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Source of the Jurassic Oil in the Western Mahu Sag of Junggar Basin, NW China

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In recent years, important breakthroughs have been made in the exploration of the northwestern margin of Mahu sag in Junggar basin. The estimated amount of oil deposits in this region seems to be as large as 100-million-ton lithologic reservoir. A certain scale of oil reservoirs was found in the Jurassic Badaowan formation, which indicates that the Jurassic reservoir has promising prospects for exploration. The geochemical characteristics of Jurassic crude oil and Permian source rocks and oil accumulation factors are studied in this paper. The results show that carbon isotope values ($\delta^{13}\text{C}$) and the biomarker parameters ($\gamma/\text{C}_{30}\text{H}$ and $\text{C}_{24}\text{Tet}/\text{C}_{26}\text{TT}$) have a good application in oil source correlation. Crude oil in Jurassic reservoir was generated from Permian Fengcheng (P_{1f}) source rock. The main hydrocarbon expulsion period of the P_{1f} source rock was between late Permian and middle Cretaceous. The crude oil migrated upward into the Jurassic lithologic traps through faults or superimposed sand bodies.

Keywords

Geochemistry, Permian source rock, Oil source correlation, Jurassic reservoir, Junggar basin, Accumulation mechanism

1. Introduction

The Junggar basin is the second-largest inland basin in China, with a lot of oil and gas resources. The Mahu sag is a sub-order negative tectonic unit in the northwest of the central depression of Junggar basin. In recent years, continuous exploration breakthroughs have been made, showing a good development prospect. Oil and gas are most abundant in the northwestern margin of the Mahu sag. In particular, since 2012 Xinjiang Oilfield Company of PetroChina has stepped up its exploration of the western margin of the Mahu sag, and made a major breakthrough in Triassic Baikouquan formation (T_{1b}), forming a 100-million-t quasi continuous lithologic reservoir. During this process, a certain scale of oil and gas reservoirs has also been found in the Jurassic reservoir, such as well AH8, well AH11, well AH12 and well M26, which have good oil and gas display in the Jurassic Badaowan reservoir (J_{1b}), indicating that the Jurassic reservoir also has good exploration and development prospects.

At present, it is believed that the main source rocks

of the Mahu sag are distributed in the Jiamuhe Formation (P_{1j}), Fengcheng Formation (P_{1f}) and lower Wuerhe Formation (P_{2w}) of the Permian system. They have high organic matter abundance, have reached the mature stage, and have good hydrocarbon generation potential^{1)~3)}. In the past studies on the source of oil in the western margin of the Mahu sag, scholars held different views. Chen *et al.* (2016) and Yu *et al.* (2018) held that the crude oil in the west slope of the Mahu sag originated from the P_{1f} source rock^{2),3)}, while Hang *et al.* (2016) thought that the crude oil was the mixture of P_{1j} and P_{2w} source rock⁴⁾. Some scholars suggested that all the three sets of source rocks of Permian system have contributed to the crude oil^{1),5)}. Therefore, the source of crude oil in Jurassic reservoir in the western margin of the Mahu sag need further study.

This paper studies the geochemical characteristics of P_{1j}, P_{1f} and P_{2w} source rocks and J_{1b} crude oil in the west slope of the Mahu sag. By comparing and analyzing the oil sources, the source of Jurassic crude oil in the western margin of the Mahu sag is clarified. On this basis, the oil accumulation factors in the west margin of the Mahu sag is combed, and the accumulation mechanism of Jurassic crude oil in the west margin of the Mahu sag is put forward.

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Fig. 1 Location of Study Area (a) and Stratigraphic Column Chart (b)

2. Geological Background

Junggar basin is located in Xinjiang Uygur Autonomous Region of China, at the junction of Siberian plate, European plate and Tarim plate, and is an important part of Central Asia orogenic belt^(6,7). Its northwest boundary is Hala'alat mountains and Zaire mountains, covering an area of about 130,000 km². The Mahu sag is located in the northwest of Junggar basin, with a northeast-southwest distribution and an area of about 5000 km²^(8,9). The west margin of the Mahu sag is adjacent to orogenic belt, which is accompanied by Wuxia, Kebai and Hongche faults zones from north to south. These fault zones control the tectonic morphology of the west margin of the Mahu sag, and the north-western margin of the Mahu sag can be divided into 3 slopes—northern, western and southern slope based on the geological morphology. Most of the study area in this paper is within the range of western slope (Fig. 1a).

