Discovery and reservoir-forming geological characteristics of the Shenmu Gas Field in the Ordos Basin

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Abstract

By the end of 2014, the giant Shenmu Gas Field had been found in the Ordos Basin with an explored gas-bearing area of 4069 km\(^2\) and the proved geological gas reserves of 333.4 billion m\(^3\). This paper aims to review the exploration history of this field and discusses its reservoir-forming mechanism and geological characteristics, which may guide the further discovery and exploration of such similar gas fields in this basin and other basins. The following research findings were concluded. (1) There are typical tight sand gas reservoirs in this field primarily with the pay zones of the Upper Paleozoic Taiyuan Fm, and secondly with those of the Shanxi and Shihezi Fms. (2) Gas types are dominated by coal gas with an average methane content of 88% and no \(\text{H}_2\text{S}\) content. (3) The gas reservoirs were buried 1700\(-2800 \text{ m beneath with multiple pressure systems and an average pressure coefficient of 0.87. (4) The reservoir strata are composed of fluvial delta facies sandstones with an average porosity of 7.8% and permeability of 0.63 mD, having high pressure sensibility and a strong water-locking effect because the pore throat radius are mostly less than 1 \(\mu\)m. (5) There are different dynamics at various stages in the gas reservoir-forming process. The abnormal well-developed strata pressure was the main reservoir-forming force at the Early Cretaceous setting stage while the fluid expansibility became the main gas-migrating force at the uplift and denudation stage after the Early Cretaceous period. (6) Gas reservoirs with ultra-low water saturation are mainly controlled by many factors such as changes of high temperature and high pressure fields in the Late Jurassic and Early Cretaceous periods, the charging of dry gas at the highly-mature stage, and the gas escape and dissipation at the post-reservoir-forming periods. (7) Natural gas migrated and accumulated vertically in a shortcutting path to form gas reservoirs. At such areas near the source rocks, large-scale gas reservoirs were easily found with plenty of gas sources and high gas saturation; but at those far from the source rocks, relatively small-scale and mostly secondary gas reservoirs were discovered.

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Keywords: Ordos Basin; Shenmu Gas Field; Late Paleozoic; Tight sand gas reservoir; Coal gas; Gas reservoir characteristic; Reservoir-forming mechanism

According to the \textit{China Energy} published on April 20, 2015, the proved oil and gas reserves of China kept rapid increase in 2014 to a new record, with newly increased oil reserves of 10.61 \times 10^8 \text{ t and newly increased gas reserves of 1.1 \times 10^{12}\text{ m}^3. The proved gas reserves have maintained the growth momentum since the “10th Five-year Plan”, with newly increased gas reserves of 9437.72 \times 10^8 \text{ m}^3, an increase of 53% year on year, and newly increased proved recoverable gas reserves of 4749.56 \times 10^8 \text{ m}^3. There are five giant gas fields with newly increased reserves of over 1000 \times 10^8 \text{ m}^3, among which, the Shennu Gas Field in the Ordos Basin is the largest, with newly increased gas reserves of over 2000 \times 10^8 \text{ m}^3. In this paper, the exploration history, gas reservoir geological characteristics and gas reservoir-forming mechanism of Shennu Gas Field are systematically summarized, in the hope to provide guidance for the exploration of gas in this basin and similar gas reservoirs in other basins.

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1. Discovery and exploration history of the Shenmu Gas Field

Located in Yuyang District and Shenmu Country, Yunlin City, Shaanxi Province, the Shenmu Gas Field borders Yulin, Daniudi, Zizhou and Mizhi Gas Fields (Fig. 1), with an exploration area of $2.5 \times 10^4$ km$^2$. Structurally, this gas field is located in the secondary structural unit, northeastern Yishan Slope, in the Ordos Basin, and its structural form is a gentle west-dipping slope, with a gradient of 6–10 m/km and dip angle of less than 1°. On the monoclinic background, there are multiple rows of low and gentle nose uplifts of NE-trending, with an amplitude of about 10 m, width of 4–5 km and length of 25–30 km. The Upper Paleozoic Carboniferous – Permian system, a set of marine-terrigenous coal-bearing strata, includes Benxi Fm (C$_2$b), Taiyuan Fm (P$_1$t), Shanxi Fm (P$_1$s), Shihezi Fm (P$_2$sh) and Shiqianfeng Fm (P$_3$q) (Fig. 1) from bottom to top.

![Fig. 1. Geographic location, gas reservoir profile and composite stratigraphic column of the Shenmu Gas Field.](image-url)
The major gas reservoirs in the Shenmu Gas Field are giant tight sandstone gas reservoirs with low production rate, ultra-low abundance and moderate buried depth. Up to now, this gas field has proved gas geological reserves of $3334 \times 10^8$ m$^3$ and gas-bearing area of 4069 km$^2$; and its major pay zone is the Upper Paleozoic Permian Taiyuan Fm, followed by Shanxi Fm and Shihzei Fm, with individual gas layer thickness of 5—10 m and cumulative gas layer thickness of 10—20 m (Fig. 1).

1.1. Early exploration in the surrounding area

In the 1980s, under the guidance of the coal-derived gas theory, the natural gas exploration targets in the Ordos Basin shifted to structural-lithological and stratigraphic traps from structural traps, and the exploration domain turned from the margin to the heart of the basin. In 1987, Well Zhenchuan2 revealed a gas flow of $1.14 \times 10^4$ m$^3$/d in the sandstone of Shihezi Fm during well testing, leading to the discovery of Mizi Gas Field; and gas layers were also discovered in the sandstone and limestone of Taiyuan Fm in some wells [1].

