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Experimental feasibility of dual-energy X-ray tomography for two-phase density analysis in bentonite during water infiltration

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SAGE Bentonite seminar 2025

Introduction to the methods
Water content measurement

Dual-energy X-ray CT

- Spatial distributions of bentonite and water utilising the energy dependence of the attenuation coefficient
- Material identification after the reconstruction
- Experimentally implemented beam hardening and scatter corrections
- Classification of voxels based on the energy information before the density analysis
- Energy information is obtained by varying the voltage and filtering of the X-ray tube

Reference methods

X-ray CT method based on displacement measurements (REF XCT)

- Comparison of the successive tomographic images during the wetting of the bentonite clay sample – deformations due to wetting are measured

Physical slicing of the sample

Introduction to the methods

In both X-ray CT methods:

1. The calculations are based on the linear combination form of the linear attenuation coefficient:
   - $\boldsymbol{\mu(\vec{r}, E) = \rho_b(\vec{r})c_b(E) + \rho_w(\vec{r})c_w(E)}$
   - $\rho_{b/w}$ are the partial densities of bentonite and water ($\rho_x = \frac{m_x}{V_{\text{tot}}}$) and $c_{b/w}$ are the mass attenuation coefficients of bentonite and water
2. Experimental calibration of the mass attenuation coefficients
   - Based on the average initial and final densities
3. Preprocessing of projection images
   - Signal-to-thickness (STC) beam hardening correction based on imaging of aluminium plates
   - Scatter correction based on beam-stop-array (BSA)

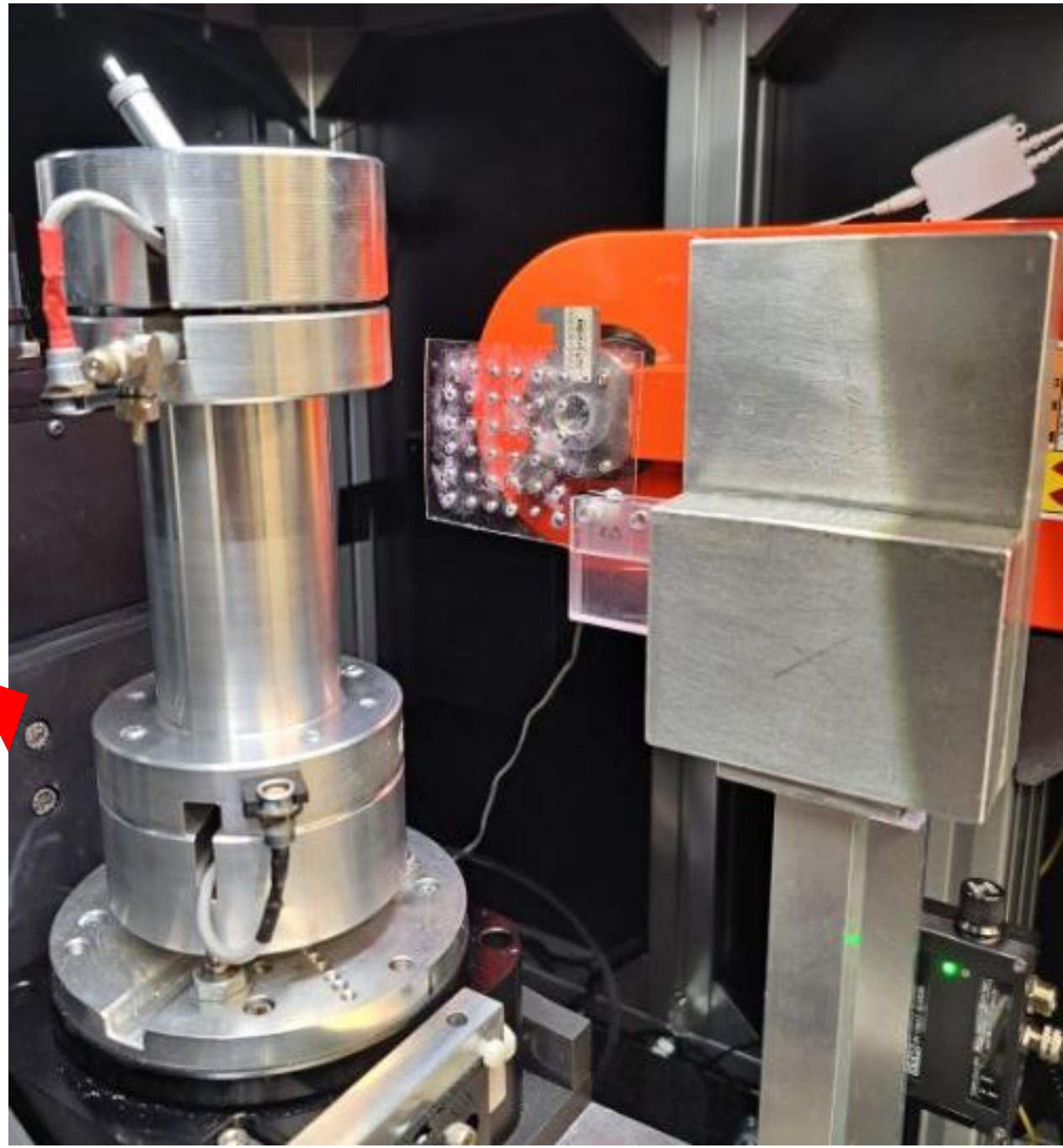
Preprocessing of projections
Beam hardening and scatter corrections

