

Article

Pore Structure Characteristics and Reservoir Classification of Tight Sandstones within the Upper Permian Longtan Formation in the Laoshan Uplift, South Yellow Sea Basin: Implications for Hydrocarbon Exploration

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Abstract: The Upper Permian Longtan Formation in the Laoshan Uplift of the South Yellow Sea Basin hosts thick and distinctive tight sandstones. However, a comprehensive understanding of its pore structure and reservoir classification remains lacking. This study investigates the fully cored well, CSDP-2, utilizing thin section analysis, scanning electron microscopy, energy spectrum analysis, X-ray diffraction, high-pressure mercury intrusion, and nuclear magnetic resonance to characterize its petrophysical properties, pore space, and movable fluid characteristics. Additionally, fractal principles are further employed to examine reservoir heterogeneity and conduct a quantitative assessment, considering the complexity of tight sandstone pore structures. The findings reveal that the sandstones predominantly comprise feldspathic litharenites, with an average porosity of 1.567% and permeability of 0.099 mD, primarily containing intragranular pores. Two distinct sets of pores with significantly different sizes ($r < 2 \mu\text{m}$; $r > 6 \mu\text{m}$) were identified, displaying relatively high fractal dimensions and discrete distribution. Movable fluids primarily occupy pores with radii $> 0.019 \mu\text{m}$, reflecting pronounced overall heterogeneity. The reservoir was classified into three categories utilizing permeability, median radius, and movable fluid saturation as key evaluation parameters, with Class I representing a relatively high-quality reservoir. These findings advance our understanding of the pore development mechanism of tight sandstone reservoirs and provide geological evidence for further hydrocarbon exploration in this study area.

Keywords: tight sandstone; pore structure; fractal; reservoir evaluation; Laoshan Uplift; South Yellow Sea Basin



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1. Introduction

As conventional oil and gas reserves dwindle, attention has shifted towards unconventional resources, notably tight sandstone oil and gas reservoirs with matrix permeability of less than 0.1 mD and porosity of less than 10%, which have seen significant development globally [1–5]. In China, exploration efforts have been concentrated in basins such as the Sichuan, Ordos, Tarim, Junggar, and Songliao. In 2021, tight sandstone gas and oil production in these locations totaled approximately $526 \times 10^8 \text{ m}^3$ and $300 \times 10^4 \text{ t}$, respectively [6].

Permian tight sandstone, particularly in the northern Ordos Basin, is crucial for unconventional oil and gas exploration. Notably, the Sulige Gas Field, the largest onshore integrated tight sandstone gas field in China, has seen annual gas production surpassing $230 \times 10^8 \text{ m}^3$ since 2014, reaching more than $260 \times 10^8 \text{ m}^3$ in 2020 [7–9]. The Linxing Gas

Field, located in the Permian He 2 Member tight sandstone reservoir at the eastern margin of the Ordos Basin, has emerged as one of the largest gas fields in this basin [10]. In the Bohai Bay Basin, significant oil and gas flows have been discovered in the Permian Upper Shihezi Member tight sandstone, notably at the well sites such as Guangu 1601, Yinggu 1, and Yinggu 2 in the southern Dagang area [11]. Furthermore, Well Hua 3 in the Huangqiao area of the Lower Yangtze region has achieved a daily oil production of 1.5 tons from the Longtan tight sandstones, nearing industrial capacity [12]. Variations in pore-volume abundance, pore size, and pore-network connectivity in tight sandstones significantly influence hydrocarbon storage capacity and deliverability [5,13,14]. A comprehensive understanding of the heterogeneous pore structure is crucial for the successful exploration and development of these tight sandstone reservoirs [2,3,5,15,16].

The South Yellow Sea Basin, adjacent to the onshore Lower Yangtze region, has similar geological structures to that region. With a relatively complete development of Paleozoic-Mesozoic marine strata, it exhibits multi-source and multi-stage accumulation characteristics that could signify the formation of large oil and gas fields [17,18]. However, no significant hydrocarbon exploration breakthroughs have yet occurred in this basin.

In recent years, advances in seismic detection technology and drilling—notably the full-core drilling well CSDP-2, carried out in the Laoshan Uplift of the South Yellow Sea Basin—have confirmed thick layers of tight sandstones in the Upper Permian Longtan Formation, with multiple oil and gas indications [18,19]. While previous studies of the Longtan Formation in the Laoshan Uplift, situated in the central part of the basin with promising hydrocarbon exploration potential, have provided valuable insights into its seismic stratigraphy, tectonic evolution [17,20], sedimentary environments [21,22], source rock characteristics [23,24], and reservoir features [25], research on the pore structure of this formation remains insufficient, and a systematic understanding of reservoir quality has not been established.

This paper presents an in-depth study conducted on the petrophysical properties, pore structure characteristics, and movable fluid features of the Longtan tight sandstones collected from Well CSDP-2. Additionally, fractal theory was employed to discuss Longtan tight sandstone reservoir heterogeneity, and multiple parameters were integrated to classify and evaluate this reservoir, providing further theoretical support for the investigation and exploration of hydrocarbons in the South Yellow Sea Basin.

2. Geological Setting

Situated in the eastern waters of China, the South Yellow Sea spans an area of approximately 3×10^5 km² [26–28]. Tectonically, it extends from the Yangtze Platform into the sea area and represents the primary section of the Lower Yangtze region [28]. The South Yellow Sea Basin originated on the Archean-Proterozoic metamorphic basement, over which Paleozoic-Mesozoic marine and Mesozoic-Cenozoic continental sedimentary basins were superimposed [17,28]. Geologically, the basin comprises three secondary tectonic units: the Yantai Depression, Laoshan Uplift, and Qingdao Depression, arranged respectively from north to south (Figure 1).

To date, only 30 wells have been drilled, primarily concentrated in the Yantai and Qingdao Depressions [19]. Notably, Well CSDP-2, drilled in 2016, marked the first drilling endeavor in the Laoshan Uplift. This well achieved a depth of 2843.18 m, with an impressive average core recovery rate of 97.7%. It successfully penetrated through the Triassic, Permian, Carboniferous, Devonian, and Silurian strata beneath the Neogene strata [18]. Specifically, the Upper Permian Longtan Formation, with a thickness of approximately 453.4 m, primarily comprises littoral swamp and deltaic deposits, with the predominant lithological constituents including black mudstone, coal seams, and gray silt-fine sandstone [22,23,25].

