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Petrographic characteristics and depositional environment of No. 6 coal from Xiaoyugou Mine, Jungar Coalfield, China

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Abstract This paper discussed the petrographic characteristics of No. 6 coal from the Xiaoyugou mine, Jungar Coalfield, Ordos Basin, China. 10 samples (7 coal, 1 parting mudstone and 2 floor mudstone) were analysed by microscopical and geochemical methods. Four maceral compositions and several associated elements parameters were selected as indicators and corresponding diagrams were drawn to explicate the sedimentary environment. The results indicate that the maceral is dominated by vitrinite and minerals are mainly kaolinite in the No. 6 coal. The sedimentary facies vary from barrier island system to tidal-flat which is a deposition process of water body shallowing and the coal-forming plants are herbs and woody plants formed in swamps.

Keywords Xiaoyugou coal mine · Maceral · Sedimentary environment · Jungar coalfield

1 Introduction

In recent years, coal associated with Li, Ga and REY (REE+Y) ore deposits have been found in Jungar Coalfield, China (Dai et al. 2006a; Sun et al. 2009, 2010a, 2012a, b, c, 2013; Seredin et al. 2013). In order to study the enrichment mechanism of the trace elements, the depositional environments of the peat moors should be well known. Coal petrology is a very important way to analyze peat moors and associated elements (Zhao et al. 2014).

Ordos Basin is located in the west of the Northern China Platform. Jungar Coalfield is situated on the northeastern margin of Ordos Basin. The coalfield is 65 km long (N–S) and 26 km wide (W–E), with a total area of 1,730 km^2. The coal-bearing strata belong to Permo-Carboniferous, which were deposited in marine-terrigenous facies. Dai et al. (2006b, 2008) studied the geochemistry and mineralogy of the No. 6 coal and its coal combustion products from the Heidaigou and Haerwusu Surface Mines in the Jungar Coalfield. But the Petrographic characteristics and depositional environment of Xiaoyugou have not been studied so far. Xiaoyugou Mine (Fig. 1) is situated in the northeast margin of Jungar coalfield. The mine area is 2.79 km long (N–S) and 1.39 km wide (W–E), with a total area of 3.9893 km^2. The coal-bearing strata include Benxi Formation, Taiyuan Formation and Shanxi Formation with a total thickness of 110–160 m (Fig. 2). The No. 6 coal is the main coal seam, with the thickness of approximate 11 m.

2 Sampling and methods

Sampling was conducted from the floor to the center of the coal field about 5 m. 10 samples (7 coal, 1 parting mudstone and 2 floor mudstone) were collected from the workface of No. 6 coal in the Xiaoyugou Mine, Jungar Coalfield, Ordos Basin following the Chinese Standard Method GB482-2008. From the bottom to top, the 7 samples of coal are XYG6-1 to XYG6-7, and 2 floor samples are XYG-F1 and XYG-F2, respectively. The only parting sample was gotten between XYG6-1 and XYG6-2. The

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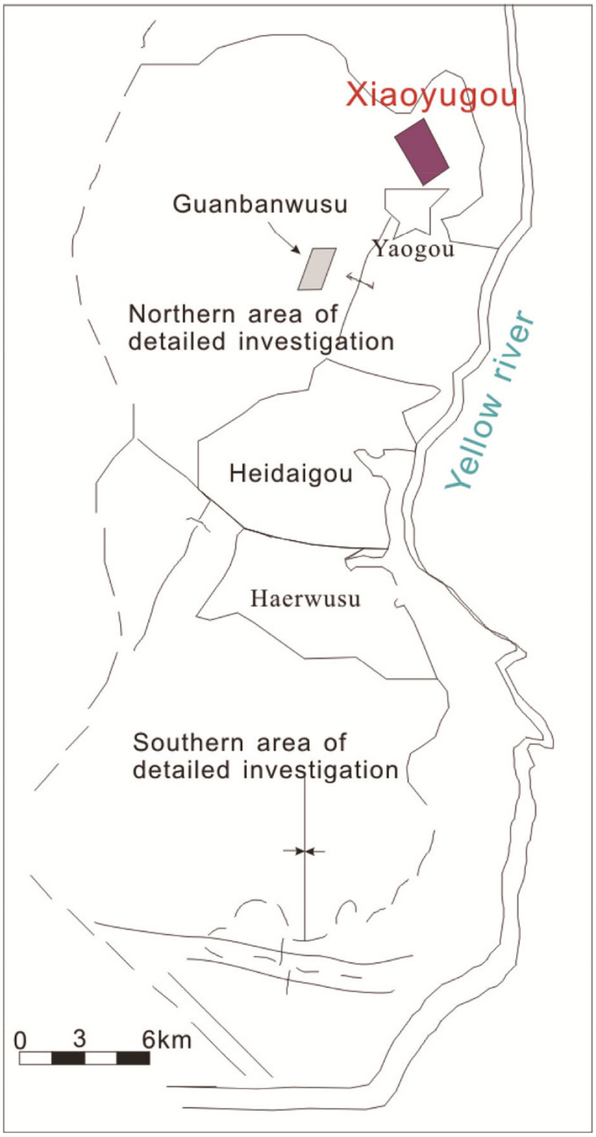

