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Perspective

Construction of multi-mineral digital rocks for upscaling the numerical simulation of tight rock physical properties

Jiamin Hu[1], Zhanshan Xiao[2], Hao Ni[1], Xuefeng Liu[1]*

[1]*College of Science, China University of Petroleum, Qingdao 266580, P. R. China*

[2]*China Petroleum Logging CO. LTD., Xi'an 710077, P. R. China*

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Abstract:
Tight sandstone reservoirs are characterized by multi-scale pore space and high clay content, resulting in intricate rock physical responses. In this work, multi-scale imaging techniques, including computed tomography and stitched scanning electron microscopy, are applied to identify the large intergranular pores and micropores within major minerals. The pore structure of tight sandstones is quantitatively investigated using multi-scale images. Besides, multi-mineral digital rocks are constructed by performing registration and segmentation processing on the images obtained from microcomputed tomography and energy-dispersive scanning electron microscopy. These digital rocks are treated as composite materials consisting of different mineral types and micro-porosities, which enables the upscaling of the numerical simulation of rock physics properties. The results reveal that residual intergranular pores are interconnected through micropores within clay minerals, which significantly influences the electrical conductivities and permeabilities of tight sandstones. The proposed upscaling method can effectively couple the contribution of formation brine in multi-scale pores and clay minerals to bulk rock physics properties. This approach is suitable for the numerical simulation of diverse rock physical properties and can be applied to various tight reservoirs.

1. Introduction

Compared with conventional reservoirs, tight sandstones are characterized by strong heterogeneity, complex pore structure and high clay content, which results in complex relationships between the rock physical properties and reservoir parameters. Digital rock physics has emerged as a promising tool for quantitatively analyzing the impact of microstructure on the rock physical properties. Micro X-ray computed tomography (micro-CT) has been extensively employed to generate binary digital rocks, with a spatial resolution typically in the range of a few microns. These digital rock models serve as a foundation for numerical simulations of rock physics properties. Meanwhile, there are still numerous sub-resolution micropores in tight sandstone, and the porosity identified through micro-CT imaging is significantly lower than the helium porosity. Several multi-scale methods have been proposed to integrate the pore space identified with different resolutions, such as the hybrid superposition method, multi-scale pore network model, and image-based fractal characteristic approach. However, clay minerals in tight sandstones play a significant role in the rock physical properties. To accurately estimate these properties, it is crucial to identify pores of different scales and distinguish the major mineral types. In this work, we re-summarize and discuss pore-scale characterization via multi-scale imaging techniques and the upscaling numerical method based on multi-mineral digital rocks.

2. Pore-scale characterization of tight sandstones by multi-scale imaging techniques

Multi-scale imaging techniques are implemented to analyze the pore structure and identify the primary controlling factors that impact the rock physical properties of tight sandstones (Liu et al., 2017). A micro-CT scanner with a spatial resolution of 6.78 μm is employed to acquire three-dimensional (3-D)

*Corresponding author.
E-mail address: s21090042@s.upc.edu.cn (J. Hu); lh_xiaozs@cnpc.com.cn (Z. Xiao); nihao@upc.edu.cn (H. Ni); liuxf@upc.edu.cn (X. Liu).

