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RESEARCH PAPER

Upper Paleozoic coal measures and unconventional natural gas systems of the Ordos Basin, China

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Abstract Upper Paleozoic coal measures in the Ordos Basin consist of dark mudstone and coal beds and are important source rocks for gas generation. Gas accumulations include coal-bed methane (CBM), tight gas and conventional gas in different structural areas. CBM accumulations are mainly distributed in the marginal area of the Ordos Basin, and are estimated at 3.5×10^{12} m^3. Tight gas accumulations exist in the middle part of the Yishan Slope area, previously regarded as the basin-centered gas system and now considered as stratigraphic lithologic gas reservoirs. This paper reviews the characteristics of tight gas accumulations: poor physical properties (porosity < 8%, permeability $< 0.85 \times 10^{-3}$ μm^2), abnormal pressure and the absence of well-defined gas water contacts. CBM is a self-generation and self-reservoir, while gas derived from coal measures migrates only for a short distance to accumulate in a tight reservoir and is termed near-generation and near-reservoir. Both CBM and tight gas systems require source rocks with a strong gas generation ability that extends together over wide area. However, the producing area of the two systems may be significantly different.

1. Introduction

With increasing fossil fuel consumption, unconventional resources are becoming more important. The Ordos Basin is the second largest coal-bearing basin and the third largest natural gas-producing basin in China. The Upper Paleozoic coal-bed methane (CBM) resource of the basin is estimated to be 3.5×10^{12} m^3 (almost 1/3 of total CBM resource in China) and the in-situ tight gas resource is 3.36×10^{12} m^3. These rich, unconventional gas resources make the Ordos Basin special in comparison with other gas-producing basins in China. There are numerous papers on the characteristics and distribution of Upper Paleozoic natural gas accumulations in the Ordos Basin (Lei and Zhang, 1998; Li et al., 2000; Min et al., 2000;

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Sun et al., 2001; Shi and Yu, 2002; Wang et al., 2003; Hou et al., 2004; Zhang et al., 2004b; Xiao et al., 2005). There is general consensus on the distribution and concentration of CBM accumulations (Zhao et al., 1998; Wang et al., 1998; Feng et al., 2002; Su et al., 2003), but understanding and exploration of the tight gas accumulations in the Ordos Basin are unresolved and incomplete, and there is disagreement concerning the mechanism and controlling factors of gas accumulation. Some geologists consider that the natural gas accumulations are of deep basin origin (Li et al., 1998; Min et al., 2000; Sun et al., 2001) following the classic basin-center gas model (Law and Curtis, 2002), which presumes the whole northern part of the Yishan Slope area of the basin as a single gas system. Others consider that the natural gas accumulations are conventional stratigraphic lithologic reservoirs (Fu et al., 2000; Yang et al., 2008). Reservations about the model of basin-centered gas accumulations have been expressed by Shanley et al. (2004) and Camp (2008), and Meckel and Thomasson (2008) had simplified the criteria for definition of tight gas accumulation. In this paper, we review the Upper Paleozoic gas accumulations in the Ordos Basin as a whole and re-identify the controlling factors.

2. Geologic setting

The Ordos Basin, 26×10^4 km^2, is located in the central part of the North China Plate, and is a large asymmetric syncline with a broad gently-dipping eastern limb and narrow, steeply-dipping western limb, and with the Tianhuan Sag forming the axis. Tectonically, the basin can be subdivided into six sub-structures: the Weibei Uplift in the south, Yimeng Uplift in the north, Jinxi Fold Belt in the east, the Tianhuan Sag and western edge thrust belt in the west, and Yishan Slope in the central part (Fig. 1). The Yishan Slope has a 2°−3° dip and covers the greatest area of the basin. Folds and faults are well developed in the marginal areas and are associated with igneous rocks.

The Ordos Basin has experienced four evolutional stages: Early Paleozoic shallow marine platform, Late Paleozoic offshore plain, Mesozoic intra-continental basin and Cenozoic faulting and subsidence (Zhang et al., 1995; Yang and Pei, 1996). Lower Paleozoic carbonate rocks were deposited unconformably on Silurian and Devonian strata overlying Archeozoic and Proterozoic metamorphic basement rocks. During the Late Paleozoic, ca. 600−1700 m of marine and marine-terrestrial sediments were deposited (Fig. 2). During the Mesozoic, the structural framework of the basin was largely developed and the source rocks buried to gas generation window depths. Subsequent late Mesozoic regional uplift terminated hydrocarbon generation. During the Cenozoic, subsidence began in which the margins of the basin were delineated by faults to produce the present tectonic framework of the Ordos Basin (Guo et al., 1994).

Late Carboniferous−Early Permian coal measures are widespread, and rich in organic matter, in which type III kerogen is predominant. Fluvial-deltaic sandstone of the coal measures has low porosity and permeability. Mudstone of the lower Shihezi Formation form the local caprocks with shale and mudstone of the upper Shihezi Formation and Triassic rocks form the regional caprocks (Fig. 2).

