Earth Energy Science

Road to Net Zero: UK-China Workshop on CO2 Geological Storage, 15th of November, 2025

Pore-scale studies on capillary trapping of carbon dioxide in carbonate rocks

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Outline

1. Multiscale pore structures of carbonate rocks

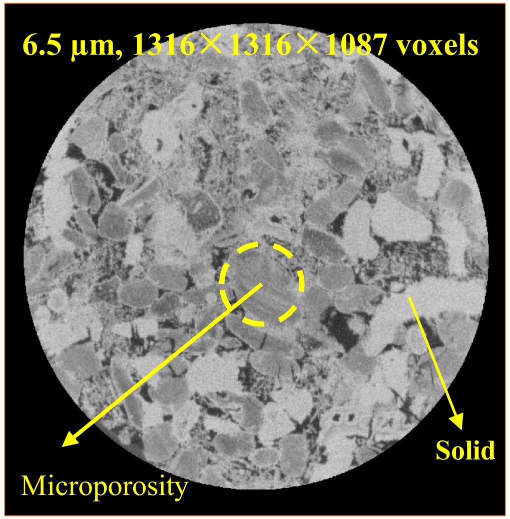
2. The multiscale pore-network model and verification

3. Predictions of capillary trapping

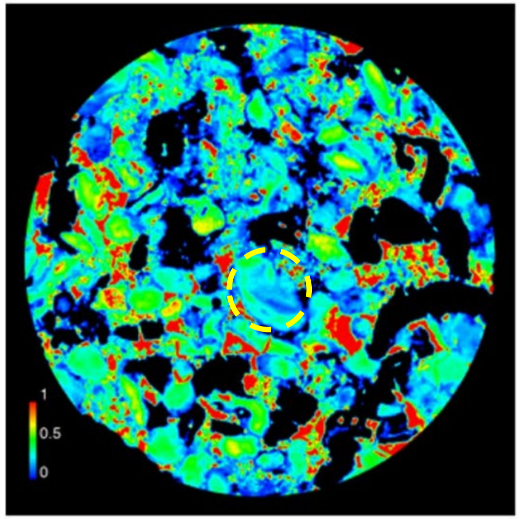
4. Conclusions and outlook

Multiscale pore structures of carbonate rocks

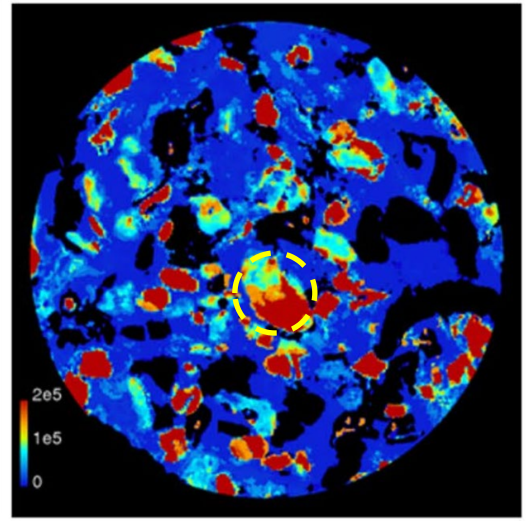
(*Wang et al., WRR, 2022*)



CT grey-scale map

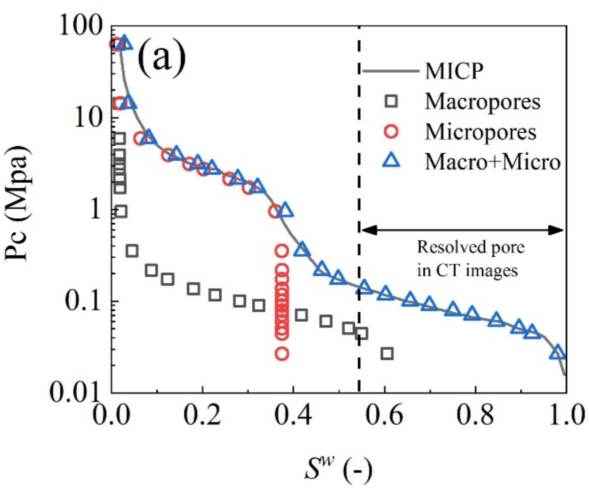


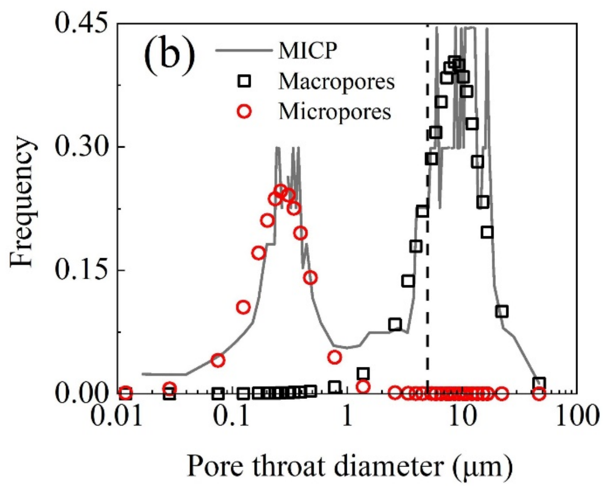
Porosity map



Entry pressure map

In-situ CT scanning of quasi-static drainage process





Bimodal of VG

$$S_e^w = \sum_{i=1}^{2} w_i \left[1 + (\alpha_i P_c)^{N_i} \right]^{-M_i}$$

(*Durner, WRR, 1994*)

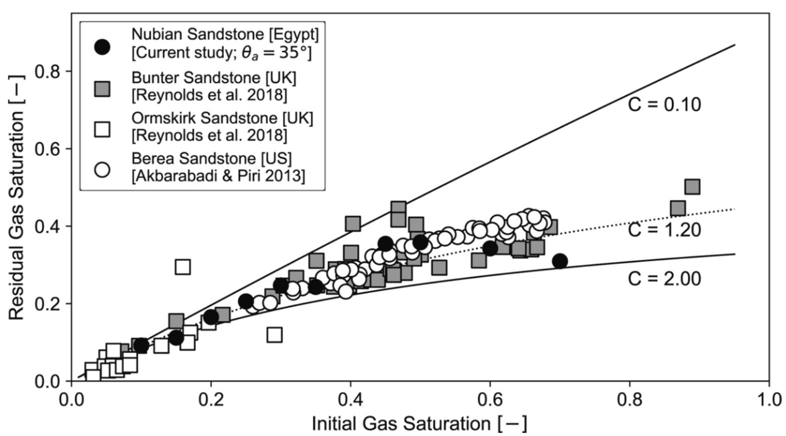
Questions

1. How does the **heterogeneity** of pore structures influence Land trapping coefficient?
2. How does **wettability** influence Land trapping coefficient?

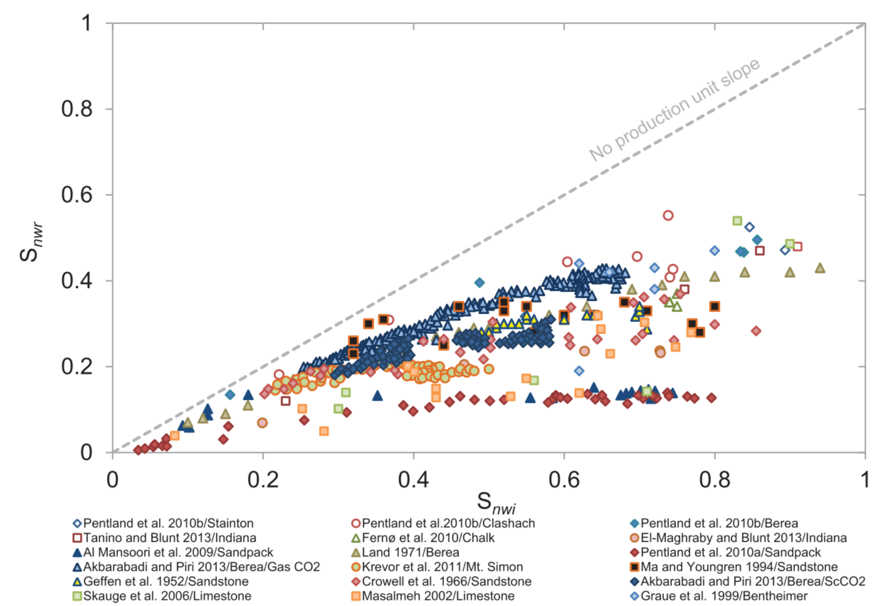
$$S_{nw,r} = \frac{S_{nw,i}}{1 + CS_{nw,i}}$$

