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Research Article

Geochemical Characteristic and Source Correlation of Biodegraded Oils from the Western Halaalate Area of Junggar Basin

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The relationship between biodegraded oil and its source has long been a complex and contentious topic. The Western Halaalate area is located in the Piedmont area on the northwest margin of the Junggar Basin. Source rocks of the Fengcheng Formation exist both locally and in the nearby Mahu Depression. In order to determine the source of biodegraded crude oil in this area, the molecular marker characteristics of biodegraded crude oil were analyzed by gas chromatography-mass spectrometry. The results showed that the vitrinite reflectance (Ro) of source rocks of the Permian Fengcheng Formation in the nearby Mahu Depression is greater than 1.3% and has entered a high mature stage of condensate oil and moisture gas; the source rock of Permian Fengcheng Formation in Western Halaalate area is in a mature stage with Ro of 0.79%~1.13%. The ascending configuration of tricyclic terpenes C_{20}-C_{21}-C_{23} for the crude oil samples found in the Carboniferous strata of the Western Halaalate Area is consistent with the characteristics of the Fengcheng Formation source rocks, which are present in both the Western Halaalate Area and the nearby Mahu Depression. Chromatography spectrometry examination shows that crude oils have undergone a varying degree of biodegradation. The Carboniferous oil was originated from the in situ Fengcheng Formation source rocks based on the application of molecular markers resistant to biodegradation, such as maturity parameters, salinity parameters, the new gammacerane index, and aromatic hydrocarbon parameters, combined with the analysis of hydrocarbon migration pathway. In addition, the oil biodegradation alteration rules in the Western Halaalate area were clarified, which advances regional knowledge of the relationship between biodegraded oil and source rocks.

1. Introduction

Oil-source correlation is an important link in the process of oil and gas exploration, and the reliability of its results has great guiding significance for the evaluation of hydrocarbon accumulation resources and target selection [1–3]. The accuracy of its findings is crucial for evaluating oil and gas resources and choosing exploration targets [4, 5]. The difficulty of conducting oil-source rock correlation is increased due to some traditional source correlation parameters becoming slightly skewed as a result of the biodegradation effects of microorganisms on oil [3, 4, 6]. To identify the source of biodegraded crude oil, researchers use geochemical parameters that are resistant to biodegradation. For exam-

ple, Holba et al. [7] suggested that the long-chain tricyclic terpane (TT) index ETR $(C_{28}$ TT + C_{29} TT$)/(C_{28}$ TT + C_{29} TT + Ts$)$ is an ideal parameter for oil-source rock correlation for biodegraded oil and later was applied to the Liaodong Bay region for heavy oil-source rock correlation [8]. While some parameters will change with the increase of biodegradation within a certain range [3, 4, 6], for example, the $C_{29}\beta\beta/(\alpha\alpha + \beta\beta)$ ratio and gammacerane index will increase due to the effect of biodegradation.

Although the crude oil in the research area has undergone a mild to moderate biodegradation process, the Carboniferous strata still display favorable hydrocarbon displays. In the past, some scholars believed that hydrocarbons migrated upward primarily through thrust faults and
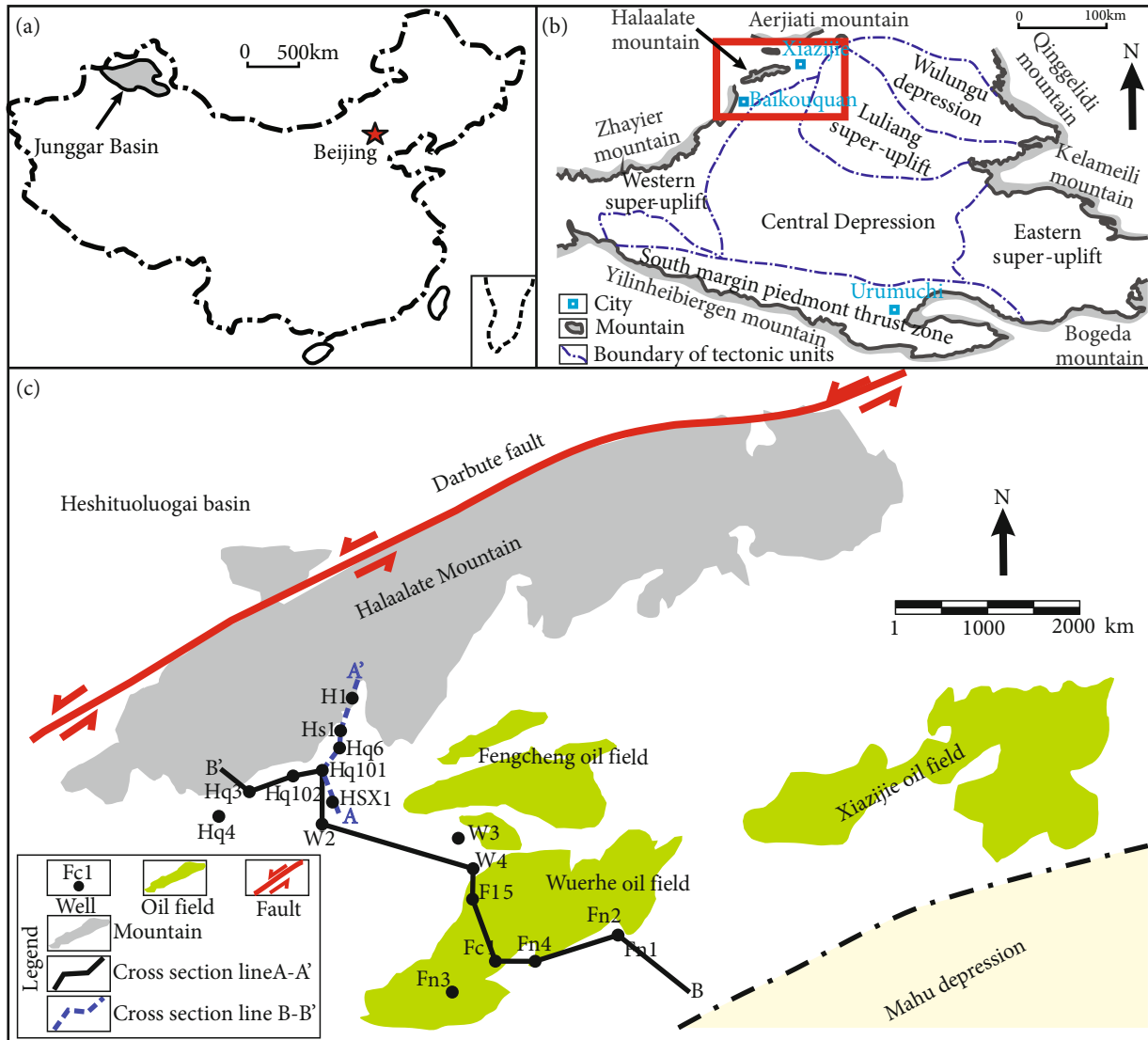
FIGURE 1: Maps showing the (a) location of Junggar Basin, the (b) location of the Western Halaalate, and the (c) structural units of the Western Halaalate.

accumulated in structural traps and Carboniferous traps in thrust belts [9]. It is found that there are two potential outcomes: "near source" vertical migration and "far from source" stepwise migration. The biodegraded oil in the reservoirs of the Permian Fengcheng Formation under the thrust belt and the reservoirs of Carboniferous quasiautochthonous superposition system may be from the in situ Fengcheng source rock below the reservoirs or from the Fengcheng source rocks in the Mahu Depression (Figures 1 and 2). Therefore, the question is, which set of source rocks does the biodegradable crude oil in the study area come from?

In order to determine the source of biodegradable crude oil in the study area, based on the analysis of molecular markers characteristics of the Carboniferous biodegradable crude oil, this study selected biodegradable parameters with strong antidegradation ability, such as gammacerane index with strong antidegradation ability and parameters related to aromatics, to distinguish two sets of similar source rocks,

and analyzed the possible oil migration pathway through the changes in parameters. The research results can provide a reference for the oil-source rock correlation of biodegradable crude oil and can provide a basis for the strategic deployment of petroleum exploration in the study area.

2. Regional Geological Background

Western Halaalate Area is situated in the Junggar Basin's northwestern region (Figure 1). It is close to Mahu Depression to the south and Halaalate mountain to the north. The Halaalate area covers a favorable petroleum exploration area of $1000 \, km^2$, and it is distributed in the direction of NE-SW. In recent years, there is a significant breakthrough of the oil exploration in this area, and Fengcheng, Wuerhe, and Xiazijie oilfields were found. At present, the exploration targets of multilayer complex oil-bearing system, including Carboniferous, Permian, Triassic, Jurassic, and Cretaceous
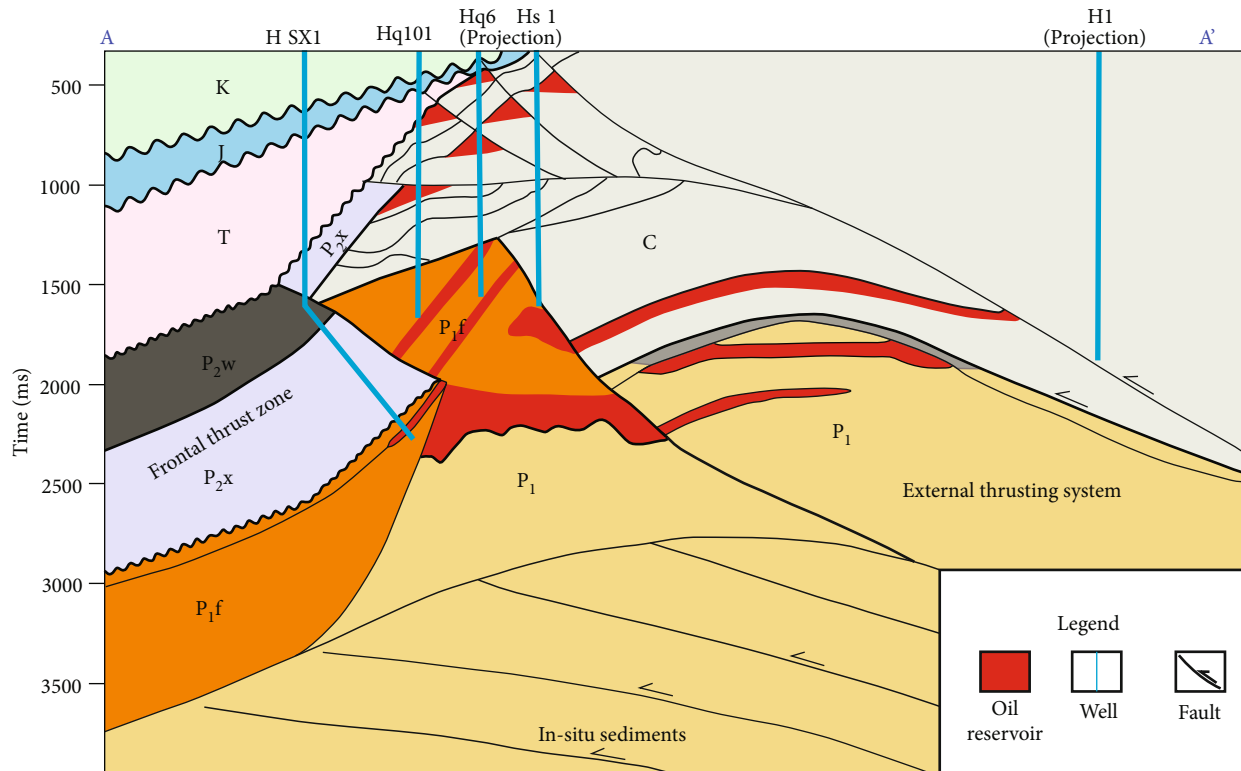
FIGURE 2: The time section in the study area (modified from [29]). The section was marked by A-A' in Figure 1(c). Abbreviations: C = Carboniferous; P_1f = Fengcheng Formation; P_1 = Lower Permian; P_2x = Xiazijie Formation; P_2w = Wuerhe Formation; T = Triassic; J = Jurassic; K = Cretaceous.

