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The construction of carbonate digital rock with hybrid superposition method

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ABSTRACT

Carbonate reservoirs are inherently heterogeneous and the pore sizes can vary over orders of magnitudes, the pores at different scales have a great impact on interconnectivity and flow properties. It is necessary to describe the microscopic pore characteristics of carbonate rocks at different scales and its influence to flow mechanism.

In this paper, 2D thin section carbonate images with different resolutions are collected with scanning-electron microscopy (SEM). The lower resolution image shows macropore properties while the higher resolution image shows micropore properties. With two different scale resolution images, a hybrid superposition method is proposed to construct superposition digital rock with two steps, the first step is to reconstruct macropore digital rock with simulated annealing method and micropore digital rock with Markov Chain Monte Carlo (MCMC) method, and the second step is to construct the carbonate digital rock with superposition method. Finally, pore space microscopic structure analysis method and lattice Boltzmann method are used to analyze the pore structure and flow properties.

Results show that, the hybrid superposition method could combine the advantages of simulated annealing method and Markov Chain Monte Carlo method, which could reconstruct macropore digital rock with a better morphology description and micropore digital rock with a less computation time. The carbonate superposition digital rock has a bimodal pore size distribution which could describe the macropore and micropore characteristics simultaneously, it also has a higher percolating volume fraction and absolute permeability than both of macropore and micropore digital rock, which shows that micropores have an important influence on the total connectivity in carbonate rocks. This method has a research platform for the study of multiscale pore characteristics and microscopic flow mechanism in carbonate rocks.

1. Introduction

More than 50% of the world's hydrocarbon reserves are contained in carbonate rocks. The carbonate rocks are highly heterogeneous and many of them contain a complex pore structure with a wide range of length scales. While the macroscopic physical properties are the reflection of microstructure, it is necessary to study the microscopic pore structure and multi-phase flow mechanisms in carbonate rock.

At present, digital rock has been an important platform to understand and predict petrophysical and multiphase flow properties in porous media (van Dijke and Piri, 2007). There are two main methods to construct digital rocks including physical experiments and numerical reconstruction. Meanwhile, the physical experiments include serial sectioning (Tomutsa et al., 2007), laser scanning confocal microscopy (Fredrich et al., 1995), X-ray computed microtomography (Dunsmuir et al., 1991) etc. Numerical reconstruction methods include Gaussian simulation (Joshi, 1974; Quiblier, 1984; Adler et al., 1990), simulated annealing (Hazlett, 1997; Yeong and Torquato, 1998), processed-based (Bryant and Blunt, 1992; Oren and Bakke, 2002), multiple-point statistic (Okabe and Blunt, 2004) and MCMC (Wu et al., 2006) etc. After the construction of 3D digital rock, Lattice-Boltzmann (LB) method is usually used to predict fluid flow properties directly without further simplification.

Although a number of 3D reconstruction methods are available for sandstones, it is difficult to construct a similar model for carbonate rock. In carbonate rocks, a wide size range of pores are produced during the processes of sedimentation and diagenesis through chemical dissolution, reprecipitation, dolomitization, which result in complex pore distribution. Due to these reasons, it is difficult to fully classify and characterize the pore scale microstructure of carbonate rocks, and it is challenging to predict petrophysical and multiphase flow properties in carbonates.

Many carbonate rocks have bimodal pore size distributions which play an important role in forming the reservoirs. In recent years, many scholars have studied the microscopic multiscale

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characteristics of carbonate rocks. Arns (Arns et al., 2005) used a high resolution X-ray microtomography to image a reservoir carbonate core plug in 3D over a range of length scales and found that the apparent porosity of the core increases with enhanced image resolution indicating a substantial presence of sub-micron porosity. Knackstedt (Knackstedt et al., 2006a, 2006b, 2008) also imaged the outcrop and reservoir carbonate core plugs using high resolution X-ray microtomography in 3D over a range of length scales and showed good agreement between the image based calculations of petrophysical properties and experimental data. Biswal (Biswal et al., 2007, 2009) proposed a stochastic geometrical model for the diagenetic process in carbonate rocks and reproduced both the complex pore scale geometry and the basic petrophysical properties. Ghous (Ghous et al., 2008) used microcomputed tomography and focused ion beam microscopy to describe 3D imaging of macropores and micropores in carbonate core samples respectively. Al-Kharusi (Al-Kharusi and Blunt, 2008) followed a multistage workflow to extract networks from pore space images and predict multiphase transport properties for subsurface carbonate samples. However, the existing microstructure models are either not very good or highly simplified representations of carbonate rocks.