Strata from bottom to top of the study area from Permian to Jurassic are Paleozoic Permian Jiamuhe Formation (P_{1j}), Fengcheng Formation (P_{1f}), Xiazijie Formation (P_{2x}), lower Wuerhe Formation (P_{2w}) and upper Wuerhe Formation (P_{3w}); Mesozoic Triassic Baikouquan Formation (T_{1b}), lower Karamay Formation (T_{2k₁}), upper Karamay Formation (T_{2k₂}) and Baijiantan Formation (T_{3b}); Mesozoic Jurassic Badaowan

Formation (J_{1b}), Sangonghe Formation (J_{1s}), Xishanyao Formation (J_{2x}) and Toutunhe Formation (J_{2t}) (Fig. 1b). Among them, the thickness of P_{1j} source rock is 50-225 m, with medium-high abundance of organic matter, and the organic matter type is humic (mainly type II-III kerogen). It has evolved to a high-maturity stage, mainly gas generation^(1,2,8). The thickness of P_{1f} source rock is 50-300 m, with high abundance of organic matter, whose type of kerogen is mainly type II, and there are also a small part of type I kerogen. It is currently in the mature stage and possesses excellent hydrocarbon generation ability^(1,2,8). The thickness of P_{2w} source rock is 50-250 m, with medium abundance of organic matter, and the type of organic matter is mainly type II. The evolution degree of P_{2w} source rock is relatively low, and the hydrocarbon generation potential is relatively limited^(1,2,8).

The Permian in Mahu sag was generally in a transitional sedimentary environment between marine and lacustrine facies^(10~12). The P_{1j} period was a semi closed marine environment accompanied by volcanic activities. In the P_{2w} period, Mahu sag had been completely transformed into a terrestrial freshwater lake basin. The sedimentary environment of P_{1f} was in the transitional stage between P_{1j} and P_{2w}. Matched with the sedimentary environment, there are mainly brown mudstone, volcanic tuff and conglomerate in P_{1j} stratum. Black mudstone, tuff and argillaceous dolomite

Table 1 Biomarker Compound of Source Rocks and Crude Oil in the Study Area

Member	Well	Depth [m]	Isoprene alkanes (TIC)			Terpane compounds (m/z 191)		Sterane compounds (m/z 217)		
			Pr/Ph	Pr/ <i>n</i> -C17	Ph/ <i>n</i> -C18	C24Tet/ C26TT	γ /C ₃₀ H	C27 [%]	C28 [%]	C29 [%]
J ₁ b	AH8	2068.96	1.26	0.84	0.80	0.36	0.23	24.44	34.81	40.74
	AH11	1856.35	1.14	0.72	0.72	0.50	0.36	25.08	33.88	41.04
	AH12	2438.56	1.25	0.77	0.73	0.43	0.24	21.83	31.69	46.48
	AH15	2382.33	1.13	0.75	0.76	0.50	0.34	22.38	34.97	42.66
P ₂ w	AC1	4359.15	1.79	0.71	0.79	1.77	0.09	26.83	26.22	46.95
		4403.72	1.40	0.61	0.70	1.27	0.15	23.03	16.36	60.61
		5048.93	1.28	0.94	1.06	1.51	0.24	30.83	28.33	40.83
P ₁ f	X40	4567.84	1.16	0.83	0.66	0.49	0.14	22.46	30.43	47.10
		4579.54	1.12	0.77	0.65	0.55	0.15	18.60	34.11	47.29
		4638.35	1.21	0.75	0.68	0.43	0.29	19.40	33.58	47.01
P ₁ j	FC1	5952.66	1.04	0.77	0.74	0.79	0.63	14.06	31.25	54.69
		5962.31	1.03	0.92	0.88	0.78	0.68	13.85	32.31	53.85
		6032.75	1.07	0.84	0.85	0.71	0.63	13.95	31.78	54.26

Note: Pr, Ph, TT, Tet, H and γ respectively represent pristane, phytane, tricyclic terpane, tetracyclic terpane, hopane, gammacerane.

are deposited in P₁f stratum. Black mudstone and gray-green conglomerate are mainly developed in P₂w stratum^{10)~12)}.

