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The key stage and moment of coalbed gas reservior evolution in the Qinshui Basin, China

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Abstract **The evolution of coalbed gas reservoir is characterized by coalbed gas geochemistry and gas content. On the basis of burial history and thermal history, the forming process of coalbed gas reservoir and the gas accumulative history in the Qinshui Basin are discussed in this paper. The difference of the thermal history, geochemistry characteristic, and gas accumulative history between Yangcheng and Huozhou areas shows that the formation of coalbed gas reservoir in the Qinshui Basin is controlled by the geological process in the critical stage and the critical moment. The components and isotopes of coalbed methane are determined by the stage at which the coal maturation reaches its maximum rank. The coalbed methane accumulative history is related to the temperature and pressure of the coal burial history, because the coalbed gas is mainly in adsorptive state. It is stated that the gas content in the coal seam is controlled by the moment when the coal seam is uplifted to the shallowest position.**

Keywords: burial history, key stage and moment, gas accumulative process, Qinshui Basin.

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1 Introduction

The geochemistry characteristic of coalbed gas is the key aspect of coalbed methane geology, and has been endeavored by many researchers for a long time[1−8]. Up to now, the origin of coalbed gas has been well understood[4,5,9], but few investigations relate to the relationship between the geochemistry characteristics of coalbed gas and the formation and evolution of coalbed gas reservoir. The difference between coalbed gas composition and methane $\delta^{13}C$ value is very great. This is caused by coal maceral, coal rank, gas generating process, burial depth, temperature, and pressure[4,6,7]. The coalbed methane $\delta^{13}C$ value is generally lighter than natural gas with similar maturity. This is controlled by the maturity, the isotopic fractionation caused by desorption-diffusion-migration, the generation of secondary biogenetic gas, and the isotopic exchange reaction between CO_2 and CH_4[6,8,10−12]. The gas content is controlled by coal rank, burial depth, the lithology of coal roof and floor, and the fault[13−17].

Based on the study of burial and thermal history, the geochemistry characteristic and the gas content in critical stage and moment during the coalbed gas reservoir evolution are discussed, and the forming process of coalbed gas reservoir and the history of gas accumulation in the Qinshui basin are shown in this paper. Furthermore, it is concluded that the critical period is one of the most important factors on the gas geochemistry and gas content in the coal seam for the coalbed gas reservoir evolution.

2 Geological setting

The Qinshui Basin lies in the southeast of Shanxi Province, and covers 23.5×10^3 km^2. The sedimentary rocks include the Ordovician, the Upper Carboniferous Benxi and Taiyuan Formations, the Lower Permian Shanxi and Xiashihezi Formations, the Upper Permian Shangshihezi and Shiqianfeng Formations, the Triassic, and the Quaternary in the Qinshui Basin. The Carboniferous Taiyuan Formation and the Permian Shanxi Formation are the main coal-bearing sequences, in which No. 15, No. 3, and No. 2 are the main coal seams for coalbed gas exploration development[16,18,19].

The Taiyuan Formation of Upper Carboniferous: The Formation is 68.28—140.64 m thick, averagely 97 m, and consists of limestone, mudstone, sandy mudstone, siltstone, sandstone, and 7—16 coal seams, in which No. 15 coal seam is the main. The thickness of No. 15 coal seam is about 0.80—5.92 m, averagely 2.77 m. No. 9 coal seam and No. 16 exist locally.

The Shanxi Formation of Lower Permian: The Formation is 32.79—71.64 m thick, averagely 45 m, and consists of sandstone, sandy mudstone, mudstone, siltstone, and 3—4 coal seams, in which No. 3 coal seam is the main in Yangcheng district with thickness of 3.50—7.70 m and 5.63 m on average. No. 2 coal seam is the main in Huozhou district. The thickness of No. 2 is 1.50—5.60 m, averagely 3.26 m.

Up to now, more than 70 coalbed gas wells have been drilled in the south of Qinshui Basin. A coalbed methane reservoir with high permeability and gas content is discovered in this district. The previous investigations on coal distribution, coal rank, gas content, coal adsorption, reservoir permeability, sealing condition, and hydrodynamics indicated that the south of Qinshui Basin is an optimal district for coalbed gas development[17,18,20,21].