3. Coal measures

3.1. Distribution

Upper Paleozoic coal measures of the Ordos Basin are mainly developed in the middle Carboniferous Taiyuan Formation and

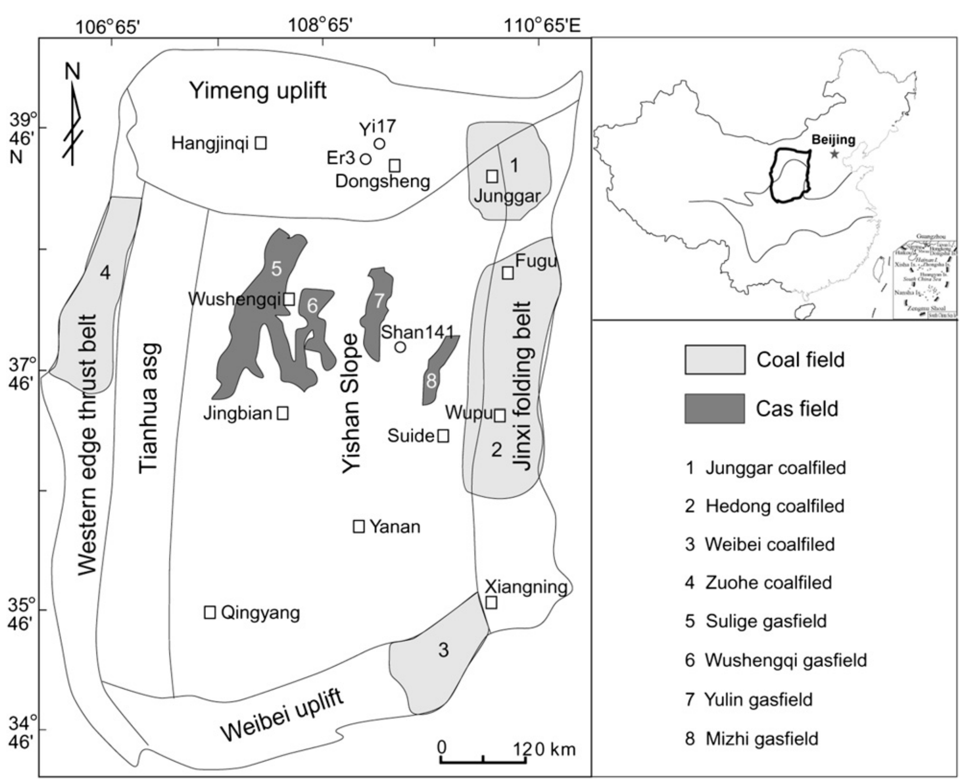

Figure 1 Map of the Ordos Basin showing structural divisions and distribution of Upper Paleozoic gas fields.

Early Permian Shanxi Formation. The coal beds are ordered from 1 to 10 from the top to the bottom, respectively (Fig. 2). Coal measures extend over most of the basin and are thickest in the western part, thinner in the eastern part, and thinnest in the middle part (Fig. 3A). In the upper part of the Taiyuan Formation, five to eight coal beds have variable thickness. The average thickness is 6.7 m in the eastern margin of the basin (coal beds Nos. 8, 9 and 10) and decrease in thickness southward to Xiangning County, where they are not suitable for mining. Coal beds in the Shanxi Formation also have variable thickness, e.g., the coal beds No.4 and 5 in the Donghe coalfield have an average thickness of 7.82 m, but the thickness of No.3 coal bed in the Weibei coal field ranges from 5 to 0.8 m (Fig. 3A).

3.2. Maceral composition of coal

The maceral composition of the Upper Paleozoic coal measures, consists of ∼58%–79% vitrinite, ∼14%–43% inertinite, and ∼6%–15% exinite (Wang, 1996; Yang et al., 1997). Vitrinite makes up more than 60% of the marceral component in the Taiyuan Formation that extends over most of the Yishan Slope area, and in the eastern and western margin of the basin the vitrinite content is >80% (Dai et al., 2006).

3.3. Organic matter abundance

The organic carbon component of the amount of total carbon of the coal beds is ∼ 53.48%–63.13% and between ∼ 1.92%–2.34% in associated dark mudstone. Extract bitumen “A” and total hydrocarbon (HC) in the coal measures also has high organic matter (Table 1).

3.4. Organic matter thermal evolution

Thermal evolution history of the Upper Paleozoic coal measures varies widely in different areas of the Ordos Basin. During the Late Jurassic, only coal measures in the southern area of the Yishan Slope matured and produced significant gas with $R_0 > 1.0\%$. In the Early Cretaceous, coal measures of the Yishan Slope entered the main stage of gas generation that was interrupted between 90 and 70 Ma due to basinal uplift. At this time, source rocks in the Tianhuan Sag continued to generate gas. The Carboniferous–Permian source rocks re-entered their main stage of gas generation during Early Cretaceous subsidence of the basin (Zhao et al., 1996; Xiao et al., 2005). At the Present time all the Carboniferous–Permian coal in the Ordos Basin has reached the stage of thermal maturation. Coal rank increases from flame coal (vitrinite reflectance R_0 0.58%) in the northeast Junggar Coalfield to anthracite (vitrinite reflectance R_0 3%) in the southwestern part of the Yishan Slope. Most coal beds of the Yishan Slope have vitrinite reflectance R_0 values ranging from 1.20% to 2.8% (Fig. 3B).

3.5. Gas generation capacity

Hydrocarbon generation kinetic experiments using samples from the Upper Paleozoic coal measures show they have potential for

