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RESEARCH ARTICLE

Permo-Carboniferous coal measures in the Qinshui basin: Lithofacies paleogeography and its control on coal accumulation

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Abstract The Qinshui basin in southeastern Shanxi Province is an important base for coalbed methane exploration and production in China. The methane reservoirs in this basin are the Carboniferous and Permian coals. Their thickness is strongly controlled by the depositional environments and the paleogeography. In this paper, sedimentological research was undertaken on the outcrop and borehole sections of the Taiyuan and Shanxi formations in the Qinshui basin and the basin-wide lithofacies paleogeography maps for these two formations have been reconstructed. The Taiyuan Formation is composed of limestones, aluminous mudstones, siltstones, silty mudstones, sandstones, and mineable coal seams, with a total thickness varying from 44.9 m to 193.48 m. The coal seams have a thickness ranging between 0.10 and 16.89 m, averaging 7.19 m. During the deposition of the Taiyuan Formation, the northern part of the basin was dominated by a lower deltaic depositional system, the central and southern parts were dominated by a lagoon environment, and the southeastern corner was occupied by a carbonate platform setting. Coal is relatively thick in the northern part and the southeastern corner. The Shanxi Formation consists of sandstones, siltstones, mudstones, and coals, with the limestones being locally developed. The thickness of the Shanxi Formation is from 18.6 m to 213.25 m, with the thickness of coal seams from 0.10 to 10 m and averaging 4.2 m. During the deposition of the Shanxi Formation, the northern part of the Qinshui basin was mainly dominated by a lower deltaic plain distributary channel environment, the central and southern parts were mainly an interdistributary bay environment, and the southeastern part was occupied by a delta front mouth bar environment. The thick coals are distributed in the central and southern parts where an interdistributary bay dominates. It is evident that the thick coal zones of the Taiyuan Formation are consistent with the sandstone-rich belts, mainly located in the areas of the northern lower deltaic plain and southeastern barrier bar environments, whereas the thick coal zones of the Shanxi Formation coincide with the mudstone-rich belts, located in the areas of the central and southern interdistributary bay environments.

Keywords Qinshui basin, Shanxi Formation, Taiyuan Formation, coal measures, delta, barrier-lagoon, Permian, Carboniferous

1 Introduction

The Qinshui basin in southeastern Shanxi, northern China has become a hot point for coalbed methane exploration and production in recent years (Liu et al., 1998; Zhang and Wang, 1999). The coalbed methane resource in this basin is estimated to be 3.28×10^8 m^3 (China National Administration of Coal Geology, 1998) and 5.52×10^8 m^3 (Zhang et al., 2002). Because of this large resource, the Qinshui basin has attracted extensive coalbed methane exploration and development from a variety of authorities including the China United Coalbed Methane Co. Ltd., China National Petroleum Corporation, overseas joint ventures, as well as some local coal-mine administrations such as the Jincheng Coal Industry Group Co. The highest coalbed methane production is 16 000 m^3/d per well, and the average is 2,000–4,000 m^3/d per well. Exploration has confirmed that coalbed methane reservoirs in this basin are of high permeability and high gas content, and are dominated by semi-anthracite and anthracite with vitrinite reflectance between 2.2% and 4.5% (Su et al., 2005).

Over the last decades, the Qinshui basin has been widely investigated, including structural geology, depositional

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environments, coal accumulation and coal measure stratigraphy, as well as coalbed methane geology such as variation in coalbed methane reservoir thickness, coal rank, permeability, gas content, and hydrodynamics (Qin et al., 1997; Chen and Liu, 1998; Sun et al., 1998; Wei et al., 2002; Ye et al., 2002; Su et al., 2005). In particular, the depositional environments of the coal measures (Taiyuan and Shanxi formations) have been extensively studied (Ge et al., 1985; Institute of Geological Exploration CCMRI and Shanxi Provincial Coal Exploration Company, 1987; Huang et al., 1989; Cheng, 1992; China National Administration of Coal Geology, 1997, 1998; Zhang et al., 2001). It is generally accepted that the coal measures were formed within delta and barrier-lagoon depositional systems (Liu et al., 1998). However, work focusing on the depositional controls of distribution of the No. 3 and No. 15 coal seams, the targeted seams for methane extraction, is scarce, and this would influence the design of coalbed methane exploration and extraction. In addition, a basin-wide synthesis of paleogeography and coal distribution has not been provided. Studies on the paleogeographical evolution and its controls on the coal accumulation should be of significance for coalbed methane exploration and production in this basin.

Therefore, this paper focuses on the paleogeographic characteristics and coal accumulation research within the Qinshui basin, based on 89 selected data points including outcrop sections and boreholes.

2 Geological setting

The Qinshui basin is located in southeastern Shanxi Province, with geographical coordinates of N35°–38° and E111°00′–113°50′. The basin is a syncline elongated along an NNE direction and its total area is over 30,000 km^2, with a width of 120 km from west to east and a length of 330 km from south to north (Zhang and Wang, 1999). For development and exploration purposes, the basin has been subdivided into a number of mining and exploration areas, including the Shouyang, Yangquan, Heshun–Zuoquan, Tunliu–Zhangzi, Gaoping–Fanzhuang, Jincheng, Qinbei–Huodong, and Qinyuan areas (Fig. 1).

