advanced image analysis to elucidate coupled problems in porous media

work performed at the DMEX Center for X-ray Imaging

by Syrine Ben Elhadj Hamida, Hannelore Derluyn, Jelle Dhaene, Peter Moonen and co-workers

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real applications are complex

cultural heritage preservation

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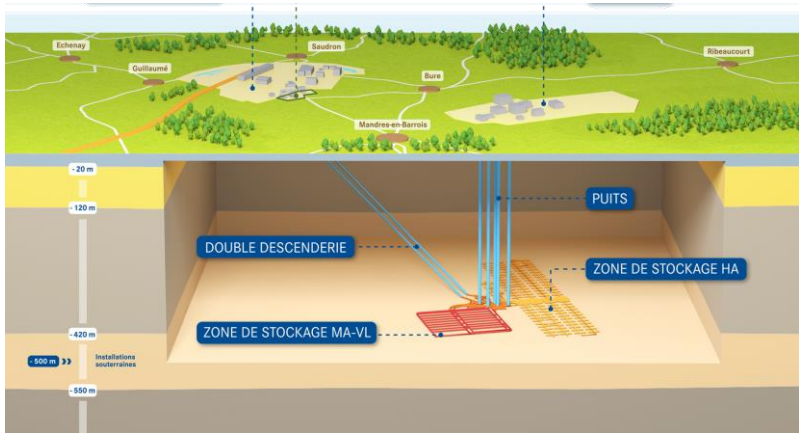
nuclear waste storage



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natural hydrogen production

coupled

- cracking
- heat
- moisture
- reactions
- biology
- …

the study of coupled processes

- is challenging
- requires a combination of experimental and numerical research

our group uses X-ray (& neutron) imaging

- non-invasive
- three-dimensional + time

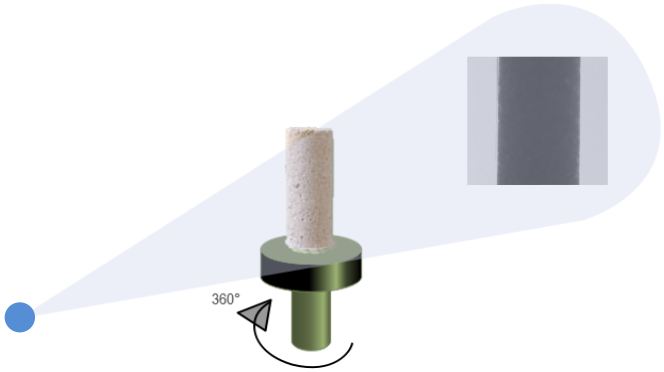
we develop acquisition and analysis protocols with focus on in situ/operando studies

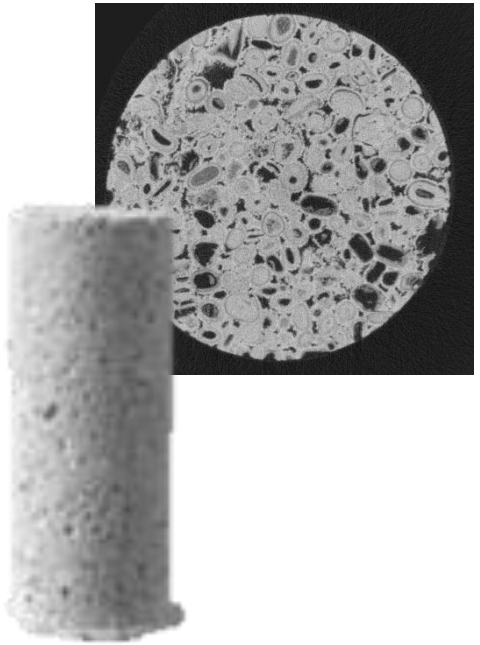
tomographs @ DMEX (UPPA, Pau, France)

Excite Network

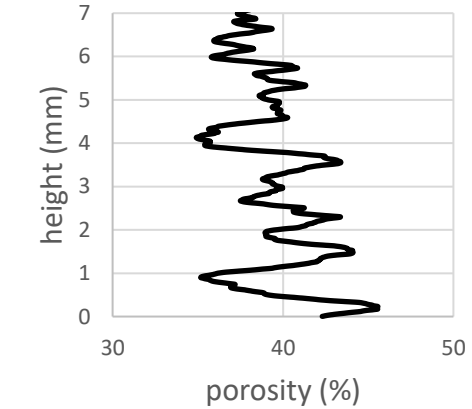
	high resolution	high contrast	high-speed
			
source :	30-160 keV, 10W	20-180keV, 300W	40-130keV, 39W
CCD :	4 MPx; 0.61 fps	8 MPx; 100 fps	2.8 MPx; >100 fps
sample size :	mm-range	cm-range	cm-range
voxel size :	≥0.3 µm	75-3 µm	37.5-5 µm
	low blur	spectral ability	no sample motion

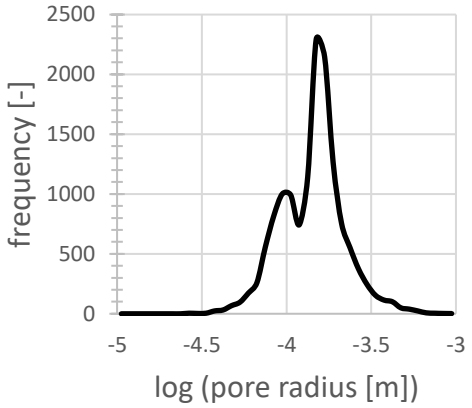
conventional workflow





- filtering
- segmentation
- …



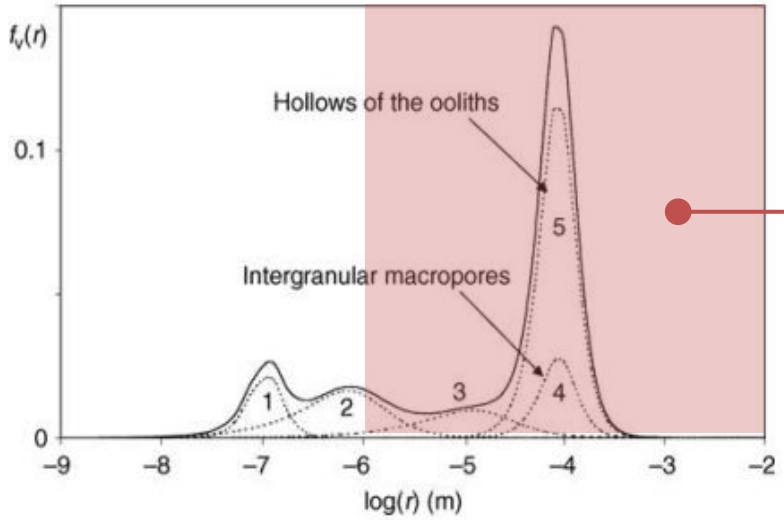


acquisition → reconstruction → analysis

material & process

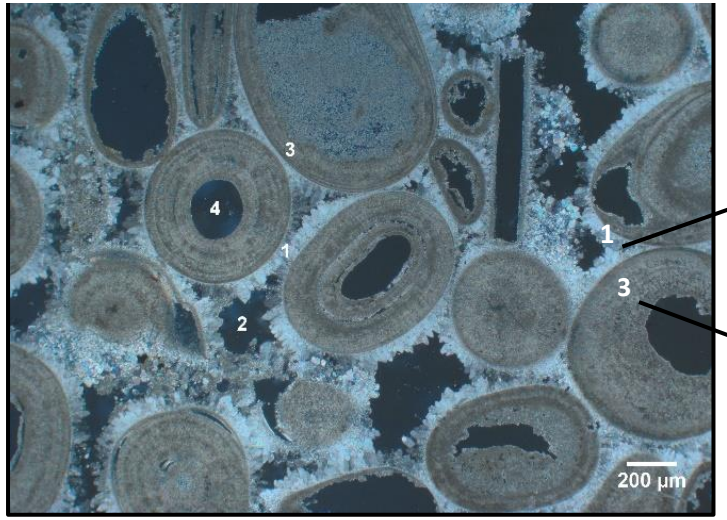
LIMITS OF THE CONVENTIONAL WORKFLOW

multiple scales



direct observation by
lab-based X-ray tomography

© Peter Haas



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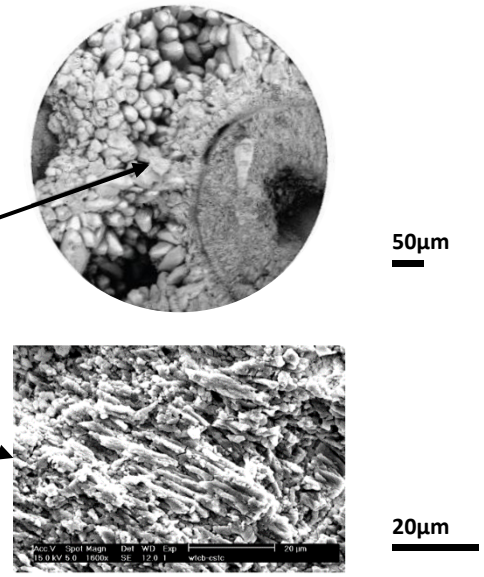

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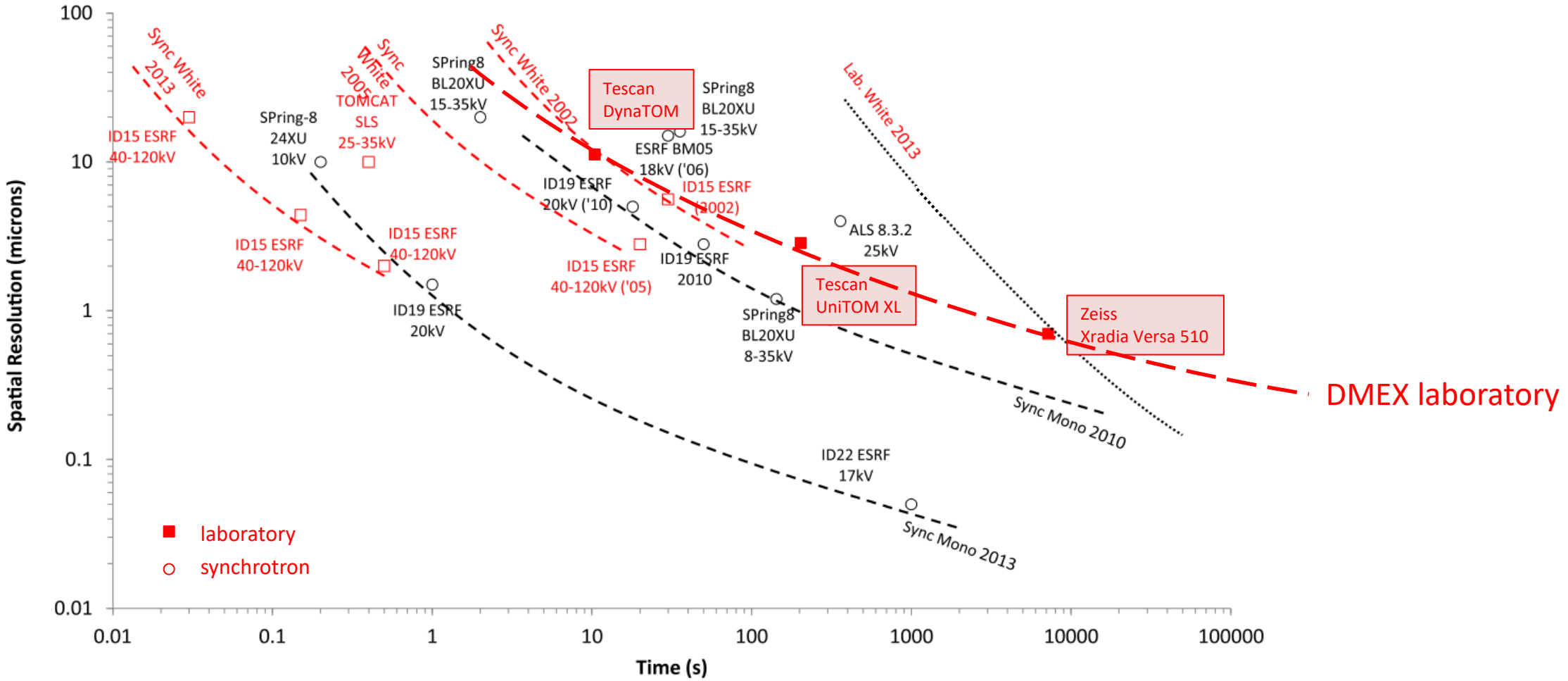
tens of meters — cm — mm — µm

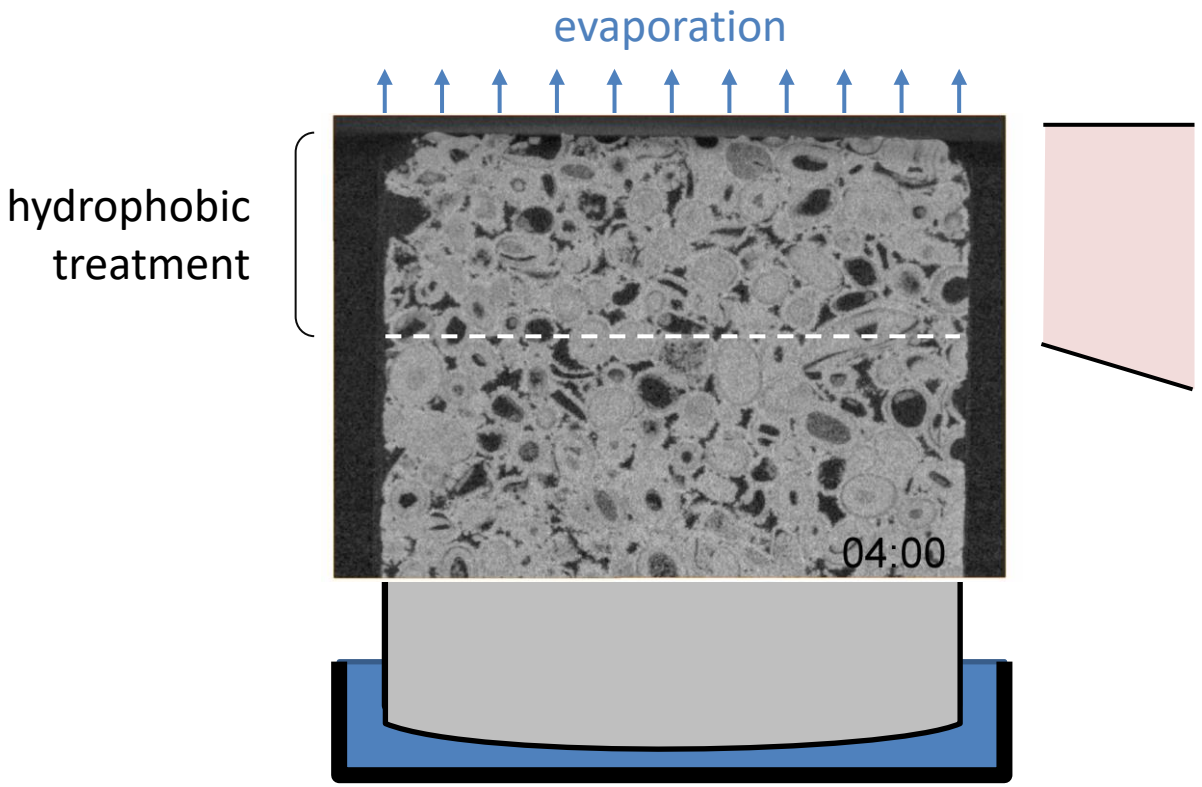
spatio-temporal instrumental constraints