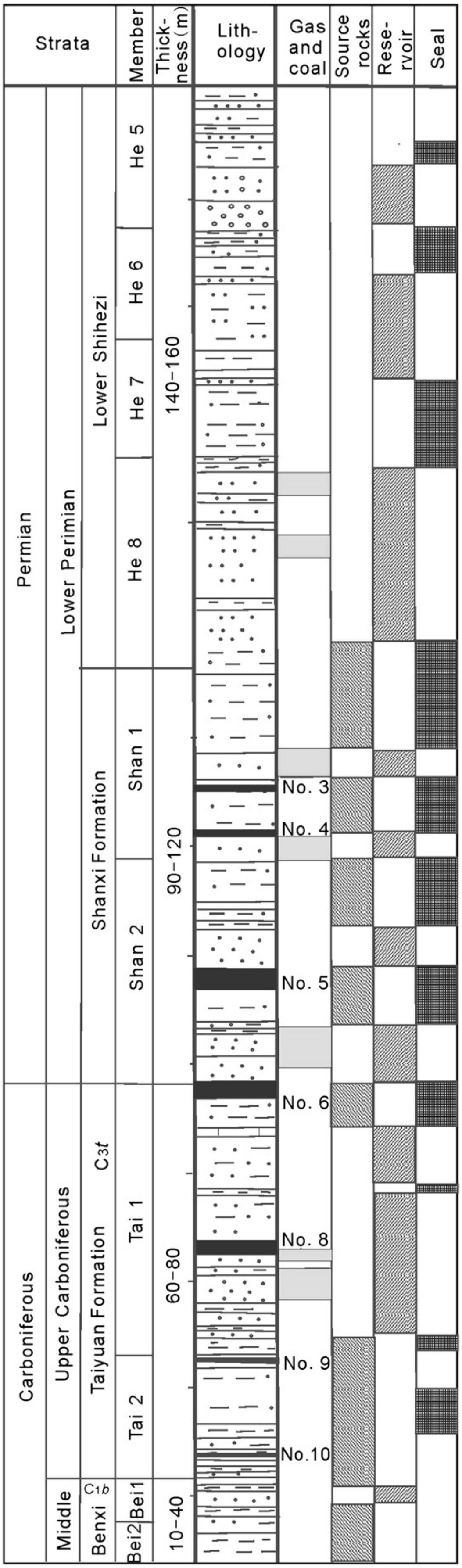

Figure 2 Upper Paleozoic chronolithology and gas-bearing layers in the Ordos Basin (data collected from Li et al., 2000; Dai et al., 2006; Dai et al., 2007; Yanghua et al., 2008).

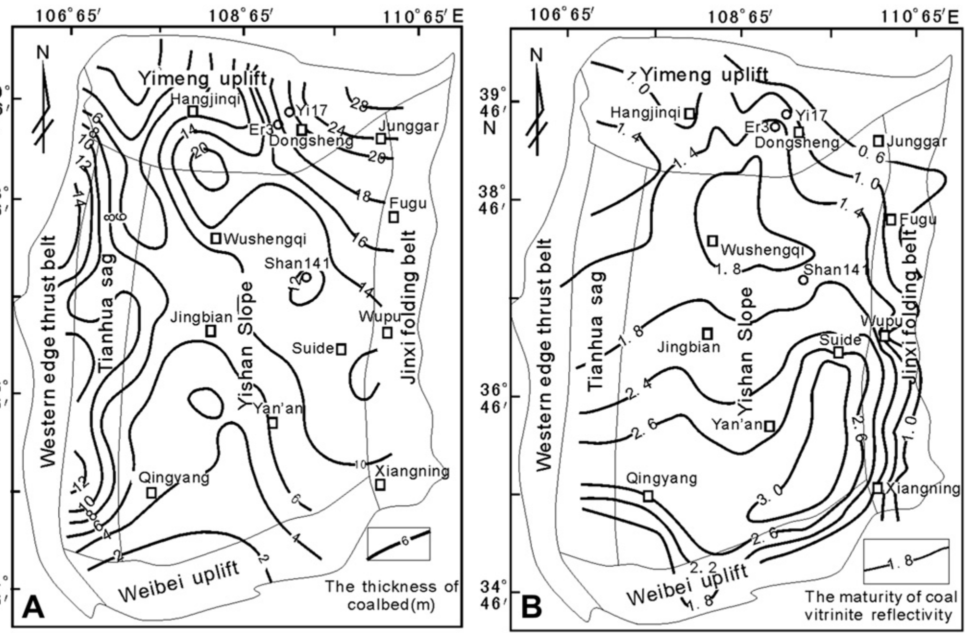

Figure 3 Upper Paleozoic coal bed thickness and rank in the Ordos Basin. A: coal thickness, data from Wang (1996); B: coal rank, data from Yang et al. (1997).

gas generation (Table 2). S_1+S_2 of the coal can amount to 71.9–78.1 mg·HC/g·TOC and the hydrocarbon transform ratio is 6.9%–11.2% (Dai et al., 1997). The gas generation intensity of the coal measures shown in Fig. 4 indicates that gas generation area extends over a wide area of the middle part of the Ordos Basin.

According to the latest national resource assessment estimate, the accumulative gas generation volume amounts to 503.32×10^{12} m^3, in which gas generation volume of the Yishan Slope is the highest at 56%, the Jinxi fold and fault belt at 15% and 29% for the remaining four structural parts of the basin. Accumulative gas generation intensity is highest in Jinxi fold and fault belt with 33.17×10^8 m^3/km^2, followed by 27.45×10^8 m^3/km^2 in the Yishan Slope, and 7.65×10^8 m^3/km^2 in the Yimeng uplift zone.

4. Coal bed methane (CBM)

A considerable thickness of high quality source rocks provides abundant gas supply for CBM accumulation. In addition, the gas adsorption capacity and reservoir properties of the coal measures such as permeability, fracture density, pressure gradient hydrologic setting and the sealing conditions also play very important roles in impact CBM accumulations (Johnson and Flores, 1998; Zhao et al., 1998; Ayers, 2002; Scott, 2002). Wang (1998) summarized four criteria to judge whether target areas have high gas concentration and high yield: (1) stable tectonic conditions and sedimentation; (2) coal rank higher than long flame coal and lower than anthracite; (3) accumulative coal bed thickness > 10 m, with single coal bed thickness > 1 m, and where coal bed methane concentration is >4 m^3/t; and (4) coal seam depth between 300 and 1500 m.

4.1. Gas adsorption capacity

Data of gas adsorption capacity in the Ordos Basin are given in Table 3. The table shows that the eastern edge of the basin has considerable gas-bearing content although it varies with location.

