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Multiscale microstructural controls on swelling behaviour of cemented bentonite

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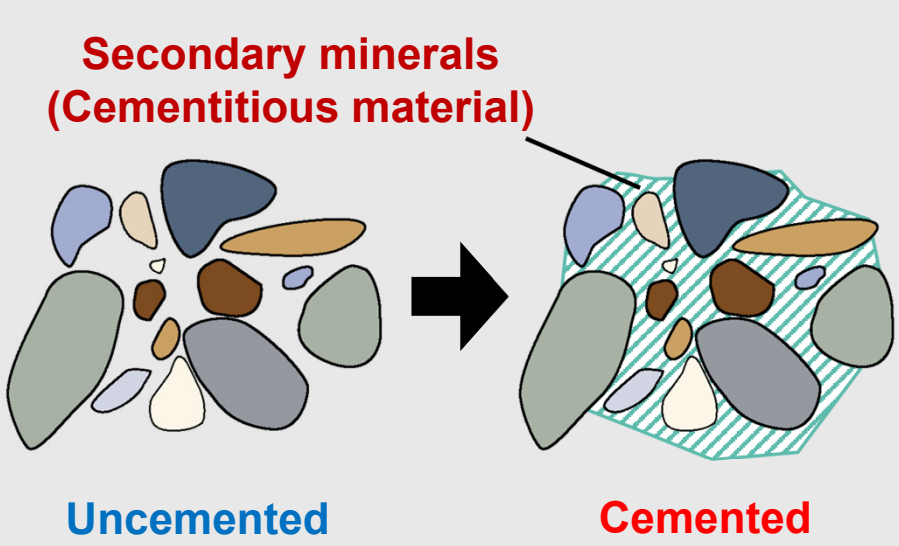
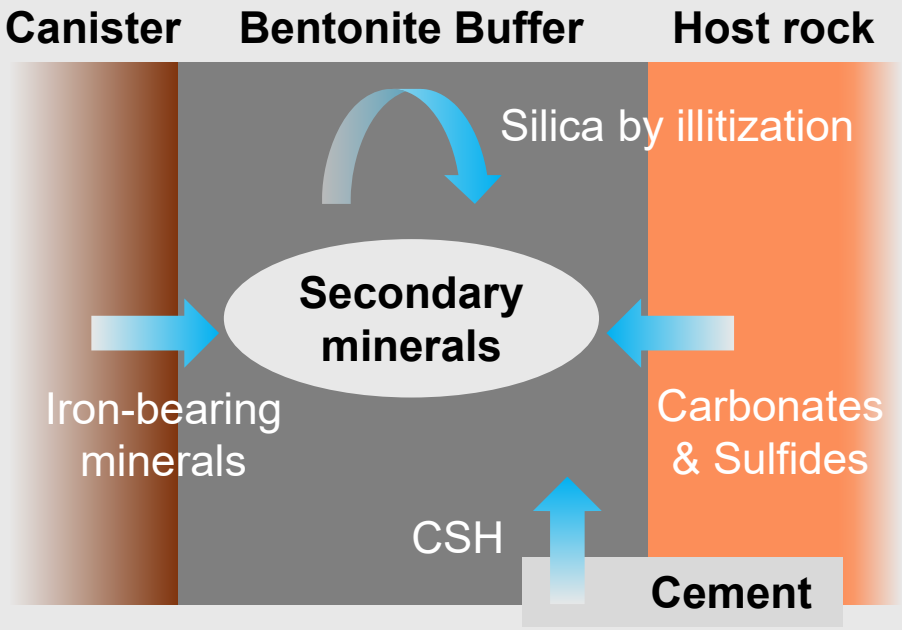
Cementation of Bentonite

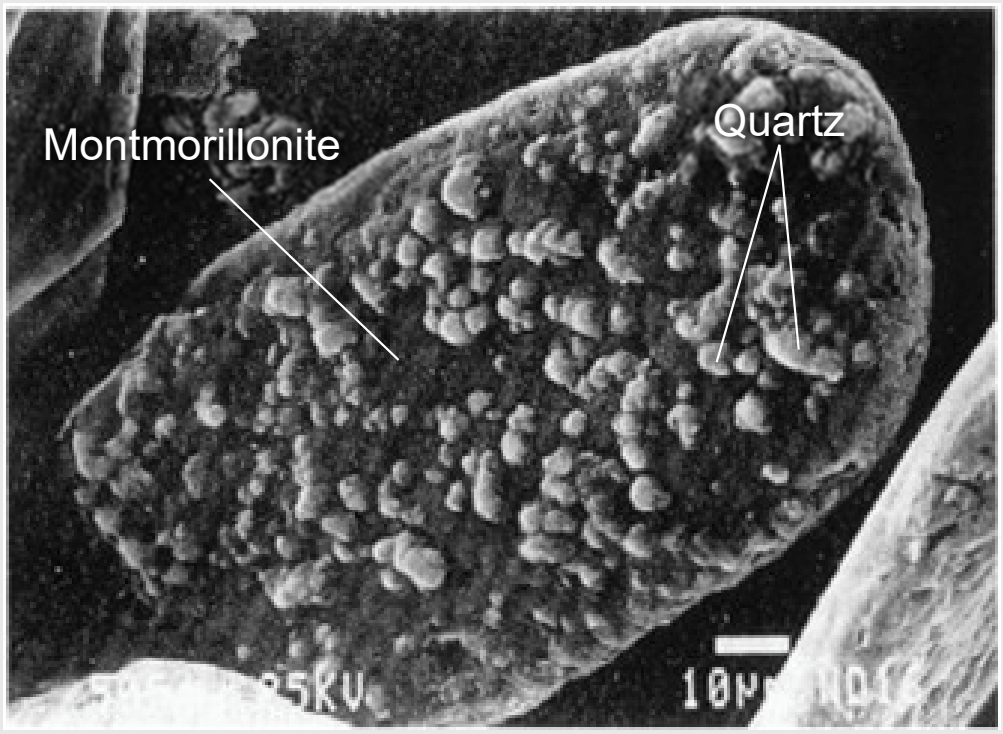
- **Swelling property** of bentonite is essential for the safety of geological disposals
- **Secondary minerals** precipitate within pores and at pre-existing mineral interfaces
- **Swelling pressure decrease** *(e.g. Wersin et al., 2007; Arthur and Zhou, 2005)*



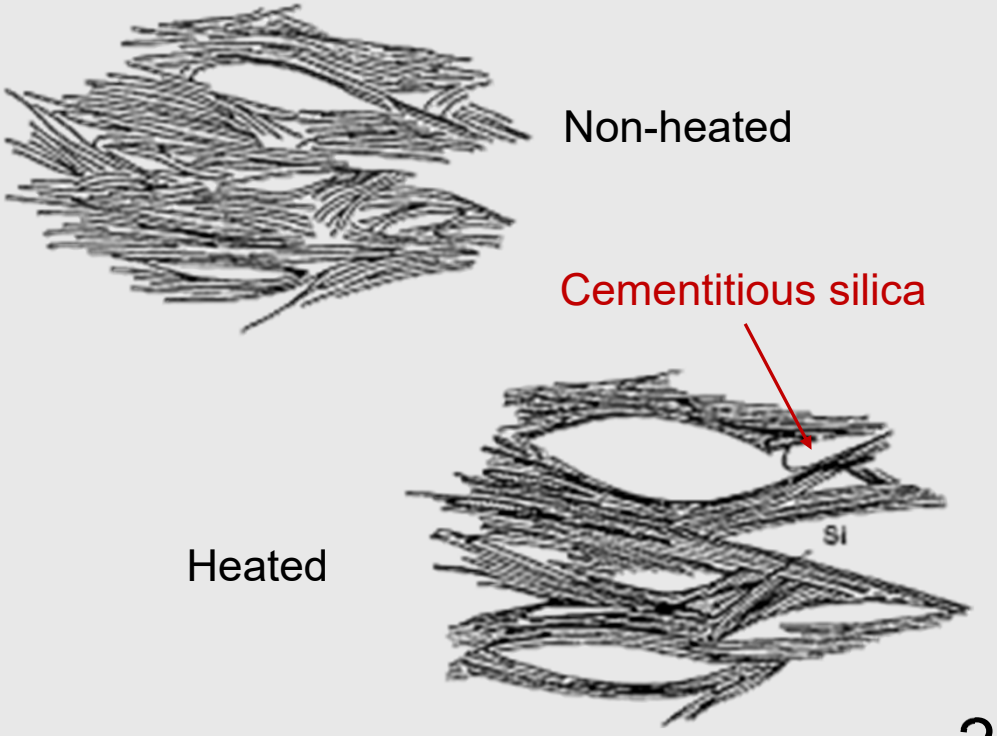


Microscopic Evidence of Cementation

- **Micro particles** on montmorillonite surface may hinder swelling *(Pusch et al., 2010a, b)*
- **Swelling states** in cemented bentonite are **unclear**



Pusch et al., Engineering Geology 116 (2010a) 21–31



Pusch et al., Applied Clay Science 47 (2010b) 113–119s

Objective & Key Approach

Objective

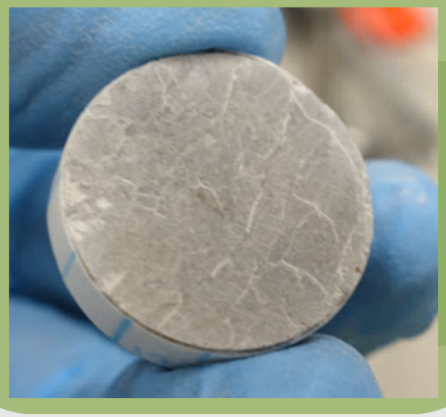
To understand the mechanisms of swelling pressure reduction by cementation