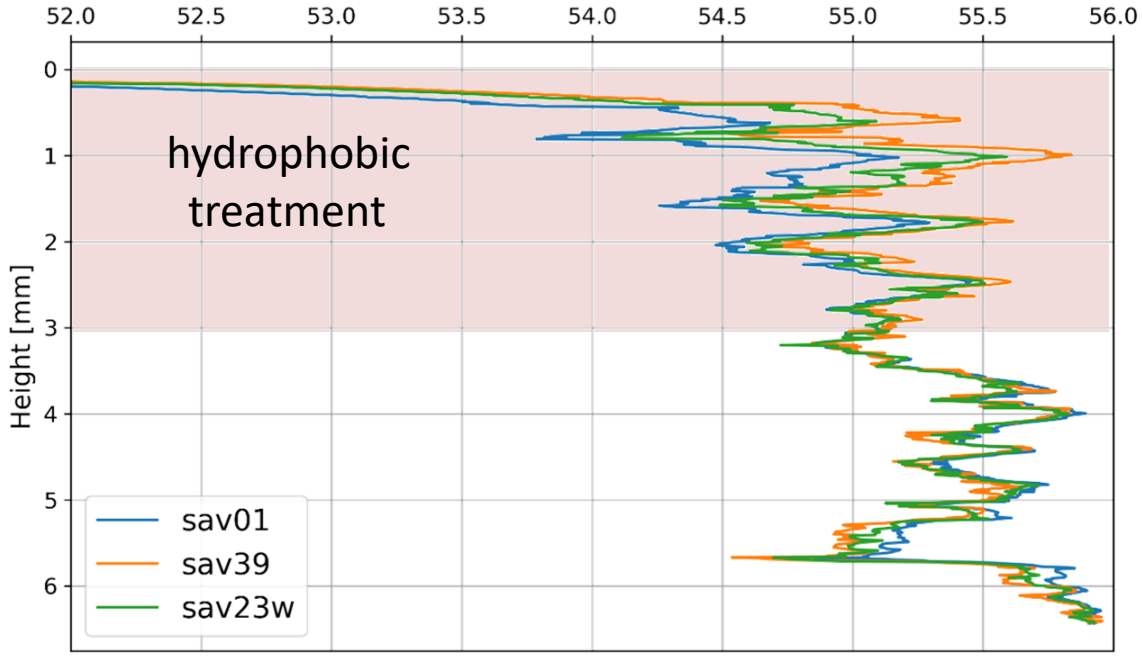
adapted from Bultreys et al. 2016

coupled processes

Savonnières sample (ϕ=8.4mm, H=9mm)



cross-sectional area over time
[mm]

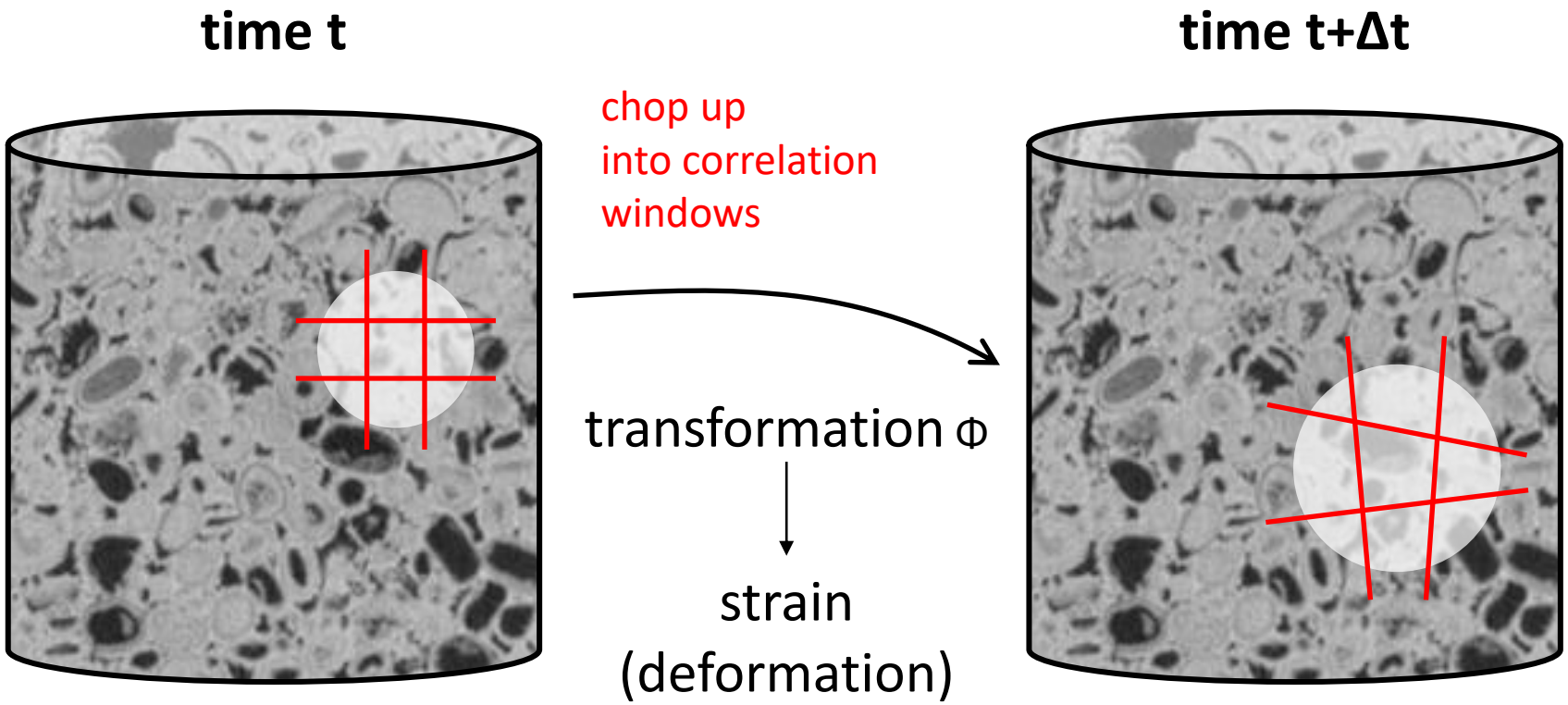


dimensional changes
→ direct comparison different time points difficult

accounting for deformation

DIGITAL VOLUME CORRELATION (DVC)

principle of (local) DVC

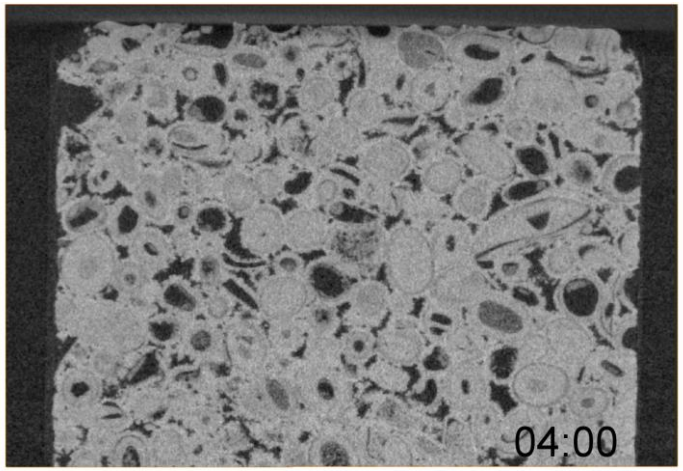


→ implemented in tools such as SPAM (spam-project.dev, Stamati et al. 2020)

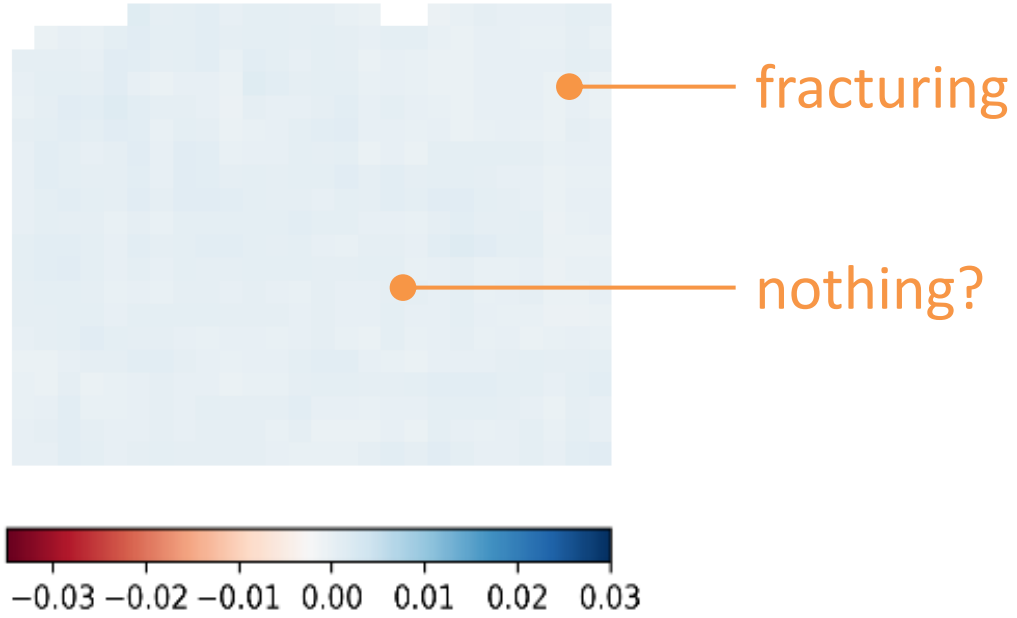
DVC applied to a drying sample (1/2)

PRD-Trigger Grant n°850853

raw data



volumetric strain [-]



→ high positive volumetric strain = fractures

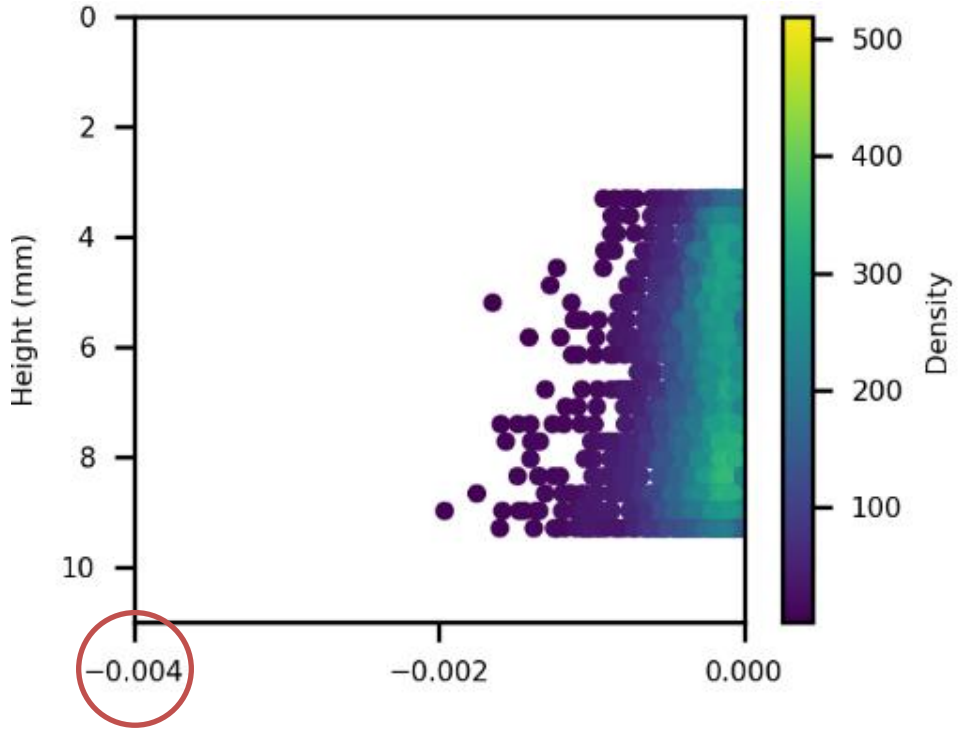
→ bulk of sample: small volumetric strain

DVC applied to a drying sample (2/2)

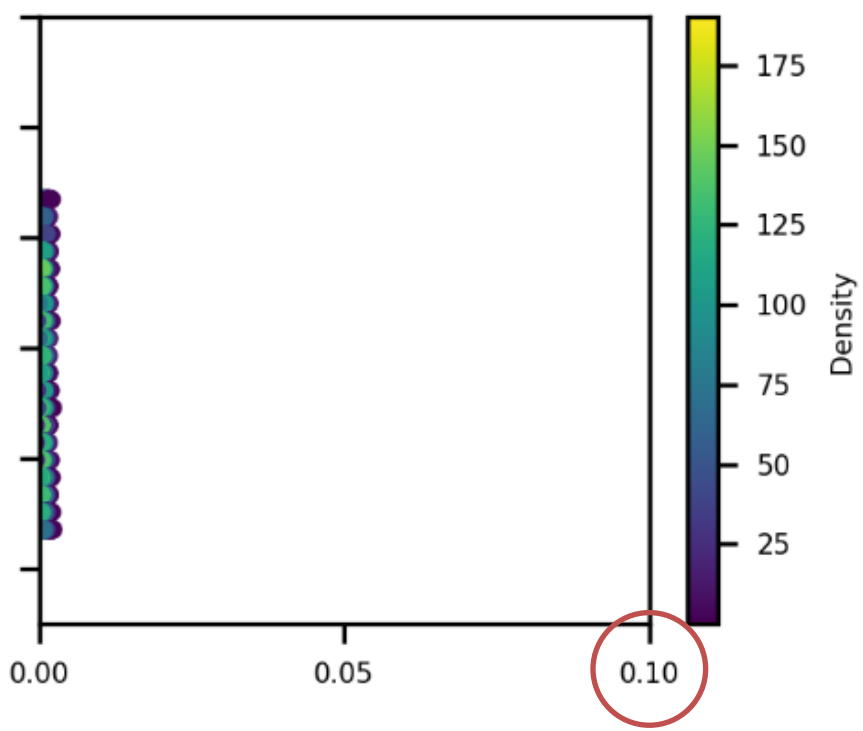
PRD-Trigger Grant n°850853

90 min drying

negative volumetric strain distribution



positive volumetric strain distribution



note scale difference

DVC applied to a drying sample (2/2)

