重庆大学
CHONGQING UNIVERSITY

多尺度孔隙结构与流动传输数值研究

Multiscale pore structures and multiscale numerical modeling of flow and transport

秦朝中，史博文，王馨，赵星圆，蒋函，王志伟 (Chongqing University, China)
郭波 (University of Arizona, USA)

研究学术 造就人才 佑启乡邦 振导社会

Outline

煤矿动力学灾害与控
制全国重点实验室

重庆大学科学中心

多尺度渗流力学团队（Multiscale Flow and Transport in Porous Media Group）

秦朝中

- 2019.11~至今，重庆大学资源与安全学院，教授，博士生导师，重庆大学百人计划特聘研究员
- 2016.11~2019.10，荷兰埃因霍温理工大学（机械工程），达西研究中心，执行主管
- 2005.09~2016.10，西安交通大学学士、中国科学技术大学硕士、荷兰乌特列支大学/通用汽车欧洲研究院博士、博后
- 从事数字岩心分析技术、多尺度渗流力学等方面的研究，主持（研）国家自然科学基金面上、联合重点基金、中比国际合作与交流、通用汽车工业应用研究项目、荷兰科学研究组织项目、欧盟研究委员会项目和瑞士国家科学基金，以主要作者发表学术论文50多篇，现担任Advances in Water Resources杂志副主编、Earth Energy Science杂志执行副主编、InterPore中国分会委员、InterPore MS-05分会场（Physics of multiphase flow in diverse porous media）负责人。

蒋 函

- 重庆大学资源与安全学院，讲师、助理研究员
- 2021年，博士毕业于澳大利亚新南威尔士大学石油工程专业，从事数字岩心分析技术与渗流理论研究
- 主持（研）国家自然科学基金、博士后基金等多项科研项目，在Water Resources Research、Physical Review E、Journal of Petroleum Science and Engineering等顶级期刊发表论文10余篇

田 键

- 重庆大学资源与安全学院，讲师、助理研究员
- 2021年，博士毕业于西南石油大学油气井工程，从事油气储层保护与开发，致密油气藏提高采收率理论与技术
- 主持（研）国家自然科学基金、博士后基金等多项科研项目，在石油学报、Physics of fluids、Journal of Petroleum Science and Engineering等顶级期刊发表论文20余篇

Outline

Engineering 14 (2022) 10–14

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Views & Comments

Flow in Porous Media in the Energy Transition

Martin J. Blunt [a], Qingyang Lin [b]

[a] Department of Earth Science and Engineering, Imperial College London, London SW7 2BP, UK
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Hangzhou 310027, China

InterPore JOURNAL

Invited Commentary

RESEARCH NEEDS IN POROUS MEDIA FOR THE ENERGY TRANSITION

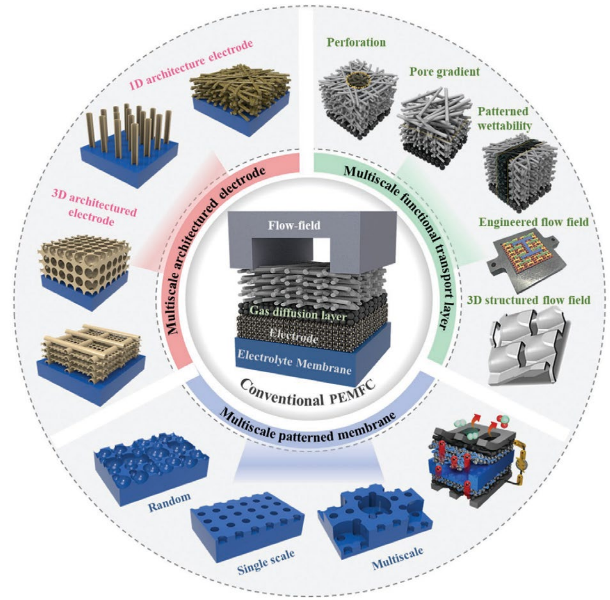
Martin J. Blunt[1], Aimy Bazylak[2], Michelle Brook[3], Ann Muggeridge[1], Franklin M. Orr Jr.[4]

[1] Imperial College London, Faculty of Engineering, Department of Earth Science & Engineering, London, UK; [2] University of Toronto, Department of Mechanical & Industrial Engineering, Faculty of Applied Science & Engineering, Toronto, Ontario, Canada; [3] British Geological Survey, Keyworth, Nottingham, UK; [4] Stanford University, Department of Energy Science & Engineering, Stanford, California, USA

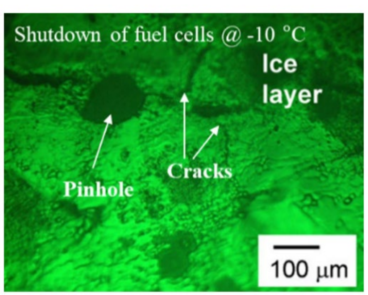
渗流力学推动能源转型的
关键技术与应用基础研究

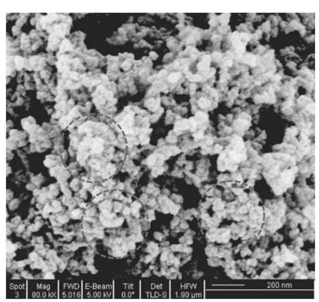
电化学装置：low-temperature PEM fuel cells

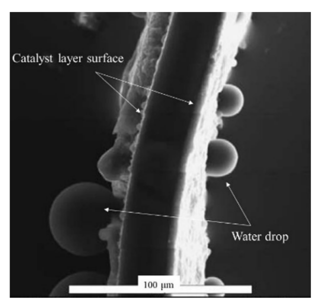
1. 多尺度电池结构、多尺度孔隙结构
2. 非等温多组分气水两相流动
3. 孔隙结构优化设计与润湿性调控
4. 多尺度流动与传输（从纳米孔隙到各层到单元到电池堆）
5. 高效定量的预测模型

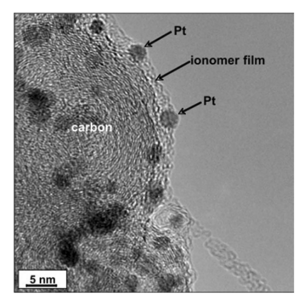


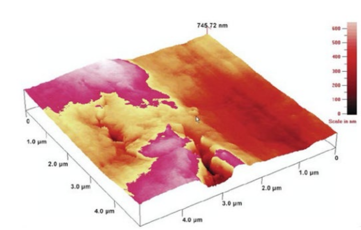
Adv. Mater. 35, 2204902, 2023









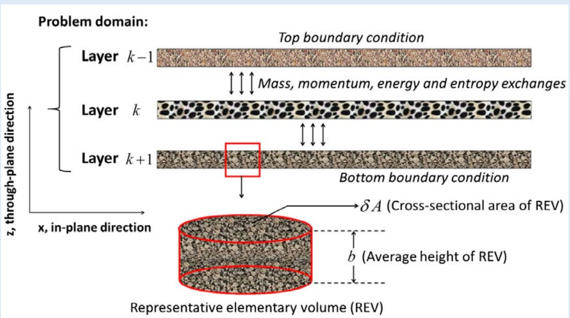


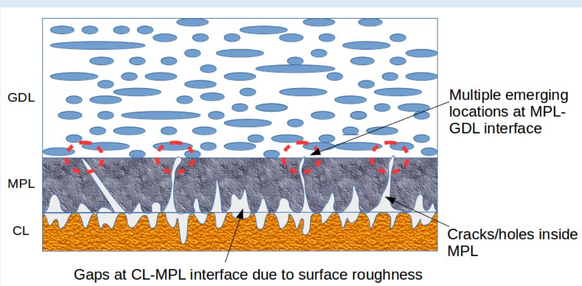
Electrochem. Energ. Rev. 6, 13, 2023

电化学装置：low-temperature PEM fuel cells

超薄多孔介质

Reduced Continua Model



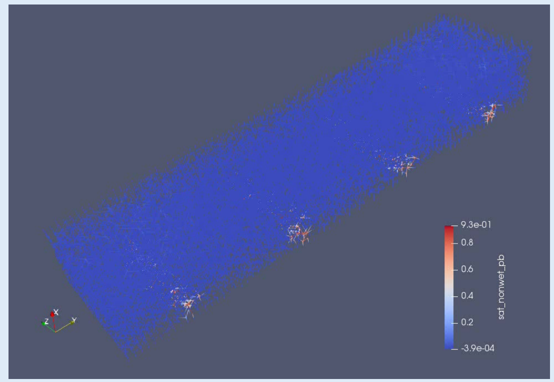


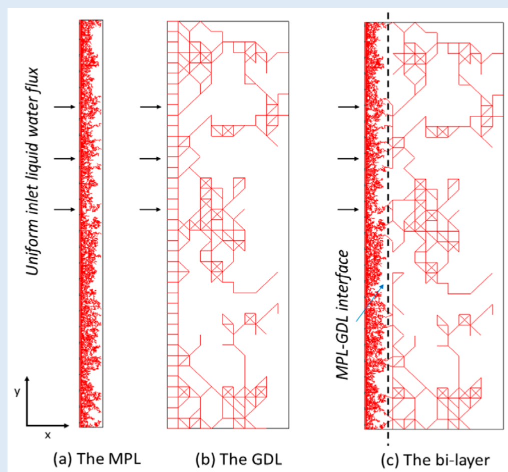
1. 有较强的物理意义
2. 交换系数考虑层间隙影响
3. 计算效率高

Int. J. Heat Mass Transfer. 2014; Int. J. Hydrogen Energy. 2015

孔隙尺度模拟

Pore-Network Model

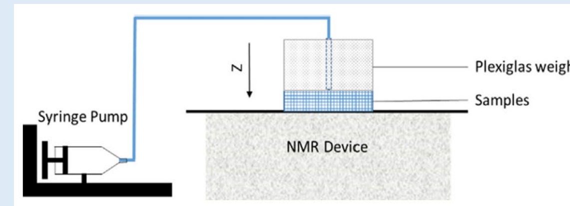


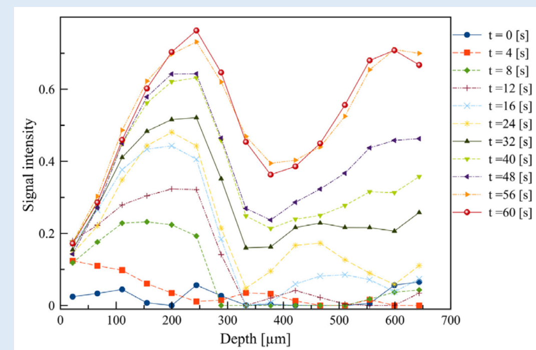


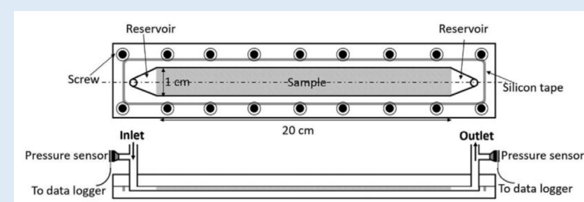
J. Electrochem. Soc. 2015; Chem. Eng. Sci. 2019

渗流参数测量

Two-phase flow properties



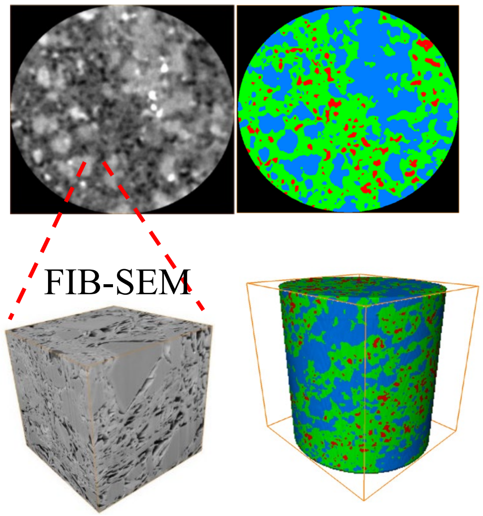




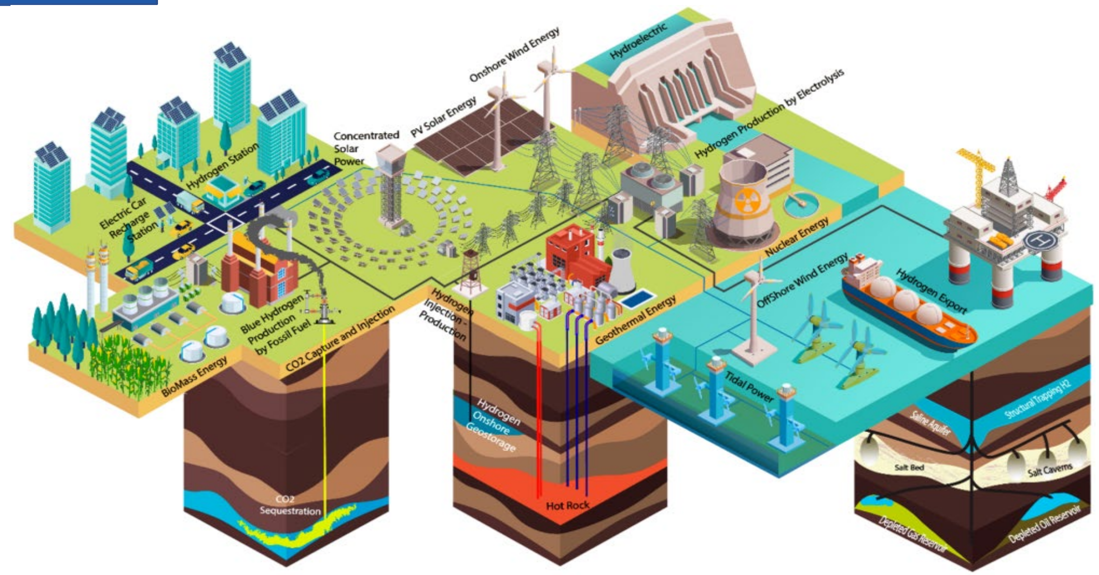
Text. Res. J. 2023; Chem. Eng. Sci. 2019