Challenges:

- Assumption: mass attenuation coefficients don't depend on position.
  - Beam hardening effect and influence of X-ray scattering are ignored in that assumption.
- We are working with the **effective attenuation coefficient**.
  - Depends on the temporal and spatial variations of the X-ray spectrum and the camera response.

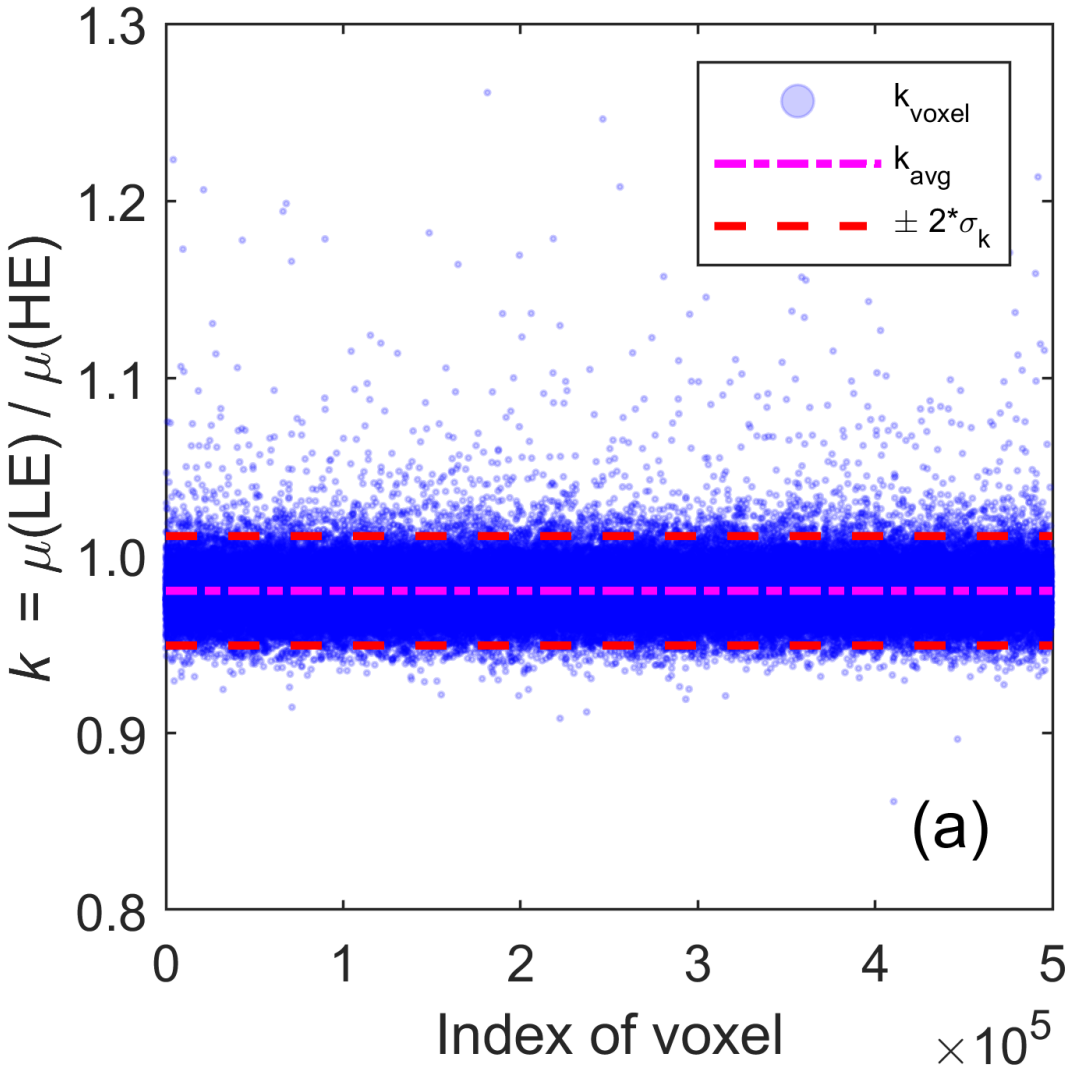
Solution:

