Characteristics and accumulation mechanism of tight sandstone gas reservoirs in the Upper Paleozoic, northern Ordos Basin, China

Liu Guangdi[1]*, Sun Mingliang[1], Zhao Zhongying[1, 2], Wang Xiaobo[1, 2] and Wu Shenghe[1]

[1] State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing 102249, China
[2] Research Institute of Petroleum Exploration & Development, PetroChina, Beijing 100083, China

Abstract: The Ordos Basin is a significant petroliferous basin in the central part of China. The Carboniferous and Permian deposits of transitional and continental facies are the main gas-bearing layers in the north part of the basin. The Carboniferous and Permian natural gas reservoirs in the northern Ordos Basin are mainly tight sandstone reservoirs with low porosity and low permeability, developing lots of "sweet spots" with comparatively high porosity and permeability. The tight sandstones in the study area are gas-bearing, and the sweet spots are rich in gas. Sweet spots and tight sandstones are connected rather than being separated by an interface seal. Sweet spot sand bodies are vertically and horizontally overlapped, forming a large gas reservoir group. In fact, a reservoir formed by a single sweet spot sand body is an open gas accumulation. In the gentle dipping geological setting and with the source rocks directly beneath the tight reservoirs over a large area, the balance between gas charging into tight reservoirs from source rocks and gas loss from tight reservoirs through caprock is the key of gas accumulation in tight sandstones. Both the non-Darcy flow charging driven by source-reservoir excess pressure difference and the diffusion flow charging driven by source-reservoir gas concentration difference play an important role in gas accumulation. The results of mathematical modeling indicate that the gas accumulation cannot be formed by just one of the above mechanisms. The diffusion of gas from source rocks to reservoirs is a significant mechanism of tight sandstone gas accumulation.

Key words: Tight sandstone, gas accumulation, gas diffusion, Upper Paleozoic, Ordos Basin

1 Introduction

Tight sandstone gas plays an important role in natural gas resources and also will become a significant target for future exploration and development of natural gas. These gas reservoirs are tight, strongly heterogeneous, and the gas saturation changes a lot within the reservoir. Gas accumulation mechanisms, distribution of sweet spots, and many other aspects of this kind of gas reservoir are still unclear, which largely limit the exploration and development of tight sandstone gas. Chinese and foreign researchers have emphasized their studies on sealing mechanisms with regard to the accumulation of tight sandstone gas. They have proposed hydrodynamic sealing, relative permeability, lack of buoyancy and stratigraphic diagenesis sealing theories (Berry, 1959; Masters, 1979; Gies, 1981; Jones, 1980; Brown et al, 1982; Rahmani, 1984; Welte et al, 1984). Past studies of charging, migration and accumulation mechanisms

of tight sandstone gas reservoirs were mainly on deep basin gas, and piston-like pushing migration and dynamic accumulation have been proposed (Gies, 1982; 1984; Brown et al, 1986; Berkenpas, 1991; Masters, 1984; McPeek, 1981; Shanley et al, 2004; Law and Dickinson, 1985). However, the Upper Paleozoic tight sandstone gas reservoirs in the northern Ordos Basin mainly have low porosity and low permeability with source-reservoir overlap contact over a large area, and the accumulation mechanism and conditions are obviously different from deep basin gas, which results in a significant difference in gas enrichment. Therefore, studies on the charging mechanisms and enrichment of the Upper Paleozoic tight sandstone gas in the northern Ordos Basin are theoretically and practically important for exploration and development of this kind of gas accumulation.

2 Geological setting

The Ordos Basin is located in the vast loess plateau and desert steppe region of central China, which is to the north of the Qinling Mountains, south of the Yin Mountains, east of the Helan Mountains and west of the Lüliang Mountains, with

