An improved method to characterize the pore-throat structures in tight sandstone reservoirs: Combined high-pressure and rate-controlled mercury injection techniques

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Abstract
The pore-throat size determines the oil and gas occurrence and storage properties of sandstones and is a vital parameter to evaluate reservoir quality. Casting thin sections, field emission scanning electron microscopy, high-pressure mercury injection and rate-controlled mercury injection are used to qualitatively and quantitatively investigate the pore-throat structure characteristics of tight sandstone reservoirs of Xiaoheba Formation in the southeastern Sichuan Basin. The results show that the pore types include intergranular pores, intragranular dissolved pores, matrix pores, intercrystalline pores in clay minerals, and microfractures, and the pore-throat sizes range from the nanoscale to the microscale. The high-pressure mercury injection testing indicates that the pore-throat radius is in range of 0.004–11.017 μm, and the pore-throats with a radius >1 μm account for less than 15%. The rate-controlled mercury injection technique reveals that the tight sandstones with different physical properties have a similar pore size distribution (80–220 μm), but the throat radius and pore throat radius ratio distribution curves exhibit remarkable differences separately. The combination of the high-pressure mercury injection and rate-controlled mercury injection testing used in this work effectively reveals the total pore-throat size

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distribution in the Xiaoheba sandstones (0.004–260 μm). Moreover, the radius of the pore and the throat is respectively in range of 50–260 μm and 0.004–50 μm. The permeability of the tight sandstones is mostly affected by the small fraction (<40%) of relatively wide pore-throats. For the tight sandstones with good permeability (>0.1 mD), the larger micropores and mesopores exert a great influence on the permeability. In contrast, the permeability is mainly influenced by the larger nanopores. Furthermore, the proportion of narrow pore-throats in tight sandstones increases with reducing permeability. Although the large number of narrow pore-throat (<100 nm) makes a certain contribution to both reservoir porosity and permeability, they have contribution to the former is far more than to the latter.

Keywords
Tight sandstone, pore structure, rate-controlled mercury injection, southeastern Sichuan Basin, Xiaoheba Formation

Introduction
With the increasing depletion of conventional oil and gas reservoirs, tight oil and gas reservoirs are becoming an area of increased research interest in the current geological community (Camp, 2011; Ghanizadeh et al., 2015a, 2015b; Yin and Gao, 2019). Recently, due to advances in microscale pore-throat characterization methods and horizontal drilling and hydraulic fracturing techniques (Benzagouta, 2015; Fall et al., 2015; Lu et al., 2015; Nelson, 2009; Rezaee et al., 2012), significant achievements have been obtained in the exploration and development of tight oil and gas reservoirs globally, such as the Cardium Formation in the Alberta Basin (Fic and Pedersen, 2013), the Barnett Formation in the Fort Worth Basin (Hill et al., 2007), and the Bakken Formation in the Williston Basin (Ghanizadeh et al., 2015a,b; Shen et al., 2018). There are also plenty of tight oil and gas resources in China’s oil-bearing basins, for example, the Yanchang Formation in the Ordos Basin, the Carboniferous and Cretaceous Formations in the Tarim Basin, and the Xujiahe Formation in the Sichuan Basin (Wang et al., 2018; Yin et al., 2018; Zou et al., 2012). Tight sandstones, as an important component of global oil and gas reservoirs, are defined as reservoirs with a porosity lower than 10%, an air permeability lower than 1 mD or an in situ permeability lower than 0.1 mD (Higgs et al., 2007; Spencer, 1985; Zou et al., 2015). A set of typical marine tight sandstones sandwiched between the overlying thick mudstones of the Hanjiangian Formation and the underlying shales of the Longmaxi Formation is developed in the Xiaoheba Formation of the Lower Silurian system, southeastern Sichuan Basin, thereby forming a good source–reservoir–caprock association. In the petroleum exploration practices in the Sichuan Basin, indications of oil and gas were encountered in the Xiaoheba Formation (Zhu et al., 2016). In recent years, a significant breakthrough has been made in the exploration of the shale reservoirs of the Longmaxi Formation, which contributed to establishing the first shale gas reservoir in China. Based on this breakthrough, further study has been facilitated on the shale gas of the Longmaxi Formation and its overlying Xiaoheba Formation tight sandstone strata containing gas (Wang et al., 2019). In contrast to conventional reservoirs, tight sandstone reservoirs generally experience a complicated burial evolution with strong heterogeneity, resulting in various types of pores and very narrow throats in complex pore structures (Yin
et al., 2019b; Zhu et al., 2016). As a result, it is essential to determine the structure of these microscale pore-throats and traits of the size distribution, which can realize an increased production in tight oil and gas reservoirs.