systems, have been preliminarily formed, indicating an excellent exploration potential. This area belongs to the Piedmont overthrust belt, and the tectonic uplift in the west and north Junggar basin and the Tarboot fault is responsible for the tectonic evolution in the study area, which is roughly divided into four main stages: the impact-extrusion stage in the late Carboniferous to the early Permian, the back-arc extrusion stage in the late Permian to the Triassic, the rift stage in the early Jurassic, and the regeneration foreland stage in the late mid-Jurassic.

The Carboniferous, Permian, Triassic, Jurassic, Cretaceous, Paleogene, Neogene, and Quaternary strata were developed from the bottom up (Figure 2). Among them, the Permian Fengcheng Formation in Mahu Depression has characteristics of deep-water deposition, and its source rocks have features of high salinity and maturity relative to the local Permian Fengcheng source rocks in the Western Halaalate area. The lithology of the Permian Fengcheng Formation is very complex, including dolomitic rocks, clastic rocks, and volcanic rocks. The proportions of different rock compositions vary greatly from region to region, and the carbonates are the major component in the center of the lake. Its thickness is in the range of 0 to 1710 m, and the source rocks are mainly mudstones and shales with a thickness of 0 to 250 m. The whole sequence of alkaligenous evolution and alkaline minerals was reported in the Fengcheng sediments, reflecting that they belong to alkaline lacustrine deposition.

In addition, the Fengcheng sediments are predominantly developed in the Central Depression, which is difficult to drill due to a large burial depth (~4000 to 6000 m). However, in the Western super-uplift, the Fengcheng Formation was buried in a shallower depth, and it was discovered by many wells, e.g., well Hq6 in the Halaalate region and well Fn7 in the Mahu Depression. The estimated thickness of the Fengcheng sediments in this region reaches up to 700 m, which is thicker than that in the deposition center of Mahu Depression. Thus, the studied region was thought to be the depocenter rather than the Mahu Depression during their deposition. Abundant organic geochemical work has been conducted on the Fengcheng mudstones in Mahu Depression, and they are regarded as fair to good source rocks. Abundant oil and gas have been discovered in Mahu Depression. However, organic geochemical properties of the Fengcheng organic-rich mudstones in the Halaalate region have not been understood well. In recent years, the oil generated from the Fengcheng organic-rich rocks in the Halaalate region has been found; thus, the Halaalate region was thought to be the breakthrough area of petroleum exploration in the future.

3. Experimental Methods

3.1. Sample Selection. In order to ensure the accuracy of the study, a total of 30 samples were selected for chromatographic analysis, including 12 oil samples from the

TABLE 1: Gas chromatography data of crude oil and source rock from Hashan area and Mahu Depression.

Types	Wells	Depth (m)	Strata	Pr/Ph	Pr/nC$_{17}$	Ph/nC$_{18}$	$\sum$C$_{21}^{-}$/$\sum$C$_{22}^{+}$	OEP	CPI	Carbon number	C$_{21}$ + C$_{22}$/C$_{28}$ + C$_{29}$	Major carbon
Crude oil	Hq 102	454.0~458.0	C	0.53	1.09	1.62	0.12	1.01	1.32	/	0.14	29
		535.2		1.05	0.79	0.45	0.07	1.08	1.03	/	0.19	26
		854.0~860.0		0.58	1.00	1.38	0.22	0.98	1.20	/	0.35	28
	Hq3	1174.0~1183.0		0.78	0.68	0.53	0.80	0.85	1.15	/	/	26
		1324.0~1328.0		0.87	0.57	0.80	1.03	1.01	1.27	/	2.17	17
		1354.0~1358.0		0.81	0.62	0.96	1.09	0.98	0.95	/	1.68	17
		1360.0~1374.0		0.37	0.79	1.51	0.70	1.08	0.97	/	2.51	23
	Hq 6	302.2		0.87	1.60	2.30	0.79	1.12	1.00	14~29	0.66	29
		301.4~301.9		0.88	1.50	2.20	0.82	1.10	0.99	14~29	0.73	29
		648.1~648.2		0.85	1.40	2.00	0.81	1.06	1.02	13~28	0.79	28
	Hq 101	1452.5		0.64	1.51	2.12	0.60	1.06	0.93	14~30	1.17	24
		1742.5		0.91	1.58	2.00	0.63	1.09	1.18	14~31	1.36	23
Mudstones in Hashanxi area	Hq 6	1325.0~1335.0	P$_1$f	0.45	1.01	2.54	0.66	1.03	1.08	/	1.09	23
		1360.5		0.55	0.98	2.60	1.21	1.02	1.08	/	1.86	17
		1365.0~1380.0		0.38	1.04	2.67	0.53	1.02	1.07	/	1.18	24
		1410.0~1425.0		0.48	0.71	1.37	0.53	0.85	0.85	/	1.34	24
		1460.0~1470.0		0.46	0.86	1.66	0.43	0.92	0.97	/	1.01	26
		1476.0~1486.0		0.37	0.91	2.02	0.42	0.96	1.07	/	1.02	24
		1494.0~1502.0		0.27	0.62	1.65	0.48	0.98	0.96	/	1.35	22
		1700.0~1752.0		0.44	0.92	2.17	0.67	1.02	1.05	/	1.20	24
		2541.7		0.64	1.32	3.69	3.34	1.06	0.84	/	3.95	17
		2540.0~2540.6		0.59	1.21	5.90	0.81	0.91	1.32	14-29	0.99	17
		2703.1		0.40	1.12	4.46	0.97	1.05	1.21	14-31	1.70	17
	Hq 1	2099.9	P$_1$f	0.75	0.72	1.01	0.73	0.98	1.01	14-32	1.84	22
		2156.4		0.37	1.55	7.42	0.80	0.91	1.13	14-32	1.52	17
Mudstones in Mahu Depression	Fn4	4227.2	P$_1$f	0.96	1.38	1.36	0.52	1.17	1.20	12-36	1.25	25
		4228.5		0.97	1.27	1.33	0.51	1.18	1.20	13-37	1.25	25
	Fn1	3119.0~3134.0	P$_1$f	1.07	1.35	1.86	0.94	1.36	1.19	10-36	1.19	17
		3119.0~3134.0		1.09	1.47	2.00	0.78	1.27	1.08	10-36	1.76	23
		3960.0~3976.0		0.96	1.44	1.85	1.91	1.10	1.12	9-36	2.31	17

Note: OEP: odd-even predominance index; CPI: carbon preference index (CPI); /: no data.

Carboniferous reservoir in the study area, 13 source rock samples from the in situ Fengcheng Formation, and 5 source rock samples from the Mahu Depression (Table 1). A total of 33 samples were analyzed with mass spectrometry of saturated hydrocarbon, including 13 crude oil samples from the Carboniferous reservoir, 14 in situ source rock samples, and 6 source rock samples from the Mahu Depression (Table 2). In addition, a total of 11 samples, including 8 samples from the Western Halaalate area, and 3 source rock samples from Mahu Depression, were chosen for the mass spectrometry of aromatics to conduct oil-source rock correlation.

3.2. Experimental Methods. Sample processing and testing were done at the Petroleum Geological Testing Center of Shengli Oilfield Exploration and Development Research Institute, SINOPEC. All of the test equipment was thoroughly cleaned to remove impurities using potassium dichromate lotion, washed with distilled water, burnt at 450°C for four hours, and purified again. Furthermore, all of the organic chemicals and tools utilized in the experiment—including n-hexane, dichloromethane, methanol, n-hexadecane, copper sheet, cotton, filter paper, anhydrous sodium sulfate, silica gel, and alumina—have been painstakingly purified.

Soluble organic matter was extracted from source rocks using the Soxhlet extraction method, desulfurized by a copper sheet, and the solvent used is a mixture of dichloromethane and methanol (v : v = 83 : 17). After the asphaltene precipitation of the source rock extract and crude oil, the sample's saturated and aromatic hydrocarbons were separated by a silica gel or alumina mixture column. N-Alkanes and iso-alkanes were isolated from saturated hydrocarbons by urea complexation.

Both saturated and aromatic molecular markers were investigated using gas chromatography-mass spectrometry (GC-MS) in accordance with GB/T18606-2001. Multiple-

Table 2: Terpene and sterane data of crude oil and source rock from Hashanxi area and Mahu Depression.