Observations of **swelling state** of cemented bentonite **across multi scales**

Macro

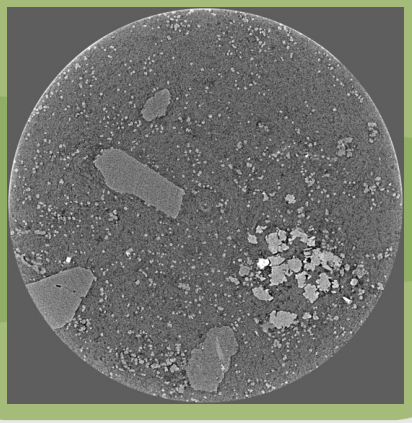
Mechanical Testing

(JAEA & RWMC, 2023)



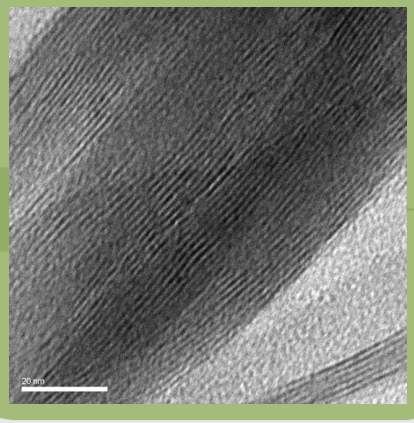
Meso/Micro

Synchrotron μCT



Micro/Nano

Electron Microscopy

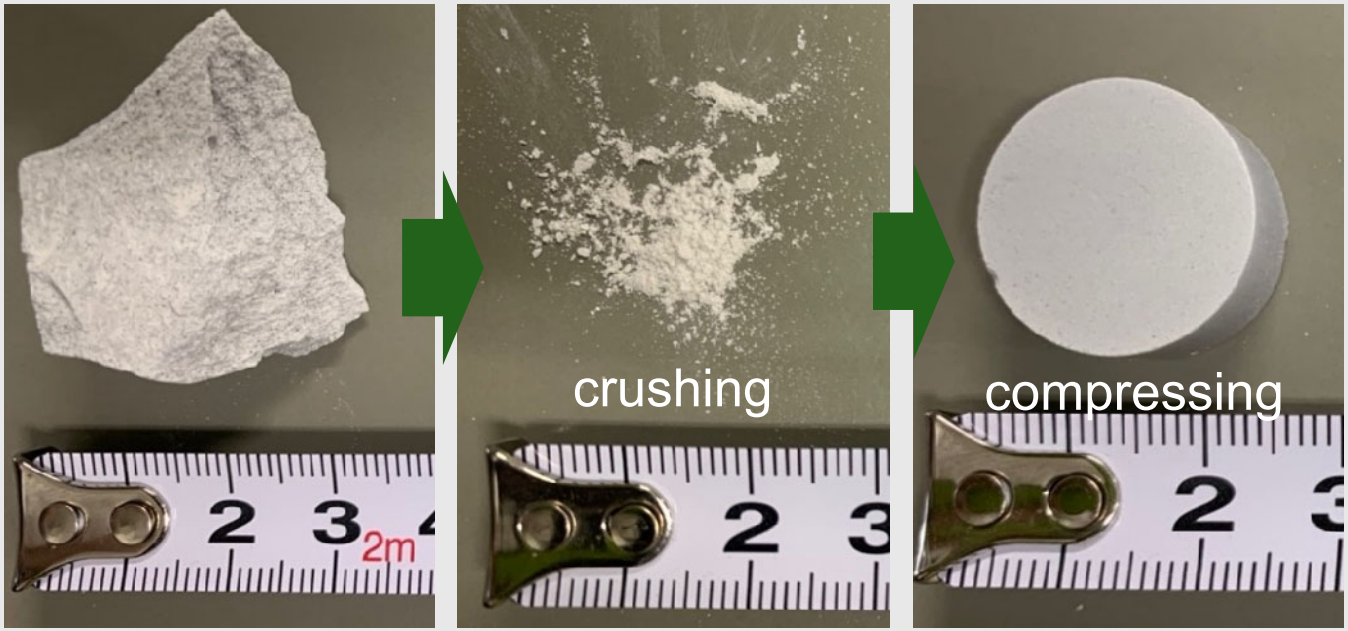


Natural Analogue of Cemented Bentonite

- **Natural bentonite sample** from Tsukinuno bentonite deposit in northeast Japan

