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Deep Coal Reservoir Characteristics and Gas-bearing Potential of the Ordos Basin, China

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***Abstract*—Previously, the study of the coal reservoir characteristics in China has been focused on the shallow coal seam (<1500 m), but less attention has been paid to the deep coal reservoir (>1500 m). Thus, the exploration and development of CBM resources is hindered. This paper aims to investigate the deep CBM at 1755m-1764m in the second member of the upper Paleozoic Shanxi Formation and that at 1815m-1833m in the second member of the upper Paleozoic Taiyuan Formation with the gas content and other parameters from wireline coring in Well Gu 1.The results show that the Shenmu area has the low-medium rank coal with the high vitrinite content and the medium-high gas-bearing potential. This study provides insight into the gas content of the coal seam deeper than 1500m and establishes a basis for evaluating the 1500m-2000m deep CBM resources within the Ordos Basin.**

Keywords—deep coalbed methane; coal reservoir characteristics; coal seam gas bearing potential; Ordos Basin

I. INTRODUCTION

The deep CBM involved in this study refers to CBM at 1500 m-2000 m in the Shenmu area of the Ordos Basin, China. The Shenmu area is located in the northern part of the eastern margin of the Ordos Basin, spans the Jinxi flexure belt and the Yi-Shaan slope and covers Shenmu and Fugu Counties in Shaanxi Province and Hequ and Baode Counties in Shanxi Province. The Shenmu area is 90 km long from north to south and 127 km wide from east to west and covers 11,430 km2 of CBM exploration region. The coal seam shallower than 800m in the eastern margin has a high exploration level, but the coal seam deeper than 800m in the Shenmu area is the blank horizon of CBM exploration (Fig.1). Currently, China's proven CBM reserves are less than 1,500m deep and mostly buried less than 1,000m[1,2]. Thus, it is thought that the burial deeper than 1,500m is unfavorable for CBM exploration. The fundamental geology of the deep CBM needs further study to make breakthrough in the CBM industry[3]. The CBM exploration in the Ordos Basin goes deeper and deeper[1,4]. The Shenmu area is a new region for the CBM exploration[5]. Within the Ordos Basin and even in China. Currently, a lot of progress has been made on geological study of shallow coal reservoirs in terms of the gas content, the gas saturation, the reservoir pressure, the critical desorption pressure and the preservation conditions. Moreover, much attention has been paid to the deep CBM[6,7,8,9,10].

wing characteristics.tory well within the Shenmu area in the the eastern Ordos Basin, is located in GuoJiaXingZhai Village, LanGanBao Town, Shenmu County, Shaanxi, China, and the well depth is 2000m. The well is adjacent to Jungar Banner-Shenmu area within the Ordos Basin. The dominant coal seam is thick (5# coal seam: 7m, 8# coal seam: 15m) and has the stable distribution and excellent structural conditions, which are favorable for CBM accumulation. It is predicted that the gas content of the Shanxi Formation 5# coal seam in the Shengmu area is 10-12m^3/t, that of the Taiyuan Formation 8# coal seam is 14-15m^3/t, both coal seams have the gas saturation more than 75%, the main coal porosity of 5%-10%, the permeability higher than $5\times10^{-3}\mu m^2$, and the CBM resources of these two coal seams are $8900\times10^8 m^3$. However, these CBM parameters are obtained from prediction and should be verified through analysis of coal seam core. Thus, the 27m long core was cut from the interval at 1755m-1764m in the Shan-2 Member and that at 1815m-1833m in the Tai-2 Member in Well Gu 1, and the field desorption test was carried out to obtain coal reservoir characteristics, gas-bearing properties, etc. in the Shenmu area and to evaluate the CBM resources deeper than 1500 m in the northern part of the eastern Ordos Basin.