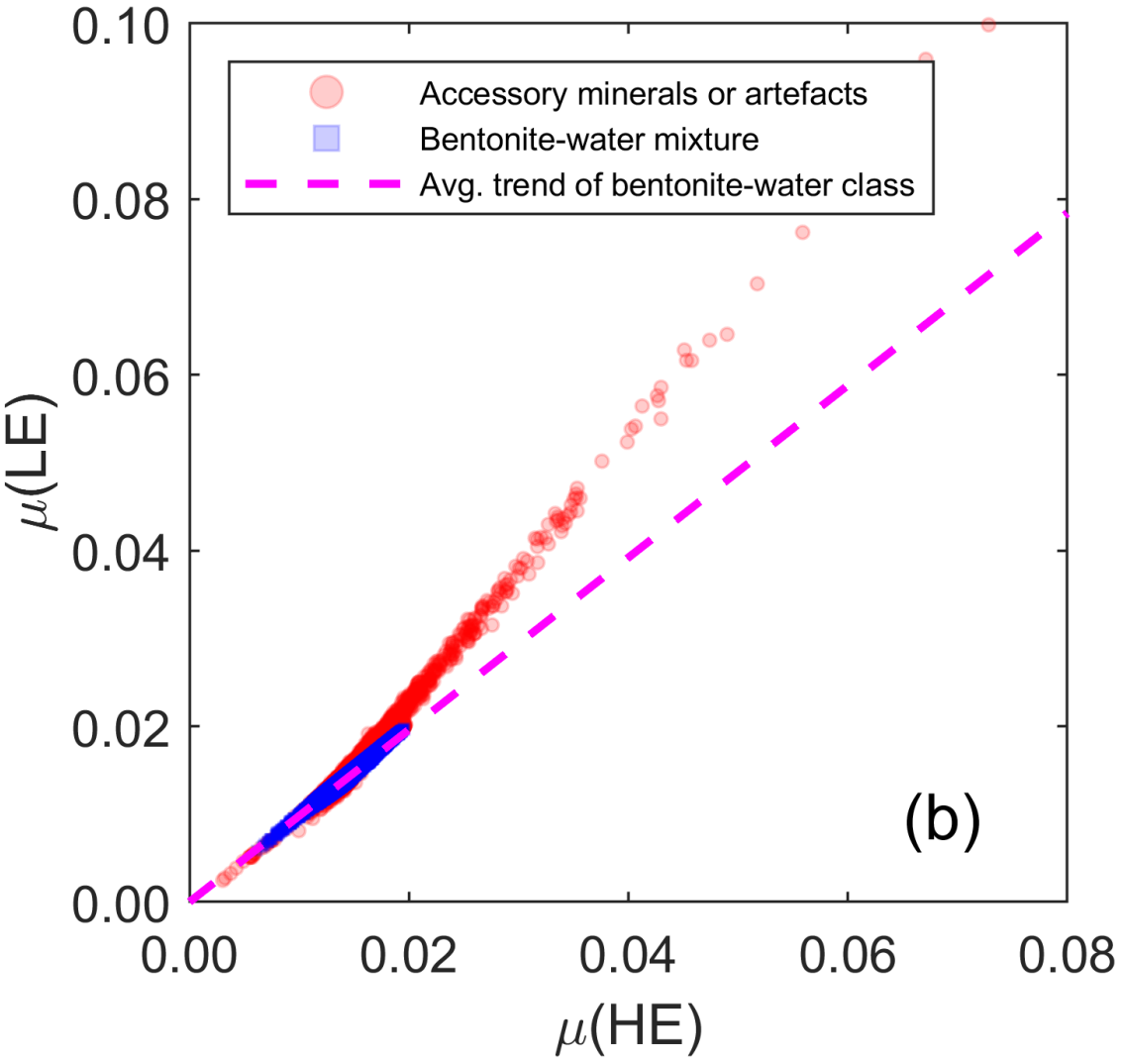
- STC beam hardening correction and scatter correction using BSA
  - From X-ray CT point of view, aluminium similar to bentonite
  - BSA: secondary signal measured behind the lead spheres
  - By moving the BSA, scatter background is estimated