4.2. CBM accumulation

Here we take the Hedong coal field as an example to give a brief introduction of CBM accumulation in the Ordos Basin. Upper Paleozoic coal beds in the eastern margin of the basin consist of 3–7 coal beds in the Taiyuan Formation (with total thickness of 4.3–14.6 m) and 4–8 coal beds in the Shanxi Formation (with total thickness of 3.1–12.8 m) (Feng et al., 2002). There were numerous wells drilled for assessing CBM accumulation in the Ordos Basin. Seven wells drilled in the Liulin area produce 1000–3000 m^3/t per day of coal bed methane, and one even more than 7000 m^3/t per day. Some wells drilled in the Hancheng area

Table 1 Organic abundances of Upper Paleozoic coal measures, Ordos Basin (from Dai et al., 1997).

Formation	Lithology	Organic C (%)	"A" (%)	HC($\times 10^{-6}$)
Shanxi	Coal	53.48	0.6469	2406.6
	Dark mudstone	1.92	0.0633	195.84
Taiyuan	Coal	63.13	0.8519	3219.63
	Dark mudstone	2.09	0.0706	227.2
Benxi	Coal	62.97	1.0782	2896.2
	Dark mudstone	2.34	0.1004	348.6

Table 2 Gas generation capacity of Upper Paleozoic coal, Ordos Basin.

Sample	Formation	Kerogen Type	Vitrinite (%)	Exinite (%)	Inertinite (%)	R_o (%)	C_{1max}(mL/g kerogen)	$C_{2\sim 5max}$(mL/g kerogen)
Palougou	Tianyuan	III	55	15	35	0.66	210	25
Zhao8	Shanxi	III	38	2	60	0.88	225	65

C_{1max} and $C_{2\sim 5max}$ refer to the maximum CH_4 and hydrocarbon with carbon number from 2 to 5 generated from kerogen and hydrocarbon cracking (data from Fu et al., 2003).

produce over 1000 m^3/t per day (Feng et al., 2002; Su et al., 2003). In the central part of the Hedong coal field, from Fugu in the north to the Suide-Wupu in the south, the burial depth of coal increases, coal rank becomes higher, the hydrodynamic activity gradually disappears along with improvement of the sealing effectiveness. This results in an increase of CH_4 content in the CBM accumulations i and a decrease in associated water production (Table 4). The $\delta^{13}C_1$ of CBM accumulations in Fugu is low, suggesting a predominance of biogenetic-derived gas. $\delta^{13}C_1$ becomes higher southward (up to −30‰), indicating increasingly more thermogenic-derived gas (for a discussion of the relationship of $\delta^{13}C_1$ in CBM reflecting its origin see Clayton, 1998). The trend of $\delta^{13}C_1$ in the gas could be a function of coal maturity and biogenetic process which are closely related to the burial depth and hydrodynamic activity.

4.3. CBM resource

The Hedong, Weibei and Zuohe coal fields are considered to be the preferable areas for Upper Paleozoic CBM accumulation

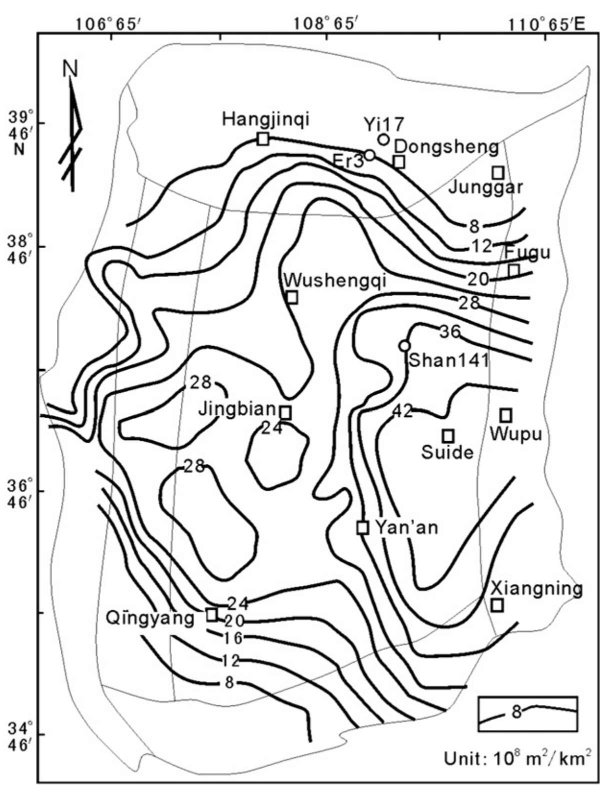

Figure 4 Upper Paleozoic gas generation intensity contours, Ordos Basin.

(Fig. 1). The latest national coal bed methane resource estimate for the Upper Paleozoic rocks of the Ordos Basin is listed in Table 5, and the approximated total resource of CBM could be 3.5×10^{12} m^3 (Yang et al., 1997).