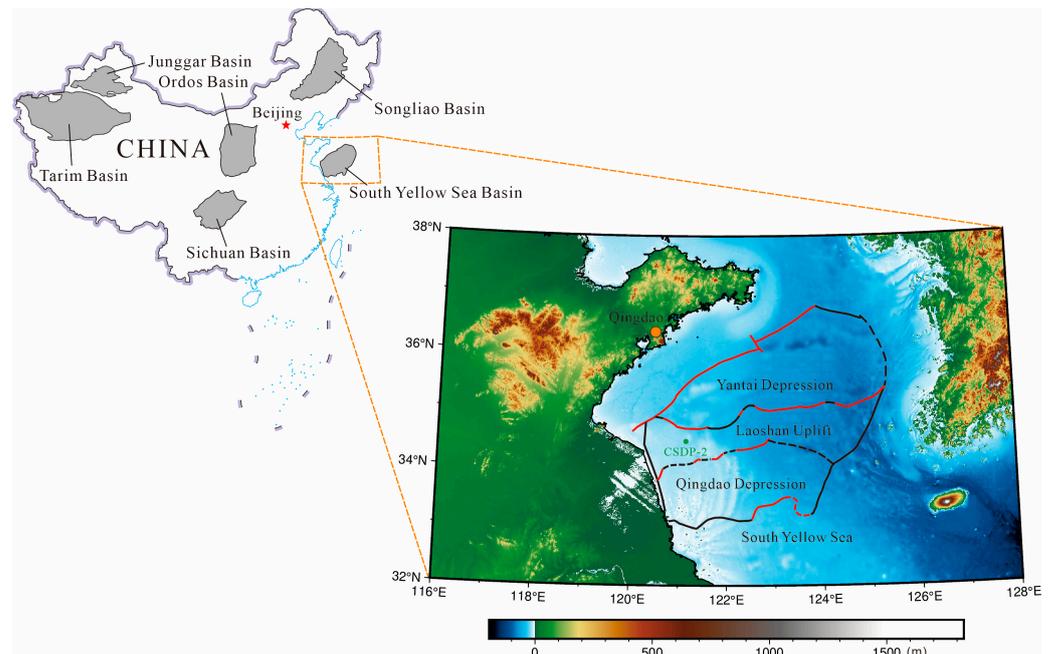


Figure 1. Regional location and tectonic zoning of the South Yellow Sea Basin [17,28]. Digital elevation data source: <https://www.generic-mapping-tools.org> (accessed on 30 October 2023).

3. Materials and Methods

3.1. Samples and Experimental Methods

Tight sandstone samples were selected from 1020 to 1175 m depths of the Upper Permian Longtan Formation from Well CSDP-2. Subsequent analysis focused on petrological characteristics, physical properties, pore structure, and movable fluid properties.

The identification of minerals such as quartz, feldspar, carbonate, and clay minerals in the samples was conducted using a LEICA DM2500 P polarizing microscope (Leica Microsystems, Wetzlar, Germany). Prior to observation, thin sections underwent cleaning, polishing, and staining with a mixture of alizarin red-S and potassium ferrocyanide solutions to enhance the identification of carbonate minerals. Additionally, epoxy resin-stained thin sections were prepared for examining the pore structure. Mineral composition was determined using a Dmax-2500 X-ray diffractometer (Rigaku Corporation, Tokyo, Japan) under specific conditions: 40 kV accelerating voltage, 40 mA current, 0.02° scanning step, 2 s time step, and 2θ range from 0° to 50° . Scanning electron microscopy and energy spectrum analysis were carried out using a MIRA 3 thermal field emission scanning electron microscope (TESCAN, Brno, Czech Republic) equipped with an Oxford X-Max SDD energy dispersive spectrometer (Oxford Instruments plc, Abingdon, UK). The operating parameters included an acceleration voltage of 10–20 kV and a working distance ranging from approximately 5 to 15 mm.

Reservoir petrophysical property testing and analysis were performed on core plugs measuring 2.5 cm in diameter. This was accomplished using an AP-608 automated permeameter-porosimeter (pressure sensor accuracy $\pm 0.1\%$; Coretest Systems Inc., Morgan Hill, CA, USA) to measure porosity and permeability at 19°C , 30% humidity, and an atmospheric pressure of 1031 hPa. The AP-608 instrument is cost-effective and applied Boyle's law to measure the porosity and Klinkenberg effect to measure the permeability. For nuclear magnetic resonance (NMR) analysis, the above core plugs were cleaned oil and saturated in a NaCl saline solution under vacuum for 24 h. NIUMAG MicroMR series NMR core analyzers (Niumag Corporation, Shanghai, China) were used, employing a Carr–Purcell–Meiboom–Gill sequence with specific parameters: a main radiofrequency signal frequency of 12 MHz, an RF signal frequency offset of 100,673.89 Hz, a sampling bandwidth of 250 kHz, a repetition sampling interval of 4000 ms, an echo time of 0.1 ms,

8000 echoes, a preamplifier gain of 3, and 32 scans. High-pressure mercury intrusion (HPMI) experiments were conducted using a MicroActive AutoPore V-9600 fully automatic mercury intrusion porosimeter (Micromeritics Instrument Corporation, Norcross, GA, USA). This experiment, recognized for its invasive and destructive nature, was carried out as the concluding experimental procedure. Samples, which were cut into 1 cm³ cubes and pre-treated by drying in an oven at 70 °C for over 48 h, were subjected to pressures ranging from 0 to 420.9 MPa, with a contact angle of 130°.

3.2. Fractal Theory and Computational Methods

Fractal theory offers a methodology to explore the internal structure of irregular bodies through self-similarity [29]. Objects exhibiting fractal characteristics are described by the fractal dimension D , which can be used to quantify the complexity and irregularity of reservoir pore structures, with values typically ranging between two and three [30]. A D value nearing two indicates greater reservoir homogeneity and simpler pore structures, while a D value closer to three suggests heightened reservoir heterogeneity and more complex pore structures [31,32].

According to fractal theory, the cumulative volume percentage $S(<r)$ of pores with diameters smaller than r in the reservoir can be expressed as follows [29]:

$$S(<r) = \frac{r^{3-D} - r_{\min}^{3-D}}{r_{\max}^{3-D} - r_{\min}^{3-D}} \tag{1}$$

where r denotes the pore radius (μm), r_{\min} stands for the minimum pore radius, r_{\max} represents the maximum pore radius, $S(r)$ is the density distribution function of the pore radius, and D is the fractal dimension.

