Reservoir-forming condition analysis and favorable zone prediction for the shale gas in the Upper Paleozoic Taiyuan Formation in the Ordos Basin

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Abstract
Shale gas is a hydrocarbon gas occurring in organic-rich argillaceous shale in a free and adsorbed state. The shale in shale gas reservoirs is source rock and also container rock, which is different from the situation in conventional gas reservoirs; the gas content in shale is mainly related to the abundance, type, and evolution degree of organic matter. The Taiyuan Formation in the Ordos Basin is marine-continental transitional sediments; the argillaceous shale of the Taiyuan Formation has features such as high organic matter abundance and high thermal evolution degree and has better reservoir-forming conditions, compared with the shale gas reservoirs outside China. The argillaceous shale in the Taiyuan Formation strata is mixed with thin gas-bearing sand layers, which indicates a high hydrocarbon-generating potential of the argillaceous shale. According to the main reservoir-forming conditions of shale gas, it is predicted that the favorable zones of shale gas in the Taiyuan Formation are primarily located in areas such as the northwestern corner of the Tianhuan Depression, the northeastern corner of the Shanbei Slope Belt, and the central and southern parts of the Ordos Basin. With the rapid progress in shale gas exploration and exploitation technologies, the shale gas in the Taiyuan Formation in the Ordos Basin has become an important exploration target because of its huge potential.

Keywords: Ordos Basin; Marine-continental transitional facies; Organic carbon content; Vitrinite reflectance; Favorable zone prediction

1. INTRODUCTION
Shale gas is a hydrocarbon gas occurring in organic-rich argillaceous shale in a free state and adsorbed state and its reservoir formation and distribution have geological characteristics such as short migration distance, multiple sealing mechanisms, hidden accumulation and reservoir formation, and gas-saturated strata. Their self-generation, self-storage, and adsorption mechanisms and the large-scale accumulation are important geological features of shale gas (Law and Curtis, 2002; Curtis, 2002; Mavor
and Corporation, 2003; Zhang et al., 2004; Bowker, 2005; Zhang et al., 2008). The exploration and exploitation of shale gas has been successful in North America, where commercial exploitation has been achieved in multiple basins in Michigan, Indiana, and other regions of the United States (USA) (Montgomery et al., 2005; McCallister, 2006; Pollastro et al., 2007; Liu et al., 2010). The total shale gas output for the USA reached $1.378 \times 10^9$ m$^3$ in 2010, accounting for about 23% of total natural gas output in the whole USA, and is expected to be $(2.600-2.800) \times 10^9$ m$^3$ in 2015, accounting for about 1/3 of the country’s total natural gas output. Therefore, increasing attention has been paid to the huge potential of shale gas.

The Ordos Basin is an important oil- and gas-bearing basin in China, with a main body area of more than 200 thousand square kilometers (Liu et al., 2009; Sun et al., 2009). It can be divided into six first-level tectonic units based on the current tectonic form, basement nature, and tectonic feature of the basin: the Yimeng Uplift in the north, the fault fold belt on the western margin, the Tianhuan Depression in the west, the Shanbei Slope in the center, the Weibei Uplift in the south, and the Jinxi Flexural Fold Belt in the east (Fig. 1). There are four sets of effective

![Figure 1. Structural framework and shale thickness contour map of Taiyuan formation in Ordos basin.](image)
hydrocarbon source rock grown vertically from top to bottom: Lower Paleozoic marine carbonate rock type hydrocarbon source rock, Upper Paleozoic marine carbonate rock type hydrocarbon source rock, Upper Paleozoic Permo-Carboniferous coal and dark argillite type hydrocarbon source rock, and Mesozoic Triassic Yanchang Formation containing lacustrine dark argillite type hydrocarbon source rock (Xu and Bao, 2009). Large conventional gas fields, including Jingbian, Sulige, Wushenqi, Yulin, and Daniudi, have been discovered so far, which indicates that the Upper Paleozoic shale gas in the Ordos Basin will have significant exploration potential. We studied the reservoir-forming conditions and exploration potential of shale gas in the formation with the Upper Paleozoic Lower Permian Taiyuan Formation in the Ordos Basin as the target.

2. RESERVOIR-FORMING CONDITION ANALYSIS FOR THE SHALE GAS IN THE TAIYUAN FORMATION IN THE ORDOS BASIN

2.1. Shale sedimentary facies and shale distribution

After the Middle Carboniferous Epoch, sea water had extended from the east, west, and south to the north with the settlement of the basin. Since the Late Taiyuan Age, owing to tectonic uplift, there had been deltaic deposits entering the tidal flat setting in the epicontinental seas in the northwest, north, northeast, and southwest to form an interlaced marine-terrestrial sedimentary framework.