非常规油气开发与地下储能

泥岩盖层
可分辨大孔-红色，微孔区-绿

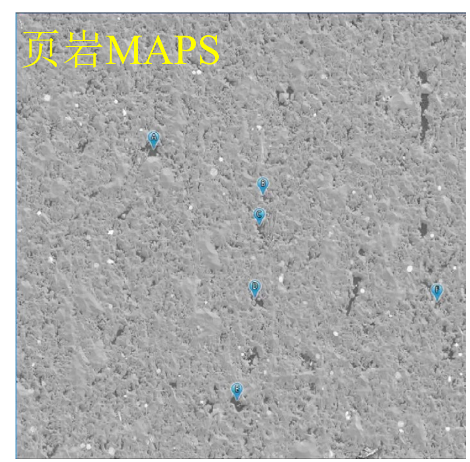


J. Hydrol. 2023

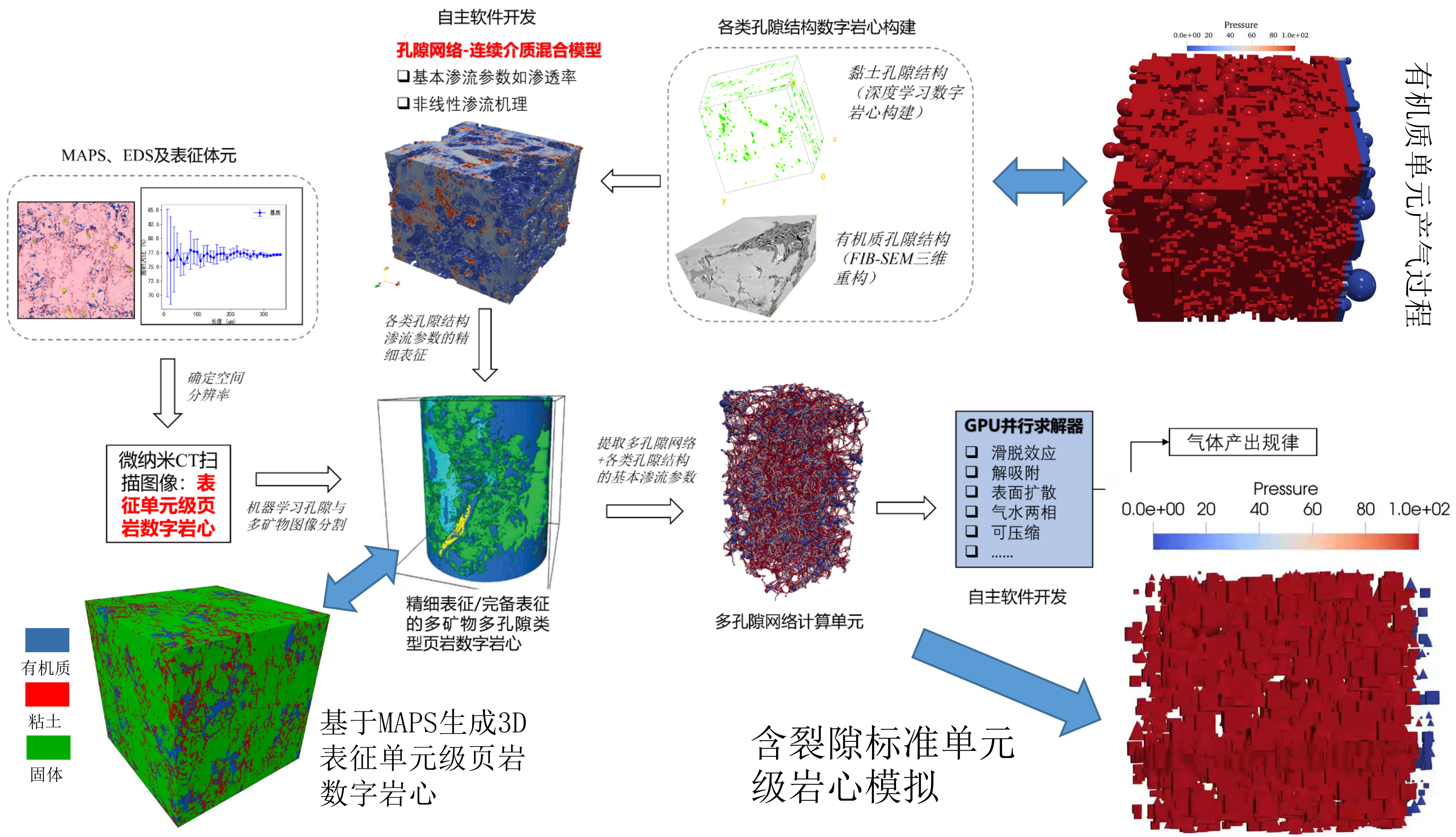


二氧化碳封存　　非常规油气　　地下储氢

1. 我国富煤、少气、贫油，开发非常规油气具有战略意义
2. 储层、盖层呈现多尺度孔隙结构
3. 多矿物组成导致润湿性复杂
4. 高效定量的预测模型，调控流动与传输



非常规油气开发与地下储能：页岩气微纳流动



Phys. Fluids, 2025; Front. Earth Sci. 2025

共性的关键科学问题与挑战

China Energy transition:

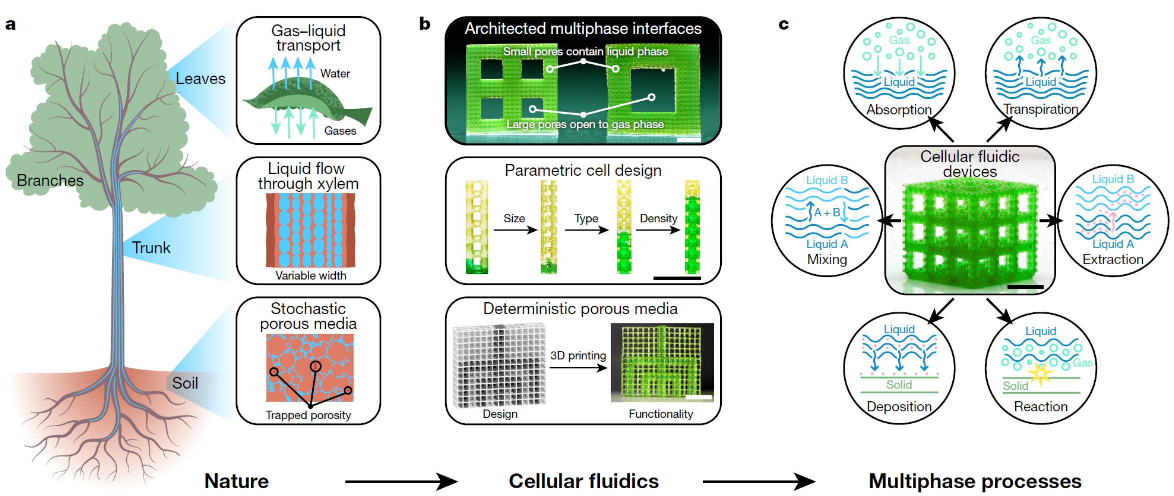
1. Unconventional oil and gas recovery
2. Energy storage (e.g., underground hydrogen storage and sequestration of CO_2)
3. Electrochemical devices

Porous Media →

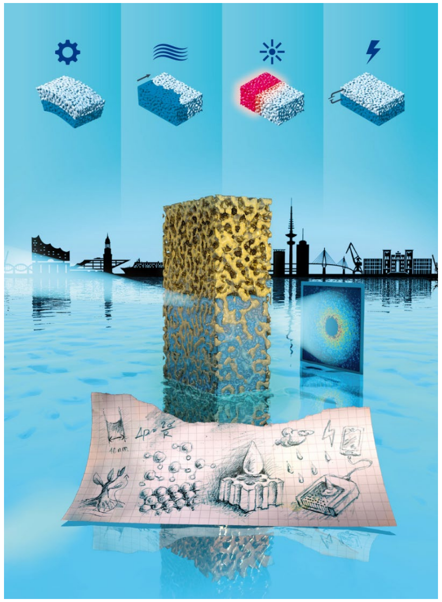
Challenges and opportunities:

1. Heterogeneity and multiscale pore structures
2. Wettability and its alteration/control
3. AI-based predictions and material optimization

Dual-porosity



Nature, 2021



BlueMat: Water-Driven Materials

Outline

多重成像与流体注入法

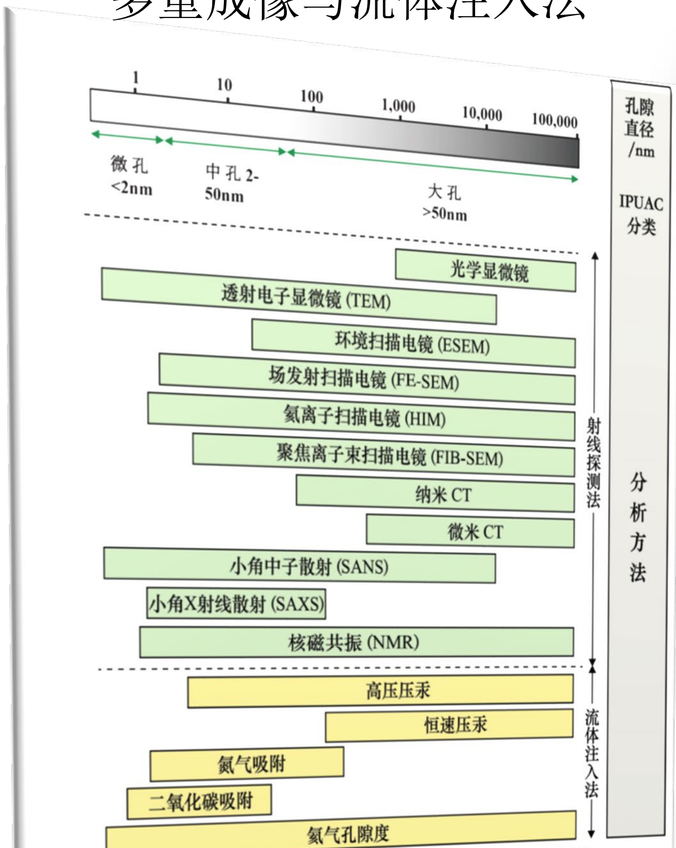


图 1-1 泥页岩储集空间表征实验分类及适用范围

01 多尺度渗流力学团队

02 研究背景与科学问题

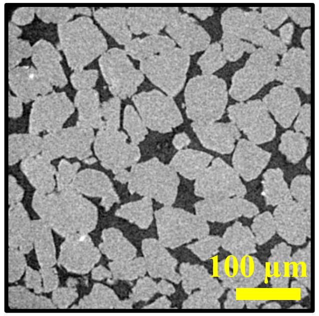
03 **多尺度孔隙结构精细表征**

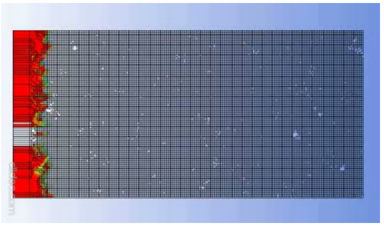
04 数字岩心渗流模拟技术

05 结论与展望

Digital Core Analysis (DCA)

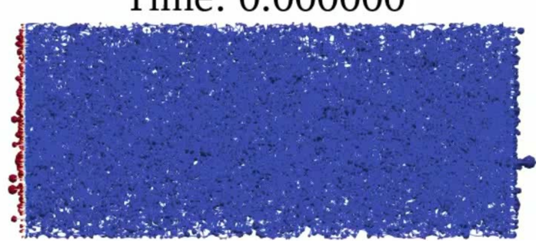
Nubian sandstone





VOF modeling of water imbibition, 100×100×200 image

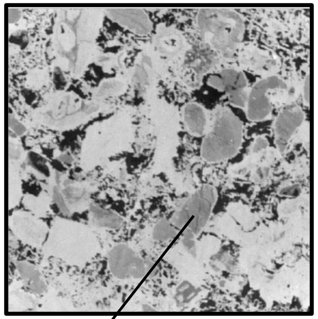
(*Qin et al., AWR, 2021*)



