Review of 3D digital core reconstruction methods for deep shale gas reservoir

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Abstract. Conventional digital core reconstruction methods are not suitable for deep shale gas reservoirs with low porosity and permeability, anisotropy and complex mineral composition, and conventional single resolution three-dimensional digital core structure model cannot fully describe the core structure of shale gas reservoirs of different scales. In this paper, the advantages and disadvantages of different digital core reconstruction methods are summarized by analyzing examples. It is found that MCMC core reconstruction method is more suitable for image reconstruction of 3D digital structure model core of deep shale gas reservoir in China; Finally, in view of the problems existing in conventional digital core reconstruction methods, combining CT imaging with ion beam focused electron microscopy (FIB-SEM) imaging technology, a 3D digital core structure model with multi-scale, multi-component and corresponding macro pore and micro pore of the corresponding reservoir is proposed. The micro spatial distribution structure of the model is similar to that of real shale gas reservoir core, it overcomes the difficulty that the resolution of single scale 3D digital gas reservoir core model and the micro size characteristics of gas reservoir core cannot be perfectly considered. It can not only accurately describe the micro pore space distribution structure of real core gas reservoir, but also accurately describe the macro heterogeneity of deep shale gas reservoir core.

Key words: Shale gas reservoir, 3D digital core, multi-scale, multi-component, dual porosity.

1. Introduction
Shale is mainly composed of clay sized minerals and granular rocks. Its mineral pore space composition is complex and rich in a large amount of organic matter. Moreover, the matrix pores are extremely underdeveloped and the permeability is very low. Therefore, the process of rock physical
exploration and development is relatively difficult. Compared with conventional physical exploration experiments on pore surface of reservoir rocks, deep shale gas reservoir is characterized by strong heterogeneity, anisotropy and deep physical depth. Therefore, experimental research in the field of deep shale gas exploration is more difficult, and even the most important theoretical and technical research is severely restricted. Different from other methods, 3D digital core experiment is mainly based on reservoir rock microstructure information, so that core pore space and its components can be reflected by 3D rock physical image. It displays different pore space components of reservoir rocks with different values and shapes, and stores the physical properties of different components of rocks as 3D image information. According to the properties of reservoir rocks, 3D numerical simulation of pore physical characteristics of reservoir rocks can be directly carried out. The reconstruction of 3D images of deep shale gas reservoir rocks can provide better guidance for the research and development of deep shale gas reservoir rock pore space physics.

This paper reviews the development of different digital core reconstruction methods, analyzes and compares their advantages and disadvantages. The single resolution 3D digital core scanning model may not be able to fully describe the scale structure information of deep shale gas reservoir cores. Combining CT and FIB-SEM scanning technology, the composition and composition of core skeleton of deep shale reservoir are comprehensively considered, and the advanced Markov chain Monte Carlo core scanning method (MCMC) is used to reconstruct a multi-scale and multi-component dual porosity digital core model more suitable for deep shale gas reservoirs with special and complex components.

2. Overview of research methods of digital core reconstruction

Digital core is an important advanced simulation technology of core experiment. Scholars at home and abroad have carried out extensive discussion and Research on this, and put forward a variety of digital core reconstruction methods. There are two main methods for the discussion and research of shale gas reservoir 3D digital core reconstruction technology and methods at home and abroad: one is based on the use of 3D X-ray scanning CT (computer tomography) image Scanning digital core, using 3D image scanning processing algorithm to scan two-dimensional image into three-dimensional digital core; second, based on the analysis of rock two-dimensional image information (such as casting thin section of rock and analysis of rock particle size image data, etc.), using 3D digital core reconstruction method and image processing algorithm to successfully build 3D image scanning digital core [1]. In the early stage, some American scholars Rosenberg successfully established 3D image scanning digital core for sandstone by using CT imaging scanning [2]. Liu Yang [3] carried out slice analysis on core reservoir, obtained the number of shale gas remaining oil reservoir and the parameters of residual oil and related pore throat reservoir required by core, and realized digital analysis and visualization of reservoir by using algorithm. Youssef [4] and others have made a great progress in digital core reconstruction with process method, completed two-phase segmentation and statistics of pore throat reservoir parameters, established shale gas remaining oil model for different wettability temperature conditions, and calculated reservoir volume and reservoir content. Liu Xiangjun et al. [5] established the pore throat network model of shale gas micro flow by using COMSOL software. For the first time, pan [6] and others applied the lattice method to the study of two-phase fluid simulation of pores, and used the method of pore water displacement to digitize the sandstone reservoir medium model.

