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RESEARCH ARTICLE

Influence of depositional environment on coalbed methane accumulation in the Carboniferous-Permian coal of the Qinshui Basin, northern China

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Abstract Based on analyses of the lithofacies palaeogeography of the Taiyuan and the Shanxi Formations in the Qinshui Basin, the spatial variations of the coal seam thickness, coal maceral composition, coal quality, and gas content, together with the lithofacies of the surrounding rocks in each palaeogeographic unit were investigated. The results show that the thick coals of the Taiyuan Formation are mainly distributed in delta and barrier island depositional units in the Yangquan area in the northern part of the basin and the Zhangzi area in the southeastern part of the basin. The thick coals of the Shanxi Formation are located within transitional areas between delta plain and delta front depositional units in the central southern part of the basin. The Taiyuan Formation generally includes mudstone in its lower part, thick, continuous coal seams and limestones in its middle part, and thin, discontinuous coal seams and limestone and sand-mud interbeds in its top part. The Shanxi Formation consists of thick, continuous sandstones in its lower part, thick coal seams in its middle part, and thin coal seams, sandstone, and thick mudstone in its upper part. From the perspective of coal-bearing sedimentology and coalbed methane (CBM) geology, the lithology and thickness of the surrounding rocks of coal seams play more significant roles in controlling gas content variation than other factors such as coal thickness, coal macerals, and coal quality. Furthermore, it is found that the key factors influencing the gas content variation are the thicknesses of mudstone and limestone overlying a coal seam. At similar burial depths, the gas content of the Taiyuan coal seams decreases gradually in the lower delta plain, barrier-lagoon, delta front, barrier-tidal flat, and carbonate platform depositional units. The CBM enrichment areas tend to be located in zones of poorly developed limestone and well-developed mudstone. In addition, the gas content of the Shanxi Formation is higher in the coals of the delta front facies compared to those in the lower delta plain. The CBM enrichment areas tend to be associated with the thicker mudstones. Therefore, based on the lithologic distribution and thickness of the rocks overlying the coal seam in each palaeogeographic unit of the Taiyuan and Shanxi Formations, the areas with higher gas content are located in the north-central basin for the Taiyuan coals and in the southern basin for the Shanxi coals. Both of these areas should be favorable for CBM exploration in the Qinshui Basin.

Keywords depositional environment, coalbed methane, enrichment condition, gas content, Taiyuan Formation, Shanxi Formation

1 Introduction

The depositional environment of coal measures not only controls the accumulation of coal seams, but also determines the lithofacies of the surrounding rocks, thus influencing the conditions for coalbed methane (CBM) accumulation (Yin and Zhang, 1987; Marchioni et al., 1996; Wei and Sang, 1997). Regionally, this pattern has been proven to effectively predict the distribution of gas content and high-gas coal mines based on depositional facies. According to a study of the relationship between depositional environment and gas content variation of the coal seams within the Late Permian Longtan Formation in

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southern China, the majority of the high-gas ranked coal mines are located within coal measures deposited in shore-delta and coastal plain environments, while the low-gas ranked mines are mainly located within coal measures deposited in coastal alluvial plain, shallow marine, and carbonate platform environments (Yin and Zhang, 1987). Meanwhile, with the exception of individual areas, the coal seams of the Lower Permian Shanxi Formation from a shore-delta depositional environment have a higher gas content than those of the Taiyuan Formation from a carbonate platform environment in the same region (Qin et al., 2000). Therefore, the depositional environment of coal measures has an influence on their gas-bearing properties and the accumulation of CBM to some degree.

The three main factors that influence CBM enrichment are sedimentary environment, tectonics, and hydrodynamic conditions (Wei and Sang, 1997; Fu et al., 2017). The latter two factors reflect the influence of coal rank and coal depth on CBM enrichment and are closely related to geological transformation. It is accepted that gas content increases gradually with increasing coal burial depth and from the run-off area to the stagnant zone (Song et al., 2013). However, the hydrocarbon potential of coal seams in one coalfield can be determined to some extent by the sedimentary facies of coal-bearing measures. In addition, for areas that are poorly studied, the sedimentary environment would be analyzed first; thus it is significant for CBM exploration to have an understanding of the depositional environment controls on CBM enrichment.

Coal is not only a special geological archive of paleogeographic and palaeoenvironmental information (Greb, 2013), but also a significant global energy resource (Holdgate et al., 2000; Ruppert et al., 2002). Therefore, a study on the exploration and utilization of coal and coal-bearing units is an extremely important subject area (Hou et al., 2017a; Lin et al., 2018). As a crucial aspect for predicting the distribution of coal seams, studying the depositional environment of coal-bearing strata is ongoing in the field of coal geology (Petersen et al., 1996; Moore and Shearer, 2003; Zhu, 2008; Deschamps et al., 2017). Based on analyses of depositional environments or facies, three aspects influencing CBM accumulation can be further studied comprehensively: 1) coal thickness and distribution (Shao et al., 2007; Durska, 2008); 2) the quality, petrology, and micro-fracturing of the coal reservoir (Zdravkov and Kortenski, 2004; Misiak, 2006; Farhaduzzaman et al., 2013; Miao, 2016); and 3) the sealing abilities of the CBM influenced by the conditions in the surrounding rock (Wei and Sang, 1997; Li et al., 2014a, b). Generally, a thick coal seam has a higher potential to generate gas and a better sealing ability (Zhang et al., 2015). Previous work also indicates that a greater methane adsorption capacity exists in coals with a lower moisture content (Perera et al., 2012), lower ash yield (Hou et al., 2017b), higher specific surface area (Bustin and Clarkson, 1998; Mastalerz et al., 2008), and larger vitrinite content (Laxminarayana and Crosdale, 2002; Hildenbrand et al., 2006). As strata lithology and thickness after the coal-forming period are controlled by the depositional environment, gas content should be varied in different sedimentary units of coal-bearing strata (Fu et al., 2017). Furthermore, endogenetic fractures are more likely to be found in vitrinite than in inertinite, indicating that maceral contents determined by the depositional environment would potentially play an important role in influencing pore connectivity and coal seepage ability (Wang et al., 2015).

The Qinshui Basin is an important industrial region for CBM exploitation in China. CBM exploration has taken place in the basin over the last 20 years and a large gas content dataset has been assembled, along with significant research on the depositional facies of coal measures (Su et al., 2005a; Shao et al., 2007, 2015). It is generally acknowledged that gas content tends to increase with increasing burial depth in the basin (Su et al., 2005b). In terms of CBM enrichment in the basin, previous studies have focused on influencing factors such as tectonic and hydrodynamic conditions (Su et al., 2005a, b; Liu, 2007). However, the effect of depositional environment on gas content variability has rarely been reported. In this study, based on interpretations of the lithofacies, palaeogeography of the Carboniferous-Permian Qinshui Basin, the relationships between coal seam thicknesses, physical properties of the coal reservoirs, sealing conditions of the surrounding rocks, and gas content of various depositional units were analyzed. This paper also shows the dominant sedimentological influences on gas content variation in the basin. Regions of CBM enrichment were then predicted using these influencing factors, a process that could be used to develop a decision-making framework for future exploration and development.