II. GEOLOGICAL SETTING

The late Paleozoic coal-bearing strata within the Ordos Basin are divided with various schemes. In this study, with the plan proposed by CNPC Changqing Oilfield Branch in 1997, the strata are divided into the Carboniferous Benxi Formation and Taiyuan Formation and the Permian Shanxi Formation and 21 coal seams from bottom to top. The Shanxi Formation has 9 coal seams, including 2-3 minable coal seams (thicker than 0.8m). The Taiyuan Formation has 10-13 coal seams, including 3-5 minable coal seams. The strata of Benxi Formation are coal-bearing. However, the coal seams in the Benxi Formation are dominated by the thin coal seam or the shed coal, and only one minable coal seam is developed locally. Due to several coal seams and coal seam branching and wedge-out, coal seams are named with different rules in different coal areas. Thus, coal drilling data and geological survey reports from some mining areas in the eastern Ordos Basin were collected for coal seam division. According to the coal seam division scheme of the Taiyuan Xishan Mountain standard section and in combination with the specific geological conditions of the Ordos Basin, the Shanxi Formation coal seams are named as 1#-5# from top to bottom, and 4# and 5# coal seams are dominant, and the Taiyuan Formation coal seams are named as 6#-10# from top to bottom, and 8# and 9# coal seams are dominant.

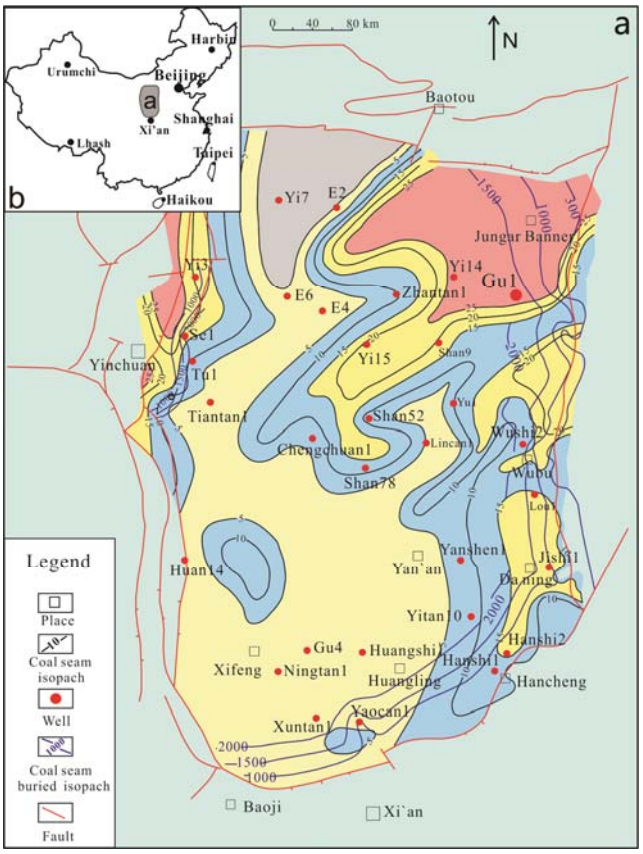

FIGURE I. STATUS OF THE COALBED GAS EXPLORATION IN THE ORDOS BASIN, CHINA

III. SAMPLES AND EXPERIMENTS

The well logging is an effective method of studying the coal seam characteristics[11.12]. A large number of logging curves of gas exploration wells within the study area were used to calculate the coal seam thickness, create the isopach map and characterize the distribution of thickness and depth of dominant coal seams. The applied logging curves cover the lateral resistivity, natural gamma, acoustic wave and natural potential. The coal seam displays the high resistivity with the value of 500-700 Ω.·m, the low natural gamma with the value of 5-30API, the larger acoustic time difference, and the smaller negative natural potential.

The cores was cut from the coal seam in Well Gu 1(Figure.1), and the cores were collected for geochemical analysis, including comprehensive analysis (proximate analysis, maceral analysis and vitrinite reflectance analysis), reservoir analysis and gas content analysis. The coal reservoir characteristics and the gas-bearing potential of the upper Paleozoic deep coal seam in the Shenmu area were studied. The coring and analysis test were carried out in the Exploration and Development Research Institute of CNPC Changqing Oilfield Branch based on the industry standards.