Types	Wells	Depth (m)	Strata	Tricyclic terpanes											Pentacyclic triterpenes										Sterane		
				a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x
Crude oil	Hq6	299.3	C	0.73	0.67	0.18	0.39	0.71	0.08	0.80	0.12	0.20	0.35	0.47	0.95	0.27	0.56	0.56	0.58	0.54	0.58	0.80	0.09	0.24	0.70	0.32	0.39
		302.2		0.74	0.63	0.19	0.39	0.71	0.07	0.85	0.08	0.22	0.37	0.55	0.98	0.33	0.53	0.54	0.57	0.52	0.49	0.89	0.12	0.17	0.68	0.31	0.37
		300.2~300.3		0.72	0.65	0.19	0.38	0.72	0.09	0.78	0.13	0.20	0.34	0.55	0.95	0.03	0.56	0.53	0.60	0.54	0.59	0.75	0.08	0.29	0.80	0.33	0.39
		301.4~301.9		0.77	0.67	0.18	0.37	0.71	0.10	0.83	0.10	0.22	0.36	0.48	0.94	0.27	0.55	0.54	0.61	0.54	0.59	0.87	0.09	0.22	0.81	0.33	0.41
		304.3~304.4		0.76	0.68	0.18	0.38	0.73	0.10	0.84	0.09	0.19	0.37	0.50	0.99	0.26	0.55	0.56	0.61	0.54	0.57	0.72	0.08	0.22	0.77	0.31	0.39
		304.6		0.74	0.63	0.20	0.33	0.69	0.10	0.84	0.09	0.19	0.39	0.56	1.01	0.31	0.55	0.55	0.59	0.52	0.59	0.76	0.11	0.00	0.64	0.30	0.39
		648.1~648.2		0.81	0.73	0.19	0.39	0.82	0.09	0.85	0.10	0.18	0.31	0.34	0.65	0.24	0.56	0.56	0.59	0.55	0.57	0.70	0.07	0.18	0.73	0.34	0.38
		650.5~650.8		0.81	0.72	0.19	0.38	0.80	0.09	0.86	0.09	0.17	0.31	0.33	0.64	0.24	0.55	0.57	0.58	0.54	0.59	0.71	0.07	0.15	0.81	0.35	0.39
		812.1		0.83	0.72	0.18	0.38	0.85	0.09	0.89	0.07	0.18	0.31	0.34	0.65	0.25	0.55	0.55	0.58	0.55	0.57	0.73	0.07	0.15	0.80	0.34	0.37
		812.6~812.7		0.81	0.72	0.18	0.38	0.81	0.09	0.86	0.09	0.18	0.32	0.33	0.63	0.24	0.55	0.56	0.59	0.54	0.56	0.76	0.08	0.16	0.76	0.34	0.38
	Hq101	1452.5		0.57	0.74	0.22	0.45	0.84	0.08	0.79	0.14	0.15	0.26	0.34	0.75	0.29	0.55	0.57	0.56	0.46	0.50	1.10	0.09	0.23	0.78	0.42	0.4
		1742.5		0.95	0.91	0.20	0.40	0.86	0.07	0.79	0.20	0.25	0.32	0.38	0.51	0.56	0.50	0.50	0.50	0.49	0.49	1.09	0.23	0.17	0.85	0.37	0.41
	Hq3	1324.0~1328.0		0.56	0.53	0.20	0.35	0.87	0.07	0.92	0.10	0.29	0.37	0.38	0.51	0.51	0.49	0.52	0.54	0.46	0.50	0.63	0.13	0.38	1.02	0.41	0.37
Mudstones in Mahu Depression	Fn1	4326.1	P_1f	0.90	0.92	0.19	0.54	0.74	0.13		0.06	0.11	0.18	0.72	1.28	0.57	0.61	0.40	0.59	0.62	0.64	1.06	0.13	0.16	0.78	0.57	0.45
	Fn2	4037.0~4043.0		0.65	0.46	0.22	0.50	0.76	0.08	0.89	0.08	0.14	0.23	0.54	0.64	0.29	0.59	0.56	0.55	0.66	0.53	1.04	0.12	0.08	0.75	0.55	0.45
		4099.0~4104.0		0.74	0.56	0.22	0.49	0.77	0.08	0.92	0.08	0.10	0.24	0.49	0.80	0.46	0.58	0.61	0.58	0.58	0.53	0.97	0.12	0.07	0.69	0.51	0.43
	Fn3	3909.0~3912.0		0.52	0.83	0.20	0.53	0.99	0.11	0.87	0.04	0.14	0.16	0.52	0.54	0.25	0.61	0.63	0.60	0.65	0.46	0.74	0.07	0.30	0.71	0.52	0.45
	Fn4	4227.8		0.91	0.73	0.17	0.46	0.73	0.08	0.86	0.06	0.08	0.11	0.52	1.22	0.41	0.57	0.61	0.60	0.68	0.55	0.95	0.11	0.19	0.73	0.57	0.53
		4227.5		0.70	0.75	0.17	0.57	0.77	0.16	0.80	0.03	0.07	0.12	0.54	0.61	0.28	0.57	0.55	/	0.66	0.55	/	0.00	0.20	0.72	0.57	0.51
Mudstones in Western Halaalate area		1360.5	P_1f	0.77	0.68	0.15	0.34	0.44	0.03	0.66	0.18	0.59	0.25	0.22	0.56	0.44	0.42	0.32	0.45	0.42	0.44	0.70	0.05	0.37	0.69	0.25	0.16
		1562.3		0.65	0.78	0.22	0.32	0.31	0.00	0.59	0.23	0.55	0.17	0.38	0.56	0.38	0.41	0.18	0.37	0.41	0.35	0.40	0.02	0.58	0.46	0.29	0.14
		1918.2		0.92	0.88	0.14	0.28	0.73	0.03	0.52	0.20	0.31	0.19	0.32	0.67	0.45	0.49	0.39	0.49	0.56	0.44	0.67	0.06	0.28	0.43	0.34	0.16
		2540.0~2540.6		0.88	0.95	0.24	0.42	0.70	0.01	0.54	0.24	0.27	0.26	0.29	0.66	0.27	0.50	0.43	0.48	0.47	0.50	0.24	0.04	0.18	0.71	0.22	0.23
		1325.0~1335.0		0.83	0.81	0.18	0.40	0.84	0.07	0.60	0.22	0.34	0.31	0.26	0.58	0.28	0.44	0.37	0.55	0.46	0.48	0.78	0.07	0.35	0.72	0.26	0.21
		1365.0~1380.0		0.82	0.79	0.17	0.38	0.81	0.06	0.74	0.13	0.35	0.30	0.27	0.63	0.34	0.44	0.37	0.57	0.48	0.53	0.78	0.06	0.33	0.74	0.26	0.22
	Hq6	1410	P_1f	0.74	0.72	0.16	0.36	0.78	0.06	0.69	0.16	0.39	0.28	0.23	0.55	0.30	0.44	0.36	0.58	0.45	0.50	0.76	0.06	0.46	0.77	0.27	0.19
		1460.0~1470.0		0.73	0.78	0.17	0.40	0.68	0.05	0.68	0.17	0.40	0.27	0.26	0.65	0.35	0.44	0.36	0.52	0.43	0.45	0.68	0.06	0.47	0.74	0.29	0.21
		1476		0.71	0.72	0.18	0.37	0.79	0.05	0.66	0.17	0.35	0.26	0.26	0.66	0.32	0.45	0.36	0.55	0.44	0.50	0.68	0.06	0.40	0.73	0.28	0.2
		1494		0.50	0.61	0.22	0.41	0.94	0.07	0.54	0.23	0.33	0.24	0.23	0.58	0.28	0.49	0.45	0.52	0.54	0.55	0.77	0.06	0.38	0.70	0.28	0.23
		1360.5		0.78	0.61	0.19	0.33	0.59	0.03	0.51	0.28	0.45	0.24	0.21	0.51	0.34	0.44	0.36	0.56	0.46	0.47	0.80	0.07	0.38	0.71	0.27	0.18
		1700.0~1752.0		0.77	0.64	0.16	0.32	0.85	0.06	0.73	0.15	0.38	0.29	0.33	0.84	0.40	0.47	0.43	0.51	0.48	0.48	0.79	0.08	0.29	0.71	0.25	0.2
	Hs1	2099.9		0.82	0.61	0.19	0.31	0.61	0.07	0.86	0.08	0.32	0.32	0.16	0.25	0.15	0.53	0.52	0.54	0.49	0.44	0.76	0.05	0.44	0.74	0.19	0.25
		2156.4		0.91	0.55	0.17	0.24	0.75	0.06	0.81	0.09	0.25	0.30	0.34	0.57	0.27	0.53	0.48	0.49	0.51	0.45	0.64	0.08	0.07	0.82	0.18	0.27

Note: a: $C_{20}TT/C_{21}TT$; b: $C_{21}TT/C_{23}TT$; c: $C_{22}TT/C_{21}TT$; d: $C_{24}TeT/C_{23}TT$; e: $C_{24}TeT/C_{26}TT$; f: $C_{24}Tet/C_{30}H$; g: ETR; h: $Ts/(Ts + Tm)$; i: C_{29} normortane/C_{29} norhopane; j: C_{30} mortane/$C_{30}H$; k: $G/C_{30}H$; l: $G/C_{31}HH$; m: new gammacerane index = gammacerane/$(2 \times C_{29}$ norhopane); n: $C_{31} - 22S/(22S + 22R)$; o: $C_{32} - 22S/(22S + 22R)$; p: $C_{33} - 22S/(22S + 22R)$; q: $C_{34} - 22S/(22S + 22R)$; r: $C_{35} - 22S/(22S + 22R)$; s: $C_{35}HH/C_{34}HH$; t: C_{27}/C_{27}; u: C_{27} diasterane/C_{28} sterane; v: C_{28} sterane/C_{29} sterane; w: $C_{29}\beta\beta/(\beta\beta + \alpha\alpha)$; x: $\alpha\alpha\alpha C_{29}20S/(20S + 20R)$; TT. = tricyclic terpenes; TeT. = tricyclic terpenes; H = hopane; HH = homohopane; G = gammacerane.

TABLE 3: Rock-Éval data of Fengcheng Formation source rock samples from Haqian 6 well and Hashan 1 well.

