Reservoir heterogeneity of the Longmaxi Formation and its significance for shale gas enrichment

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Abstract
To better determine the sweet spot in the vertical profile of the Longmaxi Formation, the shale heterogeneity was systematically investigated. A series of experiments were conducted on 40 shale samples collected from the Lower Silurian Longmaxi Formation in the Weiyuan shale gas field. The results indicated that total organic carbon (TOC), the mineral composition, methane adsorption capacity, and porosity of the four sub-layers in the Longmaxi shale varied significantly. In terms of the TOC, the mid-lower Long1\textsubscript{1} had the highest value, followed by Long1\textsubscript{3}, while the TOC values of Long1\textsubscript{2} and Long1\textsubscript{4} were quite low. As for mineral composition, the mid-lower Long1\textsubscript{1} had the highest quartz content, Long1\textsubscript{2} and Long1\textsubscript{3} had equivalent quartz, carbonate, and clay mineral contents, and Long1\textsubscript{4} had higher clay mineral and carbonate contents, but a lower quartz content. Shale porosity and methane adsorption capacity were the highest in the mid-lower Long1\textsubscript{1}, followed by Long1\textsubscript{3}, Long1\textsubscript{2}, Long1\textsubscript{4}, and the upper Long1\textsubscript{1}. The micro-heterogeneity represented by the fractal dimension ranged from 2.590 to 2.750, with an average of 2.670. The mid-lower Long1\textsubscript{1} had the largest fractal dimension, followed by Long1\textsubscript{3}, Long1\textsubscript{2}, Long1\textsubscript{4}, and the upper Long1\textsubscript{1}. The micro-heterogeneity represented by the fractal dimension ranged from 2.590 to 2.750, with an average of 2.670. The mid-lower Long1\textsubscript{1} had the largest fractal dimension, followed by Long1\textsubscript{3}, Long1\textsubscript{2}, Long1\textsubscript{4}, and the upper part of Long1\textsubscript{1} had the smallest fractal dimension. The sedimentary environment controls the macro-heterogeneity in the vertical profile. The micro-heterogeneity depends on diagенesis, which can be investigated by the different effects of minerals on micropore development. The strong micro-heterogeneity results in better preservation conditions for shale gas. The mid-lower Long1\textsubscript{1} was rich in gas generation material (TOC) with enough storage space and is characterized by good preservation conditions, leading to the highest gas content of the four sub-layers. In addition, the high brittle mineral content is conducive to fracturing and the formation of a fracture network. Thus, the middle -Long1\textsubscript{1} is the “sweet spot” in the vertical profile for the shale gas development.

Keywords
controlling factors, heterogeneity, shale gas enrichment, the Longmaxi Formation
1 | INTRODUCTION

The Longmaxi Formation in Weiyuan shale gas field is one of the most important marine shale gas exploration formations in Sichuan Basin, China. Many breakthroughs have been achieved, and the shale gas production reached $29.79 \times 10^8 \text{ m}^3$ in 2019. However, the Longmaxi Formation is noticeably heterogeneous,\textsuperscript{1-6} leading to difficulties in determining the most favorable sweet spot in the vertical profile to locate the horizontal wells.\textsuperscript{7-9} Although many studies on marine shale reservoir have been mainly conducted, most studies focused on lateral heterogeneity and microstructure characterization.\textsuperscript{10-13} The heterogeneity in the vertical profile, the origins of the heterogeneity, and the significance of this heterogeneity in Weiyuan shale gas field are poorly understood, which to some degree impedes the rapid development of shale gas exploration and development.

According to the research by Zhu et al.,\textsuperscript{14} the heterogeneity of the shale can be divided into macroscopic and microscopic heterogeneity. Macroscopic heterogeneity includes lithology, mineral composition, texture, TOC, and physical properties, while the microscopic heterogeneity mainly comprises pore size, volume, area, shape, and connectivity.\textsuperscript{14,15} These heterogeneities underpin the amounts of hydrocarbon that can be generated, stored, and preserved, and are related to the hydrocarbon adsorptive capacity, the seepage and diffusion capacity, and the ability of the rock to fracture. Therefore, to investigate the characteristics of these heterogeneities, understand the drivers and figure out the significance of these heterogeneities are crucial for shale gas plays. Currently, many techniques and methods can be used to study the shale heterogeneities. As to quantifying the microscopic heterogeneity, the fractal theory proposed by Mandelbrot\textsuperscript{16} and the fractal dimensions are usually applied to understand the pore surface irregularity and pore structure complexity, which have been successfully utilized in both clay and shales.\textsuperscript{17-20} Although there have been many investigations of the fractal characteristics of the Longmaxi Formation, most studies were based on the outcrop samples. Due to weathering, the pore structure of outcrop samples may change, and thus, outcrop samples are unable to reflect the actual pore structure characteristics of the shale. Studies on downhole samples have been mainly concentrated in the Jiaoshiba area.\textsuperscript{21,22} However, no corresponding research has been conducted in the Weiyuan area, which is one of the three most important shale gas demonstration areas in China. Furthermore, low pressure N$_2$ adsorption (LPNA), as the most widely used technique, has been validated to characterize the tight rock reservoir.\textsuperscript{15,23-26} Therefore, fractal dimensions calculated from LPNA data can be used to determine the degree of the heterogeneity of pores.

The purpose of this paper was to describe both macroscopic and microscopic heterogeneities in vertical profile, analyze the controlling factors, and discuss the significance of these heterogeneities on shale gas enrichment. To achieve this goal, samples from Wd2 were systematically collected and a series of experiments were carried out. Additionally, statistical analyses of petrology, physical properties, geochemical indices, and elemental data were conducted to provide a comprehensive understanding of the sweet spot in the vertical profile in order to facilitate shale gas exploration and development.