Digital core reconstruction is mainly focused on the analysis and construction of core structure [7,8]. At present, the pores of digital cores in shale gas reservoirs are distributed from nanometer to millimeter. Therefore, the single resolution shale core model can not guarantee the integrity and correctness of micro pores in shale digital cores.

Therefore, we need to integrate a variety of technologies and multi-scale core structure information to describe the structural characteristics of digital core. Sok et al. [9] Based on CT, combined with BESM, FIB-SEM and other advanced imaging technologies, completed multi-scale structural imaging of carbon rock samples under multi-resolution conditions, and analyzed core pore distribution characteristics under multi-scale. Khalilki et al. [10] carried out multi-scale imaging of carbon rock
samples, sublimation of physical and chemical properties of carbon rock samples and multi-scale simulation. In acoustic simulation, Wang Chenchen et al. [11] successfully constructed a multi-scale digital core electrical model of double porosity carbon rock samples by using the multi-scale image superposition method. It is found that in the electrical simulation of digital core, the pore structure, shale, cement, mineral content and their distribution in the pores have a significant impact on the digital core simulation, and it has a greater impact on the complex and dense shale minerals [12].

To sum up, there are still many problems in the 3D digital image simulation of deep shale gas reservoir, no matter the mineral composition, the environment, or the constraints and other factors have a large or small impact on the 3D digital core. The current development trend should be as far as possible to multi-scale, multi-component, multi-pore digital core reconstruction discovery development, gradually improve its digital core reconstruction method, can do for each area of rock samples using advanced and effective 3D digital core reconstruction method for digital core reconstruction, better for the development of physical experiments and oil and gas development and so on.

3. Multi-scale, multi-component, dual porosity 3D digital shale core reconstruction

According to the investigation results of various digital core reconstruction methods and related literatures, it is shown that X-ray CT scanning digital core reconstruction method will be considered as the most important micro structure digital core reconstruction tool and method in the future due to its fast, accurate and non-destructive advantages. It is more suitable for the establishment of conventional and low-permeability cores, but it may lose its micro structure at the same time. The results show that, when the resolution of the hybrid method is higher, the microscopic characteristics of the core are more detailed, but there may also be some problems such as unable to directly obtain the information of representative larger volume element; because of the advantages of low cost and high efficiency of digital core reconstruction, random simulation method, under the condition and premise of high accuracy of its microstructure model, will be applied to the construction of core micro structure model. It is considered that it is an important tool and method of digital core reconstruction; the hybrid rule, which combines the common advantages of various digital core reconstruction tools and methods, is the best choice of digital core reconstruction method to establish dual porosity fracture network or core microstructure model including pore fracture and other complex types of digital network.

Due to the special and complex composition of shale gas reservoir, digital core pores are distributed from nanometer to millimeter. Therefore, the single resolution core model can not guarantee the integrity and correctness of micro pores in digital cores. X-ray (CT) scanning alone cannot solve the contradiction between field of view and micro pore resolution. Therefore, we need to integrate a variety of technologies and multi-scale core structure information to describe the structural characteristics of digital core.

After comparing the results of different design methods and literature research, it is found that MCMC method is more suitable for 3D shale gas reservoir 3D image and digital core assignment reconstruction, but we still need a series of targeted improvement and improvement to meet the design requirements of multi-component and complex gas reservoir structure.

MCMC method is based on three-dimensional Markov chain of three-dimensional state model sequence, that is, the state model value of each node position in the state sequence depends on the three-dimensional node state of the previous finite node positions, and the calculation formula of the position and probability of the three-dimensional node state is called the probability of obtaining conditions (i.e., the probability of node transition). The main method and idea of MCMC method for 3D image reconstruction is to use the idea of 3D Markov chain to calculate the probability of 3D Node conditions, and then use the probability algorithm in 3D conditional model to assign and reconstruct the image (Fig. 1). MCMC first adopts the idea of three-dimensional Markov chain, and uses the concept of neighborhood state model to calculate the probability of obtaining conditions, that is, the position and state model of each three-dimensional node are determined by the location and state
model of a finite number of three-dimensional nodes around it. The calculation formula of MCMC chain state model is as follows:

\[ p(X_{ijk}|X_{lmn}: 0<l<i, 0<m<j, 0<n<ijk|X_{i-1, j, k}, X_{i, j-1, k}, X_{i, j, k-1}) \]