Fig. 1 Location of the Xiaoyugou Mine, Jungar Coalfield, Inner Mongolia, China

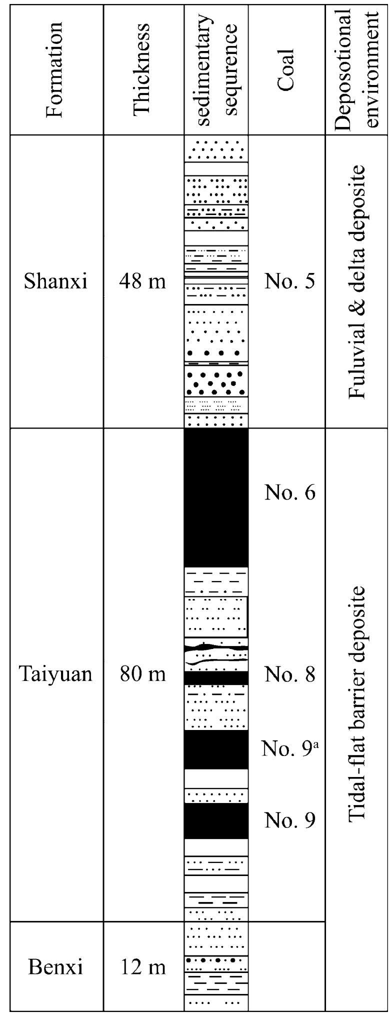

Fig. 2 Stratigraphic column and sedimentary environment of the Xiaoyugou mine in Junger Coalfield (Ye et al. 1997)

polished section are made of epoxy-bound pellets with coal particles which were crushed and ground to between 0.25–1 mm and prepared to the final fineness with 0.05 μm alumina. The macerals were analyzed on polished pellet under reflected white light using a swift point counter (Sun et al. 2002). The maceral groups were determined by counting more than 500 points each sample. Secondly, only the macerals of fluorescing liptinite was measured under blue light excitation of 450–490 nm wavelength (Sun 2003). Some representative and special maceral pictures (Fig. 3) were taken and the vitrinite reflectance (R_o) which was deemed to represent the maturation of samples was determined using an oil immersion objective (32×) with a 546 nm filter. The measurement was calibrated using a Leitz glass standard ($R_o = 0.89$ %) (Sun et al. 2010b). The experiment was finished at the Key Laboratory of Resource Survey and Research of Hebei Province.

Samples for geochemical analysis in Xiaoyugou mine were crushed and ground to less than 200 mesh. X-ray fluorescence spectrometric analysis was used to judge the oxides of the major elements, including Na, Mg, Al, Si, Fe, Ca, K, Mn, Ti, and P (Dai et al. 2006b).