5. Tight gas

Deep basin gas accumulation used to be the popular term widely used to characterize gas accumulations in the Upper Paleozoic tight reservoirs of the Ordos Basin (Zhang et al., 1994, 2004b; Yang et al., 1997; Min et al., 2000; Sun et al., 2001; Wang et al., 2003). Such gas accumulations are also referred to as tight gas, basin-centered gas (Law and Curtis, 2002), or source-contacting gas (Zhang et al., 2003, 2004a). Law and Curtis (2002) proposed a classic model of basin-centered gas defined by regionally pervasive gas accumulation, abnormal pressure, lack of down-dip water contact and a low-permeability reservoir. However, new observations require this model to be modified (Meckel and Thomasson, 2008; Camp, 2008). Cumella et al. (2008) simplified the criteria for basin-centered gas accumulations, viz: (1) low-permeability sandstone reservoirs; (2) abnormal original reservoir pressure; and (3) gas saturated reservoirs lacking well-defined gas−water contacts. Thus, new basin-centered gas models need not rely on accumulation size (i.e., regionally pervasive), trap mechanism (i.e., lateral capillary seals), or amount of water production. The classic basin-centered gas accumulations model has been used to explain natural gas accumulations developed over a wide area of the Yishan Slope (Li et al., 1998; Min et al., 2000; Sun et al., 2001), but it can not provide a reasonable explanation for a number of new observations such as the presence of multi-pressure systems, complicated gas-water contacts, etc. Therefore, geologists have come to the conclusion that the gas accumulations in the Ordos Basin are not unconventional gas accumulations but stratigraphic lithologic reservoirs (Fu et al., 2000; Yang et al., 2008).

5.1. Reservoir distribution and property

Upper Paleozoic clastic reservoirs consist of coarse-grained sandstone and glutenite interbedded with coal beds, coal seams and shale, developed in the delta or fluvial plain environment. Fig. 5 shows the distribution of a tight reservoir from the Shan 2 member of the Shanxi Formation across the most of the central − northern part of the Ordos Basin. The sandstones are quartz-rich, frequently interbedded with shale or silty sandstone, and are in contact with coal measures(Fig. 1; Fu et al., 2000; Xiao et al., 2005). The porous-type of sandstone consists of primary inter-grain pores, secondary pores and micro-fractures. The widespread sandstones are a typical tight reservoir with poor petrophysical properties, i.e., average porosity < 8%, average permeability < 0.8×10^{-3} μm^2.

Table 3 Coal bed methane in various permo-Carboniferous coal districts, Ordos Basin.

Coal fields	District	Gas-bearing content (m^3/t)	
		Coal Science Research Institute, Xi'an Branch (2000), cited from Feng et al. (2002)	Zhang and Li (1996)
East edge of Ordos Basin	Fugu	<5	2.11–2.73
	Liulin-Wubao	2.46–18.36	2.46–17.76
	Xiangning	3.18–4.19	0.12–29.25
Weibei	Hancheng	4.53–23.25	
	Chenghe	4.05–11.97	
	Tongchuan	5.52–6.44	
Zuohe	Shizuishan	3.5–8.4	
	weizhou	4.12–7.2	

Data from Zhang and Li (1996), Feng, et al. (2002), Hu, et al. (2004), Wang, et al. (2003).

Table 4 CBM composition and isotope composition in Hedong coalfield, Ordos Basin.

District	Depth (km)	Hydro-dynamic condition	Capping quality	Gas phase	CH_4 (%)	Non-HC (%)	$\delta^{13}C_1$ (‰)	water/gas ratio
Fugu	<0.4	Active	Poor	Dissolved	<75	>25	−70 to −55	>>1
Liulin	0.4–0.6	Weak	Poor	Dissolved- adsorbed	75–98	2–25	−65 to −59	>1
Suide-Wupu	0.6–1.8	Weak	Good	Adsorbed -free	>98	<2	−50 to −30	<<1

Data from Zhao et al. (1998).

Only in one part of the Yimeng area is there a local high permeability sandstone reservoir and few structural gas traps (Fu et al., 2000).

5.2. Composition and isotopic nature of gas

The gas-bearing area in the Upper Paleozoic is estimated to be 20×10^4 km^2, covering nearly 80% of the Ordos Basin. Statistical data up to 2002 shows that 98% of wells drilled in the middle part of the Yishan Slope encountered gas layers or gas-bearing layers (Wang et al., 2002). So far, four large-sized gas fields with reserve in the amplitude of 10^{12} m^3, termed as Sulige, Wushenqi, Yulin, and Mizhi gas fields have been discovered (see Fig. 1 for locations). Studies of the natural gas composition, isotopes, and distribution in these gas fields have been carried out by Yuan et al. (2000), Xiao et al. (2005), Yang, et al. (2004). Dai et al. (2005), and Xu and Shen (1996). The gas has CH_4 content of 87.5%–93.86%, with only insignificant light hydrocarbon and condense oil (Xiao et al., 2005). The $\delta^{13}C_1$, $\delta^{13}C_2$, $\delta^{13}C_3$ values of the gases range from −34‰ to −32‰, −27‰ to −23‰, and −25‰ to −24‰, suggesting the gas is derived from coal measures (Dai et al., 2005).

5.3. Water-gas contact

Water-gas contacts are complicated over the whole basin, and allow division of basin into three zones: (1) gas zone, (2) gas water transition zone and (3) water zone. Reservoirs in the Yishan Slope area are mostly gas saturated with gases and contain no water. Eastward and northward the reservoirs grade into a water-gas zone over a distance of ∼20–30 km. The water zone is distributed along the eastern and northern edges of the basin, and has a width of 40–50 km (Xiao et al., 2005). It is estimated that in the down-dip position of the basin, 86%–97% of the Upper Paleozoic tight gas sandstone reservoirs contain gas without water except in a few wells (Li et al., 1998), 61% of sandstone reservoirs from the Yimeng Uplift area, and 100% from the Jinxi fault-fold belt in the up-dip area of the basin contain gas and water, or water only, which defines the transitional and water zones (Li et al., 1998).

Table 5 Coal bed methane resource, Ordos Basin.

Coalfield	Area (km^2)	Coal bed methane ($\times 10^8$ m^3)	Gas resources at various depths ($\times 10^8$ m^3)		
			300–1000 m	1000–1500 m	1500–2000 m
Hedong	16310.68	19962.27	5025.69	5860.48	9076.11
Weibei	7467.39	7011.02	1209.23	2134.25	3667.54
Zuohe	4357.48	7829.14	1362.28	1904.38	4562.47

Data from Feng et al. (2002).

