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Research paper

Pore structure characteristics of tight sandstones in the northern Songliao Basin, China

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ABSTRACT

Understanding the pore structure characteristics of tight gas sandstones is the primary purpose of reservoir evaluation and efforts to characterize tight gas transport and storage mechanisms and their controls. Due to the various pore types and multi-scale pore sizes in tight reservoirs, it is essential to combine several techniques to characterize pore structure. Scanning electron microscopy (SEM), nitrogen gas adsorption (N_2GA), mercury intrusion porosimetry (MIP) and nuclear magnetic resonance (NMR) were conducted on tight sandstones from the Lower Cretaceous Shahezi Formation in the northern Songliao Basin to investigate pore structure characteristics systematically (e.g., type and size distribution of pores) and to establish how significant porosity and permeability are for different pore types. The studied tight sandstones are composed of intergranular pores, dissolution pores and intercrystalline pores. The integration of N_2GA and NMR can be used as an efficient method to uncover full pore size distribution (PSD) of tight sandstones, with pore sizes ranging from 2 nm to dozens of microns. The full PSDs indicate that the pore sizes of tight sandstones are primarily distributed within 1.0 μm. With an increase in porosity and permeability, pores with larger sizes contribute more to porosity. Intercrystalline pores and intergranular/dissolution pores can be clearly distinguished on the basis of mercury intrusion and surface fractal. The relative contribution of intercrystalline pores to porosity ranges from 58.43% to 91.74% with an average of 79.74%. The intercrystalline pores are the primary contributor to pore space, whereas intergranular/dissolution pores make a considerably greater contribution to permeability. A specific quantity of intergranular/dissolution pores is the key to producing high porosity and permeability in tight sandstone reservoirs. The new two permeability estimation models show an applicable estimation of permeability with R^2 values of 0.955 and 0.962 for models using D_{max} (pore diameter corresponding to displacement pressure) and D_f (pore diameter at inflection point), respectively. These results indicate that both D_{max} and D_f are key factors in determining permeability.

1. Introduction

In contrast to shale oil and gas, tight sandstone gas is the most feasible resource type to develop and has great potential. It has been successfully developed in the Ordos, Sichuan and Tarim Basins of China (Zou et al., 2010; Dai et al., 2012; Li et al., 2015b). Compared with conventional natural gas, tight sandstone gas accumulations have unclear trap boundaries and a continuous distribution, are near the source rocks, and have a low abundance of natural gas (Dai et al., 2012), all of which result in a significant increase of exploration risk. Therefore, research on the pore structure characteristics in tight sandstone reservoirs is necessary to characterize tight sandstone gas transport and storage mechanisms and their controls (Nelson, 2009; Clarkson et al., 2012a, 2013; Li et al., 2016; Xiao et al., 2016b). However, there are major challenges in evaluating the pore structure characteristics in tight sandstones due to the extensive development of nanopore networks and broad PSD, which are usually caused by extensive compaction and cementation (Rezaee et al., 2012).

In recent years, numerous researchers have used qualitative and quantitative experimental approaches to study pore structure

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characteristics of tight sandstones, including scanning electron microscopy (SEM), transmission electron microscopy (TEM), nitrogen gas adsorption (N_2GA), mercury intrusion porosimetry (MIP) and nuclear magnetic resonance (NMR) (Bustin et al., 2008; Loucks et al., 2009, 2012; Clarkson et al., 2012a, 2013; Xi et al., 2016). However, all of these techniques have their own strengths and limitations. SEM and TEM images can directly observe the size, morphology, and type of pores from the nano-to micron-scale. However, it is difficult to obtain the quantitative parameters (e.g., pore volume and pore size distribution) using these techniques, and there also is a major tradeoff between the resolution and vision area of an image (Curtis et al., 2012; Li et al., 2015a). The N_2GA technique has failed to detect pores larger than 200 nm due to the experimental mechanism used and sample size. Mercury can intrude into smaller pores with greater mercury intrusion pressure, whereas high mercury intrusion pressure may give rise to the potential risks of particles breaking, rocks compressing and pore networks becoming damaged (Clarkson and Bustin, 1996). Although the NMR technique is nondestructive and time-saving, the result derived from this technique is in the time domain and therefore needs to be converted to PSD in the length domain using other experimental results. The echo spacing and grain surface relaxivity codetermine the minimum measured pore size of NMR.

