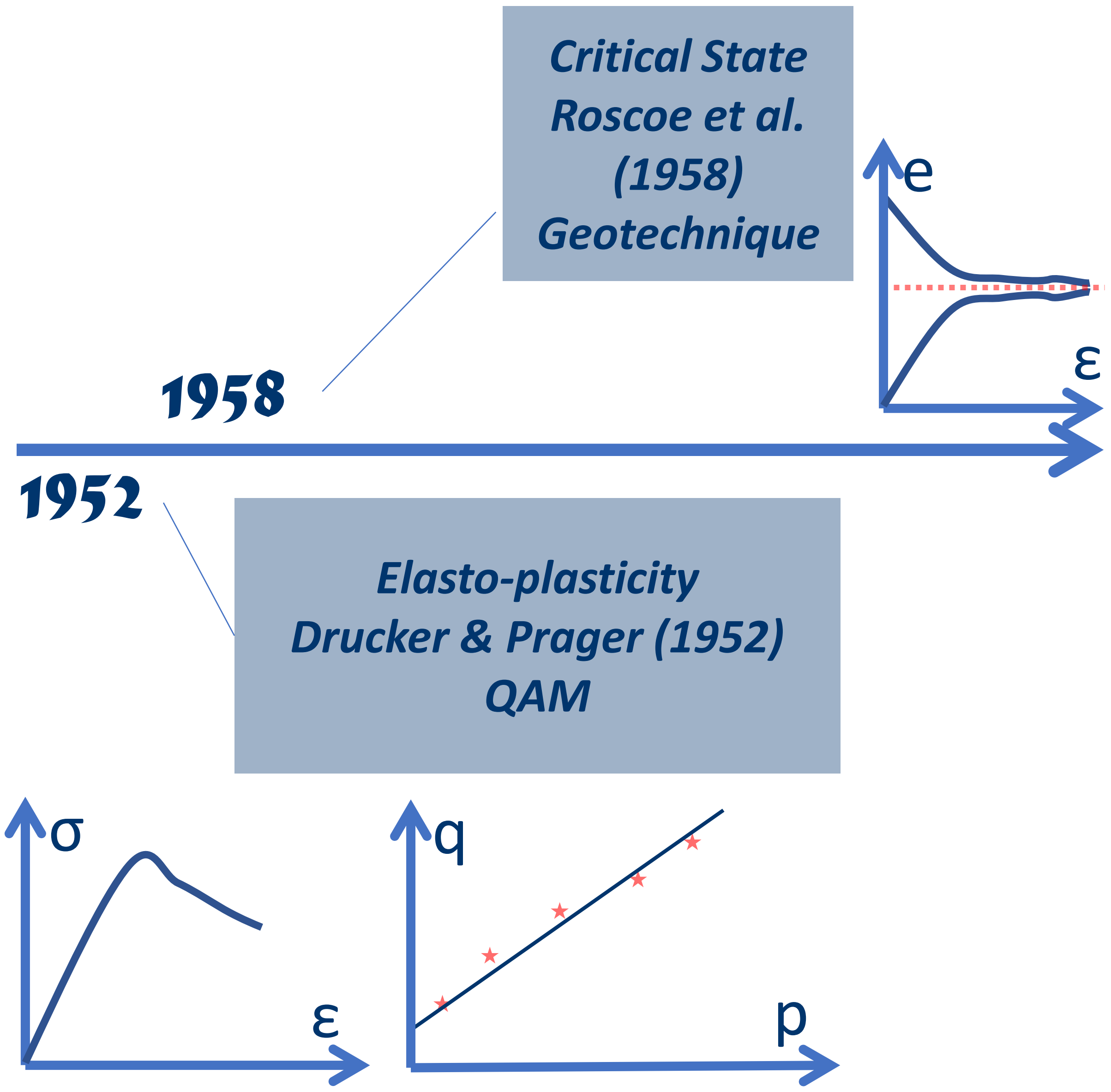
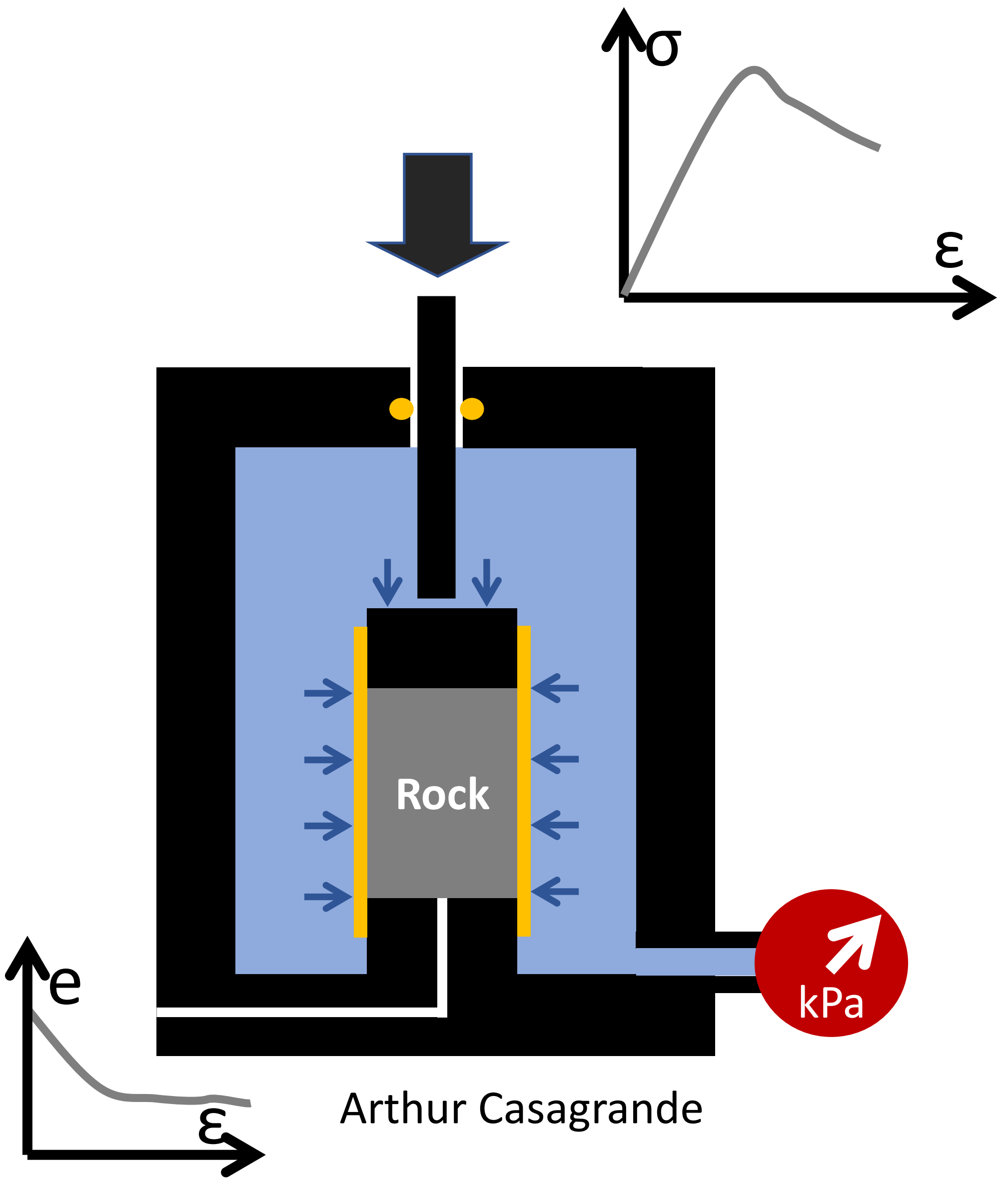
Rock Characterization through

Imaging

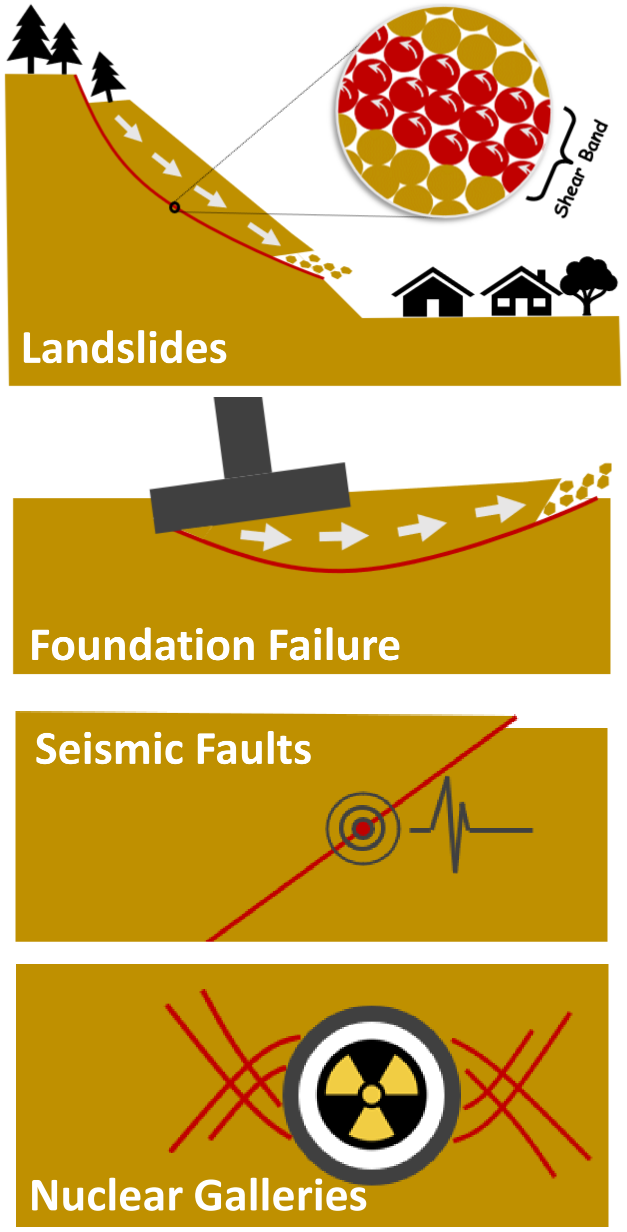
Ghassan SHAHIN

From Drucker-Prager to Breakage Mechanics

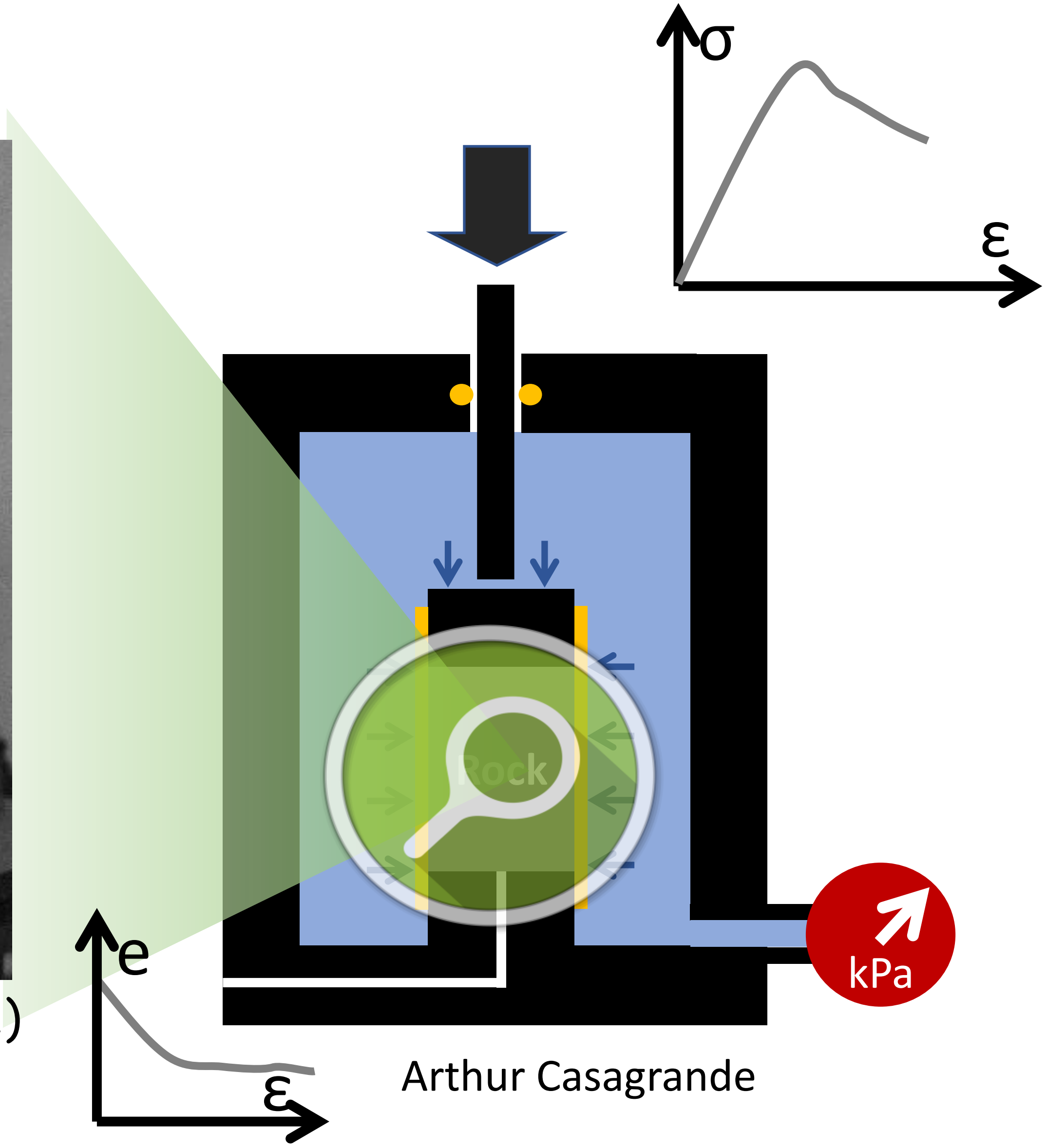




From Drucker-Prager to Breakage Mechanics



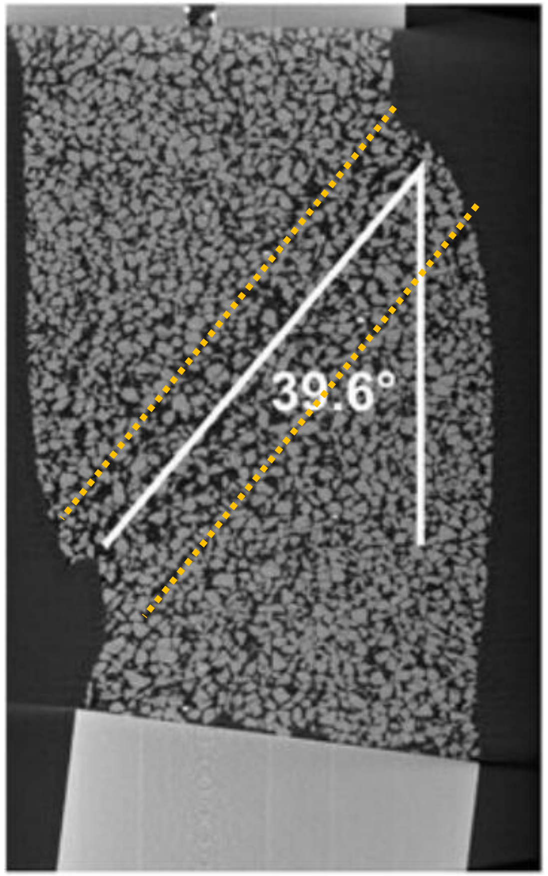
Desrues & Chambon (2002)



Arthur Casagrande

From Drucker-Prager to Breakage Mechanics

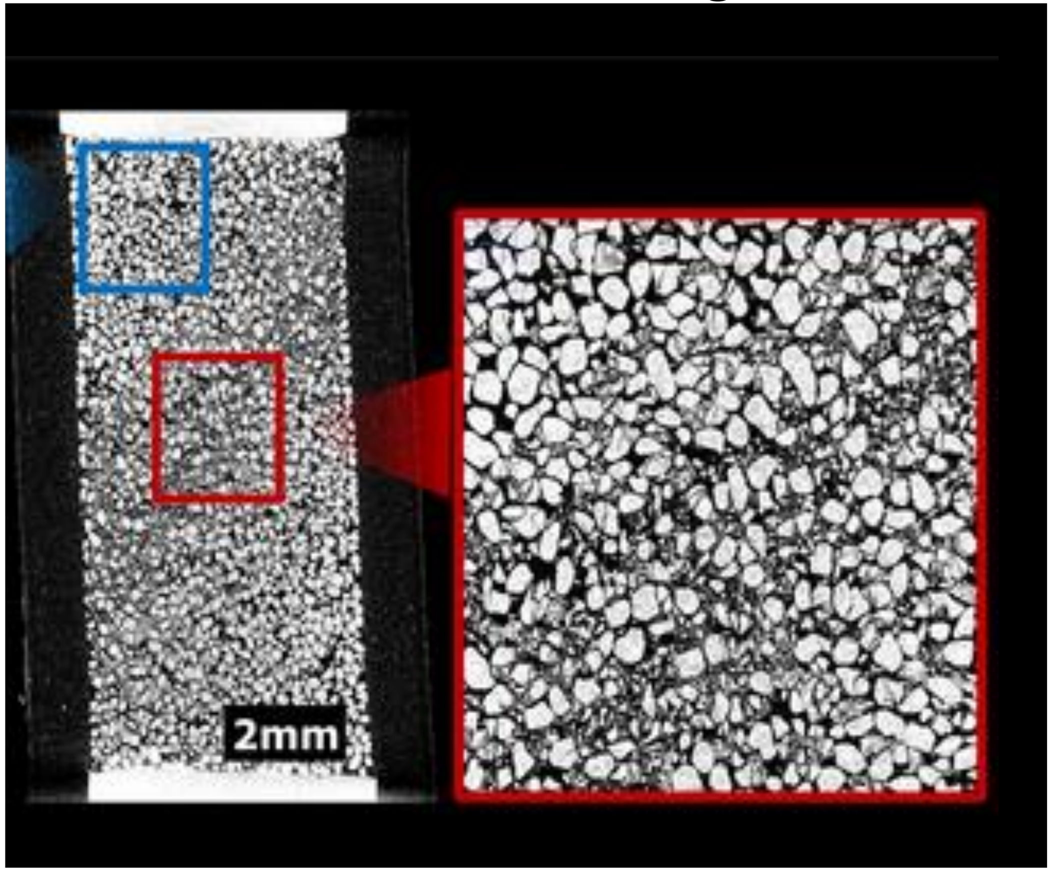
Increase in porosity
Contact Sliding



Wiebicke et al. (2017)

Desrues & Chambon (2002)

Decrease in porosity
Contact Sliding
Grain Breakage

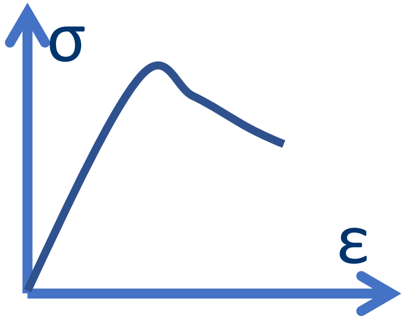


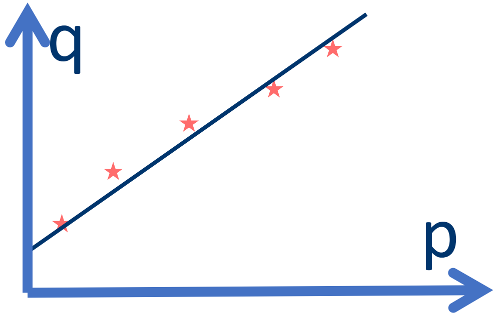
Shahin & Hurley (2022)

From Drucker-Prager to Modern Geomechanics

1952

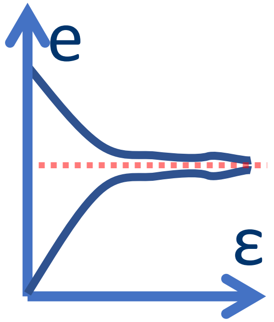
Elasto-plasticity
Drucker & Prager. (1952)
QAM





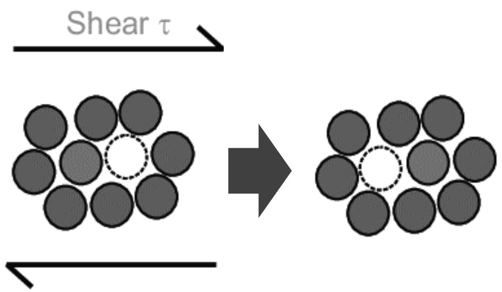
1958

Critical State
Roscoe et al.
(1958)
Geotechnique

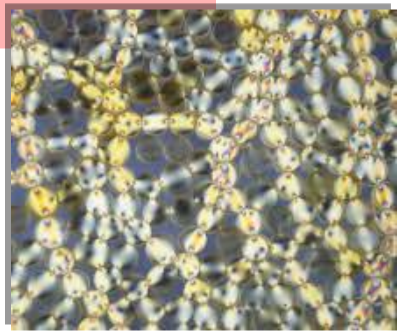


2004

Shear Transform.
Zone
Falk et al. (2004)
APS

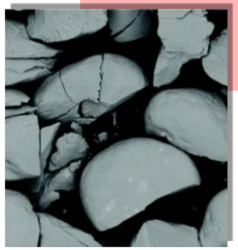


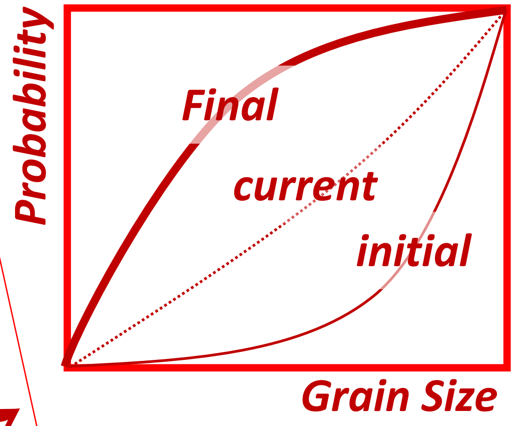
Force Chains
e.g. Peters et al.
(2005) PRE



2007

Grain Breakage
Einav. (2007)
JMPS

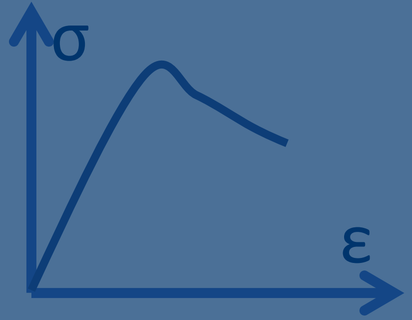


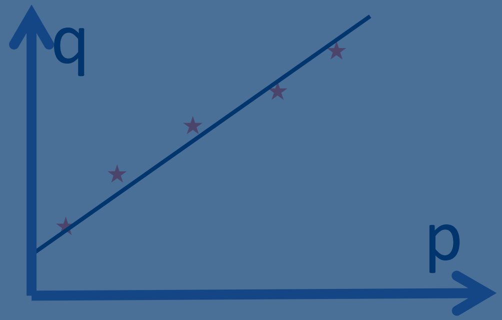


From Drucker-Prager to Modern Geomechanics

1952

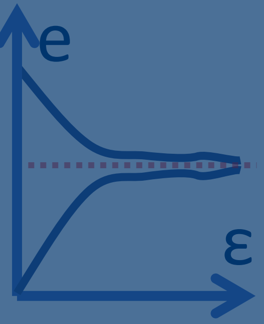
Elasto-plasticity
Drucker & Prager. (1952)
QAM





1958

Critical State
Roscoe et al.
(1958)
Geotechnique

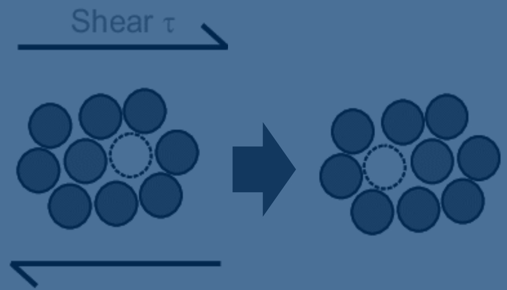


2004

Kinematic

Shear Tr... m.