In HPMI experiments, Equation (1) can be reformulated in terms of mercury saturation as follows:

$$S(<r) = 1 - S_{\text{Hg}} = \frac{r^{3-D_P} - r_{\min}^{3-D_P}}{r_{\max}^{3-D_P} - r_{\min}^{3-D_P}} \tag{2}$$

where S_{Hg} represents the cumulative mercury saturation (%) when the pore radius is r , and D_P is the fractal dimension of HPMI. Due to $r_{\max} \gg r_{\min}$, Equation (2) simplifies to

$$S(<r) = 1 - S_{\text{Hg}} = \frac{r^{3-D_P}}{r_{\max}^{3-D_P}} \tag{3}$$

Taking the logarithm of Equation (3), the formula for computing the fractal dimension D_P based on pore size in HPMI experiments is derived as follows:

$$\log(1 - S_{\text{Hg}}) = (3 - D_P)\log r - (3 - D_P)\log r_{\max} \tag{4}$$

Equation (4) reveals a linear relationship between $\log(1 - S_{\text{Hg}})$ and $\log r$. The fractal dimension D_P can therefore be determined using double logarithmic coordinates.

In contrast to HPMI experiments, which directly correlate pore size and volume, NMR testing typically utilizes the transverse relaxation time T_2 to reflect surface relaxation determined by the specific surface area and relaxation rate [33]. The relationship between T_2 and r is expressed by the following equation:

$$\frac{1}{T_2} = \rho \left(\frac{S}{V} \right) = F_s \frac{\rho}{r} \tag{5}$$

where ρ denotes the surface relaxation rate (considered constant), T_2 represents the transverse relaxation time (m/ms), S/V is the ratio of pore space surface area to volume. F_s is a constant geometric shape factor, where F_s equals 1, 2, or 3 for planar, cylindrical, and spherical models, respectively [33]. For this study, cylindrical pores are assumed, and the constant value (F_s) is set to 2.

According to Equation (5), T_2 obtained from NMR experiments is directly proportional to the ratio of specific surface area and pore size, with r_{max} corresponding to T_{2max} and r_{min} corresponding to T_{2min} . Combined with Equation (1), the fractal dimension D_N obtained based on NMR testing T_2 values can be expressed as follows:

$$S(< r) = \frac{T_2^{3-D_N} - T_{2min}^{3-D_N}}{T_{2max}^{3-D_N} - T_{2min}^{3-D_N}} \tag{6}$$

Since $T_{2max} \gg T_{2min}$, Equation (6) simplifies to

$$S(< r) = \frac{T_2^{3-D_N}}{T_{2max}^{3-D_N}} \tag{7}$$

Taking the logarithm of Equation (7), we obtain

$$\log(S(< r)) = (3 - D_N)\log(T_2) - (3 - D_N)\log T_{2max} \tag{8}$$

There exists a linear relationship between $\log(S(<r))$ and $\log T_2$. Under the condition of satisfying the fractal theory, the fractal dimension D_N can be determined using double logarithmic coordinates in NMR experiments.

4. Results

4.1. Petrophysical Properties, Lithological Characteristics, and Pore Types

The porosity of Longtan Formation samples from Well CSDP-2 ranges from 1.192% to 2.323%, with the permeability varying between 0.000259 and 0.9185 mD, indicating typical tight sandstones (Table 1).

Table 1. Summary of petrophysical properties, high-pressure mercury injection, and nuclear magnetic resonance parameters of the Longtan tight sandstones of Well CSDP-2, South Yellow Sea Basin.

Sample No.	Well Depth/m	Petrophysical Characteristics		High-Pressure Mercury Injection Test				Nuclear Magnetic Resonance Test		
		Porosity/%	Permeability/mD	Maximum Mercury Saturation/%	Threshold Pressure/MPa	Average Pore Radius/ μ m	Median Radius/ μ m	$T_{2Cut-off}$ /ms	Movable Fluid Saturation/%	Bound Fluid Saturation/%
G-21	1020.00	1.958	0.01014	96.52	0.002691	1.4112	222.57	0.51	6.54	93.46
G-22	1030.00	1.210	0.012	89.78	0.006762	0.02167	185.58	1.87	5.65	94.35
C-3	1110.8	2.054	0.0154	98.16	0.069138	0.02915	183.34	1.15	18.48	81.52
C-4	1114.7	1.216	0.000259	95.03	0.047196	0.1108	202.47	1.06	12.83	87.17
C-5	1121.25	1.314	0.1036	99.74	0.016491	0.01413	82.68	0.98	7.52	92.48
C-6	1125.00	1.292	0.0246	93.20	0.005037	0.08554	121.95	1.25	11.37	88.63
C-8	1135.00	1.395	0.000634	73.60	0.003864	0.04688	132.79	0.71	9.50	90.50
C-14	1157.00	1.192	0.00275	88.38	0.165462	0.9472	235.29	4.94	5.84	94.16
C-16	1161.00	2.323	0.9185	85.28	0.050094	0.07395	331.76	8.7	34.83	65.17
C-19	1167.00	1.933	0.00206	98.24	0.053682	0.29405	265.56	0.47	7.00	93.00
C-22	1175.00	1.439	0.00374	97.60	0.079212	0.04882	206.06	0.9	23.72	76.28

The Longtan Formation consists mainly of tight sandstones with linear contacts, with some samples exhibiting concave-convex contacts. Comprising mainly fine sandstones and siltstones, the predominant grain size ranges from 0.09 to 0.25 mm, featuring subangular to subrounded grain shapes. X-ray diffraction analysis indicates that the detrital components of the Longtan tight sandstone of Well CSDP-2 primarily comprise quartz and feldspar (Table 2). The quartz content predominantly falls within the range of 59.8% to 78.0%, with an average of 67.8%. Following quartz, the feldspar content ranges from 4.1% to 26.3%, with an average content of 16.1%. The prevailing sandstone type is feldspathic litharenite. Observations from thin sections and scanning electron microscopes reveal that the studied tight sandstones primarily develop intragranular dissolution pores (Figure 2c,d), alongside residual minor amounts of intergranular pores and developed fractures (Figure 2a,b,e).

Table 2. Relative content of sandstone minerals in the Longtan tight sandstones in Well CSDP-2.

