Accumulation characteristics of tight sandstone gas reservoirs in the Upper Paleozoic in the Shenfu block of the Ordos Basin

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Abstract. The Shenfu gas field on the eastern margin of the Ordos Basin is one of the key blocks of CNOOC’s land tight sandstone gas field development in recent years. In order to further analyze the physical properties and accumulation and evolution characteristics of the Upper Paleozoic tight sandstone gas reservoirs in the Shenfu block, we characterized the reservoir pore structure, diagenetic evolution, and natural gas accumulation stages, combined with fluid inclusions, the types of tight sandstone gas reservoirs in the Upper Paleozoic are studied, revealing the main controlling factors for the natural gas accumulation in the study area. Studies have shown that the core porosity of tight sandstone reservoirs in the Upper Paleozoic in the Shenfu block is less than 10%, and the permeability is less than 1mD. Compaction and cementation are the main factors for reservoir tightness. The results of porosity evolution and homogenization temperature of fluid inclusions indicate that the Upper Paleozoic sandstone tightness is formed during the Middle-Late Triassic-Early Jurassic, which is earlier than the Late Jurassic-Early Cretaceous period of large-scale natural gas accumulation.

1. Introduction
China is rich in tight sandstone gas resources. As of the end of 2019, 16 large tight sandstone gas fields have been discovered, with proven reserves exceeding 55% of the total proven reserves of large gas fields in the country and has become the mainstay of China’s natural gas production growth in recent years. The large tight sandstone fields in China are mainly distributed in the Ordos, Sichuan, and Tarim Basins[1]. From the perspective of the main conditions for tight gas field formation, the maturity of source rocks is one of the important conditions for tight gas reservoir formation[2].

The Shenfu exploration block is located on the eastern margin of the Ordos Basin. The structural location is the Yishan slope of the Ordos Basin and the flexure zone in the west of Shanxi. The terrain is high in the east and low in the west, high in the north and low in the south. Tight gas exploration block on land of CNOOC. The main exploration horizons of the Upper Paleozoic in the Shenfu block are Benxi Formation (C2b), Taiyuan Formation (P1t), Shanxi Formation (P1s), Shihezi Formation (P2sh) and Shiqianfeng Formation (P3s). In recent years, the exploration of the Shenfu block has achieved great success[3]. Among them, the daily gas production of the SM-02-4D well during the fracturing completion and gas test reached 6.6×10^4m³/d.

Current exploration results show that the Upper Paleozoic tight sandstone gas reservoirs in the Shenfu block have the characteristics of low reservoir porosity, low permeability, wide distribution, strong heterogeneity, and large differences in gas-bearing production. In the study of reservoir types, it
is important to clarify the impact of sandstone reservoir diagenesis, sandstone reservoir tightness period, and sandstone tight period diagenesis on large-scale natural gas charging[4]. Based on the analysis of diagenesis and the analysis of fluid inclusions, this paper compares the tightness time of the Upper Paleozoic sandstone reservoirs finally and the accumulation time of a large amount of natural gas to determine the type of natural gas accumulation.

2. Methods and materials

The experimental equipment includes: ZT-1 rock porosity casting instrument, Quattro ESEM scanning electron microscope, Zeiss Primotech polarizing microscope, DYX-1 full diameter core permeability tester, MiniX automatic specific surface area and pore size distribution tester, core nuclear magnetism Resonance analyzer, core CT scanner, core holder, etc[5].

Several core samples are obtained from drilling in different gas-bearing layers in the Shenfu block, and core casting thin sections are prepared according to the relevant operating procedures of the experimental equipment, and core samples to be tested are prepared.

3. Results and analysis

3.1. Reservoir physical characteristics

Experimental analysis of core porosity and permeability shows that the porosity of the samples with more than 70% of the Upper Paleozoic sandstone reservoirs in the Shenfu block is mainly distributed in 4%-11%, with an average value of 8%, and the permeability distribution of 80% of the rock samples is between 0.01-1mD (Figure 1).

![Figure 1. Histogram of porosity and permeability distribution of tight sandstone in Upper Paleozoic in Shenfu block (a, porosity; b, permeability).](image)

The experimental results of the core pore type structure show that the total borehole ratio of the core is between 3.1% and 5.4%, and the average borehole ratio is 4.1%. Among them, lithic dissolved pores and feldspar dissolved pores are developed, and the average borehole ratio is 1.5% and 1.1%, respectively, followed by intergranular pores, with an average borehole ratio of 0.7%. Residual intergranular pores and micro-cracks have the smallest borehole ratio, with an average aperture ratio of 0.4%. The pore types and content of different layers are different. The average total borehole ratio of the He8 section is the highest at 5.4%, followed by the average total borehole ratio of the Qian5 section of 4.3%. The average total borehole ratio of the Tai2 section is 4.1%, and the average total borehole ratio of the Shan2 section is 3.5%. The average total borehole ratio of the Ben 1 is 3.1%, which is the lowest. Different levels of dissolution occurred in each layer, among which the He8 Member and Tai2 Member are the most obvious, and the borehole ratio generated by the dissolution could reach 3.5% and 3.3%, respectively. The following four types of pores are identified: remaining intergranular pores
(primary pores), dissolved intergranular pores, dissolved intragranular pores, and intercrystalline pores [6].

