Gas Flow Simulation in Multiscale and Multimineral Digital Rocks of Shale Samples

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Outlines

1. Motivation
2. Modeling methods
   - 2.1 Modeling method I: CT-QSGSM
   - 2.2 Modeling method II: QSGSM-QA
   - 2.3 Modeling method III: Template Matching
   - 2.4 Modeling method IV: Object-based modeling
   - 2.5 Modeling method V: Multipoint statistics method
3. Applications
   - 3.1 Pore network modeling of gas flow
   - 3.2 Effects of OM pores on shale properties
4. Conclusions
5. Acknowledgements

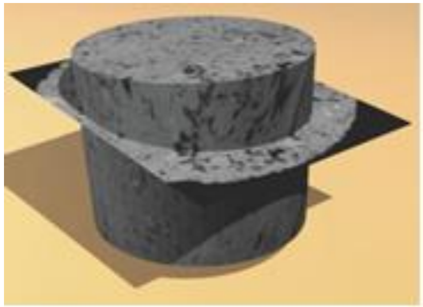
1. Motivation

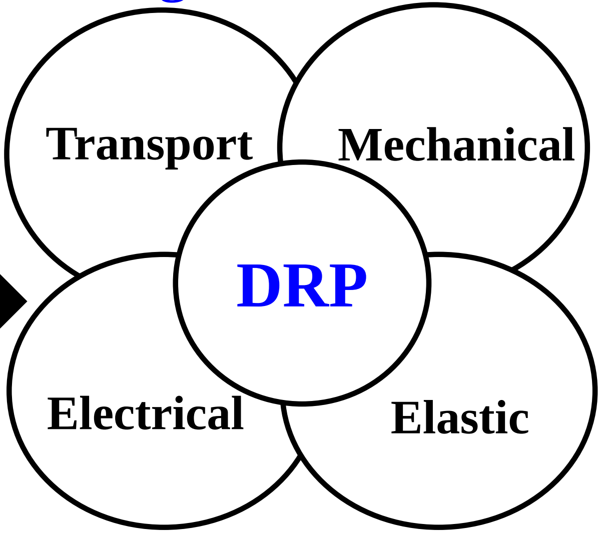
1.1 Digital rock physics (DRP)

Simulate the rock properties based on the digital rocks

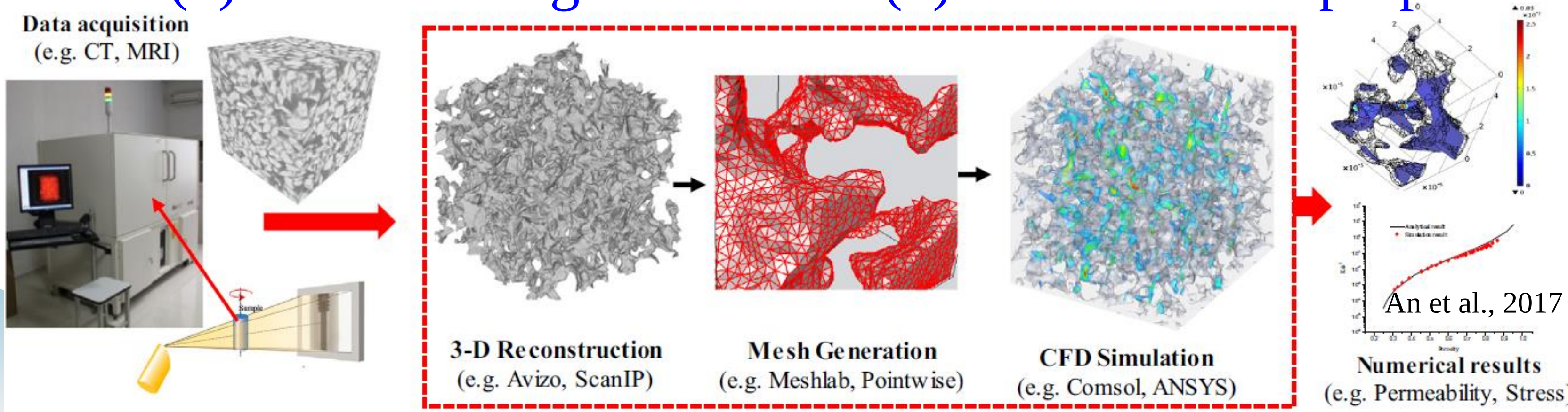
Rock samples

Digital rocks





(1) Construct digital rocks (2) Simulate rock properties



1. Motivation

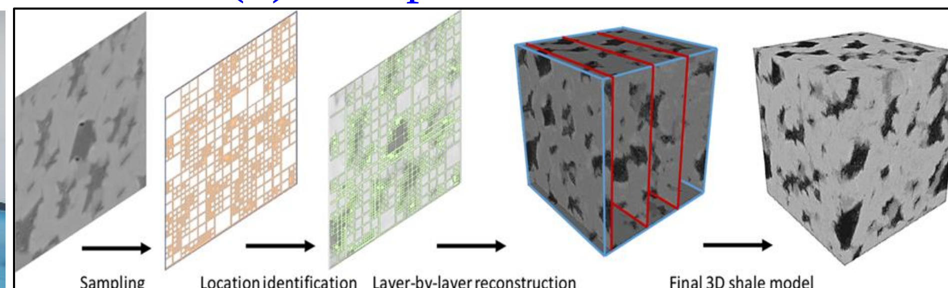
1.2 Construction of digital rocks

Widely-used modeling methods of digital rocks

(1) Experimental Techniques

Construct digital rocks by the imaging machines, e.g., CT/FIB-SEM

(2) Computational Methods



Tahmasebi, et al., 2020

Reconstruct 3D digital cores by using some algorithms based on 2D images

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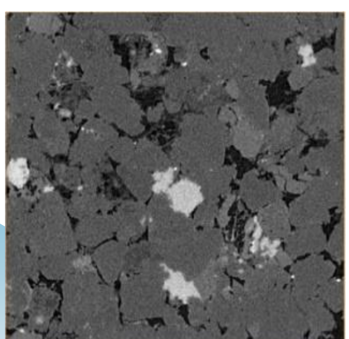
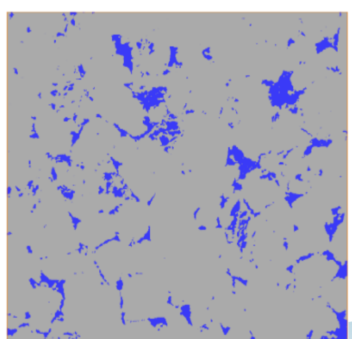
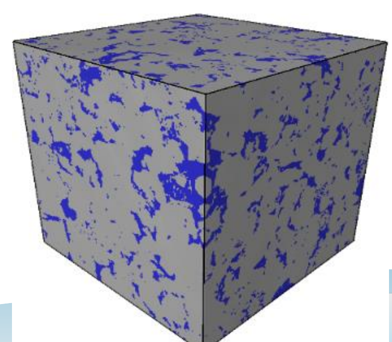
It is difficult to use the conventional methods to construct multimineral digital rocks!



2D CT image



After segmentation



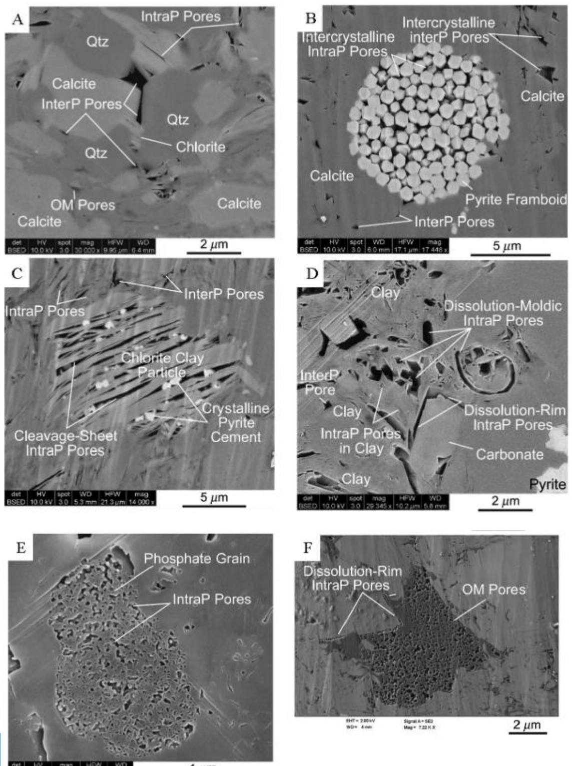
Single-mineral digital rock

Q1: How to construct multimineral digital rocks?