an area of 25×10^4 km^2. The thickness of sedimentary rocks in the basin is 5,000-18,000 m, and the basin is a large wide west-dipping monocline in structure with a regional gradient of 3-5 m/km (Fig. 1).
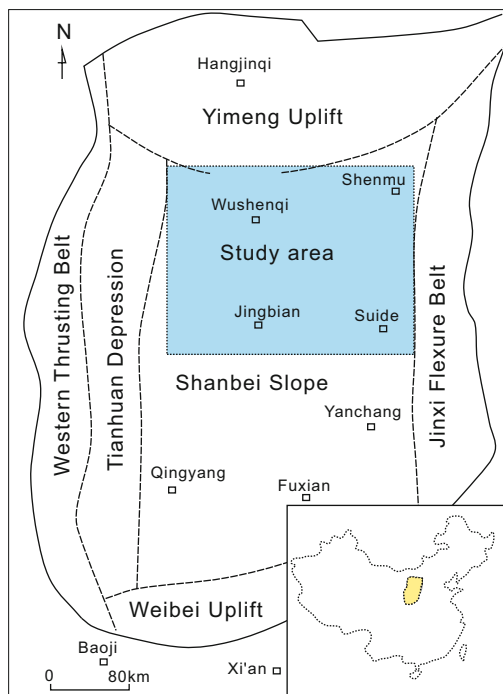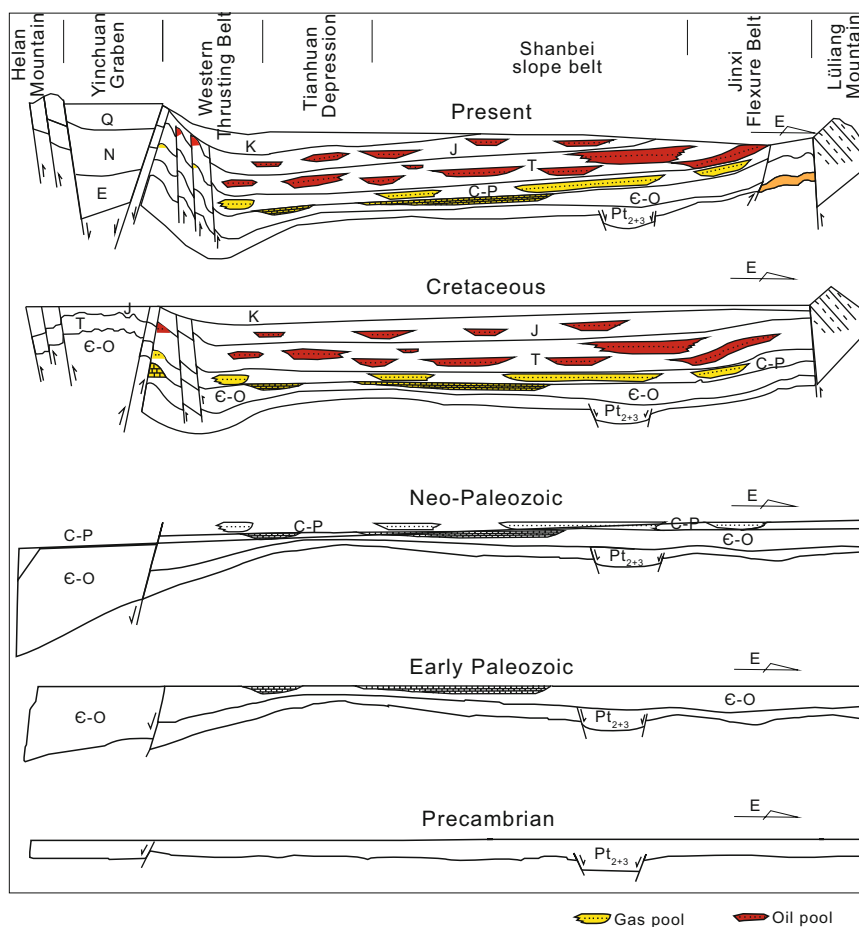

Fig. 1 Location of the Ordos Basin (Modified after Yang, 2002)

The Ordos Basin is a residual cratonic basin in the western end of the Paleozoic North China platform (Yang, 2002; He, 2003), and it has experienced five evolutionary stages, i.e. Middle-Late Proterozoic aulacogen, Early Paleozoic epeiric sea, Late Paleozoic coastal plain, Mesozoic inland basin and Cenozoic circumferential fault depression (Fig. 2).

The Upper Paleozoic in the basin are sediments of transitional and continental facies of the Carboniferous Benxi Formation and Taiyuan Formation, and the Permian Shanxi Formation, Lower Shihezi Formation, Upper Shihezi Formation and Shiqianfeng Formation. The coal-bearing strata of the Benxi, Taiyuan and Shanxi formations are the main source rocks, the fluvial-deltaic sandstones of the Shanxi and Lower Shihezi formations are the main reservoir rocks, and the thick lacustrine mudstones of the Upper Shihezi and Shiqianfeng formations serve as the regional seal rocks. The Suilge, Yulin, Daniudi and other huge gas fields have been found in the Upper Paleozoic of the northern Ordos Basin. Among them, the Suilge gas field is the largest gas field in China at present.