3 Sample analysis

15 samples of vitrinite reflectance and 5 samples of gas analysis are completed in this study. Vitrinite reflectivity is measured under the Leitz MPV-SP microphotometer. The composition of coalbed gas is carried out under HP-5880GC. The methane $\delta^{13}C$ value is measured using

Finngan MAT—252 mass spectroscope, the packed column of coalbed gas fractionation is Porapak Q, 2mx1/8 SS6, the maximum temperature is 200℃, and the rising rate of temperature is 8℃/min. The analysis errors are less than 0.3‰ when the analytical standard is compared with GBW04405 referenced gas. The measured and collected data are shown in Table 1. The methane $\delta^{13}C$ values are greatly different between Yangcheng district in the south of Qinshui Basin and Huozhou district in the west, which indicates that the coal seams experienced the different thermal evolution.

Table 1 Coalbed methane $\delta^{13}C$ value

District	Well	Source of sample	$\delta^{13}C$ value (‰)			source of date
			No. 2 coal	No. 3 coal	No. 15 coal	
Yangcheng	JS1	well		−31.2		Hu et al., 2001
	JS2	well		−31.8	−32.1	
	JS3	well		−33.56	−35.39	
	JS5	well		−30.1	−29.63	
	JS6	well		−30.48		
	JS1	well				Zhang et al., 2000
	JS1	well		−29.99—−33.67	−28.96—−29.35	
	JS2	well		−29.9—−35.7	−34—−33	
	JS3	well		−29.9—−34.75	−38.69	
	JS4	well		−26.6—−27.6	−20.8—−26.3	
	JS5	well			−30.7	
	Sihe coal mine	coal mine		−36.4		measured in this investigation
	Pan1	well		−35.2		
	FZ002	well		−34.2		
	FZ003	well		−36.7		
	TL003	well		−34		
Huozhou	Xinzhi coal mine	coal mine	−47.6			
	Xinzhi coal mine	coal mine	−51.7			

4 Results and analysis

4.1 Burial history

4.1.1 Geothermal gradient. Before the Jurassic to Cretaceous Yanshanian Orogeny, the Qinshui Basin, same as the Ordos Basin, is not an absolute subsidence basin, but a part of the North China Craton Basin. The Middle Yanshanian Orogeny from the Late Jurassic to the Early Cretaceous is an important tectonic movement in North China. The movement not only made an end of the evolutive history of North China Craton Basin, but also formed two interior basins, the Ordos Basin and the Qinshui Basin, which have different tectonic styles[19]. The thermal history and burial history controlled coalification, gas generation, and gas accumulation in the Qinshui Basin. The thermal event in the Middle Yanshanian Orogeny from the late Jurassic to the early Cretaceous is the most important factor that influenced coalbed gas generation and accumulation[22−24]. The geothermal gradient in the Qinshui Basin is given in Table 2.

4.1.2 The burial history in Yangcheng and Huozhou District. The Taiyuan and Shanxi Formations in the Qinshui Basin have experienced five evolution stages by Sang Shuxun et al.[24]

(1) Stage I was a slow subsidence stage from the Late Carboniferous to the Early Permian period. The average depositional rate was commonly not more than 25 m/Ma (82 ft/Ma). At the end of the Early Permian, the maximal burial depth of No. 15 coal seam was nearly 300 m.

(2) Stage II was a rapid subsidence stage from the Late Permian to the end of Late Triassic period. The average depositional rate was 80—100 m/Ma (263—328 ft/Ma). The burial depth of coal seams was rapidly increased. The sedimentation center was in Yangcheng-Jincheng-Houma, where the maximum burial depth of No. 15 reached 4800 m at the end of Later Triassic.

(3) Stage III was an uplifting and erosion stage in the Early Jurassic period. Because of the Yanshanian Orogeny, the coal-bearing sequence was uplifted and eroded extensively with the maximum uplift exceeding 1000 m (3281 ft).

