TIGHT SANDSTONE GAS RESERVOIRS (EXPLORATION) IN UPPER PALEOZOIC OF ORDOS BASIN

YANG Hua  FU JinHua  WEI XinShan REN JunFeng
(PetroChina Changqing Oilfield Company, Xi’an, 710018, China)

Key words: Ordos basin, Upper Paleozoic, Tight sand, Reservoir

1 Introduction
Over the past decade, in the Upper Paleozoic of Ordos basin, PetroChina Changqing Oilfield Company has been eye-catching for a large 100-billion-cubic-meters-level gasfield found every two years averagely. Especially in recent years, a situation of progressive incremental of 500 billion cubic meters natural gas reserves submitted annually has been formed in the Sulige exploration area. The rapid growth of proven gas reserves makes Sulige region become the first unitary large-scale natural gas district with trillion cubic meters in China [1-4]. The annual gas production from tight sandstone reservoirs reaches more than 10 billion cubic meters.

For tight sandstone gas reservoirs in Ordos basin, a number of scholars have been carried out a lot of discussion in the relevant literatures [5-34]. But most of them concentrated in the discussion of common features such as low porosity, low permeability, low abundance, low-pressure, no bottom-water, no edge-water etc., and less attention to the characteristics of their personality. At present, nearly 1000 wells are drilled through the Upper Paleozoic of the basin. Yulin, Zizhou and Sulige gas fields have been put into large-scale development one after another. In-depth exploration and development of Upper Palaeozoic tight sandstone gas reservoirs provides favorable conditions for revealing the characteristics and controlling factors of accumulation. Based on natural gas exploration and development practice and comprehensive geological study results of the basin’s Upper Paleozoic in recent years, the authors mainly discuss the geological features and unique reservoir controlling factors of this type of gas reservoirs in the paper, looking forward to improve constantly the geological theory of tight sandstone gas accumulation and to promote continuous deepening of exploring for such gas reservoirs.

2 Geological background
Located in the middle part of China’s mainland, the Ordos basin is the country’s second largest sedimentary basin covering a total area of $37 \times 10^4$
The basin has experienced five stages of evolution, that is, the Mid-Late Proterozoic aulacogen, Early Paleozoic shallow foreshore platform, Late Paleozoic coastal plain, Mesozoic inland basin, and Cenozoic faulting depressions surrounding the basin, as a large-scale natural gas-rich polycyclic superimposed basin. According to the characteristics of Mesozoic structures the basin can be divided into six first-level tectonic units of the Ih Ju Meng uplift, Ih Ju Meng - Shaanxi slope, Weibei uplift, western margin of thrust belt, Tianhuan depression, and Western Shanxi flexible fold belts, of which Ih Ju Meng - Shaanxi slope is a west-inclined gentle slope, with a formation dip of less than 1°, undeveloped structures. The slope is the main structural unit natural gas accumulated in the basin (Figure 1).

Proterozoic, Paleozoic, Mesozoic and Cenozoic sedimentary strata were developed in the basin from bottom to top. The average thickness of sedimentary rocks is 6000m, of which the Upper Paleozoic average thickness is 800 ~ 1000m, mainly including the gas-bearing strata intervals of Carboniferous Benxi Formation, Permian Taiyuan Formation, Shanxi Formation, Shihezi, and Shiqianfeng Formations (Figure 2).

3. Gas reservoir characteristics of Upper Paleozoic tight sandstone

3.1 Gas reservoirs are distributed in large-scale, with multiple gas-bearing series of strata.

The tight sandstone gas reservoirs of Upper Paleozoic are distributed in a large linked-up area. The six major gasfields of Yulin, Uxin Qi, Sulige, Zizhou, Mizhi, and Shenmu discovered in the Upper Paleozoic by Changqing Oilfield Company have a total gas-bearing area of 30 000 km², accounting for 1/4 of the area of Ih Ju Meng - Shaanxi slope. The