Sample No.	Quartz (%)	Feldspar (%)	Calcite (%)	Pyrite (%)	Clay Minerals (%)
C-5	64.2	22.2			13.6
C-6	67.1	22.3	0.8		9.8
C-8	75.9	13.1			11.1
C-14	59.8	14.0			26.3
C-16	78.0	14.2	2.2	1.4	4.1
G-21	67.6	13.2			19.2
G-22	65.8	18.0			16.2

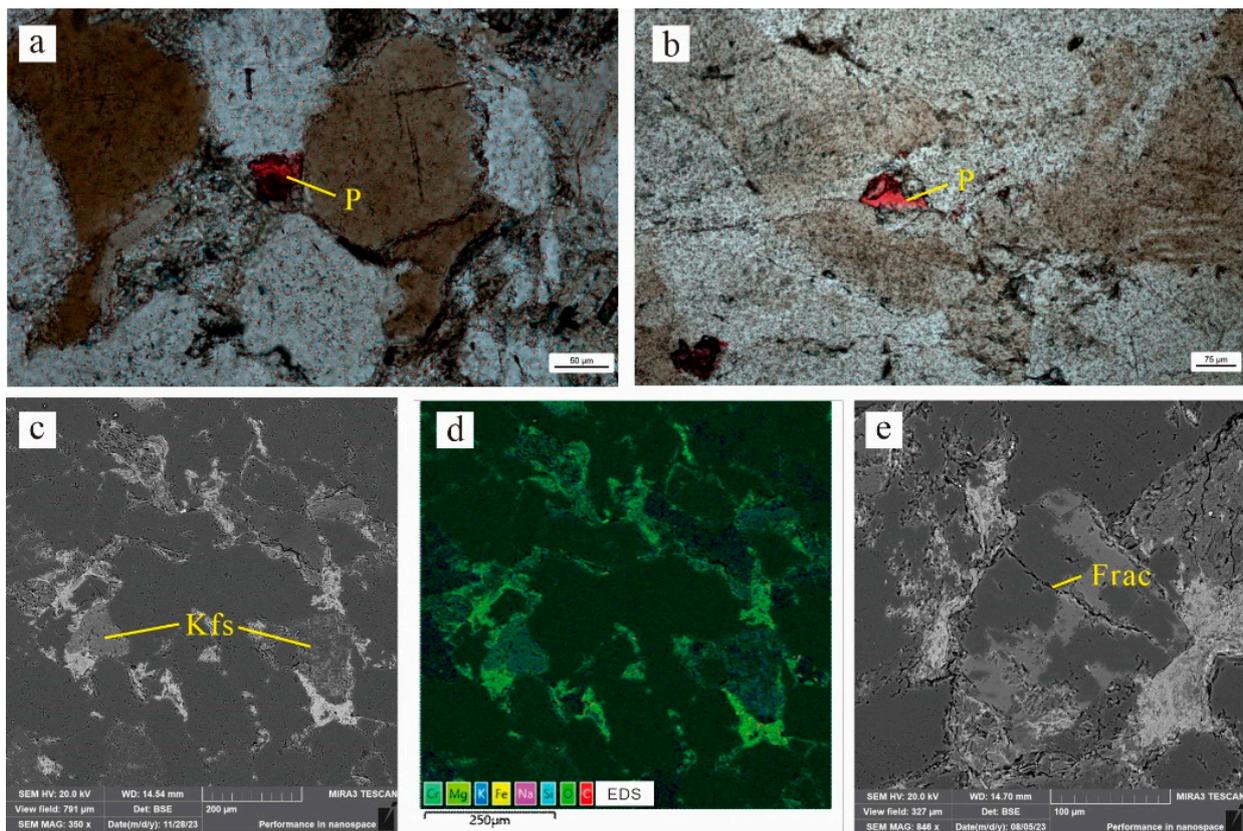


Figure 2. Microscopic characteristics of pore space in the Longtan tight sandstones, Well CSDP-2. (a) Development of residual intergranular pores, plane-polarized light, C-8, 1135.00 m; (b) development of residual intergranular pores, plane-polarized light, C-16, 1161.00 m; (c) SEM image showing development of intragranular dissolution pores in potassium feldspar grains, C-8, 1135.00 m; (d) corresponding energy spectrum scan result to (c). EDS—energy dispersive spectroscopy. Color-coded EDS element maps are overlaid on SEM images; (e) SEM image showing development of micro-fractures within grains, C-8, 1135.00 m. P—pore; Kfs—potassium feldspar; frac—micro-fractures/cracks; SEM—scanning electron microscope.

4.2. Pore structure Characteristics

4.2.1. High-Pressure Mercury Injection Characteristics

HPMI analysis enables both qualitative and quantitative analysis of the inherent pore structure characteristics within the reservoir [34–36]. This is achieved by integrating capillary pressure curves with pore structure parameters. In the Longtan Formation of Well CSDP-2, the mercury saturation of tight sandstones ranges from 73.60% to 99.74%, with threshold pressures spanning 0.003 to 0.079 MPa. Various forms of capillary pressure curves are evident in the tight sandstone reservoirs of the study area (Figure 3a). Notably,

sample C-16 demonstrates the smoothest overall capillary pressure curve and exhibits superior petrophysical properties. Conversely, samples C-4 and C-8 display shorter smooth segments in their capillary pressure curves and are characterized by multiple broken line segments and frequent steep increases, indicating poorer petrophysical properties.

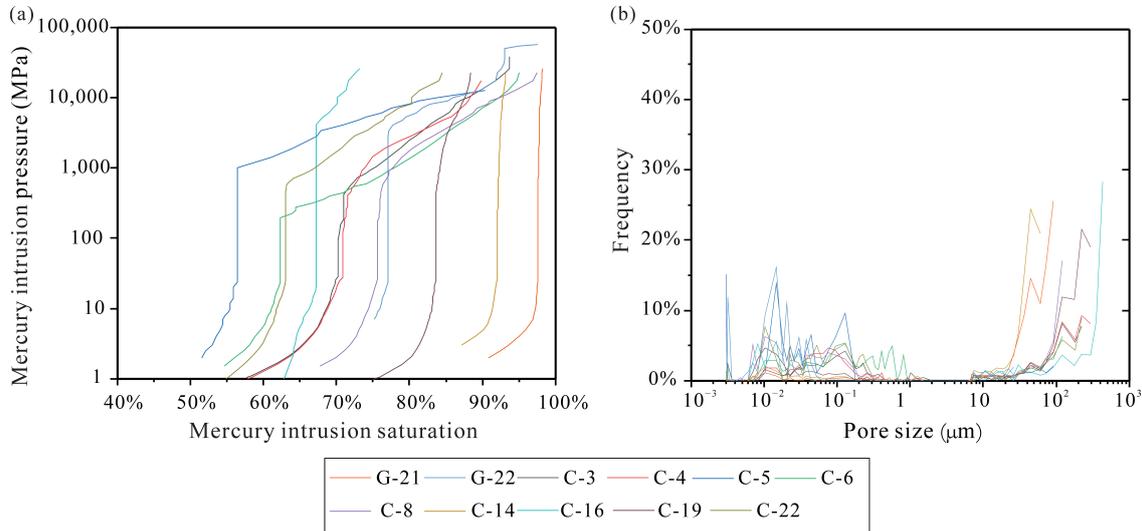


Figure 3. High-pressure mercury injection curves of the Longtan tight sandstones of Well CSDP-2. (a) Capillary pressure curves with the saturation profiles differing dramatically due to differences in pore size distribution; (b) pore size distribution curves indicating concentration primarily in the <2 μm and >6 μm intervals, with notable variations in frequency.