900×900 ×2000 image

Dynamic pore-network modeling of cocurrent spontaneous imbibition

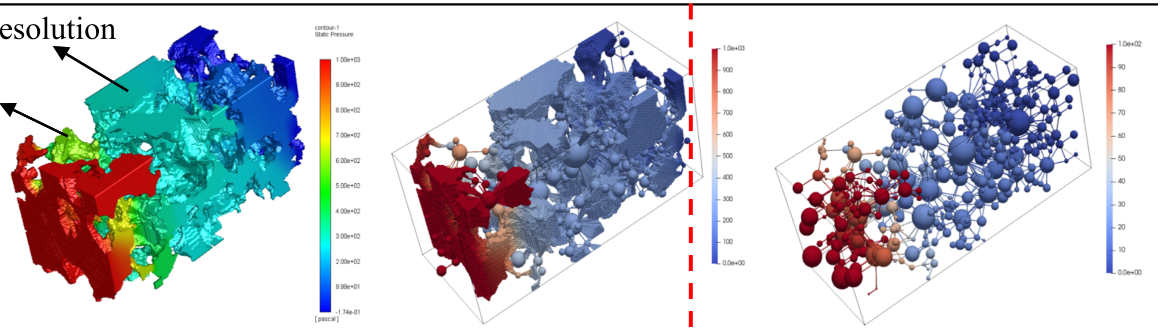
Estaillades carbonate



Subresolution microporosity

subresolution

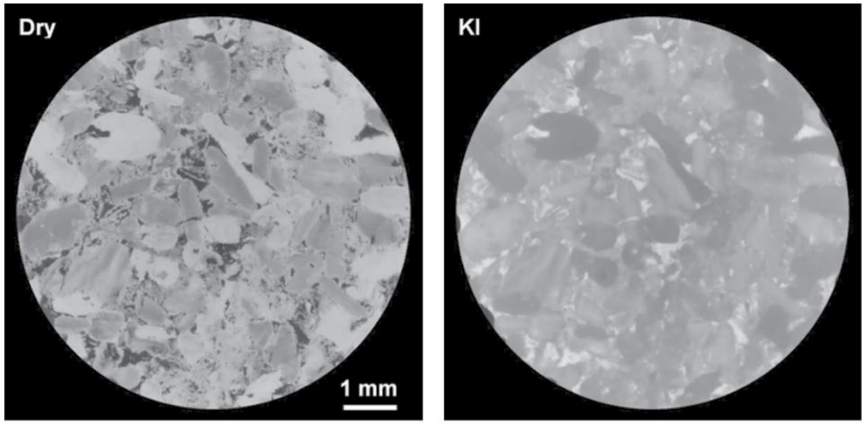
Macropore



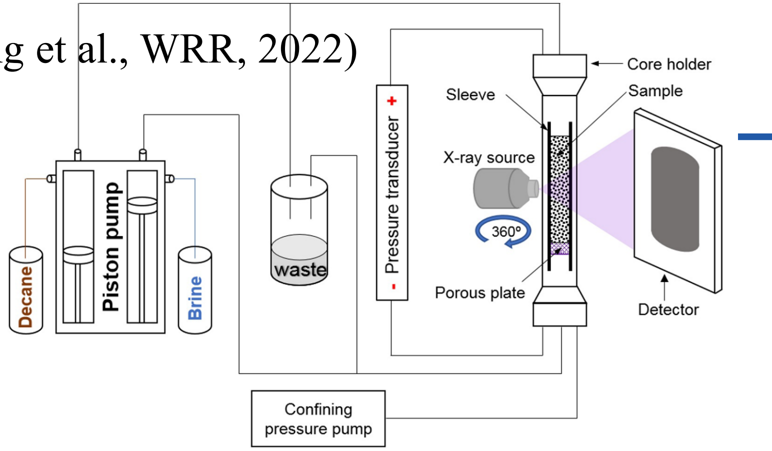
DNS	Hybrid model	Dual PNM
304 mD	295 mD	340 mD

碳酸盐岩：多尺度孔隙结构

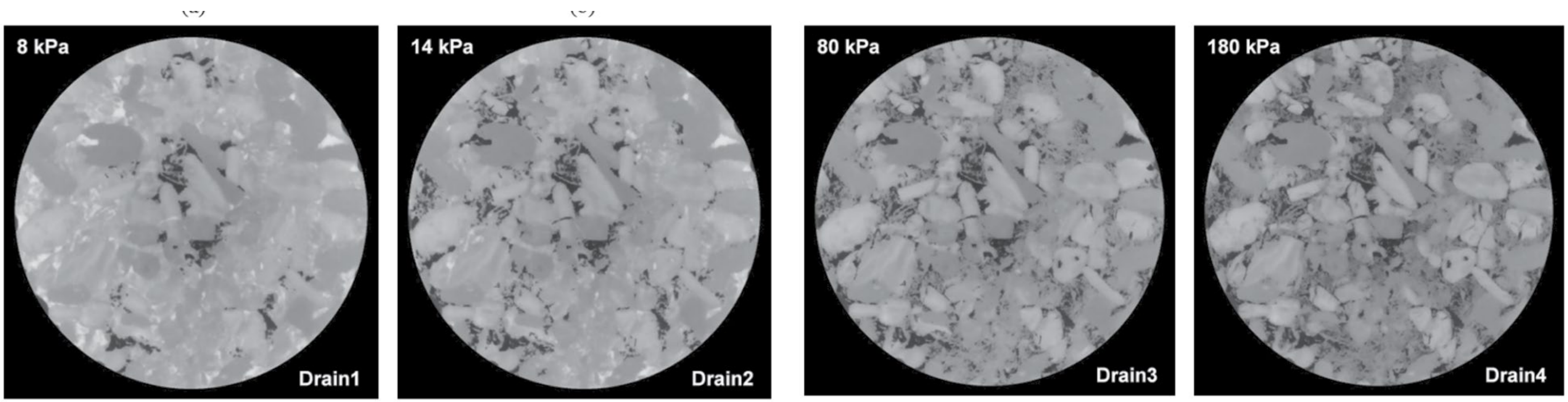
(Wang et al., WRR, 2022)



有效孔隙度分布



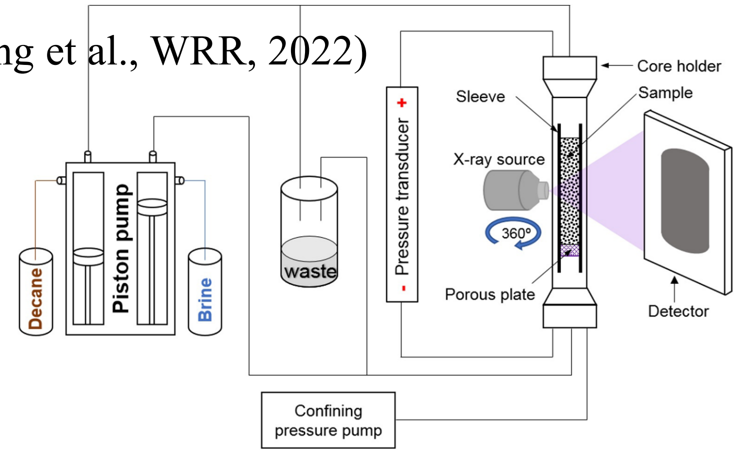
原位CT扫描



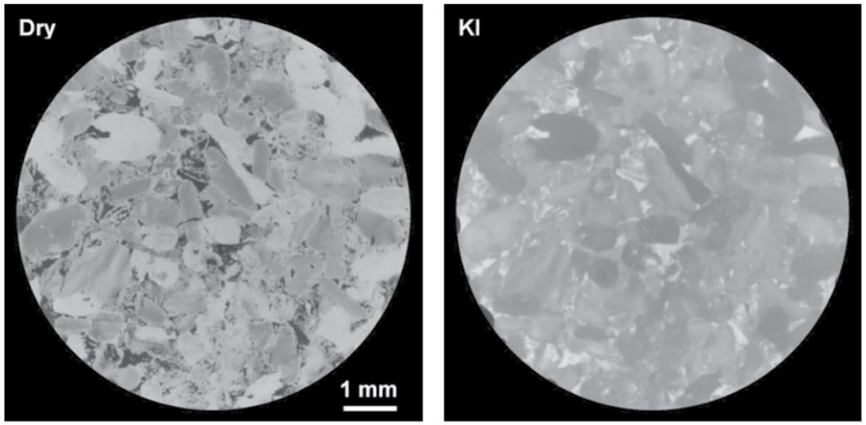
连续用油准静态驱替饱和盐水

碳酸盐岩：多尺度孔隙结构

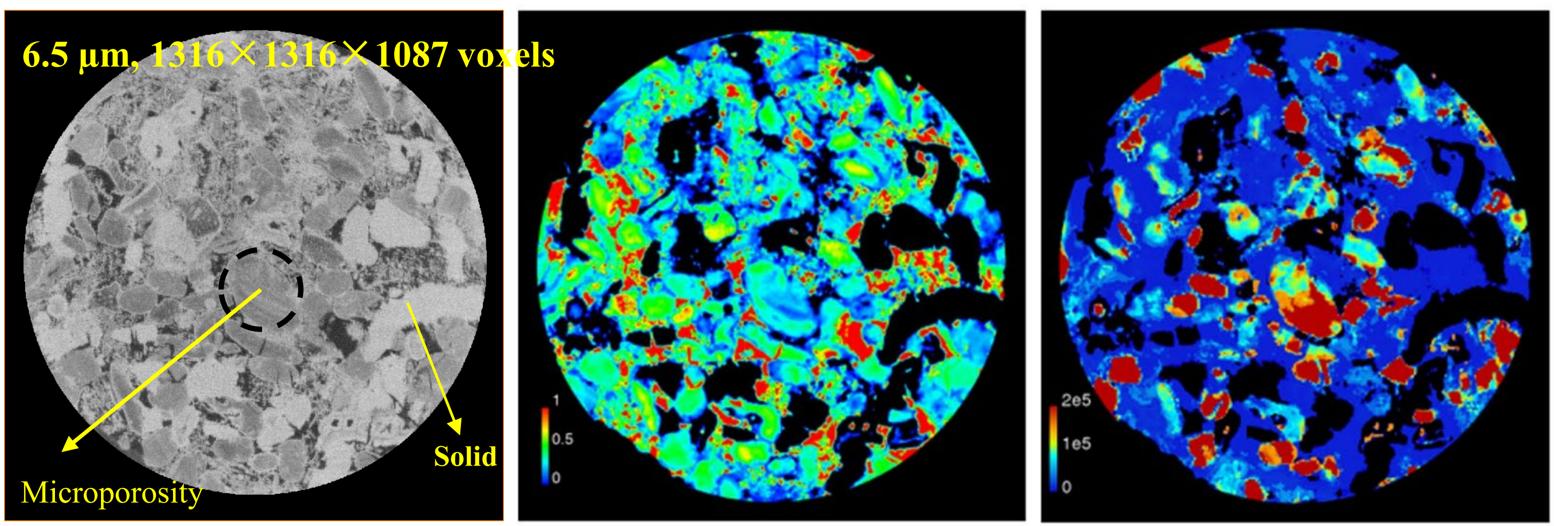
(Wang et al., WRR, 2022)



原位CT扫描



有效孔隙度分布



CT grey-scale map

Porosity map

Entry pressure map

1. 孔隙度与孔径不相关

2. 有一定的相关长度

碳酸盐岩：高压压汞曲线

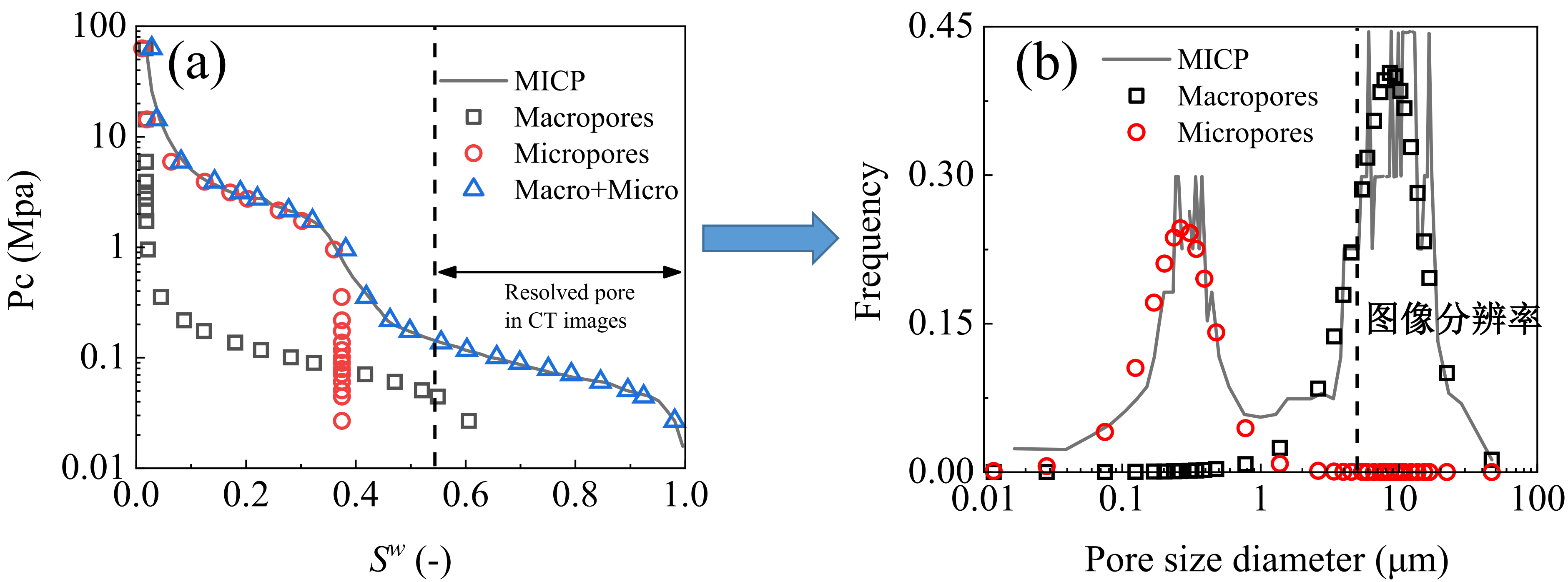
(Adv. Water Resour. Submitted, 2025)

