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Geochemical characteristics and significance of aromatic hydrocarbons in crude oil from the East Fukang Sag, Junggar Basin, NW China

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The aromatic compounds of twenty crude oil samples from different formations in the East Fukang Sag were studied by the gas chromatography–mass spectrometry technique. Through analysis of the composition of the main aromatic hydrocarbons, the studied crude oil samples were generally divided into two types: Oil type I had the relatively high content of the naphthalene series, biphenyl series and dibenzofuran series, while the samples from Oil type II contained relatively high abundance of phenanthrene series, fluorene series, triaromatic steroid series, and obvious methyltrimethyltridecylchromans. The geochemical parameters reflecting the source and sedimentary environment in naphthalene series, phenanthrene series, biphenyl series, three-fluorene series, and triaromatic steroid series were systematically analyzed. Analysis of the results showed that studied oil samples from the East Fukang Sag were of continental origin and deposited in a weakly oxidizing to weakly reducing environment with fresh-brackish water. Oil type I was characterized by considerably abundant terrestrial higher plant organic matter inputs, while Oil type II was typical with obviously lower aquatic organisms. Maturity-related parameters calculated from alkyl naphthalenes, alkyl phenanthrenes, alkyl dibenzothiophenes, and methyltrimethyltridecylchromans showed that all the studied oil samples have reached the mature stage.

KEYWORDS

aromatic hydrocarbons, sedimentary environment, thermal maturity, Fukang Sag, source of organic matter

1 Introduction

The source of organic matter, depositional environment, and maturity of crude oil are of great significance for oil and gas exploration. They can be used to identify the possible source rocks and maturation stage of oil expulsion, and understand the rules of oil and gas accumulation in the region (Guo and He, 2009). As important components ubiquitous in crude oil and source rocks, the aromatic hydrocarbons, have drawn more and more attention in recent years. Compared with saturated hydrocarbons, aromatic hydrocarbons are more resistant to biodegradation, which can also provide significant information on the origin of organic matter (Püttmann and Villar, 1987; Alexander et al., 1988; Radke et al., 1994), depositional environment (Fan et al., 1990; Li and He, 2008), thermal maturity (Radke et al., 1982, 1986; Radke and Willsch, 1994), oil-source correlation (Alexander et al., 1992), and oil migration (Li et al., 2011; Fang et al., 2016). Moreover, the maturity parameters based on aromatic hydrocarbons have a wider indication range than the sterane and hopane isomerization parameters of saturated hydrocarbons in evaluating the degree of thermal evolution. Therefore, it is a useful supplement to the study of saturated hydrocarbons (Peters and Moldowan, 1993; Peters et al., 2005).

The Fukang Sag is the largest hydrocarbon-generating sag within the Junggar basin, and is one of the main oil and gas source kitchens in the eastern, southern, and hinterland of the Junggar Basin (Zhang et al., 2020). The study area has experienced polycyclic tectonic-sedimentary evolution, forming multiple sets of favorable source-reservoir-seal assemblages (Wang et al., 2018). Hence, the crude oil in the East Fukang Sag shows various properties and complex oil-source relations (Chen et al., 2016; Liu et al., 2020). Previous studies in this area have primarily focused on the tectonic evolution and depositional characteristics (Wu, et al., 2013; Ma C. et al., 2019; Luo et al., 2019), reservoir characteristics (Cao et al., 2017; Wang et al., 2018; Ma S. et al., 2019), hydrocarbon accumulation characteristics (Wu et al., 2013; Shi, 2017), geochemical characteristics of source rocks (Fu et al., 2011; Bai et al., 2017; Shi et al., 2018; Yang et al., 2019; Qiao et al., 2020; Zhang et al., 2020) and geochemical characteristics of saturated hydrocarbons in crude oil (Yang et al., 2012; Pan et al., 2015; Wang et al., 2016; Liu et al., 2020; Song et al., 2020; Chen et al., 2022). However, rare reports described in detail the geochemical characteristics of aromatic hydrocarbons in crude oil from the East Fukang Sag (Yang et al., 2005; Liu, et al., 2020). Therefore, in this paper, twenty crude oil samples from the East Fukang Sag were investigated by gas chromatography (GC) and gas chromatography–mass spectrometry (GC–MS) techniques. We systematically analyzed the geochemical characteristics of aromatic hydrocarbons, discussed the biological source and depositional setting of organic matter, and determined the oil maturity, which can be an important supplement for the study of the geochemical characteristics of crude oil in this area. It is expected to provide some geochemical basis for the genesis of hydrocarbons and identification of oil sources in this area.

2 Geological setting

The Junggar Basin is located in the northern part of Xinjiang Uygur Autonomous Region, NW China. It is shaped like a subtriangle narrow in the north and wide in the south and surrounded by mountains ranges from the western, northeastern, and southern sides, which covers an area of about 130,000 km^2 (Cao et al., 2017; Figure 1A). It is a large superimposed basin which is underlain by part of Hercynian folded basement and Precambrian crystalline basement (Wu et al., 2005; Qiao et al., 2020). The basin has experienced Hercynian, Indosinian, Yanshanian, and Himalayan tectonic movements, which can tectonically be divided into three evolutionary stages: the rift basin stage, depression basin stage, and foreland basin stage (Wan et al., 2015; He et al., 2018; Figure 2). The Fukang sag lies in the east of Junggar Basin which belongs to the Central depression. The study area is located in the eastern part of Fukang Sag (Figure 1B).

The sedimentary strata in the study area are completely developed, including Carboniferous to Quaternary sediments with a total thickness of 10 km (Qiao et al., 2020; Figure 2). The Carboniferous strata developed typical marine sediments and pyroclastic sediments. The Permian mainly consisted of fluvial and lake deposits. The middle Permian Lucaogou Formation (P_2l), deposited in fresh-brackish deep to semi-deep lakes, is the most important source rock in the study area. The sedimentary range of Triassic was larger than that of Permian. The middle and upper Triassic were mainly fluvial, lake, and deltaic deposits, containing amounts of glutenite. The Jurassic strata were mainly deposited in a shallow lake and swamp environment with the source rocks being mainly dark mudstone, carbon mudstone, and coal seams. The Cretaceous mainly belonged to fluvial deposits where sandstones were abundant. The Cenozoic strata were dominated by alluvial fan and fluvial clastic deposits (Chen et al., 2016; Bai, et al., 2017; Cao et al., 2017). Thereinto, four sets of source rocks (i.e., Carboniferous, Permian, Triassic, and Jurassic) and multiple oil-bearing series (i.e., Carboniferous, Permian, Triassic, Jurassic, Cretaceous, Paleogene, and Neogene) were developed (Chen et al., 2016).

3 Samples and methods

3.1 Samples

In this study, twenty crude oil samples from different depths and reservoirs in East Fukang Sag were obtained for geochemistry analysis. The well locations of these samples were shown in Figure 1C, and the basic characteristics of the samples were presented in Table 1.

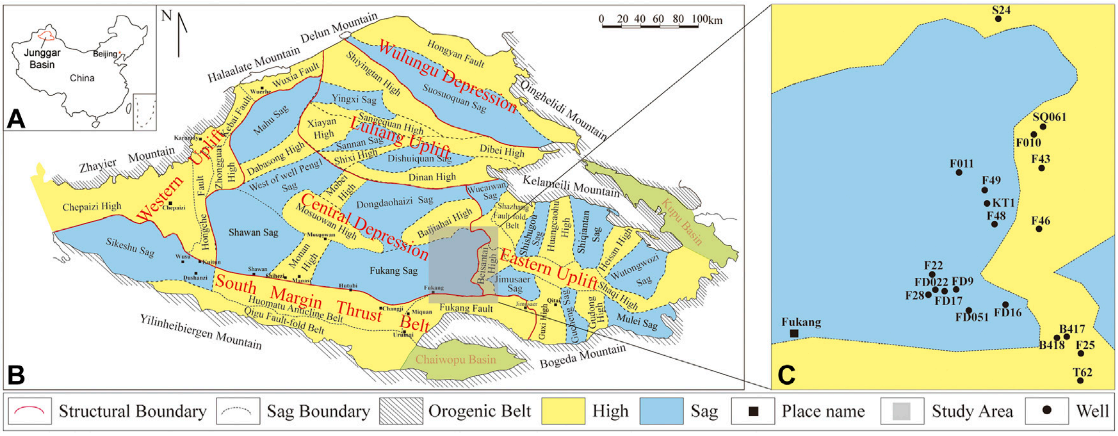
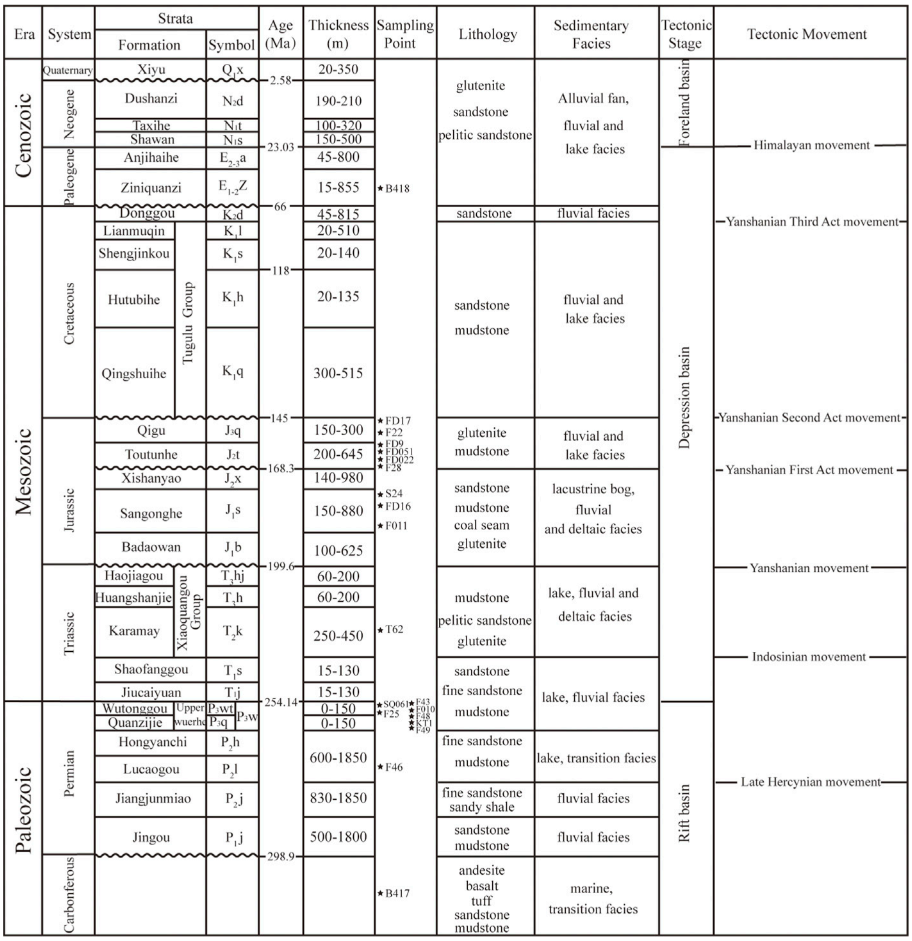