Tectonically, the Qinshui basin belongs to the middle zone of the North China platform, and is a residual structural basin formed in the setting of continuous strengthening, shearing, and expansion of the uplifts during the Yanshanian orogeny. The shear and compression stress was intensified during the Yanshanian period; and as a result, the great North China basin gradually retreated toward the Ordos area. The Shanxi block became an uplifted area at the middle stage of the Yanshanian orogeny (Late Jurassic-Early Cretaceous), accompanied by the final consolidation of the Qinshui basin, a superimposed synclinorium (Chen and Liu, 1998).

The Carboniferous-Permian strata in the Qinshui basin include the Benxi, Taiyuan, Shanxi, Lower Shihezi, Upper Shihezi, and Shiqianfeng formations, in which the Taiyuan Formation and Shanxi Formation are the main coal measures. The boundary between the Late Carboniferous and Permian is put at the base of the Miaogou limestone marker of the Taiyuan Formation (Kong et al., 1996). The No. 15 coal seam in the Taiyuan Formation and the No. 3 coal seam in the Shanxi Formation are widely and stably distributed in the whole basin, and constitute the main workable coal seams and the main coalbed methane reservoirs.

As a part of the North China platform, the Qinshui basin in the Late Paleozoic was dominated by a paralic setting. The Benxi and Taiyuan formations were mainly deposited in a barrier-lagoon and offshore carbonate shelf depositional system. The Shanxi and Lower Shihezi formations were formed in a delta depositional system, the Upper Shihezi Formation was formed in an alluvial plain system, and the Shiqianfeng Formation was formed in a lacustrine-dominated system.

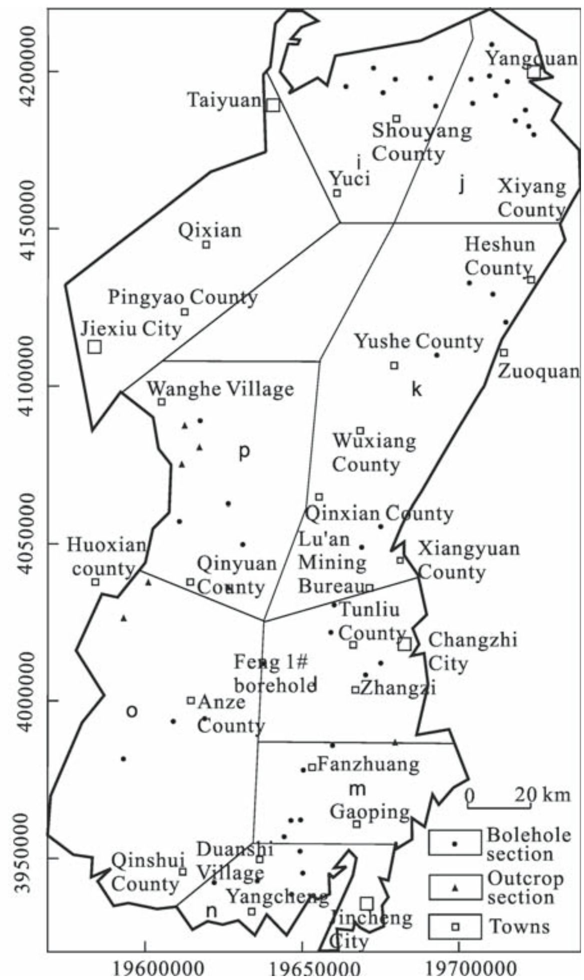

Fig. 1 Division of the mining and exploration areas in the Qinshui basin
I. Shouyang; II. Yangquan; III. Heshun–Zuoquan; IV. Tunliu–Zhangzi; V. Gaoping–Fanzhuang; VI. Jincheng; VII. Qinbei–Huodong; VIII. Qinyuan.

3 Sedimentary facies and lithofacies paleogeography of the Taiyuan Formation

3.1 Sedimentary facies characteristics of the Taiyuan Formation

The Taiyuan Formation is composed of coal seam, limestone, aluminous mudstone, siltstone, silty mudstone, and sandstone. The limestone markers, namely, "Miaogou," "Maoergou," and "Xiedao" limestones, are mainly bioclastic limestones, widely developed with stenohaline fossils such as brachiopods, fusulinids, and crinozoan, as well as trace fossils such as *Zoophycos* and *Rhizocorallium*. In addition, hummocky cross-beddings and graded beddings can also be found in the limestone. These characteristics suggest an offshore carbonate shelf environment for the limestones in the Taiyuan Formation. The gray mudstones and siltstones in this formation contain abundant sideritic oolites and concretions that are developed with horizontal beddings and lenticular beddings, as well as burrows. These characteristics indicate that these mudstones and siltstones were formed in a lagoonal setting. The medium to fine-grained quartz arenites in the Taiyuan Formation have a high compositional maturity and a moderate-good sorting, commonly developed with large-scale cross beddings, especially low-angle cross beddings. These sandstones are normally developed with an upward-coarsening succession and are believed to be barrier bar deposits. In addition, the sandstones at the top of the Taiyuan Formation represent a delta front mouth bar and deltaic distributary channel complex, developed with an upward-coarsening succession and an erosional base as well as the wedge-shaped cross beddings. Overall, the Taiyuan Formation has experienced an offshore carbonate shelf, barrier-lagoon, and delta environments, which form several transgression-regression sedimentary cycles (Fig. 2). The coal-forming mires were developed in a barrier-lagoon system.