Land trapping coefficient

(Land, 1968)



(Hefny, Qin, Saar, and Ebigbo, Int. J. Greenhouse Gas Control, 2020)



(Alyafei and Blunt, AWR, 2016)

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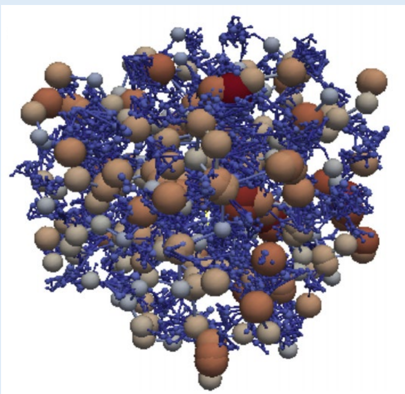
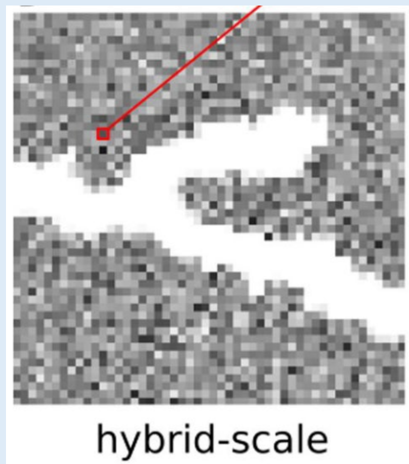
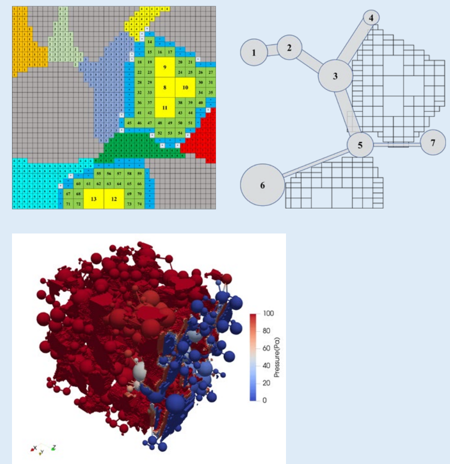
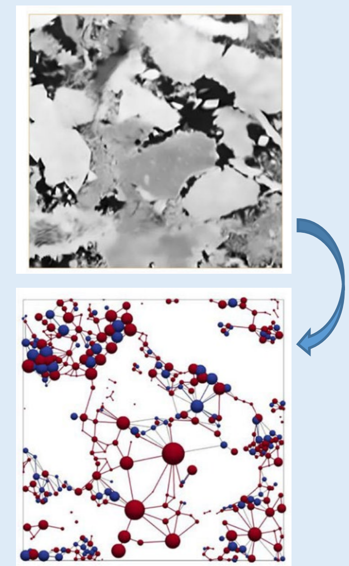
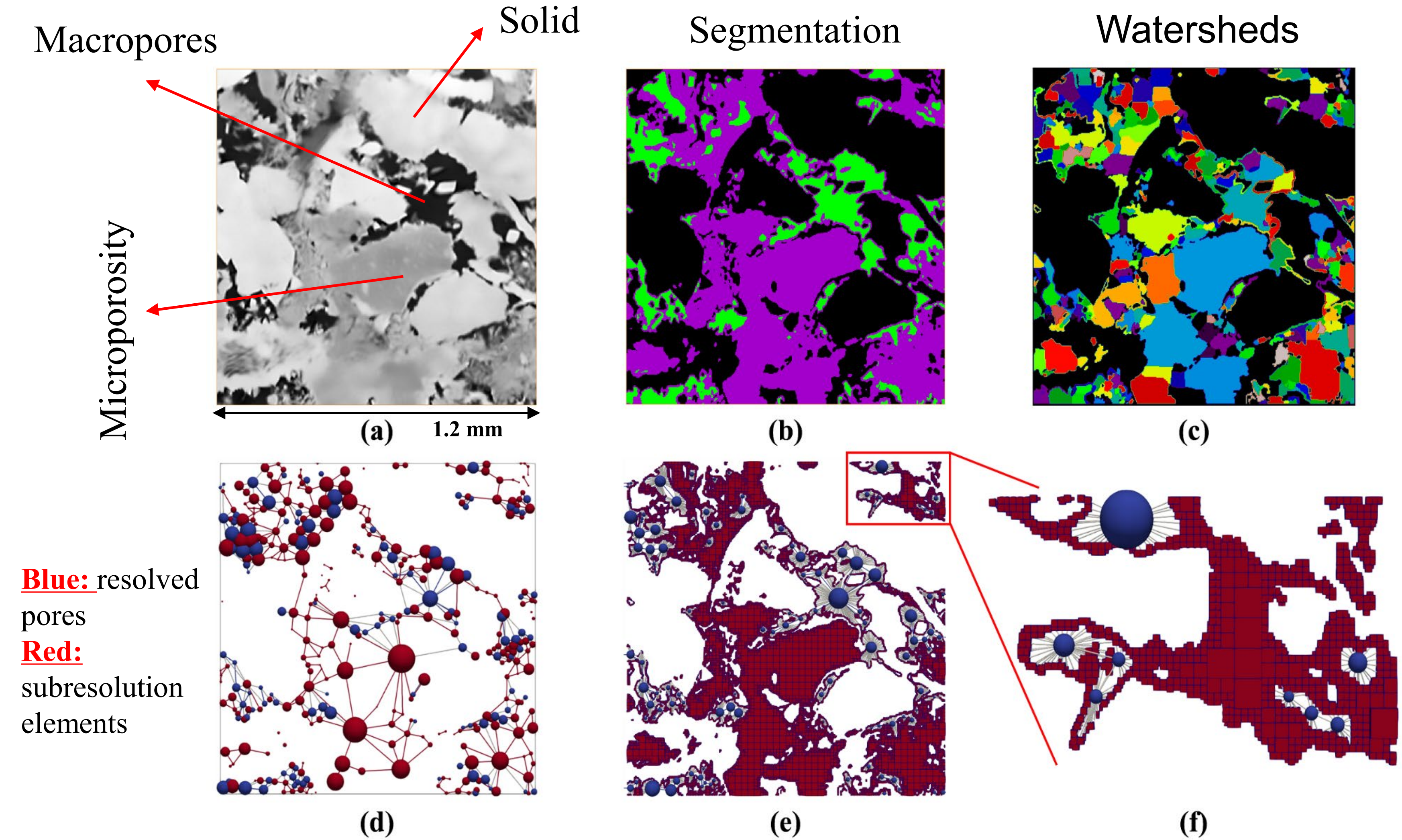
Numerical models for multiscale porous media

Dual-pore-network model (DPNM)	Micro-continuum model (MCM)	Pore-network-continuum model (PNCM)	Multiscale pore-network model (MPNM)
 Mehmani, 2014	 Soulaine, 2023	 Qin, 2024	

❑ The MPNM is most efficient, but **it needs calibration and verification**.

❑ The PNCM can **balance efficiency and accuracy**.