3 Results and discussion

3.1 Coal chemistry and vitrinite reflectance

According to the proximate analysis, the moisture content and volatile matter rise from XYG6-1 to XYG6-7 of the No. 6 coal. The vitrinite reflectance can reflect the maturity

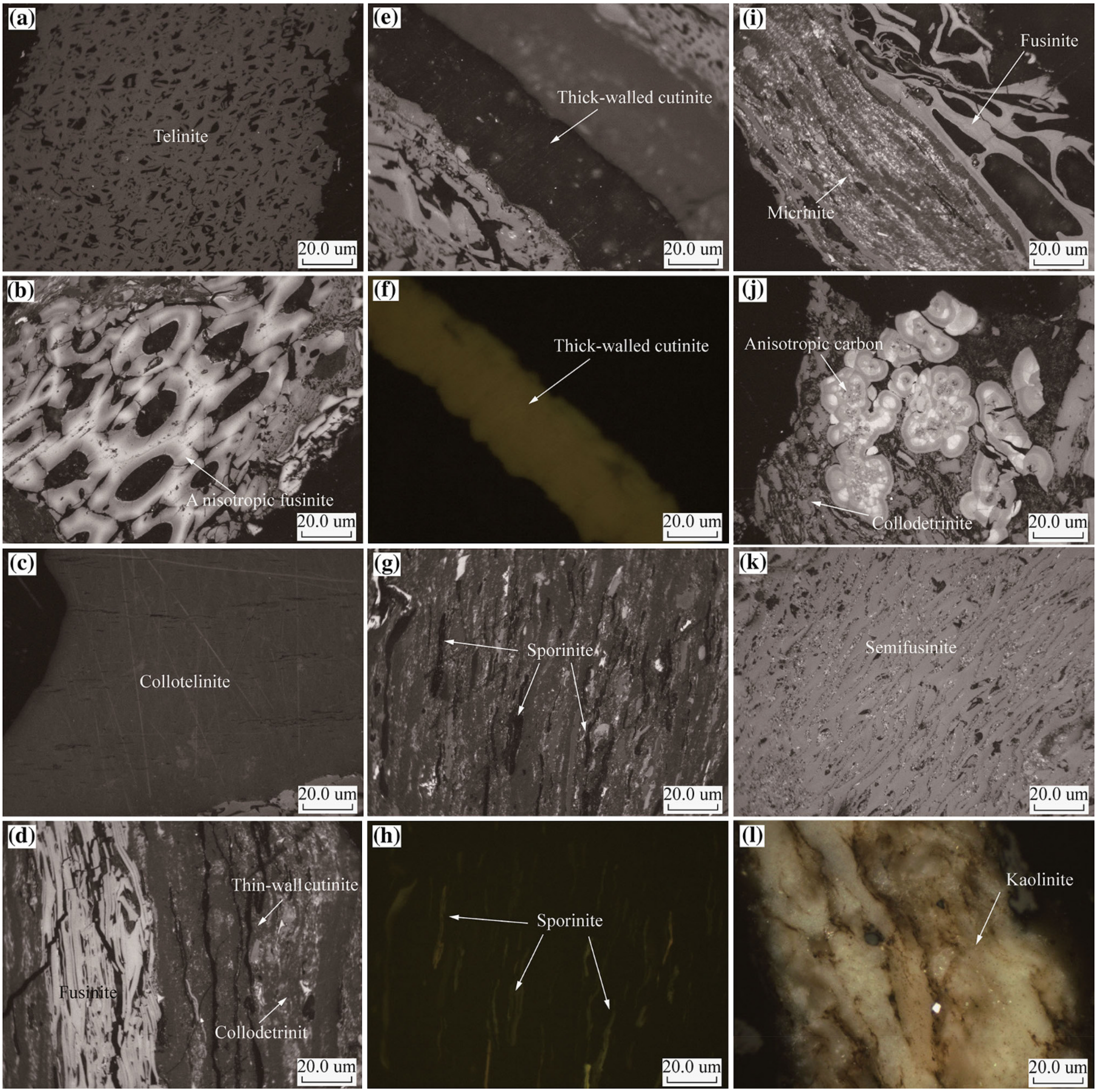

Fig. 3 Macerals of the samples from the No. 6 coal under oil immersion reflected light. **a** telinite in XYG6-7; **b** fusinite with signs of oxidized shows obvious anisotropy in XYG6-8; **c** colotelinite in XYG6-5; **d** fusinite on the left and thin-wall cutinite embedded in the colodetrinite on the right in XYG6-8; **e**, **f** thick-walled cutinite in XYG6-4; **g**, **h** sporinite filled in colodetrinite in XYG6-6; **i** micrinite filled in colodetrinite and fusinite in XYG6-8; **j** anisotropic only appeared in XYG6-5; **k** semifusinite filled with micrinite in XYG6-5; **l** kaolinite in XYG6-6

of coal. The random vitrinite reflectance (R_o) and the average volatile matter value of No. 6 are 0.59 % and 26.93 % respectively, indicating that the rank of the coal is medium-volatile bituminous.