FIGURE 1
(A) The location of the Junggar Basin in China, **(B)** its structure outline map and **(C)** the study area.



Era	System	Strata: Formation		Strata: Symbol		Age (Ma)	Thickness (m)	Sampling Point	Lithology	Sedimentary Facies	Tectonic Stage	Tectonic Movement
Cenozoic	Quaternary	Xiyu		Q_1x		2.58	20-350		glutenite sandstone pelitic sandstone	Alluvial fan, fluvial and lake facies	Foreland basin	
	Neogene	Dushanzi		N_2d			190-210					
		Taxihe		N_1t			100-320					
		Shawan		N_1s		23.03	150-500					Himalayan movement
	Paleogene	Anjihaihe		$E_{2-3}a$			45-800				Depression basin	
		Ziniquanzi		$E_{1-2}Z$		66	15-855	★B418				
Mesozoic	Cretaceous	Donggou		K_2d			45-815		sandstone	fluvial facies		Yanshanian Third Act movement
		Lianmuqin	Tugulu Group	K_1l			20-510		sandstone mudstone	fluvial and lake facies		
		Shengjinkou		K_1s		118	20-140					
		Hutubihe		K_1h			20-135					
		Qingshuihe		K_1q		145	300-515					Yanshanian Second Act movement
	Jurassic	Qigu		J_3q			150-300	★FD17 ★F22	glutenite mudstone	fluvial and lake facies		
		Toutunhe		J_2t		168.3	200-645	★FD9 ★FD051 ★FD022 ★F28				Yanshanian First Act movement
		Xishanyao		J_2x			140-980		sandstone mudstone coal seam glutenite	lacustrine bog, fluvial and deltaic facies		
		Sangonghe		J_1s			150-880	★S24 ★FD16 ★F011				
		Badaowan		J_1b		199.6	100-625					Yanshanian movement
	Triassic	Haojiagou	Xiaoquangou Group	T_3hj			60-200		mudstone pelitic sandstone glutenite	lake, fluvial and deltaic facies		
		Huangshanjie		T_3h			60-200					
		Karamay		T_2k			250-450	★T62				Indosinian movement
		Shaofanggou		T_1s			15-130		sandstone fine sandstone mudstone	lake, fluvial facies		
		Jiucaiyuan		T_1j		254.14	15-130					
Paleozoic	Permian	Wutonggou	Upper wuerhe	P_3wt	P_3w		0-150	★SQ061 ★F25 ★F43 ★F010 ★F48 ★KT1 ★F49			Rift basin	
		Quanzijie		P_3q			0-150					
		Hongyanchi		P_2h			600-1850	★F46	fine sandstone mudstone	lake, transition facies		
		Lucaogou		P_2l								Late Hercynian movement
		Jiangjunmiao		P_2j			830-1850		fine sandstone sandy shale	fluvial facies		
		Jingou		P_1j		298.9	500-1800		sandstone mudstone	fluvial facies		
	Carbonferous							★B417	andesite basalt tuff sandstone mudstone	marine, transition facies		

FIGURE 2
Generalized stratigraphic column of the eastern Junggar Basin (modified from Cao et al., 2017; Bai, et al., 2017; He et al., 2018).

TABLE 1 Basic characteristics of crude oil in the East Fukang Sag.

Sample No.	Well	Fm	Depth (m)	Density (g/cm³)	Viscosity (mPa·s)	Wax content (%)	Freezing point (°C)	$\delta^{13}C$ (‰)			Fractions (%)			Sat/ Aro	$C_{19}TT/C_{23}TT$	$C_{24}TeT/C_{23}TT$	Regular steranes			Oil type
								Full	Sat	Aro	Sat	Aro	Res+Asphal				C_{27}%	C_{28}%	C_{29}%	
1	F22	J_3q	3092 ~ 3095	0.81	2.25	7.52	13.6	−27.59	−27.92	−26.8	87.40	8.95	3.65	9.77	1.82	1.74	24.00	21.89	54.11	I
2	F011	J_1s_2	3470 ~ 3473.5	0.81	1.91	8.00	6.00	−27.23	−27.87	−26.43	75.74	16.34	7.92	4.64	5.83	4.21	19.87	21.88	58.25	
3	F28	J_2t	3340 ~ 3382	0.80	2.27	8.05	8.50	−27.68	−28.34	−26.43	82.29	10.71	7.01	7.69	2.29	2.33	27.24	19.89	52.88	
4	FD022	J_2t	3297 ~ 3318	0.79	1.40	4.09	−8.00	−27.36	−27.6	−26.91	85.03	9.28	5.68	9.16	1.30	1.00	28.95	25.74	45.30	
5	FD17	J_3q	2869 ~ 2875	0.82	2.19	7.58	9.00	−27.35	−27.89	−25.53	83.69	11.72	4.59	7.14	2.30	1.91	27.52	21.80	50.68	
6	FD16	J_1s	2350 ~ 2354	0.85	5.83	5.34	10.00	−28.17	−28.93	−27.6	70.87	15.40	13.72	4.60	0.99	1.00	30.39	24.72	44.89	
7	FD9	J_2t	2813 ~ 2879	0.86	9.79	8.84	17.00	−29.09	−29.62	−28.42	66.89	20.98	12.13	3.19	0.44	0.61	24.44	32.86	42.70	
8	FD051	J_2t	2940 ~ 2958	0.85	8.19	3.88	-4.00	−28.57	−29.46	−27.91	62.93	24.16	12.92	2.61	0.68	0.73	25.05	30.81	44.14	
9	S24	J_1s	1930 ~ 1933	0.82	3.17	14.80	9.00	−27.57	−26.99	−25.72	82.52	12.58	4.90	6.56	3.71	3.33	24.60	25.78	49.63	
10	F46	P_2l	3157 ~ 3165	0.86	10.58	9.20	18.00	−32.23	−32.15	−31.05	72.30	16.56	11.14	4.37	0.11	0.36	30.97	28.87	40.16	II
11	T62	T_2k	2720 ~ 2726	0.87	24.20	14.37	17.80	−31.45	−32.04	−30.8	72.47	15.09	12.43	4.80	0.13	0.42	19.97	39.83	40.20	
12	B418	E	1773 ~ 1779	0.91	200.50	4.76	18.20	−31.32	−31.95	−30.01	60.88	13.04	26.08	4.67	0.49	0.44	21.53	38.24	40.23	
13	B417	C	2998 ~ 3025	0.89	118.50	6.60	11.30	−31.2	−31.93	−30.81	66.55	11.99	21.46	5.55	0.14	0.41	18.57	41.68	39.75	
14	SQ061	P_3wt	1969 ~ 1973	0.85	13.30	9.44	11.50	−30.6	−31	−29.75	75.77	16.10	8.13	4.71	0.14	0.33	24.95	37.19	37.87	
15	F010	P_3w	2756 ~ 2779	0.85	10.41	5.84	17.40	−30.66	−31.22	−30.01	68.21	18.52	13.27	3.68	0.15	0.31	25.53	35.36	39.11	
16	KT1	P_3w_1	5116 ~ 5121	0.83	5.94	5.80	14.00	−30.93	−30.98	−29.54	81.79	9.94	8.28	8.23	0.15	0.19	27.96	34.95	37.10	
17	F48	P_3w	4579 ~ 4629	0.85	9.49	6.40	18.00	−30.58	−31	n/a	79.05	17.39	3.56	4.55	0.16	0.27	24.72	40.01	35.27	
18	F43	P_3w	3132 ~ 3214	0.85	9.49	7.10	9.00	−31.56	−31.8	−29.21	76.26	19.07	4.67	4.00	0.14	0.33	26.33	35.95	37.72	
19	F49	P_3w_1	5615 ~ 5672	0.84	5.85	7.00	14.00	−30.8	−31.19	−29.92	83.81	13.33	2.86	6.29	0.19	0.12	36.25	29.54	34.21	
20	F25	P_3wt	2775 ~ 2783	0.81	14.20	10.35	21.60	−31.45	−31.84	−30.64	76.93	11.69	11.39	6.58	0.14	0.40	17.67	42.17	40.16	

Notes: viscosity is measured at 50°C; Fm, formation; Sat, saturates; Aro, Aromatics; Res, Resin; Asphal, Asphaltenes; $C_{19}TT/C_{23}TT$, C_{19} tricyclic terpane/C_{23} tricyclic terpane (m/z=191 of saturates); $C_{24}TeT/C_{23}TT$, C_{24} tetracyclic terpane/C_{23} tricyclic terpane (m/z=191 of saturates); C_{27}, C_{28}, C_{29}, 5α,14,17-cholestanes (m/z=217 of saturates); n/a, not available.