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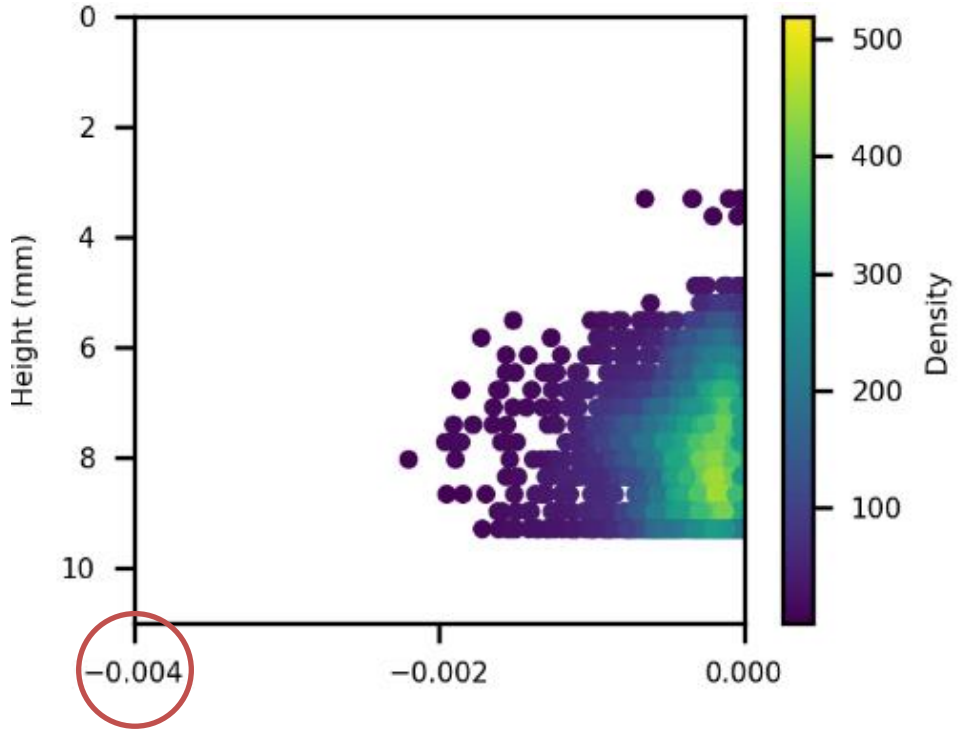
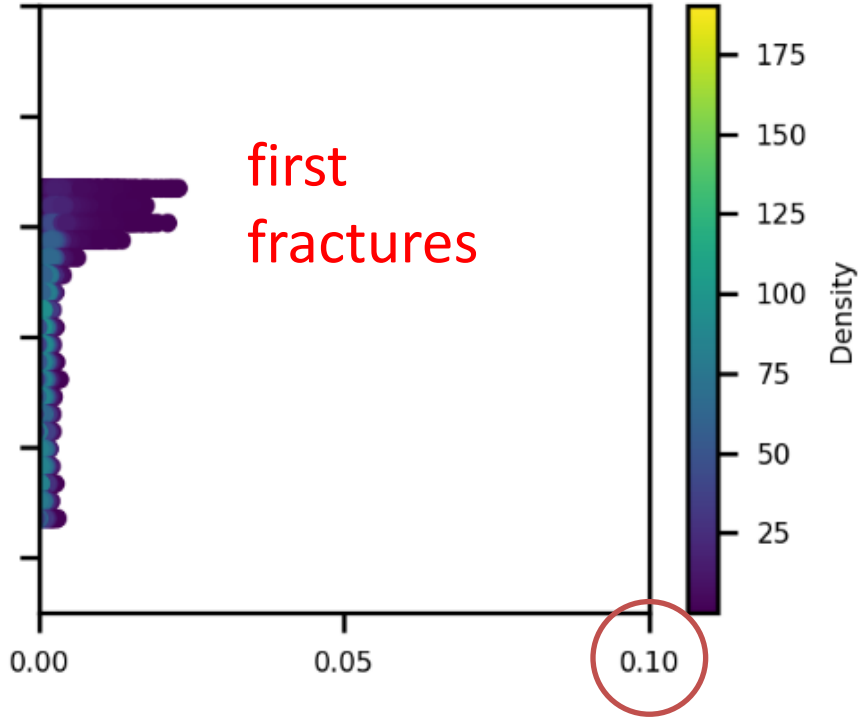
270 min drying

negative volumetric strain distribution



positive volumetric strain distribution



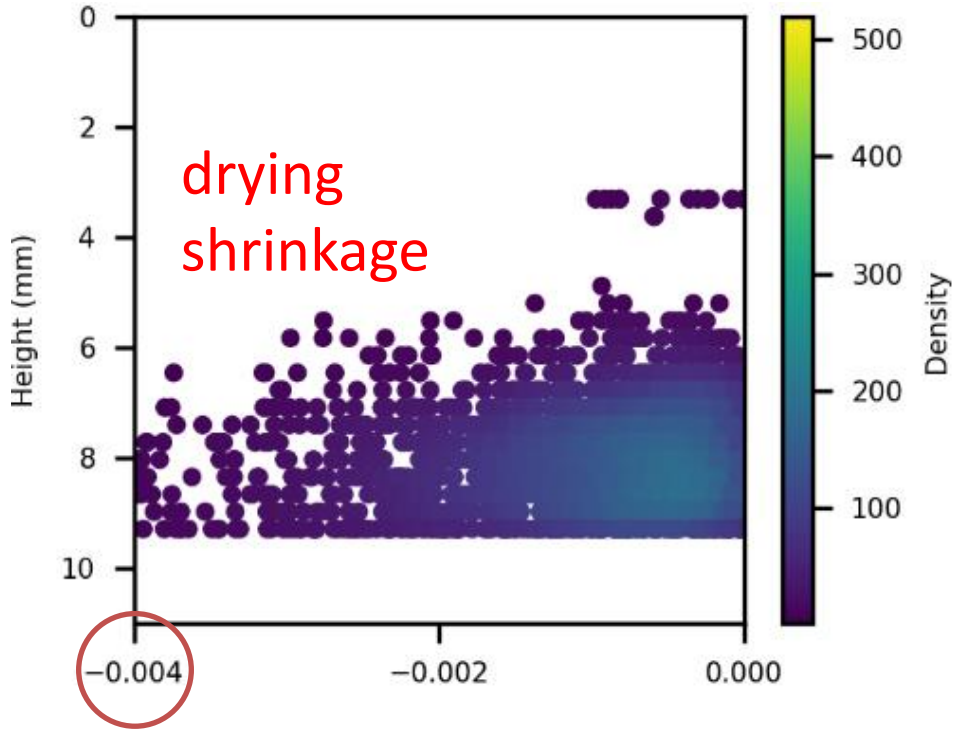
note scale difference

DVC applied to a drying sample (2/2)

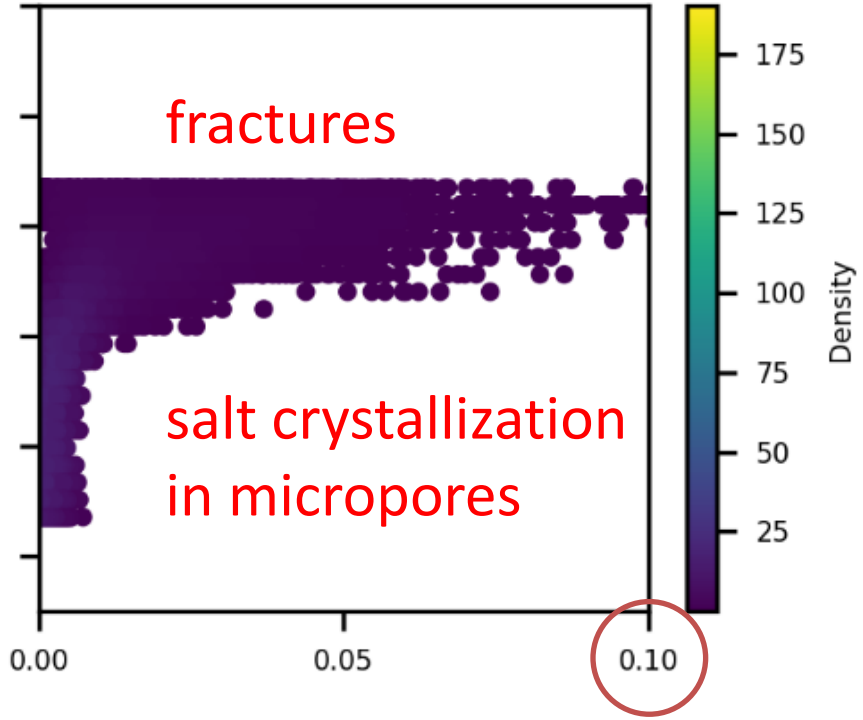
PRD-Trigger Grant n°850853

1200 min drying

negative volumetric strain distribution



positive volumetric strain distribution



note scale difference

extracting fluid saturation

DVC-CORRECTED DIFFERENTIAL IMAGING

Ben Elhadj Hamida et al. (in preparation)

motivation

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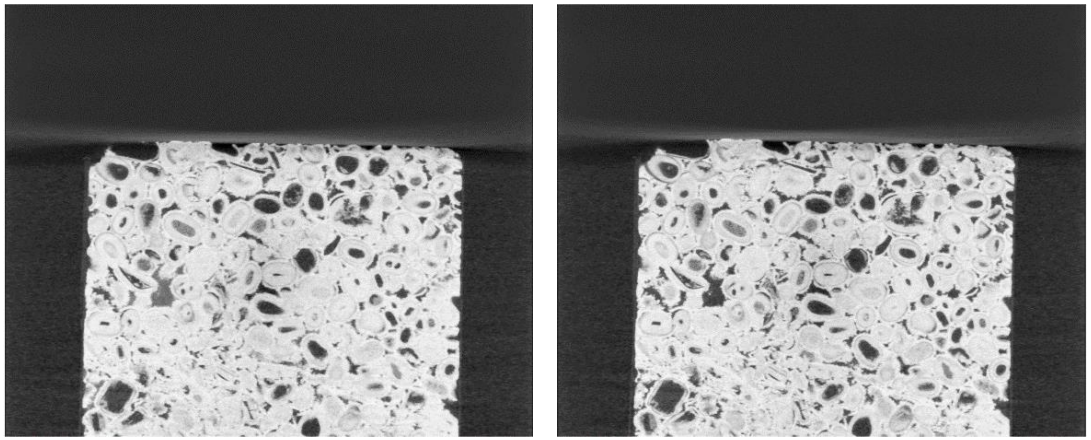
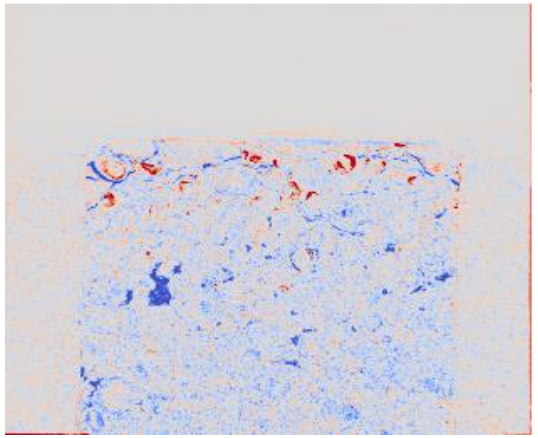
time t **time t+Δt** **residual field**



IM(t+Δt) – IM(t)

IM(t+Δt) – IM(t,Φ(x))



positive differences = salt crystallization

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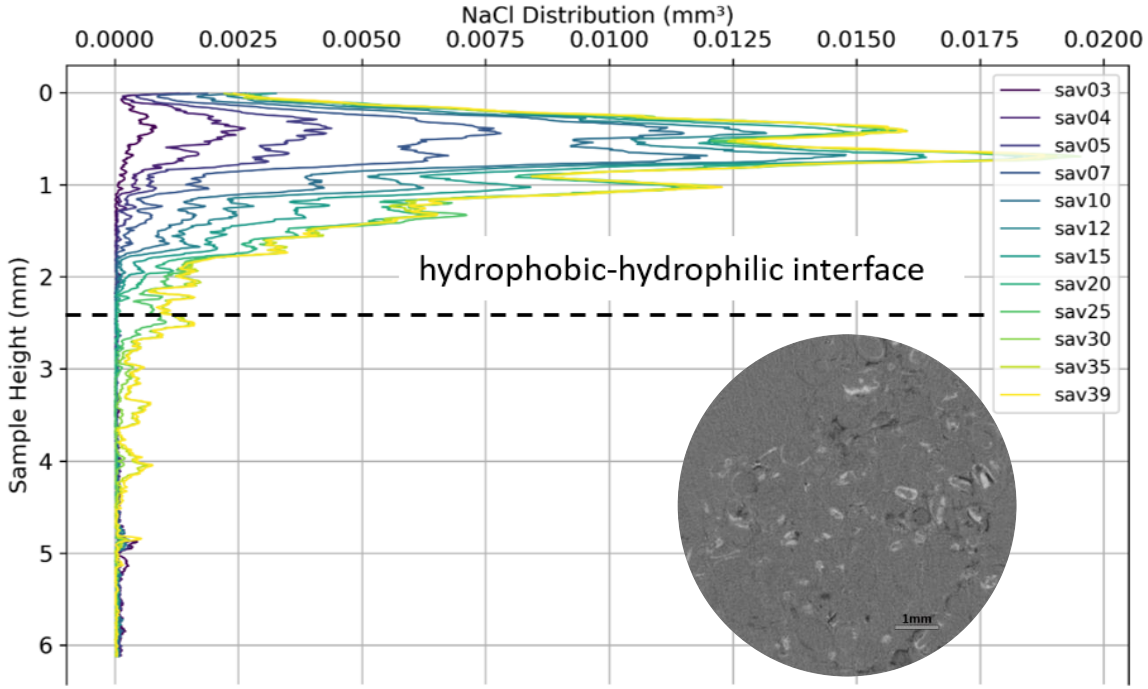
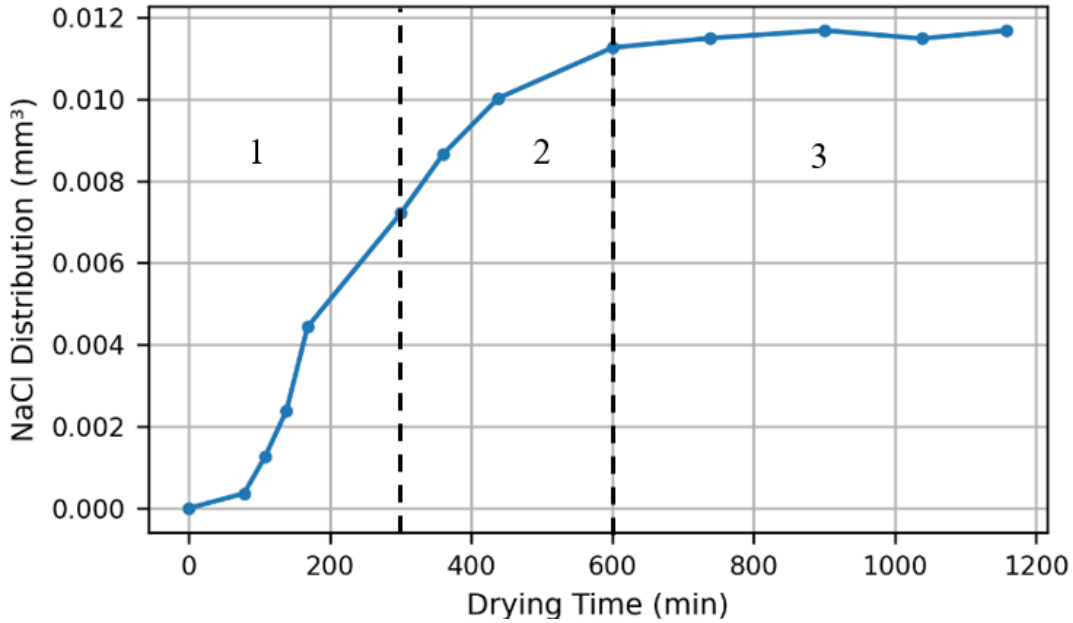
crystal volume over height