The Taiyuan Formation continuously settled onto the Benxi Formation, and the strata spread in most areas of the basin. In the Taiyuan Formation, the areas with thicker argillite layers are located in the Tianhuan Depression district and the areas to the north of Suide and Shenmu; the argillite thickness in these areas is more than 40 m and the central part of the Tianhuan Depression has an argillite thickness of more than 50 m; the argillite thickness in the central part of the basin is generally 10–30 m (Fig. 1). The lithology of the Taiyuan Formation is mainly micritic biolithite, gray black-black argillite, arenaceous argillite, and gray white quartz sandstone, as well as coal seam (Fig. 2).

Figure 2. Shale contrasting profile of Taiyuan formation in Ordos basin (Profile Position: Line A-B in Fig. 1).
2.2. Geochemical characteristics

2.2.1. Organic matter abundance

Organic matter abundance is the most fundamental indicator to evaluate hydrocarbon source rock (Meng et al., 2012). The organic matter abundance of hydrocarbon source rock is generally expressed by the contents of total organic carbon (TOC), chloroform bitumen "A" and total hydrocarbon (HC), in which the total organic carbon is a parameter that controls the last two and also a basic parameter for oil and gas resource evaluation (Houseknecht and Weesner, 1997; Jin et al., 2001; Carr et al., 2009; Li et al., 2010). The total organic carbon content is also used as the main indicator of organic matter abundance in shale gas evaluation.

The total organic carbon content is universally higher in the argillite of the Taiyuan Formation in the Ordos Basin (Fig. 3, Table 1). Statistical analysis shows that the

![Figure 3. The distribution frequency of measured TOC of the Taiyuan Formation shale in the Ordos Basin.](image)

<table>
<thead>
<tr>
<th>Well &amp; Outcrop</th>
<th>Lithology</th>
<th>Measured TOC %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4</td>
<td>Shale</td>
<td>Min: 1.01, Max: 2.08, Average: 1.65</td>
</tr>
<tr>
<td>HT1</td>
<td>Shale</td>
<td>Min: 0.68, Max: 5.57, Average: 2.16</td>
</tr>
<tr>
<td>FT1</td>
<td>Shale</td>
<td>Min: 0.75, Max: 21.89, Average: 6.91</td>
</tr>
<tr>
<td>DT1</td>
<td>Shale</td>
<td>Min: 2.33, Max: 4.22, Average: 3.13</td>
</tr>
<tr>
<td>Outcrop_1</td>
<td>Shale</td>
<td>Min: 0.51, Max: 4.5, Average: 1.58</td>
</tr>
<tr>
<td>Outcrop_2</td>
<td>Shale</td>
<td>Min: 2.81, Max: 11.69, Average: 7.31</td>
</tr>
</tbody>
</table>

* outcrop_1: Chengjiajiang outcrop;
* outcrop_2: Palougou outcrop;
average TOC is 3.5%, with samples with TOC > 1.0% accounting for more than 75% of total samples and those with TOC > 2.0% accounting for more than 50% of total samples. Influenced by the sedimentary environment, the horizontal change in TOC content in the argillite of the Taiyuan Formation shows a gradual ascending trend from west to east in the basin, and the TOC content is higher in local northern areas of the basin and its northeast; the TOC content in the main body of the basin is generally more than 1.0% (Fig. 6).

The TOC of gas-generating shale in the five basins in North America (i.e., Michigan Basin, Appalachian Basin, Fort Worth Basin, San Juan Basin, and Illinois Basin) was generally 0.3%–24%, so we thought that 0.5% of TOC in argillaceous shale can be used as a lower limit of gas-generating shale and the relatively favorable TOC in gas-generating shale should be higher than 2.0%. In terms of organic matter abundance, the argillite of the Taiyuan Formation in the Ordos Basin belongs to argillaceous shale with relatively high organic matter abundance.

2.2.2. Organic matter type
There are many methods for evaluation of organic matter types, including use of the atomic ratio of kerogen, the rock pyrolysis parameter, the kerogen type index, and the carbon isotope $\delta^{13}C$ indicator of kerogen. The rock pyrolysis parameter method is used to calculate the hydrogen index (S2/TOC, IH) and the oxygen index (S3/TOC, IO), respectively, according to the adsorbed hydrocarbon (S1), kerogen pyrolyzed hydrocarbon (S2), and carbon dioxide (S3) determined from rock pyrolysis, so as to identify the organic matter type in oil-generating rock.