Currently, there are various methods to characterize the pore-throat structure of tight sandstones, including polarizing light microscopy (PLM), field emission scanning electron microscopy (FE-SEM), electron backscatter diffraction microscopy (EBSD-SEM), focusing ion beam microscopy (FIB-SEM), micro/nanoscale X-ray computed tomography (X-CT) nuclear magnetic resonance (NMR), nitrogen adsorption, high-pressure mercury injection (HPMI), and rate-controlled mercury injection (RCMI) (Bera et al., 2011; Geet et al., 2001; Liu et al., 2019; Xu et al., 2019; Zhou et al., 2019). Although each method has its own advantages in characterizing the structure of pore-throats, there are also respective limitations: PLM and various SEM methods are applied directly to examine the pore-throat size, geometry, and type but fail to obtain quantitative parameters (Loucks et al., 2009). NMR can quantify the size distributions of pores and throats, but its evaluation of the pore-throat structure of ultra-tight reservoirs is still being explored (Rosenbrand et al., 2015; Zhang et al., 2016). Nano- and microscale CT can obtain analog 3D images of the pore-throat network inside sandstones, but the threshold setting is controlled by artificial factors that influence the measurement accuracy (Gane et al., 2004). NGA technique can describe pore-throat types and structures of tight reservoirs, but it has a narrow test range dominated by nanometer scale pores (Yao and Liu, 2002). HPMI technique can only indirectly measure the very narrow throats but shields the numerous relatively large pores (Medina et al., 2017). Compared with the HPMI technique, the RCMI technique can overcome this drawback and quantitatively characterizes the pore and throat size distributions separately. However, due to the restricted experimental conditions, this method cannot measure pore-throats smaller than 0.12 μm (Zhao et al., 2015). Based on the above statements, a single method may fail to characterize the full-scale pore-throat structure of tight sandstone reservoirs. Thus, a combination of several experiments is an effective method for tight sandstones pore-throat characterization.

Previous research on the Xiaoheba Formation has primarily focused on the sedimentation process, the sequence stratigraphic framework, the thermal evolution of the source rocks and the basic characteristics of the reservoirs (Gong et al., 2017; Hu et al., 2017; Li et al., 2015; Wang et al., 2011; Zhu and Chen, 2012; Zhang et al., 2017). Few studies have focused on the pore-throat structure of the tight sandstone reservoirs, i.e., quantifying the pore and throat size distributions. However, the pore-throat structure determines the storage and seepage properties of tight reservoirs and is a significant factor for reservoir evaluation. In this work, taking the tight sandstones in the Lower Silurian Xiaoheba Formation, southeastern Sichuan Basin, PLM, FE-SEM, HPMI, and RCMI are conducted to investigate the pore-throat systems. The main purposes in our study are to: (a) intuitively describe the pore morphologies and types of tight sandstone reservoirs; (b) quantitatively characterize full-scale pore size distribution of tight sandstone reservoirs with an improved method (combination of HPMI and RCMI testing); and (c) clarify the specific contribution of pore-throats with different sizes on reservoir physical parameters.

**Geological background**

The tectonic location of the southeastern Sichuan Basin is surrounded by the south-central region of the Yangtze plate, the north margin of the central Guizhou ancient uplift, and the west region of the central Sichuan ancient uplift, where the geological tectonics is complex.
Figure 1. Geological maps of the Sichuan Basin and Structural location of the study area (Modified from Yuan et al., 2012). Signs from P1 to P8 represent the following outcrops: Xiaohe, Sanquan, Haokou, Huangcaochang, Xiaojitan, Shuangliuba, Lengshuixi, Liziya, respectively. CSPU: Central Sichuan Paleo-uplift; CGOL: Central Guizhou Oldland; CKFB: Chengkou Fracture Belt; HYFB: Hanyuan Fracture Belt; LMSFB: Longmenshan Fracture Belt; QYSFB: Qiyueshan Fracture Belt.

and Qiyueshan fracture zones run through the area (He et al., 2013; Guo et al., 2004; Yuan et al., 2012) (Figure 1). The Xiaoheba Formation was deposited in the late period of the Early Silurian. Due to the influence of the Caledonian movement, the South China plate has compressed and spliced the Yangtze plate toward the northwest, which has caused the integral uplift of the Yangtze plate. In addition, the center of sedimentation has gradually moved to the northwest, and water has become shallow, which has developed a typical delta sedimentary sequence with reverse graded bedding (Zhu and Chen, 2012) (Figure 2). The Xiaoheba Formation sediment is thicker in the southeastern Sichuan Basin, with the thickness ranging from 200 to 300 m. The ratio between the sandstone and stratum thicknesses is from 0.47 to 0.81, with an average of 0.59. The lithologic association of the Xiaoheba Formation shows slight differences in each observed section, which, overall, can be divided into two segments—the upper segment is mainly composed of interbedded fine siltstones and mudstones, and the lower segment chiefly consists of medium and thick siltstone layers. Furthermore, several sedimentary structures are developed in each observed section, including wavy bedding, cross-bedding, parallel bedding and horizontal bedding. As a valuable stratum for petroleum exploration in the southeastern Sichuan Basin, the Xiaoheba Formation, vertically, is sandwiched between the black carbonaceous shale of the Longmaxi Formation and the grayish-green thick mudstone of the Hanjiangian Formation, which has formed excellent source–reservoir–caprock combinations with both sufficient source rocks and a large mudstone caprock thickness.
Samples and experimental methods

Samples

Presently, there are no wells with complete cores in the Xiaoheba Formation, southeastern Sichuan Basin; therefore, all the experimental samples (totaling 290) were obtained from the fresh rocks of seven survey sections (the Xiaohe, Sanquan, Haokou, Huangcaochang, Shuangliuba, Lengshuixi, and Xiaojitan sections) (Figure 1). In the process of sample
preprocessing, the rock pieces were cut into cylindrical core plugs with a diameter of 2.5 cm. All core plugs were cleaned with organic solvents to remove any residual oil and bitumen and then dried under vacuum at 105°C for 24 h. Porosity and permeability tests were performed first, and then these core plugs were divided into four parts for thin-section observation, FE-SEM, HPMI, and RCMI experiments.

