Pore Structure Characteristics and Permeability Stress Sensitivity of Jurassic Continental Shale of Dongyuemiao Member of Ziliujing Formation, Fuxing Area, Eastern Sichuan Basin

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Abstract: A shale condensate gas reservoir with a high clay content and a high formation pressure was found in the Jurassic shale of the Dongyuemiao Member in the Fuxing area of the eastern Sichuan Basin. Reservoir characteristics and formation pressure have a significant influence on optimal development. The present study investigated the continental shale of the Dongyuemiao Member in Well F. The petrological properties, physical properties, and pore structure of the Dongyuemiao Member were studied using X-ray diffraction (XRD), field emission scanning electron microscopy (FE-SEM), N$_2$ adsorption, and mercury intrusion porosimetry (MIP). The permeability stress sensitivity characteristics of the shale reservoirs are discussed based on the change in shale porosity and permeability under overburden pressure. The tested shale samples yielded total organic carbon (TOC) and S$_1$ + S$_2$ values ranging mainly from 1.0 wt.% to 1.5 wt.% and from 0.39 to 2.28 mg/g, respectively, which was in the high maturity stage of the thermal evolution of organic matter (OM). The shales of the Dongyuemiao Member were found to contain high average clay mineral contents (more than 50%) of calcite and quartz, as well as albite, pyrite, dolomite, and halite. The main developments were identified as silica-rich argillaceous shale lithofacies, argillaceous shale lithofacies, and mixed argillaceous shale lithofacies. The pores were found to mainly be plate-like and flake-like interlayer pores of clay minerals and OM pores with various shapes. The pore size was mainly concentrated below 110 nm, and the pore volume increment increased in flakes with pore diameter. The average porosity and permeability of shale were found to be 4.827% and 0.243 mD, respectively. Clay minerals and quartz are beneficial for improving the porosity and permeability of reservoirs, while carbonate minerals have the opposite effect. The permeability of the shale showed a negative exponential change with increasing effective stress under overburden pressure. When the effective confining pressure was greater than 20 MPa, the decline rate of the shale permeability decreased with increases in the effective stress. The higher the clay mineral and TOC content, the stronger the stress sensitivity of shale permeability. The higher the carbonate mineral content, the weaker the stress sensitivity of shale permeability. The porosity sensitivity exponent indicates that matrix pores and micro-fractures are both developed in the Dongyuemiao Member, and the development of internal fractures is the main factor in the strong stress sensitivity of the shale permeability in the study area.

Keywords: stress sensitivity of permeability; continental shale reservoir; Jurassic; eastern Sichuan Basin

1. Introduction

With the successful revolution of marine shale hydrocarbon in the United States, the world energy landscape has transformed [1–5]. Micro-nano scale pores and fractures in shale affect oil hydrocarbon occurrence form and reservoir capacity [6,7]. Domestic and international scholars have analyzed pore structure from many aspects, including pore type, pore size and shape, pore volume and specific surface area, spatial distribution, and connectivity [8–11]. Large-scale organic-rich shale has developed in terrestrial strata such...
as Permian in Junggar Basin, Triassic in Ordos Basin, Jurassic in Sichuan Basin, Cretaceous in Songliao Basin, and Paleogene in Bohai Bay Basin, which has become a national strategy for replacing conventional hydrocarbon resources in China [10,12–15]. Compared with marine shale in North America, continental shale reservoirs in China have diverse rock minerals, complex lithofacies, and a strong heterogeneity of strata. Previous domestic exploration experience showed that the high clay content of continental shale is a key factor that restricts shale mining [16], but under high formation pressure, the significance of clay minerals in condensate gas reservoirs needs to be further discussed. Pore structure is an important index reflecting the size, type, distribution, and connectivity of pores and throats in rocks. The pore structure of different minerals in shale has a great influence on the enrichment and subsequent exploitation of petroleum in condensate gas reservoirs [17]. Previous studies on the pore structure of shale mainly focused on pore structure inversion [18,19], pore size characterization, pore connectivity and wettability [13,14,20], and influencing factors of pore development [21,22]. Few have correlated reservoir pore structure with permeability changes under overburden pressure. In a reservoir with stress sensitivity, the pressure gradient between the reservoir and the production well and the permeability stress sensitivity of the reservoir affect oil well production, and their reasonable combination is beneficial in improving the production life of the reservoir [23]. This study is more important in the face of continental shale condensate reservoirs with special fluid properties and complex phases. In 1952, Fatt and Davis found that reservoir permeability decreased with increases in effective stress through sandstone flow experiments, and permeability stress sensitivity has since been a researcher hot spot in petroleum exploration and development [24]. Dong et al. [25] and Ju et al. [26] believe that the worse the physical properties of a reservoir and the more complex its pore structure, the stronger the permeability stress sensitivity. Wang et al. [27] observed that the presence of organic matter in shale can lead to the significant deformation of matrix pores. Permeability stress sensitivity is one of the important reasons that restrict the long-term efficient development of shale hydrocarbon. Julia et al. [28] experimentally analyzed the permeability variation of shale under different stresses and the effects of fractures, maceral content, and water content on the permeability of coal reservoirs. The drilling of Jurassic Dongyuemiao shale in the Fuxing area of the Sichuan Basin revealed a special reservoir-type shale condensate gas reservoir [29]. Changes of pressure in a formation have a great influence on the exploitation of condensate gas reservoirs. At present, there are two main development methods of depletion development and pressure-holding development. The content of clay minerals in the shale of the Dongyuemiao Member is very high, thus providing the main petroleum reservoir space, but the clay minerals are easy to squeeze and deform. Mineral deformation under different pressure conditions changes the characteristics of a reservoir space [30], which affects the pressure in a formation and ultimately affects the occurrence state of condensate gas. Therefore, it is necessary to further clarify the pore structure of minerals in continental shale and the change of physical properties of reservoirs under overburden pressure in order to provide some theoretical support for accurately evaluating changes of reservoir seepage capacity, predicting the productivity of petroleum wells, and optimizing reasonable fracturing flowback systems. Here, the Dongyuemiao Member in the Fuxing Area of the eastern Sichuan Basin was selected as the research object. The petrological, organic geochemical, pore structure, and physical properties of continental shale in the Dongyuemiao Member were analyzed using the TOC content, XRD, FE-SEM, N2 adsorption, and MIP, and a permeability sensitivity analysis was carried out according to the characteristics of porosity and permeability under overburden pressure, providing some theoretical support for the optimal development of shale condensate gas reservoirs.