In the 1990s, along with the expanding exploration in the basin, the Upper Paleozoic gas exploration theory was gradually improved. Based on the recognition that the Upper Paleozoic source rocks are vast in gas generation and supply areas, and the Upper Paleozoic gas reservoirs are predominantly controlled by the distribution of fluvial-deltaic sands of Shanxi Fm and Shihezi Fm, large-scale exploration was performed, resulting in the discovery of Yulin Gas Field. In 1996, Well Shan 201 tapped a commercial gas flow of $2.69 \times 10^4$ m$^3$/d through gas test in the sandstone of Taiyuan Fm, revealing that Taiyuan Fm contained gas. Thus, the geological study and seismic sandstone reservoir prediction technology for the gas reservoirs of Taiyuan Fm got started.

However, restricted by geological recognition and technologies at that time, only a few sporadic exploration wells in the Shenmu Gas Field drilled the gas layer of Taiyuan Fm, and no natural gas exploration breakthrough was made due to the limited gas reservoir distribution and low gas test production of individual wells.

1.2. Discovery of the Shenmu Gas Field

The discovery of Yulin Gas Field revealed the huge potential in the Upper Paleozoic of the Ordos Basin, extended the exploration idea, and motivated gas explorers to start systematic study on the accumulation pattern of the Upper Paleozoic sandstone gas pools in the basin. In 2003, in the expanding exploration to both sides of the Yulin Gas Field, Well Shuang 3 encountered 11.9 m gas layers in the sandstone of Taiyuan Fm, and produced a commercial gas flow of $2.54 \times 10^4$ m$^3$/d, revealing good gas potential of Taiyuan Fm in this area. The study results showed that Taiyuan Fm is mainly marine shallow deltaic depositional system, with distributary channel sands as major reservoirs; coal-measure source rocks and sandstone reservoirs laminated, forming source-reservoir in one assemblage, and having favorable geological conditions for the formation of large-scale lithological gas reservoirs. Based on the recognition above and further exploration, the gas-bearing sands of Taiyuan Fm in Wellblock Shuang 3 were found to be characterized by stable distribution, good gas potential and high production rate, laying solid foundation for expanded exploration [2].

Based on the previous study on the distribution features of the sandstone reservoirs of Taiyuan Fm and the natural gas migration and accumulation rules, systematic evaluation and exploration of Wellblock Shuang 3 were carried out to confirm the gas-bearing area, then, a significant breakthrough was made: $934.99 \times 10^8$ m$^3$ proved gas geological reserves were submitted in 2007 and the Shenmu Gas Field was discovered.

1.3. Scale exploration of the Shenmu Gas Field

The discovery of the Shenmu Gas Field reveals the great gas potential in tight sandstone in this area, accelerating the exploration of the entire area. However, the subsequent exploration did not go smoothly and a number of exploration problems emerged gradually: ① the sandstone reservoirs of Taiyuan Fm are missing in some exploration wells, making it difficult to find out the reservoir distribution rule; ② except for Taiyuan Fm, other gas-bearing layers are to be confirmed in gas enrichment rules; ③ since the reservoirs are tight sandstone, the formation mechanisms of sensitivity, such as stress, and protection measures need to be further investigated; ④ the tested gas production of individual wells and individual layers is generally between $1 \times 10^4—2 \times 10^4$ m$^3$/d, therefore, how to improve the production of individual wells and individual layers and the producing degree of multiple layer series is another question. The problems above hindered the natural gas exploration pace, making the exploration sink into standstill time and again.

In order to solve the problems above, explorers initiated a new round of comprehensive study and technological research. Firstly, the Upper Paleozoic sedimentary system is studied. Through the gradual improvement of the transgressive shallow water delta depositional model of Taiyuan Fm, and strengthening research on sandstone reservoir seismic prediction technology, the sandstone reservoir distribution rule of Taiyuan Fm has been figured out. It has been clarified that the Shenmu area is developed in distributary channel sands stable in distribution. Thus, the exploration idea for Taiyuan Fm of taking Wellblock Shuang 3 as center, confirming the reserves scale northeastwards and enlarging the gas-bearing area southwards has been determined, pointing out a clear direction for future exploration. Secondly, the Upper Paleozoic natural gas migration and accumulation mechanisms are investigated. Through the construction of the multilayer composite reservoir-forming model, it is pointed out that there are 3 sets of gas-bearing assemblages in Upper Paleozoic, namely, in source, near source and far-source gas-bearing assemblages, and that the Shihezi Fm, Shanxi Fm and Benxi Fm in the area have favorable geological conditions for forming large-scale lithological gas reservoirs too. Thus, multilayer stereoscopic exploration idea should be adhered to. Thirdly, the features of tight sandstone reservoirs and the formation mechanisms of
stress, mineral sensitivity and water-locking are actively investigated. The in-depth study on waterless cement slurry system and low-damage fracturing fluid technology has lowered the damage to reservoirs and effectively protected the reservoirs, which laid a foundation for individual well production increase. Fourthly, in-depth study is conducted on reservoir fracturing and stimulation technology aiming at “enhancing individual layer production and producing degree of multilayers”, which resulted in the emergence of casing sleeve continuous separate layer fracturing (TAP) and mechanical packer continuous separate layer fracturing, and in turn the increase of individual layer production and multilayer producing degree, which provides technical support for the scale exploration of this gas field.