During the Jurassic stratigraphic sedimentary period, the sedimentary environment of the western margin of the Junggar basin was characterized by shallow water, multi-source, medium-high slope and long-distance river facies. Alluvial fans were confined to the edge of the basin, forming a river-lake system. From early to middle Jurassic, large shallow Braided River Delta and swamp were formed due to the wide lake basin and warm and humid climate¹³⁾. In particular, during the sedimentary period of the early Jurassic Badaowan Formation, the basin was flat and the average water depth was much shallower than that of the late Triassic. The shallow lake delta sand bodies developed in the large lake basin provided conditions for the development of lithologic reservoirs, affecting the main distribution and enrichment of oil producing zones¹⁴⁾.

3. Samples and Methods

A total of 13 samples were collected from study area, including 4 oil samples of J₁b Formation, 3 mudstone samples of P₂w Formation, 3 mudstone samples of P₁f Formation and 3 mudstone samples of P₁j Formation (See Fig. 1a and Table 2 for well location).

3.1. Rock Extraction Experiments

All rock samples were put in Soxhlet extractor and extracted with chloroform at 78 °C for 36 h. The extracts were put in rotary evaporator for concentration and dissolved with *n*-hexane. Then the mixture and J₁b crude oil will be centrifuged for 5 min in a centrifuge, and the supernatant was taken and separated by silica gel/alumina (3 : 2) chromatography column. The transparent liquid obtained by slowly dropping

25 mL of *n*-hexane into the column contains saturated hydrocarbons.

3.2. GC-MS Analysis

The separated saturated hydrocarbon components were analyzed by gas chromatography-mass spectrometry (GC-MS) with an Agilent 7890A/7000 GC/MS system. The analysis of *n*-alkanes and isoprenoid alkanes is based on the total ion-flow chromatogram (TIC), the analysis of terpenes is based on m/z 191 chromatogram, and the interpretation of sterane is based on m/z 217 chromatogram. The ratio of geochemical parameters of the samples was calculated according to the peak height. The peak identification in the chromatogram was based on the method described in Peters *et al.* (2005) and 5 β -cholestane was selected as the internal standard of saturated hydrocarbon fraction in GC-MS¹⁵⁾. The geochemical parameters used in this paper are shown in Table 1.

3.3. Carbon Isotope Analysis

The carbon isotope in extracts were determined using a Thermo Delta V mass spectrometer (MS) equipped with an Agilent 6890N GC. The stable carbon isotopic values were reported in δ notation in per mil (‰) relative to VPDB standard, whose analytical precision is within ± 0.3 ‰. The carbon isotope values ($\delta^{13}\text{C}$) used in this paper are shown in Table 2.

4. Results

4.1. Biomarker Characteristics of Source Rocks

The ratio of pristane (Pr) to phytane (Ph) is closely related to the sedimentary environment. It is generally believed that $\text{Pr/Ph} > 3$ reflects the oxidation environment, $\text{Pr/Ph} < 1$ reflects the reduction environment, and $1 < \text{Pr/Ph} < 3$ reflects the oxidation-reduction environment^{16),17)}. The Pr/Ph ratio of P₂w source rock is

Table 2 Carbon Isotope Characteristics of Source Rocks and Crude Oil in the Study Area