Cemented ore

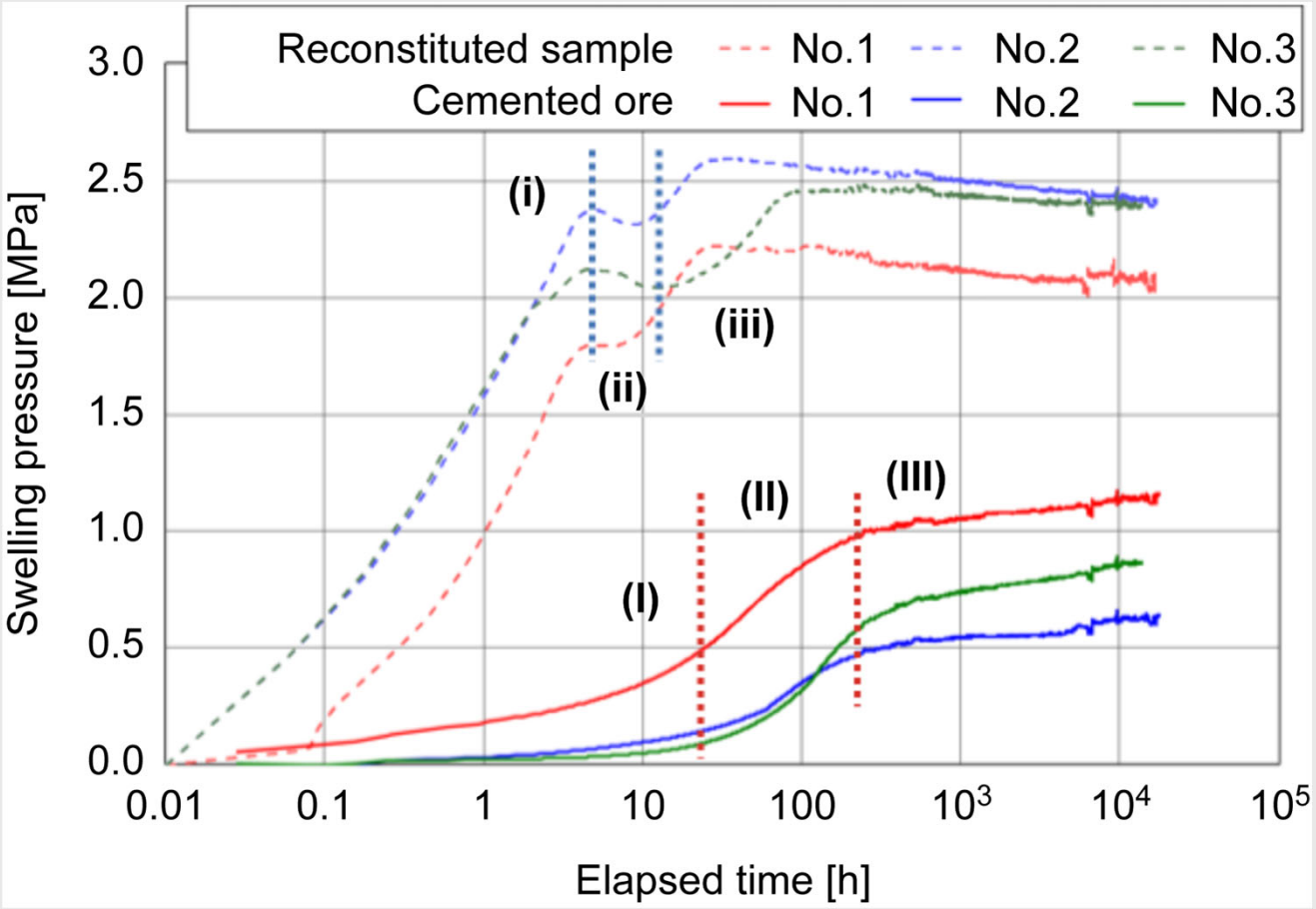
cemented



Reconstituted sample

uncemented

Swelling Pressure Testing



Time dependent swelling pressure evolution
modified from *JAEA & RWMC (2023)*

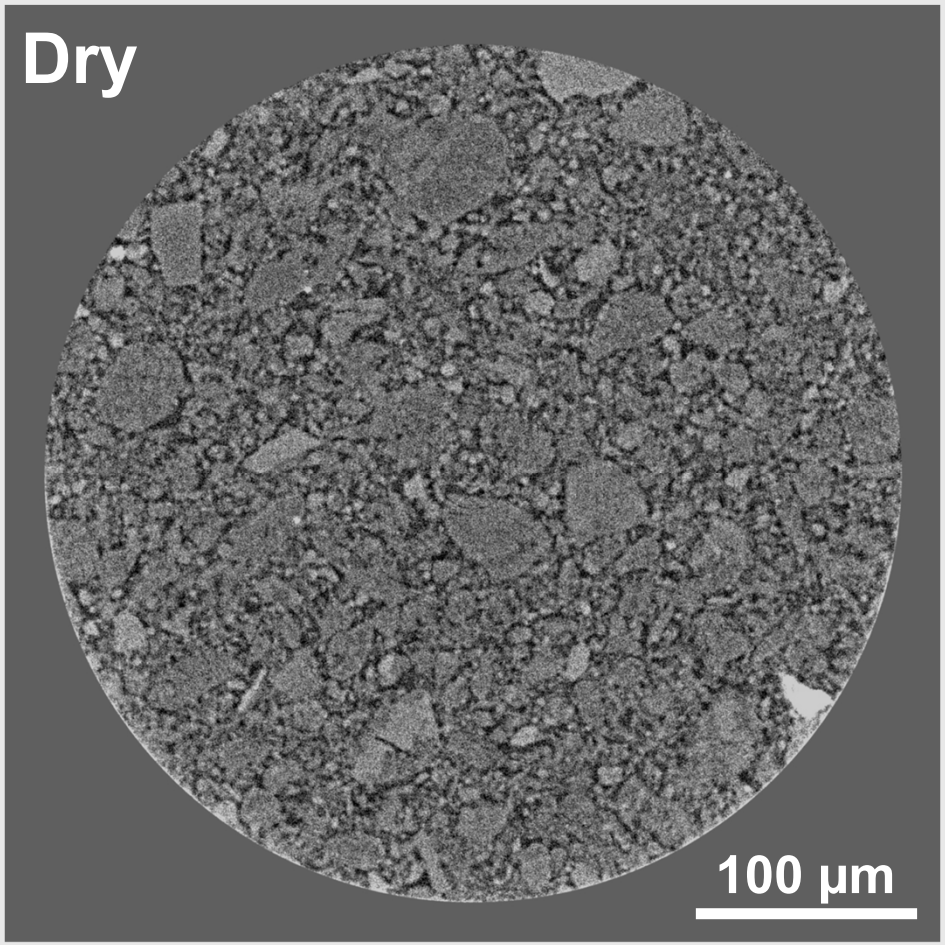
Reconstituted Sample

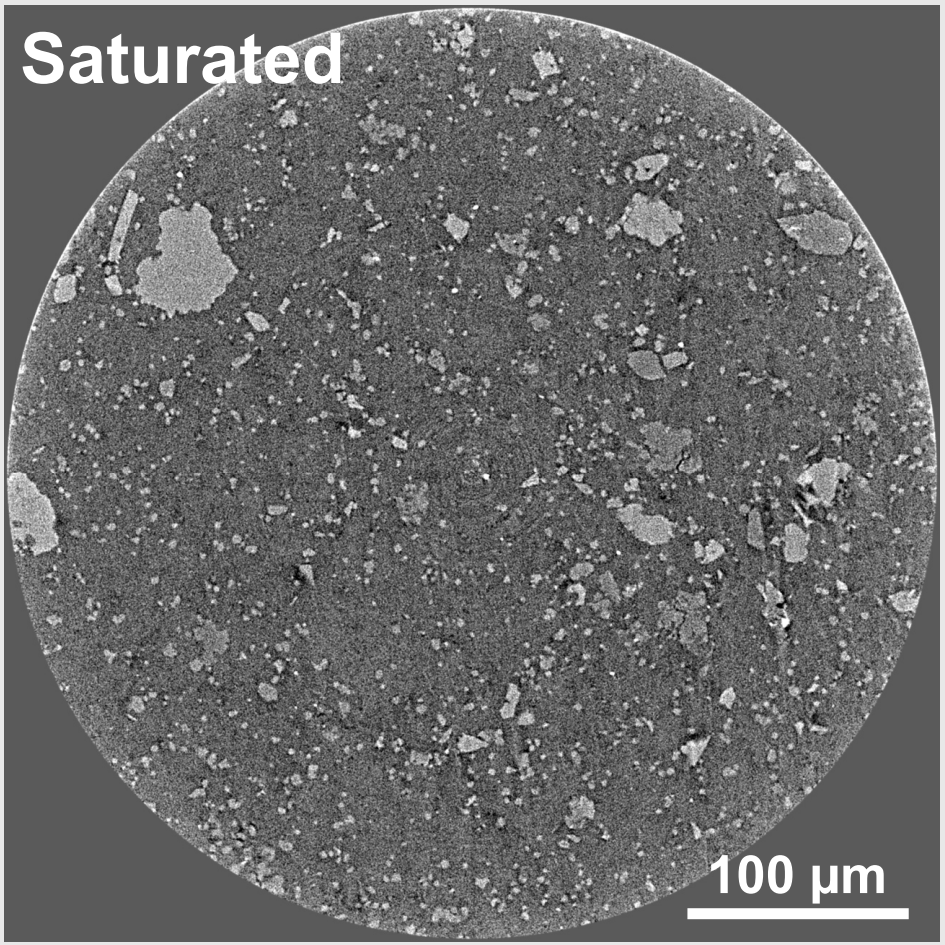
- Typical 3-stage evolution
  (e.g. Massat et al., 2016)

Cemented ore

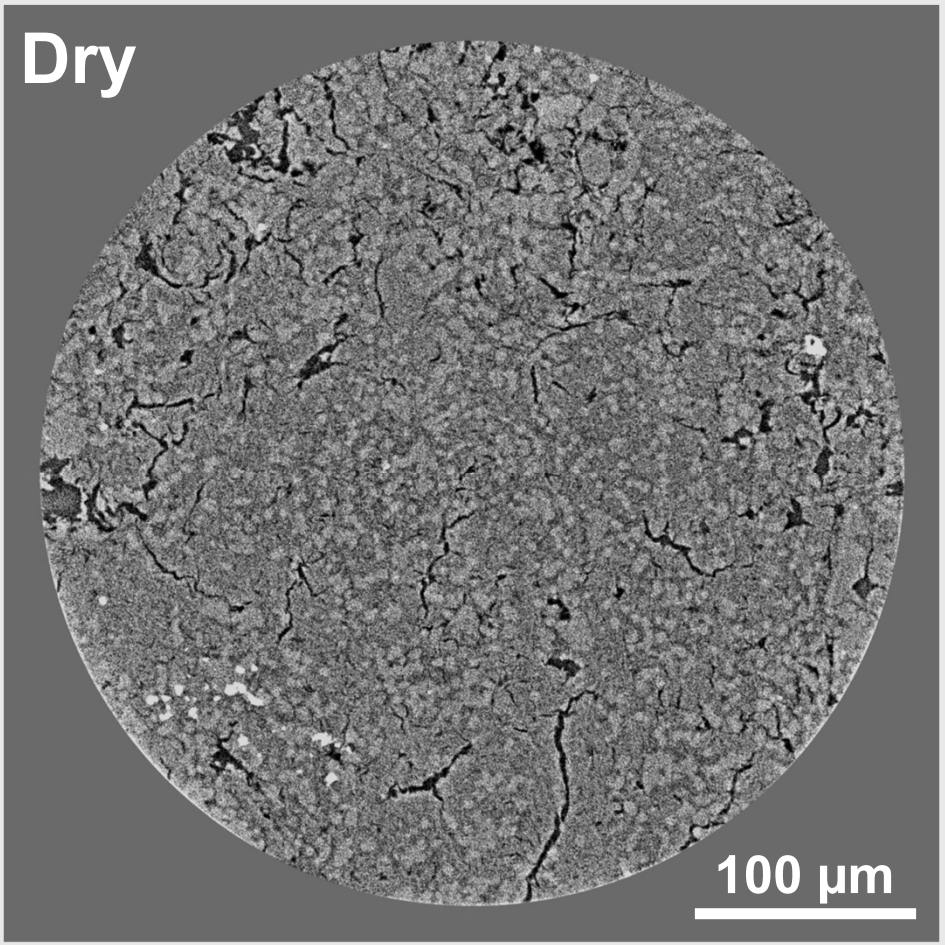
- **Slower increase**
- **Lower final values**

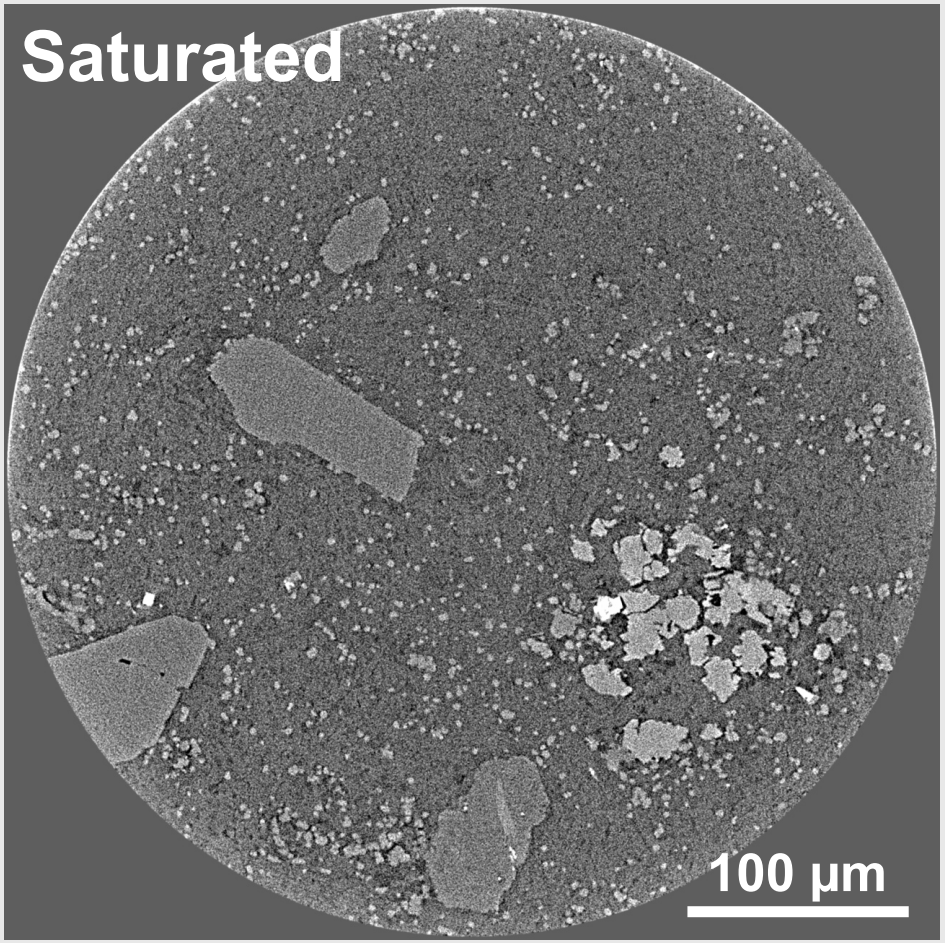
Reconstituted Sample (μCT)



