Pore-Structure Characterization of the Eocene Sha-3 Sandstones in the Bohai Bay Basin, China

Kaixun Zhang,*†‡ Yingchun Guo,*† Guoping Bai, ‡ Zongxiu Wang, ‡ Bingda Fan, § Jianping Wu, § and Xinjie Niu§

†Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081, China
‡State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, China
§Petrochina Huabei Oilfield Company, Renqiu, Hebei 062552, China

ABSTRACT: Mercury intrusion capillary pressure (MICP), nuclear magnetic resonance (NMR), routine core analysis, thin sections, and scanning electron microscope (SEM) analysis were used to gain insight into the pore structure of the Eocene Sha-3 (the third member of the Shahejie formation) low-permeability sandstones in the Raoyang sag, including pore type, pore geometry, and pore size. Quantitative NMR parameters and petrophysical properties were integrated to build up the relationship between microscopic pore structure and macroscopic performance. The pore systems of Sha-3 sandstones are dominantly of residual intergranular pores, intragranular dissolution pores, and intercrystallite micropores associated with authigenic clay minerals. The high threshold pressure and low mercury withdrawal efficiencies from MICP analysis indicate the poor pore connectivity and strong heterogeneities. Both un- and bimodal transverse relaxation time (T2) spectrum can be found because of the coexistence of small and large pores, and the T2 of major pore size occurring at about 1.0 to 100 ms. The Sha-3 sandstones have a relatively high irreducible water content and short T2 components in the T2 range. Long T2 components can only be observed in samples rich in large pores or microfractures. T2gm (the geometric mean of the T2 distribution) correlates well with irreducible water saturation and permeability. A methodology for pore structure classification is presented integrating NMR parameters of T2gm, bulk volume of immovable fluid (BVI), and petrophysical parameters such as reservoir quality index (RQI) and permeability. Consequently, four types of pore structures (types A, B, C, and D) are identified, and characteristics of individual pore structure are summarized. The comprehensive analysis of NMR measurements combined with thin sections, SEM and MICP analysis is useful for describing microscopic pore structure, which is important to maintaining and enhancing petroleum recovery in low-permeability sandstone reservoirs.

1. INTRODUCTION

The Raoyang sag, famous for the discovery of the Renqiu Oilfield in 1975, is a prolific oil-producing province in Jizhong Depression of Bohai Bay Basin.1–3 Previous studies and exploration practice suggested the Eocene Shahejie formation in the Raoyang sag as effective source rocks and hydrocarbon-producing reservoirs.1,4 Recently, considerable hydrocarbons have been produced from the fan to braided deltaic sandstones in the Shahejie formation.2,5 Numerous studies, including depositional environments, geochemistry, diagenesis, and tectonic setting, have exhibited significant hydrocarbon potential in the Shahejie formation.2–6 The Eocene Shahejie formation was deposited in a lacustrine to fan-braided deltaic environment, and the lithology is dominated by deltaic fine–medium-grained sandstones interbedded with lacustrine dark-gray mudstones.1–3 Although formed in favorable tectonic setting and sedimentary facies,1,2 the Shahejie formation sandstones in the Raoyang sag are generally characterized by deep burial depth, low porosity, and ultralow permeability as well as strong heterogeneities due to the complicated deep-burial diagenesis.5,8 To help the successful exploration and efficient development of hydrocarbons in these low-permeability sandstones, the connection between micropore throat structures and macroscopic reservoir performances should be clarified9–12 because microscopic pore throat geometry controls the macroscopic petrophysical properties and petroleum charging, migration, and accumulation in low-permeability sandstones.13,14