Member	Well	Depth [m]	$\delta^{13}\text{C}$ [‰]			Sample number
			bitumen "A"	saturated	aromatic	
J ₁ b	AH8	2068.96	−28.49	−28.40	−27.77	1
	AH11	1856.35	−28.39	−28.47	−27.92	2
	AH12	2438.56	−28.73	−29.01	−28.46	3
	AH15	2382.33	−28.61	−28.72	−28.26	4
P ₂ w	AC1	4359.15	−22.67	−23.78	−21.25	5
		4403.72	−21.15	−22.84	−20.32	6
		5048.93	−24.45	−24.95	−22.37	7
P ₁ f	X40	4567.84	−27.58	−27.65	−27.04	8
		4579.54	−27.66	−27.83	−27.36	9
		4638.35	−29.54	−29.61	−29.02	10
P ₁ j	FC1	5952.66	−24.57	−24.68	−24.13	11
		5962.31	−27.65	−27.54	−27.01	12
		6032.75	−26.73	−26.86	−26.15	13

between 1.28 and 1.79, with an average of 1.49. The Pr/Ph ratio of P₁f source rock is between 1.12 and 1.21, with an average of 1.16. The Pr/Ph ratio of P₁j source rock is between 1.03 and 1.07, with an average of 1.05 (Table 1). The above data shows that the three sets of source rocks are all formed in oxidation-reduction sedimentary environment, and the oxygen content of the water body gradually increases from P₁j source rock to P₂w source rock.

The C₂₄Tet/C₂₆TT (Tet stands for tetracyclic terpenes and TT for tricyclic terpane) ratio of P₂w source rock is between 1.27 and 1.77, with an average of 1.52; the γ /C₃₀H (γ stands for gammacerane and H for hopane) ratio is between 0.05 and 0.24, with an average of 0.16. The C₂₄Tet/C₂₆TT ratio of P₁f source rock is between 0.43 and 0.55, with an average value of 0.49; the γ /C₃₀H ratio is between 0.14 and 0.29, with an average value of 0.19. The C₂₄Tet/C₂₆TT ratio of P₁j source rock is between 0.71 and 0.79, with an average value of 0.76; the γ /C₃₀H ratio is between 0.63 and 0.68, with an average value of 0.65 (Table 1). It is generally believed that high C₂₄Tet reflects evaporation deposition environment^(18),19), while γ is an indicator of water column stratification, which is usually caused by high salinity vertically^(15),20),21). The content of C₂₄Tet in P₂w source rock is much higher than that in P₁f and P₁j source rocks, indicating that the climate was dry during the deposition of P₂w source rock. From P₁j source rock to P₂w source rock, the γ value decreases gradually, indicating that the water column stratification characteristics gradually weaken. Generally speaking, the stratification effect of sea water is more obvious than that of continental water. The characteristics reflected by γ are consistent with the sedimentary transformation from lacustrine facies to marine facies in Permian source rocks. These characteristics reflect that the high γ value in Permian source rocks in Mahu sag is caused by high salinity of seawater.

The distribution of steranes in P₂w source rock is

C₂₈ < C₂₇ < C₂₉. The distribution of steranes in P₁f and P₁j source rock is C₂₇ < C₂₈ < C₂₉ (Fig. 2 and Table 1). Steranes come from sterols in eukaryotes. The C₂₉ sterane content in the source rocks formed by the input of terrigenous higher plants is relatively high, while the C₂₇ sterane content in the source rocks formed mainly by plankton is relatively high. The high C₂₈ sterane content may represent the lacustrine and marine environment^(22),23). Judged from the ternary diagram of steranes C₂₇, C₂₈ and C₂₉ of the three sets of source rocks (Fig. 3), the organic matter of P₂w, P₁f and P₁j source rocks are mainly derived from terrestrial organisms.

4. 2. Biomarker Characteristics of Crude Oil

The Pr/Ph ratio of J₁b reservoir extracts is between 1.13 and 1.26, with an average value of 1.20 (Table 1), indicating that the source parent materials of J₁b crude oil were formed in an oxidation-reduction sedimentary environment. The C₂₄Tet/C₂₆TT ratio of J₁b reservoir extracts is between 0.36 and 0.50, with an average value of 0.45. The γ /C₃₀H ratio is between 0.23 and 0.36, with an average value of 0.29. It indicates that the source of J₁b crude oil possesses the features of weak evaporation and low salinity during the sedimentary process. Sterane distribution of J₁b crude oil is C₂₇ < C₂₈ < C₂₉ (Fig. 2 and Table 1). The ternary diagram of C₂₇, C₂₈ and C₂₉ steranes of J₁b crude oil shows that the source organic matter of J₁b crude oil were mainly deposited in terrigenous environment (Fig. 3).

