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DEPARTAMENTO DE GEOCIENCIAS
RESEARCH GROUP IN GEOPHYSICS

PETROLEUM GEOLOGY

Geological Characteristics of Unconventional Gas in Coal Measure of Upper Paleozoic Coal Measures in Ordos Basin, China

Jinxian He,[1,2*] Xiaoli Zhang,[1,2] Li Ma,[1,2] Hongchen Wu,[1,2] Muhammad Aqeel Ashraf[3]

[1]School of Resources and Geosciences, China University of Mining and Technology, Xuzhou, Jiangsu, 221116, China;

[2] Key laboratory of Coalbed Methane Resource and Reservoir Formation Process, Ministry of Education(China University of Mining and Technology), Xuzhou 221008 China;

[3] Faculty of Science and Natural Resources, University Malaysia Sabah 88400 Kota Kinabalu Sabah, Malaysia

* Corresponding author: Jinxian He, email: jxhe@cumt.edu.cn

ABSTRACT

There are enormous resources of unconventional gas in coal measures in Ordos Basin. In order to study the geological characteristics of unconventional gas in coal Measures in Ordos Basin, we analyzed and summarized the results of previous studies. Analysis results are found that, the unconventional gas in coal measures is mainly developed in Upper Paleozoic in Eastern Ordos Basin, which including coalbed methane, shale gas and tight sandstone gas. The oil and gas show active in coal, shale and tight sandstone of Upper Paleozoic in Ordos Basin. Coalbed methane reservoir and shale gas reservoir in coal measures belong to "self-generation and self-preservation", whereas the coal measures tight sandstone gas reservoir belongs to "allogenic and self-preservation". The forming factors of the three different kinds of gasses reservoir are closely related and uniform. We have the concluded that it will be more scientific and reasonable that the geological reservoir-forming processes of three different kinds of unconventional gas of coal measures are studied as a whole in Ordos Basin, and at a later stage, the research on joint exploration and co-mining for the three types of gasses ought to be carried out.

Keywords: Ordos Basin, Unconventional gas in coal measure, coalbed methane, shale gas, tight sandstone gas, Upper Paleozoic.

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Introduction

Unconventional gas in coal measures is all natural gasses which are generated through evolution when the parent materials of source rocks underwent coalification of biochemistry and physiochemistry. It includes gasses such as coalbed methane, shale gas, tight sandstone gas, natural gas hydrate (Cao et al., 2014; Wang et al., 2014). Unconventional gas resources of coal measures have a huge amount (Table 1). According to the principle of "giving priority to coal, comprehensive exploration, comprehensive evaluation" of the geological survey of coal resources in China (Deng et al., 2006), improving the research of the gas resources associated with coal in coal measures is of great significance.

Table 1. Distributional situation of gas resources of coal measures in Ordos basin and China (Zhao et al., 1998; Feng et al., 2002; Liu et al., 2009; Jie, 2010; Zhang et al., 2012a; Yang et al., 2015)

	coalbed methane /$\times10^{-12}$ m^3	shale gas /$\times10^{-12}$ m^3	tight sandstone gas /$\times10^{-12}$ m^3
China	36.8	36.1	9.2~13.4
Ordos basin	10.72	-	>5
The eastern margin of Ordos basin	5.72	-	-

In Chinese coal measure strata, because the coal seam, dark mud shale, and tight sandstone interbedded deposit, the geological phenomenon which several kinds of coal measures gasses jointly preserve is relatively prevalent. Scholars have agreed to take unconventional gas in coal measures as a system of research and development. They also agreed to carry out joint exploration and exploitation for multi-gasses (Qin et al., 2014; Cao et al., 2014; Wang et al., 2014; Gao et al., 2014). The comprehensive research of unconventional gas in coal measures is the trend in the future(Qin et al.,2016; Liang et al.,2016a).It may improve the production of the single well, reduce production cost and increase economic benefit that multi-gasses are jointly exploited from a well(Qin et al.,2016; Liang et al.,2016a). Additionally, in coal mining, because the surrounding rock gas of coal seam is a primary source of the coal mine gas, the coal measures' gas (not only coalbed methane) drainage helps reduce the hazard of coal mine gas and efficiently reduce greenhouse gas emissions.