1. Motivation

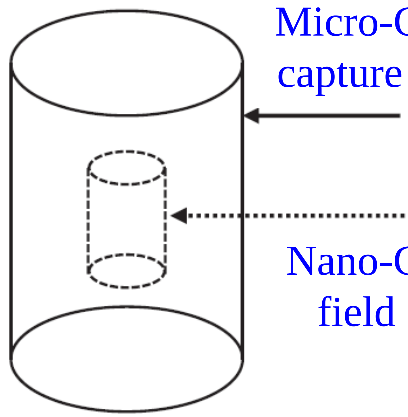
1.2 Construction of digital rocks

Multiscale pore systems: micrometer/nanometer pores



Loucks et al., 2012, *AAPG Bulletin*

Current 3D imaging techniques either cover the large-scale structures at a low resolution or cover a small region at a high resolution

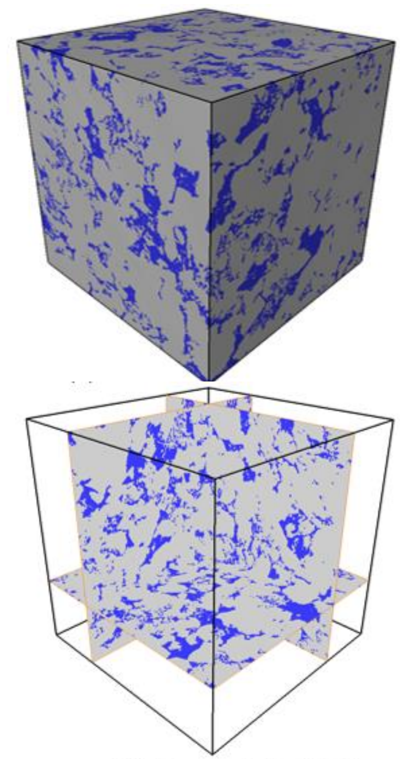


Micro-CT: Cannot capture nanopores

Nano-CT: Small field of view

CT scanning

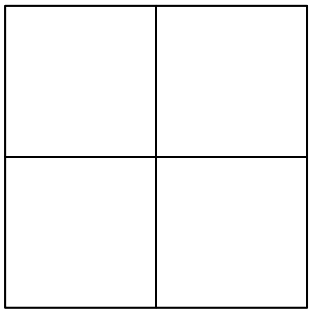
Digital rock constructed by X-ray CT scanning technique (CT)



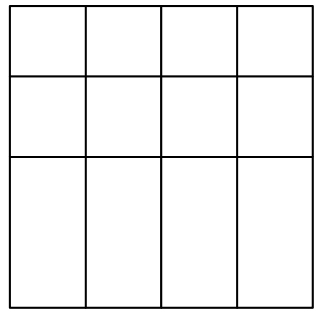
Lose nanopores

Q2: How to construct the digital rocks that contain multiscale pore systems?

2.1 Modeling method I: CT-QSGSM



Increase voxel number



Resolution: 1um/voxel

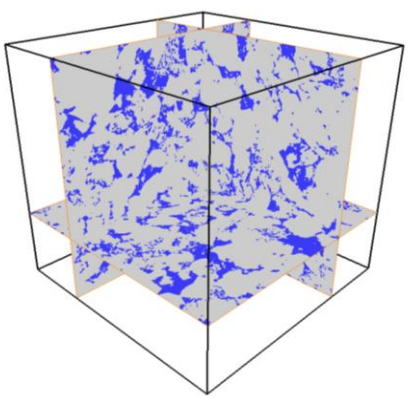
Resolution: 0.5um/voxel

Solution:

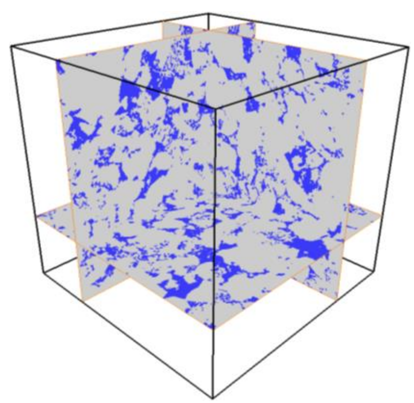
① Digital rocks constructed by Micro-CT

② Increase voxel number and resolution

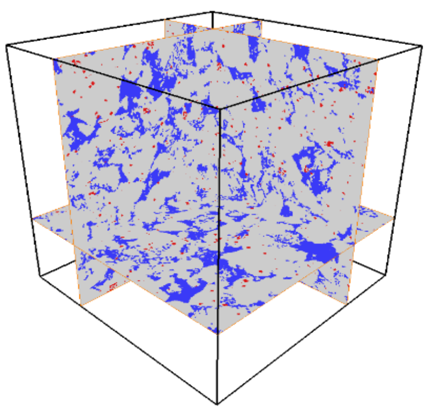
③ Insert nanopores into the digital rock



Increase voxel number



Insert nanopores



Resolution: 1um/voxel

Resolution: 0.5um/voxel

Resolution: 0.5um/voxel

Digital rocks from micro-CT

Digital rocks containing micro- and nano- pores

2. Methods

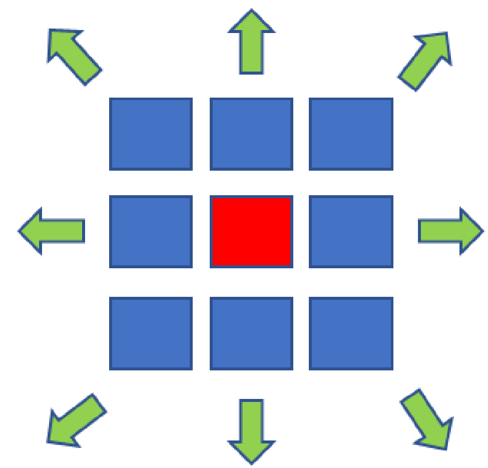
2.1 Modeling method I: CT-QSGSM

Quartet structure generation set method (QSGSM)

① Randomly select some nodes in the solid as the center of nanopores

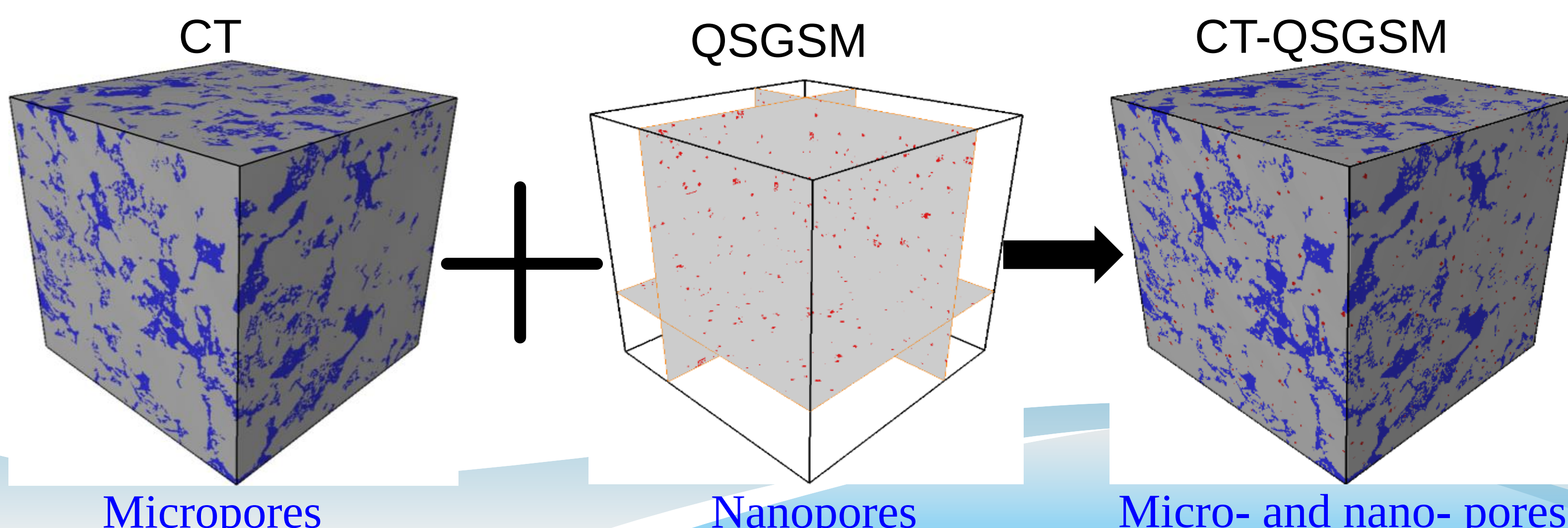
② The seeds grow towards 26 directions under the constraints of a growth probability

③ The growth will stop when the fraction of nanopores reaches the predefined value.



Yuqi Wu, et al., International Journal of Coal Geology, 2020, 218:103368.