原位CT精细表征亚分辨率孔隙：

- ❑ 3D孔渗参数的完备表征，精确度高
- ❑ 耗时、成本高、不适用于页岩等

Bimodal van Genuchten model (Durner, 1994)

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



利用bimodal VG模型定义大孔与微孔，注意亚分辨区域包括不可分辨的大孔和微孔

碳酸盐岩：高压压汞曲线

(Adv. Water Resour. Submitted, 2025)

原位CT精细表征亚分辨率孔隙：

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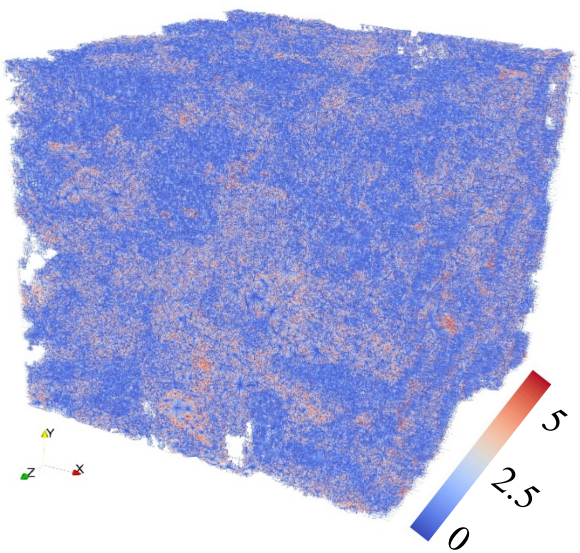
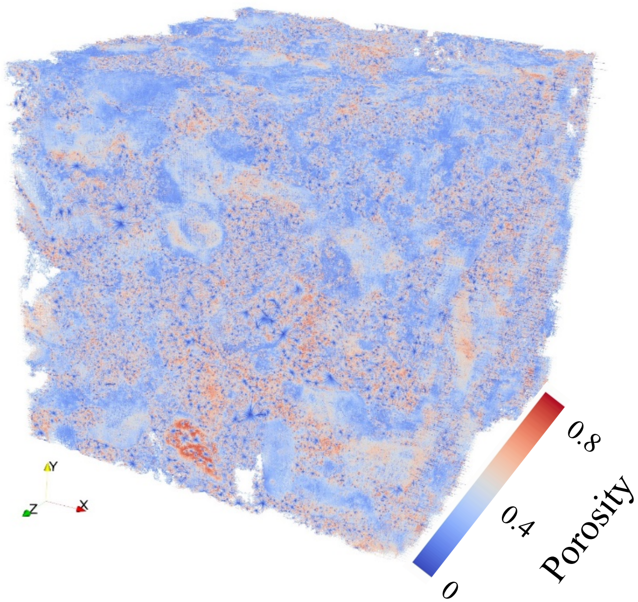


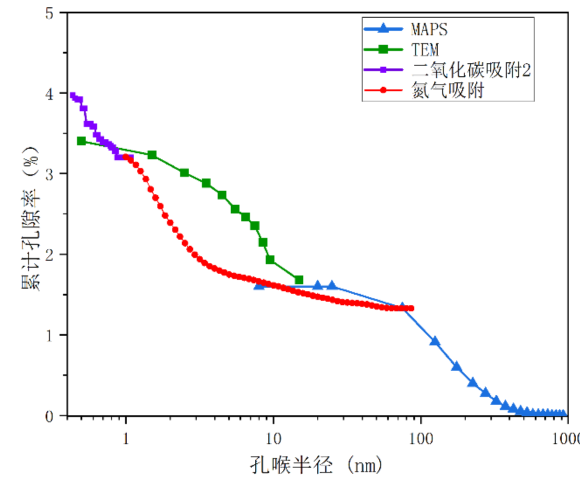
Entry-pressure radius (μm)



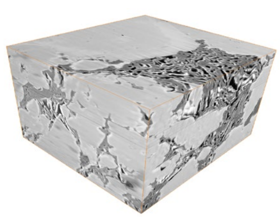
不可分辨大孔的孔径随意赋予高孔隙度体素，微孔的孔径随意赋予其他体素

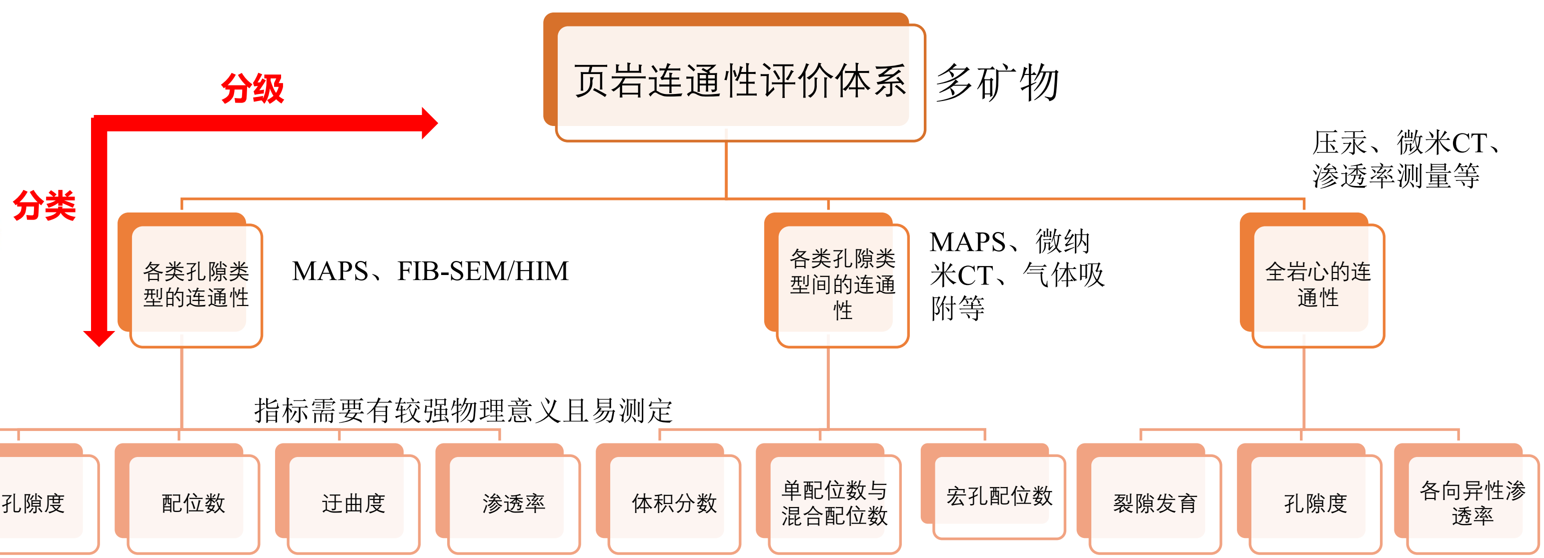
多尺度孔隙结构精细表征：小结

1. 原位CT驱替实验的表征精度高，但是耗时、成本高、适用范围受限
2. 利用孔径分布数据表征，具有随机性，需要考虑孔渗参数的相关长度
3. 发展多源信息融合技术，精细表征页岩等孔隙结构跨度大的多孔介质



