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Geochemical Evidence for Coal and Carbonaceous Mudstone as the Possible Major Oil Source Rock in the Jurassic Turpan Basin, Northwest China

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Abstract: Petroleum geologists have debated whether the hydrocarbons from Jurassic coal measures are derived from the coals, carbonaceous mudstones or coal-measure mudstones in the Turpan Basin. Based on the geochemistry analysis of the 20 crude oils and 40 source rocks from the Turpan Basin, some data have been obtained as follows: carbon preference index and methylphenanthrene index of the Jurassic oils are 1.16–1.45 and 0.28–0.80, and the ααα C_{29} sterane 20S/(20S+20R) and C_{29} sterane ββ/(ββ+αα) are 0.44–0.51 and 0.4–0.54 respectively, which show the normal maturity of oils; the vitrinite reflectance of the source rocks from the Xishanyao to Badaowan Formations range from 0.47% to 0.97%, which indicate immature to mature thermal evolutionary stage and sufficient conditions for generating mass mature oil. The effect of hydrocarbon expulsion should be considered when studying the source of coal-derived oil by using Biomarkers. Biomarkers in the Jurassic oils from the basin are similar to those in the coals and carbonaceous mudstones, with a strong predominant content of pristane, relatively high ratio of C_{15}/C_{16} sesquiterpenoids (>1), a relatively high content of low carbon number tricyclic terpanes and C_{24} tetracyclic terpane, little gammacerane and C_{29} Ts detected, an absolute predominant content of C_{29} sterane and a relatively high content of diasterane. However, the opposite characteristics are shown in mudstones, with an approximately equal content of pristane and phytane, relatively low ratio of C_{15}/C_{16} sesquiterpenoids (<1), a relatively high content of high carbon number tricyclic terpanes and a low content of C_{24} tetracyclic terpane, peaks of gammacerane and C_{29} Ts detected obviously and an increasing C_{27} sterane content. All of these characteristics identify the coals and carbonaceous mudstones as the possible major oil source rocks in this area, and they were formed in the stronger oxidizing environment with shallower water than mudstones.

Key words: biomarker, coal-derived oil, oil-source correlation, coal, carbonaceous mudstone, mudstone, Jurassic, Turpan Basin

1 Introduction

Since the late 1960s, a number of important oil and gas fields related to Mesozoic and Cenozoic coal measure have been found in the Gippsland and Cooper Basins of Australia, Mahakam Delta of Indonesia, Beaufort Mackenzie Basin of Canada and San Juan Basin of America and so on, arousing the public's great interests of coal-derived oil research (Huang et al., 1992, 1995). Extensive studies have shown that coal-bearing strata not only can generate oil, but expel enough quantities of petroleum to form commercial coal-derived oil accumulation (Allan and Larter, 1983; Durand and Paratte, 1983; Hvoslef et al., 1988). But various disputes still exist on many questions, especially whether the large quantity of coal-derived oils are derived primarily from the coals, carbonaceous mudstones or coal-measure mudstones (Scott and Fleet, 1994).

Turpan Basin is the largest coal-derived oil basin of China. After 20 years of exploration and research, it is a

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consensus that the Jurassic crude oils are derived from the source rocks of the Middle-Lower Jurassic (Yuan et al., 2002). However, agreement has not been reached on which are the possible major oil source rocks of the Jurassic oils in the coal-bearing strata: the coals, carbonaceous mudstones, or mudstones. Primary studies showed that the coals are the major source rocks (Cheng et al., 1994, 1999; Zhao and Cheng, 1995; Wu and Zhao, 1997; Zhao et al., 1998; Wang et al., 1998). Hu et al. (1997, 1998) questioned this view on the basis of the maturity of the Jurassic source rocks and crude oils, as well as the thickness of mudstones, and then some experts considered mudstones as the major source rocks (Chen et al., 1998a, 1998b, 1999, 2001; Li et al., 2001; Li and Pang, 2004; Shuai et al., 2009). According to the distribution of Ts/Tm, C_{29}Ts/C_{29} norhopane, C_{30} diahopane/C_{30} hopane, Tm/C_{30} hopane, C_{31} homohopane / C_{30} hopane, Chen et al. (1999) determined that the coal measure mudstones have a genetic relationship with the Jurassic crude oils. However, as the above parameters are greatly influenced by maturity and hydrocarbon expulsion of coal, the reliability of the conclusion was doubted. Meanwhile, Li and Pang (2004) used the similar parameters, and the reliability of their conclusion was also questioned. According to pyrolysis simulation experiment in confined gold vessels, Shuai et al. (2009) pointed out that the oil-generating potential of per unit mass kerogen of mudstone is about six times as that of coal. However, this cannot stand for the oil-generating potential of per unit mass of mudstone and coal. For instance, the simulation experiment of Wang et al. (1998) shows that the top C_{12}^{+} total hydrocarbon production rate of mudstone is 102.1mg/gTOC, but of coal is only 38.8 mg/gTOC. After converting to the hydrocarbon production potential of per unit mass rock, the top C_{12}^{+} total hydrocarbon production rate of coal could get 2.87% higher, but the rate of mudstones is only 0.43%. Therefore, Wang et al. (1998) pointed out the hydrocarbon production of coal is higher than that of coal measured mudstone because of the high organic carbon content of coal, which is the crucial basis of coal as the main oil source rock in coal measure strata.

Besides, other scholars believed that the Jurassic oils from the eastern Taibei Sag in the Turpan Basin are derived from coal and carbonaceous mudstone, while the oils from the west of the basin are derived from coal-measure mudstone (Yuan et al., 2002). After the studies of the carbon isotope of individual hydrocarbons of the Jurassic source rocks and crude oils, Sun et al. (2000) suggested crude oils from the Sakesang and Baka oil-bearing structures in the Taibei Sag are derived from coals, and oils of Shanshan, Qiuling, Shanle are related to mudstones. Therefore, due to the similarity of the organic matter input between coal and mudstone, the results of oil-source correlation from different experts are widely divergent.

On the bases of a great amount of sample analyses, some biomarker parameters are selected in this paper for researching oil-source correlation. The parameters should be slightly influenced by maturity and hydrocarbon expulsion, and could accurately reflect the organic matter input and depositional environment. Finally, this paper reveals the genetic relationship between Jurassic crude oils and coals with carbonaceous mudstones.

2 Geological Setting

The Turpan Basin, the joint triangle area of Kazakhstan, Siberia and Tarim plates, is located at the southeast of the Kazakhstan Plate, belonging to a part of Junggar-Turpan Block. This basin can be divided into three first-order tectonic units: the Turpan Depression, the Liaodun Uplift and the Hami Depression (Li et al., 2010). As the main hydrocarbon enrichment zone of the Turpan Depression, the Taibei Sag in the Turpan Depression can be subdivided into Xiaocaohu, Qiudong and Shengbei Sub-Sags from east to west.

The Jurassic strata of the Turpan Basin are composed of three sets of formations: Badaowan (J_1b) and Sangonghe (J_1s) Formations of Lower Jurassic, Xishanyao(J_2x), Sanjianfang (J_2s) and Qiketai (J_2q) Formations of Middle Jurassic, Qigu (J_3q) and Kalazha (J_3k) Formations of Upper Jurassic. The Middle-Lower Jurassic source rocks are the major source rocks in this basin, which are divided into coal-measure source rocks from the Badaowan to Sanjianfang formation and lacustrine source rocks of the Qiketai Formation.