Based on the rock pyrolysis method, the organic matter in argillite was categorized according to the hydrogen index and the oxygen index, and the organic matter in the argillite of the Taiyuan Formation was found to contain mainly Type I and Type II1 and a little Type II2 and Type III (Fig. 4).

![Figure 4. Graph of organic matter type classified by HI/OI in the Ordos Basin.](image-url)
2.2.3. Thermal evolution degree of organic matter

The thermal evolution degree of organic matter (i.e., the maturity of organic matter) is an important parameter to characterize the hydrocarbon-forming effectiveness and product nature of organic matter.

Vitrinite reflectance is also called vitrain reflectance ($R_o$), and because it is a function of temperature and effective heating time and has irreversibility, it is one of the best parameters to identify the stage of coalification. Dow (1977) proposed that the logarithm of vitrinite reflectance ($\log R_o$) has a linear relationship with the burial depth. According to statistical results of data on the vitrinite reflectance of the organic matter in the Upper Paleozoic argillite in the Ordos Basin, we conducted a regression analysis to determine the relationship between vitrinite reflectance and burial depth of the organic matter in the Upper Paleozoic argillite (Fig. 5) and obtained the following expression:

$$R_o = e^{\left( \frac{H - 2081}{2611} \right)}$$

The maturity of organic matters in the argillite of the Upper Paleozoic Taiyuan Formation in the Ordos Basin is 1.5% on average, and the maturity of organic matter is higher along the Qingyang, Huachi, Wuqi, and Jingbian districts, with its maximum reaching 2.0%, and decreases gradually toward the perimeter (Fig. 6).

2.3. Physical properties of argillite

Shale gas is a kind of self-generating, self-storage natural gas resource, and its container rock is organic-rich (argillaceous) shale (i.e., argillaceous hydrocarbon source rock).

The lower argillite of the Taiyuan Formation is pure in quality, slightly light in color, and hard and brittle. The upper argillite is primarily black, contains rich organic

![Figure 5. Regression curve of $R_o$ and buried depth of organic matter.](image-url)
matter, is hard owing to the contained silt, and has a high content of pyrite, which is mostly crystal-like. After being weathered, the argillite is mostly fragment-like and its color turns red brown. The argillite of the Taiyuan Formation has a high organic matter content and has coal seams in between locally.

X-ray diffraction analysis of total-rock minerals shows that the argillite of the Taiyuan Formation in the Ordos Basin has an average quartz and feldspar content of 54%, an average clay mineral content of 37.6%, and an average content of other minerals of 8.4% (Fig. 7).

The clay minerals include mainly kaolinite (57.1%) and illite (25.5%) and also a little chlorite (8.9%) and mixed-layer illite/smectite (8.5%) (Table 2). The argillite contains rich organic matter. The argillite has developed micropores with commonly
seen denuded pores, and microfissures formed by clay minerals are also more
developed (Fig. 8).

The average porosity of the argillite samples of the Taiyuan Formation was 4.66% (with a 0.66% minimum and a 9.12% maximum), establishing their low porosity; and the average permeability of the argillite samples of the Taiyuan Formation was 0.129 $\times 10^{-3}$ $\mu m^2$ (with a 0.00052 $\times 10^{-3}$ $\mu m^2$ minimum and a 0.37 $\times 10^{-3}$ $\mu m^2$ maximum).

\begin{table}[h]
\centering
\caption{Measured data of shale clay minerals of the Taiyuan Formation.}
\begin{tabular}{|c|c|c|c|c|}
\hline
Sample no. & Depth & I,\% & K,\% & C,\% & I/S,\% \\
\hline
LL8B & outcrop_1 & 17 & 63 & 0 & 20 \\
LL–9 & outcrop_1 & 26 & 16 & 40 & 18 \\
C–2 & outcrop_1 & 75 & 25 & 0 & 0 \\
C–3 & outcrop_1 & 15 & 55 & 0 & 30 \\
PLG–9 & outcrop_2 & 37 & 50 & 10 & 3 \\
P–1 & outcrop_2 & 12 & 83 & 5 & 0 \\
P–3 & outcrop_2 & 12 & 84 & 4 & 0 \\
P–4 & outcrop_2 & 20 & 77 & 3 & 0 \\
S6–4 & 2188.56 & 18 & 59 & 13 & 10 \\
Y14–4 & 2282.97 & 36 & 36 & 11 & 17 \\
Qi2–3 & 2563.80 & 21 & 69 & 8 & 2 \\
Zhao8–6 & 2901.19 & 6 & 81 & 10 & 3 \\
Y36–4 & 3031.58 & 42 & 36 & 11 & 11 \\
Sh247–4 & 3173.43 & 20 & 65 & 10 & 5 \\
\hline
\end{tabular}
\end{table}
3. FAVORABLE ZONE PREDICTION OF THE SHALE GAS