2. Methodology

Two-dimensional SEM images are used here as we cannot obtain 3D images with the required resolution to image the microstructure of carbonate rocks, and the reconstruction method will be used to obtain the 3D digital rock. With two different scale resolution images, a hybrid superposition method is proposed to construct superposition digital rock with two steps. The first step is to reconstruct 3D macropore digital rock with simulated annealing method and micropore digital rock with MCMC method; the second step is to construct the carbonate digital rock with superposition method.

2.1. Simulated annealing method

Simulated annealing method was first applied to construct porous media by Hazlett (1997). It could reconstruct a variety of different stochastic statistical functions based on the Gaussian filtering method. During the reconstruction process, the statistical functions most used include porosity, auto-correlation function and linear-path function etc. For a typical simulated annealing method, the reconstruction procedure of a two phase isotropic porous medium is described as follows. A 3D porous media which is composed of pore space and skeleton space is produced with the same porosity as the 2D rock image. Then, the energy E of is calculated as follows:

$$E=\sum_k \alpha_k [S_r^{(k)}(r)-S_0^{(k)}(r)]^2 \tag{1}$$

where E is the sum of the squared differences of statistical properties between the 2D image and reconstructed digital rocks; $S_r^{(k)}(r)$ is the statistical properties of reconstructed digital rock and $S_0^{(k)}(r)$ is the statistical properties of 2D images; k is the kth statistical property, and α_k is the weight. If only auto-correlation function is considered, the equation above is simplified to

$$E=[A_3(r)-A_2(r)]^2 \tag{2}$$

where $A_3(r)$ is the auto-correlation function of reconstructed 3D digital rock and $A_2(r)$ is that function of referenced 2D image.

In this paper, 2D images with different resolutions are collected. While the low resolution 2D image is collected from SEM to describe the macropore characteristics in carbonate rocks. Then based on the 2D binary image (Fig. 1a), simulated annealing method is used to construct 3D macropore digital rock (Fig. 1b). Fig. 2 shows the statistical functions of macropore digital rock with the simulated annealing method. As can be seen in the figure, when $r=0$, the value of each function is 0.206 which equals the image porosity. For auto-correlation function curve (Fig. 2a), the curve becomes stable when r is larger than 40, and the auto-correlation function in the first 40 voxels are chosen as the reference function during modeling process. For linear path function curve (Fig. 2b), the curve becomes stable when r is larger than 60, and the linear path function in the first 60 voxels are chosen as the reference function during modeling process.

2.2. Markov Chain Monte Carlo method

MCMC method is a specific Monte Carlo method; Markov Chain is applied into Monte Carlo to realize the dynamic simulation. The main idea of MCMC method is to construct a Markov Chain $p(x)$ with stable distribution. The spatial structure information that is derived from 2D thin section image data is considered to obtain all the transition probabilities and the input data is taken from image analysis. This MCMC reconstruction approach and the models it generates are referred to as “pore architecture models”, or PAMs. Generally speaking, four procedures are used to reconstruct the 3D digital rock and the details of the PAMs and reconstruction procedures are described in Wu et al. (2006).