As to the oil and gas reservoirs discovered, oil reservoirs are distributed mainly in the Qiuling-Shanshan structural belt in central Turpan Basin and Shengbei Sub-Sag in the west, and condensate gas reservoirs in the Qiudong and Xiaocaohu Sub-Sags in the eastern and central basin (Fig. 1). On the horizon of occurrence, Xishanyao, Sanjianfang and Qiketai Formations in the Middle Jurassic are the primary formations.

3 Samples and Experimental Methods

Source rock samples used in this research include 40 Jurassic cores and are divided into four different types: coal, carbonaceous mudstone, coal-measure mudstone (J_1b-J_2s) and lacustrine mudstone (J_2q) (Table 2). Twenty Jurassic oil samples from the Turpan Basin were also analyzed and sample locations are shown in Table 1 and Fig. 1. The source rocks were soxhlet extracted with chloroform for approximately 72 h.

Gas chromatography (GC) analyses of the whole crude

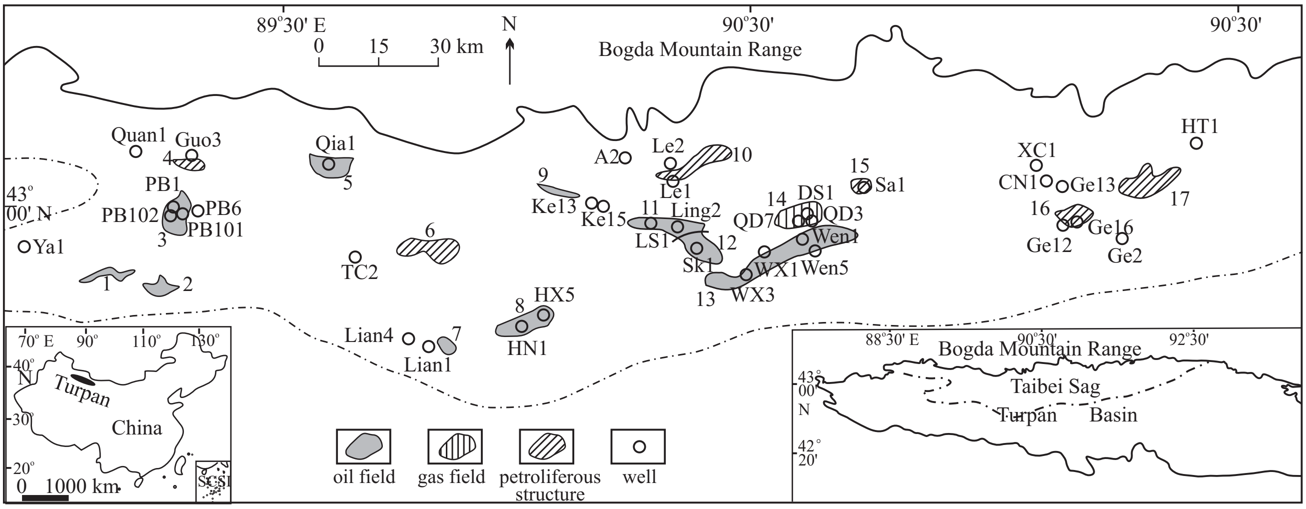

Fig. 1. Location map showing the distribution of the samples and the Jurassic oil and gas field in the Taibei Sag of the Turpan Basin

Oil and gas field location: 1, Shengnan; 2, Shenquan; 3, Pubeu; 4, Yuguo; 5, Qialekan; 6, Shengbei; 7, Lianmuqin; 8, Hongnan; 9, Baka; 10, Shanle; 11,Qiuling; 12, Shanshan; 13, Wenjisang; 14, Qiudong; 15, Sakesang; 16, Gedatai; 17, Hongtai.

Table 1 Parameter table of the biomarkers of the Jurassic crude oils in the Turpan Basin

Structural belt	Well	Interval (m)	Age	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	MPI_1	R_c
Hongtai	Hongtai 1	1375–1400.2	J_2s	4.57	1.79	4.16	5.42	2.55	0.03	1.67	0.58	0.16	0.31	0.50	0.46	0.46	1.16	2.84	20.10	0.57	0.74
	Ge 2	911–917	J_2s	5.88	1.79	5.33	8.09	3.43	0.06	1.16	0.56	0.18	0.34	0.42	0.43	0.47	1.24	2.83	18.41	0.28	0.57
Wenjisang	Wen 1	2764–2819	J_2x	7.77	2.07	6.27	15.04	2.51	0.05	1.44	0.60	0.28	0.36	0.63	0.46	0.39	1.45	3.28	24.82	0.30	0.58
	Wen 5	2410.2–2424.4	J_2s	4.22	2.11	4.35	6.58	3.96	0.05	1.83	0.56	0.15	0.37	0.74	0.47	0.48	1.21	2.25	19.76	0.56	0.74
	Wenxi 1	2926.6–2938	J_2x	3.94	1.97	5.44	7.32	2.80	0.05	1.81	0.56	0.19	0.39	0.47	0.47	0.49	1.17	2.42	21.35	0.47	0.68
	Wenxi 3	2314–2323	J_2s	3.92	1.47	5.14	7.16	2.91	0.06	1.51	0.56	0.19	0.37	0.49	0.47	0.47	1.23	2.29	20.18	0.55	0.73
	Sa 1	3087–3090	J_2x	5.90	1.43	2.79	3.62	3.07	0.03	1.87	0.59	0.13	0.25	0.34	0.48	0.50	1.29	2.52	17.70	0.45	0.67
	Qiudong 7	3364.4–3381	J_2x	5.69	1.94	5.69	8.75	3.69	0.03	1.69	0.59	0.18	0.25	0.40	0.44	0.41	1.37	2.73	22.36	0.36	0.61
	Qiudong 3	3382–3434	J_2x	6.11	1.88	7.02	10.98	4.04	0.02	1.76	0.60	0.18	0.24	0.39	0.46	0.40	1.36	2.74	22.50	0.35	0.61
	Qiudong 3	3105–3141.5	J_2x	6.28	1.98	7.73	6.82	2.92	0.03	1.39	0.58	0.26	0.31	0.51	0.44	0.40	1.40	2.79	23.49	0.31	0.58
Shanle	Le 1	2677–2687	J_2s	5.07	1.86	2.33	3.05	1.96	0.04	2.06	0.58	0.14	0.33	0.46	0.46	0.49	1.34	2.53	22.03	0.51	0.71
Qiuling	Ling 2	2748.7–2758.4	J_2s	4.35	1.87	2.76	3.50	1.89	0.04	1.84	0.58	0.16	0.36	0.51	0.48	0.48	1.28	2.99	23.39	0.60	0.76
	Ke 13		J_2x	4.16	1.95	5.42	7.98	3.09	0.03	1.74	0.58	0.13	0.27	0.56	0.48	0.47	1.27	2.56	19.38	0.66	0.80
Shengbei	Hongxi 5	653–669	J_2s	4.48	1.94	5.76	7.61	3.58	0.08	1.15	0.58	0.30	0.33	0.50	0.50	0.48	1.22	2.14	13.83	0.64	0.78
	Lian 1	3372–3379	J_2x	4.45	1.72	3.68	5.10	3.75	0.06	1.60	0.58	0.20	0.37	0.33	0.49	0.42	1.29			0.45	0.67
	Taican 2	4746–4774.4	J_2x	3.40	1.19	15.01	12.85	2.56	0.10	2.49	0.58	0.23	0.47	0.58	0.50	0.54	1.16	2.61	20.74	0.80	0.88
Pubei-Qialekan	Pubei 1	3467.5–3473.5	J_2s	4.90	1.83	8.06	8.99	6.28	0.05	1.63	0.59	0.18	0.41	0.54	0.51	0.53	1.24	2.72	19.76	0.60	0.76
	Pubei 101	3453.9–3460.8	J_2s	3.19	1.81	6.54	8.24	4.12	0.06	1.81	0.58	0.13	0.40	0.61	0.50	0.51	1.21	3.16	29.44	0.60	0.76
	Pubei 6	3547–3550	J_2q	3.29	1.94	5.09	8.51	4.76	0.05	2.08	0.58	0.14	0.38	0.53	0.50	0.53	1.22			0.54	0.73
	Qia 1	1739–1793	J_2s	3.59	1.14	4.15	5.50	4.26	0.09	1.69	0.57	0.19	0.39	0.35	0.47	0.47	1.16	2.34	20.72	0.54	0.73