3.2 Lithofacies paleogeographic analysis for the Taiyuan Formation

Paleogeographic analysis is usually based on sandstone–mudstone (S:M) lithological ratios, assisted by the drawing of some single lithological parameters such as contours of sandstone and conglomerate thickness, limestone thickness, and coal seam thickness. Within the 89 selected boreholes, the total thickness of the Taiyuan Formation varies between 44.90 m and 193.48 m, averaging 105.02 m, with the greatest thickness being in the Shouyang–Yangquan–Heshun–Zuoquan area (Table 1). The total thickness of sandstones and conglomerates varies from 4.50 m to 79.96 m, averaging 27.77 m, with the greatest thickness in the Shouyang-Yangquan area. The percentages of sandstones in the whole Taiyuan Formation range from 4.89% to 56.49%, averaging 25.66%, with the highest percentage in the Shouyang–Yangquan area. The total thickness of mudstone is from 46.61 m to 90.88 m, and the percentages of mudstones in the Taiyuan Formation range between 50.56% and 57.18%, with the highest percentage being in the Qinyuan area. The total thickness of limestone ranges between 0.10 m and 25.51 m, averaging 13.76 m, with the greatest thickness located in the Jincheng area. The coal in this formation has a total thickness from 0.10 m to 16.89 m, averaging 7.19 m, with the thickest coal distributed around the Yangquan area in the north of the Qinshui basin.

The sandstone–mudstone (S:M) lithological ratios can be used to indicate the development and distribution of sandbodies, and are commonly used in the reconstruction of paleogeography. The contours of the S:M ratios of the Taiyuan Formation are shown in Fig. 3, from which it can be seen that two sandstone-rich zones existed in the north and south of the basin. The northern sandstone-rich zone is mainly located to the north of Qinxian, including the Pingyao, Qixian, Yuci, Shouyang, Yangquan, Xiyang, Heshun, and Zuoquan areas. The S:M ratios in this zone are commonly higher than 0.4, with maximum ratios of up to 1.2 in the Shouyang and Yangquan areas, except the narrow area along Qinxian–Wuxiang–Yushe in this zone, which has an S:M ratio lower than 0.4. In contrast to the northern zone, the southern zone has generally lower S:M ratios, except the northern side of the Qinshui–Lu'an where the S:M ratios are a little higher than 0.4.

The limestones of the Taiyuan Formation in the Qinshui basin thin toward the north. In the southern zone around the Gaoping–Changzhi area, the total limestone thickness is higher than 25 m; in the middle zone around the Qinshui–Wuxiang–Yushe area, the total thickness ranges between 10 m and 15 m; and in the northern zone around the Qixian–Yuci–Taiyuan–Shouyang area, the total thickness is less than 5 m.

Based on the spatial lithological variations and the sedimentary facies analysis of outcrop sections, the northern sandstone-rich zone (Yuci–Shouyang–Yangquan–Heshun–Zuoquan) is proposed to have been a lower delta plain depositional setting, and the southern sandstone-rich zone at the Qinshui–Lu'an was a barrier sandbar depositional setting. The middle zone was a broad area dominated by a lagoon setting. The Gaoping–Changzhi belt at the southeastern corner of the Qinshui basin was an offshore carbonate shelf environment (Fig. 4).

In summary, during the deposition of the Taiyuan Formation, the northern zone of the Qinshui basin was a lower delta sedimentary system, the middle and south parts were barrier-lagoon sedimentary systems, whereas the southeastern corner was an offshore shelf sedimentary system. The marine water transgressed into this basin from the southeast, with the provenance being the Yinshan Mountain paleocontinent at the north, far from the Qinshui basin, and the Zhongtiao paleocontinent near the southwest of the basin.