<table>
<thead>
<tr>
<th>Gas field</th>
<th>Series of strata</th>
<th>Gas layer thickness/m</th>
<th>Porosity/ %</th>
<th>Permeability</th>
<th>Reserves abundanc e</th>
<th>Pressure coefficient</th>
<th>Burial depth of gas layer</th>
<th>Natural productivity before acidization/fracturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulige</td>
<td>Permian Shan-1 Member, He-8 Member</td>
<td>8.2</td>
<td>9.8</td>
<td>0.774</td>
<td>1.10</td>
<td>Lower than 1.00, average 0.87</td>
<td>3250-3390</td>
<td>Industrial gas flow is hardly seen</td>
</tr>
<tr>
<td>Wushenqi</td>
<td>Permian He-8 Member</td>
<td>8.0</td>
<td>10.4</td>
<td>0.629</td>
<td>0.60-1.20</td>
<td>Lower than 1, average 0.85</td>
<td>3000-3300</td>
<td>Industrial gas flow is hardly seen</td>
</tr>
<tr>
<td>Yulin</td>
<td>Permian Shan-2 Member</td>
<td>8.9</td>
<td>6.5</td>
<td>2.050</td>
<td>0.60-1.20</td>
<td>0.93-0.98</td>
<td>2600-3100</td>
<td>0-20000</td>
</tr>
<tr>
<td>Zizhou</td>
<td>Permian Shan-2 Member</td>
<td>8.5</td>
<td>6.4</td>
<td>1.780</td>
<td>0.81</td>
<td>Lower than 0.10, average 0.95</td>
<td>2100-2600</td>
<td>Industrial gas flow is hardly seen</td>
</tr>
<tr>
<td>Shenmu</td>
<td>Permian Taiyun Formation</td>
<td>8.8</td>
<td>7.8</td>
<td>0.643</td>
<td>0.93</td>
<td>average 0.93</td>
<td>2500-2800</td>
<td>Industrial gas flow is hardly seen</td>
</tr>
</tbody>
</table>
gas-bearing area of the single gasfield exceeds 1000 km². Vertically, each porous thin bed of the entire Paleozoic profiles under the regional cap rock (Upper Shihaihezi Formation) contains gas. There were totally 11 gas bed sets developed from the Upper Carboniferous Benxi Formation of the lower part to the Upper Permian Shiqianfeng Formation. Therefore, the Upper Paleozoic of the northern basin is a huge and continuous gas-bearing aggregation, with vertical and horizontal characteristics performance of both large-scale distribution and multiple gas-bearing series of strata.

3.2 The reservoirs are mainly of low porosity and low permeability. Mid-coarse-grained quartz sandstone reservoirs have good capability of oil/gas reserving.

Upper Paleozoic gas-bearing sandstone takes quartz sandstone and lithic quartz sandstone as the dominated, locally arkose or feldspar sandstone (Figure 3). The average reservoir porosity is less than 8% in general, with the average permeability of less than 0.5 × 10⁻³ μm², but in the local reservoirs, the porosity usually ranges from 8% ~ 14% and the permeability 1 ~ 10 × 10⁻³ μm² (Table 1). It shows that the Upper Paleozoic reservoirs belong as a whole to a set of low porosity and low permeability reservoirs, but with relatively hypertonic local. Exploration and further researches show that such a relatively hypertonic area is generally located in the mid-coarse-grained quartz sandstone developed zones, namely, the type of mid-coarse-grained quartz sandstone is with good reservoir quality.

