Analysis on Geological Features and Development Potential of Coalbed Methane in China

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I. Introduction

Oil and gas supply has become the bottleneck for the sustainable development of national economy due to the increasing demand of total energy consumption and clean energy consumption in the phase of China's industrialization and urbanization. According to the uprising of the CBM industry, it is realized that CBM is the most practical alternative energy currently. The CBM enrichment zone is close to natural gas transmission piplines, the state preferential policies on CBM exploration are available, and the surface development of CBM can effectively improve coal mining safety and atmospheric environment, all of which provide a broad market space for national CBM industry development.

The surface development of CBM began in early 1990s in China, and made faster steps recently in supporting development technology for CBM, and good gas productivity have been achieved in the south of Qinshui Basin, east of Ordos Basin and Liujia Block of Fuxin Basin. Till the end of 2011, there are altogether more than 4,000 CBM gas wells drilled in the developed zones, with CBM capacity of $25\times10^8 m^3$ and annual productivity of $14.5\times10^8 m^3$. Regarding the gas production effect, gas production of single well is still below the designed production of $2000 m^3/d$, what is more, the development technology for depth below 800 m is still under way, and the development technology for low rank CBM is nowhere. Therefore, it is critical for CBM industrial development to do research on the geological features of CBM and analyze its potential in development.

II Geological Features of CBM in China

(I) Distribution of CBM Resources

China has abundant CBM resources, distributed in 5 gas reservoirs, 38 coal-bearing basins and 68 coal accumulation units. The resources quantity which burial depth is less than 2000m come to more than 36.8 trillion m^3 (TCM), ranking the 3rd of the word according to the recent resource evaluation.

China's CBM resource is about 27.3 trillion m^3 at burial depth of 300-1500 m, in which there is 17.13 trillion cubic meters in North China's gas accumulation area, and 7.26 trillion m^3 in South China, 2.15 trillion m^3 in Northwest China, 0.4 trillion cubic meters in Northeast China, and few in Yunan-Tibet. The basins with CBM resources of more than 1 trillion m^3 above 2000m include 11 coal-bearing basins (areas), such as Sanjiang-Muling River, Huainan, Huaibei, Qinshui, Pingle, Ordos, South Sichuan-North Guizhou, Liupanshui, Junggar, Tuha and Yining, accounting for 90% of national resources with a total amount of 20.56 trillion m^3 [1].

According to the coal ranking, CBM resources of the high rank lean coal-anthracite III ($1.9\% < R_o < 2.5\%$) is 7.8 trillion m^3, accounting for 21.1%; CBM resources of middle rank gas-lean coal ($0.7 < R_o < 1.9\%$) is 14.3 trillion m^3, accounting for 38.9%; CBM resources of low rank brown-long flame coal ($R_o < 0.7\%$) is 14.7 trillion m^3, accounting for 40%.

(II) Geological Conditions Comparison of CBM Accumulation among Different Coal Ranks

1. Gas Source Conditions

Gas source conditions are the basis of CBM accumulation, as only sufficient gas source can lead to rich accumulation of gas reservoir. The geochemical features of CBM help identify the resource rock and its genesis.

High rank CBM is dominated by thermogenic gas, while low rank CBM is by primary biogenic gas. The genesis of Low rank mature CBM is complex, including secondary biogenetic gas, and primary-secondary biogenetic gas. Based on the analysis of conventional natural gas genesis classification and data tested in the lab, the correlation between carbon isotope and vitrinite reflectance of 72 samples (from 5 typical basins is drawn (Fig 1). Fig 1 shows $\delta^{13}C_1$ value is -34.80‰~-28.70‰ for high rank CBM, being of thermogenesis; $\delta^{13}C_1$ value is -62.00‰~-55.60‰ for low rank CBM, dominated by biogenesis, with mixed genetic gas. In terms of current gas content, the content of high rank coalbed is obviously higher than that of low rank. For example , The gas content of high rank CBM in Qinshui basin is mostly over18m^3/t, while the gas content of low rank CBM in Tuha basin is mostly below 2m^3/t.