1, pristane/phytane; 2, C_{15}/C_{16} sesquiterpenes; 3, C_{20}/C_{23} tricyclic terpane; 4, C_{19+20}/C_{23+24} tricyclic terpanes; 5, C_{24} tetracyclic terpane/C_{26} tricyclic terpanes; 6, gammacerane /C_{31} homohopanes; 7, C_{30} diahopane/C_{29}TS; 8, C_{31} homohopane 22S/(22S+22R); 9, C_{27}/C_{29} steranes; 10, C_{28}/C_{29} steranes; 11, C_{27} diasteranens/C_{27} regular steranes; 12, ααα C_{29} sterane 20S/(20S+20R); 13, C_{29} sterane ββ/(ββ+αα);
14, $CPI=([C_{25}+C_{27}+C_{29}+C_{31}+C_{33}]/[C_{24}+C_{26}+C_{28}+C_{30}+C_{32}]+[C_{25}+C_{27}+C_{29}+C_{31}+C_{33}]/[C_{26}+C_{28}+C_{30}+C_{32}+C_{34}])/2$; 15, isoheptane value; 16, heptane value; 17, $MPI_1=1.5*([2\text{-}MP]+[3\text{-}MP])/(P+[1\text{-}MP]+[9\text{-}MP])$

oils and chloroform bitumen “A” were performed on an HP6890N equipped with a 30 m × 0.25 mm × 0.5 μm HP-PONA fused silica capillary column in which the flow of carrier gas was kept at 1.0 mL/min. The GC oven was programmed and the temperature was kept at 35°C for 5 min, then ramped to 300°C at a rate of 4°C/min, then held at 300°C for 20 min. The detector temperature was 300°C.

Gas chromatography-mass spectrometry (GC-MS) analyses of the whole crude oils and chloroform bitumen “A” were performed on an HP6890-GC/5973MSD equipped with a 30 m × 0.25 mm × 0.5 μm HP-5MS fused silica capillary column in which the flow of carrier gas was at a constant rate of 1.0 mL/min. The GC oven was programmed to hold at 50°C for 2 min, then ramped to 310°C at a rate of 3°C/min, then held at 310°C for 18 min. The MSD was operated in multiple ion detection mode (MID).

4 Results and Discussion

4.1 Maturity of the crude oils and source rocks of Jurassic

Various geochemical parameters (Table 1) show that the crude oil of Jurassic in the Turpan Basin is mainly of normal mature oil with very few low-mature oil, and its parent material just enters the infancy of the stage of mass oil generation.

The chromatogram map of the Jurassic crude oils in the Turpan Basin shows normal distribution or prepeak type

Table 2 Parameter table of the biomarkers of the Jurassic source rocks in the Turpan Basin

