Differential Characteristics of the Upper Ordovician-Lower Silurian Wufeng-Longmaxi Shale Reservoir and Its Implications for Shale Gas Exploration and Development in the Sichuan Basin and Its Periphery

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Abstract: The Upper Ordovician Wufeng-Lower Silurian Longmaxi shale is widely distributed in the Sichuan Basin and its periphery and is the key stratum of marine shale gas exploration and development (E&D) in China. Based on sedimentary environment, material basis, reservoir space, fracability and reservoir evolution data, the reservoir characteristics of the Wufeng-Longmaxi shale and their significance for shale gas E&D are systematically compared and analyzed. The results show that (1) the depocenter of the Wufeng (WF)-Longmaxi (LM) shale gradually migrates from east to west. The high-quality shale reservoir in the eastern Sichuan Basin is mainly siliceous shale, which is primarily distributed in the graptole shale interval of WF2-LM5. The high-quality reservoirs in the southern Sichuan Basin are mainly calcareous-siliceous and organic-rich argillaceous shales, which are distributed in the graptole shale interval of WF2-LM7. (2) The deep shale gas (burial depth>3500 m) in the Sichuan Basin has high-ultrahigh pressure and superior physical properties. The organic-rich siliceous, calcareous-siliceous and organic-rich argillaceous shales have suitable reservoir properties. The marginal area of the Sichuan Basin has a higher degree of pressure relief, which leads to the argillaceous and silty shales evolving into the direct cap rock with a poor reservoir/good sealing capacity. (3) Combining shale gas exploration practices and impacts of lithofacies, depth, pressure coefficient and brittle-ductile transition on the reservoir properties, it is concluded that the favorable depth interval of the Wufeng-Longmaxi shale gas is 2200~4000 m under the current technical conditions. (4) Aimed at the differential reservoir properties of the Wufeng-Longmaxi shale in the Sichuan Basin and its periphery, several suggestions for future research directions and E&D of shale gas are formulated.

Key words: shale gas, reservoir, physical property, fracability, evolution, Wufeng Formation, Longmaxi Formation, Sichuan Basin
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1 Introduction

As an important supplement and replacement for conventional oil and gas resources, shale oil and gas have become hot spots in global oil and gas E&D. There are several sets of Paleozoic and Mesozoic organic-rich shale deposits with huge potential for shale gas resources in the Upper Yangtze area of southern China (Zou et al., 2016). Since 2009, a large number of shale gas evaluations and E&D studies have been carried out in the Sichuan Basin and its periphery, and remarkable results and rich understanding have been achieved (Fan et al., 2018; Nie et al., 2015, 2016, 2017, 2018; Liu et al., 2011; Hu et al., 2015, 2018; Lin et al., 2016; Nie and Jin, 2016; Botjigin et al., 2017; Chen et al., 2017, 2018; Dong et al., 2018a, 2018b; Li and Ou, 2018; Zhai et al., 2018). The discovery of the Fuling shale gas field in Chongqing marks a major breakthrough in the E&D of shale gas in China (Guo et al., 2014; Jin et al., 2016) and has far-reaching implications for the E&D of China's unconventional oil and gas and optimization of the energy structure. The shale gas development plan issued by the National Energy Administration of China (2016–2020) plans to establish 5 key shale gas production areas of Fuling, Changle, Xuansui, Zhongtian and Yongchuan, all of which are located in the Sichuan Basin and its periphery with target strata of the Upper Ordovician Wufeng-Lower Silurian Longmaxi Formations (Fms). The Sichuan Basin and its periphery have a wide distribution of Wufeng-Longmaxi shale, which is a key area for the E&D of marine shale gas in China. Although the Wufeng-Longmaxi shale in the Sichuan Basin is generally buried deeper than 3500 m, the current commercial-scale development of shale gas is achieved only in areas that are shallower than 3500 m and overpressured (Long et al., 2018). The commercial development of normal-pressure shale gas and deep shale gas is key to the rapid growth of shale gas production in the Sichuan Basin. With the continuous advancement of shale gas E&D in southern China and deepening of the practical understanding, the deep shale gas in the basin and the normal-pressure shale gas outside the basin have gradually attracted the attention of enterprises and scholars.

The characteristics of shale reservoirs are jointly controlled by the sedimentary environment, spatial and temporal evolution of organic and inorganic mineral components, tectonics, and diagenesis (Zhao et al., 2016, 2017; Jin et al.,...
The reservoir characteristics of shale are quite different under different geological conditions, which determines the developmental characteristics and distributions of high-quality shale (total organic carbon content >2%) reservoirs in the Wufeng-Longmaxi shale. Therefore, based on the sedimentary environment, mineralogy, organic geochemistry, reservoir space characteristics, and shale gas exploration practice in the Sichuan Basin and its periphery, shale reservoirs in different areas are systematically compared and analyzed in terms of lithologic and physical properties, gas content, fracability, and formation pressure (preservation condition) data. In addition, the differences in shale reservoir properties and their effects on shale gas E&D are discussed to provide a reference for the E&D of marine shale gas in southern China.

2 Geological Settings

2.1 Regional tectonic background

The Sichuan Basin is located in the eastern Sichuan Province and Chongqing City and is a superimposed basin that developed on the Upper Yangtze Craton. During the Late Ordovician, the Paleo Central Sichuan Uplift and Xuefeng Uplift were basically formed. The central Guizhou Uplift and Yichang elevation formed under the influence of the Duyun (Middle-Late Caledonian) movement, transforming the Sichuan Basin from an open marine environment during the Middle Ordovician into a restricted shallow water surrounded by uplifts (Fig. 1a); a depositional environment that was characterized by low energy, undercompensation and anoxic conditions was formed (Zhao et al., 2016). Under the influence of tectonic movements and two global transgressions, a set of black shales with graptolite was widely distributed in the Upper Ordovician Wufeng-Lower Silurian Fms in the Sichuan Basin and its periphery (Fig. 1b).