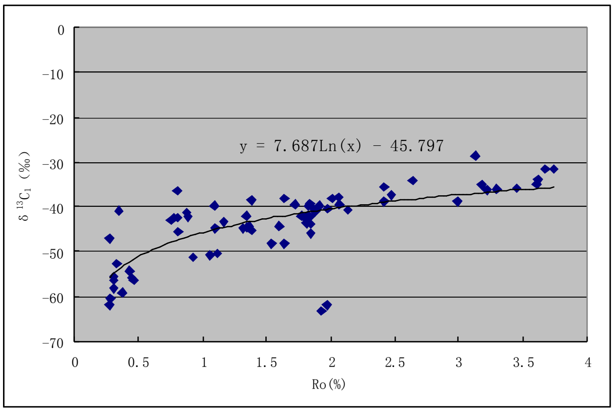

Fig 1. Correlation between CBM$\delta^{13}C_1$ and R_o[2]

2. Reservoir Physical Properties

CBM migration simulation is carried out by Langfang branch of Research Institute of Petroleum Exploration and Development, Petro -China, so as to do research on the permeability changing principles of high-low CBM reservoir in depressurization. The test results show that high rank coalbed is of cleat–fracture type reservoir, where outcropping under uplift or denudation means the drop of formation pressure and the decrease of overburden pressure and ground stress, leading to opening of cleats, fractures and increasing of permeability; while low rank coalbed is of matrix pore type reservoir, where outcropping under uplift or denudation means the drop of reservoir pressure and the increase of migration pressure difference, leading to decreasing of permeability (Fig 2). In terms of differences in pore features, low rank coal is mainly of matrix pore type, the coal rock in depressurization is characterized by volumetric strain and gas slippage secondly; while high rank coal in depressurization, due to its cleats and fractures, is characterized mainly by gas slip and secondly volumetric strain. This shows the stimulation of high rank coal reservoir is more difficult than low rank coal.

3. Hydrodynamic Force

The formation water is involved in the CBM accumulation, so its dynamic feature is closely related to the CBM accumulation. Active hydrodynamic force is the primary driving force for low rank CBM generation, and proper salinity of formation water is critical for its generation. The methane bacteria carried by hydrodynamic force migrates to the media with reduction of its oxygen, nitrate and most sulfate, where methane bacteria can grow and generate. Take Powder River basin as an example, based on the correlation between δ2H and (δ18O) isotopics and global meteoric water lines, together with the analysis of δ2H isotopics, it is concluded that the water in Fort Union coalbed came from atmospheric precipitation as early

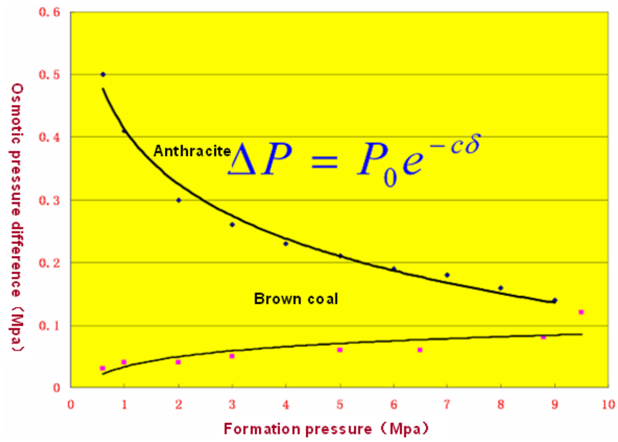

Fig 2 Relations between Osmotic Pressure Difference for High Rank Coal and Pressure

as 1952, which indicates atmospheric precipitation entered the formation in geological history. Fort Union coalbed has been under biodegradation to a certain degree, with reference to qualitative observation, especially to the generation of uncertain complex compounds and IC of saturated hydrocarbons. It is proved to be dominated by biogenetic gas, as most coal in Fort Union formation of Tertiary system is brown coal (R_o=0.3~0.4 %), and of the CBM, $\delta^{13}C$ value is -60.0‰~-56.7 ‰, δD is -307‰~-315 ‰. [4]