2 Regional geological context

2.1 Location and tectonic setting

The Qinshui Basin is located in the southeastern Shanxi Province of northern China, with geographical coordinates between 35°N −38°N and 111°E−114°E (Fig. 1(a)). The basin is a syncline, elongated in a NNE direction, with a total area of approximately 2.35×10^4 km^2 (Shao et al., 2015). During the Carboniferous and Permian periods, the Qinshui Basin was part of the North China Plate, which belonged to a large cratonic basin (Liu et al., 2013), suggesting that there was a stable base during this coal-forming period. The present-day Qinshui Basin is a residual structural basin formed by shearing and uplift events that occurred during the Yanshanian (Late Jurassic to Early Cretaceous) orogeny (Hsü, 1989), which pro-

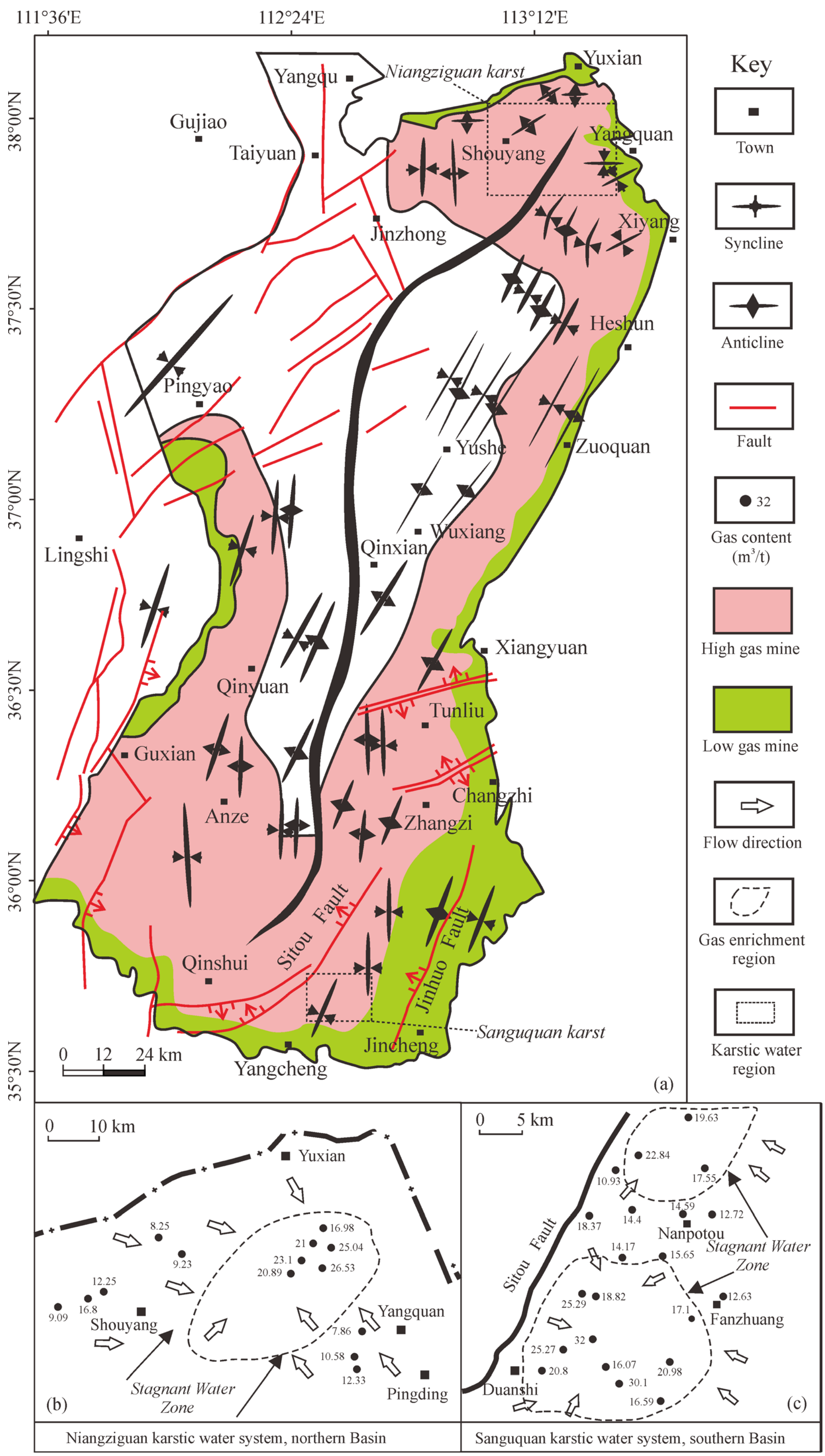


Fig. 1 (a) The tectonic outline map with the distribution of mine gas grade in the Qinshui Basin; (b) the changes of gas content close to the Niangziguan karstic groundwater system in the northern basin; (c) the variation of gas content close to the Sanguquan karstic groundwater system in the southern basin; gas content data from Song et al. (2013).

moted fracture development and increased coal permeability to some degree (Su et al., 2005a, b). The burial depths of main coal seams are generally less than 2000 m and the coalification degrees are higher than those of fat coal.

2.2 Coal-bearing measures

The Upper Carboniferous and Lower Permian Taiyuan Formation along with the Lower Permian Shanxi Formation are the major coal measures in the Qinshui Basin. The cumulative coal thickness of these two formations is between 1.2 m and 23.6 m, with a maximum single coal seam thickness of 7.8 m. The No. 15 coal seam in the Taiyuan Formation and the No. 3 coal seam in the Shanxi Formation are considered as the main targets for CBM exploration due to their thickness and stable distribution. The lithology of the Taiyuan Formation consists of coal, limestone, bauxitic mudstone, siltstone, and silty mudstone. It also includes 8–10 coal seams and a number of marker beds, such as the Miaogou, the Maoergou, and the Xiedao limestones (Fig. 2). The lithological types of the Shanxi Formation are coal seams, medium and fine sandstones, and mudstones, including several marker beds such as the Beichagou sandstone (K_7) and Nos.1–3 coal seams (Fig. 2).

2.3 Regional gas content distribution

The burial depth of coal seams increases from the margin to the center of the basin, ranging in structure from steeply dipping zones at the margins to gently folded zones at the center, and from low-gas coal mines at the margins to high-gas mines at the center (Fig. 1(a)). Local CBM occurrences are also influenced by hydrogeological conditions, such as the regions nearby the Sanguquan karst groundwater system in the southern part of the basin and the Niangziguan karst groundwater system in the northern part of the basin. In these regions, the gas content increases gradually from the run-off area to the stagnant zone (Figs. 1(b) and 1(c)).

2.4 Depositional environments of the coal measures

During the depositional period of the Taiyuan and Shanxi Formations, seawater came from the southeastern platform and the main sedimentary source in the basin was a large amount of terrigenous clastic rock generated by the uplift of the Yin Mountains (Shao et al., 2007). According to previous investigations (Shao et al., 2015), the sedimentary facies of the Taiyuan Formation consist of offshore carbonate shelf facies in the southeastern basin covering the Jincheng, Gaoping, and Zhangzi areas; the barrier island and lagoon facies in the Qinshui, Mabi, and Anze areas; the barrier island and tidal flat facies in the Changzhi, Tunliu, and Xiangyuan areas; and the delta front and lower delta plain in the northern basin (Fig. 3). In terms of the Shanxi Formation, the sedimentary environments are lower delta plain facies in the Tunliu, Wuxiang, Zuoquan, Heshun, Yangquan, and Shouyang areas in the northern basin with well-developed distributary channels and a higher sandstone to mudstone ratio; and delta front facies in the Jincheng, Gaoping, and Zhangzi areas in the southern basin, with occasional mouth bar facies with high sandstone to mudstone ratios (Fig. 4).

3 Methods

The division of palaeogeographic units of the Taiyuan and Shanxi Formations was carried out in a previous investigation and was referenced in this study (Shao et al., 2015). A database was established that included coal thickness, coal maceral content, ash yield and sulfur content. The data was collected from 98 boreholes covering the entire basin (Su et al., 2005a, b; Liu, 2007). The 179 gas content measurements from coal seams No. 9 and No. 15 in the Taiyuan Formation and another 236 measurements from coal seam No. 3 in the Shanxi Formation, were also collected and analyzed. These gas content data were obtained from underground coal mines or CBM boreholes, where magmatic intrusion was not observed, to ensure all data were accurate. Furthermore, zones affected by major fault structures and the six springs in the basin were also avoided during gas content data collection, in order to minimize the additional influence of geological structures and hydrogeology on the gas content data.

Previous work has established that gas content is highly influenced by coal rank and coal depth (Bustin and Clarkson, 1998; Fu et al., 2017). Therefore, in order to reduce the influence of coal rank and burial depth on gas content, samples analyzed in this study were from coals at similar burial depths among the different depositional units. The sequential process for studying the influence of the coal-bearing depositional environment on coalbed methane accumulation of the Carboniferous-Permian coal in the Qinshui Basin is as follows: 1) illuminate the controls of depositional environment on the coal thickness distribution, coal maceral content, ash yield, and sulfur content variations, along with the lithological development of the surrounding rocks; 2) analyze the relationships between coal thickness, coal maceral content, ash yield, sulfur content, along with the lithology of surrounding rocks and the gas content variation in the basin (from obtained data); 3) compare the gas content variation at similar burial depths in different depositional units. Finally, the dominant factor influencing gas content variation can be generalized from a sedimentological perspective.