The Sichuan Basin experienced a number of complex tectonic movements, including the Caledonian, Hercynian, Indosinian, Yanshanian (Jurassic-Late Cretaceous) and Himalayan movement. The Yanshanian movement controls the differential tectonic evolution of the eastern and western regions, which has had a major impact on the distribution, depth and preservation conditions of marine shale strata (He et al., 2016; 2017a). The tectonic uplifts of the Mesozoic and Cenozoic in the southeast of the Sichuan Basin are characterized by E–W blocks, N–S belts, and progressive deformation (Li et al., 2012). The main deformation period in the west of the southeastern margin of the Sichuan Basin is the Late Cretaceous (70–100 Ma), in which the degrees of tectonic deformation and uplift are small, and shale gas...
enrichment and preservation conditions are generally suitable. However, the deformation period of the eastern margin of the basin is Late Jurassic (140–160 Ma), and the period of uplift is early and the deformation is strong. The differential tectonic evolution makes the evolution of shale reservoirs and their preservation conditions more complicated in the Sichuan Basin and its periphery, which greatly limits the E&D of shale gas.

2.2 Sedimentary environment and distribution of shale

The Wufeng-Longmaxi shale developed in a stable continental shelf sedimentary environment in the Sichuan Basin and its periphery. The deep shelf shale has a high abundance of organic matter (OM) and is the most favorable sedimentary face for shale gas enrichment. The Wufeng-Longmaxi shale lithofacies are dominated by siliceous shale, argillaceous shale, calcareous shale and silty shale. The high-quality shale at the bottom of the Wufeng-Longmaxi shale is characterized by thin layers, is organic-rich and silicon-rich and is subject to deep water and low sedimentation rates, which is the core interval of shale gas E&D (Hu et al., 2018). According to the graptolite zone division of the Wufeng-Longmaxi shale (Chen et al., 2000; Nie et al., 2017), the Wufeng-Longmaxi shale could be divided into three shale intervals: (1) the WF2-WF3 graptolite interval in the lower part of the Wufeng Formation (restricted by its depositional environment, the distribution of the WF1 graptolite interval is limited), (2) The WF4 graptolite interval (Guanyinqiao Member) consists of limestone/argillaceous limestone/calcareous shale. The top of the Guanyinqiao Member has a conformable contact with the bottom of the Longmaxi Formation. (3) The LM1-LM5 graptolite interval in the lower part of the Longmaxi Formation. By combining lithostratigraphy with biostratigraphy, changes in the lithology of shale and graptolite zones could be well analyzed. The lithofacies types and their distributions in the Wufeng-Longmaxi shale in this paper are based on the research results of Zhao et al. (2016) and Hu et al. (2018).

The shale in the Wufeng Formation (the graptolite interval of WF2-WF3) developed in a continental shelf sedimentary environment, with a thickness generally ranging from 2 to 10 m. The two sedimentary centers of WF2-WF3 shale are the Nanchuan-Fuling-Wulong-Shizhu-Wuxi area in the eastern Sichuan Basin and Changning-Yongchuan-Western Chongqing area in the southern Sichuan Basin (Fig. 1b and Fig. 2); their sedimentary environments are siliceous deep shelf and calcareous-siliceous deep shelf, respectively. The depositional period of the Guanyinqiao Member (the graptolite interval of WF4) corresponds to the large-scale retreat of the sea level in the late Hirnantian glacial period of the Wufeng period, forming a shallow-water calcareous deposit generally containing marker fossils of Hirnantia fauna, and the thickness is generally between 0.2 and 1 m (Nie et al., 2017). In the early depositional period of the Longmaxi Formation (the graptolite interval of LM1-LM5), global transgression occurred again under the influence of glacier ablation due to global warming. The sedimentary environments of the LM1-LM5 shale in the eastern Sichuan and southern Sichuan areas are dominated by siliceous deep-water shelf and calcareous-siliceous deep-water shelf, respectively (Fig. 1b), whose depocenters have a certain inheritance from the depositional period of the WF2-WF3 shale (Nie et al., 2017; Hu et al., 2018).

Influenced by the global transgression and tectonic framework, the depocenter of the WF2-LM9 shale migrated from the east boundary of the Sichuan Basin to the northeastern and southwestern areas within the basin (Hu et al., 2018), which controlled the development of organic-rich shales and quality of the reservoir (Fig. 1b and Fig. 2). The WF2-LM5 shale in the eastern Sichuan-Yongchuan area is dominated by siliceous shale, has a large thickness and high TOC content and is a high-quality shale interval. However, the WF2-LM4 shale in Weiyuan in the southern Sichuan Basin is thinner. Due to migration of the depocenter, the LM5-LM8 shale interval is thicker and the material basis is superior to that of the shale in the eastern Sichuan Basin. Thus, the high-quality shale interval in this area is the WF2-LM7 shale with lithofacies dominated by calcareous-siliceous and organic-rich argillaceous shales. In addition, the localized area represented by the Wuxi area in northeastern Sichuan is always in a deep shelf environment, and the high-quality shale interval can be extended to the middle of the LM8 shale interval.

According to shale gas E&D practices globally, shale gas is generally divided into deep and shallow shale gas with a burial depth range of 3500 m (Long et al., 2018; Dong et al., 2018a). As shown in Fig. 1b, the distribution areas of the Wufeng-Longmaxi shale with burial depths less than 3500 m are mainly located in the eastern and southern margins of the Sichuan Basin (such as the Fuling, Wulong and Changning areas) and near the pinch zone in the western Sichuan Basin (such as the Weiyuan area). The burial depth of the Wufeng-Longmaxi shale in the Sichuan Basin is generally greater than 3500 m, and the deep area is approximately twice as large as that of the shallow layers. In addition, the deep shale gas referred to has a burial depth of greater than 4500 m in half of the region. The deep shale gas resource has great potential but is still in the early stage of exploration.