3.2 Methods

The studied oil samples were performed to precipitate with an excess of n-hexane, then the *n*-hexane soluble portion of samples was further separated by column chromatography into saturated, aromatic and resin fractions using silica gel/alumina (2:1, v/v) columns by gravimetric analysis. The saturated fraction was eluted with *n*-hexane, the aromatic fraction was eluted with dichloromethane/*n*-hexane (2:1, v/v) and the resin fraction was eluted with dichloromethane/methanol (93:7, v/v). The collected saturated and aromatic fractions evaporated the solvent at room temperature and then transferred into 2 ml sample vials for GC and GC–MS analysis.

GC analysis of the pristane and phytane in the saturated fractions were conducted on an Agilent 7890A gas chromatograph fitted with an HP-5MS fused silica capillary column (60 m × 0.32 mm × 0.25 μm film thickness). Nitrogen was the carrier gas. The oven temperature was programmed to start at 40°C for 2 min, increasing to 310°C at 4°C/min, and then holding for 20 min. Data were acquired using an Agilent ChemStation.

GC–MS analysis of the saturated and aromatic fractions were performed on an Agilent 7890A-5975C GC–MS system equipped with an HP-5MS fused silica capillary column (60 m × 0.25 mm × 0.25 μm film thickness). The GC operating conditions were as follows: the initial temperature was held at 40°C for 2 min, heating to 300°C at a rate of 4°C/min, and then holding for 30 min. Helium was used as the carrier gas. The injector temperature was set to 300°C. The MS was operated at 70 eV in the EI (electron ionization) mode over a scan range from m/z 50 to 600. Compounds were identified by searching the NIST library and comparing with published mass spectra, as well as the retention indices from literature data. Ratios used in this study were calculated by measuring the peak areas in the appropriate molecular ion chromatograms.

The stable carbon isotope analysis of crude oil and its components were completed by the CNPC Xinjiang Oilfield Company. They were performed on a Thermo Fisher MAT-253 instrument coupled to a Flash EA 1112. The whole oil and its saturated and aromatic fractions were burned into CO_2 in the EA combustion furnace (about 980°C). The stable carbon isotope values were calibrated relative to the Vienna Pee Dee Belemnite (VPDB) standard. Every sample was measured at least twice consecutively until the error was less than 0.1‰.

4 Results and discussion

4.1 Basic geochemical characteristics of crude oil

In this study, most crude oil samples were light oil with low viscosity, especially crude oil from Jurassic (Table 2). Except for Samples 12 and 13, the density of studied crude oil was between 0.79 and 0.87 g/cm^3 (average 0.83 g/cm^3) and the viscosity at 50°C ranged from 1.4 mPa·s to 24.2 mPa·s (average 7.70 mPa·s). The wax content of studied crude oil varied in the range of 3.88%–14.80% (average 7.82%), which belonged to medium-high wax crude oil. The freezing point was relatively low, ranging from −8.00°C to 21.60°C, with an average of 11.26°C. The group composition of crude oil samples was predominately saturated hydrocarbon, ranging from 60.88% to 87.40% (average 75.57%). The aromatic hydrocarbon accounted for 8.95%–24.16% (average 14.04%). The ratios of saturated/aromatic hydrocarbon ranged from 2.61 to 9.77 (average 5.64), suggesting that the maturity of crude oil samples was relatively high (Cheng et al., 2020).

The distribution of *n*-alkanes in all crude oil samples was complete, typically varying from $n\text{C}_{10}$ to $n\text{C}_{31}$, which indicated that crude oil was not biodegraded basically. Hence, these crude oil samples can represent the original geochemical information of crude oil generation. The C_{27}-C_{28}-C_{29} regular steranes and tricyclic terpanes in crude oil showed different distribution characteristics, indicating that the organic matter input of crude oil in East Fukang Sag had both lower aquatic organisms and terrestrial higher plants (Philp and Gilbert, 1986; Figure 3).

4.2 Composition characteristics of aromatic hydrocarbons

Generally, there are three peaks on the TIC of aromatic compounds in crude oil: naphthalene and alkylnaphthalenes (dicyclic compounds), phenanthrene and alkylphenanthrenes (tricyclic compounds), other polycyclic aromatic hydrocarbons plus aromatic steroids and terpenoids. The aromatic hydrocarbons in immature-low mature oils are dominated by tetracyclic and pentacyclic compounds and the TICs show back or bimodal peaks, while chromatograms of aromatic hydrocarbons from crude oil with moderate to high maturity show the front peaks of dicyclic and tricyclic compounds in predominance. In this study, a total of 14 series of more than 170 aromatic compounds were detected in the samples, mainly including naphthalene series, phenanthrene series, biphenyl series, three-fluorene series (dibenzofuran series, dibenzothiophene series, and fluorene series), fluoranthene series, pyrene series, chrysene series, triaromatic steroid series, benzofluoranthene, benzopyrene series, benzofluorene series and methyltrimethyltridecylchromans (MTTCs) (Figure 4). The relative contents of all the compounds were calculated by normalizing the peak areas, and the results showed that the TICs of aromatic hydrocarbons in the studied crude oil exhibited a front peak distribution of bicyclic and tricyclic compounds (accounting for over 80%), which indicated relatively high maturity of the crude oil samples (Figure 5). According to the relative contents of main aromatic compounds, the studied crude oil could be divided into two types: Oil type I showed the highest content of naphthalene series (44.6%–59.2%, with an average of 52.17%), followed by the relative content of biphenyl series (11.13%–23.92%, with an average of 17.15%) and phenanthrene series

TABLE 2 Geochemical parameters of aromatic compounds in crude oil from the East Fukang Sag.

Sample No.	Well	Fm	Depth (m)	Aromatic compounds abundance (%)					1,2,5-TMN/TMNs (%)	1,2,5,6-TeMN/TeMNs (%)	Ca/∑Ns	Re/P	DBT/P	TFs abundance (%)			Pr/Ph	GI	α-MTTC/∑MTTCs	β-MTTC/γ-MTTC	Oil type
				Ns	Ps	BPs	TAS	MTTTCs						F	DBT	DBF					
1	F22	J_3q	3092 ~ 3095	47.50	12.57	21.91	0.26	—	9.46	15.35	0.57	0.33	0.12	32.67	11.78	55.54	2.62	0.09	n/a	n/a	I
2	F011	J_1s_2	3470–3473.5	49.88	18.39	12.80	0.06	—	7.29	12.33	0.38	0.12	0.06	51.80	10.36	37.84	2.25	0.06	n/a	n/a	
3	F28	J_2t	3340 ~ 3382	56.00	11.54	16.62	0.47	—	10.77	17.17	0.64	0.34	0.10	25.64	7.31	67.05	2.90	0.05	n/a	n/a	
4	FD022	J_2t	3297 ~ 3318	51.41	10.97	23.92	0.20	—	7.79	13.60	1.00	0.31	0.13	39.87	12.70	47.43	2.29	0.10	n/a	n/a	
5	FD17	J_3q	2869 ~ 2875	44.63	14.57	23.26	0.08	—	7.65	13.48	0.59	0.22	0.11	40.44	11.67	47.89	2.35	0.06	n/a	n/a	
6	FD16	J_1s	2350 ~ 2354	57.39	10.62	15.53	0.12	—	13.70	17.93	0.61	0.13	0.10	14.63	9.93	75.44	2.21	0.07	n/a	n/a	
7	FD9	J_2t	2813 ~ 2879	59.26	11.76	13.78	0.63	0.04	13.03	18.46	1.03	0.22	0.08	24.10	10.47	65.44	1.94	0.09	100	n/a	
8	FD051	J_2t	2940 ~ 2958	50.05	15.21	15.37	1.01	0.05	14.39	20.10	1.31	0.28	0.10	23.45	12.83	63.72	2.64	0.09	100	n/a	
9	S24	J_1s	1930 ~ 1933	53.39	18.01	11.13	0.02	—	7.11	12.12	0.29	0.07	0.07	54.16	10.73	35.11	2.59	0.07	n/a	n/a	
10	F46	P_2l	3157 ~ 3165	40.50	31.31	2.94	6.80	0.67	4.76	9.61	0.29	0.04	0.03	81.09	8.10	10.80	1.42	0.16	82.90	3.01	II
11	T62	T_2k	2720 ~ 2726	56.39	24.90	4.67	3.20	0.99	7.70	16.63	0.17	0.03	0.04	45.23	21.34	33.43	1.28	0.13	82.92	1.49	
12	B418	E	1773 ~ 1779	53.84	23.67	5.82	5.16	0.81	8.72	18.63	1.88	0.11	0.05	46.86	18.28	34.86	1.30	0.14	80.78	1.76	
13	B417	C	2998 ~ 3025	46.52	24.20	10.76	6.35	2.07	18.58	24.66	0.50	0.05	0.09	20.15	39.53	40.32	1.16	0.15	82.73	1.58	
14	SQ061	P_3wt	1969 ~ 1973	51.37	23.38	10.59	1.88	0.66	5.50	12.21	0.42	0.10	0.05	29.01	11.68	59.31	1.55	0.16	89.17	3.17	
15	F010	P_3w	2756 ~ 2779	46.91	27.52	7.25	0.86	—	4.44	9.39	0.31	0.08	0.04	18.24	19.71	62.05	1.46	0.18	n/a	n/a	
16	KT1	P_3w_1	5116 ~ 5121	42.78	32.22	7.16	0.00	—	1.36	4.28	0.07	0.00	0.02	91.59	4.11	4.31	1.43	0.43	n/a	n/a	
17	F48	P_3w	4579 ~ 4629	41.03	32.20	8.17	0.05	—	2.88	5.33	0.11	0.01	0.03	76.79	7.05	16.16	1.40	0.32	n/a	n/a	
18	F43	P_3w	3132 ~ 3214	42.39	32.98	6.26	0.99	0.02	3.58	6.93	1.16	0.03	0.04	73.95	8.70	17.35	1.51	0.15	100	n/a	
19	F49	P_3w_1	5615 ~ 5672	35.98	35.48	8.59	0.00	—	1.15	3.90	0.11	0.00	0.01	95.61	2.00	2.39	1.52	0.56	n/a	n/a	
20	F25	P_3wt	2775 ~ 2783	45.40	27.76	10.36	3.91	0.69	12.62	21.52	0.31	0.02	0.05	9.73	23.01	67.26	1.32	0.15	84.27	2.98	