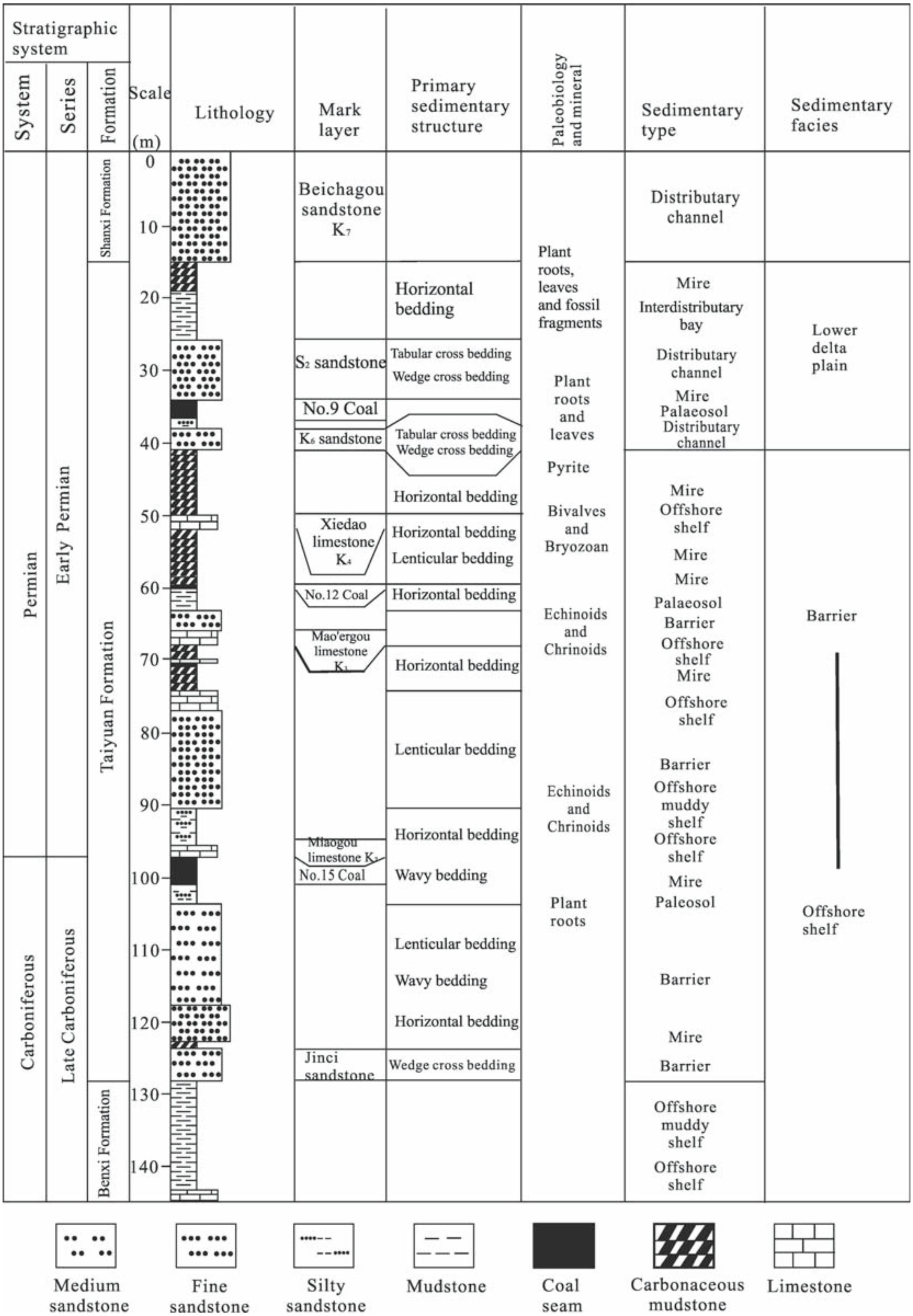

Fig. 2 Vertical facies sequence of the Taiyuan Formation in the Shouyang mining area

Table 1 The thickness and percentages of the main lithological types in the Taiyuan Formation of the Qinshui basin

Coal field		Shouyang	Yangquan	Heshun-Zuoquan	Tunliu-Zhangzi	Qinyuan	Gaoping-Fanzhuang	Jincheng	Qinbei-Huodong
Number of boreholes		13	14	8	5	9	19	12	5
Total thickness of Taiyuan Formation/m		125.33	122.4	112.71	90.88	88.69	96.71	91.0	84.27
Sandstone	Total thickness/m	43.86	36.44	30.56	21.49	20.02	21.82	16.29	20.1
	Percentage/%	35.0	29.76	27.12	23.65	22.58	22.56	17.9	23.85
Mudstone and siltstone	Total thickness/m	63.37	64.15	60.74	48.75	50.71	53.45	49.77	46.61
	Percentage/%	50.56	52.2	53.88	53.64	57.18	55.27	54.69	55.30
Sandstone-mudstone lithological ratio		0.69	0.57	0.50	0.24	0.39	0.41	0.33	0.43
Limestone	Total thickness/m	9.85	12.52	13.77	14.18	13.48	15.75	18.25	13.59
	Percentage/%	7.86	10.23	12.22	15.60	27.43	16.28	20.05	16.13
Total thickness of coal seam/m		8.25	11.3	7.6	6.46	4.47	5.69	6.69	3.98
Coal bearing index/%		6.6	9.2	6.8	7.1	5.0	5.9	7.4	4.7

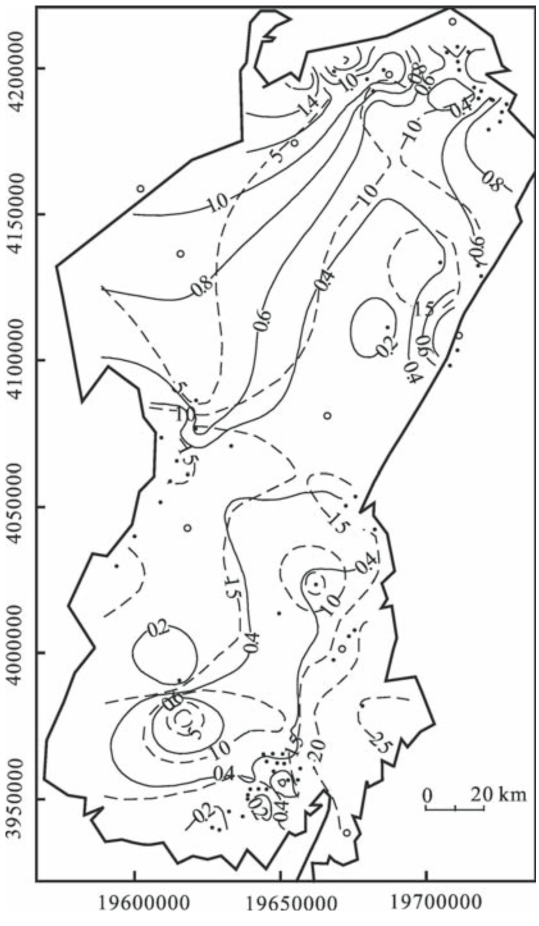

Fig. 3 The contours of sandstone-mudstone lithological ratio (solid line) and limestone thickness (dotted line, unit: m) of the Taiyuan Formation in the Qinshui basin (black spots represent data points)