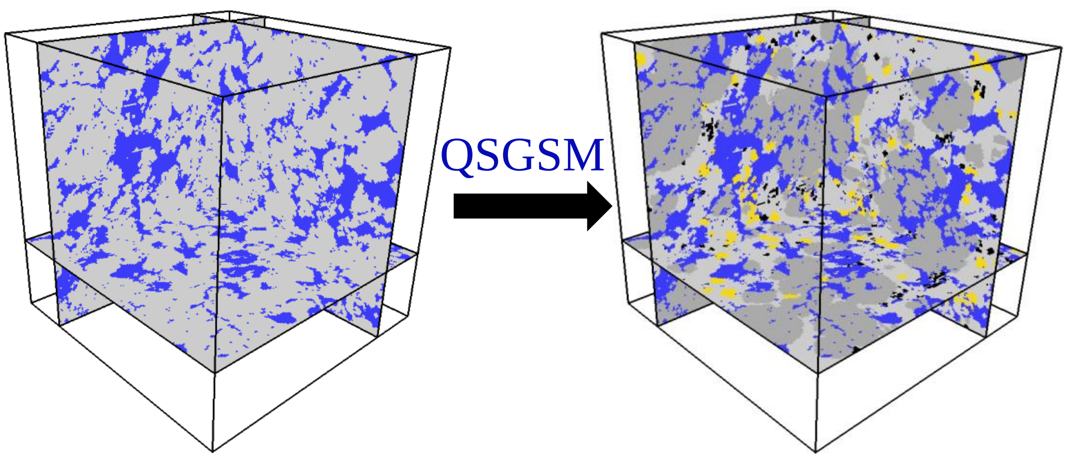
XRCTST-QSGSM for constructing multiscale digital rocks



2. Methods

2.1 Modeling method I: CT-QSGSM

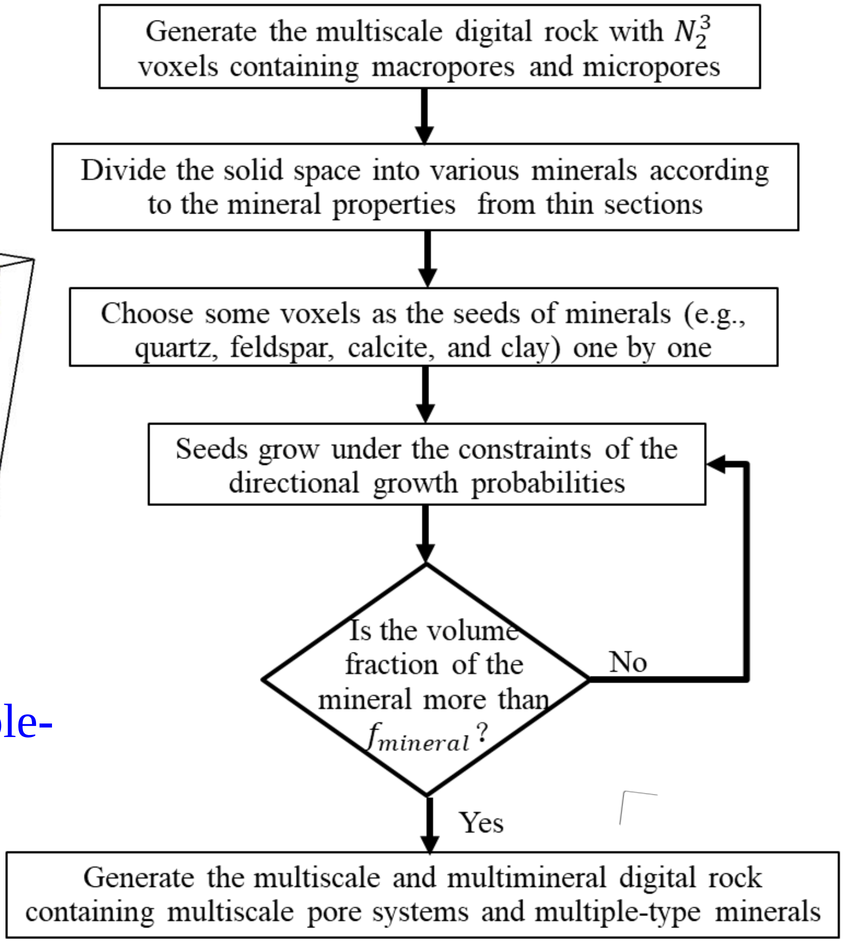
QSGSM was used to divide the solid space in the digital cores into various minerals



Previously published: Single-mineral model

This study: Multiple-mineral model

Quartz
Calcite
Pore
Feldspar
Clay mineral

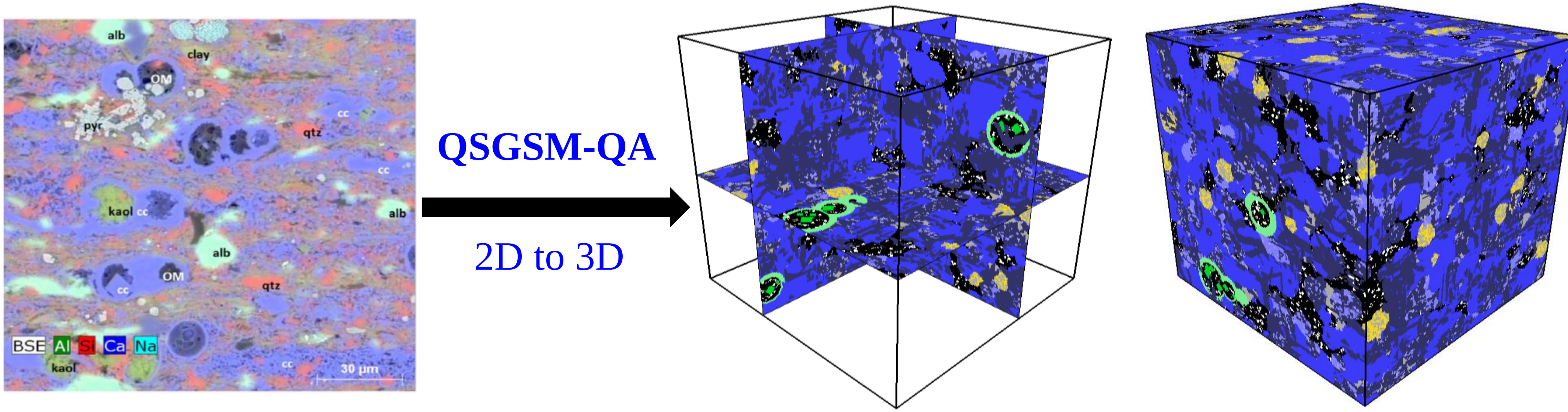


Workflow of constructing multimineral digital rocks by CT-QSGSM

Yuqi Wu, et al., JGR: Solid Earth, 2020, 125(1):e2019JB018309.

2. Methods

2.2 Modeling method II: QSGSM-DA



2D SEM-EDS image

Multicomponent models

Dilation algorithm (DA)

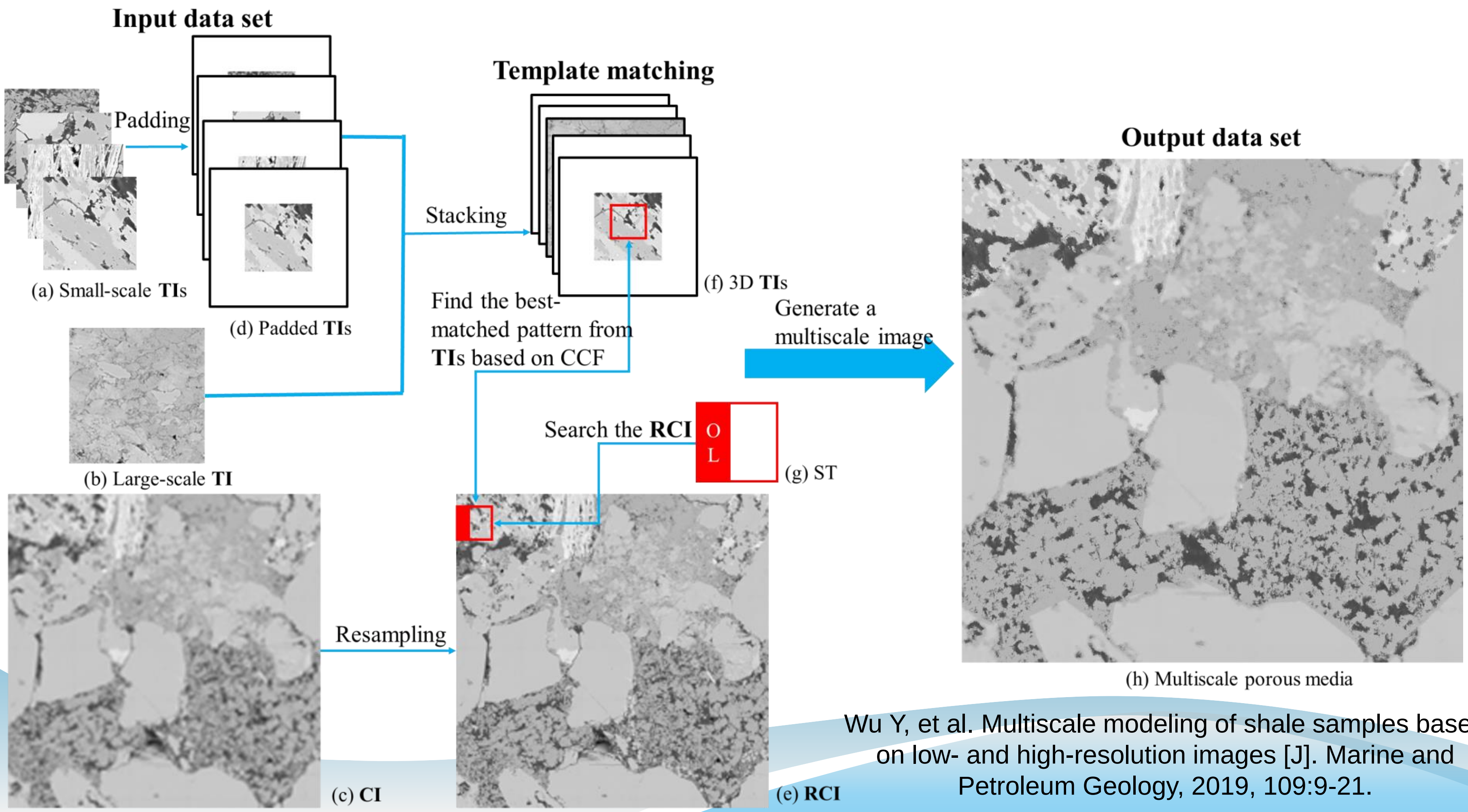
Dilation algorithm can add some structuring elements to the original objects in the image to expand the surface of the particles, so the method is used to simulate the cementation.