**Experimental methods**

Two hundred ninety samples stained with blue epoxy resin under vacuum were processed into thin sections with a thickness of 0.03 mm, and all thin sections were then polished on both sides to perform petrographic, mineralogical, and pore type analyses with the polarizing light microscopy instrument (Leica DM4500P) (Leica Microsystems Inc, Wetzlar, Germany).

The samples used for FE-SEM (Quanta 250 FEG) (FEI, Hillsboro, OR, USA) were cut into small cubes with a volume of approximately 1 cm³ and were gold-coated. A relatively flat surface selected on the cube was used to examine the pore-throat geometry and type. Furthermore, energy spectrum analysis was conducted to identify the mineral compositions. This analysis was performed at a working voltage ranging from 0.1 to 20 kV at a room temperature of 20°C and a humidity of 53%.

Eighty core plugs selected for the HPMI experiments (Auto Pore IV 9500) (Micromeritics Company, USA) were preprocessed under vacuum at a temperature of 110°C for 2 h, and mercury was then injected into the samples. After reaching the maximum pressure, the pressure was gradually reduced, and the mercury was ejected from the core plugs. Finally, injection and ejection curves were acquired from the HPMI experiments.

Six typical samples selected from among the 80 HPMI core plugs were used to perform RCMI experiments (ASPE-730) (Coretest Systems, Inc., Reno, NV, USA). To maintain the injection rate quasi-static, mercury injection was conducted at a low constant rate of 0.00005 ml/min. Through detection of the pressure fluctuations during the mercury injection process, the pores were determined in accordance with the sudden reductions in capillary pressure, and the throats were recognized by augmenting the capillary pressure. In these experiments, the highest injection pressure was 900 psi (approximately 6.25 MPa), and its corresponding pore-throat size lower limit was 0.12 μm. The RCMI experiments not only provided several structural parameters, such as the pore body volume and radius, throat volume and radius, and pore body-to-throat ratio, but the RCMI experiments also provided individual capillary pressure curves of the total pore-throats, pores and throats.

**Results**

**Petrophysical characteristics**

Based on the identification results of the 290 thin sections, the lithologies of the Xiaoheba Formation reservoirs in the southeastern Sichuan Basin are dominated by feldspathic and lithic quartzarenites (Figure 3(a)). The detrital mineralogy is dominated by quartz (mostly monocrystalline), which ranges from 74.5% to 97.0%, with an average of 87.5%. Feldspar, consisting of K-feldspar and plagioclase, ranges from 2.0% to 15.5%. The rock fragments range from 1.0% to 16% with an average of 5.0%, which are mainly metamorphic rocks, with trace amounts of igneous and sedimentary rocks. The interstitial material is mainly
composed of a mudstone matrix with an average content of 11.53% and some carbonate cement (calcite) with an average of 5.19% (Figure 3(b)). The siliceous cement content is lower, and the average content is approximately 3% (Figure 3(b)). The particle size analysis showed that the clastic particle size is mainly fine silt and coarse silt, and a small number of particles reach the fine grain size (Figure 3(c)). Under laboratory pressure, the helium porosities of the samples range from 0.6% to 17.3% (mainly 2%–10%), averaging 3.1% (Figure 4(a)). The horizontal permeability ranges from 0.003 to 9.1 mD (mainly <0.1 mD), averaging 0.18 mD (Figure 4(b)). Therefore, the target member is clarified as a typical tight sandstone reservoir following the reservoir classification scheme in previous studies (Higgs et al., 2007; Spencer, 1985; Zou et al., 2015).

**Pore types**

FE-SEM and casting thin-section observation revealed that there are five types of pores in the tight sandstone samples of the Xiaoheba Formation in the southeastern Sichuan Basin: intergranular pores, intragranular dissolved pores, matrix pores, intercrystalline pores and microcracks. Intergranular pores, mainly composed of intergranular dissolved pores, are formed by the partial dissolution of carbonate cement and matrix (Figure 5(a)). These pores were further enlarged by the dissolution of adjacent clastic particles (Figure 5(b)), and the enlarged pores ranged from 30 to 300 μm. In addition, there are a small number of triangular or polygonal residual primary intergranular pores. The energy spectrum analysis showed that some of the pore fillings were ferruginous matrix material, secondary quartz and clay minerals, and the pores ranged from 50 to 120 μm (Figure 5(a) and (c) to (e)). The intragranular dissolved pores are mainly developed in the feldspar particles, and feldspar is dissolved along cleavage planes to form network-like or trough-like pores (Figure 5(f)). The long axis of the pores is approximately parallel to the cleavage plane, whose diameter is

Figure 3. Petrologic characteristics of tight sandstone in the Xiaoheba Formation. (a) Classification of the sandstone samples using Folk’s classification; (b) interstitial material distribution; and (c) lithology distribution.
generally approximately 30 µm, and the minor axis diameter is approximately 1 µm. Some of the feldspar particles are completely eroded to form moldic pores whose size is approximately 30 µm (Figure 5(g)). Furthermore, the edges of detrital quartz particles are slightly eroded, forming irregular harbor-like intragranular pores of only a few micrometers (Figure 5(b)). Matrix pores, formed by selective dissolution of the clay matrix, are relatively developed due to the high matrix content in this study area. The morphology of the matrix pores varies, as well as the size (Figure 5(h)). The intercrystalline pores are distributed between clay mineral crystals or occur inside aggregates, such as layered illite (Figure 5(i)), flaky chlorite (Figure 5(j)) and mixed layers of illite-smectite (Figure 5(k)). Microcracks, which can be used as channels to connect microscopic pores, are also commonly observed in the tight sandstone samples, and these microcracks spread like tree branches (Figure 5(l)).