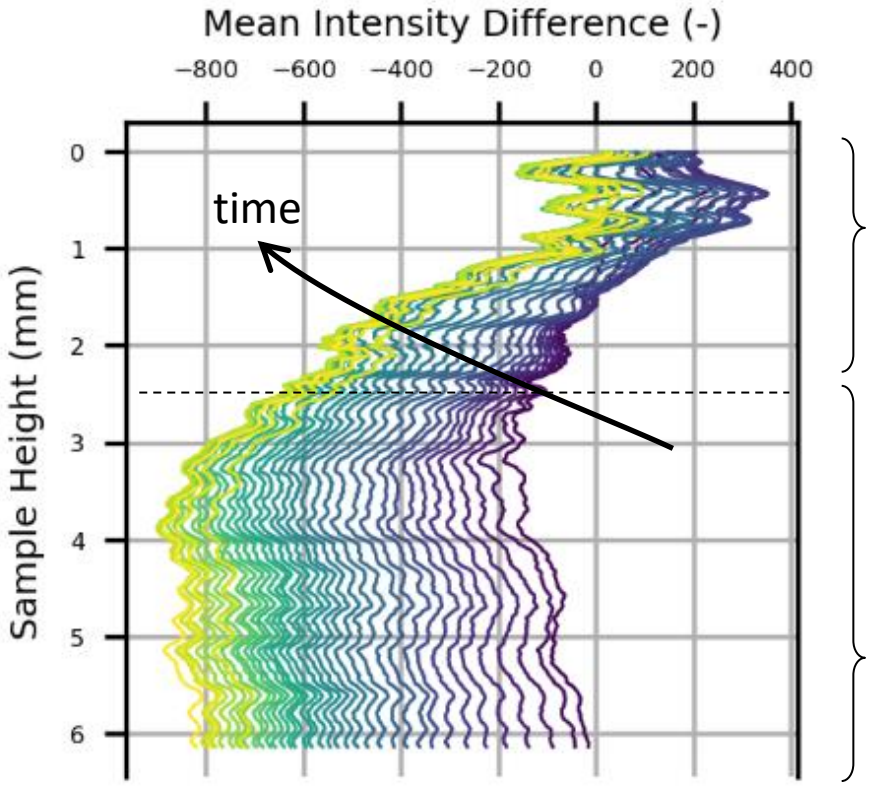
cumulative salt volume

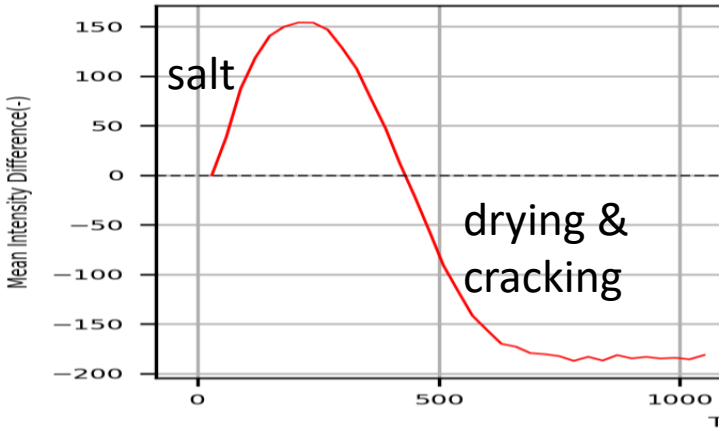


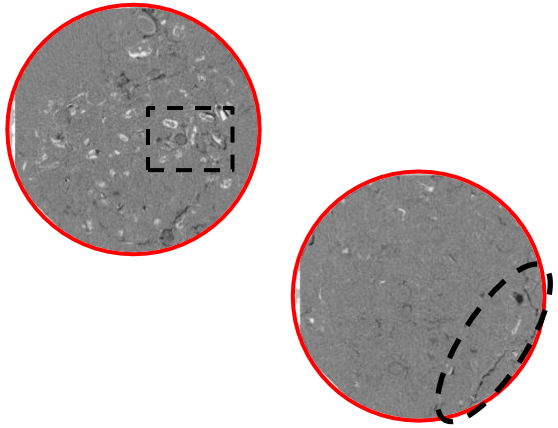
→ enables studying crystallization kinetics and localization

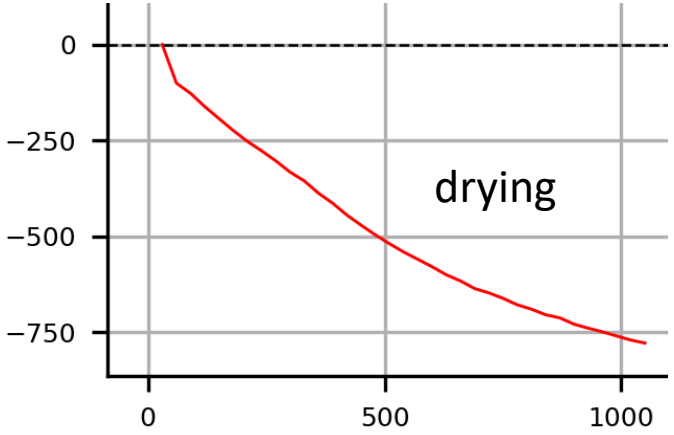
negative differences = decrease in saturation

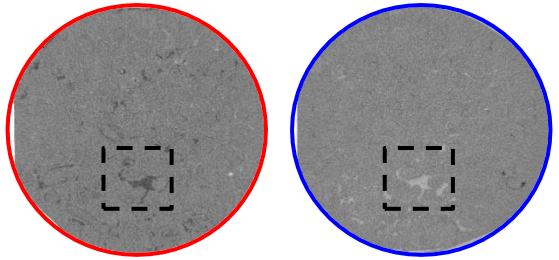
PRD-Trigger Grant n°850853











→ enables studying macro-scale transport kinetics

towards a meso-scale analysis

MACHINE LEARNING

Ben Elhadj Hamida et al. (in preparation)

role of each pore family

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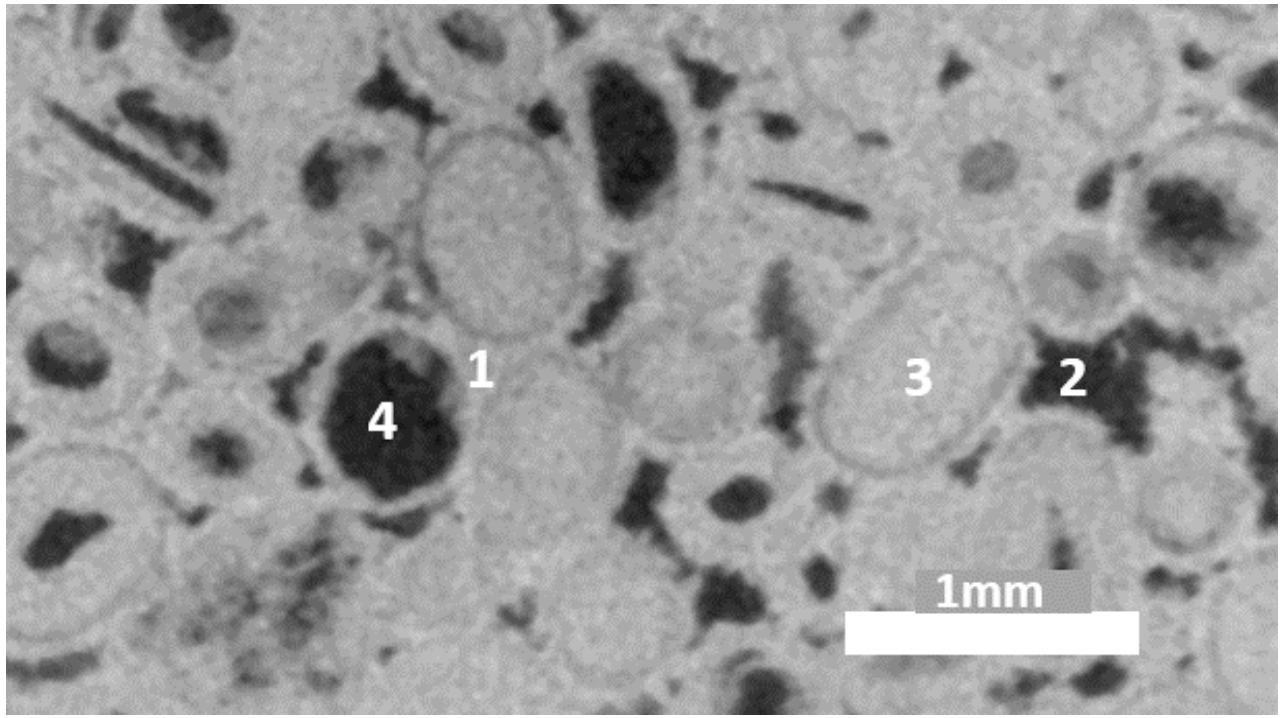
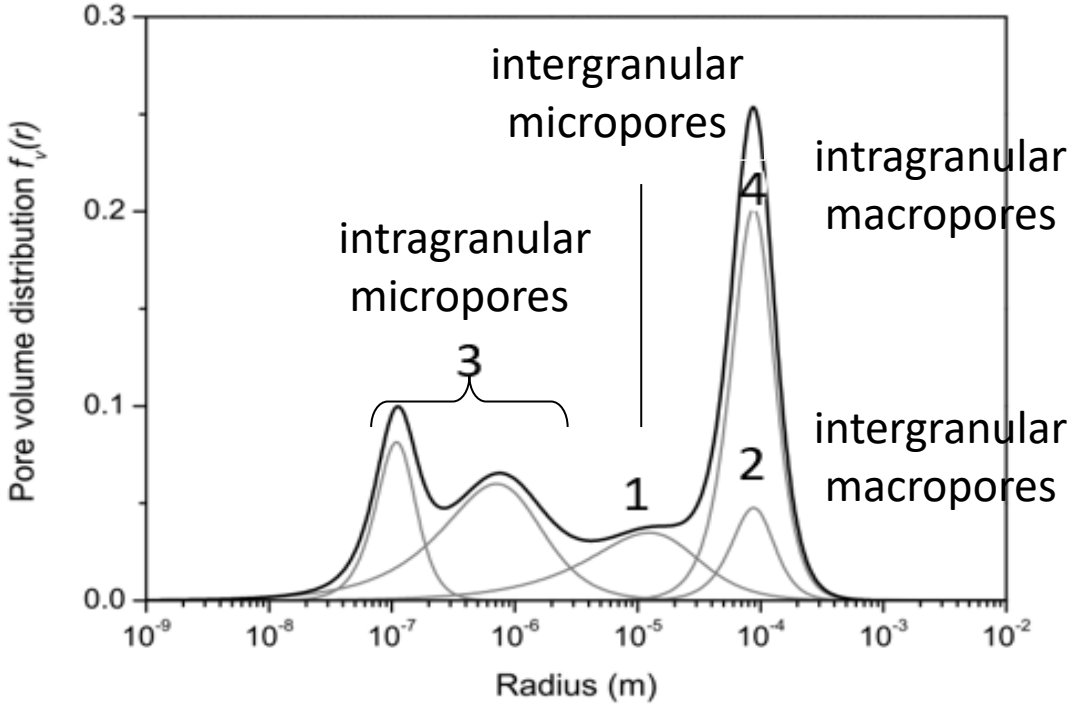
representative x-ray slice



real pore size distribution



→ how can we distinguish between 1 and 3 (both unresolved)

deep learning segmentation: preparation

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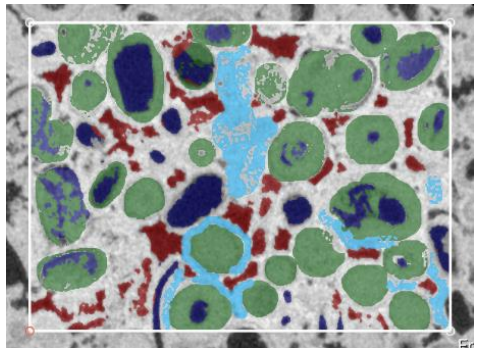
step 1: manual labelling

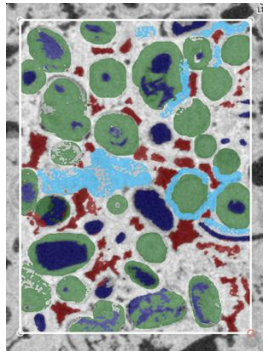


*Intra*granular macropores
Intergranular macropores
*Intra*granular *micro*pores
Intergranular *micro*pores

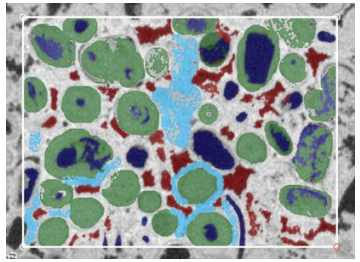
10 slices

step 2: data augmentation

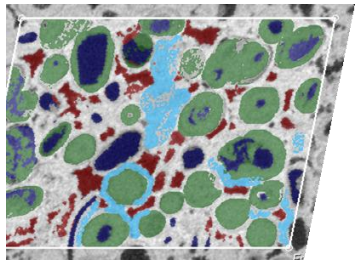
rotate



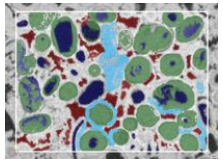
flipping



shearing



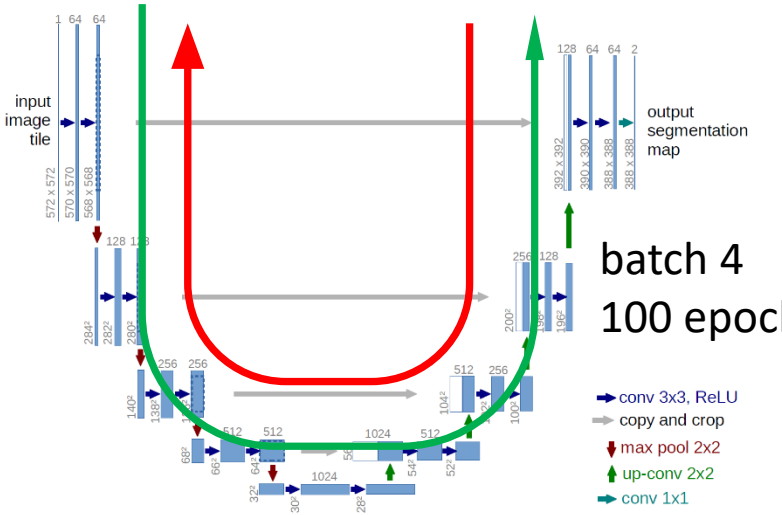
scaling



1000 slices

step 3: model training

a) forward pass
b) backpropagation



batch 4
100 epochs

808 slices (80%)