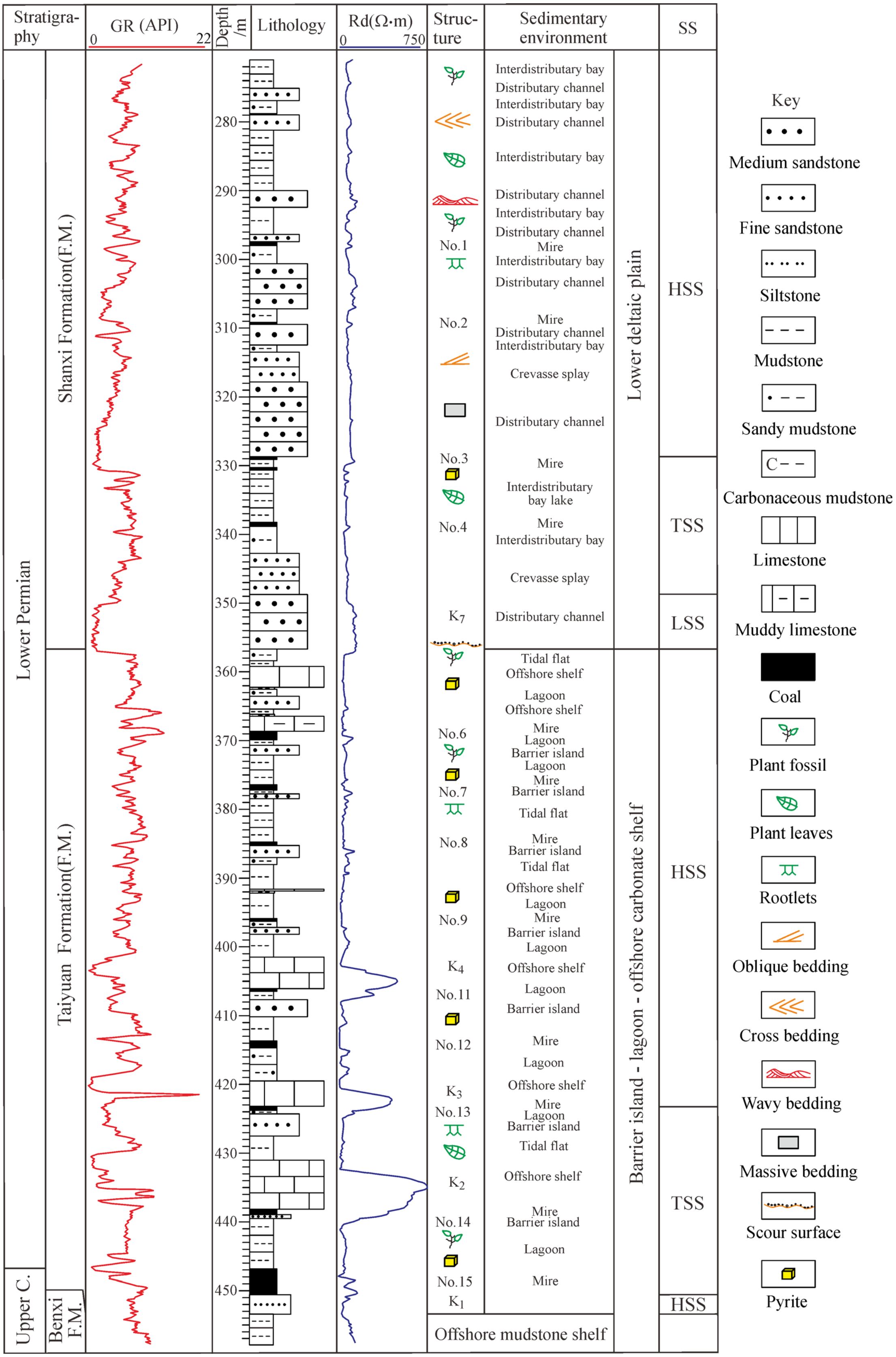


Fig. 2 Columnar section of sedimentary facies and sequence stratigraphic delineation of the 511 borehole in the Wangjiayu coal mine, Wuxiang county, Qinshui Basin (C. – Carboniferous; F.M. – Formation; SS – sequence sets; HSS – high-stand sequence set; TSS – transgressive sequence set; LSS – low-stand sequence set; K_1–K_4, K_7 – marker beds of limestone or sandstone).

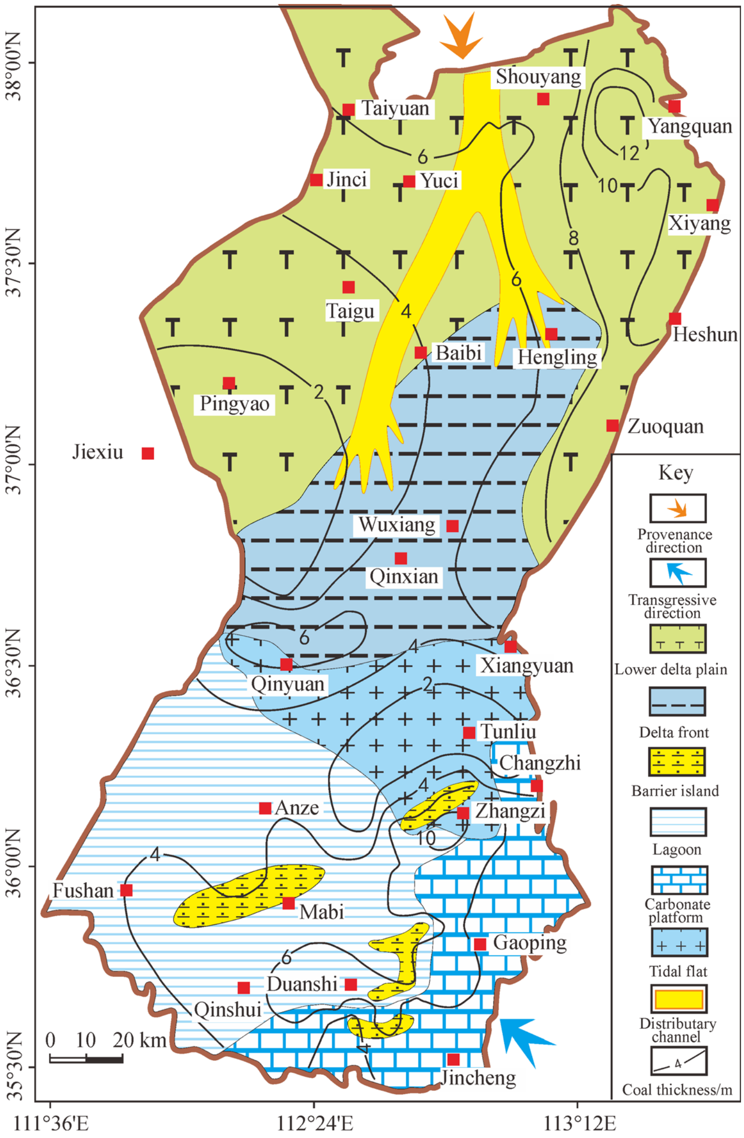


Fig. 3 Lithofacies palaeogeography and coal accumulation of the Taiyuan Formation in the Qinshui Basin (Shao et al., 2015).

4 Influence of coal-bearing depositional environment on coalbed methane accumulation

4.1 Thickness distribution of coal seams and its influence on gas content

4.1.1 Influence of depositional environment on coal thickness

The coal measures of the Taiyuan Formation deposited in barrier island, lagoon, and offshore shelf environments were formed when the accommodation space increased at a slightly higher rate relative to peat accumulation (Shao et al., 2007). The relatively deep water was located in the southeastern basin, covering the Jincheng, Mabi, Gaoping, and Zhangzi areas, which was not suitable for continual coal accumulation (Bohacs and Suter, 1997; Holz et al., 2002). However, for some regions in the barrier island depositional environment with higher sandstone to-mudstone ratios, thick coal seams were deposited. Meanwhile, their thicknesses pinch out at the bilateral lagoon and tidal flat environments (Fig. 3). In the northern basin within delta settings, water depth was shallow relative to the southern basin and, continuous accumulation of thick coal seams was favoured. As a result, the coal seams of the Taiyuan Formation generally thicken towards the northern section of the basin (Fig. 3).