3 Samples and Methods

More than 500 black shale samples from the Wufeng-Longmaxi and shale were collected from the shale gas wells in the Sichuan Basin and its periphery to conduct experiments and tests. The field-emission scanning electron microscopy (FE-SEM) observations, total organic carbon (TOC) content, X-ray diffraction (XRD) and helium porosity/permeability analyses were conducted at the State Key Laboratory of Shale Oil and Gas Enrichment Mechanisms and Effective Development. The TOC content was measured using a CS–230 carbon and sulfur analyzer. The organic petrological characteristics were examined by observing isolated kerogen under transmitted light and fluorescence using an optical microscope. The type of the organic matter was identified following the Chinese Oil and Gas Industry Standard of SY/T 5152–2014. A Bruker D8 advance X-ray diffractometer with Cu Ka radiation (40 kV, 40 mA) and scanning speed of 1 (20)/min was used on pulverized shales to analyze the mineral compositions of the shale samples. The helium porosity/permeability of shale samples were analyzed using a KXD-II Porometer.
Fig. 2. The distribution of high-quality shale and corresponding graptolitic zone of the Wufeng-Longmaxi shale (the section location is shown in Fig. 1; modified from Nie et al., 2017).
4 Results

4.1 Material basis of shale gas generation

4.1.1 Organic geochemistry

In general, the Wufeng-Longmaxi shale has few changes in the TOC content, organic matter type and maturity in the Sichuan Basin and its periphery. The TOC content is generally between 0.5 and 6.0%, and the highest content value is 8.6%. The distribution of TOC content gradually decreases from the bottom to the top. High-quality shales at the bottom of the Wufeng-Longmaxi shale with a TOC content greater than 2% are mainly distributed in the eastern and southern Sichuan Basin. The thickness of high-quality shale in the eastern Sichuan Basin is between 30 and 44 m, with an average TOC content between 3.6 and 3.9%. The thickness of high-quality shale in the southern Sichuan Basin is between 27 and 60 m, and the average TOC content is between 2.6 and 4.0%.

Based on the carbon isotope composition, organic petrology and organic geochemistry of kerogen, the kerogen types are mainly type I and a mixed type of I-II1, and lower plankton are the main source of hydrocarbon generation material (Nie et al., 2016; Jin et al., 2018). Although the Wufeng-Longmaxi shale in the Sichuan Basin and its periphery is quite different, the equivalent vitrinite reflectance ($R_o$) is concentrated in the 2.3%–3.1% interval, which already indicates the overmature stage. In addition, there is no correlation between the shale thermal maturity and current burial depth, meaning there is no risk of an extremely high thermal maturity. In addition, only two areas have higher thermal maturities and $R_o$ values of greater than 2.8%, which are the Xuanhan-Shizhu area in the northeastern Sichuan Basin and the Yibin-Luzhou area in the southern Sichuan Basin.

4.1.2 Mineral composition

The sedimentary environments of the Sichuan Basin and its periphery in the depositional period of the Wufeng Formation are quite different, as are the mineral compositions of shale. Statistical results show that (Fig. 3a), the quartz content of the Wufeng shale in the eastern Sichuan Basin is generally higher than 50%, the clay mineral content is generally lower than 35%, the carbonate mineral content is lower than 10%, and the quartz content decreases gradually from the northeast to the southwest of the Sichuan Basin. The quartz content of the Wufeng shale in the Weiyuan, Luzhou, Changning and Rhenhui areas of the southern Sichuan Basin is commonly lower than 40%, and the carbonate mineral content is commonly higher than 15%. In particular, the carbonate mineral content of the Wufeng shale in the Weiyuan area is generally higher than 25%.

Due to the global transgression of the early Silurian, the deep shelf environment of the bottom of the Longmaxi shale was extensively developed. The difference in shale mineral composition between different areas of the Sichuan Basin is lower than that of the Wufeng shale (Fig. 3). The variation in mineral composition of the high-quality shale at the bottom of Longmaxi shale is similar to that of the Wufeng shale and generally has a tendency to decrease from northeast to southwest of the Sichuan Basin and its periphery (Fig. 1 b and Fig. 3). The quartz content of the Longmaxi shale in the eastern Sichuan Basin is generally higher than 40%, while the southern Sichuan Basin is affected by the Central Sichuan and Central Guizhou Uplift, receiving a larger terrigenous clastic supply (Fig. 1a). In the southern Sichuan Basin, the contents of clay and carbonate minerals of the Longmaxi shale are higher, and the quartz content is generally lower than 35% (Fig. 3b).
and LM6 shales and has certain features of the correlations between the TOC and quartz contents in the LM4 and LM6 shale, representing transitional characteristics of the sedimentary environment and organic-inorganic mineral composition (Fig. 4a). The correlation between the quartz and TOC contents in different shale intervals in the Yongchuan and Weiyuan areas shows that the quartz content of WF2-LM7 shale has a good correlation with the TOC content with a high proportion of bioquartz. However, the quartz content of the LM8 shale is weakly correlated with the TOC content, indicating a higher content of detrital quartz (Fig. 4b-c).

It is worth noting that the carbonate mineral content in the Wufeng-Longmaxi shale in the Weiyuan area is higher than that in the Yongchuan area and eastern Sichuan Basin, resulting in a slightly lower quartz content of shale than that of the typical siliceous shale in the eastern Sichuan Basin (Fig. 3b). The increase in carbonate mineral content has a good correlation between the carbonate mineral content and the TOC content. When the carbonate mineral content is higher than 15%–20%, there is a negative correlation between the carbonate mineral and TOC contents (Fig. 4d), at which time the carbonate source is dominated by terrigenous debris.

Fig. 4. Relationships between the mineral and TOC contents in the Wufeng-Longmaxi shale. (a) Correlations between the TOC and quartz contents of shale in the eastern Sichuan Basin (Nie et al., 2016); (b) correlations between the TOC and quartz contents of shale in the Yongchuan area; (c) correlations between the TOC and quartz contents of shale in the Weiyuan area; and (d) correlations between the TOC and carbonate mineral contents of shale in the Weiyuan area.