Core CT scan results show that the core pore types of different layers in the Shenfu block are diverse, but mainly connected micropores, with uneven distribution of micropore throats. Different types of micropore throats have different connectivity and different extension directions. Both small-volume pores and large-volume pores are distributed in isolation [7].

The analysis of rock types shows that the main sandstone type of Benxi Formation is quartz sandstone with a small amount of feldspar sandstone [8]. The main sandstone type of Taiyuan Formation is feldspar lithic sandstone and lithic sandstone. The main sandstone type of Shanxi Formation is feldspar lithic sandstone and a small amount of detrital quartz sandstone. The main sandstone types of Shihezi Formation are feldspar detrital sandstone, detrital sandstone, and detrital feldspar sandstone. The sandstone type of Shiqianfeng Formation (Qian5 Member) is the same as that of Shihezi Formation, and the main sandstone type is feldspar detrital sandstone and detrital sandstone, followed by detrital feldspar sandstone. On the sandstone classification triangle map, most of the data points are concentrated near the Q-R line, indicating that the feldspar content is relatively low. At the same time, from bottom to top, from the Benxi Formation to the Shiqianfeng Formation, the overall trend of feldspar content increases, reflecting the difference in the nature of the parent rock in different periods (Figure 2).

![Figure 2. Classification map of Upper Paleozoic tight sandstone in Shenfu block (I, Quartz sandstone; II, Feldspar quartz sandstone; III, Lithic quartz sandstone; IV, Feldspar sandstone; V, Lithic feldspar sandstone; VI, Feldspar lithic sandstone; VII, Lithic sandstone).](image)

3.2 The impact of diagenesis on the reservoir
Diagenesis is a geological process that significantly alters the porosity and permeability of the reservoir after the early sedimentary environment. The Upper Paleozoic sandstone diagenesis of the Shenfu block is complex, experienced early compaction and dissolution, early and late cementation of authigenic minerals such as clay minerals, chlorite, calcite, and large amounts of hydrocarbon source rocks from coal measures. The released organic acids dissolve unstable minerals in the reservoir. Among them, dissolution is an important way to improve reservoir porosity and permeability.

Compaction and cementation are important diagenesis effects of porosity reduction, but they have different ways of reducing porosity and restrict each other. Compaction is irreversible for the reduction of porosity between rock particles. When the compaction is too strong, external fluids cannot enter the pores to inhibit cementation. On the contrary, if the formation is buried, a large amount of external fluids enters and the external mineral ions are abundant. This process is helpful for cementation to occur, which can not only keep the pores between rock grains, but also can form secondary pores through dissolution.

According to the analysis of the core hole ratio and cement content evaluation chart, the porosity in the study area is mainly reduced by compaction, followed by cementation. Compaction is the first factor that causes tight sandstone reservoirs (Figure 3). The sample points on the diagonal and close to the...
diagonal represent high cement content, mainly siliceous cement and some authigenic clay minerals, but the maximum is not more than 25%. The stratum is from shallow to deep, from lower to upper, from the Benxi Formation to the Shiqianfeng Formation. The sample points gradually shift from the upper right to the lower left. Although the trend is weak, it can still be seen that the lower strata in the study area are relatively similar to the upper strata. For section 5, the cementation is enhanced, and the compaction is weakened, that is, the compaction has a greater impact on the upper strata with relatively shallow burial. As the buried depth of the strata increases, the appropriate temperature, pressure and pore water properties promote the cementation, reducing the pores between rock grains.

Figure 3. Evaluation of compaction and cementation of Upper Paleozoic tight sandstone in Shenfu block.

3.3. Accumulation periods of tight sandstone natural gas in the Upper Paleozoic

The determination of the time of oil and gas filling and accumulation is an important research field in petroleum geology. At present, organic fluid inclusions are commonly used to determine the age of oil and gas accumulation. Organic inclusions are fluid inclusions containing organic matter formed by the oil and gas fluids captured by larger particles from the reservoir during the diagenesis of the reservoirs in the petrolierous sedimentary basin. Therefore, the relative time of fluid activity and hydrocarbon accumulation, paleo-temperature, and geological structure environment information during accumulation can be provided.

According to the observation results of the core in the Shenfu block, fluid inclusions can be divided into three types according to the location where they occur. The first type is salt water inclusions, which are colorless under single polarized light. The second type contains a small amount of hydrocarbon inclusions. These hydrocarbon inclusions mainly exist on the secondary enlarged edge of quartz, which is irregular or elliptical. They are mostly 3-4μm, with less hydrocarbon content, generally around 2.5%~5.2%, and are colorless or light yellow under single polarized light. The third type of inclusions account for more than 65% of the samples, mainly in the micro-cracks of the quartz particles, followed by the quartz secondary enlarged edges and dissolved pores, which are distributed in regular strips. They are usually 3-6μm, and can reach 11-13μm, with a high hydrocarbon content. They show light brown under single polarized light, and blue white under fluorescence.
According to the statistical results of the uniform temperature of organic inclusions, the accumulation time of the Upper Paleozoic tight sandstone gas reservoirs in the Shenfu block was from the Late Jurassic to the Early Cretaceous, and the accumulation period was all after 152 Ma. The accumulation period is different. Because the lower gas reservoir Tai2 member is close to the coal-measure source rock, its accumulation time is the earliest, followed by the He8 member. The upper layer Qian5 member has the latest accumulation period.