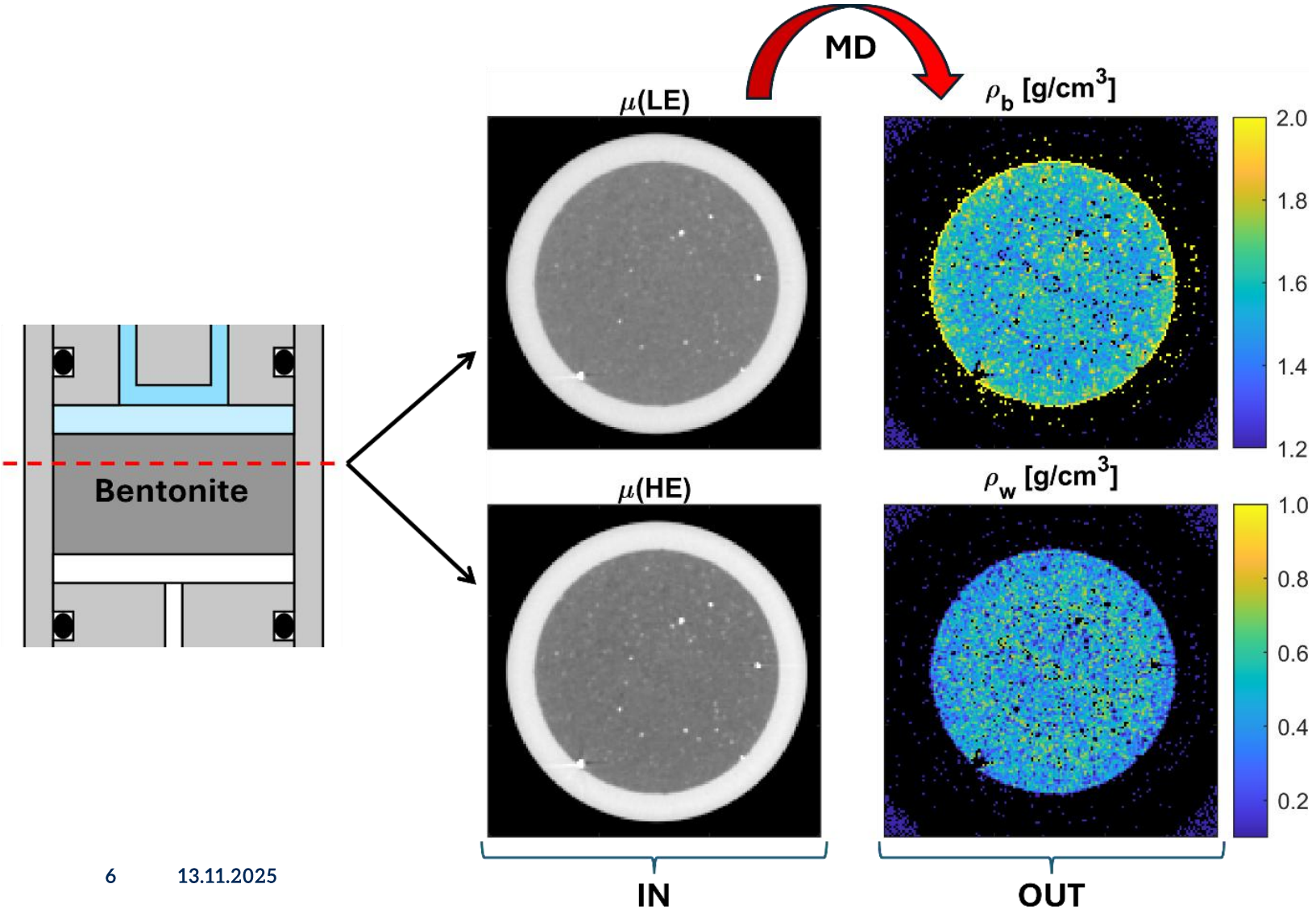
DECT Results: Classification of voxels into material categories based on dual-energy ratio