IV. RESULTS

The Shanxi and Taiyuan Formations in the Shenmu area have 10 coal seams, which are named as 1#-10# from top to bottom, and 5# and 8# coal seams are dominant. The burial of coal seam in the Shenmu area is controlled by the structure and is characterized by "deep in the east and shallow in the west". The 5# coal seam is buried at 0-2200m, it is buried shallower than 1500m in 2/3 of the region to the east of the Yellow River and deeper than 1500m to the west of the Yellow River. The depth distribution form of 8# coal seam is similar with that of 5# coal seam, except that 8# coal seam is 30m-60m deeper than 5# coal seam. The previous research on the CBM in the Ordos Basin suggest that the coal seam is buried at 300-1500m.

Most of the Shenmu area has the semi-light coal, but the eastern edge is dominated by the semi-dull coal. According to the coal proximate analysis , the water content is 0.63%-2.92%, averaging 1.03%, and the average water content of 5# coal is 1.54% higher than that of 8# coal. The coal ash mainly comes from the inorganic components. The coal in the Shenmu area has the ash content of 15%-25%, averaging 19.3% and is classified as the medium ash coal, indicating the good porosity, which is favorable for CMB accumulation. The volatile content is controlled by the genetic type, coalification degree and coal petrology. The volatile content is 19.93%-31.12% and gradually reduces from north to south, which is mainly due to the increase of thermal evolution. The coal in the Shenmu area is the bituminous coal with low water content, medium ash content and high volatile content.

The vitrinite content is less than 60% in the Luotuoye mining area and Baode 1 Well in the Jungar Banner in the northeastern Shenmu and increases to 82% in the south toward Sunjiagou of Baode County.The coal with the higher vitrinite content indicates the better coal quality and the better developed cracks, which are favorable for CBM dispersion. This indicates that main factors for high CBM production exist in the Shenmu area[13].

The 5# and 8# coal seams in Well Gu 1 have the permeability less than $1\times10^{-3}\mu m^2$, and those in other areas of the Ordos Basin have the permeability of $(1\text{-}5)\times10^{-3}\mu m^2$ and are defined as the medium porosity and permeability coal seams. The coal reservoirs within the Shenmu area have the higher porosity and permeability[2]. The porosity and permeability within the Shenmu area decrease as the coal seam (coal rank) goes deeper.

The test of specific surface and pore size of 8 coal samples from Well Gu 1 shows the small specific surface area, which is 0.135 m^2/g-0.4 m^2/g, averaging 0.2818 m^2/g, and the pore size of 7.5 nm-11.21 nm, averaging 9.89 nm. The adsorption isotherm and pore size curves of Well Gu 1 (8# coal seam) indicate that under the low pressure the adsorption amount firstly increases rapidly and then increases slowly, and the pore size curve is bimodal.

The coalification is related to depth, temperature, pressure, etc. The higher temperature results in the increased coalification. The coal thermal evolution is indirectly influenced by the pressure. As the pressure increases, the formation temperature increases, and thus, the coalification increases. Therefore, the coalification degree is also called the coal thermal evolution degree, which is measured by the vitrinite reflectance value (Ro). R_0 is an key parameter which reflects the coal thermal evolution and is one of main parameters for coal rank classification[14].

Ro is slightly low in the northern part of the Fugu-Jiajiamao area and slightly higher in the De-Sunjiagou area. R_0 of 8# coal seam increases from north (Ro<0.7%) to south (Ro>1.2%). At the same point, Ro of 5# coal seam is 0.1%-0.3% lower than that of 8# coal seam. The long-flame coal, gas coal, fat coal and coking coal are developed within the Shenmu area. From north to south, the coal ranks gradually increase, forming a low-medium coal rank distribution area.

V. Coal Reservoir Gas Bearing Properties

A. Coal Adsorbability

The coal isothermal adsorption curves reflect the adsorbability to the methane under different pressures and a given temperature (usually coal seam temperature). The reservoir capacity and CBM production capacity depend on the coal seam adsorbability to the methane. The isothermal adsorption test shows that the Langmuir volumes in 4 coal samples are 4.71-18.49cm^3/t, averaging 12.425cm^3/t, indicating a certain adsorbability and development potential. The higher Langmuir pressure of 1.27-4.6MPa with an averaging of 3.045cm^3/t, is favorable for CBM development.