Analysis of HPMI pore size distribution curves reveals that the pore sizes are primarily concentrated in the <2 μm and >6 μm intervals (Figure 3b). The median pore radii of the samples in the study area vary from 82.68 to 331.76 μm, demonstrating significant discrepancies. These variations reflect the intricate structure and pronounced heterogeneity of the tight sandstones in the study area.

4.2.2. Nuclear Magnetic Resonance Characteristics

The NMR T_2 spectrum serves to depict the presence of water within core pores, and whether it is movable or bound (Figure 4a). The T_2 cutoff value, denoted where the incremental curve of bound water reaches its apex and intersects with that of saturated water, delineates the boundary (as illustrated in Figure 4b). If T_2 of the pore fluid exceeds the $T_{2\text{cutoff}}$, the fluid is classified as movable; otherwise, it is considered bound. The proportion of movable fluid in the total fluid is termed movable fluid saturation, while the percentage of bound fluid in total fluid is referred to as bound fluid saturation. Movable fluid saturation can serve as an indicator of reservoir fluid mobility, with lower levels indicating weaker corresponding reservoir storage and permeability [37–39]. In the study area, the distribution of movable fluid saturation among the Longtan sandstone samples ranges from 5.65% to 34.83%, with an average of 13.03%.

The T_2 spectrum acquired through NMR can elucidate the pore size and distribution characteristics of rock samples, with longer T_2 values corresponding to larger pore sizes [33,40]. A linear relationship between T_2 spectrum and pore size exists, described as follows [41,42]:

$$r = CT_2 \tag{9}$$

Following the determination of the conversion coefficient C between T_2 and the pore size (herein, $C = 0.009 \mu\text{m}/\text{ms}$), the mutual conversion between NMR T_2 spectrum and the pore radius can be conducted, enabling the calculation of the pore size distribution of the tight sandstone samples (Figure 5). Here, bound fluid predominantly occupies pores with

a radius of $<0.019 \mu\text{m}$, while movable fluid is primarily located in pores with a radius of $>0.019 \mu\text{m}$.

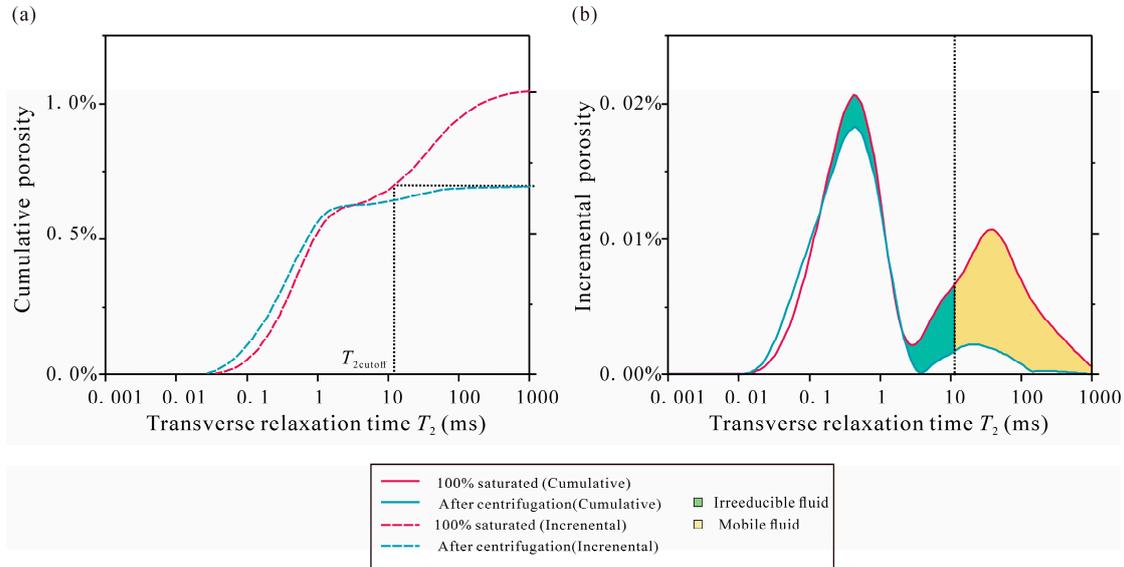


Figure 4. Distribution characteristics of nuclear magnetic resonance T_2 spectra in Longtan tight sandstones in Well CSDP-2. (a) Schematic diagram of $T_{2\text{cutoff}}$ value; (b) Schematic diagram of movable and bound fluid, C-16, 1161.00 m.

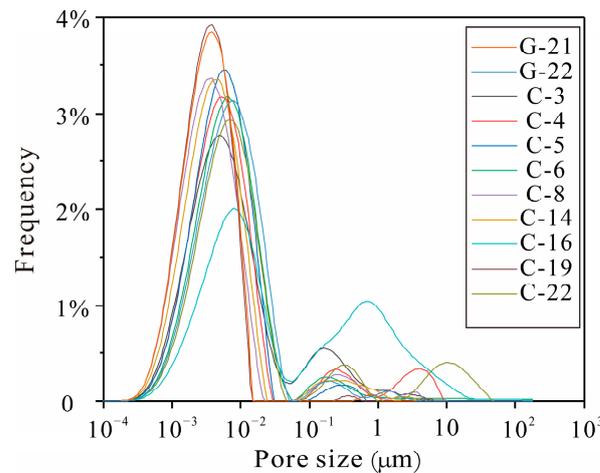


Figure 5. Pore size distribution of the Longtan tight sandstones of Well CSDP-2 obtained from nuclear magnetic resonance (NMR).

4.3. Fractal Characteristics

4.3.1. Fractal Analysis of High-Pressure Mercury Injection in Tight Sandstone

The HPMI fractal curves of tight sandstone samples from Well CSDP-2 display segmented features. For representative samples (C-3, 1110.80 m; C-4, 1114.70 m), these fractal curves correspond to their respective pore size distributions. The relationship between $\log(1 - S_{\text{Hg}})$ and $\log r$ reveals two distinct inflection points (Figure 6). Based on this relationship, the pore space of the samples can be categorized into “large” and “small” pores. D_{P-1} represents the fractal dimension of small pores, associated with a pore radius of approximately $<2 \mu\text{m}$; these fractal dimensions range from 2.22 to 2.96, with a mean of 2.68. D_{P-2} represents the fractal dimension of large pores, corresponding to a pore radius of approximately $>6 \mu\text{m}$; these fractal dimensions range from 2.29 to 2.90, with a mean of 2.78 (Figure 6a; Table 3). The overall fractal dimension of the Longtan tight sandstones is

relatively high, suggesting considerable heterogeneity of the samples across various pore size intervals. The pore distribution exhibits discrete patterns.