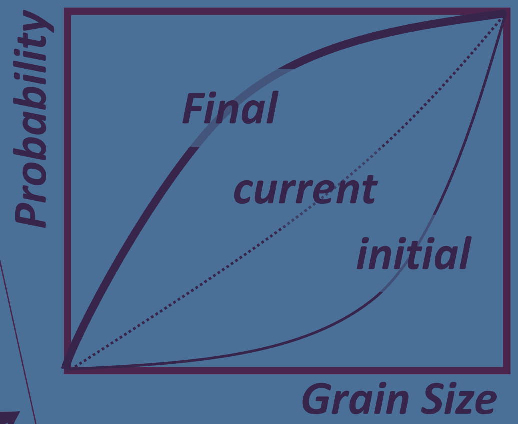
APS

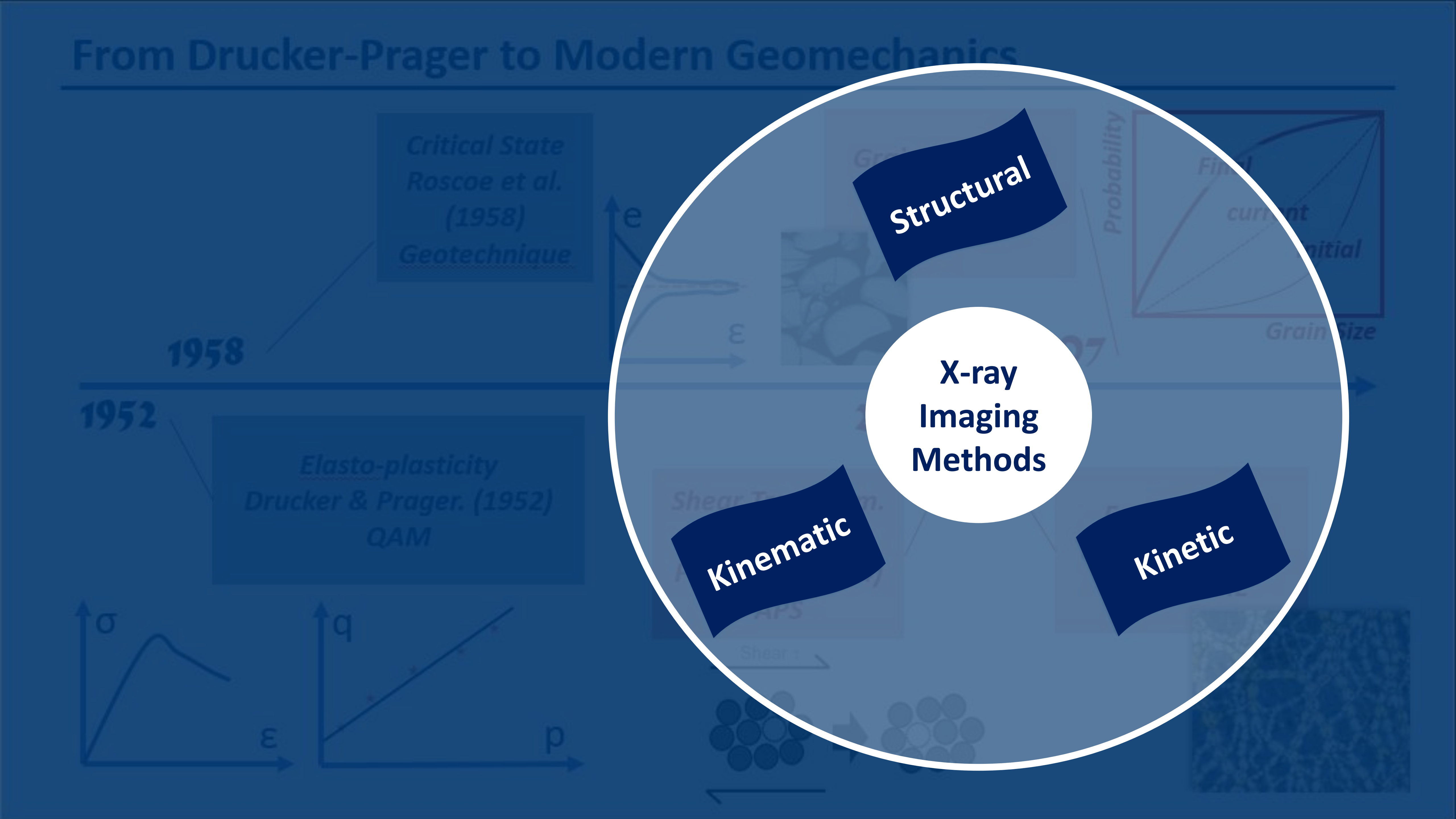


Kinetic

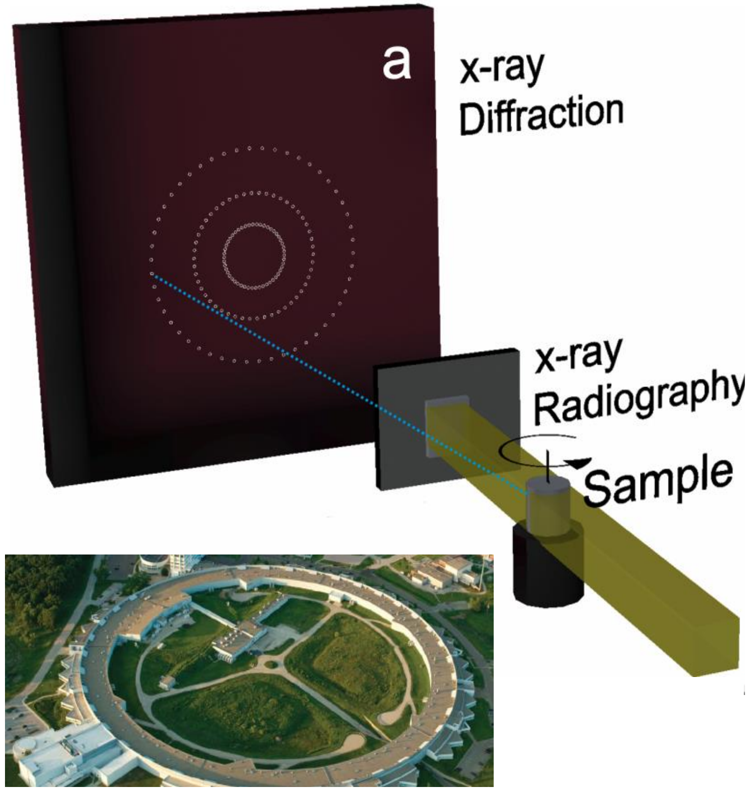
2007

Structural




From Drucker-Prager to Modern Geomechanics
Critical State
Roscoe et al.
(1958)
Geotechnique
1958
1952
Elasto-plasticity
Drucker & Prager. (1952)
QAM
σ
ε
q
p
e
ε
Probability
Grain Size
Structural
X-ray
Imaging
Methods
Kinematic
Kinetic

Lecture Outline



X-ray Methods
measuring grain resolved stress & strain

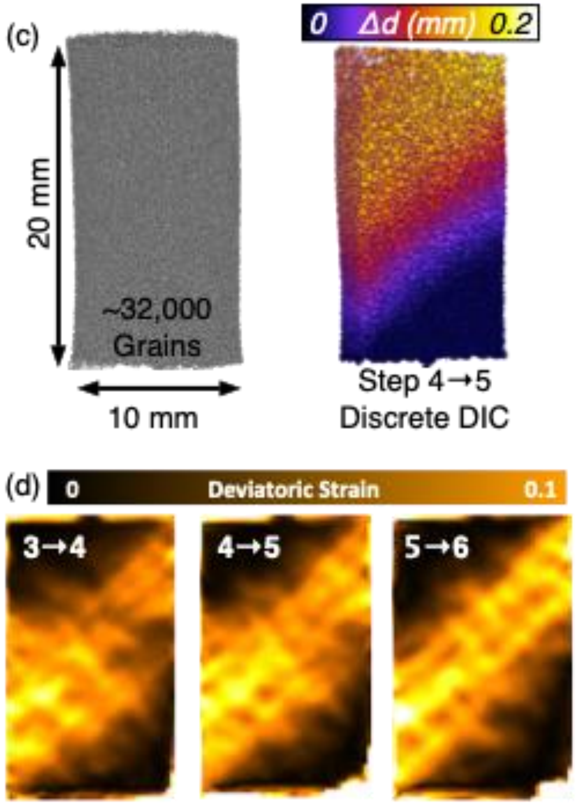
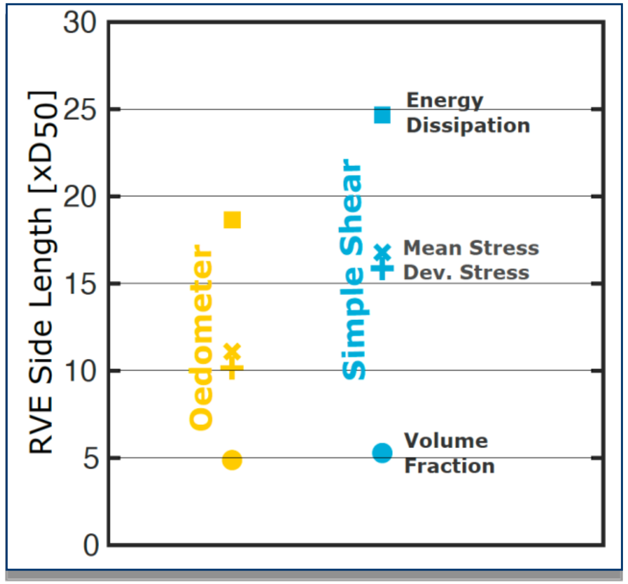


Image Analysis
quantifying morphology, stress, and strain evolution

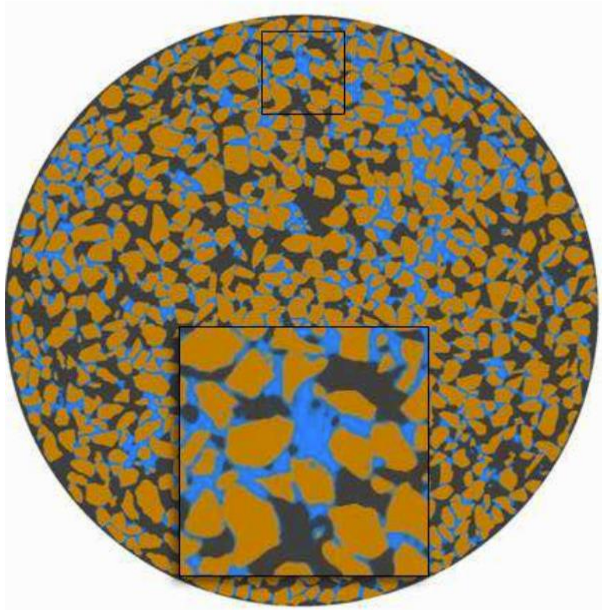


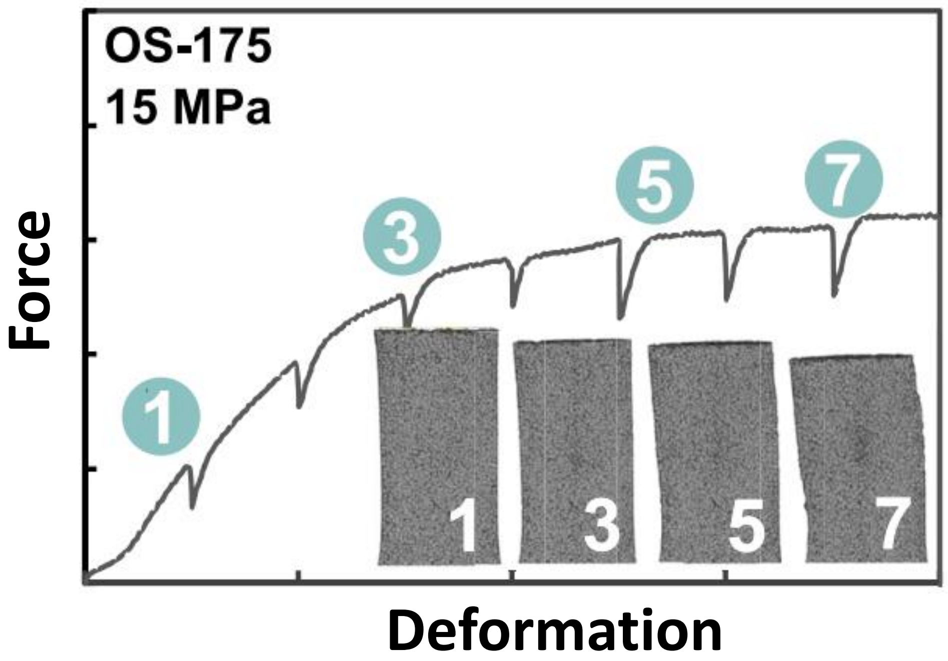
Applications
addressing fundamental and applied quests

X-ray Computed Tomography (Micro-CT)

High resolution imaging of internal structures of any materials from mm scale down to the sub micron scale

It is **three-dimensional** and **non-destructive**





Examples

Principles of X-ray Imaging

Beer-Labert Law

Path Length

$$I = I_0 \exp^{-\mu x}$$

Attenuation Coefficient

The attenuation coefficient for x-rays tends to follow the atomic number

Iron
Aluminum
Concrete
SiO2
PMMA
Tissue-Soft

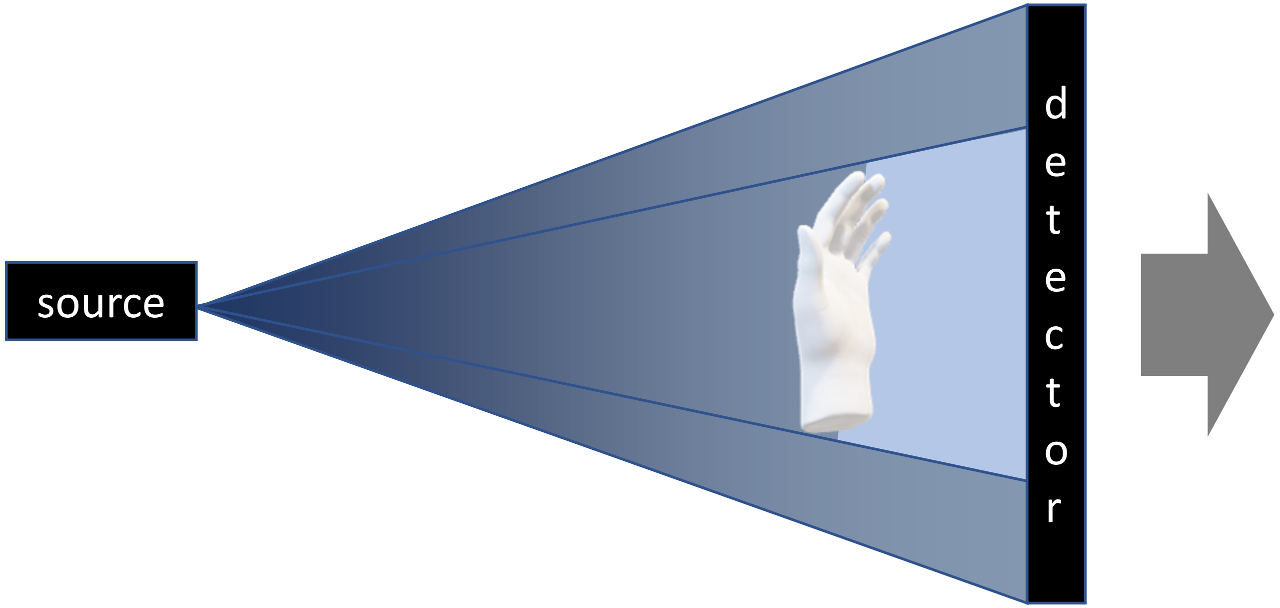
Target Material:	He
X-Ray Energy [keV]:	100 -> 10?
Target length [mm]:	10
Pressure (only gases) [atm]:	1
	Calculate!

http://web-docs.gsi.de/~stoe_exp/web_programs/x_ray_absorption/index.php

KeV->Kilo Electron Volts

X-ray to Radiography

A panel detector records the transmitted x-ray and converts it to a 2D matrix of values (called Radiograph)



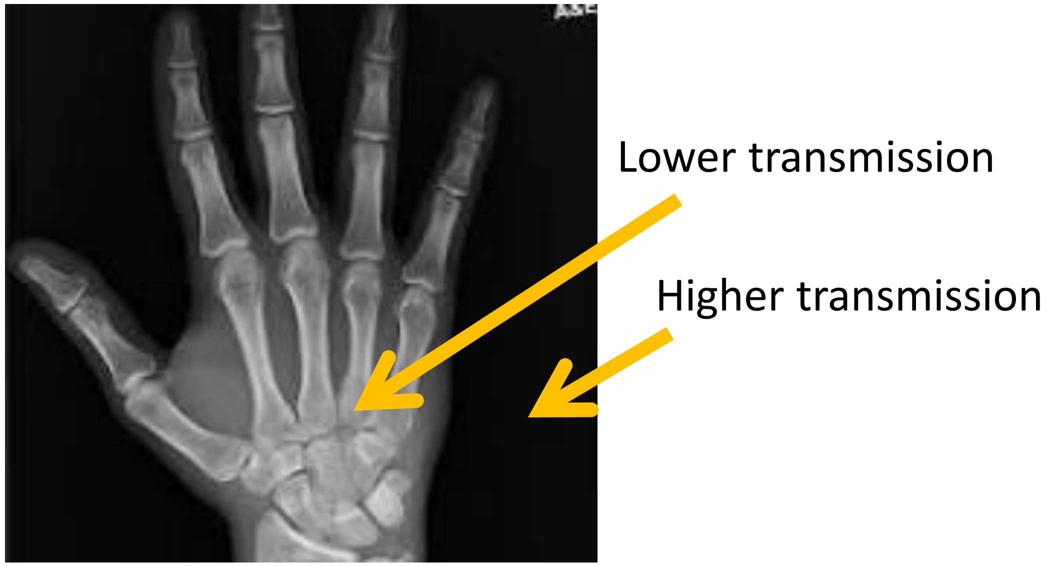
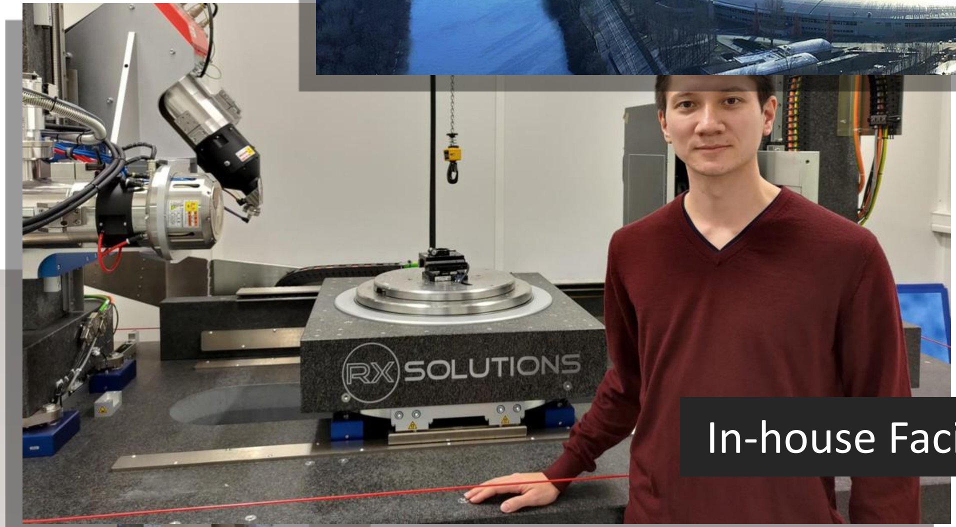


Image quality is controlled by the exposure time and intensity of transmitted x-ray

X-ray Sources

Wilhelm Conrad Roentgen (1895)

Synchrotron

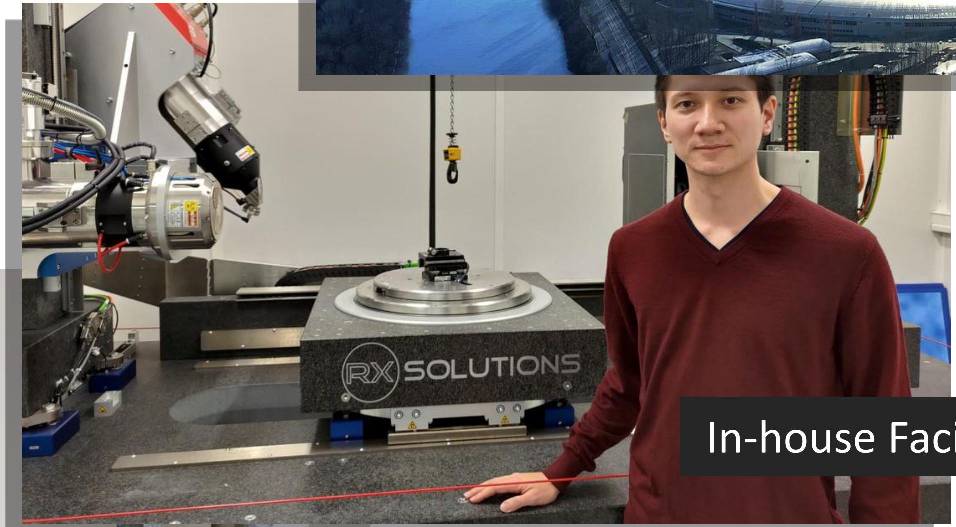


In-house Facilities

Clinical/medical

X-ray Sources

Synchrotron

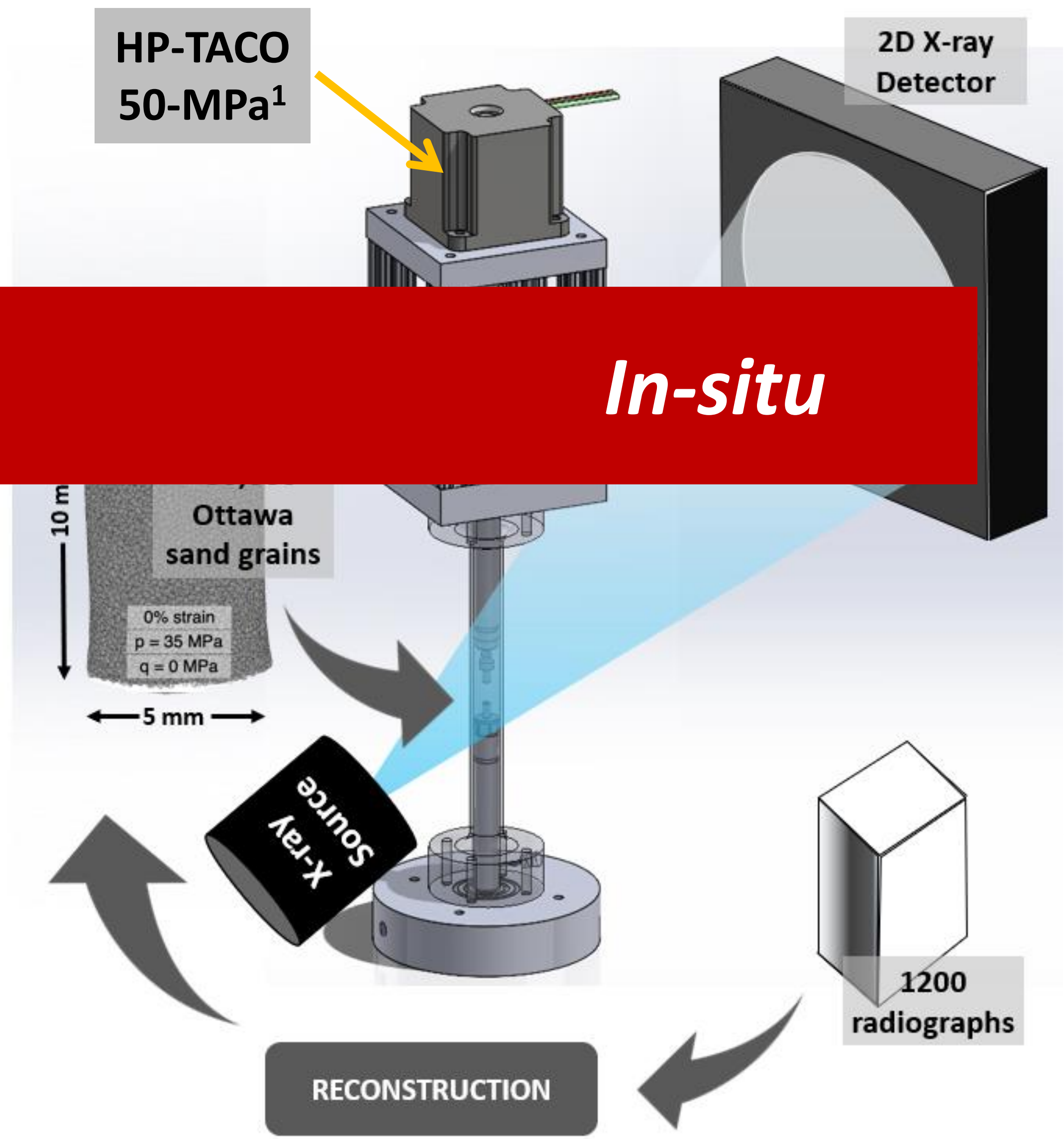


In-house Facilities

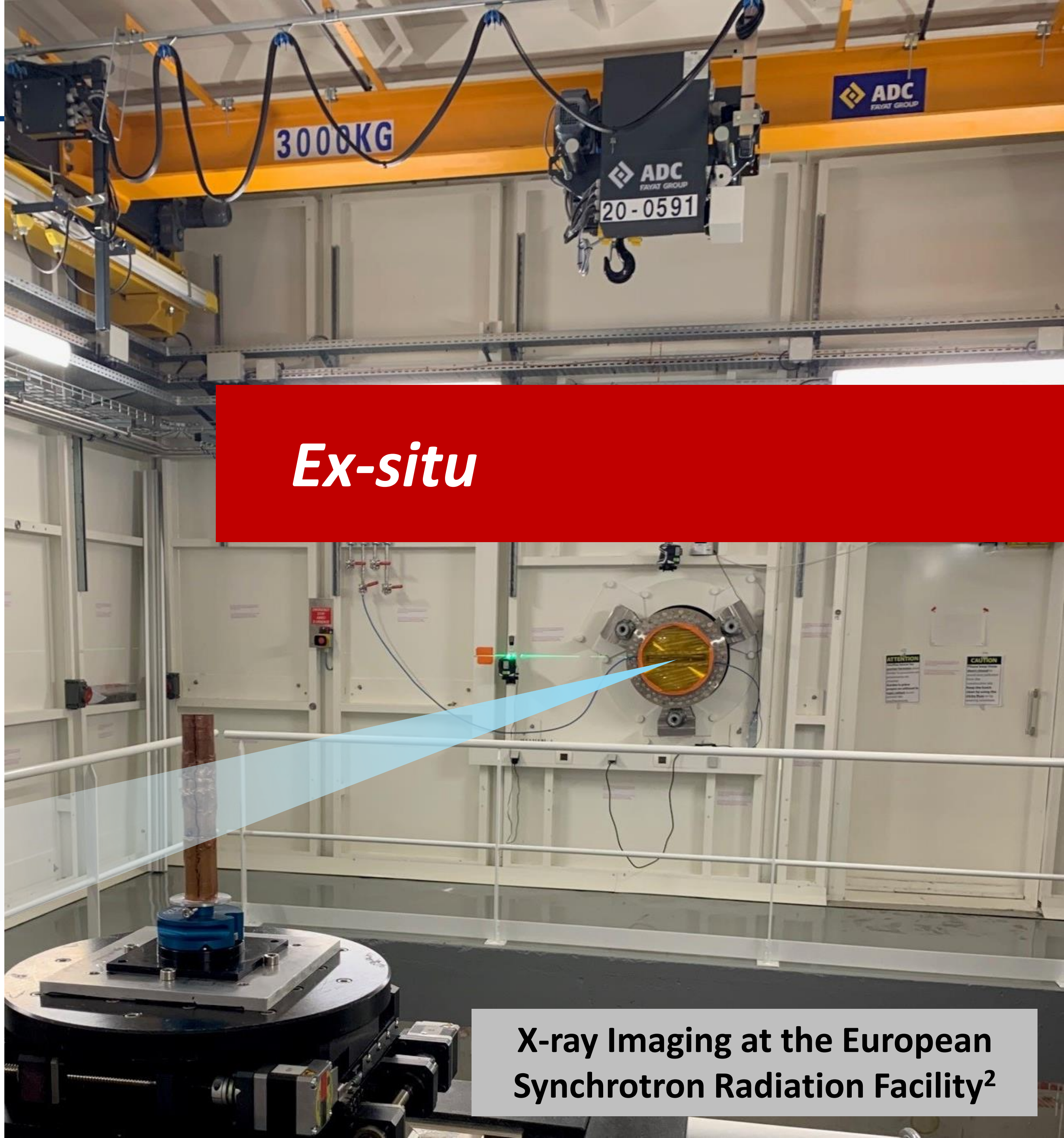
Clinical/medical

X-ray Imaging Approaches

In-situ



Ex-situ

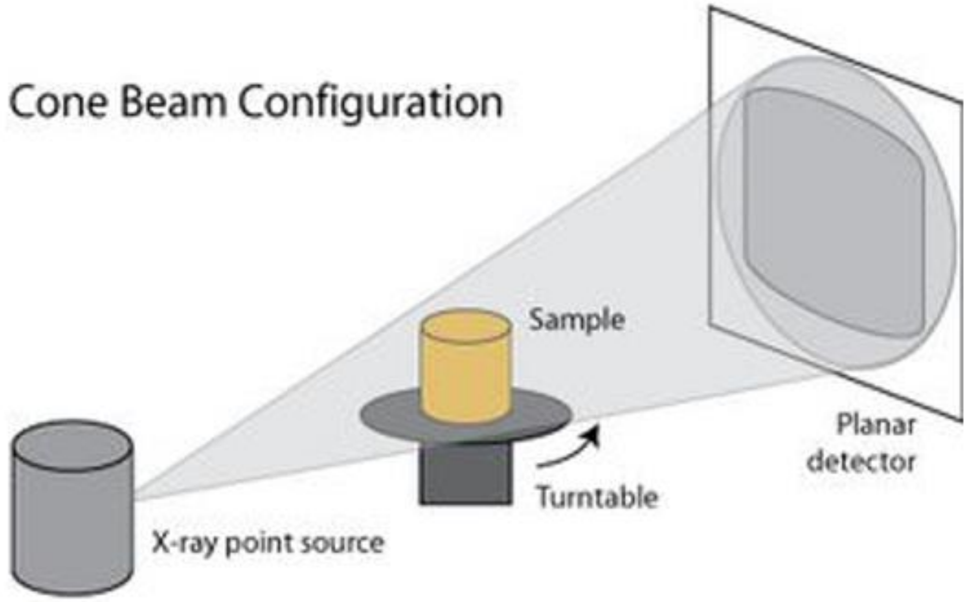


X-ray Imaging at the European Synchrotron Radiation Facility[2]