Notes: Ns, naphthalene series; Ps, phenanthrene series; BPs, biphenyl series; TAS, triaromatic steroids; "—" denotes below detection limit; Ca/∑Ns, cadalene/total naphthalene series; Re/P, retene/phenanthrene; DBT/P, dibenzothiophene/phenanthrene; TFs, three-fluorene series; Pr/Ph, pristane/phytane; GI (Gammacerane index), gammacerane/C_{30}-hopane.

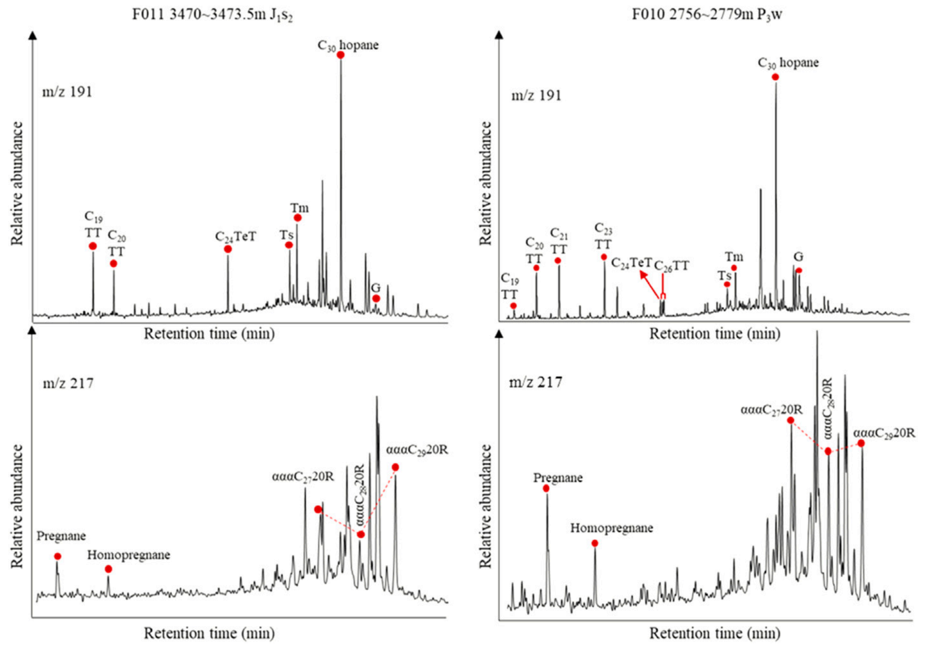


FIGURE 3
Typical biomarker chromatograms of saturated hydrocarbons in crude oil in the East Fukang Sag. m/z 191= terpanes, m/z 217=steranes, Ts=C_{27}-18α(H) trisnorhopane, Tm=C_{27}-17α(H) trisnorhopane, G=gammacerane.

(10.62%–18.39%, with an average of 13.74%). The relative abundance of other aromatic hydrocarbon series decreased in the order of three-fluorene series (the content of dibenzofuran series was the highest), chrysene series, fluoranthene series, triaromatic steroid series, benzofluorene series, while the contents of the remaining four aromatic hydrocarbon series were very low. In comparison, Oil type II was dominated by naphthalene series (35.98%–56.38%, with an average of 45.73%) and phenanthrene series (23.38%–35.48%, with an average of 28.69%), while the biphenyl series was in a rather low amount (2.94%–10.76%, with an average of 7.51%), then followed by the content of three-fluorene series (the content of fluorene series was the highest), triaromatic steroid series, chrysene series, pyrene series and MTTCs. The contents of the remaining four aromatic hydrocarbon series were very low (Figures 4, 5).

4.3 Sources of organic matter

4.3.1 Carbon isotope composition of aromatic hydrocarbons

The carbon isotopes of whole oil and its fractions are inherited from those of sedimentary organic matter, and generally, the difference of stable carbon isotope values ($\delta^{13}C$) of crude oil from the same source due to different maturity is no more than 2‰–3‰ (Schoell, 1984; Peters and Moldowan, 1993). Therefore, the carbon isotope characteristics can be a good indicator of oil-oil and oil-source correlation. The $\delta^{13}C_{aro}$ values of Oil type I ranged from −25.53‰ to −28.42‰, while that of Oil type II were light with $\delta^{13}C_{aro}$ from -29.21‰ to -31.05‰ (Figure 6), indicating that the two types of crude oil were generated from different source rocks and the Oil type II had obvious lower aquatic organisms organic matter input (Li et al., 2003). In addition, Oil type I showed a strong dominance of the C_{29} sterane, ranging from 42.70% to 54.11% (average 49.18%), Oil type II were relatively more enriched in C_{28} and C_{29} steranes, with relative abundance of 28.87%–42.17% (average 36.71%) and 34.21%–40.23% (average 38.34%), respectively (Table 2). Meanwhile, the values of $C_{19}TT/C_{23}TT$ and $C_{24}TeT/C_{23}TT$ of Oil type I (ranging from 0.44 to 5.83 and 0.61–4.21, respectively) were much higher than those of Oil type II (ranging from 0.11 to 0.49 and 0.12–0.44, respectively). The characteristics of these biomarkers also reflected that the organic matter input of Oil type I was mainly terrestrial higher plants and Oil type II was mainly lower aquatic organisms (Peters et al., 2005; Gong et al., 2019).

4.3.2 Naphthalene and its alkyl derivatives

The naphthalene series in the samples included naphthalene (N; m/z 128), methylnaphthalenes (MNs; m/z 142), ethylnaphthalenes (EtNs; m/z 156), dimethylnaphthalenes (DMNs; m/z 156), trimethylnaphthalenes (TMNs; m/z 170), tetramethylnaphthalenes (TeMNs; m/z 184) and

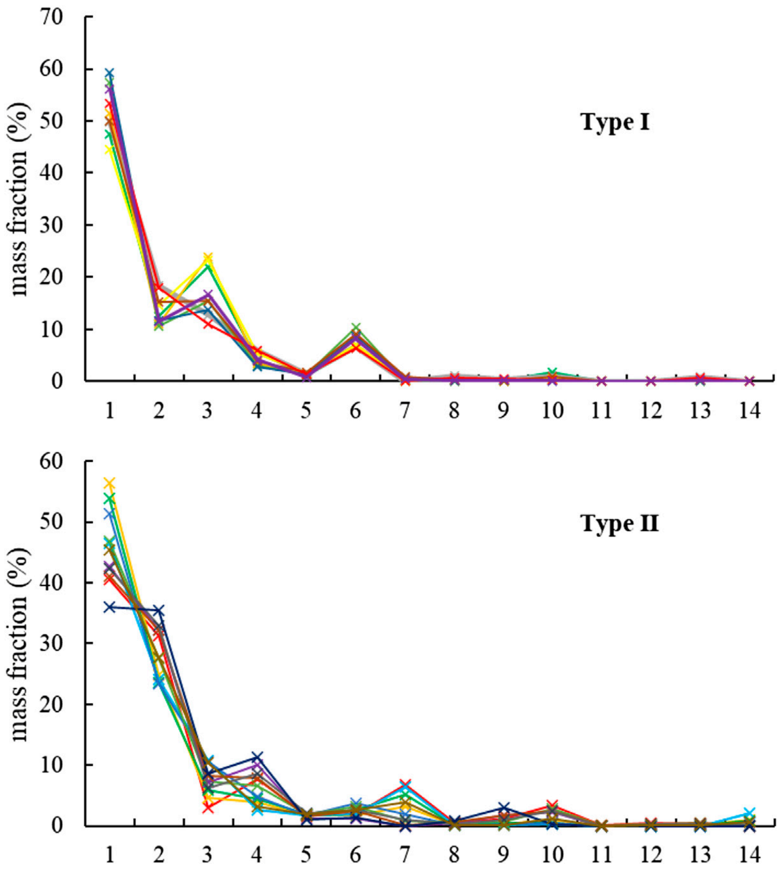


FIGURE 4
The composition characteristics of aromatic hydrocarbons in crude oil from the East Fukang Sag. Notes: 1) Naphthalene series, 2) Phenanthrene series, 3) Biphenyl series, 4) Fluorene series, 5) Dibenzothiophene series, 6) Dibenzofuran series, 7) Triaromatic steroid series, 8) Fluoranthene series, 9) Pyrene series, 10) Chrysene series, 11) Benzofluoranthene, 12) Benzopyrene series, 13) Benzofluorene series, 14) MTTCs.