(4) Stage IV was another slow subsidence stage in the Middle Jurassic period. The average depositional rate was about 16 m/Ma (52 ft/Ma) in this stage. Because of the Yanshanian Orogeny, the Qinshui Basin rudiment formed. The maximum subsidence exceeded 400 m.

(5) Stage V was mainly an uplifting stage from the Late Jurassic to the present. The whole basin is uplifted from the Late Jurassic to the Paleocene. The coal-bearing sequences and their overburden were severely eroded. The secondary faulted basin developed in this stage owing to the Himalayan Orogeny. The local district was filled by

the Neogene and Quaternary deposits and the maximum subsidence exceeded 1000 m in the northwest basin.

Based on the burial history of the Qinshui Basin and the measured R_o of Taiyuan and Shanxi Formations, the burial history diagrams in Yangcheng and Huozhou districts are matching by BASIN-MOD software. The strata in the two districts went through different sedimentary and burial process. The strata in the Yangcheng district were in a slow uplifting and erosion stage from the Late Jurassic to the Early Cretaceous and in a rapid uplifting and erosion stage from the Late Cretaceous to the Neogene (Fig. 1). The strata in the Huozhou district were in a rapid uplifting and erosion stage from the Late Jurassic to the Early Cretaceous and in a normal uplifting and erosion stage from the Late Cretaceous to the Neogene (Fig. 2).

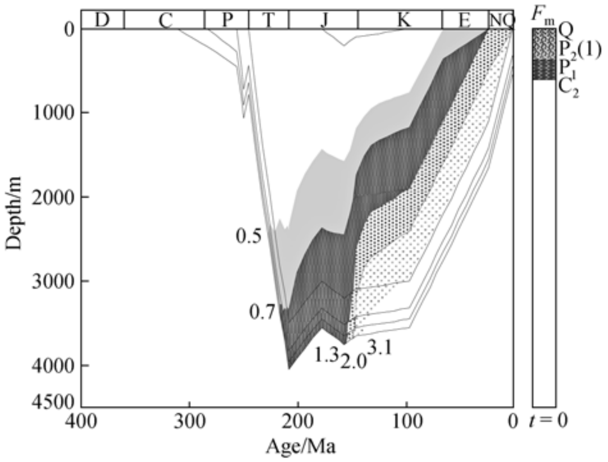

Fig. 1. The burial and thermal history in Yangcheng district.

Table 2 The history of geothermal gradient in the Qinshui Basin

Era	Uplift and subsidence	Geothermal gradient (℃/100 m)
E—Q	rapid subsidence locally	2.8—3
K_2—N	uplift	2.8—3
J_3—K_1	uplift	5.0—6.1
J_2	slow subsidence	3
J_1	uplift	3
P_2—T	rapid subsidence	3
C_2—P_1	slow subsidence	3

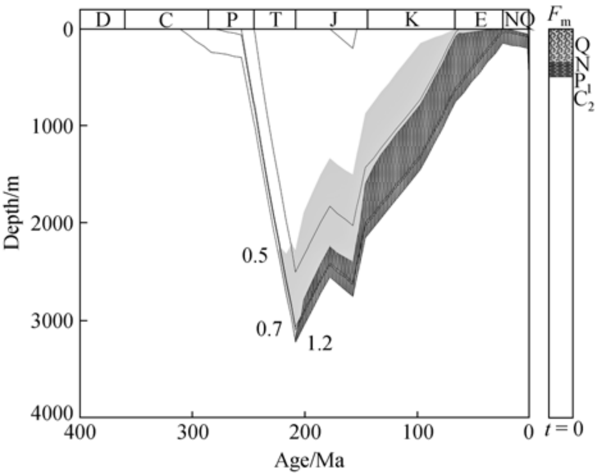

Fig. 2. The burial and thermal history in Huozhou district.