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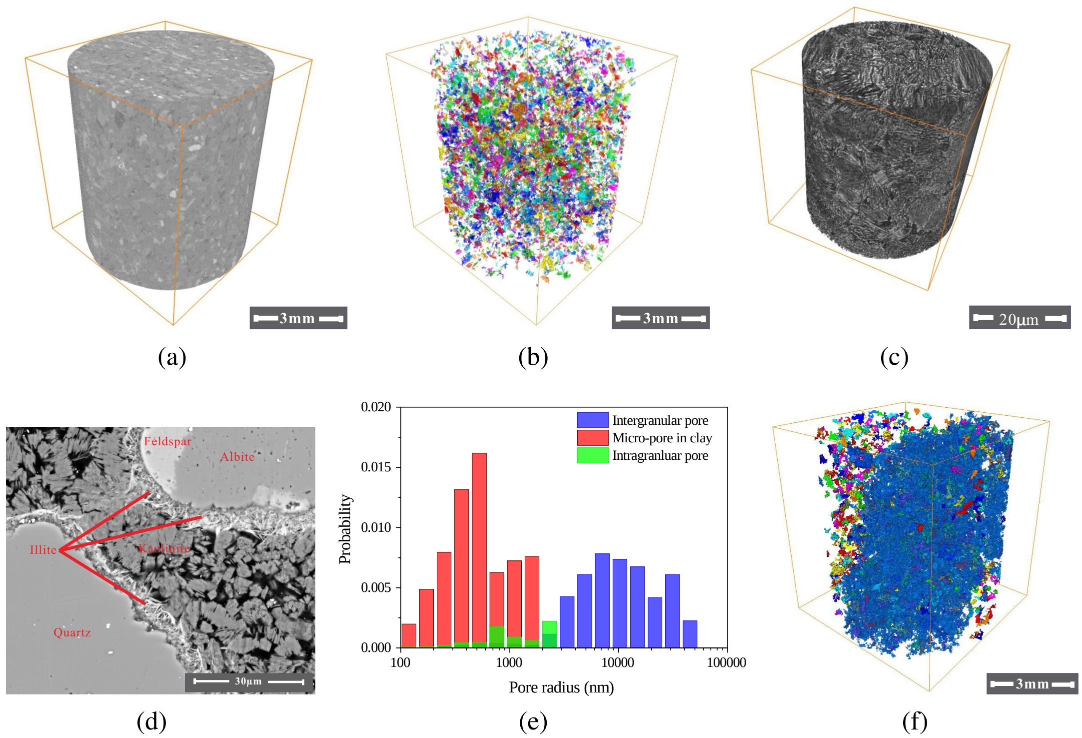

Fig. 1. (a) 3-D grayscale images, (b) Isolated pore clusters formed by CT-resolved intergranular pores, (c) 3-D grayscale images of kaolinite, (d) 2-D stitched SEM image, (e) Pore size distributions of different pore types and (f) percolation clusters formed by clay minerals and resolved intergranular pores (Modified from Liu et al. (2017)).

grayscale images of samples with a diameter of 25.4 mm (Fig. 1(a)). This imaging technique can only identify large intergranular and dissolved pores, which collectively contribute to less than 10% of the total porosity. The resolved pore space consists of isolated pore clusters and is unable to form a continuous conductive path throughout the sample (Fig. 1(b)). This suggests that the estimation of electrical conductivity or permeability based on binary digital rocks constructed by micro-CT is not feasible. The nano-CT technique is applied to obtain high-resolution 3-D images of kaolinite, with a spatial resolution of 65 nm (Fig. 1(c)). The micro-porosity of kaolinite can be calculated based on the obtained grayscale images, yielding an estimated value of approximately 45%. The micro-porosities of other major minerals are determined by stitched two-dimensional (2-D) scanning electron microscopy (SEM) images (Fig. 1(d)). An algorithm and the corresponding program are developed for the automatic differentiation of pore types, the quantification of pore size distribution, and the calculation of micro-porosity from the 2-D SEM images. The results indicate that tight sandstone has a wide pore size distribution range, characterized by a bimodal distribution (Fig. 1(e)). The findings demonstrate that chlorite, k-feldspar and illite possess micro-porosities of 5%, 10% and 45%, respectively. It is important to note that most intergranular pores are filled by clay minerals, resulting in a substantial decrease in both porosity and permeability. The micropores within pore-fillings cannot be identified using micro-CT due to the limitation of spatial resolution, which explains why the porosity determined by micro-CT is significantly lower than the helium porosity. Clay minerals and discernible intergranular pores are considered as a unified component for the analysis of their spatial connectivity. The results reveal that the micropores within the clay minerals predominantly connect most of the intergranular pores (Fig. 1(f)). The analysis of pore structure suggests that the electrical conductivities and permeability of tight sandstones are primarily governed by the existence of micropores and clay minerals.