The No. 6 coal is a low-ash and low-sulfur coal, according to Chinese Standard GB 15224.1-2010 (coals with ash yields 10.01 %–20.00 % are low-ash coal) and GB/T 15224.2-2004 (coals with total sulfur content 0.5 %–0.9 % are low-sulfur coal). The XYG6-2 is higher in sulfur content (1.26 %) than other samples (0.27 %–0.73 %).

3.2 Maceral composition

The maceral characteristics of No. 6 coal of Xiaoyugou Mine, Jungar Coalfield (Table 1) are as follows:

Table 1 Maceral composition of the No. 6 coal samples

Sample	Industrial indicators (%)				Vitrinite (%)						Liptinite (%)				Inertinite (%)							Mineral (%)			$R_{o,ran}$ (%)
	M_{ad}	VM_{daf}	A_d	$S_{t,d}$	Tel	CT	CD	CG	VD	V	Sp	Cu	Re	L	SF	F	Ma	FG	Mi	ID	I	Clay	Py	M	
XYG6-7	5.41	37.03	6.53	0.73	8.97	17.41	22.71	1.47	2.75	53.31	7.51	4.95	0.55	13	8.48	9.16	2.56	0.18	7.82	4.01	32.21	1.28	0.18	1.47	0.54
XYG6-6	4.68	33.25	3.96	0.54	12.5	5.21	11.92	3.96	14.58	48.17	5.42	5	0.21	10.63	6.96	4.04	1.46	0	4.79	6.67	23.92	16.88	0.42	17.3	0.55
XYG6-5	3.92	26.88	4.25	0.48	4.2	15.6	18.8	0.6	9.8	49	6	1.8	0.4	8.2	4.4	5.4	2	2.8	5.8	7	27.4	15.4	0	15.4	0.58
XYG6-4	4.56	27.82	6.17	0.48	14.8	1.2	22.4	1.4	14.4	54.2	7.6	6.6	0.6	14.8	7.4	10.8	2.6	0.4	5	3	29.2	2.8	0	2.8	0.55
XYG6-3	2.81	21.76	38.65	0.49	1.83	2.94	16.33	0.18	16.51	37.8	0.73	1.47	0.37	2.57	2.02	2.94	1.28	0	1.1	13.94	21.28	38.35	0	38.35	0.62
XYG6-2	3.05	24.37	34.01	1.26	5.5	2.83	12.33	0.17	18.5	39.33	2.17	7.5	0.83	10.5	2.67	3.83	1	0	0.67	5.67	13.84	25	11.33	36.33	0.56
XYG6-1	1.69	17.41	40.67	0.27	3.13	1.46	7.92	0.83	19.5	32.84	0.42	1.46	0.63	2.51	1.88	4.38	1.04	0.21	1.67	8.08	17.25	47	0.42	47.42	0.69
Average	3.73	26.93	19.18	0.61	7.28	6.66	16.06	1.23	13.72	44.95	3.8	4.11	0.57	8.89	4.83	5.79	1.71	0.51	3.84	6.91	23.59	20.96	1.76	22.72	0.58

M_{ad} Moisture as received, VM_{daf} volatile matter on a dry and ash-free base, A_d ash on a dry base, $S_{t,d}$ total sulfur on a dry base, *Tel* telinite, *CT* collotelinite, *CD* collodetrinite, *CG* corpogelinite, *VD* vitrodetrinite, *V* vitrinite, *Sp* sporinite, *Cu* cutinite, *Re* resinite, *L* liptinite, *SF* semifisinite, *F* fusinite, *Ma* macrinite, *FG* funginite, *Mi* micrinite, *ID* inertodetrinite, *I* inertinite, *Clay* clay Mineral, *Py* pyrite, *M* mineral

The maceral is mainly composed of vitrinite with an average content of 44.9 % varying from 30.83 % to 54.20 %. Desmocollinite (7.93 %–22.71 %) and vitrodetrinite (2.75 %–18.50 %) are the dominant vitrinite macerals with average content of 15.63 %–13.43 %, respectively. From XYG6-1 to XYG6-7, the content of telinite and collotelinite tends to increase.