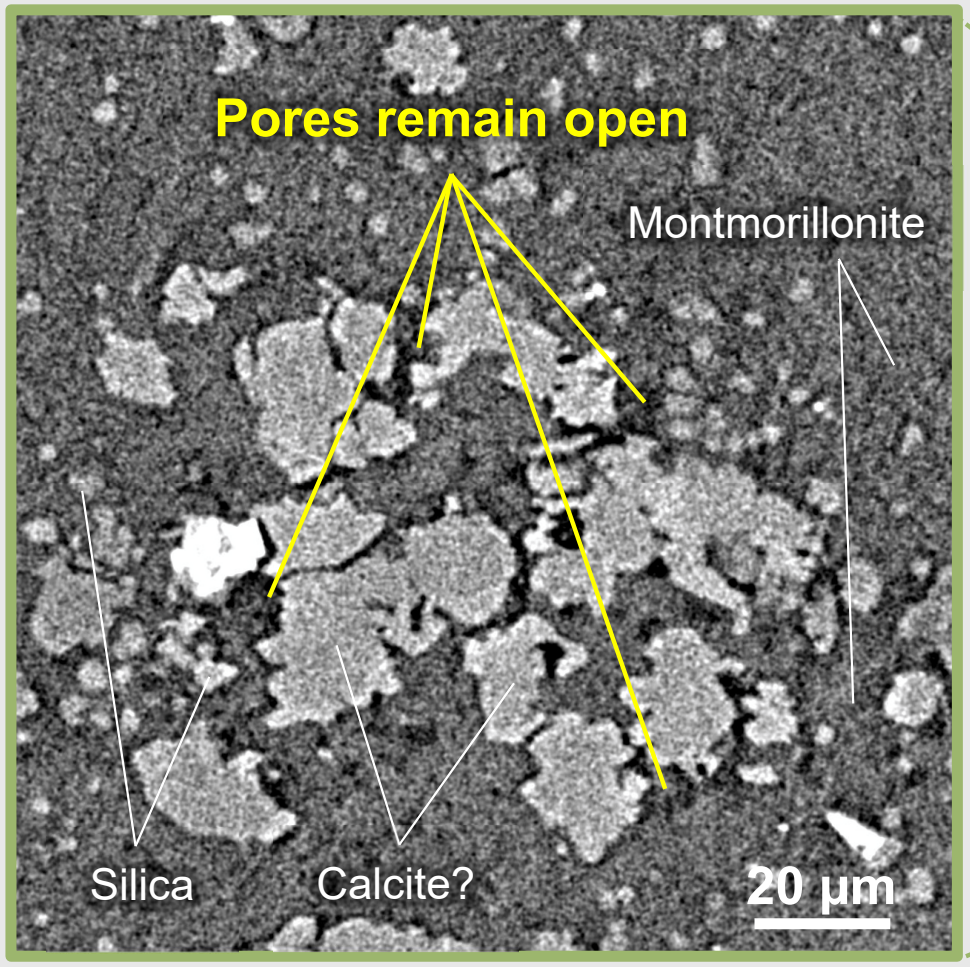


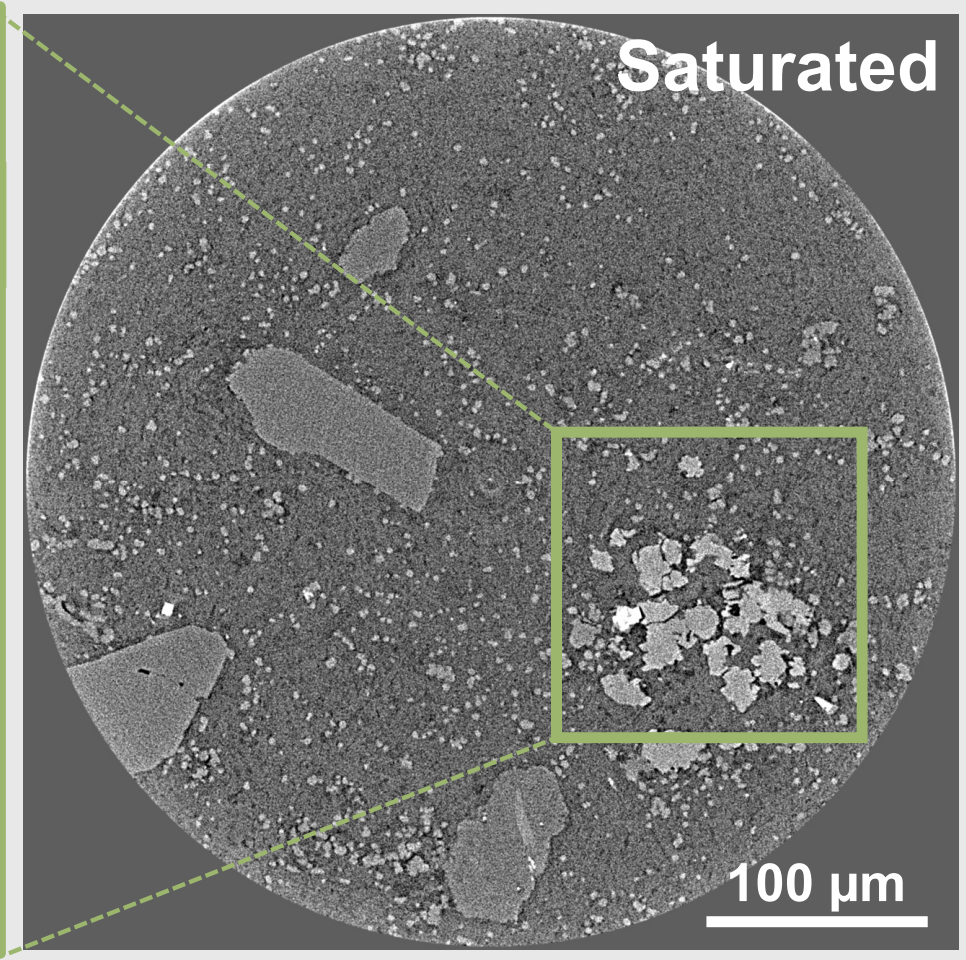
Cemented Ore (µCT)





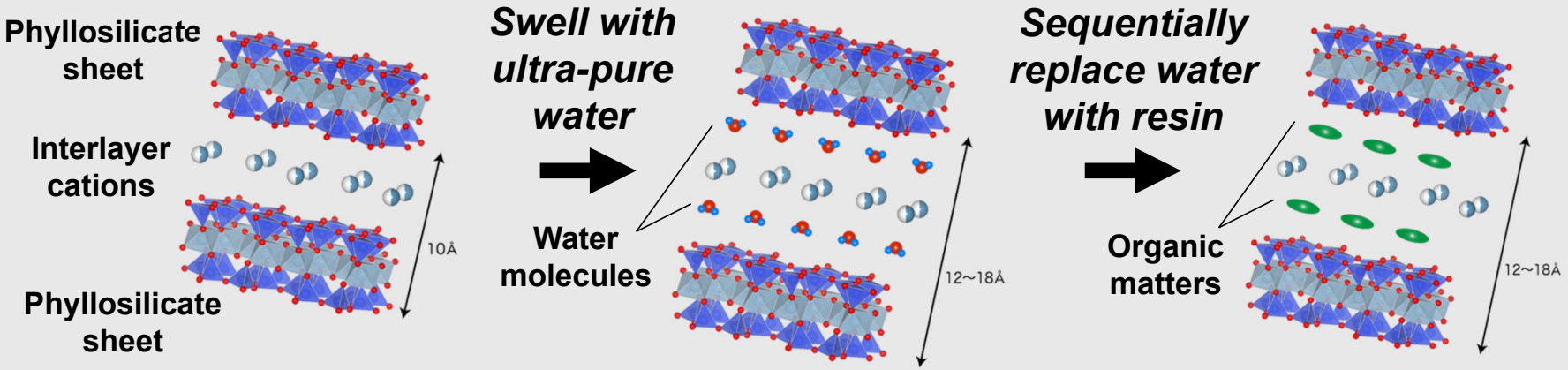
Cemented Ore (µCT)





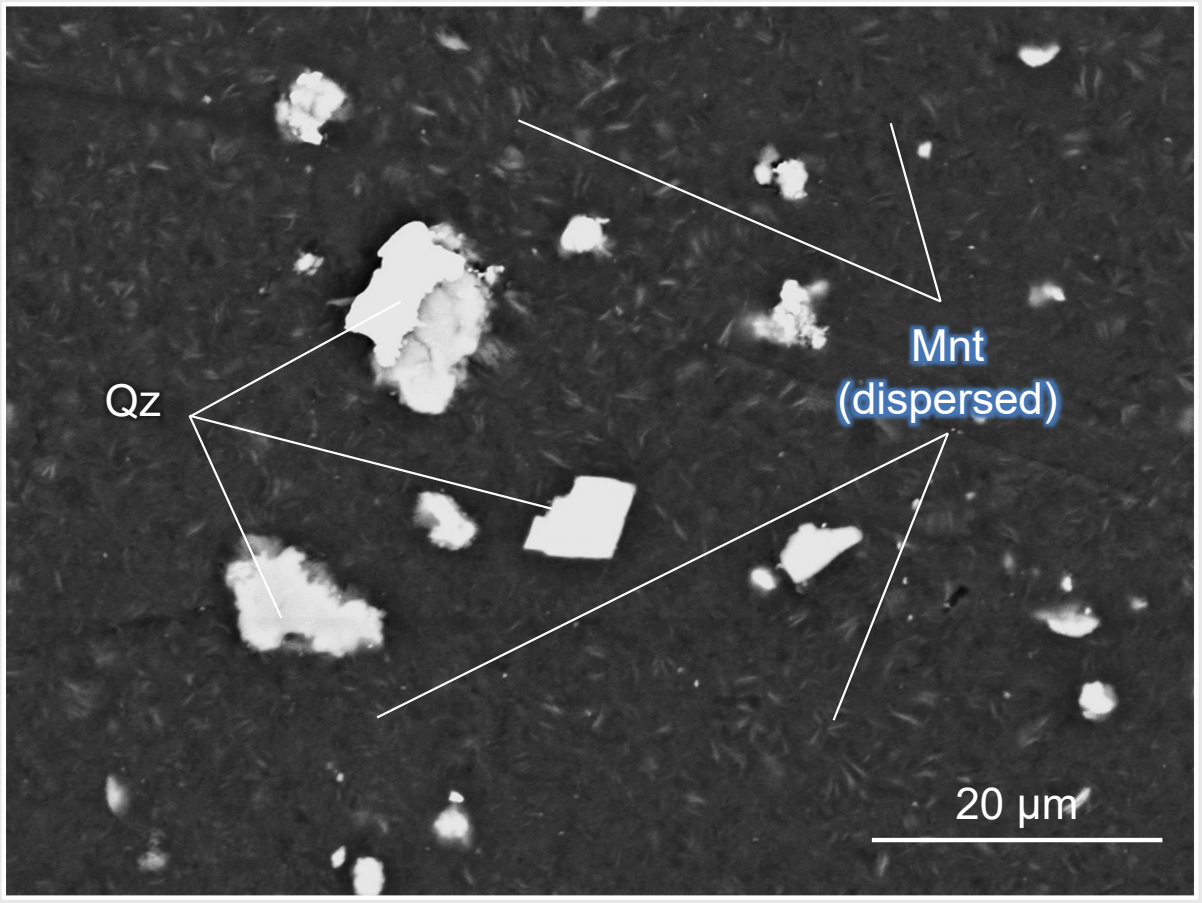
Sample Preparation for Electron Microscopy (EM)