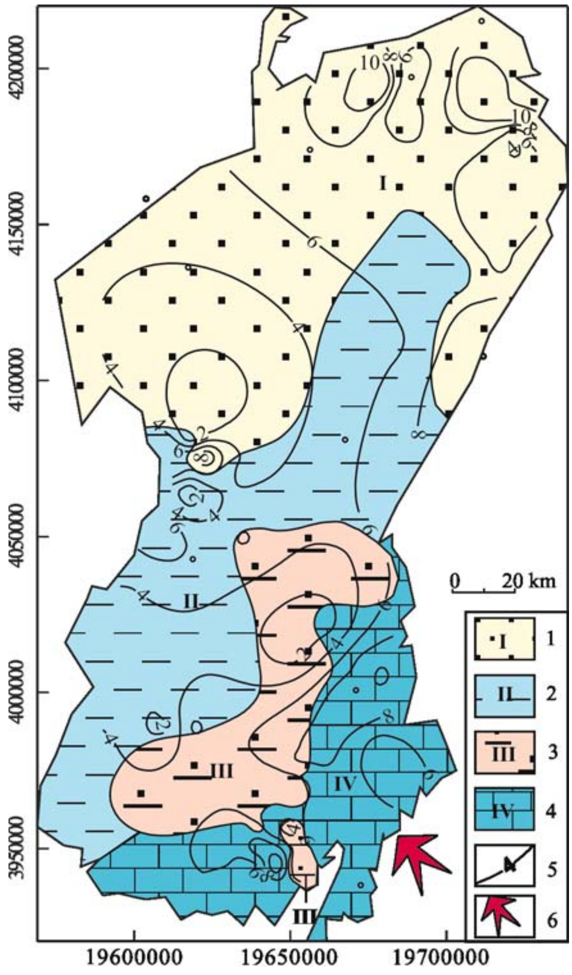

Fig. 4 A paleogeography map of the Taiyuan Formation in the Qinshui basin, with the contours representing the thickness of coal seams

1. Lower delta plain; 2. Lagoon; 3. Barrier bar; 4. Offshore carbonate shelf; 5. Coal thickness (m) and contours; 6. transgression direction.

4 Sedimentary facies and lithofacies paleogeography of the Shanxi Formation

4.1 Sedimentary facies characteristics of the Shanxi Formation

The Shanxi Formation in the Qinshui basin is composed of sandstone, siltstone, mudstone, and coal seams, with limestones being locally developed. The Beichagou sandstone at the bottom of this formation is medium-to coarse-grained and wedge-shaped cross-bedded, with the basal lenticular conglomerate lags containing mud pebbles and fossil wood. It was an incised valley fill deposit formed during lowstand distributary channel incision. Overlying deposits consist of fine-grained sandstone, siltstone, mudstone, and coal seams, representing a complex of the lower delta plain setting. The sandstones are well sorted, and were developed with wedge shaped beddings, low angle cross beddings, trough cross beddings, and convolute beddings as well as muddy pebbles. These characteristics indicate a river mouth bar depositional environment and the sand has been repetitively winnowed by waves and tides at the river mouth. The upward-coarsening sequence is associated with typical logging curves characterized by a reverse-bell shape, abrupt/gradual contact at the top, and gradual contact at the bottom. The mudstone intercalations with marine fossils illustrate that seawater transgressed into this basin frequently, and the Shanxi Formation is considered to have been dominated by the lower delta plain depositional facies (Fig. 5).