$$\mathcal{O} \oplus \mathcal{E} = \left\{ z \in E \,\middle|\, \left(\mathcal{E}^{s}\right)_{z} \cap \mathcal{O} \neq \varnothing \right\},$$

Yuqi Wu, et al., JGR: Solid Earth, 2020, 125(1):e2019JB018309.

2.3 Modeling method III: Template Matching

Template matching: fuse the spatial information from the multiscale and multiresolution images into a multiscale high-resolution image.

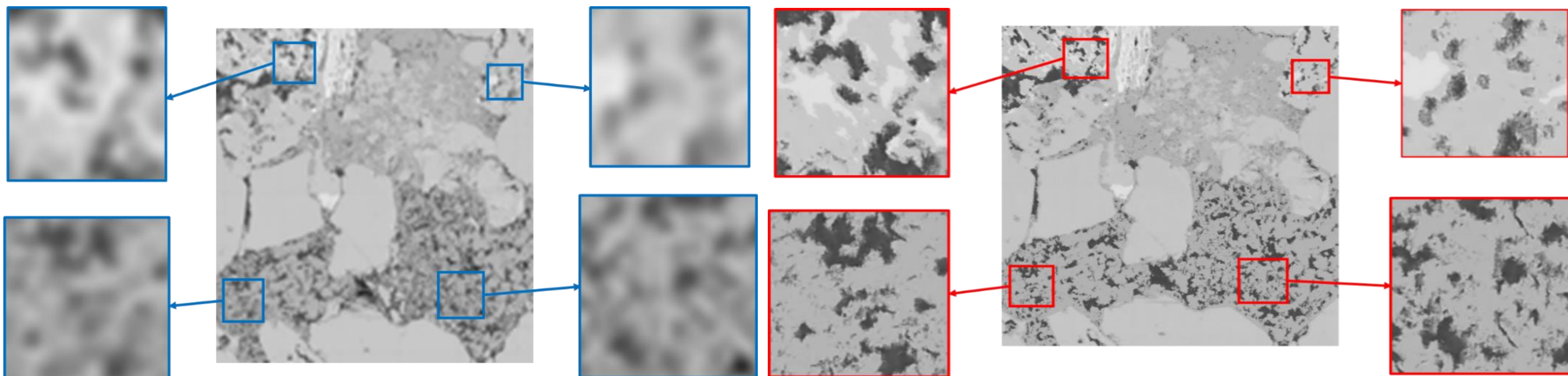


Wu Y, et al. Multiscale modeling of shale samples based on low- and high-resolution images [J]. Marine and Petroleum Geology, 2019, 109:9-21.

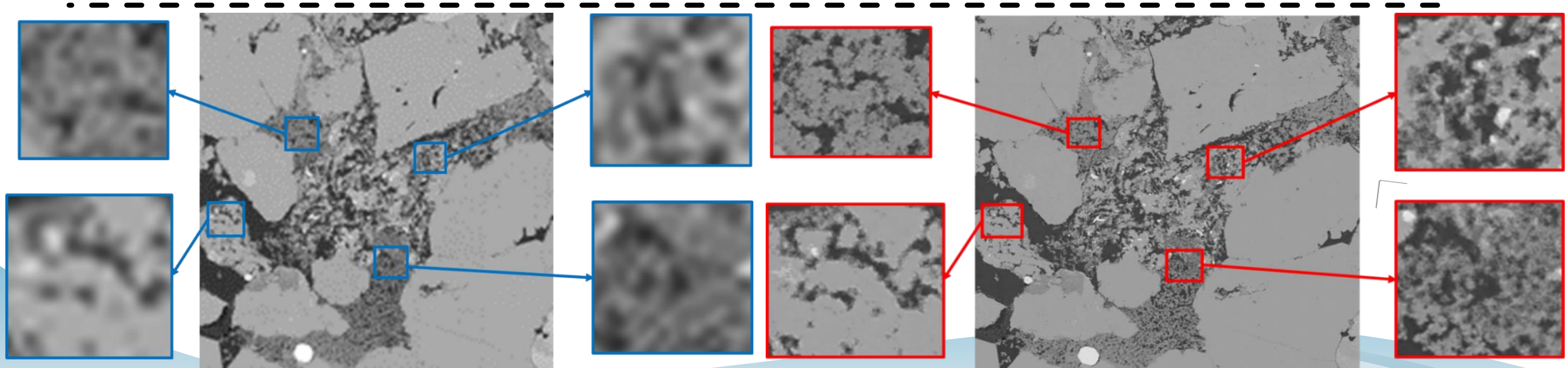
2. Methods

2.3 Modeling method III: Template Matching

Template matching method was used to improve the resolution of 2D images.



Low-resolution 2D image High-resolution 2D image

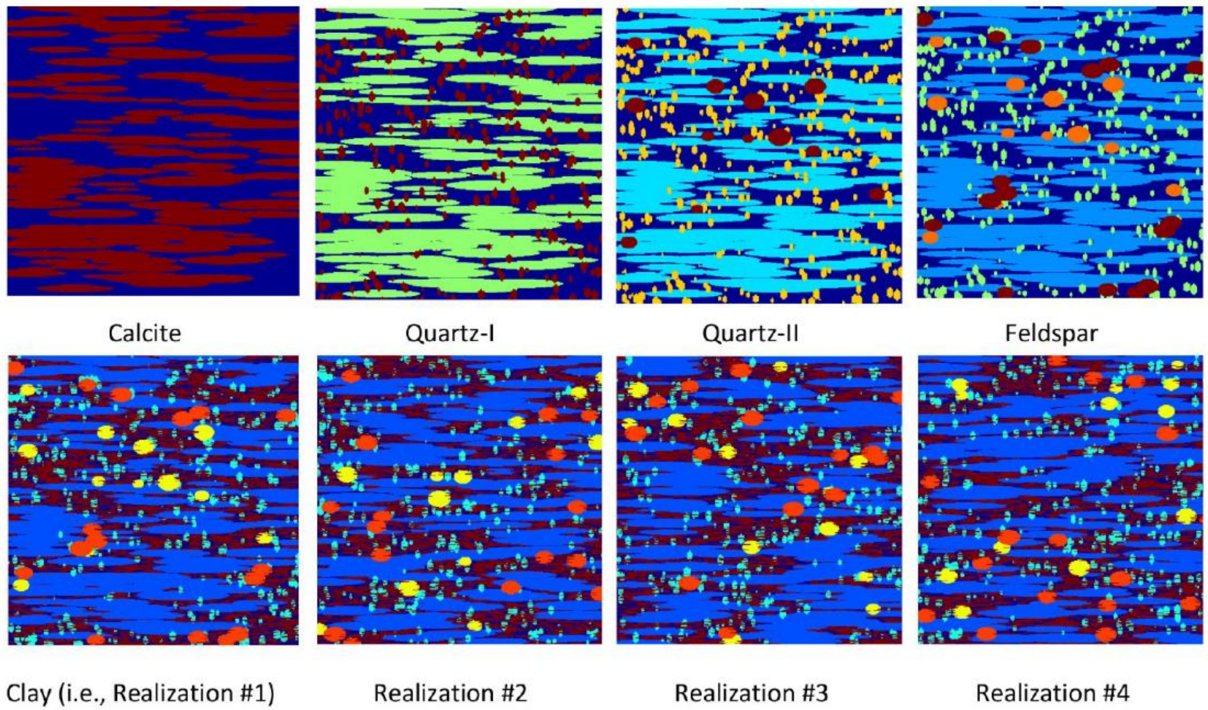


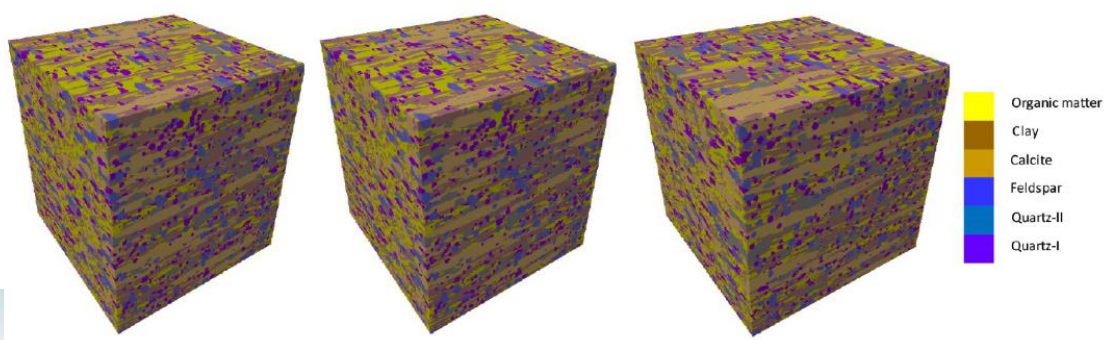
Low-resolution 2D image High-resolution 2D image