3 The basic features of tight sandstone gas accumulation

The Upper Paleozoic natural gas of the Ordos Basin mainly comes from coal strata of the Carboniferous Benxi Formation and Lower Permian Shanxi Formation, and is

Fig. 2 Structure development of the Ordos Basin (Modified after Yang, 2002)

mainly preserved in tight sandstones of the Permian Shanxi Formation and Lower Shihezi Formation, in which the fluvial-deltaic sandstones developed in the second member of the Shanxi Formation and the eighth member of the Lower Shihezi Formation are the main reservoir rocks and the Upper Shihezi Formation mudstones are the main cap rocks. The source rocks and reservoir rocks directly contact in a large area (Fig. 3). This source and reservoir combination pattern creates generally gas-bearing tight sandstones. The sweet spots have relatively high gas saturation and relatively high yield, but the widely distributed tight sandstones have low gas saturation and low natural gas yield, which is a characteristic of the Upper Paleozoic tight sandstone gas accumulation of the Ordos Basin.
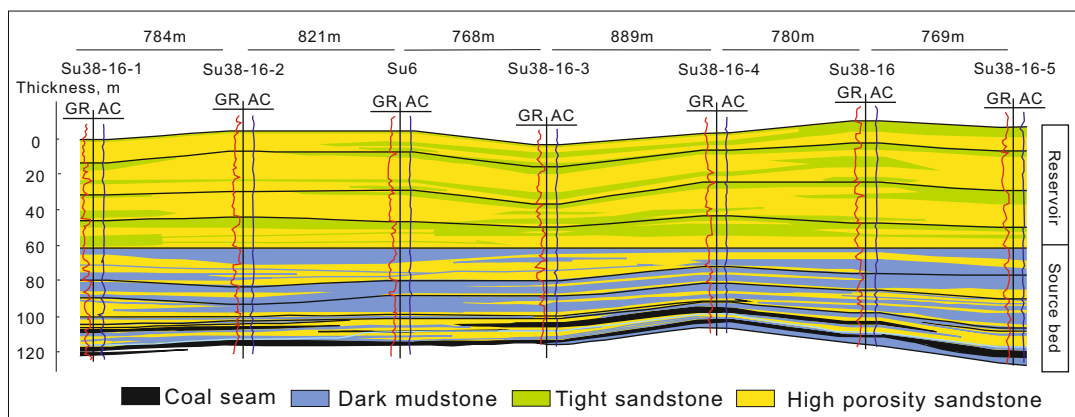

Fig. 3 Section of the Shanxi Formation-He8 in the Sulige Field

3.1 Tight sandstone reservoir developing sweet spots

According to the current classification of clastic rock reservoirs in China, reservoirs with porosity lower than 10% and permeability lower than $1 \times 10^{-3} \mu m^2$ are categorized as low porosity and low permeability reservoir. Reservoirs with permeability lower than $0.1 \times 10^{-3} \mu m^2$ are categorized as the lowest permeability reservoir. The statistics of porosity and permeability of the Upper Paleozoic gas reservoir in the northern Ordos Basin indicate that the reservoir is a typical low porosity and low permeability reservoir (Fig. 4) since its porosity is between 2% and 10%, with a maximum of 18%, and its permeability is between $0.01 \times 10^{-3} \mu m^2$ and $0.5 \times 10^{-3} \mu m^2$. For the main gas producing reservoir, i.e., the sweet spot, the porosity is generally greater than 6% and the permeability is usually above $1 \times 10^{-3} \mu m^2$, which means that sweet spots develop locally in the low porosity and low permeability background. Hence the first feature of the gas accumulation in the northern Ordos Basin is that the reservoirs are tight sandstones with low porosity and low permeability, but sweet spots have developed with relatively high porosity and permeability.
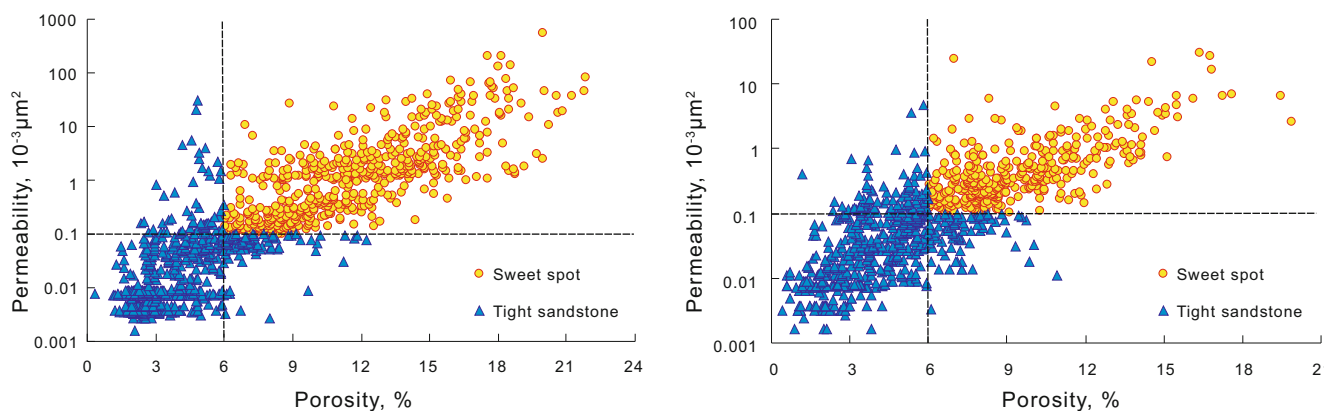