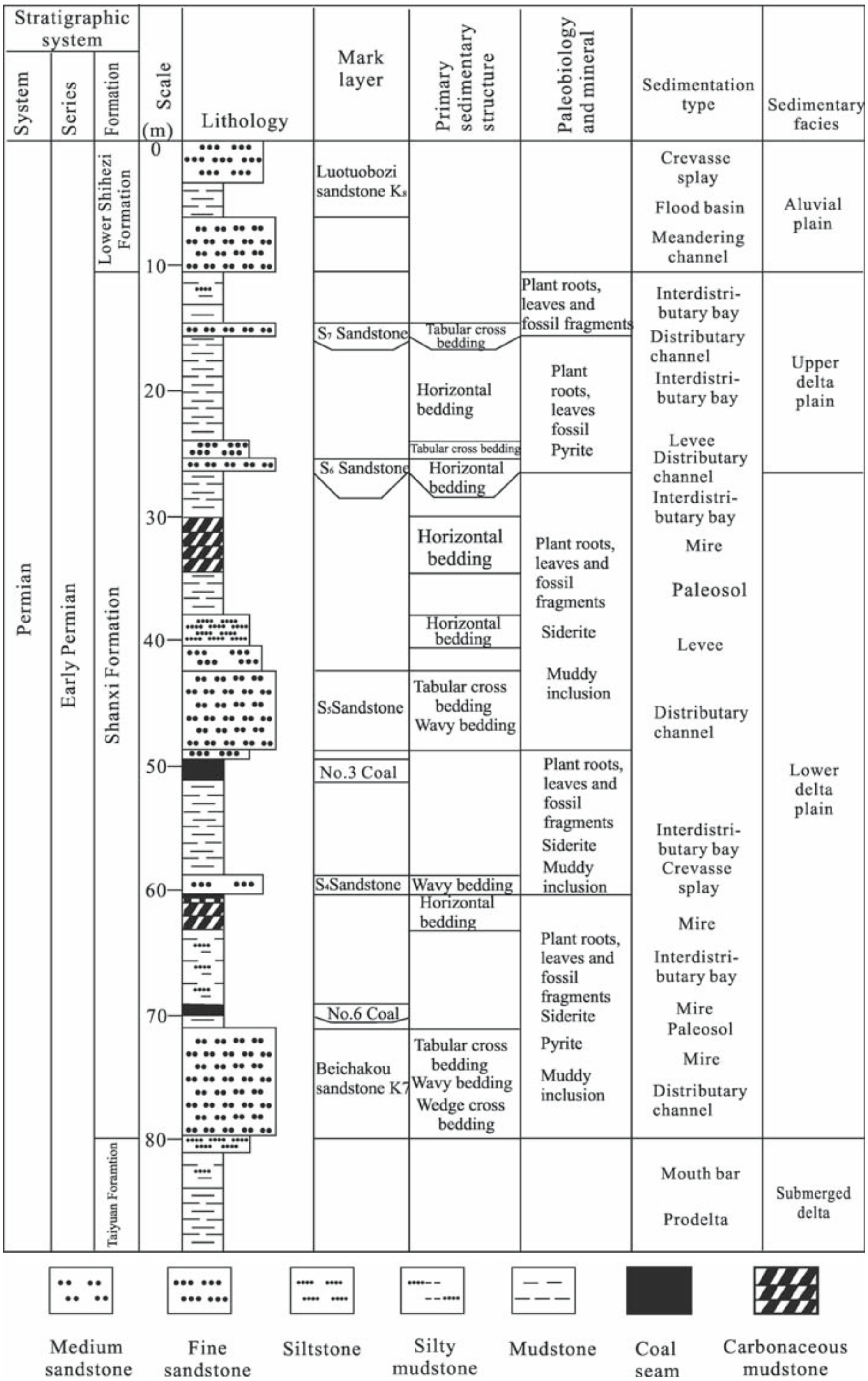

Fig. 5 Vertical facies sequence of the Shanxi Formation in the Yangquan mining area

Table 2 The variation of thickness and percentage of the main lithological types in the Shanxi Formation of the Qinshui basin

Coal field		Shouyang	Yangquan	Heshun-Zuoquan	Tunliu-Zhangzi	Qinyuan	Gaoping-Fanzhuang	Jincheng	Qinbei-Huodong
Number of borehole		12	18	8	6	7	19	12	6
Total thickness		57.56	58.77	80.37	70.85	102.43	43.63	48.37	57.87
Sandstone	Total thickness/m	20.64	23.05	18.8	19.83	29.75	10.19	12.55	17.62
	Percentage /%	35.86	39.22	23.40	27.99	29.04	23.35	25.95	30.45
Mudstone and siltstone	Total thickness/m	34.28	33.32	58.04	45.16	71.36	27.62	29.48	35.09
	Percentage/%	59.55	56.69	72.22	63.74	69.67	63.31	60.95	60.63
S:M ratio		0.60	0.69	0.32	0.44	0.42	0.37	0.43	0.50
Limestone	Total thickness/m	0.26	0	0	0.27	0	0	0	0.17
	Percentage/ %	0.45	0	0	0.38	0	0	0	0.29
Total thickness of coal seam/m		2.39	2.41	3.56	5.59	1.32	5.82	6.34	5.0
Coal bearing index/%		4.2	4.1	4.4	7.9	1.3	13.3	13.1	8.6

4.2 Lithofacies paleogeographic analysis for the Shanxi Formation

The Shanxi Formation has a thickness varying from 18.60 m to 213.25 m, averaging 60.12 m (Table 2), and thickest in the Qinyuan area. The sandstones and conglomerates have a total thickness between 0.10 m and 45.23 m, averaging 18.07 m, with the thickest sandstones developed in the Yangquan area. The percentages of the sandstone and conglomerate range between 0.10% and 83.08%, averaging 30.83%, with the highest value being found in the Yangquan area. The S:M ratios range from 0.10 to 4.91, averaging 0.79, with the highest in the Shouyang–Yangquan area at the north of the Qinshui basin. The total thickness of coal seams varies from 0.10 m to 10 m, averaging 4.20 m, with the greatest thickness and the highest-bearing index present at the Gaoping–Fanzhuang and Jincheng areas at the south of the Qinshui basin.

The contours of the S:M ratios are shown in Fig. 6, with the sandstones mainly enriched in the northern part of the Qinshui basin, and the S:M ratios commonly higher than 0.5, even higher than 1.5 in the Shouyang–Yangquan area, except the Qinxian–Wuxiang–Yushe belt where the S:M ratios are lower than 0.5. The S:M ratios in the southern part are relatively smaller, mostly lower than 0.5, except the areas around the Qin 3 borehole and along the northwest of Jincheng-Gaoping belt, where the S:M ratios are higher than 0.5.

The lithofacies paleogeography map is reconstructed mainly based on the contours of the S:M ratios, supported by contours of other single lithological parameters such as sandstone percentages and mudstone thickness, as well as facies analysis on the outcrop and borehole sections (Fig. 7). The northern sandstone-rich zone was dominated by a lower delta plain represented by distributary channels and interdistributary bay environments, and the southern sandstone-rich zone was dominated by mouth bar environments. The area between these two zones was dominated by interdistributary bays. The transgression came from the southeast, and the provenance was the Yinshan Mountain paleocontinent to the far north of the Qinshui basin and the Zhongtiao paleocontinent to the southwest of the basin.