pentamethylnaphthalenes (PMNs; m/z 198). They were characterized by predominant DMNs and TMNs (accounting for more than 60% of total naphthalenes), followed by the content of MNs, N, EtNs and PMNs. Relative distribution of naphthalene series is related to the nature of source and depositional environment (Strachan et al., 1988; Radke et al., 1994), but the current understanding of the biogenesis of naphthalene series is not clear enough (Armstroff et al., 2006). Tuo, 1996 believed that naphthalene series may be closely related to terrestrial higher plant sources. It is commonly accepted that 1,2,5-TMN and 1,2,5,6-TeMN can be useful indicators of the input of higher plants in crude oil (Püttmann and Villar, 1987; Alexander et al., 1988; Strachan et al., 1988). 1,2,5-TMN/TMNs ratio of studied oil samples varied from 1.14% to 18.58%, and the average values of Oil type I and Oil type II were 10.13% and 6.48%, respectively. In addition, 1,2,5,6-TeMN accounted for 3.89%–24.66% of TeMNs, the average values of Oil type I and Oil type II were 15.62% and 12.10%, respectively. Based on the study by Zhu (1996), it potentially indicated that the studied crude oil was of continental origin. Besides that, cadalene (1,6-dimethyl-4-isopropylnaphthalene) is thought to originate from compounds with the cadalene carbon skeleton, which are especially abundant in plant resins and essential oils derived from land plants (Singh et al., 1994). The content of cadalene in studied crude oil accounted for 0.07%–1.88% of total naphthalene series (Table 2). The abundance of cadalene in Oil type I was higher (average 0.77%) than that (average 0.48%) of Oil type II. Therefore, it indicated that the original organic matter of crude oil in the study area had a certain amount of terrestrial higher plant input, and the input of Oil type I was more than that of Oil type II.

4.3.3 Phenanthrene and its alkyl derivatives

The phenanthrene series detected in the samples contained phenanthrene (P; m/z 178), methylphenanthrenes (MPs; m/z 192),

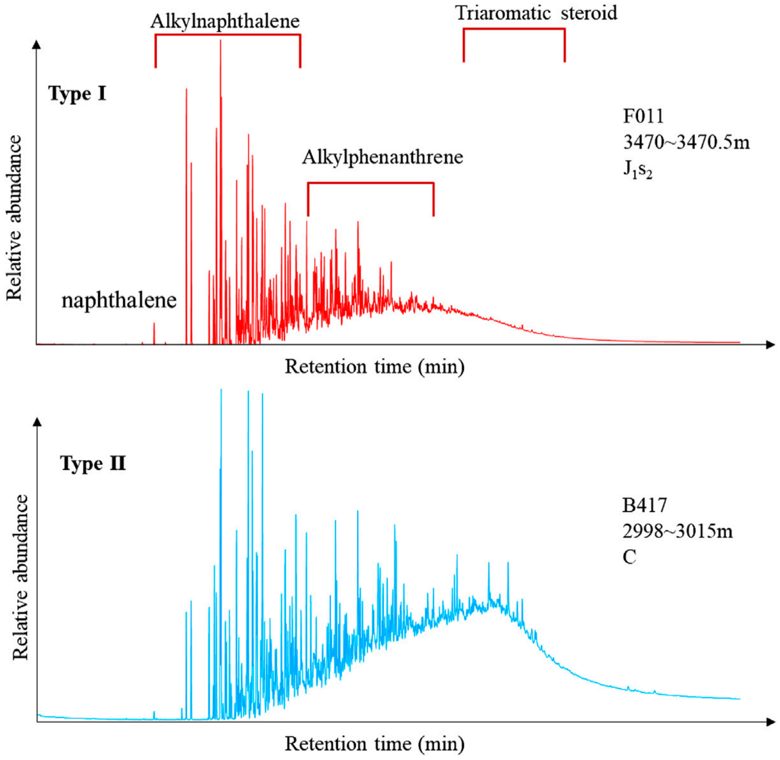


FIGURE 5
Total ion chromatograms (TIC) of aromatic fractions in crude oil from the East Fukang Sag.

dimethylphenanthrenes (DMPs; m/z 206), trimethylphenanthrenes (TMPs; m/z 220), tetramethylphenanthrenes (TeMPs; m/z 234) and trace ethylphenanthrenes (EtPs; m/z 206). They were characterized by predominant DMPs (25.07%–32.43%, with an average of 29.22%) and MPs (23.14%–32.51%, with an average of 27.73%), the content of TMPs was slightly lower (18.00%–28.58%, with an average of 21.58%), while P, TeMPs, and EtPs were in a rather low amount. Similar to naphthalene series, phenanthrene series are also related to the effects of source and depositional environment (Budzinski et al., 1995; Armstroff et al., 2006). However, unlike naphthalene series which may be derived from terrestrial higher plants, phenanthrene series are closely related to lower aquatic organisms (Tuo, 1996; Xu et al., 2019), and there was an obvious negative correlation between the relative content of phenanthrene series and biphenyl series in the studied oil samples (Figure 7). The abundance of phenanthrene series of Oil type II varied from 23.38% to 35.48% (average 28.69%), which was much higher than that of Oil type I whose content ranged from 10.62% to 18.39% (average 13.74%). This might indicate that the organic matter of Oil type II had more abundant lower aquatic organism input. Moreover, retene (1-methyl-7-isopropylphenanthrene, Re) is probably derived from conifer resins, which is usually used to indicate terrestrial higher plant input (van Aarssen et al., 2000). The Re/P ratio of Oil type I ranged from 0.07 to 0.33 (average 0.22), and that of Oil type II was between 0 and 0.11 (average 0.04, Table 2). It showed that the terrestrial higher plant input of Oil type I was much higher than that of Oil type II.

4.3.4 Biphenyl and its alkyl derivatives

The biphenyl series detected in the studied oil samples included biphenyl (BP; m/z 154), methylbiphenyls (MBPs; m/z 168), ethylbiphenyls (EBPs; m/z 182), dimethylbiphenyls (DMBPs; m/z 182) and trimethylbiphenyls (TBPs; m/z 196). The relative abundance of these compounds in Oil type I decreased in the order of DMBPs > MBPs > TMBPs > BPs > EBPs, while Oil type II showed the distribution of MBPs > DMBPs > BPs > TMBPs > EBPs. Generally, biphenyl series are interpreted to be derived from the lignin of higher plants (Alexander et al., 1986; Cumbers et al., 1987; Tuo, 1996). The relative amount of biphenyl series in Oil type I (13.78%–23.92% of total aromatic hydrocarbons, with an average of 18.53%) was much higher than that of Oil type II (2.73%–10.76% of total aromatic hydrocarbons, with an average of 6.58%),

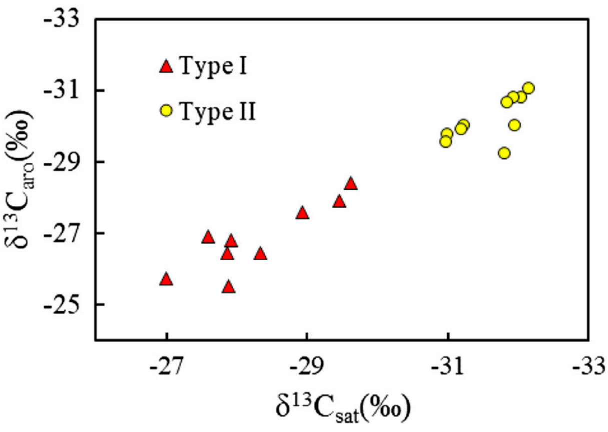


FIGURE 6
The plot of carbon isotope between saturated hydrocarbons and aromatic hydrocarbons of studied oil samples in the East Fukang Sag.

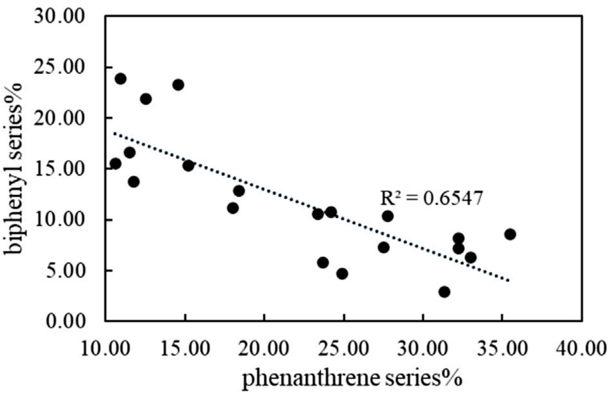


FIGURE 7
The correlation between the relative contents of phenanthrene series and biphenyl series.