Laboratory nuclear magnetic resonance (NMR) measurements, which record the spin axis relaxation times (longitudinal being T1 and transverse being T2) of protons in the presence of pulsed and static magnetic fields,15 could directly provide the relaxation time distributions and consequently uncalibrated pore size distributions.16–18 Therefore, NMR measurements can be used to quickly and nondestructively characterize pore structure and fluid type and state in reservoir rocks.15,19 In addition, NMR measurements are widely used to determine fluid type and the proportion of fluid volumes and construct capillary pressure curves.15,20–24 Combined with thin sections, scanning electron microscopy (SEM), and mercury intrusion capillary pressure (MICP) measurements, NMR measurements can be used to construct pore size distribution, estimate macroscopic petrophysical property such as permeability, and quantitatively evaluate the complexity of pore structures.15,16,22,25–29 MICP analysis, which can measure pore throat size ranging from the micron scale to the nanoscale (about 3 nm),30 is widely used for pore throat structure characterization in sandstones.31–34
The main goals of this study are to improve our understanding of the pore structure of the Eocene Sha-3 low-permeability sandstone reservoir and provide insights into pore structure classification and evaluation using a combination of routine core analysis, thin section, SEM, MICP, and NMR measurements. The paper could be divided into six parts: (1) briefly describing the microscopic pore structure and macroscopic behaviors with thin section, SEM, and routine core analysis; (2) analyzing pore throat structure by MICP analysis and investigating the NMR $T_2$ spectrum; (3) quantitatively calculating NMR parameters including $T_{2\text{gm}}$, $T_{2\text{cutoff}}$, bulk volume of immovable fluid (BVI) and free fluid index (FFI); (4) investigating the relationships between NMR parameters and petrophysical properties; (5) classifying and evaluating pore structure using the NMR analysis; and (6) summarizing the characteristics of various pore structures.

2. GEOLOGICAL SETTING

The Bohai Bay Basin, a typical Mesozoic and Cenozoic rifted lacustrine basin, is located in the eastern portion of the North China Craton, which is regarded as a hydrocarbon-resourcing basin in China.3 The basin can be divided into six major sub-basins or depressions, including the Liaohe sub-basin in the northeast, the Jizhong sub-basin in the west, the Huanghua and the Jiyang sub-basins in the southeast, the Bozhong sub-basin in the east, and the Dongpu sub-basin in the southwest.3,6,36 The Jizhong depression is bounded by the Eastern Taihangshan fault to the west, the Cangxian uplift to the east, and the Xingheng uplift to the south3 (Figure 1). The Raoyang sag is a subtectonic unit lying in the southwest of the Jizhong depression, which is an important oil- and gas-producing province in East China. Besides the famous Renqiu oil field discovered in 1975, several large oil fields in the Raoyang sag have been discovered in recent years.37 A total of 40 representative core plugs (about 1 in. in diameter and 2 in. in length) of the Eocene Sha-3 sandstones were taken from 11 petroleum exploration wells, including the Liu 99 well, Liu 101 well, Chu 22 well, Liu 425, Liu 498, Chushen 1, Liu 446, Liugu 2, etc. These samples were subjected to a laboratory workflow including: (1) mineralogy and thin section analysis, (2) porosity and permeability measurements, (3) SEM analysis to determine pore systems and clay minerals, (4) MICP analysis, and (5) NMR measurements.

3. ANALYTICAL METHODS

A total of 40 representative core plugs (about 1 in. in diameter and 2 in. in length) of the Eocene Sha-3 sandstones were taken from 11 petroleum exploration wells, including the Liu 99 well, Liu 101 well, Chu 22 well, Liu 425, Liu 498, Chushen 1, Liu 446, Liugu 2, etc. These samples were subjected to a laboratory workflow including: (1) mineralogy and thin section analysis, (2) porosity and permeability measurements, (3) SEM analysis to determine pore systems and clay minerals, (4) MICP analysis, and (5) NMR measurements. Routine core analysis (grain density, porosity, and permeability) was performed on 140 core plugs with the aim to characterize the flow potential (permeability) and the storage capacity (porosity) of the reservoir. The He porosity and permeability were measured using the CMS-300 instrument at a net confining pressure of 800 psi.