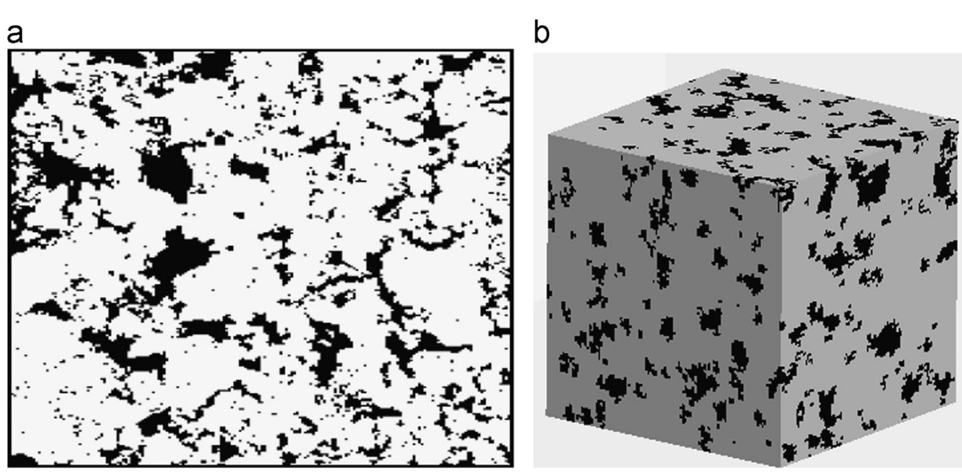

Fig. 1. Macropore digital rock based on simulated annealing method. (a) 2D binary image with low resolution 1.34 μm/pixel (the matrix space is shown white and the pore space is shown black) and (b) reconstructed macropore digital rock (the matrix space is shown gray and the pore space is shown black), the voxels size is 100 × 100 × 100.

The high resolution 2D image is collected from SEM to describe the micropore characteristics in carbonated rocks. Based on the 2D binary image (Fig. 3a), MCMC method is used to construct 3D micropore digital rock with the assumption that the 3D digital rock is isotropic. The reconstructed 3D microdigital rock is shown in Fig. 3b.

2.3. Superposition method

The data of digital rock are stored in the form of 0 and 1, and 0 represents pore space while 1 represents matrix space. Based on the macropore and micropore digital rocks, superposition method is introduced to construct superposition digital rock. The

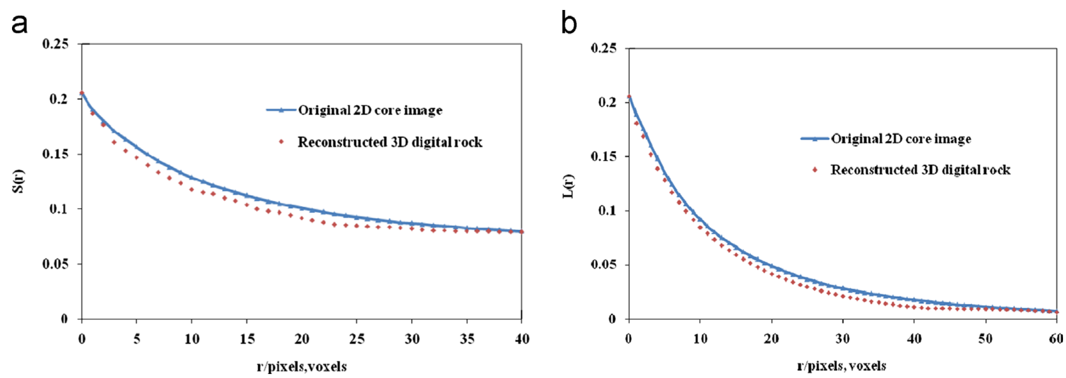

Fig. 2. Curve of statistical functions of macropore digital rock with simulated annealing method. (a) Auto-correlation function and (b) linear path function.

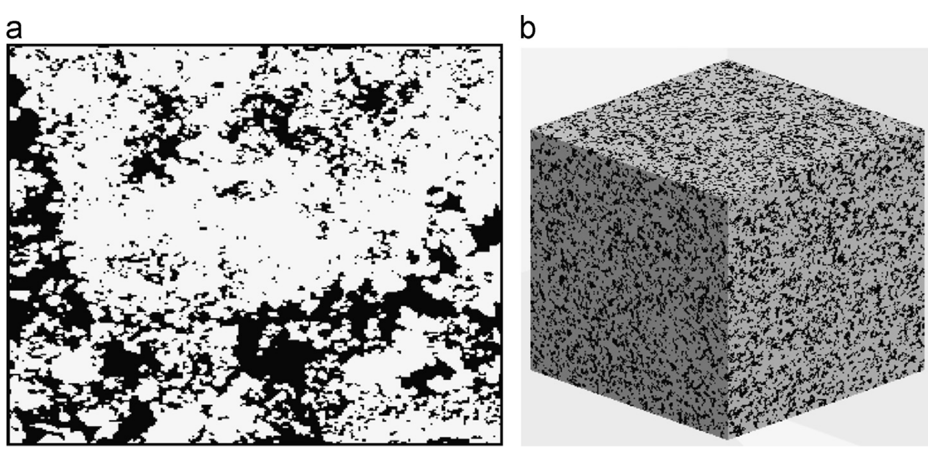

Fig. 3. Micropore digital rock with MCMC method. (a) 2D binary image with high resolution 0.335 μm/pixel (the matrix space is shown white and the pore space is shown black) and (b) reconstructed macropore digital rock (the matrix space is shown gray and the pore space is shown black), the voxel size is 400 × 400 × 400.