Two categories of quartz sandstone and lithic quartz sandstone are mainly developed in the mid-coarse-grained quartz sandstone reservoirs of the Upper Paleozoic of the basin. The quartz sandstone includes two types. One was those formed in the marine-facies deltaic sedimentary systems and developed in the Shan2 Member of the Shanxi Formation of Yulin and Zizhou gasfields, with mainly intergranular pores type, characterized by electrical properties of low natural gamma (≤ 35API), low transitional time (192 ~ 210 ms/m), low compensated neutron (≤ 6%), low Pe (≤ 1.8 b/e), high resistivity (100 ~ 1000 Ω.m), and the best reservoir properties; The other was those formed in the continental facies fluvial-lake shallow water deltaic depositional system and developed in He8 Member of Lower Shihaihezi Formation of Sulige, Uxin Qi gasfields, with mainly reservoir pore space of intergranular pores and dissolution pores, and the main electrical features of lower natural gamma (≤ 35 API), low-mid resistivity (40 ~ 80 Ω.m), mid-high interval transit time (220 ~ 240 μs/m), and reservoir properties the second place. Also the lithic quartz sandstone was formed respectively in marine deltaic depositional system and fluvial-lake shallow water deltaic depositional system, and developed in He8 Member of Taiyuan and Lower Shihaihezi Formations of Shenmu gasfield and Eastern District of Sulige gasfield, with dissolution pores as the main pore type, and the main electrical features of mid-high natural gamma (<55API), low-mid acoustic wave slowness (210 ~ 230 μs/m), low-mid compensated neutron (8~12 %), low-mid resistivity (30 ~ 80 Ωm), and relatively poor reservoir properties (Table 2, Figure 4, Figure 5).

### Table 2 Characteristic of Three Types of Quartz Sandstones of Upper Paleozoic in Ordos Basin

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Quartz (%)</th>
<th>Pore Structure</th>
<th>Logging characters</th>
<th>Sedimentary Facies</th>
<th>Permeability</th>
<th>Gas Fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz sandstone</td>
<td>&gt;90%</td>
<td>Mainly of intergranular pores</td>
<td>High resistivity, low interval transit time, low gamma ray</td>
<td>Marine-facies shallow deltaic</td>
<td>best</td>
<td>Yulin, Zizhou</td>
</tr>
<tr>
<td></td>
<td>&gt;90%</td>
<td>Mainly of dissolved pores, some of intergranular pores</td>
<td>Low resistivity, high interval transit time, low gamma ray</td>
<td>Fluvial deltaic facies shallow deltaic</td>
<td>better</td>
<td>Sulige, Wushenq lắp</td>
</tr>
<tr>
<td>Lithic quartz sandstone</td>
<td>&gt;75%</td>
<td>Mainly of dissolved pores</td>
<td>Low resistivity, high interval transit time, high gamma ray</td>
<td>Marine-facies shallow deltaic, fluvial deltaic facies shallow deltaic</td>
<td>bad</td>
<td>Shenmu, Eastern Sulige</td>
</tr>
</tbody>
</table>

3.3 The vertical superimposition relationship of gas reservoirs and source rocks
According to source rocks and gas reservoirs distribution relationship, gas migration and accumulation of Upper Paleozoic tight sand gas reservoirs can be further divided into three types: within source rocks, above source rocks, and far from source rocks (Figure 6).

To the type within source rocks, the relationship of gas reservoirs and source rocks is interbedded superimposition, with competent gas injection and sufficient hydrocarbon supply, so gas saturation is high, generally over 70%, such as Benxi Formation, Taiyuan Formation in Shenmu gas field, and S2 of Shanxi Formation in Shenmu gas field. To the type above source rocks, gas reservoirs are on the top of coal source rocks, and vertical distance is less than 55m, so that the vertical distance of gas migration and accumulation is close, hydrocarbon supply relatively is sufficient, and gas saturation relatively is...
high, generally 65 – 70 °, such as H8 of Shanxi Formation and S1 of Shanxi Formation in Sulige and Shenmu gas field. To the type far from source rocks, gas reservoirs are on source rocks, with relatively long vertical distance. This kind of gas reservoirs generally develop within the regional cover, with small scale and low gas saturation, such as Shihezi Formation top, and Shiqianfeng Formation.