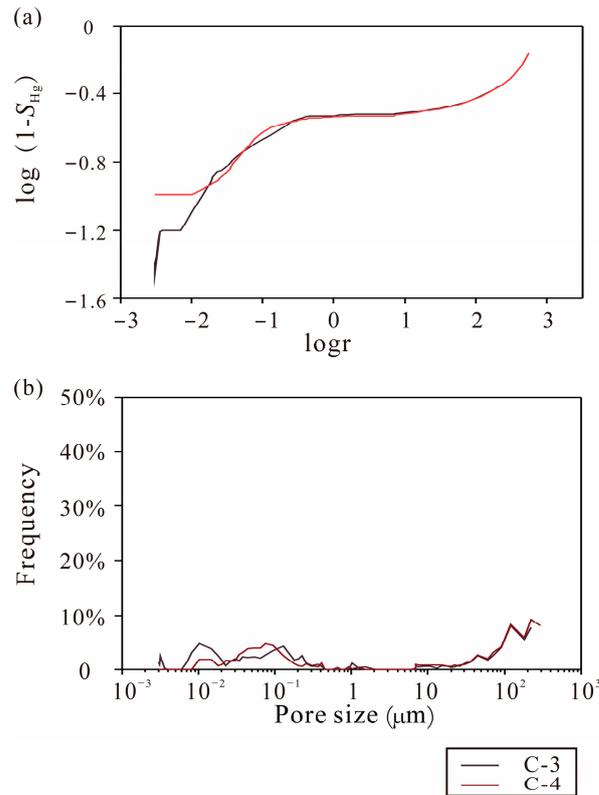


Figure 6. Fractal characteristic curves of high-pressure mercury injection in the Longtan tight sandstone samples, Well CSDP-2. (a) Different pore space fractal characteristics; (b) pore size distribution curve, C-3, 1110.80 m; C-4, 1114.70 m.

Table 3. Fractal dimensions of tight sandstone in the Longtan Formation of Well CSDP-2.

Sample No.	High-Pressure Mercury Injection				Nuclear Magnetic Resonance			
	Small Pores		Large Pores		$T_2 < T_{2\text{cutoff}}$		$T_2 > T_{2\text{cutoff}}$	
	D_{P-1}	R^2	D_{P-2}	R^2	D_{N-1}	R^2	D_{N-2}	R^2
G-21	2.94	0.87	2.29	0.94	-0.53	0.80	2.97	0.99
G-22	2.62	0.83	2.88	0.89	0.36	0.78	2.99	0.96
C-3	2.55	0.96	2.90	0.90	0.18	0.77	2.97	0.92
C-4	2.61	0.98	2.85	0.86	0.05	0.79	2.98	0.96
C-5	2.47	0.86	2.90	0.83	0	0.80	2.99	0.81
C-6	2.50	0.98	2.89	0.88	0.11	0.79	2.98	0.95
C-8	2.22	0.75	2.76	0.82	-0.26	0.78	2.98	0.94
C-14	2.96	0.94	2.52	0.92	1.01	0.69	2.99	0.86
C-16	2.95	0.85	2.90	0.98	1.01	0.70	2.94	0.83
C-19	2.90	0.96	2.77	0.78	-0.61	0.81	2.99	0.84
C-22	2.75	0.98	2.90	0.80	-0.13	0.81	2.98	0.94

4.3.2. Fractal Analysis of Nuclear Magnetic Resonance in Tight Sandstone

The $T_{2\text{cutoff}}$ value of tight sandstones in the study area functions as a critical point, delineating the scatter plot relationship curve of $\log S_v$ and $\log T_2$ for each sample into segments of $T_2 < T_{2\text{cutoff}}$ and $T_2 > T_{2\text{cutoff}}$ (Figure 7). These segments correspond to the fractal dimensions D_{N-1} and D_{N-2} of bound fluid and movable fluid, respectively. The fractal dimensions obtained from NMR for each sample were presented previously in Table 3. The fractal dimension D_{N-1} of bound fluid ranges from -0.53 to 1.01, with a

mean of 0.115, indicating that the pore space in the $T_2 < T_{2\text{cutoff}}$ segment lacks fractal characteristics. Conversely, the fractal dimension D_{N-2} of movable fluid ranges from 2.94 to 2.99, with a mean of 2.977 and an average coefficient of determination R^2 of 0.91, indicating that the pore space occupied by movable fluid demonstrates fractal characteristics, along with significant heterogeneity and complexity.

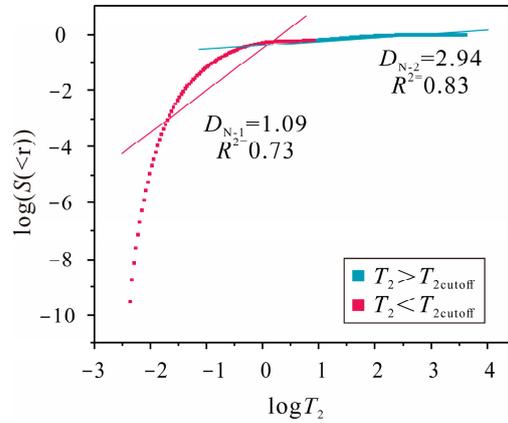


Figure 7. Fractal characteristic curves of nuclear magnetic resonance in the Longtan tight sandstone samples, Well CSDP-2, C-16, 1161.00 m. The scatter plot relationship curve exhibits two segments based on the $T_{2\text{cutoff}}$ value.

5. Discussion

5.1. Variances in Full-Scale Pore Size Distribution Identified through Multiple Testing Methods

Numerous prior studies have indicated the intricate nature of the pore structure in tight sandstone, demonstrating significant heterogeneity; however, accurately characterizing its pore structure using a single testing method poses a challenge [43,44]. While each testing method can capture pore size information in tight sandstone, they all come with inherent limitations. Therefore, integrating multi-scale detection methods is crucial for its comprehensive characterization. Mercury, being a non-wetting phase, presents challenges in measuring pores smaller than 1.8 nm using HPMI analysis [45]. In NMR experiments, when calculating surface relaxation (the primary relaxation mechanism), the influence of diffusion relaxation is often not accounted for [46]. However, overlooking the diffusion relaxation mechanism in larger pores can introduce errors in pore size characterization [47].