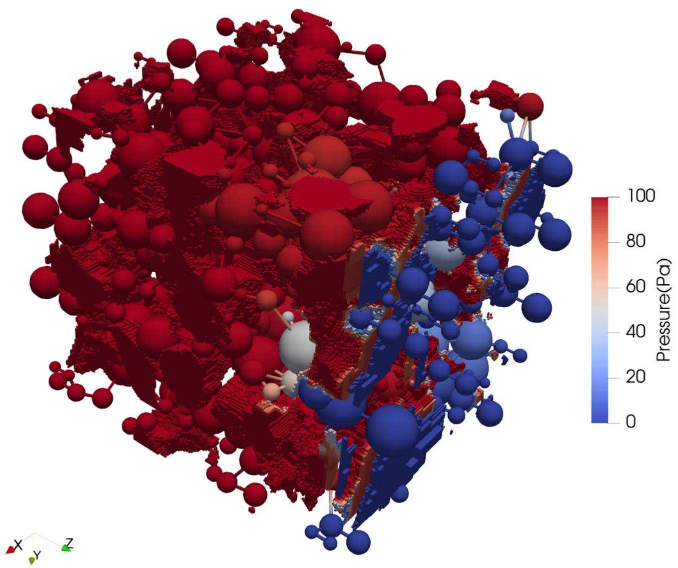
多源数据



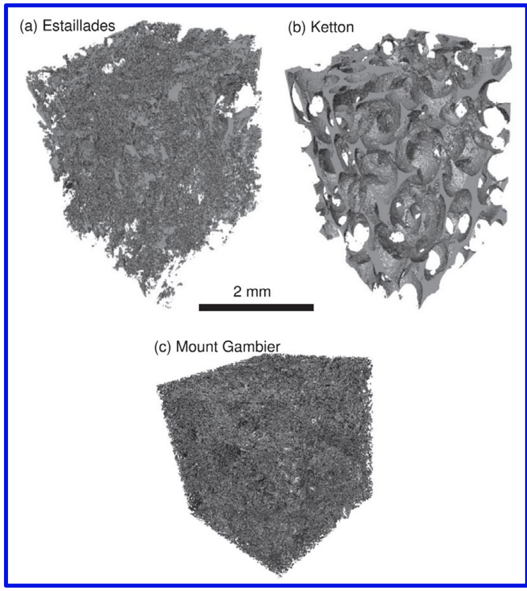


Outline

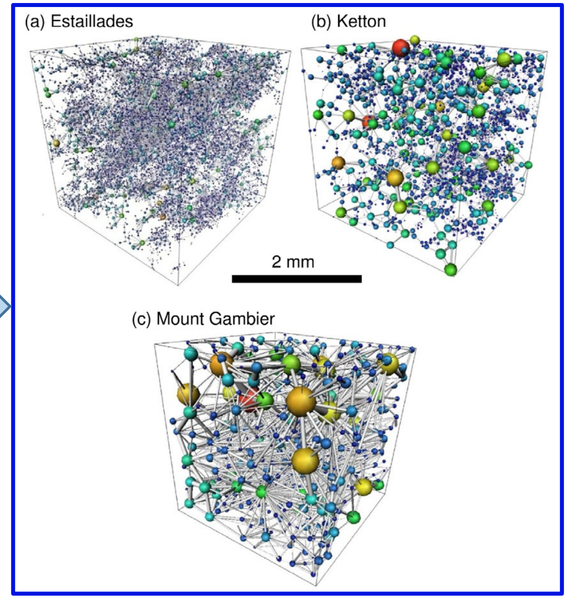
泄压过程



孔隙网络模型（The Pore-Network Modeling）

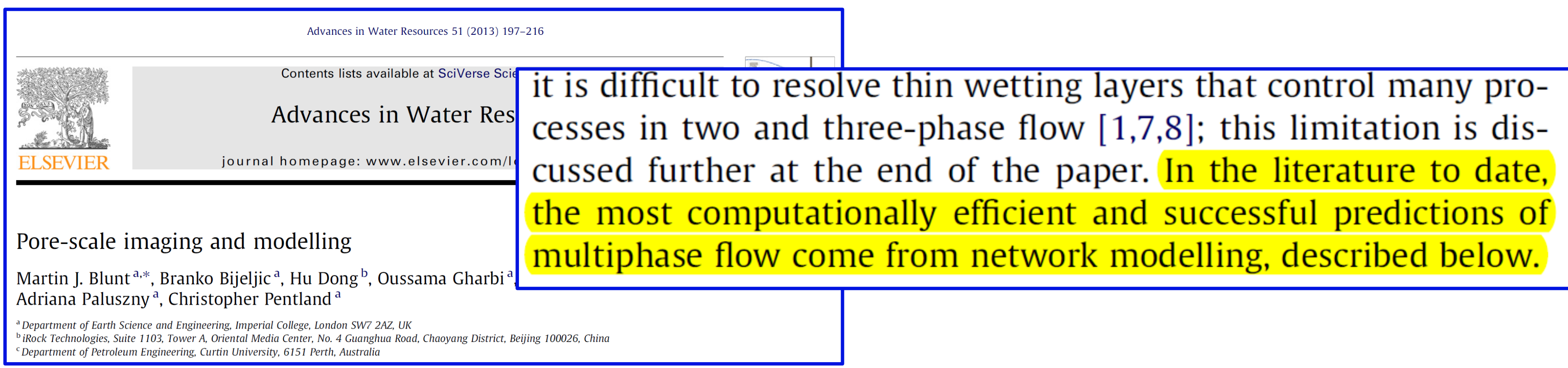


孔隙网络提取



流动与传输：

- ❑ 准静态两相驱替、渗吸
- ❑ 动态两相驱替、渗吸
- ❑ 反应流动与传输
- ❑ 非牛顿流体流动
- ❑ 矿物质溶解、沉淀
- ❑ 。。。。。。


Advances in Water Resources 51 (2013) 197–216

Contents lists available at SciVerse Scie

Advances in Water Res

journal homepage: www.elsevier.com/l

ELSEVIER

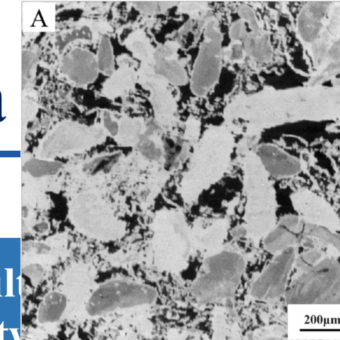
Pore-scale imaging and modelling

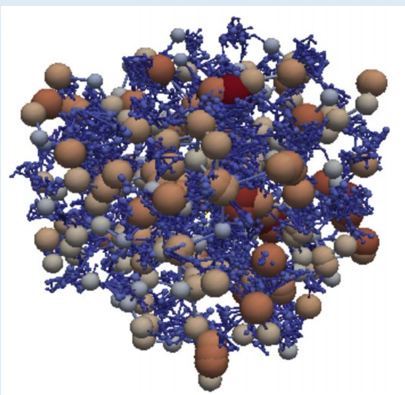
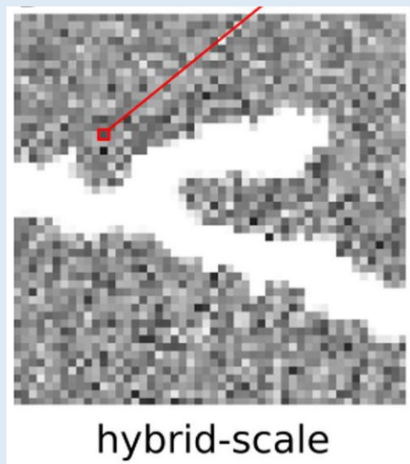
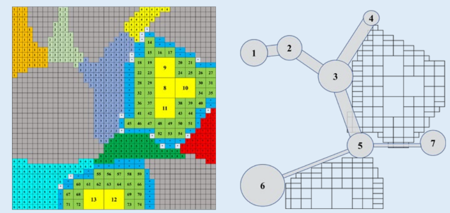
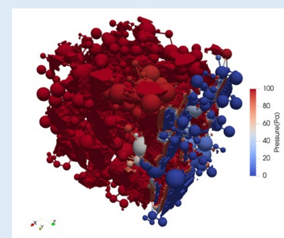
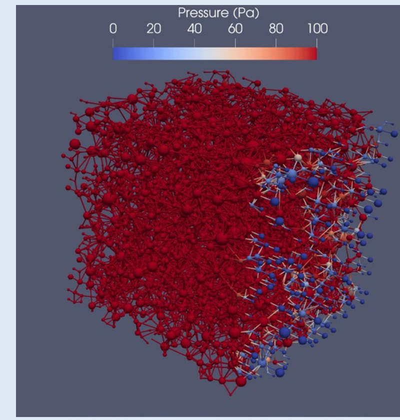
Martin J. Blunt [a,*], Branko Bijeljic [a], Hu Dong [b], Oussama Gharbi [a], Adriana Paluszny [a], Christopher Pentland [a]

[a] Department of Earth Science and Engineering, Imperial College, London SW7 2AZ, UK
[b] iRock Technologies, Suite 1103, Tower A, Oriental Media Center, No. 4 Guanghua Road, Chaoyang District, Beijing 100026, China
[c] Department of Petroleum Engineering, Curtin University, 6151 Perth, Australia

it is difficult to resolve thin wetting layers that control many processes in two and three-phase flow [1,7,8]; this limitation is discussed further at the end of the paper. In the literature to date, the most computationally efficient and successful predictions of multiphase flow come from network modelling, described below.

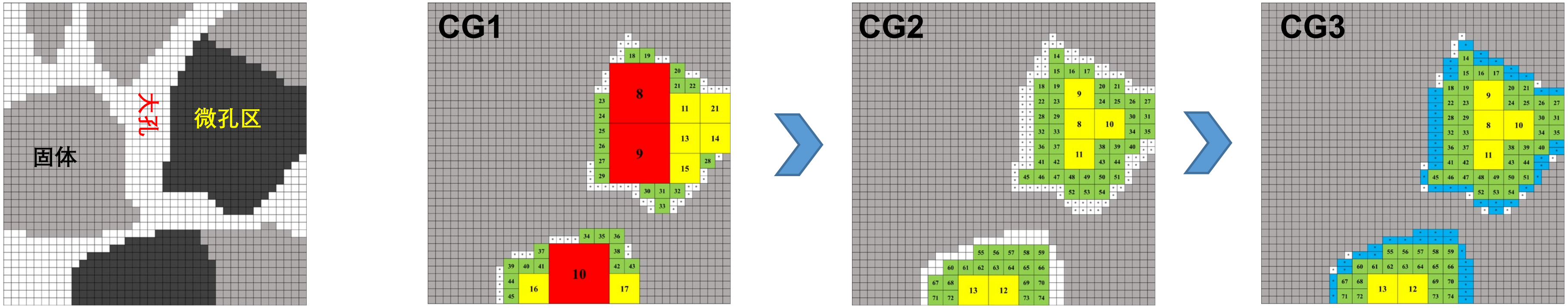
Numerical models for multiscale porous media

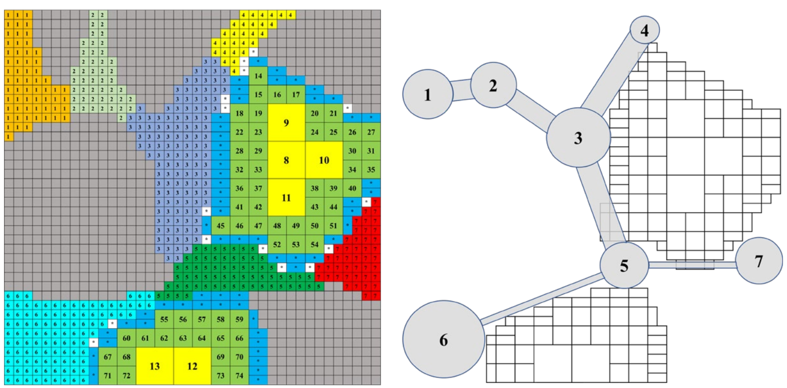


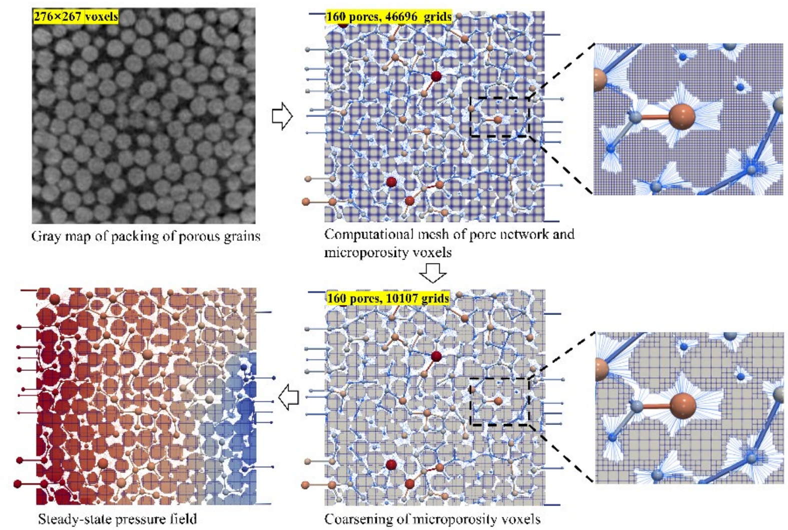
Dual-pore-network model (DPNM)	Micro-continuum model (MCM)	Pore-network-continuum model (PNCM)	Mul[illegible] network model (MPNM)
 Mehmani, 2014	 Soulaine, 2023	  Shi, 2024	 Zhao, 2024
定性研究	精度高	兼顾精度与效率	效率高

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

孔隙网络-连续介质模型（Pore-Network-Continuum Model)