**HPMI results**

According to the results of the eighty HPMI samples (Figure 6), the displacement pressure ($P_d$) of the tight sandstone samples ranges from 0.3 to 8.4 MPa, with an average of 2.4 MPa (Figure 6(a)). The median pressure ($P_{50}$) is higher, mainly distributed from 50 to 150 MPa with an average of 120.6 MPa (Figure 6(b)). Moreover, the maximum mercury injection saturation of the tight sandstone samples is also higher, mainly varying between 50% and 90% with an average of 75.1% (Figure 6(c)), but the mercury ejection efficiency is lower, mainly ranging from 5% to 35% with an average of 15.7% (Figure 6(d)). These results indicate that the tight sandstone has some storage capacity, but a large amount of residual mercury was trapped in the pores because of the low seepage capacity. Previous studies illustrate that low-permeability tight reservoirs have high heterogeneity, complex pore structures and significant differences in pore and throat distributions; therefore, the shielding effect of very small pores leads to a large amount of mercury being retained in the pores (Gane et al., 2004; Kaufmann et al., 2009; Pittman, 1992).

Six typical samples with various $P_d$ values were selected from the eighty samples, of which the capillary pressure curve morphology showed remarkable differences (Figure 7(a)). For the samples with a low $P_d$ (lower than 5 Mpa), the mercury injection curves exhibit an approximately horizontal stage during the initial period of mercury injection, and the
lower $P_d$ leads to a wider horizontal stage, such as samples HK-30 and SLB-5 (Figure 7(a)). However, horizontal stages are hardly observed in the samples with a higher $P_d$ (higher than 5 MPa), in which the pressure exhibits a sustained increase during the whole process of mercury injection, such as samples SLB-7 and HLC-5 (Figure 7(a)). The capillary pressure

Figure 5. Polarizing light microscopy and field emission scanning electron microscopy (FE-SEM) images of typical pore types in Xiaoheba tight sandstone reservoirs. (a) Intergranular pores, Shuangliuba section; (b) intragranular pores and enlarged intergranular dissolution pores, Huilongchang section; (c) primary intergranular pores, Lengshuixi section; (d) and (e) energy spectrum analysis of SEM showing the intergranular pores and dissolved pores filled with ferruginous matrix, Shuangliuba section; (f) feldspar dissolution pores, Shuangliuba section; (g) moldic pores filled with ferruginous matrix, Huilongchang section. (h) Matrix dissolution pores, Haokou section; (i) microfracture within layered illite, Shuangliuba section; (j) intercrystalline pores within schistose chlorite aggregates, Xiaoji section; (k) honeycomb intercrystalline pores between the layers of illite and smectite, Lengshuixi section; (l) microfracture, Xiaohe section. AQ: authigenic quartz; Ch: chlorite; DQ: detrital quartz; F: feldspar; I: illite; Iep: intergranular pores; I/S: mixed-layer illite/smectite; MP: moldic pore.
curves of the six typical samples were converted into corresponding pore-throat size distribution curves by the Washburn equation (Washburn, 1921) (Figure 7(b)). The results show that the distributions of the pore-throat size differ among the tight sandstone samples with different permeabilities (Figure 7(c)). For the samples with a permeability higher than 0.1 mD, the pore-throat distribution curves have a wider range and a higher peak (Figure 7(d)). In contrast, the pore-throat distribution curves of the samples with a permeability lower than 0.1 mD have a narrower range, a lower peak and fluctuations (Figure 7(b)). In general, as the permeability of the samples decreases, the main peak of the pore-throat distribution moves to the left, the distribution range correspondingly narrows, and the volatility of the curve increases. It can be shown that there is a relatively complicated pore-throat size distribution and various types of pore-throats in the tight sandstones, which leads to a reservoir with strong heterogeneity.

The HPMI results reveal that the pore-throat size ranges from 0.004 to 11.02 μm, and the throats wider than 1 μm account for less than 15%. However, petrographic microscopic observation shows that there are many pore-throats wider than 50 μm in the tight sandstone reservoirs (Figure 5), which means that HPMI can only effectively characterize very narrow pore-throats instead of relatively wide ones.
RCMI results

In contrast to HPMI, RCMI is carried out at a low mercury injection pressure and a constant mercury injection rate. RCMI mainly measures the relatively large pores that cannot be measured by HPMI. Moreover, RCMI can divide the total mercury injection curve into mercury injection curves of the pores and throats, both of which are used to characterize the pore and throat size distributions, respectively (Wu et al., 2018; Yuan and Swanson, 1989). By comparing the test results of the six samples, the RCMI curves can be divided into two types, such as samples SLB-5 and HLC-5 (Figure 8), and the specific pore-throat structure parameters are listed in Table 1. For sample SLB-5 (Figure 8(a)), $P_d$ is 0.42 MPa, and the pore capillary pressure curve approximately overlaps the total capillary pressure curve at the early stage of mercury injection. As the pressure increases, the pore body gradually becomes filled with mercury, which renders the pore capillary pressure curve increasingly steep. In addition, the throat capillary pressure curve gradually becomes consistent with the trend of the total capillary pressure curve. The final mercury injection...
saturation of the pores is 36.01%, and the mercury injection saturation of the throats is 18.08%. This indicates that the total mercury injection saturation of these samples is mainly controlled by the pores, and the pore mercury injection saturation is typically higher than the throat mercury injection saturation. For sample HLC-5 (Figure 8(b)), \( P_d \) is 3.54 MPa, which is much higher than that of sample SLB-5, and the throat capillary pressure curve almost overlaps the total capillary pressure curve. The final mercury injection saturation of the throats is 28.91%, while the mercury injection saturation of the pores is only 9.25%, which indicates that the total mercury injection saturation of such samples is mainly controlled by the throats, and its pore mercury injection saturation is usually lower than the throat mercury injection saturation. Overall, in terms of the samples of the tight sandstones in the Xiaoheba Formation, the total mercury injection saturation gradually increases with decreasing \( P_d \) (Figure 8 and Table 1). When \( P_d \) is lower than 1 MPa, the pore capillary pressure curve nearly overlaps the total capillary pressure curve in the early period of mercury injection, such as sample SLB-5 (Figure 8(a)). When \( P_d \) is higher than 1 MPa, there is a large degree of overlap between the throat capillary pressure curve and the total capillary pressure curve at the early stage of mercury injection, such as sample HLC-5 (Figure 8(b)).