Wells	Strata	Depth (m)	R_o Values (%)	Measurements	Error	TOC (%)	S_1 (mg/g)	S_2 (mg/g)	$S_1 + S_2$ (mg/g)	t_{max} (°C)	I_H (mg/g)	C_p (%)	D (%)
Hq6		1360.5	0.79	15	0.08	1.59	0.210	8.13	8.34	421	511.3	0.69	43.54
		1562.3	0.94	16	0.08	0.92	0.090	3.97	4.06	441	431.5	0.34	36.63
	P_1f	1590.0	/	/	/	0.43	0.049	3.35	3.40	423	780.0	0.28	65.69
		1918.2	1.02	13	0.05	0.36	0.040	4.45	4.49	431	1236.1	0.37	93.52
		2540.0~2540.6	1.13	12	0.07	1.32	0.210	5.70	5.91	433	431.8	0.49	37.16
Hs1	P_1f	2099.9	0.82	14	0.08	2.06	0.170	9.29	9.46	440	451.0	0.79	38.12
		2101.5	/	/	/	1.19	0.220	5.08	5.30	428	426.9	0.44	36.97
		2156.4	0.86	8	0.07	0.90	0.670	4.44	5.11	430	493.3	0.42	47.13

Note: TOC: total organic carbon; S_1: free hydrocarbon; S_2: kerogen pyrolytic hydrocarbon; t_{max}: pyrolysis peak temperature; I_H: hydrogen index; D: degradation rate; C_p: effective carbon; D: C_p/TOC; /: not detected.

ion detection GC–MS was performed on a Finnigan Voyager GC-MS, and the GC equipment is equipped with a DB-5-MS fused silica capillary column (60 m × 0.25 mm) coated with a silica gel film having a thickness of 0.25 μm. Helium (purity of 99.999%) was introduced as the carrier gas with an injection port temperature of 300°C and transmission-line temperature of 300°C. The flow rate of the carrier gas was set at 1 mL/min. During the experiment, the GC oven started out at 80°C and remained stable for 2 minutes before increasing by 3°C/min to 300°C and holding that temperature for 30 minutes. The GC-MS interface temperature was 250°C, and the ion source temperature was 250°C. The split ratio was 20 : 1, and the precolumn pressure was 170 kPa. The mass spectrometer was set to the electron impact ionization (EI) mode with an electron energy of 70 eV and a scanning range of 50–600 Da. Selective ion monitoring (SIM) was utilized to identify the steranes (217 m/z), triterpenes (191 m/z), triaromatic steroids (m/z 231), etc. Individual organic compounds were identified using retention times and published mass spectral data and quantitated using peak areas in characteristic ion chromatograms.

4. Results and Discussion

4.1. Geochemical Characteristics of Source Rocks and Crude Oil

4.1.1. Organic Matter Type Identification.
The study of source rocks in Mahu Depression began in the 1980s. Using Well Aican 1 as an example, the evolution characteristics of source rocks and the oil generation threshold in this region have been systematically studied and determined. The Permian Fengcheng Formation source rocks in this well have reached a high maturation to postmaturation stage (vitrinite reflectance Ro > 1.3%), with a high hydrocarbon generation potential [10, 11].

Under overthrust faults in the Western Halaalate Area, the dark argillaceous source rock of the Permian Fengcheng Formation with a thickness of more than 1000 m was discovered. Ro values ranged from 0.79% to 1.13%, which was in the stage of moderate maturity to high maturity. TOC ranged from 0.36% to 2.06%, and most of them exceeded 0.90%. The hydrocarbon generation potential parameter $S_1 + S_2$ is in the range of 3.40~9.46 mg/g, and the hydrogen index HI is in the range of 42.69~1236.1 mg/g, with most between 400 and 500 mg/g. Other pyrolysis parameters are shown in Table 3. These results suggested that the source rock belongs to medium to good source rock.

Based on the chart of kerogen type identification (Figure 3), the kerogen type of the source rocks in the Hq6 well is primarily II1-type kerogen, with only one sample belonging to a I-type kerogen, whereas all of the source rock samples of the Hs1 well are Type II1 kerogen. As a result, the Western Halaalate's source rocks of the Permian Fengcheng Formation are primarily II$_2$-type source rocks with high potential for hydrocarbon generation.

4.1.2. Chromatographic Analysis.
A chromatogram can directly reflect the molecular chemical characteristics of crude oil or source rock extract (Figure 4). In addition, it can indicate the degree of biodegradation of crude oil or source rock extract. Biodegradation is a quasistepwise process, with the saturated hydrocarbons that are sequentially removed following the order n – alkanes > alkylcyclohexanes > isoprenoids > bicyclic sesquiterpenes > hopane (with formation of 25 – norhopane) > regular sterane > hopane (without formation of 25 – norhopane) > C_{21} – C_{22} steranes > tricyclic terpanes > diasteranes > porphyrins. Peters and Moldowan [12] categorized the biodegradation levels into classes ranging from PM0 (none) to PM10 (extreme) based on the variability of these different compounds, which is one of the most widely used methods for assessing biodegradation levels. Here, the n-alkanes, alkylcyclohexanes, and isoprenoids of the crude oils are altered to different degrees (Figure 4). According to the PM scale, the biodegradation level of these oil samples is between PM2 and PM4. It is worth noting that the peak of the chromatographic baseline of Carboniferous crude oil samples from the study area becomes more prominent when compared to the source rock samples from the Fengcheng Formation. It is because the Carboniferous crude oil samples have generally undergone biodegradation modification, whereas the source rock samples have almost no biodegradation process.
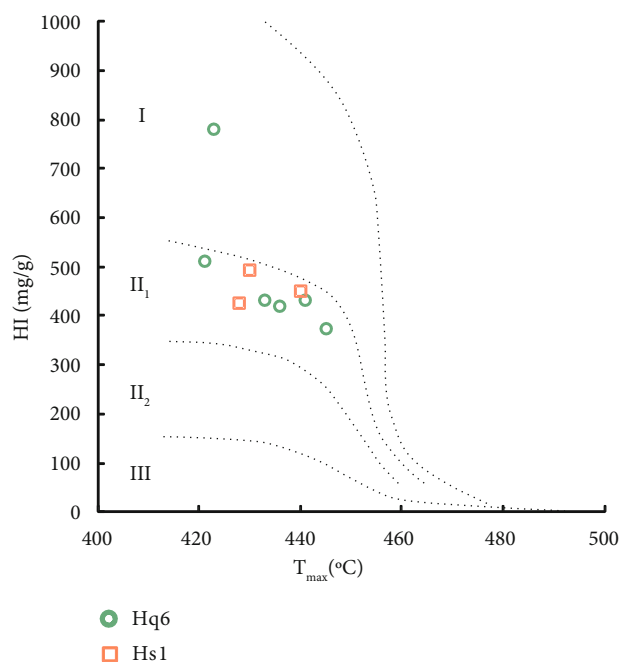
FIGURE 3: Crossplot of Tmax and Hi showing the organic matter type of Fengcheng Formation source rocks.

4.1.3. Mass Spectrometry Analysis.

Although biodegradation has a certain effect on the chromatograms of crude oil, it has no significant effect on the mass chromatograms of m/z 191 and m/z 217. The upwelling configuration of tricyclic terpenes $C_{20} \sim C_{21} \sim C_{23}$ is still very obvious (Figure 5), which is typical of source rocks of Fengcheng Formation, Junggar Basin [13]. Other tricyclic terpenes, pentacyclic triterpenes, and steranes were well preserved, showing that the effect of biodegradation on terpenes and steranes was limited. This indicates that the crude oil in this area is only mildly to moderately biodegraded. By comparing the mass spectra of source rocks of Fengcheng Formation from well Hq 6 in the Western Halaalate area and well Fn 4 in the Mahu Depression, it is found that both of them have detected the ascending configuration of $C_{20} \sim C_{21} \sim C_{23}$, and well Fn 4 contains higher gammacerane and Tm, indicating relatively high salinity in the Mahu Depression (Figure 5) [3].

Although there is little difference in the mass spectra of the source rocks in the two regions, there are differences in the ratio parameters (Table 2). Regarding water depth and salinity indicator parameters ETR and hopane index HHI ($C_{35}/\sum C_{31 \sim 35}$ homohopanes), the Western Halaalate area has low ETR and hopane index, while Mahu Depression has high ETR and honohopane index (Table 2), indicating salinity and aquatic environment differences. The former is shallower and has lower salinity than the latter, while the latter continues to sink and has deeper and higher salinity, which is consistent with the understanding of [11]. Moreover, the conversion of isomeric monomer Tm to Ts and C_{30} mortane to C_{30} hopane was inhibited in the high salinity environment Thus, a low Ts/Tm ratio and the ratio of C_{30} mortane to C_{30} hopane can indicate highly saline water bodies [3].

Considering that biodegradation can produce C_{29} nor-hopane in crude oil samples, a new gammacerane index (gammacerane/($2 \times C_{29}$ norhopane)) was introduced to indicate the water environment of parent material for biodegraded crude oil [8]. The source rocks of Mahu Depression exhibit high salinity characteristics. Although the source rocks in Western Halaalate also exhibit high salinity characteristics, they are inferior to the former.

4.1.4. Aromatics and Carbon Isotopes.

Biodegradation is a quasistepwise process in which aromatic hydrocarbon molecular markers are biodegraded only after n-alkanes, most simple branched alkanes, and some alkylbenzene has been consumed [14–16]. The Carboniferous crude oil in the study area experienced mild to moderate biodegradation, but aromatic components remained largely intact.

Comparing the mass spectra of aromatic hydrocarbons in crude oil and source rock samples (Figure 6) revealed that the composition of naphthalene compounds in crude oil samples changed slightly. In contrast, the composition of naphthalene, methyl naphthalene, and dimethyl naphthalene compounds with a low carbon number changed exceptionally slightly. Tetramethylnaphthalene, with the highest molecular weight, had the strongest resistance to biodegradation, as evidenced by the nearly unchanged content. This result is consistent with the findings of Yuan and Bao [17], namely, that the higher the number of methyl groups, the stronger the antidegradation ability of methyl naphthalene, and vice versa. Xiang et al. [18] also believed that the antidegradation ability of alkyl naphthalene is ranked as naphthalene < methyl naphthalene < dimethyl naphthalene < trimethyl naphthalene.