Fig. 4 Plot of porosity versus permeability of reservoir rocks in the He8 member (left) and Shan1 member (right) in the Sulige gas field

3.2 Sweet spots vertically and laterally overlap, forming a widely distributed effective reservoir

The main reservoir rocks in the Sulige gas field of the Ordos Basin are fluvial-deltaic deposits. The distribution range of a single channel sand body is limited and its continuity is poor with a lens-shape distribution. The general thickness of a single sand layer is 2-5 m. An isolated single sweet spot formed in a single channel is shown in section (Fig. 5). In a single sand bed of the Sulige gas field, the sweet spots are scattered in the tight sandstones (Fig. 6(a)-6(f)).

After overlapping the sweet spots of each single layer, it is found that the originally isolated sweet spots become overlapped and connected (Fig. 6(g)). After the plane

overlapping of each single layer, the area ratio of the sweet spots has increased from 15%-35% of each single layer to 96% of the whole bed. Because of the river migration, the sweet spots of different periods can be re-overlapped vertically and can also form a largely distributed and connected effective reservoir.
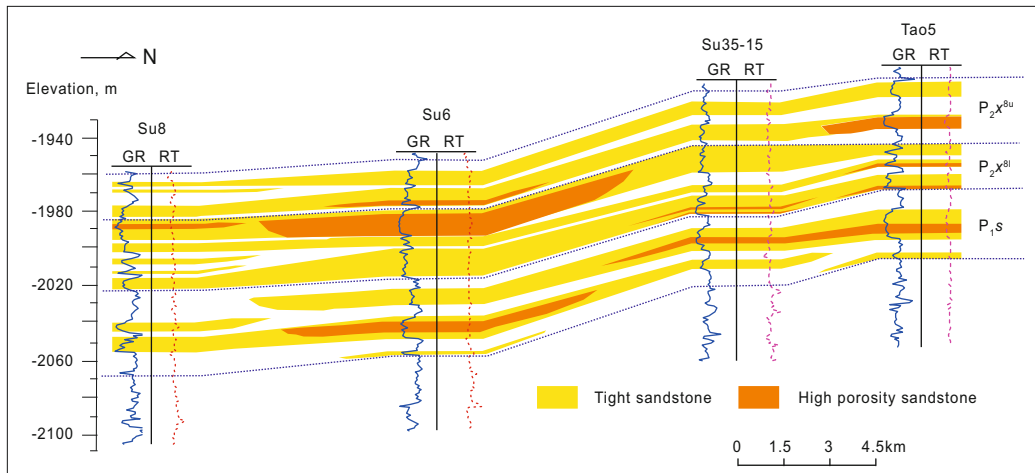
**Fig. 5** Cross section of a sand body in the Su6 Block, Sulige gas field, Ordos Basin
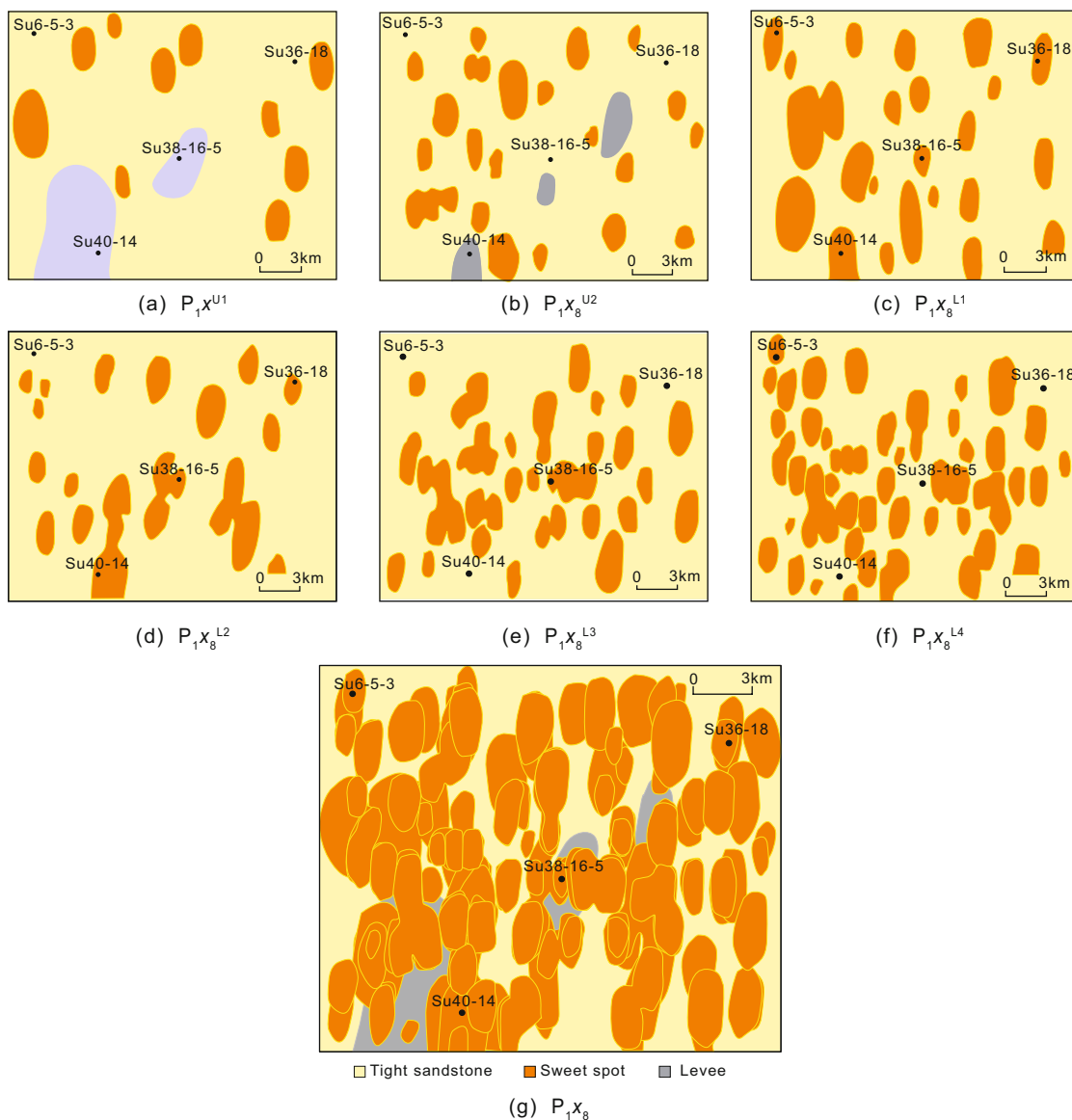
Fig. 6 Sweet spot distribution of each layer of the He8 member in Well Su6 area, Sulige gas field

3.3 Tight sandstone is widely gas-bearing and sweet spots are rich in gas

Statistics of gas saturation in the Sulige gas field indicate that in the Upper Paleozoic the widely distributed tight sandstones are all gas-bearing and the sweet spots have relatively high gas saturation.

Using logging data, the porosity, permeability and gas saturation of tight sandstones and sweet spots in 116 wells in the Sulige gas field have been interpreted and statistically