1 Regional geological characteristics

As the second largest sedimentary basin in China, Ordos basin is also an important coal-bearing and oil-bearing one. The whole basin may be divided into six first-order tectonic units. In the basin, the gas resources of

Upper Paleozoic coal measures mainly distribute in the East and principally includes the east of Yanan area in the Yishan slope and the deflection fold belt in western Shanxi (Fig. 1). In the eastern Ordos basin, greater total thickness, multi-beds, and stable distribution of coal seams developed in the Upper Paleozoic coal measure strata; at the same time, some dark mud shale and tight sandstone interceded with these coal seams. It provides the abundant material basis for preservation and development of coalbed methane, shale gas, and tight sandstone gas. Previous researches indicated that coalbed methane, shale gas, tight sandstone gas jointly developed in the Upper Paleozoic strata in the eastern Ordos basin (including Linxing area) (Guo et al., 2012; Guo and Zhao, 2014), therefore providing a favorable geological condition for carrying out joint multi-gases exploration and exploitation.

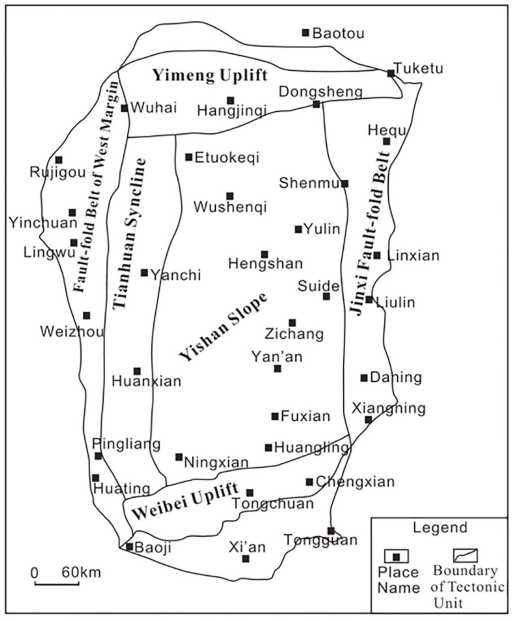

Figure 1. Sketch of regional tectonic division of Ordos basin.

The developed lithologies in Upper Paleozoic of Ordos basin are mainly coal seam, sandstone, mud shale, and few carbonatite. Benxi Formation, Taiyuan Formation, Shanxi Formation, Shihezi Formation, and Shiqianfeng Formation, from bottom to top, developed in sequence. Of them, Taiyuan Formation and Shanxi Formation are leading strata containing coal, followed by the development degree of Benxi formation (Table 2). Therefore, Taiyuan formation and Shanxi formation are also the most important target beds for exploration and exploitation of coal measures gases.

2 Coalbed methane

Coalbed methane resource in Ordos basin reached 10.72×10^{12} m^3 and accounted for about 1/3 of the country's total volume. Therefore, it played a significant role in the distribution of Chinese coalbed methane resource. In the basin, about 1/2 of the coalbed methane resources distribute in its eastern margin (Table 1), making the east margin of Ordos basin one of the most principal explored and exploited areas for coalbed methane in China. At the same time, it is also the area which is most explored in Ordos basin (Feng et al., 2002). At present, commercial exploitations for coalbed methane have been launched.

In eastern Ordos basin, it was well developed that Upper Paleozoic Carboniferous-Permian coal measure strata, the layers of coal seams are more, and the distribution is relatively stable. Coal seams concentratedly drawn up in Taiyuan Formation and Shanxi Formation. Of which Taiyuan Formation contains 3~7 layers of coal seams, and 2~4 layers can be exploited; total thickness is 4.3~7.1 m. Shanxi Formation contains 4~8 layers of coal seams, and 2~3 layers can be exploited; total thickness is 3.1~21.8 m. Burial depths of coal seams are less than 1500 m. In the eastern margin of Ordos basin, main coal seams overall take on a tendency of "thick north and thin south" (Zhang et al., 1996). The distributional ranges of coal are from long flame coal to meager coal, concentrating on medium rank coal. Moreover, the vitrinite reflectance Ro is between 0.5 and 2.2 % (Jie, 2010).

