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Permeability prediction of shale matrix reconstructed using the elementary building block model

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HIGHLIGHTS

- REV-scale structure of shale matrix is reconstructed.
- A generalized lattice Boltzmann model for porous flow with slippage.
- Permeability of the REV is predicted.
- Effects of kerogen content, grain size and interparticle pores are studied.
- Effects of slippage and adsorption are investigated.

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ABSTRACT

Representative elementary volume (REV)-scale structure of shale matrix is reconstructed based on elementary building block (EBB) model using a stochastic reconstruction method called Quartet Structure Generation Set. In the EBB model, various constituents with different pore morphologies in shale matrix including organic matter and inorganic minerals are considered as different EBBs, and in each EBB, specific structural parameters and transport properties are locally defined. A generalized lattice Boltzmann model for fluid flow through tight porous media with slippage is employed to simulate fluid flow through the reconstructed REV-scale structures. A four-EBB shale matrix including clay, calcite, pyrite and organic matter is studied and its permeability is predicted. Effects of organic content, grain size, interparticle pores on the permeability of the REV-scale matrix are investigated. It is found that smaller grain size and interparticle pores can increase the permeability. The influences of complex physical processes such as slippage and adsorption on the REV-scale permeability are also explored. Slippage effect increases as the pore size decreases. Adsorption has two opposite effects on the permeability, and which one dominates depend on pressure. The present study can help understand gas transport in shale matrix and improve reservoir scale studies.

1. Introduction

Over the past decades, shale gas exploitation from mudrocks (mudstone or shale) has rapidly increased due to advanced techniques such as horizontal drilling and multi-stage hydraulic fracturing. However, mudrocks as shale gas reservoir rocks remain poorly understood compared to conventional reservoirs, largely due to their complex microstructures and varying constituents [1,2], which show high heterogeneity and can differ dramatically between different shale plays and even within the same play [1–7]. Different constituents exist in shale matrix including organic matter (OM, also known as kerogen) and inorganic minerals [3–8]. The pore morphology (porosity, pore size, pore distribution, pore connection, etc.) in different constituents is quite different. The "elementary building blocks (EBB)" model thus has been adopted to perform quantitative analysis of pores in each constituent [3,4]. In this model, each constituent (calcite, clay, pyrite, quartz, OM, etc.) in the shale matrix can be considered as an EBB [8], where specific pore morphology can be described and unique transport properties can be defined. The highly heterogeneous microstructures and compositions of mudrocks can be obtained by combining the right amount of different homogeneous EBBs and distributing them in a proper way [8]. Due to such a structural

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heterogeneity, it is expected that fluid flow in shale matrix is very complex. Complicating matters more is the gas slippage because typical pore size in shale matrix is from a few nanometers to a few microns [6,9], leading to gas transport with relatively high Knudsen number (*Kn*, ratio between the mean free path of gas molecules and the characteristic pore size of a porous medium) [10–12]. Further, adsorbed gas in shale matrix particularly in OM with higher affinity also plays a role on the gas transport in shale matrix [13–16]. On the whole, shale gas transport in shale matrix can be described by fluid flow with complicated physics (Klinkenberg's effect, adsorption processes, etc.) in a heterogeneous porous medium with varied components and complex sub-micron structures.

Permeability is a key variable to describe the transport capacity of a porous medium, which is defined via Darcy's law in terms of the ratio of fluid rate to the pressure gradient within the porous medium [17]. Although permeability is a well-established property of most relatively uniform porous media, its actual dependence on complex geometries and topologies such as those in shale matrix is not well understood [18]. The measured permeability of a shale matrix is not only affected by the specific geometric and topological properties, but also under certain scenarios varies with operating parameters and surface phenomena due to slippage [19]. Merely structure-dependent permeability is called intrinsic permeability, where there is no slippage. However, for shale matrix with typical pore size of nanometers to microns, *Kn* number is relatively high, and gas flow can be beyond the continuous flow regime, leading to slip flow, transition flow, or even free molecular flow. Due to slippage, the measured gas permeability (apparent permeability) is higher than that of the liquid (intrinsic permeability), and the difference becomes increasingly important as *Kn* increases [20]. Finally, shale permeability is also affected by surface adsorption/desorption processes which change the volume of the void space and influence the local fluid flow near the surface [13–16].

