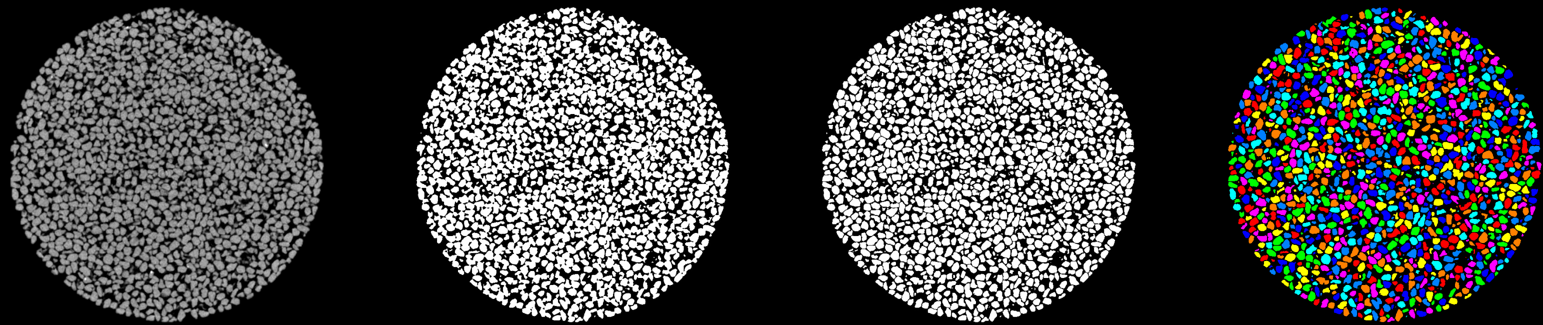


SwedNess

LUND INSTITUTE OF ADVANCED NEUTRON AND X-RAY SCIENCE

Not just pretty images…

… very pretty… but so what!

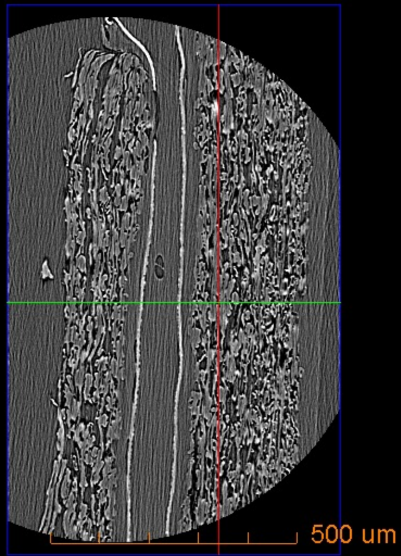
<u>Challenge</u>: *to extract pertinent, quantified information to elucidate properties*

4D IMAGING LAB
A Lund university Infrastructure

TetraPak recart - chopped tomato carton

(x-ray tomography image)

XY
488 / 975
C 22475 W 13023



YZ
392 / 616
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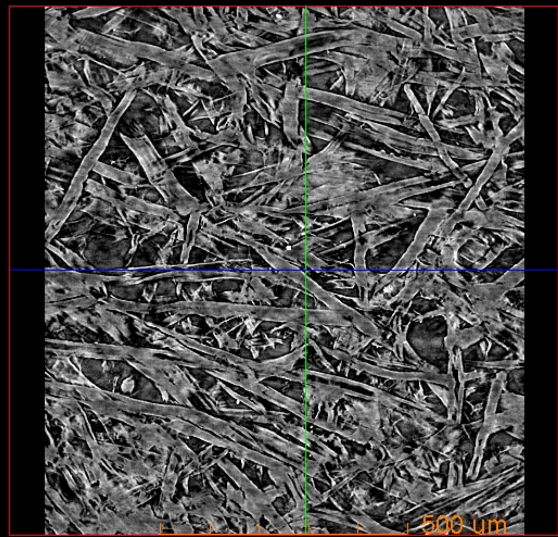

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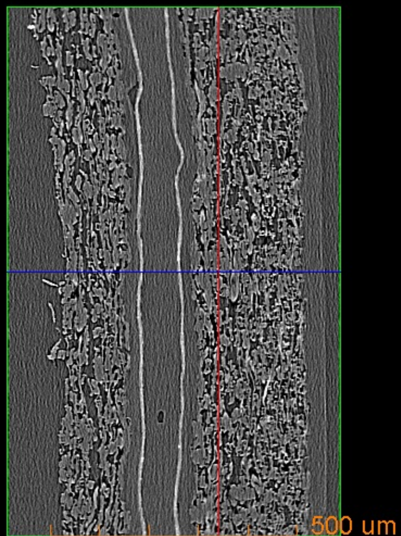
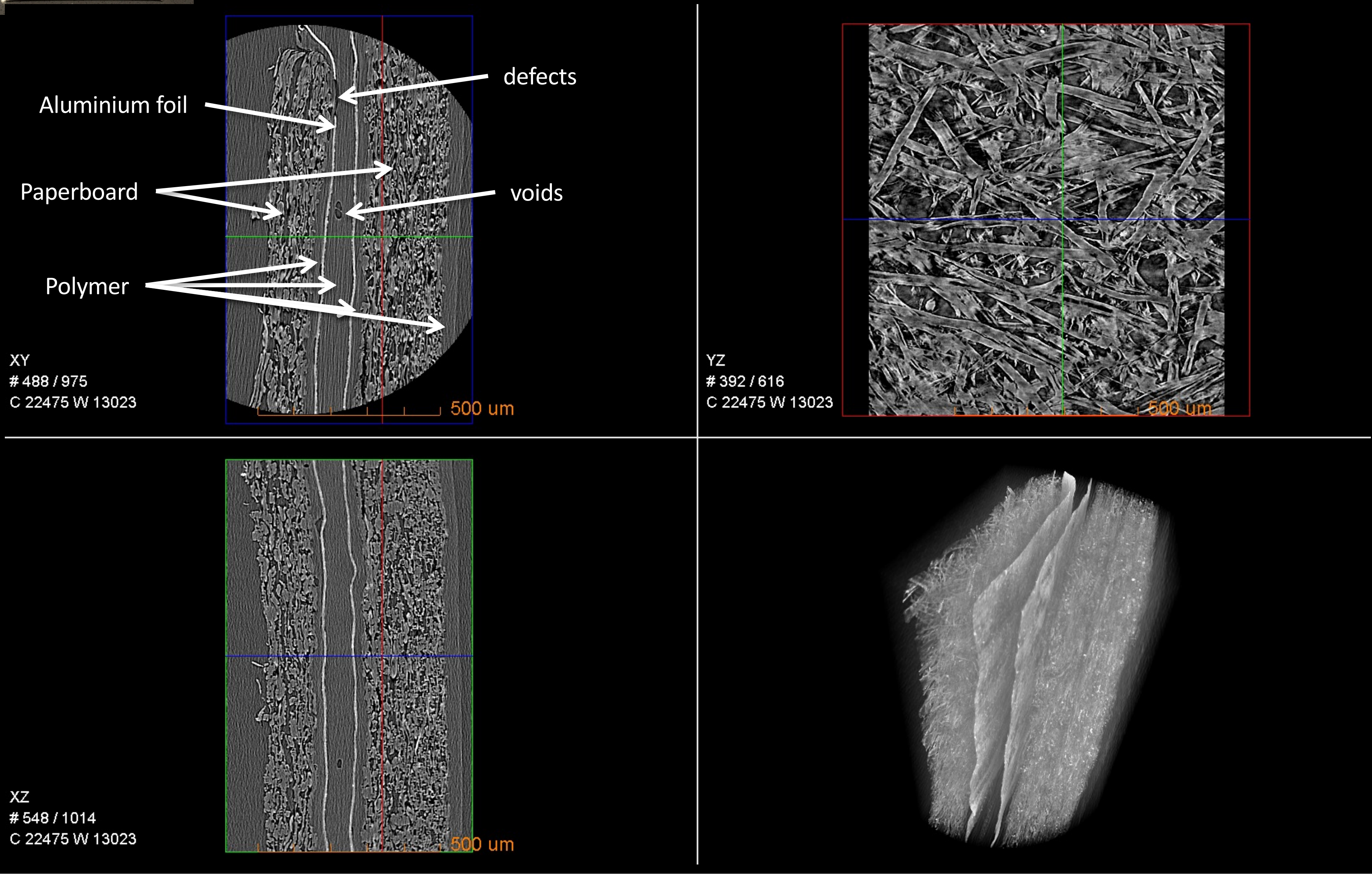


TetraPak recart - chopped tomato carton

(x-ray tomography image)



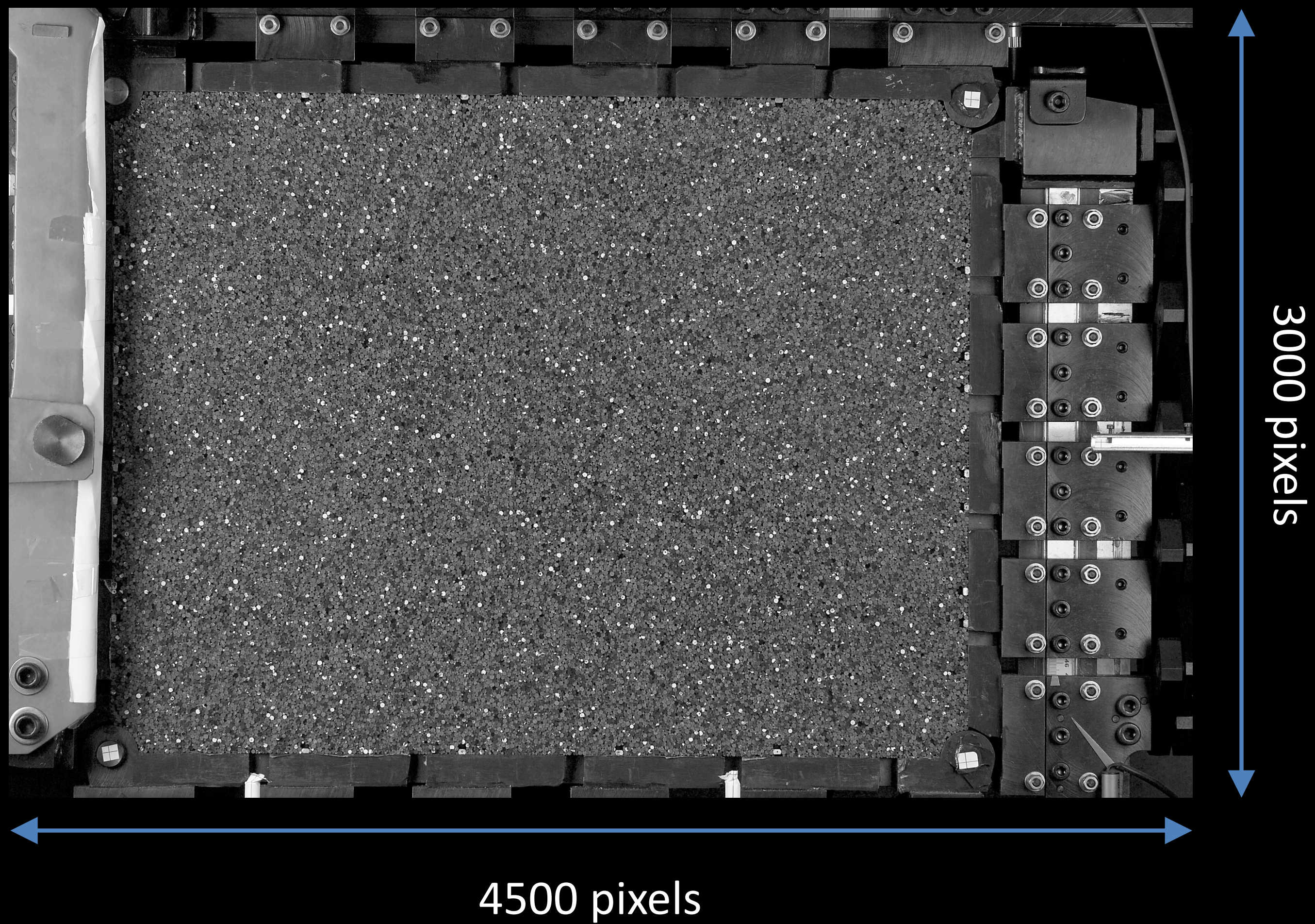
A word of warning…

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

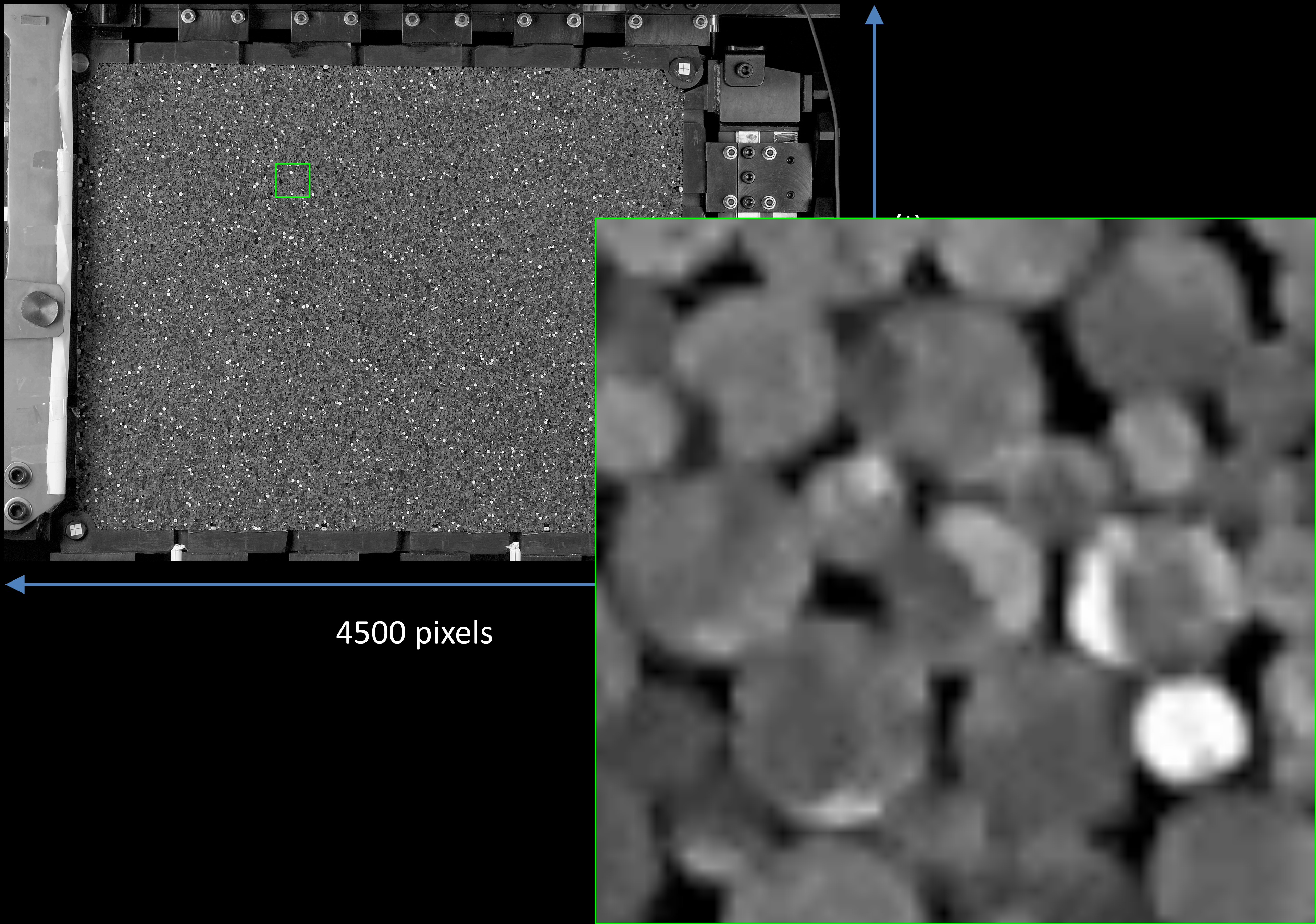
…Images are just representations of reality…

…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



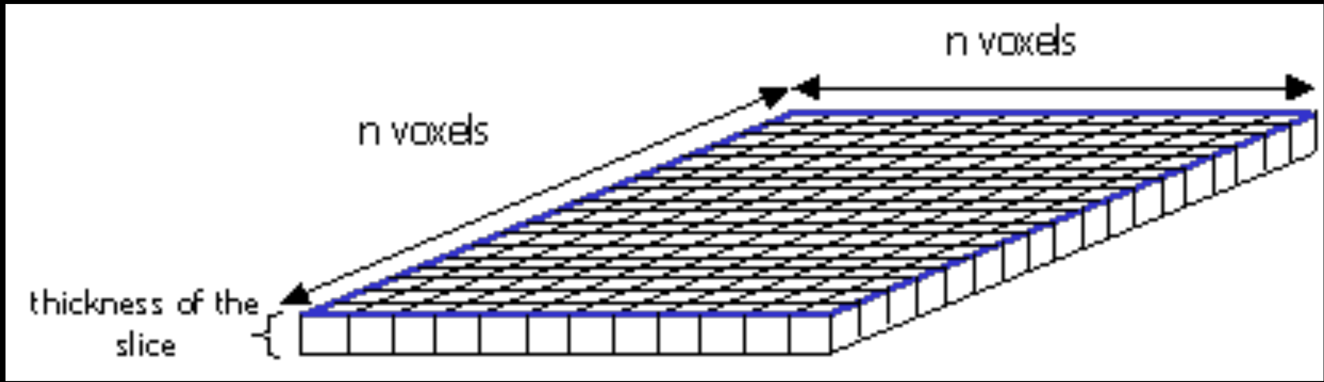
2D digital data



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

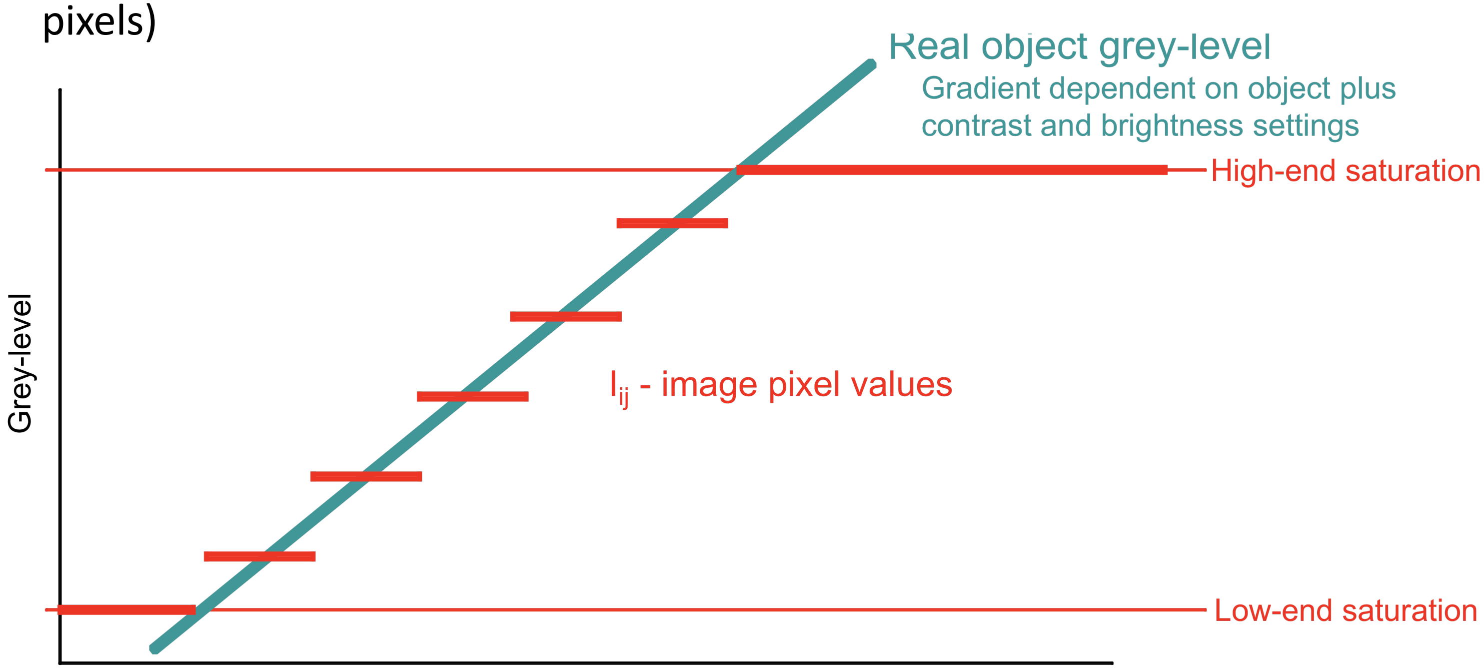
The size of the pixel/voxel is the **image “discretisation”**…

… 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 $\geq$ 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)



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)

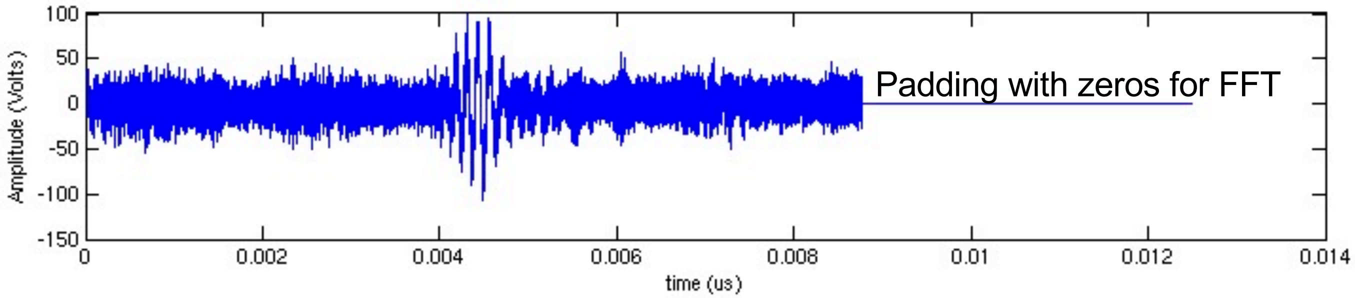
- Input to numerical simulation

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

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

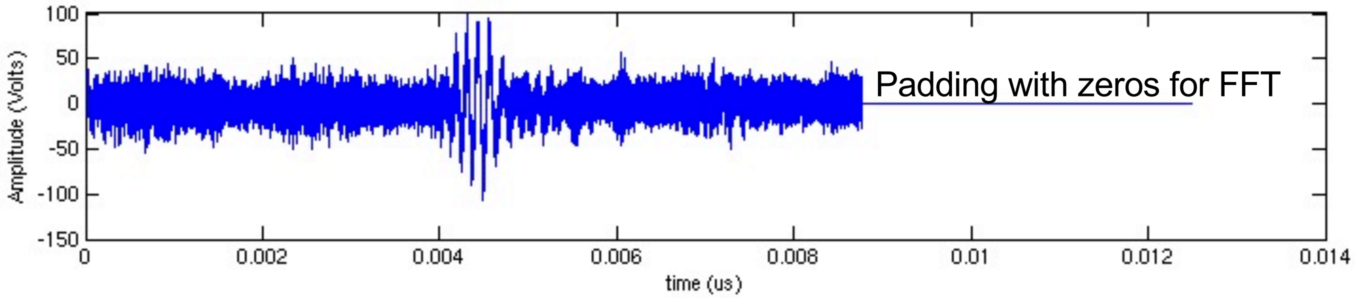
Filtering - example (ultrasonic data acquired across a sample of clay)

Original data

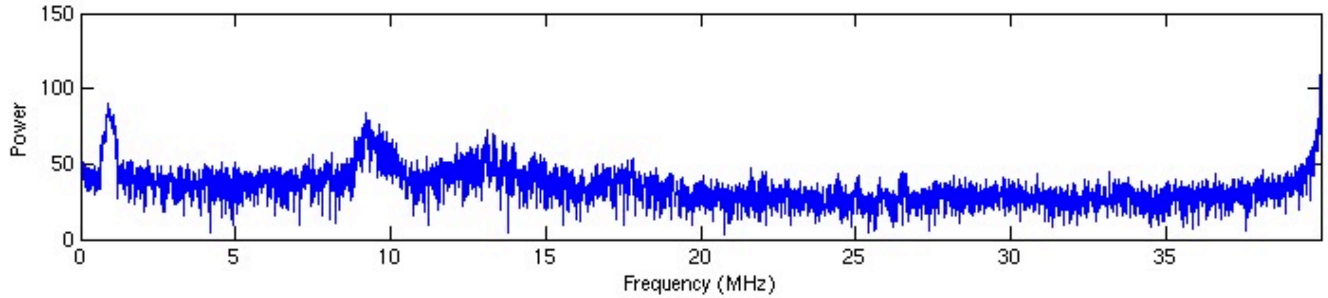


Filtering - example (ultrasonic data acquired across a sample of clay)

Original data



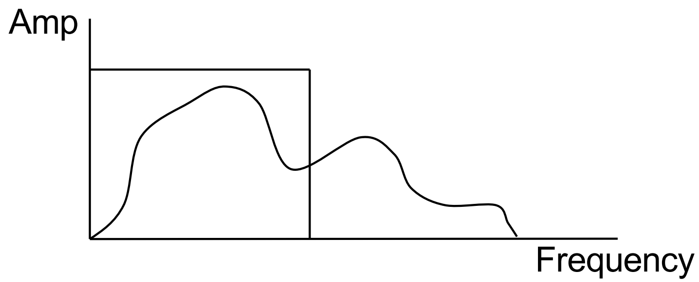
Amplitude spectrum of original data determined by fast fourier transform (FFT)