Accessory minerals with elemental compositions that significantly differ from the average composition of the bentonite-water mixture are excluded from the density analysis. (Bara-Kade bentonite)





DECT Results: Post-reconstruction density analysis for bentonite-water mixture



Bentonite

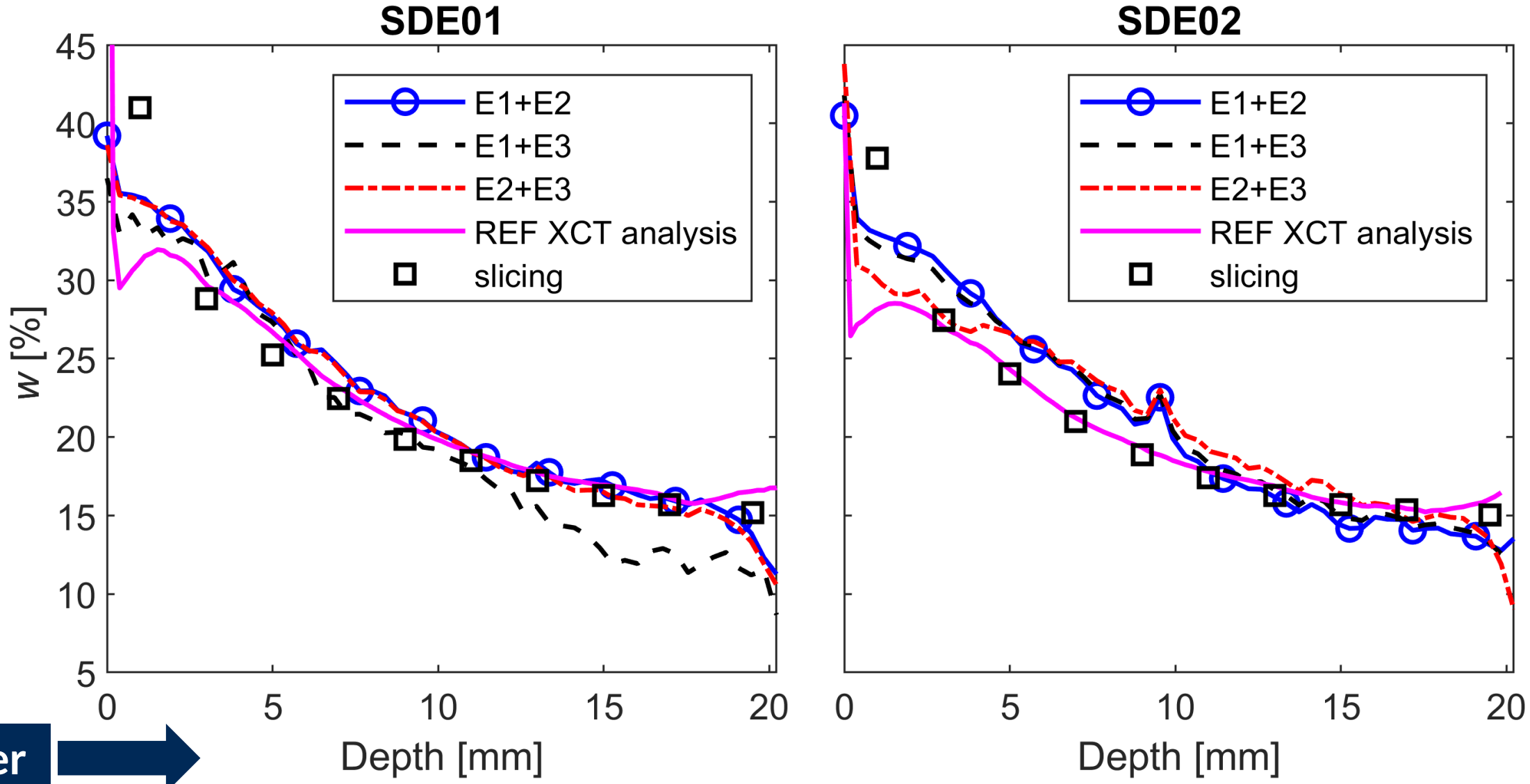
- Gravimetrical results for averages:

$\rho_b = 1.58\ \mathrm{g/cm^3}$ and $\rho_w = 0.33\ \mathrm{g/cm^3}$

- In the density maps, the black colour represents voxels identified as materials other than the bentonite-water mixture

Water

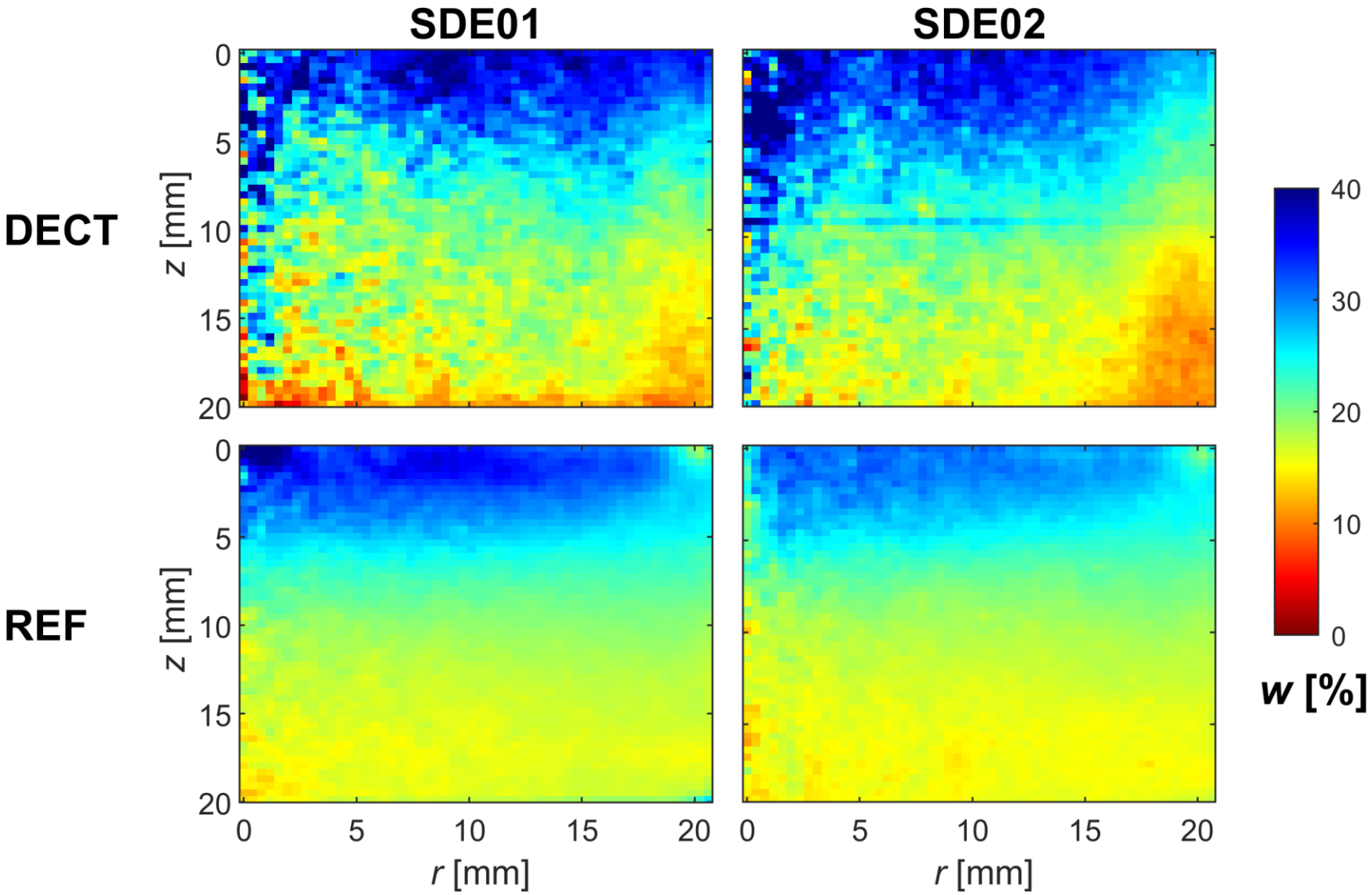
DECT Results: Depth profile of water content in bentonite – comparison to the reference methods