- **Resin-replacement technique** to preserve swelling state under vacuum *(Bozzola, 2007)*
- **Semi-quantitative proxy** for local hydration and swelling states
- Two water immersion duration (1 h & 7 d)



Reconstituted Sample (SEM)

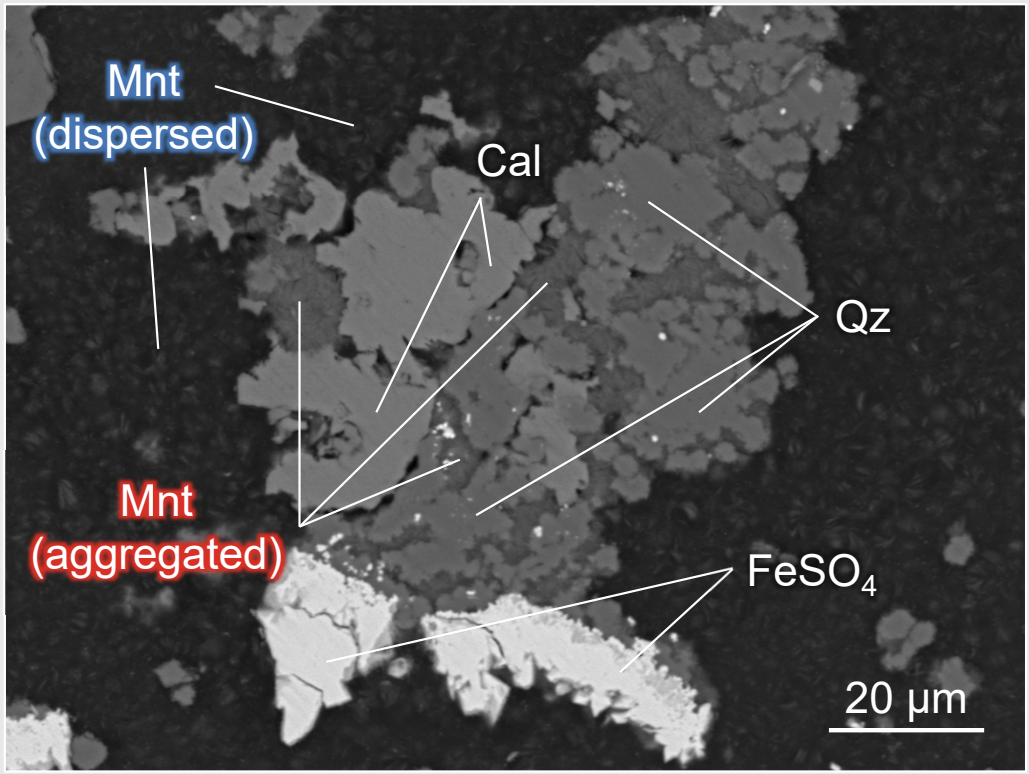
- Montmorillonite dispersed **homogeneously**



Abbreviations
Mnt: montmorillonite
Qz: quartz

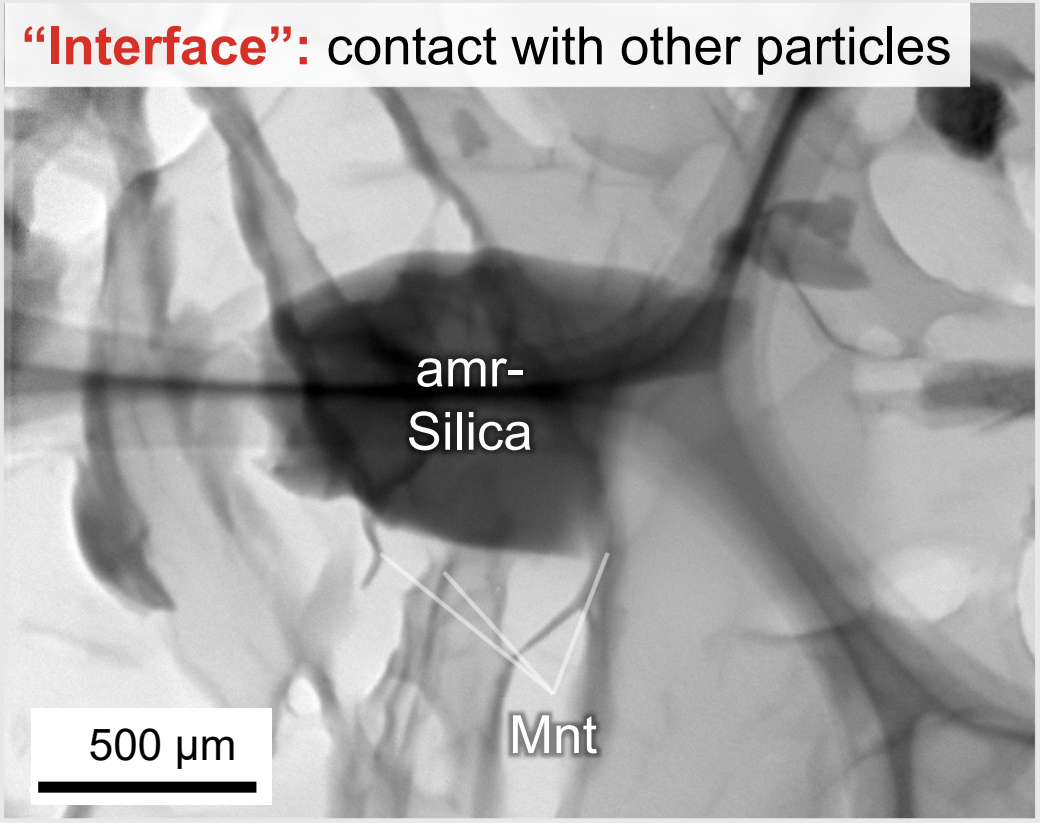
Cemented Ore (SEM)

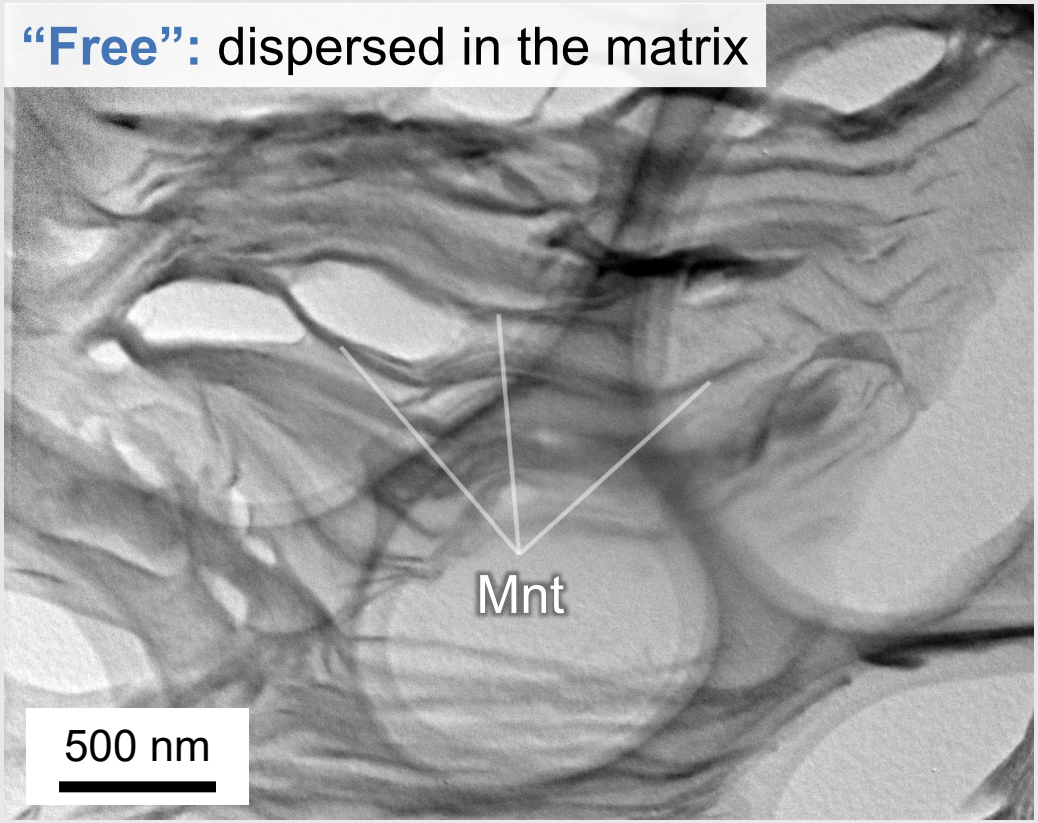
- **Clusters of mineral particles**
- Montmorillonite morphology:
  - **aggregated** within clusters
  - **dispersed** in the matrix
- **Clogging** may cause **less permeable** region in the interior of clusters
- **Persistent** after prolonged immersion