Well	Depth (m)	Age	Lithology	1	2	3	4	5	6	7	8	9	10	11	12	13	R_o
Ge 13	2625.2	J_2s	Coal	4.71	1.40	20.43	15.58	2.60	0.04	2.49	0.58	0.17	0.33	0.52	0.40	0.29	0.47
A 2	3582	J_2x		6.21	0.90	9.37	9.78	4.81	0.03	2.65	0.60	0.09	0.27	0.50	0.42	0.28	0.59
Dongshen 1	3875	J_2x		6.72	1.61	10.14	11.53	4.68	0.02	1.95	0.59	0.14	0.30	1.16	0.45	0.47	0.67
Lingshen 1	3845	J_2x		1.36	2.08	12.11	6.99	1.86	0.03	2.98	0.59	0.12	0.18	0.33	0.41	0.35	0.66
Lingshen 1	3939	J_2x		3.21	1.13	8.66	7.58	3.86	0.04	1.34	0.58	0.42	0.65		0.43	0.36	0.69
Hongnan 1	3279.8	J_2x		3.90	0.99	7.58	6.68	2.05	0.06	1.98	0.57	0.11	0.21	0.50	0.27	0.34	0.58
Quan 1	3006	J_2x		2.08	4.61	3.64	2.79	0.48	0.20	0.60	0.31	0.06	0.29	0.12	0.19	0.35	0.51
Ya 1	3001	J_1b		3.36			2.71	0.76	0.36	0.86	0.20	0.04	0.21	0.44	0.09	0.56	0.50
Ge 16	2998.6	J_2x	Carbonaceous mudstone	2.44	0.83	6.31	5.65	1.33	0.07	2.16	0.58	0.37	0.15	0.95	0.41	0.34	0.65
Le 2	3176.5	J_2x		3.83	1.26	7.32	6.09	2.70	0.09	1.14	0.55	0.09	0.27	0.45	0.29	0.31	0.59
Quan 1	3226	J_2x		1.68	2.06	3.45	3.12	2.29	0.08	1.29	0.30	0.15	0.34	0.26	0.08	0.37	0.58
Lian 4	3957	J_2x		6.07	0.49	10.20	8.55	5.29	0.05	3.29	0.58	0.22	0.36	0.57	0.38	0.30	0.67
Pubei 102	3952.2	J_2x		2.67	2.34	4.78	3.17	1.28	0.09	3.32	0.38	0.20	0.64	0.42	0.20	0.48	0.58
Ge 12	2245.3	J_2s	Coal-measure mudstone	0.79	0.68	0.93	0.84	1.33	0.25	0.82	0.55	0.55	0.57	0.20	0.41	0.39	0.47
Ge 13	2626.4	J_2s		2.48	0.84	8.25	7.63	2.23	0.12	2.53	0.58	0.15	0.35	0.39	0.38	0.29	0.58
Ge 13	2682.5	J_2s		2.24	0.88	2.33	2.35	1.93	0.08	1.87	0.57	0.24	0.45	0.34	0.37	0.39	0.58
Xiaocao 1	3407	J_2x		0.96	0.71	0.70	0.61	0.58	0.52	0.72	0.61	0.49	0.92	0.10	0.51	0.46	
Ge 13	2875.5	J_2x		1.04	0.73	0.45	0.35	0.50	0.62	0.81	0.62	0.49	0.97	0.07	0.50	0.46	0.62
Dongshen 1	3685.5	J_2x		0.55	0.35	1.73	1.38	0.81	0.19	1.26	0.59	0.42	0.78	0.15	0.48	0.40	0.69
Ke 15	2717.2	J_2x		1.55	0.83	0.92	0.73	0.81	0.28	1.08	0.59	0.27	0.77	0.11	0.51	0.45	0.52
Guo 3	3673.7	J_2x		0.72	0.35	0.34	0.24	0.48	0.51	0.98	0.64	0.30	0.90	0.05	0.51	0.50	0.65
Hongnan 1	3281.5	J_2x		1.19	0.67	1.64	1.34	1.47	0.07	2.01	0.57	0.33	0.57	0.21	0.34	0.36	0.58
Taican 2	5004	J_2x		0.90	0.96	0.00	0.50	1.98	0.20	1.43	0.59	0.56	0.72	0.29	0.46	0.45	0.97
Pubei 102	3883.38	J_2x		0.86	0.31	0.82	0.70	0.79	0.34	0.71	0.49	0.54	0.93	0.17	0.48	0.45	0.57
Qia 1	2713	J_2x		0.84	0.50	1.03	0.77	0.78	0.35	0.87	0.57	0.56	0.81	0.17	0.49	0.44	0.47
Qia 1	2761.3	J_2x		1.94	0.78	6.88	5.08	1.02	0.07	1.49	0.55	0.29	0.47	0.13	0.32	0.30	0.51
Lingshen 1	4044	J_1s		1.20	0.55	2.69	2.05	4.60	0.24	0.71	0.59	0.42	0.45	0.53	0.42	0.38	0.70
Lingshen 1	4079.5	J_1s		0.48	1.05	0.80	0.57	1.16	0.48	0.63	0.58	0.77	0.61	0.23	0.30	0.36	0.72
Le 2	3582.1	J_1s		2.49	1.87	0.00	0.73	2.07	0.06	0.97	0.59	0.18	0.32	0.83	0.45	0.38	0.60
Dongshen 1	4300.5	J_1s		0.38	0.34	0.00	0.14	0.55	0.42	0.89	0.57	0.50	0.91	0.14	0.48	0.45	0.78
Ya 1	2829	J_1s		1.11	0.51	0.68	0.62	0.77	0.36	0.66	0.42	0.52	0.76	0.28	0.44	0.42	0.49
Shanke 1	4607.8	J_1b		0.67	0.79	1.64	1.21	1.58	0.18	1.07	0.58	0.47	0.62	0.24	0.48	0.43	0.49
Shanke 1	5104	J_1b		0.76	0.26	2.72	2.02	1.19	0.15	1.16	0.59	0.44	0.82	0.23	0.47	0.42	0.90
Lian 4	4181.5	J_1b		2.26	0.83	3.30	2.87	2.61	0.03	1.47	0.58	0.30	0.36	0.59	0.28	0.41	0.63
Caonan 1	2446	J_2q	Lacustrine mudstone	1.62	1.19	0.68	0.82	2.04	0.48	0.61	0.57	0.86	0.55	0.35	0.25	0.32	0.45
Quan 1	2068.7	J_2q		0.11	0.44	1.57	0.87	0.24	0.77	0.00	0.19	0.26	0.80		0.05	0.24	0.42
Guo 3	3027	J_2q		0.68	0.72	1.67	1.74	0.55	0.41	0.92	0.20	0.66	0.52	0.10	0.07	0.32	0.49
Hongnan 1	2711	J_2q		1.08	0.35	0.62	0.49	0.64	0.40	0.82	0.59	0.48	0.83	0.12	0.50	0.43	0.50
Pubei 102	3337.4	J_2q		1.34	0.46	1.72	1.59	1.48	0.30	0.56	0.28	0.13	0.31	0.23	0.20	0.40	0.52
Taican 2	4009	J_2q		1.07	0.61	5.79	4.71	5.05	0.14	1.60	0.57	0.36	0.53	0.32	0.34	0.34	0.79

distribution, and the main peak carbon is nC_{19} or nC_8 with no obvious odd-even predominance, while the carbon preference index (CPI) range from 1.16–1.45 (Table 1) indicating the features of mature crude oil. The analysis of light hydrocarbons of the crude oils denotes the heptane values and isoheptane values are 17–29% and 2.14–3.28 respectively (Table 1), indicating mainly the features of mature crude oil with very few immature.

The ratios of ααα C_{29} sterane 20S/ (20S+20R) and C_{29} sterane ββ/ (ββ+αα), maturity parameters of steranes of the Jurassic crude oils in the Turpan Basin, are 0.44–0.51 and 0.4–0.54, respectively (Table 1, Fig. 2). The ratio of ααα C_{29} sterane 20S/(20S+20R) is 0.4 when oil begins mass production (Mackenize et al, 1980) and its balance values are 0.52–0.55 (Seifert and Moldowan, 1986), while the vitrinite reflectance (R_o) values range from 0.8% to 0.9% when it is balanced. In this study, the ratio of ααα C_{29} sterane 20S/(20S+20R) is above 0.4 which does not reach the balance value. Therefore, it is predicted that the crude oils just enter the mature stage when R_o values are about 0.7%. According to the distribution of the ratio of ααα C_{29}

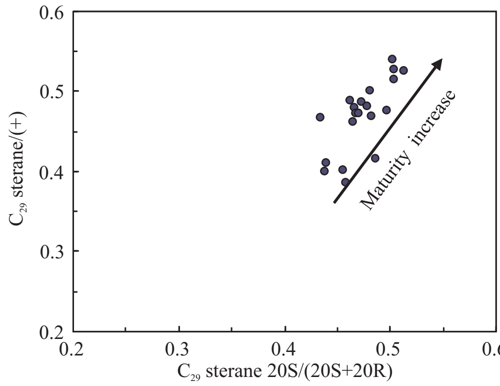

Fig. 2. Map showing the relationship of the ααα-C_{29} sterane 20S/(20S+20R) and ββ/(ββ+αα) of the Jurassic crude oils in the Turpan Basin

sterane 20S/(20S+20R), the maturity of the crude oils from the Hongtai structural belt of the east and the Wenjisang structural belt of the middle is lower than that of the midwest and west in this basin.

The isomerizate ratio of homohopane, the ratio of C_{31} hopane 22S/ (22S+22R), from all oil samples concentrated at about 0.58, which has already reached the balance value, also indicating that the oils are mature. The Ts/Tm ratio of the oils vary more greatly from 0.12 to 0.50. However, the Ts/Tm may not be suitable in this study because it is a parameter for mature to high-mature stage but the oils of this study just enter the mature stage.

The methylphenanthrene index (MPI_1) of aromatic hydrocarbon of the oils is between 0.28–0.8, and it can be deduced that the R_c values are 0.57–0.88% with all ranging around 0.7% (Table 1) according to the formula $R_c(\%) = 0.60 \times MPI_1 + 0.4$ (Radke and Welte, 1983). The R_c are 0.57–0.74% in the Hongtai structural belt of the east and the Wenjisang structural belt of the middle in the basin, indicating low-mature to mature oil, while that of the midwest and west are mostly more than 0.7%, which indicates mature oil. This distribution characteristic is almost consistent with that of ααα C_{29} sterane 20S/(20S+20R).