4.2 Reservoir space and physical properties

4.2.1 Organic matter-hosted pores

Four types of reservoir spaces can be recognized in the Wufeng-Longmaxi shale, i.e., organic matter-hosted (OM-hosted) pores, clay mineral pores, brittle mineral pores, and microfractures (He et al., 2017b; Long et al., 2017), among which the OM-hosted pores are the dominant reservoir spaces for shale gas. The developmental degree of OM-hosted pores is the main factor that restricts the occurrence and enrichment of shale gas (Jin et al., 2016; Yang et al., 2016, 2017; Nie et al., 2018). According to research of different scholars on OM-hosted pores and their carriers, OM-hosted pores are mainly developed in original deposition-associated (in situ) OM (algae and animal debris, etc.) and migrated OM (solid bitumen or pyrobitumen) (Hu et al., 2015; Nie et al., 2018). There is a good positive correlation between the porosity and TOC content of the Wufeng-Longmaxi shale in different shale gas production areas in the Sichuan Basin and its periphery (Fig. 5a). From the top to the bottom of the shale, with increasing TOC content and porosity, the proportion of OM-hosted pores increases gradually (Fig. 5b), and its proportion in the main gas production interval can reach 50%–60% (Jin et al., 2016; He et al., 2016).

In addition, the siliceous shale at the bottom of the Wufeng-Longmaxi shale has a high content of bioquartz. Bioquartz commonly appears in the form of microcrystalline, microcrystalline and microcrystalline aggregates, and its size is between 1 and 5 μm; bioquartz is formed during the syndiagenetic-early diagenetic stage (Zhao et al., 2017; Jin et al., 2018). Although microcrystalline bioquartz aggregates filled in the primary pore space and destroyed the interparticle porosity during the early diagenetic stage, the bioquartz aggregates can restrain compaction and preserve the internal pore structure as a rigid framework, which is significant for the preservation of primary pores, the filling of oil in the oil window and the preservation of later OM-hosted pores (Fig. 5c-d).

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Fig. 5. Characteristics of OM-hosted pores in the Wufeng-Longmaxi shale. (a) Correlation between the porosity and TOC content in the Wufeng-Longmaxi shale; (b) correlation between the TOC content and porosity in OM; (c) authigenic microcrystalline bioquartz and terrigenous debris form a rigid framework, which is conducive to the preservation of primary pores and the filling of oil in the oil window, Wufeng Formation, well DY A; and (d) OM-hosted pores under the support of the bioquartz framework are well developed with a high porosity in OM, Longmaxi Formation, well WY X.

4.2.2 Pore structure
The results of shale gas drilling in the Sichuan Basin and its periphery show that the high-quality shale of the Wufeng-Longmaxi shale in different gas producing wells (areas) has different pore structure characteristics. As the preservation conditions deteriorate, the formation pressure coefficient (Pc) decreases, and compaction increases. The OM-hosted pores are generally transformed from macropores with nearly circular shapes of several hundred nm to μm (Fig. 6a-c) into pores generally smaller than 200 nm with elliptical, oblate or irregular angular shapes (Fig. 6d-e). With further reduction of the formation pressure coefficient, the OM-hosted pores eventually become nanopores that are smaller than 100 nm and whose roundness is further reduced (Fig. 6f). This phenomenon further confirms the important role of overpressure for pores, specifically for the preservation of OM-hosted pores in shale.

Fig. 6. Comparison of the morphological characteristics of OM-hosted pores in the Wufeng-Longmaxi shale under different formation pressure coefficients. (a) Well WY B with Pc=1.94; (b) well Y YA with Pc=1.77; (c) well JYC with Pc=1.55; (d) well LY B with Pc=1.08; (e) well DY B with Pc=1.06; and (f) well PY A with Pc=0.96.

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Selecting the Fuling and Pengshui area in the eastern Sichuan Basin as examples, the 3D FIB-SEM (3-dimensional focused ion beam-scanning electron microscope) pore structure analysis shows that the pressure coefficient (preservation condition) controls and reflects pore structure characteristics of the OM-hosted pores in the Wufeng-Longmaxi shale. The axial ratio of OM-hosted pores in the Fuling area (with a pressure coefficient of 1.3–1.6) is mostly less than 2, indicating that most of the pore shapes are spherical and ellipsoidal and that only a few OM-hosted pores are elongated (Fig. 6c and Fig. 7a). The Wufeng-Longmaxi shale has a large total pore volume in the Fuling area, and the OM-hosted pore size is generally larger than 50 nm (Fig. 7b-c). The pore volume is mainly provided by OM-hosted pores that are larger than 150 nm (Fig. 7c). In contrast, the formation pressure coefficient in the Pengshui area is generally between 0.9 and 1.1, which is a normal-pressure shale gas field with relatively poor preservation conditions. The OM-hosted pores in the Pengshui area are mainly ellipsoidal (Fig. 6f), and the axial ratio of OM-hosted pores is concentrated in the 2–4 range (Fig. 7d). The OM-hosted pore size of the Wufeng-Longmaxi shale in the Pengshui area is distributed between 10 and 50 nm. In addition, the total pore volume of the Wufeng-Longmaxi shale in the Pengshui area is significantly smaller than that in the Fuling area, which is mainly provided by OM-hosted pores with sizes smaller than 150 nm (Fig. 7e and 7f).

Fig. 7. Comparison of the pore structure of the Wufeng-Longmaxi shale with different pressure coefficients by 3D FIB-SEM reconstruction.

4.2.3 Physical properties

(1) Porosity

The porosity of the high-quality shale in the Wufeng-Longmaxi shale indicates that the porosity has an overall positive correlation with the pressure coefficient and preservation conditions (Fig. 8). The organic-rich argillaceous shale in the eastern Sichuan Basin and Yongchuan area has the highest porosity, while the porosity of the siliceous shale is the second; the silty shale has the lowest porosity (Fig. 8). In the Weiyuan area of the southern Sichuan Basin, the porosity of the siliceous shale is the highest, followed by those of the argillaceous shale and calcareous shale. From the segmental correlation between the carbonate mineral and TOC contents (Fig. 4d) and the positive correlation between the TOC content and porosity (Fig. 5a), it is inferred that the carbonate mineral content and shale porosity also have a segmental correlation. When the carbonate mineral content is higher than 15%–20%, the increase in carbonate mineral content begins to inhibit the TOC content and porosity, resulting in the porosity of calcareous shale being lower than that of siliceous shale and organic-rich argillaceous shale. (Fig. 8).