deep learning segmentation: validation

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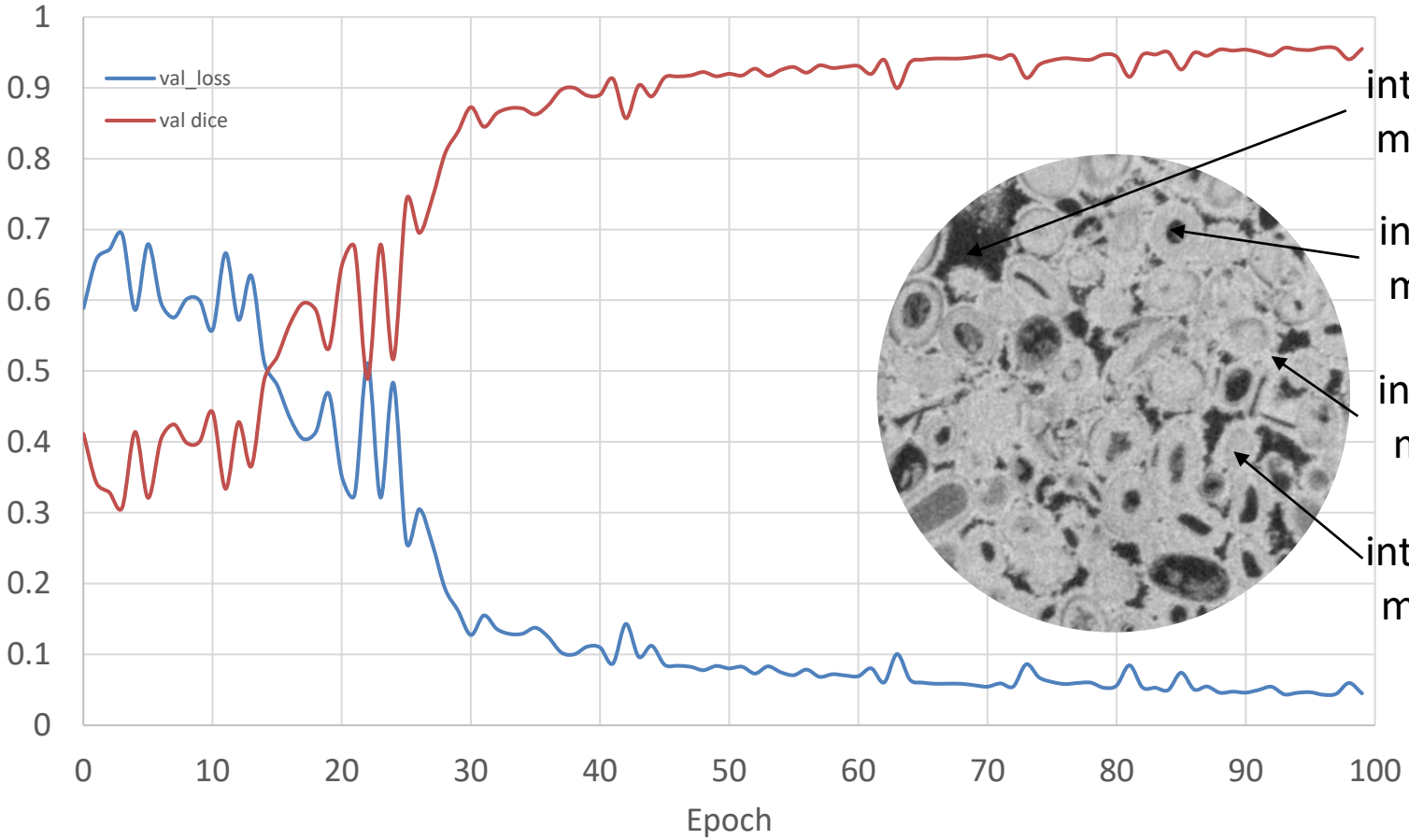

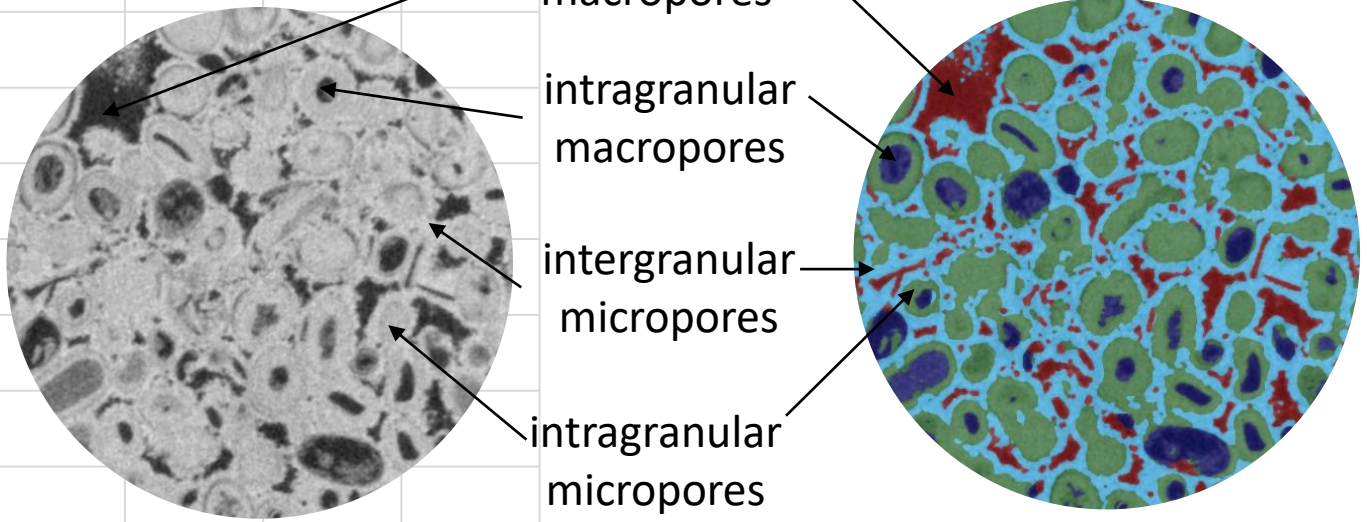

deep learning segmentation: result

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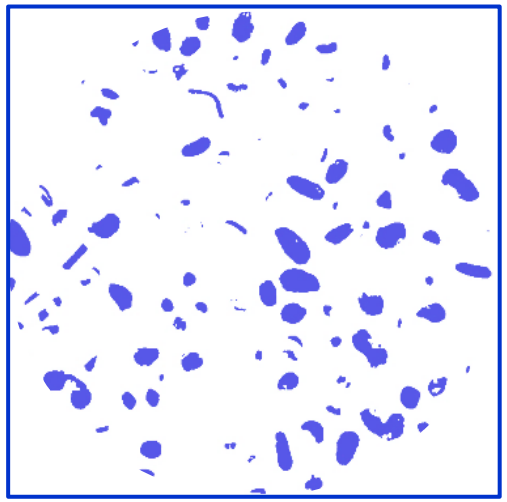
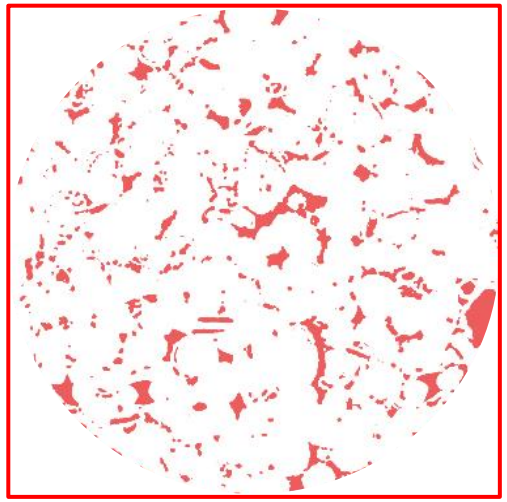
intra-granular macropores

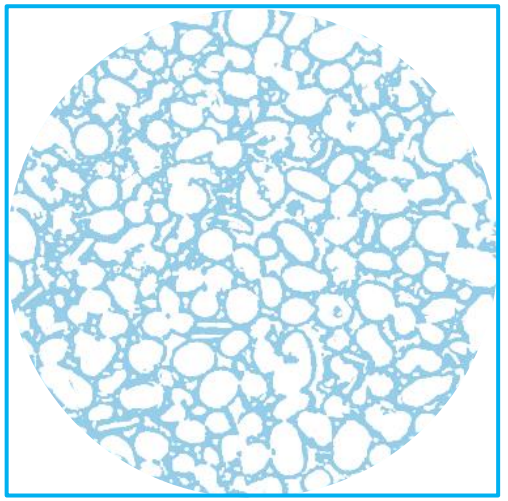


inter-granular macropores



intra-granular micropores

inter-granular micropores



→ applied on DVC-corrected reference images

→ masks for any time step

drying kinetics

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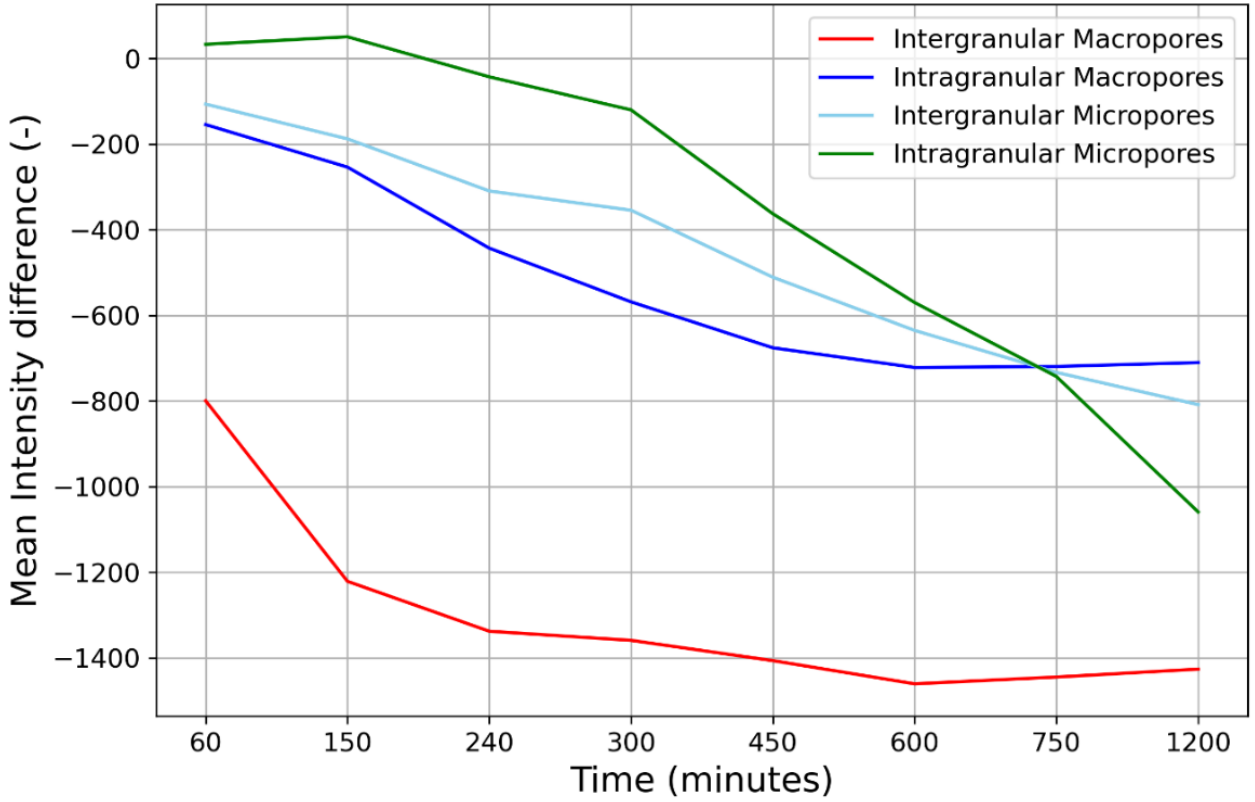
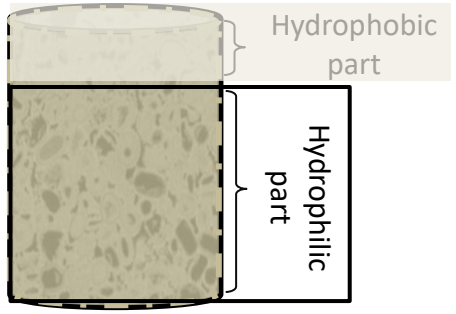
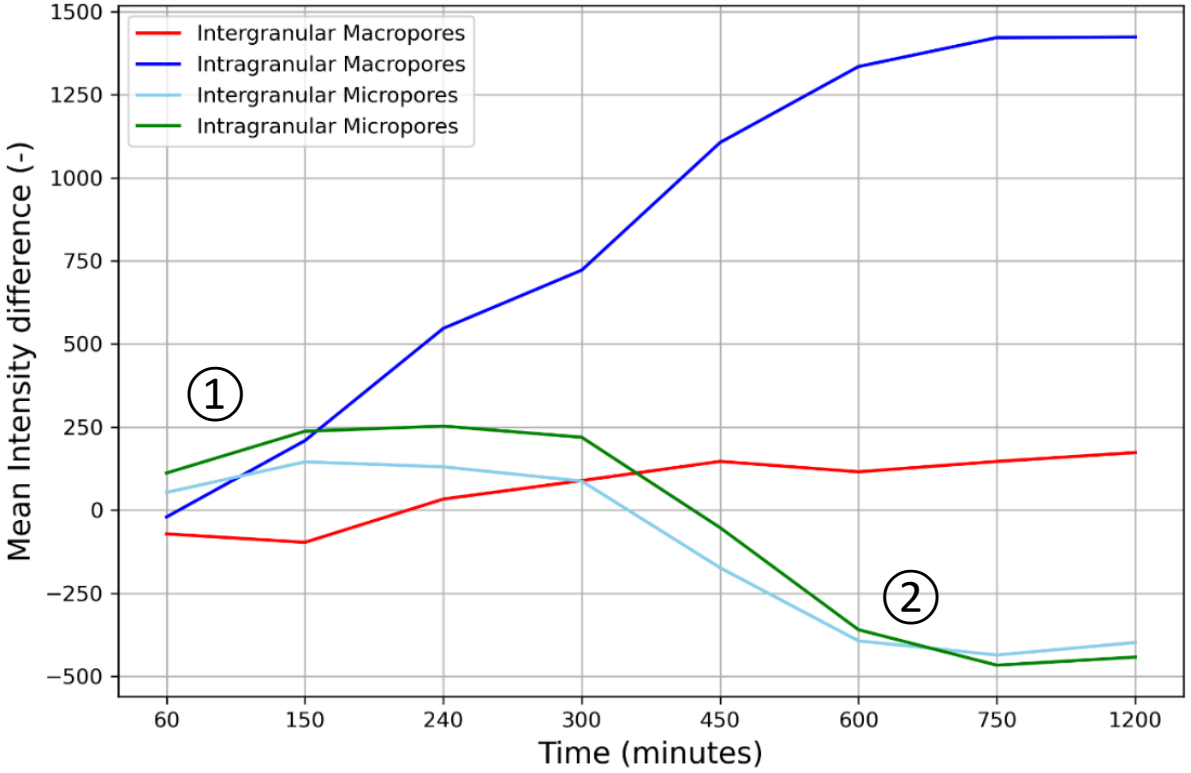