The measured R_o values of the source rock samples that were collected in this study are presented in Table 2. It is obvious that the R_o values of the Jurassic source rocks in the Turpan Basin are 0.42–0.97%. The maturity of the source rock from the Xiaocaohu Sub-Sag in the eastern basin is lower than that of Qiudong and Shengbei Sub-Sags of the middle, and the R_o of the former are 0.45–0.65%, indicating immature to low-mature stage, while that of later ones are 0.42–0.97%, which indicate immature to mature stage. The subsiding extent of the Xiaocaohu Sub-Sag is relatively small since the Cretaceous, thus the thermal evolution level of the source rock in this place is low. The maturity distribution features of the source rocks are consistent with those of the crude oils on the plane.

The bulk R_o of the source rocks from the Qiketai and Sanjianfang Formations of the Middle Jurassic range from 0.42% to 0.58%, reflecting immature to low-mature stage, while that from the Xishanyao Formation of the Middle Jurassic range from 0.47% to 0.97%, reflecting immature to mature stage and that from the Sangonghe and Badaowan Formations of the Lower Jurassic are 0.49–0.9%, reflecting immature to mature stage (Fig. 3). So far, the exploration wells of the Lower Jurassic are few, but quite thick Jurassic strata are revealed to exist in the deep basin according to the seismic data. Therefore, it is supposed that the source rocks with higher maturity existed in the deep basin, which is well qualified for mass oil generation (Chen et al., 1999).

4.2 Oil-source correlation

Based on the analysis of GC and GCMS, this research shows the biomarker composition of the crude oils is close to that of coals and carbonaceous mudstones but is quite different from that of mudstones in the Jurassic strata of the Turpan Basin.

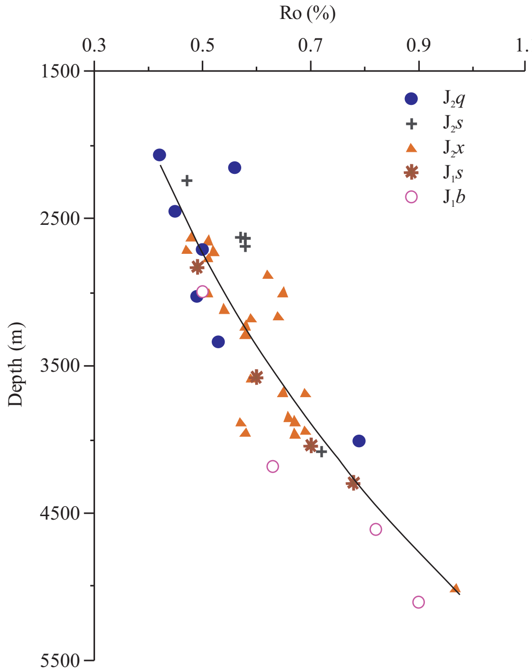

Fig. 3. Map showing the relationship of R_o and buried depth of the Jurassic source rocks in the Turpan Basin

4.2.1 Isoprenoids

The crude oils, coals and carbonaceous mudstones of the Jurassic have a quite obvious predominant content of pristine, while most of the mudstones shows an equal content of pristane and phytane. The distribution of pristane and phytane is associated with the oxidation-reduction environment. Under the strong reducing environment, the phytol (the precursor substance of pristane and phytane) is translated mainly into phytane, and into pristane while under the weak oxidizing environment. In the Jurassic strata of the Turpan Basin, the bulk Pr/Ph ratio of the crude oils, coals and carbonaceous mudstones are above 2.5, the coal-measure mudstones (J_1b-J_2s) and lacustrine mudstones (J_2q) below 2.5 (Tables 1, 2, Fig. 4). Fig. 5 shows that the absolute concentration of pristane in the extract of the coals and carbonaceous mudstones is similar to that of the mudstones, which indicates that the absolute concentration of pristane in hydrocarbons was generated from the coals and that from mudstones are comparative. Therefore, the Pr/Ph ratio is proved to be reliable. The distribution characteristics of Pr/Ph suggest that the sedimentary environment of coal and carbonaceous mudstone is in accord with that of crude oil, and the oxidizing property of the sedimentary environment of coal and carbonaceous is stronger than that of mudstone.

4.2.2 Sesquiterpenes

The C_{15} sesquiterpenes contents of the Jurassic crude oils, coals and carbonaceous mudstones are relatively

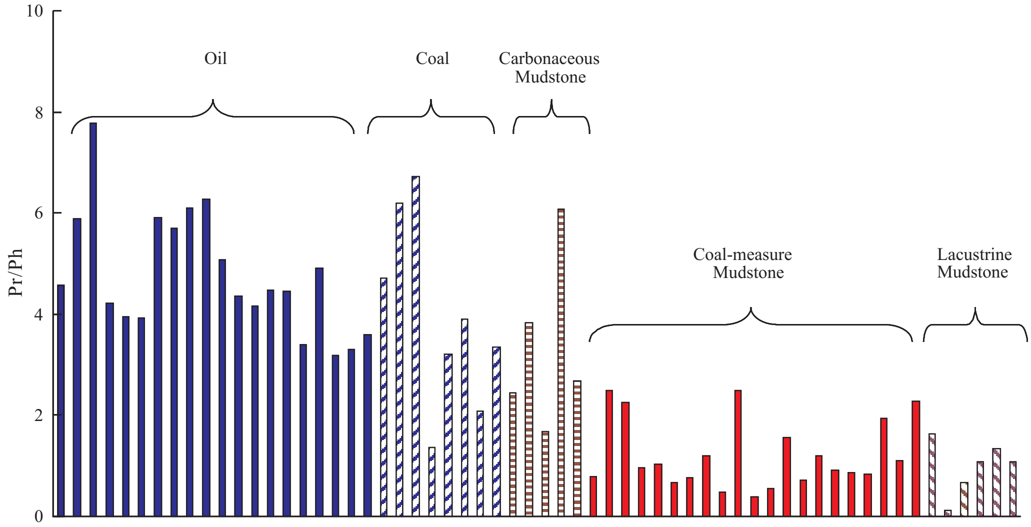

Fig. 4. Histogram of Pr/Ph of the Jurassic source rocks and crude oils in the Turpan Basin