4.2 Geothermal history and coalbed gas geochemical characteristics

4.2.1 Geothermal history. Hydrocarbon generation experienced two critical periods in the Yangcheng district of the south of Qinshui Basin (Fig. 1): The first was at the end of the Triassic, in which the first peak of hydrocarbon generation formed with the R_o value of the coal from 0.9% to 1.3%; the second was from the Late Jurassic to the Early Cretaceous, in which the second peak of hydrocarbon generation formed owing to an abnormal geothermal event in the Yanshanian Orogeny with the R_o value of the coal from 2.4% to 4.2%. The first peak of hydrocarbon generation was at the end of the Triassic with the R_o value of the coal from 0.8% to 1.2%. There was no more coal maturation or the second peak of hydrocarbon generation from the Late Jurassic to the Early Cretaceous in Huozhou District, because Huo Mountain Uplift was continuously uplifted in this stage and the regional thermal event did not affect the coal seams in this district (Fig. 2).

4.2.2 The critical period. The geological period in which the coal maturation reached the maximum rank is called critical period, which controls the gas content and the geochemical characteristics of coalbed gas. Contrarily, the coalbed gas composition and the $\delta^{13}C$ of methane can indicate the thermal history. The coalbed gas reservoir in the south of Qinshui Basin experienced the abnormal thermal event in Middle Yanshanian Orogeny and reached the maximum maturation of R_o value from 2.4% to 4.2%. Therefore, the Middle Yanshanian Orogeny is the critical period of coalbed gas reservoir formation. The geochemistry characteristic of coalbed gas in this district is controlled by the geological process in this period. Compared with Huozhou coalbed gas reservoir, the coalbed gas reservoir in Yangcheng district is lately formed. Therefore, No. 3 coalbed gas in Yangcheng is mainly made up of methane from 94.49% to 99.28%, a little N_2 from 0.25% to 3.73%, and the methane isotopes are heavier with $\delta^{13}C$

values from −29.9‰ to −36.7‰, showing over mature gas. The No. 15 coalbed gas also has an over-mature feature, with methane from 95.7% to 99.15%, N_2 from 0.21% to 3.85%. The methane $\delta^{13}C$ value is from −20.8‰ to −38.69‰.

At the end of the Triassic, No. 2 coal seam was basically on mature phase (R_o = 0.8%—1.2%) in Huozhou district. From Jurassic to present, No. 2 coal seam was not affected by the abnormal thermal event because Huo Mountain Uplift uplifted greatly. The highest maturation reached at the end of the Triassic in Huozhou district, which is the critical period. The coalbed gas reservoir is formed earlier than that in Yangcheng. The coalbed gas composition of No. 2 is CH_4 68.35% — 99.35%, N_2 4.63% — 30.87%, and the methane $\delta^{13}C$ value is −47.6‰—−51.7‰.

The differences of thermal history and coalbed gas geochemistry characteristics between Yangcheng district and Huozhou district indicate that the geological process in the critical period controls the gas composition and methane $\delta^{13}C$ value. For example, the Permian coal experienced the highest maturation (R_o = 0.8%—1.2%) in Huozhou district in the Late Triassic. Therefore, the methane $\delta^{13}C$ value is light and N_2 content is high. While the coal in Yangcheng district experienced not only the first coalification in the Late Triassic, but the second coalification in the Middle Yanshanian Orogeny, the maturation is high (R_o = 2.4%—4.2%). Therefore, the methane $\delta^{13}C$ value is high and N_2 content is low.

4.3 The history of coalbed gas accumulation

The history of gas accumulation in the middle and south of Qinshui Basin has already been simulated in the past[25]. Because the coalbed gas is mainly adsorbed on coal surface, only the adsorbed gas is discussed in this paper.

4.3.1 The temperature and pressure at the critical moment. The critical moments include the end of Triassic for the first peak of hydrocarbon generation when the burial depth of the Shanxi and Taiyuan Formations reached the maximum depth, the end of Early Cretaceous for the second peak of hydrocarbon generation when the temperature is highest, the moment when the burial depth of the coal seams is shallowest, and present (Table 3). The temperature and pressure at these critical moments control the coal adsorption capacity.