On the basis of geological studies and technical research, the multilayer stereoscopic exploration and overall exploration of Shenmu Gas Field have been strengthened, resulting in the constant confirmation and enlargement of composite gas-bearing area. In 2014, the newly increased proved geological reserves of Taiyuan Fm and Shanxi Fm were 2398.90 × 10⁸ m³, and major exploration breakthroughs were made in Shihezi Fm and Benxi Fm, proving over 5000 km² of gas-bearing area, pointing out direction for continuously expanding proved reserves scale of the gas field.

During this stage, a series of problems encountered during scale exploration of the area, such as reservoir tightness, reservoir susceptible to damage, and low test gas production of individual layers. These problems have been solved through the comprehensive study and exploration technological research, paving the way for scale exploration and propelling new exploration breakthroughs in the Shenmu Gas Field.

By the end of 2014, Shenmu, Zizhou and Mizhi Gas Fields in the eastern Ordos Basin had delivered cumulative proved gas geological reserves of 4844 × 10⁸ m³, probable reserves of 1880 × 10⁸ m³ and possible reserves of 3905 × 10⁸ m³, which were about 1.0629 × 10¹² m³ in total, forming another new giant gas province of trillion cubic meters after the Sulige Gas Field. Among them, the Shenmu Gas Field has become a new super-giant gas field of hundred billion cubic meters, with established productivity of 20.5 × 10³ m³/a at present. Its discovery is a major breakthrough in tight sandstone exploration in China, which has provided valuable experience for the exploration of gas reservoirs of the same type.

2. Gas reservoir geological features

2.1. Geochemical features

2.1.1. Features of gas composition

The composition analysis results of the Shenmu Gas Field (Table 1) show that the Upper Paleozoic natural gas is composed of hydrocarbon gas (C₁–C₄) and non-hydrocarbon gas (N₂ and CO₂), free of H₂S. Hydrocarbon gas, the main component of the natural gas in this field, accounts for 89%—99%, 96% on average. Moreover, hydrocarbon composition is characterized by a high methane content of 80%—95%, 88% on average, heavy hydrocarbon (C₂) content of 3%—17%, 8% on average, and drying
coefficient of 83%—97%, 92% on average. So, the gas is mainly dry gas, with a small amount of wet gas. Non-hydrocarbon gas has a content of 1%—11%, averagely 4.1%, in which N₂ has a content of less than 11%, averaging at 2.9%, and CO₂ has a content of less than 3%, averaging at 1.1% (Table 1).

2.1.2. Carbon isotopic features of natural gas

The Upper Paleozoic natural gas of the Shenmu Gas Field has the geochemical features of coal-bed gas, with δ¹³C₁ of −40.70‰ to −34.57‰, −37.15‰ on average, δ¹⁴C₂ of −26.44‰ to −21.96‰, −24.34‰ on average, and δ¹³C₃ of −25.07‰ to −19.01‰, −22.75‰ on average [3,4]. The carbon isotopic features of methane gas reflect that the Upper Paleozoic natural gas is of homology, with the same source rocks of the coal measure strata of Benxi Fm, Shanxi Fm and Paleozoic natural gas is of homology, with the same source rocks of the coal measure strata of Benxi Fm, Shanxi Fm and Taiyuan Fm. Occurring in all these coal measure strata, coal beds are 8—10 m thick in individual layer, pervasive, and thickening southwards; the coal and dark mudstone here mainly contain humic kerogen with high organic maturity; the coal has a high TOC content of up to 62.9%, while mudstone has a TOC content of 2.09—2.33%. Studies indicate that, located in the eastern Ordos Basin, source rocks in the Shenmu Gas Field feature extensive and broad hydrocarbon generation, with a hydrocarbon-generating strength of 28 × 10⁸—35 × 10⁸ m³ and cumulative expulsion strength of 24 × 10⁶—30 × 10⁶ m³/km² [5], providing sufficient gas source for the formation of the Shenmu Gas Field.

2.2. Features of deposition and sand distribution

Affected by tectonic subsidence, sea level changes, sediment supply and other factors, the Late Paleozoic in the Ordos Basin has various types of sedimentary facies and assemblages [6—9]. The depositional system of the Shenmu Gas Field experienced the evolution from marine lagoon-tidal flat to continental fluvial-deltic facies (Fig. 1), forming pervasive fluvial-deltic reservoir sands (Fig. 2).

During the Late Carboniferous Benxi Age, the eastern Ordos Basin took on a depositional pattern of barrier bar-lagoon-shallow water delta-meandering river, with deltaic plains and front distributary channel sands; trending nearly north—south. The basin was in fluvial-deltic-epicontinental paleogeomorphology (high in the north and low in the south) and extending length of over 100 km. During the Shan 1 Age, the sediment transited to continental delta-lake facies, with developed distributary channel sands.

During the early Middle Permian, along with the gradual closing of Xingmeng Trough, intense differential subsidence of N—S trending occurred, and the structural pattern of uplift in the north and dipping in the south was enhanced; paleoclimate turned arid to semi-arid as seawater withdrew from this region. The basin was in alluvial plain-delta-lake depositional environment from north to south, depositing a set of thick clastic rock buildup dominated by coarse sandstone, in which the sandstone was most developed in He8 Member. The He8 Member in the Shenmu area was dominated by delta plains and front distributary channel sands; trending nearly N—S, 5—15 km wide, 15—30 m thick, and over 200 km long, the sands superimpose vertically and connect into large pieces in plane.