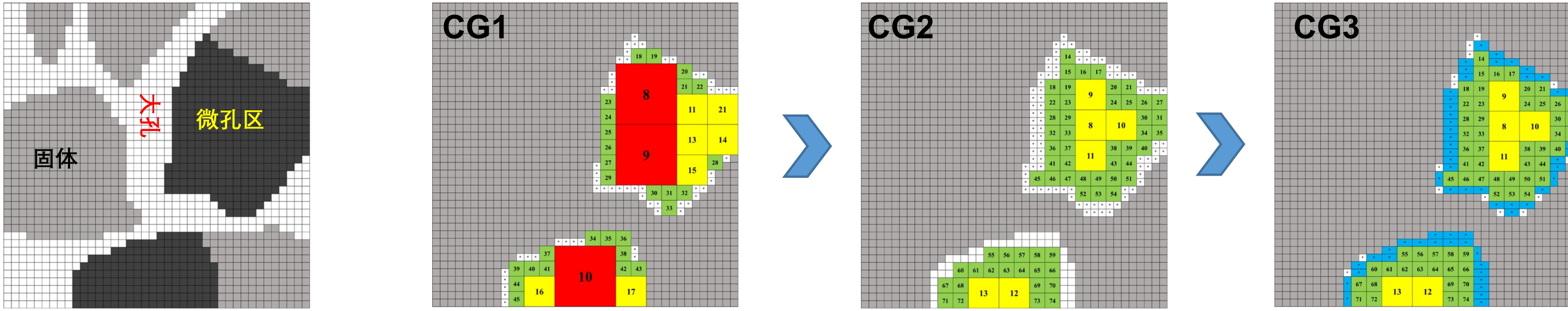
The multiscale pore-network model (MPNM)



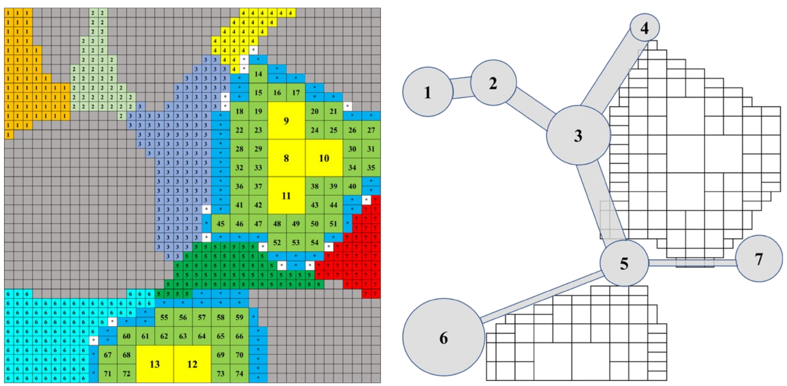
https://digitalporousmedia.org/

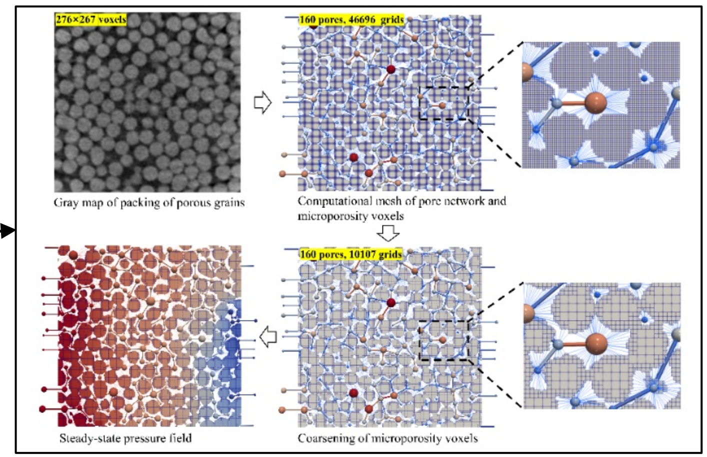
1. Modeling of permeability and formation factor of carbonate digital rocks: dual-pore-network and pore-network-continuum models. Transport in Porous Media, 152:37, 2025
2. Modeling of flow and transport in multiscale digital rocks aided by grid coarsening of microporous domains. Journal of Hydrology, 633:131003, 2024

Pore-network-continuum model – coarsening algorithm

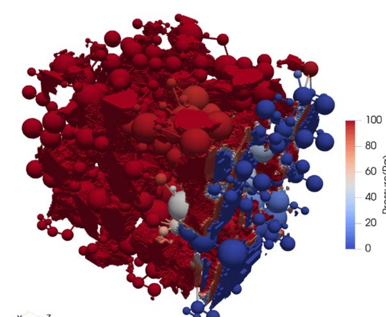


(AWR, 2024; JoH, 2024)





Packing of porous particles



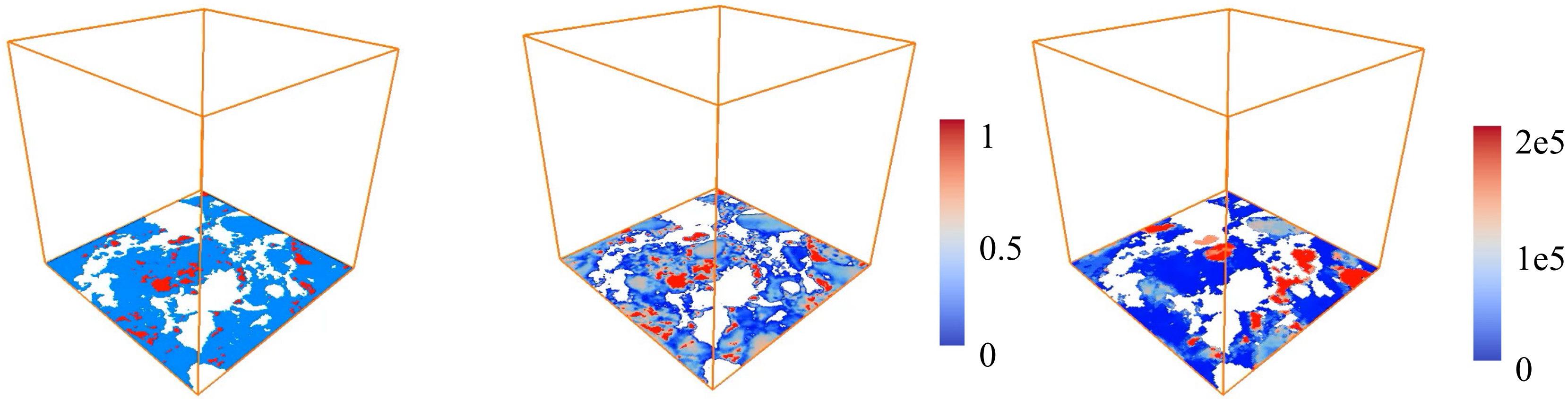
Depressurization process

Verification of MPNM: rock sample

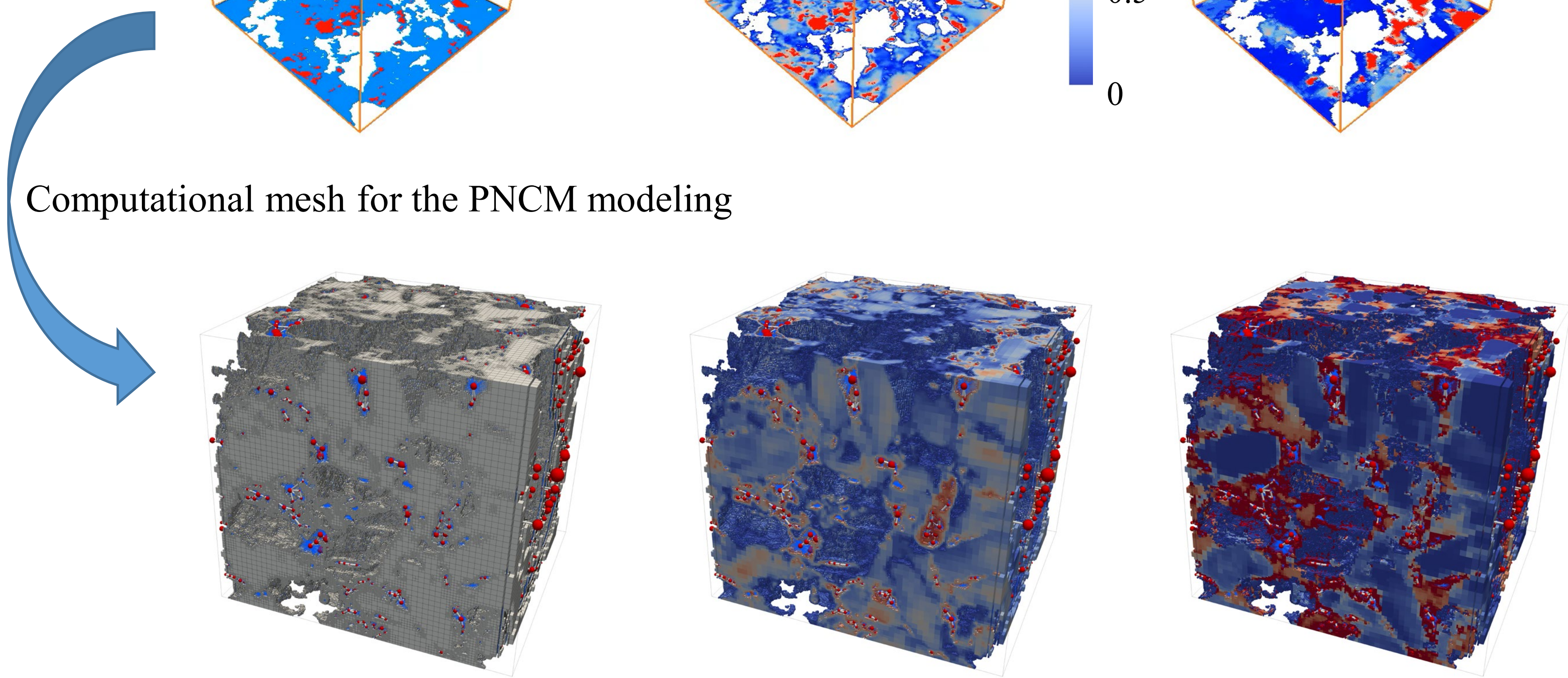
(Wang et al., WRR, 2022)