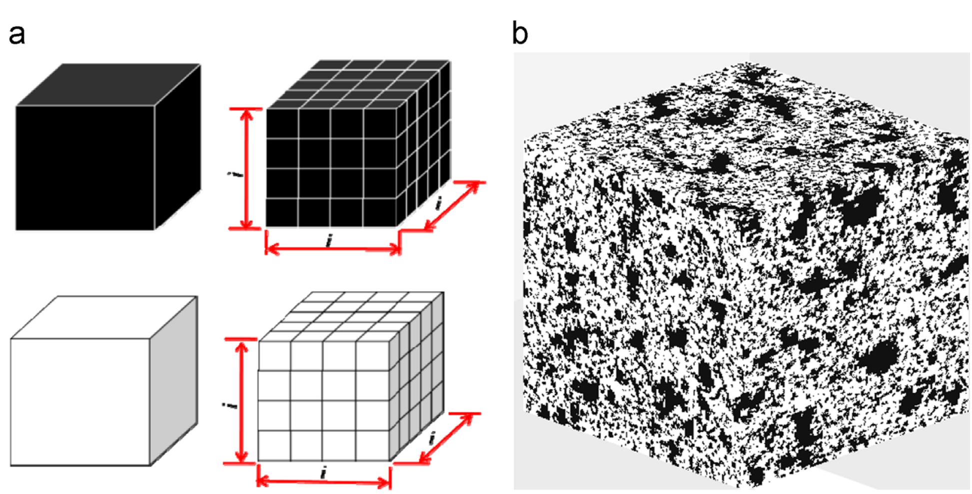

Fig. 4. Reconstruction of carbonate superposition digital rock. (a) Voxel refinement algorithm and (b) superposition digital rock.

superposition procedures are shown as follows: at first, each voxel in macropore digital rock is refining into $i \times i \times i$ voxels (Fig. 4a), i the resolution ratio of macropore digital rock and micropore digital rock and i equals 4 in this paper. The voxel refinement could make the macropore digital rock and the micropore digital rock have the same physical size (0.134 mm × 0.134 mm × 0.134 mm) and voxel size (400 × 400 × 400). Then, the superposition operations of binary data between two digital rocks are as follows: $0+0=0$, $1+0=0$, $0+1=0$, $1+1=1$.

During superposition process, the physical size of macropore and micropore digital rock should keep the same. The macropore digital rock with low resolution has a smaller voxel size, while the micropore digital rock with high resolution has a larger voxel size. Due to the voxel size requirement of macropore and micropore digital rocks, the simulated annealing which has better accuracy and longer computing time with more statistical functions is used to reconstruct the macropore digital rock, and MCMC method which has a less computing time and lower accuracy with fewer statistical function is used to reconstruct the micropore digital rock. The hybrid superposition method could combine the advantages of simulated annealing method and Markov Chain Monte Carlo to construct the carbonate digital rock with less computing time and better accuracy. The superposition digital rock with hybrid superposition method is shown in Fig. 4b. The voxel size of superposition digital rock is 400 × 400 × 400 with a resolution of 0.335 μm.

3. Parameters analysis

3.1. Pore structure analysis

The pore structure parameters such as porosity, percolating volume fraction and pore size distribution are analyzed at first. The percolating volume fraction is used to describe the volume fraction of pore space through which fluid can percolate which could denote the connection degree of the whole pore space and the pore size distribution here describe probability of distance between the point and its nearest matrix point (Zhao et al., 2007).

Table 1
Pore structure parameters comparison of each digital rocks.

Pore structure parameters	Macropore digital rock	Micropore digital rock	Superposition digital rock
Porosity	0.206	0.34	0.476
Percolating volume fraction	0.834	0.842	0.905

Based on macropore, micropore and superposition digital core, the corresponding porosity and percolating volume fraction of each could be calculated and the comparison results are shown in Table 1.

The porosity of superposition digital rock is lower than that of the sum of macropore and micropore digital rock. This is due to the overlap of pore space during the superposition process. Both the percolating volume fraction of macropore and micropore digital rock have a low value, this is due to the strong heterogeneity of carbonate rocks. However, the percolating volume fraction of superposition digital rock has a higher value than the other two digital rocks, which shows that the micropores could connect isolated macropores and make great contribution for total connectivity of superposition digital rock.