2.3. Reservoir features

2.3.1. Reservoir petrologic features

According to core observation and thin section analysis results, the Upper Paleozoic sandstone in the Shenmu Gas Field is dominated by lithic sandstone and lithic quartz sandstone, followed by quartz sandstone. With moderate-coarse, coarse grain structure, the sandstone is between 0.3 and 1.5 mm in grain size, moderately sorted, subrounded-subangular and subangular, and pore-typed in cementation. Clastic components are dominated by quartz, followed by debris, and minor feldspar (less than 1% on average). Debris is dominated by metamorphic debris, followed by volcanic rock debris and sedimentary debris. Metamorphic debris mainly consists of phyllite followed by metamorphic sandstone. Fillings are dominated by illite. Pores are dominated by dissolved pores, followed by intergranular pores.

2.3.2. Reservoir petrophysical features

The Upper Paleozoic Taiyuan-Shihezi Fm reservoirs in the Shenmu Gas Field have a porosity of 4%—10%, 7.8% on average, permeability of 0.1—1.0 mD, 0.63 mD on average, representing ultra-low porosity and low-permeability tight sandstone reservoirs with strong stress sensitivity. The pore throats of tight sandstone reservoirs are apt to close under overburden stress, resulting in significant reduction in pore throat radius and reservoir permeability [10,11]. The reservoir overburden pressure analysis of the Shenmu Gas Field shows that the larger the overburden pressure, the larger the decrease of permeability, and the smaller the normal pressure permeability, the stronger the stress sensitivity (Fig. 3-a). Under the overburden pressure of 25 MPa, the quartz sandstone samples as seawater gradually withdrew from north to south. During the Shan 2 Age, regression deltic depositional system developed in the basin, with delta plain facies distributed to the north of Hengshan-Yulin and delta front facies distributed in the south of Hengshan-Yulin. The distributary channel sands in the Shenmu area were in nearly NW—SE trending strips, generally with width of less than 15 km, thickness of 10—20 m and extending length of over 100 km. During the Shan 1 Age, the sediment transited to continental delta-lake facies, with developed distributary channel sands.
with normal pressure permeability of over 1 mD had an overburden pressure permeability decrease of 68—77%, 72.6% on average, while the quartz sandstone samples with normal pressure permeability of less than 1 mD had an overburden pressure permeability decrease of 68—86%, 77.5% on average. The water-bearing overburden pressure analysis of tight sandstone indicates the larger the water saturation, the larger the decrease of reservoir permeability, and the stronger the stress sensitivity (Fig. 3-b). For example, for the lithic sandstone samples with permeability of 0.09 mD, under 35 MPa overburden pressure, dry samples had an overburden permeability of only 0.008 mD, 8.69% of that under normal pressure; when water saturation was 23%, its overburden permeability was only 0.0001 mD, 0.11% of that under normal pressure; when water saturation was 51%, overburden permeability was only 0.00001 mD, 0.01% of that under normal pressure. Thus, it can be concluded that the overburden permeability of dry samples is 780 times that of the samples with water saturation of 51%.

2.3.3. Features of reservoir pore structure
High-pressure mercury test shows that reservoirs in the Shenmu Gas Field have an average pore radius of 0.33—1.18 μm, median radius of 0.12—0.56 μm, displacement Fig. 2. Planner distribution of sand thickness of the Upper Paleozoic major reservoir intervals in the Shenmu area.
2.3.4. Reservoir water locking damage

During the exploration and development of gas layers, the external fluids, such as drilling fluid, and fracturing fluid, would invade into reservoirs, resulting in the rise of reservoir water saturation and fall of gas permeability, which is the so-called water locking damage [12]. The permeability damage resulted from water locking is generally evaluated by water locking index (Table 2). In the eastern Ordos Basin, the average water locking index of the He 8 Member, Taiyuan Fm, and Shan 2 Member sandstones are 69.4%, 63.2%, and 57.2% respectively, indicating that the water locking degree is moderate-strong and the reservoir water locking damage is strong in general. On the other hand, the Shennu Gas Field shows strong permanent water locking damage, with the permanent water locking permeability damage rate of 26.6% at minimum, 62.3% at maximum and 39.4% on average; gas phase permeability at original water saturation is 1.4—2.7 times that at irreducible water saturation, 1.7 times on average. Therefore, preventing and removing permanent water locking damage and recovering the gas phase permeability at original water saturation are of great significance for enhancing the gas phase permeability of the reservoirs at the same petrophysical conditions and individual well production.

2.4. Features of temperature and pressure

The pressure test results of 51 well layers in the Shennu Gas Field show that the pressure in the middle part of Upper Paleozoic gas layer in individual wells is generally 19.0—23.2 MPa, or averagely 21.6 MPa. With widely-changing pressure coefficient and an average pressure coefficient of 0.87, the gas reservoirs cover low pressure, normal pressure and high pressure ones; low pressure gas reservoirs account for 60.8% and normal pressure gas reservoirs account for 19.6%, thus, low-pressure gas reservoirs are the majority. The pressure-depth relation map shows that the data points are scattered, reflecting that reservoir pressure systems are complex, and multiple, and the gas reservoirs are poorly connected with each other (Fig. 6).