The meaning of the formula can be simply described as the state of a point. The state of this point is affected by the conditional probabilities of X, y and Z components of this point and its adjacent points. In MCMC theory, these nearby points are called neighborhood. For example, if two fixed points are added to the common conditional probability of 13 nearby points, a 15 point neighborhood system can be formed (Fig. 2). In order to build 3D images in this way, the conditional probability of each two-dimensional image must be obtained by scanning, and then the two-dimensional images should be perpendicular to each other to construct three-dimensional images. However, before constructing, we should pay special attention to the scale of digital core reconstruction, that is, the scope of this model to be considered. If the scale is too large or too small, the model will be over or under considered.

Based on the above review. Inspired by Sok [9], Khalikii [10], Wang Chenchen [11], etc. At present, single resolution 3D digital core scanning model may not be able to fully describe the scale structure information of shale core. In this paper, by combining CT and FIB-SEM scanning technology, considering the composition and composition of shale reservoir core skeleton, using advanced Markov chain Monte Carlo core scanning method (MCMC), we can analyze and describe three-dimensional digital core samples as comprehensively and accurately as possible, and make full use of the spatial registration method of core scanning images to scan cores with different resolution Image registration. Then, the distribution characteristics of macropores and micropores are divided into pores and skeletons, and multi-level and multi-scale analysis are carried out, and the digital core reconstruction
of macropores and micropores is established by using superposition method. Finally, a multi-scale and multi-component dual porosity digital core model suitable for deep shale gas reservoir core is reconstructed.

3.1. Multi resolution core imaging
FIB-SEM can combine the focused ion beam of sample FIB imaging with the imaging electron beam of sample SEM, and the plug sample particles are continuously eroded by the focused ions, and are described under the action of the electron beam, which not only enables the sample to obtain higher image resolution, but also can truly image and restore the three-dimensional structural characteristics of the sample core.

3.2. Multi resolution image registration
Based on the sampling accuracy and inheritance of shale plunger scanning method, two types of high-resolution plunger scanning sample images can be analyzed and registered in space respectively, and the corresponding time and position of sub core plunger sample image in the shale plunger sample scanning image can be found, and the multi-scale shale core plunger scanning sample image can be formed.

3.3. Construction of dual porosity 3D digital core
(1) Two dimensional core slice analysis
   Based on the X-CT scanning electron microscope, the real images of low-resolution and high-resolution hole scanning characteristics of core can be obtained. Through the maximum spacing isolation method, the 2-inch scanning image is segmented in the micropores, and the binary image containing the real core is obtained. It is used to analyze and describe the characteristics of upward pore scanning in all aspects of the core. The high-resolution 2-value scanning image on each plane of the core is mainly used to describe the scanning characteristics of micro pores in each direction of the core.

(2) 3D digital core reconstruction
   A 3D digital rectangular core of shale is constructed by using Markov chain method and Monte Carlo method (MCMC) block diagram.

(3) Superposition
   The first step of using superposition method is to segment the four voxels of macroporous 3D digital core, and the segmentation diagram is shown in Fig. 3. According to the resolution and voxel ratio \( I (I = 4) \) of macropore and micropore 3D digital core, the four voxels in macroporous 3D digital core are segmented and converted into \( 1 \times 1 \times 1 \) four voxels, so that there is the same 3D voxel segmentation size between macroporous 3D digital core and microporous 3D digital core. Then, the pore systems of macroporous digital 3D core and microporous digital 3D core are superimposed.

Fig. 3 3D digital processing of double porosity carbon rock sample based on superposition method (Voxel thinning diagram(left) and double porosity digital core(right))
3.4. image segmentation
In order to eliminate the influence of filtering on noise, different noise filtering methods and algorithms can be selected according to different resolution and imaging processing effect, such as local median noise filtering, non local median filtering, etc. The method of image pore segmentation and image skeleton pore segmentation can more accurately complete the segmentation of multi-component scanning image and sample, so as to establish the 3D skeleton and digital core imaging model of multi-component scanning image and sample.