Abbreviations
Mnt: montmorillonite
Qz: quartz
Cal: calcite
$FeSO_4$: iron sulfate

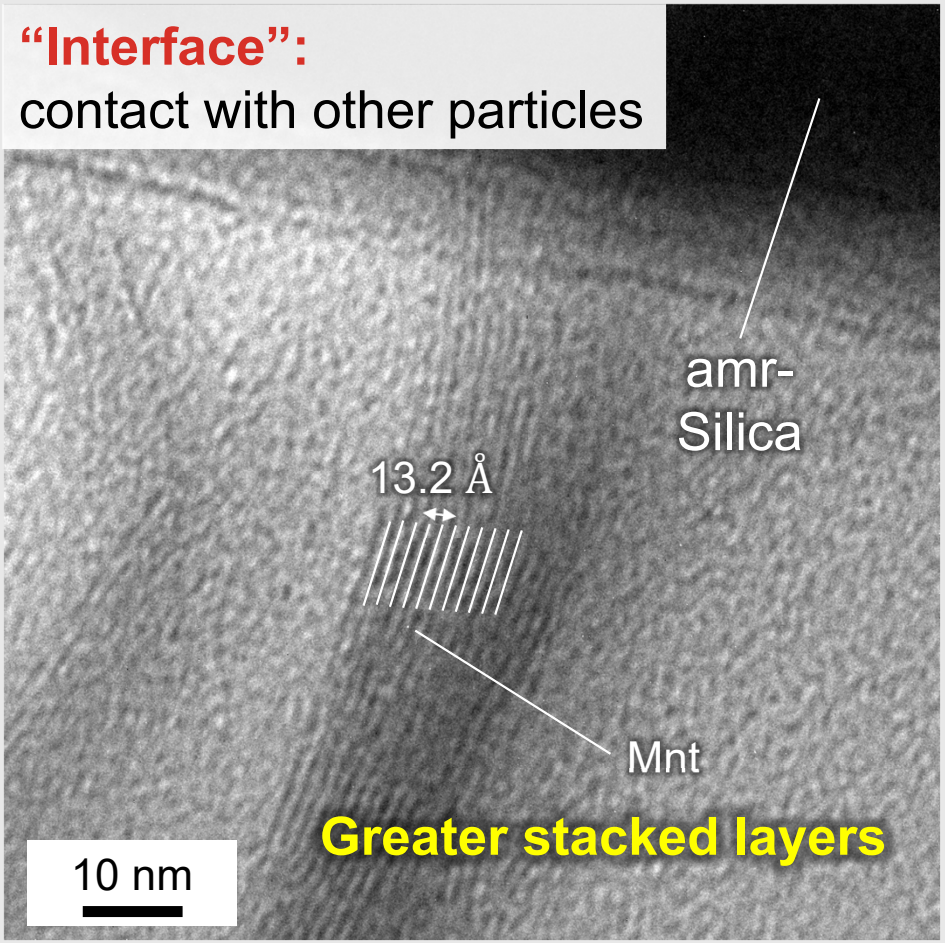
Cemented Ore (TEM)

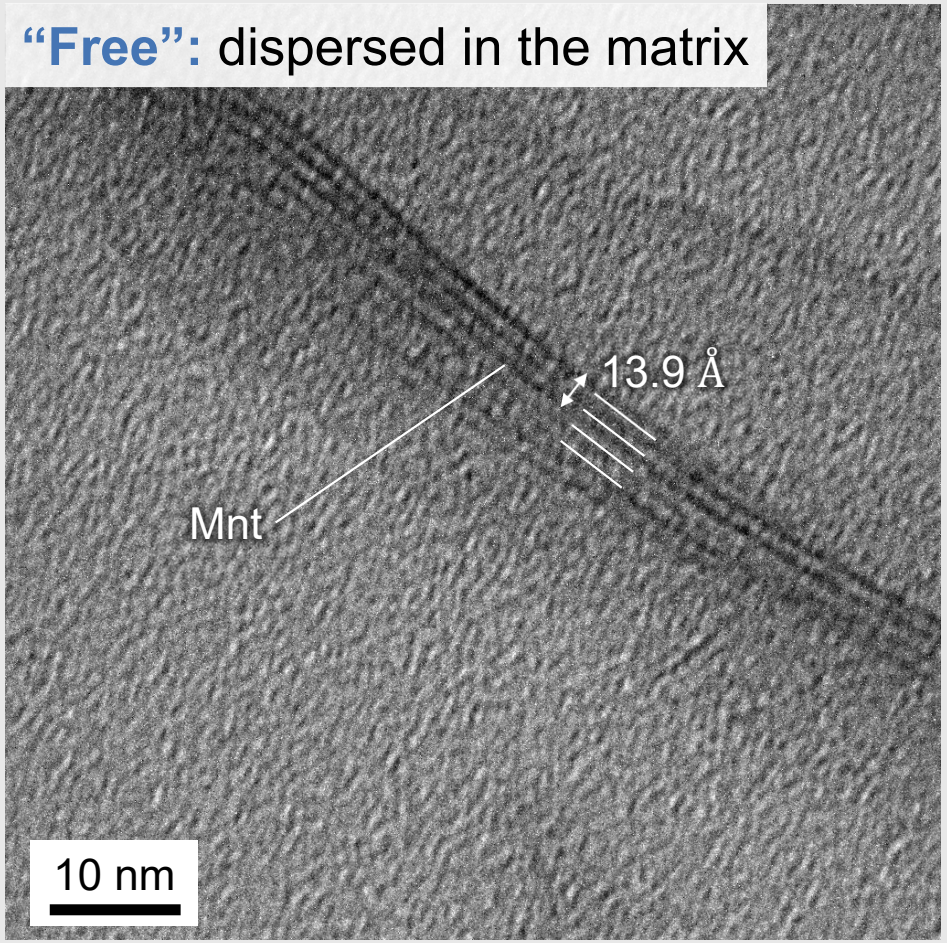




Abbreviations
Mnt: montmorillonite
amr-Silica: amorphous silica

Cemented Ore (TEM)