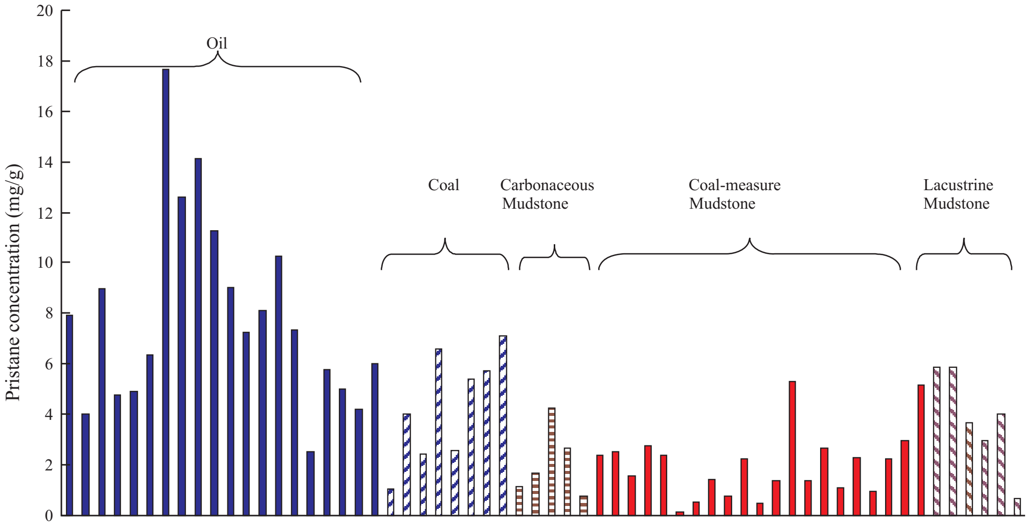

Fig. 5. Histogram of pristane absolute concentration of the Jurassic source rocks and crude oils in the Turpan Basin.

higher while the C_{16} sesquiterpenes contents of the mudstones are higher. Shen et al. (1991) pointed out that the C_{15}/C_{16} ratio of bicyclic sesquiterpenes series has obvious reflection to the sedimentary environment. Weston et al. (1989) realized that both C_{15} drimane and C_{16} homodrimane come from the same hopane precursor substance, and the kind of compound that is formed depends on the carbocycle fracture mode of the hopane precursor substance, while the mode is controlled by sedimentary environment. Thus, the C_{15}/C_{16} ratio can reflect the sedimentary environment of source rock. The bulk C_{15}/C_{16} ratio of the Jurassic crude oils, coals and carbonaceous mudstones are above 1, while those of mudstones are below 1 (Tables 1, 2), reflecting the difference of the sedimentary environments. As it is shown in Fig. 6a, the plot of Pr/Ph versus C_{15}/C_{16} sesquiterpenes can divide the crude oils, coals and carbonaceous mudstones from the mudstones.

4.2.3 Tricyclic terpanes

The crude oils, coals and carbonaceous mudstones of the Jurassic are rich in low carbon number tricyclic terpanes and C_{24} tetracyclic terpane, while the mudstones is relatively rich in high carbon number tricyclic terpanes and poor in C_{24} tetracyclic terpane (Fig. 6b, c). The tricyclic terpanes of the Jurassic crude oils, coals and carbonaceous mudstones is mainly of C_{19} or C_{20} as the main peak, with a $C_{19\text{-}21}/C_{23\text{-}25}$ ratio above 3, C_{24} tricyclic terpane/C_{26} tricyclic terpane ratio 1.28–6.28; that of the bulk coal-measure mudstones and lacustrine mudstones are mainly of C_{21} or C_{23} as the main peak, with $C_{19\text{-}21}/C_{23\text{-}25}$ ratio below 3 and C_{24}/C_{26} ratio below 2 (Tables 1, 2). The tricyclic terpanes of low carbon number (C_{19}-C_{21}) may be derived from the diterpenoid precursor of higher plants (Ekweozor and

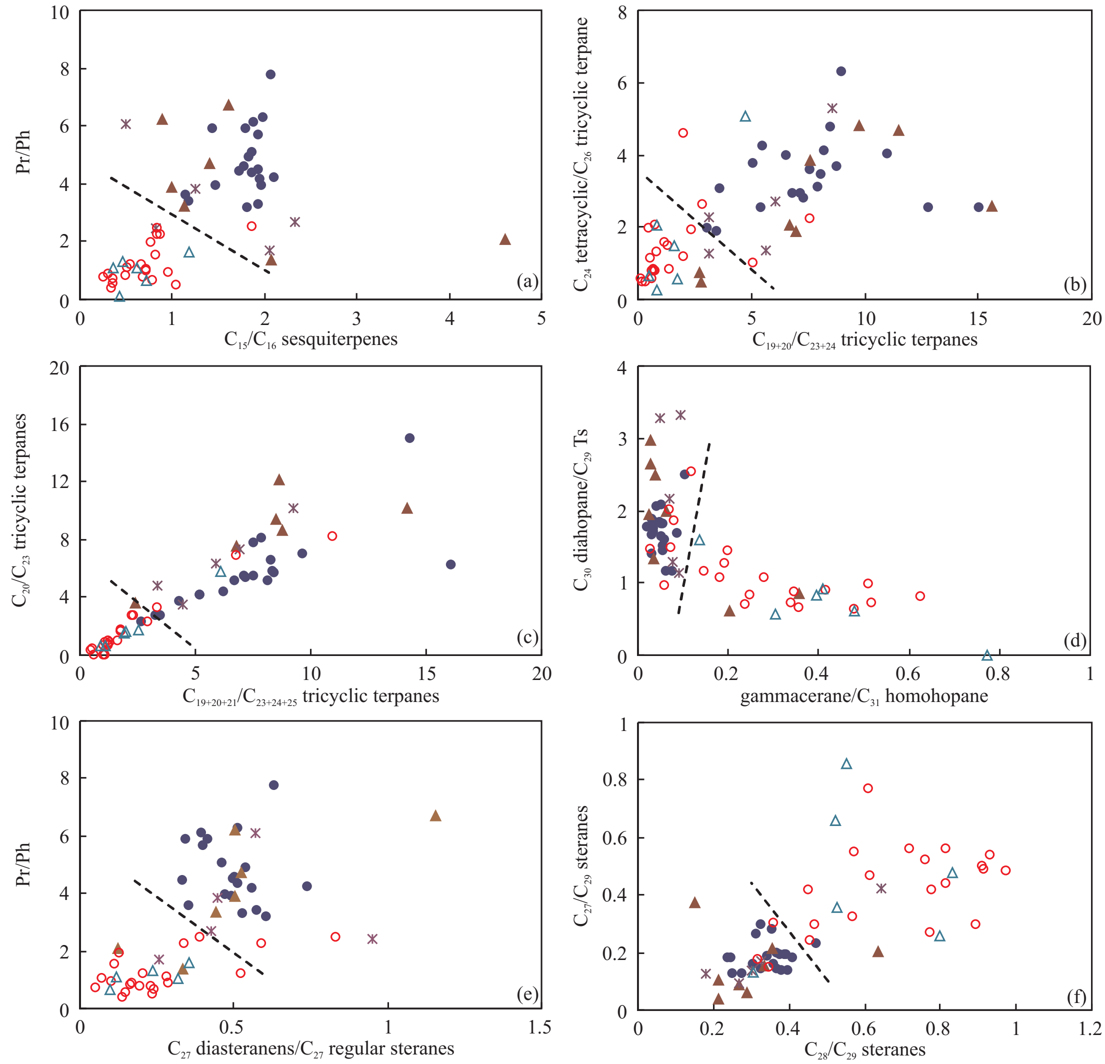

Fig. 6. The oil-source correlation of biomarkers in the Jurassic source rocks and crude oils from the Turpan Basin.
▲, coal; *, carbonaceous mudstone; ●, crude oil; ○, coal-measure mudstone; △, lacustrine-facies mudstone