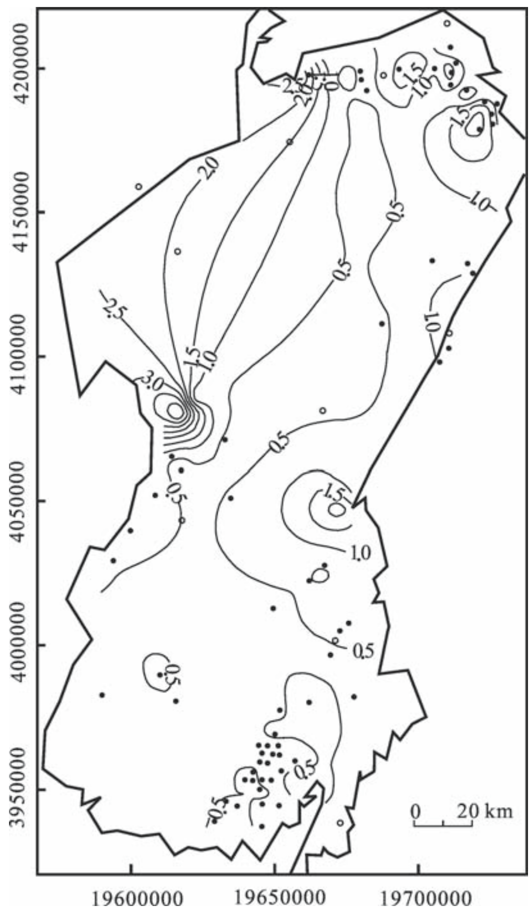

Fig. 6 The contours of sandstone-mudstone lithological ratio of the Shanxi Formation in the Qinshui basin (black spots represent data points)

5 Coal accumulation controls

The development of coal seams was controlled by various geological factors. The most important controls were tectonic subsidence and paleogeography. The former includes intensity and frequency of tectonic activities and the latter includes the paleogeographical conditions, paleovegetations, paleoclimates, and paleomire hydrology and geochemistry (Horne

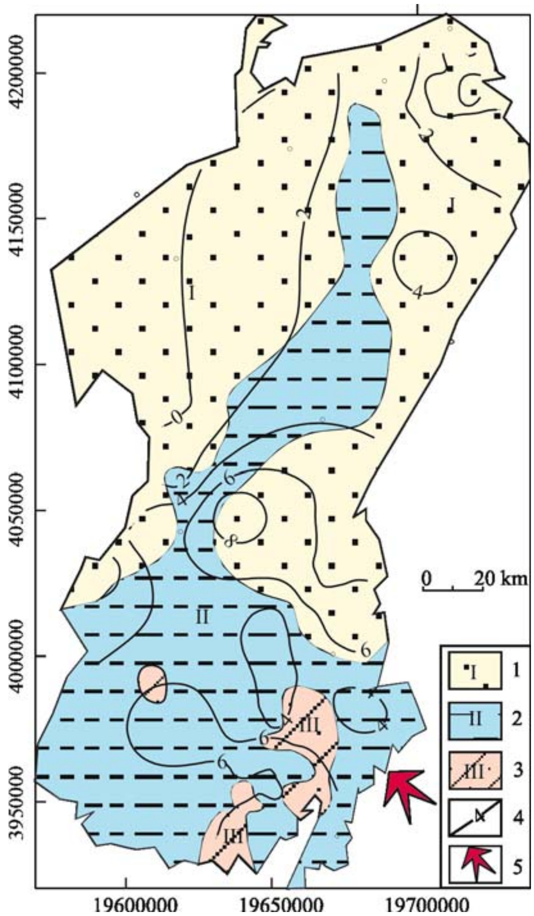

Fig. 7 A paleogeography map of the Shanxi Formation in the Qinshui basin, with the contours representing the thickness of coal seams
1. Lower delta plain; 2. Lower delta plain interdistributary bay; 3. Delta front mouth bar; 4. Coal thickness (m) and contours; 5. Transgression direction.

et al., 1978; Fielding, 1987). Based on the paleomagnetic measurement of the Carboniferous and Permian in North China, the Qinshui basin has a paleo-latitude of 13.9°N (tropic and subtropics) (Yang et al., 1998). During the Carboniferous and Permian periods, humid and rainy conditions were beneficial for coal accumulation in this basin. The direct controls on coal thickness were the paleotectonic background and the paleogeographic conditions.

5.1 Tectonic controls on coal accumulation

The Carboniferous–Permian coal measure strata in North China were formed under a relatively stable tectonic background. Before the deposition of the 15th coal seam during the early stage of the Taiyuan Formation, the tectonic status of the North China plate was transformed from “uplifting at south and subsiding at north” into “uplifting at north and subsiding at south,” and the source of marine transgression changed from the northeast to southeast. This tectonic transformation resulted in an overall slow subsidence in the North China plate and the paleo-topography was characterized by highs at the north and lows at the south of this basin, creating a stable tectonic background for coal accumulation. Under these conditions, several workable coal seams were formed, in which the No. 15 and No. 3 seams have a relatively great thickness and an extensive and consistent distribution.

5.2 Paleogeographical controls on coal accumulation

It is known that the coal seams in the Taiyuan Formation were mainly formed in the barrier-lagoon and lower delta plain settings, whereas the coal seams in the Shanxi Formation were mainly deposited in the lower delta plain interdistributary bay setting. In order to conduct a further analysis of sedimentary controls on coal thickness, the coal isopachs are mapped onto the paleogeography maps (Figs. 4 and 7), showing the relationship between the sedimentary settings and coal thickness.