The distribution curves of the typical sample pore radius, throat radius and pore-throat radius ratio are shown in Figure 9. The samples with different porosity and permeability values have similar pore radius distribution characteristics, while the distribution characteristics of both their throat radius and pore-throat radius ratio are notably different (Figure 9(a) to (c)). The pore radius distribution curve approximates a Gaussian curve. It can be observed that the pore radius mainly ranges from 80 to 220 \( \mu \)m, and the radius at the curve peaks is approximately 145 \( \mu \)m (Figure 9(a)), which is consistent with the microscopic observation of the lithofacies. The throat radius distribution curves can be divided into two types. For the samples with a permeability lower than 0.1 mD, the throat radius distribution curve is similar to a Gaussian curve with high and narrow shapes, and the throat radius ranges from 0.12 to 0.95 \( \mu \)m. The peak frequency is up to approximately 45%. However, for the samples with a permeability higher than 0.1 mD, the throat radius distribution curve approximates a wide Gaussian curve, with the throat distribution ranging from 0.12 to 2.71 \( \mu \)m and a peak frequency lower than 10%. In general, as the permeability increases, the distribution of the throat radius becomes wider, and the main peak of the throats moves to the right, indicating an increase in the number of wide throats in the sample (Figure 9(b)).

The pore radius distributions of the samples are similar, but the throat radius distributions

| Sample | \( \Phi \) (%) | \( K \) (mD) | \( R_p \) (\( \mu \)m) | \( R_t \) (\( \mu \)m) | \( \eta \) | \( S_f \) (%) | \( S_p \) (%) | \( S_t \) (%) | \( P_d \) (MPa) |
|--------|--------------|-------------|--------------------|-----------------|------|-------------|-------------|-------------|-------------|
| SLB-7  | 3.5          | 0.019       | 135.79             | 0.25            | 1007.86 | 26.56       | 10.07       | 16.49       | 3.773       |
| HLC-5  | 5.7          | 0.028       | 156.25             | 0.29            | 962.03  | 38.16       | 9.25        | 28.91       | 3.541       |
| XH-6   | 9.7          | 0.041       | 153.83             | 0.32            | 894.95  | 43.49       | 18.73       | 24.76       | 3.275       |
| HK-25  | 6.5          | 0.057       | 149.94             | 0.45            | 874.97  | 40.87       | 13.44       | 27.43       | 2.751       |
| SLB-5  | 7.4          | 0.115       | 143.86             | 0.89            | 197.73  | 54.09       | 36.01       | 18.08       | 0.415       |
| HK-30  | 8.6          | 0.186       | 150.62             | 1.18            | 157.10  | 55.06       | 32.49       | 22.57       | 0.268       |

\( \Phi \): porosity; \( K \): permeability; \( R_p \): weighted average pore radius; \( R_t \): weighted average throat radius; \( \eta \): pre-throat radius ratio; \( S_f \): final total mercury saturation; \( S_p \): pore mercury saturation; \( S_t \): throat mercury saturation; \( P_d \): displacement pressure.
are significantly different, resulting in a striking difference in pore-throat radius ratio distribution (Figure 9(c)). It is also indirectly implied that the particularity of the tight sandstone reservoirs, that is, the reservoir space, is mainly composed of large pores and narrow throats, and the reservoirs have a strong heterogeneity (Medina et al., 2017).

**Combination of HPMI and RCMI results**

The previous results show that it is challenging to characterize the whole pore-throat size distribution of tight reservoirs with a single method because there is a wider range of pore-throat sizes in tight sandstone reservoirs. Generally, HPMI can effectively characterize the very narrow pore-throats when the pressure is sufficiently high, but it fails to measure the relatively large pores (larger than 50 μm). RCMI can characterize wide pore-throats, and it can also quantitatively analyze their structural parameters, such as the distribution characteristics of the pore radius, throat radius, and pore-throat radius ratio. However, it cannot identify pore-throats narrower than 0.12 μm under the limited experimental conditions. Combining HPMI and RCMI testing should contribute to obtain the entire pore-throat size distribution in tight sandstone reservoirs.