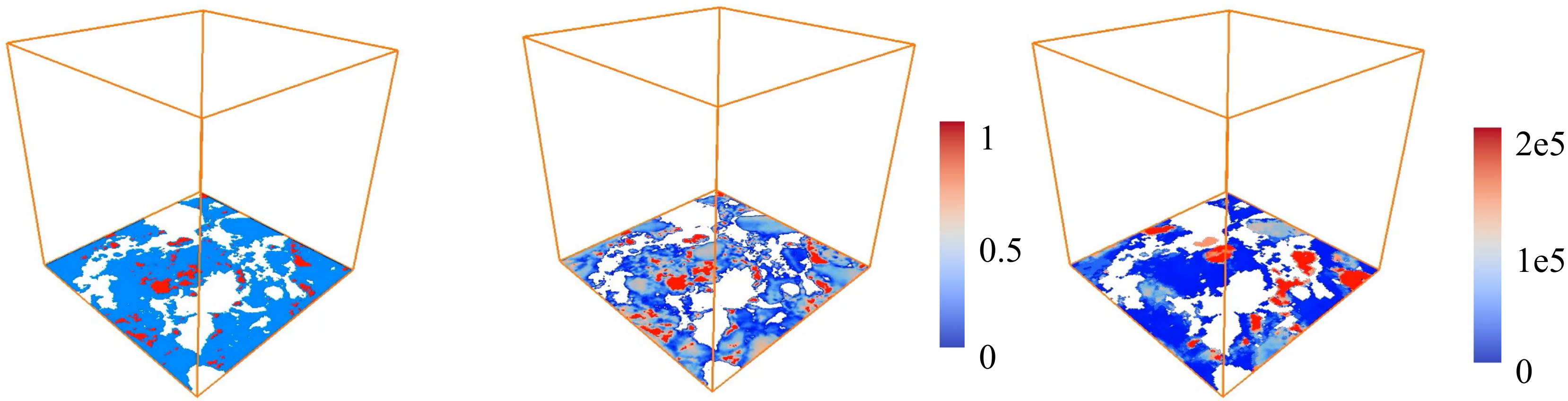


- ❑ **计算效率：** 孔隙网络模型 + 亚分辨率微孔区网格粗化技术
- ❑ **微孔区非均质性：** 高空间分辨率网格（主要的计算量）

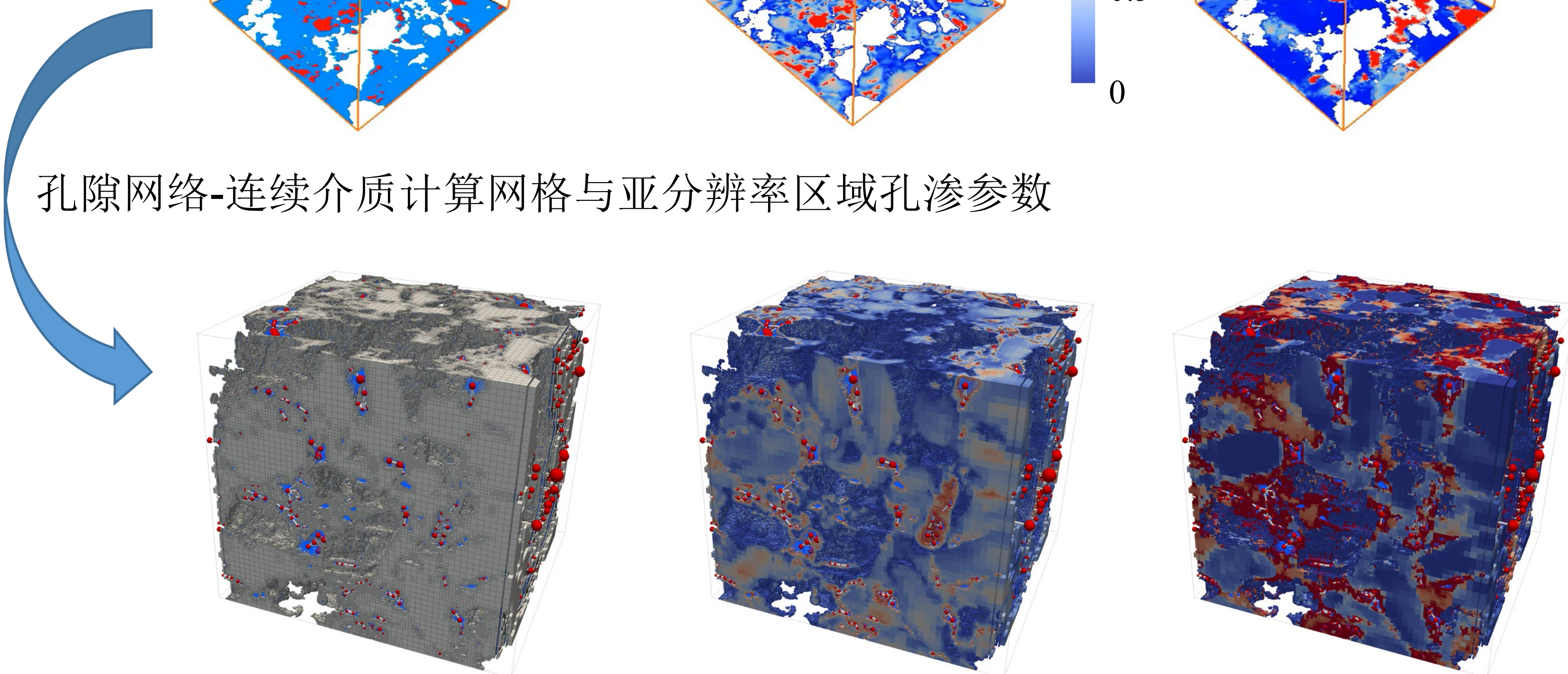
Estaillades碳酸盐岩：绝对渗透率预测

https://www.digitalrocksportal.org/

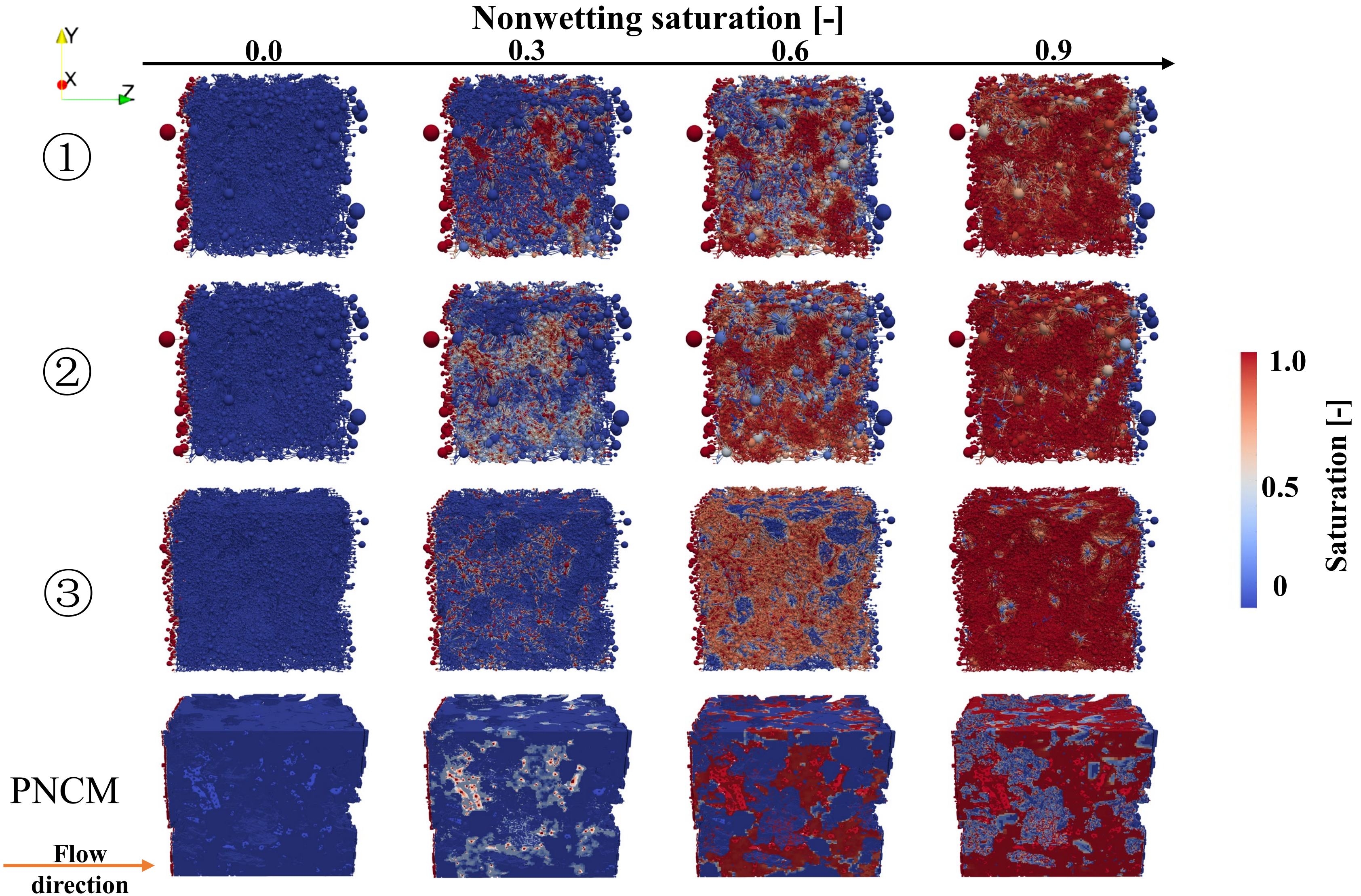
400^3的测试岩心



孔隙网络-连续介质计算网格与亚分辨率区域孔渗参数

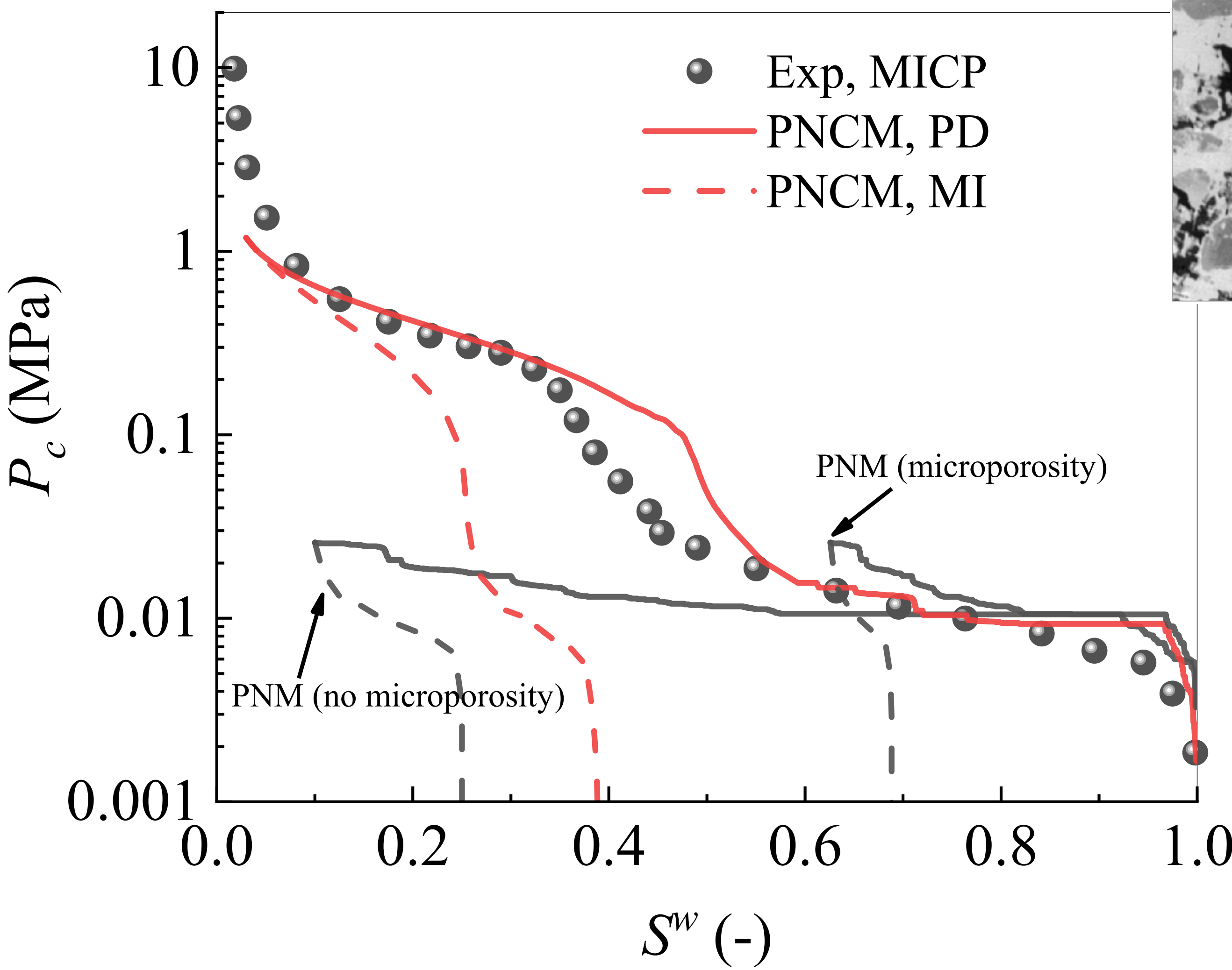


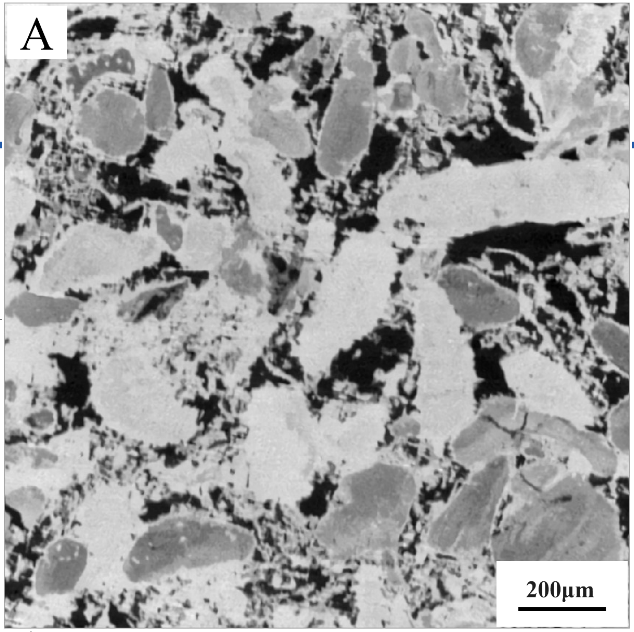
准静态两相渗流模拟：驱替与渗吸