Plotting the pore size distributions obtained from HPMI and NMR on the same coordinate system facilitates a more comprehensive characterization of the full-scale pore size distribution in the Longtan tight sandstones of Well CSDP-2 (Figure 8). Within the 0.001–1 μm pore size range, the ranges of the pore size distribution curves for each sample generally coincide, with some consistency in peak position. However, due to the incremental pressurization in HPMI, the number of pressure points measured is fewer compared to the T_2 spectrum test points, resulting in a piecewise linear shape instead of a smooth curve overall. Consequently, at the same pore size, the frequency of pore size distribution measured by HPMI is higher at the peak. For better pore size characterization of the studied Longtan tight sandstones, T_2 spectrum test data are utilized for pore sizes $< 1 \times 10^{-3} \mu\text{m}$, while data obtained from HPMI are preferred for pore sizes $> 6 \mu\text{m}$.

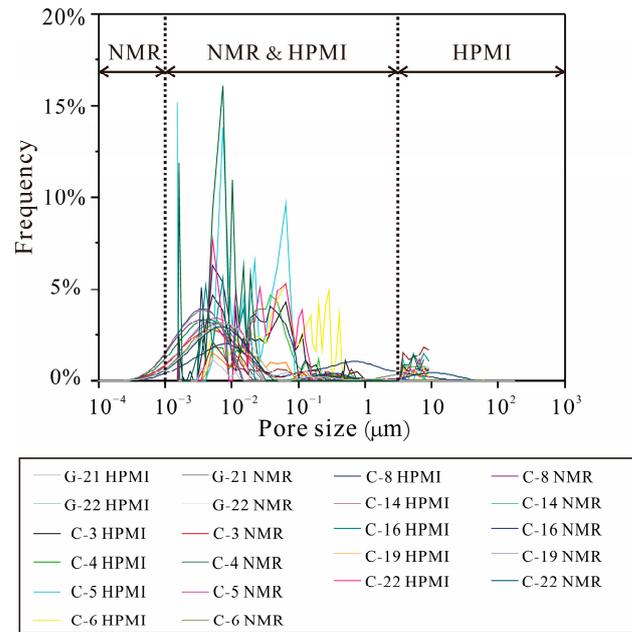


Figure 8. Combined measurement of pore size distribution in the Longtan tight sandstones in Well CSDP-2 using HPMI and NMR.

5.2. Influence of Pore Structure on Petrophysical Properties

To examine the impact of pore homogeneity on petrophysical properties, linear regressions were conducted between the fractal dimensions D_{N-1} and D_{N-2} from HPMI, D_{N-2} from NMR, and the petrophysical properties. The relationships between movable fluid saturation, median radius, and various fractal dimensions were explored to understand the influence of structural parameters on pore structure.

The fractal dimension D_{N-1} of bound fluid in the Longtan tight sandstones of Well CSDP-2 is below 2.0 (Table 3). Some scholars argue that a fractal dimension distribution outside the range of 2.0 to 3.0 lacks practical significance; for instance, it is logical to assume that if the smoothest part approaches two-dimensional characteristics (described mathematically as $D \geq 2$), the roughest part will exceed this but retain characteristics that are less than three-dimensional ($D \leq 3$) [29,48,49]. However, other opinions suggest that when D_{N-1} is below 2.0, it mainly reflects the fractal characteristics of bound fluid-occupied pores in a two-dimensional plane. Only fractal dimensions within the range of 2.0 to 3.0 can reflect the three-dimensional fractal characteristics of pores occupied by movable fluids [50]. Therefore, this study focuses on discussing the correlation between D_{N-2} and petrophysical parameters.

There is no significant correlation between the fractal dimension D_{P-1} of small pores obtained from HPMI in the studied samples and petrophysical parameters (Figure 9a). In contrast, the fractal dimension D_{P-2} of large pores obtained from HPMI shows a certain negative correlation with porosity, but no significant correlation with permeability is observed (Figure 9b). A smaller fractal dimension of large pores suggests better homogeneity of reservoir pore structure, implying that large pores with relatively good homogeneity can improve pore connectivity to some extent, but may not significantly enhance reservoir permeability.

The D_{N-2} of NMR movable fluid in the Longtan tight sandstone samples exhibits a strong negative correlation with reservoir petrophysical properties (Figure 9c), particularly with permeability. Movable fluid mainly occupies pores with radius $> 0.019 \mu\text{m}$ (Figure 5). The more complex these pore structures are, the stronger the binding effect on fluids inside the pores, leading to decreased fluid mobility within the reservoir [6], thus deteriorating reservoir petrophysical properties, particularly permeability.

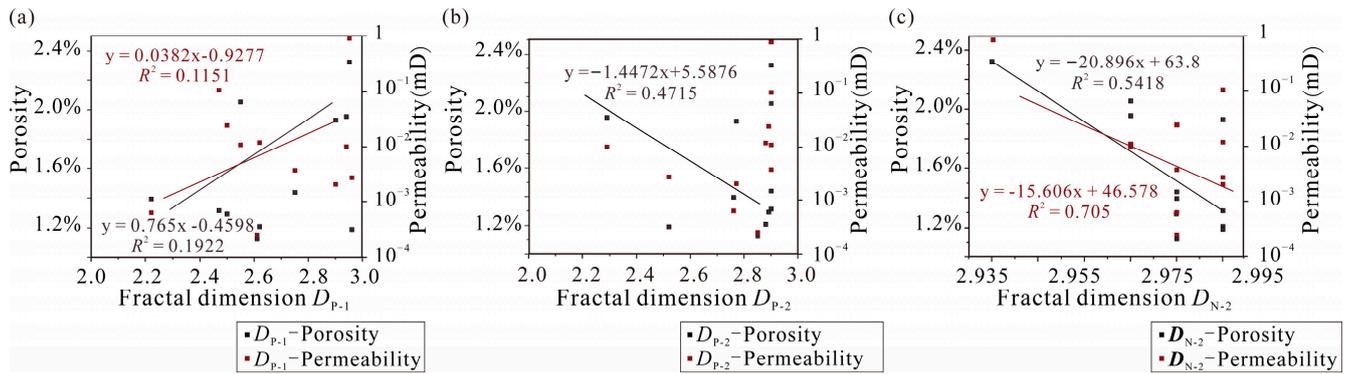


Figure 9. Relationship between fractal dimensions and pore permeability of the Longtan tight sandstones of Well CSDP-2. (a) Correlation between fractal dimensions of small pores obtained from HPMI and pore permeability; (b) correlation between fractal dimensions of large pores obtained from HPMI and pore permeability; (c) correlation between fractal dimensions of movable fluid obtained from NMR and pore permeability.