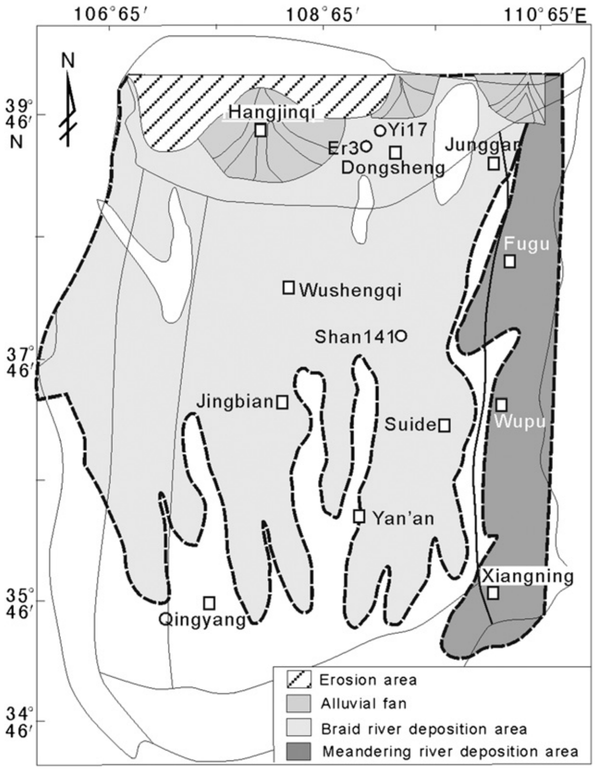

Figure 5 Distribution of tight gas reservoirs, Shan 2 member, Ordos Basin (from Zhang et al., 2009).

5.4. Formation pressure

DST data shows that the northern part of the Yishan Slope has a pressure coefficient (C_p) ranging from 0.83 to 0.95 and has abnormal negative pressure, whereas in the Yimeng Uplift and the Jinxi Fault-Fold Belt areas the pressure coefficient (C_p) ranges from 0.95 to 1.15 with a normal pressure (Xiao et al., 2005). Widespread under-pressure over the Yishan Slope gas fields in Yishan Slope is further evidence of unconventional gas accumulations.

5.5. Migration events and distance

In general, there were three phases of diagenesis and hydrocarbon charging in the Upper Paleozoic reservoir, i.e., in the Late Triassic (152–141 Ma), Late Jurassic (123–120 Ma) and at the end of the Early Cretaceous (110 Ma). Except for the Wushenqi (Uxiqi) gas field that experienced three fluid charge events, the Sulige and Mizhi gas fields indicate two events of fluid charge, in the late Triassic and late Jurassic (Fan, 2004). Only occur one gas injection event occurred in the Yulin gas field, probably at the end of Cretaceous (Fan, 2004). The diagenesis history of the Yulin gas field indicates that two phases of diagenesis occurred before gas injection. Acidic waters are believed to have entered the reservoir and caused dissolution and cementation, resulting in an increase in porosity in the Late Triassic and Late Jurassic (Zhang et al., 2007).

Previous studies considered the probability of long-distance (basinal-scale) migration of tight gas (Mi et al., 2003; Xiao et al., 2005). However, from the correlation between contours of coal