2. Methods

2.4 Modeling method IV: Object-based modeling

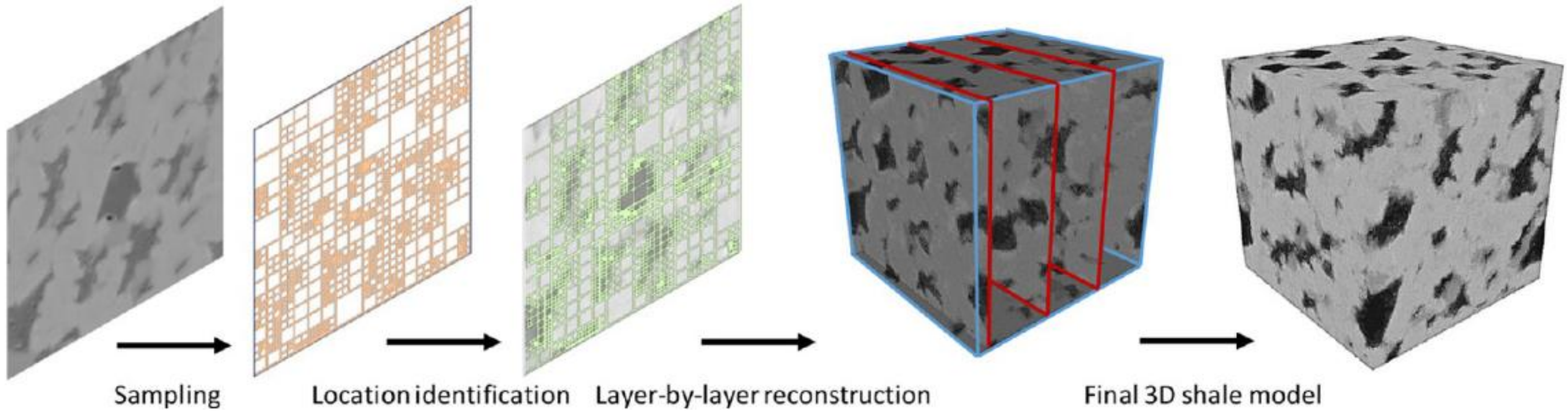
Object-based methods aim to reproduce the elements of shale samples

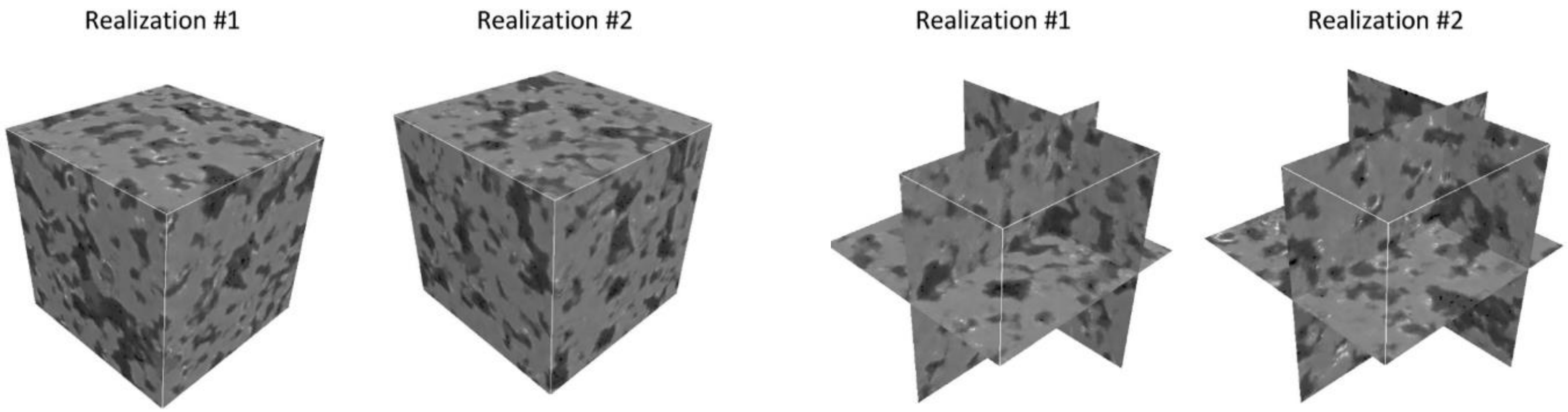




Tahmasebi, et al. Digital rock techniques to study shale permeability: A mini-review[J]. Energy and Fuels, 2020, 34(12): 15672-15685.

2.5 Modeling method V: Multipoint statistics method





Tahmasebi, et al. Digital rock techniques to study shale permeability: A mini-review[J]. Energy and Fuels, 2020, 34(12): 15672-15685.

3. Applications

3.1 Pore network modeling of gas flow

$$\nabla P(z) = \mu \nabla^2 V(x,y),$$

$$\begin{cases} Q_V = \iint_{\Omega} V(x,y)\,d\Omega \\ V_{boundary} = 0 \end{cases}$$

$$Q_{v+k} = Q_v f(Kn),$$

$$\alpha(Kn) = \frac{128}{15\pi^2} tan^{-1}(4Kn^{0.4})$$

$$Kn = \frac{ZTk_B}{\sqrt{2}\pi d_m^2 P R_e},$$

$$J_s = D_s \frac{dC_s}{dz},$$

$$C_s = C_{max}\theta.$$

$$\theta = \frac{P/Z}{P_L + P/Z}.$$

$$G = \frac{A_P}{P_{er}^2}.$$

Consider shape factor of pores, viscous flow, Knudsen diffusion, surface diffusion (OM pores)

$$Q = \begin{cases} iOM-circle: & \frac{\pi R^4}{128\mu}\nabla P.[1+\alpha(K_n)](1+\frac{\beta K_n}{1+K_n}) \\ iOM-square: & \frac{R^4}{72\mu}\nabla P.[1+\alpha(K_n)](1+\frac{\beta K_n}{1+K_n}) \\ iOM-triangle: & \frac{9\sqrt{3}R^4}{320\mu}\nabla P.[1+\alpha(K_n)](1+\frac{\beta K_n}{1+K_n}) \end{cases}$$

$$Q = \begin{cases} OM-circle: & \frac{\pi R_e^4}{128\mu}\nabla P.[1+\alpha(K_n)]\left(1+\frac{\beta K_n}{1+K_n}\right) + D_s\frac{MC_{max}Z.P_L}{\rho(P+Z.P_L)^2}\frac{dP}{dZ}\frac{\pi}{4}(R^2-R_e^2) \\ OM-square: & \frac{R_e^4}{72\mu}\nabla P.[1+\alpha(K_n)]\left(1+\frac{\beta K_n}{1+K_n}\right) + D_s\frac{MC_{max}Z.P_L}{\rho(P+Z.P_L)^2}\frac{dP}{dZ}(R^2-R_e^2) \\ OM-triangle: & \frac{9\sqrt{3}R_e^4}{320\mu}\nabla P.[1+\alpha(K_n)]\left(1+\frac{\beta K_n}{1+K_n}\right) + D_s\frac{MC_{max}Z.P_L}{\rho(P+Z.P_L)^2}\frac{dP}{dZ}\frac{3\sqrt{3}}{4}(R^2-R_e^2) \end{cases}$$