To identify clay minerals and corresponding pore characteristic, e.g., pore spaces, pore throat type, and pore throat radius, a total of eight freshly broken rock fragments were coated with a thin layer of carbon and examined with the S-4800 scanning electron microscope (SEM) equipped with a backscattered electron (BSE) detector.
Thin sections (30 μm in thickness), which were impregnated with blue-dye resin to highlight porosity, were point-count analyzed (300 points per sample) under plane-polarized and cross-polarized light to determine the volume and distribution of intergranular and intragranular porosity. Thin sections were also stained with Alizarin Red S and potassium ferricyanide for the recognition of Fe-dolomite, Fe-calcite, and nonferroan calcite.

MICP analyses were performed on 40 core samples (25 × 50 mm columnar samples) to determine the pore structures and pore throat distribution at the laboratory of China University of Petroleum (Beijing). The 9505 mercury injection apparatus applied to this experiment of which the maximum mercury injection pressure is 151.07 MPa.

NMR T$_2$ relaxation time was used to determine the pore size distribution and calculate the NMR porosity, irreducible water, and mobile water content as well as to estimate the permeability. To determine the transversal relaxation time (T$_2$) distributions of saturated and centrifuged (unsaturated) samples, including incremental and cumulative T$_2$ values, a set of 41 core samples was prepared for laboratory NMR measurements in State Key Laboratory of Petroleum Resources and Prospecting of China. The NMR apparatus (Maran-2 ultrarock spectrometer produced by Oxford Instruments) provides 2 MHz frequency of magnetic field, waiting time of 15 000 ms, and echo spacing Te of 0.3 ms. The measurement was conducted under temperature of 25 °C. A total of 128 stacks were performed to obtain the relaxation time distribution. The samples were first fully saturated with NaCl brine with a salinity of 50 000 mg/L at a net confining pressure of 20 MPa for 48 h, and then the T$_2$ distributions at this saturated status were measured. After that, the free water in core plugs was removed by keeping samples in a centrifugal machine with a rotation speed of 10 000 r/min for 1 h. The T$_2$ distributions (incremental and cumulative) of these samples were measured again at the centrifuged status.

4. RESULTS

4.1. Microscopic Pore Systems and Macroscopic Performances. The routine core analysis of the 140 core samples show that the permeability ranges from 0.012 mD to 61.03 mD, while porosity varies between 2.06% and 19.9% with an average value of 11.9% (Figure 2). Even variations in permeability of 4 orders of magnitude can be observed for the same porosity (Figure 2). A large portion of samples are characterized by high porosity but low permeability or low porosity but high permeability, indicating that the permeability is generally unrelated to the total porosity but rather controlled by pore throat structures (pore and throat types, radius, and pore connectivity; Figure 2). Samples characterized by high porosity but low permeability are interpreted to have abundant microporosity and poorly connected pores (Figure 2). In contrast, the high-permeability but low-porosity samples have large pore throat radius and may contain microfractures.

The low correlation coefficient between permeability and porosity ($R^2 = 0.47$) gives additional evidence for the heterogeneous nature of the pore throat structures (Figure 2).

Thin section observations and SEM analysis suggest that that pore systems of Sha-3 sandstones in the Raoyang sag are dominantly of residual intergranular pores, intragranular dissolution pores, or even molder pores. The residual intergranular pores, which are of primary origins and irregular shapes, are predominantly in coarser-grain sized and well-sorted samples (Figure 3A,B). The secondary dissolution pores can be found in some samples, which were resulted from partial to complete dissolution of framework grains such as feldspars (Figure 3C). Thin section analysis (presence of blue epoxy) also indicates that abundant intragranular pores occur in feldspars and rock fragments (Figure 3D). The secondary intergranular pores commonly coexist with the intergranular ones (Figure 3C,D). Molder pores due to complete dissolution of the framework grains can be occasionally observed (Figure 3E). Porosity could be quantified through thin section point-counting analysis, and also checked against routine core analysis. Total thin-section porosity of the sandstones, reveals a wide range from trace levels (<1%) to 14.50% with an average of 7.5%. Thin section analysis reveals that the clean sandstones do not contain abundant micropores (<10 μm) (Figure 3A,B). In contrast, samples with low porosity have relative high content of micropores.