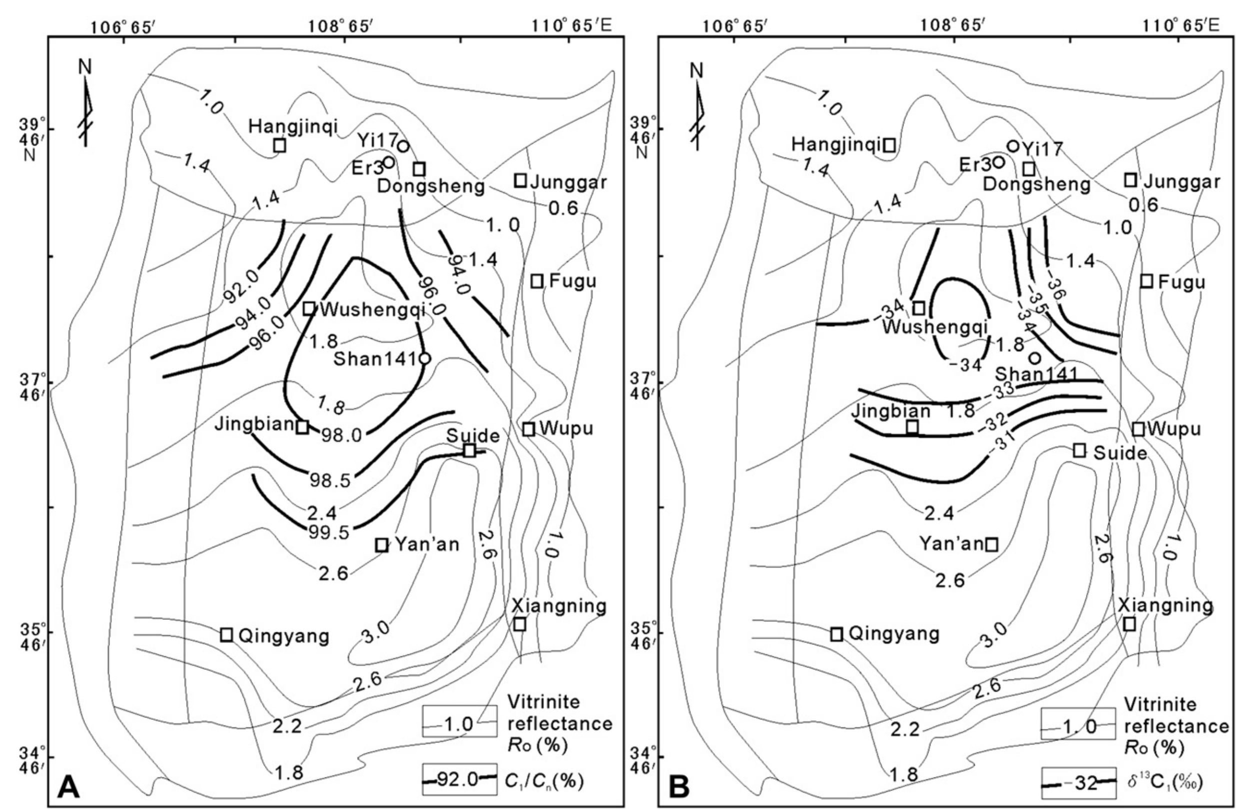

Figure 6 Maturity (vitrinite reflectance) of coal measures versus tight gas methane coefficient (A) and versus isotopic composition (B), Ordos Basin (data from Yang et al., 2004).

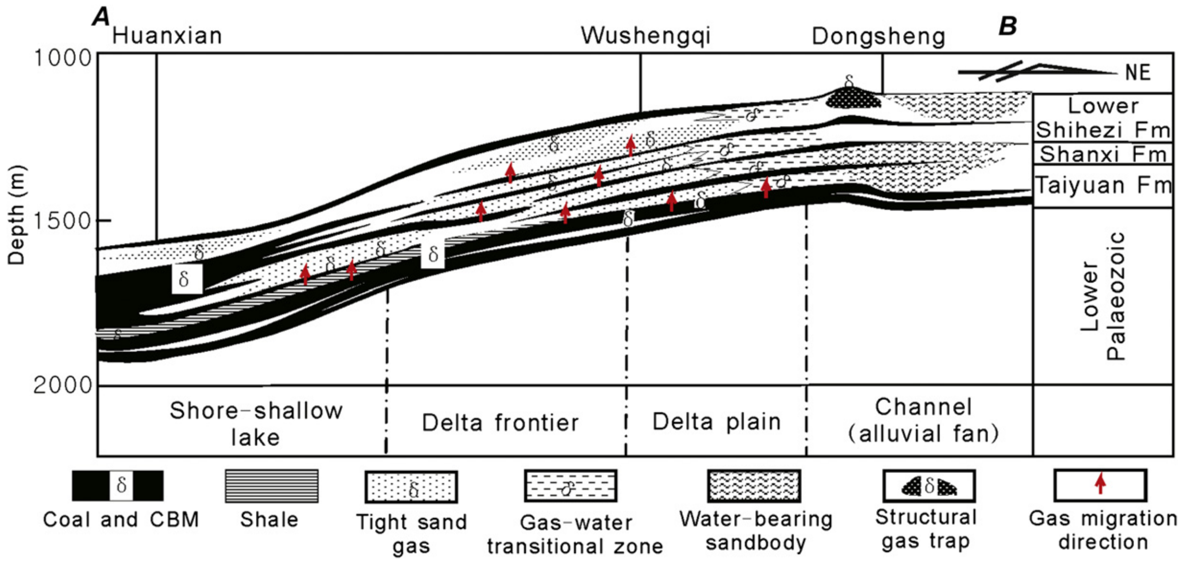

Figure 7 Schematic profile of CBM and tight sand gas accumulations, Ordos Basin.

Table 6 Comparison of unconventional gas accumulations in Upper Paleozoic rocks, Ordos Basin.

	Coal bed methane	Tight gas
CH_4 content (%)	75–98	87.5–93.38
$\delta^{13}C_1$ (‰)	−70 to −30	−34 to −32
Origin	Biogenetic and thermogenic derived	Thermogenic derived
Source rocks	Coal measures 1) Passed gas generation or gas-expulsion window. 2) Self-reservoir or adjacent or very close to the reservoir. 3) Rich in organic matter.	
Reservoir	Self-reservoir; Permeability between (0.29 −8.86) × 10^{-3} μm^{-2} (Liulin-Wupu County) The fracture (cleats) density and porosity well developed	Porosity 4%–8%; Permeability (0.1–1) × 10^{-3} μm^{-2} Low porosity reservoir; Sweet spot developed in relatively high porosity area
Formation pressure (pressure coefficient)	0.93–1.47(Liulin coalfield) Overpressure helpful to high-production	Vary from different gas field, 0.83–0.95 in Sulige gas field (underpressured) while Yulin oilfield (normal pressure)
Caprocks	Burial history, and hydrologic setting	Diagenesis traps or lateral capillary force sealing
Migration distance	No or short	Short
Gas generation peak	Last from the Late Jurassic Period to the Early Cretaceous period (evolution time: 137.8 −199.4 Ma) (Wei et al., 2010)	Late Jurassic to late Cretaceous (180–72 Ma)
Depth range	1200–3000 m	400–1500 m

measure maturity (vitrinite reflectance is used as an indicator of the evolution stage of the coal measures), gas composition (methane coefficient C_1/C_n reflects composition) (Fig. 6A), and gas origin (methane isotope values reflect gas origin) (Fig. 6B), suggests that all the gas has been derived from adjacent coal measures. In addition, effective pathways from large-scale hydrocarbon migration are precluded by the heterogeneity and low permeability of the sandstone reservoirs.