Water

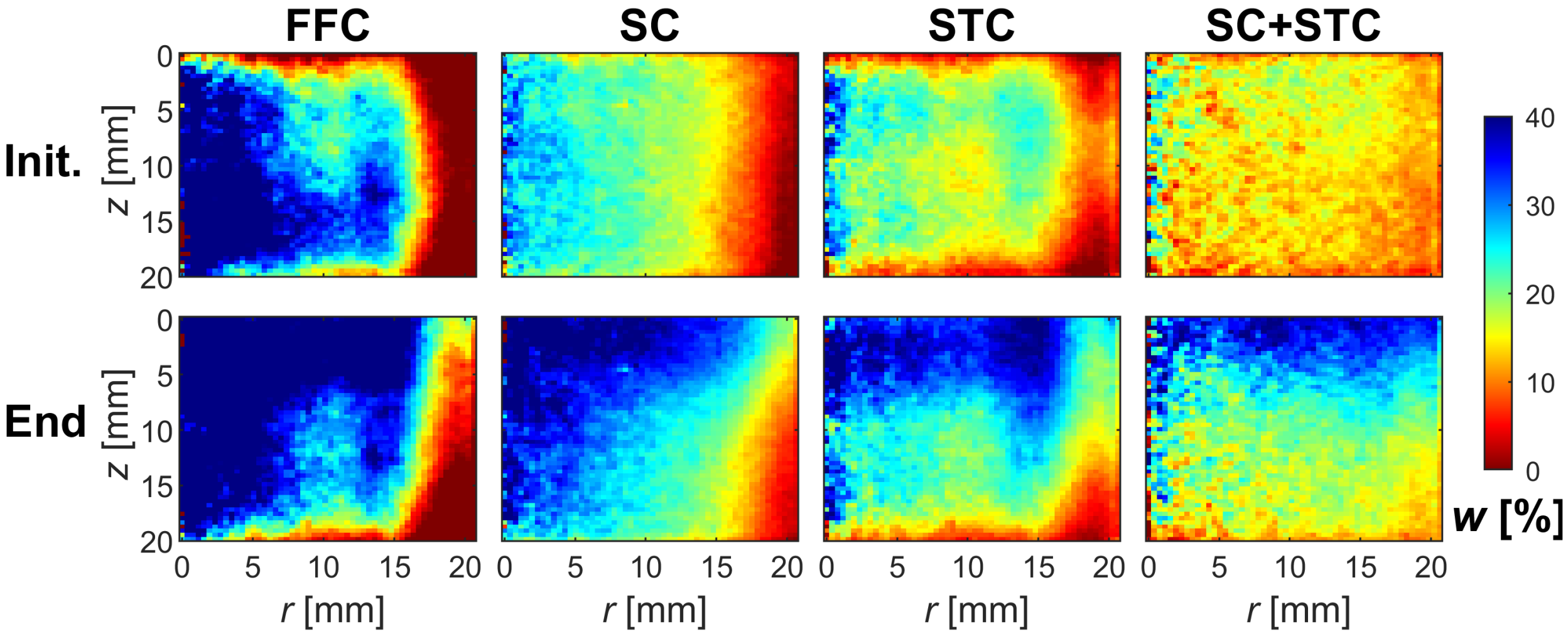
DECT Results: Azimuthally averaged water content – comparison to the reference X-ray CT method

Water



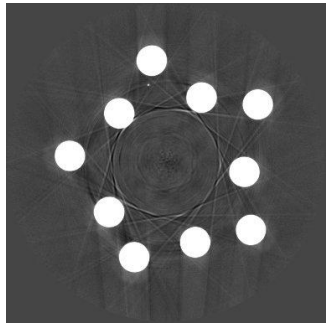
DECT Results: Azimuthally averaged water content – significance of correction methods

At the initial state, the water content is assumed to be uniform at 12 %

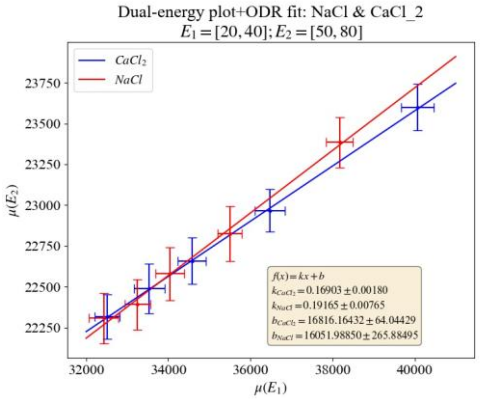


EXTRA: Multienergy analysis of salt solutions
EXCITE TNA VISIT at (UPPA) - DMEX, Pau, France