analyzed. The result indicates that the gas saturation of sweet spots is higher than that of tight sandstones. The gas saturation of the sweet spot in the He8 member is high, mainly ranging between 60% and 70%, with an average of 59%. The gas saturation of tight sandstones is low, mainly ranging between 40% and 50%, with an average of 46% (Fig. 7, left). The average gas saturation of sweet spots in the Shan1 member reservoir is 63% and the average gas saturation of tight sandstones is 46% (Fig. 7, right).
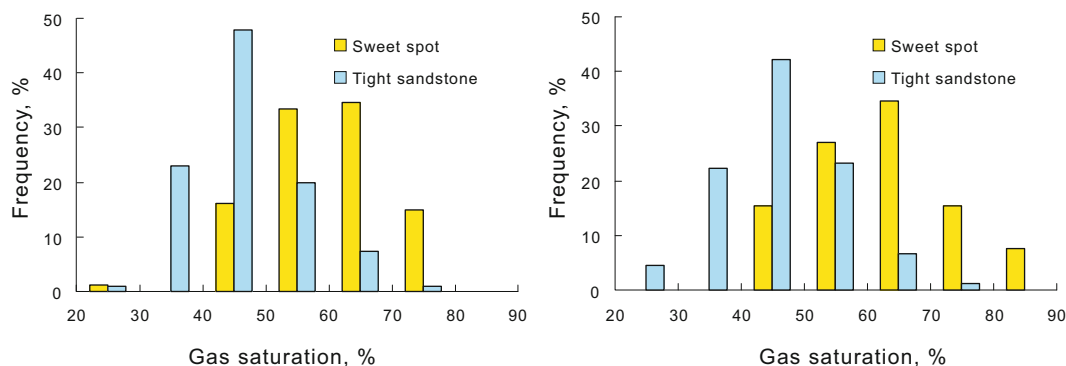
Fig. 7 Histogram of gas saturation of sweet spots and tight sandstones of the He8 member (left) and Shan1 member (right) in the Sulige gas field

3.4 No sealing interface between sweet spots and tight sandstones, forming an open gas accumulation

The analysis of sedimentary facies shows that the development of the Upper Paleozoic reservoirs in the Sulige gas field is mainly controlled by the sedimentary micro-facies. Sweet spots are mainly coarse-gained sandstone deposited in the channel bars of braided rivers, and the tight sandstone is mainly fine-grained sandstone deposited in braided channels. Sweet spots are isolated lenticularly and distributed in widespread tight sandstones. Sweet spots and peripheral tight sandstones have a sedimentary transitional relationship (Fig. 8).
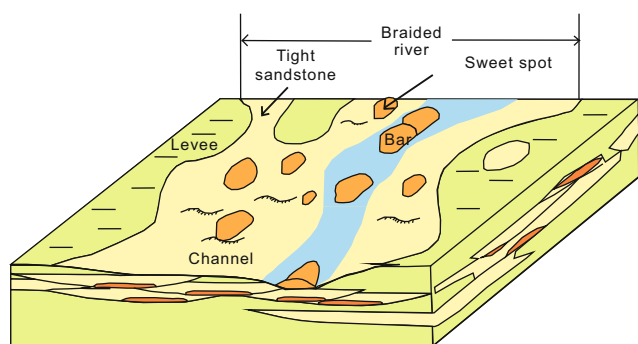
Fig. 8 Sedimentary model of the Upper Paleozoic sweet spots and tight sandstones, Sulige gas field

The calculation of the pressure system in the Ordos Basin also shows that there is no obvious sealing interface between the sweet spots and tight sandstones. A formation pressure test of the Upper Paleozoic in the Ordos Basin shows that the maximum underpressure of abnormal pressure formation is 11.4 MPa, which equals a gas column height of 1,363 m

at gas density of 0.835 kg/m^3. At the formation dip 4º, this gas column height equals a maximum gas width of 19.5 km along the formation dip, which is basically consistent with the compound sand body width of the Upper Paleozoic delta. It illustrates that the tight sandstones and sweet spots are gas-bearing overall. Therefore, it can be concluded that sweet spots and tight sandstones of the Ordos Basin are in the same pressure system and the gas can be exchanged between them. The boundary of the gas accumulation in a single sweet spot is open, forming an open gas accumulation.

## 4 Accumulation mechanism of tight sandstone gas

Since the Upper Paleozoic in the Ordos Basin has gentle dipping tight reservoirs and a large area of direct contact between source and reservoir, the accumulation mechanism and accumulation process of natural gas are obviously different from the accumulation of conventional natural gas reservoirs, and also quite different from the accumulation of North American deep basin gas. Previous studies reveal that the excess pressure difference between source and reservoir is the main driving force in the formation process of natural gas accumulation (Liu et al, 2005; 2008). Tight reservoirs have a high displacement pressure and the gas charging from source to reservoir needs higher excess pressure difference between source and reservoir. Meanwhile, the high displacement pressure increases the resistance to natural gas migration within the reservoir, which limits the free flow of natural gas in tight sandstones. Besides, the buoyancy effect is reduced because of the gentle dip of the reservoir, so lateral migration of natural gas within the tight reservoir is therefore limited in the scale and distance.