Abbreviations Mnt: montmorillonite, amr-Silica: amorphous silica

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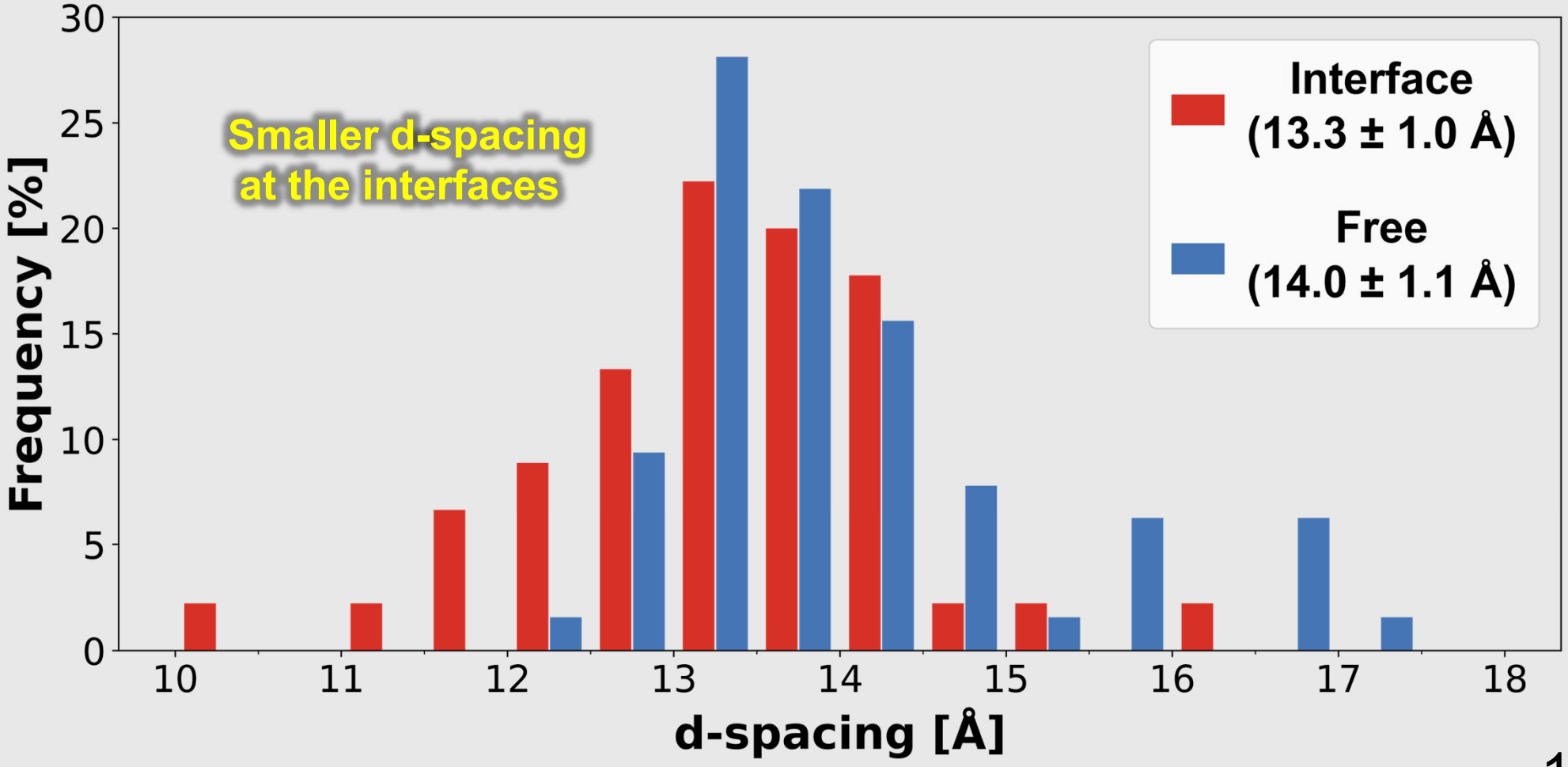
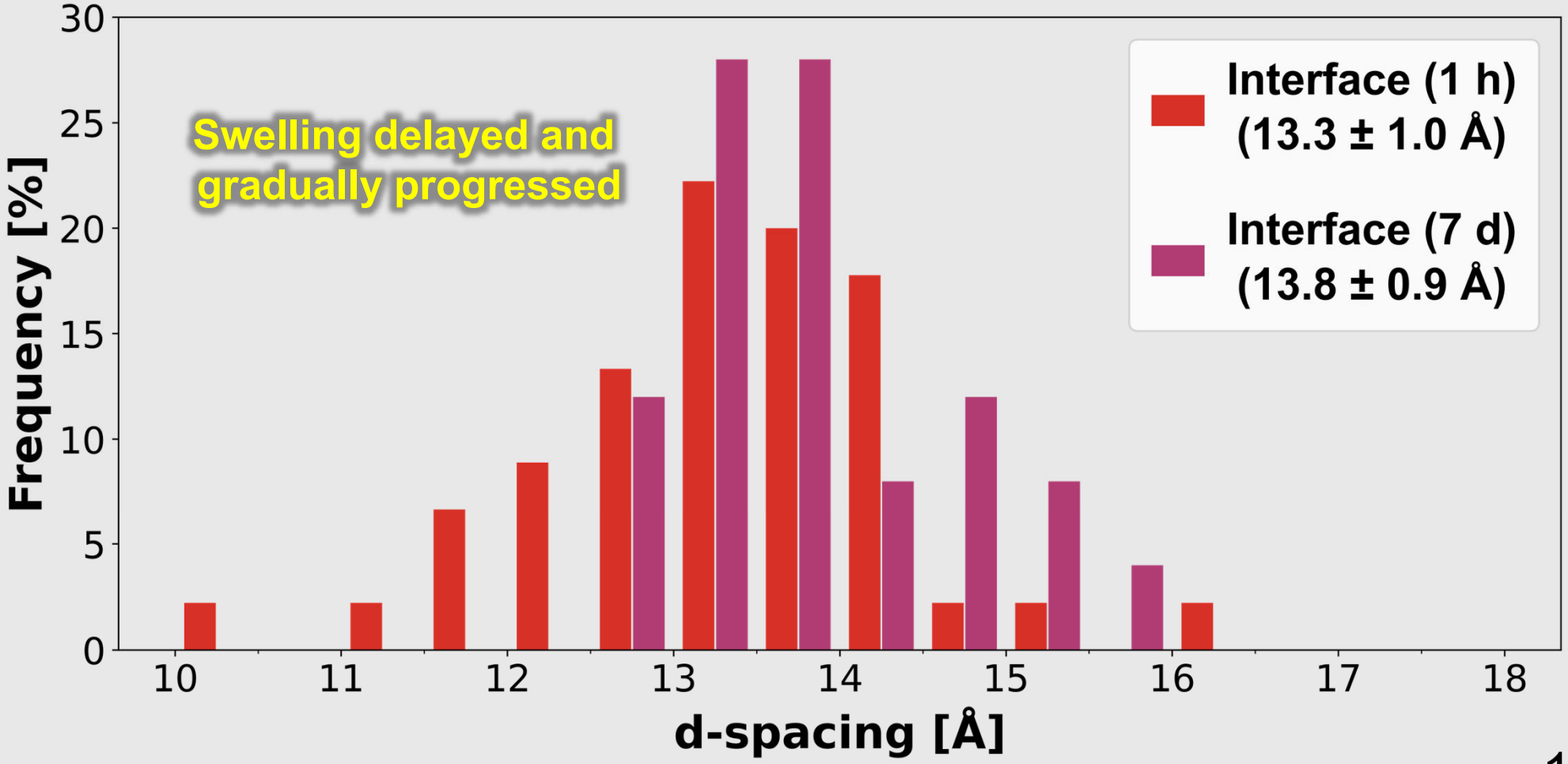
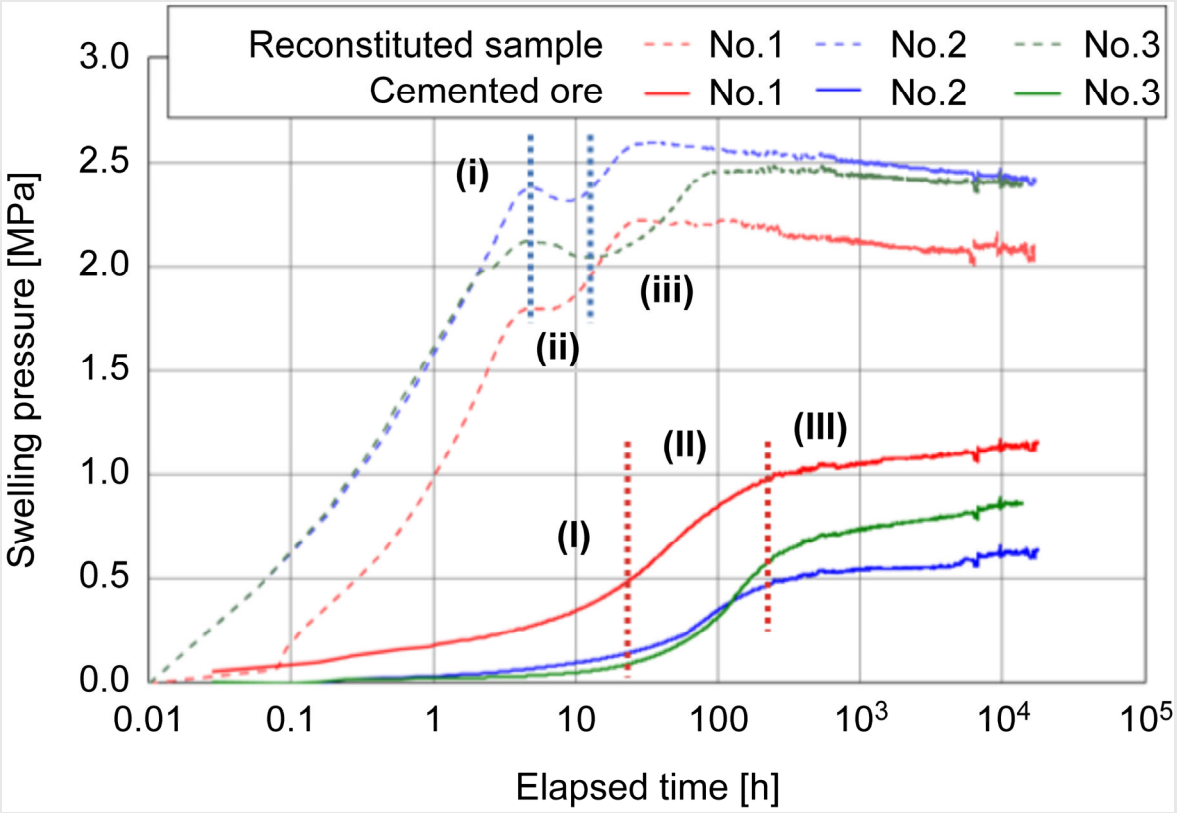


Cemented Ore (TEM)



Mechanism of Swelling Pressure Attenuation



Time dependent swelling pressure evolution
modified from *JAEA & RWMC (2023)*

Cemented ore

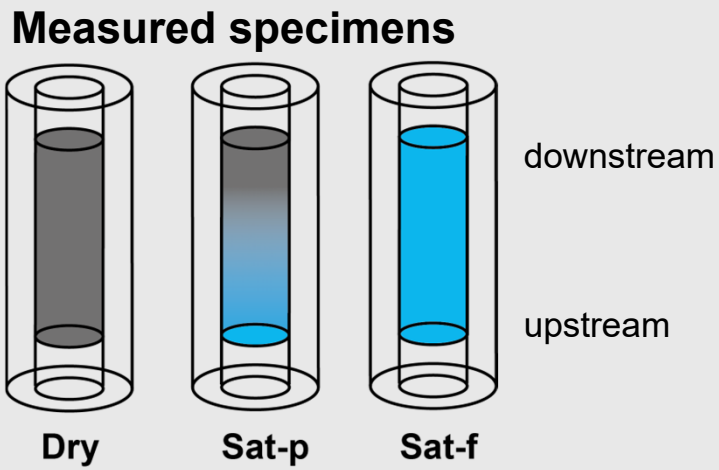
- **Slower pressure development**
  - **Delayed crystalline swelling**
- **Lower final values**
  - **Incomplete hydration in clusters**

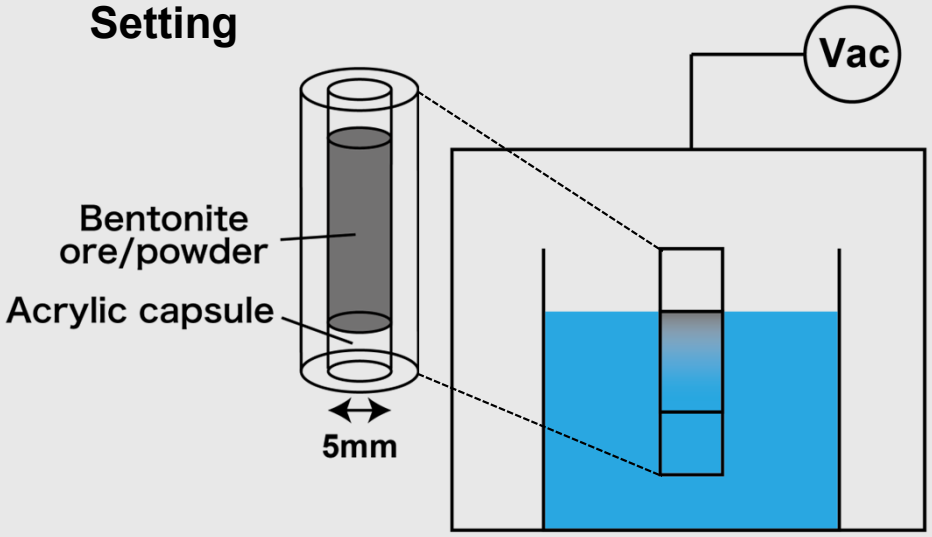
Conclusions

- **Mineral clusters** cause local clogging and limit interior montmorillonite saturation.
- Interfacial montmorillonite shows **delayed crystalline swelling**.
- Heterogeneous swelling explains the **long-term evolution of swelling pressure**.
- Cluster domains should guide **future experiments, modeling, and property prediction**.