Table 2. Stratigraphic division and lithological developing characteristics of Upper Paleozoic in Ordos basin (Yan et al., 2013)

Stratum				Main lithology	Thickness (m)	main sedimentary facies
Upper Paleozoic	Permian	Upper series	Shiqianfeng Formation	mud shale, sandstone the upper is pelite	100~250	paralic lakes
		Middle series	Shihezi Formation	intercalating sandstone; lower is interbedded sandstone and shale	120~570	lakes, rivers
		Lower series	Shanxi Formation	coal seam, sandstone, mud shale	100~400	delta and tidal flat
	Carboniferous	Upper series	Taiyuan Formation	coal seam, sandstone, mud shale, and carbonatite	50~400	tidal flat
		Middle series	Benxi Formation	coal seam, interbedded sandstone and shale, intercalating carbonatite	0~560	lagoon and tidal flat

Table 3. Geological characteristics data of main coal seam of Upper Paleozoic in Ordos basin (Jie, 2010)

Permeability ($\times 10^{-3}$ μm^2)	Gas saturation (%)	Gas content (m^3/t)	Reservoir pressure gradient (MPa/100 m)	Coal seam desorbing pressure (MPa)
0.22~8	55~86	4~20.87	0.5~0.9	1.7~4.0

In this area, the fractures of cleats of main coal seam were comparatively developed; density of endogenetic fracture is 10~30 pieces/ 5 cm. Overall, the physical characteristics of coal reservoir are relatively favorable, and permeability of main coal seam is 0.22×10^{-3} μm^2 ~ 8×10^{-3} μm^2. Reservoir pressure gradient of the main coal seam is 0.5~0.9 MPa/100 m; coal seam desorbing pressure is 1.7 ~ 4.0 MPa; and gas saturation of coal seam is 55 – 86 % (Table 3) (Jie, 2010).

The gas-bearing feature of the coal seam is relatively favorable, and gas content of the main coal seam is 4 ~ 20.87 m^3/t. In particular, coalbed gas content of Weibei block is 6 ~ 14 m^3/t; the coalbed gas content of Linfen block is 9.03 ~ 20.87 m^3/t; the coalbed gas content of Lvliang block is 4 ~ 14 m^3/t (Jie, 2010). The above data suggests an excellent potential of coalbed methane resources.

Some scholars also studied the origin of coalbed methane in the eastern margin of Ordos basin. The studying results show that the methane carbon isotope distributes in -70.5 ‰ ~ -36.19 ‰ and evidently from north to south it gradually becomes weighting. Mixed gas, including resulting biogas and thermogenic gas, occurs in the peripheral and shallow part, and thermogenic gas is within the middle and profound part (Li and Zhang, 2013). Through the study of the origin of coalbed methane in Hancheng region of southeastern Ordos basin, Ma et al. (2011) discovered that the methane carbon isotope of coal seam was in -42.978 ‰ ~ -32.200 ‰ and ethane carbon isotope belonged to -21.619 ‰ ~ -9.751 ‰. Therefore, they considered that the origin type of coalbed methane in this region was predominantly thermal degradation gas.

3 Shale gas in coal measures

In Ordos Basin, Upper Paleozoic Carboniferous – Permian source rocks are predominantly dark mud shale; organic matter is abundant; thickness is stable; the distributional area is large; the maturity is high. The rocks of origin mainly distribute in Benxi Formation, Taiyuan Formation, and Shanxi Formation.

The total thickness of mud shale is relatively high, with that of dark mud shale in Benxi Formation averaging at about 29.3 m, that of Taiyuan Formation at 39.6 m and that of Shanxi Formation at 63.2 m (Table 4). The buried depth of Upper Paleozoic mud shale is between 2000 and 3500 m (Wang et al., 2011). Therefore, it provides an appropiate material basis for the formation of shale gas reservoir of coal measures, and its resource total extent is also tremendous.

Table 4. Geological characteristics data of mud shale of Upper Paleozoic in Ordos basin (Yan et al., 2013)

Horizons	thickness of single bed of mud shale (m)		total thickness of mud shale (m)		number of beds (layer)	
	distributional range	average	distributional range	average	distributional range	average
Shanxi Formation	2.1~64.5	4.5	13.3~168.4	63.2	10~35	15
Taiyuan Formation	1.0~47.0	3.3	5.6~93.5	39.6	7~20	6
Benxi Formation	1.5~49	3.8	6.3~96.0	29.3	8~19	6

Shale gas is an unconventional kind that is self-generation and self-preservation. Mud shale is not only a hydrocarbon-generating bed but also reservoir. Geological characteristics data of the shale of Upper Paleozoic in Ordos basin can be seen in Table 5. In the basin, the average organic carbon content of Upper Paleozoic mud shale reaches 1.72 %; kerogen type is mainly III; higher maturity of organic matter; Ro value distribute in 1.6 ~ 2.82 %, thus it belongs to the mature-postmature stage and begins to generate a large quantity of gas at present. The porosity is averagely 1.12 %; permeability is $0.037\times10^{-3}\mu m^2$. Brittle mineral content in shale is generally 46.51 % ~ 54.04 %; clay content, 43.61 % ~ 47.81 %. On the whole, Upper Paleozoic mud shale possesses the condition for shale gas reservoir to form (Wang et al., 2011; Yan et al., 2014). Gas-bearing coal rock - mud shale and gas-bearing tight sandstone - mud shale are the optimal source-reservoir-cap combination type (Yan et al., 2014).