3.1 Pore network modeling of gas flow

$$R_e = R - d_m\theta.$$

$$m_i^k - m_i^{k+1} = \sum_{j=1}^{cn} Q\rho\Delta t.$$

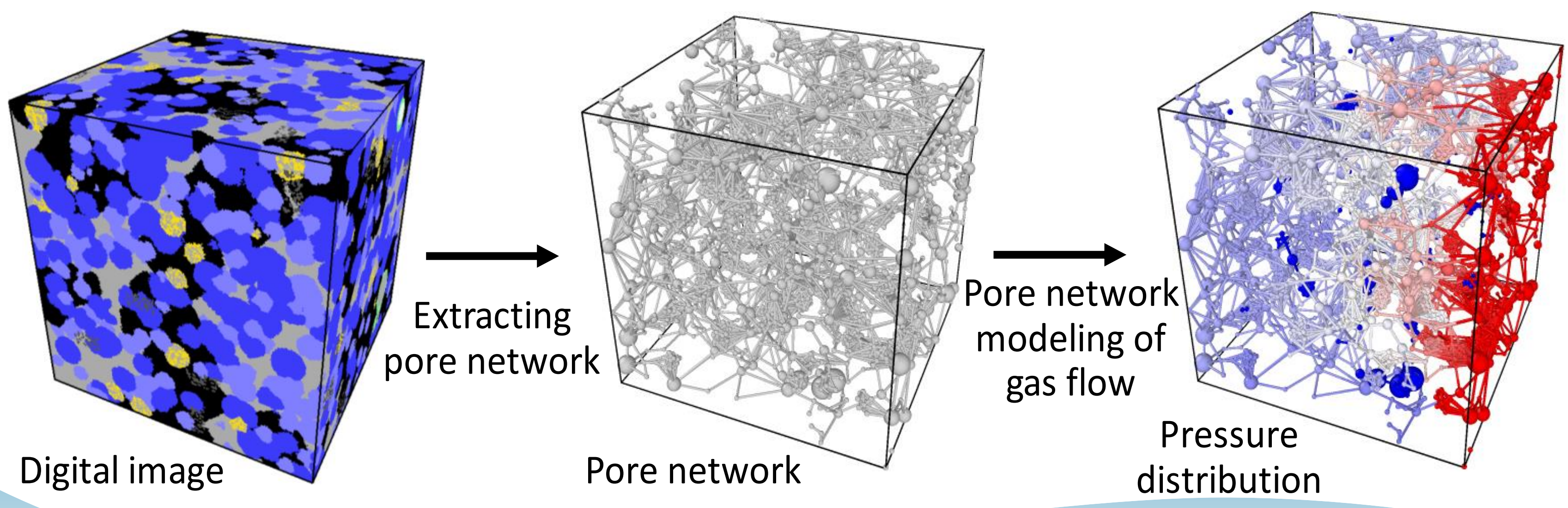
$$m_i^k = V_{throat}\frac{MP_i^k}{ZR_0T}.$$

$$P_i^{k+1} = P_i^k - \frac{ZRT}{V_{throat}M}\sum_{j=1}^{cn} Q\rho\Delta t.$$

$$P_{ij}^{k+1} = \frac{P_i^k + P_j^k}{2}.$$

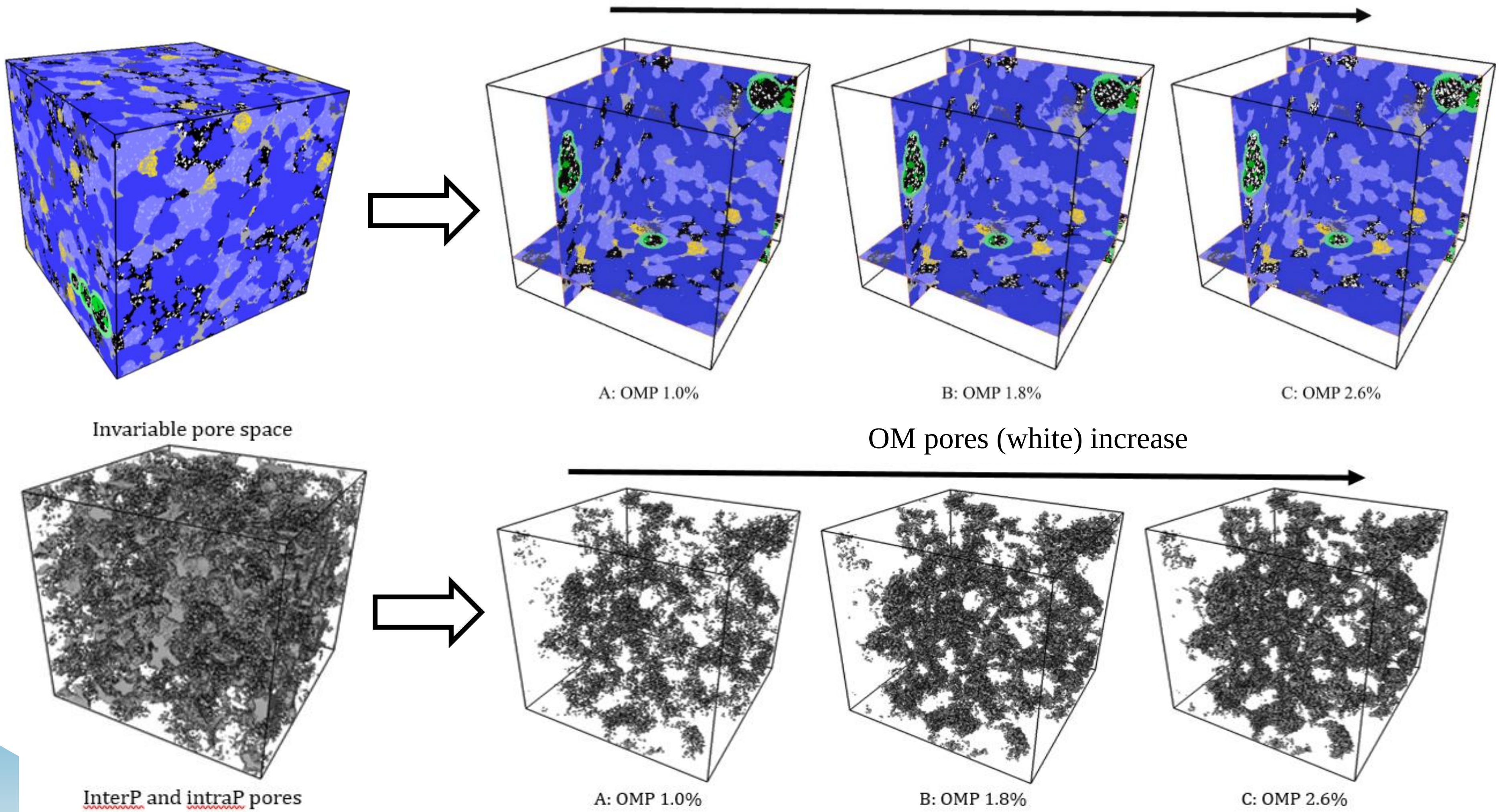
$$\nabla P = \frac{P_i^k - P_j^k}{L_{ij}^k}.$$

$$K_{app} = \frac{Q_{in}\mu_{ave}L}{A\nabla P}$$



Yuqi Wu, et al., JGR: Solid Earth, 2020, 125(1):e2019JB018309.

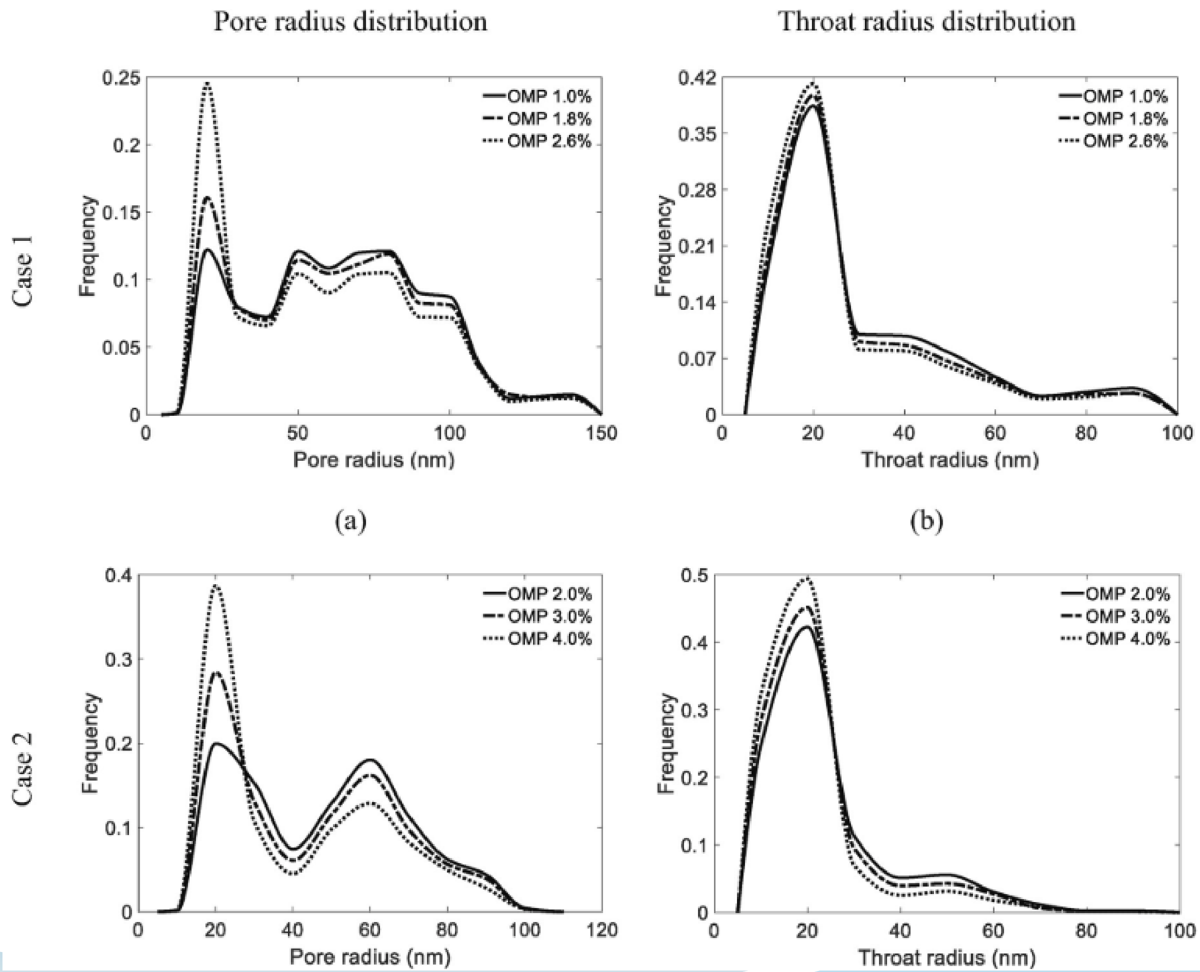
3.2 Effects of OM pores on rock properties