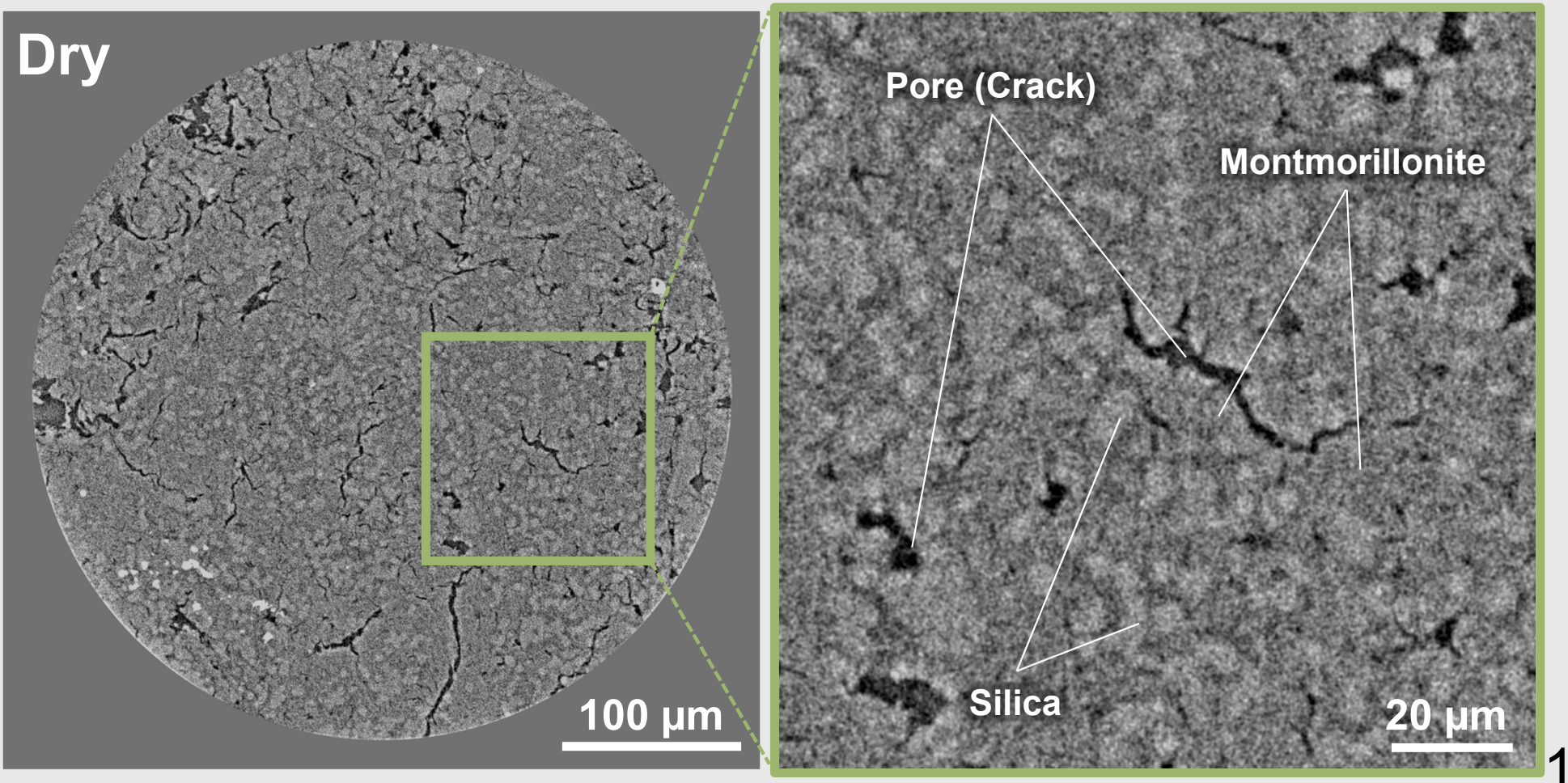
Sample Preparation for Synchrotron Micro X-ray CT (μCT)

- **Water immersion under constrained volume (~50 days)**
- **Several hydration stages**
  - Water immersion duration
  - Distance from water source
- BL47XU of SPring-8



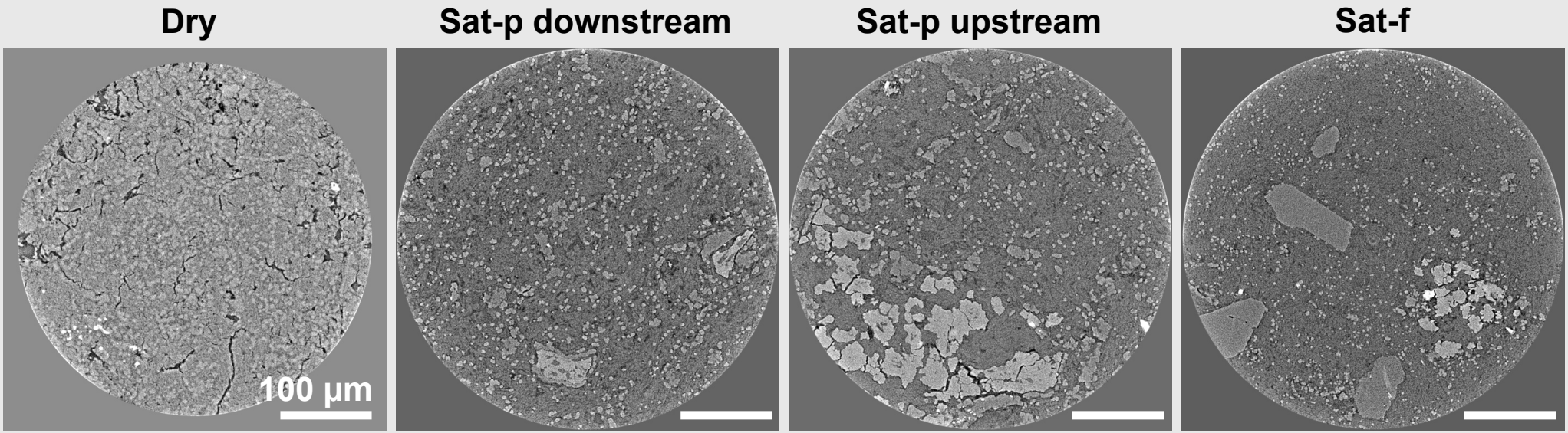


Cemented Ore (µCT)



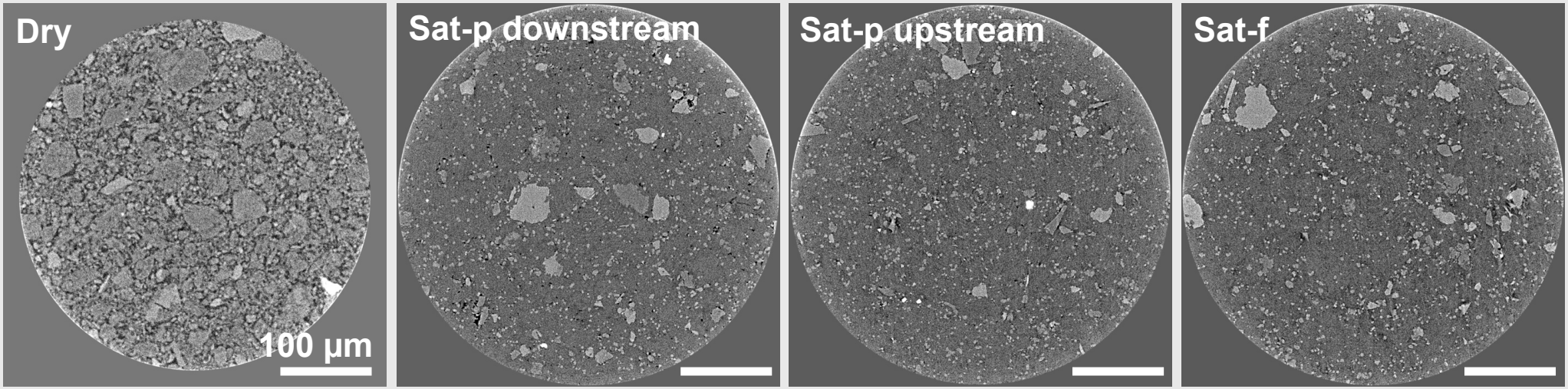
Cemented Ore (µCT)

- **Cracks enclosure upon hydration**
- **Pores remain open** near mineral clusters



Reconstituted Sample (µCT)

- Particles and Pores distributed homogeneously
- Hydration progress homogeneously



Summary of EM

Highlights

- Microtexture controls swelling reduction in cemented bentonite.
  （微細組織が膨潤性の低下の要因）

- Interfacial smectite shows limited crystalline swelling.
  （随伴鉱物界面では結晶膨潤が抑制）

- Partial swelling participation explains reduced swelling pressure.
  （十分に膨潤しないスメクタイトによって膨潤圧が低下）

Remaining challenges

- Experimental conditions (resin ≠ water, volumetric changes not constrained)
  （実際の環境の再現）

- Scale gaps and quantitative relationship with mechanical property tests
  （スケールの乖離と定量評価）