2. Geological Setting

The Fuxing area is located in the Eastern Sichuan fold belt. It is geographically located at the junction of Liangping, Dianjiang, Shizhu, Fengdu, and Zhongxian in Chongqing and northeast of Fuling. The main body of the study area is located in the Wanxian synclinorium
between the Datianchi and Fangdoushan anticline zones (Figure 1a). The Fuxing area in the eastern Sichuan Basin experienced multiple lake transgressions during the Jurassic. Three sets of organic-rich shales in Dongyuemiao, Da’anzhai, and Lianggaoshan Member 2 were formed from bottom to top [31–33]. During the period of lake transgression in the Dongyuemiao section, sedimentary water bodies generally changed from shallow to deep to shallow in Fuxing. A set of littoral-shallow, lacustrine-semi-deep, and lacustrine gray–black shale facies with thin shell limestone was deposited. The limestone stratum was shell-rich, the clay mineral content of the shale was generally high, and the thickness of the sedimentary stratum was 60–70 m (Figure 1b). Combined with core observations, logging responses, and whole-rock analysis, the Dongyuemiao Formation in the study area can be further subdivided into three sub-members and seven sub-layers from bottom to top. The Dong1 sub-member is a gray–black shale with thin shell limestone, including thin layers 1, 2, 3, and 4. The Dong2 sub-member is gray–black argillaceous limestone corresponding to thin layer 5; the Dong3 sub-member is dark gray and gray–black massive mudstone corresponding to thin layers 6 and 7 (Figure 1b) [34].

**Figure 1.** Location of the study area and wells (a–c) and stratigraphic histogram of the Dongyuemiao Member of the Ziliujing Formation in Well F (d).

### 3. Methodology

3.1. **Samples**

The research samples were derived from Dongyuemiao Member core samples collected in Well F. A total of 38 samples were collected from 2752 and 2813 m (Figure 1d and Table 1). The lithology was mainly gray–black shale with a thin shell-rich limestone.
Table 1. Stratigraphic organization and sampling information of the Dongyuemiao Member in the Fuxing area of the Sichuan Basin.

| Stratum | Lithologic Characters | Sample Depth (m) | Sample Number |
|---------|-----------------------|-----------------|---------------|
| Dongyuemiao Member | Dong1 | Dark gray and gray–black massive mudstone | 2751.0–2770.0 | 7 |
|   |   |  | 2770.0–2778.0 | 4 |
|   | Dong2 | Gray–black argillaceous limestone | 2778.0–2784.5 | 5 |
|   | Dong3 | Gray–black shale intercalated shell limestone | 2784.5–2791.0 | 7 |
|   |  |  | 2791.0–2797.5 | 5 |
|   |  |  | 2797.5–2806.0 | 6 |
|   |  |  | 2806.0–2812.5 | 4 |

3.2. **Analytical Methods**

XRD experiments were performed at the State Key Laboratory of Geological Process and Mineral Resources, China University of Geosciences (Wuhan, China) on an X’Pert PRODY2198 X-ray diffractometer (PANalytical, Amsterdam, The Netherlands) with 40 kV of CuKα radiation and a 30 mA Ni filter.

The TOC content test sample was a 0.1–0.5 g powder sample with a particle size of 200 mesh. After the inorganic carbon content was removed with a 60 °C–80 °C acidic solution (1:7 hydrochloric acid (HCl): distilled water), the TOC was determined using a LECOCS-200 analyzer (LECO, St. Joseph, MI, USA). The experiment was conducted at the Key Laboratory of Tectonics and Petroleum Resources Ministry of Education, China University of Geosciences, Wuhan, China. A Rock-Eval instrument was used to conduct rock pyrolysis in order to determine the Tmax, HI, S1, and S2 values. The experiment was conducted at the Petroleum Exploration and Development Research Institute of Jianghan Oilfield Company (Wuhan, China).

A Zeiss-Merlin FE-SEM (Carl Zeiss AG, Battenwürburg Canton, Germany) was used for the experiment, with a resolution of 0.8 nm, a maximum magnification of 2 million times, and a test acceleration voltage of 0.02–30 kV. The samples were polished with argon prior to the experiment. The experiment was conducted at the Institute of Geology and Geophysics, Chinese Academy of Sciences.

The low-temperature N₂ adsorption–desorption test was performed using an ASAP2020 automatic specific surface area and microporous/mesoporous analyzer produced by the American Mac Company (Anton, Graz, Austria). Shale samples were powdered to 0.28–0.18 mm (60–80 mesh), and experiments were conducted at −195.8 °C, a relative pressure (P/P₀) range of 0.001–0.998, and a pore size range of 0.35–500.00 nm. The sample pore volume was calculated with the BJH method [35] by measuring the amount of nitrogen adsorption and desorption under equilibrium vapor pressure. The experiment was completed in the Key Laboratory of Tectonics and Petroleum Resources Ministry of Education, China University of Geosciences, Wuhan, China.

MIP was performed using an Auto-pore IV 9520 high-pressure mercury injection instrument produced by United States Instruments (Micromeritics, GA, USA), with a maximum pressure of 413 MPa and a pore throat test range of 800 µm–3 nm. All samples were cut into 1 cm³ cubes, polished, and baked in an oven at 60 °C for 48 h to remove moisture and volatile substances. The experiment was conducted at the Key Laboratory of Tectonics and Petroleum Resources Ministry of Education, China University of Geosciences, Wuhan, China.

The overburden porosity and permeability experiment employed a PoroPDP-200 overburden porosity and permeability measuring instrument produced by Core Laboratories
The Dongyuemiao shale in Eastern Sichuan has a high TOC content and hydrocarbon generation potential, slightly better organic matter type, and higher maturity, making it a better exploration horizon for shale oil than that in western Sichuan [30]. The experimental data showed that the TOC content of the Dongyuemiao shale is closely related to depth and stratigraphic horizon. It was found that the TOC content was mainly distributed between 1.0 wt.% and 1.5 wt.% (Figure 2a). The TOC of the Dong1 sub-member ranged between 1.04 wt.% and 2.96 wt.% (average = 1.692 wt.%). The TOC of the Dong2 sub-member ranged between 1.38 wt.% and 1.01 wt.% (average = 1.188 wt.%). The TOC of the Dong3 sub-member ranged between 0.40 wt.% and 1.26 wt.% (average = 0.680 wt.%). From the point of view of the thin layer, the TOC of thin layer 4 was the highest, with an average of 1.86%, followed by thin layers 3–1, with average TOC values of 1.70 wt.%, 1.57 wt.%, and 1.04 wt.% and 2.96 wt.% (average = 1.692 wt.%). The TOC of the Dong2 sub-member ranged between 0.43 wt.% and 0.76 wt.%, and 1.19 wt.%, respectively; thin layers 5–7 had average TOC values of 1.19 wt.%, 0.84 wt.%, and 0.59 wt.%, respectively (Figure 2b).