Phenanthrene compounds are more resistant to biodegradation than naphthalene compounds [1]. Although the crude oil samples have undergone biodegradation, the composition configuration has not changed significantly compared to the source rock samples. The methyl phenanthrene composition configuration of the Carboniferous crude oil samples from well Hq 6 and well Fn 4 is very similar. Therefore, it is challenging to determine the source of Carboniferous crude oil solely through spectral comparison. Therefore, a series of parameter crossplots were used to determine the source of the crude oil.

As a result of their stable chemical structure, aromatic sterane components are highly resistant to biodegradation. Under normal conditions, only severe degradation or biodegradation can cause component changes [3]. Connan [19] discovered that C_{20} and C_{21} triaromatic sterane components were absent in severely biodegraded oil, whereas the remaining triaromatic sterane components were largely unaffected. As shown in Figure 6, compared to samples of hydrocarbon source rocks, the triaromatic sterane configuration of the Carboniferous oil samples, which underwent mild to moderate biodegradation, exhibits almost no change in each monomer composition and is comparable to hydrocarbon source rock samples in both regions of Western Halaalate and Mahu. As a result, the distribution of aromatic sterane components cannot be used to determine the source of crude oil.
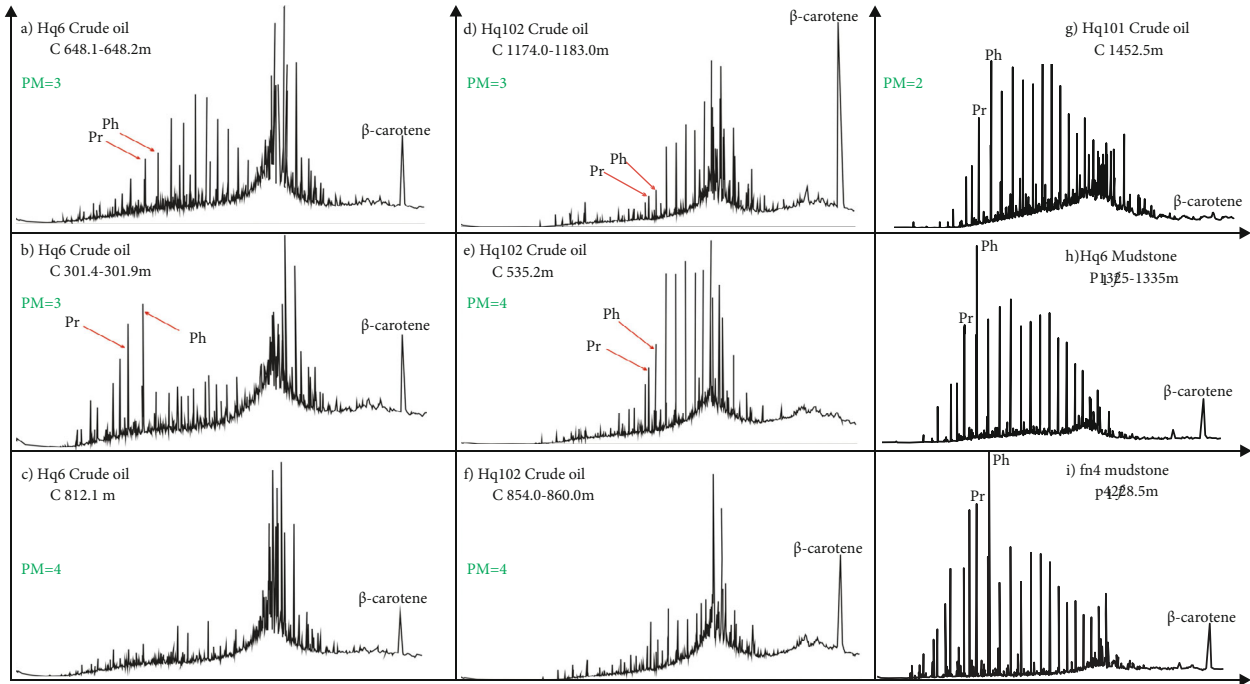
FIGURE 4: Gas chromatogram of the source rocks and biodegraded oils from Western Halaalate and Mahu Depression.
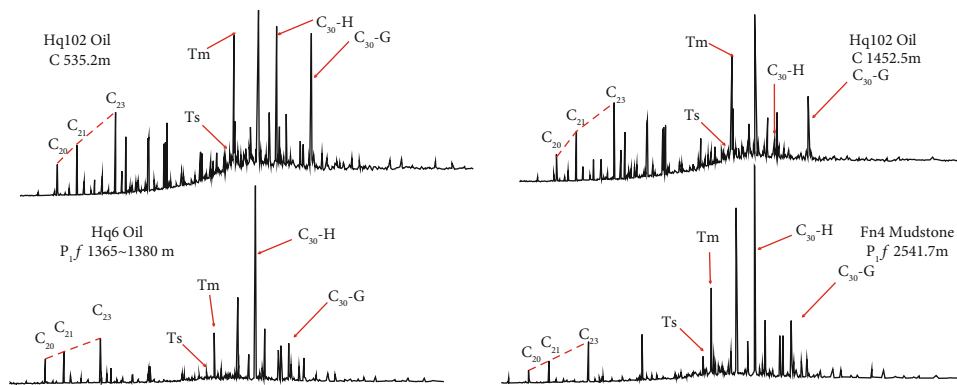

FIGURE 5: The m/z 191 mass chromatograms of biodegraded oil samples and mudstone samples from Western Halaalate and Mahu Depression.
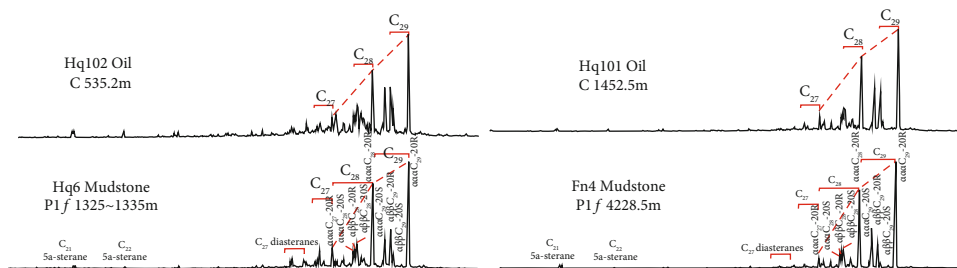

FIGURE 6: The m/z 217 mass chromatograms of biodegraded oil samples and mudstone samples from Western Halaalate and Mahu Depression.
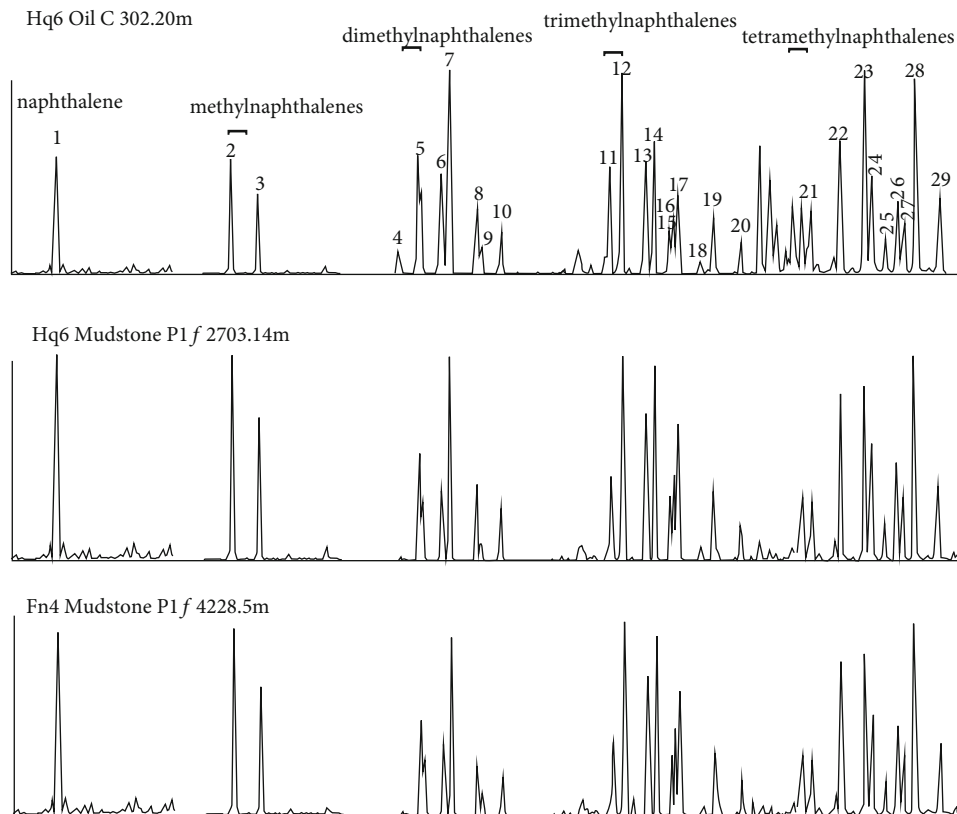
FIGURE 7: Naphthalene mass chromatograms of biodegraded oil and mudstone samples from Western Halaalate and Mahu Depression. 1 = naphthalene; 2 = 2-methyl naphthalene; 3 = 1-methyl naphthalene; 4~10 are dimethyl naphthalene series; 11~20 are trimethyl naphthalene series; 21~27 are tetramethylnaphthalene series.

4.2. Oil-Source Rock Correlation.

The strong tectonic movement pushed the deep Carboniferous system into the shallow layer, so that the crude oil samples in the Carboniferous system experienced mild to moderate biodegradation, and the chromatograms lost contrast effect (Figure 4). However, the biodegradation did not have much influence on the configuration of tricyclic terpanes, pentacyclic triterpenes, steranes, and aromatics (Figures 5–8). The distribution of Carboniferous crude oil samples is similar to that of source rock samples in two regions. Therefore, the source of crude oil cannot be determined only by mass spectrometry. For example, Liu et al. [13] argued that both of the Permian mudstone under the thrust belt in the Western Halaalate area and the mudstone in the Mahu Depression could be the source of oil in the study area. By studying the distribution characteristics of tricyclic terpenes of crude oil and source rocks C_{20}, C_{21}, and C_{23} in the Western Halaalate area, it is found that the crude oil found in the Western Halaalate area is generally in ascending type, which is consistent with the source rock of Fengcheng Formation in the previous studies. This study applied parameters reflecting salinity environment and thermal maturity to conduct oil-source correlation, and the effects of oil migration on geochemical parameters are also taken into account.