The amount of inertinite reaches up to 23.16 % dominated by fusinite (5.65 %) and inertodetrinite (6.77 %), and semifusinite only next to fusinite with a content of 4.69 %. The micrinite is relatively high with a content of 3.84 %, especially in samples XYG6-4–XYG6-**7** with an average content of 5.45 %. There was a sign of being oxidized in inertinites, such as fusinite in all samples, macrinite in XYG6-5.

Due to the high amount of micrinite, it is necessary to analyse the cause of formation, for the micrinite distributed into collotelinite, collodetrinite, the clay mineral filling in telinite. Some micrinite, which can be called anisotropy micrinite for the anisotropy in No. 6, is clearly obvious (Xiao and Ren 1988). Hydrogen-rich maceral in coal with great thermal activity is the material basis of forming micrinite such as bituminite, resinite and perhydrous vitrinite, and lipid material dispersed in the collodetrinite (Xiao and Ren 1988). According to Teichmüller (1983), micrinite first formed in candle coal. Hydrogen-rich maceral with great thermal activity began splitting, discharging liquid hydrocarbon, but due to the low temperature and coal rank, it can not flow and aggregate, so anisotropy micrinite will be formed. However, if the liquid hydrocarbon liquidity gets strong and aggregates together, anisotropic carbon will form and it appears in XYG6-5.

The content of liptinite (8.89 %) in No. 6 coal is higher than that of North China Coal Basin. According to the rearch of Wang (1996), vitrinite content is 60 %–85 %, the inertinite less than 25 %, the liptinite 5 % approximately in Taiyuan Formation, North China. The sporinite and cutinite dominate in liptinite with an average content of 3.8 %–4.11 %, respectively. The cutinite is mainly thick-walled cutinite, whereas there is also thin-walled cutinite, mainly lining the collodetrinite.

Minerals are dominanted by kaolinite. Numerous pyrite appeared in XYG6-2, however, it is infrequent in other samples.

3.3 Characteristics of coal facies

Coal facies were delimited by R. Teichmüller and M. Teichmüller (Stach et al. 1982). It is an original cause of formation type which depends on coal plant community and mire environment. The structure index of coal face was presented by Diessel (1986).

Table 2 The coal facies parameters of the No. 6 coal seam

Sample	TPI	GI	VI	GWI
XYG6-7	1.5	2.58	1.28	0.11
XYG6-6	1.43	2.81	0.75	1.2
XYG6-5	1.06	3.04	0.87	0.67
XYG6-4	1.22	2.68	0.75	0.48
XYG6-3	0.34	1.96	0.22	2.61
XYG6-2	0.78	3.31	0.34	2.11
XYG6-1	0.64	2.36	0.3	5.39
Average	1	2.64	0.62	1.2

TPI (Telinite + Collotelinite + Fusinite + Semifusinite)/(Desmocollinite + Macrinite + Inertodetrinite), *GI* (Vitrinite + Macrinite)/(Fusinite + Semifusinite + Inertodetrinite), *GWI* (Corpocollinite + Gelocollinite + Vitrodetrinite + Clay minerals)/(Telinite + Collotelinite + Collodetrinite), *VI* (Telovitrinite + Fusinite + Semifusinite + Funginite)/(Detrovitrinite + Inertovetrinite + Cutinite)

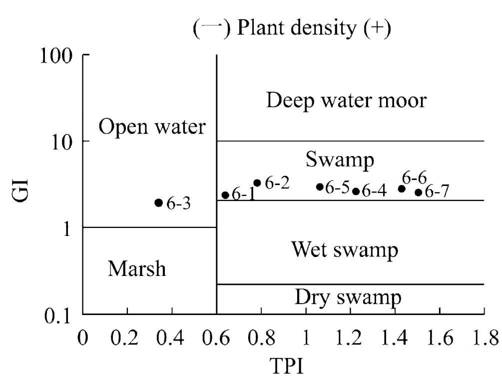

Fig. 4 TPI-GI diagramm

In this study, 4 indices, TPI, GI, VI and GWI are applied (Table 2):