![Figure 2](image_url)

**Figure 2.** Distribution interval of TOC content (a) and average TOC content each layer (b) in the Dongyuemiao Member of the eastern Sichuan Fuxing area.

The results of rock pyrolysis in the Dongyuemiao Member of the study area showed that the shale hydrocarbon generation potential ($S_1 + S_2$) ranged from 0.39 to 2.28 mg/g, and the hydrocarbon generation potential ($S_1 + S_2$) and TOC were positively correlated (Table 2). Most were high-quality source rocks, and some were good source rocks (Figure 3). Previous studies have suggested that the vitrinite reflectance $R_o$ of the shale in the Dongyuemiao Member is between 1.52 and 1.58%, which generally indicates a high thermal maturity in the condensate oil wet gas–wet gas generation stage [34]. Most OM was of type II$_1$–II$_2$, predominantly layered and dispersed [33].
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Table 2. Rock pyrolysis parameters of the Dongyuemiao shale in the Fuxing Area, Eastern Sichuan.

| Formation | Depth (m) | S_1 (mg/g) | S_2 (mg/g) | S_1 + S_2 (mg/g) | TOC (wt.%) | Tmax (°C) | HI |
|-----------|-----------|------------|------------|------------------|------------|-----------|----|
| Dong3     | 2763.82   | 0.43       | 0.64       | 1.07             | 1.17       | 480       | 55 |
|           | 2765.68   | 0.51       | 0.69       | 1.2              | 1.14       | 480       | 61 |
|           | 2771.24   | 0.7        | 0.84       | 1.54             | 1.35       | 472       | 62 |
| Dong2     | 2778.94   | 0.43       | 0.76       | 1.19             | 1.55       | 478       | 49 |
|           | 2801.68   | 0.68       | 1.25       | 1.93             | 2.48       | 480       | 50 |
|           | 2802.56   | 0.59       | 0.86       | 1.45             | 1.74       | 478       | 49 |
|           | 2835.69   | 0.24       | 0.15       | 0.39             | 0.68       | 464       | 22 |
|           | 2839.7    | 0.94       | 1.34       | 2.28             | 3.19       | 487       | 42 |
|           | 2847.41   | 0.5        | 0.81       | 1.31             | 1.71       | 492       | 47 |
|           | 2853.49   | 0.35       | 0.44       | 0.79             | 0.71       | 493       | 62 |
|           | 2856.57   | 0.45       | 0.71       | 1.16             | 1.74       | 494       | 41 |
|           | 2857.05   | 0.27       | 0.62       | 0.89             | 1.58       | 476       | 39 |
|           | 2857.2    | 0.25       | 0.46       | 0.71             | 1.22       | 494       | 38 |
|           | 2857.83   | 0.33       | 0.56       | 0.89             | 1.63       | 493       | 34 |
|           | 2857.94   | 0.37       | 0.7        | 1.07             | 1.96       | 495       | 36 |
|           | 2858      | 0.46       | 0.71       | 1.17             | 2.05       | 492       | 35 |
|           | 2864.05   | 0.42       | 0.75       | 1.17             | 1.89       | 494       | 40 |

Figure 3. Relationship between S_1 + S_2 and TOC of the Dongyuemiao shale in the Fuxing area, Eastern Sichuan. Area (a) represents poor hydrocarbon source rocks, area (b) represents medium-quality hydrocarbon source rocks, area (c) represents good hydrocarbon source rocks, and area (d) represents high-quality hydrocarbon source rocks.

4.2. Petrological Characteristics

The XRD data showed that the Dongyuemiao Member of the Fuxing area is mainly composed of clay minerals, quartz, calcite, albite, pyrite, dolomite, halite, and other minerals (Figure 4a). In the Dong1 sub-member, the clay mineral content was 52.09%–82.95% (average = 72.79%), the content of calcite was 0%–11.49% (average = 7.22%), and the quartz content was 24.2–30.73% (average = 26.67%). The contents of the main minerals, such as clay minerals, carbonate minerals, and felsic minerals are generally low. In the Dong2 sub-member, the clay mineral content was 56.00%–74.09% (average = 64.25%), the content of calcite was 0%–21.46% (average = 6.98%), and the quartz content was 13.2%–21.58% (average = 17.25%). In the Dong3 sub-member, the clay mineral content was 52.09%–82.95% (average = 50.55%), and the quartz content was 11.44%–32.61% (average = 20.93%). In the Dong1 sub-member, the clay mineral content was 52.09%–82.95% (average = 50.55%), and the quartz content was 11.44%–32.61% (average = 20.93%).
(average = 26.67%). The contents of the main minerals, such as clay minerals, quartz, and calcite, greatly varied with depth. The albite, pyrite, dolomite, and halite contents were generally low.

![Figure 4](image1.png)  
**Figure 4.** Mineral composition distribution (a) and lithofacies division (b) of continental shale samples in the Dongyuemiao Member.

With clay minerals, carbonate minerals, and felsic minerals as three-terminal elements, the shale of the Dongyuemiao Member can be divided into eight lithofacies: silica-rich argillaceous shale, argillaceous shale, mixed argillaceous shale, mixed shale, clay-rich calcareous shale, siliceous/argillaceous mixed shale, clay-rich siliceous shale, and mixed calcareous shale. The upper part of the Dong1 sub-member mainly developed argillaceous shale lithofacies, while the lower part mainly developed mixed argillaceous shale lithofacies. The Dong2 sub-member mainly developed mixed shale lithofacies, and the Dong3 sub-member mainly developed silica-rich argillaceous shale lithofacies.

4.3. Reservoir Space Characteristics

4.3.1. Porosity and Permeability Distribution

According to the statistical analysis of the physical properties of shale reservoirs in Fuxing, the helium porosity of the Dongyuemiao Member is generally lower than 10%. Vertically, the porosity of thin layers 3 and 4 of Well F was found to be advantageous (Figure 5). The porosity of shale samples was found to be concentrated at 2%–5%, accounting for 57.1% of the samples. The porosity of 23.8% of shale samples was 1%–2%, and the porosity of 14.3% of shale samples was 5%–10%. The overall permeability of the Dongyuemiao shale was found to be very low, with more than 95% of the shale samples having a permeability of less than 1 mD. In comparison, the permeability of thin layers 2–4 of the Dong1 sub-member was found to be higher; more than 80% of the shale samples showed a permeability of less than 0.5 mD, and the permeability concentration distribution range was 0.1–0.5 mD.