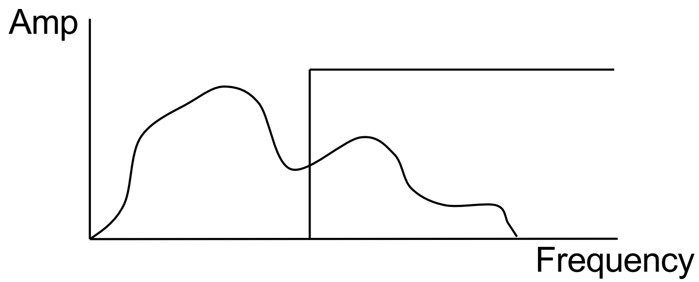
Filtering

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

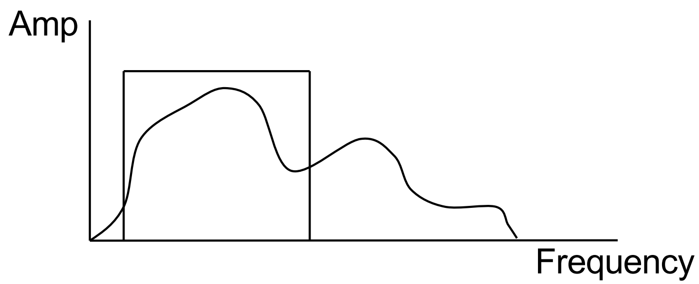
Low pass



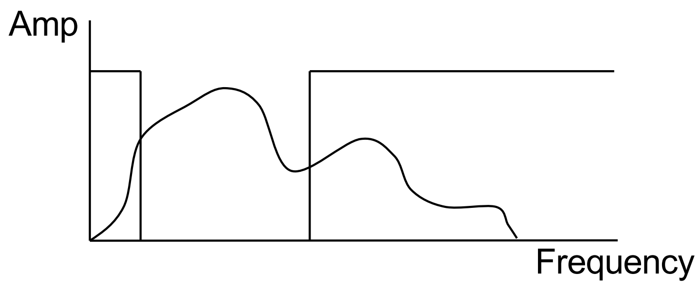
High Pass



Band Pass



Notch Pass



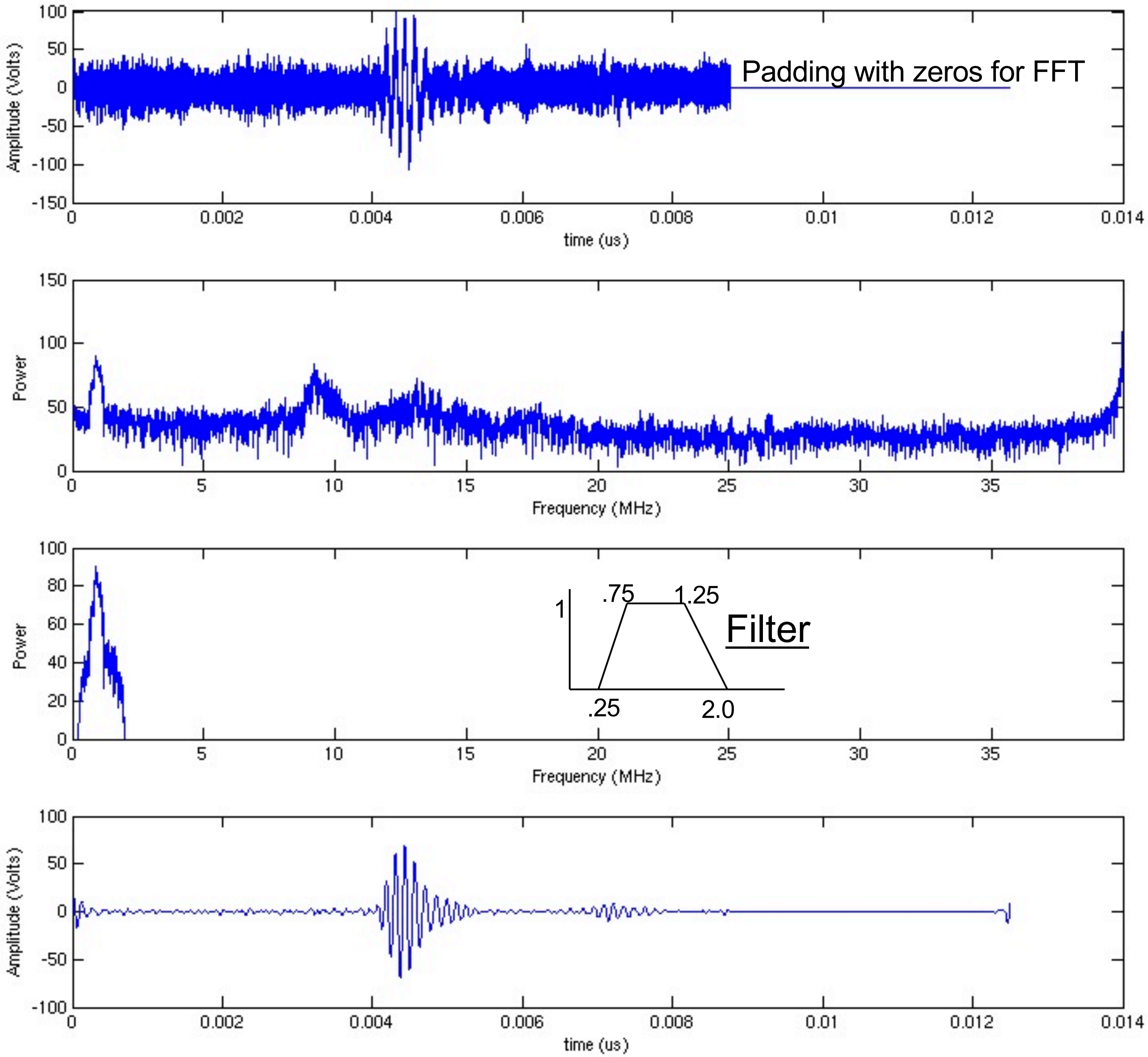
Filtering - example (ultrasonic data acquired across a sample of clay)

Original data

Amplitude spectrum of original data

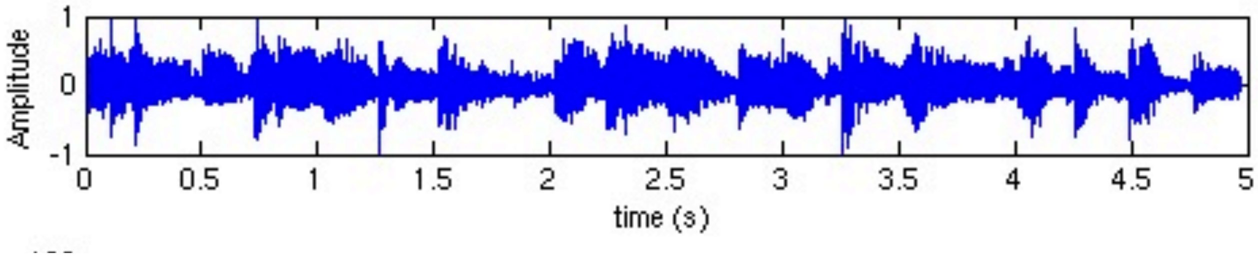
Filtered amplitude spectrum

Filtered data
(inverse transformed)



Filtering - example (Skatalites)

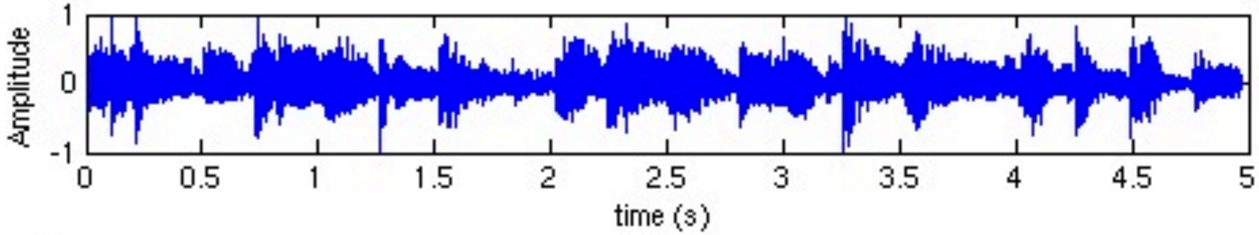
Original data



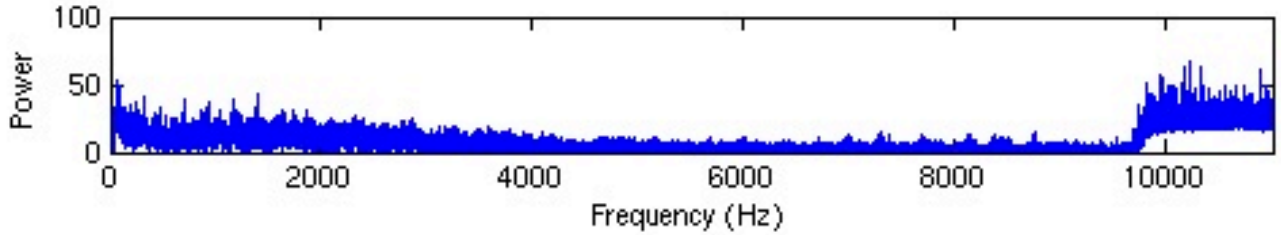
Filtering - example (Skatalites)

Low pass filter

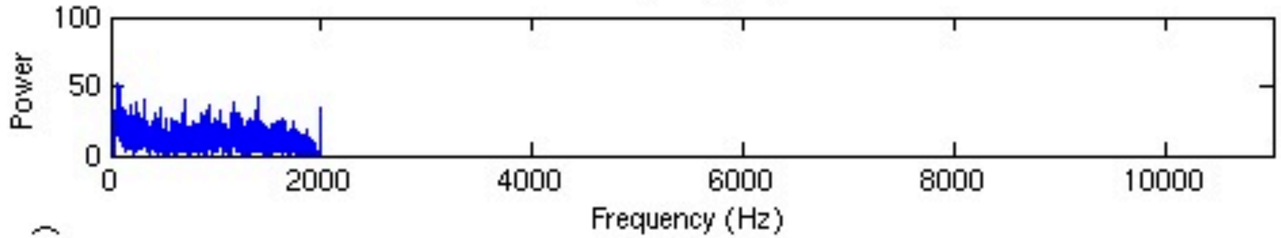
Original data



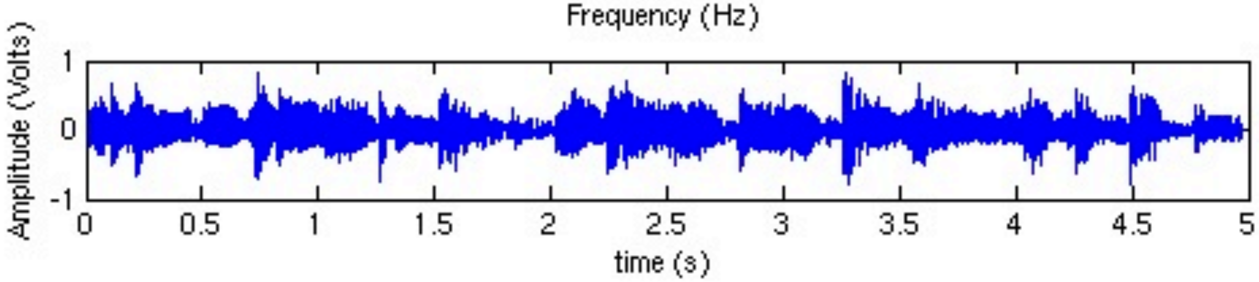
Amplitude spectrum of original data



Filtered amplitude spectrum



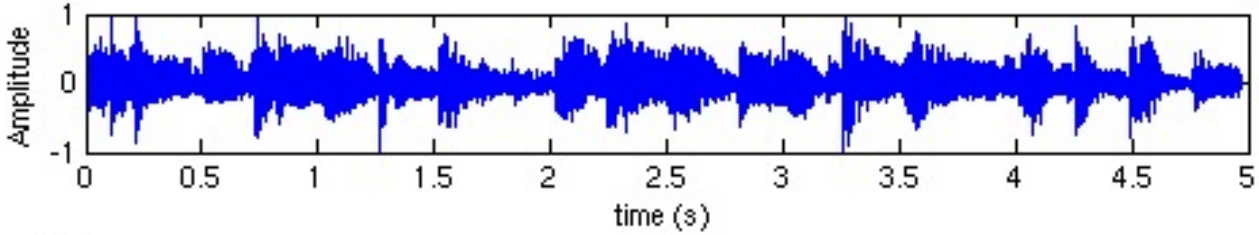
Filtered data
(inverse transformed)



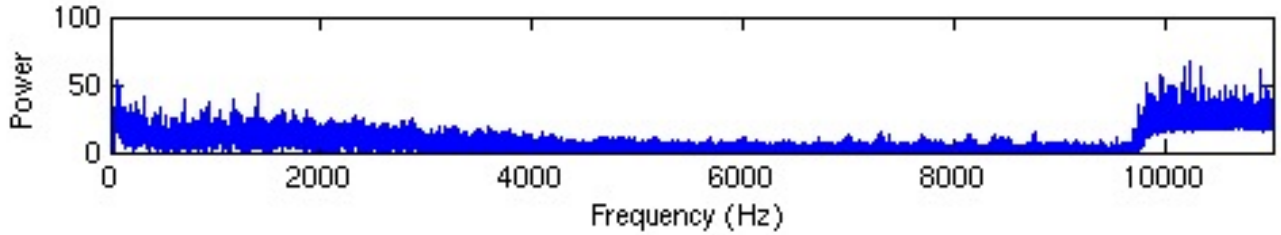
Filtering - example (Skatalites)

High pass filter

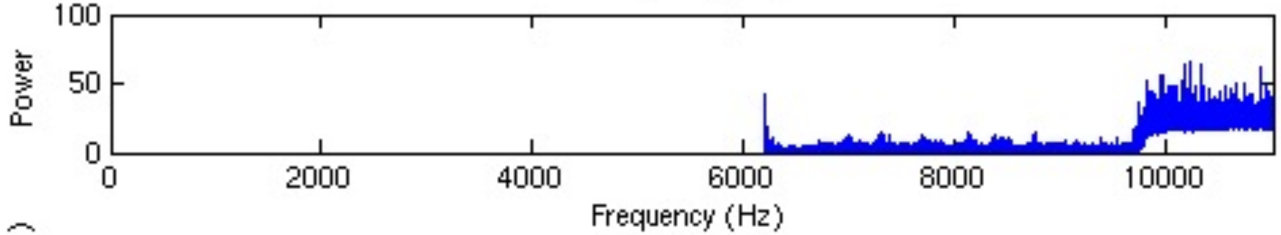
Original data



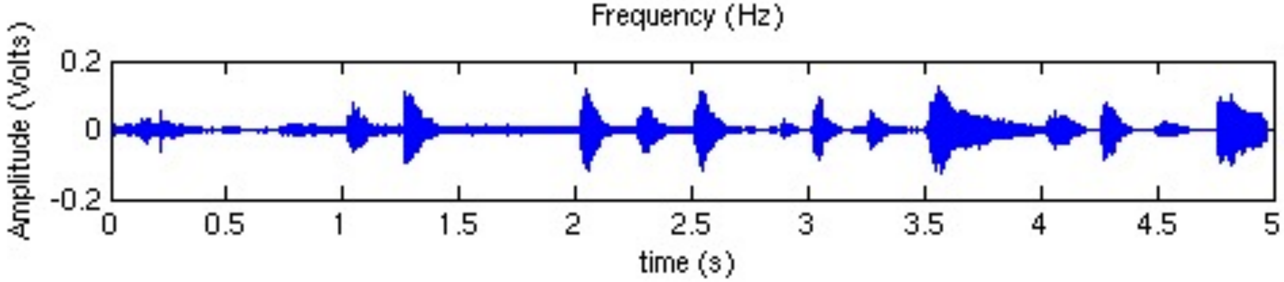
Amplitude spectrum of original data



Filtered amplitude spectrum



Filtered data
(inverse transformed)



Filtering - example (Skatalites)

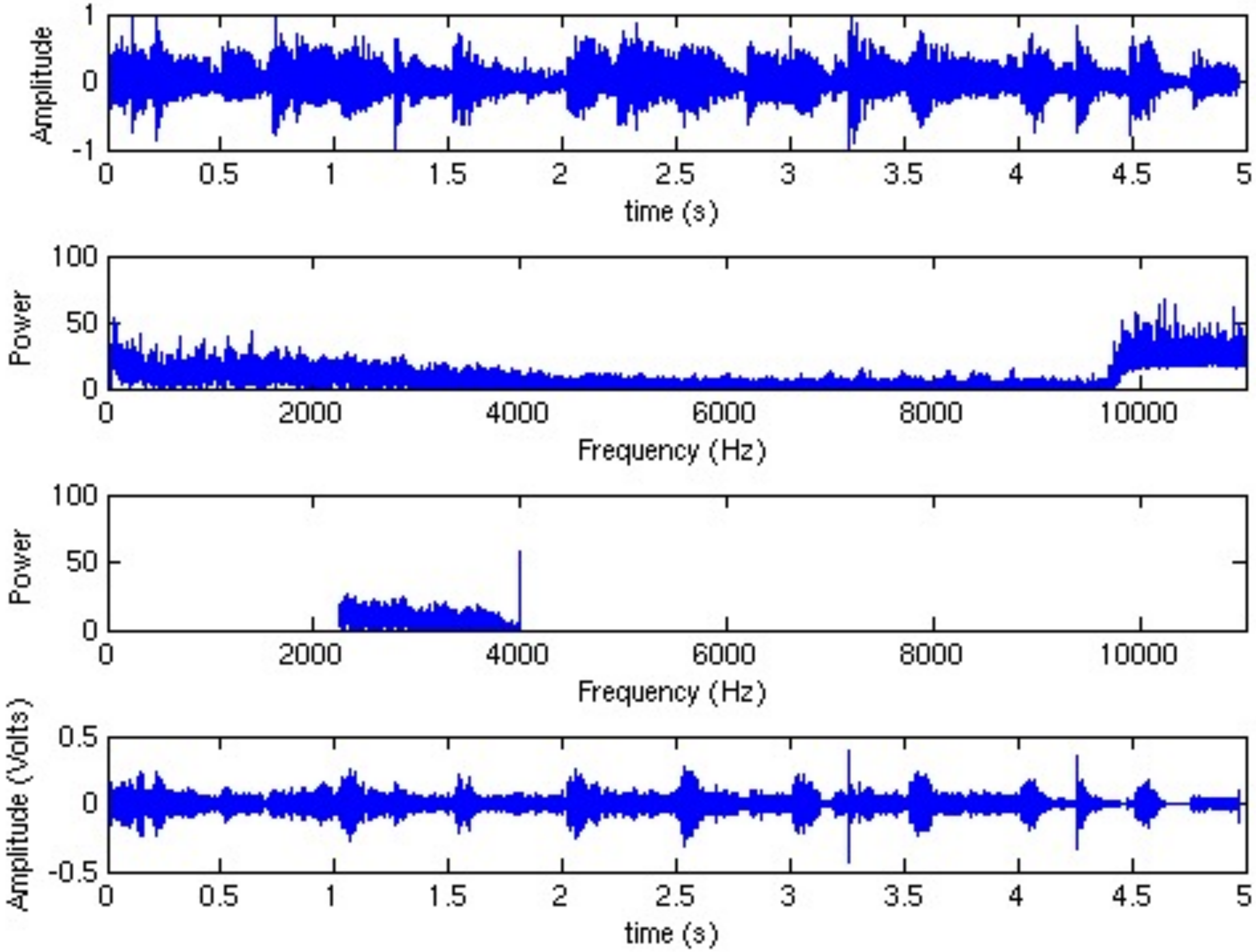
Band pass filter

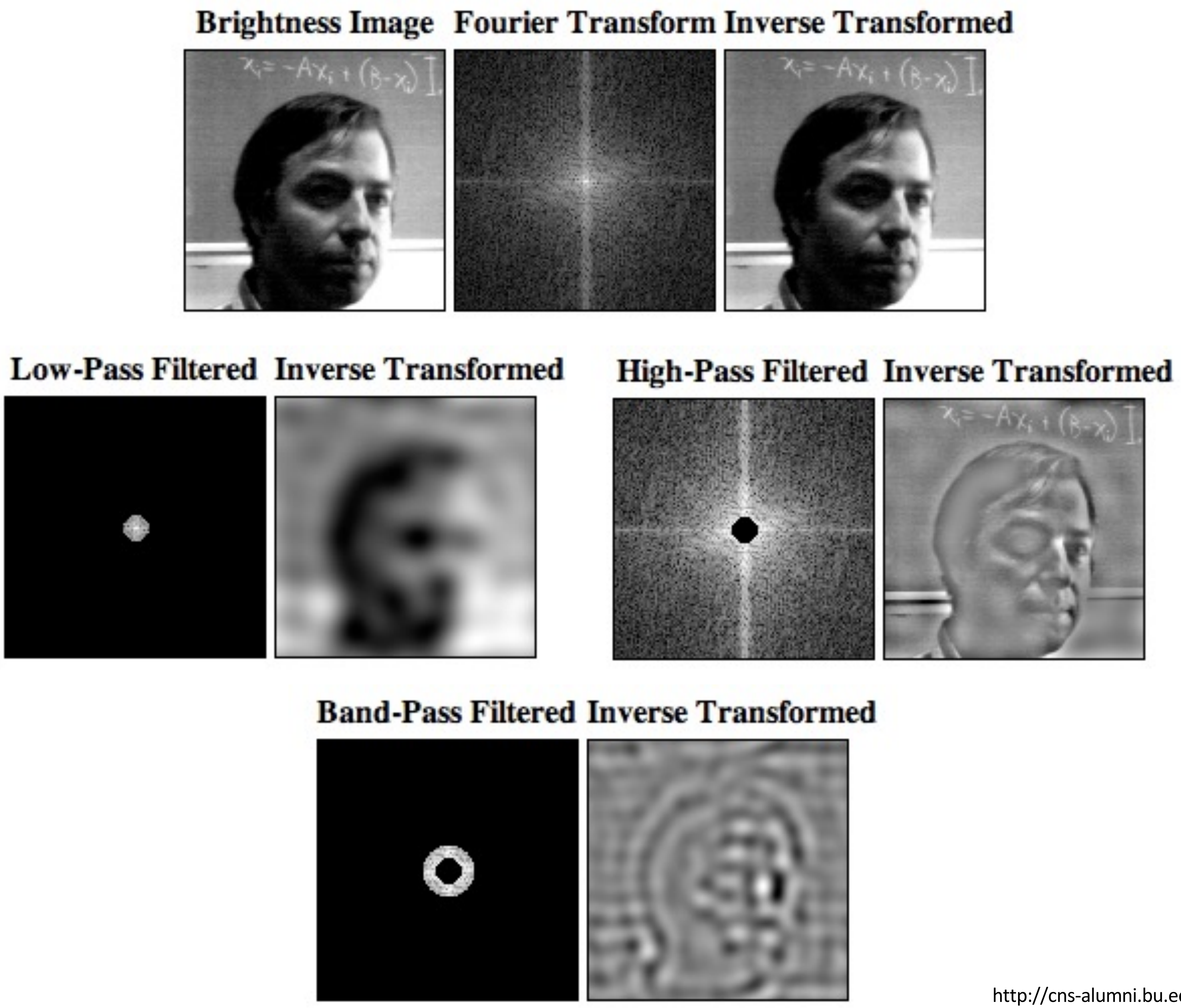
Original data

Amplitude spectrum of original data

Filtered amplitude spectrum

Filtered data
(inverse transformed)





http://cns-alumni.bu.edu/~slehar/

Spatial domain operations

Spatial domain operations

Window operations

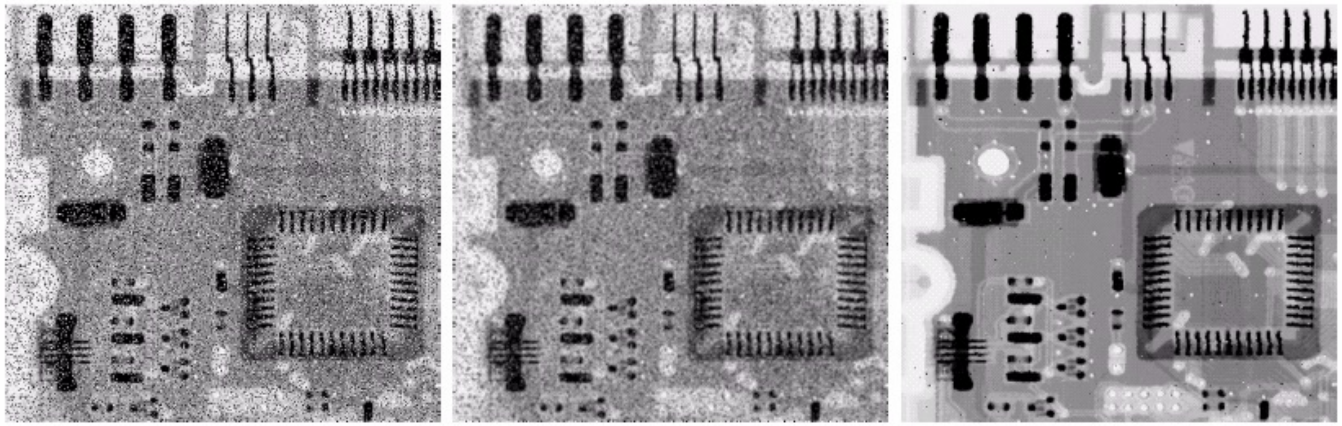
Differerent values/statistics can be determined over windows in the data

- 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



a b c

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.)