(1) Diessel (1986) drew a GI-TPI diagram to account for the coal forming moors. GI (gelification index) mainly indicates degree of peat bogs and its duration, and from low to high GI value reflects the coal forming environment from dry to wet, and swamp water from shallow to deep. TPI (Tissue Preservation Index) reflects the degradation of plant tissue and woody plants account for the proportion of raw coal plants (Dai et al. 2007). From low to high, TPI reflects the structure of plant cell damage from high to low. All GI and TPI values of the samples from the No. 6 coal were put into Table 2. 6 samples occur in the swamp, only XYG6-3 is in the open water.

(2) GWI (Groundwater Flow Index) and VI (Vegetation Index) are good parameters to response the coal plants, bog medium conditions and sedimentary environment information during peat accumulation

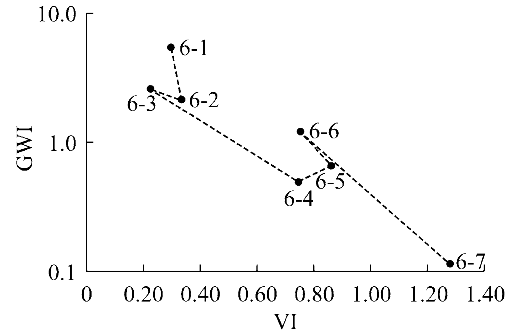

Fig. 5 VI-GWI diagramm

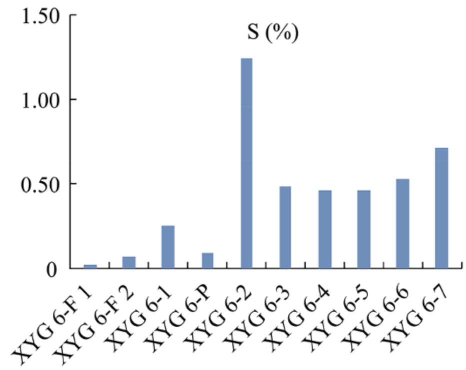

Fig. 6 Total sulfur content of the No. 6 coal

(Diessel 1982; Teichmüller 1989; Gmur and Kwiecińska 2002). GWI is used to reflect on the controlling extent of peat swamp by groundwater; VI shows the species of coal plants and its saving extent (Calder et al. 1991).

Greater GWI indicates stronger water impaction. VI > 1 indicates that the dominated pants are woody plants, otherwise herbaceous plants. The Fig. 3 shows 6 samples occur in woody plants and only XYG6-7 belongs to woody plants. The GWI values turn down from XYG6-1 to XYG6-7. GWI-VI shows from XYG6-1 to XYG6-7, plants convert from herbaceous to woody plants, at the same time water impact drops as shown in Figs. 4, 5.

3.4 Geochemical features

The main components of coal ash are major elements whose content can be used to calculate the parameters of ash composition, which are often used as the determining indexes of sedimentary environment (Ye et al. 1997; Dai 2005). Here are some parameters (Table 5) which includes S, Fe_2O_3 + CaO + MgO, SiO_2 + Al_2O_3, (Fe_2O_3 + CaO + MgO)/(SiO_2 + Al_2O_3). Some major elements abundances are listed in the Table 3.

Table 3 Part of major elements abundances of the No. 6 coal seam

	Ad	Fe_2O_3 (%)	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	MgO (%)
XYG6-7	6.53	0.28	0.07	2.86	2.61	0.02
XYG6-6	3.96	0.09	0.19	1.69	1.06	0.06
XYG6-5	4.25	0.07	0.18	2.88	1.45	0.07
XYG6-4	6.17	0.36	0.10	2.86	2.61	0.02
XYG6-3	38.65	0.55	0.11	20.67	16.04	0.07
XYG6-2	34.01	1.86	0.09	15.71	13.75	0.04
XYG6-1	40.67	2.98	0.09	18.21	17.35	0.07
Average	19.18	0.88	0.12	9.27	7.84	0.05