The alternating hydrodynamic forces shall break the dynamic equilibrium among adsorbed gas, dissolved gas and free gas. Consequently, CBM is dissolved in water, leading to lighter methane carbon isotope and decreasing adsorbed gas, which means the damage of high rank CBM accumulation, frequently happening in exploration [5]. Take Qinshui basin as an example, the gas content is normally lower within the strong runoff area of south basin boundary due to the high flow rate and strong alternating hydrodynamic forces. The gas content is 6~8m^3/t either in $3^{\#}$ coalbed of Shanxi Formation, or $15^{\#}$ coalbed of Taiyuan Formation. On the other hand, variation of its gas content is small due to the slow hydraulic gradient. The alternating hydrodynamic forces in basin's slope ring area is strongly influenced by water conduction faults and secondary folds, while the alternating hydrodynamic forces is especially strong in middle and west part of basin with its stronger water conductibility resulting from the network development of normal faults. Within the area mentioned above, the lowest gas content of $3^{\#}$ coal bed is 4m^3/t, while the lowest of $15^{\#}$ is 3m^3/t.

4. Accumulation Process

The accumulation process of high rank CBM is complex [6]. Tectono-thermal event is common among most high rank CBM accumulations, and then, secondary hydrocarbon generation occurred. While low rank CBM accumulation has been under multi-stage evolutions and at the highest evolution grade, there was no more hydrocarbon generated and consequently, it entered the stage of adjustment and transformation. Low rank coalbed accumulation process is simple with one subsiding after coalbed taking shape and the gas generation was mainly influenced by hypozonal metamorphism.Therefore, the main controlling factors for adjustment and transformation of coalbed accumulation lie in the current tectonic framework, the supply, migration, drainage and viscous flow of ground water.

III. Analysis on CBM's Development Potential in China's Key Basins

(1) CBM Resources Base

Currently CBM exploration focuses on south of Qinshui basin, and east of Ordos basin, in North China at burial depth above 800m. The exploration of CBM at burial depth of 800-1200m is still under key process and the exploration of coal bed at depth below 1200m is not possible in the short run. Based on current technology and development trends, volumetric method is applied to reevaluate CBM resources in the key basins such as Qinshui, East Ordos and Ningwu at burial depths mentioned above.

1. Qinshui basin

The main coalbeds of the area are 3# and 15#, among which 3# coalbed is buried in depth of 0~1700m, mostly at 100~1000m, with a south-north increasing tendency in terms of burial depth. In the south edge of basin, the burial depth of 3# is less than 500 m, thickness is about 5-6 m, and gas content is more than 15m^3/t; while 15# coalbed is at burial depth of 0~1800m, mostly at 100~1100m, thickness is 3m, gas content is more than 15m^3/t.

Resources evaluation shows CBM resource is classified in terms of burial depth: 1.3 trillion m^3 above 800m, 0.9 trillion m^3 at 800~1200m, 0.6 trillion m^3 at 1200~1500m, 1.1 trillion m^3 at 1200-2000m, totaling 3.9 trillion m^3.

2. East of Ordos basin

Generally speaking, 5# coalbed in east of Ordos basin is widely distributed, with a thickness variation of 0~10m. In general, the west is thicker than the east, and the north is thicker than the south. 8# coalbed is evenly distributed with a thickness of 0~16.4m. In general, the north is thicker than the south; the north-south thickness variation for the main coalbed is large, while east-west variation is smaller. According to the analysis of regional structures and tectonic settings, east part shows a shallower coalbed burial depth, while west part is buried 2000m at most. Vertically, the interval between 5# and 8# coalbeds is about 50m~70m. In the north part, gas content is normally no more than 8m^3/t, while gas content in the middle part is intermediate, about 4~12m^3/t; and gas content in the south is as high as more than 10m^3/t.

Resources evaluation shows CBM resource in east of Ordos at burial depth above 800m is about 0.5 trillion m^3, at depth of 800~1200m is about 0.4 trillion m^3, at 1200~2000m is about 0.4 trillion m^3, at 1500~2000m is about 1.1 trillion m^3, totaling 2.4 trillion m^3.