The presences of micropores in the Sha-3 sandstones in the Raoyang sag can also been confirmed by the SEM analysis. In fact, there are many micropores, which are below the resolution of the microscopic thin section analysis, can be detected by the SEM analysis. For instance, abundant honeycomb-like micropores in feldspars (Figure 3F) and intercrystalline micropores associated with authigenic clay minerals, e.g., illite (Figure 3G), and mixed layered illite and smectite (Figure 3H) can be observed in SEM images. Microfractures detected by both thin-section and SEM images, are also important pore spaces in Sha-3 low-permeability sandstones (Figure 3I).

4.2. Pore Throat and Pore Size Distributions. Reservoir porosity and permeability are macroscopic expressions of pore structure that integrate geometry (pore throat size and shape and pore size distribution) and topology (pore connectivity). In this section, MICP analysis and NMR measurements are used to identify pore throat and pore size distributions of Sha-3 low-permeability sandstones.

Pore networks of sandstone in MICP analysis refer to pores connected through by pore throats. Typical capillary pressure curves of Sha-3 low-permeability sandstones commonly exhibit a gradual increase in mercury saturation with capillary pressure (Figure 4). Importantly, the capillary curves of these sandstone samples indicate the variation of reservoir quality and microscopic complexity of pore structures, as well as heterogeneous pore networks. As can be seen from Figure 4, samples are characterized by moderate to high threshold pressures with the maximum mercury saturation of 25%–90% at the maximum injection pressure 151.07 MPa. In terms of the Sample A, the maximum mercury saturation is 92%, and the threshold pressure is low to moderate (2.1 MPa); additionally about 45% of mercury resided at the end of the extrusion (capillary pressure was gradually decreased to zero) (Figure 4A). In terms of sample D, only 26.6% of the pore volumes are
saturated with mercury at the maximum injection pressure (Figure 4), indicating poor pore connectivity. Furthermore, more than half of the injected mercury is resided at the end of the extrusion, which can be attributed to the presence of ink-bottle-shaped pores, i.e., pore geometries composed of a system of large body pores but interconnected by very narrow throats. Therefore, the low mercury withdrawal efficiencies give additional evidence to the poor connectivity of pore systems. The
transitional pore structure types are presented in Figure 4B,C. As can be observed from Figure 4, the maximum mercury saturation gradually decreases from sample A to sample D, whereas the threshold pressure gradually increases; additionally, more and more content of mercury resided at the end of the extrusion, and this implies that the microscopic pore structure and macroscopic reservoir quality become more complex and poorer from sample A to sample D (Figure 4).

MICP is sensitive to pore throat sizes rather than pore body sizes\textsuperscript{,15} while NMR relaxation time distributions are directly determined by pore size distributions with the assumption that majority of the pore volume is composed of pore bodies.\textsuperscript{15,17} The $T_2$ decay rates are mainly controlled by the surface-to-volume ratio and pore size: short $T_2$ value indicates small pores and a large surface-to-volume ratio, whereas long $T_2$ means a small surface-to-volume ratios and, therefore, large pores.\textsuperscript{12} NMR porosity measured in the NMR measurements follows a good linear trend with increasing water porosity trend (Figure 5A), while the high coefficient correlation ($R^2 > 0.98$) suggests a good relationship between NMR porosity and He porosity (Figure 5B). Therefore, the NMR analysis can measure almost the entire pore systems saturated with the brine. However, it should be noted that not all pore systems can be saturated with 100% brine, even when they were kept at a confining pressure of 20 MPa for 1 h. As can be seen from Figure 5B, there are some data points below the “unit slope line” ($y = x$), which indicates that some micropores may not be saturated with brine due to the poor connectivity of pore systems.