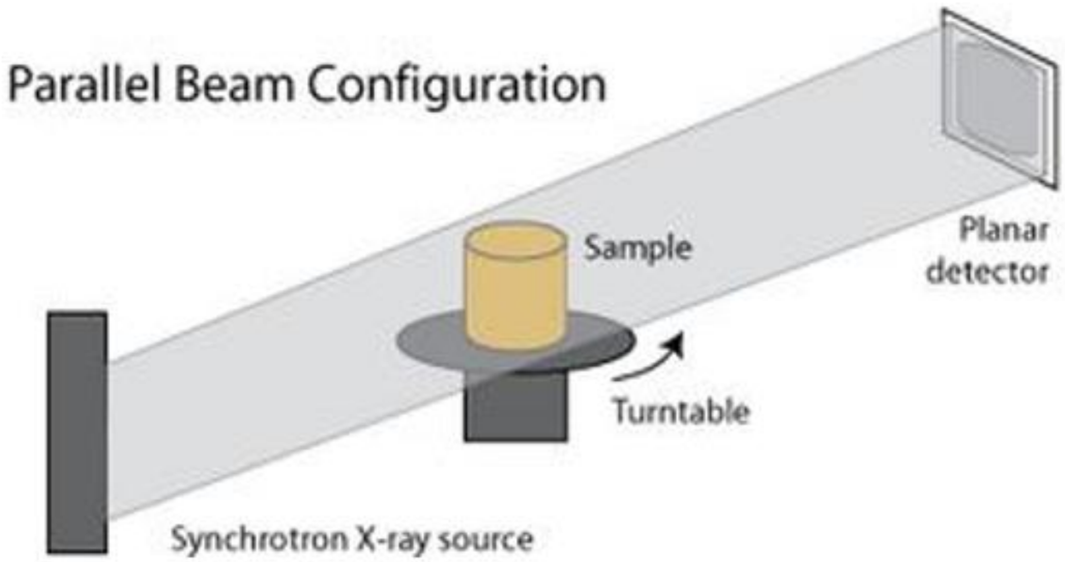
[1]Shahin and Hurley, *RSI,* (2022). [2]Meyer et al. (in prep)

X-ray Beam Configuration

X-ray sources used in CT feature either a Cone Beam configuration or a Parallel Beam configuration



Variable Resolution

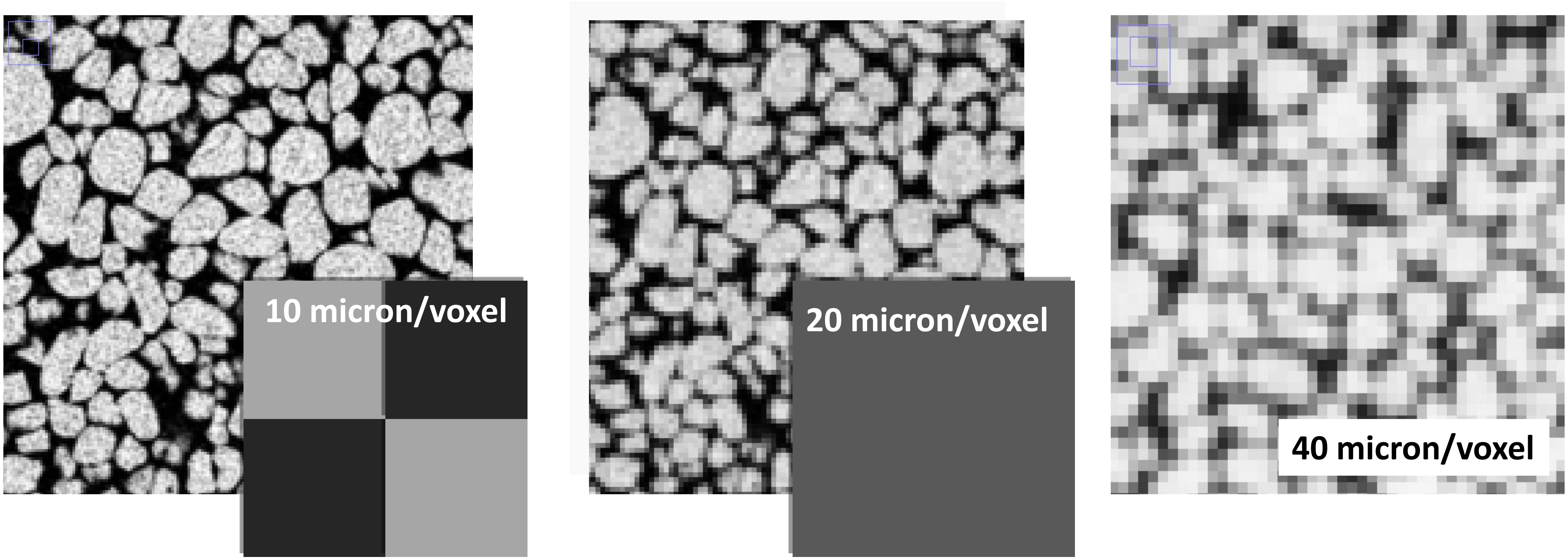


Fixed Resolution

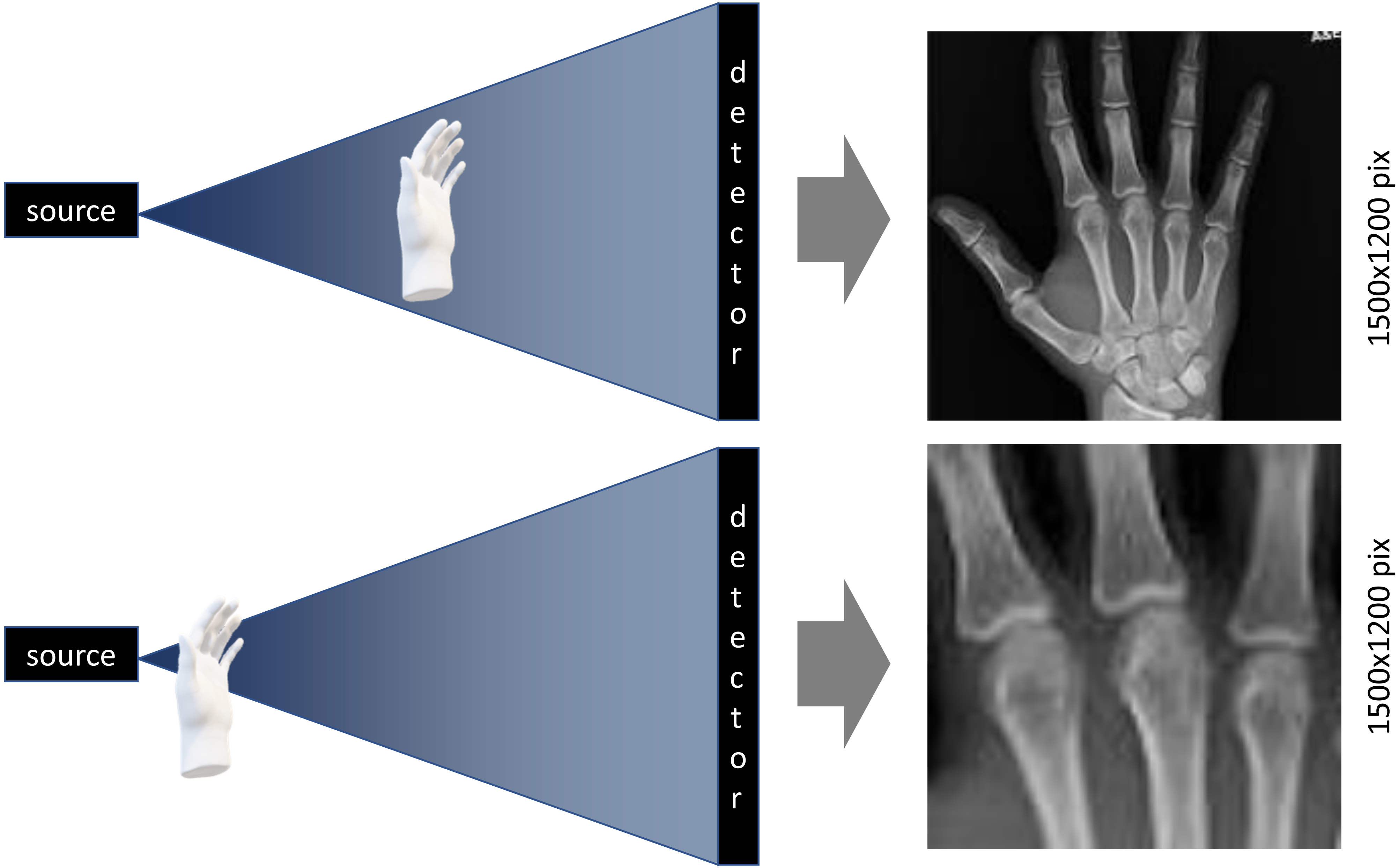
Resolution

Image resolution indicates the level of details microstructures are characterized through imaging and is:

- In cone beams: varies depending on the source-sample-detector distances
- In parallel beams: geometry independent

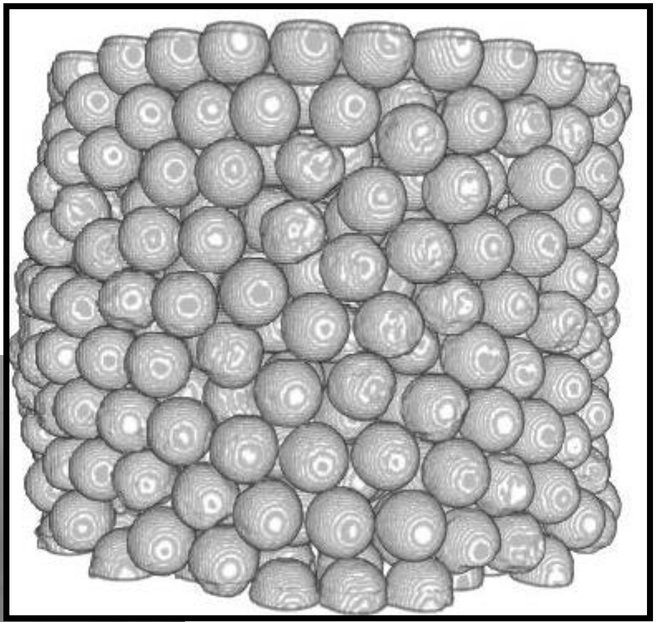


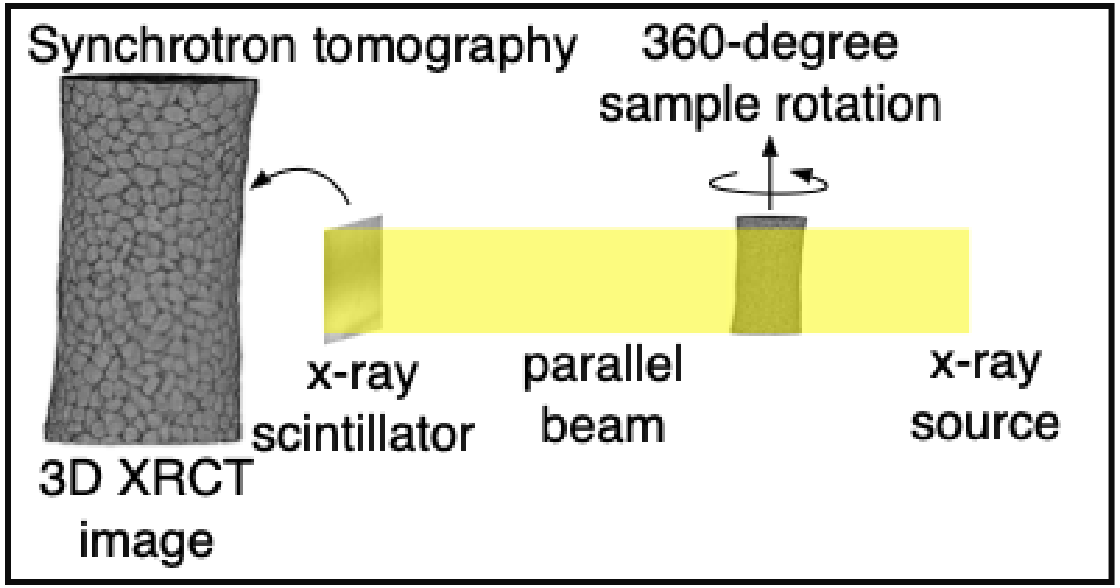
Resolution


source
detector
1500x1200 pix
source
detector
1500x1200 pix

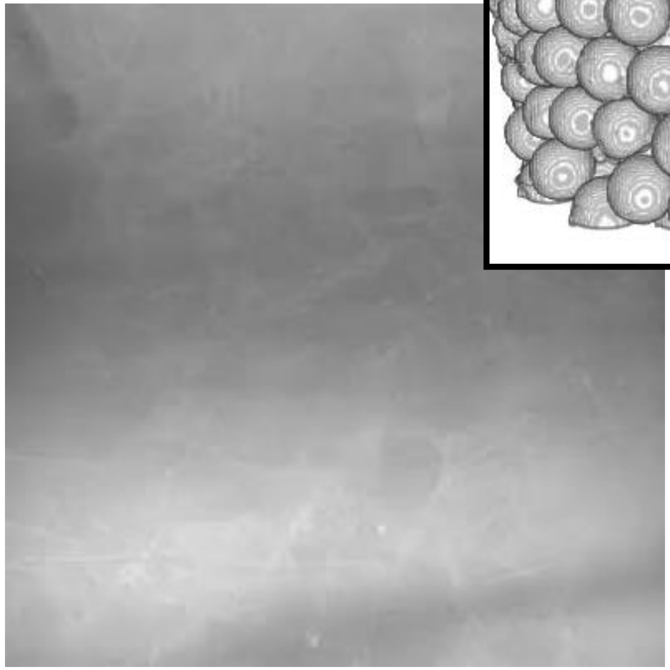
From Radiography to Tomography

X-ray tomography is acquired through successive scans of a sample rotating 360 degrees at small increments. Algorithms are used to reconstruct 3D visualization (tomography) from the 2D X-ray projections (radiography)



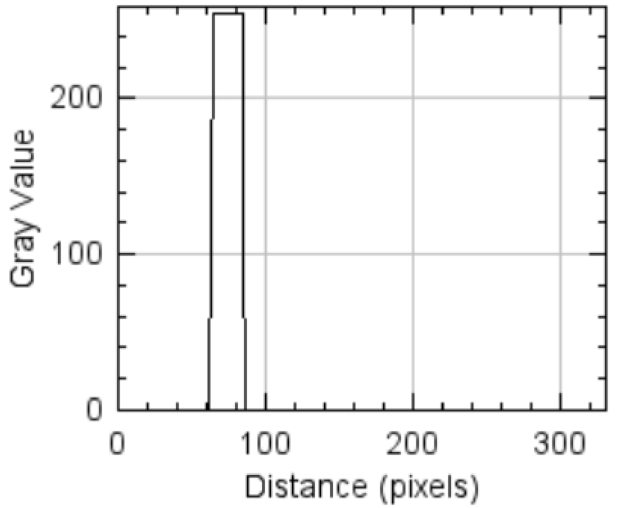


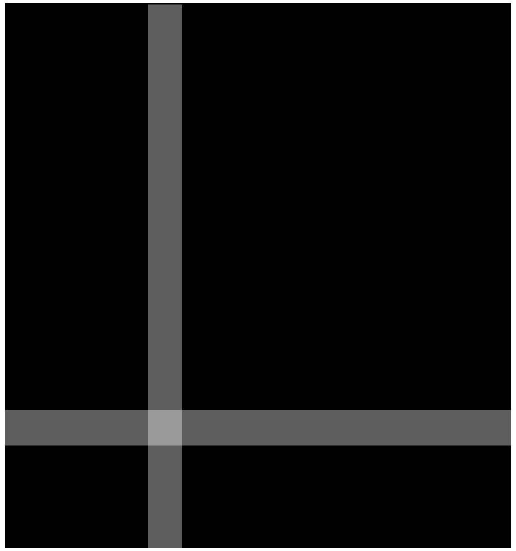
Principle of synchrotron XRT

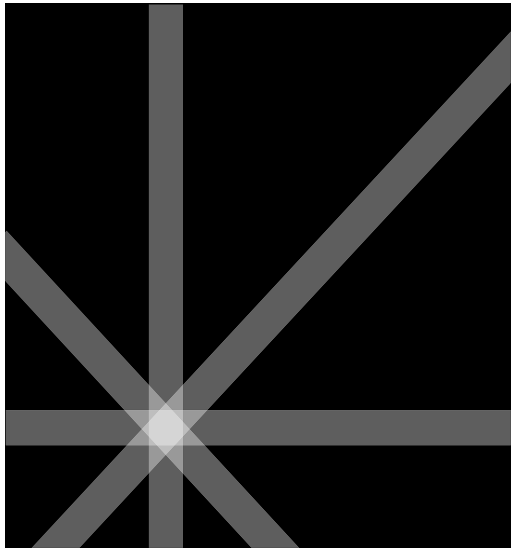


View of angular quartz on scintillator during 360°sample rotation.