400^3的测试岩心

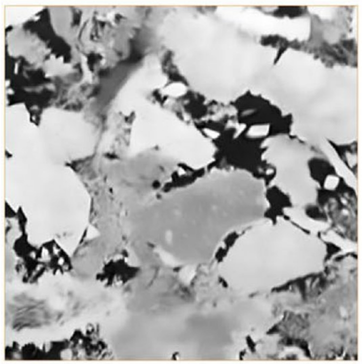
https://www.digitalrocksportal.org/

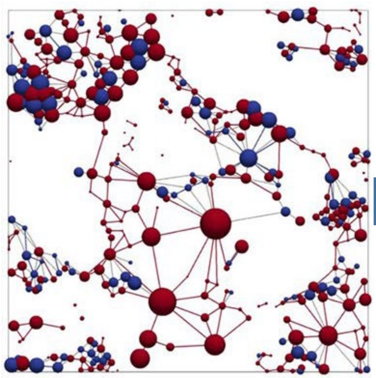


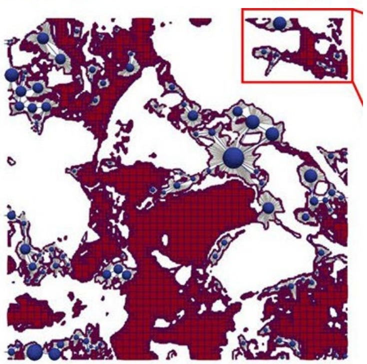
Computational mesh for the PNCM modeling



Verification of MPNM: mean pore size of watershed







① Average based on sphere-assumption

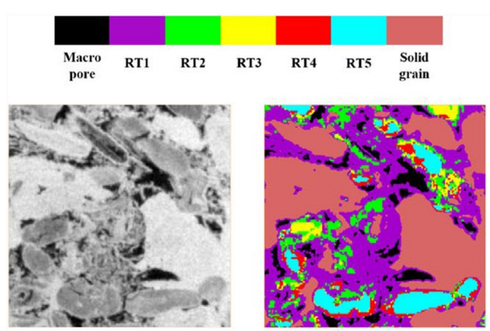
$$\bar{r}_i = \left(\frac{3}{4\pi} \frac{\sum_{k=1}^{N_i} V_k \varepsilon_k}{\sum_{k=1}^{N_i} M_k} \right)^{1/3}$$

$$M_k = V_k \varepsilon_k / \left(4\pi r_k^3 / 3 \right)$$

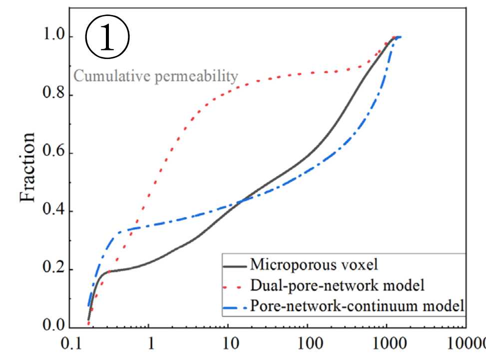
② Average based on voxel-counting

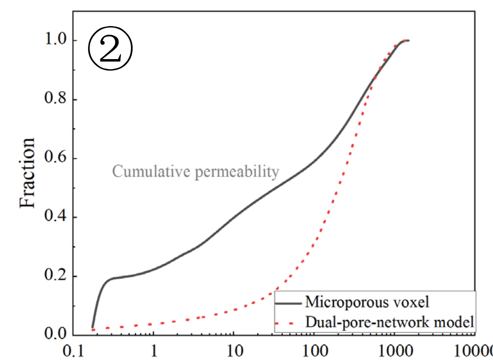
$$\bar{r}_j = \frac{\sum_{k=1}^{N_i} \sum r}{N_i}$$

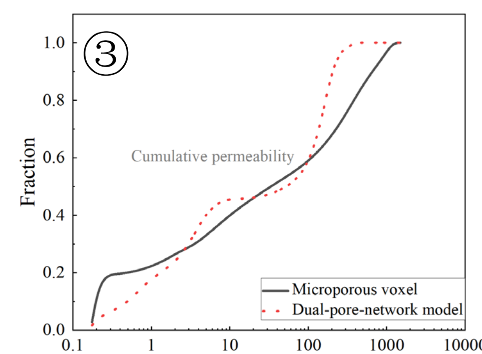
③ Entry-pressure-based sub-rock typing (*Wang et al., 2022*)



Estimation of microporosity permeability distribution







Verification of MPNM: absolute permeability and formation factor

Digital rock	Mean pore size (µm)	By the MPNM (mD)	By the PNCM (mD)	By the reference model (mD)
ES3.1	0.61	109	116	117
ES3.6	0.74	34	37	37
ES6.5-1	1.81	28	18	18
ES6.5-2	Estimated by entry pressure	12① / 205② / 112③	128	174

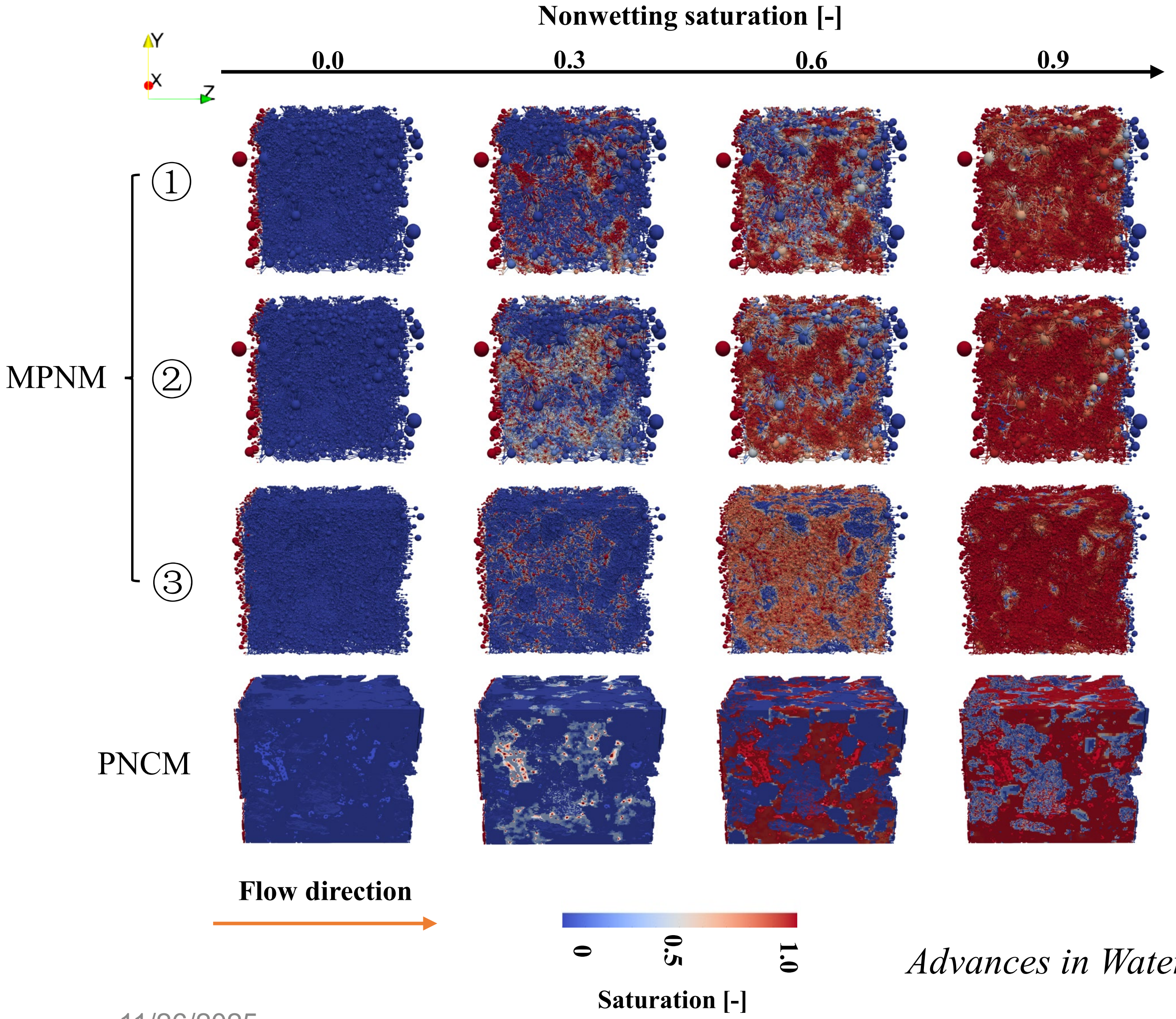
The sub-rock typing is essential to the MPNM