The incremental and cumulative $T_2$ spectrum (transversal relaxation time distribution) in Figure 6 provide significant information about the interactions between pore fluids and grain surfaces and, therefore, pore structure.\textsuperscript{12,53} The NMR relaxation time distributions of saturated sample range from 0.1 to 1000 ms with corresponding $T_2$ of major pore size occurring at about 1.0 to 100 ms (Figure 6). In NMR measurements, the pore systems are classified into small pores with irreducible water and large pores holding movable fluids and contributing to the flow system.\textsuperscript{12} The capillary and clay-bound irreducible water (BVI) in small pores can be separated from the FFI in large pores using a NMR parameter, named $T_2\text{cutoff}$.\textsuperscript{22,41,53,54} By the drawing of a horizontal projection line from the centrifuged cumulative curve, the intersection of this projection line at the saturated cumulative curve could be used to determine the $T_2\text{cutoff}$ value (Figure 6).\textsuperscript{22,54} The $T_2\text{gm}$ can be calculated as the amplitude weighted mean on a logarithmic scale.\textsuperscript{12}

The cumulative $T_2$ distributions for saturated status display unimodal and bimodal behaviors, which represents a geometrical arrangement composed of small to large pore size domains. About 75% of the samples are characterized by bimodal $T_2$ distributions (Figure 7A), indicating the variation of pore sizes
and the coexistence of small pores and large pores, which is agreement with the thin section observation and SEM analysis. The wide range of pore sizes in the Sha-3 heterogeneous sandstones contributes to the bimodal $T_2$ spectrum (Figure 7A). The bimodal $T_2$ distributions can be divided into two parts: a short component ($T_{2s}$) associated with the presence of micropores in clay minerals and capillary pore sizes and a long component ($T_{2l}$) corresponding to the large intergranular pores and microfractures\textsuperscript{12,53} (Figure 7A). Lacking of the macropores in the low-permeability sandstones, the main $T_2$ component appears as a major dominant peak at the shorter $T_2$ times, and there are minor peaks or a tail distribution of $T_2$ larger than 300 ms that are most likely associated with the remaining larger pores\textsuperscript{28} (Figure 7A). However, long $T_2$ components can be observed in samples with microfractures, and there are tail distributions of $T_2$ relaxation time larger than 100 ms.\textsuperscript{12,55}

The unimodal $T_2$ behaviors refer to the $T_2$ spectrum of only one representative modal with no or weak $T_{2l}$ components (Figure 7B). No evident tail distributions and long $T_2$ components greater than 100 ms, which are associated with the large pores or microfractures, can be observed. In contrast, the high content of short relaxation time components suggest abundant poorly connected micropores, which correspond to the short relaxation time components in the $T_2$ distribution, and these micropores have a great effect on the heterogeneity.\textsuperscript{12} High irreducible water content and low movability of water of samples resulted in NMR signal amplitudes with no evident deviation under saturated and centrifuged conditions (Figure 6).

The NMR measurements performed on 40 samples show that the $T_{2\text{cutoff}}$ ranges from 1.04 to 43.29 ms, with an average value of 12.5 ms. The BVI values vary significantly from 31.49% to 97.93%, with an average value of 65.42%, which means more than half of the pore systems are associated with clays minerals and within capillary pore sizes. The high BVI content indicates poor connectivity and complicated pore systems. The $T_{2\text{gm}}$ parameter, which is the geometric mean of the NMR $T_2$ distribution, is in the range from 0.62 to 44.03 ms and averaged as 8.12 ms. Generally, the macroscopic reservoir quality and the microscopic pore structure are positively related to the $T_{2\text{gm}}$ whereas a moderate to strong negative relationship occurs between BVI and $T_{2\text{gm}}$ with a correlation coefficient ($R^2$) of 0.77, which indicates that a large proportion of micropores can result in a low $T_{2\text{gm}}$ value and, therefore, a high irreducible water content (Figure 8A). Furthermore, a high exponential relationship ($R^2$ of 0.78) between permeability and $T_{2\text{gm}}$ (Figure 8B) indicates that samples with high permeability tend to have more large pores and, therefore, high content of long-$T_2$ components (Figure 8B). Thus, $T_{2\text{gm}}$ is a sensitive NMR parameter for both the microscopic pore structure and the macroscopic petrophysical properties.
5. DISCUSSIONS

Because low-permeability sandstones commonly are characterized by complicated microscopic pore structures and various pore types and multiscale pore sizes,

\[ R^2 = 0.814 \]

pore structure classification and evaluation is significant for sweet-spot prediction and production optimization.\(^{51,59,60}\) Previous studies from Coates et al.,\(^{61}\) Ge et al.,\(^{22}\) Lai et al.,\(^{12}\) Daigle and Johnson,\(^{17}\) and Zhao et al.\(^{18}\) suggested that NMR measurement is an important approach for pore structure classification and evaluation of low-permeability sandstones reservoirs because NMR could nondestructively determine porosity, pore size distributions and estimate permeability.