3.1. Gas content

Shale gas primarily includes adsorbed gas and free gas; the adsorbed gas content is directly obtained from desorption of gas-bearing shale samples in general and can also be indirectly obtained from an isothermal adsorption experiment. Through the isothermal adsorption experiment, the Langmuir volume (the gas content of the sample under infinite pressure) and the Langmuir pressure (the pressure corresponding to the gas content of the sample equal to half of the Langmuir volume) were obtained first, and then the equation \( G_a = \frac{G_LP_L}{P + P_L} \) (where \( G_a \) is the calculated adsorbed gas content under the stratum condition, \( G_L \) is the Langmuir volume, \( P_L \) is the Langmuir pressure, and \( P \) is the stratum pressure) was used to calculate the adsorbed gas content of shale under the stratum pressure condition. Experiments have proved that the adsorbed gas content measured has a very good correlation with that calculated through the isothermal adsorption experiment (Pan et al., 2011). There were no available measured data for the adsorbed gas content in the shale of the Taiyuan

![Shale SEM photograph of the Taiyuan formation. (a) spherical carbon chips; (b) albite with dissolved pore; (c) flaky kaolinite distributed in illite-smectite mixed layer.](image)
Formation in the Ordos Basin, so we referenced other research results and used the calculated adsorbed gas content that is corrected to substitute for the actual adsorbed gas content.

Organic matter content is an essential factor that influences shale gas enrichment, and it determines the quantity of shale gas generated and directly influences the gas content in shale. Since the organic matter in shale has an important adsorption function on the gas, a large quantity of gas in the gas-bearing shale is adsorbed to the kerogen surface in an adsorption state. Therefore, high TOC means a high quantity of gas generated and a large amount of adsorbed shale, yielding a positive correlation between the adsorbed gas content and total organic carbon content in argillaceous shale. Experimental data show that there is a good correlation between the adsorbed gas content and total organic carbon content in the argillaceous shale of the Taiyuan Formation in the Ordos Basin (Fig. 9).

The adsorbed gas content is directly related to the TOC content in the argillaceous shale, so the horizontal change of the adsorbed gas content has a strong correlation with that of the TOC content: The adsorbed gas content in the argillaceous shale of the Taiyuan Formation is 1.58 m³/t on average (ranging from a minimum of 1.01 m³/t to a maximum of 2.79 m³/t) and increases gradually from the basin center to the basin perimeter; the maximum adsorbed gas content occurs in Shenmu and Fugu districts in the northeastern corner of the basin and the adsorbed gas content is relatively high in local areas to the northwest of Suide in the middle eastern part of the basin.

The free gas in shale has an occurrence state in strata similar to that of conventional natural gas, so the free gas content in shale can be calculated with the equation for conventional natural gas. Li et al. found that when the burial depth of shale is less than 1,500 m, the adsorbed gas content is more than the free gas content in the shale gas; and when the burial depth of shale is more than 1,500 m, the free gas content is more than the adsorbed gas content in the shale gas. Therefore, the total average gas content in the organic-rich shale of the Taiyuan Formation is not less than 2.0 m³/t, which is larger than the lower limit for viable shale gas exploitation in North America (0.8–1.0 m³/t).

Figure 9. Correlation between TOC and adsorption gas.
3.2. Resource potential evaluation

All of the six shale-gas-reservoir-forming elements (i.e., generation, storage, coverage, migration, accumulation, and conservation) are concentrated in the same argillaceous shale layer and a great amount of hydrocarbon gas stays and accumulates in hydrocarbon source rock; therefore, shale gas has relatively simple reservoir-forming control factors and can form a huge resource.

Compared with the argillaceous shale in the basins of the USA, from which shale gas has been successfully exploited (Zhao et al., 2008; Zhang et al., 2008), the argillaceous shale of the Taiyuan Formation in the Ordos Basin similarly has good reservoir-forming geological conditions (Table 3). Organic-rich argillaceous shale is widely distributed in the Taiyuan Formation in the Ordos Basin, is thick (generally about 10−40 m), has a high organic matter abundance (with a TOC content of 0.51%−20%), a high evolution degree ($R_o > 1.0\%$), and a very strong hydrocarbon-generating capability, and belongs to favorable hydrocarbon source rock. Oil and gas exploration in Ordos proves that the tight sandstone sandwiched in the argillaceous shale layers of the Taiyuan Formation has a very good gas-bearing property, which indicates that the argillaceous shale of the Taiyuan Formation has a strong hydrocarbon-generating potential. Moreover, most of the generated natural gas stays in the argillaceous shale strata by dint of the adsorptability and low permeability of the argillaceous shale strata, so the shale gas in the Taiyuan Formation in the Ordos Basin has a good resource potential.