4.3.2 The history of coalbed gas accumulation.

(1) Relationship between adsorption capacity and temperature/pressure. The coal adsorption capacity is mainly described with Langmuir equation[26]. The coal adsorption capacity is controlled by the coal properties, temperature, and pressure[26,27]. The adsorption capacity is only controlled by temperature and pressure when coal formed and reached certain maturity. The adsorption capacity is lower with temperature being higher and pressure being lower. Under the normal geothermal gradient, the coal adsorption capacity reaches its maximum at about 1500 m burial depth due to the influence of temperature and pressure, and has a decline trend with the burial depth over 1500 m[27]. According to Zhao et al., the isothermal adsorption parameters of Well. JS1 in Yangcheng district are: P_L of No. 3 is 3.034 MPa and V_L 39.91 m^3/t; P_L of No. 15 is 3.184 MPa and V_L 46.84 m^3/t[28]. According to Li et al., isothermal adsorption parameters of No. 2 in Xishan area of the western Qinshui Basin are: P_L in Huozhou district is 2.76 MPa; V_L is 22.85 m^3/t[1)].

Table 3 The temperature and pressure at the critical moments*

District	Critical moment	No. 2 coal	No. 3 coal	No. 15 coal
Yangcheng	end of Triassic		139℃/40.80 MPa	141℃/41.82 MPa
	end of Early Cretaceous		256℃/37.74 MPa	262℃/38.76 MPa
	end of Neocene		30℃/5.5 MPa	32℃/6.0 MPa
	present		35℃/6.0 MPa	38℃/6.5 MPa
Huozhou	end of Triassic	115℃/31.62 MPa		
	end of Early Cretaceous	140℃/13.57 MPa		
	end of Eocene	25℃/1.5 MPa		
	present	37℃/5.10 MPa		

* Surface temperature: 20℃; density of groundwater: 1.02 g/cm^3.

Based on a great deal of data, two curve lines showing the relationship between the adsorption capacity and the burial depth for two different rank coals are established in Fig. 3. In the figure, the solid part of the lines less than 1000 m in depth is supported by the exploration data, and the dotted part more than 1000 m in depth is mainly hypothetical. The coal rank with R_o = 1.0% corresponds to the maturity at the end of the Triassic in the south of Qinshui Basin, and the coal rank with R_o = 3.5% corresponds to the maturity at the end of the Early Cretaceous in the south of Qinshui Basin. Therefore, the gas accumulative history in Yangcheng and Huozhou can be conformed using the temperature and pressure at the critical moment.

(2) The history of coalbed gas accumulation. The

1) Li Jianwu, Zhang Xiaowen, Li Jing et al., The evaluation of coalbed gas exploration target in Xishan and Luan areas, Research Report, 1996.

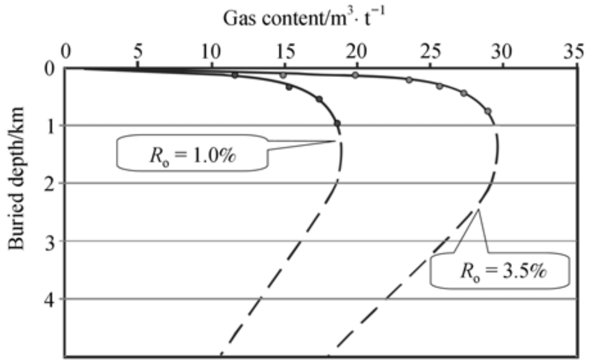

Fig. 3. The relationship between No. 3 coal adsorption capacity and the burial depth.

history of No. 3 coalbed gas accumulation in Yangcheng district is shown in Fig. 4. The burial depth of No. 3 coal seam was about 4 000 m at the end of Trassic. Because of the temperature influence, the adsorption capacity is low and about 15 m^3/t. The middle Yanshanian Orogeny is the geological period when the coal experienced the highest temperature, but the absorption capacity is also low. The adsorption capacity reaches its maximum when the burial depth of coal was about 1500 m. Therefore, the current coalbed gas content is mainly controlled by the adsorption capacity at the shallowest burial depth in the geological history. The range of the calculated current adsorption capacity is 24—27 m^3/t, averagely 26.68 m^3/t. The actual No. 3 coalbed gas content is: Well. JS1 is 21.97—27.17 m^3/t at 522.4—519.5 m depth, averagely 25.29 m^3/t; Well. JS2 is 20.16—26.70 m^3/t at 514.42—519.5 m depth, averagely 22.48 m^3/t; Well. JS3 is 15.2—21.91 m^3/t at 510.0—518.0 m depth, averagely 17.1 m^3/t; Well. JS4 is 21.97—27.17 m^3/t at 524.6—529.56 m depth, averagely 25.25 m^3/t. The saturation of No. 3 coalbed gas reservoir is high with 68%—98.2% in this district. The current actual coalbed gas content is lower than the calculated value due to the gas escaping by the diffusion.