4. 3. Carbon Isotope Characteristics

Source rocks and crude oil originated from different sources and developed in different environments have different kerogen carbon isotope compositions. Generally, lighter carbon isotopes reflect higher contribution of aquatic organisms and correspond to better organic matter types. On the contrary, heavier carbon isotopes reflect that terrigenous organisms contribute more, corresponding to worse organic matter types^(12),24),25). The

Fig. 2 m/z 217 Chromatogram of Typical Source Rocks and Crude Oil

Fig. 3 Ternary Diagram of Steranes C27, C28 and C29 of Source Rocks and Crude Oil on the Feng *et al.* (2020) Diagram⁸⁾

Fig. 4 Carbon Isotope Crossplot of Saturated Hydrocarbons and Aromatic Hydrocarbons in Source Rocks and Crude Oil on the Sofer (1984) Diagram²⁶⁾

$\delta^{13}\text{C}$ values of $\text{P}_{2\text{w}}$ source rocks ranges from -24.45 to -21.15 ‰, with average values of -22.76 ‰. The $\delta^{13}\text{C}$ values of $\text{P}_{1\text{f}}$ source rock ranges from -29.54 to -27.58 ‰, with average values of -28.26 ‰. The $\delta^{13}\text{C}$ values of $\text{P}_{1\text{j}}$ source rock ranges from -27.65 to -24.57 ‰, with average values of -26.32 ‰ (Table 2). The comparison shows that the contribution of aquatic organisms in $\text{P}_{1\text{f}}$, $\text{P}_{1\text{j}}$ and $\text{P}_{2\text{w}}$ source rocks decreases in sequence, while that of terrigenous organisms increases gradually. The $\delta^{13}\text{C}$ value of $\text{J}_{1\text{b}}$ crude oil ranges from -28.73 to -28.39 ‰, with an average value of -28.56 ‰, reflecting that $\text{J}_{1\text{b}}$ crude oil contains higher contribution of aquatic organisms.

Sofer (1984) once used carbon isotope characteristics of saturated hydrocarbon and aromatic hydrocarbon components in crude oil to predict whether the oil was derived from terrigenous organic matter or from marine organic matter^{26),27)}. The $\delta^{13}\text{C}$ values of saturated hydrocarbon and aromatic hydrocarbon in $\text{P}_{2\text{w}}$, $\text{P}_{1\text{f}}$ and $\text{P}_{1\text{j}}$

source rocks ranges from -24.95 to -22.84 ‰ and -22.37 to -20.32 ‰, -29.61 to -27.65 ‰ and -29.02 to -27.04 ‰, -27.54 to -24.68 ‰ and -27.01 to -24.13 ‰, respectively. The $\delta^{13}\text{C}$ values of saturated hydrocarbon and aromatic hydrocarbon in $\text{J}_{1\text{b}}$ crude oil ranges from -29.01 to -28.40 ‰ and -28.46 to -27.77 ‰, respectively (Table 2). The sample data points are put on the $\delta^{13}\text{C}$ crossplot of saturated hydrocarbon *versus* aromatic hydrocarbon (Fig. 4), which shows that the organic matter of $\text{P}_{2\text{w}}$ source rock mainly came from terrigenous organism, while that of $\text{P}_{1\text{f}}$ source rock, $\text{P}_{1\text{j}}$ source rock and $\text{J}_{1\text{b}}$ crude oil mainly came from marine organism.