After the special processing of pore segmentation (Fig. 4) and skeleton 3D pore segmentation, the shale scanning image forms a grid with different scales. After processing, a new three-dimensional digital core structure model with different scales and components can be obtained (Fig. 5). Compared with other conventional core structure models that use 0 and 1 to represent pores and skeletons respectively, the structure description of cores after pore and skeleton segmentation is more comprehensive and accurate. For any grid point of the core model, the components needed to be included and the proportion of each scale component can be accurately given.

![Pore segmentation results of shale plunger sample low resolution image](image1)

![Multi scale and multi-component core 3D digital core](image2)

4. Conclusion
In the physical digital core reconstruction method, if X-ray CT scanning method can solve the contradiction between resolution and sample scale. It is undoubtedly a very important digital core reconstruction method in the future, especially for conventional low permeability rocks.

Combined with FIB-SEM and X-CT image analysis technology, the three-dimensional image registration analysis algorithm based on strata characteristics is used to accurately match the scanning image data of shale core with different resolutions. The multi-scale threshold method is used for segmentation, and then the pore, skeleton and shale minerals of shale core are divided and superimposed by superposition method. The 3D digital core model of double porosity deep shale gas
reservoir with multi-scale and multi-component is reconstructed. The micro spatial pore distribution structure of the model is similar to that of the real core, which basically overcomes the problem that the real core pore size and resolution of the single scale 3D digital core model cannot take into account. Multi scale and multi-component 3D digital core model of double porosity deep shale gas reservoir can obtain large-scale high-resolution and small-scale digital low-resolution core models at the same time. However, there are still obvious problems, such as: how to integrate the pore throat and reservoir structure of large and small-scale digital core, which is still a major technical problem in the analysis and application of digital core, which needs to be solved by advanced theory and technology.

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References
[1] Liu Xuefeng, 2010. Micro Numerical Simulation of rock acoustic and electrical properties based on digital core [D]. Qingdao: China University of Petroleum (East China). DOI:10.7666/d.y1778072.
[2] Rosenberg, LynchJ, GuéroultP, et al, 1999. High Re-solution 3D Reconstructions of Rocksand Composites [J].Oil & Gas Science & Technology.54(4):497-511.
[3] Liu Yang, 2007. Process method for digital core construction [d]. Qingdao: University of petroleum of China (East China). DOI:10.7666/d.y1214536.
[4] YoussefS, RosenbergE, GlandNF, et al, 2007. High Resolution CT And Pore-Network Models To Assess Petrophysical Properties Of Homogeneous And Heterogeneous Carbonates[C] //SPE/EAGE Reservoir Characterization and Simulation Conference; 20071028-31; Abu Dhabi, UAE(AE).1-12.
[5] Liu Xiangjun, Zhu Honglin, Liang Lixi, 2014. Sandstone digital petrophysical experiment based on Micro CT technology [J]. Acta geophysics Sinica.57(4):1133-1140.
[6] PanC, HilpertM, MillerCT, 2004. Lattice-Boltzmann Simulation of Two-Phase Flowin Porous Media[J].Water Resources Research,40(1):62-74.
[7] Zhang Li, sun jianmeng, sun Zhiqing, et al, 2012. Application of multipoint geostatistics in digital core reconstruction of 3D core por distribution [J]. Journal of China University of Petroleum (NATURAL SCIENCE EDITION).36(2):105-109.
[8] WuK, NunanN, Crawford JW, et al, 2004. An Efficient Markov Chain Model for The Simulation of Heterogeneous Soil Structure[J].Soil Science Society of America Journal. 68(2):346-351.
[9] SokRM, VarslotT, GhoussA, et al, 2010. Pore Scale Characterization of Carbonatesat Multiple Scales:Integration of Microct, BSEM and FIBSEM[J].Petroleum.51(6):379-387.
[10] KhaliliAD, ArnsJY, HussainF, et al, 2013. Permeability Upscaling for Carbonates from the Pore Scaleby Use of Multiscale X-Ray-CT Images[J]. SPE Reservoir Evaluation and Engineering.16(4):353-368.
[11] Wang Chenchen, Yao Jun, Yang Yongfei, et al, 2013. Structural characteristics of double porosity digital core of carbon rock sample [J]. Journal of China University of Petroleum (NATURAL SCIENCE EDITION).37(2):71-74.
[12] ShabroV, KellyS, Torres-VerdinC, et al, 2014. Pore-Scale Modeling of Electrical Resistivityand Permeabilityin FIB-SEM Images of Organic Mudrock[J].Geophysics. 79(5):D289-D299.