![Figure 5](image2.png)  
**Figure 5.** Distribution characteristics of the porosity and permeability of the Dongyuemiao Member.
4.3.2. Scanning Electron Microscopy

FE-SEM images showed that the main pore types of the shale in the Dongyuemiao Member include interlayer pores of clay minerals, intragranular pores of calcite, intergranular pores of pyrite, OM pores, and microfractures. Clay minerals were shown to be the most developed in the Dongyuemiao Member, and the interlayer pores of clay minerals were shown to be the most developed pore types. The pores were mostly plate-like and flake-like, with some connectivity (Figure 6a,b). Intragranular pores mainly developed inside the calcite particles as isolated pores (Figure 6c). Pyrite developed intergranular pores, and, due to the strong compressive resistance of rigid particles, intragranular pores could be seen in the periphery of pyrite. Some intragranular pores were found to be filled with OM, and OM pores developed in them. Pyrite protected the interlayer pores of clay minerals from being completely compacted to a certain extent, mostly as curved sheets (Figure 6d,e). The OM pores were irregular, slit shaped, and oval (Figure 6f). The formation of microfractures in the Dongyuemiao shale is related to clay minerals and OM. Layered clay minerals are more likely to form microfractures with a greater degree of bending under the action of in situ stress (Figure 6g,h). Most of the micro-fractures related to OM developed at the contact between OM and other minerals, which is related to the hydrocarbon generation evolution of OM (Figure 6i). ImageJ software was used to process the pore area and pore diameter curves corresponding to the FE-SEM images. The pore diameters were mainly found to be 0.01–10 μm, the pore area of the sample began to increase after 1 μm, and the pore area in the picture with microfractures and clay mineral interlayer holes more obviously changed with the jagged change in pore size.

![Image](image_url)

**Figure 6.** FE-SEM images of the Dongyuemiao Member: (a) 2787.96 m, thin layer 4 of Dong1, pore rate is 9.28%; (b) 2800.51 m, thin layer 2 of Dong1, pore rate is 9.43%; (c) 2790.53 m, thin layer 4 of Dong1, pore rate is 1.10%; (d–f) 2796.01 m, thin layer 3 of Dong1, pore rate is 14.46%, 20.78%, and 3.54%, respectively; (g) 2766.46 m, thin layer 7 of Dong3, pore rate is 2.22%; (h) 2757.11 m, thin layer 7 of Dong3, pore rate is 4.23%; (i) 2774.01 m, thin layer 6 of Dong3, pore rate is 0.73%.
4.3.3. Pore Structure Characterization

Samples were selected in each thin layer for N2 adsorption and MIP to reflect the pore structure of the Dongyuemiao shale (Table 3).

Table 3. Distribution characteristics of shale pore volume in the Dongyuemiao Member.

| Sample  | Depth (m) | Lithofacies                  | TOC (wt.%) | Micropore $(10^{-3} \text{ cm}^3/\text{g})$ | Mesopore $(10^{-3} \text{ cm}^3/\text{g})$ | Macropore $(10^{-3} \text{ cm}^3/\text{g})$ | Total Pore $(10^{-3} \text{ cm}^3/\text{g})$ |
|---------|-----------|------------------------------|------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|
| F-7-2   | 2760.05   | Silica-rich argillaceous shale | 0.59       | 0.8449                                    | 11.3092                                   | 3.2710                                    | 15.4250                                   |
| F-6-1   | 2770.89   | Silica-rich argillaceous shale | 0.76       | 1.2198                                    | 12.6972                                   | 3.4071                                    | 17.3241                                   |
| F-5-2   | 2779.9    | Mixed shale                  | 1.00       | 0.7447                                    | 8.5013                                    | 2.0862                                    | 11.3321                                   |
| F-4-2   | 2787.96   | Argillaceous shale           | 1.46       | 1.4264                                    | 11.0236                                   | 8.0161                                    | 20.4661                                   |
| F-3-5   | 2791.45   | Mixed argillaceous shale     | 1.70       | 1.7314                                    | 10.2266                                   | 5.9013                                    | 17.8593                                   |
| F-2-4   | 2800.51   | Mixed argillaceous shale     | 1.49       | 0.8956                                    | 8.3810                                    | 5.4010                                    | 14.6776                                   |
| F-1-2   | 2807.35   | Silica-rich argillaceous shale | 1.04       | 0.7361                                    | 6.7610                                    | 3.7734                                    | 11.2705                                   |

According to the IUPAC classification [36], the adsorption isotherms of N2 was of type IV, the maximum adsorption capacity was between 5 and 12 cm$^3$/g, and the hysteresis loop showed H4 type characteristics, indicating that parallel plate-like slit-type pores were developed in the shale. This type of pore is conducive to gas flow and easy to compress. The adsorption isotherm of the Jurassic Dongyuemiao shale hydrocarbon reservoir in the Fuxing area of Eastern Sichuan showed an anti-‘S’ shape. In the low-pressure stage $(P/P_0 < 0.05)$, the gas adsorption capacity rapidly increased with increases in the relative pressure, which is the single molecule adsorption of micropores. In the medium-pressure stage $(0.95 < P/P_0 < 0.05)$, adsorption mainly occurred through multi-molecular layer adsorption. In the final high-pressure stage, the adsorption capacity rapidly increased, and there was no adsorption saturation phenomenon, which is a characteristic of macropores and microfractures. In the N2 desorption process, the relative pressure decreased from the maximum value. When $0.45 < P/P_0 < 1$, the adsorption amount corresponding to the same pressure was higher than that in the adsorption process, forming a hysteresis loop that indicated the existence of nanoscale slit-like pores [37]. When $P/P_0 < 0.45$, the desorption and adsorption curves almost coincided (Figure 7a). Based on the BJH theoretical model, the pore size distribution curves of shale samples in different pore size ranges were obtained by processing the experimental data of N2 desorption. The curve shows that the pore size of the shale was mainly distributed within 10 nm (Figure 7b).

The MIP experiments could better reflect the characteristics of pore throat distribution and pore throat connectivity. Many nanoscale pores were developed in the Dongyuemiao shale, including some mesopores and nanoscale/micron macropores. When the mercury inlet pressure was less than 17,000 Psia (pore size range greater than 10 nm), the mercury inlet curve showed a large difference. The sudden increases in mercury saturation at 25 Psia and 100 Psia may have been caused by microfractures. When the mercury injection pressure was greater than 17,000 Psia (pore size range greater than 10 nm), more mercury flowed into the sample, and the different sample curves were not significantly different. The hysteresis loop showed that there was nearly 60% mercury retention, which may have been because some funnel-shaped pores in the sample limited the mercury removal process (Figure 7c). The pore-size distribution of the Dongyuemiao Member calculated from the MIP data had multi-peak characteristics, and the peaks were distributed from
nanometers to micrometers. The maximum pore volume increment of shale in Well F was approximately 0.0035 cm³/g, the pore volume displaying 3–30 nm pore diameters was approximately 70%–80%, and the pore volume displaying 50–200 nm pore diameters was approximately 10%–15% (Figure 7d).