In the conventional and deep basin gas reservoirs, diffusion charging of gas from source to reservoir was generally not considered as an effective process for natural gas accumulation. However, because of the large area of direct contact between source and reservoir in the Ordos Basin, gas diffusion from source to reservoir occurs at a large scale, hence, the amount of gas charged from source to reservoir by diffusion is greatly increased. If the gas amount charged by diffusion is more than the gas loss from the reservoir by diffusion, the diffusion charging will have a constructive effect on the accumulation of the tight sandstone gas.

4.1 Non-Darcy flow charging driven by excess pressure difference between source and reservoir

Sandstone samples with different permeabilities from the Sulige gas field have been selected for a simulation experiment of natural gas flow charging. The permeability of samples is $(0.011-1.37) \times 10^{-3}$ μm^2. The methane charging experiment is under the condition of 10 MPa/m, 8 MPa/m and 4 MPa/m pressure gradient, recording the charging time and quantity. By analyzing the experimental results, the correlation between starting pressure gradient and starting permeability under the experimental conditions can be generated after regression (Fig. 9). Fig. 9 shows that the minimum starting pressure gradient is 0.1 MPa/cm when the permeability is 0.1×10^{-3} μm^2, and decreases to about 0.02 MPa/cm when the permeability is 1×10^{-3} μm^2. This result suggested that the gas flow charging from source rocks to tight sandstone reservoirs was a non-Darcy flow and the driving force was an excess pressure gradient between source and reservoir.
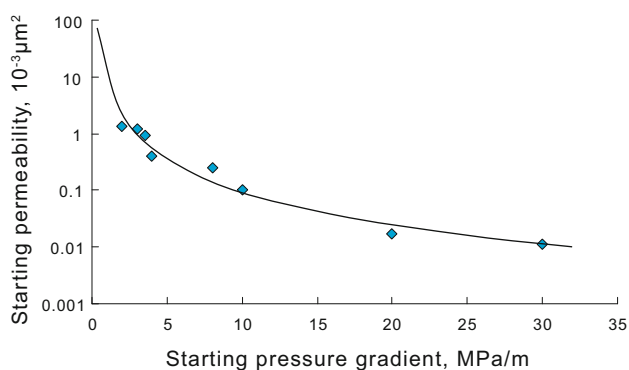
Fig. 9 Plot of starting pressure gradient versus starting permeability in simulation experiment

Previous studies showed that there was an abnormally high pressure in the Upper Paleozoic in the burial process of the Sulige gas field, and the pressure coefficient was more than 1.6. The pressure in the Upper Paleozoic decreased in the later uplift period due to a temperature decrease and gas diffusion (Yang et al, 2004; Yuan and Liu, 2005). At present the pressure is normal or low-amplitude under-pressure and the pressure coefficient is mostly less than 1. Based on mudstone compaction curves and fluid inclusion pressure calibration, the pressure evolution history of the source rocks and reservoirs in the Sulige gas field has been restored

by using basin modeling. Studies on the excess pressure of source rocks of the Shan2 member and reservoirs of He8 and Shan1 members reveal that there are characteristics of "high excess pressure, low excess pressure difference" between source rocks and reservoirs in the Sulige gas field. The excess pressure of source rocks and reservoirs is high, generally greater than 15 MPa, and the excess pressure difference between source rocks and reservoirs is low, generally less than 3 MPa (Fig. 10). This result demonstrates that because the source rocks are close beneath the reservoir, this excess pressure difference will drive natural gas from source rocks to charge into the reservoir by non-Darcy flow.
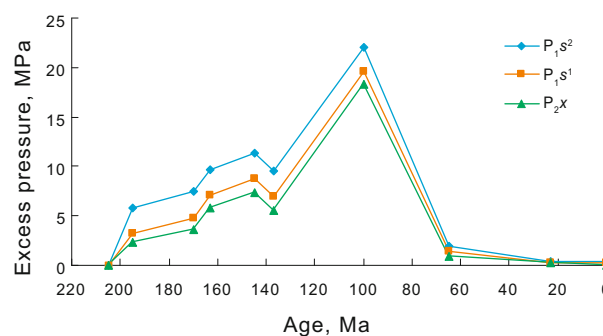
Fig. 10 Excess pressure evolution of source rocks and reservoir rocks in Well Su6, Sulige gas field

4.2 Diffusion flow charging driven by source-reservoir hydrocarbon concentration difference

The destructive effect of diffusion on natural gas accumulation has long been recognized by geologists. There are significant achievements in determination of the diffusion coefficient, diffusion modeling, calculation of diffusion amount and geochemical changes of natural gas caused by diffusion (Wang and Gao, 2005; Zhang and Krooss, 2001; Krooss and Leythaeuser, 1988; 1997; Krooss et al, 1992; Hao et al, 1991; Nelson and Simmons, 1995; Huang and Hao, 1996; Prinzhofer and Pernaton, 1997; Fang et al, 2001; Fu and Su, 2004; Wilson, 1996). However, there are few studies about the charging effect of natural gas except the early study of Leythaeuser et al (1982). Furthermore, there are even fewer studies on the effects of diffusion in natural gas accumulation.