3. Upscaling numerical method based on multi-mineral digital rocks

An upscaling method based on 3-D multi-mineral digital rocks is proposed through merging information from multi-scale images (Liu et al., 2021). By integrating a 3-D grayscale image obtained by micro-CT and a 2-D color mineralogy images acquired via energy-dispersive SEM (Fig. 2(a)), a multi-mineral digital rock is constructed by the processes of image registration and multi-threshold segmentation. According to the mineral composition of tight sandstone, the digital rock is divided into five components: pore space, kaolinite/illite, quartz/albite, K-feldspar, and chlorite (Fig. 2(b)). It is important to note that, except for clay minerals, the volume contents of the other major minerals match well with the results obtained by X-ray diffraction (XRD) analysis. The clay mineral contents in digital rocks are significantly

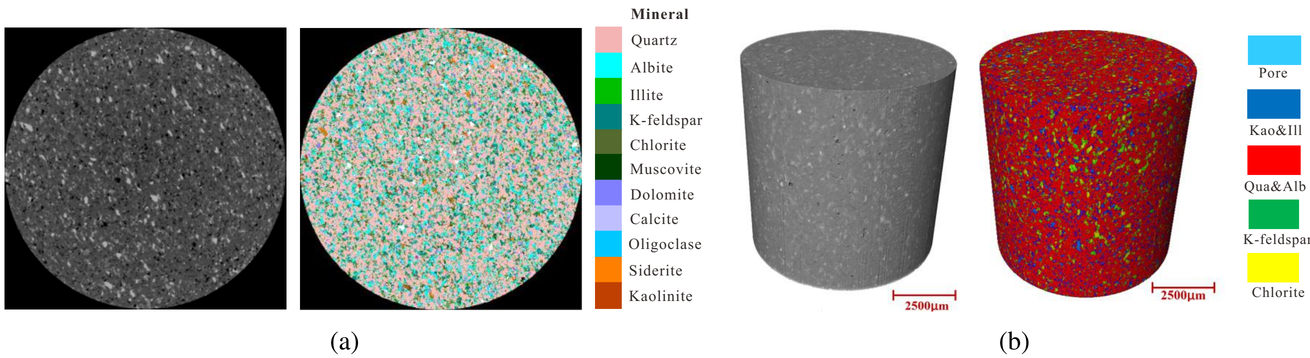

Fig. 2. (a) 2-D section of a 3-D grayscale image and its color mineralogy image, (b) volume renderings of a grayscale image and a multi-mineral digital rock (modified from Liu et al. (2021)).

higher compared to those obtained by XRD measurement, because both clay minerals and micropores within clays are categorized as clay components in the 3-D grayscale image. Subsequently, the bulk porosities of the multi-mineral digital rocks are calculated by taking the average of the micro-porosities, weighted by the volume fraction of the major minerals. Remarkably, the obtained bulk porosities agree well with helium porosity, indicating that the multi-mineral digital rocks exhibit similar porosity and major mineral contents to those of true samples.

In the upscaling numerical simulations of rock physics properties, multi-mineral digital rock is treated as a composite consisting of multiple mineral components with distinct properties. Each component is comprised of solid mineral grains and micropores. Taking the numerical simulation of electrical conductivity as an example, the equivalent conductivities of clay mineral components are determined using the Waxman and Smits model based on the cation exchange capacity and micro-porosities (Waxman and Smits, 1968). The equivalent conductivities of non-clay mineral components are calculated using Archie's equation based on their micro-porosities (Archie, 1942). The effective conductivity of each component, as well as the multi-mineral digital rocks, are the inputs to the finite element method solver. Laplace's equation is solved numerically to obtain the equivalent electrical conductivities. The contributions of formation brine in multi-scale pores and clay minerals are simultaneously considered in the upscaling method. By utilizing this simulation method, the accuracy of numerical simulation results for various physical properties, including electrical conductivity, elastic modulus and permeability, can be improved.

4. Conclusions

Multi-scale imaging techniques provide a powerful tool to quantitively analyze the pore structure of tight sandstones from the nm to the cm scale. It has been observed that intergranular pores are interconnected through micropores, that is, these micropores and clay minerals dominate the rock physical properties of tight sandstone. The accuracy of estimated properties can be improved by the upscaling method based on multi-mineral digital rocks without a substantial increase in computation cost. This method can be applied to other tight reservoirs, such as shale and tight conglomerate reservoirs.

However, the construction of multi-mineral digital rocks does not consider the interface gaps between different mineral grains that have a significant impact on the rock physical properties of tight sandstones. Therefore, it is essential to address this limitation in future research to further enhance the accuracy and reliability of estimating the rock physical properties of tight sandstones.

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Conflict of interest

The authors declare no competing interest.

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