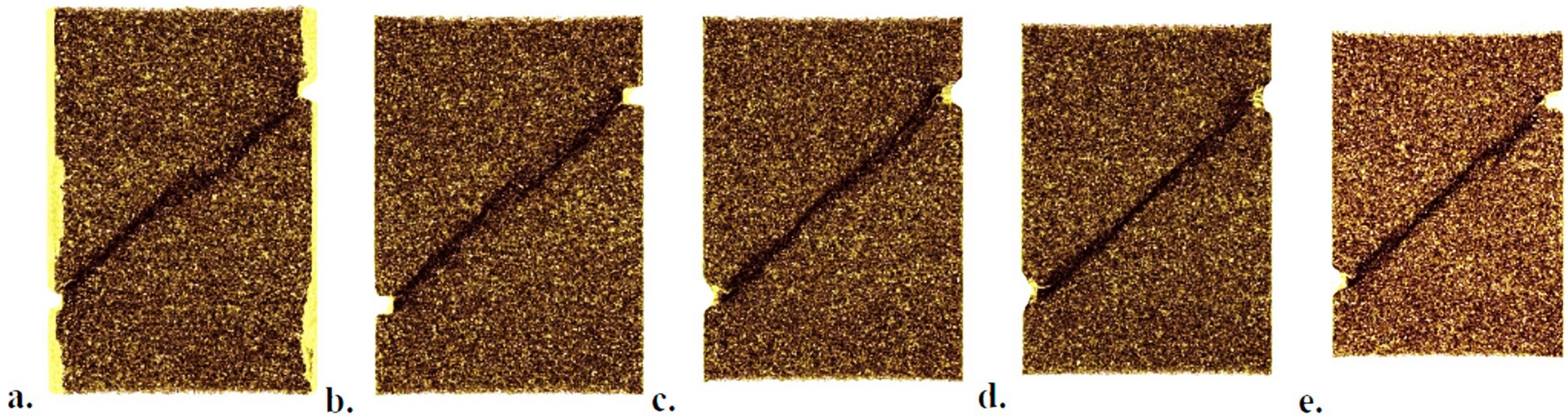
From Y. Wang - eeweb.poly.edu/~yao/EE3414/image_filtering.pdf

- 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

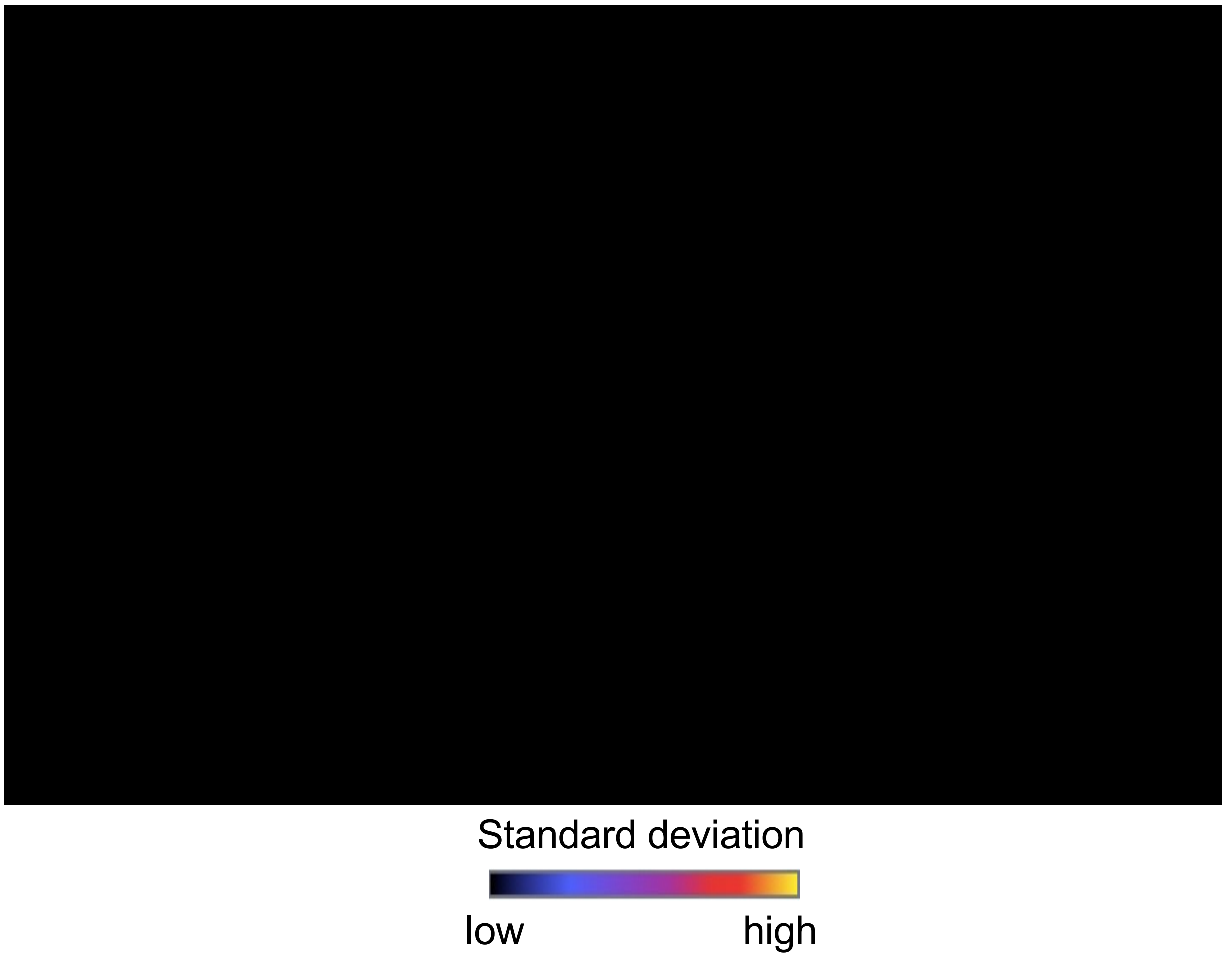


- Localised deformation appears as higher density zones
  (dark = higher density)
- Two bands meeting in middle of sample

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



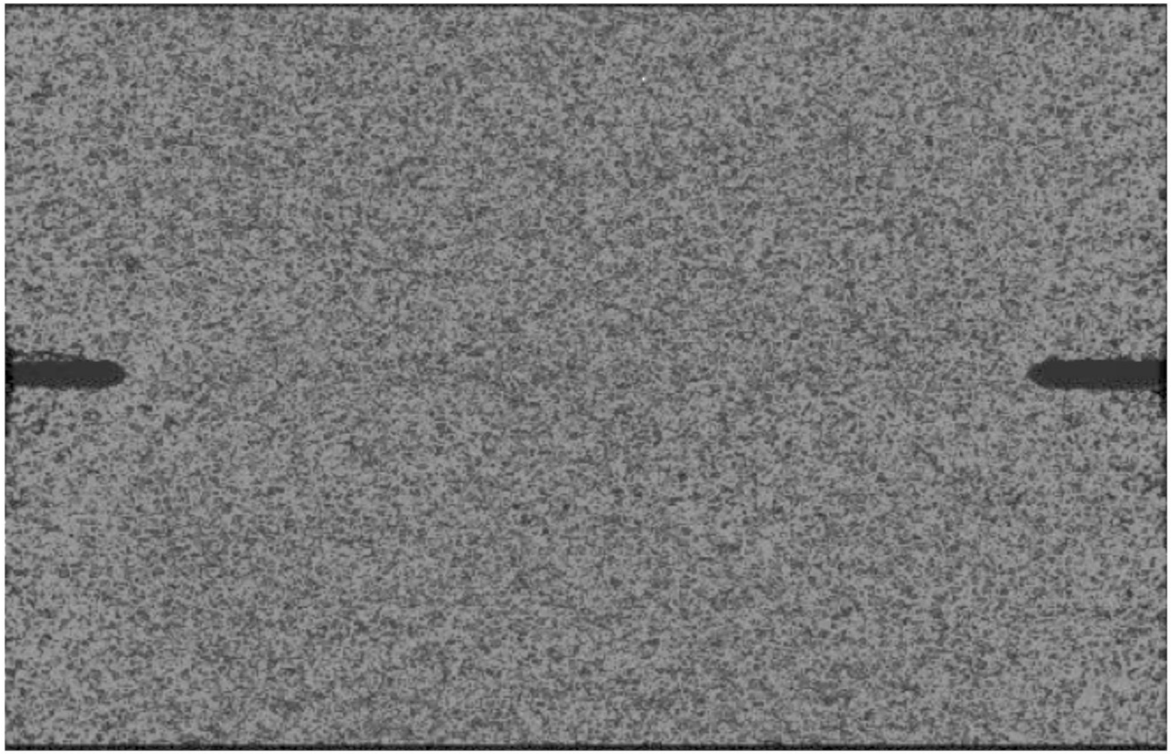
Localised deformation appears as lower standard deviation

- 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

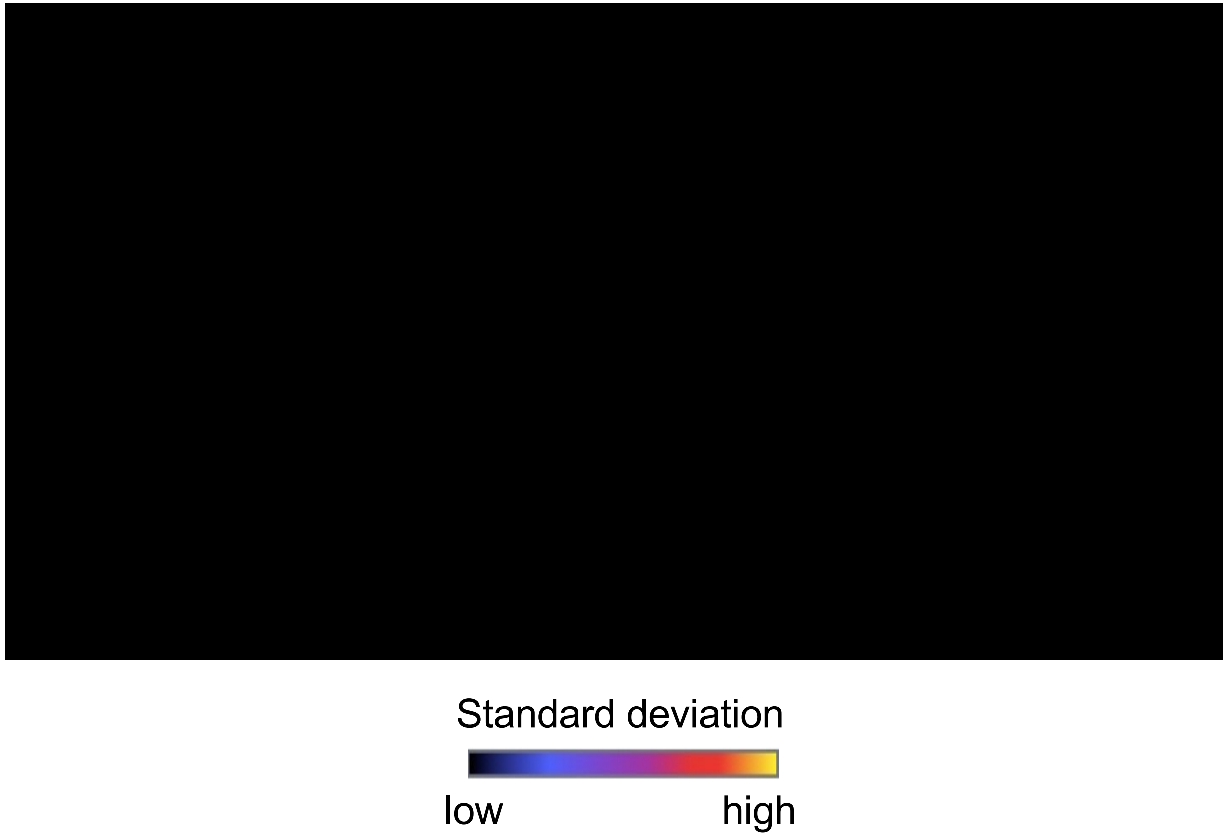


- No evidence (to the naked eye) of localised deformation

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

Local standard deviation analysis:

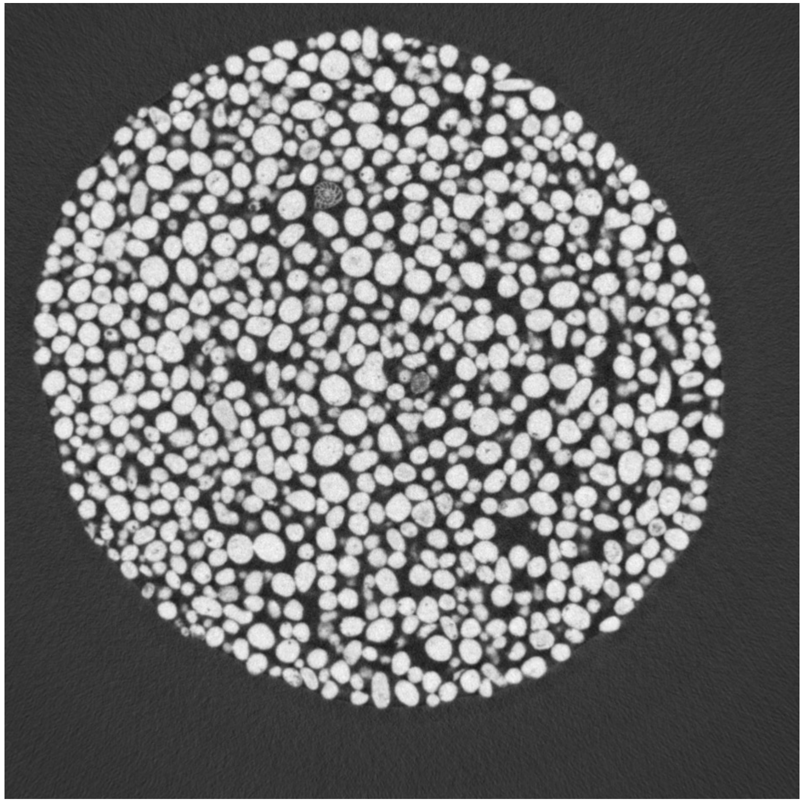
- **VE6** (130 MPa conf. pres.)
- High resolution scans ~30 μm voxel size

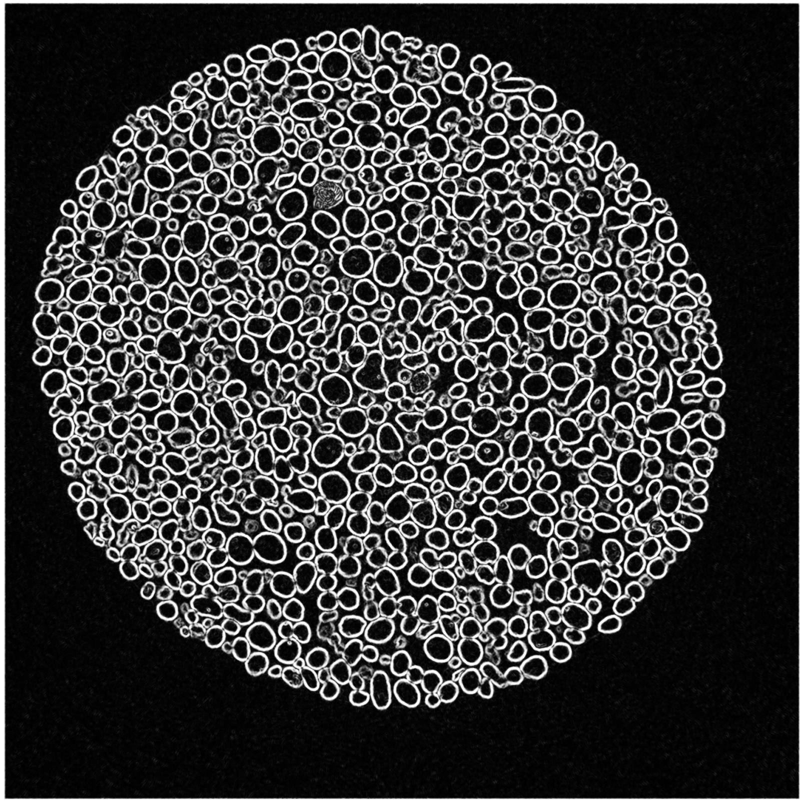


- localised deformation revealed

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

Example: Local image gradient

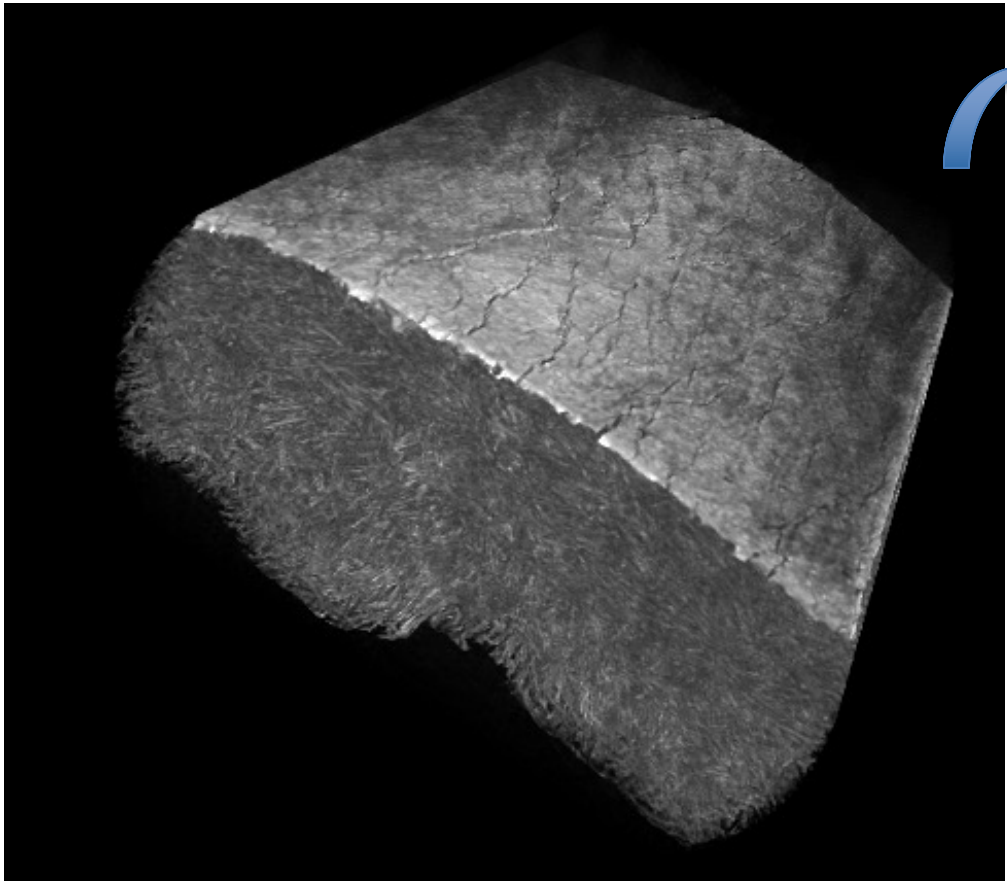




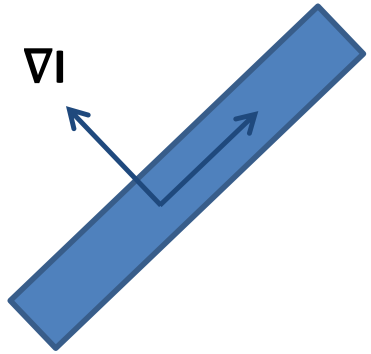
Images from E. Andò

Example: Local image gradient → orientation

3D imaging of folded paper board



Quantification of fabrics

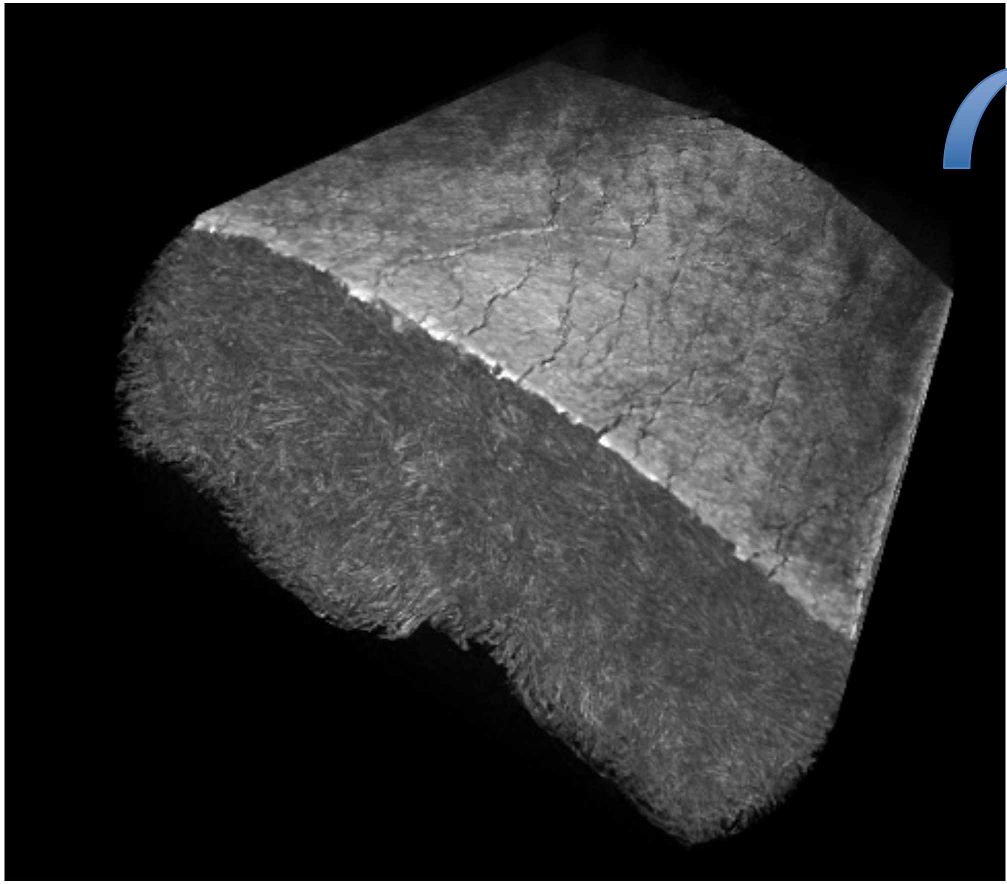


- Least variation of intensity along fibers
- Direction of smallest directional derivative
- Perpendicular to the gradient in 2D
- Can be found with the structure tensor or Hessian in 3D

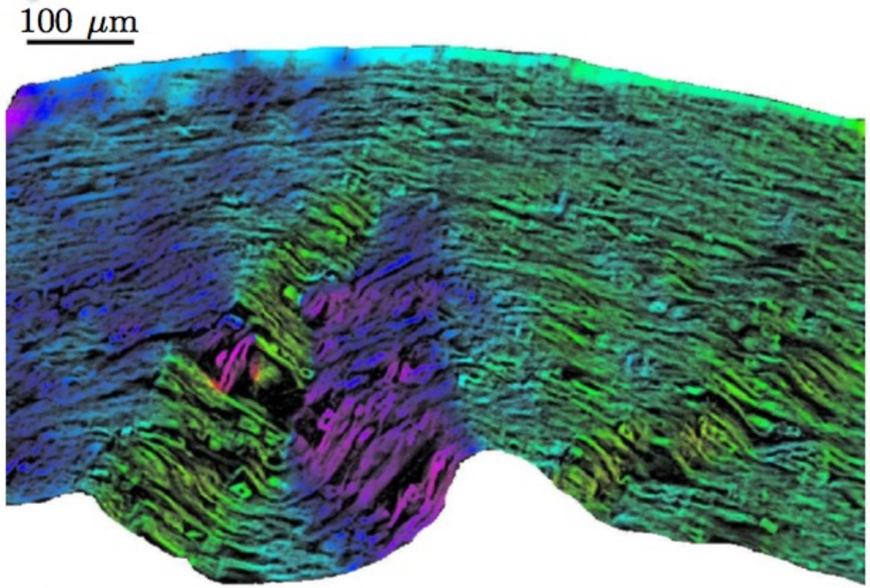
PhD project E. Borgqvist, Solid Mechanics, LTH
In collaboration with TetraPak

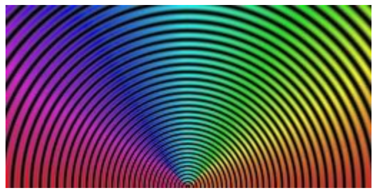
Example: Local image gradient → orientation