The Upper Paleozoic gas reservoirs in the Shennu Gas Field are generally buried at a shallow depth of 1700—2800 m; the temperature in the middle part of the gas layers ranges at 62.1—98.2 °C, or averagely 74.7 °C; the geothermal gradient ranges at 2.63—3.34 °C/100 m, or averagely 2.85 °C/100 m.
3. Natural gas accumulation mechanism

3.1. Dynamic evolution of natural gas accumulation

The dynamic evolution of the Shenmu Gas Field can be divided into three phases: the abnormal pressure in Early Cretaceous subsidence phase, the gas expansion force in Late Cretaceous-Early Miocene tectonic uplift phase and the buoyancy since the early Miocene.

3.1.1. Abnormal pressure in subsidence phase

During Early Cretaceous, the Ordos Basin had a subsidence of over 1600 m and subsidence rate of 30–50 m/Ma [13]. By the end of Early Cretaceous, the buried depth of the basin had reached the maximum in the geological history, the tectonic-thermal events had resulted in an abnormally-high geothermal field with a geothermal gradient of 3.3–4.5 °C/100 m [14,15], and the source rocks had entered the peak of hydrocarbon generation and expulsion. Buried deep, the source rocks were very low in porosity and permeability, and little in rock compressibility, so fluid was difficult to discharge, thus, making abnormal pressure likely to occur [16,17]. Well logs of more than 70 wells were collected, based on which, the overpressure profile of Early Cretaceous end (the period when the buried depth was the maximum) was drawn through calculation (Fig. 7). It can be seen from the figure that the overpressure begin to emerge in Upper Permian Shiqianfeng Fm, generally less than 10 MPa, which increases with the increase of buried depth in the upper part of Shihezi Fm and Shihezi Fm, but decreases with the increase of buried depth in the lower part of Shihezi Fm, Shanxi Fm, Taiyuan Fm and Benxi Fm. Shihezi Fm has high overpressure, generally over 20 MPa. In this period, abnormal pressure was

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Table 2
Water locking test analysis results of the sandstone reservoirs in the Shenmu Gas Field.

<table>
<thead>
<tr>
<th>Well</th>
<th>Horizon</th>
<th>Well depth/m</th>
<th>Gas logging permeability/mD</th>
<th>Porosity</th>
<th>Permeability at irreducible water saturation/mD</th>
<th>Water locking index</th>
<th>Water locking degree evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shuang 2</td>
<td>He 8 Member</td>
<td>2628.6</td>
<td>0.109</td>
<td>12.1%</td>
<td>0.039</td>
<td>64.0%</td>
<td>Moderate-strong</td>
</tr>
<tr>
<td>Yu 74</td>
<td>He 8 Member</td>
<td>2502.23</td>
<td>0.023</td>
<td>8.4%</td>
<td>0.009</td>
<td>61.0%</td>
<td>Moderate-strong</td>
</tr>
<tr>
<td>Mi 7</td>
<td>He 8 Member</td>
<td>2003.17</td>
<td>0.009</td>
<td>5.8%</td>
<td>0.003</td>
<td>72.3%</td>
<td>Strong</td>
</tr>
<tr>
<td>Zhenchuan 4</td>
<td>He 8 Member</td>
<td>2078.15</td>
<td>0.005</td>
<td>8.2%</td>
<td>0.001</td>
<td>80.3%</td>
<td>Strong</td>
</tr>
<tr>
<td>Shuang 4</td>
<td>He 8 Member</td>
<td>2524.26</td>
<td>0.013</td>
<td>9.0%</td>
<td>0.005</td>
<td>58.8%</td>
<td>Moderate-strong</td>
</tr>
<tr>
<td>Shuang 11</td>
<td>He 8 Member</td>
<td>2269.79</td>
<td>0.013</td>
<td>9.2%</td>
<td>0.003</td>
<td>79.9%</td>
<td>Strong</td>
</tr>
<tr>
<td>Shuang 16</td>
<td>Taiyuan Fm</td>
<td>2789.87</td>
<td>0.4592</td>
<td>8.2%</td>
<td>0.165</td>
<td>64.1%</td>
<td>Moderate-strong</td>
</tr>
<tr>
<td>Shuang 16</td>
<td>Taiyuan Fm</td>
<td>2790.6</td>
<td>1.2294</td>
<td>9.2%</td>
<td>0.586</td>
<td>52.7%</td>
<td>Moderate-strong</td>
</tr>
<tr>
<td>Shuang 16</td>
<td>Taiyuan Fm</td>
<td>2791.13</td>
<td>1.4252</td>
<td>8.7%</td>
<td>0.580</td>
<td>59.3%</td>
<td>Moderate-strong</td>
</tr>
<tr>
<td>Shuang 16</td>
<td>Taiyuan Fm</td>
<td>2797.71</td>
<td>0.4738</td>
<td>7.4%</td>
<td>0.138</td>
<td>70.9%</td>
<td>Strong</td>
</tr>
<tr>
<td>Shuang 16</td>
<td>Taiyuan Fm</td>
<td>2798.39</td>
<td>0.417</td>
<td>7.2%</td>
<td>0.129</td>
<td>69.0%</td>
<td>Moderate-strong</td>
</tr>
<tr>
<td>Mi 41</td>
<td>Shan 2 Member</td>
<td>2555.9</td>
<td>0.223</td>
<td>6.9%</td>
<td>0.113</td>
<td>49.5%</td>
<td>Moderate-strong</td>
</tr>
<tr>
<td>Mi 41</td>
<td>Shan 2 Member</td>
<td>2556.97</td>
<td>0.335</td>
<td>6.4%</td>
<td>0.118</td>
<td>64.8%</td>
<td>Moderate-strong</td>
</tr>
</tbody>
</table>

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Fig. 5. Throat radius distribution frequency of the sandstone reservoirs in the Shenmu Gas Field.