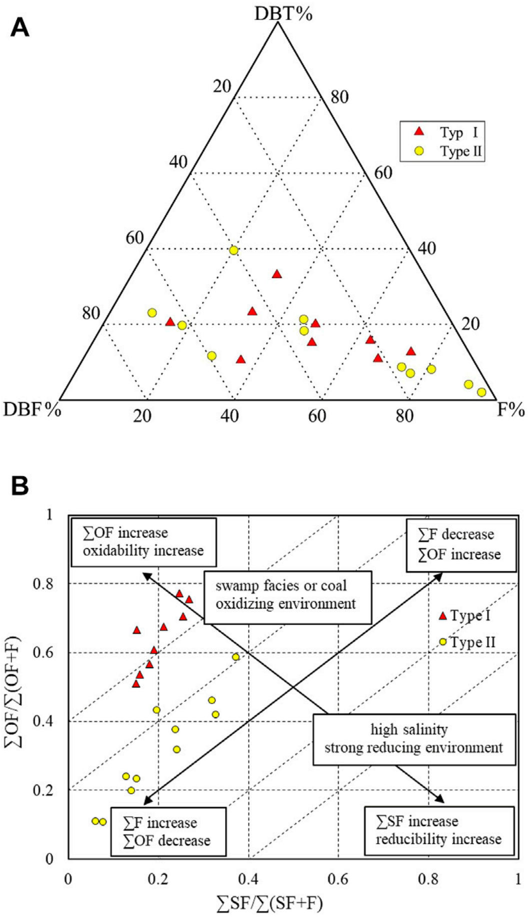


FIGURE 8
(A) Ternary diagram of DBT, F, and DBF of crude oil from the East Fukang Sag, **(B)** The correlation between ∑OF/∑(OF+F) and ∑SF/∑(SF+F) of crude oil. ∑F, ∑OF and ∑SF refer to the contents of C_0-C_2 fluorenes, dibenzofurans, and dibenzothiophenes respectively.

which indicated that the source of Oil type I was richer in terrestrial higher plant organic matter than that of Oil type II.

4.4 Sedimentary environment

4.4.1 Fluorene, dibenzofuran, benzothiophene and their alkyl derivatives

Fluorene (F; m/z 166), dibenzofuran (DBF; m/z 168), dibenzothiophene (DBT; m/z 184) and their alkyl derivatives are deeply studied compounds in aromatic hydrocarbons, they are usually used to indicate the depositional environment, thermal maturity of crude oil and source rocks, and oil migration. Normally, dibenzothiophenes are enriched in strong reducing environments of marine and salt-lake facies, the content of fluorenes is abundant in normal reduction environments, and the content of dibenzofurans is in predominance in an oxidizing environment of swamps and coal measures (Fan et al., 1990; Huang et al., 2006). However, relative contents among DBT, F, and DBF cannot differentiate transitional facies well, and the correlation between ∑OF/∑(OF+F) and ∑SF/∑(SF+F) is believed to be the solution (Li and He, 2008). Consequently, it can be concluded from Figure 8 that the studied crude oil was deposited in a weakly oxidizing to weakly reducing environment (Figure 8A), whereas the depositional environment of Oil type I was more oxidized compared to Oil type II (Figure 8B). It had the same effect as

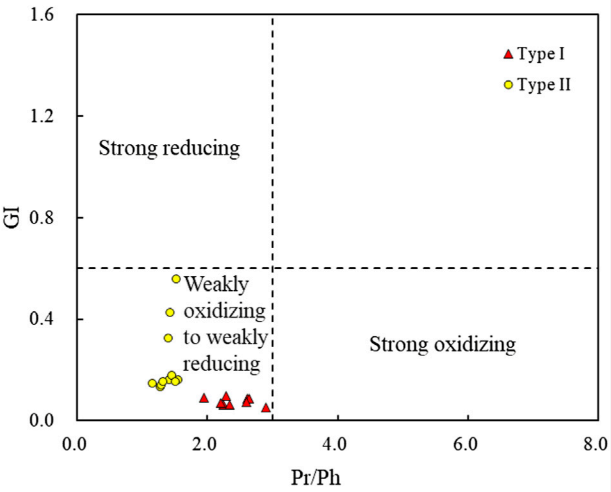


FIGURE 9
Correlation between GI and Pr/Ph of crude oil from the East Fukang Sag.

distinguishing the depositional environment by using GI and Pr/Ph (Li and He, 2008; Figure 9).

Hughes et al. (1995) proposed that the dibenzothiophene/phenanthrene (DBT/P) ratio could be used to classify crude oil source rock depositional environments. Crude oil derived from strong reducing environments, especially source rock lithology with marine carbonates, show the ratios of DBT/*p* > 1, while in lacustrine depositional environments having ratios of DBT/P < 1. The ratios of DBT/P in studied crude oil from the Fukang Sag were far less than 1, within the range of 0.01–0.13 (Table 2), reflecting the original source of studied crude oil formed in lacustrine depositional environments.

4.4.2 Triaromatic steroids

Triaromatic steroids (TAS) may originated by aromatization and demethylaiton from monoaromatic steroids. Since monoaromatic steroids could be derived from sterols through steranes during diagenesis, triaromatic steroids and steranes potentially share the same precursors (Peters et al., 2005; Li et al., 2012; Li et al., 2015). Triaromatic steroid series in the studied oil samples included triaromatic steroids (m/z 231) and methyl triaromatic steroids (m/z 245). The relative content of TAS of Oil type I ranged from 0.02% to 1.01% (average 0.32%), while that of Oil type II varied from 0% to 6.80% (average 2.65%). In general, the abundance of TAS decreases with the increase of maturity (Jia et al., 2009; Bao et al., 2020). Consequently, the Samples 16 and 19 in Oil type II cannot detect TAS may be linked to their relatively high maturity (Table 3). Crude oil and source rocks deposited in freshwater environments have been reported to have high concentration of C_{28}-TAS, while in saline and brackish water environments it is abundant with C_{26}-TAS (Peters et al., 2005). Ratios of C_{26}20S-TAS/C_{28}20S-TAS of Oil type I were within the range of 0–0.11, showing the characteristics of coal-bearing sedimentary environment of fresh water, the same ratios of Oil type II were within the range of 0.13–0.32, indicating lacustrine environment of fresh-brackish water (Meng et al., 2011, Figure 10). In addition, the cross plot of C_{27}20R-TAS/C_{28}20R-TAS versus C_{26}20S-TAS/C_{28}20S-TAS can be used for oil family classification and oil-source correlation (Peters et al., 2005; Zhu et al., 2009). As shown in Figure 11, it can be seen that two types of crude oil were well divided and the organic matter type of Oil type II was better than Oil type I, probably showing a higher proportion of bacteria and algae input (Li et al., 2015).

4.5 Thermal maturity evaluation

The well-established maturity indicators in saturated hydrocarbons, the sterane and hopane isomerization ratios, have been used in many studies to evaluate the maturity of crude oil and source rocks in this area, and good results have been obtained (Yang et al., 2005; Fu et al., 2011; Bai et al., 2017; Gong, et al., 2019). Therefore, they were used as the basis for comparative study in this study. C_{31}22S/(22S+22R) ratio in 17α (H)-extended hopanes was found to be within the range of equilibrium value (0.57–0.62) in most examined crude oil samples (Table 3), implying the maturity of their source rocks was presumed to correspond to Ro > 0.6% (Waples and Machihara, 1990). The ratios of C_{29}20S/(20S + 20R) and C_{29}αββ/(ααα+αββ) sterane for the oil samples were in the range of 0.4–0.48 and 0.36 to 0.56, respectively (Figure 12), both of them were below the equilibrium values, supporting that the oil samples reached the mature stage (Justwan et al., 2006; Stojanović et al., 2007a), and the maturity degree of Oil type II had a wider range than that of Oil type I.

4.5.1 Alkyl naphthalenes

With alkylnaphthalenes and alkylphenanthrenes, the isomers which are substituted in β-positions are thermodynamically more stable than substituents in α-positions. Consequently, the abundance of the α-substituted isomers decreases, relative to those of the β-substituted isomers, with increasing maturity (Stojanović et al., 2007b). Based on this notion, many maturity parameters are defined between these isomers, including methylnaphthalene ratio (MNR), dimethylnaphthalene ratio (DNR), trimethylnaphthalene ratios (TNR-1 and TNR-2), and tetramethylnaphthalene ratio (TeMNr) (Table 3). They generally increase with increasing maturity. In this study,

TABLE 3 Aromatic hydrocarbon maturity parameters in crude oil from the East Fukang Sag.