4.2.1. Pentacyclic triterpene and Steranes.

Crossplots of maturity parameters $C_{29} - \beta\beta/(\alpha\alpha + \beta\beta)$ and $\alpha\alpha\alpha - 20S/(20$ S + 20R) are frequently used to describe the maturity of source rocks or crude oil [20]. However, biodegradation has a significant influence on it. Rullkötter and Marzi [21] found that both biodegradation and high salinity effects could cause higher $\beta\beta/(\alpha\alpha + \beta\beta)$ ratios. As shown in Figure 9(a), the $\beta\beta/(\alpha\alpha + \beta\beta)$ ratios of the Carboniferous crude oil samples are larger than that of the source rock samples in the Western Halaalate area, indicating that the oil is more likely to be derived from the local source rock in the Shanxi area.

The ratio of $Tm/(T_S + T_m)$ decreases as the rate of biodegradation increases [22], but T_m with poor thermal stability is more resistant to biodegradation than T_S, which is consistent with the previous conclusion that T_m has a more remarkable ability to resist microbial erosion than T_S [23]. Here, the T_S/T_m ratios of crude oil samples are slightly higher than that of source rocks in the Mahu Depression and lower than that of source rocks in the Hashanxi area. The 22R and 22S isomers of C_{31} homohopanes have similar ability to resist biodegradation, while S-type is slightly stronger [21]. The ratios in the crude oil samples are higher than that in the Western Halaalate mudstones, as shown in Figure 9(b), indicating that the Western Halaalate mudstones are more likely to be the source rocks for the oil.

C_{19}-C_{35} tricyclic terpanes are highly resistant to biodegradation and can be found even after the degradation of all hopanes [3]. The C_{24}/C_{26} ratio of the source rock samples
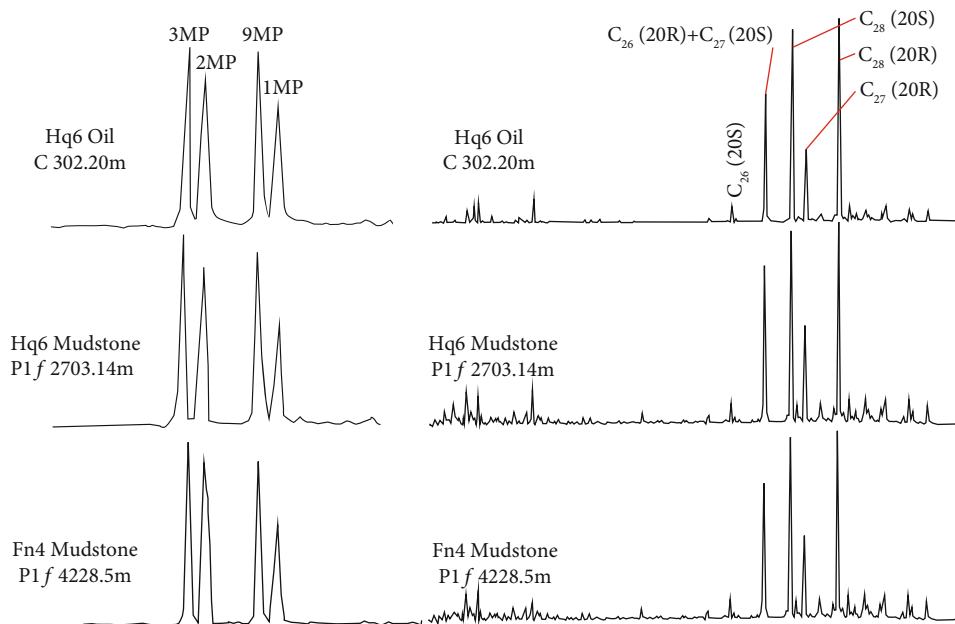
FIGURE 8: Phenanthrene and aromatic sterane mass chromatograms of biodegraded oil and mudstone samples from Western Halaalate and Mahu Depression.

in Mahu is >0.9, whereas it is <0.9 for the source rock and crude oil samples in Western Halaalate. Therefore, as shown in Figure 9(c), it is assumed that the Carboniferous oil may originate from the local source rocks.

Deep water and a high salinity water environment may inhibit the transformation of C_{30} mortane to C_{30} hopane [24]. Therefore, a low C_{30} mortane/C_{30} hopane ratio is frequently used to denote water with high salinity. The two ratios in the hydrocarbon source rocks of Mahu Depression are small: C_{30} mortane/C_{30} hopane ratio is <0.3, while C_{29} normortane/C_{29} norhopane ratio is <0.2. Both of the ratios for the crude oil and source rock samples are slightly higher in the Western Halaalate area because of its shallow water environment and denudation geohistory, as shown in Figure 9(d). The C_{29} norhopanes were used to replace C_{30} hopane in the gammacerane index as the new gammacerane index = gammacerane/($2 \times C_{29}$ norhopane) in a previous study [25], which was considered to be more accurate in reflecting the water environment of parent material for biodegraded oil. In this paper, this parameter was used to cross with gammacerane/C_{31} homoopane, and the result showed that the crude oil and source rock samples from the two regions can be distinguished by the boundary of 1.18 for the gammacerane/C_{31} homoopane and the boundary of 0.4 for new gammacerane index, which classified the samples from the two regions into two different ranges.

Connan discovered that the ability of 17α and 21β hopanes (e.g., hopane, norhopane, and hopane) against degradation increases with carbon number [19]. Consequently, the ratio of 22S/(22S + 22R) with a high carbon number tends to have a stronger resistance to biodegradation, roughly equal to 0.58 of the $C_{34} - 22S/(22S + 22R)$ ratio, which divides the samples from the two areas into

two ranges, and the ratio of petroleum samples is slightly higher than that of source rock samples, as shown in Figure 9(f).

4.2.2. Aromatic Hydrocarbon. The distribution characteristics of naphthalene and alkyl naphthalene frequently exhibit a clear rule due to biodegradation [3], and it has been frequently used in oil-source rock correlation of biodegraded oil. Volkman et al. [15] and Connan [19] began researching on the alkyl naphthalene with low carbon number in the 1980s, focusing primarily on the resistance of methyl naphthalene and dimethyl naphthalene isomers to biodegradation. Fisher et al. [26] investigated the trimethyl naphthalenes and tetramethylnaphthalenes and discovered that alkyl naphthalene with methyl-substituted at the 6-position has the weakest ability to resist biodegradation, whereas the other naphthalene components were almost unaffected. In the crossplot of aromatic hydrocarbon ratios, there is a significant difference between oil samples and the mudstones from Western Halaalate and Mahu Depression. The ratio of 2-/1-methyl naphthalene at the boundary of 1.1 can be used to distinguish samples from the two regions, and the ratio decreases with the increase of biodegradation degree (Figure 10(a)).

Bennett and Larter [14] and Xiang et al. [18] found that in the biodegradation process, the sequence of methyl phenanthrene isomer alteration is as follows: 2-methyl, 1-methyl phenanthrene, 3-methyl-Philippine, and 9-methyl; that is, 9-methyl phenanthrene has the strongest resistance to degradation. Therefore, biodegradation will increase the ratio of 9-/1-methyl phenanthrene and decrease the ratio of 2-/1-methyl phenanthrene in the methyl phenanthrene series. This law is also found in the studied samples, as shown in Figure 10(b). Samples from the two regions fall into
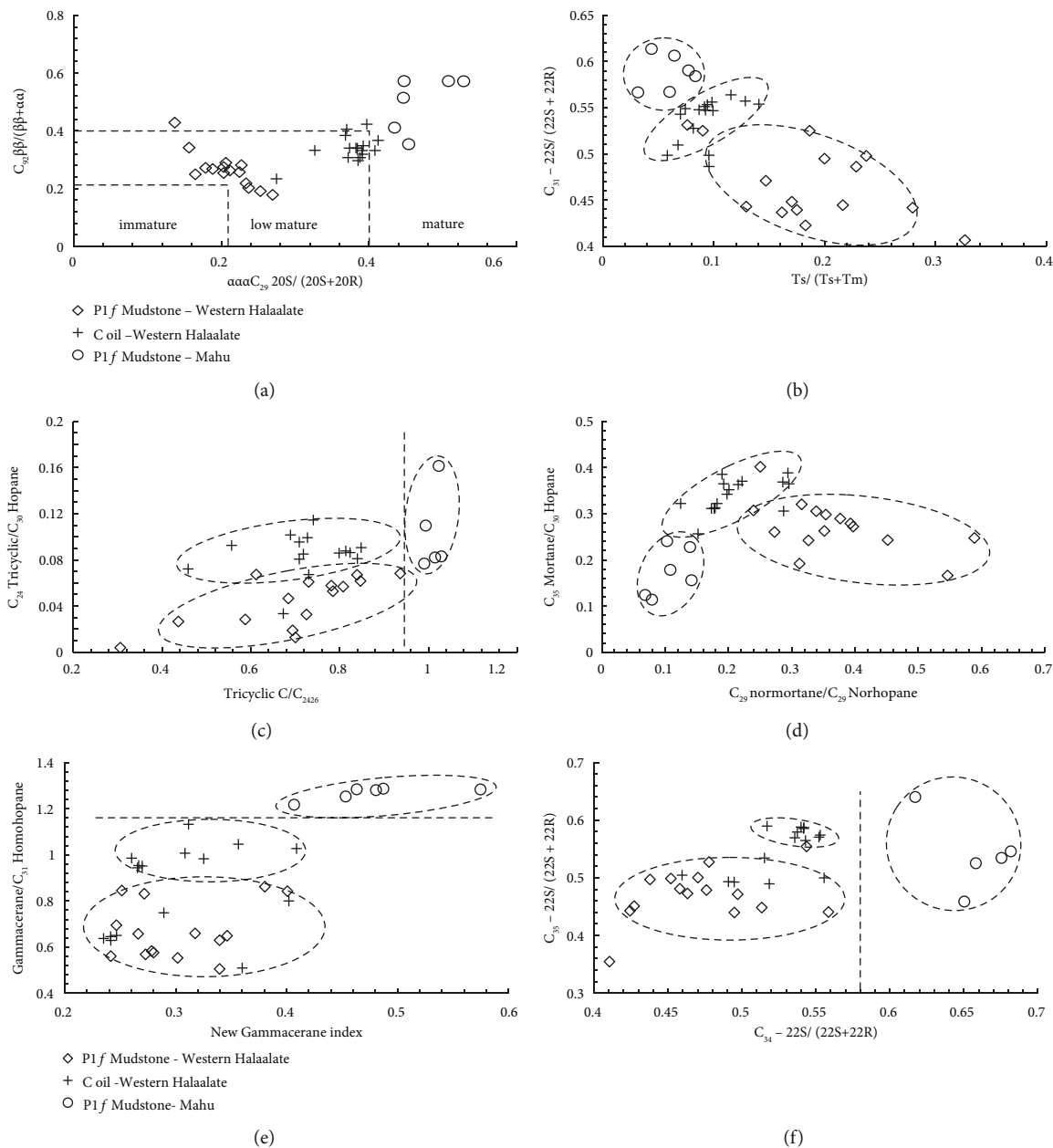
(a)