During the depositional period of the Shanxi Formation, the ocean was regressing, and coal measures were formed in a shore delta environment. The rate of accommodation space increase generally decreased compared to that of peat accumulation (Shao et al., 2007). The Jincheng, Gaoping, and Zhangzi areas in the southern basin, were located in the delta front with relatively deeper water, and resulted in moderately thick coal seams ranging from 4 m to 6 m thick (Fig. 4). The Tunliu and Qinyuan areas in the central basin were located in the lower delta plain, far from the sediment source, which was suitable for continual peat accumulation with appropriate water depths. Thus 6–8 m thick coal seams were formed in these areas with consistent lateral distribution. In contrast, the Wuxiang, Yangquan, and Shouyang areas in the northern basin were located in the lower delta plain, but nearer to the sediment source. At this shallower water depth, peats were easily exposed and eroded by well-developed distributary channel sand bodies, which resulted in the absence of coal seam No. 3 in areas such as Pingyao. In general, the coal seams in the Shanxi Formation are thicker in the central part of the basin, and become thinner in the northern and southern regions of the basin (Fig. 4).

4.1.2 Relationship between coal thickness and gas content

Thick coal seams can not only produce more methane gas, but can also provide greater reserve space in terms of methane gas sealing (Paul and Chatterjee, 2011). As a result, thick coal seams usually have relatively high gas contents (Fu et al., 2017). For the middle-high coal rank coals in this study, there is a positive trend between gas content and coal thickness in both formations (Fig. 5). However, this trend is not very strong, suggesting that gas content variation is also affected by other factors such as coal maceral content and sealing conditions. Due to poor

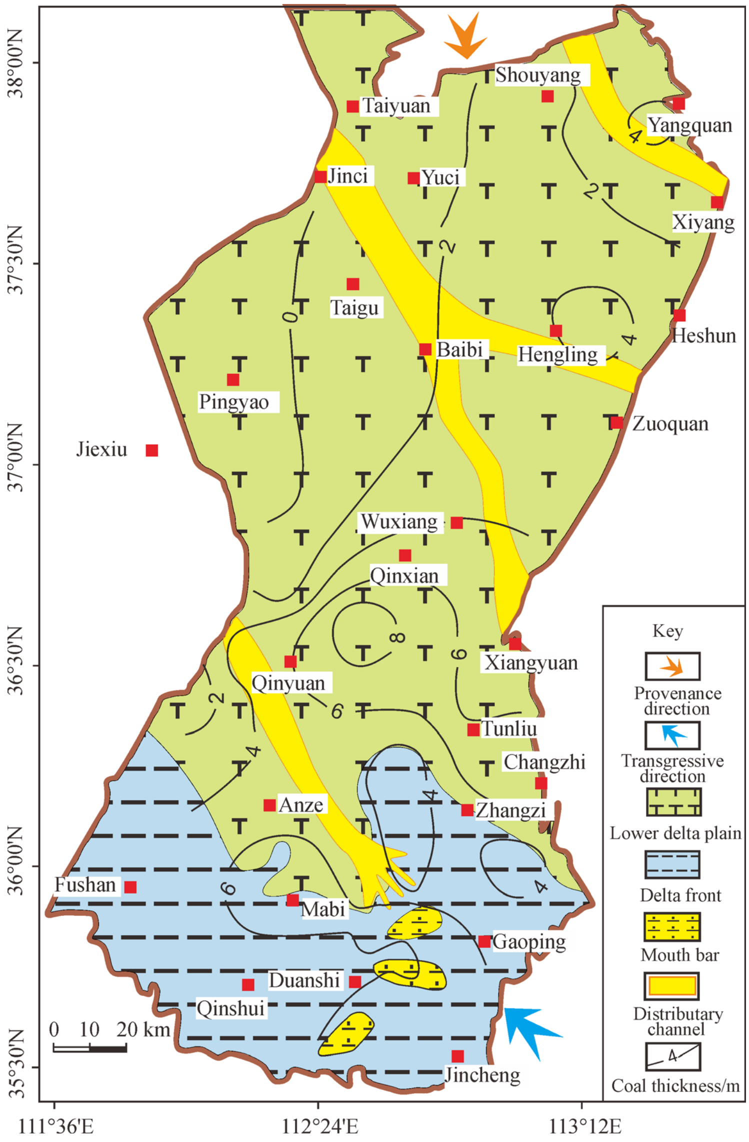


Fig. 4 Lithofacies palaeogeography and coal accumulation of the Shanxi Formation in the Qinshui Basin (Shao et al., 2015).

sealing ability, thick coal seams deposited in the barrier island environment would have lower gas contents than those of the thin coal seams deposited in the lagoon and tidal flat environments. Therefore, coal thickness is not the only dominant factor that controls gas content variation in the Qinshui Basin.

4.2 Coal maceral composition, coal quality, and their relationship with methane accumulation

Samples for the following analytical data were collected from 28 coal mines in the basin. The No. 15 coal seam in the Taiyuan Formation is a low ash, high sulfur coal with an average vitrinite content of 75.3%, inertinite content of 18.7%, ash yield of 20.2%, and sulfur content of 3%. The No. 3 coal seam in the Shanxi Formation is a low ash, low sulfur coal with an average vitrinite content of 73.7%, inertinite content of 19.9%, ash yield of 18.1%, and sulfur content of 0.5%.

4.2.1 Coal macerals and their implications for gas generation

The vitrinite content of coal seam No. 15 is generally higher than that of coal seam No. 3; both have an average value over 70%. For coal measures in the Taiyuan and Shanxi formations, the vitrinite content decreases northward in the basin while the inertinite content increases in the same direction. The highest vitrinite to inertinite ratio occurs on the southern basin margin, and also decreases northward (Figs. 6 and 7) which would be caused by water depth shallowing from south to north during the coal-forming period. Coal seam No. 15 in the Taiyuan Formation, which accumulated in a deltaic environment in the northern basin, has a lower vitrinite to inertinite ratio

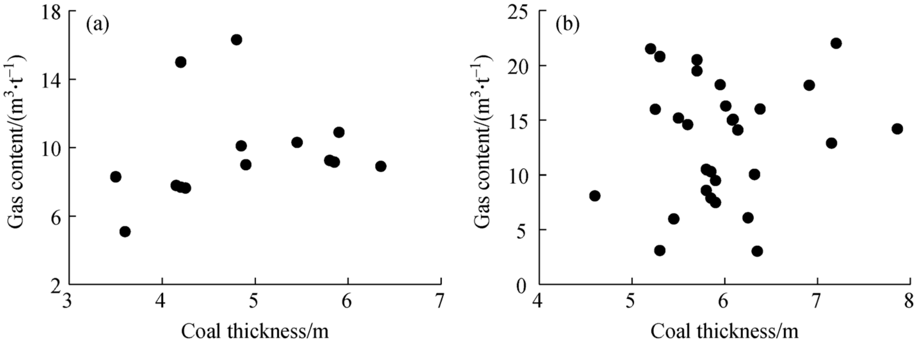


Fig. 5 Relationship between coal thickness and gas content. (a) No. 15 coal seam of Taiyuan Formation in the Heshun Tianchi coal mine; (b) No.3 coal seam of Shanxi Formation in the northern Shizhuang Block; data of Fig. 5(b) from (Hu et al., 2016).