5. Discussion

5.1. The Source of Jurassic Crude Oil

Based on the above analyses of biomarker parameters and carbon isotope characteristics of source rocks and

Fig. 5 Pr/n-C17 and Ph/n-C18 Crossplot of Source Rocks and Crude Oil Samples on the Feng *et al.* (2020) Diagram⁸⁾

Fig. 6 The $\gamma/C_{30}H$ and $C_{24}Tet/C_{26}TT$ Intersection Diagram of Source Rocks and Crude Oil

crude oil, it is believed that the three sets of Permian source rock and Jurassic crude oil were all formed in an oxidation-reduction sedimentary environment. The P1j source rock has medium evaporation and high salinity, and the organic matter came from marine and terrestrial organisms, corresponding to its deposition in semi closed marine environment. The P1f source rock has weak evaporation and medium salinity, and the organic matter was derived from marine and terrestrial organisms, which corresponds to the sedimentary environment of transitional marine and lacustrine facies. The P2w source rock has strong evaporation and low salinity, which corresponds to the arid lacustrine sedimentary environment, and the organic matter came from terrestrial organisms. The formation environment of J1b crude oil was characterized by weak evaporation and medium salinity. The organic matter of J1b crude oil mainly came from marine and terrestrial organisms.

The intersection diagram of Pr/n-C17 and Ph/n-C18 (Fig. 5) shows that the distribution of P2w, P1f and P1j source rocks and J1b crude oil are similar, and they are all formed in the mixed sedimentary environment. Thus, it is difficult to use the relative content of isoprene alkanes for accurate oil source correlation. Besides, although there are some differences in the distribution of steranes C27-C28-C29 of source rocks and crude oil, it is still difficult to directly clarify the relationship between J1b crude oil and source rocks. On

Fig. 7 Comparison Chart of Carbon Isotope Values of Source Rocks and Crude Oil

the m/z 217 chromatogram (Fig. 2), the sterane distribution characteristics of P2w source rock and crude oil are obviously different, which excludes the hydrocarbon supply of P2w source rock. However, P1f and P1j source rocks have similar sterane distribution characteristics as crude oil, so it is difficult to judge whether the crude oil was generated by P1f or P1j source rock. In the ternary plot of steranes C27, C28 and C29 (Fig. 3), the relationship between J1b crude oil and source rocks is very poor, indicating that steranes are not suitable for oil source correlation.

The differences of water salinity and evaporating environment are obvious when the three sets of source rocks were deposited, so the geochemical indexes reflecting salinity and evaporating rocks content can be used for oil source comparative analysis. It can be seen from the crossplot of $\gamma/C_{30}H$ and $C_{24}Tet/C_{26}TT$ (Fig. 6) that the distribution range of J1b crude oil and P1f source rock is similar, which is obviously different from P2w and P1j source rocks, proving that Jurassic crude oil is most likely supplied by P1f source rock.

In addition, the difference in carbon isotope value ($\delta^{13}C$) of crude oil is related to the original hydrocarbon generating parent materials, which are only second to biomarker compounds, and have good application prospects in oil source correlation^{28),29)}. In Fig. 4, the $\delta^{13}C$ values of saturated and aromatic hydrocarbons show that the organic matter of J1b crude oil, P1f source rock and P1j source rock are all from marine environment, while the organic matter of P2w source rock is from continental environment. It excludes the possibility that P2w source rock provides hydrocarbon for Jurassic reservoir. By comparing the $\delta^{13}C$ values of three sets of Permian source rocks and Jurassic crude oil in the study area (Fig. 7), it can be seen that the $\delta^{13}C$ values of P1f source rock and J1b crude oil are the closest, which also proves that the crude oil in Jurassic reservoir in the study area came from P1f source rock.

Fig. 8 Seismic Interpretation Profile in the Study Area³²⁾ (The location is shown in Fig. 1.)