准静态两相渗流模拟：毛管力曲线

基于MICP表征亚分辨率微孔区孔渗参数

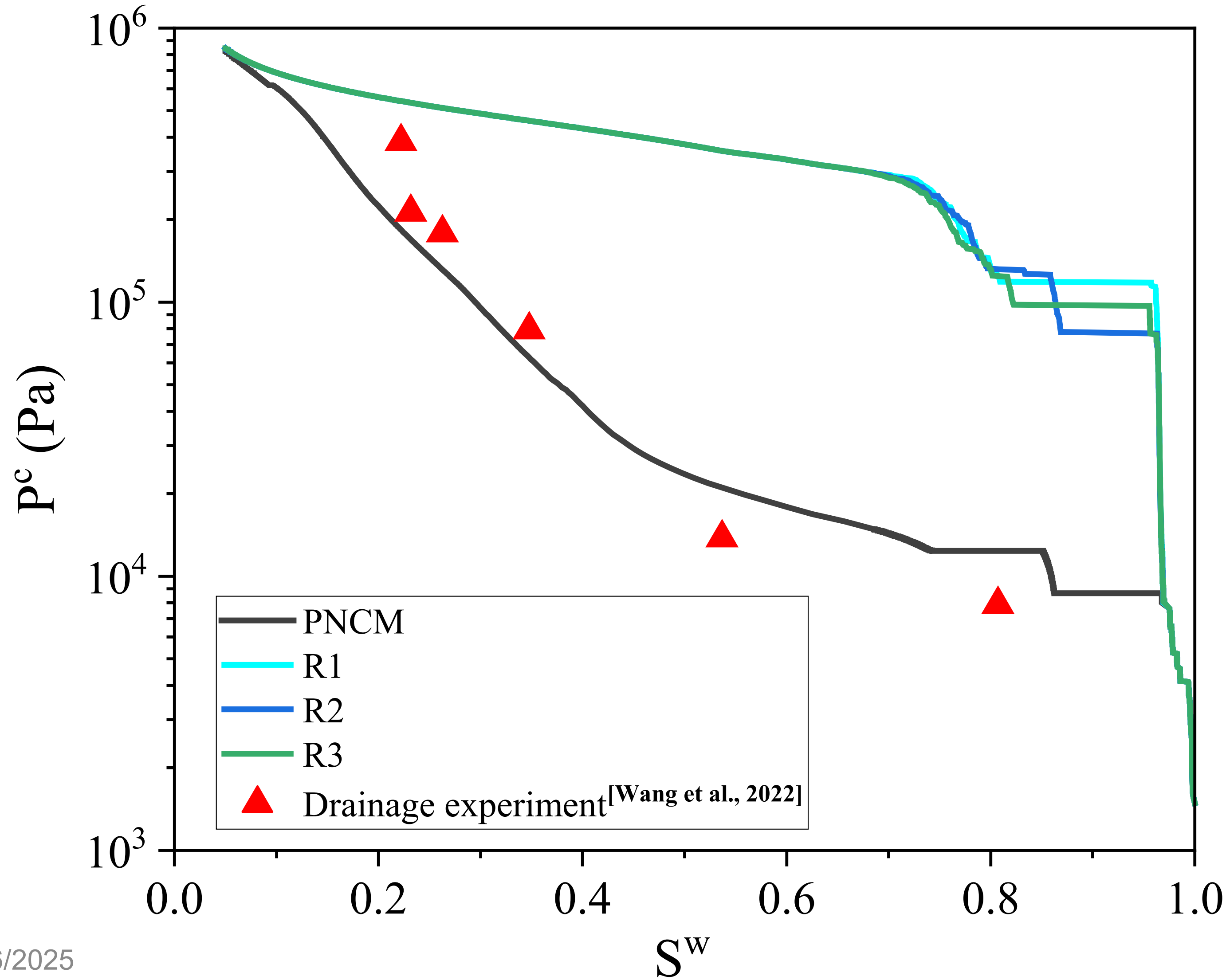




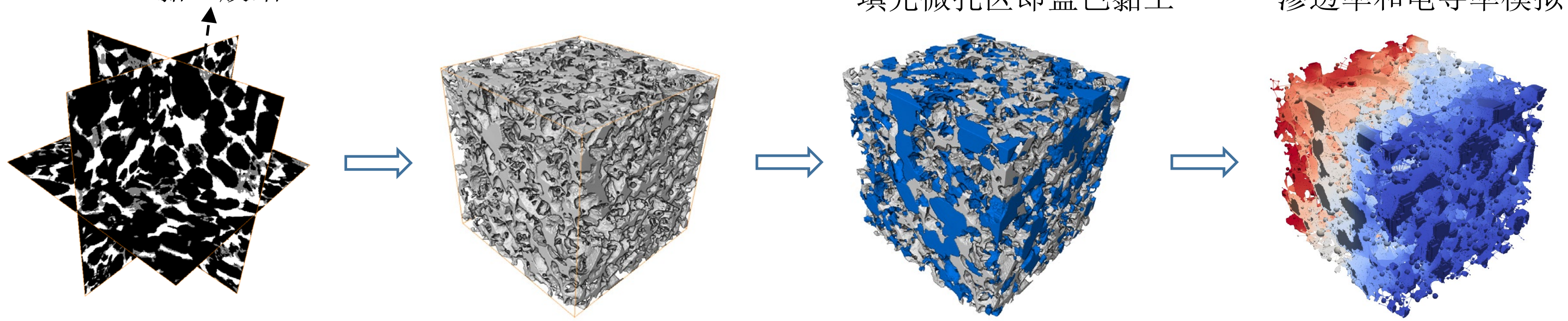
非润湿相先挤入连通的大孔，然后挤入介于大孔与微孔间的过渡孔隙及被连通的大孔，最后挤入孔径较小的微孔孔隙。

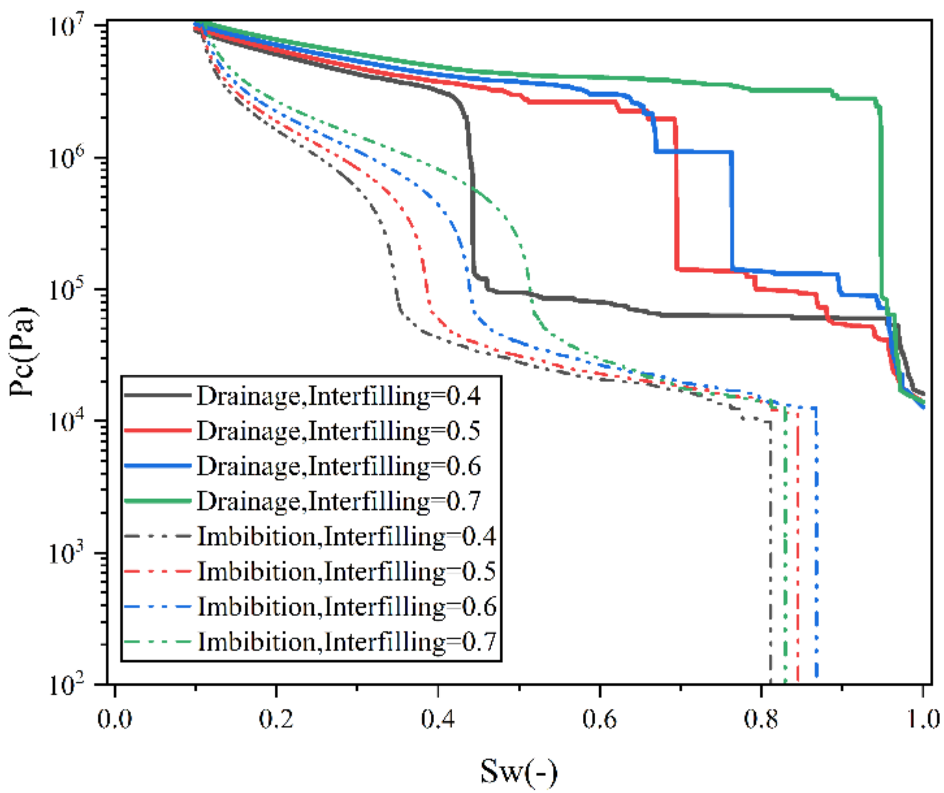
准静态两相渗流模拟：毛管力曲线

基于原位CT驱替实验表征亚分辨率微孔区孔渗参数



准静态两相渗流模拟：毛管力曲线

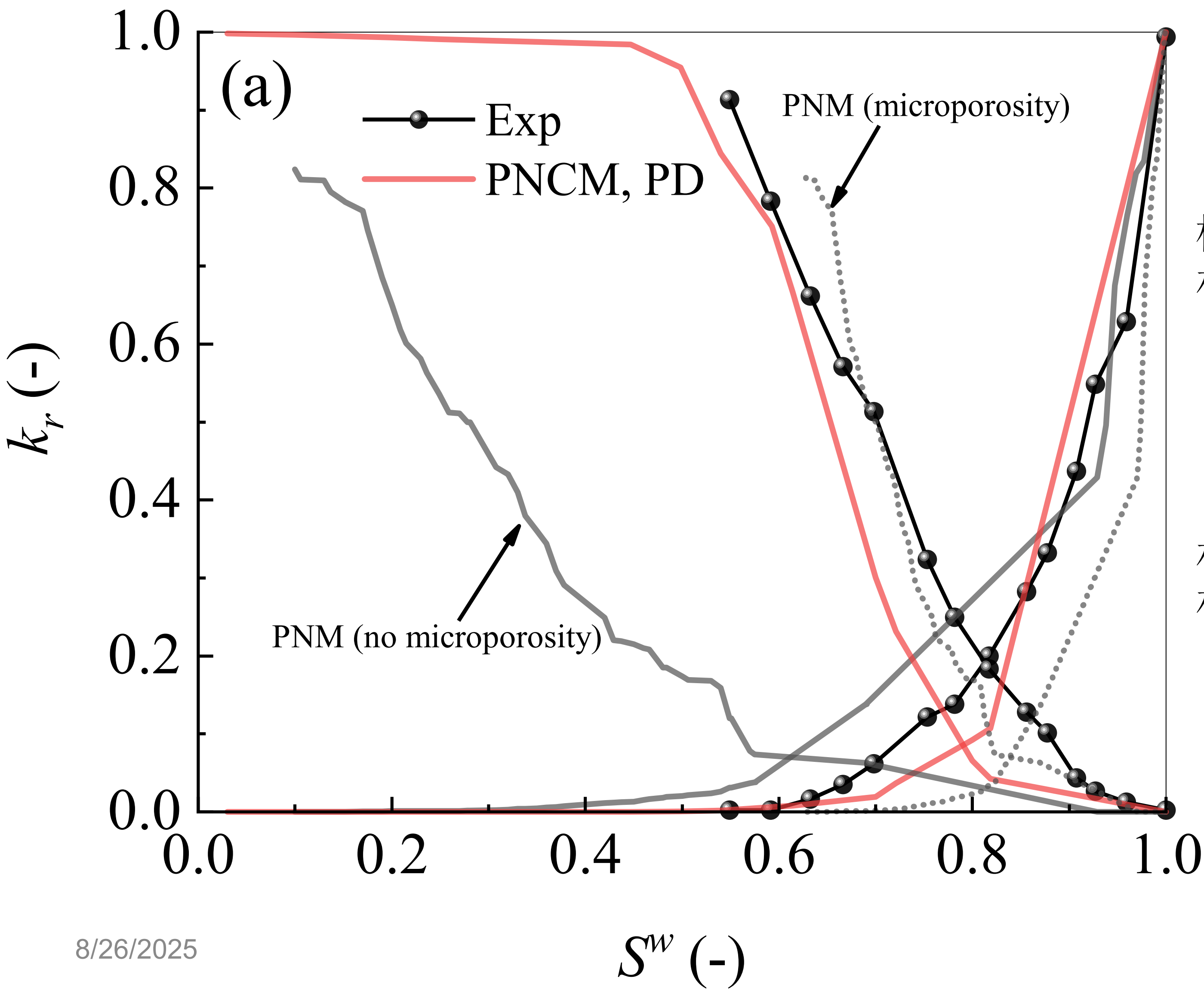




1. 随着粘土填充量增大，大孔从连通到孤立，<u>微孔区主控毛管力</u>，曲线逐渐上抬；
2. 台阶状曲线是由于大孔填充，且大孔与微孔<u>孔径分离</u>显著