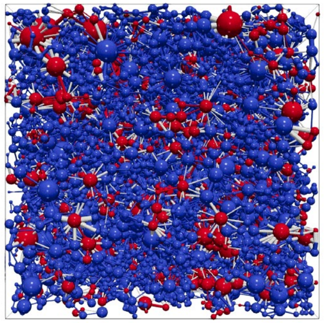
Digital rock	By the multiscale pore-network model (-)	By the pore-network-continuum model (-)	By the reference model (-)
ES3.1	17.24	19.61	19.23
ES3.6	23.81	23.81	23.26
ES6.5	18.52	20.41	19.23

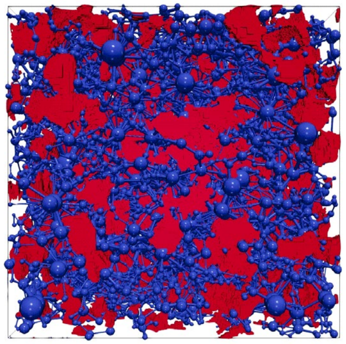
The prediction of electrical formation factor is satisfied

Transport in Porous Media, 152:37, 2025

Verification of MPNM: capillary pressure curve

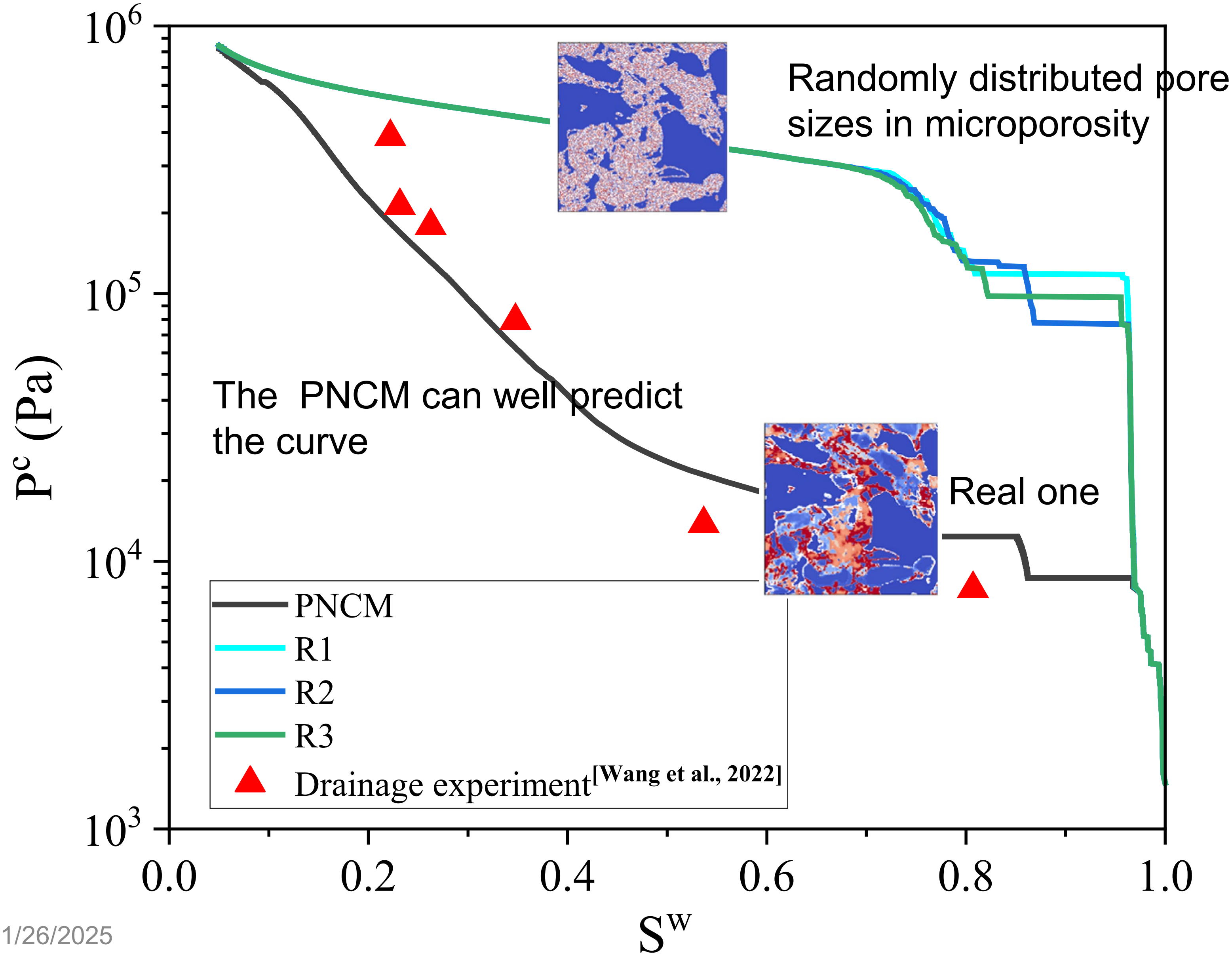




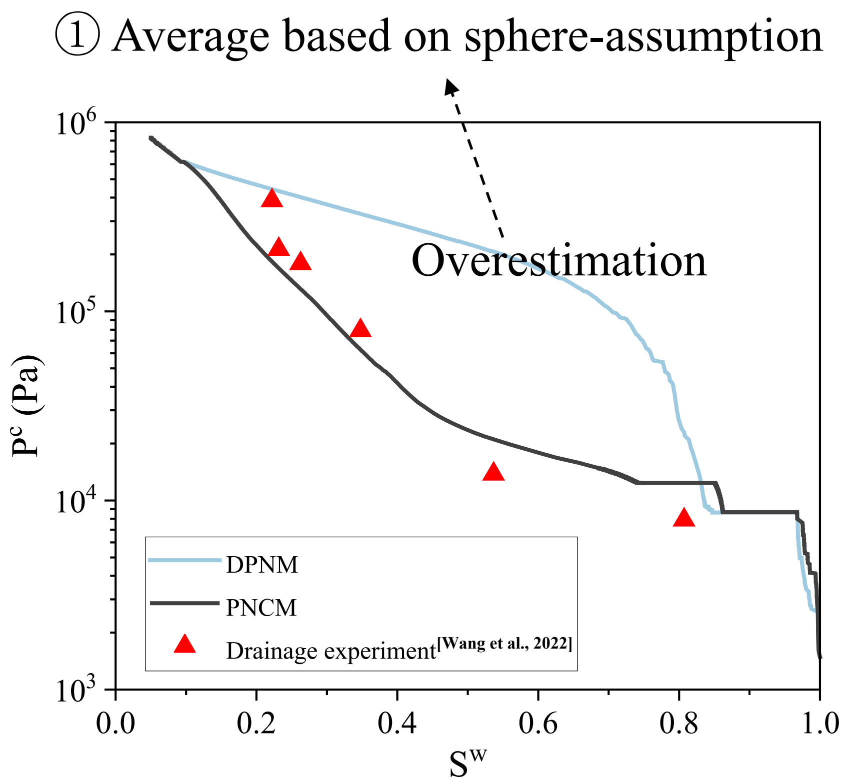


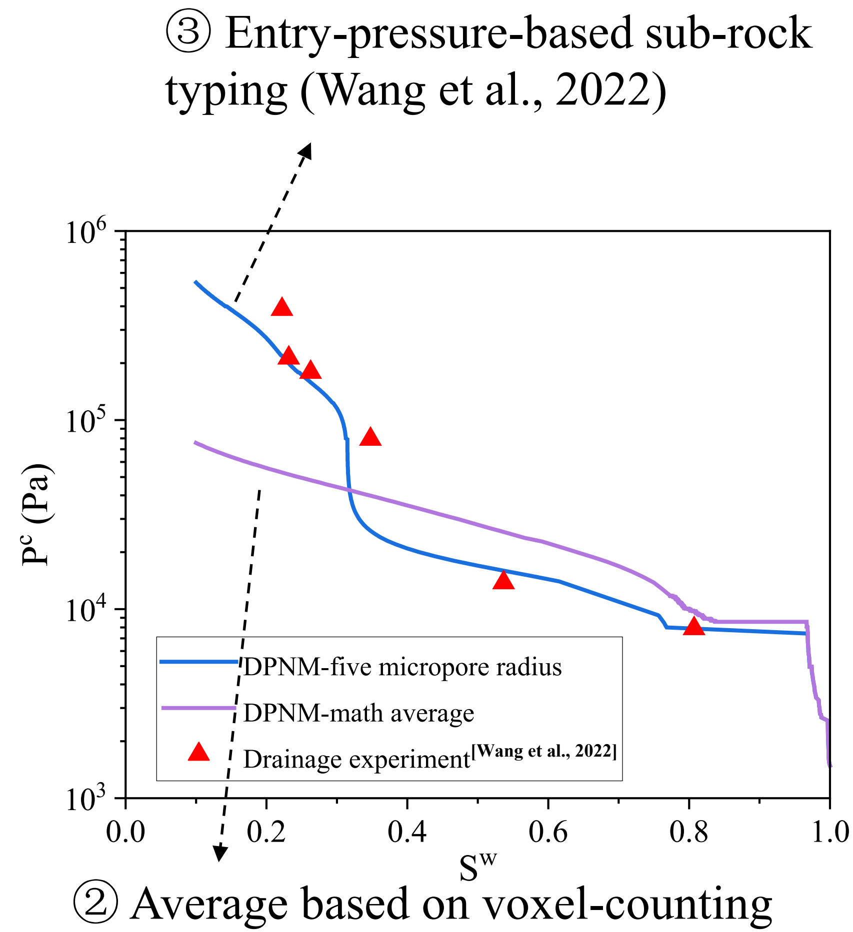
Advances in Water Resources 206 (2025) 105138

Verification of MPNM: capillary pressure curve



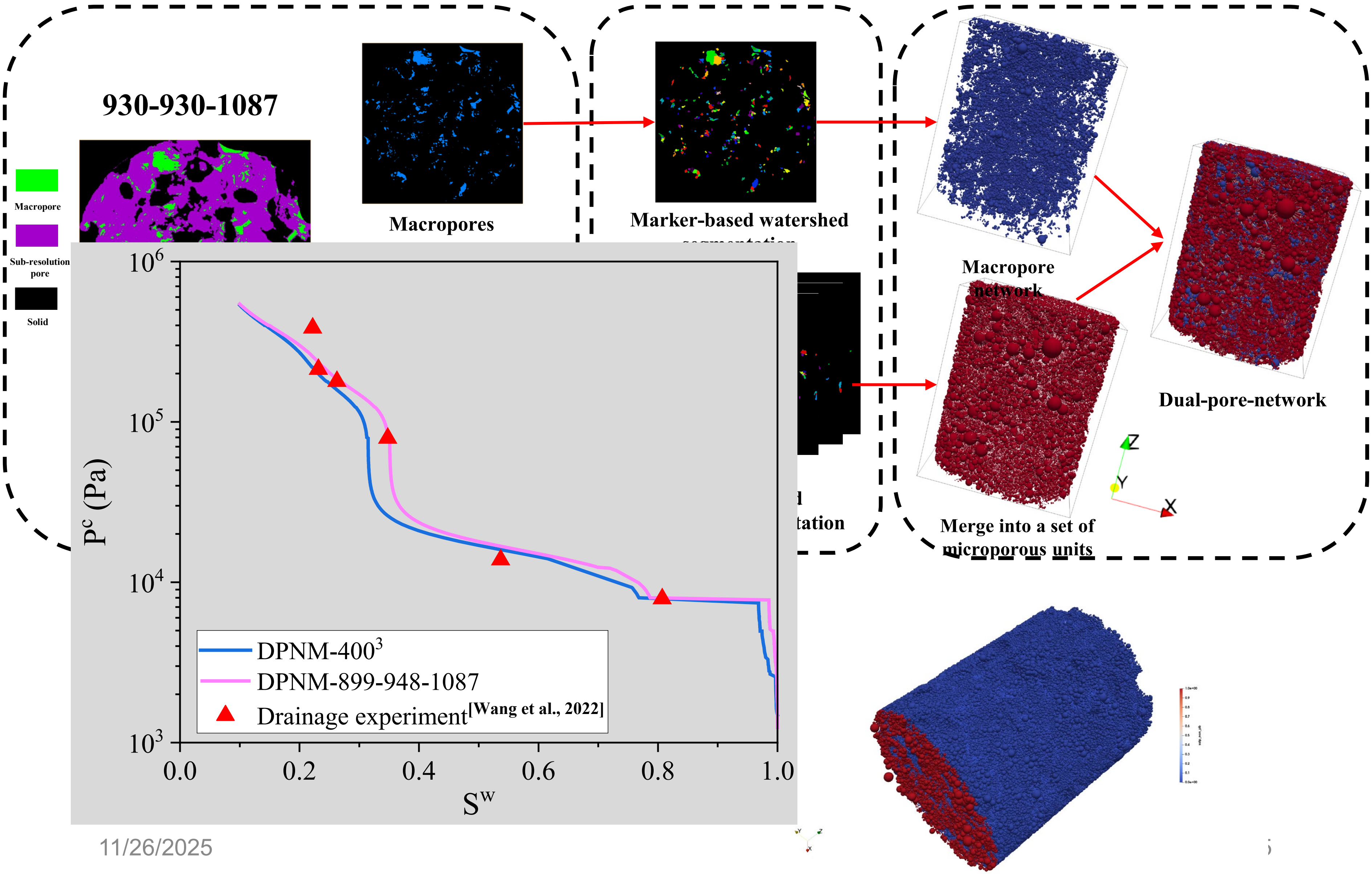
Verification of MPNM: capillary pressure curve