2 | GEOLOGICAL BACKGROUND

The Weiyuan shale gas field is located in the southwestern part of the Sichuan Basin, with an area of approximately 6500 km$^2$. Structurally, it belongs to the low fold belt of the Guzhong Slope in southwestern Sichuan Province and develops the Weiyuan anticline. The Longmaxi Formation is in conformable contact with the Upper Ordovician Wufeng Formation, and the burial depth of the Wufeng Formation in the study area is 1500-4000 m, deepening to the southeast direction (Figure 1A). The Longmaxi Formation is dominated by black carbonaceous shale and black silty shale, with the color becoming darker and the grain size finer with increasing depth. Based on the lithology and characteristics of the logging response, the Longmaxi Formation can be subdivided into the Long1 and Long2 members, of which the Long1 member is well preserved in the Weiyuan area, with a thickness of 140-240 m and a stable regional distribution. Based on the lithology, sequence, and electricity characteristics, the Long1 member can be divided into Long1$_1$ and Long1$_2$ sub-members from bottom to top. The Long1$_1$ sub-member is a set of black carbonaceous shale of 36-48 m thickness and rich in organic matter, with well-developed laminations and a large number of graptolites. The Long1$_1$ sub-member can be further divided into four sub-layers: Long1$_1^1$, Long1$_1^2$, Long1$_1^3$, and Long1$_1^4$ from bottom to top (Figure 1B) by using the data of petrology, sedimentary structures, paleontology, and electrical properties, as well as other information. At present, the shale gas production is primarily derived from the Long1$_1$ sub-member, and the samples in this study were taken from the four Long1$_1$ sub-layers.

3 | SAMPLES AND METHODS

3.1 | Samples

All of the samples were collected from the four sub-layers of the Long1$_1$ sub-member in well Wd2. The samples were divided into mineralogical and chemical-equivalent aliquots in order to conduct TOC, X-ray diffraction (XRD), LPNA, methane adsorption, elements, porosity, and scanning
electron microscopy (SEM) experiments. The details of the results are listed in Table 1 and Table 2.

### 3.2 TOC and mineral composition analysis

The TOC content was tested using a LECO CS230 carbon sulfur analyzer. The entire test process complied with national standard GB/T19145-2003.

The mineral composition was measured using a Bruker Corp. AXS D8 Discover X-ray diffractometer. Approximately 10 g of 200-mesh sample powder was weighed for section preparation. The specific test procedures were described by Chen et al.27

### 3.3 LPNA and methane isothermal adsorption

The LPNA experiment was completed by using the Quantachrome Nova4200e instrument. In LPNA experiments, shale samples were crushed before measurement. Since there was no standard particle size for the crushed shale, the most widely used grain size of approximately 60-80 mesh (180-250 μm) was applied in the sample preparation. The entire test process complied with national standard GB/T19587-2004. The Brunauer-Emmitt-Teller (BET)-specific surface area was calculated using the data for relative pressure of 0.05-0.35.

The methane isothermal adsorption experiment was completed by using the Rubotherm high-temperature and high-pressure gravimetric adsorption instrument produced by Ankersmid BV. The detailed experimental procedures were referred to the report by Yu et al.28

### 3.4 SEM observations and porosity test

The SEM observation experiments were performed at the Micro-Nano Structure Imaging Laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences. The instrument was a FEI Helios 650 field emission SEM (FIB-SEM) with a minimum resolution of 6 nm. The sample surface was polished with argon ions and then plated with carbon prior to the FE-SEM imaging.

The porosity test was completed using the Coreval 700 burden pressure porosity and permeability apparatus produced by the Vinci Company. The entire test process complied with national standard GB/T29172-2012.

### 3.5 Elemental testing

Elemental test was processed and analyzed in the Beijing Research Institute of Uranium Geology. The major elements were characterized by X-ray fluorescence spectrometer (XRF), and the trace element concentrations were measured.
| Sample | Depth  | Layer  | TOC   | Quartz  | Feldspar | Pyrite  | Carbonate | Clay  | Porosity | Methane adsorption capacity | BJE pore volume | BET specific surface area | Fractal dimension |
|--------|-------|--------|-------|---------|----------|---------|-----------|-------|----------|----------------------------|----------------|---------------------------|------------------|
| W1     | 2541.41 | Long1  | 1.70  | 31.60   | 5.60     | 4.00    | 15.50     | 43.30 | 4.50     | 0.0487                     | 18.60 | 2.626                     |                  |
| W2     | 2543.76 |        | 2.80  | 21.00   | 3.90     | 2.60    | 38.70     | 33.80 | 3.20     | 0.056                      | 14.60 | 2.645                     |                  |
| W3     | 2546.96 |        | 5.20  | 40.80   | 3.80     | 2.90    | 31.40     | 21.10 | 5.80     | 0.0477                     | 13.00 | 2.679                     |                  |
| W4     | 2547.96 |        | 4.00  | 28.50   | 5.80     | 3.80    | 17.90     | 44.00 | 3.50     | 0.0477                     | 15.80 | 2.681                     |                  |
| W5     | 2549.66 |        | 2.10  | 15.90   | 8.10     | 2.50    | 37.00     | 36.50 | 4.30     | 0.0586                     | 12.20 | 2.625                     |                  |
| W6     | 2550.56 |        | 2.70  | 20.20   | 4.90     | 2.00    | 41.90     | 31.00 | 3.00     | 0.0424                     | 19.20 | 2.647                     |                  |
| W7     | 2551.50 |        | 2.30  | 20.10   | 5.90     | 3.00    | 46.30     | 24.70 | 3.00     | 0.0415                     | 18.80 | 2.648                     |                  |
| W8     | 2553.06 |        | 3.90  | 21.80   | 6.20     | 2.70    | 41.10     | 28.20 | 3.50     | 0.0388                     | 18.30 | 2.656                     |                  |
| W9     | 2554.71 |        | 4.40  | 17.80   | 4.70     | 4.90    | 44.20     | 28.40 | 5.30     | 0.0406                     | 21.00 | 2.653                     |                  |
| W10    | 2555.31 |        | 3.60  | 13.50   | 3.30     | 2.10    | 50.60     | 30.50 | 4.30     | 0.0425                     | 19.60 | 2.653                     |                  |
| W11    | 2556.16 |        | 0.73  | 18.20   | 5.10     | 4.50    | 37.00     | 35.20 | 4.50     | 0.0350                     | 18.00 | 2.659                     |                  |
| W12    | 2557.96 |        | 4.40  | 16.50   | 4.30     | 6.30    | 41.80     | 31.10 | 5.00     | 0.0379                     | 15.00 | 2.659                     |                  |
| W13    | 2563.70 | Long1  | 6.70  | 28.40   | 6.80     | 8.70    | 27.50     | 28.60 | 5.30     | 0.0341                     | 18.20 | 2.683                     |                  |
| W14    | 2560.56 |        | 5.60  | 23.60   | 5.30     | 5.00    | 29.40     | 36.70 | 6.20     | 0.0532                     | 23.00 | 2.672                     |                  |
| W15    | 2562.31 |        | 3.50  | 31.50   | 3.20     | 5.10    | 27.10     | 33.10 | 4.90     | 0.0450                     | 21.00 | 2.683                     |                  |
| W16    | 2564.16 |        | 3.50  | 30.20   | 9.20     | 5.80    | 23.30     | 31.50 | 4.10     | 0.0595                     | 22.00 | 2.663                     |                  |
| W17    | 2565.04 |        | 2.40  | 23.70   | 10.90    | 5.80    | 32.10     | 27.50 | 3.00     | 0.0390                     | 16.40 | 2.645                     |                  |
| W18    | 2565.81 | Long1  | 2.20  | 28.80   | 12.50    | 2.00    | 29.00     | 27.70 | 3.00     | 0.0298                     | 14.00 | 2.664                     |                  |
| W19    | 2565.97 |        | 2.20  | 28.10   | 9.50     | 4.30    | 29.00     | 29.10 | 3.10     | 0.0387                     | 18.60 | 2.667                     |                  |
| W20    | 2568.05 |        | 2.40  | 30.60   | 9.80     | 3.10    | 29.80     | 26.70 | 3.60     | 0.0441                     | 18.70 | 2.641                     |                  |
| W21    | 2568.66 |        | 2.50  | 29.10   | 9.40     | 2.70    | 29.10     | 29.70 | 5.00     | 0.0408                     | 19.20 | 2.661                     |                  |
| W24    | 2569.09 | Upper  | 2.75  | 43.20   | 10.80    | 3.80    | 18.90     | 23.30 | 5.80     | 0.0360                     | 21.15 | 2.645                     |                  |
| W25    | 2569.11 |        | 2.20  | 23.30   | 8.90     | 5.50    | 22.10     | 40.20 | 6.50     | 0.0446                     | 21.20 | 2.660                     |                  |
| W26    | 2569.66 |        | 3.16  | 31.60   | 8.80     | 4.90    | 21.50     | 33.20 | 5.50     | 0.0475                     | 20.20 | 2.623                     |                  |
| W27    | 2569.67 |        | 4.00  | /       | /        | /       | /         | /     | /        | 0.0290                     | 20.80 | 2.646                     |                  |
| W29    | 2571.20 | Mid    | 4.49  | 46.90   | 1.50     | 2.90    | 37.30     | 11.40 | 6.40     | 0.0529                     | 22.61 | 2.680                     |                  |
| W30    | 2571.61 |        | 4.19  | 61.10   | 1.00     | 2.40    | 28.40     | 7.10  | 6.40     | 0.0375                     | 20.68 | 2.686                     |                  |
| W31    | 2571.71 |        | 5.50  | 42.20   | 4.10     | 4.60    | 32.10     | 17.00 | 6.60     | 0.0426                     | 23.70 | 2.693                     |                  |