3D imaging of folded paper board



Quantification of fabrics





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

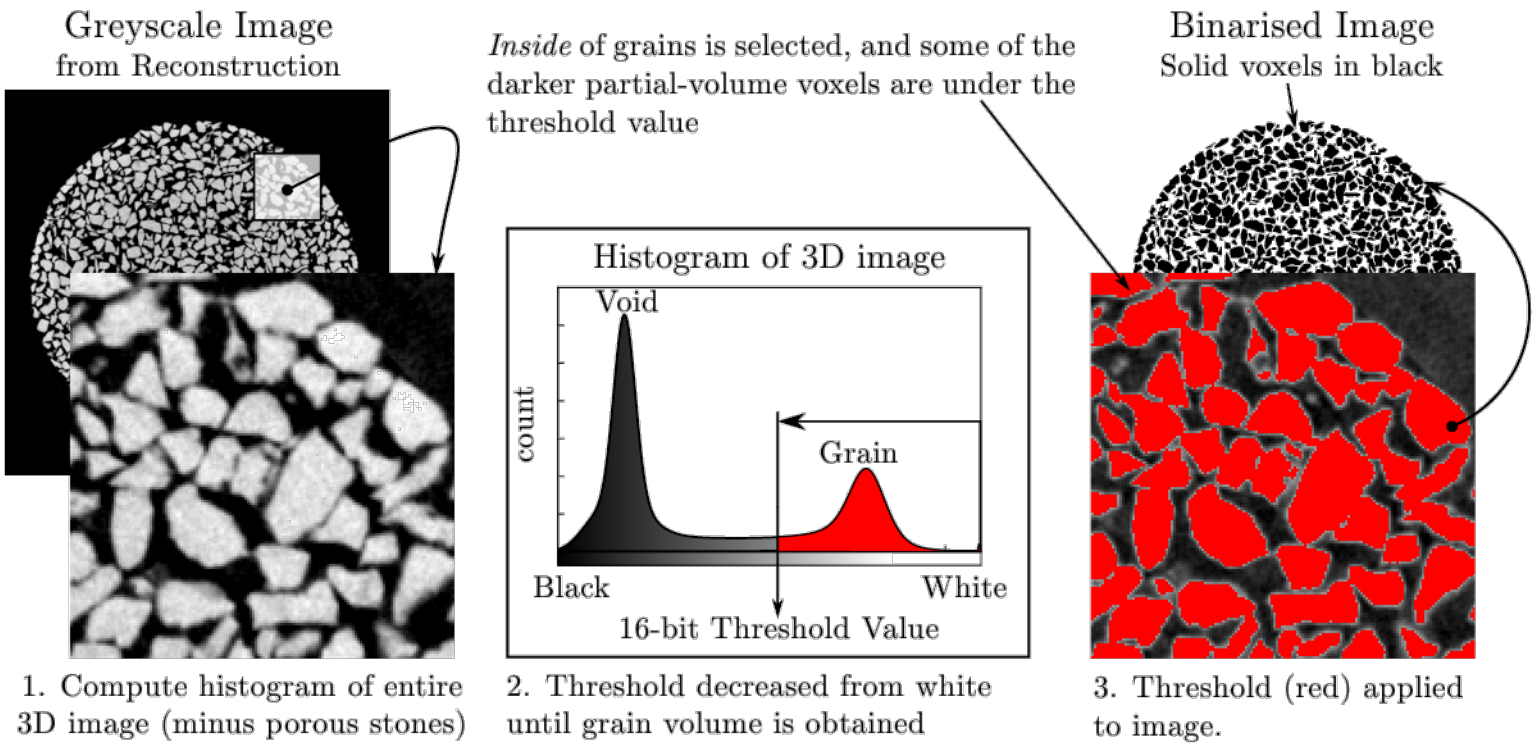
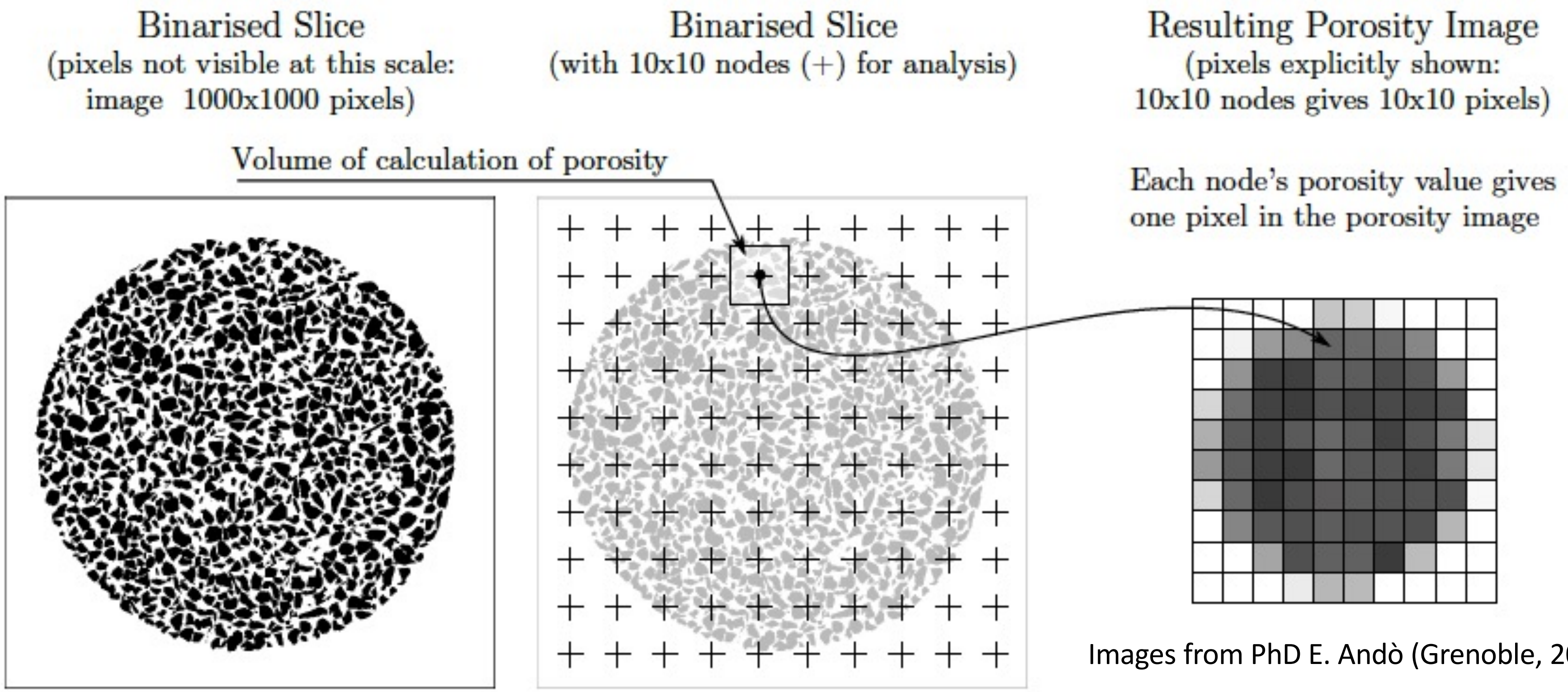


Figure 4.2: Illustration of the application and calculation of a threshold value to a slice from test HNEA03. The voxels selected by the threshold (in red) show that the darker partial volume voxels on the outsides of the grains lie below the threshold and are thus not selected.

Image from PhD E. Andò (Grenoble, 2013)

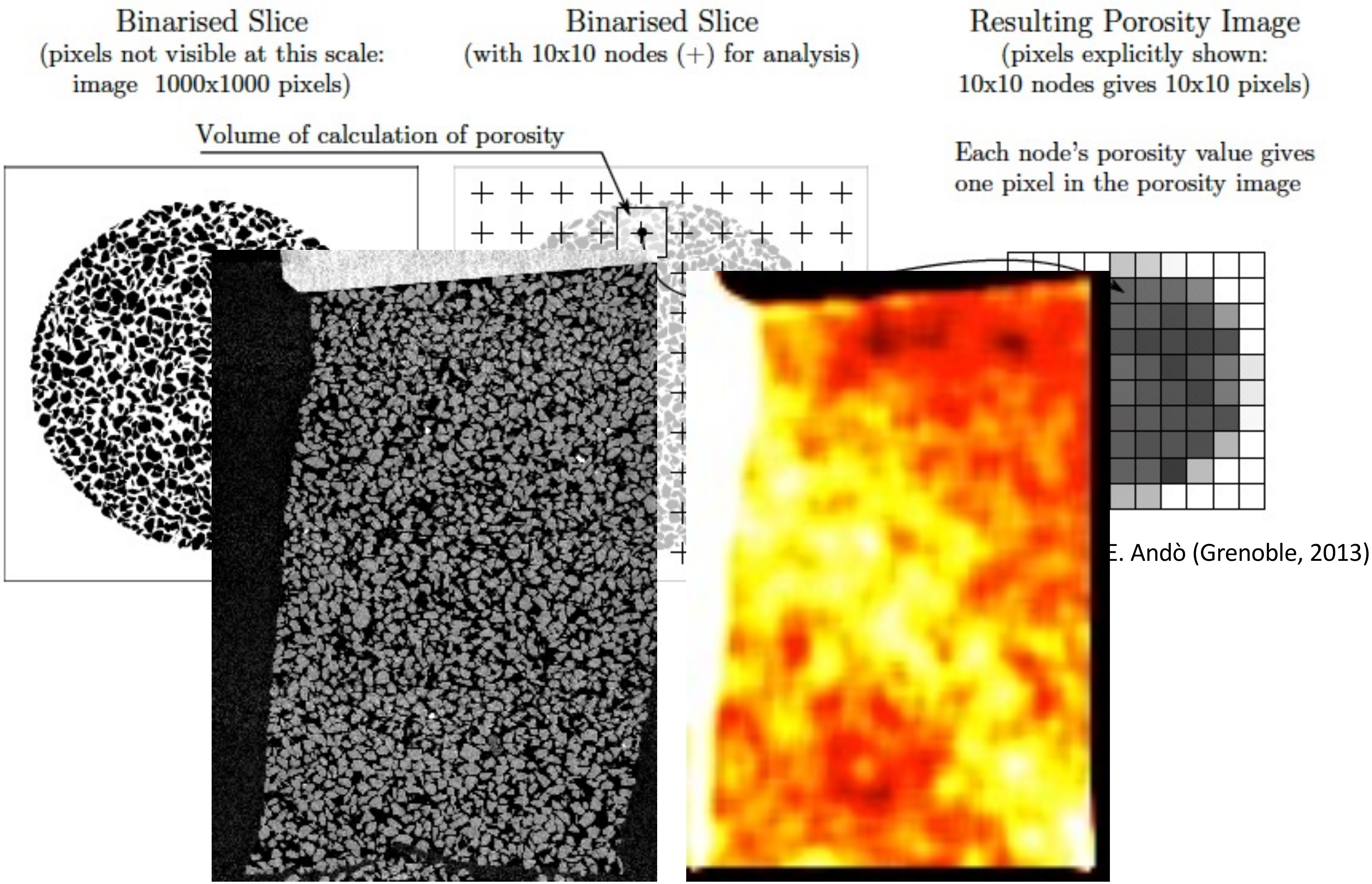
Can be extended to multiple phases, e.g., trinarisation of grain, water and air in images of partially saturated sand

Porosity



Images from PhD E. Andò (Grenoble, 2013)

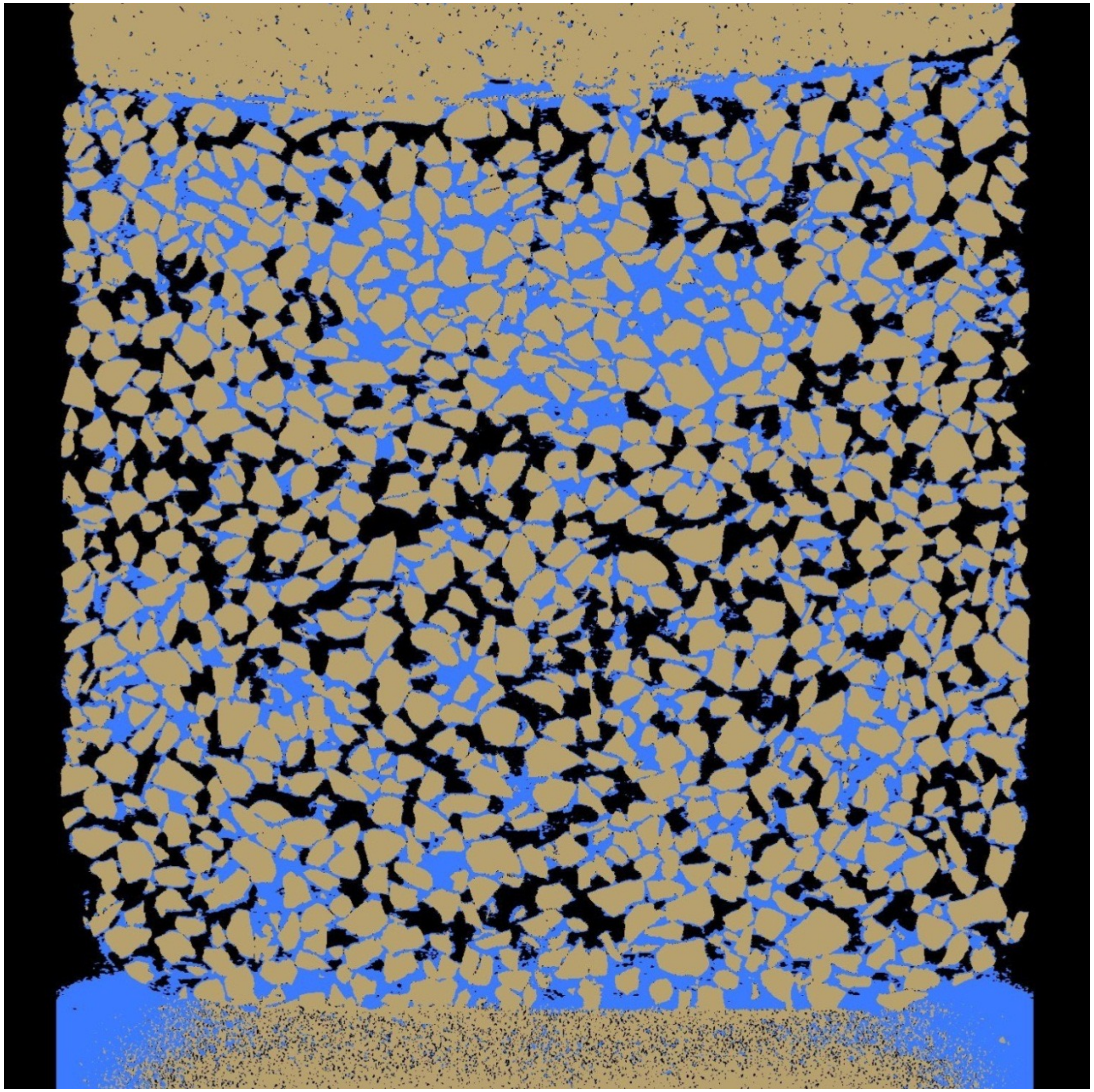
Porosity



Tomo

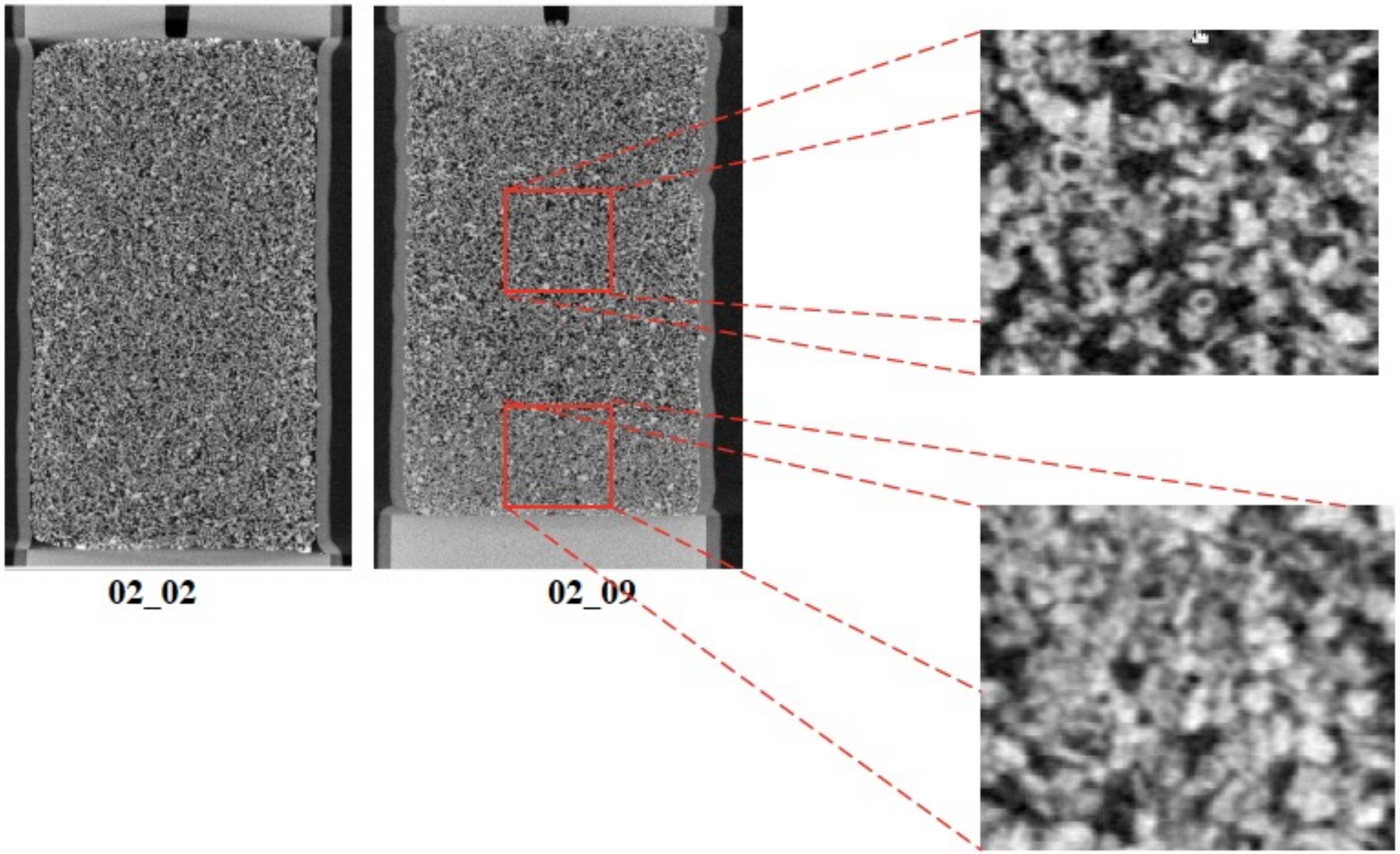
Porosity

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

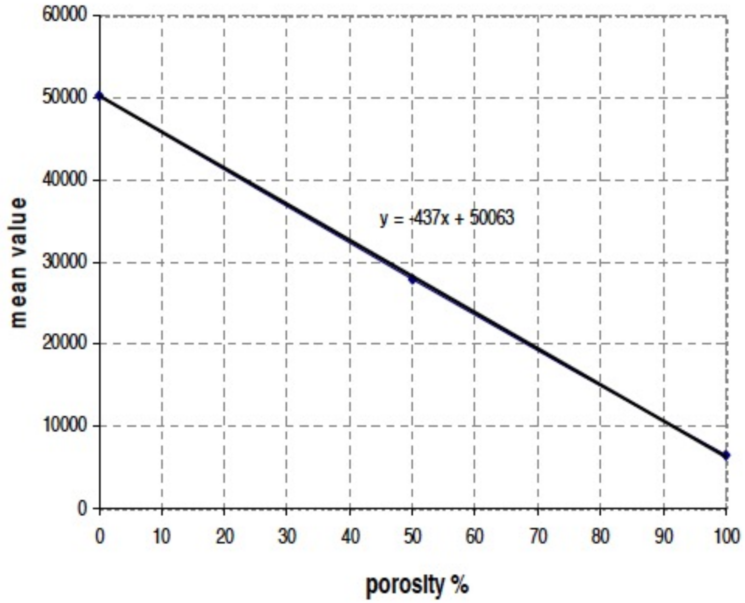


Tuffeau de Maastricht

Image from MSc A. Moldovan (Grenoble, 2010)

Porosity - grey-scale

Tuffeau de Maastricht



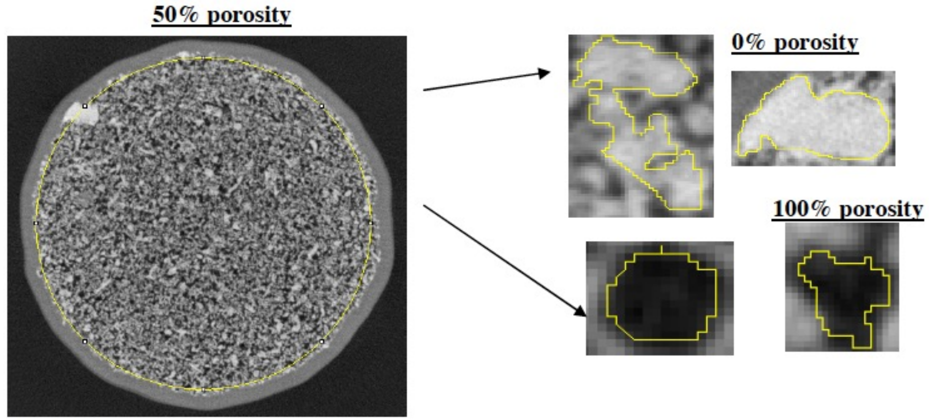
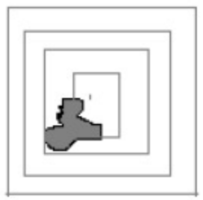


Fig.4.19 Concept of porosity determination

4..3.2 Porosity analysis



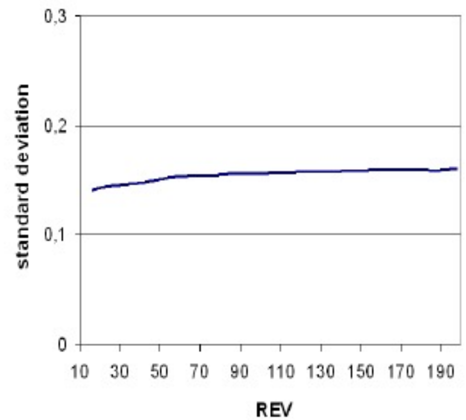


Image from MSc A. Moldovan (Grenoble, 2010)

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.

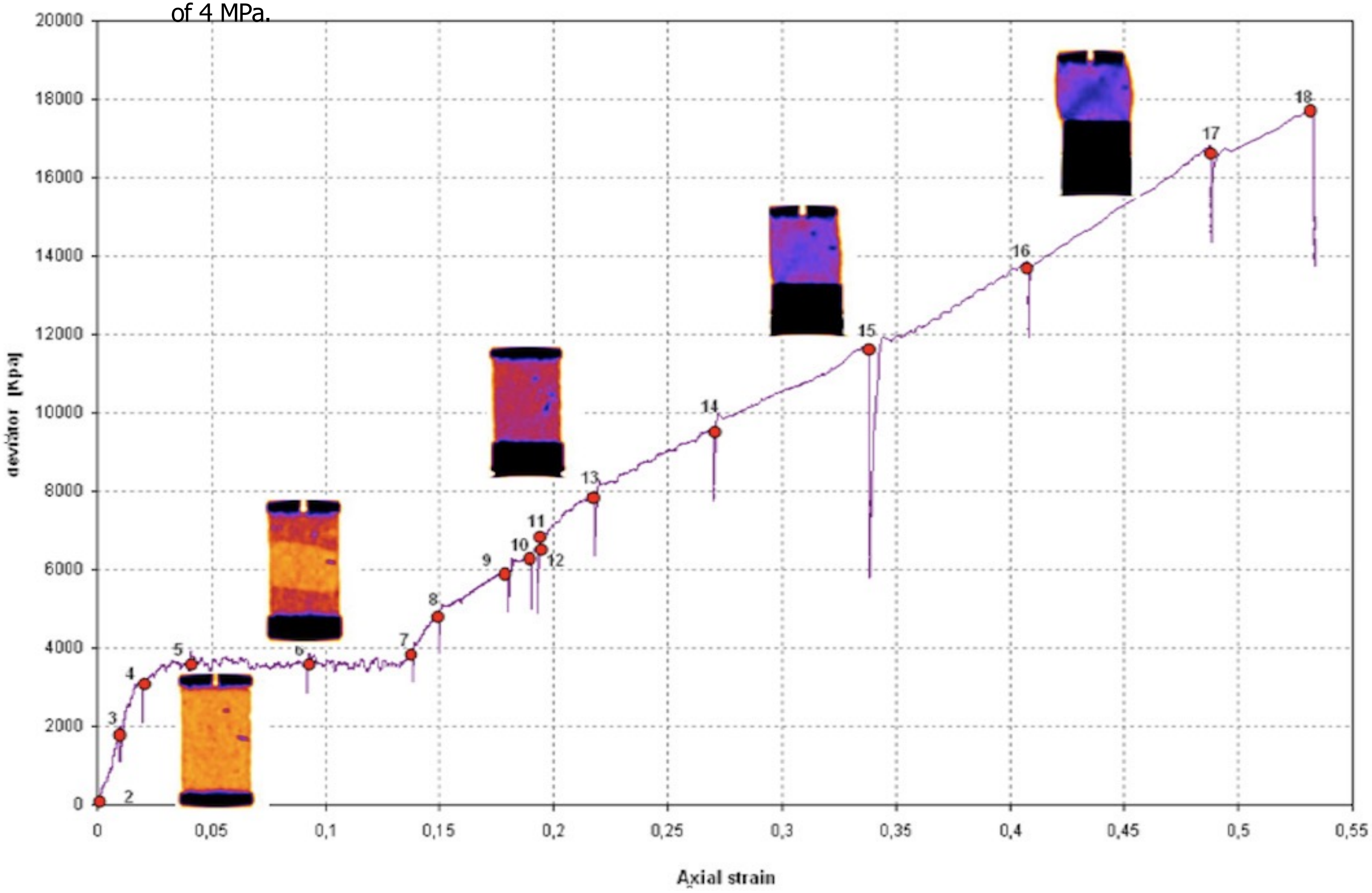


Image from MSc A. Moldovan (Grenoble, 2010)

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…

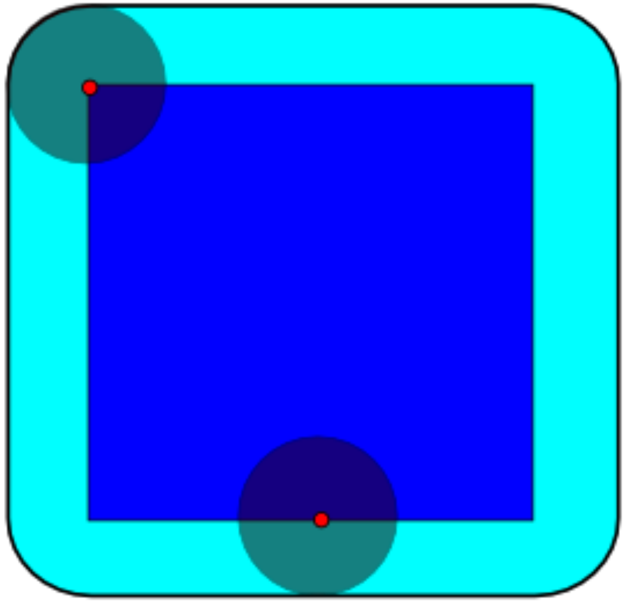
(after wikipedia)

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

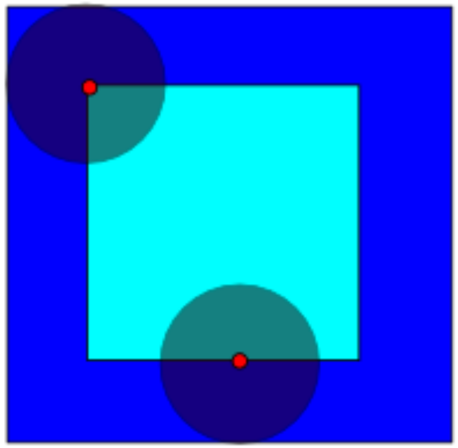
http://en.wikipedia.org/wiki/Mathematical_morphology

Dilation and erosion

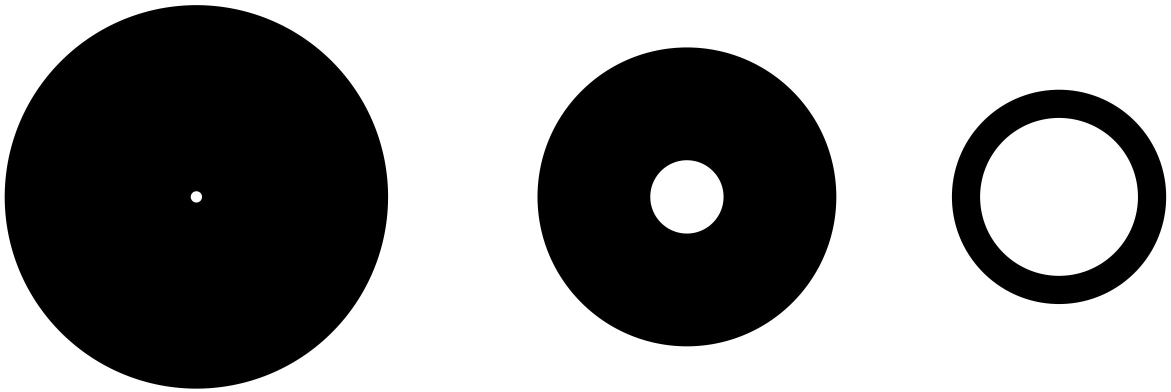
The **dilation** of the dark-blue square by a disk, resulting in the light-blue square with rounded corners.