B. Gas-bearing Potential of Coal Seam

The CBM content is the sum of lost gas, desorbed gas and residual gas contents[15]. According to the chart of gas content in the coal seam , the desorbed gas content in the CBM in the Shenmu area is 76.37%- 97.45%, averaging 87.67%, and the lost gas content is 1.6%-22.82%, averaging 11.11%, and the residual gas content is 0.77.%-1.4%, averaging 1.19%, which reflects the desorption characteristics of China's CBM[16].

The CBM content increases with the depth. The CBM content of 5# coal seam is 5.71m^3/t-9.71m^3/t, averaging 8.35m^3/t, and that of 8# coal seam is 8.23 m^3/t-19.95 m^3/t, averaging 13.9m^3/t. The coal reservoirs in the Shenmu area feature the high CBM saturation. The CBM saturation of 5# coal seam is 57%-99%, indicating a nearly-saturated state. The CBM saturation of the upper part of 8# coal seam is 45%-82%, and that in the lower part of 8# coal seam is more than 100%, indicating a supersaturated state.

VI. Discussion

A. The Thick of Deep Coal Seam (1500-2000m) in the Shenmu Area is Favorable for CBM Accumulation

The total coal thickness in the Shenmu area is characterized by "thick on the east and west sides and thin in the north and south parts". Both 5# and 8# coal seams are thicker than 3m, and the total coal thickness on east and west sides is above 10m, indicating that the coal hickness meets requirements for CBM exploration and development[17].

B. The Deep Coal in the Shenmu Area Provides the Parent Material Conditions Favorable for the CBM Accumulation

The water content of the deep coal in the Shenmu area is lower than that in shallow coal (Table 1), which is favorable for the methane adsorption by coal seam. In China's shallow key CBM area, the vitrinite is the key parent material for CBM generation. The components of coal in the Shanxi Formation and the Taiyuan Formation show banded distribution. The vitrinite content is more than 8%, and it ranges from 20% to 56% in the shallow layer in the southeastern Ordos Basin and is higher than 70% in other coal field or mining areas[18]. It can be seen that the commercial CBM is distributed both in the coal with low and high vitrinite contents, and the vitrinite content in the Shenmu area varies from 20% to 82%, indicating the favorable parent material conditions for CMB accumulation. The vitrinite content in the Shenmu area is close to 80% and has the characteristics of the shallow commercial CBM in the eastern margin of the Ordos Basin (Table 2), indicating the favorable parent material conditions for CBM accumulation.

TABLE I. INDUSTRIAL ANALYSIS OF SHALLOW (LESS THAN 1000M) C-P COAL ROCK IN THE SHENMU AREA, ORDOS BASIN

Areas	Well Name	Coal seam	Water content (%)	Ash content (%)	Volatile component (%)
Daning-Ji County	Lou 1	5#	0.92	7.60	29.40
		8#	0.45	8.00	30.10
	Pu1	5#	2.25	10.16	29.41
		8#	3.10	8.40	32.70
Wupu	Yu 5	5#	0.28	17.25	11.30
		8#	0.36	7.85	20.20
	Yu 12	5#	0.26	21.75	19.75
		8#	0.08	3.45	19.90
Shenfu		C—P	0.47	34.49	17.26
Hengshanpu Renjia Village		C—P	1.14	28.49	30.42
Mingzhu	Mingzhu Mining Area	5#	1.03	23.46	20.99
		8#	0.98	23.04	21.86

TABLE II. MACERAL ANALYSIS OF SHALLOW (LESS THAN 1000M) CARBONIFEROUS-PERMIAN COAL IN THE SHENMU AREA IN THE ORDOS BASIN

Area/Well name	Coal seam	Vitrinite (%)	Fusinite (%)	Liptinite (%)	Inorganic component (%)
MaTower Village	5#	58.8	40.8	0.4	
Yu 12	8#	89.8	0.2	8.8	1.2
	5#	79.0	10.2	5.4	3.2
Yu 15	8#	86.2	11.0	2.0	0.8
	5#	78.0	10.7	6.5	3.1
Yu 5	8#	70．0	22．7	6．5	0．4
	5#	81．0	18．4	0．3	0．2
Liulinda Village	8#	79．0	20．0	0．4	0．1
	5#	72．0	13．8	7．9	2．3
Lou 1	8#	83．0	/	/	/
	5#	75．0	/	/	/
Pu 1	8#	85．0	/	/	/
	5#	82．5	/	/	/
Songshan Mine	8#	92．0	5．7	3．0	/
	5#	85．0	11．6	2．1	3．0
Ji 1	8#	88．0	/	/	/
	5#	76．5	/	/	/
Yu 13	8#	84.0	12.7	2.1	0.8
	5#	70.0	27.4	0.8	1.0