Based on the pore size distribution function, the pore size and cumulative pore size distribution probability could be seen in Fig. 5. As can be seen in the figure, the average pore size of macropore is 1.3 μm, which mainly describes the macropore characteristics of intrapores; the average pore size of micropore network is 0.54 μm, which mainly describes the micropore characteristics of intrapores. And the superposition digital rock with average pore size 1 μm has a bimodal pore size distribution, which could capture the pore structure properties both of macropore and micropore digital rock and describes the multiscale characteristics of intrapores in carbonate rocks.

3.2. Transport analysis

Here the lattice Boltzmann method is applied to analyze the transport properties and the D3Q19 LBGK model is chosen to calculate the absolute permeability (Masa, 2005). While lattice

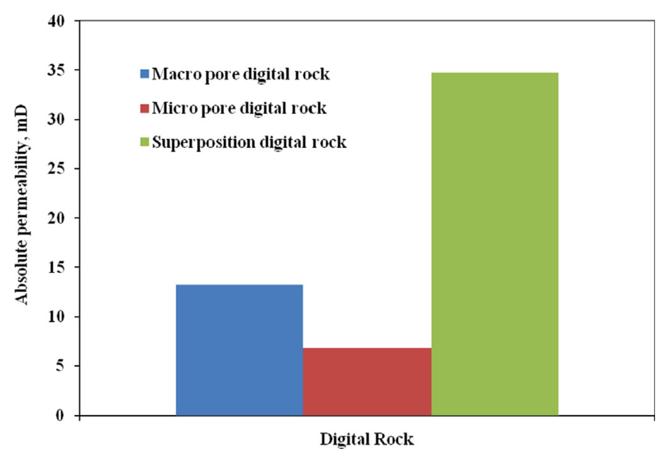

Fig. 6. Absolute permeability of digital rocks with Lattice Boltzmann method.

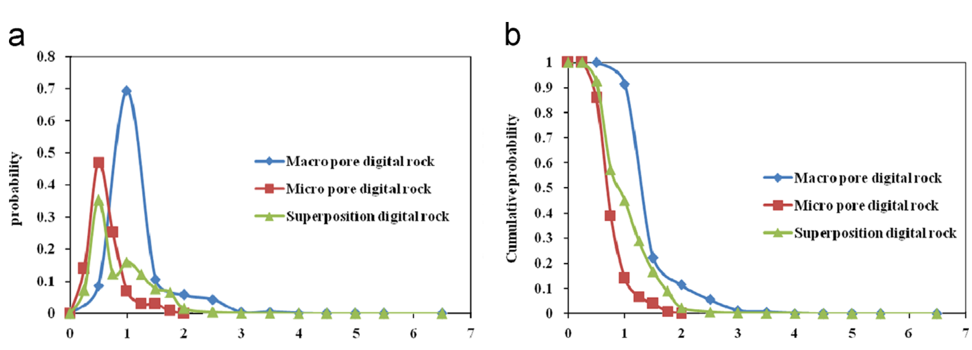

Fig. 5. Pore size distribution function. (a) Pore size distribution probability and (b) cumulative pore size distribution probability.

Boltzmann method is used to calculate the absolute permeability of each digital rock, the comparison results are shown in Fig. 6. The absolute permeability of superposition digital rock is 34.8 mD, which is higher than the permeability sum of macropore digital rock (13.2 mD) and micropore digital rock (6.8 mD). This is due to the micropores connect the poorly connected macropores well during superposition process, which improves the total connectivity and increases the absolute permeability.

4. Conclusions

In this paper, simulated annealing method is used to reconstruct the macropore digital rock and Markov Chain Monte Carlo method is used to reconstruct micropore digital rock, then a superposition method is used to construct the carbonate digital rock. After analysis of pore and transport properties in each digital rock, we could obtain the following conclusions: (1) the hybrid superposition method could combine the advantages of simulated annealing method and Markov Chain Monte Carlo method, which could reconstruct the macropore digital rock with a better morphology description and the micropore digital rock with a less computation time; (2) the superposition digital rock has a bimodal pore size distribution, which could capture the pore structure properties both of macropore and micropore digital rock and describe the multiscale characteristics of intrapores in carbonate rocks; (3) although the micropores are usually ignored in former study because of their low permeability, the influence of micropores should be paid more attention while they could improve the total connectivity and have a great contribution to the transport properties in heterogeneous carbonate rocks.

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