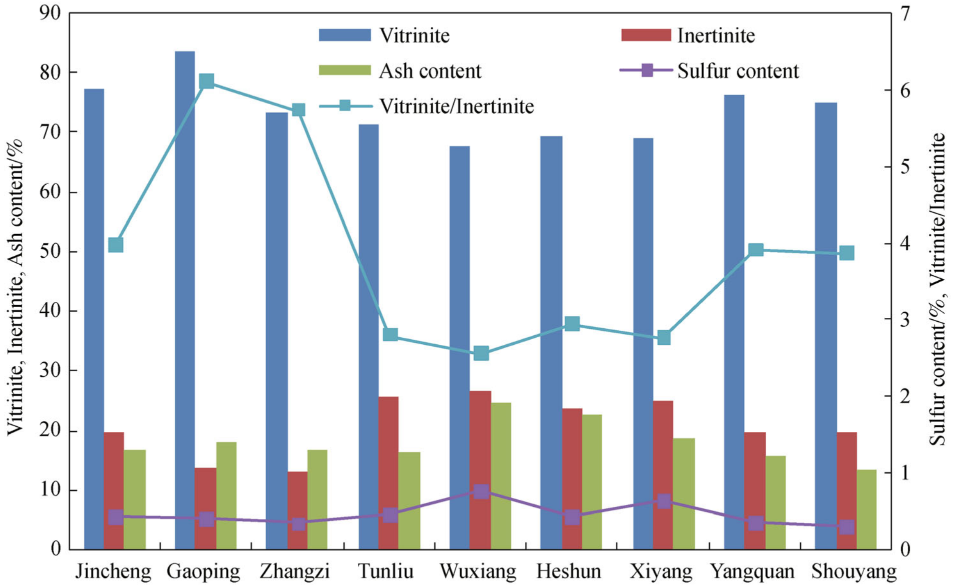


Fig. 6 The coal macerals and coal qualities of No. 15 coal seam of the Taiyuan Formation in the Qinshui Basin.

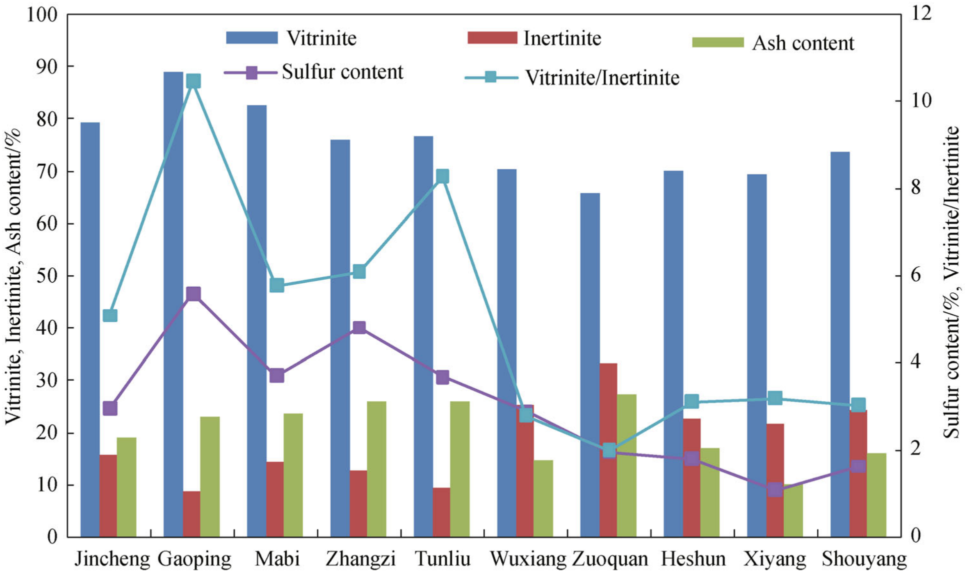


Fig. 7 The coal macerals and coal qualities of No. 3 coal seam of the Shanxi Formation in the Qinshui Basin.

than that in the south-central basin (Fig. 6). Coal seam No. 3 of the Shanxi Formation accumulated in a lower delta plain environment especially in the northern parts of the Wuxiang, Zuoquan, and Heshun areas, which has a relatively low vitrinite to inertinite ratio in the north-central basin due to the influences of both shallow water depths and the presence of distributary channels (Fig. 7).

Previous work has shown that exinite has the strongest potential for hydrocarbon generation in terms of coal macerals, followed by vitrinite, then inertinite (Adegoke et al., 2015). The macerals found in this basin during the Carboniferous and Permian are mainly vitrinite and inertinite, with only a small amount of exinite (Liu, 2007). The maceral content, spatially controlled by the depositional environment of the peat swamp, consists of relatively high inertinite contents in dry and oxidizing environments but relatively high vitrinite contents in deep-water environments (Teichmüller, 1982). Therefore, based on the variations of coal macerals in the basin, coals in the southern basin should have greater potential for methane generation than those in the northern basin.

4.2.2 Coal quality and its relationship to methane adsorption

The No. 15 coal seam of the Taiyuan Formation in the southern basin accumulated in barrier, lagoon, and offshore shelf environments has a sulfur content that is, overall, relatively high due to the long-term effect of seawater invasion. The sulfur content in the coal seam decreases northwards. In contrast, the No. 3 coal seam of the Shanxi Formation accumulated in a shore delta environment and generally has a lower sulfur content due to the minimal presence of seawater. The ash yield was influenced by both terrigenous clastics and seawater invasion (Ye et al., 1997). Mires affected by seawater have the potential to produce more Fe_2O_3, MgO, and CaO. These minerals can also lead to an increase in the ash yield. Thus, the variation in the ash yield of coal seam No. 15, which is mainly controlled by seawater invasion, decreases northwards with the same trend as sulfur content (Fig. 6). Coal seam No. 3, in the Wuxiang, Zuoquan, and Heshun areas of the central basin, was strongly influenced by the main distributary channels, therefore the ash yield is relatively high (Fig. 7). Coal with a higher ash yield generally has lower porosity because the ash yield (mainly in minerals) can effectively fill the pores and fractures of the coal system (Hou et al., 2017b). A negative correlation between ash yield and methane adsorption ability has been shown in many investigations (Bustin and Clarkson, 1998; Hou et al., 2017b). Therefore, for coal measures in the Taiyuan Formation, coals in the northern basin should have greater methane adsorption abilities than those in the southern basin. A lower methane adsorption ability can also be predicted for the Shanxi coals in the central basin compared with those in the southern and northern basin.

4.3 Surrounding rock distribution and its influence on gas content

4.3.1 Lithofacies association of the surrounding rocks

During the deposition of the Taiyuan Formation, the lateral sedimentary facies were offshore carbonate shelf facies in the southeastern basin; barrier island, lagoon, and tidal flat facies in the central basin; and lower delta plain facies in the northern basin. Because seawater invasion came from the southeast, the number and thickness of the limestone strata decreased northwards (Figs. 3 and 8). The vertical stratigraphic pattern generally shows mudstone at the bottom; continuous, thick coal seams and limestones in the middle; and discontinuous, thin coal seams, limestones, and sand-mud interbeds at the top of the section (Fig. 8). During the depositional period of the Shanxi Formation, the lateral sedimentary facies were relatively simple, with delta front facies in the southern basin and lower delta plain facies in the north-central basin (Fig. 4). The vertical stratigraphic pattern consists of continuous, thick distributary channel and mouth bar sandstones at the bottom; lenticular sandstones and continuous, thick coal seams in the middle; and thin coal seams, sandstone, and thick mudstones on the top of the section (Fig. 9).

4.3.2 Relationship between surrounding rock characteristics and methane enrichment

It is generally accepted that the surrounding rock types such as thick oil shale, mudstone, and silty mudstone are better for CBM preservation in coal measures than sandstone and carbonate. Carbonates can be classified into two types. The first type is distributed in tectonically stable areas, with undeveloped karst caves and fractures, which has some preservation ability. The other type is distributed in tectonically active areas, with well-developed karst caves and fractures, and has poor preservation ability (Yao et al., 1999).

Based on the lithofacies association of surrounding rocks, the combination of surrounding rock types was classified within various palaeogeographic units, including type I−VI of the Taiyuan Formation, and type VII−VIII of the Shanxi Formation (Figs. 8–10).