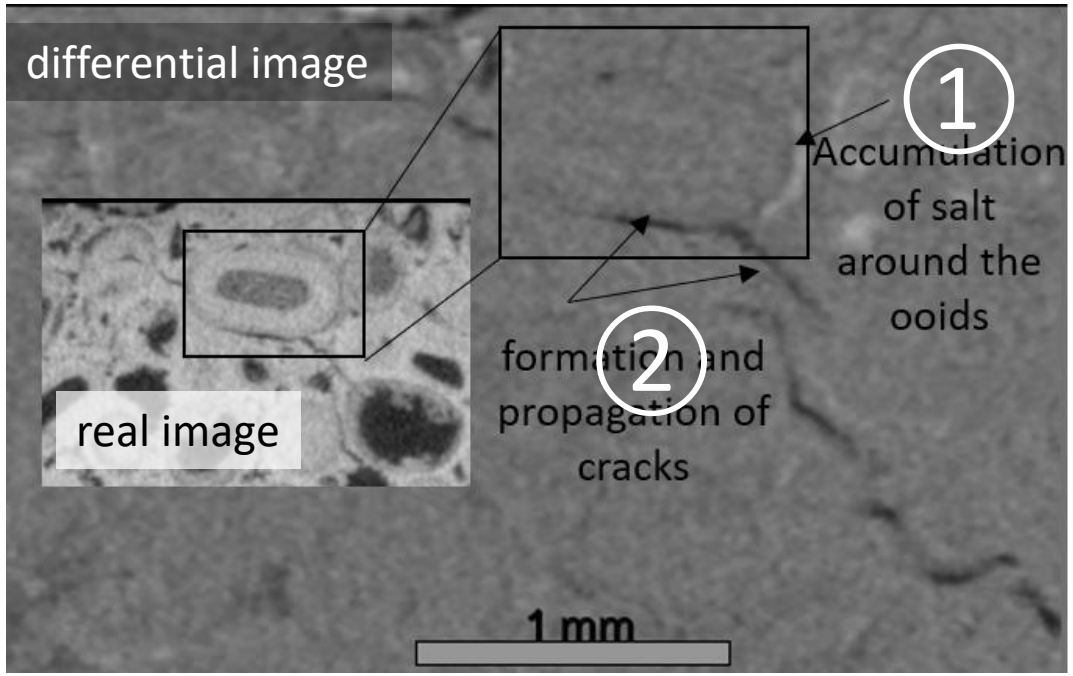


drying sequence:
inter, intra macropores
inter, intra micropores

→ enables studying transport kinetics *for each pore family*

salt crystallization





①

salt deposition at interface intra/intergranular micropores

②

crack initiation around ooids, propagating into matrix (intergran. micropores)

calibration-free quantification of grey levels and their changes

PHYSICS-BASED IMPROVEMENTS

step 1: initial geometry

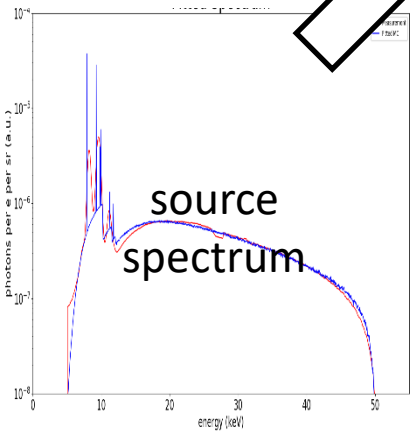
physics-based forward projector

source

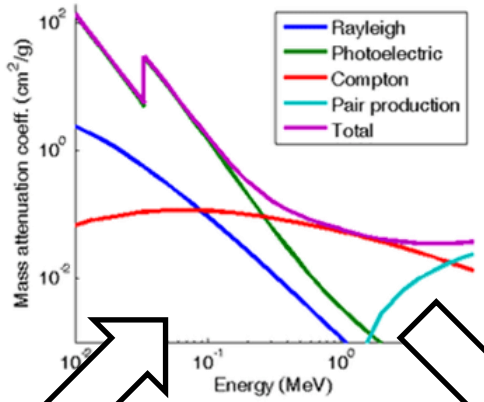
sample

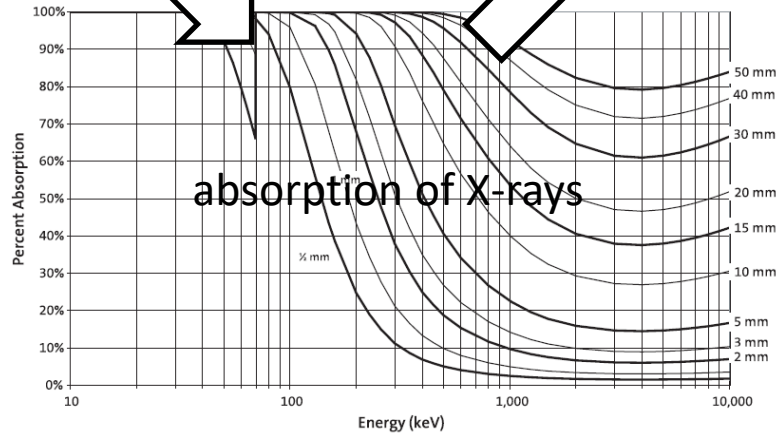
scintillator

CCD camera

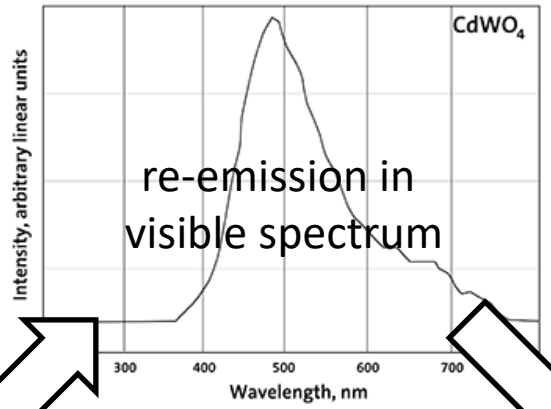


source spectrum

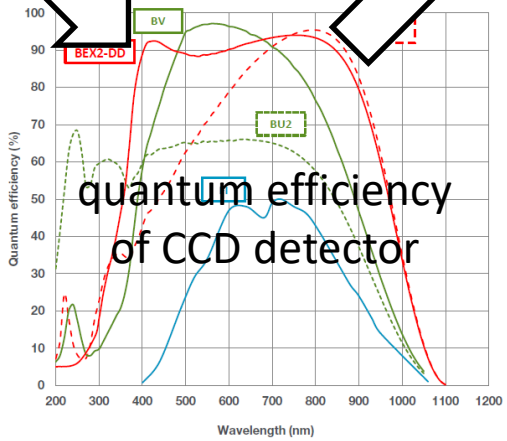




absorption of X-rays



re-emission in visible spectrum

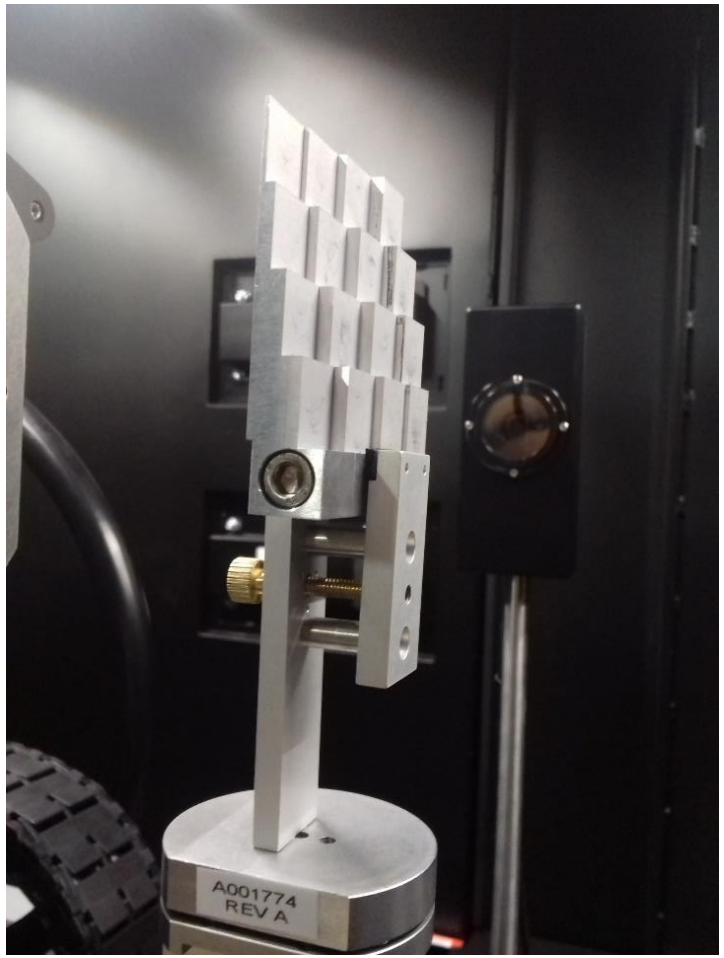


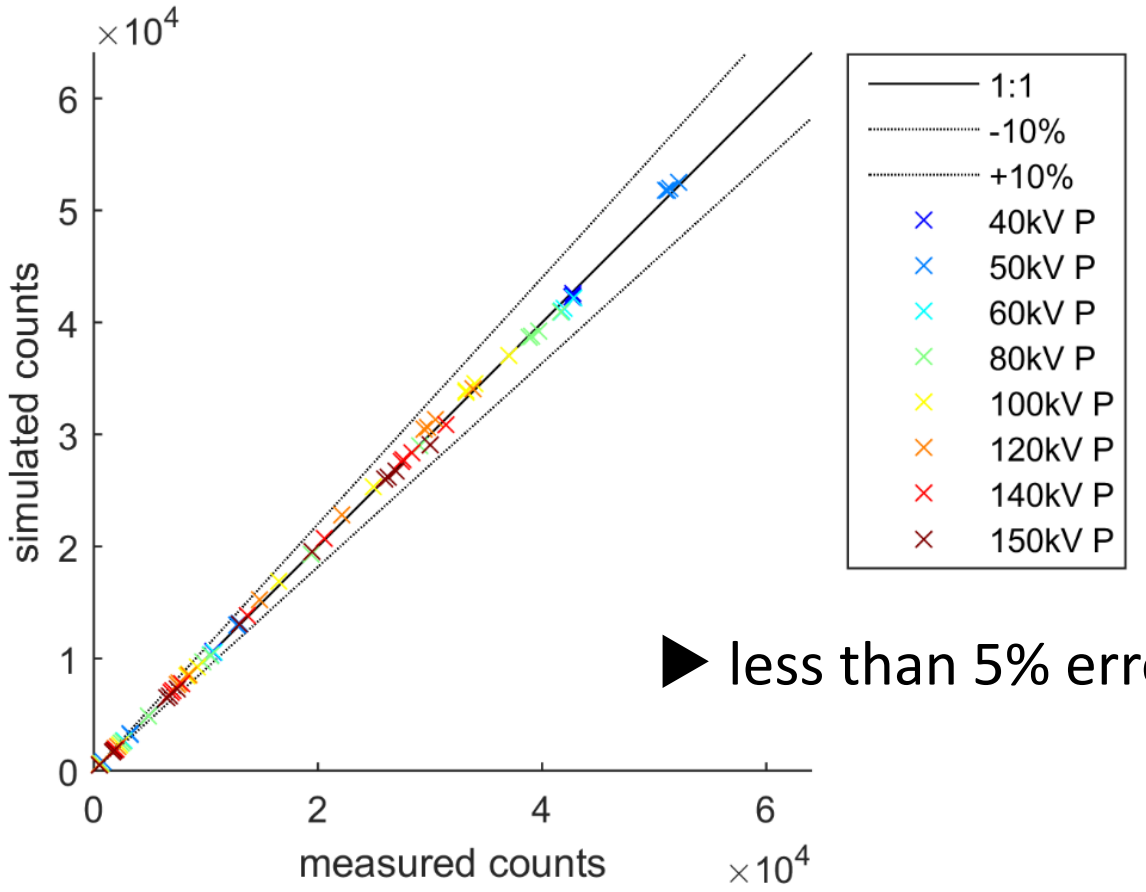
quantum efficiency of CCD detector

add dark current, amplifier & readout noise

physics-based forward projector

s

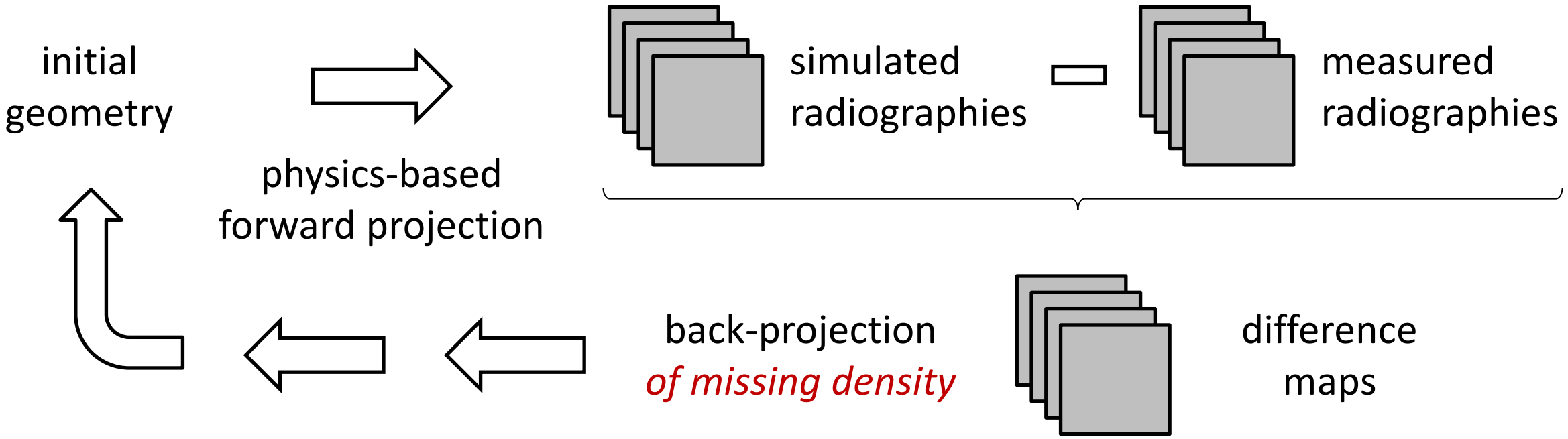




▶ less than 5% error on full range

iterative reconstruction framework

- POLYSART (POLYchromatic Simultaneous Algebraic Reconstruction Technique)