(b)

(c)

(d)

(e)

(f)

Figure 9: Terpane and sterane crossplot of biodegraded oil and mudstone samples from Western Halaalate and Mahu Depression.

different ranges with the boundary values of 9-/1-methyl phenanthrene ratio and 2-/1- methyl phenanthrene ratio as 2.0. The ratios of crude oil and source rock samples from the Western Halaalate region are smaller than those from the Mahu region, and the ratios of 2-/1-methyl phenanthrene of the Carboniferous oil samples are smaller than those of source rock samples. Yu [27] discovered that the phenanthrene components with higher carbon number are more resistant to degradation. The ratios of phenanthrene compounds with stronger resistance to degradation also can be used in distinguishing crude oil from the two regions (Figures 10(c) and 10(d)), and samples of different degradation levels changed regularly.

Under normal conditions, even severe biodegradation does not affect the constituents of aromatic steranes, but

under certain extreme conditions, the ratio of constituents will be slightly altered [26]. Since then, numerous scholars have backed this viewpoint. For example, Connan and Fisher et al. [19, 26] discovered that the C_{20}/C_{21} ratio of triaromatic steranes tends to rise during severe biological decomposition. Therefore, biodegradation will make C_{19}-/C_{20} triaromatic steranes, C_{20}-/C_{21} triaromatic steranes, C_{21}-/C_{22} triaromatic steranes, and C_{21}~22-/C_{26}~28 triaromatic steranes which all exhibit a decreasing trend. These ratios of Carboniferous crude oil samples are significantly lower than those of the Western Halaalate source rock samples and also significantly different from those from Mahu Depression (Figures 10(e) and 10(f)).

In conclusion, the influence of biodegradation on the parameters of aromatic hydrocarbons suggests that the
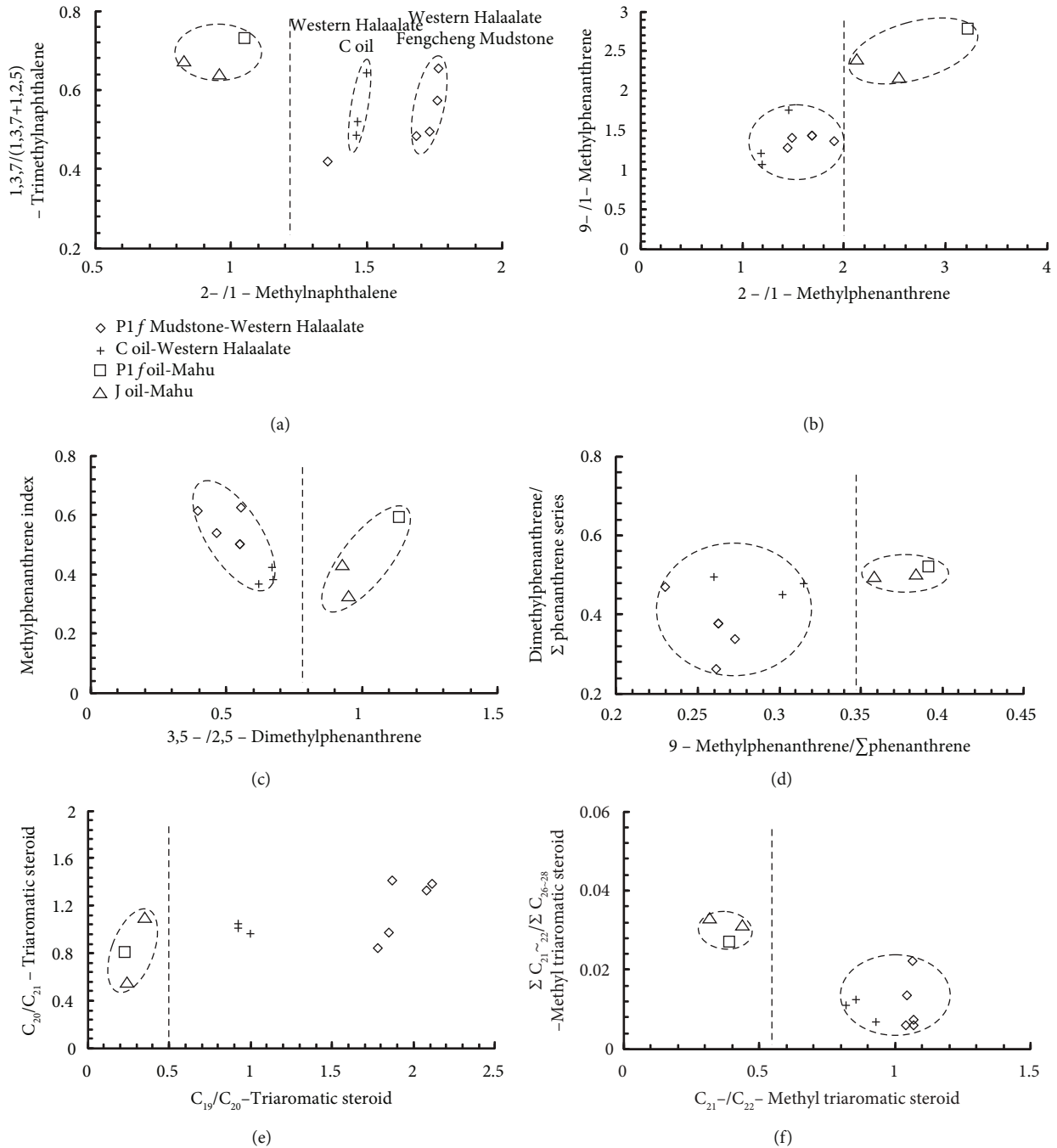
FIGURE 10: Aromatic hydrocarbon crossplots of biodegraded oil and mudstone samples from Western Halaalate and Mahu Depression.

Carboniferous crude oil is derived from the local Western Halaalate source rock.

4.2.3. Migration Parameters. Due to the selective adsorption of mineral grains during the migration process, small molecule compounds have priority into the reservoir rock; thus, some parameters can be used to represent the migration of oil, such as $\sum$tricyclic terpanes/$\sum$pentacyclic terpenes, C_{19}terpanes/C_{35} hopanes, and pregnanenorpregnane/C_{27-29} regular steranes, and these ratios increase as migration distance increases [28]. Therefore, if the Carboniferous oil in

the Western Halaalate region is sourced from local source rocks, this should be characterized by short migration distances and limited migration effect.

As shown in Figure 11, the range of $\sum$tricyclic terpanes/$\sum$pentacyclic terpenes of source rocks in wells Fn 1, Fn2, Fn3, and Fn4 in Mahu Depression is 0.23–0.32, while the ratios of wells Fc 1, F15, Wu 2, Wu 3, and Wu 4 are 0.73–2.46, showing an increasing trend and reflecting the influence of the migration effect. However, the ratios of wells Hq 3, Hq 6, Hq 101, and Hq 102 ranged from 0.23 to 0.95, and the ratio values of deep samples were all less than 0.3.
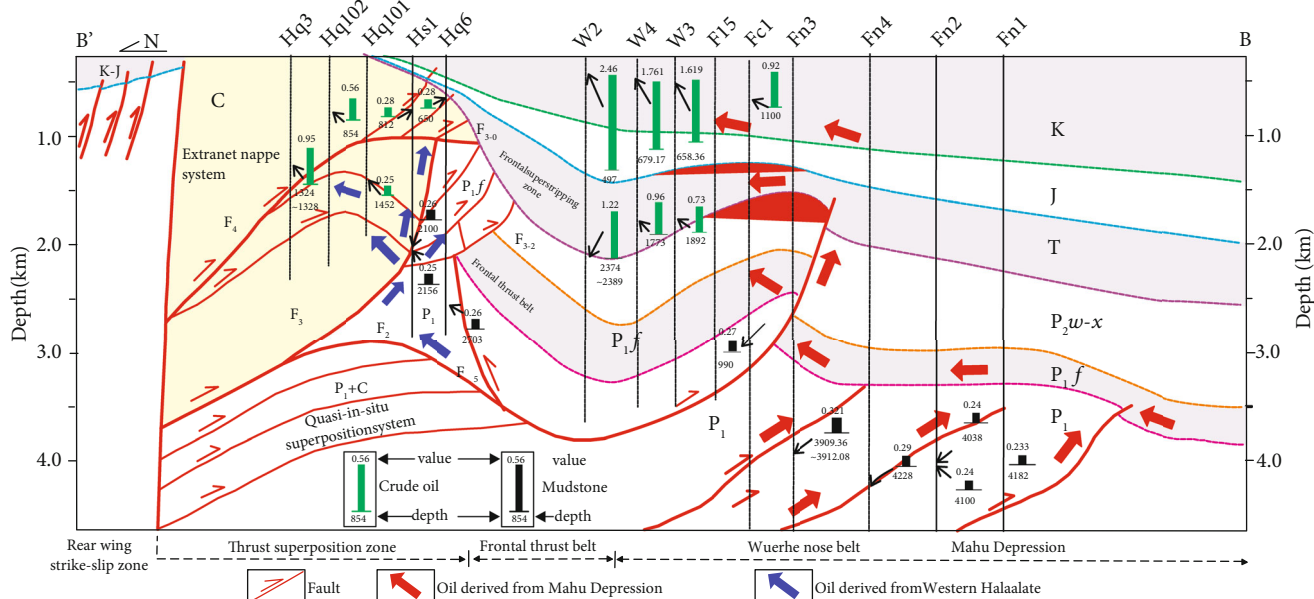
FIGURE 11: The distribution of parameter ∑tricyclic terpanes/∑pentacyclic terpanes in the profile showing migration direction. The section was marked by B-B' in Figure 1(c).