The parameter of reservoir quality index (RQI) is introduced here for pore structure classification and evaluation of low-permeability sandstones reservoirs because NMR could non destructively determine porosity, pore size distributions and estimate permeability.

\[ \text{RQI} = \sqrt{\frac{K}{\phi}} \]  

(1)

where RQI is reservoir quality index in micrometers, \( K \) is the permeability in square micrometers, and \( \phi \) is the fractional porosity.

Regression analysis shows that RQI is strongly correlated with \( T_{2gm} \) with a high correlation coefficient \((R^2)\) of 0.89 (Figure 9).

Previous study also confirmed that the NMR parameter \( T_{2gm} \) could be used for the characterization of pore structure and reservoir quality index.\(^{12,18,32}\) In this study, the \( T_{2gm} \) is integrated with the RQI as well as permeability to comprehensively characterize and classify pore structures in Sha-3 sandstones in the Raoyang sag. The classification standards for pore structure based on NMR parameters and reservoir quality are presented in Table 1 and Figure 9. A total of four types of pore structures are identified on the basis of the NMR parameters (BVI and \( T_{2gm} \)) and petrophysical parameters (permeability and RQI; Table 1 and Figure 9).

The \( T_2 \) spectrum of type A pore structure is characterized by a wide spectrum, a bimodal behavior as well as obvious right-skewed distribution (lower left peak but higher right peak) (Figure 10). Samples with type A pore structure commonly have high permeability and low immobile water (Table. 1). Large residual intergranular pores or moldic pores are typical type A pore structures, which are connected by large pore throats and can make a significant contribution to permeability (Figure 10).\(^{11,45,65,66}\) Therefore, type A pore structure may have a highest maximum mercury saturation and relatively high efficiency of mercury withdrawal (Figure 4A), which implies a good pore connectivity. Also, microfractures in some samples result in high core-measured permeability. Due to the presences of large intergranular pores and microfractures, abundant long \( T_2 \) components can be observed, and minor peaks associated with small pores are present. Therefore, the irreducible water content will be low. In some cases, long \( T_2 \) tails can be observed with main peak at \( T_2 \) values higher than 100 ms (Figure 11). High content of movable water makes the NMR signal amplitudes under saturated and centrifuged conditions deviate significantly (Figures 10 and 11) because most of movable water can be removed by the centrifugal machine.

The NMR \( T_2 \) spectrum of type B pore structure has a wide range from 0.1 to 700 ms; however, they may show unimodal behaviors (Figure 7B) or bimodal behaviors (Figure 12). The main peaks of the \( T_2 \) spectrum occur at \( T_2 \) between 10 and 100 ms (Figure 12). Although long \( T_2 \) components occur in type B
pore structures, short $T_2$ components can be found in some samples, which is attributed to the existence of irreducible water (Figure 12). Type B pore structures are generally characterized by high permeability of 1 to 10 mD but a moderate BVI value. Type B pore structures also have a high maximum mercury saturation and relatively high efficiency of mercury withdrawal (Figure 4B), which indicates that more than 70% of the pore throat systems can be invaded by mercury at the maximum injection pressure. Different from type A pore structures, type B pore structures have much lower full NMR signal (especially the right peak representing the large intergranular pores) without the occurrence of tail (Figures 10 and 12). This pore system is characterized by the coexistence of large intergranular pores and secondary dissolution pores or micropores (Table 1 and Figure 12).