Fig. 8. Porosity distribution of the lower Wufeng-Longmaxi shale in different areas.

The shale reservoirs in different shale intervals of the Wufeng-Longmaxi shale have significant differences in lithology, graptolite type, and mineral and OM composition in the vertical direction (Nie et al., 2017; 2018; Hu et al., 2018; Jin et al., 2018), resulting in differences in the shale physical properties under different in situ conditions. The

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stress sensitivity of porosity in the Wufeng-Longmaxi shale gradually increases from the bottom to the top (Fig. 9). In the eastern Sichuan Basin, the porosity of the WF2-LM5 shale has the lowest stress sensitivity, and the porosity reduction at the equivalent burial depth of 3500-5000 m is generally less than 15%; the porosity reduction in the upper LM6-LM7 shale with a higher clay mineral content is generally between 15.0 and 17.1% (Fig. 9a). Due to migration of the depocenter in the depositional period of the Longmaxi Formation, the high-quality shale interval in the southern Sichuan Basin is the WF2-LM7 shale with lithofacies dominated by calcareous-siliceous and organic-rich argillaceous shales (Fig. 2 and Fig. 4). In the southern Sichuan Basin, the shale in the interval of the WF2-middle LM7 has the lowest stress sensitivity of porosity with a porosity reduction that is less than 15%–20% at the equivalent burial depth of 3500-5000 m; the porosity sensitivity of the organic-lean argillaceous shale above the LM7 shale interval is notable, and the porosity decreases by more than 20% and even up to 40% (Fig. 9b). Therefore, the WF2-LM5 shale in the eastern Sichuan Basin and WF2-LM7 shale represented by the Weiyuan area in southern Sichuan Basin are the optimal reservoir intervals, which is closely related to their high anticompaction capability of bioquartz and biocarbonate (Zhao et al., 2016; Jin et al., 2018; Wang et al., 2018a).

In terms of the porosity sensitivity and porosity retention under in situ pressure conditions, the eastern Sichuan Basin has a high degree of tectonic deformation, an early deformation period and relatively low pressure maintenance (He et al., 2016; 2017a). The Wufeng-Longmaxi shale in the eastern Sichuan Basin is strongly compacted, and its physical sensitivity is lower than that in the high-ultrahigh pressure basin area. However, the overall porosity of the bottom shale has slight differences in stress sensitivity values of the porosity, and the vertical variation in the sensitivity is similar, indicating that the bottom siliceous shale has the highest anticompaction capability, which is conducive to the preservation of reservoir space (Fig. 9).

Fig. 9. Porosity variation in the Wufeng-Longmaxi shale in different areas under overburden pressure.

Overpressure is an important factor for a high gas content and high yield of shale gas, and is also an important indicator reflecting preservation conditions. The practice of shale gas E&D in the Sichuan Basin shows that there is a significant positive correlation between the single-well production and the pressure coefficient (Jin et al., 2016; Dong et al., 2018a). The statistical results from Dong et al. (2018a) show that the burial depth and pressure coefficient of shale exhibit a good positive correlation in the Sichuan Basin. At present, the burial depth of the Wufeng-Longmaxi shale gas production interval currently under commercial development is generally between 2000 and 3800 m, and the pressure coefficient is between 1.2 and 2.0. The correlation between the pressure coefficient and porosity of the Wufeng-Longmaxi shale in the Sichuan Basin and its periphery shows that the porosity has a positive correlation with the pressure coefficient (Fig. 8).

The correlation between the porosity and burial depth of the Wufeng-Longmaxi shale in the Sichuan Basin and its periphery is shown in Fig. 10. The porosity of the high-quality shale in the Sichuan Basin with overpressure is generally greater than 4.3%, and the depth is generally greater than 2200 m. In the normal-pressure areas, except for the porosity of well LYA in the Wulong area, which is 4.8%, the shale porosity in other areas is generally lower than 3.5% with a lower gas content. At present, the shale gas drilling data show that the porosity and depth have a segmental correlation; that is, the porosity increases gradually with increasing depth; however, when the depth is greater than 4000 m, the porosity decreases (Fig. 10). Therefore, the depth range of 2200–4000 m is favorable for porosity retention.

Fig. 10. Correlation between the porosity and depth of the Wufeng-Longmaxi shale in the Sichuan Basin and its periphery.
(2) Permeability

According to statistics of the permeability of the Wufeng-Longmaxi shale (Fig. 11), with overpressure and suitable preservation conditions, the permeability of the upper organic-rich argillaceous shale is commonly higher than that of the lower siliceous shale. In areas with normal-pressure and relatively suitable preservation conditions, the permeability is lower than that in overpressure areas, and the permeability gradually decreases from the bottom to the top, indicating a suitable property of self-sealing. This phenomenon is beneficial to the physical sealing (capillary sealing) of the direct cap rock, which is conducive to the preservation of shale gas in the normal-pressure areas outside the basin.

The shale reservoir with nanoscale pores as the dominant reservoir space has low porosity, low permeability and strong vertical self-sealing characteristics. The orientation and compaction of flaky clay minerals facilitate the development of bedding fractures and interlayer microfractures, resulting in a higher horizontal permeability than vertical permeability. In the eastern Sichuan Basin, the vertical permeability of the Wufeng-Longmaxi shale is generally lower than 0.0005 mD, and the corresponding horizontal permeability is generally greater than 0.03 mD. The difference between the horizontal and vertical permeability is generally between 2 and 4 orders of magnitude (Fig. 12). In the southern Sichuan Basin, the vertical permeability of shale is generally less than 0.001 mD, which is slightly higher than that in eastern Sichuan Basin. The corresponding horizontal permeability is generally between 0.01 and 0.1 mD, which is lower than that in eastern Sichuan Basin. The difference between the horizontal and vertical permeability is between 2 and 3 orders of magnitude, which is lower than that in the eastern Sichuan Basin (Fig. 12).