准静态两相渗流模拟：相渗曲线、非饱和电阻率曲线

基于MICP表征亚分辨率微孔区孔渗参数

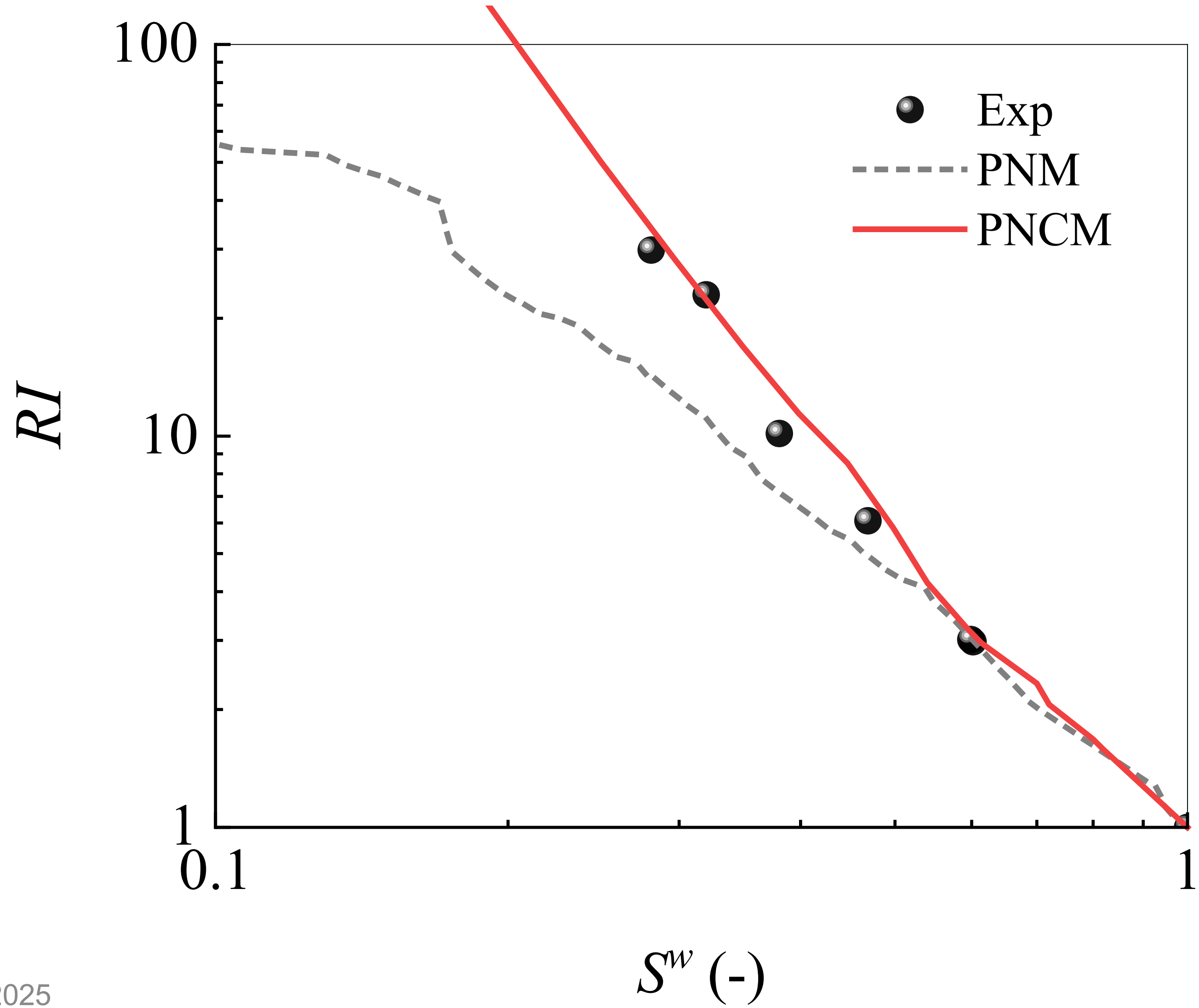


模型可以较好地预测相渗曲线

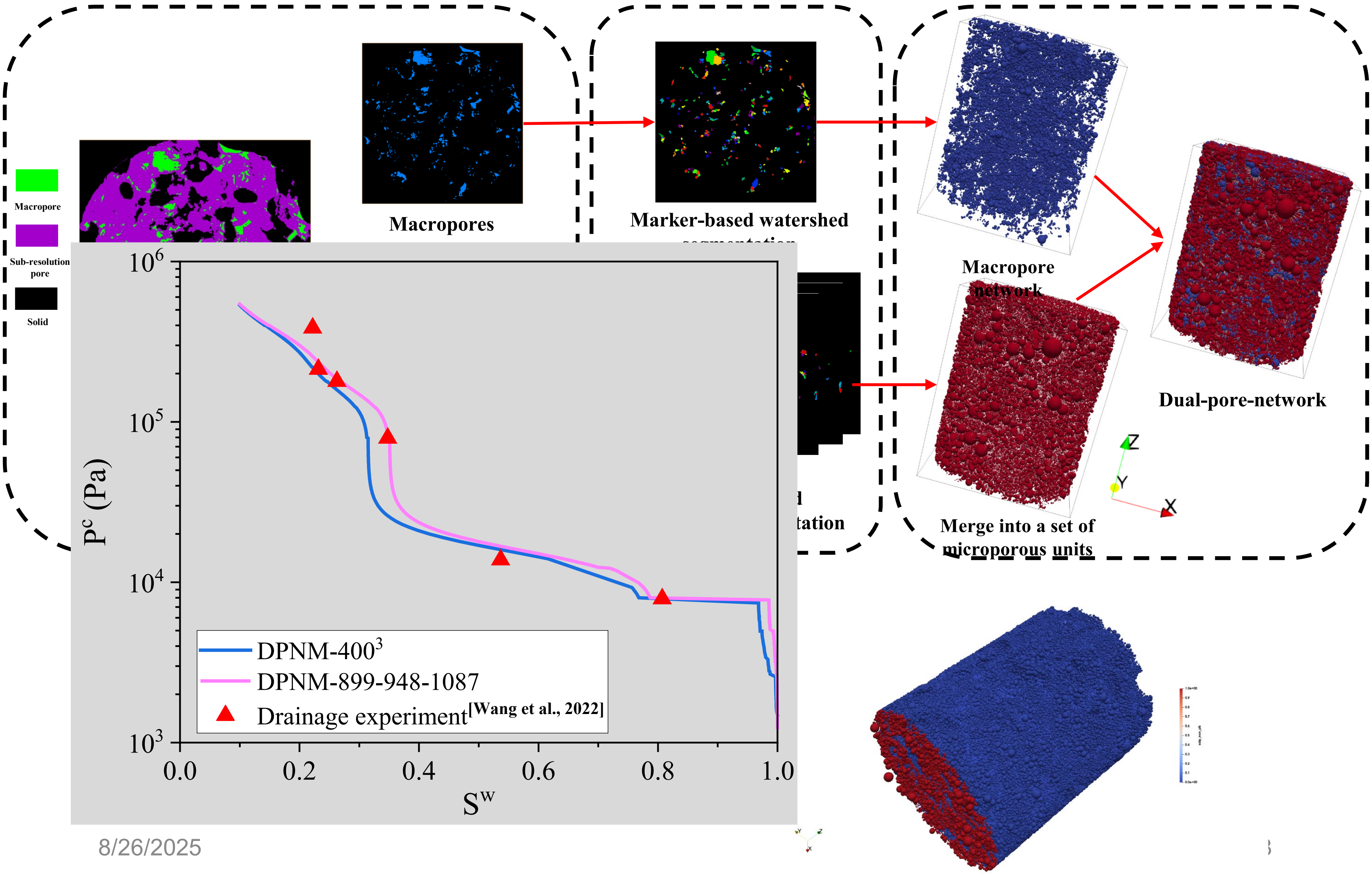
相比均质孔隙结构，相渗曲线右移

准静态两相渗流模拟：相渗曲线、非饱和电阻率曲线

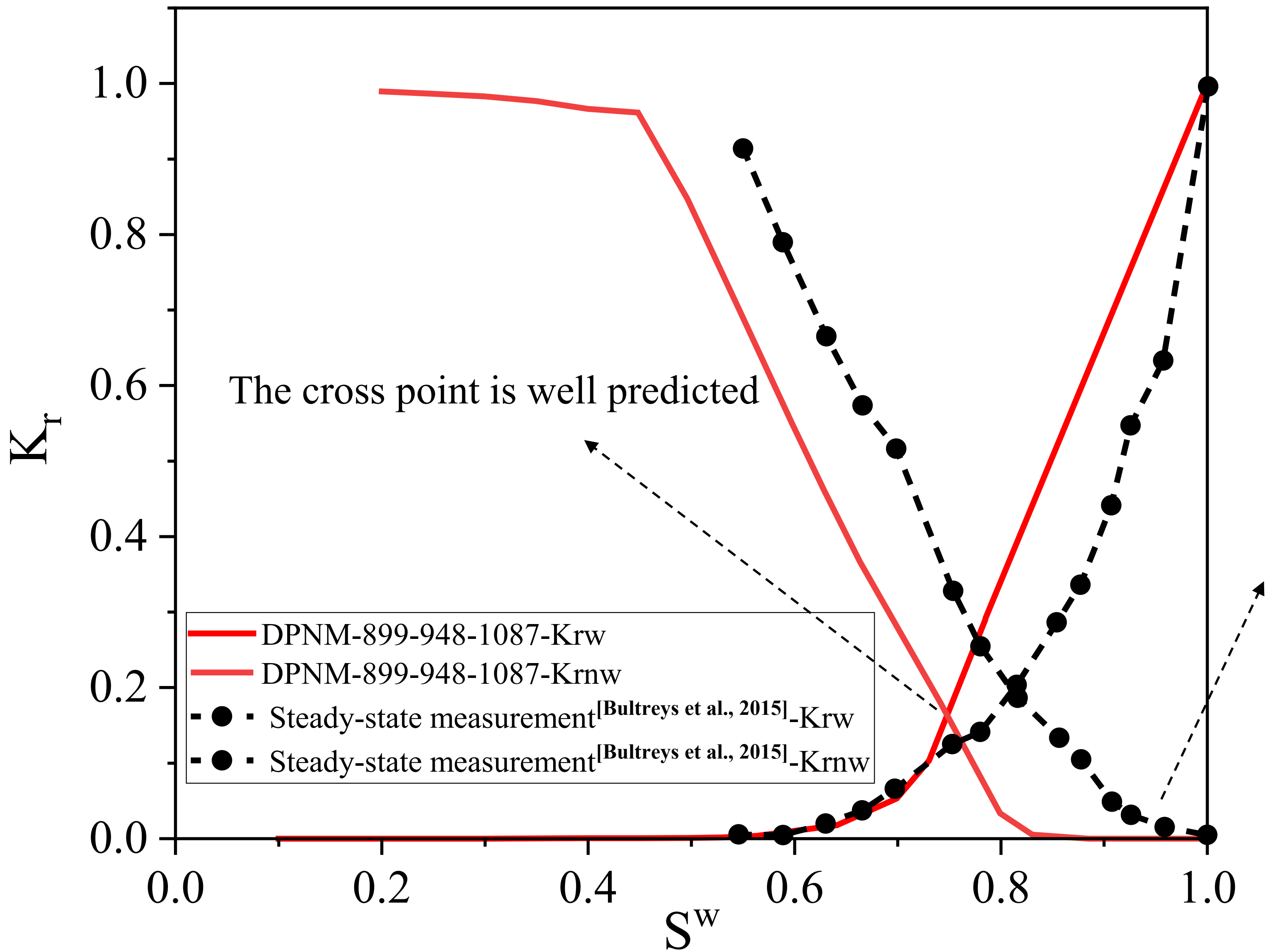
基于MICP表征亚分辨率微孔区孔渗参数



全岩心相渗曲线模拟（多尺度孔隙网络模型）

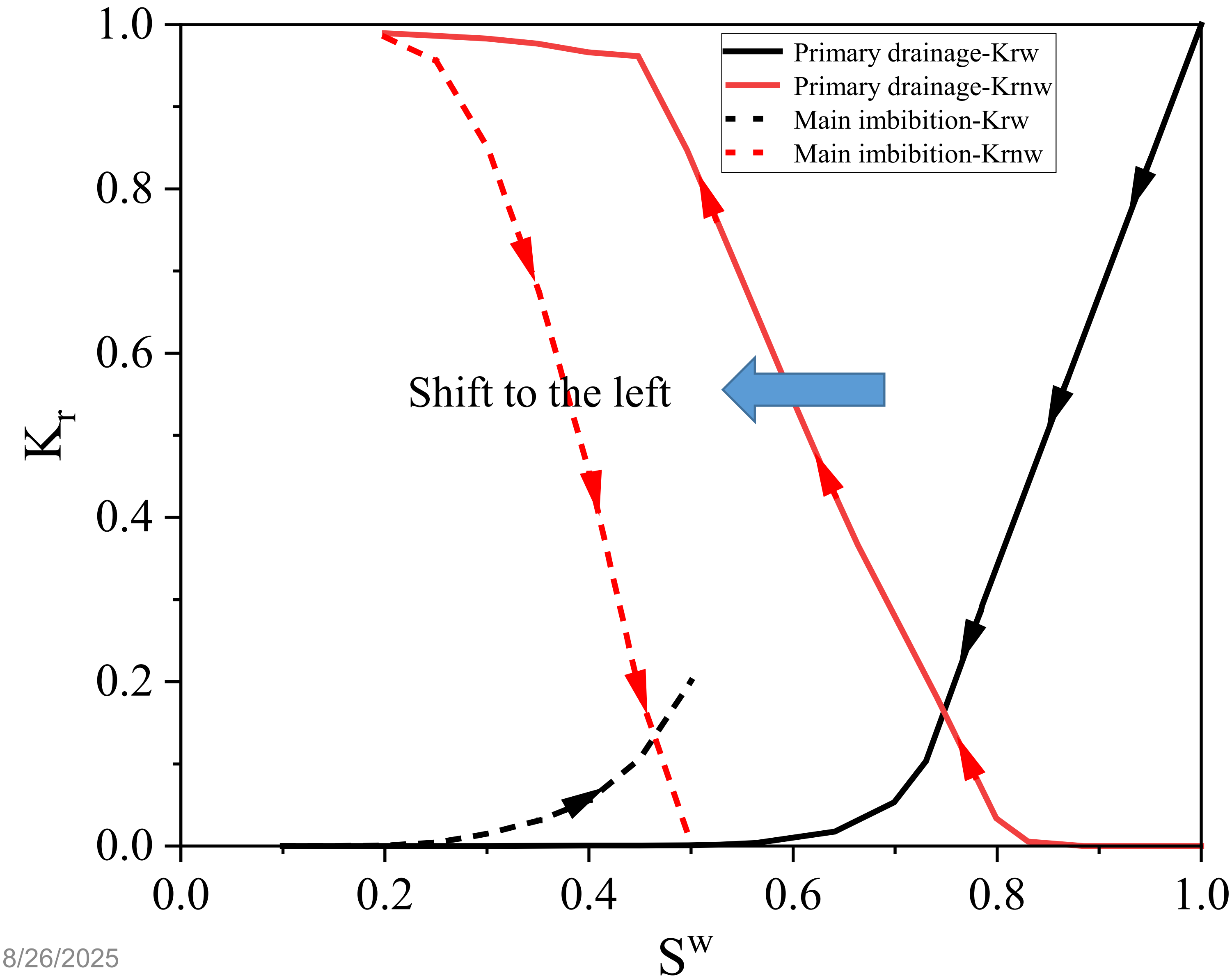


Relative permeability (full-size ES6.5)



Early flow pathways of the nonwetting

Relative permeability (full-size ES6.5)



Outline

Conclusions and outlook

Conclusions

- Porous media and flow and transport therein play an important role in energy transition-related applications.
- We present the state-of-the-art characterization of multiscale pore structures.
- We develop two hybrid numerical models for flow and transport in multiscale pore structures, i.e., the multiscale pore-network model and pore-network-continuum model.
- We can well predict single-phase and two-phase flow properties including absolute permeability, formation factor, capillary pressure and relative permeability.

Outlook

- Advance the modeling framework to two-phase flow dynamics.
- Understand how multiscale pore structures influence material properties, and extend capillary pressure and relative permeability empirical models.
- Seek more applications involving multiscale pore structures.

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1. X. Zhao, B. Shi, X. Wang, J. Zhao, F. Jiang, C.Z. Qin. 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. B. Shi, H. Jiang, B. Guo, J. Tian, and C.Z. Qin. Modeling of flow and transport in multiscale digital rocks aided by grid coarsening of microporous domains. ***Journal of Hydrology***, 633: 131003, 2024.

3. C.Z. Qin, H. van Brummelen, M. Hefny, and J. Zhao. Image-based modeling of spontaneous imbibition in porous media by a dynamic pore network model. ***Advances in Water Resources**,* 152: 103932, 2021.

4. L. Zhang, B. Guo, C.Z, Qin, Y. Xiong. A hybrid pore-network-continuum modeling framework for flow and transport in 3D digital images of porous media. ***Advances in Water Resources***, 190: 104753, 2024.

5. H. Jiang, C. Arns, Y. Yuan, C.Z. Qin. SVM-based fast 3D pore-scale rock-typing and permeability upscaling for complex rocks using Minkowski functionals. ***Advances in Water Resources***, 183: 104605, 2024.

6. C.Z. Qin, X. Wang, M. Hefny, J. Zhao, S. Chen, and B. Guo. Wetting dynamics of spontaneous imbibition in porous media: from pore scale to Darcy scale. ***Geophysical Research Letters***, 49, e2021GL097269.

Thank you for your attention!

页岩：高压压汞曲线、气体吸附、多重成像