(Continues)
by a VG PQ2 Turbo inductively coupled plasma source mass spectrometer (ICP-MS), as described by Yan et al.\textsuperscript{29}

### 3.6 Fractal dimensions from LPNA

Fractal theory has been widely used to describe irregular and fragmented systems with no characteristic length scale. The fractal dimension ($D$), which is strongly influenced by irregular geometry and surface roughness, usually falls between 2 and 3.\textsuperscript{30} A value of $D$ equal to 2 indicates a perfectly smooth surface, while a fractal dimension approaching 3 indicates a more heterogeneous pore structure or a completely irregular and rough surface.\textsuperscript{26,31} The fractal dimension calculated from LPNA data has been demonstrated to be useful in characterizing pore structure heterogeneity.\textsuperscript{21,32,33} Among several models, such as the Langmuir model, the thermodynamic model, and the BET model, which can be used to measure the fractal dimension of shale using LPNA data, the Frenkel-Halsey-Hill (FHH) model is considered as the most extensively applicable model for fractal dimension calculations and has been widely applied in porous materials. The FHH model can be described by the following equation:

$$\ln \left( \frac{V}{V_0} \right) = K \left[ \ln \left( \frac{P_0}{P} \right) \right] + \text{constant},$$

where $V$ (cm$^3$/g) denotes the adsorbed gas volume at the equilibrium pressure; $V_0$ (cm$^3$/g) is the monolayer coverage volume; $P_0$ (MPa) is the saturation pressure; $P$ (MPa) is the equilibrium pressure; and $K$ is the slope of the fitting curve, which depends on the adsorption mechanism. The fractal dimension can be obtained from the slope of the plot for $\ln V$ vs $\ln(P/P_0)$. Then, the fractal dimension ($D$) can be calculated using either Equation (2) or (3):

$$D = K + 3,$$

$$D = 3K + 3.$$  \hspace{1cm} (3)

Equation (2) is used when capillary condensation is the main mechanism of gas adsorption, while Equation (3) is applied in the case of the van der Waals force.\textsuperscript{34,35}