For the Taiyuan Formation (Fig. 4), the coals thicker than 6 m were distributed in the northeastern Qinshui basin around the Shouyang and Heshun-Zuoquan area, along the eastern margin of the basin, and near the southeastern margin of the basin. These belts coincide mostly with the sandstone-rich zones, typically in the Shouyang and Heshun-Zuoquan areas where a lower delta plain setting was favorable for coal accumulation. The southeastern margin sandstone-rich zone, around the Jincheng area, was occupied by a barrier bar environment, which is another good setting for coal accumulation. The overall southward thinning of coals in the Taiyuan Formation is believed to be related to the overall southward deepening of water. In the northern part, the water was relatively shallow and suitable for peat or coal accumulation. As a result, thick coal was accumulated. In contrast, the southern part of the Qinshui basin was dominated by lagoonal and offshore shelf settings with a deeper water condition that is not beneficial for peat or coal accumulation, and thus thinner coal was deposited. The locally developed barrier bar setting near the southeastern corner of the basin supported a shallower environment which is also favorable for peat or coal accumulation, and thicker coals were found in this area. Figure 8 shows the relationship between the sandstone percentages and the total thickness of coals of the Taiyuan Formation in different areas of the Qinshui basin. The sandstone percentages and coal thickness demonstrably decrease towards the south, and the areas with thick coals coincide with the sandstone-rich areas.

For the Shanxi Formation (Fig. 7), the thicker coals are distributed in the Heshun-Zuoquan, eastern Qinyuan-Lu’an, and Huodong areas. All were located around the mudstone-rich areas, especially the Huodong and Jincheng areas where the lower delta plain interdistributary bay setting was developed, and the thickest coals were accumulated. The appropriate water depth of the delta plain interdistributary bay in the southern part of the basin was a key factor for the continuous development of paleomires and peat or coal accumulation. In contrast to this, in the northern part of the basin, the distributary channel sandstones were extensively developed, and the frequent migration of these channels, as well as a relatively shallow water table was not beneficial to the steady development of paleomires, and thus thinner coals were developed. Fig. 9 shows the relationships between the sandstone percentages and total thickness of coals in the Shanxi Formation in different areas of the Qinshui basin. A reverse relationship can be found between these two parameters, i.e., the northern part developed with thinner coals has higher sandstone percentages, whereas the central and southern parts of the basin developed with thicker coals were associated with lower sandstone percentages. In summary, the interdistributary bay environments in the central and southern parts of the basin were more favorable for peat or coal accumulation than the distributary channel environments in the northern part.

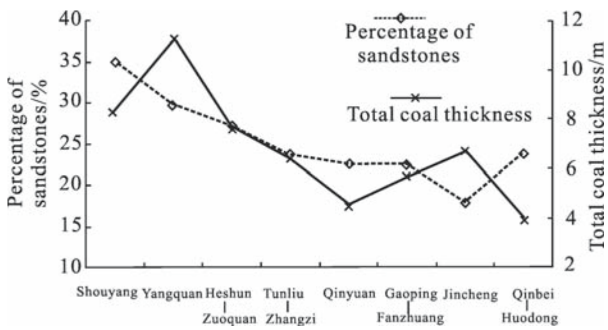

Fig. 8 Relationships between the percentages of the sandstones and conglomerates and the total thickness of coals of the Taiyuan Formation in different areas of the Qinshui basin

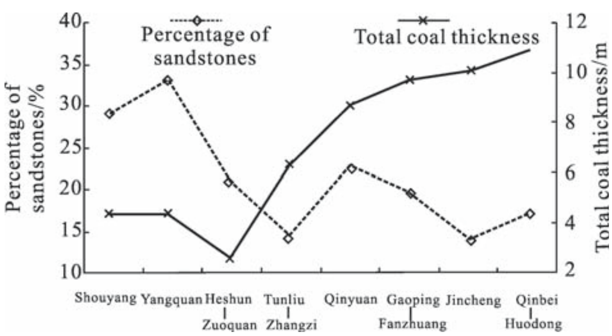

Fig. 9 The relationships between the percentages of the sandstones and conglomerates and the total thickness of coals of the Shanxi Formation in different areas of the Qinshui basin

6 Conclusions

1. Coal accumulation was controlled by tectonic subsidence and depositional environments. During the early stage of the Taiyuan Formation, the North China plate was turned from "uplifting at south and subsiding at north" into "uplifting at north and subsiding at south," resulting in a general paleogeography characterized by a status of "high at north and low at south".

2. The paleogeography of the Taiyuan Formation in the Qinshui basin shows that the northern part was occupied by a lower delta depositional system, the central and southern parts were occupied by a barrier-lagoonal depositional system, and the southeastern corner was dominated by an offshore shelf depositional system. The paleogeography of the Shanxi Formation in the Qinshui basin indicates that the northern part was mainly dominated by a lower deltaic plain distributary channel environment, the central part was mainly an interdistributary bay environment, and the southeastern part was occupied by a river mouth bar environment. Transgression during deposition of both the Taiyuan and Shanxi formations came from the southeast, and the provenance was the northern Yinshan Mountain paleocontinent to the far north and the Zhongtiao paleocontinent near the southwest of the basin.

3. Coals in the Taiyuan Formation are thicker at the north and thinner at the south and the coal-rich belts mostly coincide with the sandstone-rich belts, with the thick coals being formed in the lower delta plain and barrier bar environments. Coals in the Shanxi Formation were thinner at the north and thicker at the south. The coal-rich belts mostly coincide with the mudstone-rich belts, with the thick coals being formed in the interdistributary bay environments in central and southern parts of the basin.

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