Type I is deposited in the inter-distributary bay of lower delta environments in the upper Taiyuan Formation in the northern basin, covering the Zuoquan, Xiyang, Shouyang, and Yangquan areas. For this type, the lithology of the rock overlying coal seams is mainly mudstone and sandy mudstone. This section of the Taiyuan Formation has the highest average gas content of 11.22 m^3/t (Fig. 10). Type II is deposited as the lower part of the Taiyuan Formation in the northern basin, and contains thin limestones, thick

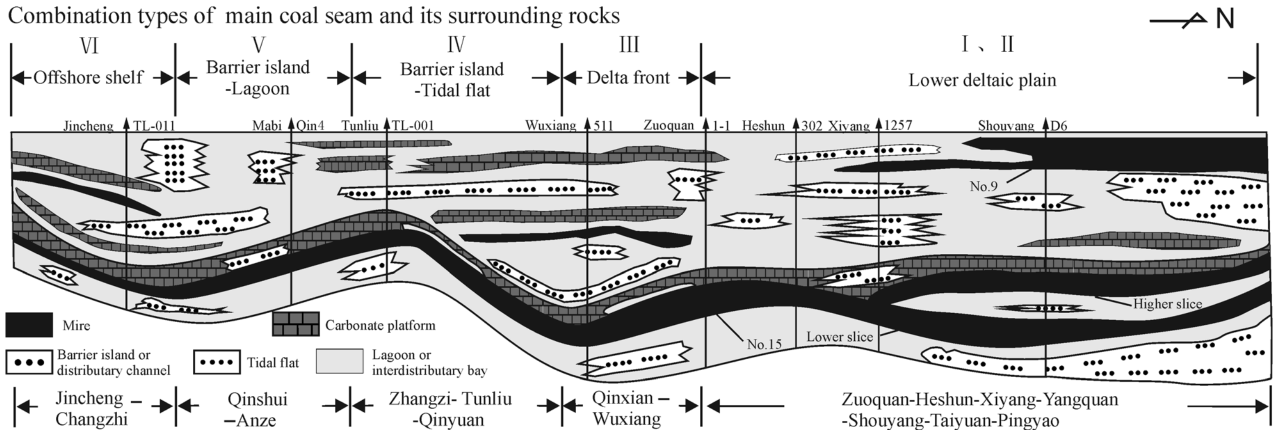


Fig. 8 Sedimentary facies and surrounding rocks of coal measures in the Taiyuan Formation, Qinshui Basin.

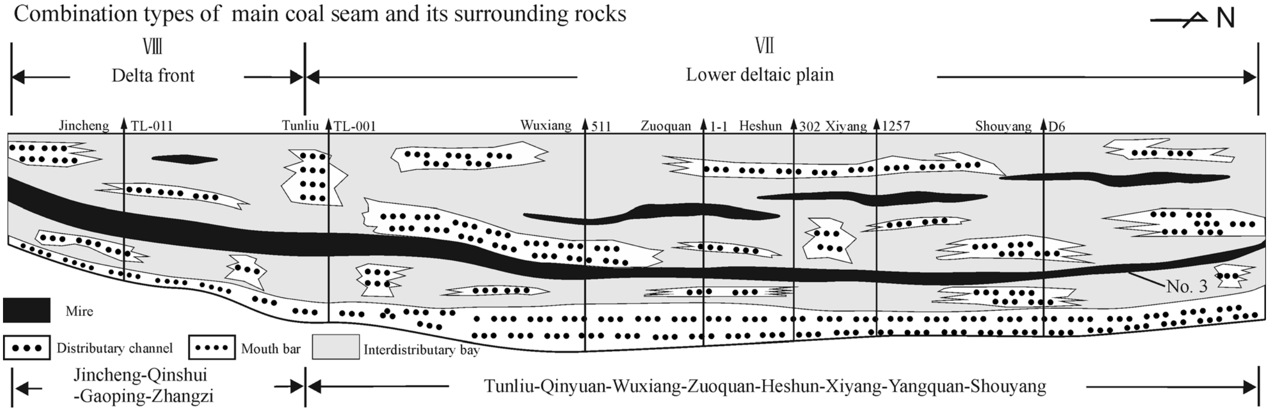
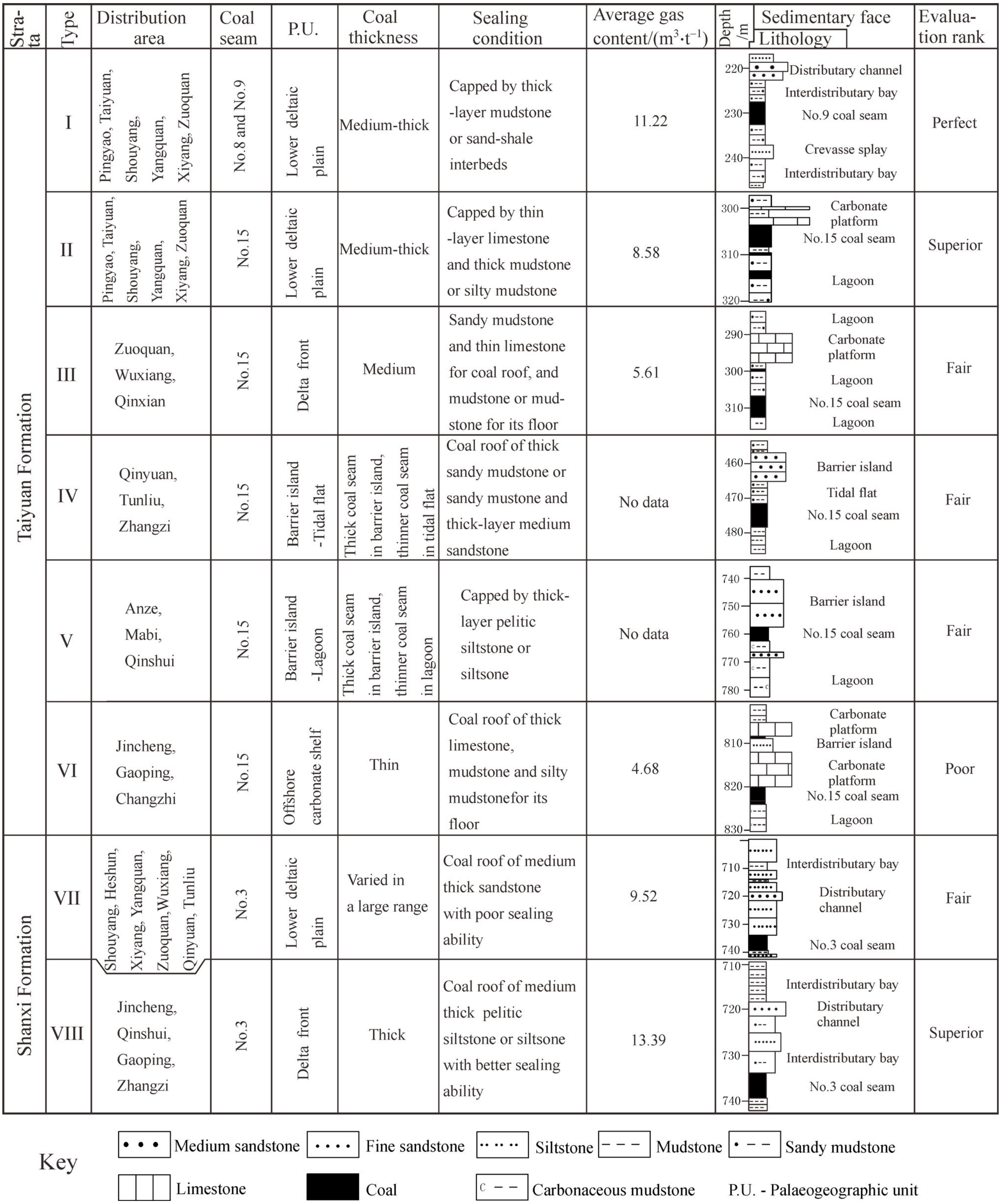


Fig. 9 Sedimentary facies and surrounding rock combination characteristics of the Shanxi Formation in the Qinshui Basin.