### 4 RESULTS

In this paper, shale heterogeneity was divided into macroscopic and microscopic heterogeneity. Macroscopic heterogeneity can be further divided into TOC, mineral composition, methane adsorption capacity, and porosity, while the microscopic heterogeneity mainly focused on the pore structure.
| Sample Layer       | Major elements/% | Trace elements/μg/g | Element ratios |
|--------------------|------------------|--------------------|---------------|
|                    | SiO₂              | Al₂O₃              | TiO₂           | V     | Cr   | Co   | Ni   | Cu   | U   | Th   | Zr   | V/V + Ni | V/Cr | U/Th | Ni/Co | Al Ni + Cu/|
| W1 Long1¹         | 58.44             | 15.70              | 0.596          | 258.6 | 83.3 | 11.0 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W2 Long1¹         | 63.94             | 10.20              | 0.399          | 258.4 | 83.8 | 11.8 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W3 Long1¹         | 54.92             | 14.32              | 0.481          | 258.6 | 83.3 | 11.0 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W4 Long1¹         | 60.23             | 10.24              | 0.343          | 258.4 | 83.8 | 11.8 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W5 Long1¹         | 57.59             | 11.47              | 0.477          | 258.6 | 83.3 | 11.0 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W6 Long1¹         | 51.70             | 12.47              | 0.575          | 258.4 | 83.8 | 11.8 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W7 Long1¹         | 57.59             | 11.47              | 0.477          | 258.6 | 83.3 | 11.0 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W8 Long1¹         | 58.97             | 11.68              | 0.607          | 258.4 | 83.8 | 11.8 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W9 Long1¹         | 57.01             | 11.76              | 0.594          | 258.6 | 83.3 | 11.0 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W10 Long1¹        | 57.61             | 11.00              | 0.581          | 258.4 | 83.8 | 11.8 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W11 Long1¹        | 55.54             | 16.56              | 0.527          | 258.6 | 83.3 | 11.0 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W12 Long1¹        | 58.81             | 12.5               | 0.696          | 258.4 | 83.8 | 11.8 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W13 Long1¹        | 67.20             | 20.02              | 0.186          | 258.6 | 83.3 | 11.0 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W14 Long1¹        | 74.20             | 4.02               | 0.186          | 258.4 | 83.8 | 11.8 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W15 Long1¹        | 78.18             | 4.03               | 0.186          | 258.6 | 83.3 | 11.0 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W16 Long1¹        | 75.77             | 3.43               | 0.167          | 258.4 | 83.8 | 11.8 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W17 Long1¹        | 86.37             | 1.71               | 0.072          | 258.6 | 83.3 | 11.0 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W18 Long1¹        | 84.47             | 2.09               | 0.094          | 258.4 | 83.8 | 11.8 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W19 Long1¹        | 79.11             | 3.50               | 0.194          | 258.6 | 83.3 | 11.0 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W20 Long1¹        | 68.96             | 9.50               | 0.154          | 258.4 | 83.8 | 11.8 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
| W21 Long1¹        | 77.99             | 3.34               | 0.152          | 258.6 | 83.3 | 11.0 | 0.29 | 2.86 | 1.14 | 0.58 | 0.09 | 0.77 | 1.98 | 0.38 | 5.37 |
4.1 | TOC and mineral composition

The TOC of Longmaxi shale is unevenly distributed. The TOC of the shale in Long11 is generally high, ranging from 2.8% to 7.7%, with an average of 5.3%, while that of the middle and lower parts of Long11 is much higher, ranging from 4.16% to 7.70%, with an average of 5.78%. The overall TOC of Long12 is low, ranging from 2.2% to 2.5%, with an average of 2.3%, while that of Long13 is higher, ranging from 2.4% to 6.7%, with an average of 4.3%. The TOC of Long14 varies greatly, ranging from 0.73% to 5.2%, with an average of 3.2% (Figure 2A).

XRD analysis was carried out on 39 shale samples from the Longmaxi shale. It was discovered that quartz, clay, and carbonate are the main minerals, as well as minor amounts of feldspar and pyrite. The mineral compositions of the different sub-layers vary quite significantly (Figure 2B). The quartz content of the Long14 shale samples is much lower with an average value of 22.2%, the carbonate content is much higher, with an average of 36.9%; the clay mineral content with an average of 32.3%. For the Long13 samples, the average contents of the quartz, carbonate, and clay are 27.5%, 27.9%, and 31.5%, respectively. The quartz, carbonate, and clay mineral contents are equivalent in the Long12 shale samples, with average values of 28.3%, 29.2%, and 28.3%, respectively. For the Long11 samples, quartz is the dominant mineral, ranging from 42.2% to 91.8%, with an average of 71.3%; the clay content varies from 0.0% to 23.3%, with a mean value of 5.5%, and the carbonate content ranges from 8.0% to 37.3%, with an average value of 19.15%.

4.2 | Methane adsorption characteristics and porosity distribution of shale

The methane adsorption results are presented in Figure 3A. These results revealed that the adsorption capacities of the shale samples vary widely. The Langmuir volumes (VL) range from 0.8 to 4.69 m³/t, with an average of 3.5 m³/t (Figure 3A). For the Long11 shale samples, the VL values are much higher, ranging from 3.85 to 4.67 m³/t. The VL values of the Long12 shale samples are comparable to those of the Long13 shale samples. The VL values of the Long14 samples vary greatly, ranging from 0.8 to 4.69 m³/t.

The shale samples have a porosity of 3.0%-8.5%, with an average of 5.4%. The porosity of the Long11 shale samples ranges from 4.5% to 8.5%, with an average of 6.9%. Shale samples of the middle and lower parts exhibit even higher porosity values, varying from 6.4% to 8.5%, with an average of 7.3%, while samples in the upper Long11 have an average porosity of 5.6%. The Long12 shale samples have a concentrated range of porosity, that is, from 3.0% to 5.0% with an average of 3.7%. Shale samples of Long13 have a porosity that varies from 3.0% to 6.2%, with an average of 4.7%, while the porosity of the Long14 samples is much lower, ranging from 3.0% to 5.8% with an average of 4.2% (Figure 3B).

FIGURE 2  Vertical distribution characteristics of (A) the TOC content and (B) the mineral composition of the Longmaxi Formation in the Weiyuan block
4.3 Characteristics of major and trace elements

The major and trace elements are listed in Table 2. The content of SiO$_2$ as the most important major element ranges from 10.41% to 88.55% and the average SiO$_2$ content in different strata decreases in the following order: Long1$_1$ (72.31%) > Long1$_2$ (57.85%) > Long1$_3$ (55.63%) > Long1$_4$ (46.10%). Furthermore, compared with upper Long1$_1$, the mid-lower Long1$_1$ has the highest average value of SiO$_2$ (76.10%). The Al$_2$O$_3$ content is much lower than SiO$_2$ content with the value ranging from 1.71% to 16.56%. The average Al$_2$O$_3$ content is the lowest in Long1$_1$, while the other three sub-layers have comparable Al$_2$O$_3$ content. The TiO$_2$ content ranges from 0.07% to 0.70% and the variation is consistent with Al$_2$O$_3$. Trace elements (V, Ni, Cu, U) are systematically enriched in Long1$_1$, especially in mid-lower Long1$_1$ with the average values of 953.87, 133.09, 80.65, and 23.54 μg/g, respectively. The enrichment degree of these elements decreases upwards for the Longmaxi Formation. While Cr, Co, Th, and Zr are depleted in Long1$_1$, the average values of the above trace elements are the lowest in mid-lower Long1$_1$ (40.6, 11.90, 3.69 and 23.34 μg/g, respectively). From Long1$_1$ to Long1$_4$, the contents of these elements increase to different degrees. The excess silica contents, which represent the SiO$_2$ content above an average shale background, were calculated using the formula proposed by Wedepohl.36