C. Favorable Porosity and Permeability for CBM Development

Most of the Shenmu area has the semi-light coal. The bright coal and semi-light coal contents increases and the semi-dull coal content decreases from north to south. The semi-light coal and the bright coal have better pore connectivity than the semi-dull coal and the dull coal. Thus, the deep coal within the Shenmu area provides the more favorable permeability for CBM development than the shallow coal seam in the eastern margin. The coal reservoir porosity in the Shenmu area is 2.2%-5%. Statistics of coal reservoir porosity data in 70 regions in China show the average porosity of 4.2%[18] and the permeability of $(1\text{-}5)\times10^{-3}\mu m^2$. The deep coal seam in the Shenmu area has the medium-high porosity and the medium-high permeability, which provides the favorable conditions for the CBM development.

D. High Gas Saturation Indicates the Superior Conditions for the High CBM Production

The adsorbability and the reservoir pressure are the key factors for CBM desorption. Although the adsorbability of the deep coal seam in the Shenmu area is poorer than that of shallow coal seam in the eastern margin of the Ordos Basin (Table 3). However, examples of China's CBM exploration shows that the adsorbability of deep coal seam in the Shenmu area is still favorable for high and medium CBM production. It should be noticed that the higher Langmuir pressure is more favorable for CBM development. Moreover, the high gas saturation in the Shenmu area indicates conditions for high CBM production[18].

TABLE III. ISOTHERMAL ADSORPTION TEST OF CARBONIFEROUS-PERMIAN COAL SEAM IN THE ORDOS BASIN

Well name	Coal seam	VL(m3/t)	PL(MPa)
Yu 15	8#	32.6075	3.1189
	5#	25.7683	3.8397
Wushi 1	8#	22.9885	2.3310
Yu 13	8#	27.4340	1.4000
MaTower illage	5#	37.284	1.7700

The Shenmu area has the low-medium rank coal and the higher vitrinite content. The medium rank coal is the favorable for CBM exploration. However, the low rank coal within has the big and stable thickness, the favorable porosity and permeability conditions and the high gas saturation. The CBM saturation of the shallow seam in Gu 1 Well is nearly saturated, and the deep CBM is supersaturated, and thus, even the commercial gas is still produced from low rank coal seam[18]. According to the criterion of CBM content classification[18], the Shenmu area has medium-high gas-bearing potential.

VII. CONCLUSIONS

The CBM exploration and development can go to the 1500m-2000m deep coal seam with favorable gas-bearing conditions. The coal seams within the Shenmu area show the following characteristics.

(1) The total coal seam thickness within the Shenmu area is characterized by "thick on the east and west sides and thin in the

south and south parts" and meets the requirements for CBM exploration and development.

(2) Most of the Shenmu area has the semi-light coal, and the eastern edge is dominated by semi-dull coal. The coal in the Shenmu area is bituminous coal with low water content, medium ash content and high volatile matter content.

(3) The vitrinite content of the coal in the Shenmu area is the highest and is followed by the inertinite content.

(4) The coal seam has the medium-high porosity and permeability, and the pore is dominated by micro-pore and transitional pore;

(5) From north to south, the coal ranks gradually increase, forming a low-medium rank coal distribution area.

(6) The coal has the strong adsorbability, and CBM is saturated or supersaturated and the coal seam has the great gas-bearing potential.

(7) The analysis shows that the coal reservoirs and gas-bearing conditions of the coal seam at 1500m-2000m are equal to or better than those of the shallow coal seam. Thus, the CBM exploration can goes to the depth of 1500 m.

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