Fig. 6. Pressure gradient distribution of Upper Paleozoic in the Shenmu Gas Field.
the major force driving natural gas migration, and most gas reservoirs formed.

3.1.2. Gas expansion force in the uplifting phase

During Early Cretaceous to Early Miocene, the Ordos Basin experienced overall uplifting and intense erosion and reformation. According to the study on apatite fission track, Zhao Mengwei estimated that the uplifting rate of the eastern basin was 95 m/Ma and the denudation thickness was up to 2000 m [18]. Affected by the dual effect of formation uplifting and geothermal gradient drop, the temperature reduced significantly, so pressure dropped too. Moreover, since source rocks gradually stopped expelling hydrocarbon, recharge rate insufficient to make up the diffusion amount, also resulted in pressure drop. At this period, the major driving force for natural gas migration turned from abnormal pressure to fluid expansion force.

In order to further confirm the presence of gas expansion force during the uplifting process and its influence on gas accumulation, a gas migration experiment under pressure drop condition was performed (Table 3), the simulation conditions included: the maximum confining pressure of 69 MPa, the maximum rock pore pressure of 49 MPa, the temperature ranging from room temperature to 150°C, and the flow range of 0.01–40 mL/min. The simulation results indicate that (Table 3): ① during pressure relief process, water discharges faster and in a larger amount if gas participates; ② under rapid pressure drop, gas-water system is characterized by the rapid discharge of gas-water mixed phase; and ③ under pressure relief condition, water saturation decreases, gas saturation increases in the model, in addition, under rapid pressure relief, gas saturation increases at a large magnitude.

In summary, the Ordos Basin went through overall uplifting, constant pressure drop, natural gas expansion and drop of water saturation since Early Cretaceous. Since the reservoirs were tight already, natural gas was unlikely to experience secondary migration and accumulation at large scale.

3.1.3. Gas buoyancy in the preservation phase

From Early Miocene to present, the Ordos Basin entered late preservation and slow depositional phase, when the structure was relatively stable, abnormally-high pressure disappeared and buoyancy became the major driving force for gas migration. Berkenpas pointed out that the key factor controlling gas floating was pore size [19], for formations with an inclination of 1°, buoyancy working conditions were that pore radius was greater than 100 μm and throat radius was greater than 40 μm. The sandstone reservoirs in the Shenmu Gas Field have an average pore radius of 8–24 μm, average throat radius of 0.01–0.30 μm and dip angle of less than 1°. All the indexes are less than the threshold of buoyancy working conditions proposed by Berkenpas. Thus, except high permeability reservoirs in local area, most natural gas in the Shenmu Gas Field was difficult to overcome capillary resistance to float freely.

Table 3
Experimental data of gas and water saturation and water discharge efficiency of the Shenmu Gas Field under decompression condition.

<table>
<thead>
<tr>
<th>Model no.</th>
<th>Sand–mud ratio</th>
<th>Pore volume/cm³</th>
<th>Saturated gas amount/mL</th>
<th>Original gas saturation</th>
<th>Original water saturation</th>
<th>Pressure/MPa</th>
<th>Pressure-releasing mode</th>
<th>Discharge rate/mL</th>
<th>Gas and water saturation after pressure relief</th>
<th>Water discharge efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100%</td>
<td>63.00</td>
<td>25.79</td>
<td>40.94%</td>
<td>59.06%</td>
<td>9</td>
<td>Slow</td>
<td>2.91</td>
<td>45.56%</td>
<td>54.44%</td>
</tr>
<tr>
<td>2</td>
<td>100%</td>
<td>72.69</td>
<td>8.54</td>
<td>11.75%</td>
<td>88.25%</td>
<td>9</td>
<td>Fast</td>
<td>9.46</td>
<td>24.76%</td>
<td>75.24%</td>
</tr>
<tr>
<td>3</td>
<td>50%</td>
<td>48.98</td>
<td>13.31</td>
<td>27.17%</td>
<td>72.83%</td>
<td>9</td>
<td>Slow</td>
<td>2.19</td>
<td>31.65%</td>
<td>68.35%</td>
</tr>
<tr>
<td>4</td>
<td>50%</td>
<td>48.00</td>
<td>14.02</td>
<td>29.21%</td>
<td>70.79%</td>
<td>9</td>
<td>Fast</td>
<td>3.45</td>
<td>36.40%</td>
<td>63.60%</td>
</tr>
</tbody>
</table>

Fig. 7. Overpressure profile from Well Shan 9 to Well Fu 5 in the Shenmu area.
During this period, the natural gas entered preservation phase and was unlikely to experience secondary migration and accumulation of large scale.

3.2. Formation of ultra-low water saturation gas reservoirs

Ultra-low water saturation phenomenon refers to the state that original reservoir water saturation is lower than irreducible water saturation [20]. The average original reservoir water saturation of the 13 sealed coring samples collected from the Shenmu Gas Field is 22.9% (Table 4), the irreducible water saturation measured by phase permeability method is up to 43.4%, thus, the original water saturation is 6.9—37.0% lower than irreducible water saturation. The formation of ultra-low water saturation gas reservoirs is predominantly affected by the variation of gas reservoir temperature and pressure field, dry gas charging and natural gas loss.