4.4 Pore structure characteristics from LPNA

The BET-specific surface area ranges from 13.00 to 26.00 m$^2$/g, with an average of 20.00 m$^2$/g and the Barrett-Joyner-Halenda (BJH) pore volume ranges from 0.030 to 0.060 cm$^3$/g with an average of 0.042 cm$^3$/g. For the Long1$_1$ samples, the BET-specific surface area ranges from 20.20 to 26.00 m$^2$/g, with an average of 22.30 m$^2$/g, and the BJH pore volume varies from 0.029 to 0.054 cm$^3$/g, with an average of 0.039 mL/g (Figure 4). The BET of the samples from Long1$_2$ varies from 14.00 to 19.20 m$^2$/g, with an average of 17.63 m$^2$/g and the BJH varies from 0.030 to 0.044 cm$^3$/g, with an average of 0.038 cm$^3$/g. Those of the Long1$_3$ range from 16.40 to 23.00 m$^2$/g, with an average of 20.10 m$^2$/g and 0.034-0.060 cm$^3$/g, with an average of 0.046 cm$^3$/g, and those of the Long1$_4$ vary between 12.20 and 21.00 m$^2$/g, with an average of 17.00 m$^2$/g and 0.035-0.059 cm$^3$/g, with an average of 0.045 cm$^3$/g (Table 1). The average pore diameters of Long1$_1$, Long1$_2$, Long1$_3$, and Long1$_4$ are 9.2, 10.3, 9.8, and 10.4 nm, respectively.
FIGURE 4 Vertical distribution characteristics of (A) the BET-specific surface area and (B) the BJH pore volume of the four sub-layers in Longmaxi shale, Weiyuan shale gas field.

FIGURE 5 Plots of $\ln V$ vs $\ln[\ln(P/P_0)]$ for typical shale samples from different sub-layers in the Longmaxi Formation of the Weiyuan block.
Based on the calculation principle of the fractal dimension, the data on a plot of \( \ln V vs \ln[\ln(P_{o}/P)] \) were fitted with a straight line, and all of the correlation coefficients of the linear fitting curves were determined to be above 0.98 (Figure 5), indicating obvious fractal characteristics. When calculated using Equation (2), the fractal dimension is mainly distributed between 1.780 and 2.260, with an average of 2.000, and most of the values (> 66%) are <2, which is contrary to the definition of the fractal dimension in fractal theory. Therefore, in this study, the fractal dimension was calculated using Equation (1), obtaining the values ranging from 2.590 to 2.750, with an average of 2.670. Individually, the fractal dimension \( D \) of Long1 \(_1^1 \) is 2.623-2.752, with an average of 2.888, the \( D \) of Long1 \(_1^2 \) is 2.641-2.667, with an average of 2.658, the \( D \) of Long1 \(_1^3 \) is 2.645-2.683, with an average of 2.669; and the \( D \) of Long1 \(_1^4 \) is 2.595-2.681, with an average of 2.648 (Figure 6). In general, the fractal dimension is the largest in the middle and lower parts of Long1 \(_1^1 \), and the fractal dimension of the upper part of Long1 \(_1^1 \) is equivalent to that of Long1 \(_1^2 \). The fractal dimension of Long1 \(_1^2 \) is larger than that of Long1 \(_1^1 \) and Long1 \(_1^4 \), and Long1 \(_1^4 \) has the smallest fractal dimension (Table 1).

5 | DISCUSSION

5.1 | Controlling factors for macro-heterogeneity

According to the description of the macroscopic heterogeneity, the mid-lower Long1 \(_1^1 \) is featured by high TOC, high quartz content, high porosity, and high methane adsorption capacity. Different sedimentary settings usually lead to different hydrodynamics, and the shale deposited in different environments is also quite different in properties. The major and trace elements have been widely used to evaluate the environments by comparing their types and abundances with standard values.\(^{37,38}\) In this part, the redox conditions, paleoproductivity, and detrital influx of the samples were investigated.

5.1.1 | Paleoredox

The redox conditions are crucial to organic-rich shale deposition. V/Cr, U/Th, and Ni/Co ratios are considered to be reliable redox proxies. The vertical variations of the TOC and elemental ratios are presented in Figure 7. The V/Cr, U/Th, and Ni/Co ratios in the mid-lower Long1 \(_1^1 \) are relatively high (mean values of 25.47, 8.68, and 12.02, respectively), demonstrating strong reducing environment. With the burial depth much shallower, the redox indices sharply decrease and then the values remain relatively stable with the mean values of 3.24, 0.78, and 4.30, respectively, indicating the environment changing from the strong reducing to weak reducing environment. What’s more, the redox proxies are positively correlated with TOC (Figure 8A), indicating the important role of the redox conditions in organic-rich shale deposition.

5.1.2 | Paleoproductivity

In terms of paleoproductivity, due to the strong reducing environment in the mid-lower Long1 \(_1^1 \), the biogenic Ba is dissolved in the water and becomes inaccurate as a paleoproductivity index. Therefore, Ni + Cu/Al is taking place as the effective paleoproductivity proxy.\(^{39}\) As shown in Figure 7, the paleoproductivity also reaches the highest in the mid-lower Long1 \(_1^1 \) and the mean value is 131.09 and then the value decreases upward with the average value of 23.96. The abundant Ni and Cu elements in the mid-lower Long1 \(_1^1 \) provide necessary nutrients for biological boom, which in turn promotes the enrichment of organic matter, resulting in the positive correlation between paleoproductivity and TOC (Figure 8B).
Although the reducing environment and the high paleoproductivity favor the deposition of the organic-rich shale, the detrital influx if in large amounts will significantly dilute the organic matter enrichment. The Ti and Al in shale can be used to quantify the detrital influx. The variations of the Ti and Al contents are consistent with the burial depth. The contents of Ti and Al are negatively correlated with TOC with coefficient indices of 0.58 and 0.54, respectively (Figure 8C,D). In addition, the mid-lower Long1\textsuperscript{1} corresponds to graptolite zones of *Persculptogr. persculptus*, *Akidograptus ascensus*, and *Parakidogr. Acuminatus*, and the formation of upper Long1\textsuperscript{1} to the Long1\textsuperscript{4} approximately corresponds to graptolite zones of *Cystograptus vesiculosus to Spirograptus guerichi*. Based on the graptolite biozonations, the sedimentation rate was calculated. The sedimentation rate of the mid-lower Long1\textsuperscript{1} is 2.04 m/Ma, which is much lower than the upper interval with the value of 8.02 m/Ma. In another aspect, the relatively low sedimentation rate favors the organic matter (OM) accumulation while the fast sedimentation rate dilutes the OM accumulation.
5.1.4 Effects of sedimentary environment on macro-heterogeneity