Taking sample HK-25 (obtained from the Haokou section) as an example, it is shown that there are some differences between the two kinds of capillary pressure curves obtained

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**Figure 9.** Pore size, throat size and pore-throat radius ratio distribution by rate-controlled mercury injection of the samples with different porosity and permeability. (a) Pore size distribution; (b) throat size distribution; and (c) pore-throat radius ratio distribution.
by the HPMI and RCMI techniques: the total mercury injection saturation of RCMI is slightly higher than that of HPMI when the mercury injection pressure is the same (Figure 10(a)). Previous studies suggest that these differences are due to the high mercury injection pressure, which can compact clastic particles (Clarkson et al., 2013; Medina et al., 2017). However, scholars have conducted experiments to prove that the destruction of the sandstone pore structure in HPMI is negligible (Gane et al., 2004). Comprehensive studies suggest that the primary cause of these differences is the complex pore morphology of tight sandstones. When the pore morphology is slit-like, the slit-like pores usually function as pores and throats. Under these circumstances, in theory, both the HPMI and RCMI curves tend to be consistent. However, in fact, the tight sandstones of the Xiaoheba Formation have various pore shapes and complex pore-throat structures (Figure 5). Additionally, due to the lower constant rate of mercury injection \( v = 5 \times 10^{-5} \text{ml/min} \) in the RCMI experiments, it renders the interfacial tension \( \sigma = 480 \text{mN/m} \) and contact angle \( \theta = 140^\circ \) invariant. In contrast, in the HPMI experiments, the rate of mercury injection is relatively high, resulting in a changing contact angle, which may also be the cause of those differences (Favvas et al., 2009). Although there are slight differences between these two testing results, their experimental principles have similarities. Therefore, for tight sandstone reservoirs, HPMI and RCMI experiments combined to characterize the entire pore-throat size distribution is a feasible new method.

HPMI and RCMI experiments were conducted for the sister samples from the HK-25 and the results reveal that the of pore-throat size distribution is from 0.004 to 260 \( \mu \text{m} \), with a scope from 0.12 to 50 \( \mu \text{m} \) in their overlapping region of the middle curve (Figure 10(b)). Since the HPMI experiment is based on the capillary beam model, it actually measures characteristic of the throat size distribution, which means that the two peaks in the pore-throat distribution curve severally reflect the distribution characteristics of the pore and the throat. The left peak represents the throat distribution with a radius range from 0.004 to 50 \( \mu \text{m} \), and the right peak represents the pore distribution with a radius range from 50 to 260 \( \mu \text{m} \) (Figure 10(b)). Based on two experiments, porosity and permeability of the sample HK-25 is respectively 12.36% and 0.21 mD in the HPMI testing while they are separately 9.42% and 0.24 mD in the RCMI testing. In comparison, the permeability obtained by these two methods is very close, but the porosity is significantly different, which reveals that the
permeability is primarily attributed to the relatively wide throats with a radius larger than 0.12 μm in the overlap region. Although the narrow throats (radius < 0.12 μm) have little effect on the permeability, their contribution to the reservoir porosity cannot be ignored. For sample HK-25, the maximum mercury injection saturation tested by HPMI is 93.55%, while that tested by RCMI is 40.87%, which is a difference of more than 50% (Figure 10(a)). This result also fully demonstrates that the relatively narrow pore-throats have a significant contribution to the storage space in the tight sandstone reservoirs.

Discussions

Pore size classification

Loucks et al. (2012) revised the pore classification scheme proposed by Choquette and Pray (1970) and defined a new scheme (Loucks et al., 2012; Choquette and Pray, 1970). In this scheme, the pores are divided into nanopores (<1 μm), micropores (1–62.5 μm), and mesopores (62.5–4 mm). In exploration and production practices, due to the limited conditions, the application of polarized light microscopy is still a popular and convenient method for current reservoir microscopic studies. However, the thickness of thin sections is only 0.03 mm; for such pore-throats (smaller than 0.03 mm), it is difficult to directly observe the whole pore-throat structure and morphological characteristics through thin-section microscopic identification. Therefore, on the basis of the previous pore classification schemes, it is advocated that the micropore size of a tight sandstone reservoir be adjusted to 1–30 μm, and the width of a nanopore is less than 1 μm, while the width of a mesopore ranges from 30 to 4 mm. According to this classification scheme, we plotted a histogram of pore size distribution, which is shown in Figure 11. Nanopores mercury injection saturation (MIS) range from 58.93% to 83.56%, with an average of 68.81% (Figure 11). Micropores MIS range from 1.95% to 3.76%, with an average of 2.23% (Figure 11). Mesopores MIS range from 9.25% to 36.01%, with an average of 20% (Figure 11). For the tight sandstone reservoirs of the Xiaoheba Formation, MIS of nanopores and mesopores reveal difference.

Figure 11. Pore size histogram of the analyzed tight sandstone reservoir quality by a combination of HPMI and RCMI.
between samples, while those of micropores are little different between samples. In terms of pore size classification, nanopores and mesopores are the two major pore size types, with nanopores accounting for the majority.

The previous part of this article points out that there are five pore types in the tight sandstones of Xiaoheba Formation in the southeastern Sichuan Basin. To quantitatively characterize pore sizes of each type, the software of Image J2x was used to recognize the pores in the SEM images (Figure 12). Through the image-processing of Grayscale threshold of binarization, the pore sizes and surface porosity were automatically calculated (Figure 12 and Table 2). The statistics shows that matrix pores and intercrystalline pores are two main pore types, followed by intergranular pores, and intragranular dissolved pores are relatively minimal (Table 2). The matrix pores and the intercrystalline pores have smaller sizes (5 nm to 25 μm), which are mainly nano-sized pores, and there are a multitude of these pores in Xiaoheba sandstones (surface porosity: 4.11%–4.52%) (Table 2). Petrophysical characteristics suggest that high levels of clay matrix offer the material foundation for developing these pores. And there is a positive correlation between the mudstone matrix content and the