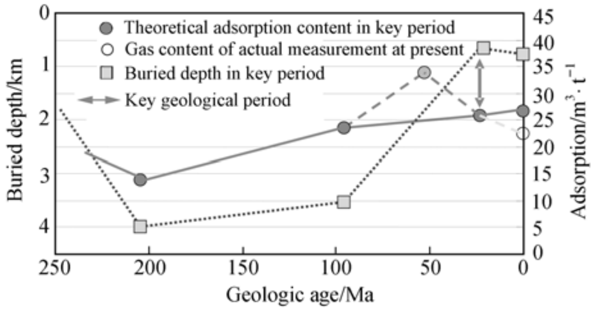

Fig. 4. The gas accumulation history of No. 3 coal seam in Yangcheng district.

The current actual gas content of No. 15 coal is: Well. JS1 is 19.03—25.19 m^3/t at 608.1—609.76 m depth, averagely 22.39 m^3/t; Well. JS2 is 20.81—23.59 m^3/t at 609.95—613.45 m depth, averagely 21.55 m^3/t; Well. JS3 is 10.52—15.44 m^3/t at 603.42—605.6 m depth, averagely 12.70 m^3/t; Well. JS4 is 15.45—32.32 m^3/t at 615.5—620.20 m depth, averagely 23.64 m^3/t. The saturation of No. 15 coalbed gas reservoir is relatively low in this district, only 38.7%—72.1%, because the sealing capability of No. 15 roof is weaker than that of No. 3.

The depositional setting and coal maceral are similar between No. 2 coal seam in Huozhou district and No. 3 coal seam in Yangcheng district. Therefore, the accumulative history of No. 2 coal seam in Huozhou district can be discussed according to the relationship between temperature/pressure and No. 3 coal adsorption capacity in Yangcheng district when R_o is 1.0% (Fig. 5). The burial depth of No. 2 coal seam is nearly 4000 m at the end of Triassic. The adsorption capacity is relatively low with gas content being about 17 m^3/t. The current maturity of coal consists with that at the end of the Triassic, because there is no thermal event in the Middle Yanshanian Orogeny in Huozhou district. The adsorption capacity is highest with gas content being about 20 m^3/t when the burial depth of coal seam is about 1500 m. The calculated adsorption capacity is only 7—8 m^3/t when the shallowest burial depth is only 300 m in this district. The calculated gas content of No. 2 coal seam is relatively high with 12—17 m^3/t, averagely 14.83 m^3/t, because of the Quaternary deposits. The current actual gas content is 2.75—8.16 m^3/t, averagely 5.07 m^3/t. Thereby, the saturation of No. 2 is very low, only 19%—55%.

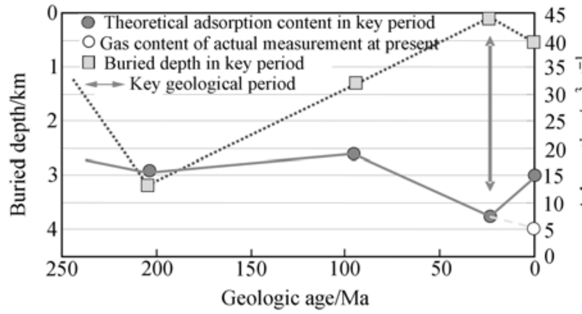

Fig. 5. The gas accumulation history of No. 2 coal seam in Huozhou district.