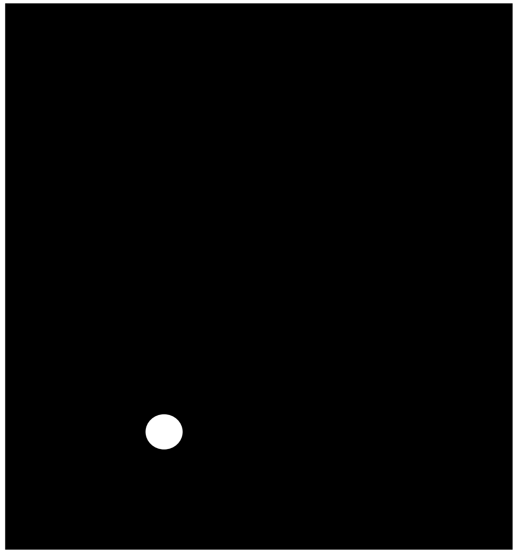
From Radiography to Tomography

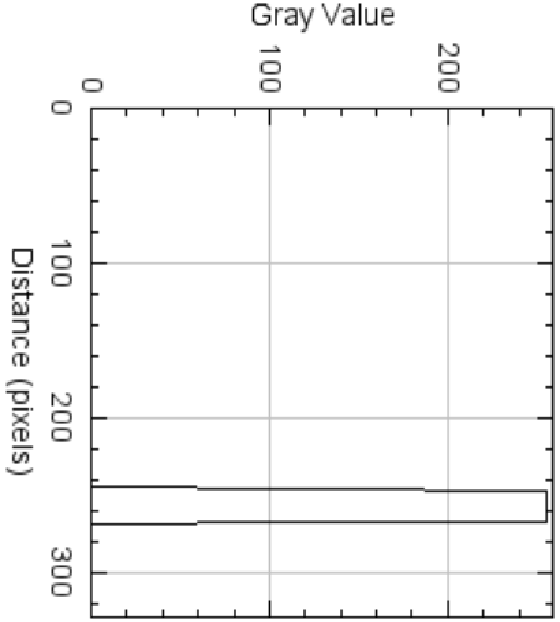


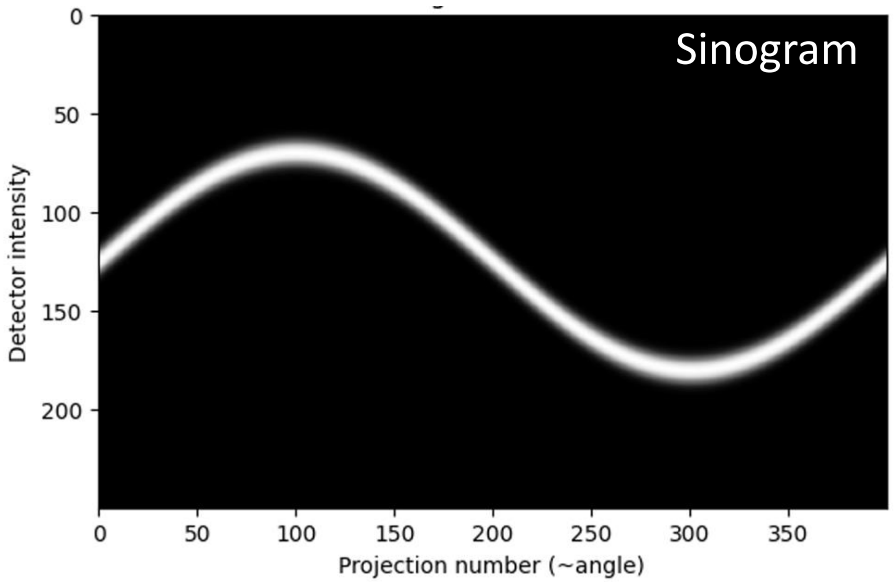




The inverse problem of Radon transform

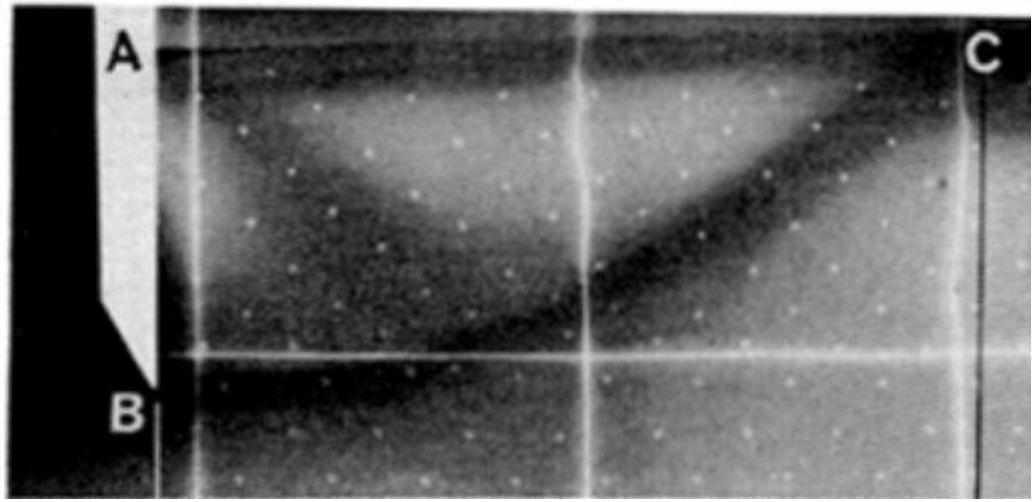






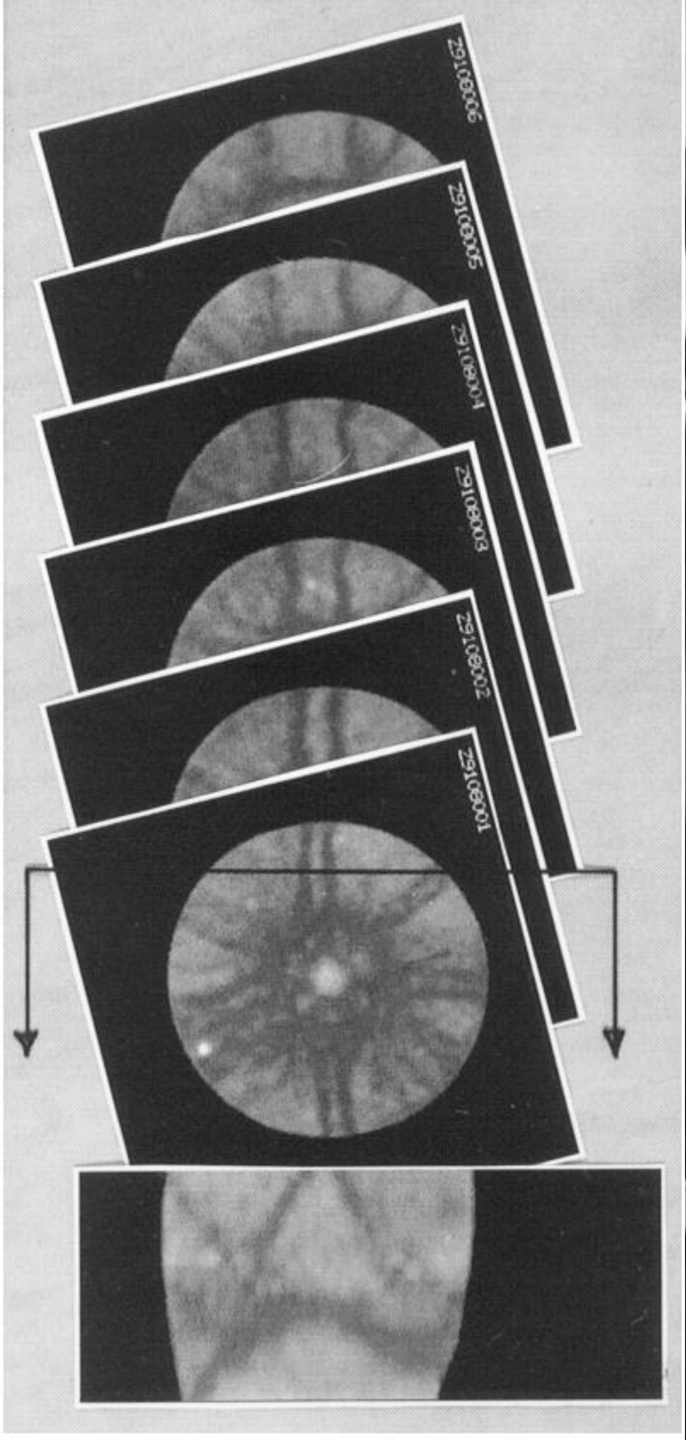
Applications in Geomechanics

First Applications



Roscoe (1970) Geotechnique
Cambridge University

First Applications

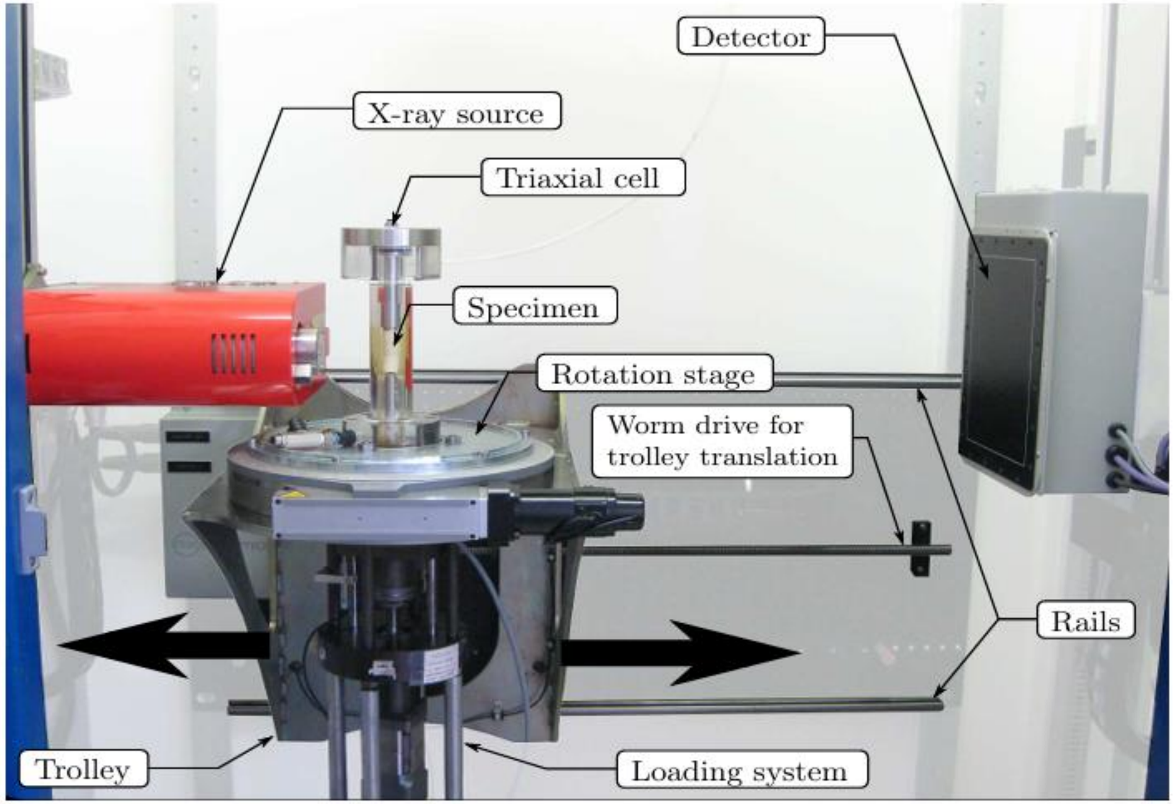


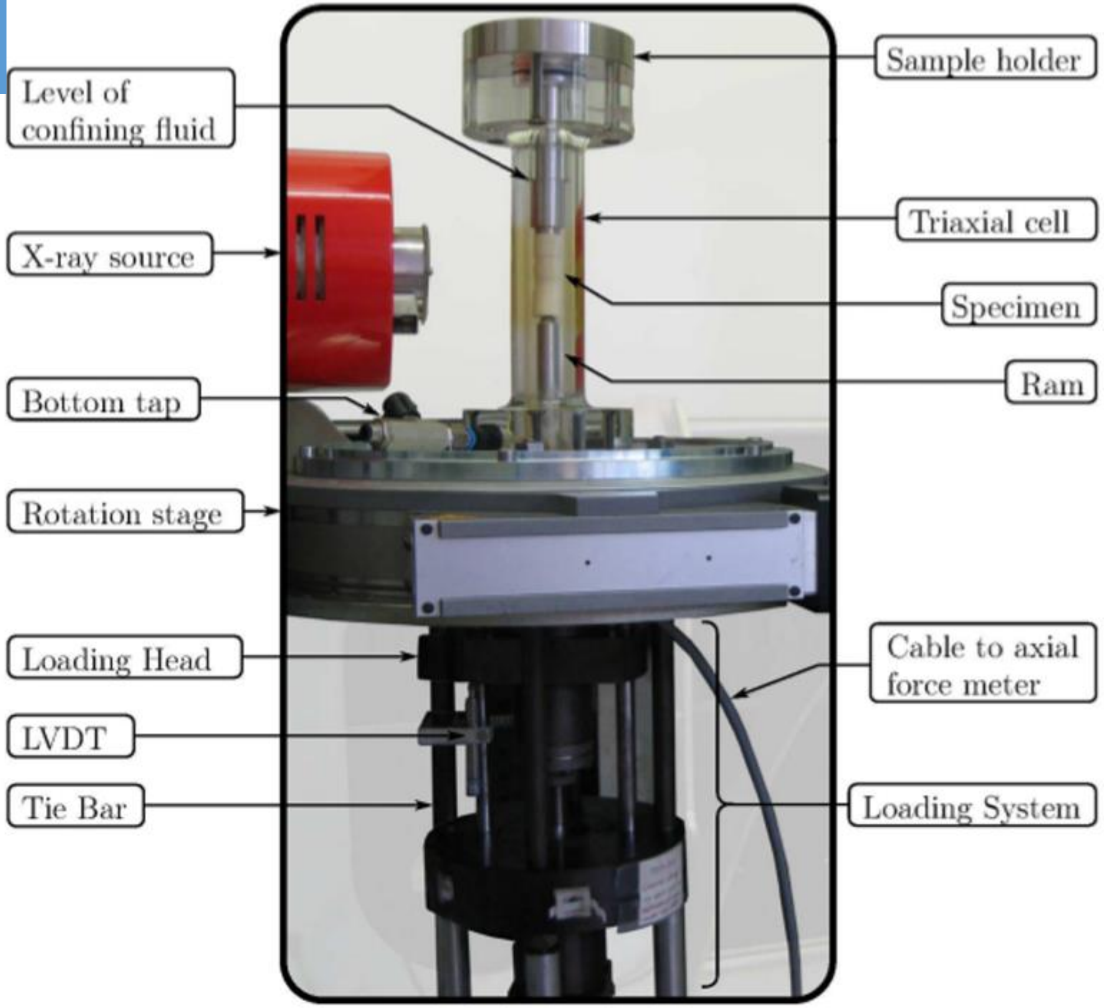
Jacques Desrues
Laboratory 3SR
Univ. Grenoble Alpes

Desrues et al (1996) Geotech.

In-situ Imaging with Mechanical Testing

Laboratory 3SR, University of Grenoble Alpes





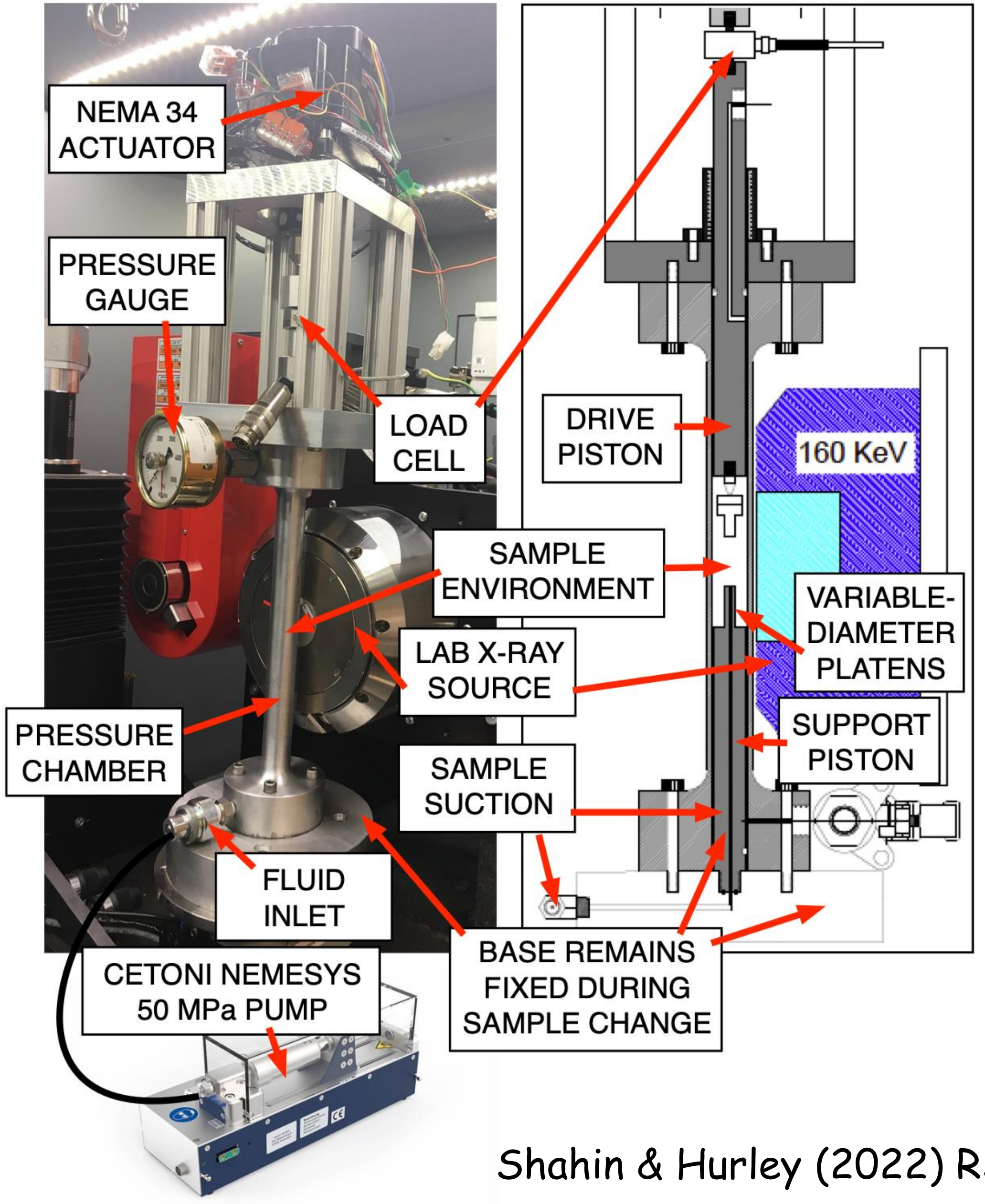
Experiments are limited to 7 MPa Confining Pressure

Andò et al. (2013) PhD thesis

In-situ Imaging with Mechanical Testing

Johns Hopkins University

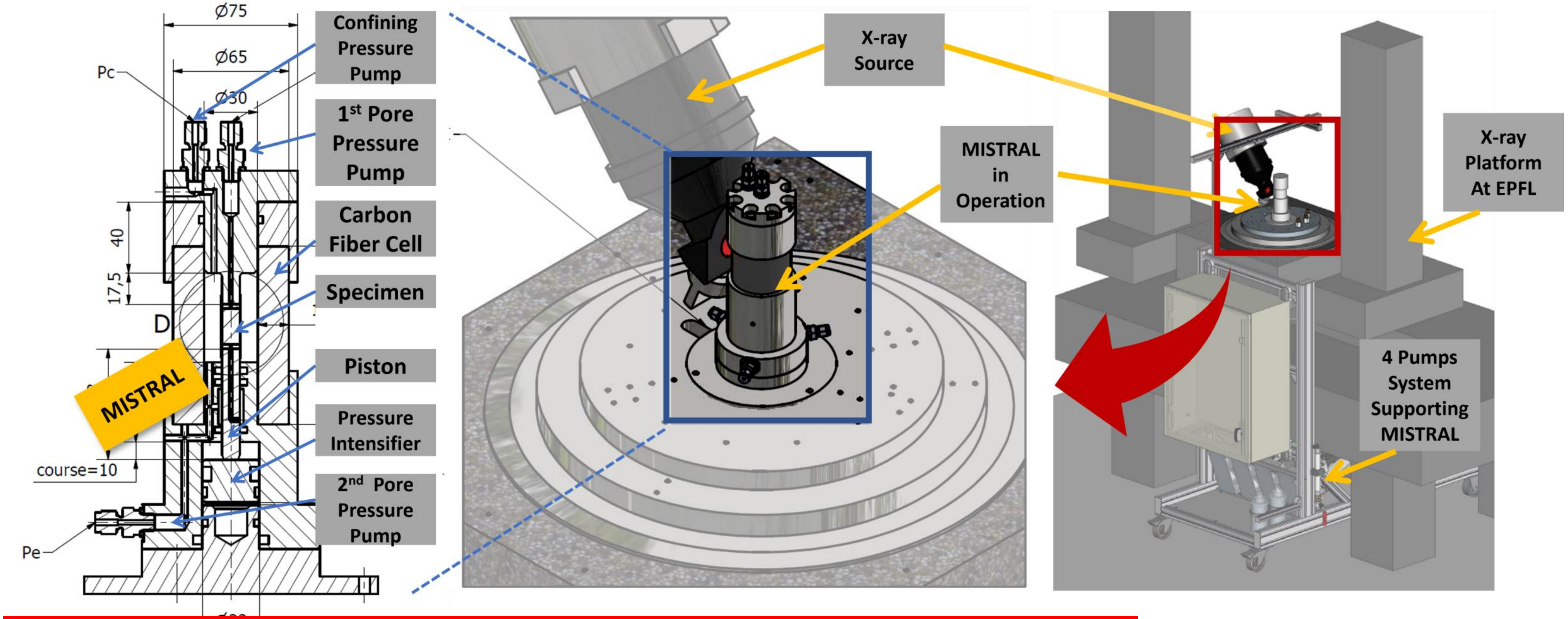
Experiments up to 50 MPa Confining Pressure



Shahin & Hurley (2022) RSI

In-situ Imaging with Mechanical Testing

EPFL

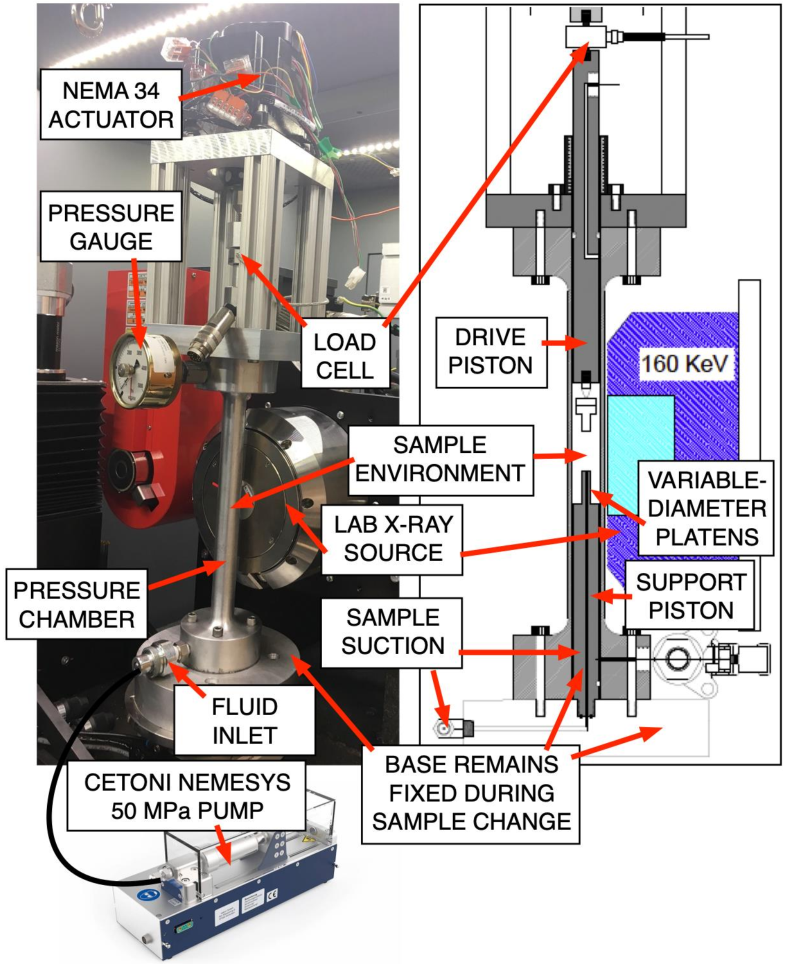


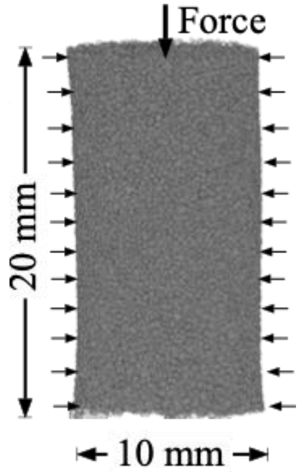
Experiments up to 150 MPa Confining Pressure

Shahin & Violay (in prep.)

Example 1: In-situ Imaging with Mechanical Testing

Compression experiments under 15 MPa and 35 MPa on Ottawa sand specimens with *in-situ* X-ray Imaging

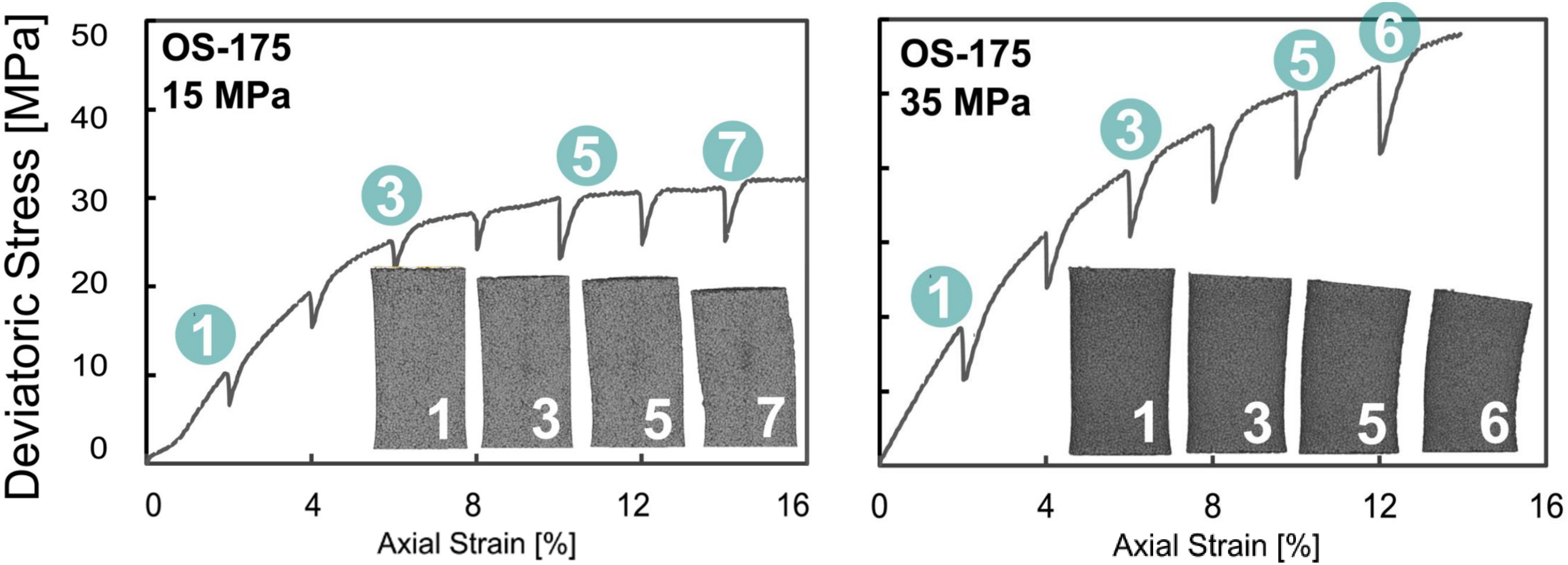




Shahin & Hurley (2022) JGR

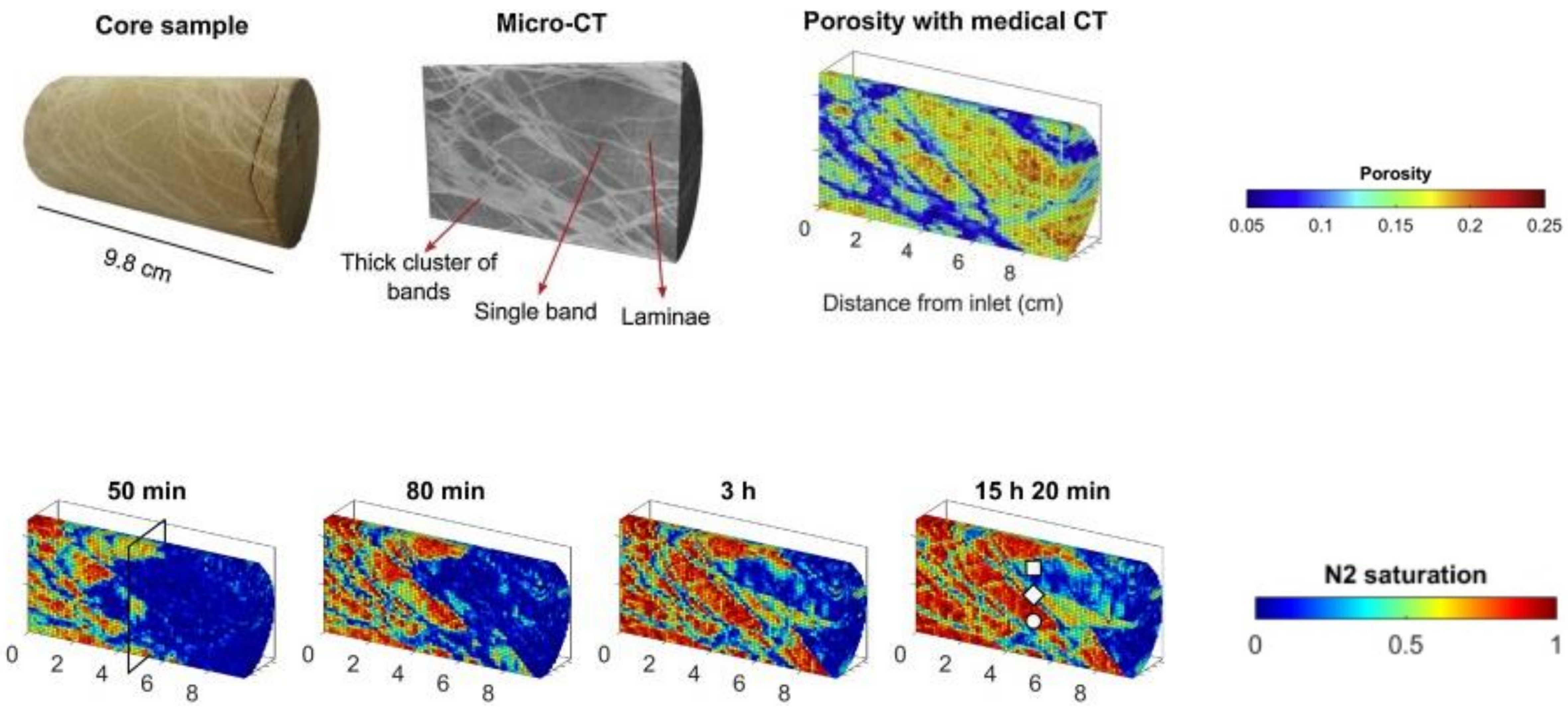
In-situ Imaging with Mechanical Testing

Compression experiments under 15 MPa and 35 MPa on Ottawa sand specimens with *in-situ* X-ray Imaging