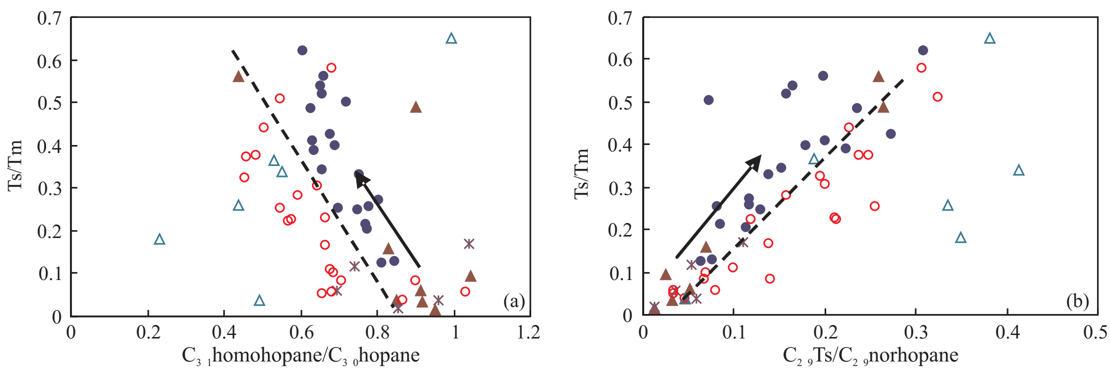

Fig. 7. Plots of Ts/Tm versus C_{31} homohopane/C_{30} hopane and C_{29} Ts/C_{29} norhopane for the Jurassic source rocks and crude oils in the Turpan Basin.

Strausz, 1983), whereas the C_{24} tetracyclic terpane is also considered to be derived from terrigenous organic matter (Philip and Gilbere, 1986; Weston et al., 1989). These data suggest that the organic matter input of crude oils, coals and carbonaceous mudstones have some differences with that of mudstones, and the input of higher plants of the former is obviously more abundant than that of the latter.

4.2.4 Hopanes

The gammacerane contents of the Jurassic crude oils, coals and carbonaceous mudstones are low and the C_{30} diahopane/C_{29} Ts ratio is high, but those of the mudstones

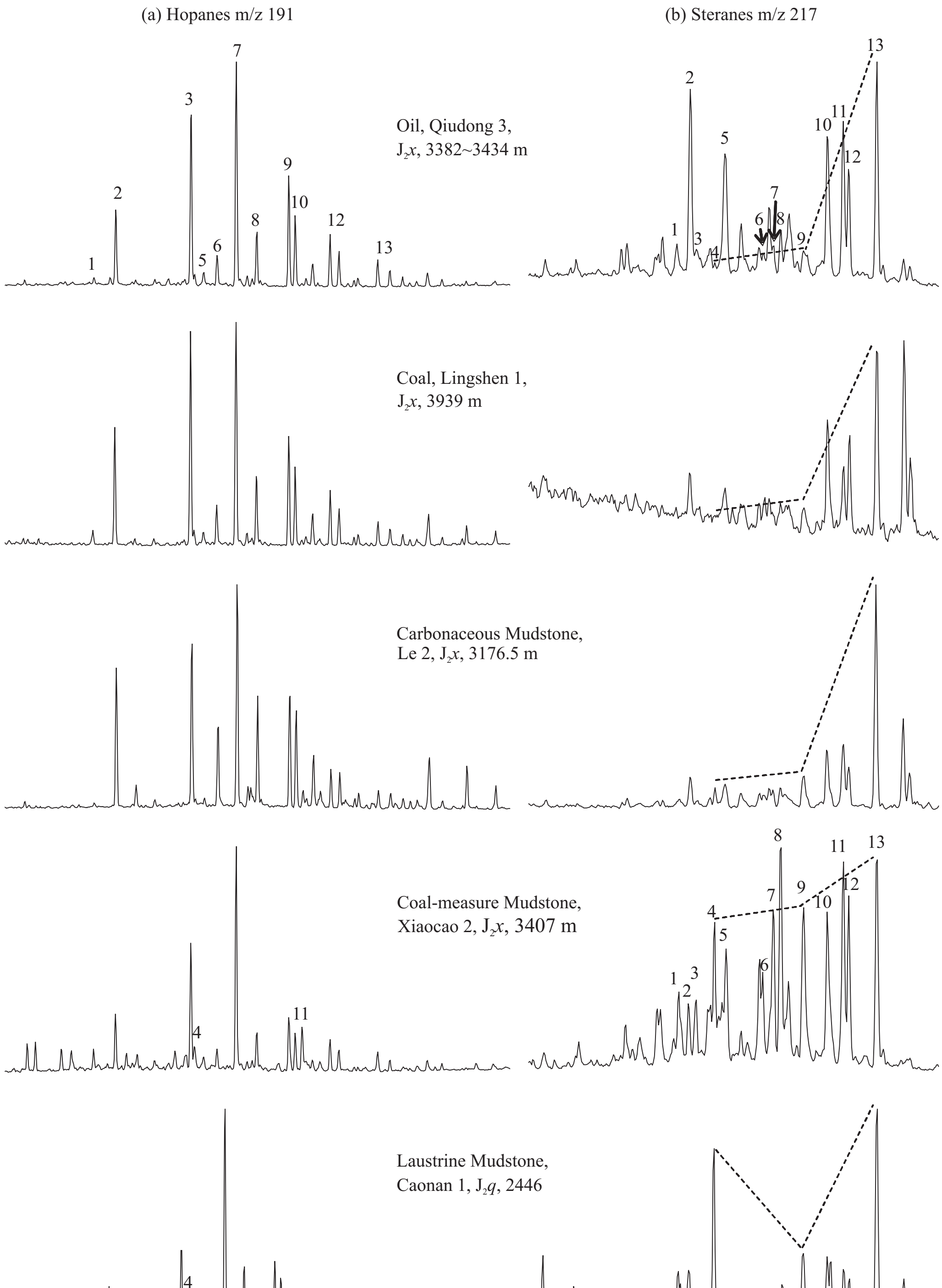

Fig. 8. Mass chromatogram of hopane (m/z 191) and sterane (m/z 217) of the Jurassic source rocks and crude oils in the Turpan Basin.