![Figure 12](image-url)

**Figure 12.** The pore size and surface porosity calculation of sandstone in Xiaoheba Formation. (a) Intragranular pores and enlarged intergranular dissolution pores, Huilongchang section; (b) and (c) the image-processing of grayscale threshold of binarization; (d) Intercrystalline pores, Huilongchang section; (e) and (f) the image-processing of grayscale threshold of binarization.

| Pore types             | Pore areas, total areas (μm²) | Pore sizes          | Surface porosity (%) |
|------------------------|-------------------------------|---------------------|----------------------|
| Intergranular pores    | 15.89, 542.35                 | 30–300 μm           | 2.93                 |
| Intragranular dissolved pores | 6.4, 351.76                  | 1–30 μm             | 1.82                 |
| Intercrystalline pores | 27.67, 673.21                 | 50 nm to 3 μm       | 4.11                 |
| Matrix pores           | 7.97, 176.37                  | 5 nm to 25 μm       | 4.52                 |
| Microcracks            | 1.53, 189.05                  | 30 nm to 20 μm      | 0.81                 |

**Table 2.** The statistics of Xiaoheba sandstones’ pore size and surface porosity in the southeastern Sichuan Basin.
porosity, which also suggests that the matrix pores developed in the tight sandstones with developing mudstone matrix (Figure 13). Intergranular pores are large and belong to mesopores with main size of 30–300 μm. But the number of pores is relatively small, and the surface porosity is less than 3%. The sizes of intragranular dissolved pores, restricted to clastic particle size and dissolution, belong to micropores with size of 1–30 μm. The number of intragranular dissolved pores is least and their surface porosity is only 1.82%. Integrating SEM image analysis and mercury injection test, the pore sizes distributions characterized by two methods are in good agreement, that is, nanopores and mesopores are the most developed in the tight sandstone of Xiaoheba Formation, and micropores are less developed. Among them, nanopores mainly include intercrystalline pores in clay minerals and mudstone matrix pores. Mesopores mainly consist of intergranular pores, while micropores are mainly some dissolved pores in feldspars and quartzs.

**Relationships between the size of the pore and the throat and reservoir physical parameters**

Based on the above studies, it is considered that the pore-throat structure of tight sandstone reservoirs is complex, and the pore-throat size is one of the important parameters in controlling the reservoir physical properties. Through the RCMI experiments, not only can the effective pore-throat size distribution be obtained but also the weighted average values of the effective pore and throat radii can be calculated separately. Using the data from the six typical samples tested by RCMI (Table 1), the weighted average values of the effective pore and throat radii are fitted as a function of the porosity and permeability, respectively (Figure 14). The results suggest that the weighted average value of the effective pore radius is weakly correlated with the porosity and permeability (Figure 14(a)), while the weighted average value of the effective throat radius, which is weakly correlated with the porosity, has a very good positive correlation with the permeability (Figure 14(b)). This means that the pore radius of tight sandstones has a weak influence on the reservoir physical properties,

![Figure 13. Relationship between mudstone matrix content of tight sandstones and reservoirs' porosity.](image-url)
while the throat radius is a significant parameter that affects the reservoir physical properties, especially the permeability.

**Contribution of pore-throat size distribution on reservoir physical parameters**

The HPMI testing can derive several parameters such as the cumulative mercury injection saturation, permeability contribution ratio and cumulative permeability contribution ratio, while the function curves between these parameters and pore-throat sizes are shown in Figure 15. The morphology of the permeability contribution ratio curve is similar to that of the Gaussian curve (Figure 15(a) to (d)), in which the pore-throat size is a narrow range and the peak value of the pore-throat radius has a positive correlation with the permeability (Figure 15(a) to (d)). According to analysis of typical tight sandstone samples with different reservoir physical parameters (porosity and permeability), the reservoir permeability is primarily controlled by a small fraction of relatively large pore-throats (larger than the peak value of the pore-throat radius) in every sample (Figure 15(a) to (d)), such as samples HK-30 and SLB-5, of which have pore-throat radii larger than approximately 1.1 and 0.8 μm, respectively (Figure 15(a) to (b)). The peak value of the pore-throat radius increases with increasing permeability (Figure 15(a) to (d)). In the initial stage of mercury injection, as mercury was first injected into these pore-throats, the cumulative permeability contribution ratio increased rapidly to approximately 98% and generated a relatively steep curve shape (Figure 15(a) to (d)). The cumulative mercury injection saturation also increased, but its increase ratio was low and formed a relatively flat curve configuration (Figure 15(a) to (d)).

With the continuous injection of mercury, a large amount of mercury entered the smaller pore-throats (smaller than the peak value of the pore-throat radius), and the cumulative mercury injection saturation then increased rapidly to form a steep curve. Moreover, the cumulative permeability contribution ratio increased slowly until a horizontal stage appeared in the curve. This means that the relatively narrow pore-throats (smaller than the peak value of the pore-throat radius) contribute very little to the permeability, but they dominate the total pore-throat volume in the tight sandstones. Taking four typical samples as the examples (Figure 15(a) to (d)), when the cumulative permeability contribution ratio was up to approximately 98%, at this point, the cumulative mercury injection saturations