5.2. Accumulation Mechanism of Jurassic Crude Oil

Tectonic activity is intense in the north western margin of Junggar basin, and a complex fault system was developed in front of the Hala'alat mountains. Wuxia fault zone and stratigraphic unconformity interfaces in the early Triassic are the main channels for oil and gas migration in the western margin of Mahu sag^{30),31)}. It can be seen from the 2D seismic profile in Mahu sag that there is obvious angular unconformity between Triassic strata and Permian strata, and the P_{3w} stratum is almost completely denuded (Fig. 8). Faults were frequently developed in the western margin of Mahu sag, connecting Permian source rocks and overlying reservoirs. However, most faults stopped extending in the middle Triassic period, and only a few faults extended upward into Jurassic strata, indicating that tectonic activities had nearly stopped when Jurassic reservoirs were sedimented. Faults did not pass through the Jurassic reservoir and its overlying reservoir, contributing to the development of Jurassic lithologic traps and the preservation of reservoirs in the later period.

A complete reservoir formation requires not only high-quality source rocks and traps, but also requires that the formation time of the hydrocarbons migration channels and traps shall be earlier than the hydrocarbon expulsion from source rocks. Otherwise, the crude oil formed during the period of massive hydrocarbon expulsion of source rocks cannot remain in the existing traps. According to the burial history of P_{1f} source rock in Mahu sag (Fig. 9), it can be seen that the hydrocarbon generation threshold ($R_o = 0.5\%$) of P_{1f} source rocks occurred in the late Permian period. The P_{1f} source rock reached the high mature stage ($R_o = 1.3\%$) in the late Cretaceous and ended oil generation. Since Cenozoic, P_{1j} source rock has reached over mature stage ($R_o > 2.0\%$), and many natural gas and condensate reservoirs discovered in Mahu sag are the products of this stage^{34),35)}. The main hydrocarbon expulsion period of P_{1f} source rock (about 70 to 255 Ma) is later than or synchronized with the formation

Fig. 9 Time Series of Hydrocarbon Accumulation Factors of the Jurassic Crude Oil in the Western Mahu Sag of Junggar Basin³³⁾

Fig. 10 The Accumulation Event of the Jurassic Crude Oil in the Western Mahu Sag of Junggar Basin

period of faults (about 235 Ma ago) and traps (about 165 to 200 Ma), which proves the rationality of the sequence of hydrocarbon accumulation events (Fig. 10), and Jurassic lithologic traps in the study area are effective.

Based on the above results, it can be inferred that the Jurassic crude oil in the western margin of the Mahu sag was generated from the Permian Fengcheng source rock, and migrated upward into the Triassic reservoirs through a large number of faults, and then a small number of faults or superimposed sand bodies lacking shelter were used as migration pathways, and continue to migrate upward to the Jurassic lithological traps to accumulate into reservoirs (Fig. 11).

6. Conclusions

(1) Three sets of Permian source rocks in Mahu sag were formed in oxidation-reduction sedimentary environment. P_{1j} source rock has medium evaporation and high salinity, and its parent materials are marine and terrestrial organisms. P_{1f} source rock has weak evaporation and medium salinity during sedimentation, and its parent materials are mainly marine and terrestrial or-

Fig. 11 Accumulation Pattern of the Jurassic Crude Oil in the Western Mahu Sag of Junggar Basin (Figure 8 is the corresponding seismic profile.)

ganisms. P_{2w} source rock has strong evaporation and low salinity, and its parent materials are mainly terrigenous organisms.

(2) The source of J_1b crude oil has weak evaporation during sedimentation and the water body has low salinity, which was generated from the parent materials from marine organisms. The carbon isotope values ($\delta^{13}C$) and the biomarker parameters ($\gamma/C_{30}H$ and $C_{24}Tet/C_{26}TT$) that reflect paleo-salinity and evaporation of the water body are used to prove that the crude oil in the Jurassic reservoir in the western margin of the Mahu sag came from P_{1f} source rock.

(3) The main hydrocarbon expulsion period of P_{1f} source rock was later than the formation period of faults and traps. At present, Jurassic crude oil in the western margin of Mahu sag was generated from Permian P_{1f} source rock and migrated upward through a large number of faults into Triassic reservoirs. And then the crude oil, using local faults or superimposed sand bodies lacking the shelter as migration channels, continued to migrate upward to Jurassic lithologic traps to accumulate into reservoirs.

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