The **erosion** 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

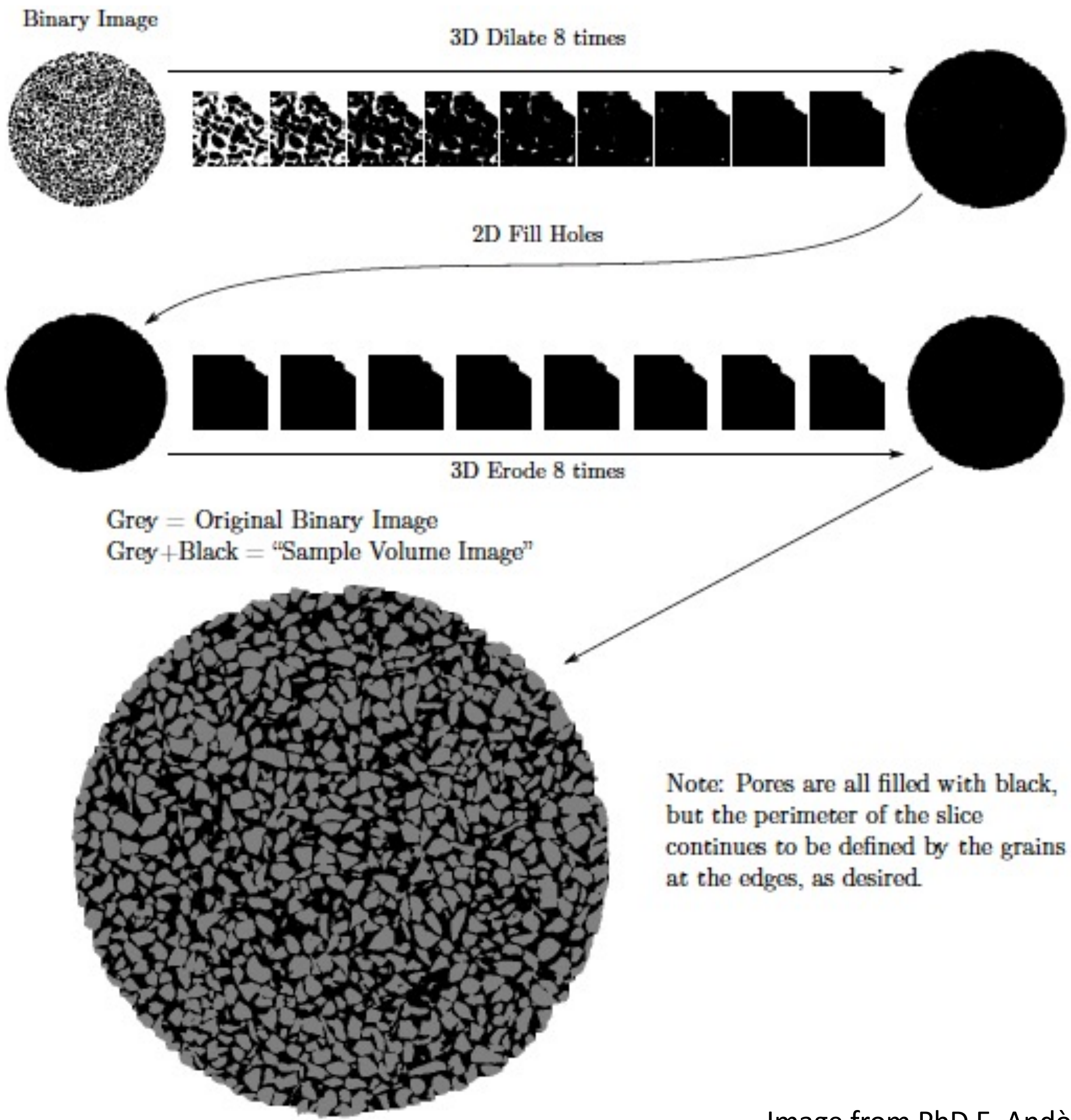
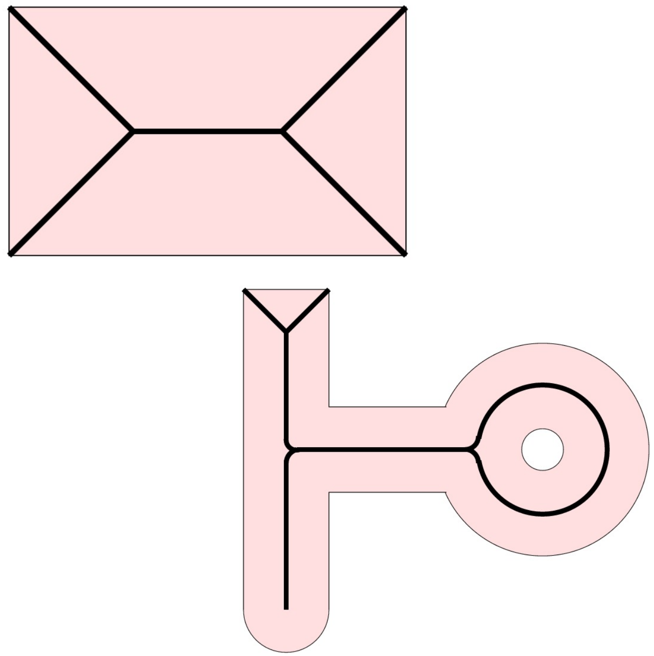


Image from PhD E. Andò (Grenoble, 2013)

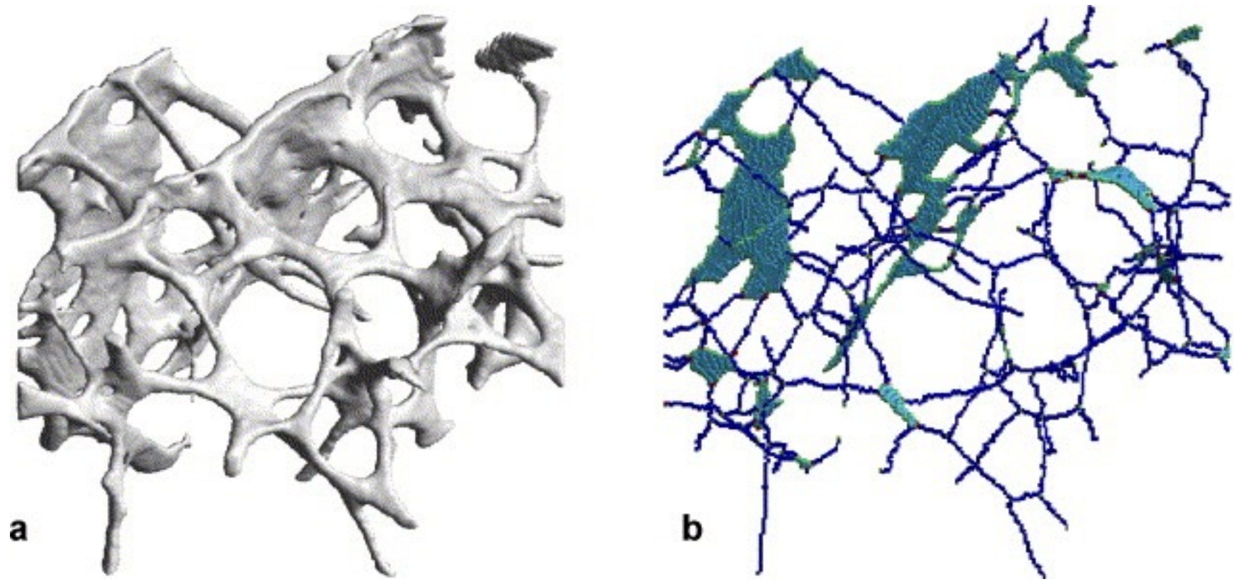
Skeletonisation

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)

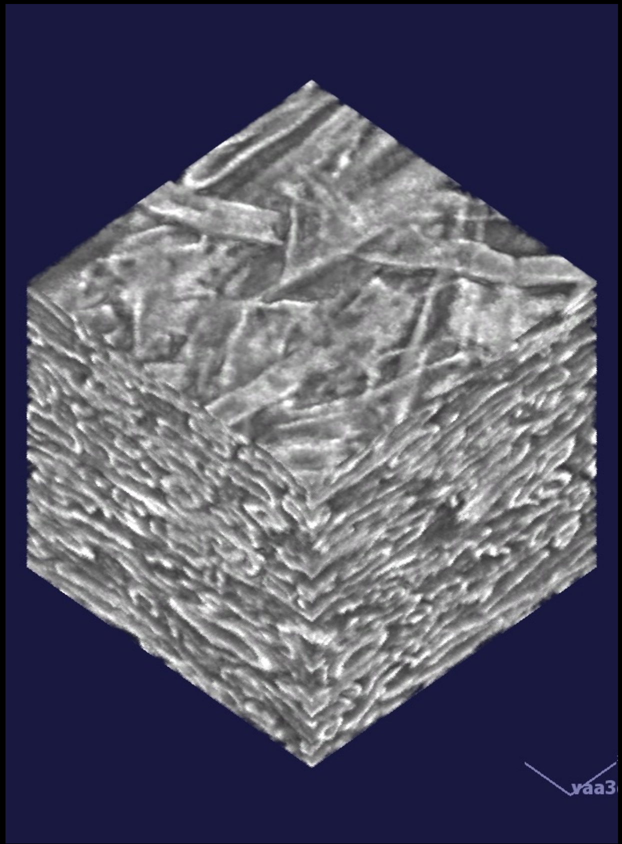


http://www.inf.u-szeged.hu/~palagyi/skel/skel.html

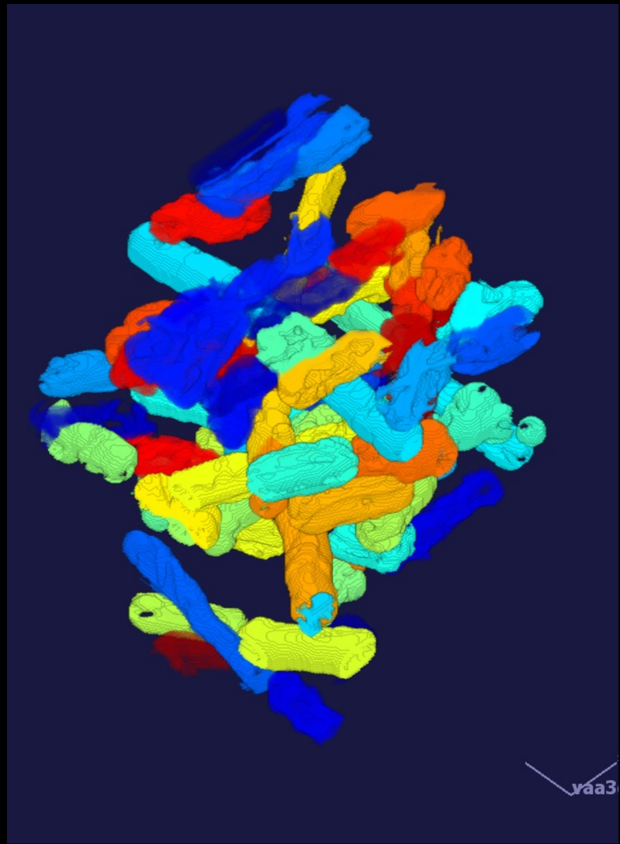


Lenthe & Müller, 2006, Bone

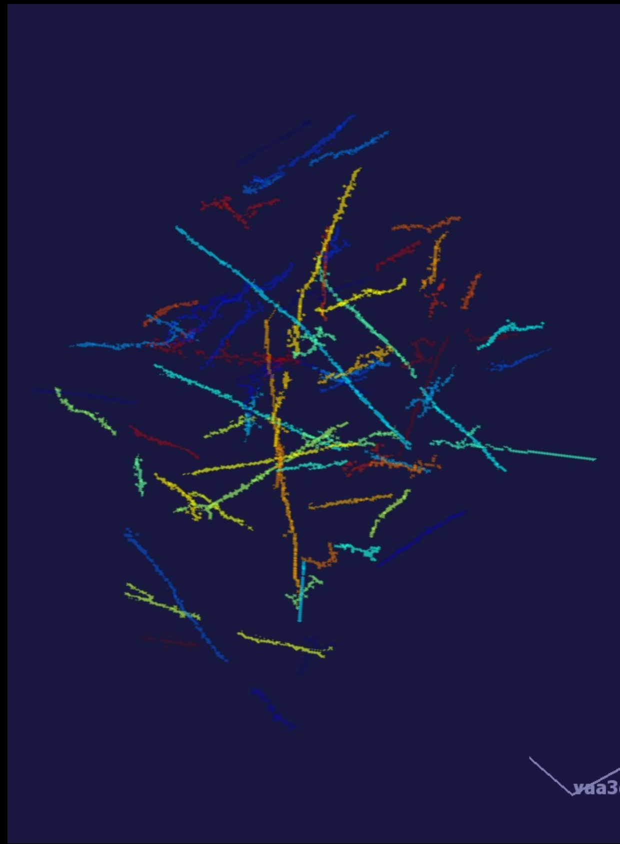
Structural imaging and characterisation:



Paperboard
(1.5 micron voxel size)

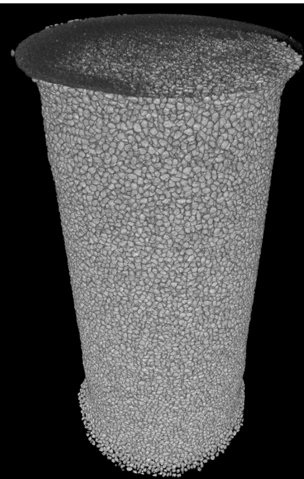


Segmented & Labelled fibres

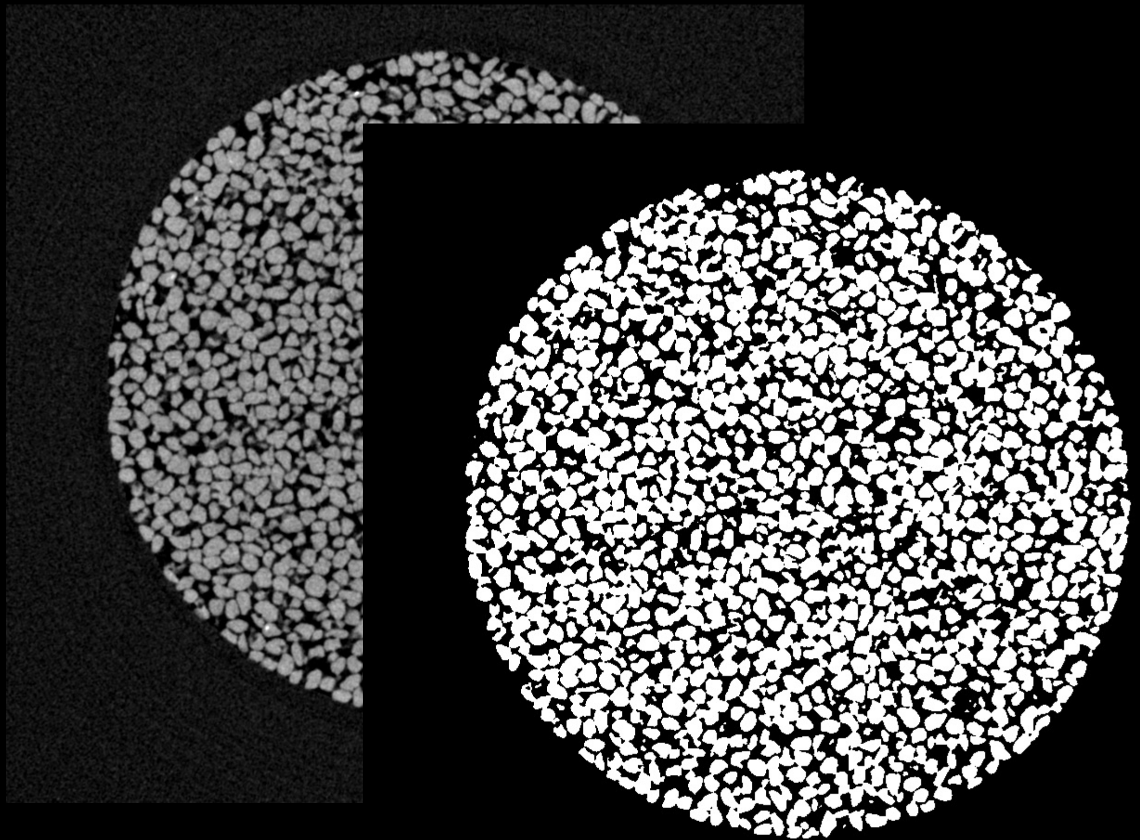


Fibre central axes

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



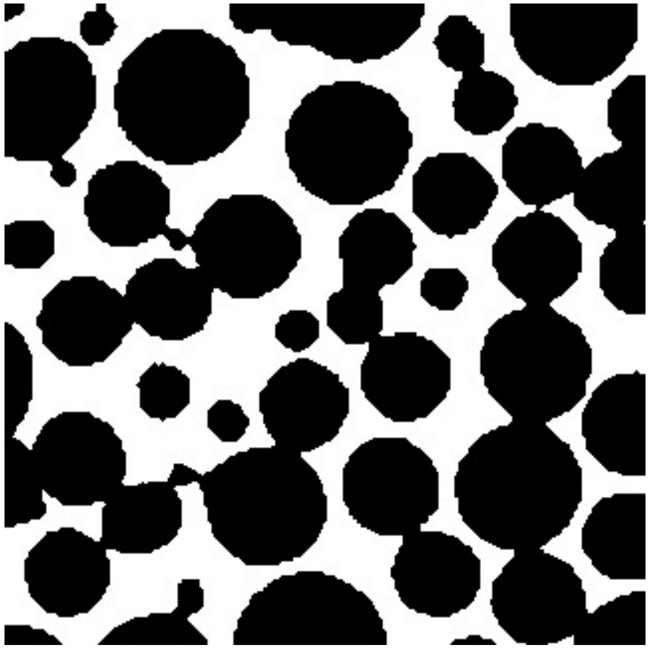
How do we see/identify and characterise microstructure?



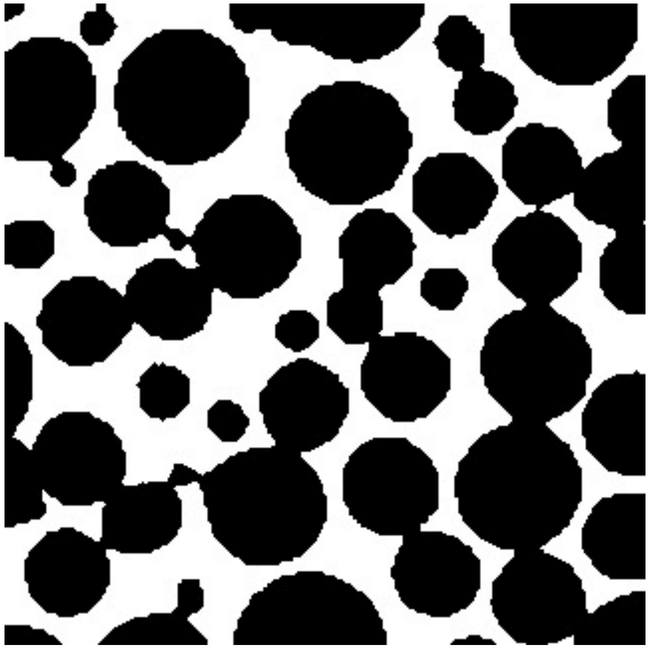
“Raw” image

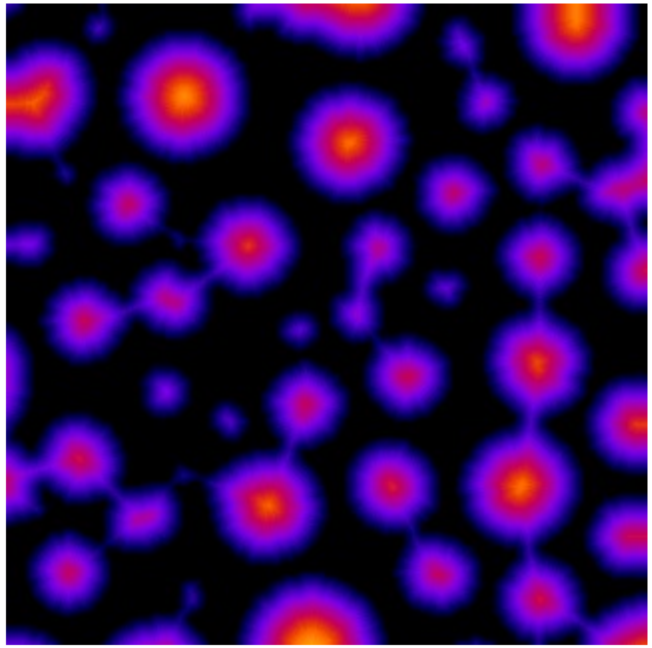
Binarise
(grains and voids)

Watershed Segmentation - introduction of distance map



Watershed Segmentation - introduction of distance map





Watershed Segmentation - introduction of distance map

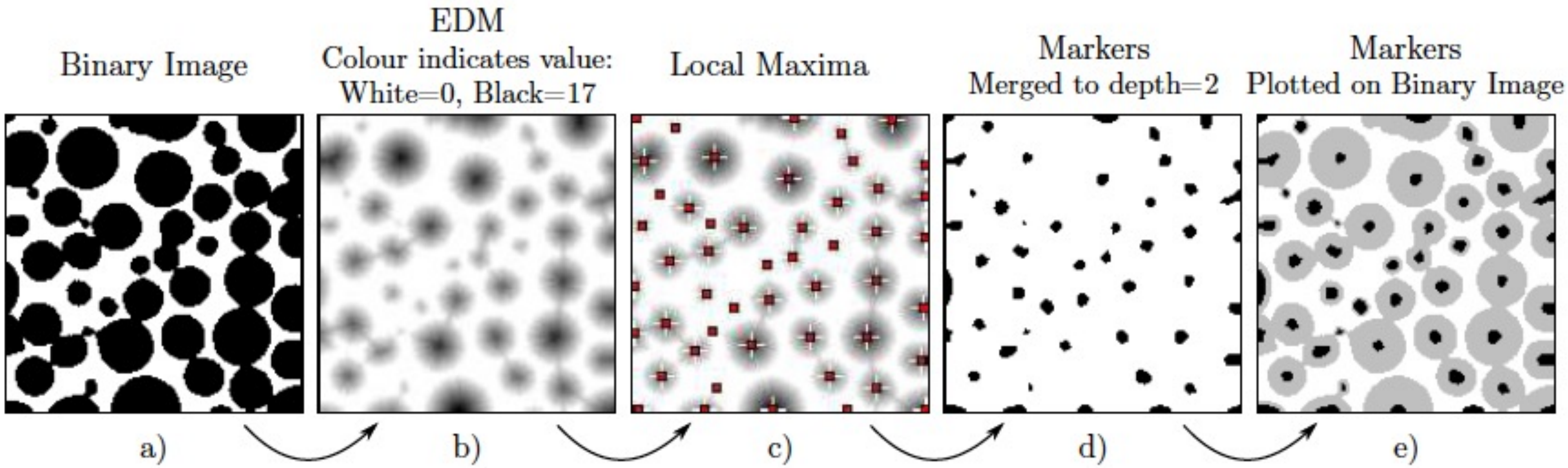


Image from PhD E. Andò (Grenoble, 2013)