3.4 Gas reservoirs are mainly large-scale lithologic trap, with indistinct trap boundaries and continuous gas reservoirs characteristics

Upper Paleozoic tight sandstone gas reservoirs are distributed in a large area with continuous gas reservoirs characteristics. First of all, gas-bearing sand body is interconnected, and a number of gas reservoirs exist in this region. This has been confirmed by gas reservoirs development, with 800m development well spacing. But in the current technical conditions, this kind of gas reservoirs boundary is difficult to determine, and the submitted reserve is generally determined by artificial-calculated boundary, which shows that continuous oil and gas reservoirs have no distinct trap boundary. In addition, in gas bearing area, specific well producing water indicates part of the region contains water, but it has no clear gas-water interface. While, it has “water-in-gas” gas-water horizontal distribution pattern.

3.5 Atmospheric pressure, low pressure, high pressure gas coexistence

By computationally analyzing the measured data of formation hydrostatic pressure, formation temperature, and other parameters, the pressure coefficient 0.95 should be the lower limit of Upper Paleozoic normal pressure. Therefore, in Ordos Basin, the Upper Paleozoic pressure coefficient 0.95 ~ 1.05 is the normal pressure, below 0.95 for low pressure, and up 1.05 for high pressure. For 33 wells in Sulige gas field, the main gas bearing formation pressure coefficients are from 0. 69 to 0. 98, with an average of 0. 87, belonging to low pressure reservoirs. For 24 wells in Yulin gas field, the main gas bearing formation pressure coefficients are from 0. 95 to 1. 02, with an average of 0. 99, belonging to atmosphere pressure reservoirs. While for other 9 wells, such as Yu4 of Mizhi gas field, the main gas bearing formation pressure coefficients are from 1. 05 to 1. 16, showing some gas reservoirs have high pressure characteristics (Table 1).

4 The formation of tight sandstone gas reservoirs

4.1 Large-scale hydrocarbon generation of coal-measure source rocks, with vertical migration and accumulation

4.1.1 Large-scale distribution and hydrocarbon generation of coal bed and carbon-bearing mudstone

Coal was steadily generated with large scale in the special paleogeographic background of epicontinental marine basin in Upper Paleozoic. Drilling and seismic data reveal that coal develops in 92% area (major in Benxi, Taiyuan and Shanxi Formation) of present-day basin with 10 ~ 30m totalized thickness, and the organic carbon content as high as 70.8% ~ 83.2%. Dark mudstone is also widely distributed in the whole basin, with thickness of about 50m, and the organic carbon content of 2.0% ~ 3.0%. Cover depth of coal strata source rocks reached the maximum in the Early Cretaceous(Figure 7), and large-scale source rocks were in the evolution phase form maturation to post-maturation, under the co-action of abnormal thermal events. Of mature source rocks is greater than 1.2%, with an area of 18×10⁶ m³/km², occupying...
72% of present-day basin. The performance of hydrocarbon source rocks with large-scale distribution, large-sized mature, and large-sized hydrocarbon generation (Figure 8), laid the material foundation of Upper Paleozoic gas reservoirs formation.

4.1.2 Migration and accumulation of natural gas are mainly vertical in close distance.

Studies show that formation process of Upper Paleozoic tight sandstone gas reservoirs, may not be a large-scale lateral migration, but vertical migration and accumulation in short distance.\(^{[43-52]}\) (Figure 6). The main bases are followed below. First, in the Upper Paleozoic 16 formations, gas bearing formation and gas-bearing bed are discovered at the moment. At the same level of evolution of source rock area, methane content increases along the vertical migratory direction, and methane isotope \(\delta^{13}C_1\) becomes light. Secondly, natural gas composition in the gas bearing formation is mainly affected by the maturity of near source rocks. In gas bearing formation, for some south region in which \(R_o\) is over 2.0\(^{\circ}\), its methane content will reach 99.5\(^{\circ}\). While for some north region in which \(R_o\) is less than 1.2\(^{\circ}\), its methane content only has about 90\(^{\circ}\). Methane isotope content distribution manifests low-South (\(\delta^{13}C_1\: -28\%) and high-North (\(\delta^{13}C_1\: -32\%\) pattern. This illustrates the lateral migration distance of natural gas is short, and north-toward-south river deltaic deposit sand zone develops in the Upper Paleozoic of the basin. Mudstone or siltstone distributes between the zones, becoming lateral barrier so that this phenomenon inhibits the upward large-scale lateral migration of
natural gas in the east-west direction.