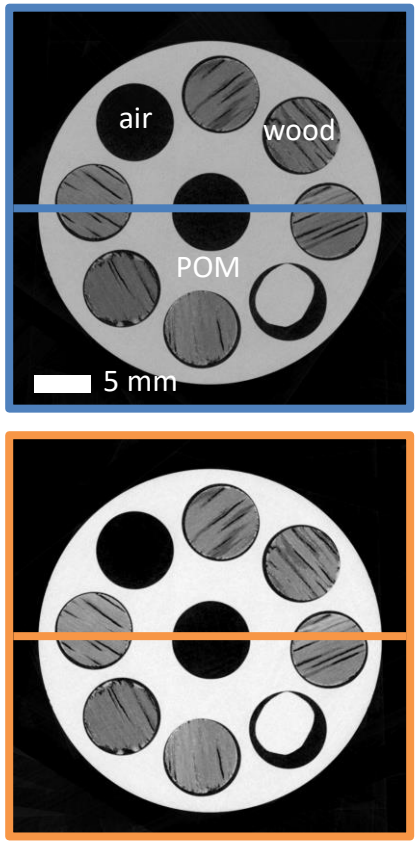


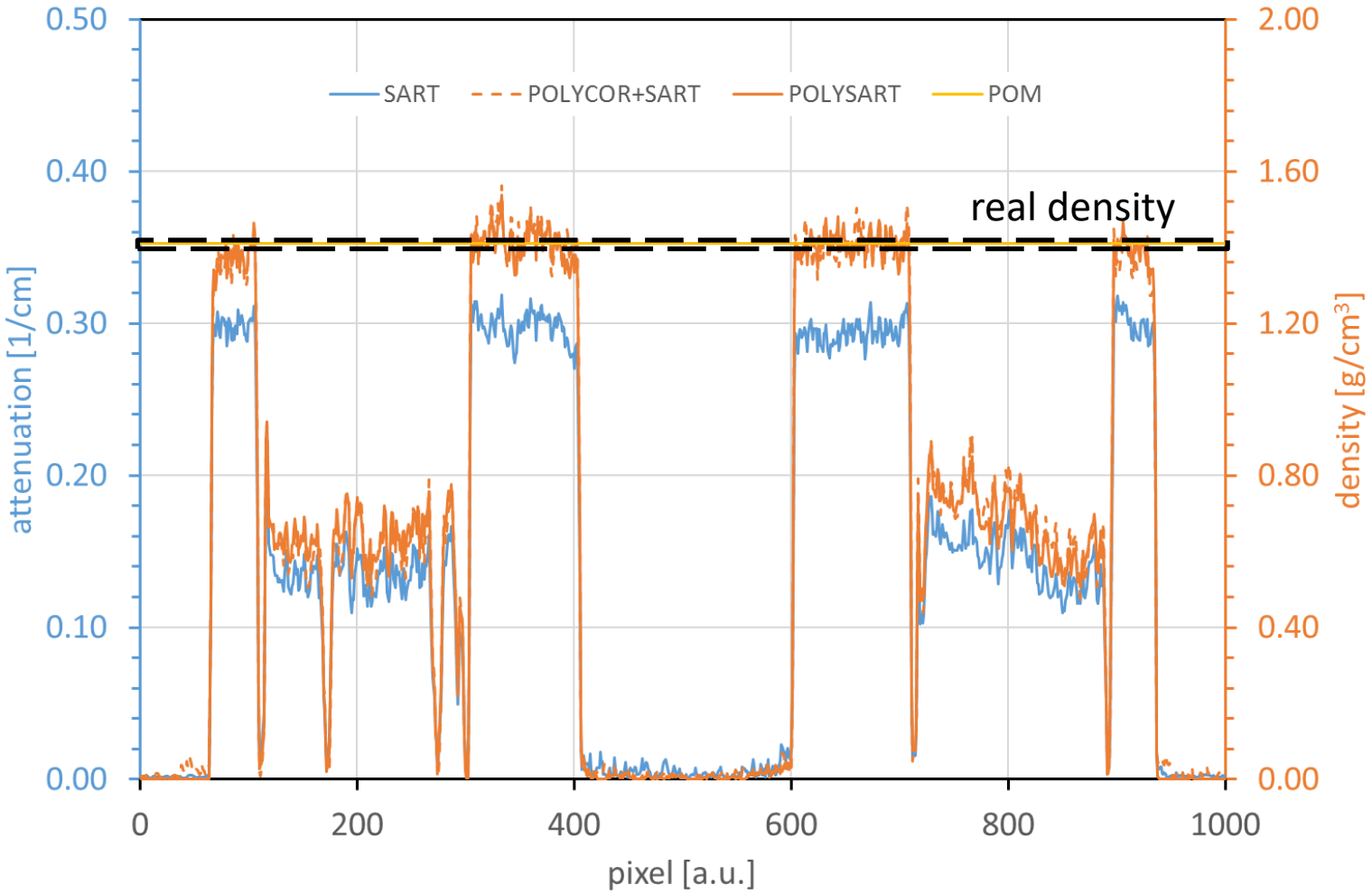
Moonen et al. 2021

application 1: densitometry

SART

POLYSART



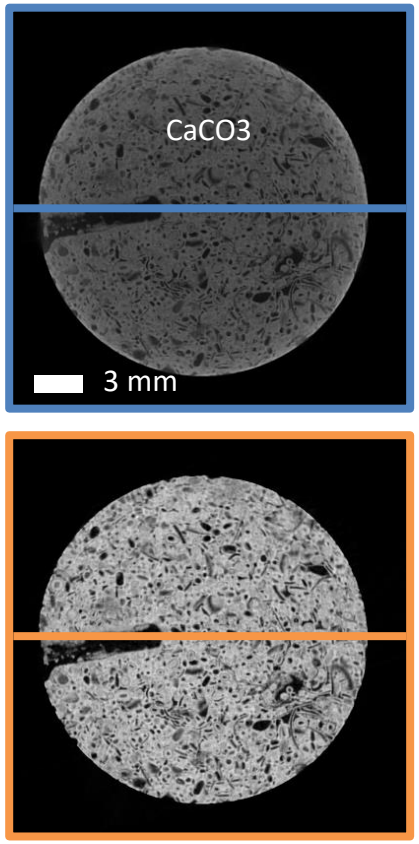


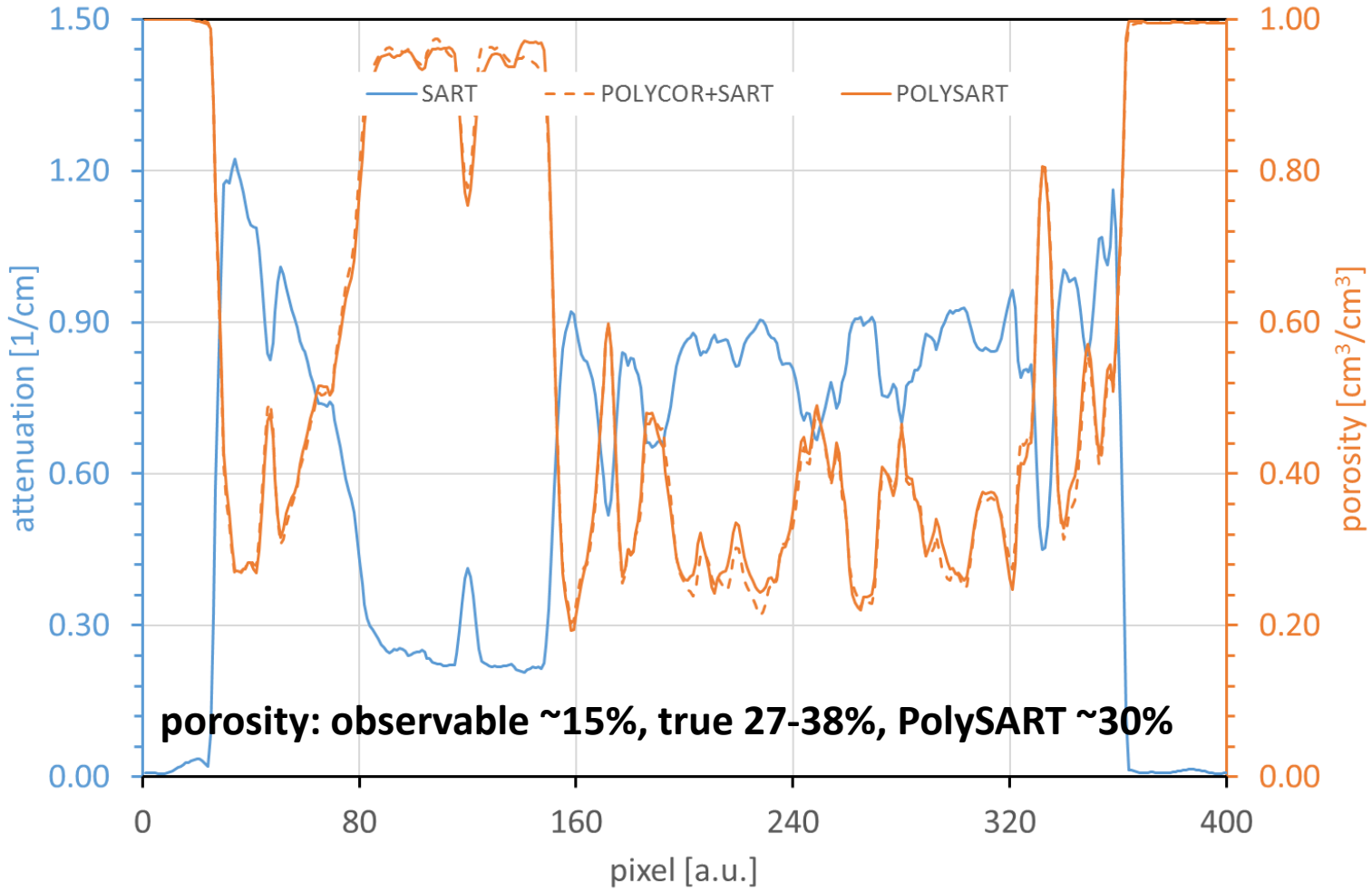
Moonen et al. 2021

application 2: sub-resolution porosity

SART

POLYSART





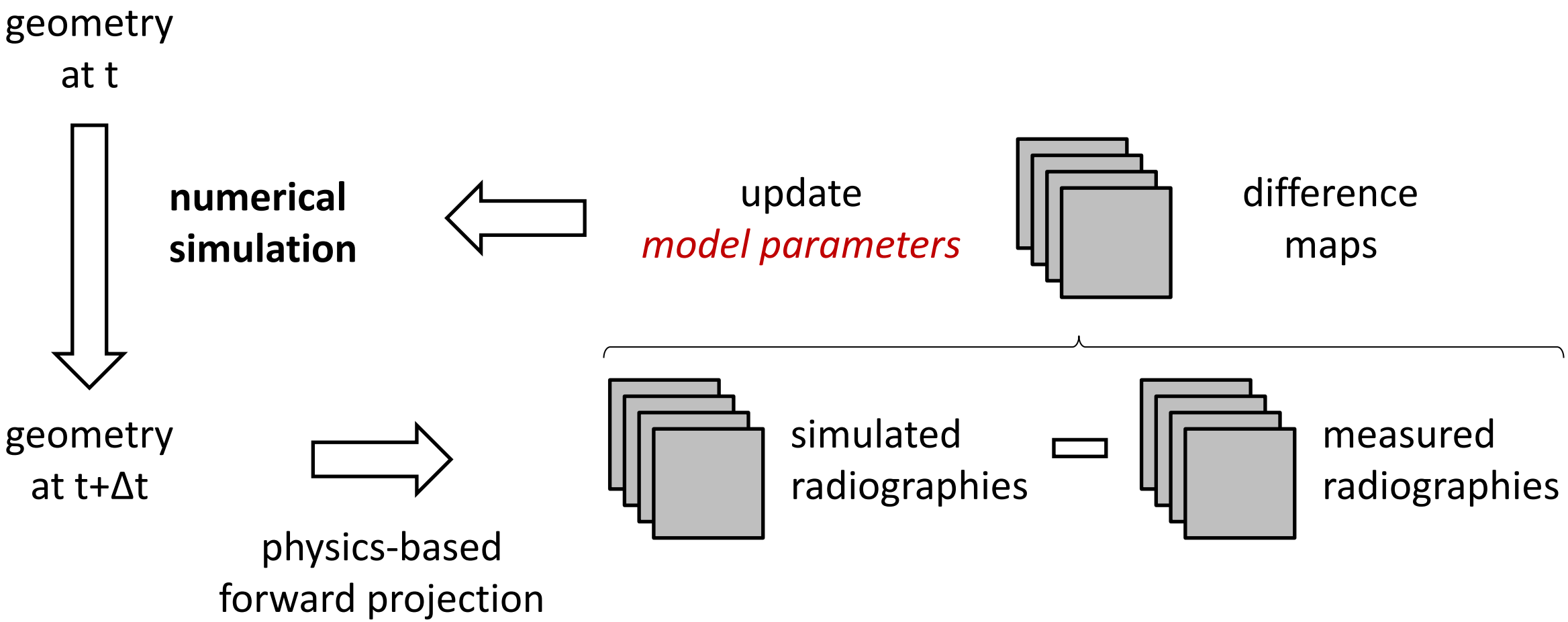
Moonen et al. 2021

calibration-free quantification of grey levels and their changes

PHYSICS-BASED IMPROVEMENTS

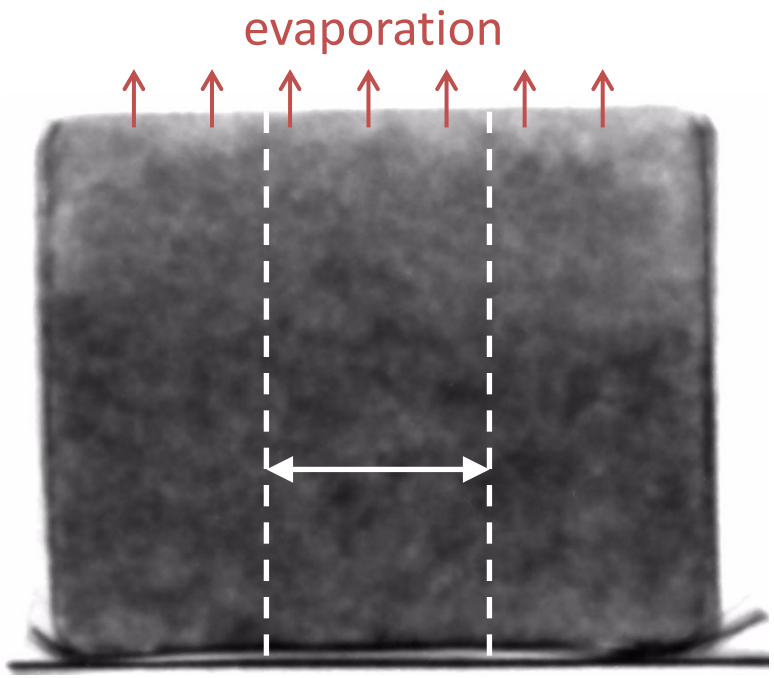
step 2: temporal evolution

physics-based registration

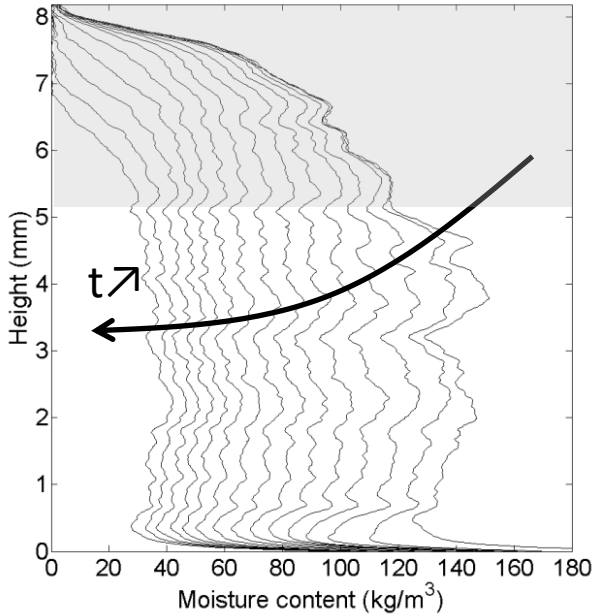


(A) experiment: evaporative drying

neutron radiography @ SINQ



post-processing with QNI



experimental details in Derluyn 2012

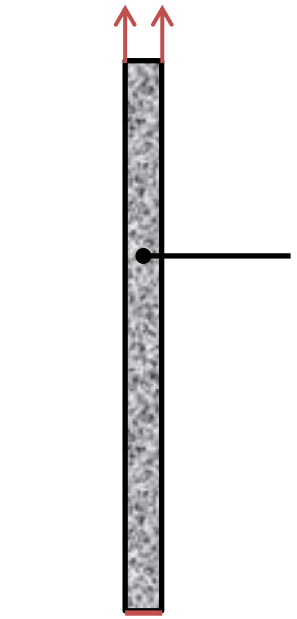
(B) simulation (toy-)model

uncertain parameter

evaporation

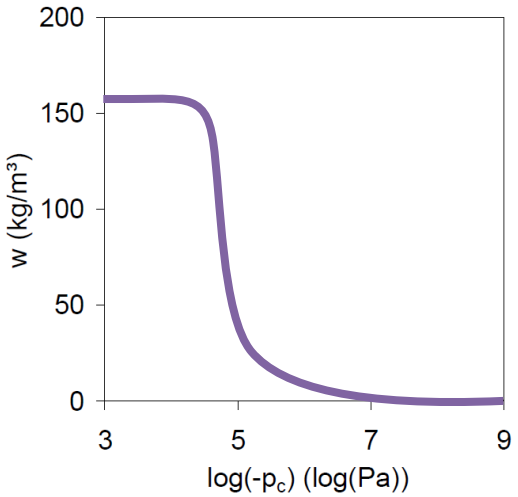
$$g_v = \beta(p_{v,atm} - p_v)$$

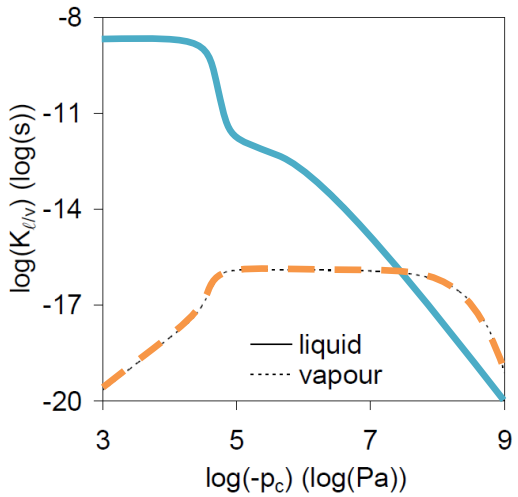
with $$p_v = p_{v,sat} exp\left(-\frac{p_c}{\rho_l R_v T}\right)$$