Based on the above discussion, the strong reducing condition, high paleoproductivity, low input of terrestrial clastic material, and low sedimentation rate of the mid-lower Long11 result in the deposition of the shale with high TOC. Moreover, the high paleoproductivity in the mid-lower Long11 facilitates the prosperity of the planktonic organisms (including siliceous skeletal organisms like radiolarians and graptolites), which in turn provide an important source for the enrichment of the authigenic quartz. Both the negative correlation between Zr and SiO₂ \( (R^2 = .74) \) and the positive correlation between TOC and excess-Si \( (R^2 = .63) \) indicate the biogenic origin of the quartz in the Longmaxi Formation (Figure 9A,B). The higher SiO₂ content and the higher excess-Si content in the mid-lower Long11 also indicate a higher productivity with more OM supply during shale deposition.

OM is well known for its pore development in marine shale and with the usage of FIB-SEM, and the pores developed in the Longmaxi Formation were systematically observed. Compared with the matrix, OM is the major host for the pore development in the shale reservoir (Figure 10A,B). By setting different gray scale values, the pore area percentages accounted by both matrix and organic matter were calculated, respectively. The pore area percentage taken by OM ranges from 53.64% to 96.26% and the mean value is 78.94% (Figure 9D), indicating the important role of the OM playing in the shale pore development. Besides, the TOC is positively correlated with the porosity with the coefficient of 0.58 (Figure 10C), which also confirms the controlling effect of the TOC on the porosity of the shale. The excess-Si is related to the authigenic quartz, and then the former can approximately represent the content of the latter.\(^4\) Because pores are usually developed in siliceous skeletal organism, the relationship between the excess-Si content and the porosity is also positive \( (R^2 = .78, \text{Figure 10E}) \). The TOC is negatively correlated with the pore size \( (R^2 = .61, \text{Figure 11A}) \), which means the pores developed in the OM are featured by much smaller size. The smaller the pore size, the deeper the adsorption potential well,\(^4\) the larger the adsorption force of the solid pore wall on gas molecules, and the stronger the adsorption capacity.\(^4\) Therefore, a positive relationship also obviously exists between TOC and micropore surface area with a correlation coefficient of 0.52 (Figure 11B). Similar correlations occur between TOC and micropore volume (Figure 11C). Thus, the shale samples with a higher TOC content tend to have more micropores, and larger surface areas, and micropore volumes, which finally results in positive relationship between TOC and methane adsorption capacity (Figure 10D). Furthermore, the mid-lower Long11 is more abundant in TOC, resulting in much higher adsorption capacity. In contrast, the upward interval is characterized by weak reducing environment, medium-low level of paleoproductivity, high input of terrestrial clastic material and high deposition rate, resulting in medium-low level of TOC, quartz content, porosity, and methane adsorption capacity. In this study, the pore size terminology of the International Union of Pure and Applied Chemistry (IUPAC), which was developed by Rouquerol et al.,\(^4\) was applied. According to this pore classification, pores are subdivided into three categories: micropores (less than 2 nm diameter), mesopores (2 and 50 nm in diameter), and macropores (greater than 50 nm in diameter). The micropore volume and surface area were mainly derived using the t-plot method.

5.2 Controlling factors for micro-heterogeneity

5.2.1 Effects of nanopore parameters on fractal characteristics

The relationships between pore volume and surface area for different pore sizes and fractal dimensions are illustrated in Figure 12. The results revealed that the fractal dimension is only positively correlated with the micropore volume and surface area, with correlation coefficients of 0.57 and 0.60, respectively. The correlations between the fractal dimension and other parameters such as the BET specific surface area, the surface area of the mesopores and macropores, the BJH pore volume, and the pore volumes of mesopores and macropores are very poor, with

\[ y = \text{constant} + \text{linear fit} \]

\[ y = \text{constant} + \text{linear fit} \]
correlation coefficients < 0.2. This indicates that the fractal dimension of the shale is mainly influenced by the development of micropores, and micropores are the main cause of the heterogeneity in shale pore structure. An increase in the number of micropores leads to an increase in the complexity of the shale’s pore structure, thereby increasing the fractal dimension. The larger fractal dimension means more micropores are developed in shale, which in turn provides more adsorption sites for gas adsorption. Therefore, the fractal dimension is positively correlated with the methane adsorption capacity ($R^2 = .73$, Figure 13).
5.2.2 Effects of minerals on fractal characteristics

Table 1 shows that quartz, clay, carbonate and feldspar are the main inorganic minerals, while TOC is the main organic material in the shale. To investigate the relationships between major minerals and fractal dimensions, the related plots are given in Figure 14. The results demonstrated that the TOC and the quartz content are positively correlated with fractal dimension, with correlation coefficients of 0.63 and 0.74, respectively (Figure 9A, Figure 10A, and Figure 14A,B). The clay, carbonate, and feldspar are negatively correlated with fractal dimension, with correlation coefficients of 0.63, 0.40, and 0.44, respectively (Figure 14C-E).
FIGURE 14  Correlations between the fractal dimension and (A) TOC; (B) Quartz; (C) Clay; (D) Carbonate; (E) Feldspar

FIGURE 15  Pore development in (A) clay minerals, (B) feldspar, and (C) carbonate of the Longmaxi Formation, Weiyuan shale gas field
Based on the above discussion, the fractal dimension increases with the development of micropores. The micropores, which are mainly derived from organic matter, increase with an increase of TOC (Figure 11B,C). That is why TOC is positively correlated with the fractal dimension. The reason for the positive correlation between the fractal dimension and the quartz content may be related to the origin of quartz. The quartz is partially biogenic origin, which has been confirmed by the enrichment of graptolite and radiolarian as well as the positive relationship between the TOC and excess-Si and the negative correlation between Zr and SiO2 (Figure 9). The authigenic quartz, usually with irregular shape, develops micropores and increases the complexity of the pore structure. Furthermore, the high quartz content increases the compression resistance capacity and brittleness of the shale, providing conditions for the preservation of pores and the development of fractures. Therefore, the quartz has positive effect on the fractal dimension.