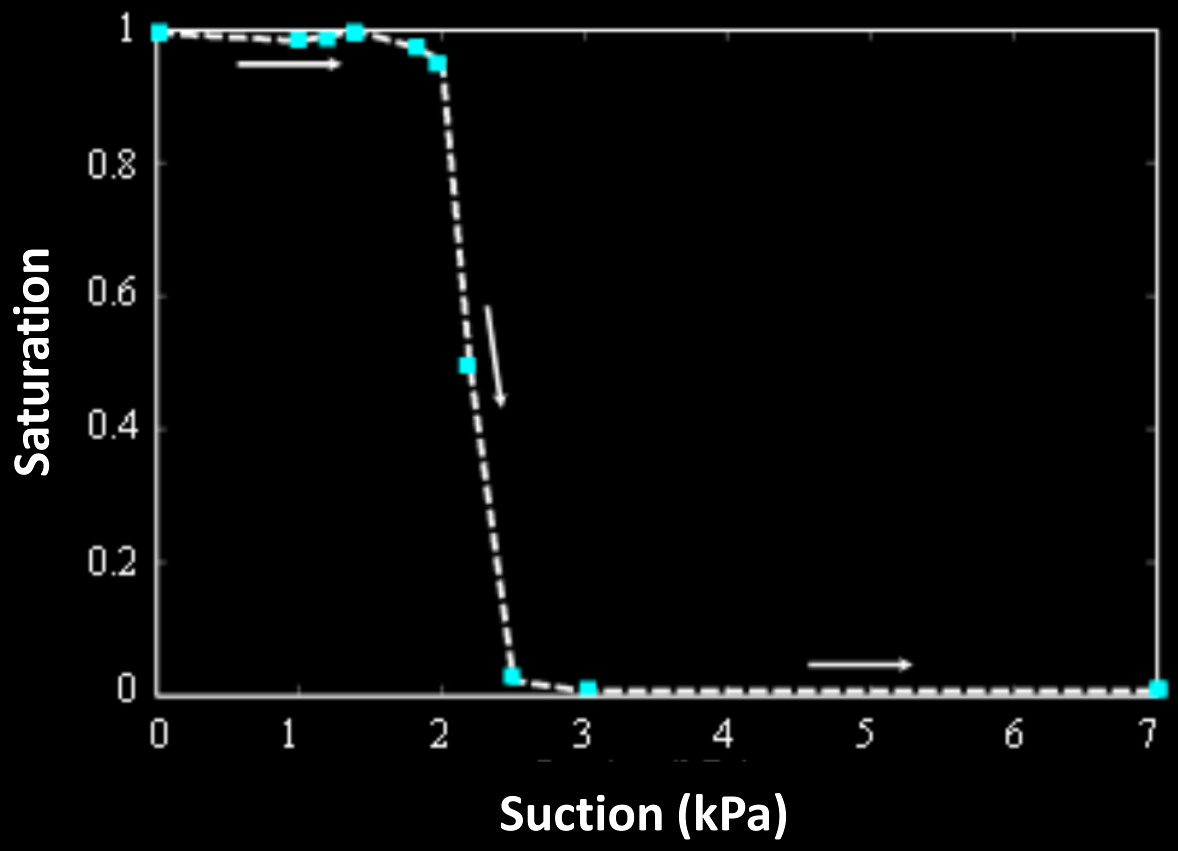
Shahin & Hurley (2022) JGR

Example 2: Tracking Saturation of N2 over Time



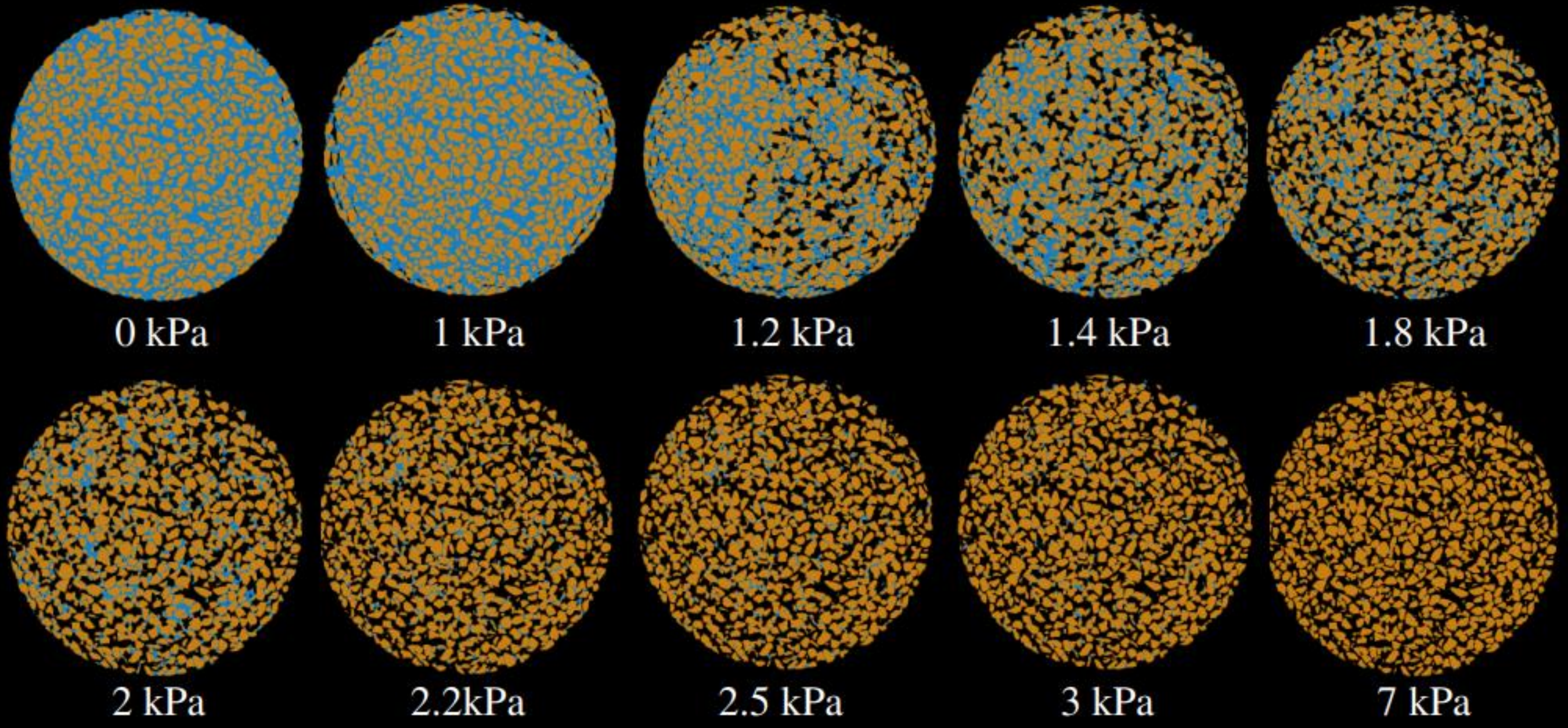
Romano et al. (2021) IJGGC

Example 3: Water Distribution during Soil Wetting and Drying



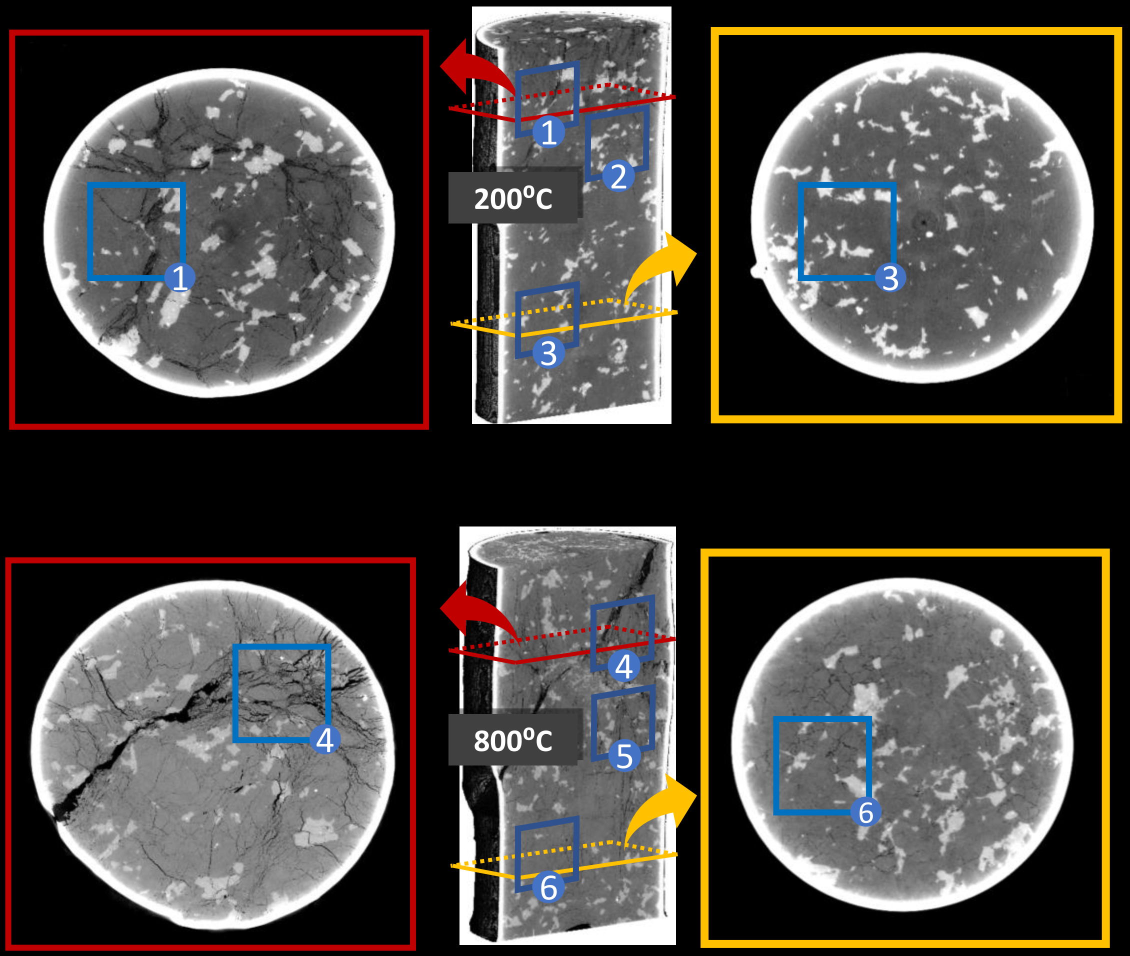
G. Khaddour (2015) PhD Thesis

Example 3: Water Distribution during Soil Wetting and Drying

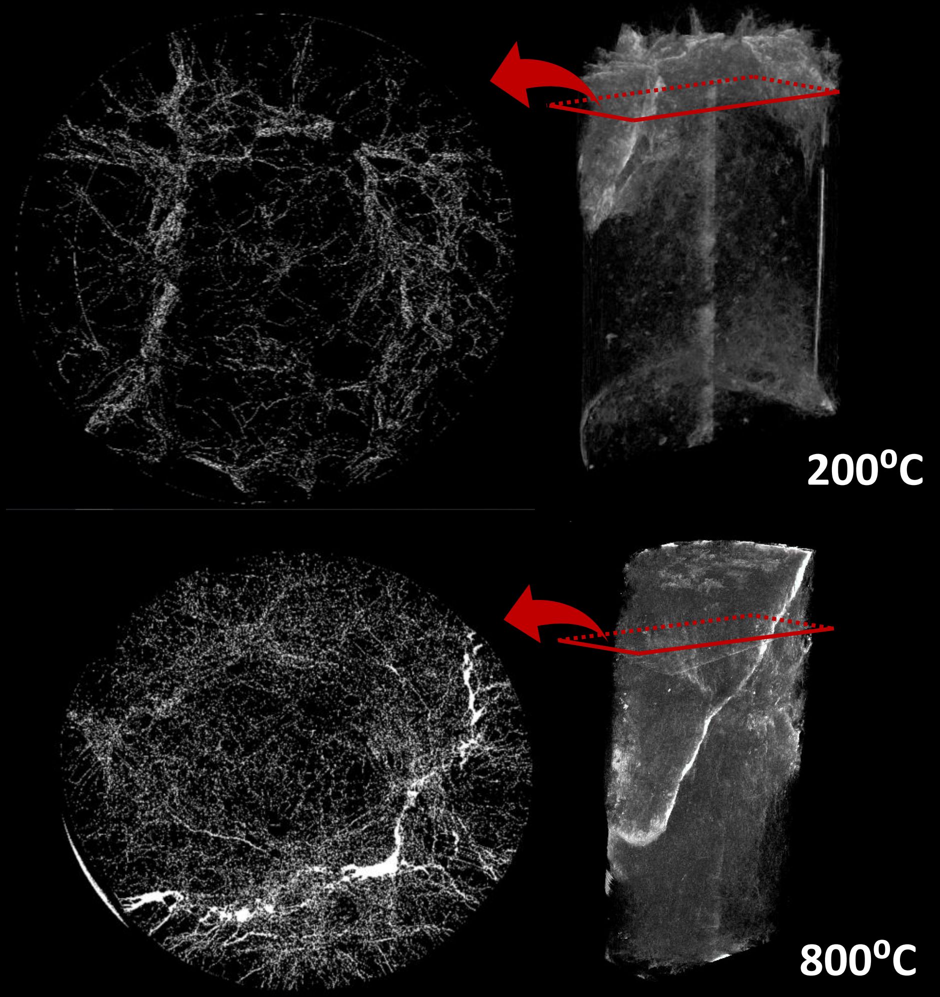


G. Khaddour (2015) PhD Thesis

Example 4: Assess Permeability In Deep Earth

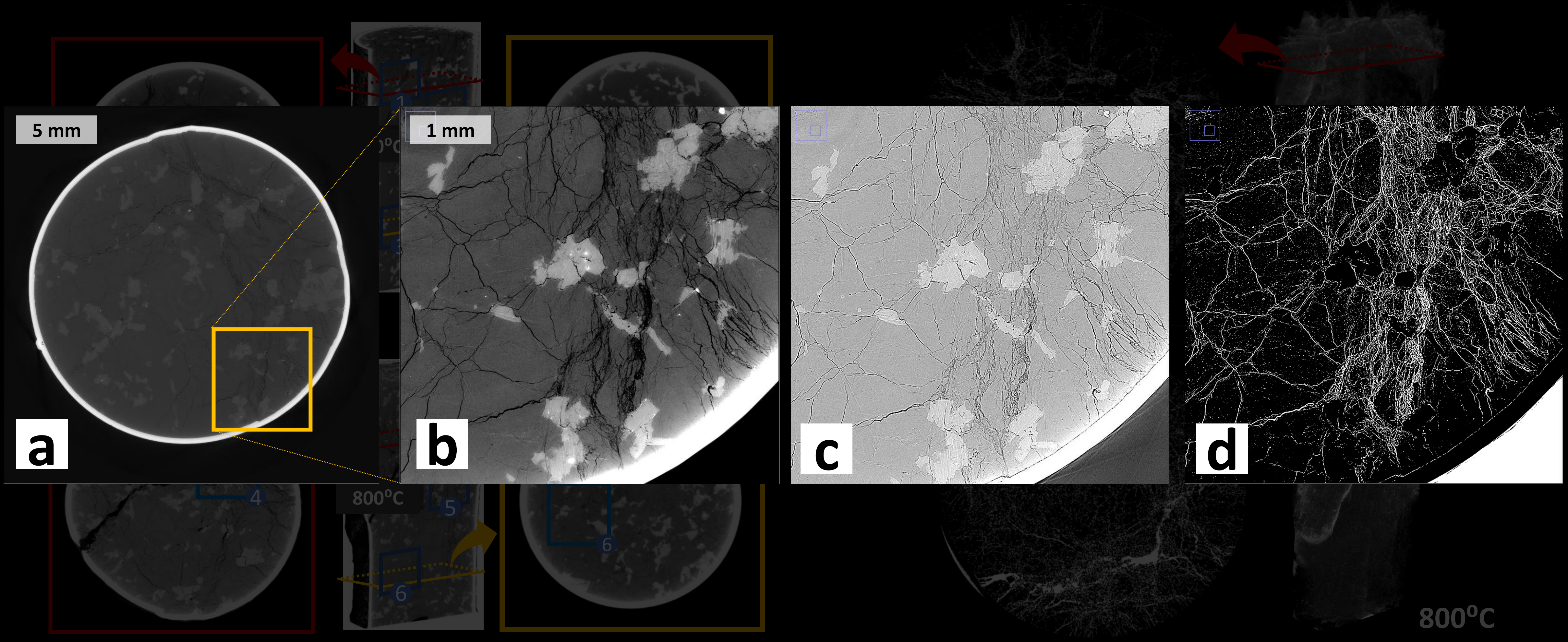


Synchrotron X-ray Tomography Images



Meyer, Shahin, et al. (submitted)

Example 4: Assess Permeability In Deep Earth

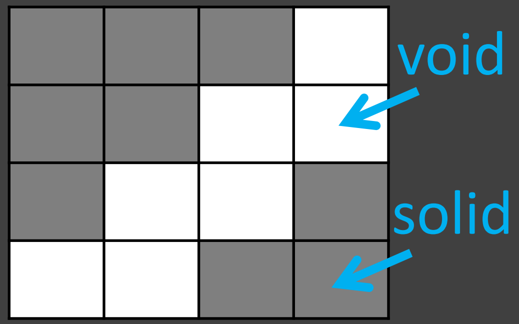


Synchrotron X-ray Tomography Images

Meyer, Shahin, et al. (submitted)

Example 4: Assess Permeability In Deep Earth

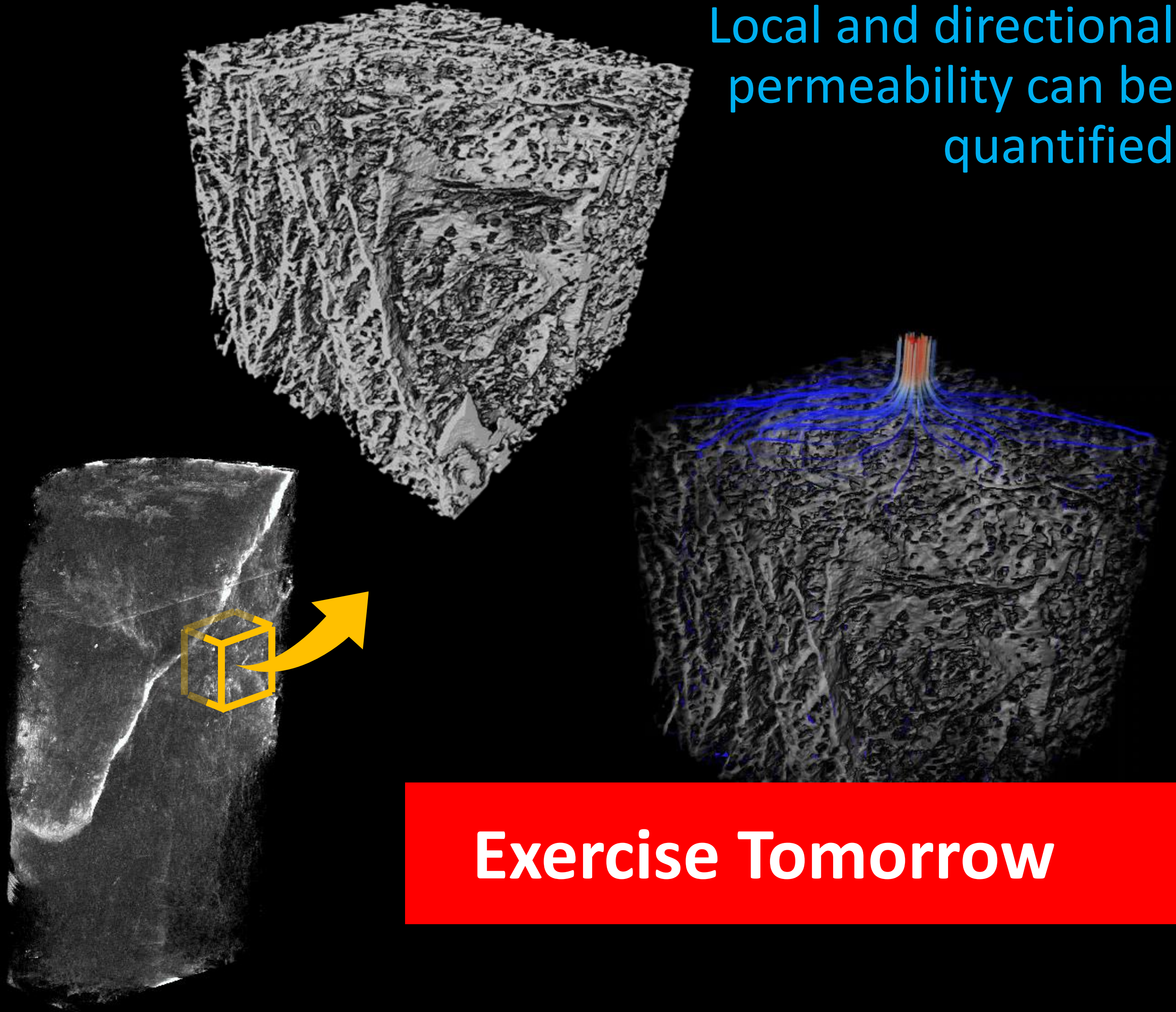
Voxels in X-ray Image



Convert to a

Finite Element Mesh

Solve Navier Stokes Eqs.



Local and directional permeability can be quantified

Exercise Tomorrow

Meyer, Shahin, et al. (submitted)

B R E A K

Image Analysis

Image Analysis for Quantitative Insights

A tomography image is a 3D structure with shades of gray that should be processed to extract meaningful quantities:

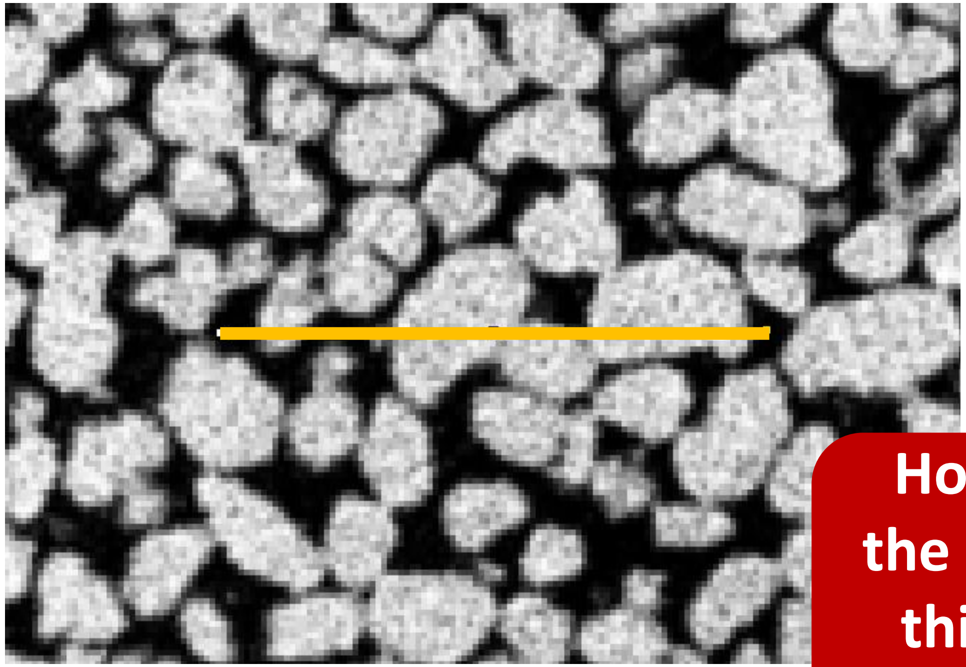
→ What is what shall be identified

→ Images may require polishing to remove defects

→ Quantify morphological, mechanical, and or hydraulic properties

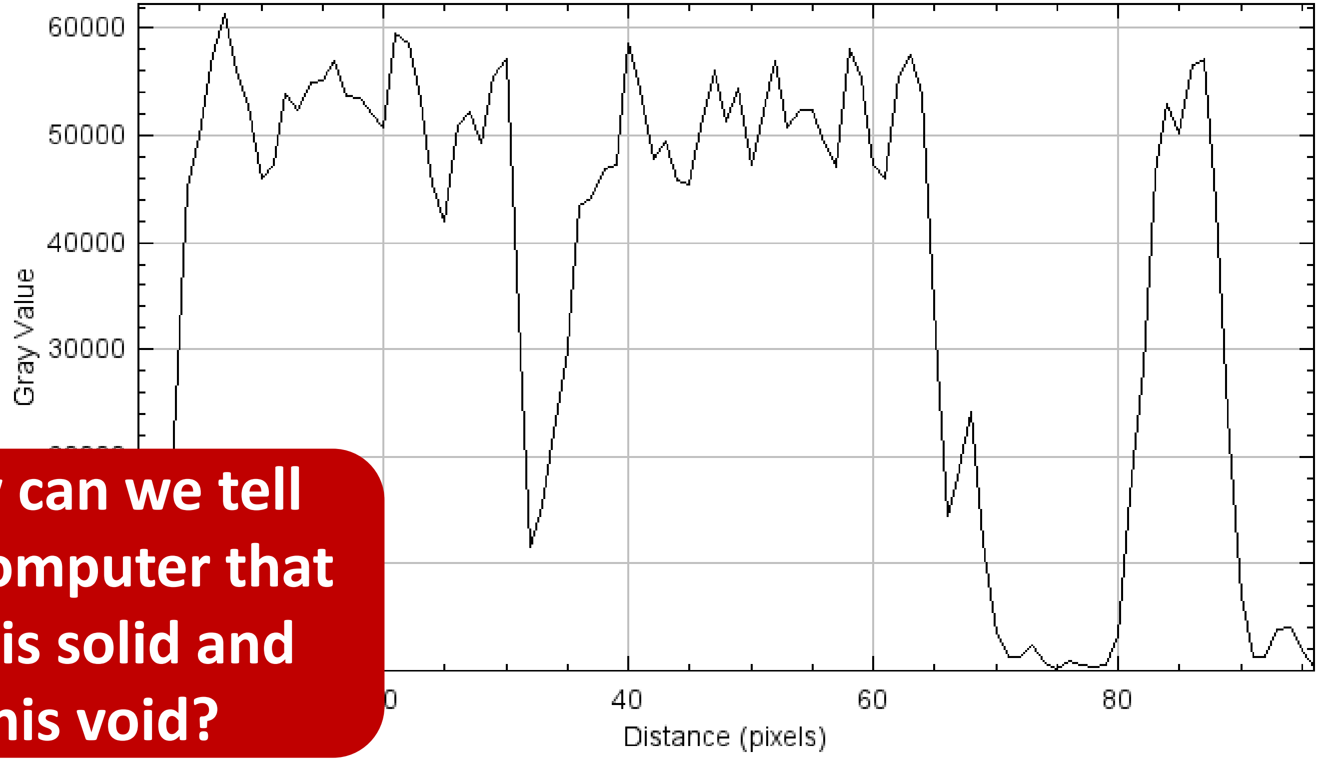
Image Analysis for Quantitative Insights