Sample No.	Well	Fm	Depth (m)	$C_{31}22S/(22S+22R)$	Naphthalene series					Phenanthrene series					Dibenzothiophene series				Equivalent vitrinite reflectance (%)			
					MNR	DNR	TNR-1	TNR-2	TeMNr	MPR	MPI-1	MPI-2	F1	F2	MDR	MDBI	DMDR-1	DMDR-2	R_{c1}	R_{c2}	R_{c3}	R_{c4}
1	F22	J_3q	3092 ~ 3095	0.60	1.45	4.79	0.62	0.76	0.61	1.04	0.71	0.74	0.44	0.23	3.46	0.36	2.07	1.49	0.86	0.83	0.82	0.86
2	F011	J_1s_2	3470 ~ 3473.5	0.60	1.37	5.26	0.64	0.77	0.68	0.97	0.68	0.68	0.43	0.23	4.81	0.37	1.91	1.73	0.86	0.81	0.81	0.84
3	F28	J_2t	3340 ~ 3382	0.58	1.51	5.28	0.64	0.76	0.57	1.00	0.70	0.72	0.46	0.24	4.22	0.34	1.76	1.51	0.86	0.82	0.87	0.82
4	FD022	J_2t	3297 ~ 3318	0.58	1.41	4.50	0.52	0.73	0.64	1.03	0.77	0.78	0.45	0.23	3.31	0.37	1.98	1.82	0.84	0.86	0.85	0.85
5	FD17	J_3q	2869 ~ 2875	0.57	1.48	5.40	0.63	0.79	0.64	1.17	0.87	0.89	0.49	0.25	5.65	0.44	2.84	1.80	0.87	0.92	0.93	0.97
6	FD16	J_1s	2350 ~ 2354	0.56	1.43	4.89	0.62	0.74	0.55	1.13	0.70	0.74	0.47	0.25	5.33	0.36	1.74	1.83	0.85	0.82	0.90	0.81
7	FD9	J_2t	2813 ~ 2879	0.56	1.36	4.29	0.59	0.72	0.53	1.12	0.67	0.68	0.46	0.23	3.58	0.37	1.54	1.44	0.83	0.80	0.87	0.79
8	FD051	J_2t	2940 ~ 2958	0.56	1.34	3.77	0.39	0.60	0.45	1.12	0.70	0.76	0.45	0.24	3.85	0.36	1.45	1.34	0.76	0.82	0.84	0.77
9	S24	J_1s	1930 ~ 1933	0.58	1.46	5.55	0.66	0.77	0.69	1.07	0.71	0.75	0.46	0.24	5.17	0.35	1.67	1.57	0.86	0.83	0.86	0.80
10	F46	P_2l	3157 ~ 3165	0.56	1.82	8.31	0.96	0.68	0.71	0.99	0.66	0.64	0.44	0.22	5.60	0.43	2.20	1.83	0.81	0.80	0.82	0.88
11	T62	T_2k	2720 ~ 2726	0.56	1.63	5.99	0.75	0.63	0.54	1.02	0.59	0.58	0.45	0.22	5.21	0.42	2.07	1.78	0.78	0.75	0.84	0.86
12	B418	E	1773 ~ 1779	0.55	1.21	5.00	0.82	0.69	0.50	0.99	0.58	0.56	0.43	0.21	4.25	0.41	1.92	1.41	0.82	0.75	0.79	0.84
13	B417	C	2998 ~ 3025	0.57	0.91	2.32	0.55	0.53	0.37	0.73	0.43	0.42	0.34	0.17	2.42	0.30	1.32	0.88	0.72	0.66	0.59	0.76
14	SQ061	P_3wt	1969 ~ 1973	0.57	1.33	6.71	0.85	0.69	0.67	1.03	0.72	0.67	0.45	0.21	3.56	0.41	2.14	1.79	0.81	0.83	0.85	0.87
15	F010	P_3w	2756 ~ 2779	0.53	1.56	9.00	1.01	0.75	0.75	1.18	0.75	0.75	0.49	0.25	5.13	0.39	2.52	2.07	0.85	0.85	0.94	0.85
16	KT1	P_3w_1	5116 ~ 5121	0.61	2.23	13.50	1.49	0.91	0.91	1.52	0.91	0.95	0.56	0.29	8.28	0.49	6.91	3.59	0.95	0.95	1.08	1.51
17	F48	P_3w	4579 ~ 4629	0.56	1.94	9.18	1.17	0.82	0.87	1.31	0.84	0.89	0.52	0.28	7.29	0.43	3.36	2.13	0.89	0.90	1.01	1.04
18	F43	P_3w	3132 ~ 3214	0.55	1.72	9.30	0.92	0.72	0.80	1.17	0.75	0.75	0.48	0.24	6.19	0.42	2.45	1.94	0.83	0.85	0.92	0.91
19	F49	P_3w_1	5615 ~ 5672	0.62	2.28	13.25	1.52	0.97	0.91	1.87	1.04	1.10	0.61	0.32	10.59	0.51	6.69	3.89	0.98	1.03	1.21	1.51
20	F25	P_3wt	2775 ~ 2783	0.56	0.95	3.73	0.78	0.61	0.46	0.95	0.46	0.47	0.41	0.21	4.58	0.35	1.80	1.24	0.77	0.67	0.75	0.82

Notes: $C_{31}22S/(22S+22R)$, 17α (H)-C_{31}hopane(22S)/17α(H)-C_{31}hopane(22S+22R) (m/z=191 of saturates); MNR, 2-MN/1-MN; DNR=(2,6-DMN + 2,7-DMN)/1,5-DMN; TNR-1, 2,3,6-TMN/(1,4,6-TMN + 1,3,5-TMN); TNR-2, (1,3,7-TMN+ 2,3,6-TMN)/(1,4,6-TMN + 1,3,5-TMN+1,3,6-TMN); TeMNr, 1,3,6,7-TeMN/(1,3,6,7-TeMN +1,2,5,6-TeMN); MPR, 2-MP/1-MP; MPI-1, 1.5 × (2-MP + 3-MP)/(P + 1-MP + 9-MP); MPI-2, 3 × (2-MP)/(P + 1-MP + 9-MP); F1, (3-MP + 2-MP)/(1-MP + 2-MP + 3-MP + 9-MP); F2, 2-MP/(1-MP + 2-MP + 3-MP + 9-MP); MDR, 4-MDBT/1-MDBT; MDBI, 4-MDBT/(DBT +1-MDBT +2- MDBT +3-MDBT +4-MDBT); DMDR-1, 4,6-DMDBT/1,4-DMDBT; DMDR-2, 2,4-DMDBT/1,4-DMDBT; $R_{c1} = 0.4 + 0.6 \times TNR\text{-}2$; $R_{c2} = 0.6 \times MPI + 0.4$ ($R_o < 1.35\%$); $R_{c3} = 2.242F1 - 0.166$; $R_{c4} = 0.14 \times DMDR\text{-}1 + 0.57$.

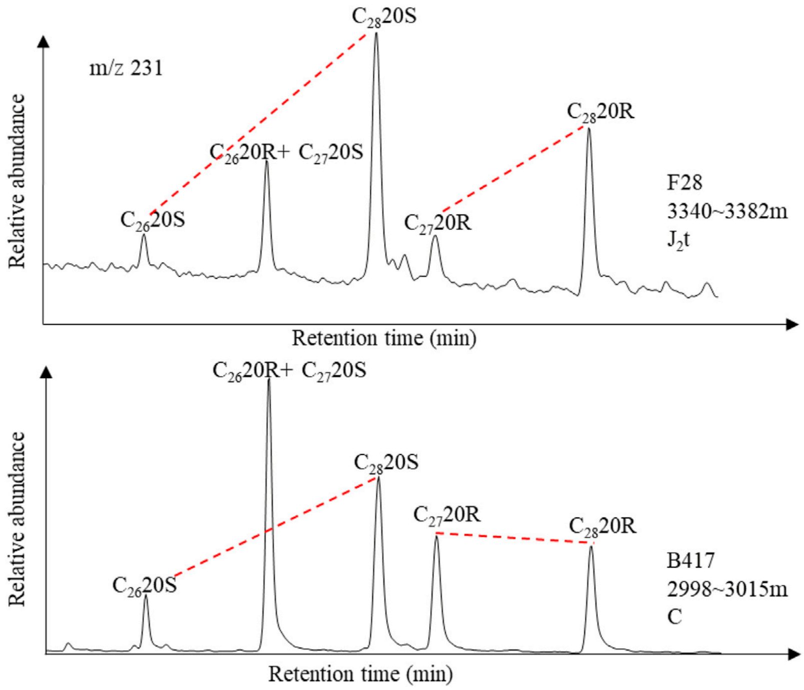


FIGURE 10
Partial m/z 231 mass chromatogram of two representative samples from two types of oil.

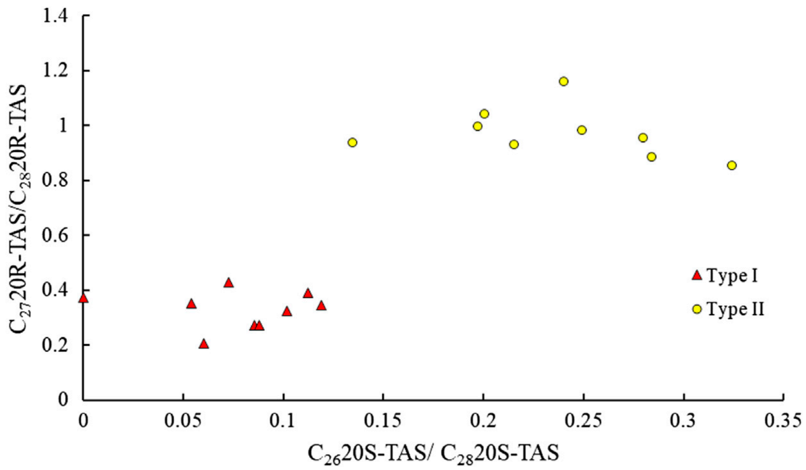


FIGURE 11
The cross plot of $C_{26}20S$-TAS/$C_{28}20S$-TAS versus $C_{27}20R$-TAS/$C_{28}20R$-TAS in crude oil from the East Fukang Sag.

they showed a good linear correlation with each other, suggesting that maturity parameters from alkylnaphthalenes can effectively indicate the maturity of studied crude oil. Thereinto, according to the empirical formula for calculating equivalent vitrinite reflectance (R_{c1}) from TNR-2 proposed by Radke et al. (1986), the R_{c1} of studied crude oil was 0.72%–0.98% (average 0.84%), and it indicated studied oil samples were in the mature stage.