4.3.3 The critical moment controlling coalbed gas content. The burial depth of coal seam is shallowest at the end of the Neogene in Yangcheng district, only 550 m, and the Quaternary deposits is only 50 m. The pressure has a slight effect on adsorption capacity because the pressure at the end of the Neogene is as much as that of nowadays. This shows that the current gas content had been decided at the end of Neogene. Therefore, the end of the Neogene is the critical moment when the coalbed gas reservoir formed (Figs. 4 and 6).

The burial depth of No. 2 coal seam is shallowest at the end of the Eocene in Huozhou district, only 150 m. The calculated adsorption capacity is 8.05 m^3/t. The thickness of the Neogene and the Quaternary is 350 m. The pressure has great effects on adsorption capacity because the pressure at the end of the Neogene is not as much as that of nowadays. Therefore, the end of the Eocene is the critical moment to decide the coalbed gas content (Figs. 5 and 6). The current actual gas content is lower than the adsorption capacity when the burial depth is shallowest because of coalbed gas escaping (Fig. 5).

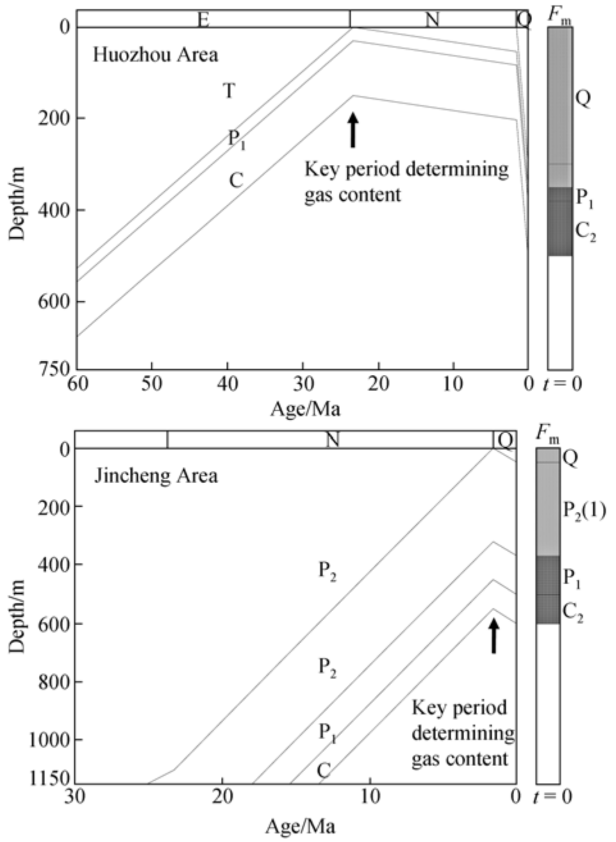

Fig. 6. The map showing the key period that determines the gas content at present in Houzhou area and in Jincheng area of Qinshui Basin.

5 Conclusion

(1) The coal seams in Yangcheng district in the south of Qinshui Basin and Huozhou district in the west experienced the different burial history. There were two hydrocarbon generating phases at the end of Triassic and the Late Jurassic to Early Cretaceous in Yangcheng district, and the coal maturity reached the highest level because of the abnormal thermal event in Middle Yanshanian Orogeny. There only went through one hydrocarbon generating phase at the end of Triassic and there were no abnormal thermal influence in Huozhou district.

(2) The geological period in which coal maturation reaches the highest level is the critical period to control the geochemical characteristics of coalbed gas. The composition of coalbed gas and the methane $\delta^{13}C$ value can also reflect the process of coalbed gas reservoir formation. The geochemical characteristics of coalbed gas in Huozhou district indicate that the coalbed gas reservoir was formed in the early stage; while in the south of Qinshui Basin it was formed in the late stage.

(3) There is a direct relation between the coalbed gas accumulative history and the coal seam burial history and the forming process of coalbed gas reservoir. Coalbed gas content depends on the critical moment of gas accumulative history. That is to say, it is the moment that the burial depth of coal seam is shallowest. The end of Neogene is the critical moment when coalbed gas reservoir in the south of Qinshui Basin formed, and the end of Eocene is the critical moment to form coalbed gas reservoir in Huozhou Uplift.

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