Strata	Type	Distribution area	Coal seam	P.U.	Coal thickness	Sealing condition	Average gas content/($m^3 \cdot t^{-1}$)	Depth/m; Sedimentary face; Lithology	Evaluation rank
Taiyuan Formation	I	Pingyao, Taiyuan, Shouyang, Yangquan, Xiyang, Zuoquan	No.8 and No.9	Lower deltaic plain	Medium-thick	Capped by thick-layer mudstone or sand-shale interbeds	11.22	220, 230, 240 Distributary channel Interdistributary bay No.9 coal seam Crevasse splay Interdistributary bay	Perfect
	II	Pingyao, Taiyuan, Shouyang, Yangquan, Xiyang, Zuoquan	No.15	Lower deltaic plain	Medium-thick	Capped by thin-layer limestone and thick mudstone or silty mudstone	8.58	300, 310, 320 Carbonate platform No.15 coal seam Lagoon	Superior
	III	Zuoquan, Wuxiang, Qinxian	No.15	Delta front	Medium	Sandy mudstone and thin limestone for coal roof, and mudstone or mudstone for its floor	5.61	290, 300, 310 Lagoon Carbonate platform Lagoon No.15 coal seam Lagoon	Fair
	IV	Qinyuan, Tunliu, Zhangzi	No.15	Barrier island-Tidal flat	Thick coal seam in barrier island, thinner coal seam in tidal flat	Coal roof of thick sandy mudstone or sandy mustone and thick-layer medium sandstone	No data	460, 470, 480 Barrier island Tidal flat No.15 coal seam Lagoon	Fair
	V	Anze, Mabi, Qinshui	No.15	Barrier island-Lagoon	Thick coal seam in barrier island, thinner coal seam in lagoon	Capped by thick-layer pelitic siltstone or siltsone	No data	740, 750, 760, 770, 780 Barrier island No.15 coal seam Lagoon	Fair
	VI	Jincheng, Gaoping, Changzhi	No.15	Offshore carbonate shelf	Thin	Coal roof of thick limestone, mudstone and silty mudstonefor its floor	4.68	810, 820, 830 Carbonate platform Barrier island Carbonate platform No.15 coal seam Lagoon	Poor
Shanxi Formation	VII	Shouyang, Heshun, Xiyang, Yangquan, Zuoquan, Wuxiang, Qinyuan, Tunliu	No.3	Lower deltaic plain	Varied in a large range	Coal roof of medium thick sandstone with poor sealing ability	9.52	710, 720, 730, 740 Interdistributary bay Distributary channel No.3 coal seam	Fair
	VIII	Jincheng, Qinshui, Gaoping, Zhangzi	No.3	Delta front	Thick	Coal roof of medium thick pelitic siltstone or siltsone with better sealing ability	13.39	710, 720, 730, 740 Interdistributary bay Distributary channel Interdistributary bay No.3 coal seam	Superior

Fig. 10 Types of main coal seam surrounding rock combinations and gas bearing evaluation of the Taiyuan and Shanxi coals in the Qinshui Basin.

mudstones, and thick silty mudstones overlying coal seams. The evaluation of gas sealing is excellent with a relatively high average gas content of 8.58 m^3/t. Type III is deposited at the delta front in the Zuoquan, Wuxiang, and Qinxian areas. For this type, the overlying lithology mainly includes sandy mudstones and thin limestones, and the underlying lithology is mudstones or sandy mudstones. Due to the limestone overlying the coal seam, this type has a medium gas content with an average value of 5.61 m^3/t. Type IV and Type V are deposited in barrier island-tidal flat and barrier island-lagoon environments, respectively. The overlying lithology in both of these two types is medium-thick sandy mudstones, siltstones and mudstones. Low to middle gas contents in these types can be predicted based on the surrounding lithology and rock thickness. Type VI, deposited in a carbonate platform environment and situated at the bottom of the Taiyuan Formation, is composed of thick limestones overlying the coal seams. The evaluation of gas-bearing is poor with average gas content of 4.68 m^3/t, though there are medium-thick mudstones and silty mudstones underlying coal seams. Therefore, in terms of sealing ability for CBM, the direct rocks overlying coal seams would play a more significant role than underlying rocks in these coal measures.

Type VII is deposited in the lower delta plain environment of the Shanxi Formation. The coal seams thin towards terrigenous areas and are overlain by thick, medium-fine sandstones or siltstones with poor sealing ability and a fair evaluation of gas-bearing potential (Fig. 10). Type VIII, deposited in the delta front environment of the Shanxi Formation, is made up of muddy siltstones or siltstones with a better sealing ability than type VII, and the evaluation of gas-bearing potential is excellent. In terms of CBM preservation conditions, mudstones and silty mudstones have a better sealing ability than the other lithologies observed. Meanwhile, the negative effect of limestone is more apparent than for other lithologies observed in the basin.

4.4 Gas content comparisons within different depositional units

4.4.1 Relationship between sedimentary environment and gas content of Taiyuan coal

The gas content values corresponding to the burial depths of coal seams No. 9 and No. 15 in the Taiyuan Formation were statistically classified according to the types of the different palaeogeographic units, including delta plain, delta front, and carbonate platform. Because the barrier-lagoon and the barrier-tidal flat units are located in the axial region of the syncline in the central basin with deep coal depths, there are currently no gas content measurement data for this region. The results show a positive correlation generally exists between gas content data and burial depth of each palaeogeographic unit, except for the methane oxidation belt of coals shallower than 200 m (Fig. 11). In addition, the hectometer gradients of the gas content decrease from the No. 9 coal seam deposited in a lower delta plain setting, to the No.15 coal seam deposited in a

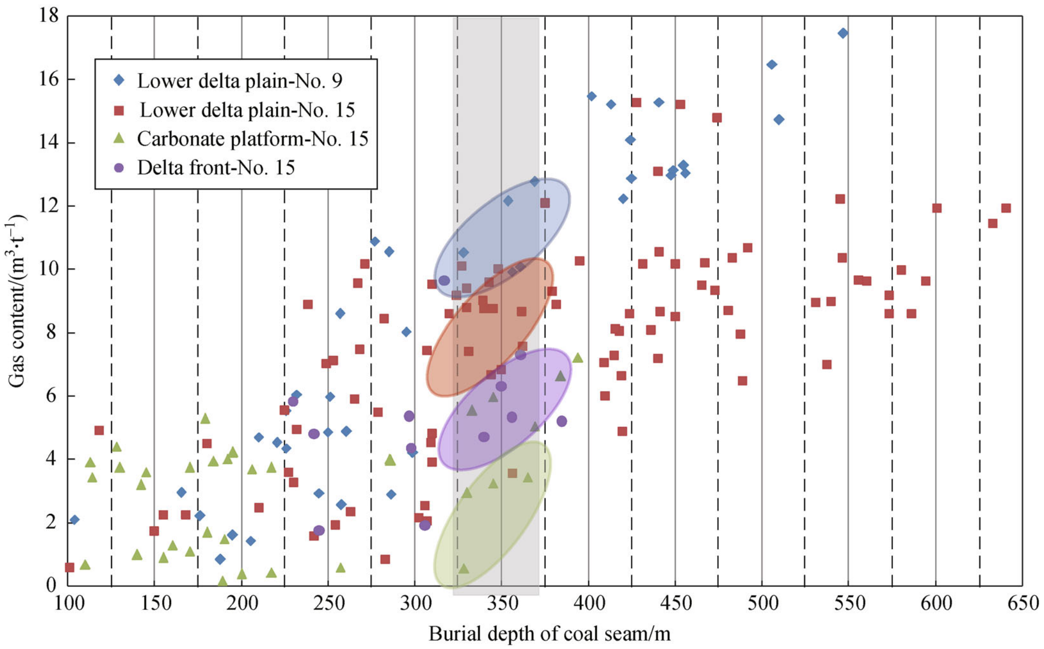


Fig. 11 Variation of gas contents within different palaeogeographic units and different burial depths, Taiyuan Formation, Qinshui Basin.

lower delta plain setting, to coals deposited in a delta front setting, and finally to coals in a carbonate platform setting (Fig. 11). It should be noted that correlation coefficients of the data points taken from the carbonate platform and delta front settings are relatively lower compared to other depositional environments, which is attributed to insufficient data and increased methane oxidation belt data.