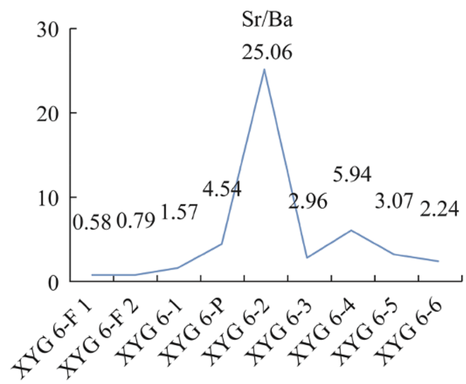

Fig. 7 Sr/Ba of the No. 6 coal

Through studying the modern freshwater, brackish water and salt water of peat bogs, many researchers found that sulfur (S) is relatively high in peat swamp nearby coast, and the S in peat formed in sea is higher than the peat in freshwater, so the S content in coal is a good indicator in identifying paleosalinity (Tang et al. 1996). The weighted mean total sulfur content of the No. 6 coal is 0.73 % in Jungar (Dai et al. 2006). According to Table 4, with the exception of sample XYG6-2 (Fig. 6), a medium sulfur coal (1.26 % total sulfur), all other samples are low-sulfur coal (under 1 %) which precisely corresponds to the characteristics of the Jugar coalfield in the period of transition.

The content of some trace elements, especially the ratios of some related elements (Sr/Ba in this paper) are good signs for distinguishing sedimentary environment (Zhao 1998). Sr/Ba is usually less than 1 in freshwater sediments, otherwise which in marine sediments is greater than 1 (Liu et al. 1991), but Sr/Ba varies in different regions and different geological era sediments. However, the same characteristic is the higher Sr/Ba, the greater salinity. The average value of Sr/Ba in Taiyuan Formation, Jungar Coalfield is 4.8 which varies from 0.7 to 16.7 (Liu et al. 1991). Based on the Fig. 7, with the exception of sample XYG6-2, all others are under or close to 4.8, which means it is a transitional environment.

The ash index of coal (acid-base ratio) (Fe_2O_3 + CaO + MgO)/(SiO_2 + Al_2O_3) is a parameter for judging sedimentary environment with 0.23 as a critical value (Ye et al. 1997). Y = CaO/(CaO + Fe_2O_3) can reflect the salinity of the sedimentary water medium, and the higher Y, the higher salinity. These parameters in Table 5 indicate that the sedimentary environment tended to a terrestrial transition.

According to these parameters, combined with the characteristics in Jungar coalfield, it indicates that the corresponding depositional environment of No. 6 in Xiaoyugou coal mine, Jungar coalfield is in transitional nature from marine to continental facies.

Table 4 Associated elements parameters of the No. 6 coal seam

	XYG6-F1	XYG6-F2	XYG6-1	XYG6-P	XYG6-2	XYG6-3	XYG6-4	XYG6-5	XYG6-6	XYG6-7	Average
S (%)	0.01	0.08	0.27	0.09	1.26	0.49	0.48	0.48	0.54	0.73	0.44
Sr/Ba	0.58	0.79	1.57	4.54	25.06	2.96	5.94	3.07	2.24	–	5.19

Table 5 Parameters of ash compositions for No. 6 coal accumulation environment (after Ye et al.)

Sedimentary environment	A_d (%)	$S_{t,d}$ (%)	Ash composition parameter			
			CaO/(CaO + Fe_2O_3)	Fe_2O_3 + CaO + MgO (%)	SiO_2 + Al_2O_3 (%)	(Fe_2O_3 + CaO + MgO)/(SiO_2 + Al_2O_3)
Peat bogs affected by seawater	<10	>1	Low	>20	<75	≥0.23
Terrestrial peat bogs	>10	<1	High	5–20	>75	≤0.22
Average	19.18	0.61	0.30	1.05	17.11	0.08

4 Conclusions

(1) The high amount of micrinite indicates there may be abundant hydrogen-rich maceral in No. 6 coal with great thermal activity which turned into micrinite. Anisotropic carbon appeared in XYG6-5 may come from liptinite.
(2) The maceral composition, combined with geochemistry parameters results, indicate that lower part of the No. 6 coal in Xiaoyugou mine, Jungar Coalfield was deposited in a transitional environment from marine to continental facies, and it was a transition from barrier island system to tidal-flat facies. The plants transformed from herbs to woody plants and upper water drops.

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