To extract quantities, we need to process the tomography images



Tomography image

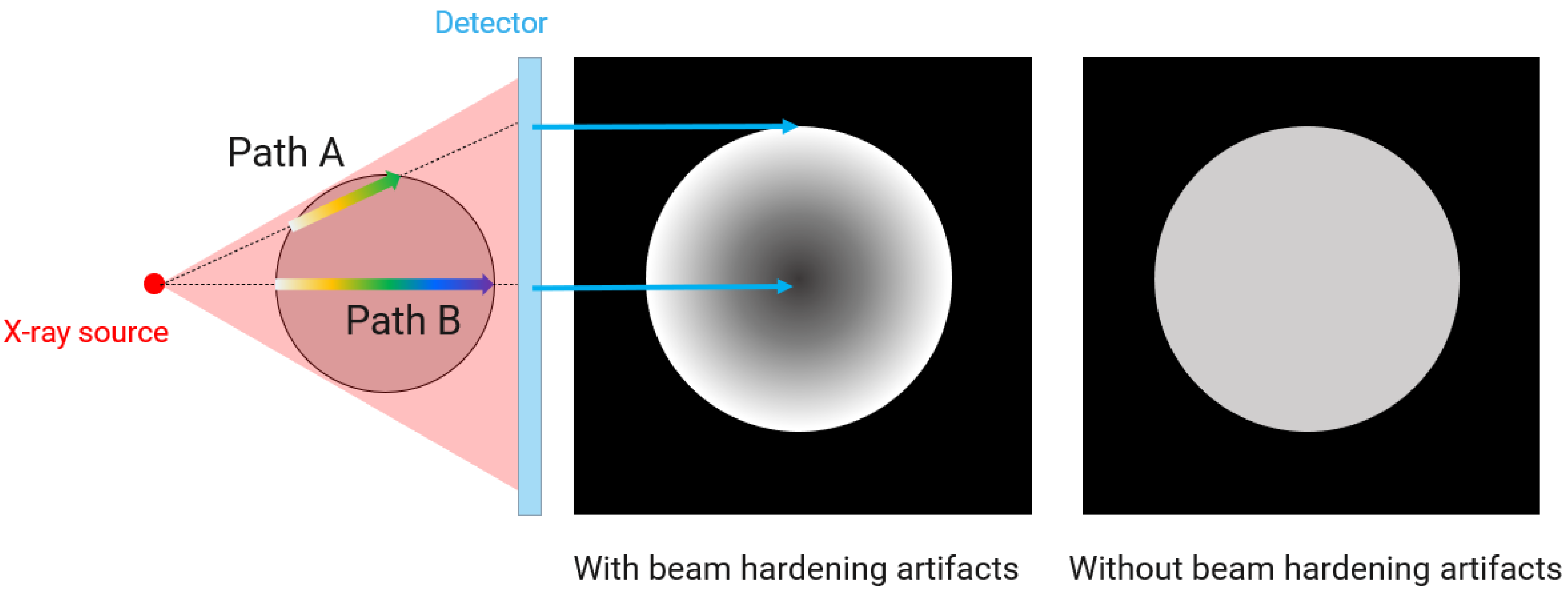
How can we tell the computer that this is solid and this void?



Gray shades throughout the yellow line

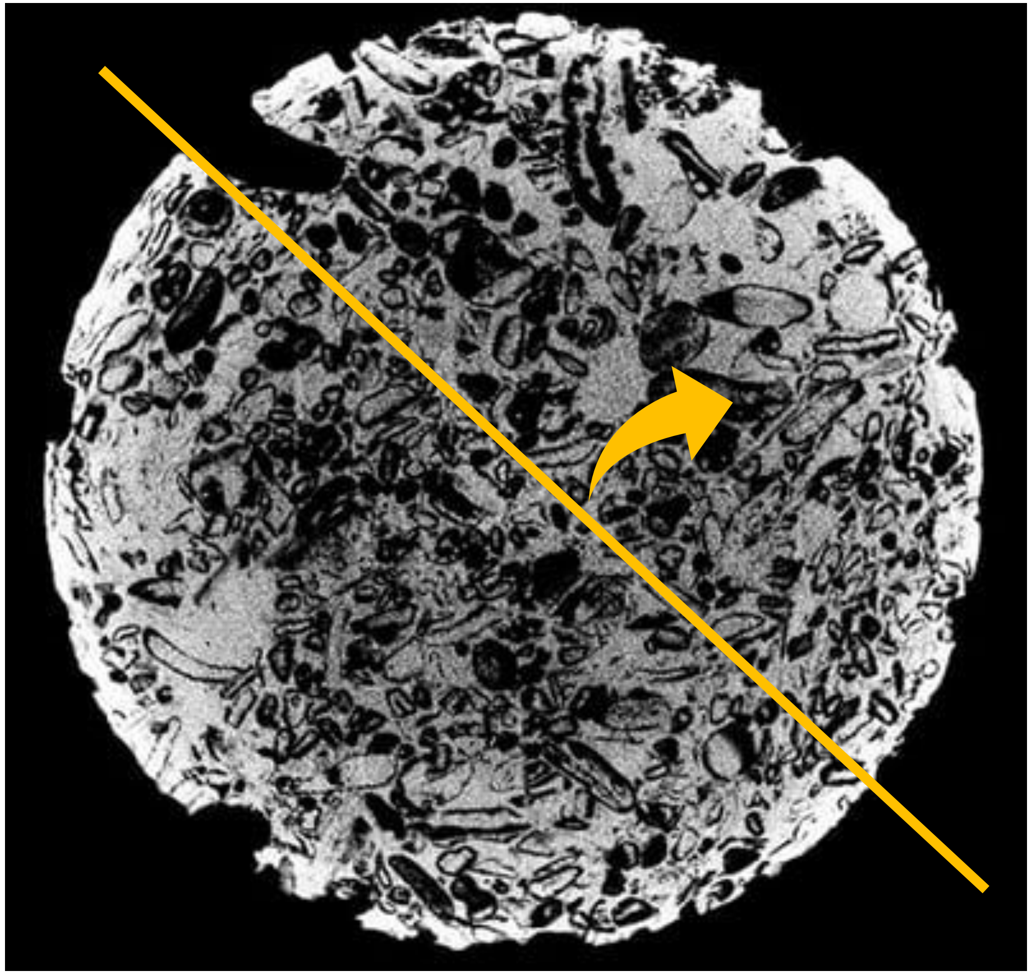
Image Analysis for Quantitative Insights

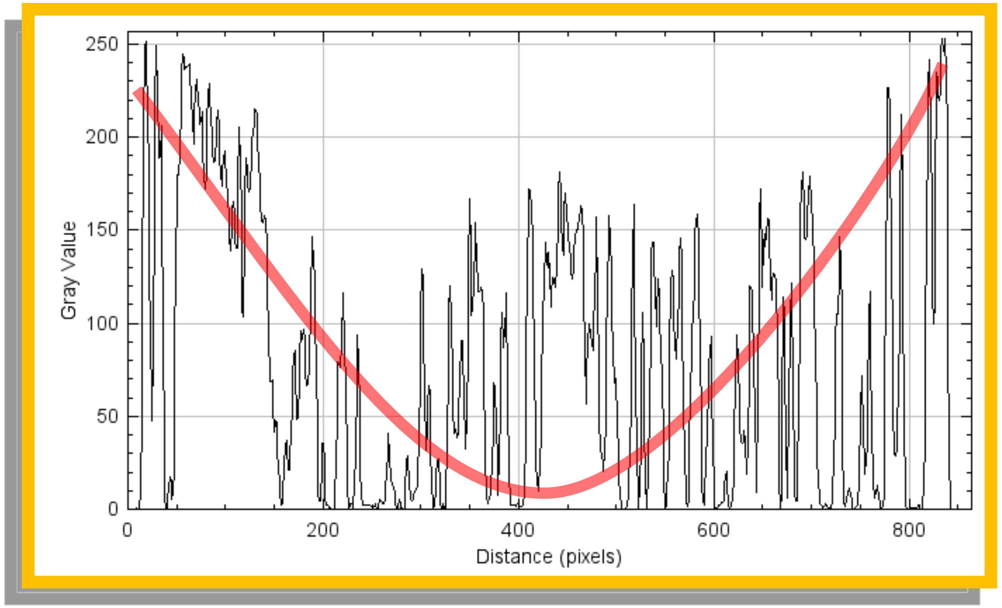
Beam Hardening may impact imaging quality



https://imaging.rigaku.com/blog/what-is-beam-hardening-in-ct

Image Analysis for Quantitative Insights





(⅓-inch diameter carbonate plug scanned at 130 kV with 1 mm Aluminum filter)

Requires special treatment

https://imaging.rigaku.com/blog/what-is-beam-hardening-in-ct

Image Analysis: Phase and Structure

Tomography Image

↓

Enhance Image

↓

Binarization

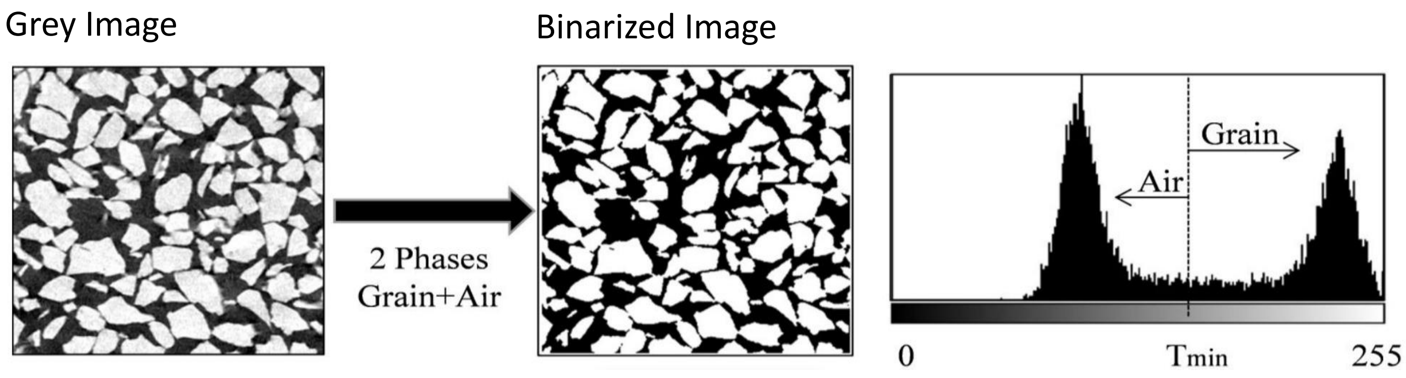
↓

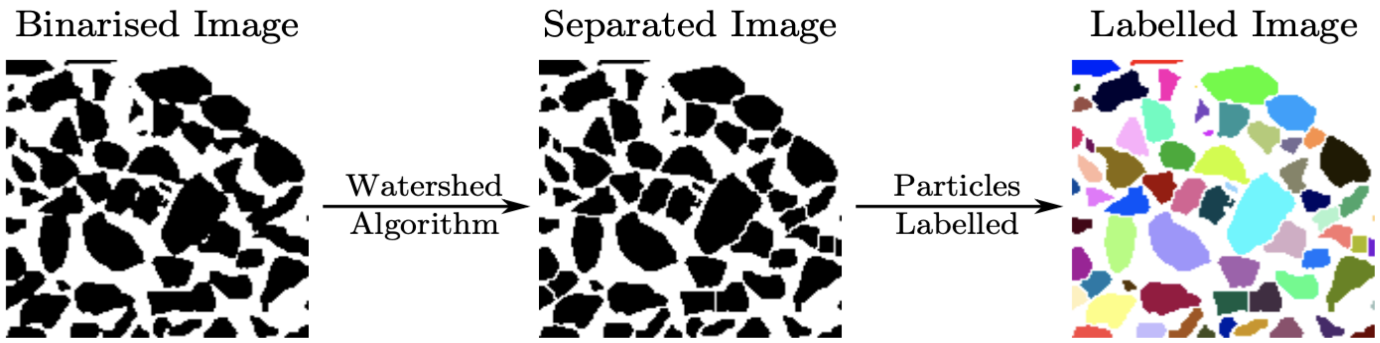
Segmentation

↓

Labeling

To extract quantities, we need to process the tomography images





Ando, Univ. Grenoble, (2012). Stamati, *et al.*, *JOSS*, (2020).

Image Analysis: Phase and Structure

Tomography Image

Enhance Image

Binarization

Segmentation

Labeling

Filters may be needed to enhance image quality

Mean Filter

Replaces the pixel value by the ***mean*** value of the pixel itself and the surrounding pixels within a given range.

23	25	30	35	30
25	30	35	37	40
45	40	**39**	43	45
38	40	43	42	46
35	40	42	45	47

Median Filter

Replaces the pixel value by the ***median*** value of the pixel itself and the surrounding pixels within a given range.

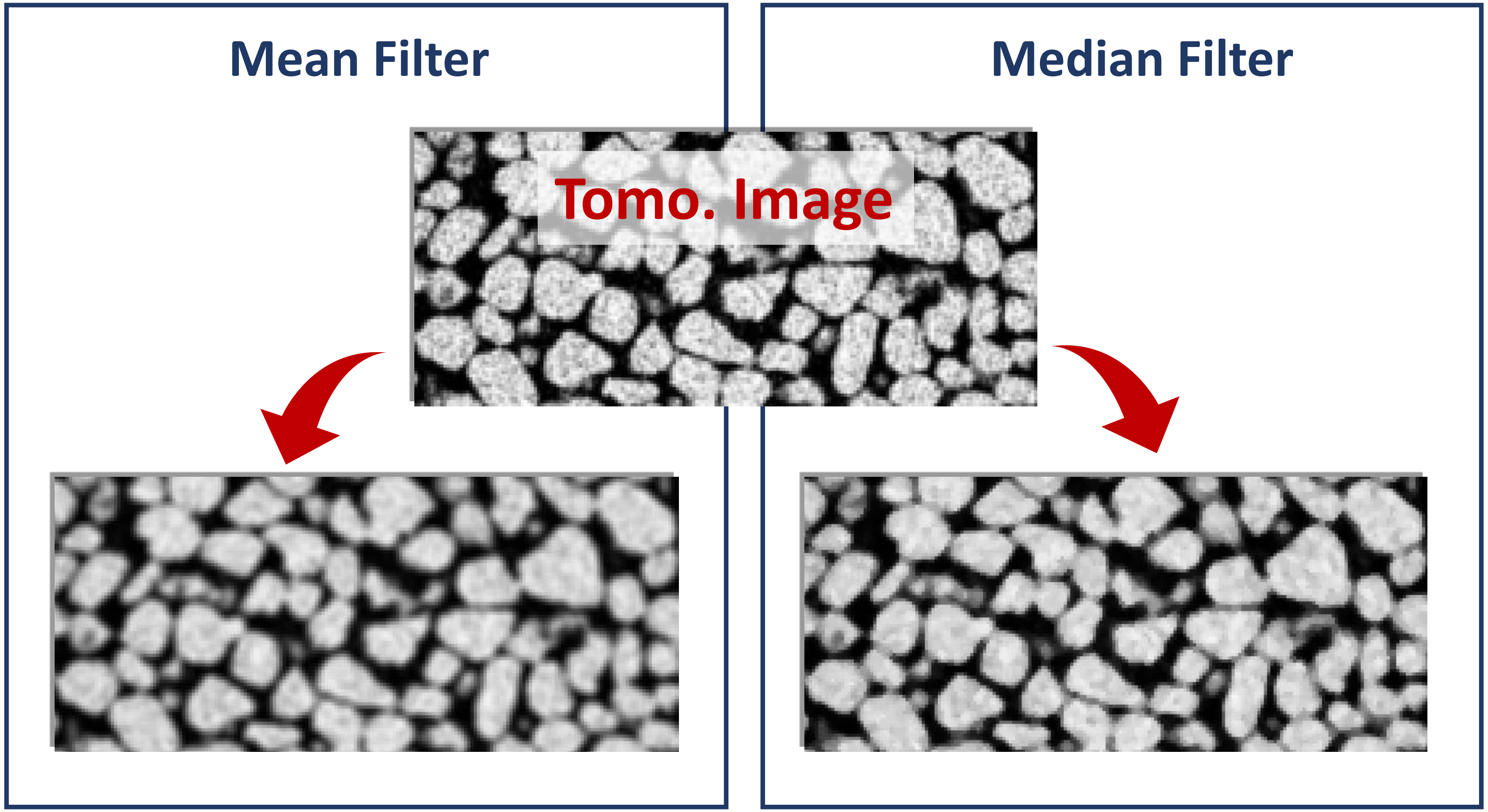
23	25	30	35	30
25	30	35	37	40
45	40	**40**	43	45
38	40	43	42	46
35	40	42	45	47

Ando, Univ. Grenoble, (2012). Stamati, *et al.*, *JOSS*, (2020).

Image Analysis: Phase and Structure

- Tomography Image
- **Enhance Image**
- Binarization
- Segmentation
- Labeling

Filters may be needed to enhance the image quality

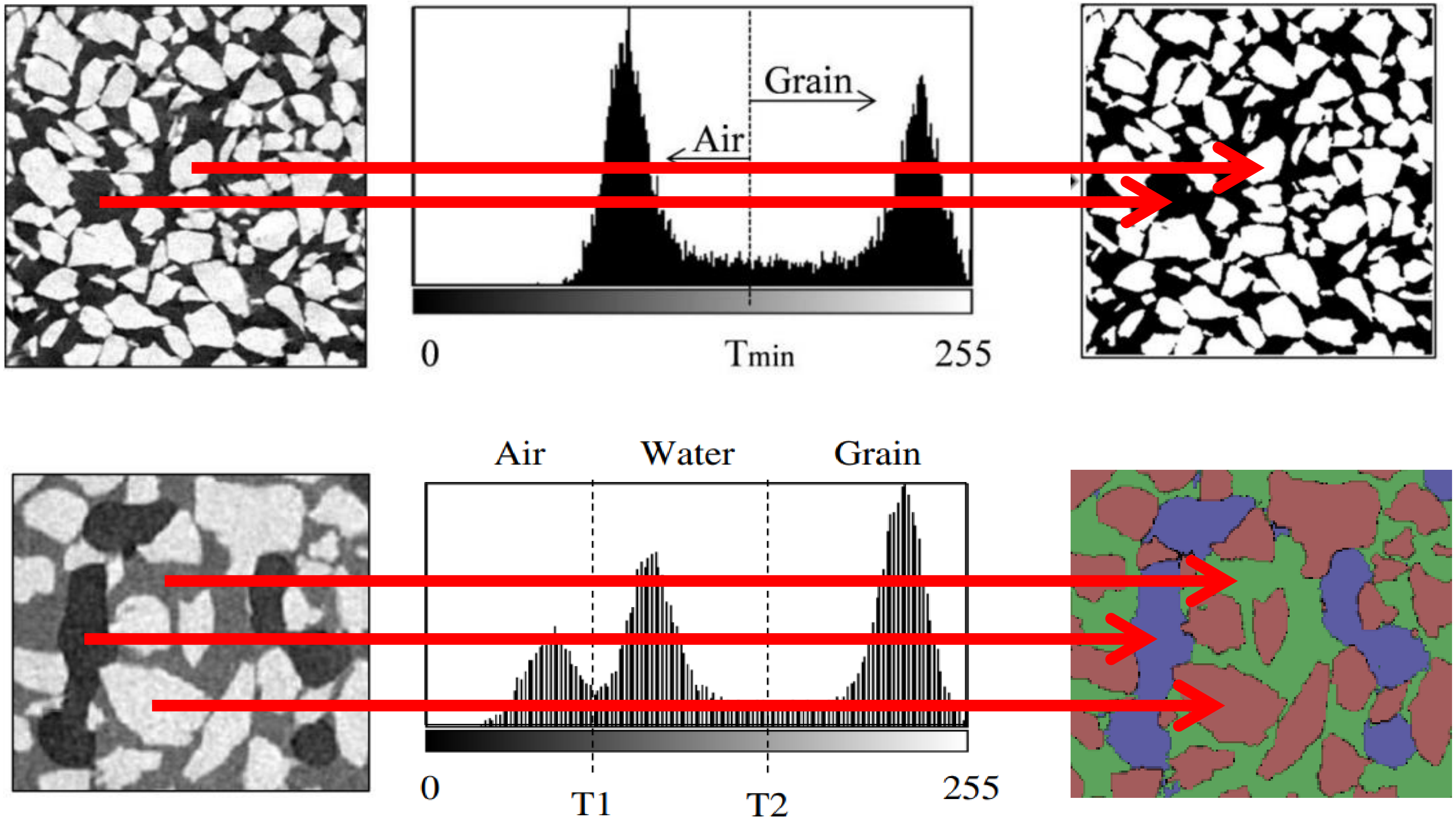


Ando, Univ. Grenoble, (2012). Stamati, *et al.*, *JOSS*, (2020).

Image Analysis: Phase and Structure

- Tomography Image
- Enhance Image
- **Binarization**
- Segmentation
- Labeling

Phases are separated based on the gray shades histogram



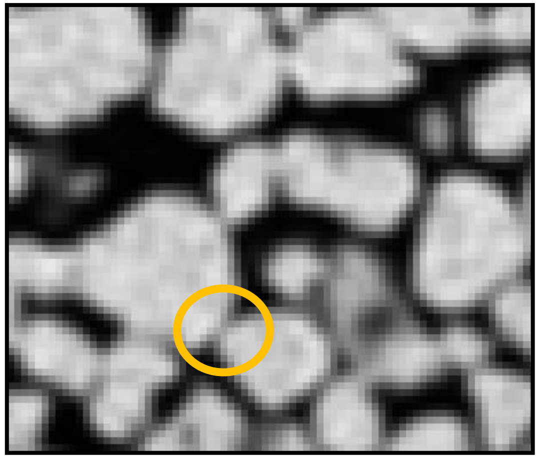
G. Khaddour (2015) PhD Thesis

Image Analysis: Phase and Structure

- Tomography Image
- Enhance Image
- Binarization
- **Segmentation**
- Labeling

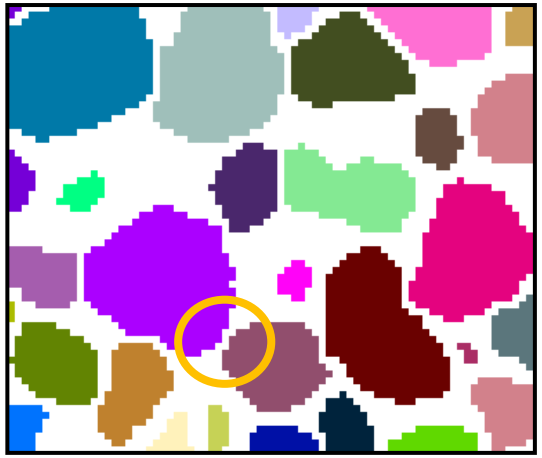
Phases are separated based on the gray shades histogram