Compared with the shale in the eastern Sichuan Basin (with a pressure coefficient of 1.2–1.6), the horizontal permeability of the Wufeng-Longmaxi shale in the southern Sichuan Basin decreases significantly with increasing burial depth, indicating a strong stress sensitivity of the permeability. Since the Wufeng-Longmaxi shale in the southern Sichuan Basin has a high-ultrahigh pressure (the pressure coefficient is 1.6–2.1), the vertical permeability is higher than that in the eastern Sichuan Basin, indicating that overpressure has an inhibitory effect on compaction, which is conducive to the preservation of reservoir space and physical properties (Fig. 8 and Fig. 12).

Natural (micro) fractures can improve the shale reservoir space and seepage capacity, increase the ratio of free gas, and improve the yield and economic benefits of shale gas (Gale et al., 2007; Jin et al., 2016; Dong et al., 2018b). As shown in Fig. 13, the permeability of fractures and matrix exhibit notable stress sensitivity, which decreases sharply with increasing effective stress. Under an effective stress of 30 MPa, the permeability dropped below 10% of the initial permeability. Although the permeability compression ratios of fractures and matrix are similar at a pressure of 35–40 MPa, the reduction rate of the fracture permeability is lower and the retention of fracture permeability is higher than those of the matrix permeability when the effective stress is less than 35 MPa (Fig. 13). Choosing the Fuling shale gas field in eastern Sichuan Basin as an example, the formation pressure coefficient is 1.5, and the densities of formation water and overlying strata are approximately 1.0 and 2.5 g/cm³, respectively. Under these conditions, an effective stress of 35 MPa is equivalent to a burial depth of 3500 m, which corresponds to the depth boundary of deep and shallow shale gas. This phenomenon indicates that fractures such as bedding fractures have a significantly higher permeability than the matrix and have an important contribution to the seepage of shale gas in the middle and shallow depths (<3500 m)
m). However, for the deep shale gas with a burial depth greater than 3500 m, the permeability reduction rate of fractures is greater than that of the matrix, and both the fracture and matrix permeability are extremely low and roughly equivalent (Fig. 13). Therefore, the seepage capacity and fracturing effect of shale reservoirs are important factors that restrict the high-efficiency development of deep shale gas in the Wufeng-Longmaxi shale.

4.3 Fracability

The brittleness of shale determines the fracability of shale reservoirs and has a significant impact on the E&D of shale gas. In the practice of E&D, rock mechanics parameters and brittle mineral contents are commonly used to evaluate the brittleness of shale. Shale with a large Young’s elastic modulus, low Poisson ratio and low tensile strength has a high brittleness and is more likely to form natural and induced fractures (Jarvie et al., 2007; Rickman et al., 2008; Wang et al., 2018b).

There are differences in the mineral composition of the Wufeng-Longmaxi shale in the Sichuan Basin and its periphery. The brittle mineral content in the eastern Sichuan Basin consists mainly of quartz, and the brittle minerals in the southern Sichuan Basin are mainly quartz and carbonate minerals (Fig. 3). The brittleness of the Wufeng-Longmaxi shale in the Changning area of the southern Sichuan Basin shows that quartz, dolomite and pyrite are the most occurring brittle minerals with the largest Young's moduli and lowest Poisson ratios, while the contribution of feldspar and calcite to the brittleness is not notable (Zhang et al., 2016). Yang et al. (2018) and Shi et al. (2019) used nanoindentation tests to study the nanomechanical properties of the Wufeng-Longmaxi shale in the Sichuan Basin. The results show that quartz, pyrite and dolomite have the highest values of the Young’s modulus; the Young’s modulus of clay minerals, calcite, and junction portions of the clay matrix and siliceous/calcareous minerals is much lower. Therefore, the mineral content of quartz, dolomite and pyrite can be used as the shale brittleness index. The brittleness index of the high-quality shale in the Fuling and Changning areas is generally higher than 40%, and the continuous thickness with a brittleness index greater than 50% is large. The brittleness index in the Weiyuan area fluctuates significantly by approximately 40%, and the continuous thickness with a brittleness index greater than 50% is smaller. Compared with the eastern Sichuan region, the brittleness of the calcareous shale and calcareous siliceous shale in southern Sichuan is slightly lower than that of the siliceous shale. It can be concluded that the brittleness of the calcareous shale and calcareous-siliceous shale in the southern Sichuan Basin is slightly lower than that of the siliceous shale in the eastern Sichuan Basin.

In addition to the above factors, the burial depth has an important influence on the shale brittleness. Shale brittleness/ductility properties, such as brittleness, semibrittleness and ductility, can mutually transform with burial depth variation. Deep shale reservoirs exhibit a brittle-ductile transition under high pressure and temperature conditions, which results in the brittleness of deep shale being significantly lower than that of shallow shale. At the same time, higher reservoir stresses and formation temperatures (commonly greater than 110 °C) result in higher requirements for wellbore stability and fracturing stimulation. According to Yuan et al. (2017), the depth intervals of shale mechanical properties are vertically divided into a brittle zone, brittle-ductile transition zone and ductile zone with increasing burial depth. Although shale in the brittle zone with a shallow burial depth is characterized by suitable brittleness, extensional and open fractures may occur under tectonic stress during uplift and erosion; thus, the overpressure and preservation conditions may have been destroyed. Shale in the ductile zone with a deep burial depth is characterized by suitable ductility and good sealing capacity, which is beneficial for the preservation of overpressure and high gas contents but is not prone to hydraulic fracturing stimulation. Therefore, the shale in the brittle-ductile transition zone with a moderate burial depth has both suitable preservation conditions and brittleness values, which is conducive to the efficient development of shale gas. The bottom boundary depth of the brittle zone of the Wufeng-Longmaxi shale in the eastern Sichuan Basin is generally between 2195 and 2763 m, and the top boundary depth of the ductile zone is approximately 4470±230 m (Yuan et al., 2017). The depth interval of the brittle-ductile transition zone is generally consistent with the favorable depth interval of physical properties and overpressure (Fig. 10).