Figure 7. Experimental results of N₂ adsorption and MIP of the Dongyuemiao Member for the N₂ adsorption–desorption curve (a), the curve of dV/d changing with the aperture (b), the mercury intrusion and mercury withdrawal saturation curve (c), and the variation curve of hole volume increment with pore diameter (d).

The combination of N₂ adsorption and MIP experiments to characterize the pore size distribution of shale reservoirs has always attracted attention. In this study, considering the advantages of N₂ adsorption and MIP experiments in the characterization of mesopores and macropores, the boundary between mesopores and macropores (pore size of 50 nm) was selected for splicing. Splicing showed that the pore volume increased with increases in pore diameter. These jagged peaks indicated that the pore sizes in the shale were not evenly distributed, the volume increment of the mesoporous pores was high, and the pore volume increment showed a multi-modal state. The full pore size characterization showed that the Dongyuemiao shale had the most developed mesopores. The pore volume of the samples generally accounted for more than 50%, followed by the macro pore volume accounting for 18.4%–39.89% and the micropore volume accounting for the lowest fraction (Table 3). The mixed shale lithofacies F-5-2 with a higher calcite content and the silica-rich argillaceous shale lithofacies F-1-2 showed a lower pore volume increment over the whole pore size range, indicating that the contribution of carbonate minerals to pore volume was not high compared with clay minerals. The macropore volumes in argillaceous shale lithofacies and mixed argillaceous shale lithofacies were larger, indicating that clay minerals were the main contributors to macropore volume (Figure 8).
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Figure 7. Experimental results of N\textsubscript{2} adsorption and MIP of the Dongyuemiao Member for the N\textsubscript{2} adsorption–desorption curve (a), the curve of \(dV/d\) changing with the aperture (b), the mercury intrusion and mercury withdrawal saturation curve (c), and the variation curve of hole volume increment with pore diameter (d).

Figure 8. Full aperture characterization diagram of the Dongyuemiao shale.

### 4.3.4. Factors Influencing Reservoirs Properties

Shale reservoir pore types are diverse and the pore size ranges are large. Different pore types and sizes affect the occurrence of shale gas [38]. The physical and chemical properties of minerals and the development of OM ultimately determine the ability of shale to form pores. Here, clay minerals were found to maintain a good positive correlation with micropores, macropores, and the total shale pore volume (Figure 9), which was conducive to pore development. The correlation between quartz and micropores, mesopores, and total pore volume in the continental shale of the Dongyuemiao Member was not obvious, and it showed a significant negative correlation with macropores in the shale, which may be related to genesis and quartz content. The high quartz content (>35%) in biogenic marine siliceous shale is conducive to the development of mesopores and micropores [21]. The quartz content in the Dongyuemiao Member was generally shown to be lower than 35%, and the quartz minerals have mainly terrigenous inputs and support clay transformations [39]. Quartz is poorly correlated with the development of micropores and mesopores, and it is important in forming a rigid skeleton for the transformation of widely developed interlayer pore clay minerals, which is not conducive to the development of macropores. Calcite showed a good negative correlation with micropores, mesopores, macropores, and the total pore volume of the shale, indicating that calcite contributed little to the shale pores. The development of calcite according to FE-SEM was mainly in intragranular dissolved pores, and the overall surface porosity of the mineral surface was not high (Figure 6c).

Organic nanopores and clay mineral interlayer pores are the most widely developed in shale [6,40], and OM is accompanied by the formation of pores during hydrocarbon generation (Figure 6f,i). In particular, shale with a high TOC content and a high thermal evolution degree has a high secondary porosity during hydrocarbon generation and transformation [41]. The OM pores formed in shale are mostly micropores and mesopores [40,42,43]. The TOC content in the Dongyuemiao Member showed a positive correlation with the micropore volume. The positive correlation between organic carbon content and macropore volume may be related to the overpressured formation environment. The formation pressure coefficient obtained after the fracturing of Well F was approximately 1.93, and it is speculated that the original formation pressure coefficient was approximately 1.70, which indicates an ultra-high pressure system [34]. The thermal evolution of OM in the formation creates high pore fluid pressure, which is conducive to the interlayer pores of clay minerals not being compacted or closed. The mesoporous development of the Dongyuemiao continental shale has been affected by many factors, and the correlation with clay minerals, quartz, and OM is not obvious.

| Sample | Depth (m) | Lithofacies | TOC (wt. %) | Pore Volume (10\textsuperscript{-3} cm\textsuperscript{3}/g) |
|-----------------|----------|-------------|------------|-----------------|
|                 |          |             |            | Micropore       |
|                 |          |             |            | Mesopore        |
|                 |          |             |            | Macropore       |
|                 |          |             |            | Total Pore      |
|                 |          |             |            | (10\textsuperscript{-3} cm\textsuperscript{3}/g) |
The use of gas to measure the porosity and permeability of shale under macroscopic conditions can well-reflect real reservoir characteristics. The TOC content of the Dong1 and Dong2 sub-members was found to be high, which is of great significance to actual production. The effects of the mineral composition and TOC on the porosity and permeability of the Dong1 and Dong2 sub-members were experimentally studied (Figure 10). The relationship among clay mineral content, porosity, and permeability was as follows: when the content was less than 20%, the porosity of most samples was less than 2% and the permeability was less than 0.2 mD. When the content of clay minerals was more than 20%, the porosity of most samples was more than 4% and the permeability of some samples was more than 0.2 mD, indicating that the interlayer pores developed by clay minerals were conducive to shale porosity development. However, owing to the influence of compaction, some interlayer pores in clay minerals were compressed, resulting in a decrease in permeability. Quartz is beneficial to the improvement of porosity and permeability; when its content was less than 15%, the porosity of most samples was less than 2% and the permeability was less than 0.2 mD. When the quartz mineral content was more than 15%, the porosity of most samples was more than 4% and the permeability was more than 0.2 mD. This shows that the presence of quartz particles is beneficial for the development of shale porosity, mainly because quartz particles can resist the overlying pressure and protect the pore space [44–46]. Overall, carbonate minerals are not conducive to reservoir porosity and permeability development. High-carbonate mineral samples were often found to correspond to thin-shell limestone interlayers developed in the Dongyuemiao Member, indicating that such interlayers have lower porosity and permeability, which is not conducive to hydrocarbon migration. Because it is affected by the thermal evolution of shale OM and its anti-compaction ability, the porosity of shale often first increases and then decreases with the TOC [47–50], and the TOC content of the Dongyuemiao Member was generally found to be low, which was slightly positively correlated with porosity and permeability.
In contrast, the minerals corresponding to the shale with high porosity and permeability had a certain combination relationship: the content of clay minerals was 20%–70%, the content of quartz was 15%–30%, and the content of carbonate minerals was less than 40%.