It has been recognized that the integration of multiple techniques may be an effective method to reveal the full PSD of unconventional reservoirs (Schmitt et al., 2013, 2015; Li et al., 2015a; Xi et al., 2016). Zhao et al. (2015) and Xi et al. (2016) proposed that the combination of the PMI (pressure-controlled mercury injection) and RMI (rate-controlled mercury injection) techniques can be used to characterize the full PSD of tight sandstone reservoirs. In fact, this method not only ignores the potential pitfalls in characterizing fine pores using such a high mercury intrusion pressure, but RMI techniques also overestimates the size of larger pores that have an irregular shape and crude surface (Desbois et al., 2011). Li et al. (2015a) stated that N_2GA and NMR can be used as complementary techniques to uncover the full PSD in shale, but specific processes were not provided in detail. The integration of N_2GA and MIP has been discussed by Schmitt et al. (2013) regarding how to determine the full PSD in seal rocks. However, the junction of two dV/dD curves (the differential of the pore volume to diameter) from N_2GA and MIP experimental data cannot be found in the studied tight sandstone samples. The fitness of this method may therefore be limited, requiring a more suitable integration approach for tight sandstones, with different petrophysical parameters and mineral compositions, to be established.

In this research, tight sandstone samples from the Lower Cretaceous Shahezi Formation in the northern Songliao Basin were used as an example. Microscopic pore structures (e.g., pore types and PSD) were systematically characterized on the basis of multiple experimental analyses. A new method was established to determine the full PSD using the integration of N_2GA and NMR techniques, and the significance of intergranular/dissolution pores and intercrystalline pores to petrophysical parameters were discussed according to the full PSD curve.

2. Materials and methods

2.1. Geological background and samples

Six tight sandstone samples were collected from the Lower Cretaceous Shahezi Formation of the central depressed zone in the northern Songliao Basin for experimental analysis. The Songliao Basin, which is one of the richest basins in oil- and gas, has an area of approximately $26 \times 10^4 km^2$ and is located in northeastern China (Zhang and Zhang, 2013). The tight reservoir of the Lower Cretaceous Shahezi Formation is composed of moderate-coarse clastic rocks, including coarse sandstones, glutenites and conglomerates, mainly corresponding to a fan delta and braided river delta sedimentary environment (Zhao et al., 2016). Due to a very deep burial depth (>2500 m), mechanical compaction, dissolution and cementation, including clay minerals, carbonate and silicate cements, are the main diagenesis types that influence the petrophysical parameters of tight reservoirs. The samples were drilled as regular core plugs with a diameter of approximately 2.5 cm. All core plugs were previously soaked in a mixed solution of alcohol and trichloromethane to remove residual bitumen. After drying, the porosity and permeability of the samples were first measured, and core plugs were subsequently cut into four parts for the SEM, N_2GA, MIP and NMR experiments.

2.2. Experimental methods

Helium porosity and nitrogen permeability were determined using a CMS-300 automatic porosity and permeability measuring instrument under a confining pressure of approximately 30 MPa. The transient pulse decay method was used to measure permeability, and all the permeability values were Klinkenberg-corrected. The gas pressures at the upstream end of the rock sample were set to approximately 0.2 MPa, 0.4 MPa, 0.6 MPa, and 0.8 MPa. The measurement error of porosity is 0.01%. SEM analysis was performed using a TESCAN MIRA 3XMU scanning electron microscope. Samples with mechanical polishing and fresh surfaces were used to observe the geometrical morphology of pores and minerals. A Quadrasorb SI surface area and pore size analyzer was used to execute the N_2GA analysis at subcritical temperature (77 K). Samples (60–80 mesh) were degassed under high vacuum for 8 h at 220°C to ensure removal of any bound and capillary water adsorbed with the clay minerals (Drits and McCarty, 2007; Srodon and McCarty, 2008). This approach can also avoid irreversible changes to the structure of clays (Kuila and Prasad, 2013). The MIP experiment was carried out using an AutoPore IV9510 porosimeter in the Daqing Oilfield Laboratory of China. Before analysis, tight sandstone samples were dried at 150 °C for at least 12 h in a vacuum oven. The maximum intrusion pressure was 100 MPa, corresponding to a pore throat radius of approximately 7 nm. A MARAN-2 MHz nuclear magnetic resonance spectrometer was used to execute NMR measurements in the CNPC laboratory of China. The samples were fully saturated in 7000 mg/L NaCl brine solution, consistent with the formation water, for at last 12 h under vacuum state. On the basis of the pre-experiment and the Chinese Oil and Gas Industry Standard SY/T 6490-2014, the experimental parameters were determined as follows: TE, 0.3 ms; waiting time, 6 s; echo numbers, 2048; numbers of scans, 128.

3. Results

3.1. Petrophysical characteristics and pore types

Porosity, permeability and mineral percentage data of six tight sandstone samples are presented in Table 1. The porosity of six tight sandstone samples ranges from 2.8% to 5.7% with an average of 4.7%. The permeability varies from 0.01 mD to 0.259 mD. Note that sample S31 has the highest porosity of six samples but corresponds to a permeability of only 0.024 mD. Table 1 shows that the tight sandstone samples consist of quartz, feldspar, clay minerals and a small quantity of dolomite, calcite and pyrite minerals. The dominant minerals are quartz and feldspar with a mean value of 44.8% and 30.2%, respectively. The content of clay minerals range from 8% to 33% with an average of 19.8%, and illite and smectite mixed layer and chlorite are predominant in clay minerals. As discussed by