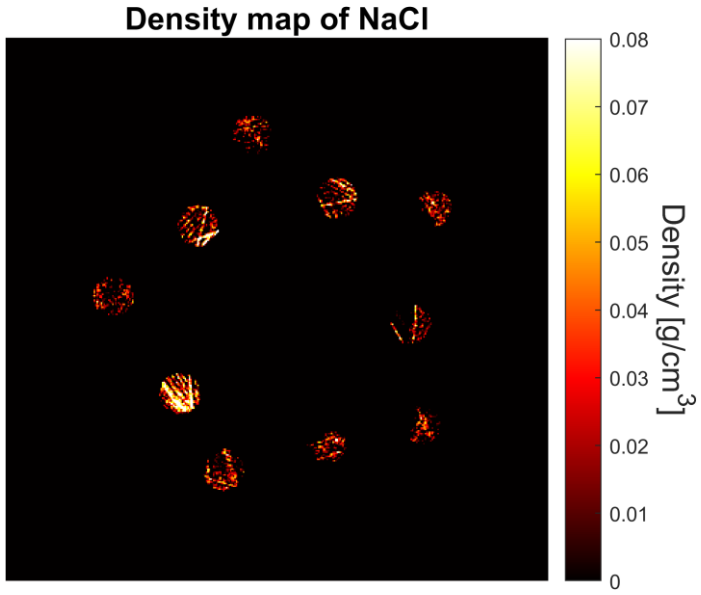
- Ground water simulants used in the bentonite wetting experiments
- Salinity of the water is changed, e.g., NaCl and $CaCl_2$
- Can spectral CT be applied to monitor the chemical composition/stability of the bentonite?
- Tests using salt solutions with five concentrations: 0, 0.00625, 0.0125, 0.025, and 0.05 g/cm^3
- **Preliminary tests without corrections for beam hardening + scattering + ring artefacts**

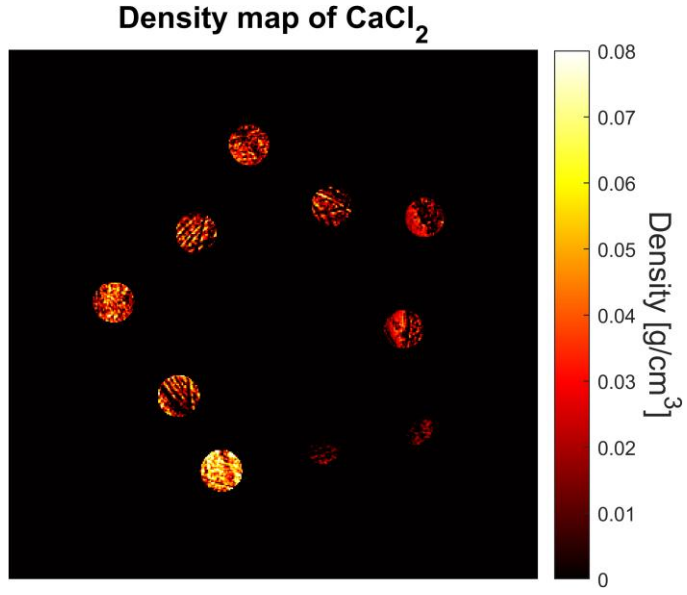


Imaging of the multi-material phantom using a spectral detector



Calibration





Inner circle NaCl, outer $CaCl_2$

Summary

- The feasibility of DECT with scatter and beam hardening corrections to analyse the 4D evolution of partial densities of dry bentonite and water was examined
- Validation results (=ref. methods) indicated that applied DECT approach can yield quantitative estimates for 4D water content in bentonite with reasonable accuracy
- Additionally, accessory minerals can be separated qualitatively from the clay matrix based on energy information
- Further method development is required to improve the accuracy and reduce the noise
  - Photon-counting detectors
- The reference X-ray CT method is generally more accurate in this application. However, it relies on the measurement of the displacements.
  - Requires details in the structure whose movement can be tracked (homogeneous structure is challenging)
  - The displacements close to the edges of the sample can be challenging to measure
- Spectral X-ray CT can provide new insights into the composition of bentonite-water mixtures that were previously unavailable with standard X-ray CT.

KIITOS!

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