The NMR $T_2$ spectrum of type C pore structures has a very narrow range from 0.1 to 100 ms, which is similar to that of type D pore structures. The one distinct peak (unimodal behavior) indicates a relatively continuous pore size distribution (Figure 14). The intercrystalline micropores, which are associated with the various types of clay minerals, are the predominant pore types in this type of pore structure. Extremely high immovable water but low permeability (<0.1 mD) occurs in this pore structure due to the poor connectivity of the pore systems. Type D pore structure also has the lowest maximum mercury saturation and highest threshold pressure (Figure 4D), indicating that the poorest pore connectivity. Additionally, the total NMR signal amplitudes under saturated and centrifuged conditions have no evident deviations (Figure 14) because most of the irreducible water cannot be removed by the centrifugal machine, even with a

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Figure 10. Typical $T_1$ spectrum of type A pore structure of the Sha-3 sandstones in the Raoyang sag.

Type C pore structure commonly has a high immobile water content larger than 50% but a low permeability between 0.1 to 1 mD (Table 1 and Figure 13). Therefore, a type C pore structure has a low to moderate maximum mercury saturation and low efficiency of mercury withdrawal (Figure 4C), indicating that most of the pore systems are not connected by effective throats.

The NMR $T_2$ spectrum of type D pore structures has a very narrow range from 0.1 to 100 ms, which is similar to that of type C pore structures. The one distinct peak (unimodal behavior) indicates a relatively continuous pore size distribution (Figure 14). The intercrystalline micropores, which are associated with the various types of clay minerals, are the predominant pore types in this type of pore structure. Extremely high immovable water but low permeability (<0.1 mD) occurs in this pore structure due to the poor connectivity of the pore systems. Type D pore structure also has the lowest maximum mercury saturation and highest threshold pressure (Figure 4D), indicating that the poorest pore connectivity. Additionally, the total NMR signal amplitudes under saturated and centrifuged conditions have no evident deviations (Figure 14) because most of the irreducible water cannot be removed by the centrifugal machine, even with a
rotation speed of 10,000 r/min for 1 h, and this gives additional evidence to the poor pore connectivity.

6. CONCLUSIONS

Thin section observations and SEM analysis show that the pore systems of Sha-3 sandstones are primarily residual intergranular pores, intragranular dissolution pores, or moldic pores. The differences of core-measured porosity and thin-section porosity suggest considerable micropores. SEM analysis confirms abundant honeycomb-like micropores in feldspars and intercrystalline micropores associated with the authigenic clay minerals. The threshold pressure of pore samples are moderate to high with relatively low maximum mercury saturation at the

Figure 11. Typical $T_2$ spectrum of type A pore structure (with microfractures).

Figure 12. Typical $T_2$ spectrum of type B pore structure of the Sha-3 sandstones in the Raoyang sag.
maximum injection pressure, indicating poor pore connectivity, which is confirmed by the low efficiencies of mercury withdrawal. The Sha-3 sandstones show either uni- or bimodal T$_2$ spectra due to the coexistence of small and large pores. Short T$_2$ components are commonly observed in the T$_2$ spectrum, and corresponding T$_2$ of major pore size occurs at about 1.0 to 100 ms. Capillary water and clay-bound irreducible water content is high in small pores, while the FFI is relatively low in large pores.

The NMR parameter T$_{2gm}$ is correlated well with irreducible water saturation, core-measured permeability, and reservoir quality index. A methodology is introduced for pore structure classification and evaluation by integrating NMR parameters, e.g., T$_{2gm}$, BVI, and petrophysical parameters, e.g., RQI and
permeability. A total of four types of pore structures (types A, B, C, and D) are identified, while characteristics of individual pore structure are summarized using the NMR T$_2$ spectrum, MICP analysis, and thin-section observations.

**AUTHOR INFORMATION**

**Corresponding Authors**

*E-mail: zhangkaixmin@126.com. Phone: +861-391-015-8696.

*E-mail: cugcupgych@163.com.

**ORCID**

Kaixun Zhang: 0000-0002-4685-7654

**Notes**

The authors declare no competing financial interest.

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