Yuqi Wu, et al., Journal of Natural Gas science & Engineering, 2020, 81:103425

3.2 Effects of OM pores on rock properties

After increasing the OM pores in the shale models, the proportion of tiny pores whose sizes are smaller than 30nm greatly increases.



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3. Applications

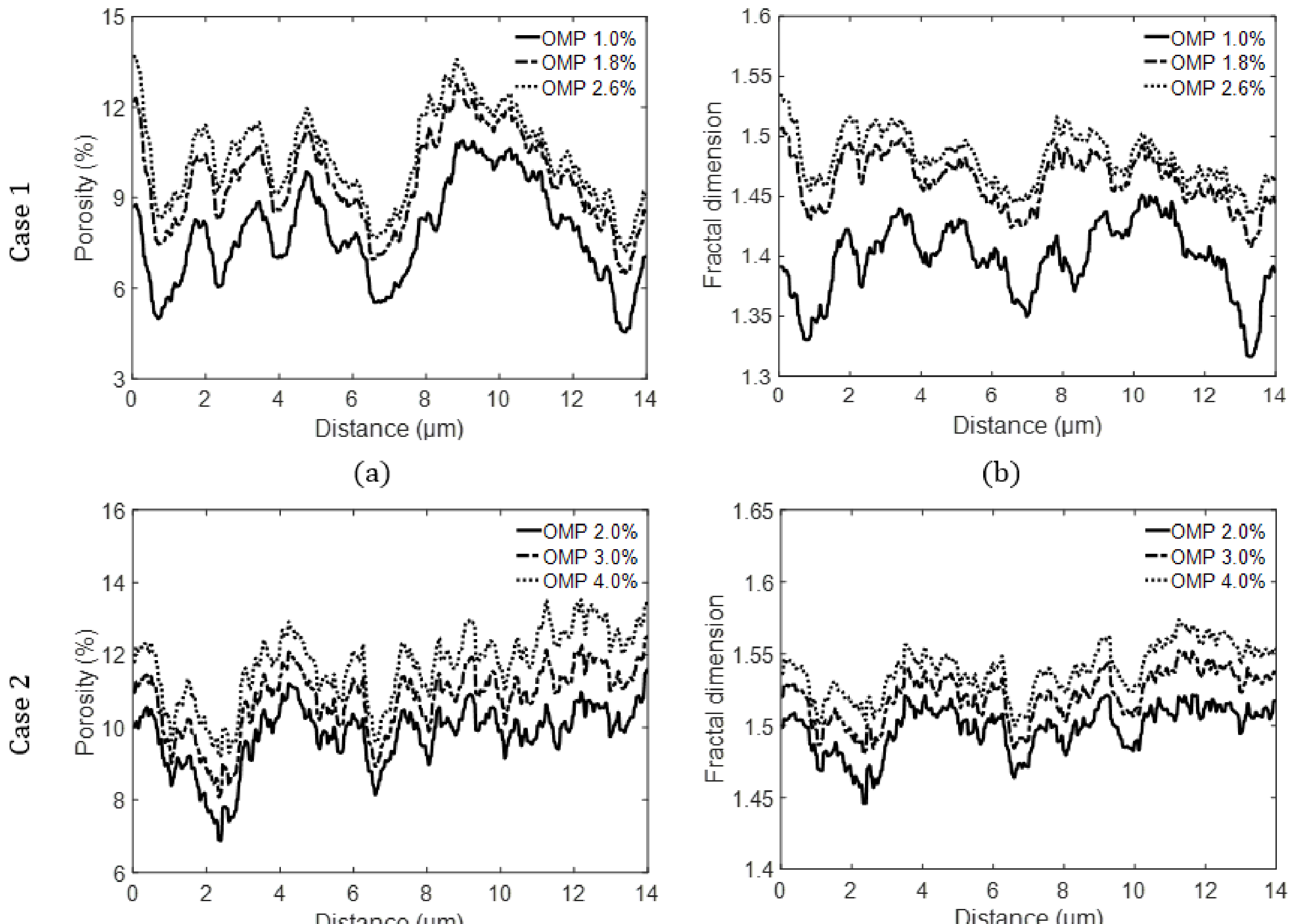
3.2 Effects of OM pores on rock properties

When OM pores are generated in the shale models, porosity of each 2D layer increases.

More OM pores make fractal dimension larger and the surface of 2D pore space rougher.

Porosity variation of each 2D layer

Fractal dimension variation of each 2D layer



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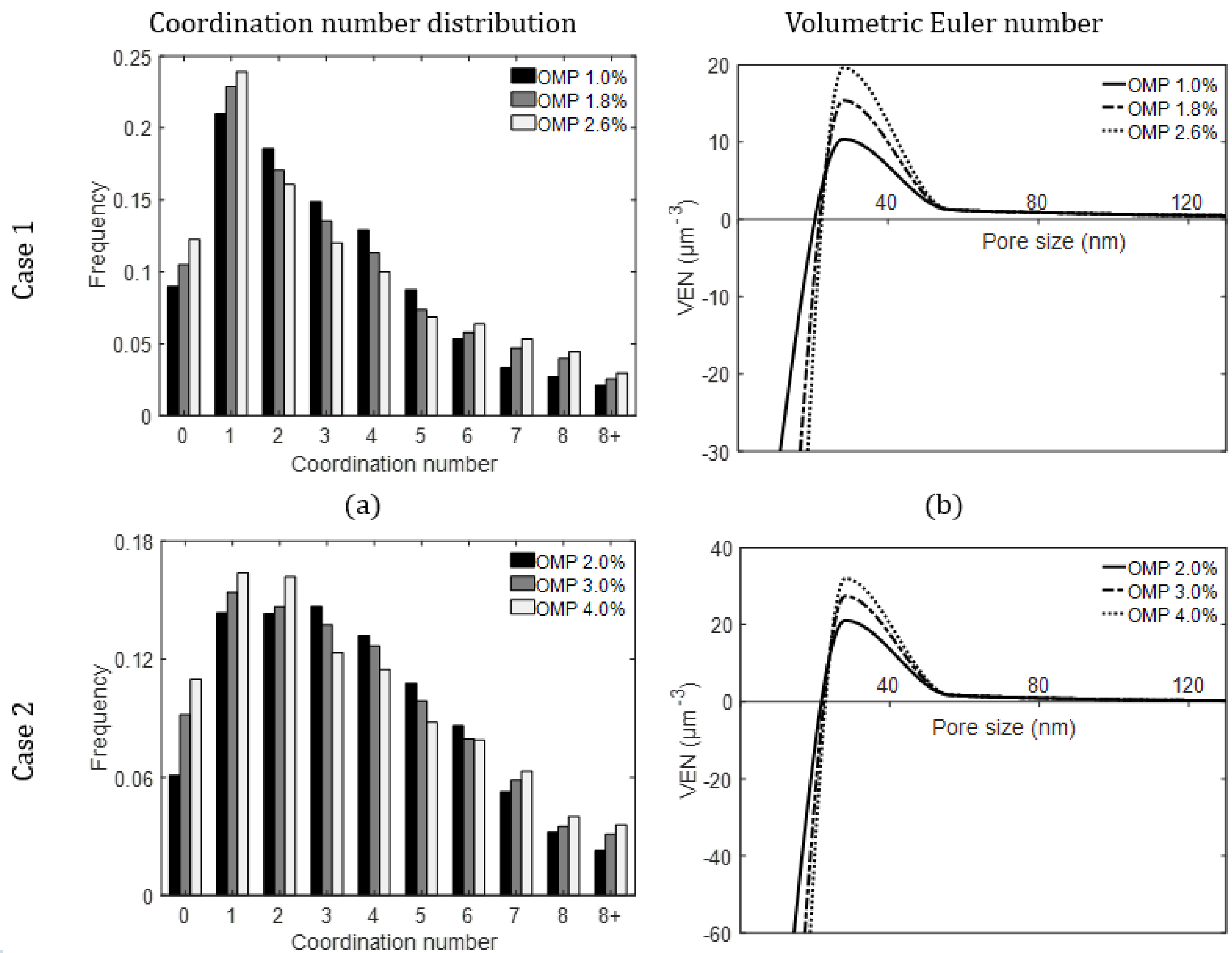
3.2 Effects of OM pores on rock properties