5. Stress Sensitivity Analysis of Continental Shale Permeability

5.1. Porosity–Permeability Characteristics of Continental Shale under Overburden Pressure

According to the functional relationship, the core stress sensitivity of a logarithmic model is the strongest, that of a power model is second, and that of an exponential or binomial model is the weakest [51]. In addition, the function model of stress sensitivity also reflects the pore geometry model of rocks, which reflects the stress sensitivity model of logarithmic and power relationships. Elliptical tube and round tube pores reflect the stress sensitivity model of a binomial relationship, and star tube pores reflect the stress sensitivity model of an exponential relationship [52]. The samples were collected from the shale core of the F well of the Dongyuemiao Member and were machined to approximately 25 mm in diameter and 57 mm in height. To better compare the stress sensitivity characteristics of the shale, a total of six samples were selected from the different lithologies of the Dong1, Dong2, and Dong3 sub-members to ensure that there was a large difference between the samples (Table 4). This experimental analysis was based on the Method for Determination of Porosity and Permeability of Rocks under Overburden Pressure (SY/T 6385-2016), and the effective stress was calculated using Formula (1).

\[ P_{\text{eff}} = P_c - n_k P_p \]  

where \( P_{\text{eff}} \) is the effective stress, \( P_c \) is the confining pressure, \( P_p \) is the pore pressure, and \( n_k \) is the permeability effective stress coefficient, which reflects the different sensitivities of rock permeability to external pressure and pore pressure. Bernabe [53] first proposed the concept of the effective stress coefficient of permeability when studying the effective stress of granite. Later, research on the effective stress coefficient of permeability showed that lithology is an important factor affecting the effective stress of permeability. Kwon et al. [54] obtained an effective stress coefficient of approximately 1 for illite-rich shale in the Wilcox Formation. The permeability effective stress coefficient of high-clay sandstone with a low stiffness ratio is around 1 [55]. Combining the characteristics of the sample and the existing research suggested that the effective stress coefficient was equal to 1.
Table 4. Basic information and mineral composition of samples.

| Sample | Depth (m) | Length (cm) | Diameter (cm) | TOC (wt.%) | Clay | Mineralogical Composition (%) |
|--------|-----------|-------------|---------------|------------|------|-----------------------------|
| F-27  | 2765.71   | 5.719       | 2.453         | 1.26       | 61.35 | 28                          |
| F-21  | 2782.01   | 5.880       | 2.462         | 1.36       | 25.66 | 11.44                       |
| F-16  | 2787.71   | 4.620       | 2.457         | 1.46       | 80.95 | 13.82                       |
| F-4   | 2805.84   | 5.792       | 2.459         | 1.59       | 69.08 | 21.58                       |
| F-33  | 2807.35   | 5.781       | 2.463         | 1.04       | 52.09 | 20.86                       |
| F-3   | 2809.15   | 5.875       | 2.459         | 1.53       | 69.31 | 20.68                       |

The burial depth of the shale in the Dongyuemiao Member of Well F was found to be between 2750 and 2815 m, the original formation pressure coefficient was approximately 1.70, the original formation pressure was approximately 48.48 MPa, and the maximum over-burden pressure of this experimental design was 30 MPa. The porosity and permeability data of continental shale under overburden pressure and the variation characteristics with pressure are presented in Table 5 and Figure 11. There was a good correlation between the porosity and permeability of the sample and the effective stress. The correlation coefficient between porosity and effective stress greatly varied, ranging from 0.7746 to 0.9161, while the correlation coefficient between permeability and effective stress was above 0.92.

Table 5. Porosity and permeability of samples under different confining pressures.

| Sample | Depth (m) | (Porosity (%))/(Permeability (× 100 mD)) |
|--------|-----------|----------------------------------------|
|        |           | 5   | 10  | 15  | 20  | 25  | 30  |
| F-27   | 2765.71   | 1.244/0.3353 | 0.852/0.1368 | 0.715/0.0769 | 0.615/0.0512 | 0.552/0.0408 | 0.493/0.0298 |
| F-21   | 2782.01   | 1.111/0.2905 | 0.730/0.1459 | 0.586/0.0709 | 0.492/0.0559 | 0.498/0.0452 | 0.427/0.0348 |
| F-16   | 2787.71   | 3.244/2.1014 | 2.582/0.8597 | 1.836/0.4431 | 2.197/0.3011 | 2.004/0.2232 | 1.664/0.1742 |
| F-4    | 2805.84   | 1.214/0.2474 | 0.898/0.1229 | 0.804/0.0689 | 0.720/0.0456 | 0.674/0.0283 | 0.633/0.0212 |
| F-33   | 2807.35   | 0.661/0.8486 | 0.479/0.4054 | 0.371/0.2561 | 0.319/0.1875 | 0.323/0.1433 | 0.295/0.1134 |
| F-3    | 2809.15   | 1.596/4.3607 | 1.185/1.7499 | 1.103/0.8590 | 1.029/0.5517 | 0.928/0.3688 | 0.890/0.2584 |

Figure 11. Variation in shale porosity (a) and permeability (b) with effective confining pressure in the Dongyuemiao Member.

With an increase in effective stress, the porosity and permeability of the sample exponentially decreased. The relationship between the shale porosity and effective stress satisfied the following equation:

\[
\phi_i = \phi_0 e^{-cp}
\]
where $\phi_i$ is the porosity under the given stress condition (%), $\phi_0$ is the porosity when the initial stress is 0 (%), $c$ is the sample pore compressibility (MPa$^{-1}$), and $p$ is the effective stress (MPa). According to the regression analysis equation between the porosity of the sample and the applied effective stress, the initial porosity $\phi_0$ and the compression coefficient $c$ of the sample were obtained. The pore compressibility coefficient of the Dongyuemiao shale was 0.021–0.035 MPa$^{-1}$, with an average of 0.028 MPa$^{-1}$ (Figure 11a). The relationship between the shale permeability and effective stress satisfied the following equation:

$$K_i = K_0 e^{-\gamma p}$$

where $K_i$ is the permeability under a given stress condition (mD), $K_0$ is the permeability when the initial stress is 0 (mD), $\gamma$ is the permeability stress sensitivity coefficient (MPa$^{-1}$), and $p$ is the effective stress (MPa). The permeability stress sensitivity coefficient of Dongyuemiao shale was found to be 0.082–0.11 MPa$^{-1}$, with an average of 0.092 MPa$^{-1}$. In addition, when the effective stress exceeded 20 MPa, the porosity and permeability of the Dongyuemiao continental shale decreased with increasing pressure (Figure 11b).