4.5.2 Alkyl phenanthrenes

Alkylphenanthrenes are not very susceptible to biodegradation and thus are good maturity indicators of

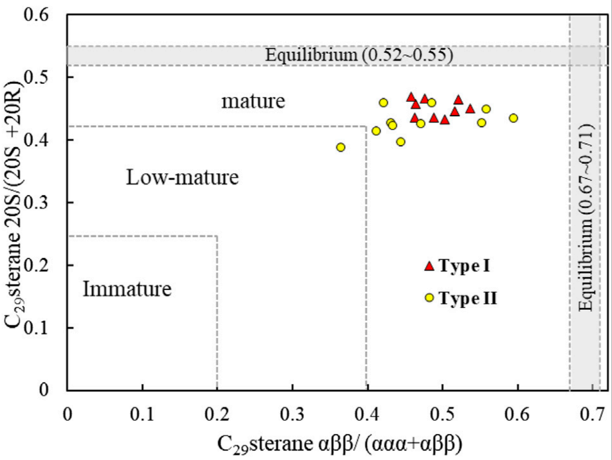


FIGURE 12
Cross plot of C_{29} sterane αββ/(ααα+βββ) and C_{29} sterane 20S/(20S+20R) maturity ratios of crude oil in the East Fukang Sag (after Justwan et al., 2006).

oils over a wide range (Volkman et al., 1984; Radke, 1988). Phenanthrene- and methylphenanthrene-related parameters have long been used for maturity evaluation. MPs include α-substituents 9-MP, 1-MP and β-substituents 3-MP, 2-MP. 3-MP and 2-MP are thermally more stable than 9-MP and 1-MP, which can be originated from the 1-MP and 9-MP by rearrangement and/or from phenanthrene through methylation reactions (Radke et al., 1982). Accordingly, parameters MPR, MPI-1, MPI-2, F1, and F2 were proposed to indicate oil maturity (Table 3). On the basis of the empirical formula from MPI-1 proposed by Radke et al. (1982), the calculated vitrinite reflectance (R_{c2}) values of crude oil samples ranged from 0.66% to 1.03%, with an average of 0.83%. Additionally, the calculated vitrinite reflectance (R_{c3}) from F1 (Kvalheim et al., 1987), ranging from 0.60% to 1.21% (average 0.88%), was in reasonably good agreement with MPI-1 measurements. As a consequence, the studied oil samples in the East Fukang Sag were generally in the mature stage, which was consistent with the results obtained from alkyl naphthalene parameters.

4.5.3 Alkyl dibenzothiophenes

Alkyl dibenzothiophenes are resistant to biodegradation and have sustained sensitivity to thermal evolution, making them effective maturity parameters of crude oil from low mature stage to high mature stage. With the increase of thermal evolution degree, methyl dibenzothiophene (MDBT, m/z 198) undergoes methyl rearrangement and demethylation. The methyl rearrangement is mainly represented by the transformation from 1-MDBT and (2+3)-MDBT to 4-MDBT, demethylation is manifested as the transformation from MDBT to DBT. Thus, two parameters, MDR and MDBI (Table 3), were proposed (Radke and Willsch, 1994; Chakhmakhchev et al., 1997; Wei et al., 2001). In addition, Chakhmakhchev et al. (1997) found that with the increase of thermal evolution level, the relative contents of 2,4-dimethyldibenzothiophene (2,4-DMDBT) and 4,6-dimethyldibenzothiophene (4,6-DMDBT) increased, while the relative content of 1,4-dimethyldibenzothiophene (1,4-DMDBT) decreased. Hence, the values of DMDR-1 (4, 6-DMDBT/1, 4-DMDBT) and DMDR-2 (2,4-DMDBT/1,4-DMDBT) increase with the increase of maturity, which can also indicate the maturity of crude oil and sedimentary organic matter. The ratios DMDR-1 and DMDR-2 showed a good positive correlation with MDR and each other (Figure 13), and the calculated vitrinite reflectance from DMDR-1 (R_{c4}) ranged from 0.75% to 1.50%, with an average of 0.92% (Luo et al., 2001). Although it was a bit higher than R_{c1}, R_{c2} and R_{c3} calculated by alkyl naphthalene and alkyl phenanthrene parameters, it could qualitatively reflect that the studied crude oil in the East Fukang Sag was mature oil.

4.5.4 Methyltrimethyltridecylchromans

A series of mono-to trimethylated 2-methyl-2-(4, 8, 12-trimethyltridecyl) chromans (MTTCs) have been reported in large numbers of sediments and crude oil. They generally occur as five isomers of δ-MTTC (8-methyl-MTTC), β-MTTC (5,8-dimethyl-MTTC), γ-MTTC (7,8-dimethyl-MTTC), ζ-MTTC (5,7-dimethyl-MTTC) and α-MTTC (5,7,8-trimethyl-MTTC) (Sinninghe Damsté et al., 1987; Figure 14). Generally, MTTCs have weak thermal stability, and their relative content gradually decreases with the increase of maturity until they disappear. Therefore, MTTCs are mainly enriched in immature and low-mature sediments and crude oil (Koopmans et al., 1998; Jiang et al., 2018). Specially, γ-MTTC and β-MTTC are sensitive to maturity variation, and β-MTTC is thermally more stable than γ-MTTC (Bao et al., 2009). Schwark and Püttmann (1990) also noticed that α-MTTC was the dominant compound in the more mature samples. In this study, MTTCs were not detectable in most crude oil samples from Oil type I and only two samples detected trace amount of α-MTTC. In comparison, MTTCs were detected in most oil samples from Oil type II, and the content was much higher than that of Oil type I. However, all of them with the characteristics of strong dominance of α-MTTC% and ratio β-MTTC/γ-MTTC > 1 (Table 3). Consequently, the thermal maturity of crude oil in the East Fukang Sag was relatively high (at least in the mature

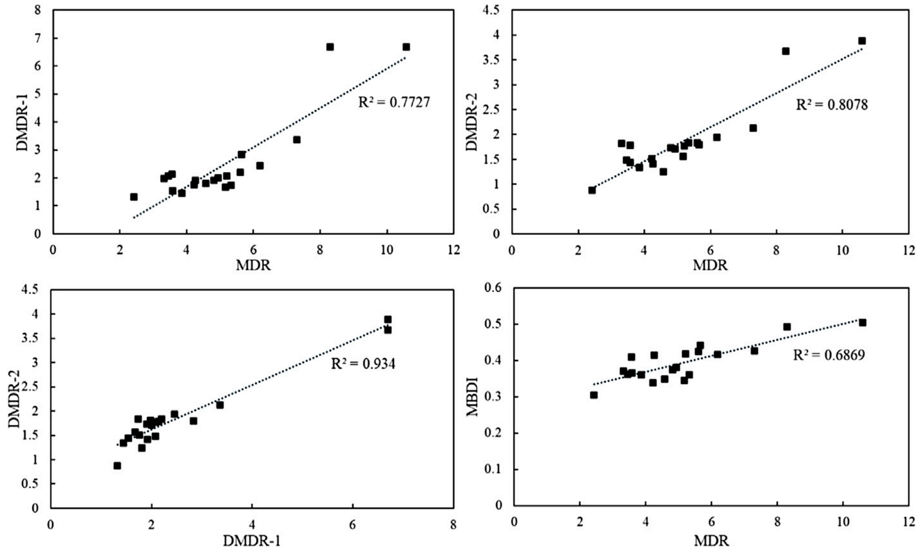


FIGURE 13
Correlation diagrams of maturity parameters of alkyl dibenzothiophenes in crude oil from the East Fukang Sag.

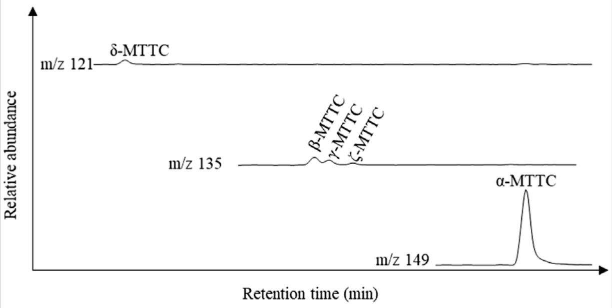


FIGURE 14
Partial m/z 121, 135, and 149 mass chromatograms of a representative sample from well B417, showing the distribution of methyltrimethyltridecylchromans (MTTCs).

stage), which was consistent with the results drawn from the above aromatic hydrocarbons.

5 Conclusion

The results of this study indicated that the crude oil samples from the East Fukang Sag contained 1-ring to 5-ring aromatic hydrocarbons, and were dominated by bicyclic and tricyclic compounds, showing a typical front peak distribution. According to the composition characteristics of the main aromatic hydrocarbons, the crude oil samples could be divided into two types. It was found that Oil type I was characterized by high abundance of naphthalene series, biphenyl series, and dibenzofuran series, while Oil type II was characterized by high abundance of phenanthrene series, fluorene series, triaromatic steroid series, and obvious MTTCs. Based on source-related and depositional environment-related aromatic parameters, two types of crude oil showed distinct geochemical characteristics. Oil type I was derived from a source containing predominantly terrestrial higher plant organic matter deposited in a partially oxidized freshwater environment, while the organic matter of Oil type II was mainly lower aquatic organism and deposited in a relatively reductive and fresh-brackish lacustrine environment.

The selected maturity parameters of alkyl naphthalenes, alkyl phenanthrenes, alkyl dibenzothiophenes and MTTCs are effective in estimating the maturity of the crude oil from the East Fukang Sag. The results revealed that the studied oil samples have entered the mature stage, despite the calculated vitrinite reflectance based on different series of aromatic hydrocarbons were slightly deviated. This was further supported by well-established maturity parameters based on sterane and hopane isomerization ratios from saturated hydrocarbons.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

YL: Investigation, Methodology, Writing—review and editing. DH: Conceptualization, Methodology, Supervision. XC and XH: Investigation, Writing—review. CN: review and English editing.

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Conflict of interest

Publisher's note

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