Hopanes m/z 191: 1, Ts; 2, Tm; 3, αβ C_{29} norhopane; 4, C_{29} Ts; 5, C_{30} diahopane; 6, βα C_{29} normoretane; 7, αβ C_{30} hopane; 8, βα C_{30} moretane; 9, αβ C_{31} homohopane 22S; 10, αβ C_{31} homohopane 22R; 11, gammacerane; 12, αβ C_{32} bishomohopane (22S, 22R); 13, αβ C_{33} trishomohopane (22S, 22R). Steranes m/z 217: 1. ααα C_{27} sterane 20S; 2. βα C_{29} diasterane 20S + αββ C_{27} sterane 20R; 3. αββ C_{27} sterane 20S; 4. ααα C_{27} sterane 20R; 5. βα C_{29} diasterane 20R; 6. ααα C_{28} sterane 20S; 7. αββ C_{28} sterane 20R; 8. αββ C_{28} sterane 20S; 9. ααα C_{28} sterane 20R; 10. ααα C_{29} sterane 20S; 11. αββ C_{29} sterane 20R; 12. αββ C_{29} sterane 20S; 13. ααα C_{29} sterane 20R

are just opposite. From Fig. 6d and Fig. 8a, we can see the gammacerane and C_{29} Ts are hardly detected in the crude oils, coals and carbonaceous mudstones, and the ratio of gammacerane/C_{31} homohopanes ratio are very low and range mainly from 0.02 to 0.10, while the C_{30} diahopane/C_{29} Ts ratio is higher and most of them are above 1.5

(Tables 1, 2). When it comes to the mudstones, the peak of gammacerane and C_{29} Ts is obvious in the m/z191 mass chromatogram; most of the gammacerane/C_{31} homohopanes ratio are above 0.1 and the C_{30} diahopane/C_{29} Ts ratio are below 1.5. Mann et al. (1987) reported that there was a negative correlation between the gammacerane content and Pr/Ph, and pointed out the richness of gammacerane is dependent on oxidizing level or salinity. Peters et al. (2005) considered that the relative contents of C_{30} diahopane and C_{29} Ts are clearly determined by sedimentary environment, thus the oil derived from oxidizing to sub-oxidizing environment has high C_{30} diahopane/C_{29}Ts value than that from oxygen-deficient environment. The composition feature of the hopanes shows that coal and carbonaceous mudstone are formed in the stronger oxidizing environment with shallower water than that of the mudstone, which is consistent with the distribution feature of pristane and phytane.

Chen et al. (1999) pointed out that the Jurassic crude oils and coal-measure mudstones in the Turpan basin have the high ratios of Ts/Tm and C_{29} Ts/C_{29} norhopane with the low ratios of Tm/C_{30} hopane and C_{31} homohopane/C_{30} hopane, while the ratios of coals and carbonaceous mudstones are oppositely different with those of the crude oils and mudstones. So they considered that the coal-measure mudstones are the major oil source rocks (Fig. 7). But the above parameters that were mentioned are affected greatly by maturity and hydrocarbon expulsion. Previous research shows that both Ts and Tm are affected by hydrocarbon expulsion for Ts has a higher migration rate than Tm (Fan and Philp, 1987; Jiang et al., 1987). The simulation experiment of hydrocarbon expulsion under low temperature done by Dai et al. (1996) shows that: the Ts/Tm ratio of residual hydrocarbon of coal is only 0.08, but that of expulsed hydrocarbon of coal is 0.31 higher; the $C_{31\text{-}35}$ hopane/C_{30} hopane ratio of residual hydrocarbon of coal is 1.17, whereas that of expulsed hydrocarbon of coal is 0.85 lower; the two ratios of residual hydrocarbon of mudstone and those of expulsed hydrocarbon of mudstone are almost the same. Therefore, as shown in Fig. 7a, the author considers that the differences between Ts/Tm ratios and C_{31} homohopane/C_{30} hopane ratios of the coals, carbonaceous mudstones and crude oils are caused by the geochromatographic effects during hydrocarbon expulsion. Though the two ratios of the crude oils are similar to those of the mudstones, it does not mean they have a genetic relationship. Fig. 7b also shows the same meaning. Dai et al. (1996) considered that the geochromatographic effects of steranes and terpanes in coal and that in mudstone are obviously different during hydrocarbon expulsion, so the effect of hydrocarbon expulsion should be considered when studying the source of coal-derived oil by using biomarker.

4.2.5 Steranes

The Jurassic crude oils have similar distribution of steranes with the coals and carbonaceous mudstones: the content of C_{29} steranes is absolutely predominant and the diasteranes content is also relatively high. Whereas, the content of C_{27} steranes in mudstones increases significantly and the diasteranes content is relatively low.

As it is shown in Figs. 6f, 8b and 9, the C_{29} steranes of the crude oils, coals and carbonaceous mudstones has absolute predominance in the sterane series, and ααα-20R C_{27}, C_{28}, C_{29} steranes present “anti-L” shape distribution. The content of C_{27} and C_{28} steranes in the mudstones increase significantly, and the bulk ααα-20R C_{27}, C_{28}, C_{29} steranes show irregular rising type or asymmetric “V” shape. The results illustrate that the organic matter input of the coals, carbonaceous mudstone and associated oils are predominantly of higher plants, while that of mudstones show a mixed input of more higher plants and less algae.

The distribution of diasteranes is not only controlled by clay minerals but also the oxidation-reduction environment, and a positive correlation between C_{27} diasteranes/(C_{27} diasteranes +C_{27} regular steranes) and Pr/Ph was reported (Moldowan et al., 1986, 1994). However, Zhu et al. (1997) pointed out the distribution of diasteranes is primarily affected by the oxidation-reduction environment, but there was no close relationship with clay minerals. Fig. 6e indicates that there is a great positive correlation of C_{27} diasteranes/C_{27} regular steranes and Pr/Ph between the crude oils and source rocks in the Turpan Basin. These two parameters in the mudstones are lower than that in the crude oils, coals and carbonaceous mudstones.

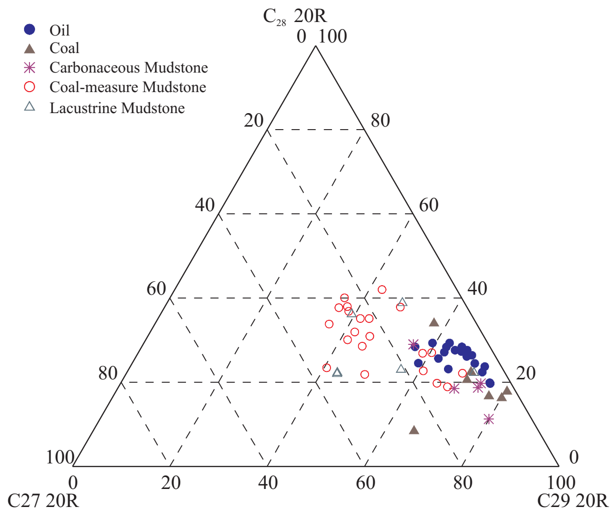

Fig. 9. Triangular diagram showing the composition of the ααα-20R C_{27}, C_{28}, C_{29} steranes of the Jurassic source rocks and crude oils in the Turpan Basin.

5 Conclusions

The analysis of oil maturity suggests the Jurassic oils in the Turpan Basin are mature crude oils and its parent material just entered the infancy of the stage of mass oil generation. Measured vitrinite reflectance values show the source rocks from the Xishanyao to Badaowan Formations are immature to mature and have promising potential to generate commercial quantities of petroleum.

Although the coals, carbonaceous mudstones and mudstones in the Turpan Basin all formed in the fluvial or lacustrine swamp environments, the analysis of biomarkers characteristics indicates that the organic matter input and the depth of sedimentary water of the coals and carbonaceous mudstones are obviously different from that of the mudstones. The former two were deposited in the stronger oxidizing environment with shallower water, and their organic matter input is rich in higher plants. On the contrary, the mudstones were deposited in the relatively anoxic environment with deeper water, and show a mixed input of higher plants and algae. The assemblage characteristics of biomarkers show strong comparability between the Jurassic crude oils and the coals and carbonaceous mudstones. Thus, the authors believe coal and carbonaceous mudstone are the possible major oil source rocks in the Jurassic Turpan Basin.

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