5.6. Resource

Upper Paleozoic in-situ tight gas resources of the Ordos Basin are estimated by the latest hydrocarbon resource assessment (unpublished report) to be 22,418.8 × 10^8 m^3, 41,122.37 × 10^8 m^3, 58,960.66 × 10^8 m^3, at the possibility of 95%, 50% and 5%, respectively using Mont Carlo resource estimation methods, They are mainly distributed in the Yishan Slope area (62% of the total gas resource in the Ordos Basin), followed by the Yimeng Uplift, Weibei Uplift and Tianhuan Sag areas.

6. Discussion

CBM and tight gas accumulations make up most of Upper Paleozoic gas resource in the Ordos Basin. Based on the two types of gas accumulation, the following models for their origin are proposed.

6.1. Tight gas model

From an analysis of gas accumulations in the Upper Paleozoic rocks of the Ordos Basin, the natural gas accumulations in the Yishan Slope area have the basic characteristics of a modified tight gas model origin as proposed by Merkel (Cumella et al., 2008) with characteristics of low porosity and permeability, abnormal pressure, and lack of well-defined gas-water contacts.

Previous studies considered all the sandstone reservoirs as a single uniform system and with a continuous gas-water contact over the entire basin. There is no water in the basin down-dip area of the basin, only in the up-dip area with a gas-water transition zone between them, a typical gas-water inversion feature in the basin-centered gas origin model. New observations show that this may be incorrect because: (1) the fluvial sandstone reservoir of the Yishan Slope area shows rapid lateral variation, has high heterogeneity and low porosity, thereby reducing permeability within the reservoir; (2) The occurrence of different formation pressure systems in various areas indicates there are several separate gas systems instead of one single system in the Ordos Basin; (3) Difference in migration events of the gas fields of the Yishan Slope indicates different of fluid histories; (4) The occurrence of a water zone is more likely to be controlled by structural location and hydrodynamic activity. Gas concentration and water distribution is the function of the gas generation capacity of the source rocks, hydrodynamic activity and the quality of the cap- rocks; (5) Short migration distance of gas accumulated in the tight reservoirs. The regional pervasive gas-bearing accumulations have resulted from short migration from adjacent coal measure source rocks. Therefore, the tight sand gas accumulation model of the Ordos Basin can be designated as an extensive tight sandstone reservoir saturated with gas derived from nearby coal measures. The reservoir varies laterally and gas-water contacts are complex. There is no uniform gas system covering the entire basin (Fig. 7).

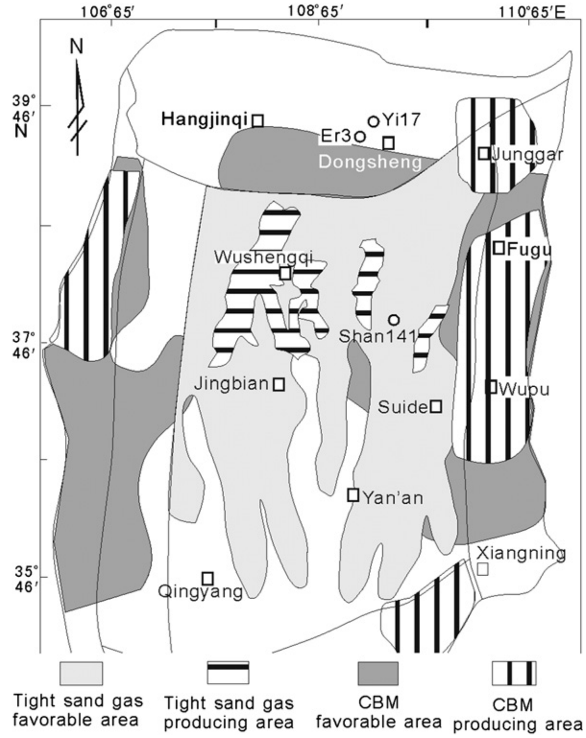

Figure 8 Unconventional gas systems and their producing areas, Ordos Basin.

6.2. Unconventional gas accumulations and their source rocks

Comparison of the Upper Paleozoic CBM and tight gas accumulations of the Ordos Basin, shows that these two kinds of unconventional gas deposits have several common features (Table 6). Coal measures are source rocks for both. CBM is self-generation and a self-reservoir, while gas is derived from coal measures and migrates only a short distance to accumulate in a tight reservoir, which can be termed as near-generation and near-reservoir. Both gas systems require source rocks with strong gas generation ability and extend together over wide area. However, their producing area may be significantly different because of differences in their producing conditions (Fig. 8).

CBM has a wider range of $\delta^{13}C_1$ (−70‰ to −30‰) than tight sand gas (−34‰ to −32‰) accumulations because coal measures at the margin of basin have experienced elevated bacterial activity. Basinward, CBM is buried deeper, and this requires higher investment and sophisticated techniques that presently available for effective recovery of the gas.

7. Conclusions

Upper Paleozoic rocks of the Ordos Basin contain widespread tight gas accumulation reservoirs and a vast amount of CBM in the margins of the basin. These are currently the largest unconventional gas accumulations in China.

Stable and well-developed coal measure sequences in the Ordos Basin are rich in organic matter, sufficiently matured to generate a large amount of gas, and possess high gas adsorptive ability.

CBM accumulations in the Ordos Basin are estimated to be up to 3.5×10^{12} m^3, and are mainly distributed in the marginal area of the basin.

Tight gas accumulations in the Ordos Basin have the typical characteristics of a modified basin-centered gas model, i.e., low-permeability reservoirs, abnormal pressure, ill-defined water-gas contact.

The Upper Paleozoic coal measures act as source rocks for both CBM and tight sand gas. CBM is self-generation and self-reservoir, with gas derived from coal measures migrating only short distances to accumulate in tight reservoirs forming tight gas accumulations which can be termed as near-generation and near-reservoir. Both gas systems require source rocks with strong gas generation ability and to be really extensive. Their producing areas may be significantly different because of differences in their producing conditions.

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