Watershed Segmentation

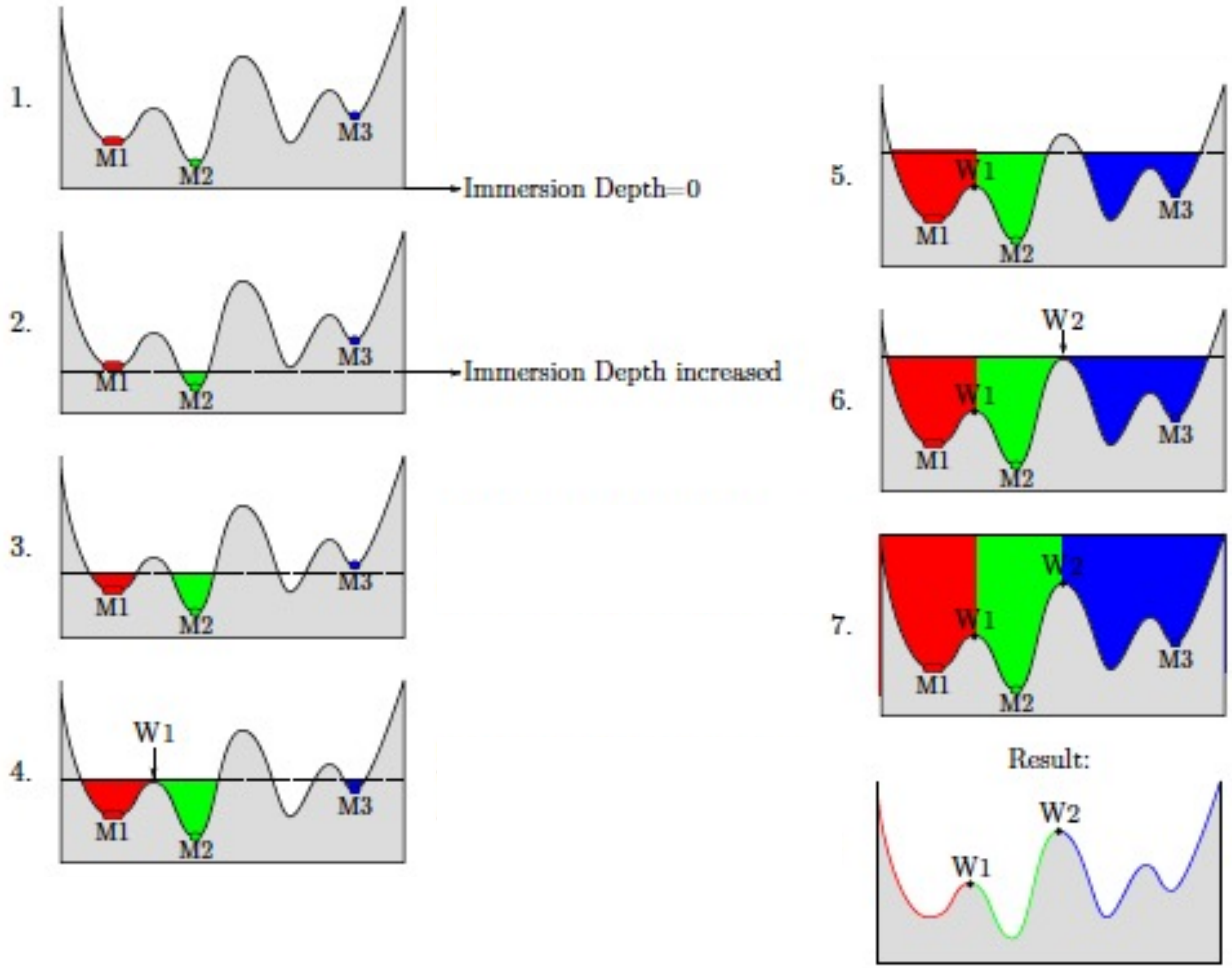
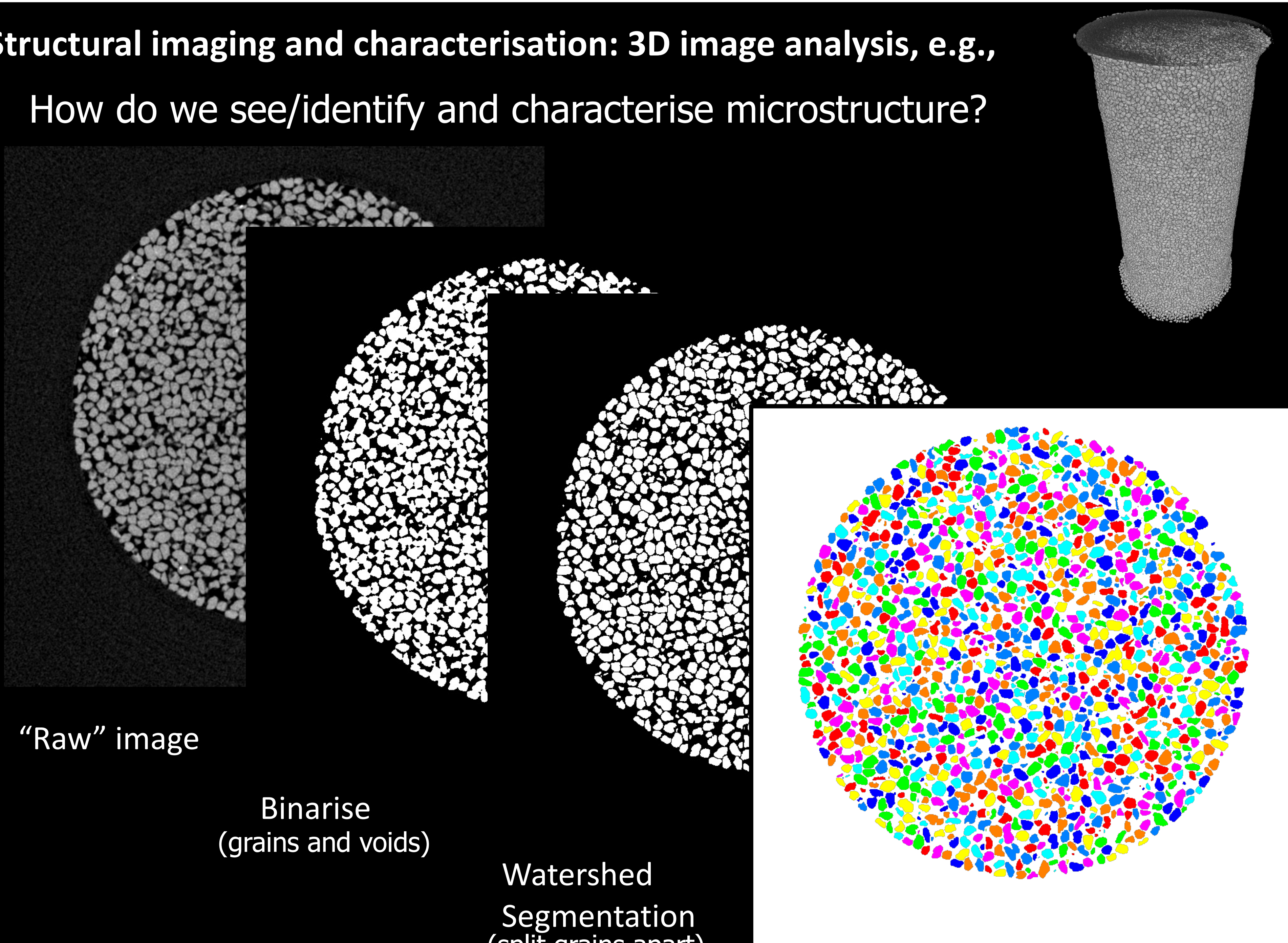


Image from PhD E. Andò (Grenoble, 2013)

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

How do we see/identify and characterise microstructure?



“Raw” image

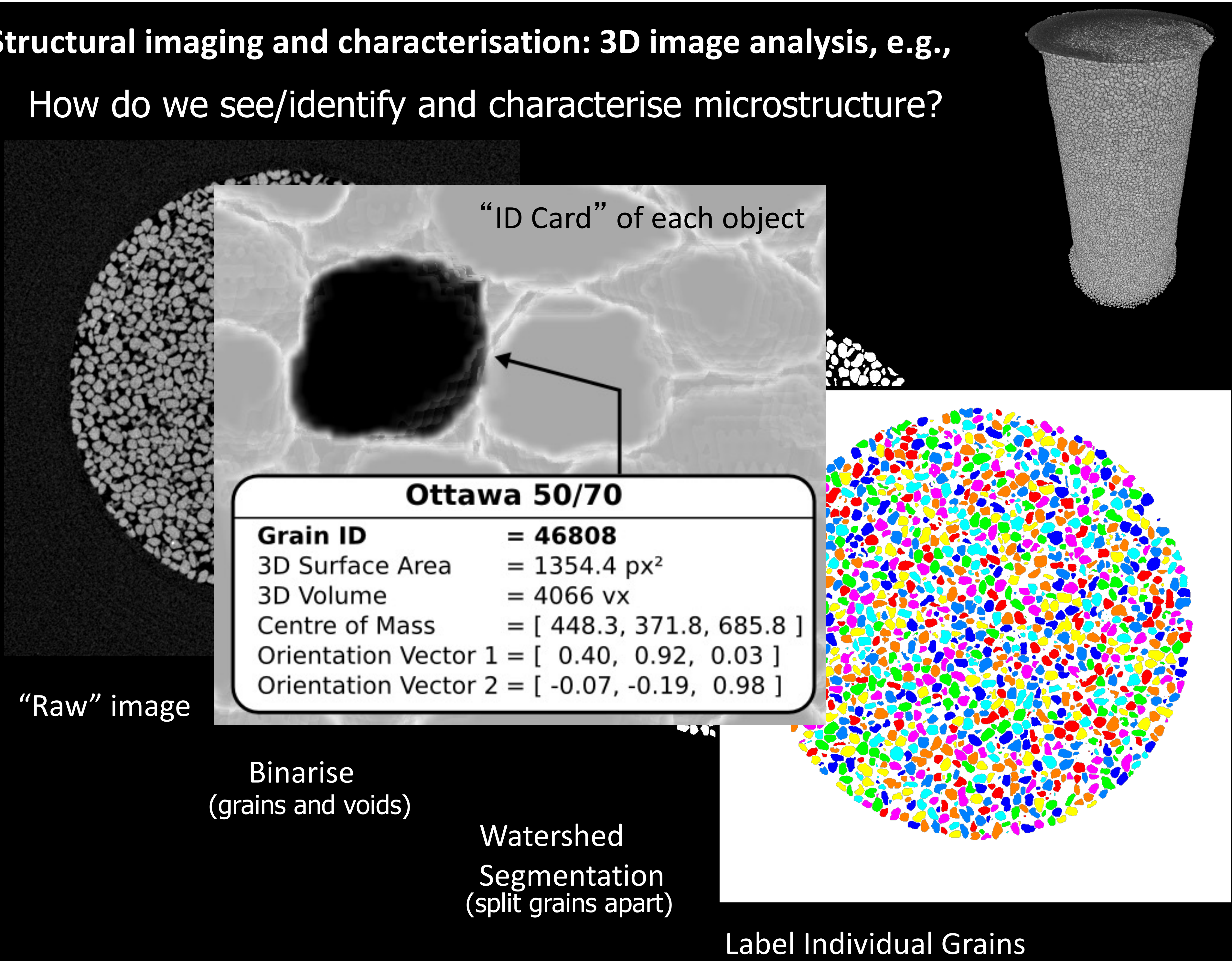
Binarise
(grains and voids)

Watershed
Segmentation
(split grains apart)

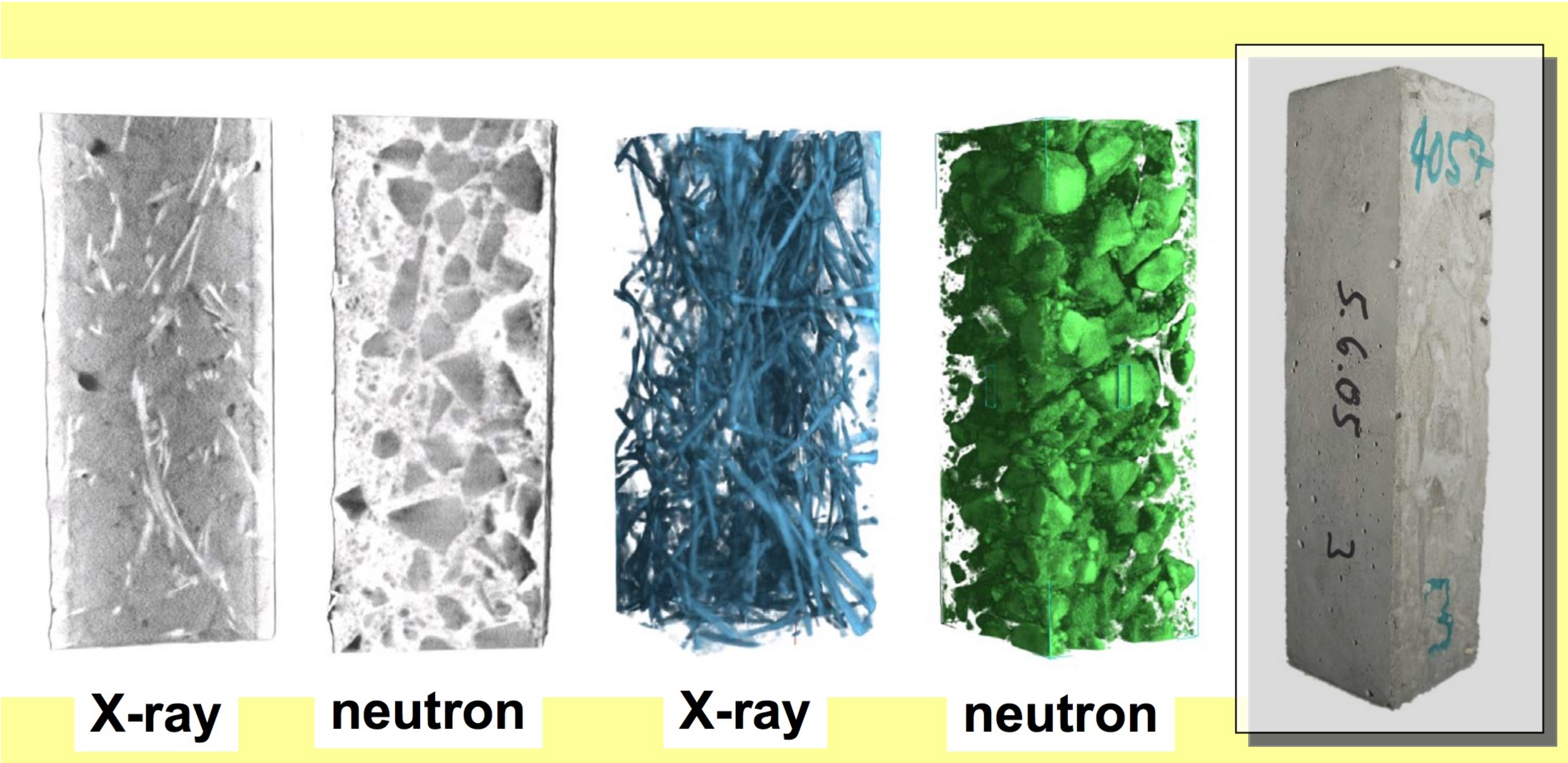
Label Individual Grains

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

How do we see/identify and characterise microstructure?



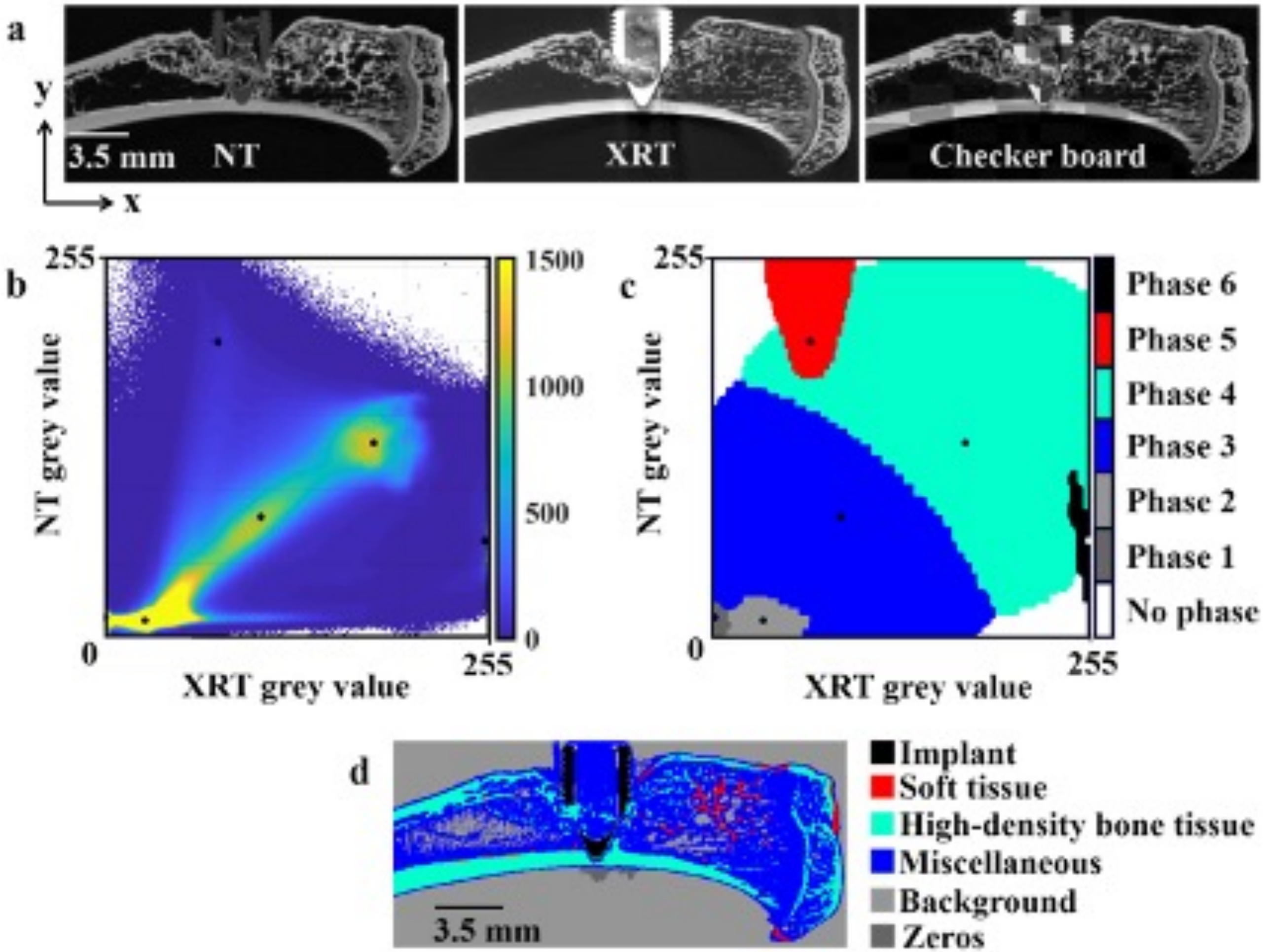
X-rays and neutrons – complementary segmentation



From E. Lehmann

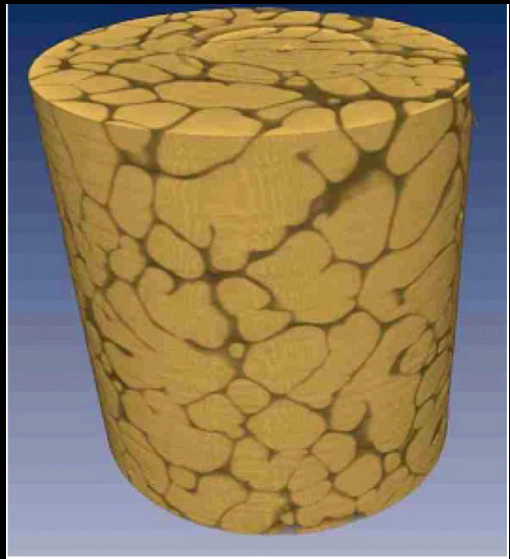
Dual modality registration and segmentation

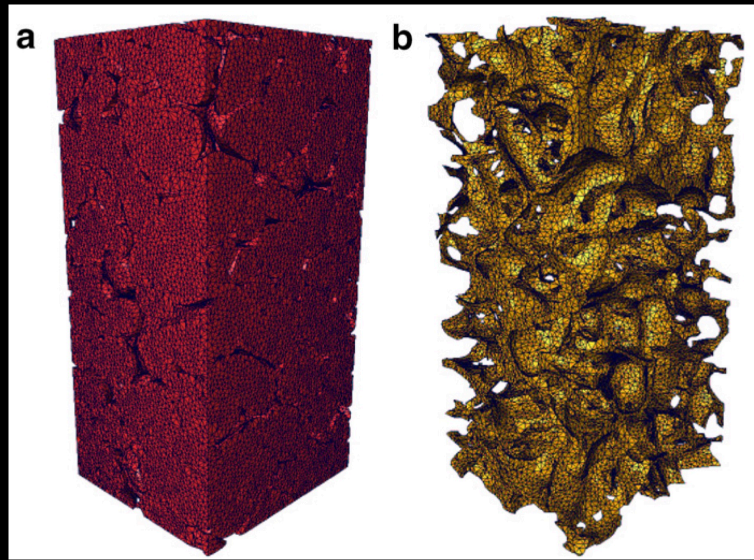
Dual modality neutron and X-ray tomography for enhanced image analysis of the bone-metal interface - Tornqvist etal., 2021



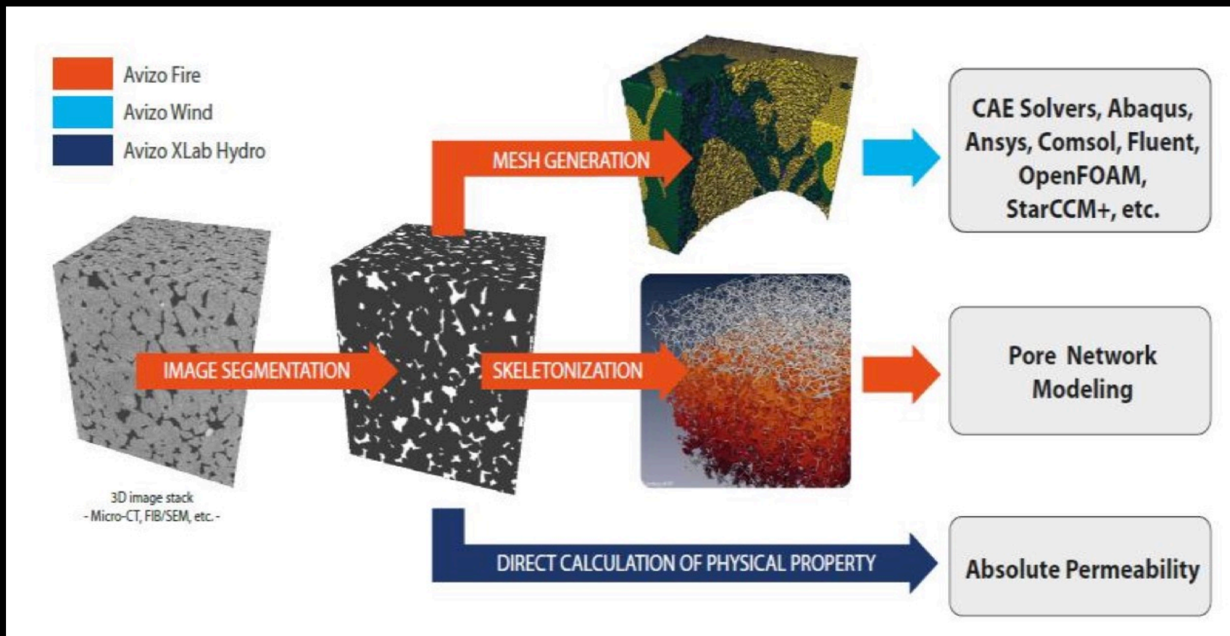
See Anders Kaestner's lecture earlier in the week

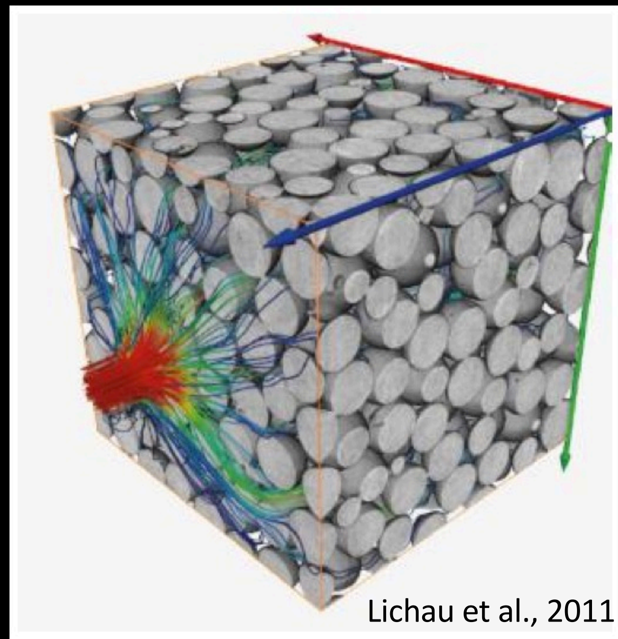
Structural imaging and characterisation → models