Table 5. Geological characteristics of mud shale of Upper Paleozoic in Ordos basin (Zhang et al., 2012b; Guo et al., 2012; Yan et al., 2013; Yan et al., 2014)

Horizon	Lithology	Organic carbon(%)	Type of organic matter	T_{max} (°C)	Ro (%)	Porosity (%)	Permeability ($\times10^{-3}\mu m^2$)
Shanxi Formation	mud shale	0.72~29.18	III	486.88	1.6~2.82	1.12	0.037
Taiyuan Formation	mud shale	1.09~7.61	III	495.05			
Benxi Formation	mud shale	2.23	III	-			

The gas content of the mud shale is an important parameter. Several scholars have studied the gas content of Upper Paleozoic mud shale in Ordos basin, and the data were collated in Table 6. Usually, 1.0 m^3/t is taken as the lowest limit of industrial standard for the gas content of mud shale. From Table 6, it can be known that gas content of mud shale in Shanxi Formation distribute in 0.96 ~ 2.71 m^3/t and the average value is 1.94 m^3/t, therefore, exceeding the minimum threshold of industrial standard. However, gas content of the mud shale of Benxi formation of Mi 35 well is slightly low, and this preliminarily reflects that the reservoir forming conditions of mud shale of Shanxi Formation are more favorable than Benxi Formation. In Xiasiwan – Yunyan region of eastern basin, gas measure and groove face of the dark mud shale interval of Shanxi Formation from more than 30 wells show active, and display good gas indicator and produced low-yield industrial gas flow (Fig. 2) (Gong et al., 2013).

Table 6. Gas content characteristics of partly Upper Paleozoic mud shale in Ordos basin (Wang et al., 2011; Fu et al., 2013; Gong et al., 2013)

Gas content (m^3/t)	Shanxi Formation	Yunyan region Shanxi Formation	Su 373 well Shanxi Formation	Mi 35 well Shanxi Formation	Mi 35 well Benxi Formation	x24 well Shanxi Formation
distributional range	0.96~2.71	1.0~5.2	0.18~0.52	0.21~1.08	0.45~0.74	0.28~1.78
average value	1.94	-	-	-	-	-

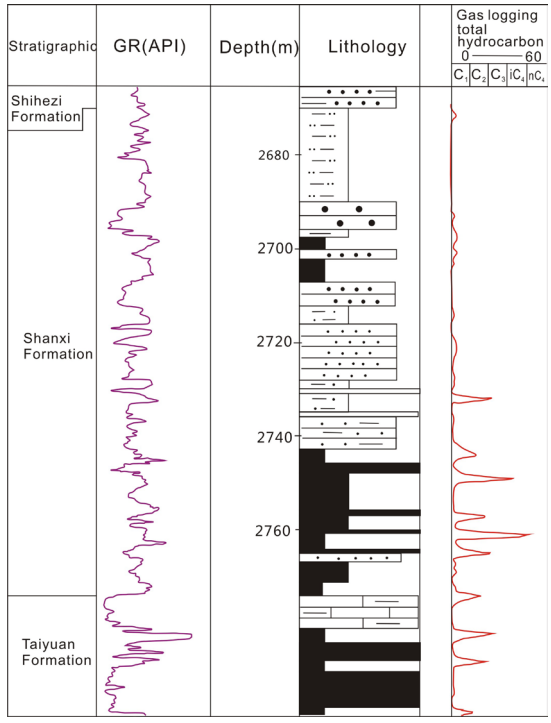

Figure 2. Gas logging of Shanxi formation of X24 well in eastern Ordos basin (Gong et al., 2013)

Several suits of mud shale developed in Ordos basin. Middle Ordovician Pingliang Formation is difficult to form a large scale of shale gas reservoir; Triassic Yanchang Formation mud shale possesses the reservoir forming condition for shale gas and tight oil. However, exploration potential of the tight oil is broader; Carboniferous-Permian sea-continental transitional facies shale is relatively favorable for shale gas reservoir. It is also the most certain strata series for exploration of shale gas (Wang et al., 2011).