3.3. Favorable zone prediction

Normally, large- and medium-scale gas fields are distributed in the gas-generating center of gas source rock and its perimeter (Wang et al., 2005), and the hydrocarbon-generating capability and quantity of the hydrocarbon source rock are closely related to the thickness, organic carbon content, and thermal evolution degree of the argillaceous shale. With the content, type, and thermal evolution degree of organic matter in argillaceous shale, and the thickness of argillaceous shale, etc. comprehensively considered, it is predicted that the favorable zones of shale gas in the

<table>
<thead>
<tr>
<th>Table 3. Parameter contrast between American shale gas reservoirs and Taiyuan formation.</th>
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</thead>
<tbody>
<tr>
<td><strong>Basin stratum</strong></td>
</tr>
<tr>
<td><strong>TOC (%)</strong></td>
</tr>
<tr>
<td><strong>$R_o(%)$</strong></td>
</tr>
<tr>
<td><strong>Natural gas origin</strong></td>
</tr>
<tr>
<td><strong>Shale Thickness (m)</strong></td>
</tr>
<tr>
<td><strong>Depth (m)</strong></td>
</tr>
<tr>
<td><strong>Production (108 m$^3$)</strong></td>
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</table>
Taiyuan Formation in the Ordos Basin are mainly located in areas such as the northwestern corner of the Tianhuan Depression, the northeastern corner of the Shanbei Slope Belt, and the central and southern parts of the basin (figure not shown).

With continuing progress in exploration technologies, the shale gas in the Taiyuan Formation may become one of the important targets in future natural gas exploration and exploitation in the Ordos Basin. Because argillaceous shale has low porosity and poor permeability, container rock transformation must be conducted for shale gas production. The clast components of the argillaceous shale of the Taiyuan Formation are mainly bristle minerals including quartz, which are quite favorable to fracturing transformation of container rock. Furthermore, a major breakthrough has been achieved for tight sandstone gas exploration of the Ordos Basin, during which the shale gas exploration in the deep part can be concurrently conducted. Li et al. suggested that the organic-rich argillaceous shale in alternating marine-continental and continental coal measure strata has a small single-layer thickness but has symbiotic conditions with tight sandstone gas and coal seam gas, making it realistic to develop multiple-layer joint-exploitation technologies for multiple types of natural gas resources including shale gas and tight sandstone gas (Li et al., 2009).

4. CONCLUSIONS

Based on our analysis, we conclude the following:

(1) The argillaceous shale of the Taiyuan Formation in the Ordos Basin has a large vertical accumulation thickness and a wide horizontal distribution over a certain scale, and it has a high organic matter abundance with an average total organic carbon content of more than 1.0%. The organic matter types are mainly saprohumolith and humosapropelic; the thermal evolution degree of organic matter is high with an average $R_o$ reaching more than 1.5%, and it belongs to the mature-high maturity stage, is favorable to gas generation through organic matter pyrolysis, and meets the fundamental geological condition for shale-gas-reservoir formation.

(2) The argillite of the Taiyuan Formation is mainly organic-rich black argillite, and the clay minerals include mainly kaolinite and illite and are primarily composed of bristle minerals including quartz, which are favorable to transforming the permeability of argillaceous shale container rock through fracturing or other methods.

(3) Compared with the main shale gas reservoirs outside China, the argillaceous shale of the Taiyuan Formation in the Ordos Basin has various geological elements that meet the shale-gas-reservoir-forming standards, and some indicators greatly exceed the standards specified by some experts at home and abroad.

(4) The favorable zones of shale gas in the Taiyuan Formation in the Ordos Basin are primarily located in areas such as the northwestern corner of the Tianhuan Depression, the northeastern corner of the Shanbei Slope Belt, and the central and southern parts of the basin.

(5) The burial depth of the Taiyuan Formation in the Ordos Basin is relatively large, making exploration and exploitation only for the shale gas in the formation less feasible; however, developing multiple-layer joint-exploitation
technologies for multiple types of natural gas resources including shale gas and tight sandstone gas could be a significant and realistic goal.

REFERENCES


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