Based on the study of the accumulation mechanism of the Sulige gas field and diffusion coefficient of natural gas in rocks (Liu et al, 2012), the geological and mathematical models of gas diffusion in different source-reservoir-cap assemblages (including diffusion charging and diffusion loss) have been established (Zhao, 2012). The charging, loss and accumulation of natural gas in tight reservoirs of the Upper Paleozoic in the Ordos Basin can be studied by a one-dimensional model based on the following facts, i.e. the lateral migration of natural gas in the reservoir can be neglected and gas mainly migrates vertically after being charged into the reservoir from source rocks due to the high displacement pressure and the gentle dipping of the Upper Paleozoic tight sandstone reservoirs. According to the natural gas migration and accumulation dynamic balance principle, the difference between the gas charged into and the gas lost

from the tight reservoir is the gas accumulated in the tight reservoir.

Modeling of the gas accumulation of Su7 well in the northern Ordos Basin has been conducted using the above model. The results (Fig. 11) show that the natural gas charging intensity by non-Darcy flow is 5.9×10^8 m^3/km^2, the charging intensity by diffusion flow is 4.7×10^8 m^3/km^2, and the sum of these two is 10.6×10^8 m^3/km^2. The gas loss intensity of this well block is 7.2×10^8 m^3/km^2. Therefore the gas accumulation intensity (retention intensity) of the Upper Paleozoic reservoirs in this well block is 3.4×10^8 m^3/km^2. It can be concluded from the results that the amount of gas into the reservoir provided by a single mechanism of non-Darcy flow charging or diffusion flow charging is not enough to make up for the gas loss. Only by including both non-Darcy flow and diffusion does the amount of gas charged into the reservoir exceed the amount of gas loss, to form gas accumulation. Therefore, non-Darcy flow charging and diffusion flow charging both play an important role in the formation of tight sandstone gas reservoirs with wide source-reservoir contact and gentle dipping such as the Ordos Basin. Diffusion is not only an important process in gas destruction but may also become an important mechanism of gas accumulation under certain conditions.
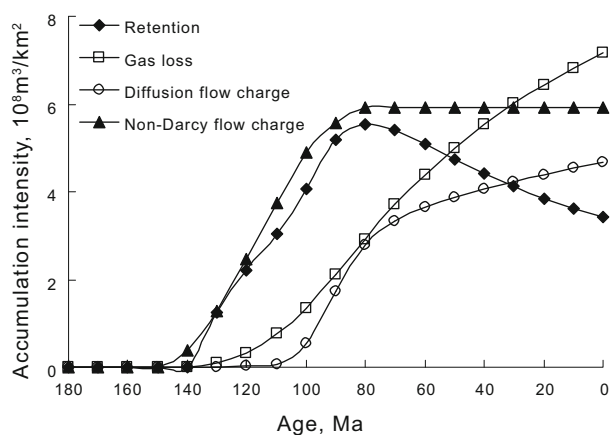
Fig. 11 Volume of gas expulsion (charging), accumulation, and diffusion of the Upper Paleozoic in Well Su7 of the Sulige gas field

5 Conclusions

1) The Upper Paleozoic gas fields in the northern Ordos Basin are open gas accumulations in sweet spots in a background of widely gas-bearing tight reservoirs. The Upper Paleozoic is mainly low porosity and low permeability, developing relatively high porosity and high permeability sweet spots. Tight reservoirs are gas-bearing, and the sweet spots are rich in gas. The sweet spots and tight sandstones are connected and there is no sealing interface between them. Sweet spot sand bodies overlap vertically and laterally, forming a widely distributed reservoir group. In fact, the reservoir formed by a single sweet spot sand body is an open gas accumulation.

2) Due to gentle dipping and widespread direct contact between source rocks and reservoirs of the Upper Paleozoic in the northern Ordos Basin, both the non-Darcy flow charging driven by source-reservoir excess pressure difference and the diffusion flow charging driven by source-reservoir gas concentration difference play an important role in gas accumulation. The diffusion of gas from source rocks to reservoirs is a significant mechanism for gas accumulation in tight sandstone reservoirs.

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