![Figure 14. Relationship between pore-throat structure parameters and petrophysical parameters. (a) Relationship between the weighted average pore radius and the porosity as well as permeability and (b) relationship between the weighted average throat radius and the porosity as well as permeability.](image-url)
only ranged from 18.3% to 39.7%, relying on the permeability. For these typical samples, the maximum mercury injection saturations were 83%-92.87%, meaning that 48.5%-74.6% of the amount of mercury injection was controlled by the relatively small pore-throats. Furthermore, with the decrease of permeability, the spectral peaks of the permeability contribution ratio shifts towards the small pore-throats, meaning that the lower the permeability is, the smaller the proportion of the relatively large pore-throats is in the tight sandstone samples (Figures 9(b) and 15(a) to (d)). Therefore, the permeability of the tight sandstone reservoirs in the Xiaoheba Formation is chiefly controlled by a small fraction of relatively large pore-throats (less than 40%). Overall, for the tight sandstones with a relatively high permeability (>0.1 mD), the permeability is chiefly controlled by the micropores (1–30 μm) and mesopores (30–100 μm) (Figure 15(a) and (b)), in contrary, the permeability is chiefly controlled by the larger nanopores (100–1 μm) and micropores (1–30 μm) (Figure 15(c) and (d)). The smaller nanopores (<100 nm) in the tight sandstone reservoirs have a negligible influence on the permeability but occupy a considerable proportion in the total pore volume. At present, the maximum mercury injection pressure of the RCMI experiments is low (approximately 6.2 MPa), so it is difficult to accurately measure the pore-throats with a radius smaller than 100 nm. However, previous analyses suggest that nanopores are of great significance for improving the physical properties of tight reservoirs, especially for

Figure 15. The specific contributions of different sized pore-throats on porosity and permeability.
improving the porosity (Higgs et al., 2007; Rezaee et al., 2012). To quantitatively analyze the influence of the smaller nanopores (smaller than 100 nm) on the physical properties of the tight sandstone reservoirs in the Xiaoheba Formation, the HPMI curves of typical samples are studied, and the pore-throat volumes controlled by the small nanopores (<100 nm) in every sample are counted, as well as its contribution to the permeability. The results reveal that the percentage of pore-throat volumes controlled by the small nanopores (<100 nm) in the tight sandstone samples is in range of 29.65%–94.54%, with an average of 69.1%, and the cumulative permeability contribution ranges from 0.05% to 12.92%, with an average of 6.25% (Table 3).

On the whole, in the tight sandstone reservoirs, as the permeability decreases, the pore-throat volume controlled by the narrower nanoscale throats (<100 nm) notably increases, and the contribution ratio to the permeability also increases correspondingly, but its contribution to the overall reservoir seepage capacity is relatively small. In other words, the narrower nanoscale pore-throats (<100 nm) have a certain impact on both the reservoir storage capacity and seepage capacity in the tight sandstones, but their influence on the former is much larger than on the latter.

**Conclusions**

- The sandstone reservoirs of the Xiaoheba Formation in the southeastern Sichuan Basin generally have poor physical properties with an average porosity of 3.1% and an average permeability of 0.18 mD, which are typical tight sandstone reservoirs. Multiple scales of pores (including intergranular pores, intragranular dissolved pores, matrix pores, intercrystalline pores and microcracks) are identified through FE-SEM analysis and casting thin sections. As for pore size classification, the nanopores and mesopores are the two major pore size types, with nanopores accounting for the majority. Overall, nanopores mainly include the intercrystalline pores in clay minerals and mudstone matrix pores. Mesopores mainly consist of intergranular pores and micropores are mainly some dissolved pores in feldspars and quartzs.
- HPMI can measure the relatively narrow throats (<50 μm), while RCMI is conducive to distinguishing the pores and throats with the radius larger than 0.12 μm. The combination of the HPMI and RCMI testings is recommended as an improved method for tight sandstone reservoirs pore-throats structure characterization. In this work the method effectively reveals the total size distribution of the pore-throats in

| Sample | Φ (%) | K (mD) | Pore volume proportion controlled by throats <100 nm (%) | Cumulative permeability contribution of throats <100 nm (%) |
|--------|-------|--------|--------------------------------------------------------|----------------------------------------------------------|
| SLB-7  | 5.7   | 0.020  | 89.38                                                  | 12.92                                                   |
| HLC-5  | 6.8   | 0.026  | 82.36                                                  | 12.63                                                   |
| XH-6   | 11.5  | 0.039  | 80.45                                                  | 5.86                                                    |
| HK-25  | 8.9   | 0.053  | 94.54                                                  | 5.27                                                    |
| SLB-5  | 9.5   | 0.099  | 38.21                                                  | 0.05                                                    |
| HK-30  | 9.8   | 0.182  | 29.65                                                  | 0.76                                                    |

Please provide text citation for figure 13.
the Xiaoheba sandstones. The overall pore-throat radius distribution ranges from 0.004 to 260 μm, while the radius of the pore and throat is respectively in range of 50–260 μm and 0.004–50 μm.

- For the tight sandstone reservoirs, the permeability is primarily controlled by a small fraction (<40%) of wider pore-throats (larger than the peak value of the pore-throat radius). When the reservoir permeability is relatively higher (>0.1 mD), the permeability is mainly controlled by micropores (1–30 μm) and mesopores (30 μm to 4 mm). Conversely, the permeability is mainly controlled by the larger nanopores (100 nm to 1 μm) and micropores (1–30 μm). In addition, the proportion of the narrow pore-throats in tight sandstones increases with the decrease of the reservoir permeability. Although the large number of narrower pore-throat (<100 nm) makes a certain contribution to both reservoir porosity and permeability, their contribution to the former is far more than that to the latter.

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