4 Tight sandstone gas

Tight sandstone gas resource of Upper Paleozoic coal measures in Ordos basin is very enormous, and the resource is preliminarily estimated to be more than $5x10^{-12}$ m^3 (Table 1). Upper Paleozoic in the basin extensively developed fine sandstone, siltite, argillaceous siltite, and other tighter sandstone. Porosity and permeability of these sandstones average at 6.58 % and 0.77×10^{-3} μm^2, respectively (Deng, 2003). For these reasons, they belong to low porosity and low permeability tight sandstone. In Ordos basin, it was developed that the fluvial-delta facies tight sandstone reservoir of Shanxi Formation and Shihezi Formation (Fig. 3), thus this paper mainly discussed the geological characteristics of tight sandstone in these two horizons. The thickness of the sandstone is large, Linxing area may be taken as an example. In this area, the thickness of Taiyuan formation reaches 4.0 ~ 40.89 m, additionally the thickness of Shanxi formation is larger than of Taiyuan formation and the distributional scope is also wider (Guo et al., 2012). The tight sandstone of coal measures staggeringly developed with mud shale and coal seam and adjoins gas source rock; therefore, it possesses the potential of tight sandstone gas. Currently, exploration in Ordos basin has made a significant breakthrough and entered the scale development stage.

The lithologic character of Shanxi Formation is mainly feldspar debris quartz sandstone, followed by a few of feldspathic lithic sandstone and lithic sandstone. Cement is predominantly silicic, and calcite cementation; grain-supported structure; type of cementation includes mainly pore and mosaic cementation (Fig. 3). Box 8 segment is chiefly feldspar debris quartz sandstone; apart from that, it also consists of a few of lithic sandstone and lithic quartz sandstone (Zhou et al., 2013).

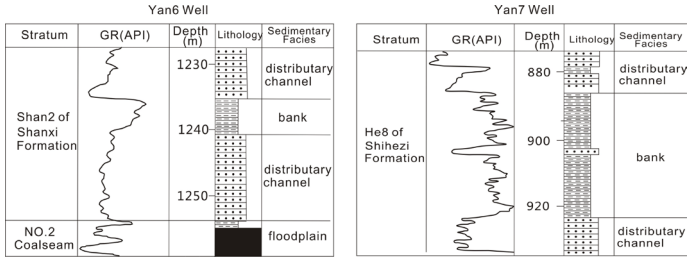

Figure 3. Developed characters of tight sandstone of coal measures in Ordos basin (Zhou et al., 2013)

When the organic matter of coal measures transformed to hydrocarbons, organic acid was constantly produced, therefore coal measures strata are rich in organic acid. Organic acid has a greater impact on the diagenesis of tight sandstone reservoir because organic acid may corrode feldspar to form a secondary pore. Organic acid plays an active and constructive role in improving the physical properties of tight sandstone reservoir.

In the basin, average porosity of the sandstone in Taiyuan Formation is 8.2 % and the permeability, porosity and permeability of Shanxi Formation average at $0.58\times10^{-3}\mu m^2$, 7.2% and $7.68\times10^{-3}\mu m^2$, respectively. Also, the median porosity of sandstone and permeability in Shihezi Formation are 9.2 % and 10.42×10-3μm2 (Table 7). Therefore, physical properties of the sandstone of Shihezi Formation are better than those of Shanxi formation and those of Taiyuan Formation are comparatively poor. Meanwhile, coal measures tight sandstone staggeringly deposited and developed with coal seam and dark mud shale riching organic matter (Fig. 2) to make a favorable condition for source rocks of tight sandstone. The gas show active in tight sandstone of Upper Paleozoic in Ordos Basin and especially in Linxiang Area(Xie et al., 2016;Liang et al.,2016b). In the southern basin, tight sandstone of segment 6 of lower Shihezi Formation underwent fracturing testing to attain daily capacity 8457 m^3 gas flow, thus, it exhibits excellent exploration potential of tight sandstone gas. Sandstone of Shan 2 segment of Yan 6 well is 12 m thick (Fig. 3). Logging showed gas anomaly, log interpretation revealed that gas reservoir was 8 m, the daily capacity including the underlain No. 2 coal seam was 6 000 m^3 gas flow (Zhou et al., 2013).