4.2 Hydrocarbon-bearing intensity dominates gas boundary.

4.2.1 Tight sand gas reservoirs development with low hydrocarbon-bearing intensity

According to Chinese scholars’ study on hydrocarbon-bearing intensity of big-and-middle-scale gas fields, these fields are ordinarily located in the regions where hydrocarbon-bearing intensity is above $20 \times 10^8$ m$^3$/km$^2$. But exploration in Ordos basin proves that large-scale gas reservoirs are still distributed in the regions where hydrocarbon-bearing intensity is $14 \times 10^8$ m$^3$/km$^2$. So tight sand gas reservoirs with low permeability, low abundance and large scale can develop with low hydrocarbon-bearing intensity, and the boundary of hydrocarbon-bearing intensity being in the range of $14 \times 10^8$ m$^3$/km$^2$. For the region below $14 \times 10^8$ m$^3$/km$^2$, gas-water commixture region forms in the neighborhood, while part of it forms gas-in-water distribution pattern.

4.2.2 The distance between source rocks and gas reservoir determines the degree of enrichment of gas reservoirs

The vertical contrast analysis of the gas reservoir showed that, due to directly being inside the coal-bearing series of Carboniferous - Permian source rock, the Carboniferous Benxi Formation - Taiyuan Formation - Shanxi Formation in the mid-lower parts of the Upper Paleozoic assume a state of alternating beds with the source rock, having sufficient gas sources. Additionally marine-transitional facies quartzose sandstone reservoirs were developed there, gas saturation of the strata was evidently higher than that of the other strata; while the gas saturation of upper Shihhezi Formation and Shiqianfeng Formation gas reservoirs on the top of the source rock was relatively low. The configuration relationship between gas reservoirs and source rocks directly determines the degree of gas enrichment (Figure 6).

4.3 The large-scaled linked-up reservoir sandbody formed by large-scale shallow-water delta deposits

Sedimentary characteristics analysis shows that typical shallow-water delta deposits were developed in the Upper Paleozoic, due to the flat basin basement in Late Paleozoic and continuing uplift of the source area in northern basin [53,54]. The reservoir sand bodies distributed in a large area are favorite place to the development of tight sandstone gas reservoirs (Figure 9, Figure 10).

4.3.1 The shallow-water delta sand body distributed in large-area and multiple strata

The sedimentary evolution of Upper Paleozoic of the basin is quite regular. From the Carboniferous Benxi Formation to Permian Shiqianfeng Formation, the sedimentary evolution experienced a course of shallow continental shelf - barrier coast - Delta - shallow lake and fluvial delta facies, developed large-area distribution and reservoir sand bodies of multi-type genesis. And the large-area distribution of sand bodies has been confirmed by drilling. Taking the He8 Member of Lower Shihhezi Formation as an example, based on statistics from 234 exploratory wells, the probability of penetration of sandbodies is 92%, and probability of penetration of gas reservoirs is 65%. Probability of penetration of sandbodies in Sulige area is more than 95%, and so is the probability of penetration of gas reservoirs.

4.3.2 High-energy facies belts and constructive diagenetic facies co-act to form "dessert" of relative hypertonic districts
Comprehensive geologic study and analysis show that, during the fluvial-delta deposition, rock composition of different sedimentary facies belts has significant differences, because of differences in hydrodynamic conditions. And it further affects the late diagenetic evolution and characteristics of porosity development. A corresponding relationship can be established between them. The main distributary channel sand body was mainly composed of mid-coarse-grained quartz sandstone, with the strongest hydrodynamic conditions, and good sorting of rock, high content of rigid particles of quartz, and increased anti-compaction. This was conducive to preservation of primary porosity, pore fluid activities and the formation of secondary pores. The dissolution diagenetic facies are mainly formed, with main pore type of intergranular and dissolution pores, and a good capability of reservoir. It generally can form a local "dessert" of relative high permeability district. Due to the weakening of hydrodynamic conditions, the edge parts of the two channels and the natural levee sites take generally fine-grains as the dominant, with sorting deteriorated, and increased content of soft components like debris. In the course of the late diagenetic evolution, the reservoirs are easily compacted and become dense, with primary pores compacted out basically. Furthermore, the tight reservoirs are not conducive to the pore fluid activities and the formation of secondary dissolution porosity. Diagenetic facies take alteration and compaction as the dominant. Reservoir properties were gradually deteriorated.