5.2. Stress Sensitivity Parameters of Permeability of Continental Shale Reservoir

In this study, we referenced the Method for Determination of Porosity and Permeability of Rocks under Overburden Pressure (SY/T 6385-2016) and the Method for Experimental Evaluation of Reservoir Sensitivity Flow (SY/T 5358-2010) for the stress sensitivity analysis of continental shale permeability. The stress sensitivity of shale was evaluated with the permeability damage rate and stress sensitivity coefficient (Table 6). The permeability damage rate reflects the percentage of reservoir permeability damage under effective stress, defined as:

$$D_k = \left( \frac{K_0 - K_i}{K_0} \right) \times 100\%$$

where $D_k$ is the permeability stress damage rate corresponding to the effective stress (%), $K_0$ represents the permeability under initial effective stress (mD), and $K_i$ is the permeability under certain effective stress (mD).

Table 6. Permeability loss rate and stress sensitivity coefficient of samples under different confining pressures.

| Sample | Depth (m) | Confining Pressures (MPa) |
|--------|-----------|---------------------------|
|        | 5         | 10 | 15 | 20 | 25 | 30 |
| F-27   | 2765.71   | 0.042/0.1381 | 0.609/0.0662 | 0.780/0.0235 | 0.854/0.0100 | 0.883/0.0060 | 0.915/0.0046 |
| F-21   | 2782.01   | 0.063/0.1365 | 0.529/0.0674 | 0.771/0.0259 | 0.820/0.0081 | 0.854/0.0070 | 0.888/0.0052 |
| F-16   | 2787.71   | 0.053/0.1466 | 0.613/0.0672 | 0.800/0.0234 | 0.864/0.0097 | 0.899/0.0056 | 0.922/0.0029 |
| F-4    | 2805.84   | 0.202/0.1039 | 0.603/0.0548 | 0.776/0.0240 | 0.853/0.0131 | 0.909/0.0077 | 0.932/0.0052 |
| F-33   | 2807.35   | 0.047/0.1118 | 0.544/0.0613 | 0.712/0.0236 | 0.789/0.0126 | 0.839/0.0083 | 0.873/0.0064 |
| F-3    | 2809.15   | 0.135/0.0436 | 0.653/0.0175 | 0.830/0.0086 | 0.891/0.0055 | 0.927/0.0037 | 0.949/0.0026 |

The permeability stress sensitivity coefficient reflects the degree of change of the formation permeability with the pressure. The larger the value of the permeability stress sensitivity coefficient, the more sensitive the permeability of the shale formation is to the pressure change, which is defined as:

$$\gamma = \frac{-1}{K_0} \frac{dK}{dp}$$

where $\gamma$ is the permeability stress sensitivity coefficient (MPa$^{-1}$), $dK$ represents the change in permeability (mD), and $dp$ represents the change in pressure (MPa).
5.3. Analysis of Influencing Factors on Permeability Stress Sensitivity

5.3.1. Effect of Petrological Characteristics on Permeability Stress Sensitivity

Different mineral compositions have different mechanical properties. The mechanical properties of rocks determine the degree of deformation of the minerals that constitute the core under pressure, which affects the permeability stress sensitivity of shale. Wang et al. [56] observed that clay minerals are an important factor affecting stress sensitivity in a study of the stress sensitivity of tight sandstone reservoirs. Clay minerals not only make pore throats smaller but also make them more irregular in shape. Li et al. [57] found that the reason for the high permeability damage rate of mudstone samples with a high clay content is that stressing rocks with a high clay content makes the pore throats smaller. Furthermore, after being subject to stress, the clay easily spalls off and migrates to block pore throats. The shale in the Dongyuemiao Member is a typical continental shale with a high clay mineral content, and the pore types are mainly interlayer pores within clay minerals. Flat interlayer pores are beneficial for improving the porosity and permeability of the reservoir, but they are more easily compressed and deformed under compression. Accordingly, the permeability damage rate and permeability stress sensitivity coefficient were found to be positively correlated with the clay mineral content (Figure 12), indicating that the higher the clay mineral content, the stronger the permeability stress sensitivity of shale, which is similar to the response observed in marine shale [58]. There is high formation pressure in actual extraction, and there are more holes and fractures in shale after hydraulic fracturing. Combined with the characteristics of its condensate gas reservoir, to ensure the sustainability of shale gas exploitation, it is recommended to adopt pressure-holding techniques to reduce the overlying formation pressure borne by the gas during extraction. Pressure is applied to a shale reservoir so that many pores and fractures in the reservoir will be closed, resulting in a decrease in extraction efficiency. Quartz and other siliceous minerals are conducive to the formation of pores in marine shale [59], but the correlation between their content and permeability stress sensitivity parameters in continental shale is poor (Figure 12), indicating that the low content of quartz in continental shale has a limited contribution to pores and that pores are more derived from other factors. The porosity and permeability of limestone formations are generally low and without fracture development. The SEM images in this study show that carbonate minerals mainly developed isolated dissolution pores, which were less likely to be compressed and closed than the flat interlayer pores developed in clay minerals. Therefore, there was a negative correlation between carbonate mineral content and permeability stress sensitivity parameters (Figure 12). The high-carbonate minerals in the Dongyuemiao Member improve the brittleness and permeability stress sensitivity of the reservoir and provide a strong fracturing and production capacity for the Dongyuemiao Member shale.

5.3.2. Effect of TOC Content on Permeability Stress Sensitivity

Under FE-SEM, these OM pores mostly appeared as round pores, stretched pores, and shrinkage cracks. The development of OM pores is controlled by many factors, such as the type and thermal maturity of the OM. The OM of the Dongyuemiao Member was found to mainly be of type II$_1$ and type II$_2$, and the $R_O$ was found to be between 1.52% and 1.58%. Overall, it was shown to be in the high-maturity stage of OM thermal evolution and the formation stage of condensate oil-wet gas [34]. OM pores are formed after hydrocarbon discharge. Compared with other pore types, it is easier for OM pores to form interconnected pore networks and enhance reservoir porosity and permeability. Wang et al. [27] noted that the presence of OM in shale can lead to the significant deformation of matrix pores, resulting in a more pronounced change in permeability with pressure, and some OM pores could be seen as flat under the scanning electron microscope in this study (Figure 6f). A high OM content reduces the mechanical properties of shale, and OM pores are more easily destroyed during compaction [60]. Therefore, the permeability of shale with a high TOC content more obviously changes with effective stress. A good positive correlation between TOC content and permeability stress sensitivity parameters was also found in this study,
indicating that the presence of OM in shale enhances the permeability stress sensitivity in this reservoir (Figure 12).