Raw Image



Binarized Image

Segmented and Labeled



G. Khaddour (2015) PhD Thesis

Image Analysis: Phase and Structure

Tomography Image

↓

Enhance Image

↓

Binarization

↓

Segmentation

↓

Labeling

Watershed Transform

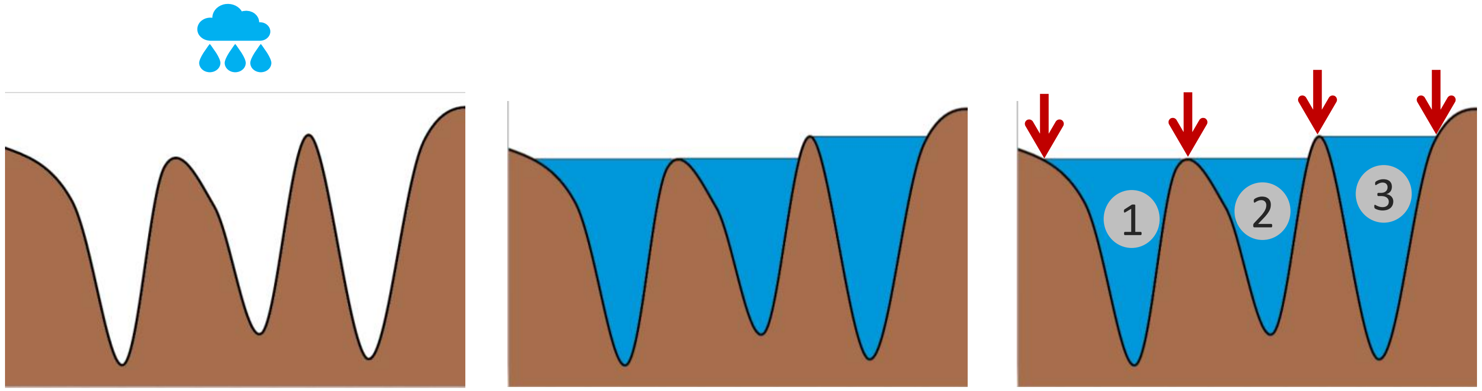


Image Analysis: Phase and Structure

Tomography Image

↓

Enhance Image

↓

Binarization

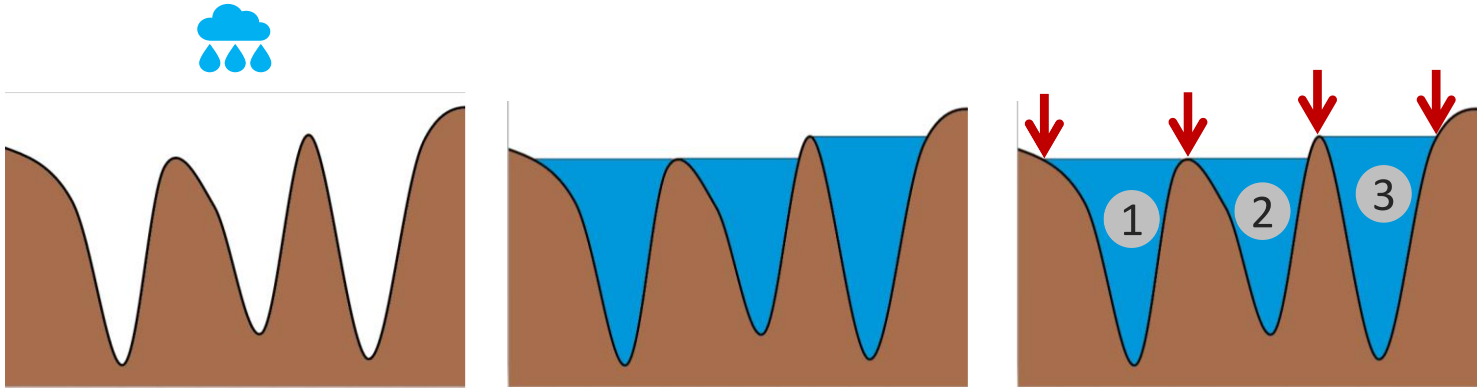
↓

Segmentation

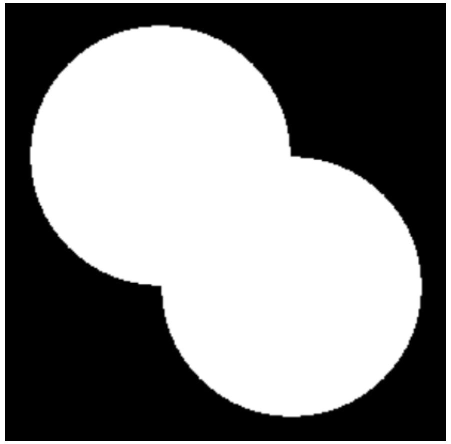
↓

Labeling

Watershed Transform



bw



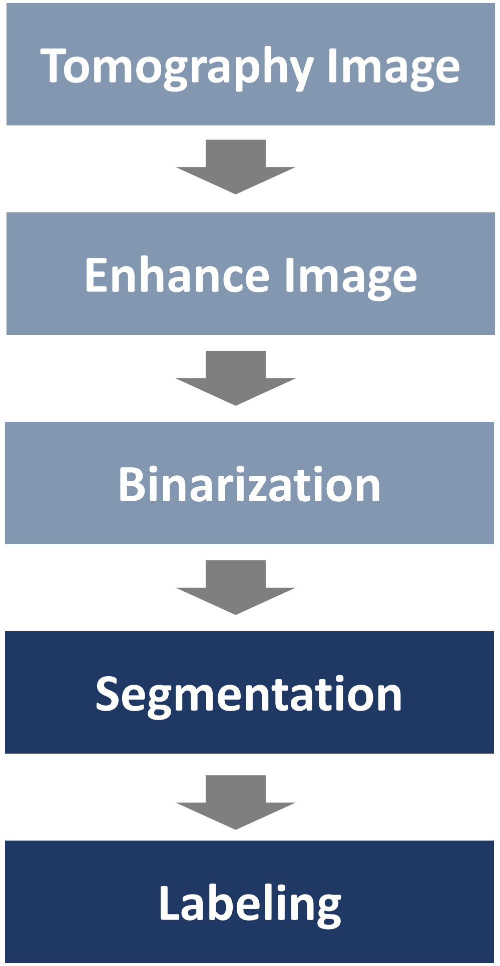
Distance Transform (*bwdist*)

replaced by the minimum distance of it to the pixel with a value of 1

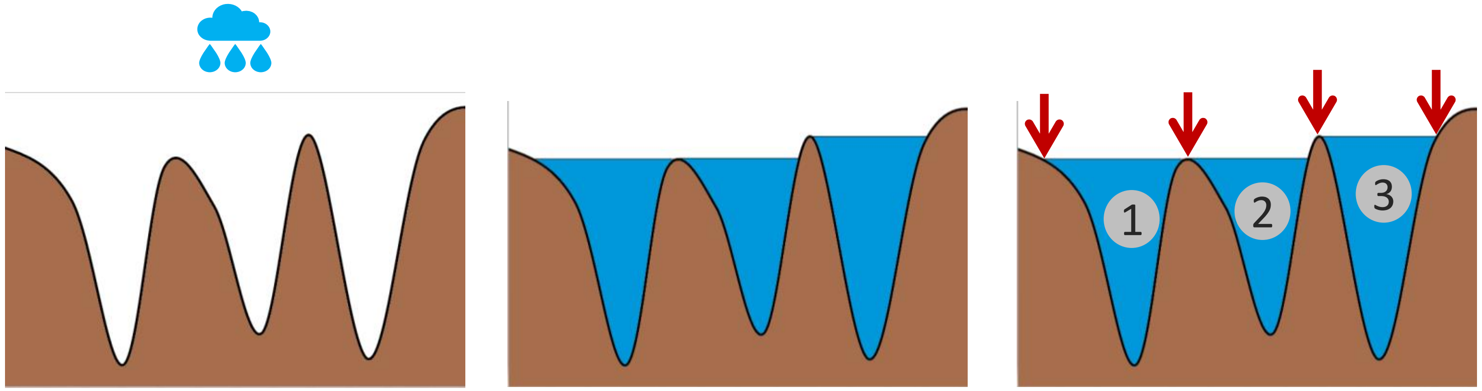
1	1	0	0	0
1	1	0	0	0
0	0	0	0	0
0	0	0	0	0
0	1	1	1	0

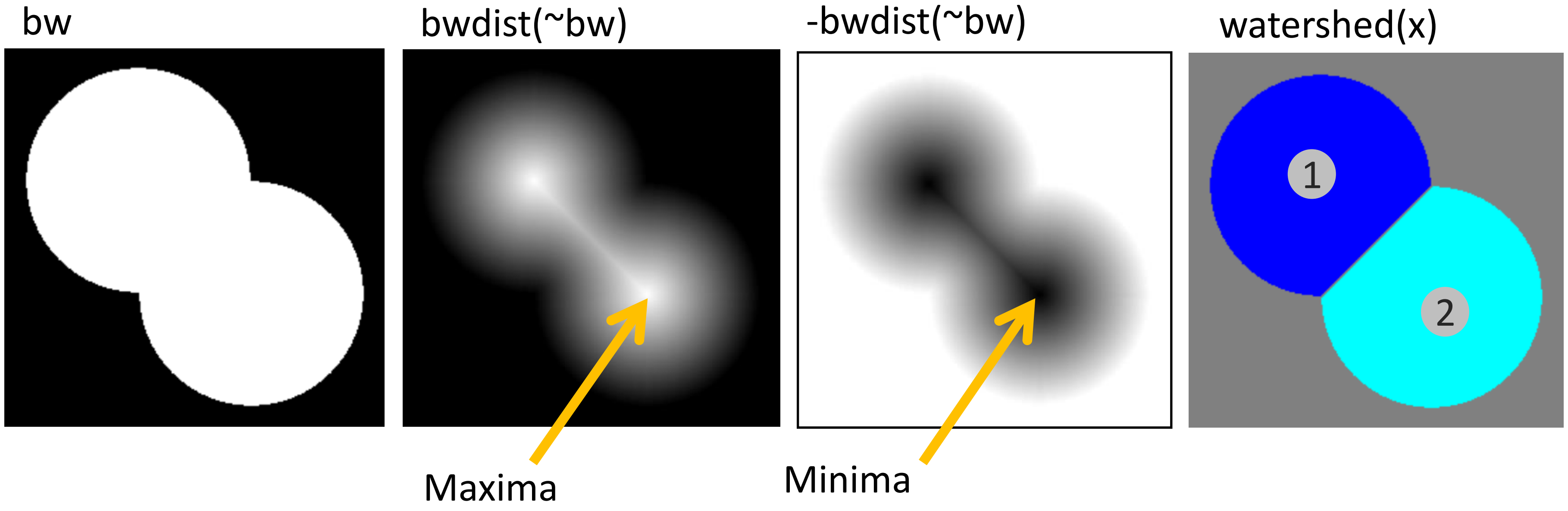
0	0	1	2	3
0	0	1	2	3
1	1	1.4	2	2.2
1.4	1	1	1	1.4
1	0	0	0	1

Image Analysis: Phase and Structure



Watershed Transform



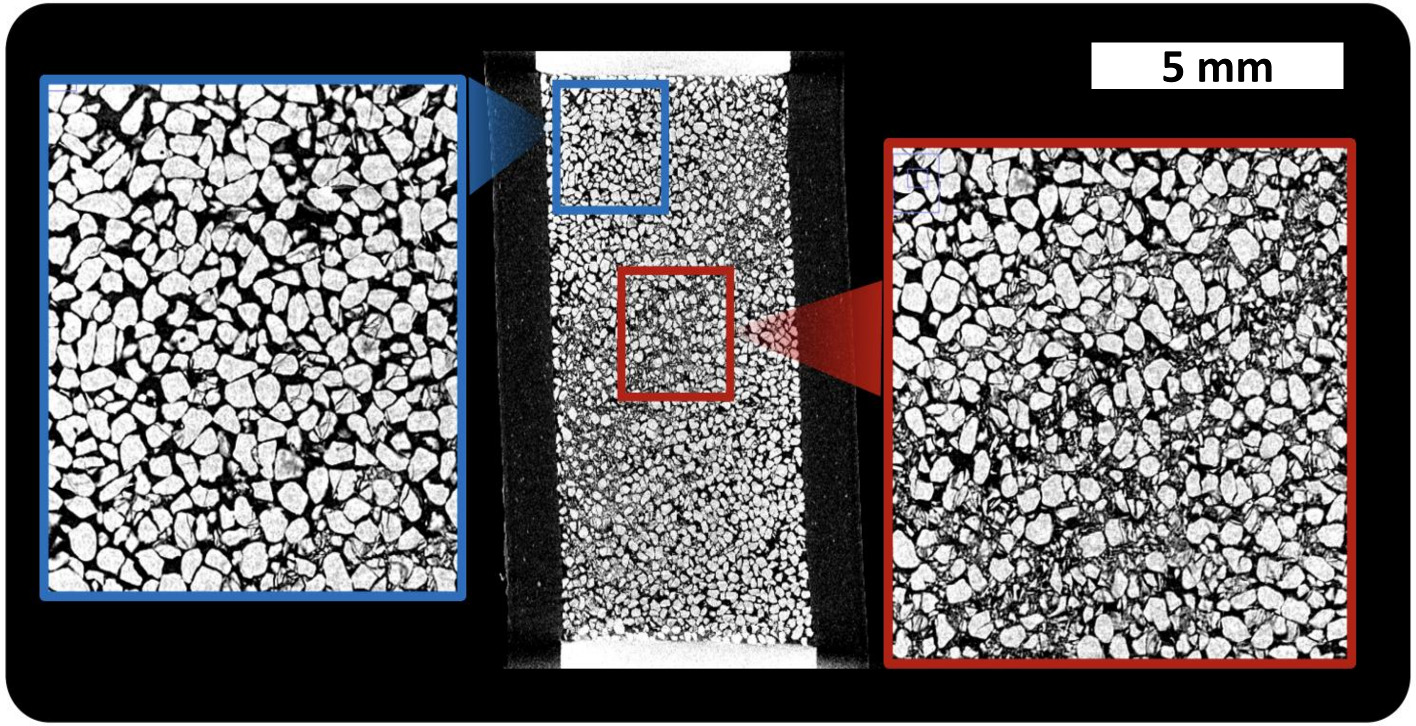


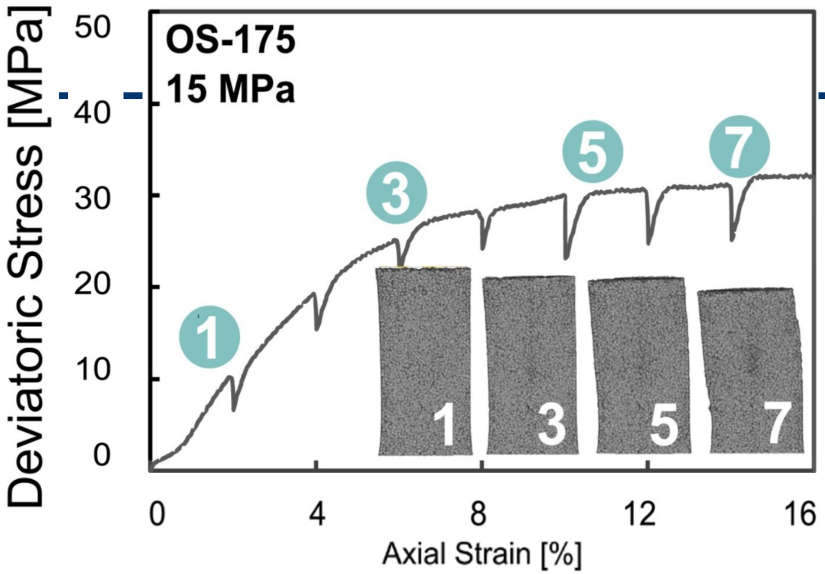
G. Khaddour (2015) PhD Thesis

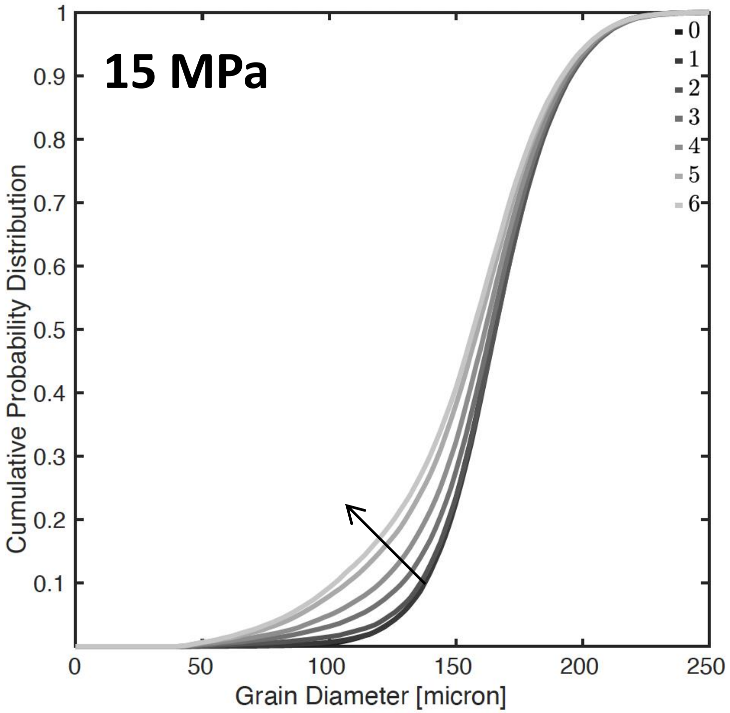
Quantitative Insights

1. Grain Size Distribution (micro-scale)

We can quantify the evolution of grain size in space and over time/deformation



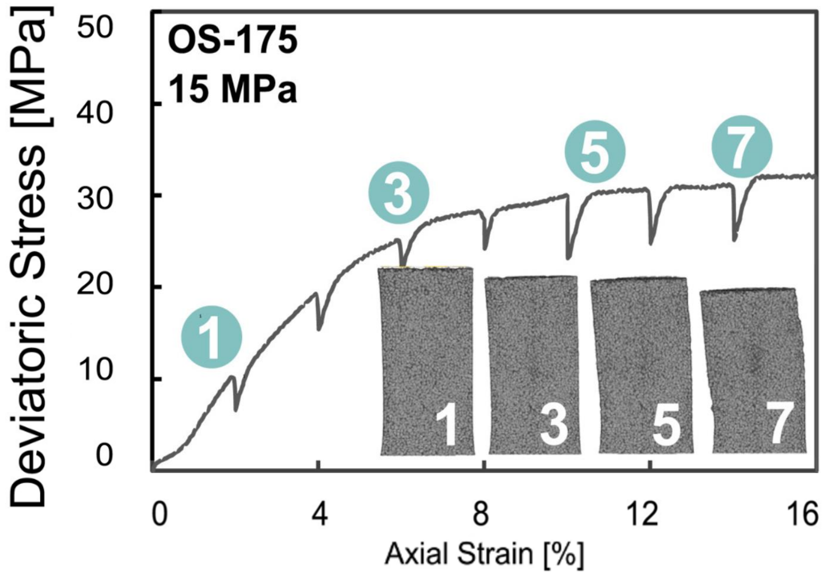


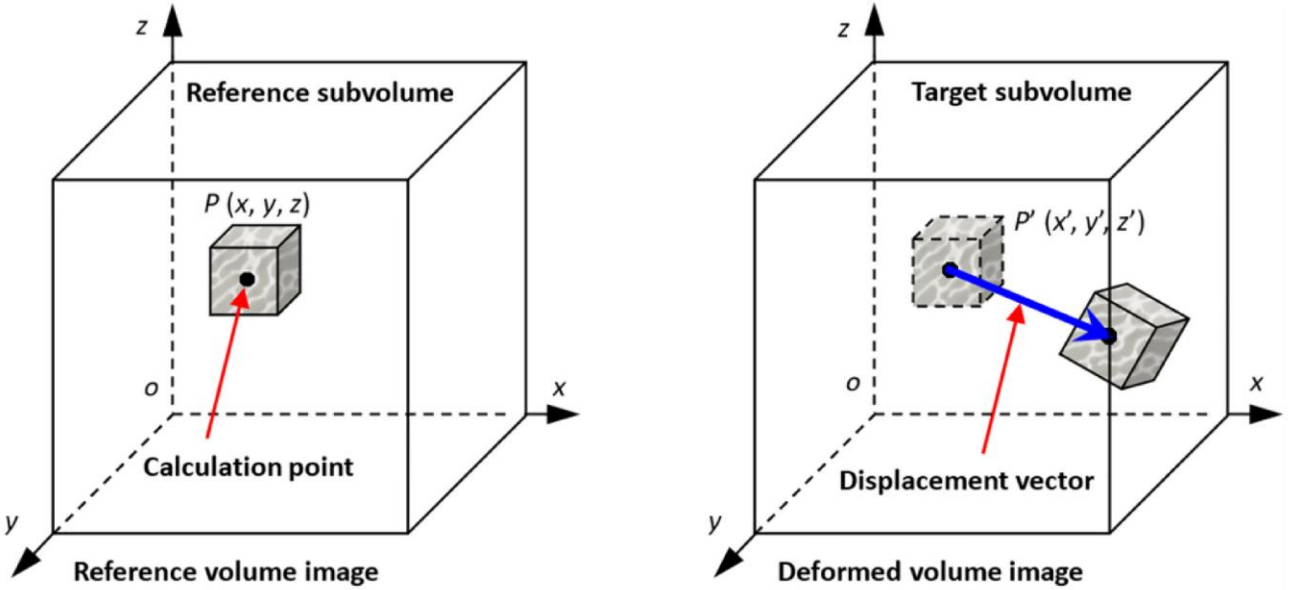


Shahin & Hurley (2022) JGR

2. Specimen Scale Deformation Fields (meso-scale)

Digital Image Correlation allows characterize spatially-resolved deformation field rising and evolving during deformation



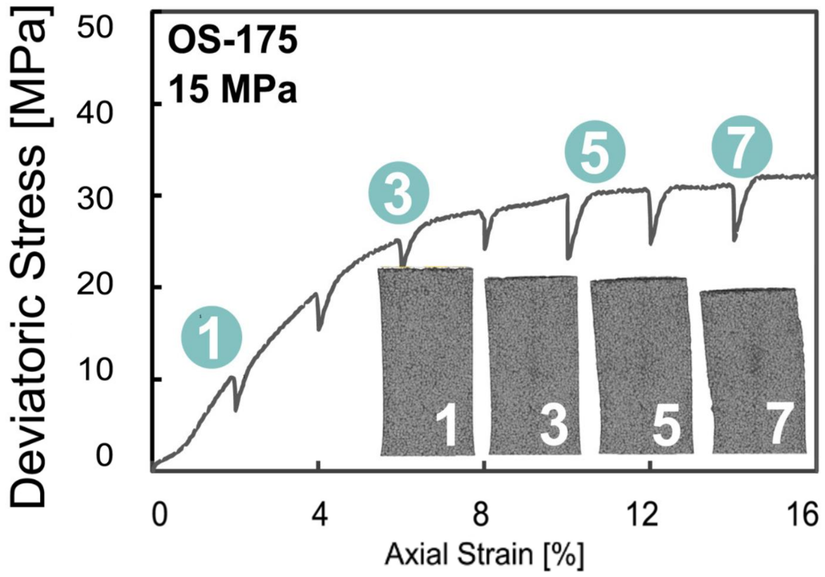


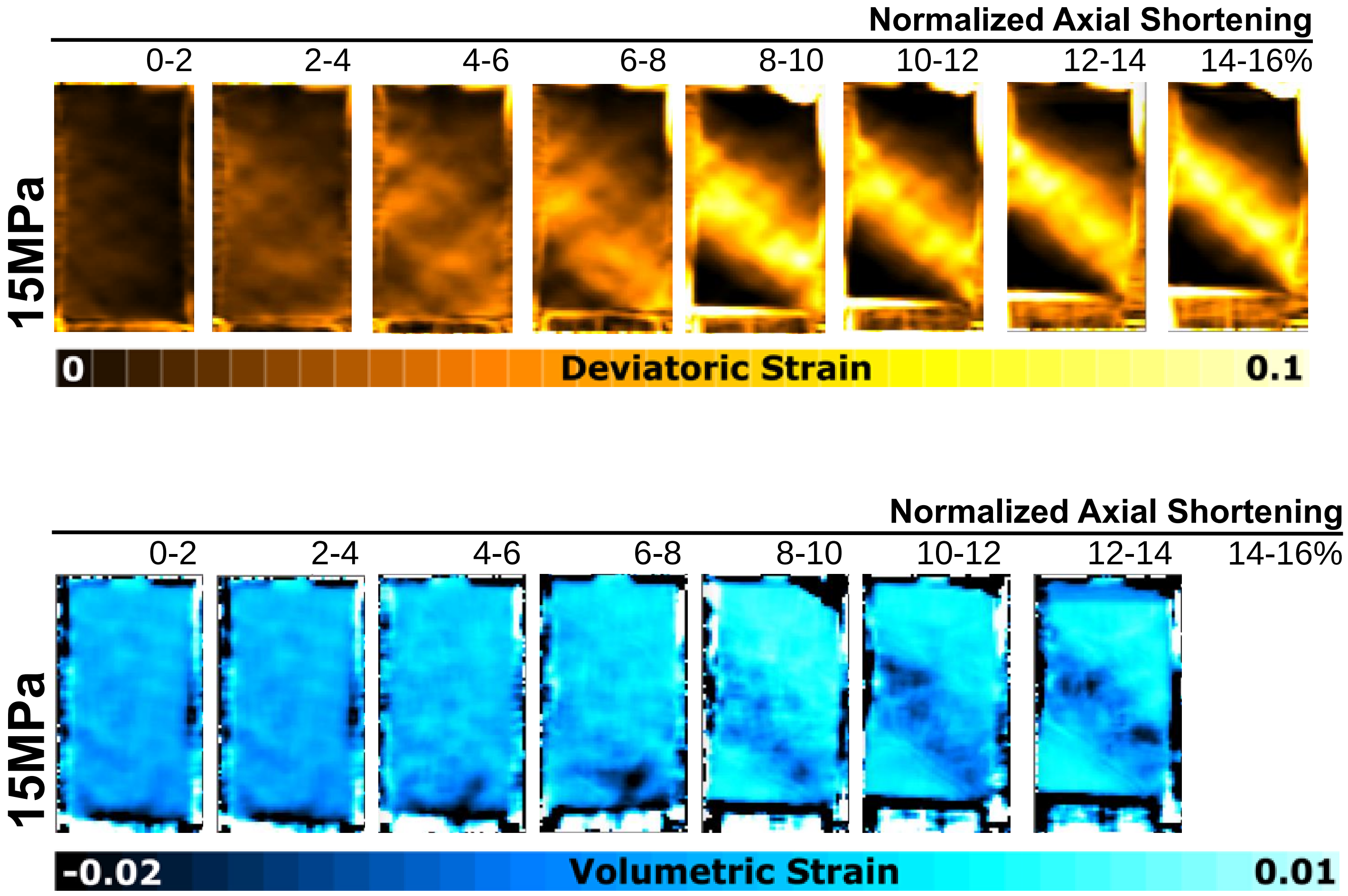
Subset-based digital volume correlation (DVC)[3] is well-suited for geomaterials. Microstructure provides a "speckle pattern".