Table 7. Physical properties characters of coal measures tight sandstone of Upper Paleozoic in Ordos basin (Fu et al., 2013)

Horizon	number of sample (piece)	Porosity (%)		Permeability ($\times10^{-3}\mu m^2$)	
		distributional range	average	distributional range	average
Taiyuan f Formation	31	5.6~12.0	8.2	0.12~4.50	0.58
Shanxi Formation	40	5.1~9.8	7.2	0.12~106	7.68
Shihezi Formation	35	6.1~14.6	9.2	0.15~25.85	10.42

5 Reservoir formation model

Unconventional gas in coal measures belongs to "continuous oil and gas reservoir", which belongs to different types. Reservoirs of coalbed methane, shale gas, and tight sandstone gas are coal rocks, mud shale, and sandstone respectively, and all of these different types of reservoirs coexisted in the same coal-bearing series. Their source types, such as sedimentary environments, structural, thermal evolutions, were in remarkable consistency. Therefore, unconventional gas in coal measures possesses paragenesis characteristics in the same basin (Cao et al., 2014).

In coal measures, coal seam and dark mud shale are rich in organic matter, which constitutes source rocks of unconventional gas in coal measures. When these organic matters reach the threshold of hydrocarbon formation to generate gaseous hydrocarbon, and then it may supply hydrocarbon for coal seam, mud shale, and tight sandstone to altogether form gas reservoirs of a coal seam, shale, and tight sandstone respectively (Fig. 4.). However, gas reservoirs of the coal seam and shale belong to self-generation and self-preservation type that display no straightforward migration process. Therefore, they are distinctly different from the formation of the conventional oil-gas reservoir. The hydrocarbon gasses generated from coal seam and mud shale migrate to tight sandstone via a short-distance to gather into reservoir. Therefore, the formation of tight sandstone gas reservoir of coal measures is similar to that of the conventional oil-gas reservoir. The slight difference that exists is that reservoir bed of tight sandstone gas reservoir of coal measures is close to hydrocarbon source rock bed, and the migration distance of natural gas is shorter than that of oil and gas of conventional oil-gas reservoir.

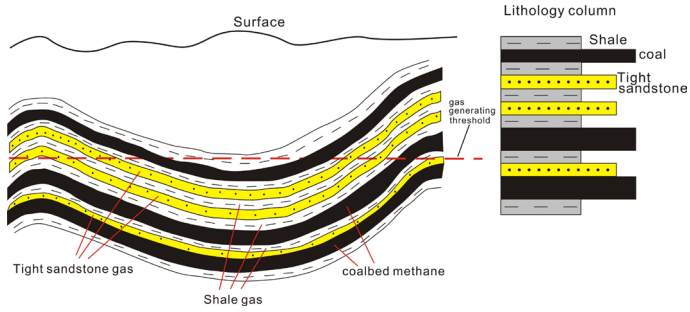

Figure 4. Gas reservoir model of Upper Paleozoic coal measures in Ordos basin(Wang et al.,2014;Cao et al.,2014)

6 Conclusions

(1) In Ordos basin, unconventional gas in coal measures, e.g. coalbed methane, shale gas and tight sandstone gas, developed in Upper Paleozoic, and the resources amounts are enormous. The geological condition of Ordos basin is favorable for three kinds of gasses occur together. Therefore, at a later stage, the research on joint exploration and exploitation of the three types of gasses ought to be carried out.

(2) Unconventional gas of Upper Paleozoic coal measures mainly distributes in the eastern Ordos basin. Currently, the geological studying level to the coalbed methane in the eastern Ordos basin is relatively high, and several areas have entered the commercial development stage. Whereas studying level to the shale gas and tight sandstone gas of coal measures in this region are relatively small. Available data indicate that in this region the oil gas shows of Upper Paleozoic mud shale and tight sandstone are favorable, and resource potential is conspicuous, about which further work is needed

(3) Unconventional gas of coal measures is accumulated through slightly different processes, of which coalbed methane reservoir and shale gas reservoir of coal measures belong to "self-generation and self-preservation", and the gas migration process almost did not happen. Whereas the coal measures tight sandstone gas reservoir belongs to "allogenic, and self-preservation" and the natural gas experienced a short distance migration. Although reservoir types of coal measures unconventional gas belonging to the same suit of strata are different, the forming factors of the gasses reservoir are closely related and uniform. Therefore, it will be more scientific and reasonable that the geological reservoir-forming processes of three different kinds of unconventional gas of coal measures are studied as a whole.

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