3. Ningwu Basin

Ningwu basin developed two coal-bearing systems in Carboniferous-Permian and Jurassic, among which the 4# coal bed of lower Shanxi Formation (P_1s) in lower Permian, and 9# coalbed of lower Taiyuan Formation (C_3t) in upper Carboniferous.Both of the coalbeds mentioned above is thick comparatively , and widely distributed.

Being a complex structured coalbed, 4# coal bed becomes thicker in the direction of north-south, with 2-5 tonsteins, mainly of semidull coal. 9# coal bed is stable in development, with a thickness of 8-14 m, generally of 10-12 m. Being a complex structured coalbed, it includes 2-3 tonsteins, mainly of semibright coal. The burial depth variation is large, with a tendency of gentle in north-south and steep in east-west. The core of syncline of main coalbed is at burial depth of more than 2600 m. The coal rank shows high in south-east and low in north-west. R_O is about 0.8~1.4%, mainly of gas coal and coking coal. It shows good gas content, with a tendency of being high in north and low in south, among which, 9# coalbed has a gas content of 6.0~20.61m^3/t.

The CBM resources of Ningwu basin can be classified in terms of burial depth as follows: 51.15 billion m^3 above 800m, 65.01billion m^3 at 800~1200m, 78.57 billion m^3 at 1200~1500m, 169.63 billion m^3 at 1200~2000m, totaling 360 billion m^3 (Table 1)

Table 1. Evaluation of CBM Resources of Key Coal Bearing Basins in North China

Area	Burial depth (m)	Shanxi Formation		Taiyuan Formation		subtotal (10^8m^3)
		Gas bearing area (km^2)	Resource (10^8m^3)	Gas bearing area (km^2)	resource (10^8m^3)	
Qinshui	300~800	8970.8	6784.4	8259.8	6276.6	13061.0
	800~1200	4936.0	4264.7	4738.0	4639.5	8904.2
	1200~1500	3109.0	2363.8	3507.0	3888.6	6252.4

	1500~2000	4098.0	2301.4	5244.0	8563.2	10864.7
	Subtotal	-	15714.4	-	23367.9	39082.2
East of Ordos	300~800	3326.3	3115.3	3092.6	2076.2	5191.5
	800~1200	1671.8	1565.7	3475.6	2333.2	3898.9
	1200~1500	3093.3	2897.0	1799.2	1207.5	4104.5
	1500~2000	6862.0	6426.6	6586.0	4422.1	10848.7
	Subtotal	-	14004.5	-	10039.0	24043.6
Ningwu	300~800	133.8	68.6	133.8	442.9	511.5
	800~1200	393.4	80.2	393.4	569.9	650.1
	1200~1500	366.6	102.4	366.6	683.2	785.7
	1500~2000	1411.8	344.8	1411.8	1351.5	1696.3
	subtotal	2305.6	596.0	2305.6	3047.6	3643.6
Total		-	30314.9		36454.5	66769.4

(II) Prediction of Potential for CBM Development

1. High Proven Rate of CBM Resources

Resources proven rate is closely related to exploration and development level. CBM reservoir, characterized by continuous and large-scale accumulation, is named “continuous type” gas reservoir, which is featured by stable distribution and higher proven rate.There is no data showing the rate of proven resources for CBM as there is no block in the late stage of development.Nevertheless,estimated from Fanzhuang block of Qinshui basin in its scale-development, $3^{\#}$ coalbed has a total resource of 40.223 billion m^3, with a proven resource of 28.794 billion m^3, the rate of proven resource being 70%. The rate shall decrease with less favorable geological conditions of CBM in increasing depths. It is estimated that the rate shall be 70% at burial depth above 1200m, and 60% at depth below 1200m.

2. Recovery Ratio of CBM Well at Depth above 800m is over 50%

CBM recovery ratio is closely related to other geological conditions, coal ranks and permeability. The CBM recovery ratio of the 6 developing basins in USA is above 50%, averaging 60~75% (Table 2).