There is no obvious long-distance migration effect, which also rules out the possibility of oil migrating from Mahu Depression, indirectly confirming that the Carboniferous crude oil system is supplied by the local source rock of Fengcheng Formation in the Western Halaalate.

5. Conclusion

The vitrinite reflectance of source rocks of the Permian Fengcheng Formation in Mahu Depression is greater than 1.3% and has entered the high mature stage of condensate oil and moisture gas. The source rock of the Permian Fengcheng Formation in the Western Halaalate area is in the mature stage with Ro of 0.79%~1.13%. The former is of higher maturity, but both of them belong to medium- to good-quality source rocks.

Numerous parameters reflecting water depth and salinity such as ETR and hopane index HHI ($C_{35}/\sum C_{31\sim35}$ homohopanes), $Ts/(Ts + Tm)$, and gammacerane index (gammacerane/($2 \times C_{29}$ norhopane)) indicated that the Permian Fengcheng source rocks of Mahu Depression exhibit high salinity and deeper water depth compared with the Permian Fengcheng source rocks in the Western Halaalate.

The compounds in the chromatogram of Carboniferous crude oil were reduced, and the hump of the chromatographic baseline was prominent. The n-alkanes, alkylcyclohexanes, and isoprenoids of the crude oils are altered to different degrees, and according to the PM scale, the biodegradation level of these oil samples is between PM2 and PM4, which belonged to mild to moderate biodegradation.

Compared with the mass spectrometry, it is found that biodegradation has little effect on the conventional parameters such as terpenes and steranes, and even less effect on the aromatic parameters, which all show a certain regularity. Combined with previous studies and considering the salinity

of water, maturity, and other factors, it is concluded that the Carboniferous crude oil comes from the local source rock of the Fengcheng Formation in the Western Halaalate area. The results show that the salinity parameter gammacerane index can distinguish different source rocks and has a strong ability to resist biodegradation, which can be used in the oil-source correlation of general degraded crude oil.

The results of this paper show that considering the migration effect is an effective complementary method for oil-source correlation. It is found that there is almost no migration effect in the samples from the Western Halaalate area, while the samples from Mahu Depression have an obvious migration effect to Fengcheng oilfield, which rules out the possibility of hydrocarbon supply from Mahu Depression and indirectly proves that the Carboniferous crude oil in study area comes from the local source rock of Fengcheng Formation in Hashanxi. It has a good guiding function for the cognition of hydrocarbon accumulation law in the northwest margin of Junggar Basin.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

References

[1] T. Hu, Y. Liu, F. Jiang et al., "A novel method for quantifying hydrocarbon micromigration in heterogeneous shale and the controlling mechanism," *Energy*, vol. 288, article 129712, 2024.

[2] T. Hu, X. Pang, and F. Jiang, "Whole petroleum system theory and new directions for petroleum geology development," *Advances in Geo-Energy Research*, vol. 11, no. 1, pp. 1–5, 2024.

[3] K. E. Peters and J. M. Moldowan, *The Biomarker Guide Interpreting Molecular Fossils in Petroleum and Ancient Sediments*, PRENTICE HALL, Englewood Cliffs, 2005.

[4] L. M. Wenger, C. L. Davis, and G. H. Isaksen, "Multiple controls on petroleum biodegradation and impact on oil quality," *SPE Reservoir Evaluation & Engineering*, vol. 5, no. 5, pp. 375–383, 2002.

[5] N. J. L. Bailey, H. R. Krouse, and C. R. Evans, "Alteration of crude oil by waters and bacteria evidence from geochemical and isotope studies," *AAPG Bulletin*, vol. 57, no. 7, pp. 1276–1290, 1973.

[6] S. Larter, H. Huang, J. Adams, B. Bennett, and L. R. Snowdon, "A practical biodegradation scale for use in reservoir geochemical studies of biodegraded oils," *Organic Geochemistry*, vol. 45, pp. 66–76, 2012.

[7] A. Holba, L. Ellis, L. Dzou, and A. Hallam, "Extended tricyclic terpanes as age discriminators between Triassic, Early Jurassic and Middle-Late Jurassic oils," Nancy: 20th International Meeting on Organic Geochemistry, 2001.

[8] J. Tian, H. Zou, and C. Xu, "The application of ETR in the comparison of severe bio degradable oil sources-the JX1-1 oilfield in Liaodong Bay area," *Journal of Oil and Gas Technology*, vol. 33, pp. 19–23, 2011.

[9] T. Hu, Z. Chen, X. Dong et al., "Oil origin, charging history and crucial controls in the carboniferous of western Junggar Basin, China: formation mechanisms for igneous rock reservoirs," *Journal of Petroleum Science and Engineering*, vol. 203, article 108600, 2021.

[10] S. Ma, D. Zhang, and Z. Jin, "The advances in the geochemistry of the biodegraded oil," *Advances in Earth Science*, vol. 20, no. 4, pp. 449–454, 2005.

[11] S. Zhang, "Identification and its petroleum geologic significance of the Fengcheng Formation source rocks in Hala'alt area, the northern margin of Junggar Basin," *Oil & Gas Geology*, vol. 34, no. 2, pp. 145–152, 2013.

[12] K. E. Peters and J. M. Moldowan, *The Biomarker Guide: Interpreting Molecular Fossils in Petroleum and Ancient Sediments*, Prentice Hall, Englewood Cliffs, New Jersey, 1993.

[13] C. Liu, X. Wang, and W. Xi, "Exploration breakthrough inspirations of Chunhui oilfield in the northern Junggar Basin," *Advances in Geosciences*, vol. 2, p. 24, 2012.

[14] B. Bennett and S. R. Larter, "Biodegradation scales: applications and limitations," *Organic Geochemistry*, vol. 39, no. 8, pp. 1222–1228, 2008.

[15] J. K. Volkman, R. Alexander, R. I. Kagi, S. J. Rowland, and P. N. Sheppard, "Biodegradation of aromatic hydrocarbons in crude oils from the Barrow sub-basin of Western Australia," *Oganic Geochemistry*, vol. 6, pp. 619–632, 1984.

[16] O. P. Strausz, T. W. Mojelsky, F. Faraji, E. M. Lown, and P. Peng, "Additional structural details on Athabasca asphaltene and their ramifications," *Energy & Fuels*, vol. 13, no. 2, pp. 207–227, 1999.

[17] L. Yuan and J. Bao, "The effect of biodegradation on the distribution and composition of alkylnaphthalene series in biodegraded crude oils," *Petroleum Geology & Experiment*, vol. 31, no. 5, pp. 512–517, 2009.

[18] T. Xiang, F. Ma, and K. Pan, "Effect of mild-to-moderate biodegradation on alkyl naphthalene and alkyl phenanthrene in crude oil," *Journal of Xi'an Petroleum University*, vol. 27, no. 1, pp. 81–86, 2012.

[19] J. Connan, "Biodegradation of crude oils in reservoirs," in *Advances in Petroleum Geochemistry*, J. Brooks and D. H. Welte, Eds., pp. 299–335, Academic Press, London, 1984.

[20] W. K. Seifert and J. M. Moldowan, "Use of biological markers in petroleum exploration," *Methods in Geochemistry and Geophysics*, vol. 24, pp. 261–290, 1986.

[21] J. Rullkötter and R. Marzi, "Natural and artificial maturation of biological markers in a Toarcian shale from northern Germany," *Organic Geochemistry*, vol. 13, no. 4-6, pp. 639–645, 1988.

[22] A. G. Douglas, J. S. Damsté, M. G. Fowler, T. I. Eglinton, and J. W. D. Leeuw, "Unique distributions of hydrocarbons and sulphur compounds released by flash pyrolysis from the fossilised alga Gloeocapsomorpha prisca, a major constituent in one of four Ordovician kerogens," *Geochimica et Cosmochimica Acta*, vol. 55, no. 1, pp. 275–291, 1991.

[23] X. Cheng, D. Hou, C. Xu, and F. Wang, "Biodegradation of tricyclic terpanes in crude oils from the Bohai Bay Basin," *Organic Geochemistry*, vol. 101, pp. 11–21, 2016.

[24] B. J. Kimble, *The Geochemistry of Triterpenoid Hydrocarbons*, Univ. of Bristol, 1972.

[25] S. Li, S. Hu, S. He et al., "Oil-source correlation for bio degraded oils in the north slope of the Biyang Depression," *Acta Petrolei Sinica*, vol. 31, pp. 946–951, 2010.

[26] S. J. Fisher, R. Alexander, R. I. Kagi, and G. A. Oliver, "Aromatic hydrocarbons as indicators of biodegradation in North Western Australian reservoirs," *The Sedimentary Basins of Western Australia*, vol. 2, pp. 185–194, 1998.

[27] C. Yu, *Geochemical Characterization of the Impact of Seconday Alteration on 1Iarine Origin Oil from Northern Uplift of the Tarim Basin*, China University of Geosciences, Beijing, 2013.

[28] D. Leythaeuser, A. S. Mackenzie, R. G. Schaefer, and U. Bunyarit, "A novel approach for recognition and quantification of hydrocarbon migration effects in shale-sandstone sequences," *AAPG Bulletin*, vol. 68, pp. 196–219, 1984.

[29] L. Ma, Y. Zhang, Z. Zhang, G. Zhang, and S. Wang, "The geochemical characteristics of the Fengcheng Formation source rocks from the Halaalate area, Junggar Basin, China," *Journal of Petroleum Science and Engineering*, vol. 184, article 106561, 2020.