impermeable

mass conservation $$\frac{\partial w}{\partial p_c}\frac{\partial p_c}{\partial t} = -\nabla(-(K_l + K_v)\nabla p_c)$$





solved with FEM

(C) « force to match »

trial-and-error

- run model for various values $\boldsymbol{\beta}$ until a “good” value is found
  - result: β
  - manual or automatic
    (e.g. Levenberg-Marquardt)
  - cost $\sim$ number of tested values

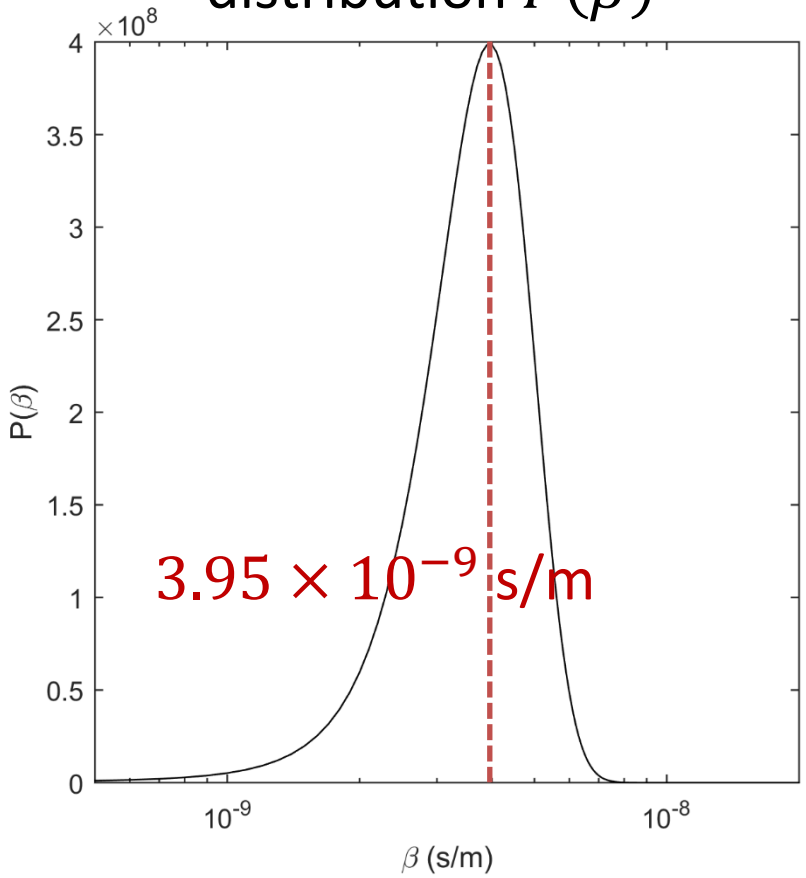
Bayesian calibration

- run model for $\boldsymbol{m}$ values of $\boldsymbol{\beta}$. Calibration yields distribution
  - result: $P(\beta)$
  - automatic
    (e.g. MCMC by Metropolis-Hastings)
  - cost = m runs

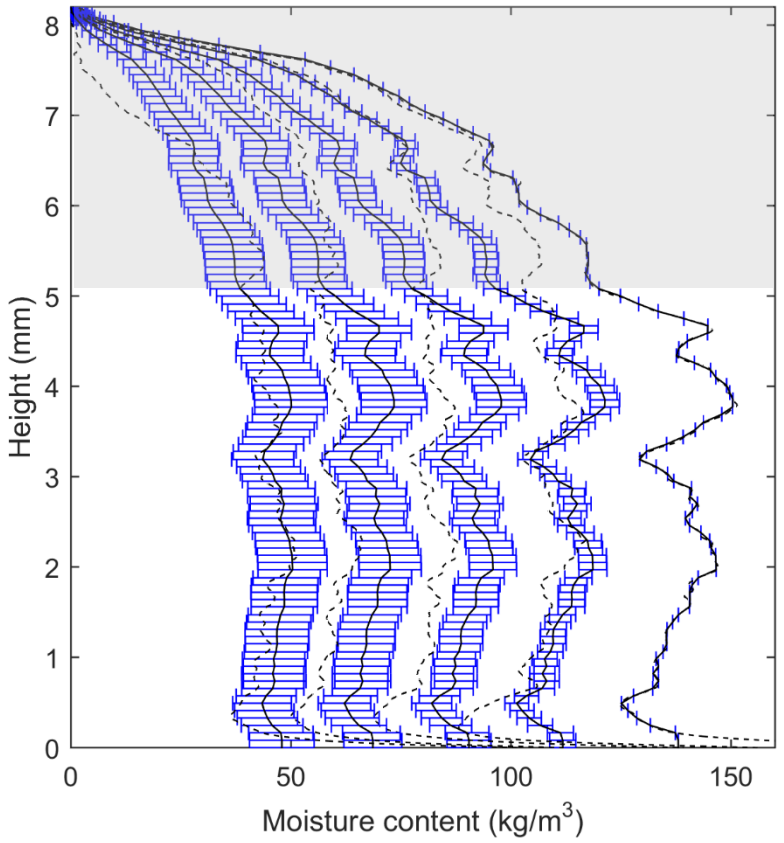
+ accounts for noise and bias

results: unknown transfer coefficient β

distribution $P(\beta)$

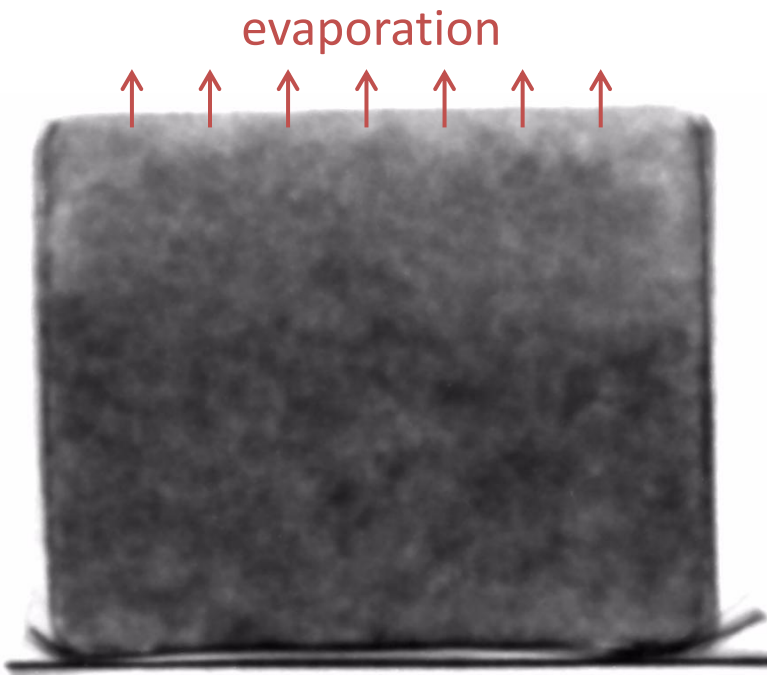


profiles @ $P(\beta)_{max}$

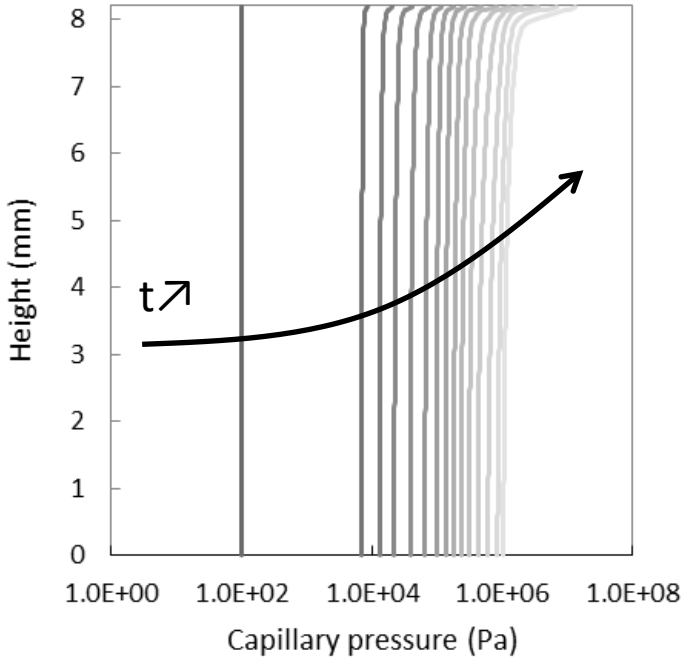


results: pressure profiles

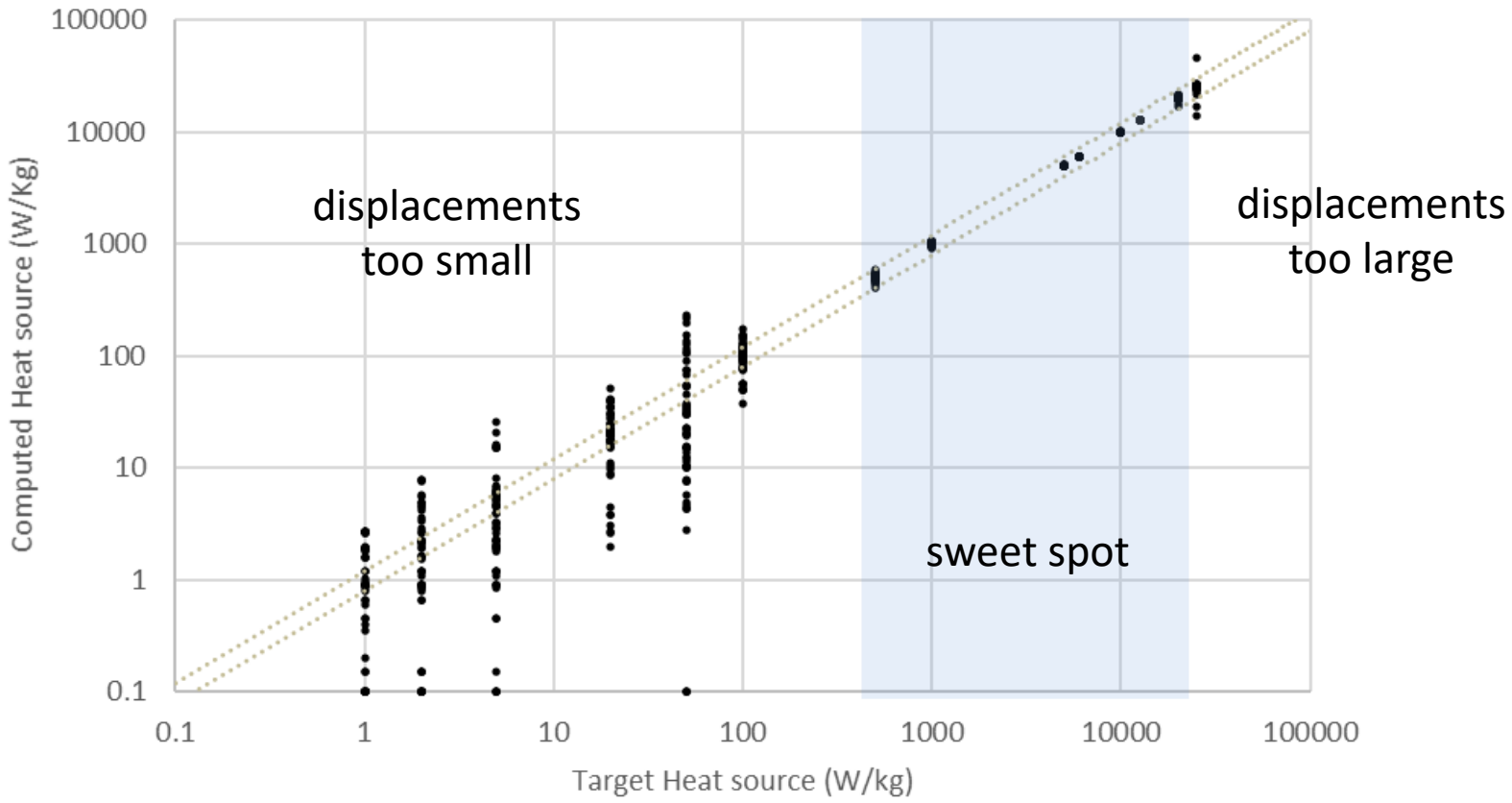
neutron radiography @ SINQ



most likely pressure profiles



similar approach used to estimate reaction heat



Ait Hamouda et al. (in preparation)

CONCLUDING REMARKS

toolbox for image analysis (1/2)

- Digital Volume Correlation (DVC)
  strains, regions with cracking

- DVC-corrected differential imaging
  macro-scale kinetics of crystallization and transport

- Machine Learning segmentation
  meso-scale kinetics of crystallization and transport

toolbox for image analysis (1/2)

- Polychromatic reconstruction (PolySART)
  calibration-free density and porosity estimates at sub-voxel scale

- Physics-based registration
  - identification of uncertain model parameters
  - identification of missing physics (via bias term)
  - yields invisible parameters (pressure, temperature, stress, …)

→ enables true analysis of coupled processes in porous media

acknowledgements

- **Syrine Ben Elhadj Hamida**
  currently postdoc at UPPA, performed DVC, DVC-corrected differential imaging and ML-based meso-scale analysis
- **Hannelore Derluyn**
  acquired the time lapse Savonnières datasets with X-rays and neutrons
  main supervisor of Syrine Ben Elhadj Hamida
- **Jelle Dhaene**
  former postdoc at UPPA, programmed and validated PolySART

thank you for your attention

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