### 4.4 Excellent preservation conditions

#### 4.4.1 Upper Shihezi Formation regional caprock with good sealing conditions

The lacustrine mudstone of Upper Shihezi Formation developed above the major gas layers of Upper Paleozoic was the regional caprock of Upper Paleozoic. This set of mudstone is distributed continuously in the whole basin, with thickness of 80 m–110 m. The average permeability of mudstone or sandy mudstone is between $10^{-10}$ and $10^{-8}$ µm$^2$, the breakthrough pressure is higher than 5 MPa, so the regional cap rock provides good sealing condition for conservation of large-scale lithologic gas reservoir.

#### 4.4.2 The stability of Cratonic block guarantees the late preservation of gas reservoirs

Destruction in the late stage was the prominent problem of continental facies oil and gas reservoirs in China [55-59]. However, the stability of craton during late evolution on Yi-Shaan slope of Ordos Basin avoids such a problem effectively, which is featured by weak magmation and steady structure and dominated by overall uplift and subsidence. Therefore, the present monocline structure with flat formation and strata dip lower than 1° was formed, providing good conservation condition for large-scale lithologic gas reservoir.

### 5 Conclusions

Upper Paleozoic of Ordos Basin develops large-scale, multi-series strata distribution of the tight sandstone gas reservoirs, with the characteristics of continuity. Exploration and geological research show that the control factors of the Upper Paleozoic formation of tight sandstone gas reservoirs include: large-scale distribution of the coal-bearing source rocks in large areas of hydrocarbon generation, and vertical migration and accumulation: large-scale sandbody of shallow-water delta deposits provided favorable natural gas gathering places for tight sandstone gas reservoirs; hydrocarbon generating intensity...
controlled the enrichment of the tight gas reservoir; a good seal of regional cap, and reservoir densification, as well as the stability of cratonic basin ensured the preservation of gas reservoir.

The exploration and development of tight sandstone gas reservoirs are difficult, but after a long-term exploration and development, Changqing Oilfield Company has formed a set of tight sandstone gas reservoir exploration technology and methods in Upper Paleozoic of Ordos Basin, mainly including high-resolution the rate of two-dimensional seismic prestack sandbody prediction, seismic prestack gas detection technology, logging of lithology recognition technology as well as the multi-line multi-layered fracturing technology for tight reservoirs. For this type of gas reservoirs exploration, we should use "the overall study, development, and evaluation, as well as the implementation of step-by-step" to construct Ordos Basin into a base of tight sandstone gas reservoir exploration and development.

Acknowledgements:
We show our sincere thanks to Mr. LIU XinSheng, ZHAO HuiTao, ZHAO TaiPing and Ms. WANG Xin, ZHAN Sha, for their helpful materials and graphics.

References:
[32] Li Zhenduo et al, A study of the Deep basin gas in the
upper Paleozoic in Ordos basin.[J], Natural Gas Industry, 1998; 18(3):10-17

[33] Li Zhenduo et al., The study and practice of deep basin gas in Ordos basin., The study of deep basin gas in Ordos basin [M]. Beijing Petroleum Industry Press,2001

[34] Li Xizhe et al., Distribution of gas and water of deep basin gas reservoir in upper Paleozoic of Ordos basin., The study of deep basin gas in Ordos basin [M]. Beijing Petroleum Industry Press, 2001


[46] Zhao Lin,Xia Xinyu,Dai Jinxin, Migration and accumulation of natural gas in Upper Paleozoic in Ordos basin [J], Geology-Geochemistry,2000,28(3):48-53