Table 2. Recovery Ratio of US Key CBM Developing Basins

Basin	Burial depth (m)	Coal rank	Permeability ($10^{-3}\mu m^2$)	Thickness (m)	Gas content (m^3/t)	Recovery rate (%)
San Juan	600-1000	Gas coal	1-50	9-30	8.5-17	80
Uinta	400-800	Brown coal	5-20	8-9.1	11.3	50
Rodan	300-800	Long flame - gas coal	1-20	5-15	9-15	55
Powder River	90-400	Brown coal	10-20	12.2-30	3-5	60
Appalachia	150-1000	Coking coal	1-15	2-6.1	11.3-22	50
Panzhuang, Shizhuang	300-600	Anthracite	0.1-1.0	5.5	16-24	54.3

China's CBM is just entering the large-scale development phrase, so most of recovery ratio calculation is based on theoretical deduction and numerical modeling.

For the development wells based on recovery calculation, CBM recovery ratio is above 50% at burial depth above 800m. Shanxi Asian American-Daning Energy Co., Ltd. drilled DNP02 well at Qinshui Daning block, where $3^{\#}$ coalbed is as thick as 5m, gas content is $12m^3/t$, permeability is $1\times10^{-3}\mu m^2$, total footage is 8,018m, control area is $0.5km^2$, and the produced geological reserves are 43 .50 million m^3. The drainage production began in December of 2004, lasting for 3.5 years and the well is shut-in after linking with laneways of coalmine, and the accumulative gas production is 21.36 million m^3, with recovery ratio of 49.1%. LJ-X well of Liujia block of Liaoning Fuxin was put into production in 2003, with early stage gas production of $4500m^3$/day, and had kept stable production for 4 years, with current gas production of $1400m^3$/day. The accumulative production is 6.8 million m^3, recovery ratio is 40% , and estimated recovery ratio is over 50%. DT-Y well of Tiefa was put into production in December of 1996, with the highest daily gas production of 13.5 thousand m^3, and the well is shut in 15 months later. In 2004 it reopened and the production was stabilized for 4 years. Currently the daily gas production is 4 thousand m^3, accumulative production is 14 million m^3, and recovery ratio is over 50%.

The coal bearing basins of North China are characterized by middle-high rank coals, permeability being 0.5~2 mD, similar to the coal rank of Appalachia basin. The CBM recovery ratio shall decrease with the increasing depths. It is estimated that recovery ratio at depth above 800m in Shanxi Province can reach 60%, at depth of 800-1200m is about 50%, and below 1200m is about 40%.

3. Prediction of Development Potential

According to the geological features, resource features and exploration and recovery status of CBM, Ningwu basin is anything but a basin ready for development, while the target areas and most practical CBM areas for scale development are south of Qinshui basin and east of Ordos basin. Based on a recovery ratio of 70% above 1200m, 60% below 1200m; 60% above 800m, 50% at 800~1200m, and 40% below 1200m, the estimated recoverable CBM of the two key basins can be classified in terms of burial depths as follows: above 800m being 766.6 billion m^3; at 800~1200m being 448.1 billion m^3; at 1200~2000m being 769.7 billion m^3, totaling about 2 trillion m^3 (Table 3).

Table 3. Potential for CBM Development above 2000m in the Two Key Basins

Burial depth (m)	Key basins	Potential for development (10^8m^3)			Subtotal (10^8m^3)		
		Resource	Estimated proven	Estimated recoverable	Resource	Estimated proven	Estimated recoverable
300~800	Qingshui	13061	9143	5486	18252	12777	7666
	East of Ordos	5191.5	3634	2180			
800~1200	Qingshui	8904.2	6233	3116	12803	8962	4481
	East of Ordos	3898.9	2729	1365			
1200~2000	Qingshui	17117.1	10270	4108	32070	19242	7697
	East of Ordos	14953.2	8972	3589			
total	Qingshui	39082	25646	12710	63126	40981	19844
	East of Ordos	24044	15335	7134			

Based on a recovery ratio of 60% and production load factor of 0.85 in the plateau period, it is estimated there shall be a recovery of 450 billion m^3 above 800 m in its plateau period, and 20 billion m^3 stabilizing for 19 years; a recovery of 268.9 billion m^3 at depth of 800~1200m in its plateau period, and 10 billion m^3 stabilizing for 22 years; a recovery of 461.8 billion m^3 at depth of 1200~2000m in its plateau period, and 20 billion m^3 stabilizing for 19 years (Fig 3).