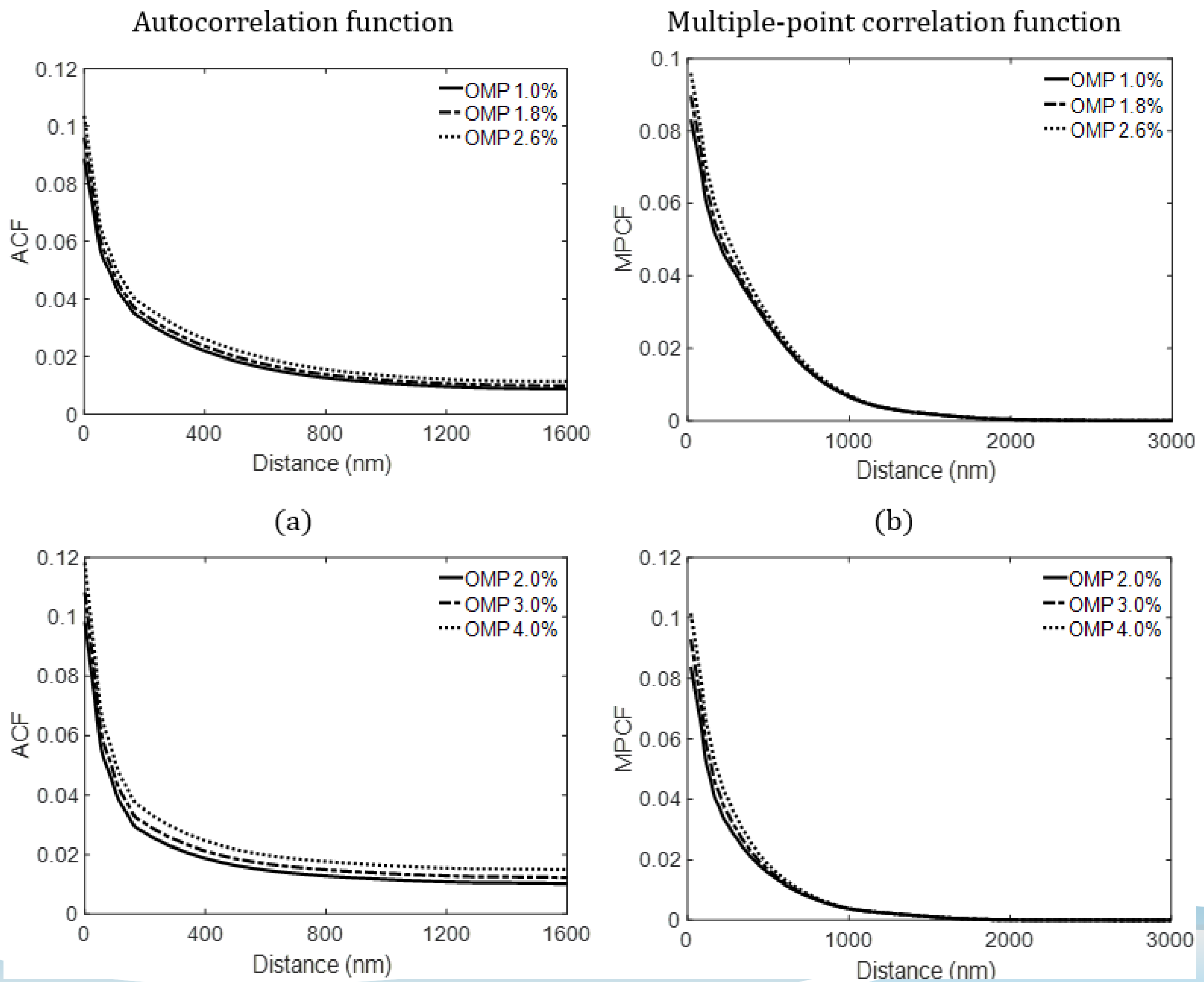
The addition of more OM pores makes the connectivity of pore space become better



Yuqi Wu, et al., Journal of Natural Gas science & Engineering, 2020, 81:103425

3.2 Effects of OM pores on rock properties

The addition of more OM pores increases the correlation of the voxels in the pore space



Yuqi Wu, et al., Journal of Natural Gas science & Engineering, 2020, 81:103425

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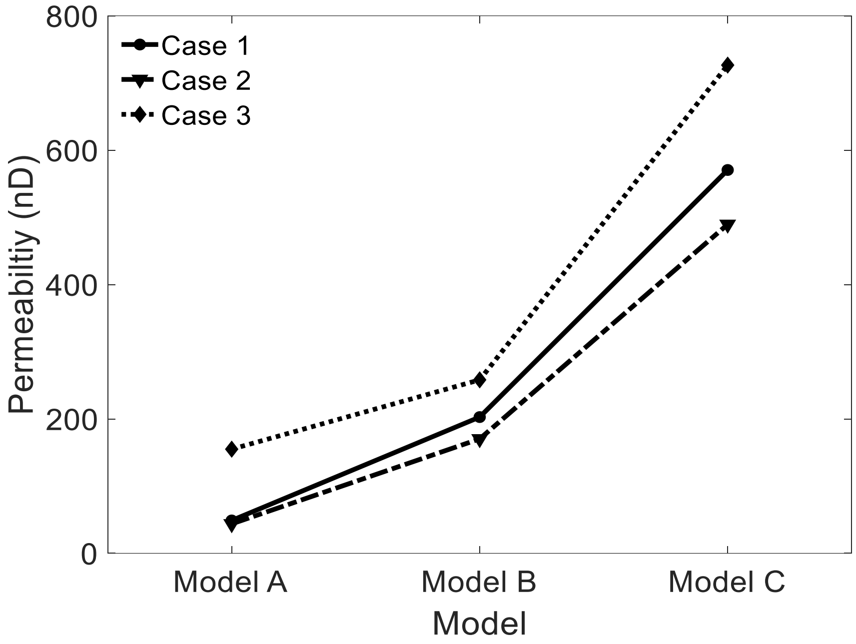
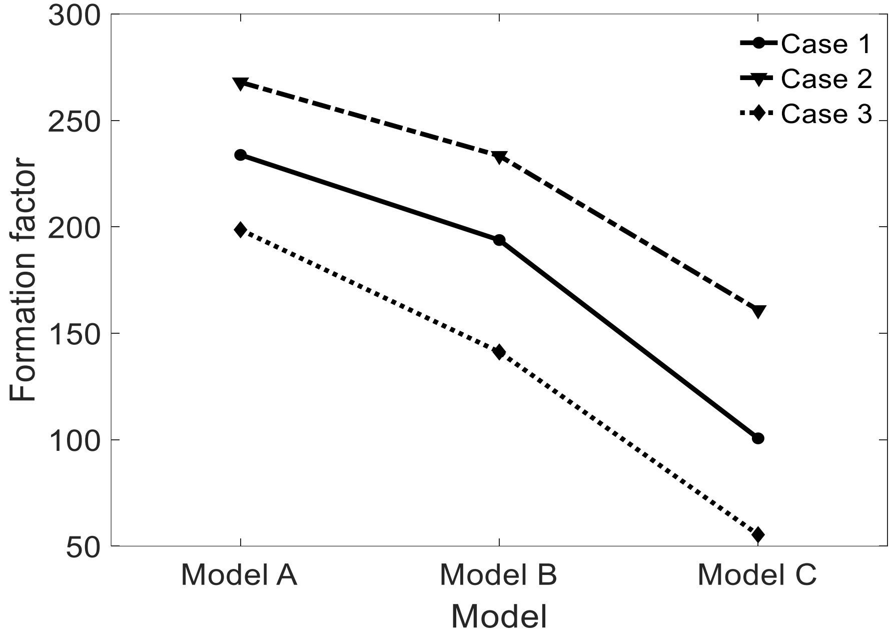
3.2 Effects of OM pores on rock properties

The addition of more OM pores improves the permeability and decreases the formation factor.





Yuqi Wu, et al., Journal of Natural Gas science & Engineering, 2020, 81:103425

4. Conclusions

- Five approaches for constructing multiscale and multicomponent digital rocks are presented: (1) Hybrid modeling method: CT-QSGSM, (2) QSGSM-DA, (3) Template matching, (4) Object-based modeling, (5) Multipoint statistics method.
- We proposed a pore network modeling method that considers the pore shape factor, viscous flow, Knudsen diffusion, and surface diffusion.
- The effects of OM pores on the geometric, topological, and transport properties and correlation functions of pore space were comprehensively evaluated within the multiscale and multicomponent digital models.

5. Acknowledgements

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Thank you! Q&A !

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