5 Discussions

5.1 Differential evolution of reservoirs

The bottom shale of the Wufeng-Longmaxi Formation is rich in siliceous organisms, providing a sufficient material basis for silicic cementation during early diagenesis. The quartz content in the high-quality shale interval is usually...
higher than 40%, and the authigenic quartz dominated by bioquartz accounts for 40 to 60% of the total quartz content. Although the microcrystalline bioquartz aggregates filled in the primary pore space and destroyed the interparticle porosity during the early diagenetic stage, the aggregates can restrain compaction and preserve the internal pore structure as a rigid framework, which is significant for the preservation of primary pores, the filling of oil in the oil window and the preservation of later OM-hosted pores (Fig. 5c-d). As the maturity of OM increases, the retained oil (migrated OM) fills in the interparticle pores cracks and is converted into solid bitumen/pyrobitumen with abundant pores, which is the main carrier for OM-hosted pores (Hu et al., 2015; Jin et al., 2018). Therefore, siliceous shale is the most favorable lithofacies (Fig. 14).

Without considering the influence of preservation conditions (pressure evolution) on reservoir evolution, the quartz content and anticompaction capacity are lower in the calcareous-siliceous shale and organic-rich argillaceous shale than those in the siliceous shale. Although carbonate minerals have a certain anticompaction capacity, their stability is weaker than that of quartz, which is easy to dissolve, metasomatisize and recrystallize, so its anticompaction capacity is slightly lower than that of quartz. The calcareous-siliceous shale with commonly developed dissolution pores has suitable reservoir properties under appropriate preservation and overpressure conditions in the southern Sichuan Basin and is a high-quality reservoir. In addition, the upper silty and organic-lean argillaceous shales have a poor material basis and the lowest anticompaction capacity, which makes the primary pores difficult to preserve and a suitable self-sealing capacity difficult to form based on the poor physical properties, i.e., the upper shale mainly acts as a direct seal. Overall, from the bottom to the top of the Wufeng-Longmaxi shale, with decreasing TOC, quartz and carbonate mineral contents, the content of authigenic quartz and calcium is correspondingly reduced, resulting in a gradual increase in the compaction, a gradual decrease in the migrated OM content, and a gradual deterioration in the shale reservoir quality.

For overmature marine shale with a complex tectonic evolution, the development of reservoir space is not only related to the material basis and internal factors, such as the TOC, R, and type of kerogen type but is also largely affected by external preservation conditions. The Wufeng-Longmaxi shale in the Sichuan Basin and its periphery was generally overpressurized before the Yanshanian movement (the period of the maximum burial depth). Xi et al. (2016) studied the paleo-pressure of fluid inclusions in shale fractures, demonstrating that the pressure coefficient of the Wufeng-Longmaxi shale in the southeastern Sichuan Basin before the Yanshanian movement is between 1.7 and 2.2. However, the current pressure coefficient is generally between 0.9 and 1.5, indicating that pressure relief (PR) is a common phenomenon. The current formation pressure coefficient in the Weiyuan and Yongchuan areas of the southern Sichuan Basin is generally between 1.6 and 2.1, and the pressure relief is significantly lower than that in the eastern Sichuan Basin, which results in the shale exhibiting an improved maintenance of the reservoir space and physical properties. Therefore, in addition to the siliceous shale, the organic-rich calcareous-siliceous and argillaceous shales in the high-ultrahigh pressure areas are high-quality and suboptimal reservoirs, respectively (Fig. 14). The eastern Sichuan Basin is greatly affected by deformation resulting from the Yanshanian movement (Li et al., 2012; He et al., 2016; 2017a), and the shale reservoir is subjected to different degrees of pressure relief. The pressure relief results in significantly deteriorated physical properties of the organic-rich argillaceous shale, silty shale and organic-lean argillaceous shale (with a lower anticompaction capacity); these shales gradually evolved into the direct cap rock in the eastern Sichuan Basin (Fig. 14).

5.2 Challenges for shale gas exploration and development

With the continuous advancement of shale gas E&D in southern China and the deepening of practical understanding, the commercial development of normal-pressure shale gas and deep shale gas is the key to the rapid growth of shale gas.
production in the Sichuan Basin. The engineering technology of China’s marine shale gas is generally mature for layers shallower than 3500 m. The localization of key technologies and equipment has been realized, and an efficient development and industrialization model has been established. However, there are several technical problems associated with layers deeper than 3500 m, which did not achieve a large-scale commercial development breakthrough. The overpressure deep shale gas in the basin and the normal-pressure shale gas outside of the basin area present a large potential, but they are significantly different from the shale gas in current production areas in terms of the reservoir characteristics, resource qualities and E&D technologies.

For deep and normal-pressure shale reservoirs, the evaluation method, fine reservoir identification and prediction, resource estimation, horizontal well drilling, completion and fracturing are in the preliminary research stage. The high temperature and stress conditions in the deep high-ultrahigh pressure areas in the Sichuan Basin pose significant challenges to shale gas drilling, completion and fracturing stimulations. The E&D of the shale gas outside of the basin is constrained by a low gas content, complex storage conditions and high cost of technology. For the deep shale gas in the Sichuan Basin, the reservoir and transport properties of shale gas should be thoroughly studied, and the technologies of drilling, completion and fracturing should be improved. In view of the shallow normal pressure to overpressure shale gas in the basin margin, the preservation conditions should be emphasized, and the evolution and characteristics of the high-quality shale reservoirs and their direct cap rock should be studied.