Pan and Wang, *Opt. Lasers Eng.* (2020)

2. Specimen Scale Deformation Fields (meso-scale)

Digital Image Correlation allows characterize spatially-resolved deformation field rising and evolving during deformation



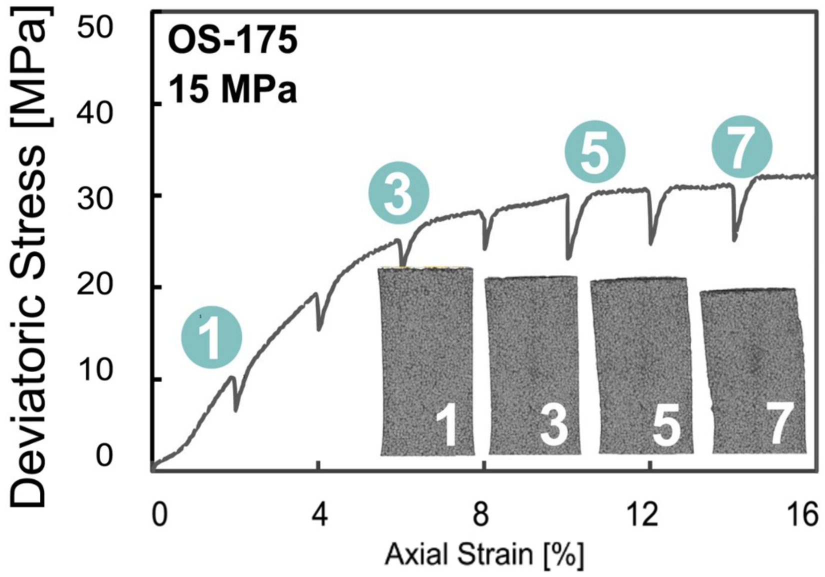


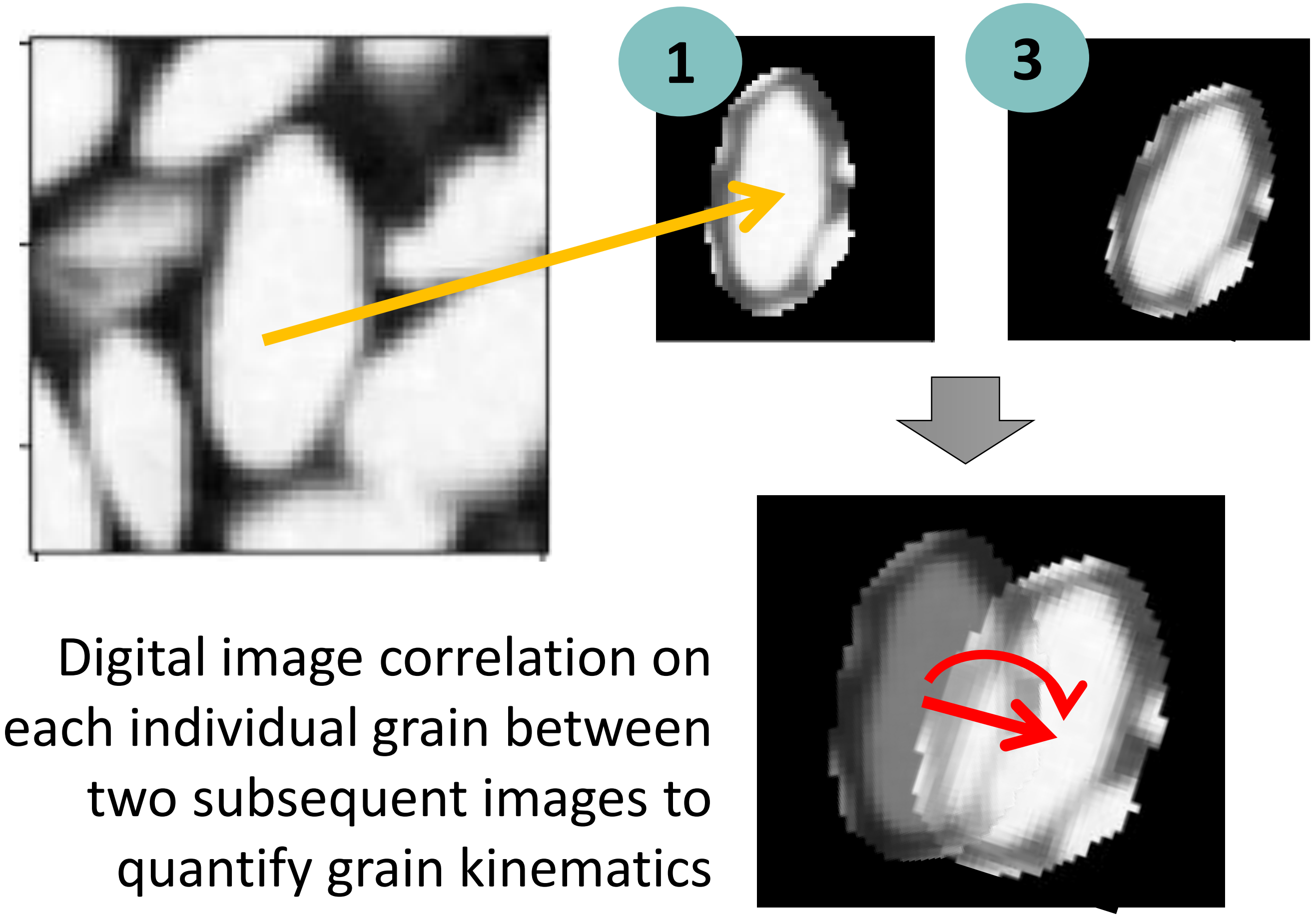
Shahin & Hurley (2022) JGR

3. Grain Kinematics (micro-scale)

Characterize grain kinematics through Discrete Digital Image Correlation:

 3 Displacements + 3 Rotations



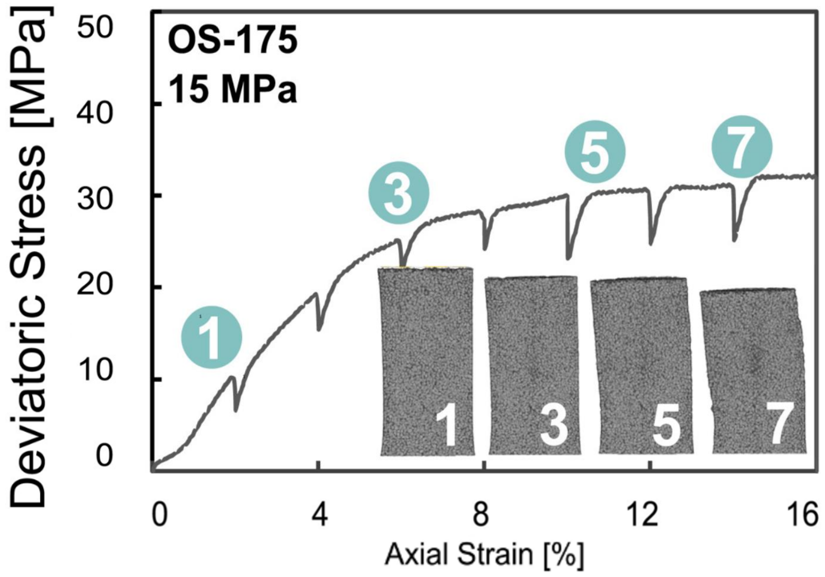


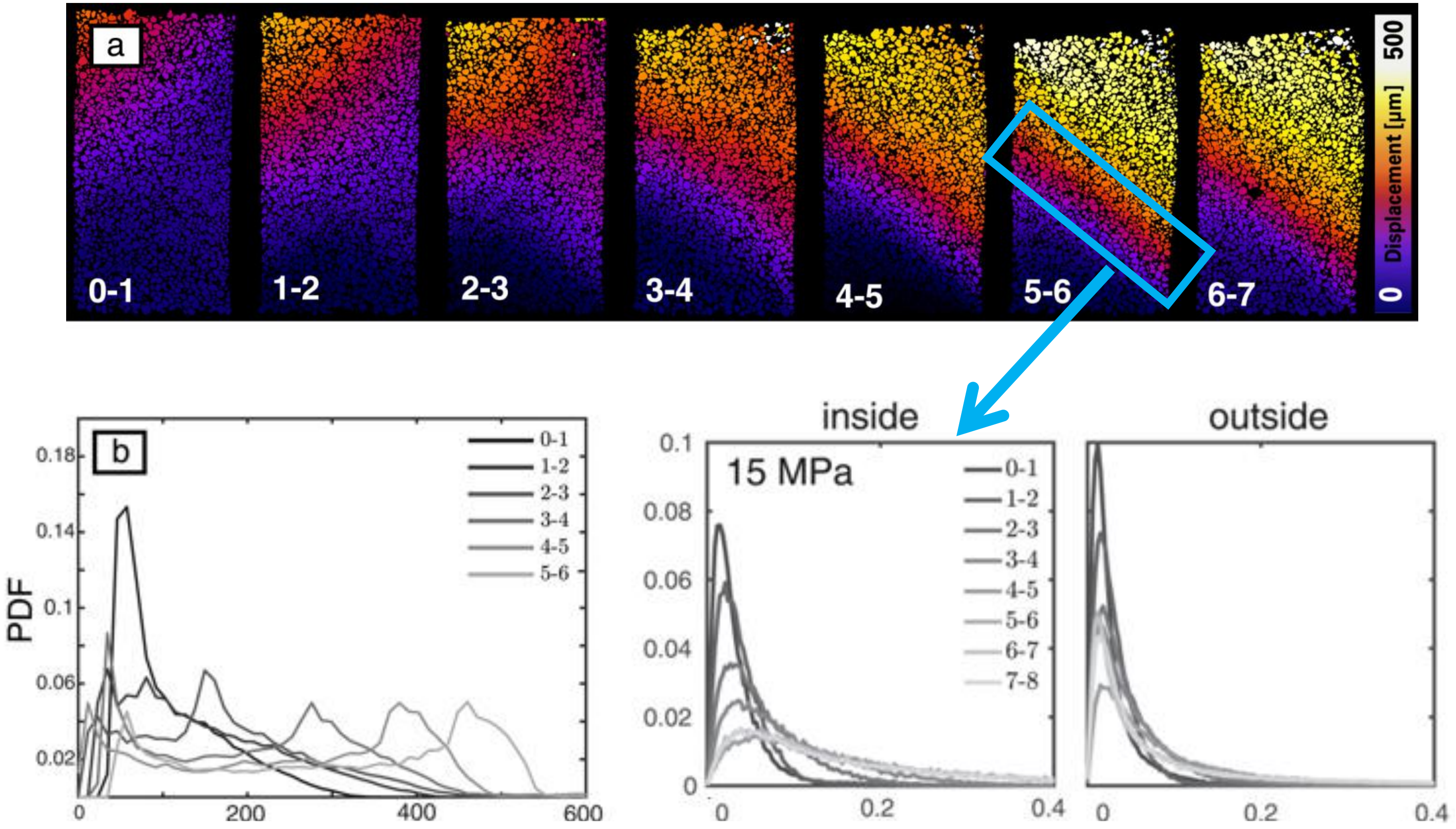
Digital image correlation on each individual grain between two subsequent images to quantify grain kinematics

https://www.spam-project.dev/docs/tutorials/tutorial-04-discreteDIC.html

3. Grain Kinematics (micro-scale)

Starting from grain kinematics, contact mechanisms including sliding and twisting can be quantified





Grains displacement during loading [um]

Contact Sliding
[Fraction of Global Deformation]

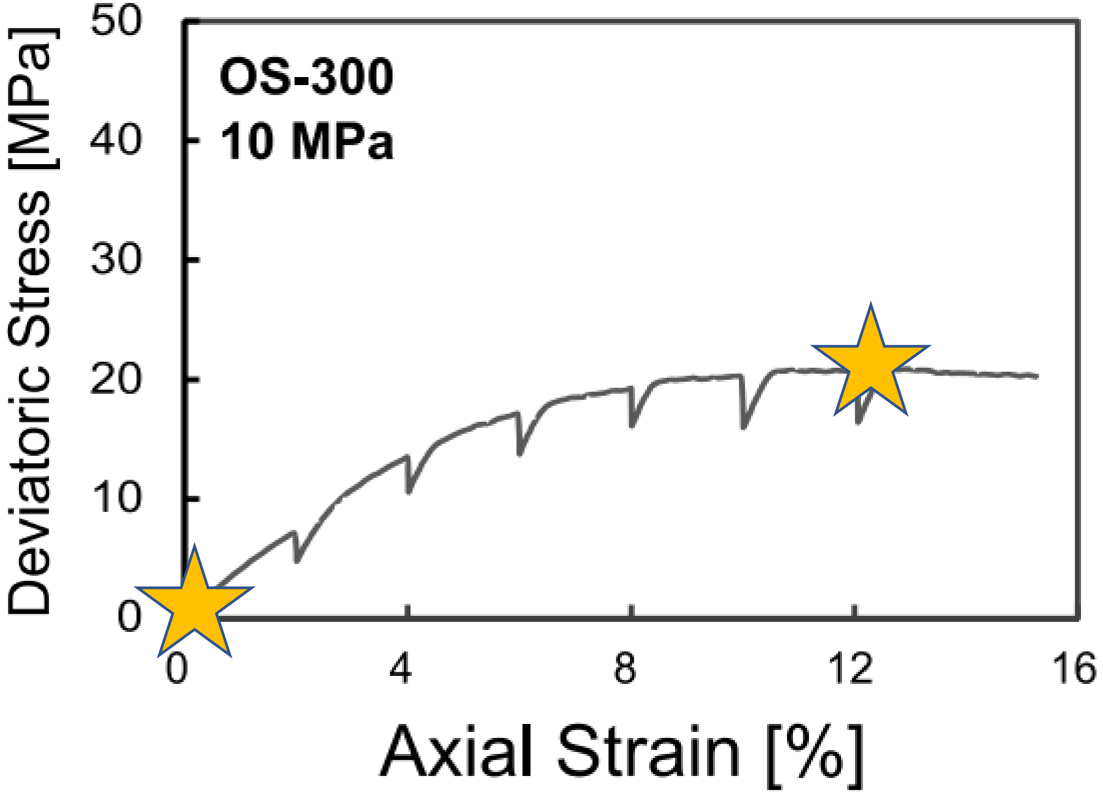
Shahin & Hurley (2022) JGR

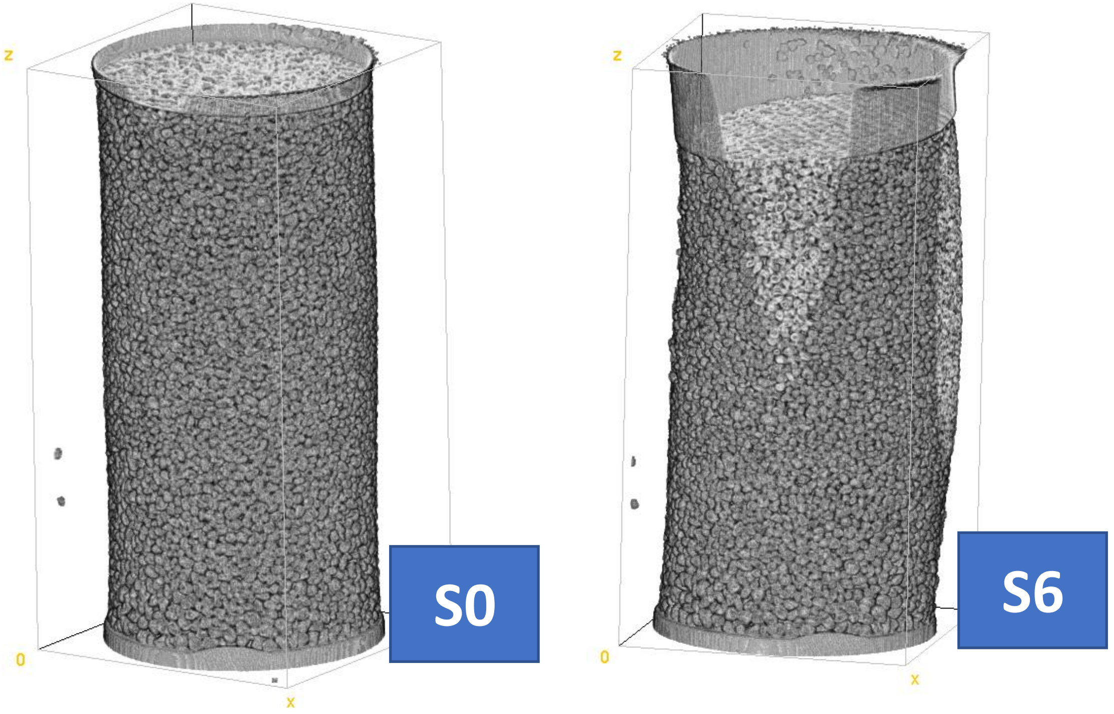
B R E A K

Image Analysis Exercise

Exercise 1

In this exercise, we will process two tomography scans at the beginning of the experiment and after deformation





1. Quantify Grain Size Distribution for S0
2. Compare Porosity Map in S0-S6

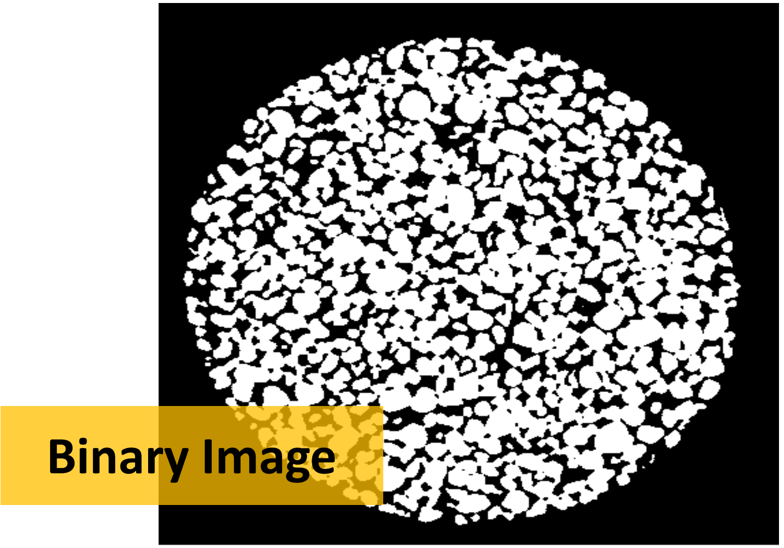
Exercise 1

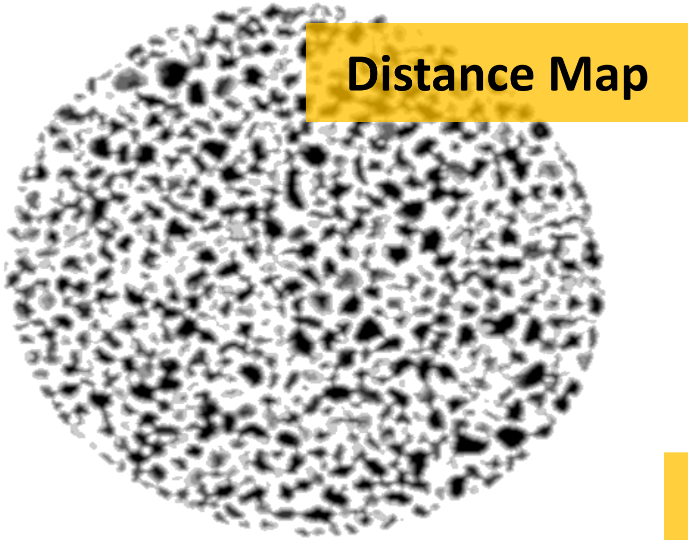
1- Get the binarized image of S0 and S6

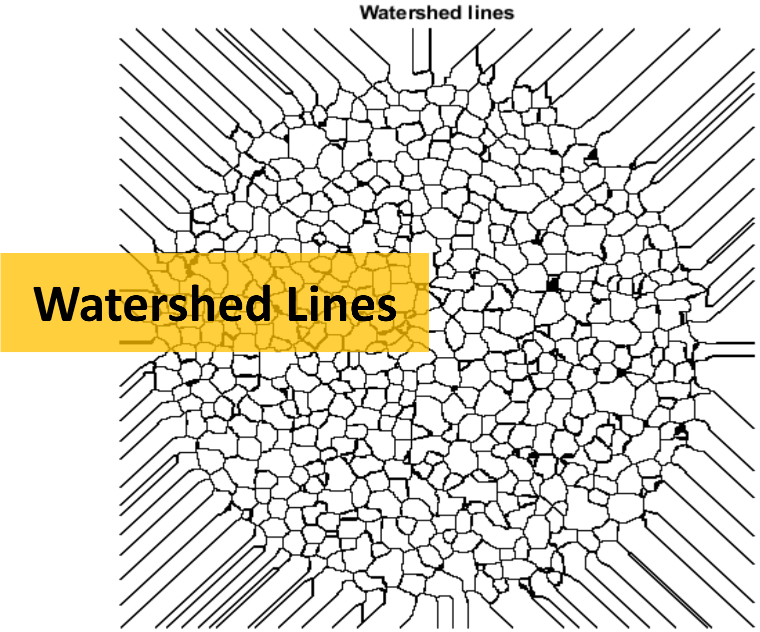
2- Grain size distribution for S0

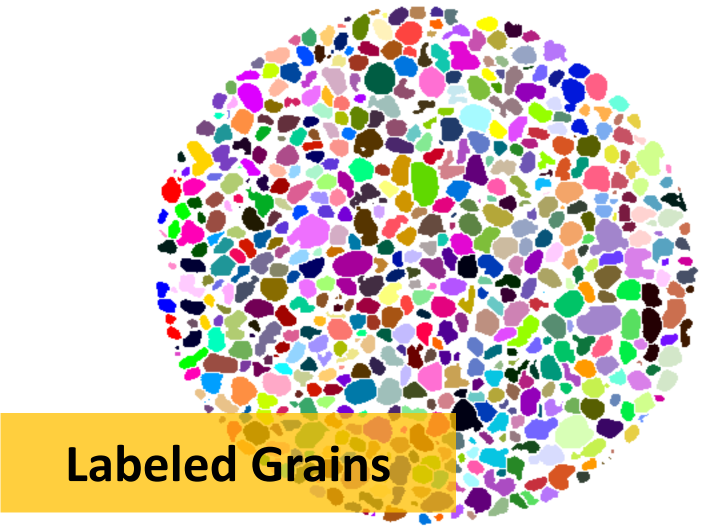
3- Porosity Map for S0 and S6

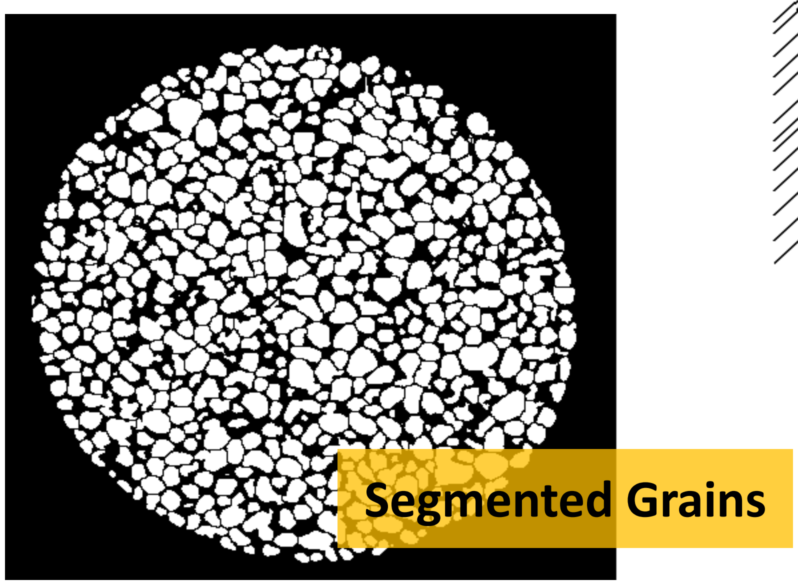
Exercise 1


Binary Image

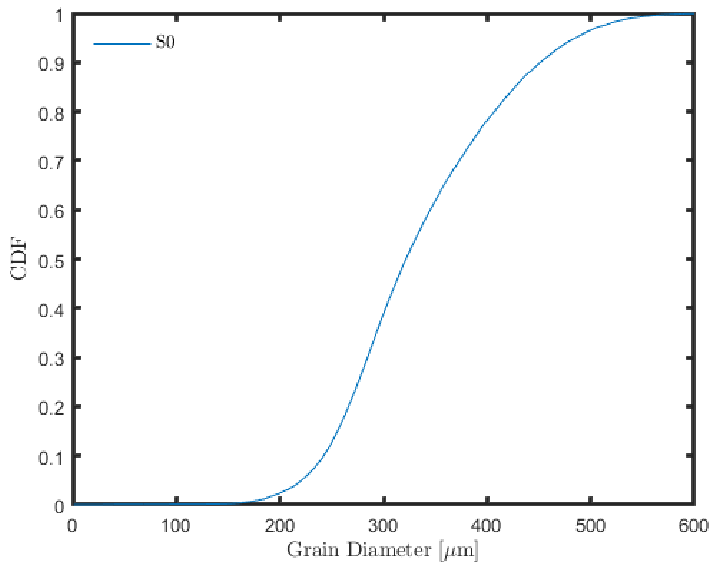

Distance Map

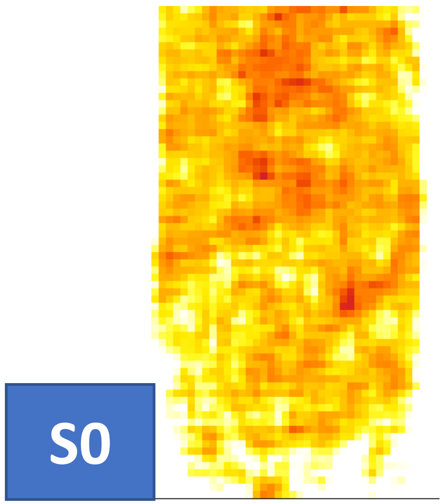

Watershed lines
Watershed Lines

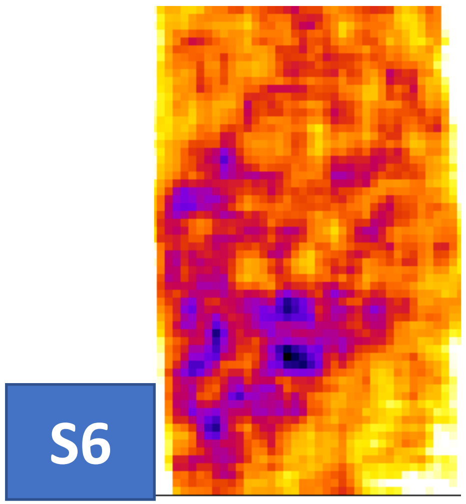

Labeled Grains


Segmented Grains

Exercise 1







1. Run Step2_Porosity_Map.m
2. The computed porosity map will be stored in the folder of the images (Por*.tif)
3. Upload Por*.tif onto ImageJ
4. Zoom in
5. Adjust color bar LUT and select (fire)
6. ctrl+shift+c to adjust the color bar
7. Press (set) and assign minimum and maximum of (260 | 400) then OK
8. A porosity value of 324 indicate 0.324 (divide by 1000)