As to the clay minerals, during long-term diagenesis, compaction caused the clay minerals to become tightly arranged, the rock to become dense, and the number of micropores to decrease. Consequently, the complexity of the pore structure decreases. From SEM images, micropores in clay minerals can be barely observed, and the pores developed in clay are all in long strips with lengths of 0.2-2 μm and widths of 0.2-0.5 μm, reflecting the intense compaction (Figure 15A). The equivalent area circle method was used to calculate the pore size, which reveals that the pores in clay minerals mainly range from 10.25 to 419.68 nm in diameter, with an average of 43.03 nm. What’s more, the higher clay contents may result in the collapse of OM pores if there are insufficient rigid grains, which further reduce the micropore development in the shale pore system and the complexity of the pores decreases. Carbonate content is negatively correlated with the fractal dimension (R² = .40, Figure 14D). It is speculated that some of the carbonate exists in the form of cement, filling pores and reducing their connectivity. Although the carbonate is easily dissolved, it contributes little to micropore development. This finding has also been reported by other researches. The pore size of the dissolved pores in carbonate mainly ranges from 31.72 to 733.32 nm, with an average of 59.8 nm (Figure 15B). The feldspar content in shale samples is low, ranging from 0% to 12%, with an average of 5.1%. Feldspar is also an easily dissolvable mineral, and larger pores are usually formed during the dissolution process. However, due to the higher carbonate content (8.0%-50.6%) of the sample, the dissolution of the feldspar is prevented. Feldspar is rich in cleavage and thus contains a large number of cleavage cracks. Based on the equivalent circle area calculation, these cracks range from 28.8 to 415.55 nm in diameter, with an average of 37.67 nm (Figure 15C). Therefore, an increase in feldspar leads to an increase in the pore size of the shale and decrease of the pore complexity, causing a negative correlation between feldspar content and fractal dimension.

5.2.3 Effects of diagenesis of fractal characteristics

As discussed in Section 5.2.1, micropore development is strongly correlated with the fractal dimension, which was also reported by other previous studies. The mineral effects on fractal dimension can be studied by the different impacts of minerals on micropore development during the diagenesis.

During the early deposition, pores developed in the shale are mainly inter-particle pores and the carbonate fills the primary pores and reduces the storage spaces by cementation, which weakens pore complexity and micro-heterogeneity. As the burial depth increases, the overlying formation pressure grows, the compaction becomes more intense, leading to the decrease of the inter-particle pores and porosity. Because the sedimentary water is mainly alkaline with pH > 8, which leads to some degrees of quartz erosion and formation of intra-particle pores in quartz. But under alkaline condition, the calcite and feldspar form precipitation, which still decreases the inter-particle pores and prohibits the connectivity of the pore system. When the burial depth continues to increase, the formation temperature and pressure become much higher, which results in hydrocarbon generation and expulsion. The formed OM pores and the organic acid and CO2 produced from hydrocarbon generation process neutralize the alkaline water, leading to the dissolution of the carbonate and the formation of dissolved pores in carbonates. The dissolution pores are mainly in macro-scale, which leads to negative correlation between carbonate content and fractal dimension. This finding was also observed in the fractal dimension study of other formations. Because of the high content of carbonate, the feldspar dissolution is prohibited and the FE-SEM images also show no dissolution pores in feldspar. However, cracks along the cleavage of the feldspar can be obviously observed, which enlarges the pore size of the shale and reduces the complexity of the pore system. The quartz, because of the partial biogenic origin, also develops intra-particle pores in this stage, which results in positive correlation between quartz content and fractal dimension. The clay minerals are ductile and become intensely compacted with formation pressure increasing, which leads to the vanishing of micropores and the development of elongated pores. Additionally, high content of clay content also facilitates the decrease of OM pores because of intense compaction, which results in negative relationship between clay content and the fractal dimension. In the late diagenetic stage,
5.3 | Reservoir heterogeneity on shale gas enrichment

The fractal dimension is controlled by the development of micropores in the shale's pore system. Small pores usually have much finer pore throats, which leads to the negative correlation between the fractal dimension and permeability. Gao et al. simulated the effects of the pore structure characteristics on the gas diffusion rate for different fractal dimensions. The results revealed that regardless of whether the pores are organic or inorganic, and the smoother the pore wall surface (i.e., the smaller the fractal dimension), the faster the gas diffusion rate within the pores, conversely, the larger the fractal dimension, and the slower the gas diffusion rate. Therefore, in the absence of fractures, the higher the fractal dimension, the more likely it is that gas will be retained within the reservoir. The reservoir parameters of the shale in well Wd2 are presented in Figure 16.

Shale gas enrichment requires sufficient gas generation material (e.g., TOC), an adequate amount of storage space (i.e., high BET surface area for adsorbed gas or high porosity for free gas, or both high BET surface area and porosity), and fairly good preservation conditions. Gas enrichment models for the 4 sub-layers in the Longmaxi Formation were established based on the macroscopic and microscopic heterogeneities of the sub-layers (Figure 17).

The Long11 sub-layer has the lowest TOC content (0.73%-5.20%, with an average of 3.20%) and the smallest fractal dimension; therefore, it has the lowest gas production capacity. The fact that its fractal dimension is the smallest indicates that its gas diffusion is the easiest. Although the TOC in Long11 is much higher, which can to some degree provides a gas source for Long11, since there is no good cap rock on the top of Long11, its gas content is actually the lowest. The total gas content analyzed using logging curves also confirms the conclusion drawn from the above analysis (Figure 15). Moreover, Long11 has much higher clay mineral content, ranging from 21.1% to 44%, with an average of 32.3%, thus its fracturing conditions are also poor. Therefore, compared with the other sub-layers, Long11 is not desirable for shale gas development.