5.3. Reservoir Classification Evaluation

The main task of reservoir classification is to evaluate the storage space characteristics and permeability of the reservoir [51]. It requires considering all factors that influence reservoir quality and selecting parameters that can represent the differences in petrophysical properties and pore structure characteristics of various samples, thereby establishing rational and accurate reservoir classification evaluation criteria. In the Longtan Formation tight sandstone samples from Well CSDP-2, there is no significant difference in porosity, while permeability exhibits exponential differences (Table 1). There is a relatively strong positive correlation between the median radius and the D_{P-1} of small pores obtained from HPMI (Figure 10a), indicating that samples with larger median radius have a higher proportion of small pores in the total pore volume. There is a good negative correlation between NMR movable fluid saturation and the D_{N-2} of movable fluid (Figure 10b), showing that as the heterogeneity of pores occupied by movable fluids increases, the reservoir storage and permeability becomes weaker. This can also serve as an important parameter for evaluating the relative quality of reservoirs. In addition to these observations, it is crucial to acknowledge the significance of characterizing fluid flow in unconventional reservoirs, which is imperative for optimizing production strategies and enhancing recovery rates in such challenging reservoirs [52–56].

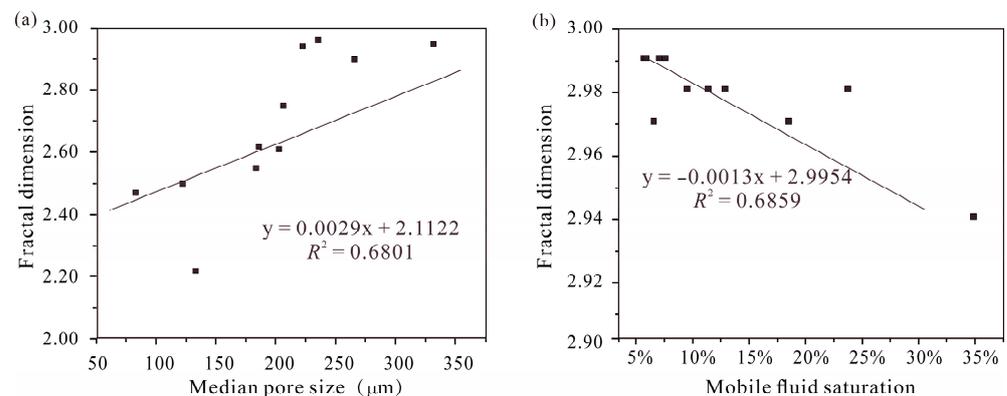


Figure 10. Relationship between fractal dimensions and pore structure parameters of the Longtan tight sandstones of Well CSDP-2. (a) Correlation between median radius and fractal dimensions of small pores obtained from HPMI; (b) correlation between movable fluid saturation and fractal dimensions of movable fluid obtained from NMR.

Based on these factors, the studied tight sandstone reservoir in Well CSDP-2 can be divided into three categories (Table 4): Classes I, II, and III. Class I reservoir sandstones (sample C-16) have a relatively high permeability, a movable fluid saturation of 34.82%, a median radius of 331.76 μm , good overall petrophysical properties, and a strong reservoir-seepage capacity. Class II reservoir sandstones (samples G-21, G-22, C-3, C-5, C-6, C-14, C-19, and C-22) have a medium level of permeability, with an average permeability of >0.001 mD, an average movable fluid saturation of 9.91%, a mean median radius of 187.88 μm , moderate overall petrophysical properties, and weaker reservoir-seepage capacity. Conversely, Class III reservoir sandstones (samples C-4 and C-8) exhibit relatively low permeability, with an average permeability of <0.001 mD, an average movable fluid saturation of 6.46%, a mean median radius of 167.53 μm , poor overall petrophysical properties, and almost no reservoir-seepage capacity. Future research on the Longtan tight sandstones should explore the correlation between these reservoir categories and log responses. Such investigation would facilitate the differentiation and mapping of each reservoir sandstone category across multi-well exploration sites, providing a means to predict sweet spots in similar tight sandstone formations. Additionally, addressing the challenges in drilling, completion, and production from unconventional hydrocarbon reservoirs is essential for maximizing the economic potential of such resources and ensuring sustainable energy production in the long term.

Table 4. Classification of tight sandstone reservoirs in the Longtan Formation of Well CSDP-2 in the South Yellow Sea Basin.

Sample Type	Permeability/mD	Median Radius / μm	Movable Fluid Saturation /%
Class I	0.92	331.76	34.82
Class II	>0.001	(265.56, 82.68)/187.88 ¹	(23.71, 5.64)/9.91 ¹
Class III	<0.001	(202.47, 132.79)/167.53 ¹	(12.83, 9.50)/6.46 ¹

¹ Note: (maximum value, minimum value)/mean.

6. Conclusions

In the Laoshan Uplift of the South Yellow Sea Basin, the Longtan Formation of Well CSDP-2 displays typical characteristics of tight sandstone reservoirs and is predominantly composed of quartz and feldspar. The prevalent pore types include intra-granular dissolution pores, residual inter-granular pores, and minor micro-fractures. High-pressure mercury intrusion (HPMI) analysis revealed mercury saturation ranging from 73.60% to 99.74%, with threshold pressures ranging from 0.003 to 0.079 MPa and median pore radii spanning 82.68 to 331.76 μm . Additionally, NMR testing indicated that movable fluid predominantly occupies pores > 0.019 μm , with saturation varying between 5.65% and 34.83%.

The HPMI-derived pore structure exhibits multiple fractal characteristics, displaying high overall fractal dimensions and pronounced heterogeneity, leading to a discrete pore distribution. While homogeneity in large pores improves connectivity to some extent, it has little impact on reservoir permeability. The fractal dimension D_{N-2} of movable fluid pore space obtained from NMR ranges from 2.94 to 2.99, indicating significant heterogeneity in fluid-occupied pores. Increased heterogeneity in such pores hinders fluid flow and storage, deteriorating reservoir properties.

By utilizing permeability differences and parameters such as movable fluid saturation and median radius, the Longtan Formation tight sandstones of Well CSDP-2 were classified into three categories. Of these, Class I reservoir sandstones exhibit favorable oil and gas storage and permeability, representing a relatively high-quality reservoir.

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