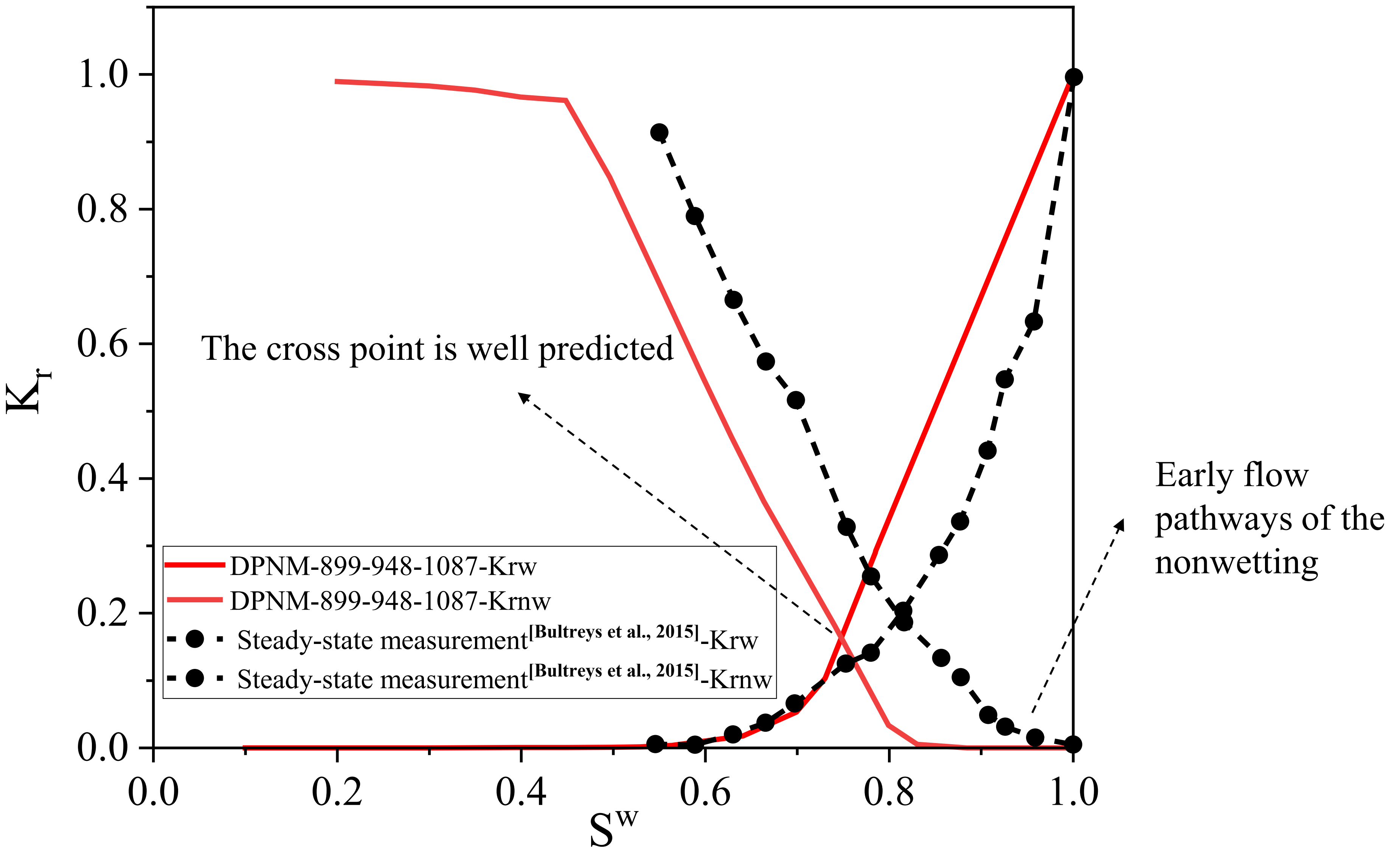


- The **sub-rock typing** is essential to the efficient multiscale pore-network model.
- 400^3 size **is adequate to** the prediction of capillary pressure curve.

Capillary pressure (the full image of ES6.5)



Relative permeability (the full image of ES6.5)



Outline

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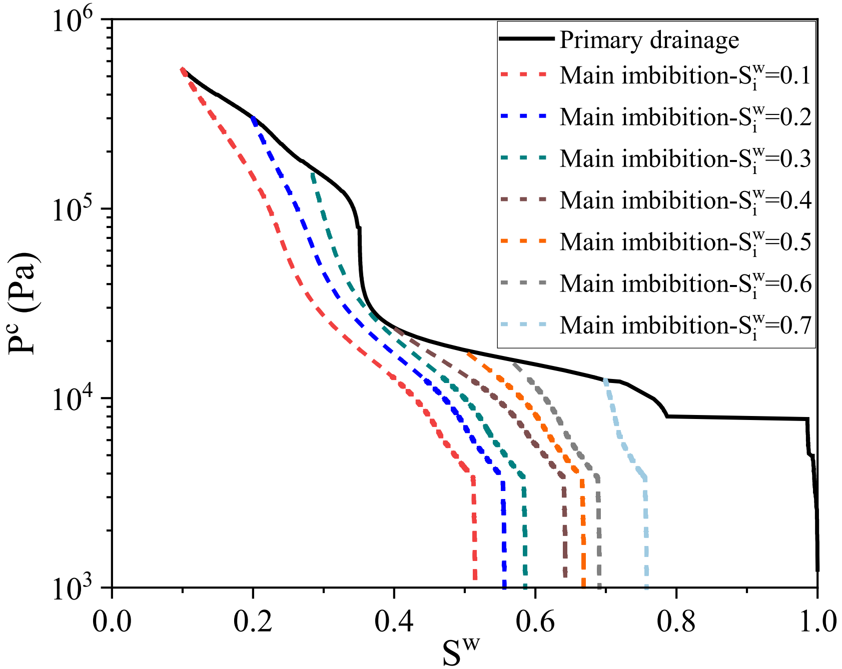
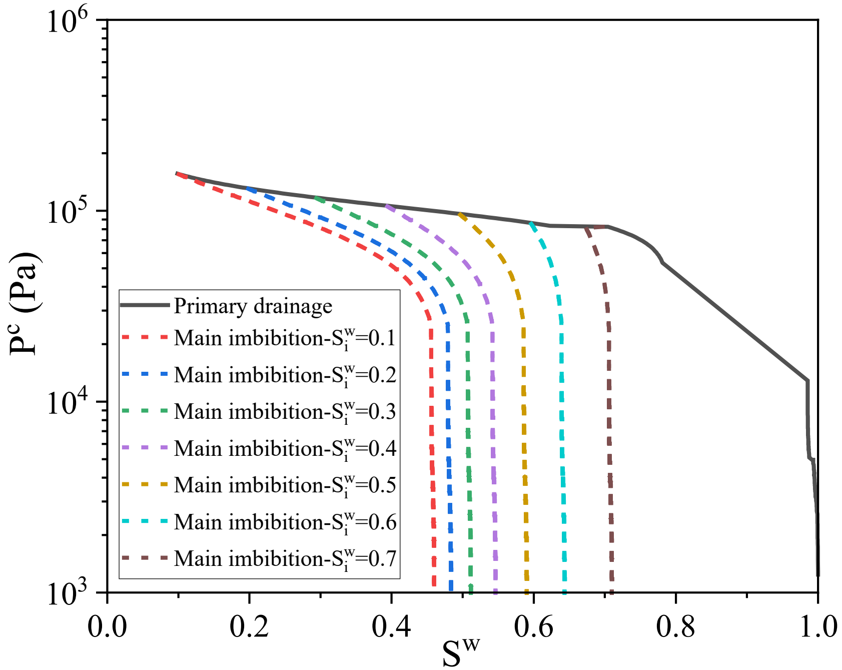
Capillary trapping