3.2.1. Influence of temperature and pressure

Gas reservoirs are formed over a long geological time. The water cut of natural gas under formation conditions depends on formation temperature and pressure. In the initial phase of gas reservoir formation, the temperature and pressure are low, but with the increase of burial depth, temperature and pressure increase, and the water-carrying capacity of natural gas gradually enhances. Benning proposed that [21] the evaporation and water-carrying capacity of natural gas was 1136.7 g/m³ at 27.57 MPa and 100 °C, and only 14.0 g/m³ at 1.013 MPa and 15.6 °C; with the increase of temperature and pressure, the water-carrying capacity of natural gas gradually enhanced, so the irreducible water in reservoirs evaporated and was carried out of reservoirs with the migration of natural gas, thus, the possibility that the formation water was carried to overburden strata increased [22], which was favorable for the formation of ultra-low water saturation gas reservoirs.

3.2.2. Dry gas charging

The statistical results of the relationship between water cut and organic matter thermal evolution maturity ($R_o$) of the coal bed in the eastern Ordos Basin indicate (Table 5) that, when $R_o$ is more than 1.2%, the water content of coal bed is much lower, suggesting that the higher the thermal evolution degree of source rocks, the lower the water vapor content in the natural gas. Since the coal measure source rocks of the Upper Paleozoic in the eastern basin have generally reached high mature and over-mature stage, thus, more dry gas would be injected into the reservoirs in late gas reservoir-forming stage. With the injection of dry gas, the irreducible water in the reservoirs would evaporate and migrate, which was favorable for the formation of ultra-low water saturation gas reservoirs.

3.2.3. Gas reservoir leakage and escape

In Late Cretaceous, the Ordos Basin was uplifted, and the intense tectonic uplifting led to the erosion of overlying strata, breaking the early migration and accumulation balance in gas reservoirs [23]. Moreover, the intense tectonic uplifting would be accompanied by some faulting activities, and in turn the formation of some faults and fractures in the Upper Paleozoic strata, thus, the natural gas formed in early stage would inevitably leak and escape upwards along the stress-relief zones with large stratigraphic denudation thickness and fault and fracture developed areas. The irreducible water would be carried out of the reservoirs along with the leakage and escape of gas after evaporation, which was conducive to the formation of ultra-low water-saturation gas reservoirs.

3.3. Gas accumulation modes

Comprehensive study results show that the gas reservoirs of the Shenmu Gas Field have the following features: (1) similar with the Upper Paleozoic tight sandstone reservoirs in the Ordos Basin, the sandstone reservoirs in the Shenmu Gas Field compacted at around 215—150 Ma ago, namely Late Triassic-Early Jurassic. During Late Jurassic-Early Cretaceous, a large quantity of natural gas generated and accumulated, thus, the gas reservoirs of the Shenmu Gas Field have the obvious feature of "compaction first and accumulation later" [24—27]; (2) the Ordos Basin is characterized by simple structure, stable subsidence and stable construction. Located in the Yishan strata increased, which was favorable for the formation of ultra-low water saturation gas reservoirs.

#### Table 4

<table>
<thead>
<tr>
<th>No.</th>
<th>Well</th>
<th>Depth/m</th>
<th>Horizon (member)</th>
<th>Physical property</th>
<th>Irreducible water saturation ($S_{iw}$)</th>
<th>Original water saturation ($S_{oi}$)</th>
<th>$S_{iw} - S_{oi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Shaung 16</td>
<td>2789.87</td>
<td>Taiyuan Fm</td>
<td>$\varphi$</td>
<td>8.2%</td>
<td>0.459</td>
<td>33.68%</td>
</tr>
<tr>
<td>2</td>
<td>Shaung 16</td>
<td>2790.60</td>
<td>Taiyuan Fm</td>
<td>K/mD</td>
<td>9.2%</td>
<td>1.229</td>
<td>29.73%</td>
</tr>
<tr>
<td>3</td>
<td>Shaung 16</td>
<td>2791.13</td>
<td>Taiyuan Fm</td>
<td>$\varphi$</td>
<td>8.7%</td>
<td>1.425</td>
<td>35.96%</td>
</tr>
<tr>
<td>4</td>
<td>Shaung 16</td>
<td>2797.71</td>
<td>Taiyuan Fm</td>
<td>K/mD</td>
<td>7.4%</td>
<td>0.474</td>
<td>34.4%</td>
</tr>
<tr>
<td>5</td>
<td>Shaung 16</td>
<td>2798.39</td>
<td>Taiyuan Fm</td>
<td>$\varphi$</td>
<td>7.2%</td>
<td>0.417</td>
<td>33.4%</td>
</tr>
<tr>
<td>6</td>
<td>Shaung 16</td>
<td>2763.60</td>
<td>Taiyuan Fm</td>
<td>K/mD</td>
<td>8.1%</td>
<td>0.733</td>
<td>33.9%</td>
</tr>
<tr>
<td>7</td>
<td>Mi 41</td>
<td>2458.70</td>
<td>He 8 Member</td>
<td>$\varphi$</td>
<td>7.2%</td>
<td>0.114</td>
<td>54.0%</td>
</tr>
<tr>
<td>8</td>
<td>Mi 41</td>
<td>2459.80</td>
<td>He 8 Member</td>
<td>K/mD</td>
<td>9.7%</td>
<td>0.306</td>
<td>44.7%</td>
</tr>
<tr>
<td>9</td>
<td>Mi 41</td>
<td>2461.20</td>
<td>He 8 Member</td>
<td>$\varphi$</td>
<td>9.2%</td>
<td>0.457</td>
<td>49.5%</td>
</tr>
<tr>
<td>10</td>
<td>Mi 41</td>
<td>2461.82</td>
<td>He 8 Member</td>
<td>K/mD</td>
<td>9.6%</td>
<td>0.850</td>
<td>30.8%</td>
</tr>
<tr>
<td>11</td>
<td>Mi 41</td>
<td>2553.95</td>
<td>Shan 2 Member</td>
<td>$\varphi$</td>
<td>6.2%</td>
<td>0.230</td>
<td>58.3%</td>
</tr>
<tr>
<td>12</td>
<td>Mi 41</td>
<td>2555.9</td>
<td>Shan 2 Member</td>
<td>K/mD</td>
<td>6.9%</td>
<td>0.223</td>
<td>50.5%</td>
</tr>
<tr>
<td>13</td>
<td>Mi 41</td>
<td>2556.97</td>
<td>Shan 2 Member</td>
<td>$\varphi$</td>
<td>6.4%</td>
<td>0.335</td>
<td>74.0%</td>
</tr>
<tr>
<td>Mean value</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.0%</td>
<td>0.473</td>
<td>43.30%</td>
</tr>
</tbody>
</table>
Slope, a secondary structural unit of the basin, the Shenmu Gas Field is a gentle west-dipping slope, where only multiple rows of low and gentle nose uplifts develop, but large faults and fractures are few, thus, there lack long-distance migration pathways for natural gas; ③ the source rocks of Shenmu have generally entered high mature-over mature phase, the extensive source rocks and pervasive sandstone reservoirs laminate, with few faults and thus no obvious dominant migration pathways, the natural gas generated by source rocks migrated and charged in diffuse mode; and ④ under the west-dipping monoclinic background, the reservoirs in N-S trend appear in strips, with extension distance of over several hundred kilometers, and combined big pieces in plane; the two sides of the sands are often tight rocks with strong sealing capacity, such as mudstone, siltstone and argillaceous siltstone of distributary interchannel microfacies, forming tight lateral barriers, which, coupling with strong reservoir heterogeneity and poor lateral connectivity, makes it difficult for natural gas to migrate a long distance in lateral direction.