Madi et al., 2006

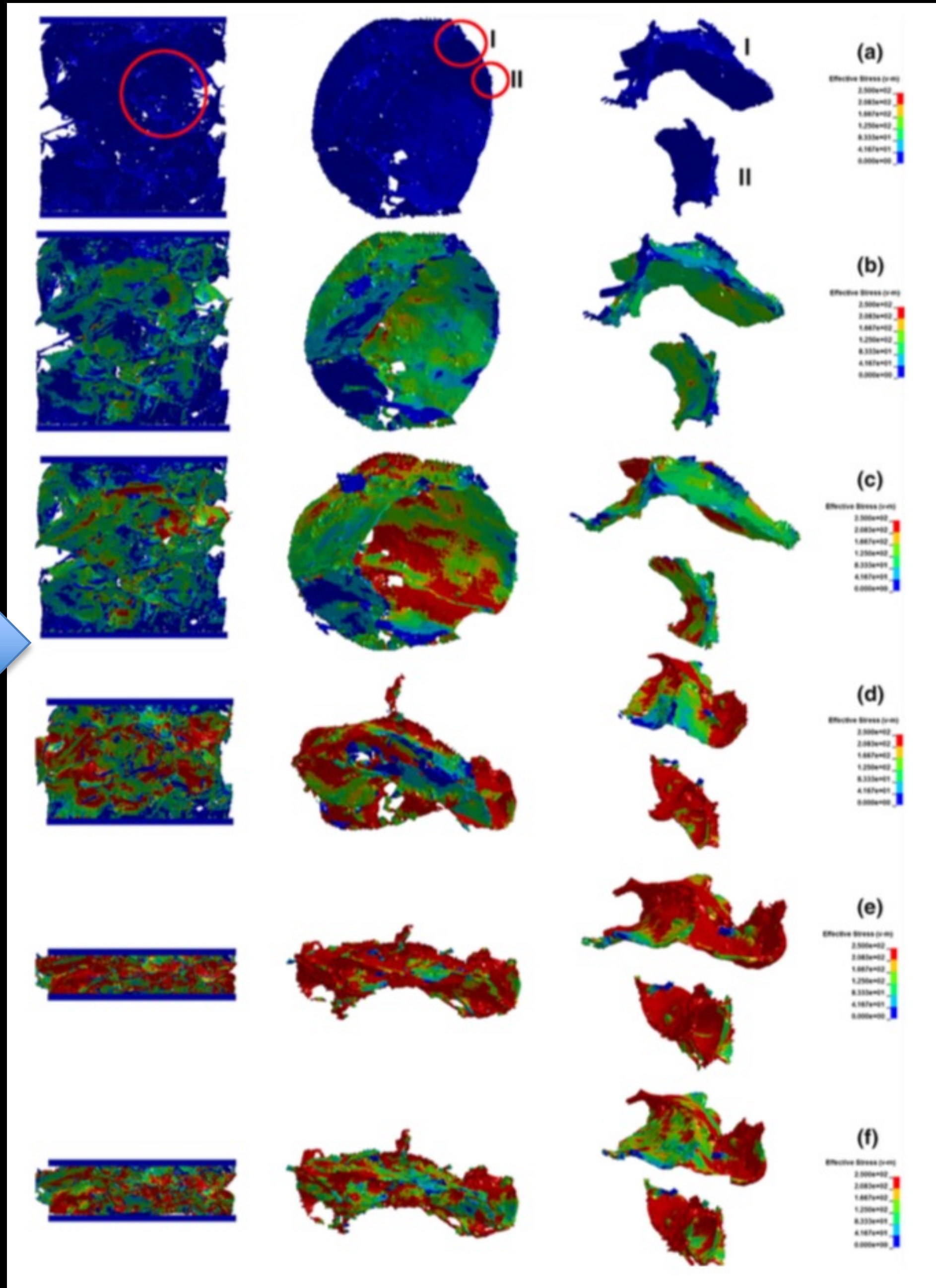




Lichau et al., 2011

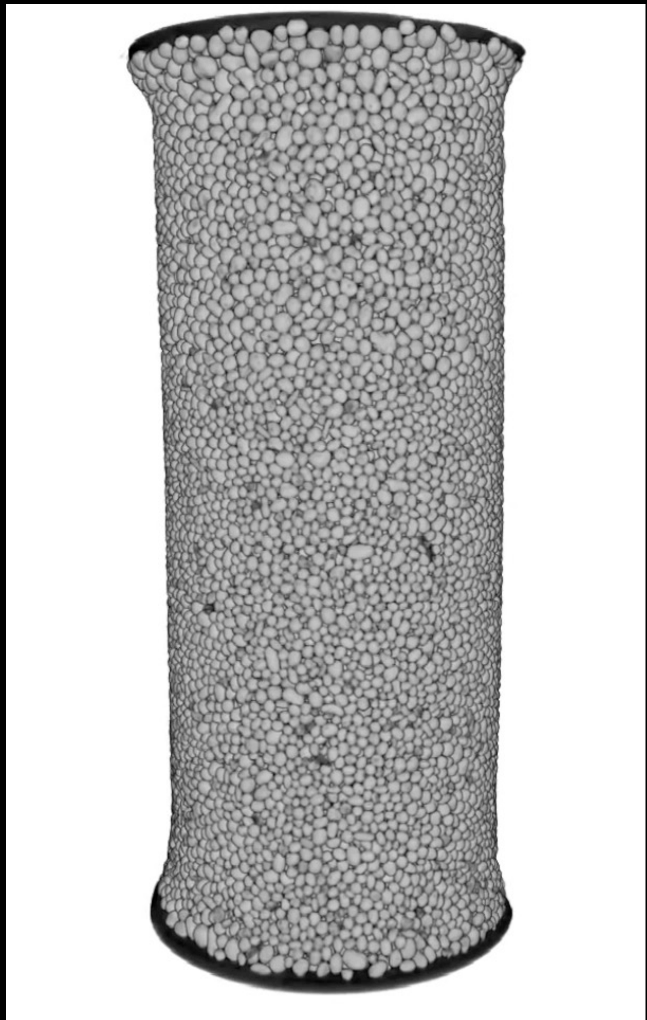
Structural imaging and characterisation → models

(Images from 4D Imaging Lab)



Srinivasa, Kulachenko , Karlberg, 2017, Cellulose

4D imaging and in-situ experiments



E Andò, CNRS,
Grenoble, France

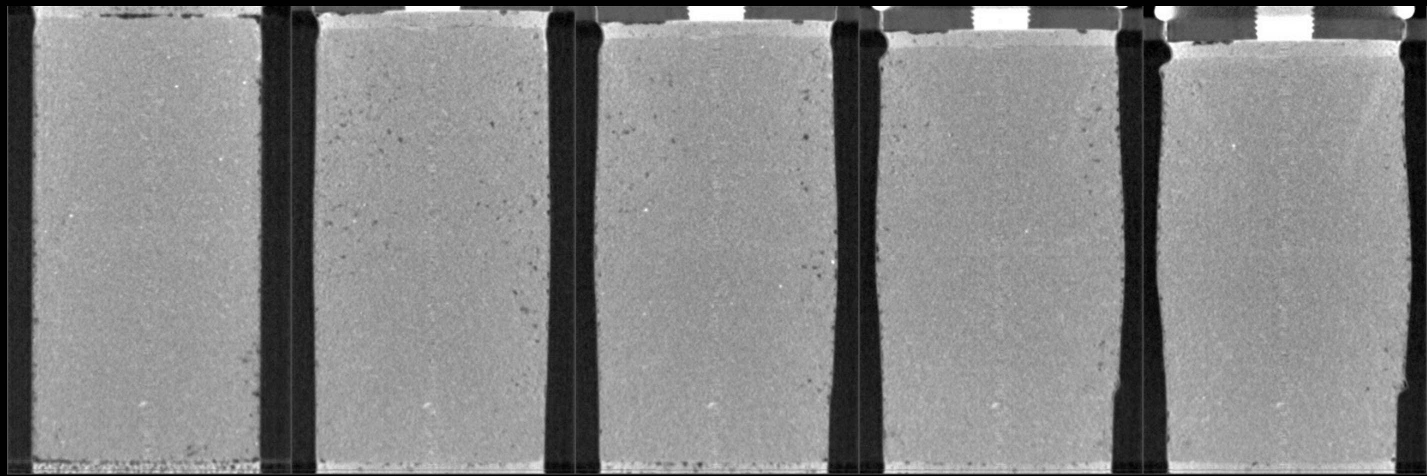
4D imaging and in-situ experiments

4D = 3 dimensions in space plus time

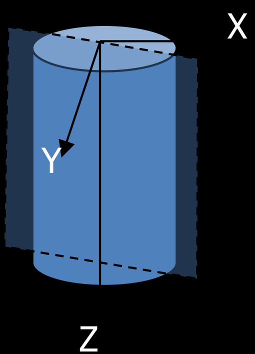
In-situ = performing an experiment within the measurement set-up, in this case within an x-ray tomograph (lab or synchrotron)

Tudisco et al, 2017

4D neutron Imaging & Digital Volume Correlation (DVC)



Rock sample deformed in-situ with neutron imaging



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

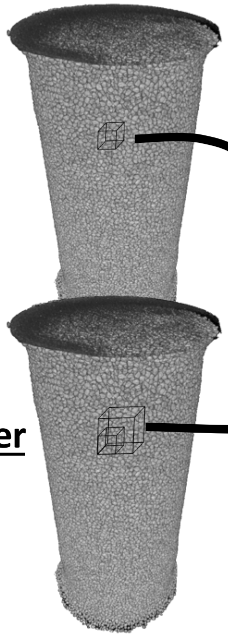
Digital Volume Correlation (DVC)

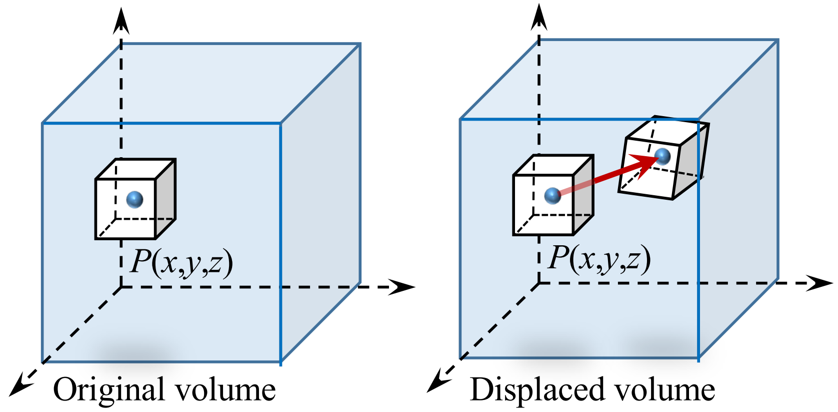
e.g., "TomoWarp2": Tudisco et al., 2017

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

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

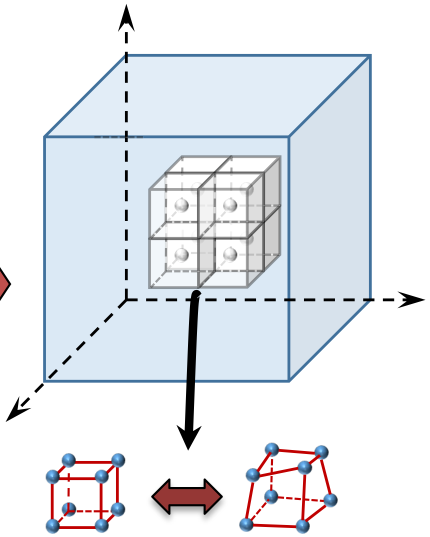
X-ray tomography image volume **after** loading





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

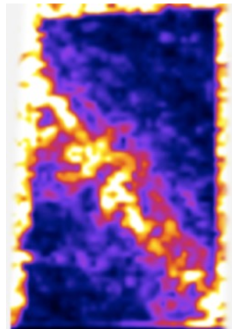
Vector displacement field



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

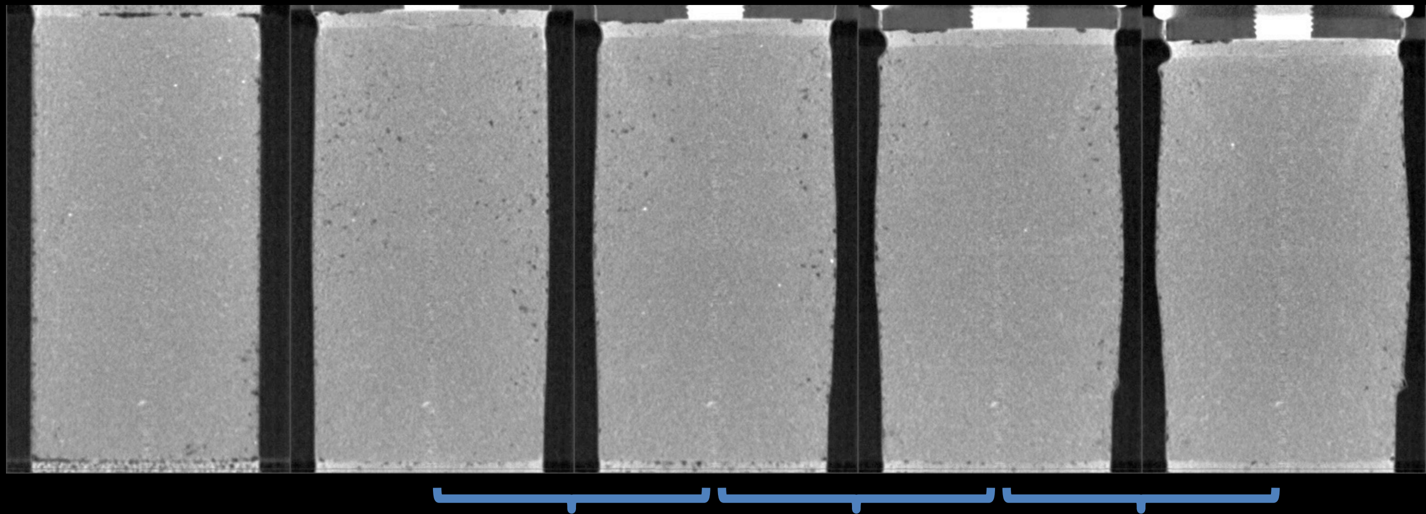
- volumetric and shear strains

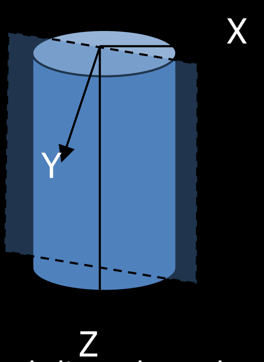
$$\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$$

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

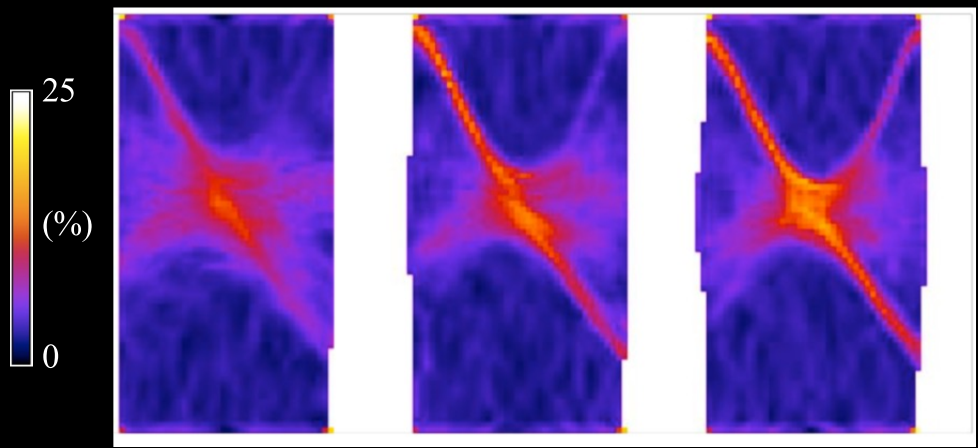
Tudisco et al, 2017

4D neutron Imaging & Digital Volume Correlation (DVC)

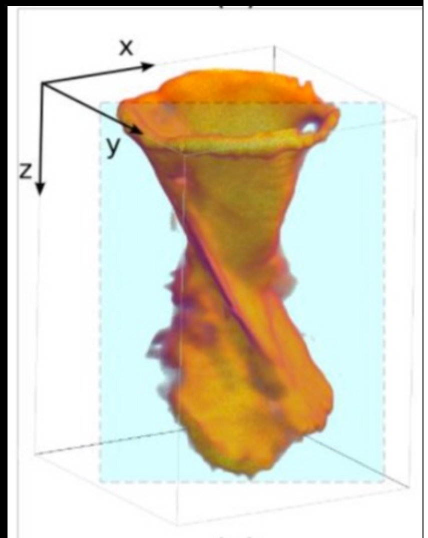




(Vertical slices through middle of volume perpendicular to main localisation)



Maximum shear strain field derived from DVC

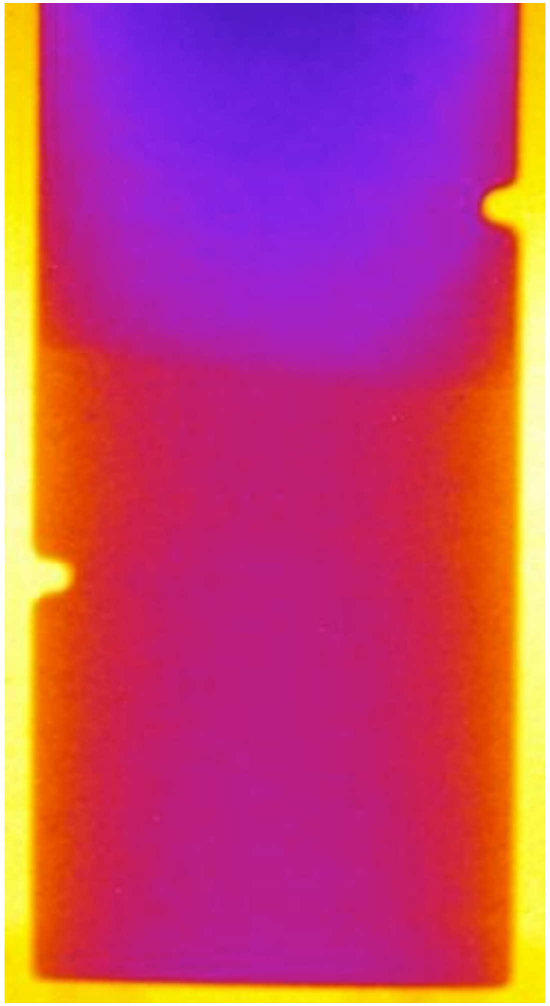


Final example - flow front tracking

Timelapse neutron radiography of “2D” specimens and two fluid phases

Oil

Dry

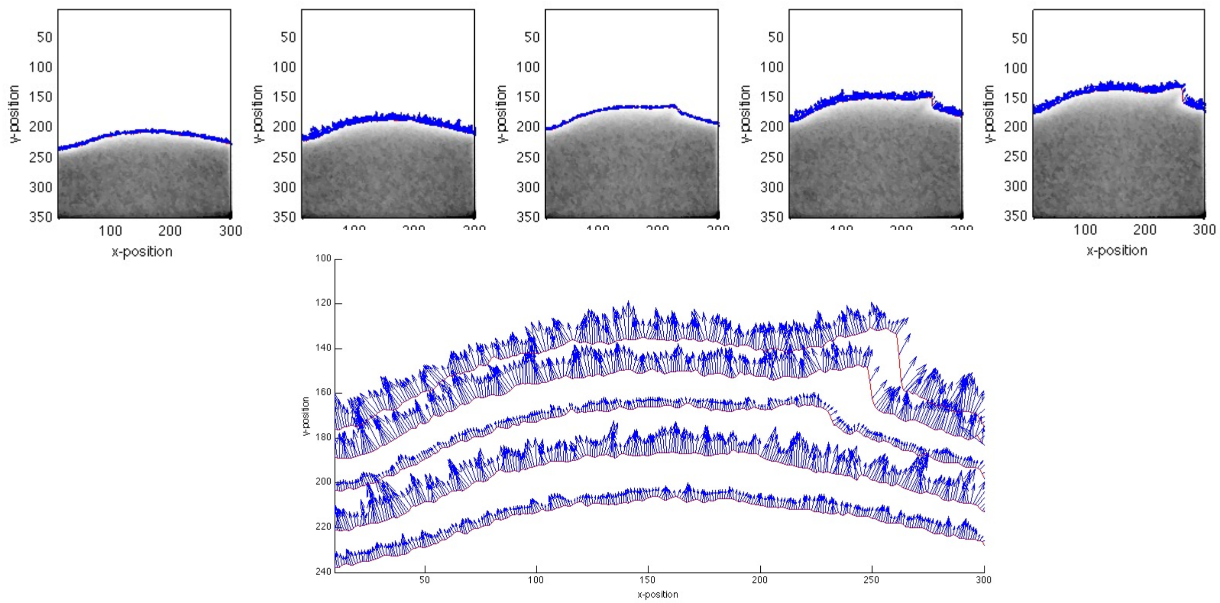


Water

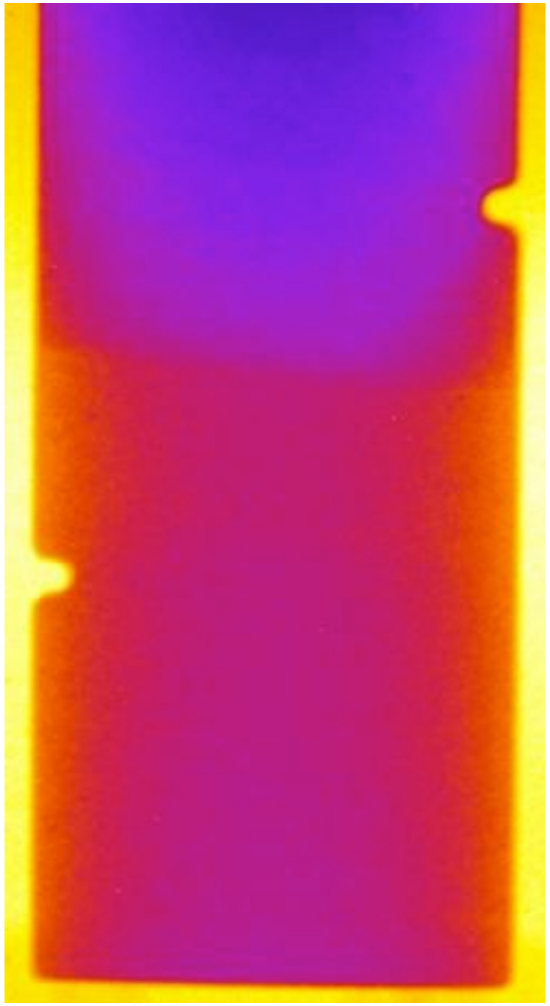
Difference with first image

Quantification

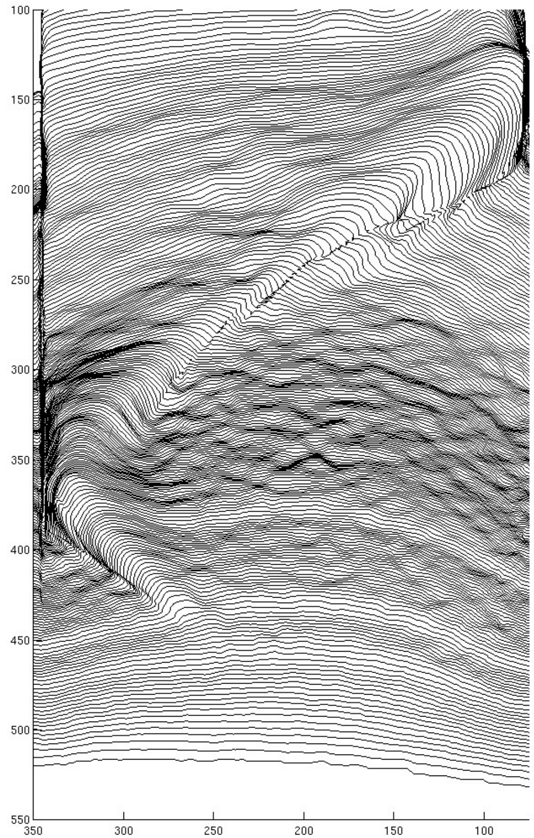
- Automatically picked fluid fronts at time N
- Track each point on the front at time N through each image for all time steps
    - Challenging due to concavities and convexities of front and need to follow points on the front through time
    - Deformable contour tracking and front propagation
    - Flow fronts at each step
    - Flow lines from start to finish
- Flow velocities from distances along flow lines and image times