In the present study, the EBB model is adopted to reconstruct the REV-scale structures of shale matrix, accounting for volume fraction, grain size and distributions of different EBBs in the shale matrix, as well as statistic structural parameters and transport properties defined in each EBB [3,4,8] (Section 2). Then, a generalized lattice Boltzmann (LB) model for fluid flow through tight porous media with Klinkenberg's effect, which is an REV-scale model developed by the authors very recently [21], is then adopted to simulate fluid flow in the reconstructed shale matrix (Section 3). The emphasis is put on predicting the effective permeability of the REV-scale shale matrix (Section 4). Effects of OM content, grain size, interparticle pores, slippage, pressure and adsorption on the REV-scale permeability are explored (Section 4). To the best of authors' knowledge, only very recently Naraghi and Javadpour [22] performed such a numerical study at the REV scale in which all the inorganic minerals were considered as a single constituent, and thus two constituents (EBBs) were studied, namely OM and inorganic minerals.

2. Elementary building block reconstruction

The microstructures and compositions of mudrocks can differ dramatically [5], and words like "*very complex*", "*widely varied*" and "*high heterogeneity*" are commonly used to describe them. Identification of pore networks is challenging due to the following distinct features of mudrock-related pores: first, these pores vary in size from nanometers to micrometers; and second, they are closely related to mineralogy [2–4]. The latter feature results in widely varied pore morphologies in different constituents under different pressure and temperature conditions. Recently, significant effort has been devoted to experimentally understanding the geometrical characteristics of shale matrix by using several measurement techniques [1–4,6,7,9,5,23,24] such as low pressure gas adsorption, mercury injection porosimetry (MIP), and small/ultra-small angle neutron scattering (SANS/USANS) [25,26]. Recently developed direct measurement techniques such as Focused ion Beam (FIB)-scanning electron microscope (SEM) and Broad ion Beam (BIB)-SEM techniques allow visualization of the nano/micro-structures and the pore characteristics of mudrocks on high quality flat surfaces, greatly enhancing our understanding of microstructures of shale matrix below the sub-micron scale [2,3,7].

Louck et al. [2] presented a thorough overview of mudrock-related pores, and they systematically classified matrix-related pores (fractures is not included) into mineral interparticle pores (InterP pores), mineral intraparticle pores (IntraP pores) and OM pores, respectively. Pores in different constituents of shale matrix show quite different characteristics of pore size, distribution and connection. Therefore, the contents and distributions of OM and different inorganic minerals in shale matrix, which are affected by the mechanical compaction and diagenesis [2], play an important role on the porosity and permeability of the shale matrix. To consider the relation of pores to mineralogy, the EBB model is employed to study the details of pore morphology in each constituent of shale matrix [3,4]. Fig. 1 shows the schematic of EBB-based reconstruction processes of REV-scale shale matrix which can be described as follows.

Step 1 – *EBB pore morphology analysis*. In shale matrix, each constituent can be considered as an EBB, and in each EBB information on porosity, pore size distribution, pore shape, distribution and connection can be analyzed using FIB-SEM and BIB-SEM. A set of morphologic parameters, including pore area, pore perimeter, pore long/short axis length, etc., can be adopted to comprehensively quantify the pore morphology related to each EBB [4].

Step 2 – *EBB classification*. Based on the classification of Louck et al. [2], the EBBs can be classified into different groups such as EBB with not-connected IntraP pores, EBB with connected IntraP pores, and EBB with InterP pores [2,8]. For example, minerals such as quartz and calcite usually have extremely low porosity with not-connected IntraP pores [8], while OM is widely observed to have relatively high porosity with connected pores [1,7]. Following the studies of Houben et al. [8], clay is highlighted in the present study as shale matrix is often clay-rich. In the present study, clay, as a basic EBB, is served as a matrix in which other EBBs are embedded.

Step 3 – *EBB content and distribution determination*. EBB contents can be analyzed by the X-ray powder diffraction measurements. Details of EBB distributions can be obtained using the FIB-SEM and BIB-SEM [2].

Step 4 – *REV-scale shale matrix reconstruction*. The highly heterogeneous microstructures and compositions of mudrocks can be obtained by combining the right amount of different homogeneous EBB (compositions) and distributing them in a proper way (distributions) [8]. In the present study, a method called Quartet structure generation set (QSGS) [27] is adopted to reconstruct the shale matrix structures based on the EBB model. The QSGS has been demonstrated to be capable of generating morphological features closely resembling the forming processes of many real porous media [27], in which the volume fraction, particle size, particle orientation, shape of each composition and interactions between different compositions can be all taken into account. The reconstruction begins with a domain $L_x \times L_y \times L_z$ merely filled with clay (L_x, L_y and L_z are the domain length along *x*, *y* and *z* direction). Then, the QSGS proceeds for generating a certain EBB, for example, **A**, including two steps: Seeding and Growth, which are described as follows.