Do not consider Ostwald ripening and remobilization



ES6.5: heterogeneous microporosity

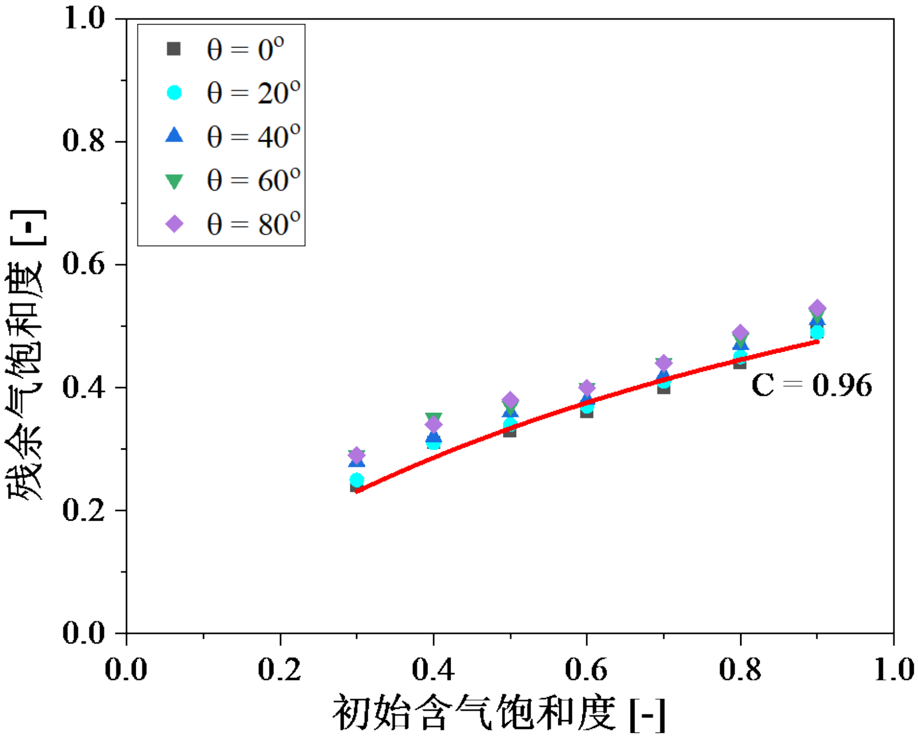


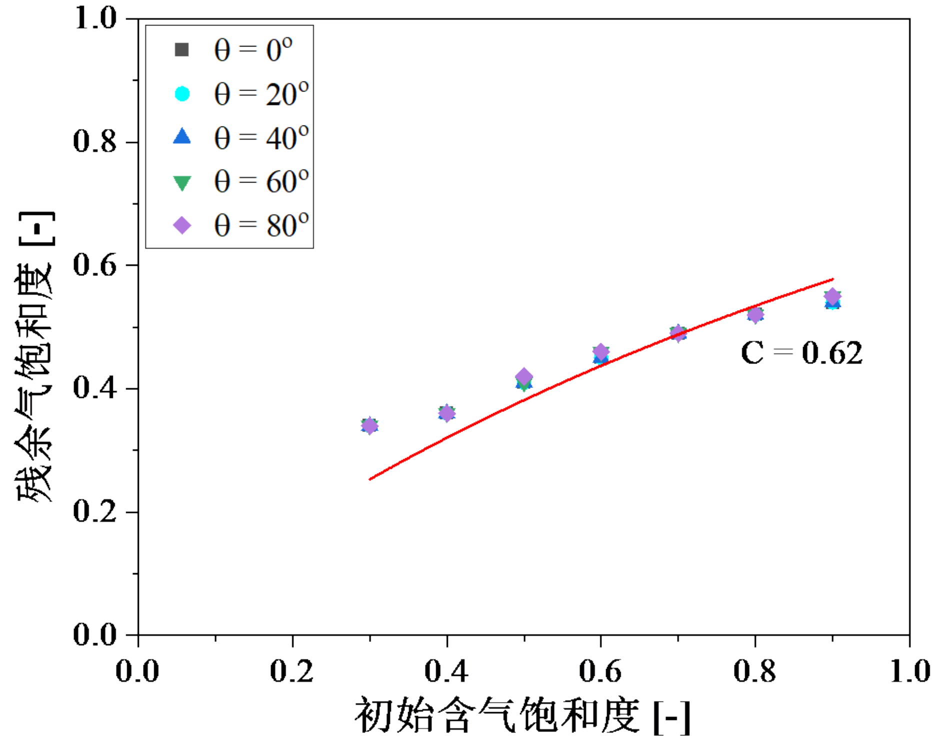
Assuming constant mean pore size of microporosity

Capillary trapping

$$S_{nw,r} = \frac{S_{nw,i}}{1 + CS_{nw,i}}$$

Tune the wettability of macropores





(b)

https://czqin.github.io/publication/zhao-master-2022

Conclusions and outlook

Conclusions

- ❑ A high-efficient multiscale pore-network model (MPNM) is developed, and verified against the high-resolution pore-network-continuum model (PNCM).
- ❑ Microporosity of ES rocks has strong heterogeneity of mean pore sizes.
- ❑ Three types of averaging microporosity voxels are tested. It is found that the sub-rock typing is necessary to guarantee the reliable predictions of both single-phase and two-phase flow parameters.
- ❑ We can predict absolute permeability, formation factor, capillary pressure and relative permeability.
- ❑ Heterogeneity of pore structures enhances capillary trapping?

Outlook

- ❑ Advance the modeling framework to two-phase flow dynamics.
- ❑ Understand how microporosity influences material properties, and extend capillary pressure and relative permeability empirical models.

Thank you for your attention!

Chao-Zhong Qin（秦朝中）

https://czqin.github.io/

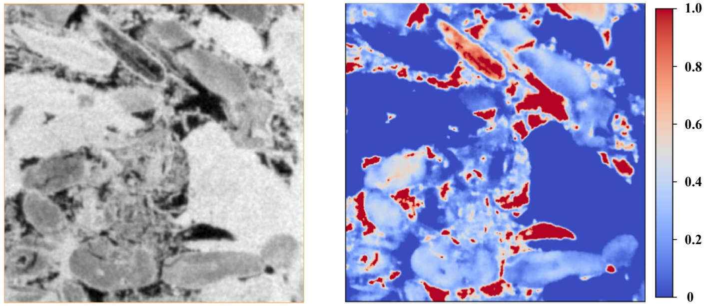
Test samples of carbonate digital rocks

https://www.digitalrocksportal.org/

Digital rock	Voxel size (μm)	Microporosity	Image size (voxels)	Total Porosity (%)	Absolute permeability (mD)
					Experimental
ES3.1	3.1	Uniform mean pore size	2000×2000×1725	25	260 ± 60
ES3.6	3.6	Uniform mean pore size	1000×1000×1000	29	/
ES6.5	6.5	Heterogeneous	1316×1316×1087	25	202.4 ± 86.9

ES3.1 and ES3.6 have the MICP curves; ES6.5 has **the porosity map and the entry-pressure map** of subresolution microporosity.

The porosity map of ES6.5



(a) (b)

Predictions of absolute permeability and formation factor

Subvolume of digital rock	Pore regions	Original voxels	Volume fraction	In the MPNM	In the PNCM
ES3.1	Macropores	6332318	9.9%	3569	3569
	Microporosity	21562493	33.7%	8375	3929815
ES3.6	Macropores	5040267	7.9%	2172	2172
	Microporosity	32676964	51.1%	13228	4494989
ES6.5	Macropores	3694907	5.8%	3827	3827
	Microporosity	40618405	63.5%	7930	4147069

90% reduction in computational grids

Why does the MPNM underestimate the absolute permeability?

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ES3.6	0.74	34	37	37
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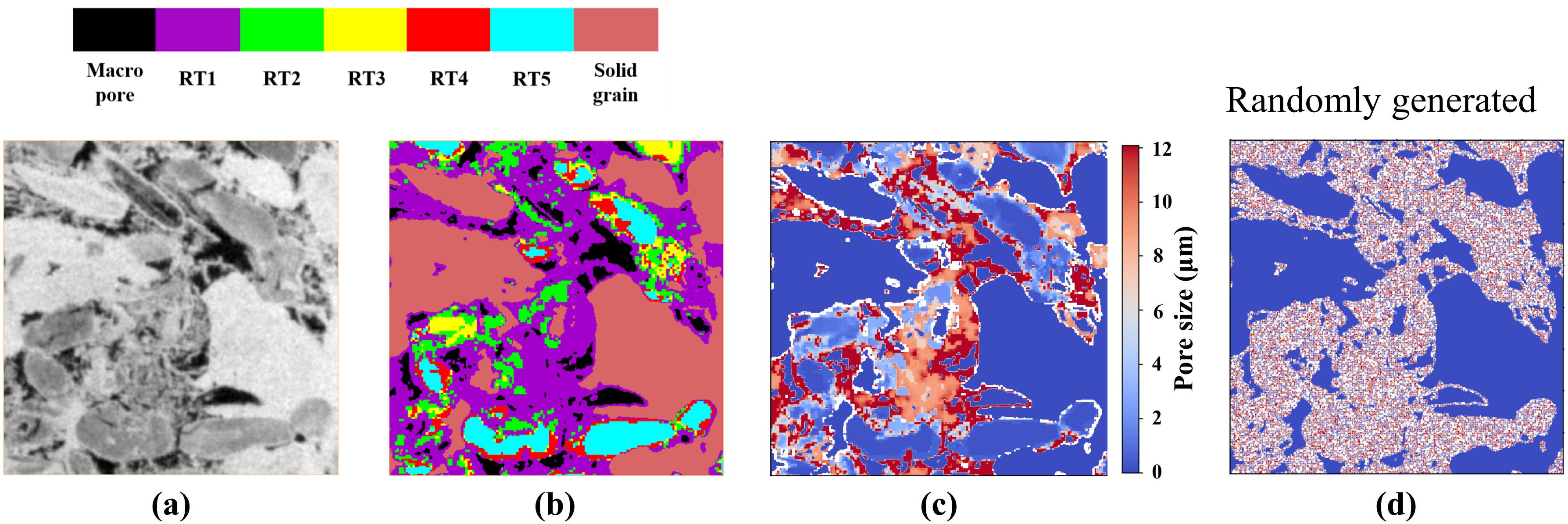
ES3.6	23.81	23.81	23.26
ES6.5	18.52	20.41	19.23

The prediction of formation factor is satisfied

Why do we need the sub-rock typing?



- ❑ The sub-rock typing helps with the prediction, but the CT-based characterization is costly and time-consuming !
- ❑ If only the MICP data is used, the correlation of pore sizes should be taken into account.