The uniform temperature distribution range of Qian5 stage is between 71°C-205°C, and the main peak temperature is between 93°C-126°C, which can be divided into 98°C-108°C and 113°C-123°C. Combining the Tibetan history-heat history chart of the Shenfu block (Figure 4), the accumulation peaks of the Qian5 Member in the Shenfu area were 135~130 Ma and 127~120 Ma, and the Qian 5 Member accumulation time is mainly in the Early Cretaceous.

The uniform temperature distribution range of the eight stages of the He8 is between 82°C and 200°C, and the main peak temperature is between 88°C and 128°C, which can be specifically divided into 88°C to 108°C and 118°C to 128°C. Based on this, it is inferred that the formation temperature during the accumulation of the He8 member is mainly 88-1108°C and 118-128°C. Combining with the buried history-heat history chart of the Shenfu block (Figure 4), the main accumulation periods of the He8 Member were 152 Ma to 137 Ma and 128 Ma to 120 Ma.

The uniform temperature distribution range of Tai2 section is between 62°C and 192°C, and the main peak temperature is between 100°C and 130°C, which can be divided into 100°C to 110°C and 120°C to 130°C. Based on this, it is inferred that the formation temperature of the Tai2 Member in the Kangning area was mainly 100~130°C during the accumulation. Combining with the burial history-heat history chart of the Shenfu block (Figure 4), the peak of the gas reservoir formation in the Tai 2 Member was 152 Ma~127 Ma, which was similar to the formation time of the He8 Member.

4. Conclusion
(1) The porosity of the main sandstone section of the Upper Paleozoic is less than 10%, and the permeability is less than 1mD, which is a typical tight reservoir. The petrological characteristics of
Upper Paleozoic sandstone are mainly lithic feldspar sandstone and feldspar lithic sandstone, accompanied by a small amount of quartz sandstone. From the lower strata of the Benxi Formation to the Shiqianfeng Formation, the feldspar content increases slightly.

(2) On the basis of porosity evolution and restoration, combined with the uniform temperature of quartz secondary enlargement edge inclusions and the burial history-thermal history restoration results, it is concluded that the sandstone reservoirs in the Upper Paleozoic have been compacted for a time ranging from 225Ma to 200Ma which is the period of Middle and Late Triassic-Early Jurassic. The large-scale accumulation period of natural gas is between 155Ma and 122Ma, and the corresponding geological period is the Late Jurassic to the end of the Early Cretaceous.

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References
[1] Du, R., Wu, K., Li, Z., Yuan, S., Bing, Z. (2016) Thermal behavior and kinetic study on the pyrolysis of Shenfu coal by sectioning method. Journal of Thermal Analysis and Calorimetry. 125: 959–966.
[2] Chen, H., Yang, H., Ju, F., Jing, W., Zhang, S. (2007) The influence of pressure and temperature on coal pyrolysis/gasification. Asia-pacific Journal of Chemical Engineering. 2: 203–212.
[3] Tian, W., Li, A., Ren, X., Josephine, Y. (2018) The threshold pressure gradient effect in the tight sandstone gas reservoirs with high water saturation. Fuel. 226: 221–229.
[4] Yin, S.L., Cheng, L.L., Liu, Z.X., Chen, L., Luo, Y.C. (2018) Evaluation of production capacity to tight sandstone reservoir based on logging and mud logging curve. Natural Gas Geoscience. 29: 1627–1638.
[5] Nicolini, J.V., Ferraz, H.C., Borjes, C.P. (2017) Effect of seawater ionic composition modified by nanofiltration on enhanced oil recovery in Berea sandstone. Fuel. 203: 222-232.
[6] Soundharajan, B.S., Adeloye, A.J., Remesan, R. (2016) Evaluating the variability in surface water reservoir planning characteristics during climate change impacts assessment. Journal of Hydrology. 538: 625–639.
[7] Tsai, C.S., Lee, G.C., Ketter, R.L. (1990) A semi-analytical method for time-domain analyses of dam–reservoir interactions. International Journal for Numerical Methods in Engineering. 29: 913–933.
[8] Firoozabadi, A., Hekim, Y., Katz, D.L. (2010) Reservoir depletion calculations for gas condensates using extended analyses in the Peng-Robinson equation of state. Canadian Journal of Chemical Engineering. 56(5), 610-615.
[9] Tsai, C.S., Lee, G.C., Yeh, C.S. (1992) Time-domain analyses of three-dimensional dam-reservoir interactions by BEM and semi-analytical method. Engineering Analysis with Boundary Elements. 10: 107-118.