![Figure 16](image-url)

**FIGURE 16** Reservoir parameters of shale in Well Wd2, Weiyuan shale gas field
The Long1\textsuperscript{3} sub-layer has geological parameters similar to those of Long1\textsuperscript{1}. Its fractal dimension ranges from 2.645 to 2.683, with an average of 2.669, which is slightly smaller than that of Long1\textsuperscript{1} and larger than that of the other sub-layers. The fractal dimension of Long1\textsuperscript{3} indicates that the gas generated in this sub-layer can remain better preserved within it. In addition, the BET surface area and porosity of Long1\textsuperscript{3} are higher than those of Long1\textsuperscript{2} and Long1\textsuperscript{4}, giving Long1\textsuperscript{3} enough space for gas storage. However, Long1\textsuperscript{3} has an organic carbon content ranging from 2.40% to 6.70%, with an average of 4.35% (Figure 15), which is lower than that of the middle and lower parts of Long1\textsuperscript{1}. Due to its low OM content, the gas production capacity and storage capacity are not as good as the middle and lower parts of Long1\textsuperscript{1}, although it can still be considered as a favorable target for the next development step.

The Long1\textsuperscript{2} sub-layer has a relatively low TOC content of 2.2%–2.5%, which is lower than that of Long1\textsuperscript{3}, and is even lower than those of the upper part of Long1\textsuperscript{1} (which has a TOC content ranging from 2.2% to 4.00%). That is to say, the gas production capacity of Long1\textsuperscript{2} is significantly lower than that of Long1\textsuperscript{1} and Long1\textsuperscript{3}. However, the fractal dimension of Long1\textsuperscript{2} ranges from 2.641 to 2.667, with an average of 2.658, which is obviously lower than those of Long1\textsuperscript{1} and Long1\textsuperscript{3}, indicating that the pore structure of Long1\textsuperscript{2} is relatively simple, which is conducive to gas diffusion and charging. Although limited in gas supply capacity, Long1\textsuperscript{2} is positioned between Long1\textsuperscript{1} and Long1\textsuperscript{3}, thus, the gas of Long1\textsuperscript{1} and Long1\textsuperscript{3} can charge into it easily. In addition, Long1\textsuperscript{1} and Long1\textsuperscript{3} can also serve as cap rocks on the top and bottom of Long1\textsuperscript{2}. Therefore, Long1\textsuperscript{2} also has a high gas content. Although the quartz content of Long1\textsuperscript{2} is not high, its overall content of brittle minerals is not low (54.30%–70.20%, with an average of 64.12%), which is also good for fracturing. However, Long1\textsuperscript{2} has a lower gas content than the middle and lower parts of Long1\textsuperscript{1}.

The middle and lower parts of Long1\textsuperscript{1}, which have the highest TOC content, provide sufficient material for shale gas generation. Since TOC has a positive influence on the specific surface area and porosity of marine shale, the BET surface area and the porosity of the mid-lower parts of Long1\textsuperscript{1} are also the highest (Figure 16), which, in turn, provides enough storage space for both adsorption gas and free gas. According to the above discussion, the quartz content and TOC content have positive effects on the fractal dimension, and both two components reach their maximum values in the middle and lower parts of Long1\textsuperscript{1} (with TOC content ranging from 4.16% to 7.70% and averaging 5.82%, quartz content ranging from 42.2% to 91.8% and averaging 76%). The clay minerals, carbonate and feldspar contents, all of which have negative effects on the fractal dimension, are the lowest in the middle and lower parts of Long1\textsuperscript{1}. Affected by the above factors, the middle and lower parts of Long1\textsuperscript{1} have the highest fractal dimensions (2.686-2.752, with an average of 2.714) where the diffusion and seepage of shale gas are restricted, leading to high gas saturation and gas content in the intervals. Figure 17 also reveals that the gas content in the mid-lower parts of Long1\textsuperscript{1} is much higher than that of any other sub-layers. Moreover, the high quartz content not only provides a portion of the reservoir space needed for free gas and adsorbed gas, but also increases the brittleness of the shale, making the shale in the middle and lower parts of Long1\textsuperscript{1} most likely to form a network of artificial fractures during fracturing. Thus, the middle and lower parts of Long1\textsuperscript{1} are the most favorable development intervals in the longitudinal direction and should take priority in terms of current development.

6 | CONCLUSIONS

The heterogeneity characteristics of the Longmaxi shale were divided into macro-heterogeneity and micro-heterogeneity.
The origins of the heterogeneity were investigated respectively, and the heterogeneity influence on shale gas enrichment was also discussed. The main conclusions were as follows:

1. The reservoir in the Longmaxi shale exhibits strong homogeneity. The TOC is the highest in the middle and lower parts of Long1_1, followed by Long1_3, while that is much lower in both Long1_2 and Long1_4. In terms of mineral composition, the middle and lower parts of Long1_1 have the highest quartz content; Long1_2 and Long1_3 have equivalent quartz, clay, and carbonate contents; while Long1_2 has a lower quartz content, but higher carbonate and clay contents. Shale porosity and methane adsorption capacity are the highest in the middle and lower parts of Long1_1, followed by Long1_3, but lower in Long1_2, Long1_4, and the upper part of Long1_1.

2. The macro-heterogeneity of Longmaxi shale is mainly controlled by sedimentary environment. Paleoredox, paleoproduction, detrital influx, and the sedimentation rate control the TOC, mineral composition, methane adsorption, and porosity variation in the vertical profile.

3. The micro-heterogeneity is represented by fractal dimension, with a fractal dimension ranging from 2.59 to 2.75 and averaging 2.67. The middle and lower parts of Long1_1 have the largest fractal dimension, followed by Long1_3, while the fractal dimension is smaller in Long1_2, Long1_4, and the upper part of Long1_1.

4. The micro-heterogeneity principally depends on diagenesis, which can be investigated by the different effects of minerals on micropore development. Due to the large number of micropores developed in the organic matter and the biogenic quartz, their contents are positively correlated with the fractal dimensions. Conversely, clay, carbonate rock, and feldspar mainly contain larger pores, and therefore, their contents are negatively correlated with fractal dimension.

5. The middle and lower parts of Long1_1 are rich in gas source, which have enough storage space, and exhibit good preservation conditions (large fractal dimension; difficult gas diffusion, desorption, and seepage); therefore, they have the highest gas content of all the four sub-layers. In addition, their high brittle mineral contents are conducive to the formation of an artificial fracture network during fracturing. Thus, the middle and lower parts of Long1_1 are the most favorable “sweet spot” intervals for shale gas development.

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