Figure 12. Relationship among TOC content, mineral composition, and permeability stress sensitivity parameters.

5.3.3. Effect of Pore Type on Permeability Stress Sensitivity

Fluid seepage in shale reservoirs is dependent on not only the matrix pores but also the fracture pores developed in shale. In an experiment on shale reservoirs in the Ordos Basin, Gao et al. [61] found that some artificial fractures were easier to close when the effective stress increased. When the effective pressure reached 24 MPa, the permeability loss rate of the fractured core was close to 100%, which was significantly larger than that of the matrix core. When the shale developed micrometer fractures, Li et al. [22] noted that micrometer fractures could not reopen after being closed under pressure, resulting in unrecoverable permeability. Ju et al. [26] observed that the permeability loss rate of unfilled natural microfractures is relatively high and that the solubility of fracture fillings has a significant influence on the permeability stress sensitivity of fractured reservoirs. Previous studies have shown that pore type affects the stress sensitivity of rock permeability. To reflect the pore types developed in shale, Zhang et al. [62,63] simplified the various types of pores in shale cores. Using the circular pore, elliptical pore, fracture, and dual-porosity models, a method for judging pore types using the porosity sensitivity exponent was established. Using Equation (6), the ratio of permeability $K_i$ to initial permeability $K_0$ under certain pressure conditions is logarithmically dimensionless, the ratio of porosity $\phi_i$ to initial porosity $\phi_0$ is logarithmically dimensionless, and the porosity permeability power exponent $\alpha$ can be obtained.

$$K_i = K_0 \left( \frac{\phi_i}{\phi_0} \right)^\alpha$$  

(6)

The influence of the morphological characteristics of porous media on stress sensitivity can be reflected by $\alpha$. In this study’s experiment, the porosity sensitivity exponent was found to be 2.1367–4.5295 (Figure 13). The pore structure developed in shale can be determined using the porosity sensitivity exponent. It can be seen that the type of shale
pore development was mainly of the dual-porosity type, and microfractures and matrix pores were developed in the continental shale (Figure 14). Implications from a pulse decay experiment on a fractured core revealed that a direct reduction in gas viscosity due to nanopore confinement may not have a straightforward impact on flow behavior in fractured shale reservoirs and that fracture permeability is much larger than matrix permeability [64]. Interlayer pores in clay minerals can be considered special microfractures (Figure 6). The width and number of microfractures are important factors affecting shale permeability [65]. Here, the permeability damage rate of the experimental samples was much higher than the porosity damage rate. Most of the pores lost in this experiment were fracture pores or flat clay mineral interlayer pores. Theoretically, in a fracture model [62,63], the relationship between permeability, fracture porosity, and fracture width in the direction of fracture parallel to bedding is as follows:

$$K_f = \frac{\phi_f b^2}{12}$$

(7)

where $b$ represents the average fracture aperture of shale formations (m), $\phi_f$ represents the average porosity of shale formation fractures (%), and $K_f$ represents the average porosity of shale formation fractures ($m^2$).

![Figure 13. The double logarithmic curve of porosity and permeability of Dongyuemiao shale.](image)

Equation (7) shows that the larger the fracture aperture, the larger the fracture porosity and the greater the permeability of the shale formation. Additionally, the influence of the fracture aperture was found to be greater than that of the fracture porosity on permeability. The matrix pores in shale were mainly distributed within 110 nm, and the microfracture aperture was shown to be the key to the stress sensitivity of the permeability. The permeability stress sensitivity coefficient of dual-porosity type II was found to be larger than that of dual-porosity type I. The change in permeability under the condition of overburden pressure also illustrates this point. When the effective stress was less than 5 MPa, the measured permeability exceeded the fitting curve. The permeability stress sensitivity in the low-pressure zone was stronger than in the high-pressure zone and showed the control of the microfractures in the shale on the permeability, whereas the permeability stress sensitivity in the high-pressure zone was lower than in the low-pressure zone (Table 6). This showed that the influence of the matrix pores in the shale on permeability was more obvious. Therefore, at present, the fracturing technology of high-density fracture volume
Conclusions

The TOC content, mineral composition, and physical properties of the Dongyuemiao Member showed obvious heterogeneity in the vertical direction. The TOC content was mainly distributed between 1.0 wt.% and 1.5 wt.%, and the TOC of thin layer 4 was the highest. The mineral composition was found to mainly comprise clay minerals, followed by quartz and calcite, and the content of clay minerals was the highest in the Dong1 sub-member (average = 72.79%). The calcite content was the highest in the Dong2 sub-member (average = 50.55%). The porosity was concentrated in 2~5%, and the permeability was concentrated in 0.1~0.5 mD. The porosity and permeability of thin layers 3 and 4 were highest.

The inorganic pores in the Dongyuemiao Member mainly include clay mineral interlayer pores, calcite intragranular pores, pyrite intercrystalline pores, and microfractures. Clay minerals were found to be the main contributors to pore volume. The pore diameter of the Dongyuemiao Member is mainly concentrated below 110 nm, and the mesopores are the most developed, followed by the macropore volume and the micropore volume. A large number of parallel plate-like clay minerals interlayer pores provide space for petroleum enrichment.

Clay minerals and OM can enhance the permeability stress sensitivity of continental shale, and carbonate minerals can reduce the permeability stress sensitivity of continental shale. The average content of brittle minerals such as quartz, calcite, feldspar, pyrite, and dolomite in the Dongyuemiao Member was found to be about 40%, which provides a certain fracturing and exploitation capacity for continental shale. Both the permeability variation and the porosity sensitivity exponent under overburden pressure indicate that microfractures and matrix pores are also developed in continental shale and have a high permeability stress sensitivity. Combined with the characteristics of the gas reservoir and the permeability stress sensitivity of the reservoir, it is recommended that Well F should be subjected to pressure-holding mining under the existing fracturing treatment featuring a “dense-fracture volume stimulation”.

Figure 14. Pore type discrimination diagram (The yellow area represents the matrix pore and the white part represents the crack) [26].
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