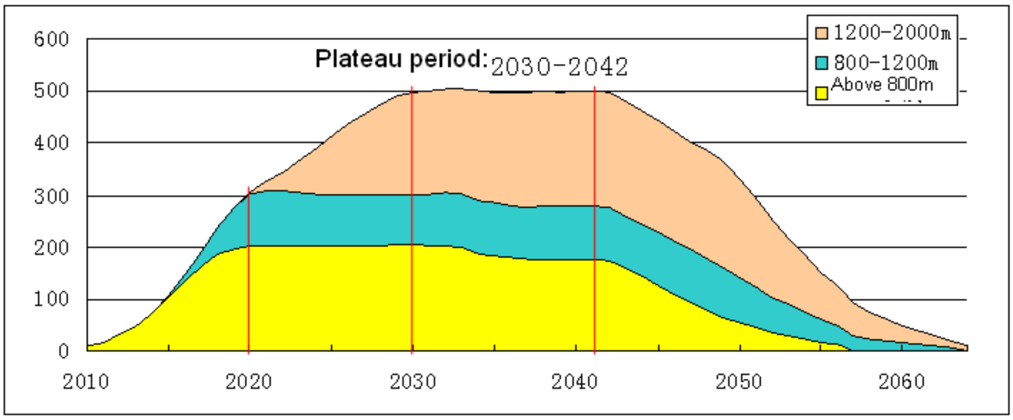

Fig 3. Profile of CBM Production Estimation in Two Key Basins of North China

In the short run, by using mature technology to develop the resource above 800m, we can achieve annual production of 10 billion m^3; if a breakthrough in development technology can be made, it is possible to achieve an annual production of 30-50 billion m^3 with resources produced at depth of 800-1200 m in the middle term, and with resources produced at depth of 1200-2000 m in the long run (Table 4).

Table 4. CBM Production Estimation in Two Key Basins of North China (10^8m^3)

Burial depth (m)	Estimated recovery	Estimated recoverable	Recovery at plateau period	Production estimation			
				Short term	Middle term	Long term	Technology
300~800	12777	7666	4600	100	200	200	Recoverable with current technology
800~1200	8962	4481	2689		100	100	Middle term production, needing breakthrough in technology
1200~2000	19242	7697	4618			200	No matured technology, needing further research
Total	40981	19844	11906	100	300	500	

IV. Conclusions and Suggestions

(1) The advantages of CBM accumulation of different ranks are: high rank CBM has high gas content. CBM within areas of viscous flow and hypersalinity is preserved well, in favor of the preservation of CBM and mining with water draining and pressure dropping. The advantages of low rank CBM accumulation are: its simple accumulation process led to coal accumulation of biogenesis and multi-source CBM accumulation is possible if outer sources of gas are provided. ② Gas production by desorption with pressure drop is easy due to the unconsolidated reservoir matrix and higher permeability.

(2) According to CBM geological features, resource features and exploration and recovery status, the most favorable CBM areas for scale development are Qinshui basin and east of Ordos basin. Based on current technology, the reevaluation of the two basins at different depths shows resources of 6.3 trillion m^3 and 2 trillion m^3 respectively, among which there are

resources of 1.8 trillion m^3 and 766.6 billion m^3 respectively at burial depth above 800m.

(3) Based on a recovery ratio of 60% and production load factor of 0.85 in the plateau period, it is estimated that In the short run, by using mature technology to develop the resource above 800m, we can achieve annual production of 10 billion m^3; if a breakthrough in development technology can be made, it is possible to achieve a n annual production of 30-50 billion m^3 with resources produced at depth of 800-1200m in the middle term, and with resources produced at depth of 1200-2000m in the long run.

As China's CBM industry is just at the threshold of scale development, various development indexes can only be under analogy and prediction with foreign indexes, leading to some errors in results. Besides, the development technology at depth below 800 m and especially below 1200m calls for a breakthrough, so an production estimation of 30-50 billion m^3 cannot be achieved without matured technology in development.

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