6 Conclusions

(1) The depocenter of the Wufeng-Longmaxi shale gradually migrates from the east to the west in the Sichuan Basin and its periphery. The high-quality shale reservoir in the eastern Sichuan Basin is mainly siliceous shale, which is primarily distributed in the graptolite shale interval of WF2-LM5 with a quartz content higher than 40% and carbonate mineral content lower than 15%. The high-quality reservoirs in the southern Sichuan Basin are mainly calcareous-siliceous shale and organic-rich argillaceous shale with a quartz content between 30 and 40%, carbonate mineral content higher than 20% and commonly developed carbonate dissolution pores, which are distributed in the graptolite shale interval of WF2-LM7. In addition, the brittleness of the high-quality shale in the southern Sichuan Basin is slightly lower than that in the eastern Sichuan Basin.

(2) Overpressure has an inhibitory effect on compaction, plays an important role in the retention of OM-hosted pores and physical properties of shale, and has a significant effect on the maintenance of physical properties in the highly stress-sensitive argillaceous shale. The eastern and southern margins of the Sichuan Basin are dominated by shallow shale gas with limited distribution, but the interior of the Sichuan Basin is dominated by deep shale gas. The deep shale gas in the Sichuan Basin has a high-ultrahigh pressure (suitable preservation conditions) and superior physical properties, resulting in the organic-rich siliceous, calcareous-siliceous and organic-rich argillaceous shales having suitable reservoir properties. However, the marginal area of the Sichuan Basin has a higher degree of pressure relief, which results in the argillaceous and silty shales evolving into the direct cap rock with a poor reservoir/good sealing capacity.

(3) The burial depth has little effect on the porosity of the high-quality shale at the bottom of the Wufeng-Longmaxi shale but has a significant effect on the permeability. For deep shale gas with burial depths greater than 3500 m, the permeability reduction rate of fractures is greater than that of the matrix, and both the fracture and matrix permeability are extremely low and roughly equivalent. The seepage capacity and fracturing effect of shale reservoirs are important factors that restrict the high-efficiency development of deep shale gas. Combining the shale gas exploration practice and impact of lithofacies, depth, pressure coefficient and brittle-ductile transition on reservoir properties, it is concluded that the favorable depth interval of the Wufeng-Longmaxi shale gas is 2200–4000 m under current technical conditions.

(4) The overpressure deep shale gas in the basin and normal-pressure shale gas outside of the basin area have a large potential, but they are significantly different from the shale gas in current production areas in terms of reservoir characteristics, resource qualities and E&D technologies. For the deep shale gas in the Sichuan Basin, the reservoir and transport properties of shale gas should be thoroughly studied, and the technologies of drilling, completion and fracturing should be improved. In view of the shallow normal pressure to overpressure shale gas in the basin margin, the preservation conditions should be emphasized, and the evolution and characteristics of the high-quality shale reservoirs and their direct cap rock should be studied. The E&D of shale gas should always focus on improving single-well production, reducing costs, improving the pertinence and effectiveness of engineering, and strengthening the development and application of novel technologies.

Acknowledgements

This work is granted by the National Science and Technology Major Project of the Ministry of Science and Technology of China (Grant No. 2017ZX05036002–001) and National Natural Science Foundation of China (No. 41202103, 41872124), SINOPEC Ministry of Science and Technology Project (Grant No. P17027–2).

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Fig. 1. Location and stratigraphic characteristics of the Sichuan Basin and its periphery.
(a) Early Silurian paleogeographic map with the distribution of lithofacies of the Yangtze area (Zhou et al., 2016); (b) lithofacies and burial depth distribution of high-quality shale in the Wufeng-Longmaxi Fms (after Hu et al., 2018; Long et al., 2018); and (c) simplified stratigraphic units in the shale gas fields in the Sichuan Basin (after Jin et al., 2018).

Fig. 2. The distribution of high-quality shale and corresponding graptolitic zone of the Wufeng-Longmaxi shale (the section location is shown in Fig. 1; modified from Nie et al., 2017).

Fig. 3. Mineralogical ternary diagram of the Wufeng-Longmaxi shale in the Sichuan Basin and its periphery.

Fig. 4. Relationships between the mineral and TOC contents in the Wufeng-Longmaxi shale.
(a) Correlations between the TOC and quartz contents of shale in the eastern Sichuan Basin (Nie et al., 2016); (b) correlations between the TOC and quartz contents of shale in the Yongchuan area; (c) correlations between the TOC and quartz contents of shale in the Weiyuan area; and (d) correlations between the TOC and carbonate mineral contents of shale in the Weiyuan area.

Fig. 5. Characteristics of OM-hosted pores in the Wufeng-Longmaxi shale.
(a) Correlation between the porosity and TOC content in the Wufeng-Longmaxi shale; (b) correlation between the TOC content and porosity in OM; (c) authigenic microcrystaline bioquartz and terrigenous debris form a rigid framework, which is conducive to the preservation of primary pores and the filling of oil in the oil window, Wufeng Formation, well DYA; and (d) OM-hosted pores under the support of the bioquartz framework are well developed with a high porosity in OM, Longmaxi Formation, well WYX.

Fig. 6. Comparison of the morphological characteristics of OM-hosted pores in the Wufeng-Longmaxi shale under different formation pressure coefficients.
(a) Well WYX with Pc=1.94; (b) well YYA with Pc=1.77; (c) well YJC with Pc=1.55; (d) well LYB with Pc=1.08; (e) well DYB with Pc=1.06; and (f) well PYA with Pc=0.96.

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Fig. 7. Comparison of the pore structure of the Wufeng-Longmaxi shale with different pressure coefficients by 3D FIB-SEM reconstruction.

Fig. 8. Porosity distribution of the lower Wufeng-Longmaxi shale in different areas.

Fig. 9. Porosity variation in the Wufeng-Longmaxi shale in different areas under overburden pressure.

Fig. 10. Correlation between the porosity and depth of the Wufeng-Longmaxi shale in the Sichuan Basin and its periphery.

Fig. 11. Permeability distribution of the Wufeng-Longmaxi shale in different areas.

Fig. 12. Comparison of vertical and horizontal permeability of the Wufeng-Longmaxi shale.

Fig. 13. Relationship between the effective stress and the permeability compression ratio in different types of pores.

Fig. 14. Evolution pattern of the Wufeng-Longmaxi shale under different preservation conditions (pressure coefficients).