In order to decrease the influence of coal rank and coal depth on the variation of gas content, the gas content data from differing paleogeographic units at similar burial depths were analyzed. The data points collected at burial depths between 325 m and 375 m were analyzed, and gas content values decrease in order from coal seams deposited in a lower delta plain setting, to a delta front setting, and finally to a carbonate platform setting (Fig. 11). Combined with divided surrounding rock types (Fig. 10), it is found that coals deposited in a lower delta plain environment have the best sealing ability for methane preservation, followed by the delta front and carbonate platform environments.

4.4.2 Relationship between sedimentary environment and gas content of Shanxi coal

For the No. 3 coal seam of the Shanxi Formation, gas content data corresponding to similar burial depths were also statistically classified according to their palaeogeographic units, consisting of lower delta plain and delta front settings. A weak positive correlation can be obtained between the gas content data for each palaeogeographic unit and their associated coal burial depths. In addition, gas content hectometer gradients decrease in the No. 3 seam from coals deposited in the delta front to those in a lower delta plain setting. This indicates that the gas contents of the delta front facies were higher than those of the lower delta plain facies at similar burial depths. Data taken from burial depths between 425 m and 475 m were analyzed in detail, and it was observed that gas contents in delta front facies are, in general, higher than those in lower delta plain facies (Fig. 12). Therefore, the No. 3 coal seam in the delta front depositional unit has a better sealing ability than the lower delta plain unit. It should be noted that the gas content of the Taiyuan coal seams in the delta front are lower than the lower delta plain, whereas the opposite is true for the Shanxi coal seams. The most likely reason for this is that limestone exists in the surrounding rocks of the Taiyuan coal seams within the delta front depositional unit (Fig. 10).

4.4.3 Analysis of factors controlling CBM enrichment

The influences of coal thickness, coal maceral content, coal quality, and surrounding rock type on CBM enrichment in the Qinshui Basin have been analyzed previously in this study. The results show a weak positive correlation between gas content and coal thickness (Fig. 5). Although coal maceral content and coal quality can affect gas content to some degree, the effect of these two factors is weaker than that of the surrounding rock type. This can be explained by considering the No. 15 coal seam in the southern basin. The coals in this region have relatively low gas contents with high vitrinite content but poor sealing ability. Therefore, the lithology and thickness of the surrounding rock are playing more significant roles than coal thickness, coal maceral content, and coal quality in controlling variation in gas content, which could be the key factor controlling CBM enrichment in the Qinshui Basin.

In order to analyze the impact of the depositional environment on gas content, depth intervals should be chosen based upon a relatively high concentration of available gas content data for each palaeogeographic unit. Therefore, coal depth ranging from 325 m to 375 m and

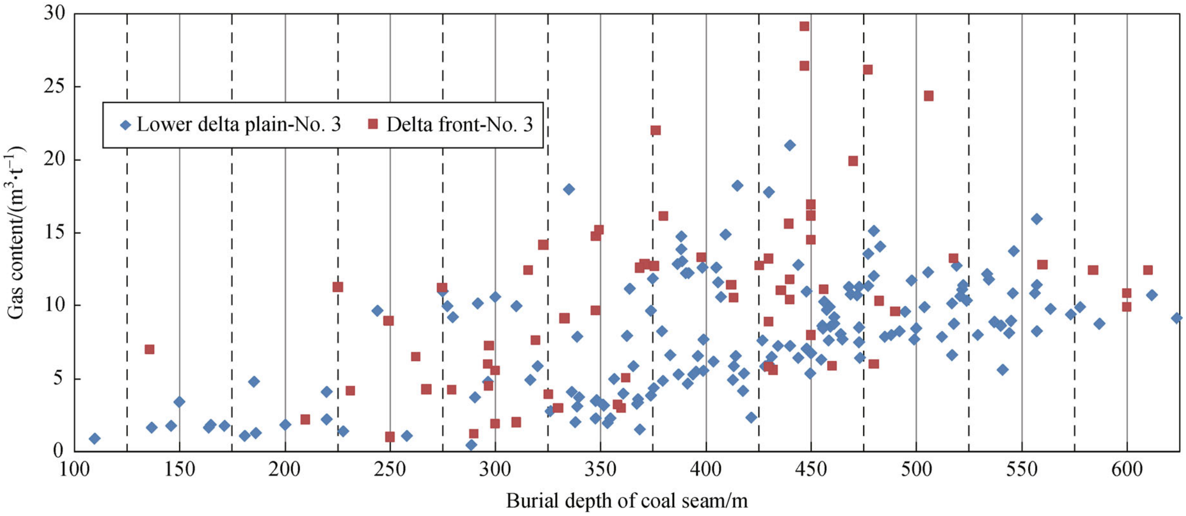


Fig. 12 Gas content variation of different palaeogeographic units and different burial depths, Shanxi Formation, Qinshui Basin.

from 425 m to 475 m corresponding to the Taiyuan and Shanxi Formations, respectively, were selected. As the cap rocks of coal seams play a more significant role in CBM sealing than the rocks underlying coal measures, the strata lithology and thickness within 20 m above main coal seam within various palaeogeographic units was recorded. For coal seam No. 9 in the Taiyuan Formation, the averaged overlying strata thicknesses of mudstone (including siltstone) and limestone of in the lower delta plain are 14.5 m and 0 m, respectively, and the average gas content is 11.22 m^3/t. The averaged thickness of mudstone (including siltstone) and limestone overlying coal seam No. 15 in the lower delta plain, the delta front, and the carbonate platform units are 11.78 m and 5.44 m, 7.14 m and 8.3 m, together with 7 m and 12.9 m, respectively, with average gas contents of 8.58 m^3/t, 5.61 m^3/t, and 4.68 m^3/t (Fig. 10). It can be seen that gas contents of the Taiyuan coal seams are negatively correlated with limestone thickness and positively correlated with mudstone thickness. With respect to the No. 3 coal seam in the Shanxi Formation, the average mudstone (including siltstone) thickness of the lower delta plain and the delta front is 8.16 m and 12.04 m, with averaged gas contents of 9.52 m^3/t and 13.39 m^3/t. These results show that the gas contents of the Shanxi Formation are proportional to mudstone thickness within 20 m above the coal seams, and this leads to the conclusion that thicker mudstone will contain higher coal seam gas content in the Shanxi Formation.

5 Conclusions

1) For the Taiyuan Formation, thick coal seams are generally located in the areas close to the barrier island depositional environment of the southern basin and the delta depositional settings of the northern basin, whereas thick Shanxi coal seams are formed in the south-central basin, in the transition between delta plain and delta front depositional unit. There is an ambiguous trend between coal thickness and gas content, indicating that coal thickness is not the only dominant factor controlling gas content variation in the Qinshui Basin.

2) The vitrinite content and vitrinite to inertinite ratio of the Taiyuan and Shanxi coal seams both reach their highest values in the southeastern margin of the basin. The vitrinite contents decrease from south to north, whereas the inertinite contents increase from south to north due to the spatial variation of the sedimentary environment. The average sulfur content of the No. 15 coal seam is much higher than that of the No. 3 seam, and the ash yield of seam No. 15 decreases northwards, while the highest ash content of seam No. 3 is located in the south-central basin.

3) The variation in gas content is closely related to lithology and the thickness of the surrounding rock. Six types of surrounding rocks in the Taiyuan Formation and two types of surrounding rocks in the Shanxi Formation were identified. In terms of the Taiyuan Formation, coals in the delta plain environment have the best sealing conditions with the greatest thicknesses of mudstone, whereas coals in the carbonate platform environment have the poorest sealing conditions with the largest thicknesses of limestone. For the Shanxi Formation, due to more fine-grained sediments, coals in the delta front environment have a better sealing ability than those in the delta plain environment.

4) At similar burial depths within the Taiyuan coal seams, the gas content values decrease in order from a lower delta plain setting, a delta front setting, and a carbonate platform setting. Generally, the gas contents of Shanxi coals in the delta front facies are higher than those in the lower delta plain facies. The CBM enrichment areas tend to be located in zones of undeveloped limestone and well-developed mudstone. Therefore, combined with coal thickness and gas content analysis, coal seams located in the north-central basin of the Taiyuan Formation and in the southern basin of the Shanxi Formation are suggested as favorable areas for CBM exploration.

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