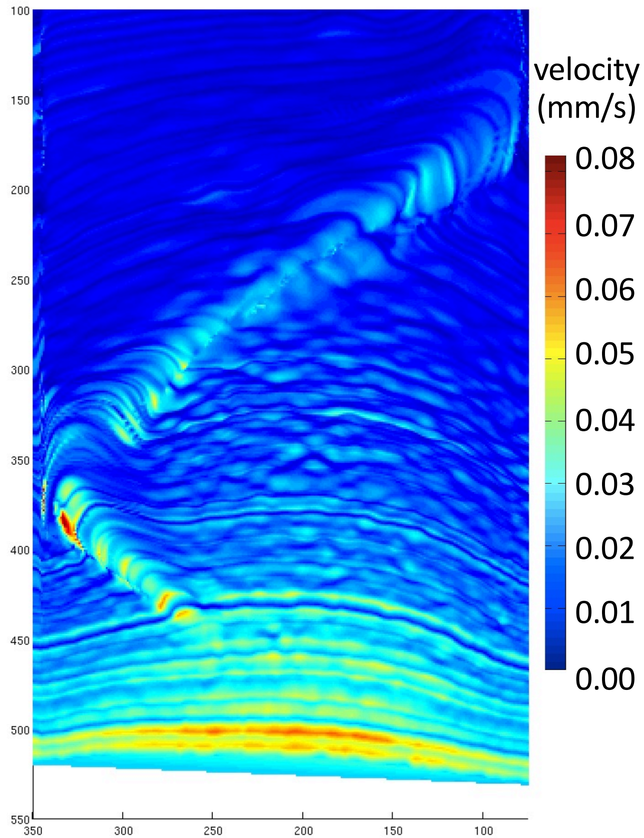
Quantification



Flow-fronts



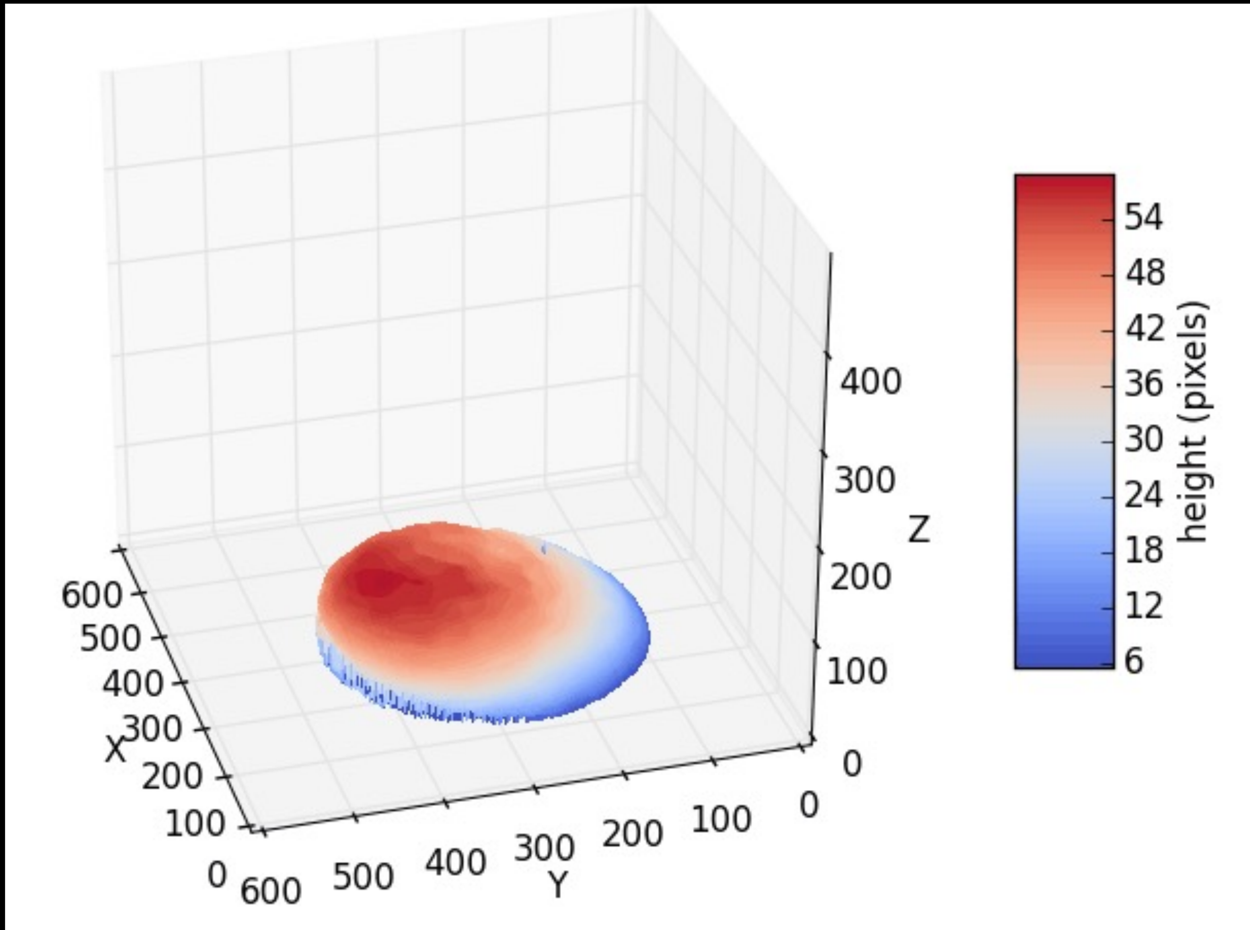
Flow-velocities



Pixel width = 0.124 mm

Hydromechanics of geomaterials: neutron imaging (fluid flow)

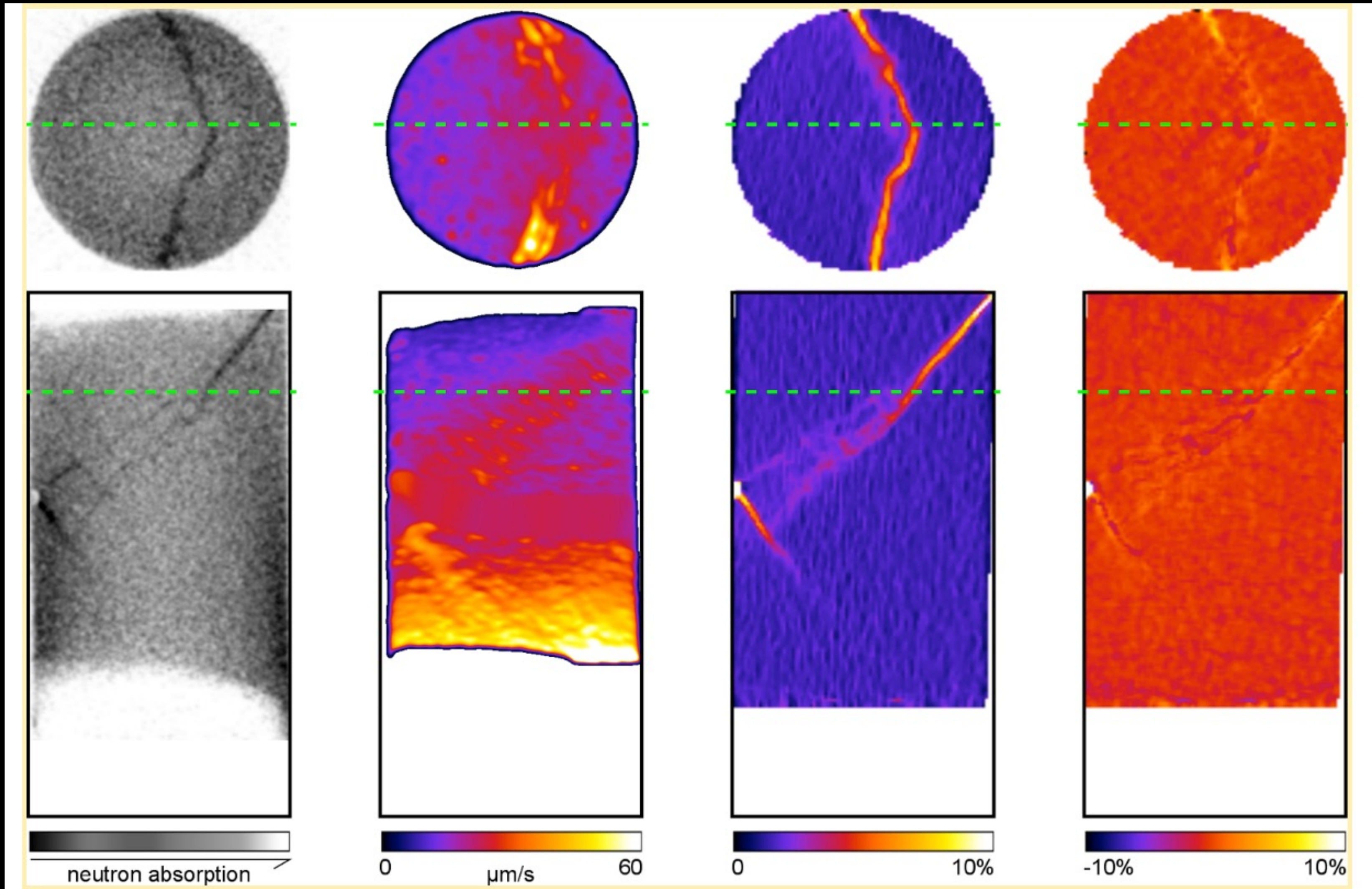
Imbibition monitoring in 3D (high-speed neutron tomography)



1 minute tomographies @ HZB

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

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



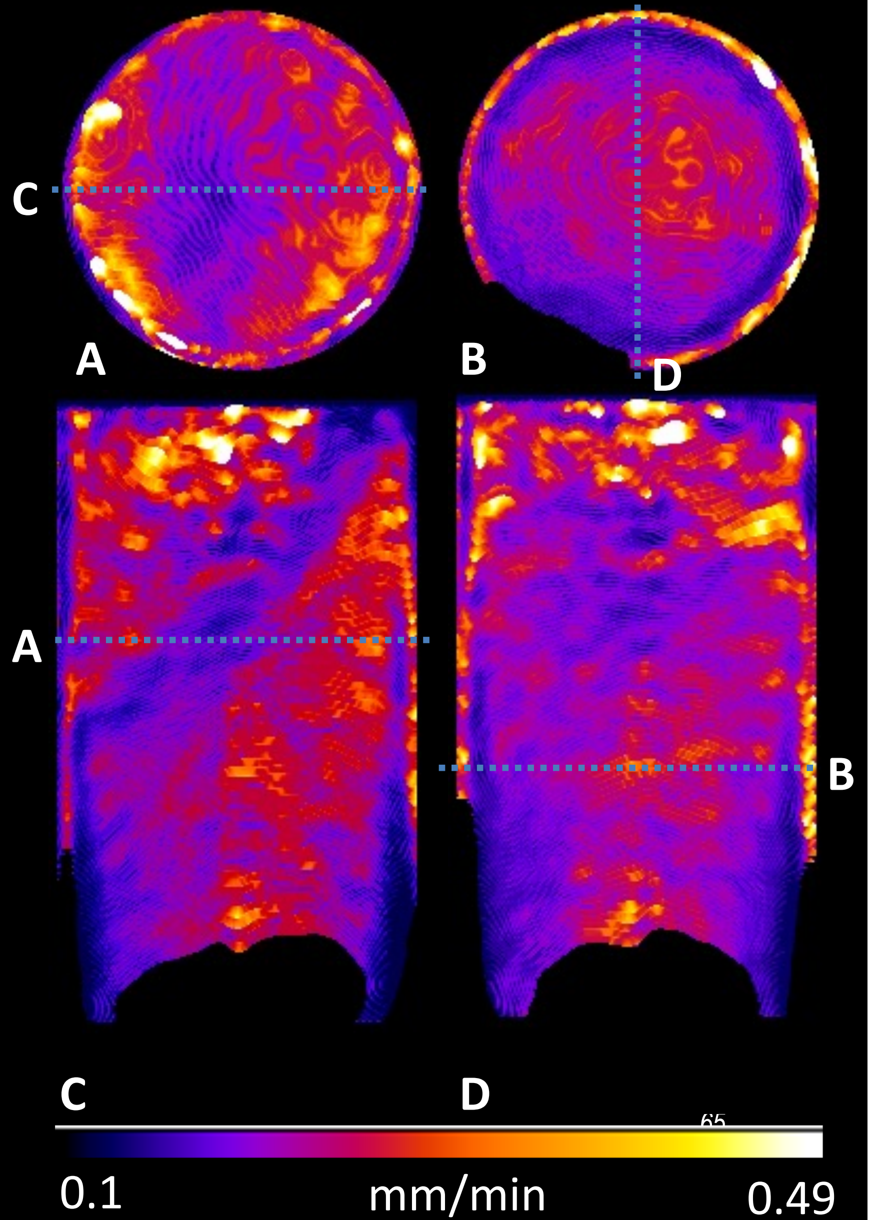
Neutron tomography | Fluid Velocity | Shear strain | Volumetric strain

(DVC based on pre- and post-deformation x-ray tomography

Collab. E. Tudisco, (Lund University) & M. Etxegarai (Univ. Grenoble)

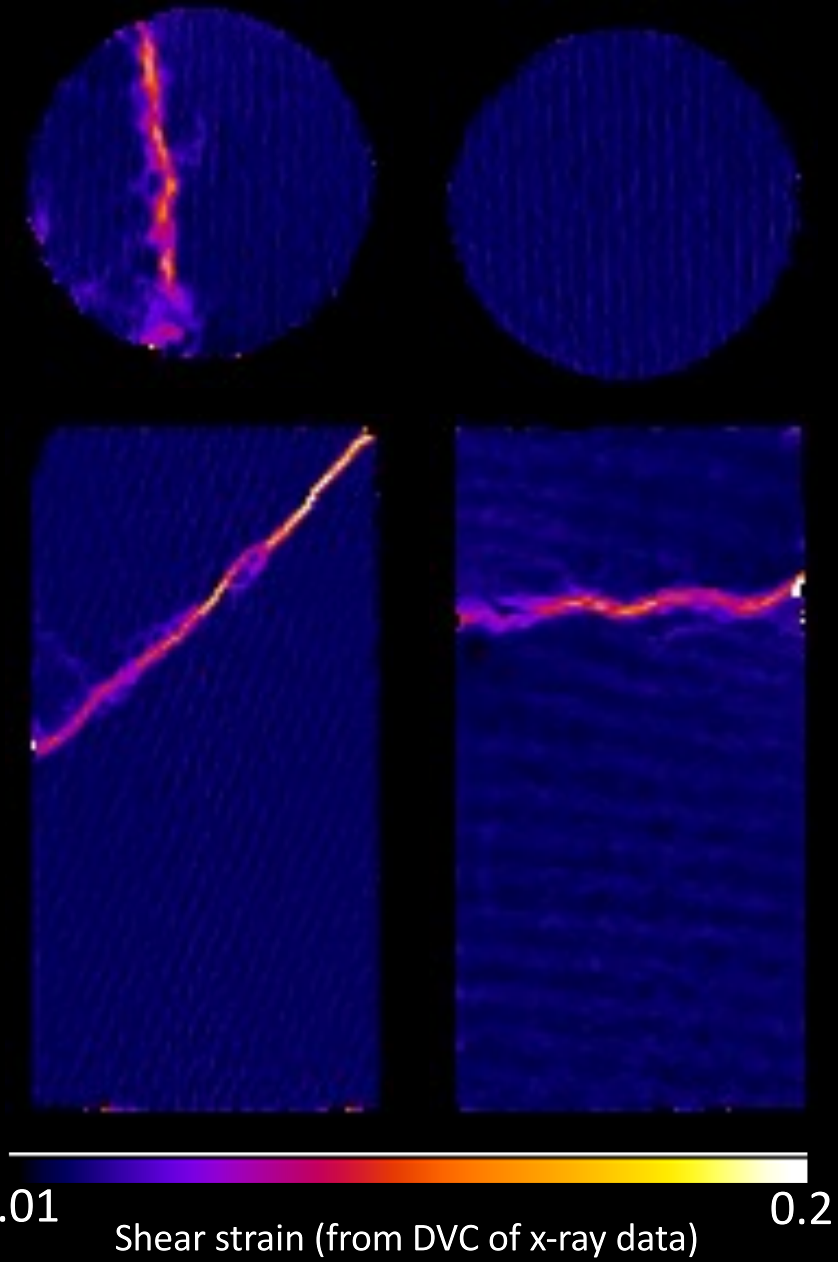
Pressure controlled H_2O flow into D_2O saturated sample

WATER FRONT SPEED

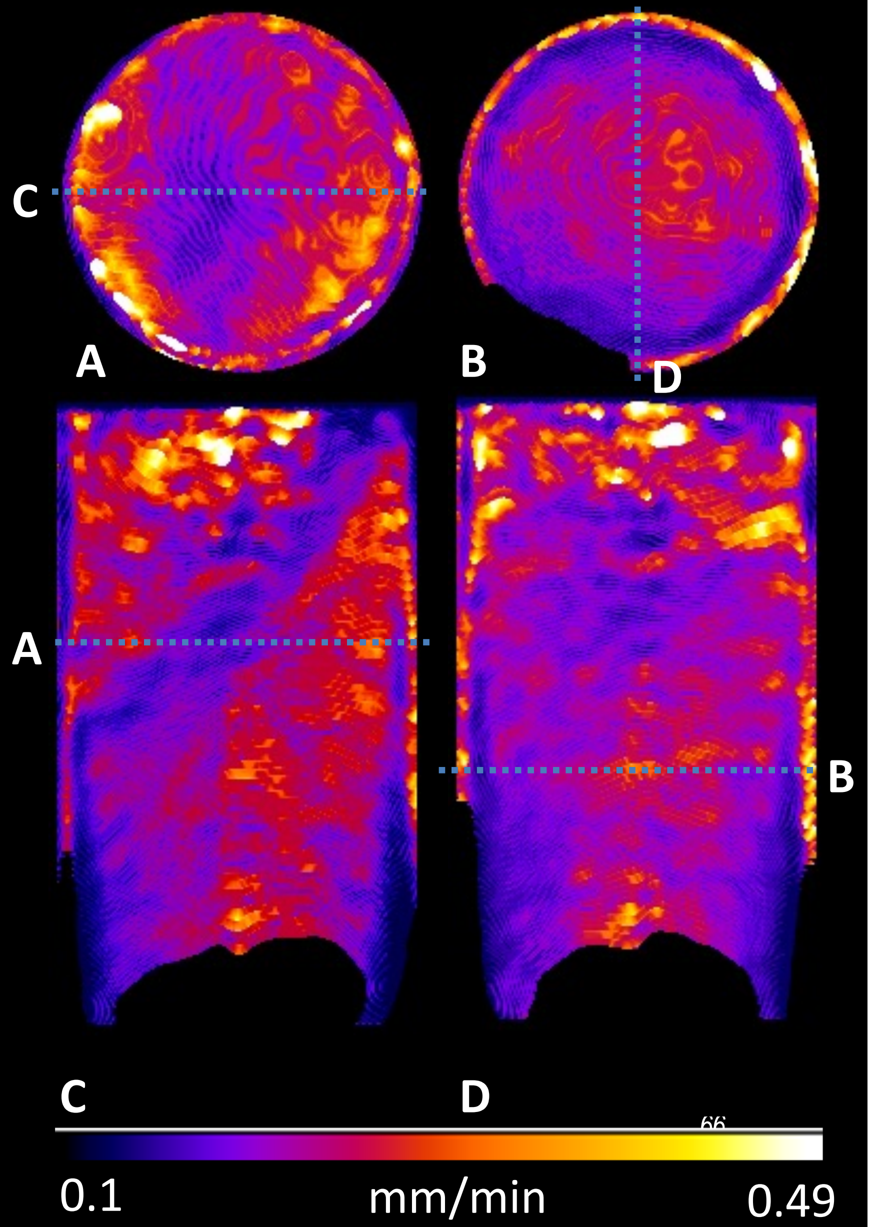


PhD project of Maddi Etxegarai (Univ. Grenoble)

Pressure controlled H_2O flow into D_2O saturated sample



WATER FRONT SPEED



PhD project of Maddi Etxegarai (Univ. Grenoble)

Dynamic imaging…?

Radiographies with evolution during rotation…

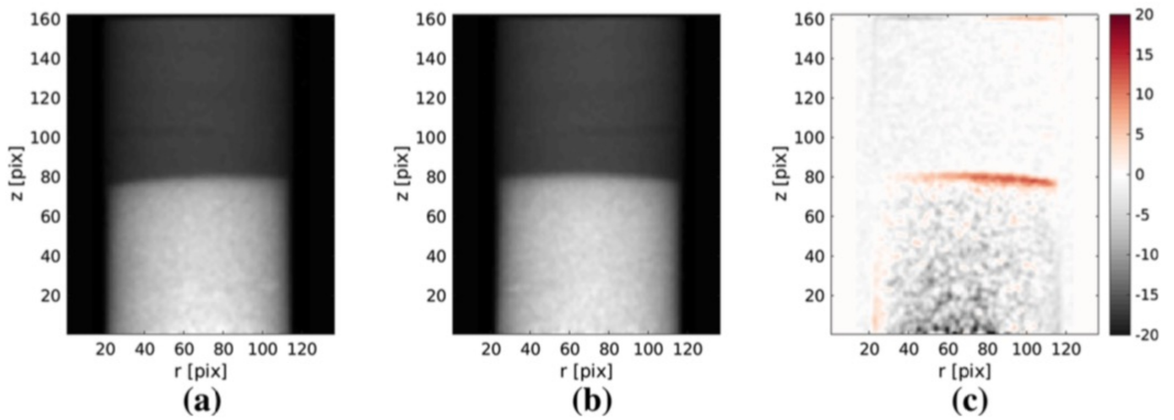


Fig. 4 Projection of the 3D column of fluid at the first **a** and last **b** angle. The difference between the first and the (mirrored) last images in **c** shows the fluid advance during the scan

Jailin et al., 2018

Dynamic imaging…?

Radiographies with evolution during rotation…

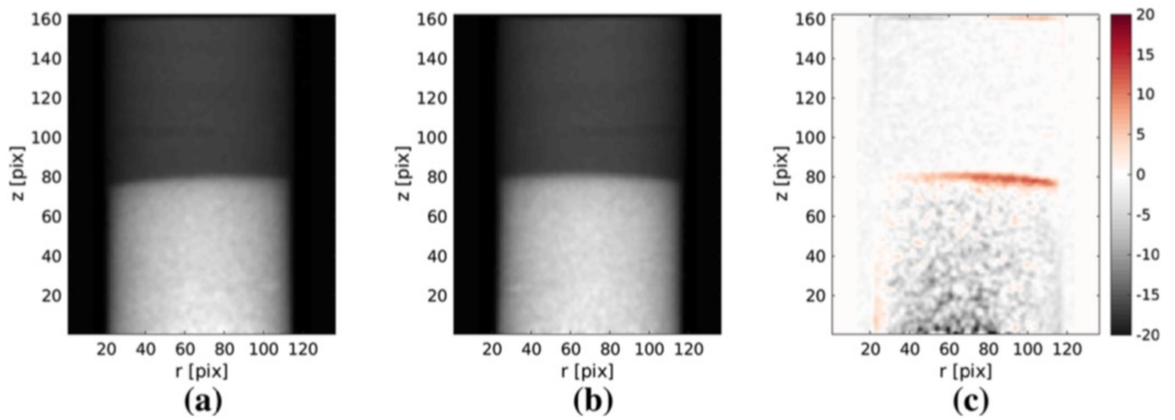


Fig. 4 Projection of the 3D column of fluid at the first **a** and last **b** angle. The difference between the first and the (mirrored) last images in **c** shows the fluid advance during the scan

Jailin et al., 2018

- 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

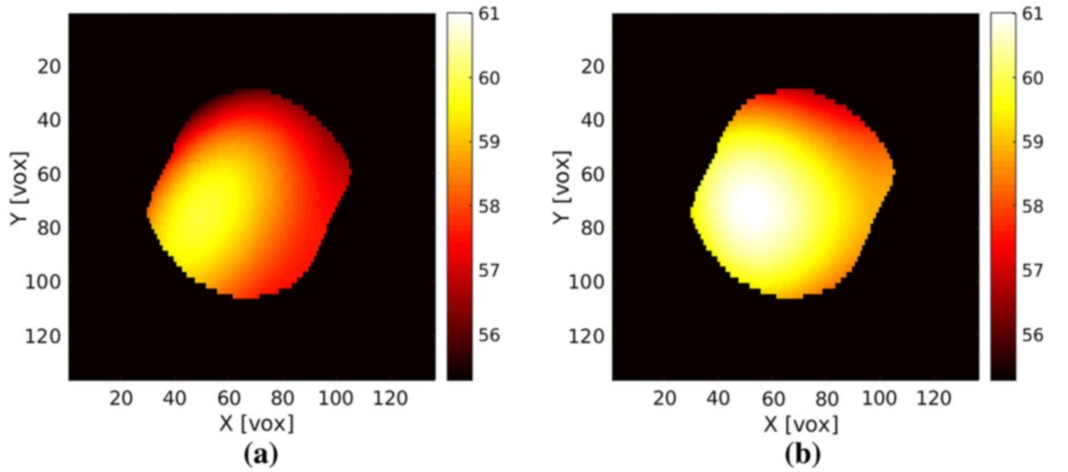


Fig. 9 Evolution of the front at different times of the scan acquisition, in voxels, reconstructed from the three modes for **a** $t = 0$ and **b** 60 s

Dynamic imaging…?

Radiographies with evolution during rotation…

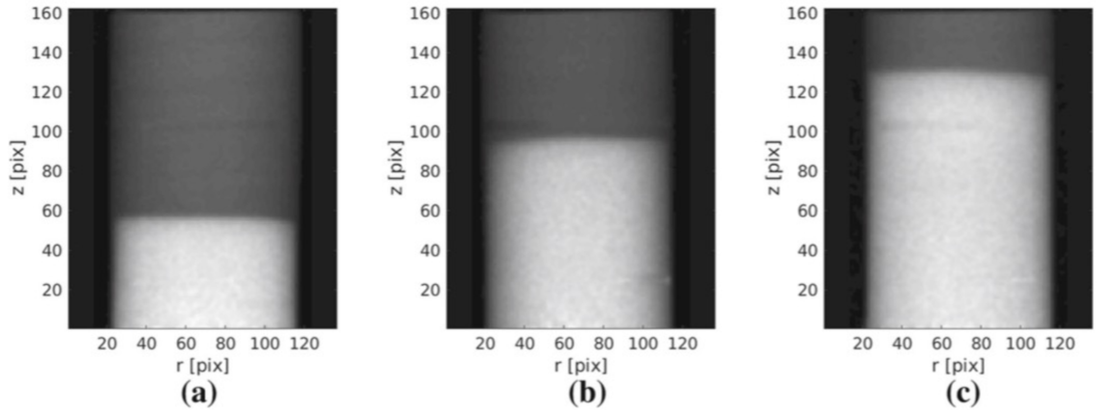


Fig. 11 Projections of the sample during the pressure-driven flow test **a** step 7, $\beta = 240°$, **b** step 21, $\beta = 0°$ and **c** step 40, $\beta = 292°$

Jailin et al., 2018

- 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

Even possible with large jumps in position during rotation

Things don’t always go to plan…..