Under the above geological background, natural gas predominantly migrated in short distance vertically. Compared with conventional gas reservoirs, the gas loss was lower during gas reservoir-forming process, which was good for gas accumulation.

When a large quantity of natural gas was generated during Middle Jurassic-Early Cretaceous, driven by the differential pressure between source rocks and reservoirs, natural gas was supplied in place from the gas generation center, forming in-source reservoir-forming assemblages, such as the gas reservoirs of Benxi, Taiyuan and lower Shanxi Fms. Natural gas migrated and charged into the upper part of Shanxi Fm and He 8 Member through the fracture system produced by gas generation pressure increase and tectonic stress [28,29], forming near-source reservoir-forming assemblages, where short vertical migration of gas gave birth to gas reservoirs in the upper part of Shanxi Fm and He 8 Member. At the end of Early Cretaceous, tectonic movements made the basin uplift on the whole and suffer erosion, subsequently, pressure-releasing pathways formed in the caprocks of Upper Shihezi Fm, thus, natural gas charged episodically into the reservoirs of Upper Shihezi Fm and Shiqianfeng Fm, giving rise to far-source secondary gas reservoirs of Upper Shihezi Fm and Shiqianfeng Fm (Fig. 8). Controlled by the charging and accumulation model of natural gas, in-source reservoir-forming assemblages have strong gas charging strength, high gas saturation, high reservoir pressure coefficient and large scale; near-source reservoir-forming assemblages have fairly strong gas charging strength, relatively high gas saturation and large gas reservoir scale; far-source reservoir-forming assemblages have low charging degree, low gas saturation and low gas reservoir pressure coefficient and scale due to the limited gas source supply.

4. Conclusions

1) The Shenmu Gas Field is a giant tight sandstone gas reservoir with low production rate, ultra-low abundance and moderate buried depth. Its exploration experienced three stages: early exploration of surrounding areas, gas field discovery and scale exploration, which was a
process of recognition-practice-recognition. Breakthroughs in understanding and technological innovation were the direct driving force behind the exploration breakthrough of this gas field.

2) The natural gas in the Shenmu Gas Field is coal-derived gas, with a methane content of 88%, and no H2S. The gas reservoir is buried in 1700—2800 m, with formation temperature of 62.1°—98.2°C, and pressure of 19.0—23.2 MPa, under multiple pressure systems (both low pressure and normal pressure) which reveal an average pressure coefficient of 0.87. The reservoirs are pervasive sandstone of fluvial-delta facies, with an average porosity of 7.8%, average permeability of 0.63 mD, most throat radius of less than 1 μm. The reservoirs are susceptible to water locking damage and have strong stress sensitivity, so reservoir protection is especially important.

3) The gas reservoir was predominantly formed in the Late Jurassic-Early Cretaceous, with the obvious feature of “compaction first and accumulation later”. The natural gas predominantly migrated in a short distance vertically. The pressure difference between source rocks and reservoirs and fluid expansion force provided driving force for natural gas migration in different phases. Affected by temperature, pressure field variation, dry gas charging and gas leakage, the gas reservoir has ultra-low water saturation. In-source and near-source gas-bearing assemblages have sufficient gas source, high gas saturation and large gas reservoir scale, while far-source gas-bearing assemblages mainly contain secondary small-scale gas reservoirs.

References


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