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Original Paper

Geochemical identification of a source rock affected by migrated hydrocarbons and its geological significance: Fengcheng Formation, southern Mahu Sag, Junggar Basin, NW China

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ABSTRACT

The Fengcheng Formation is a crucial source rock and the primary reservoir for oil accumulation in the Mahu Sag. Crude oils are distributed throughout the Fengcheng Formation, ranging from the edge to the interior of the sag in the southern Mahu Sag. These crude oils originate from in-situ source rocks in shallowly buried areas and the inner deep sag. During migration, the crude oil from the inner deep sag affects the source rocks close to carrier beds, leading to changes in the organic geochemical characteristics of the source rocks. These changes might alter source rock evaluations and oil-source correlation. Based on data such as total organic carbon (TOC), Rock-Eval pyrolysis of source rocks, and gas chromatography-mass spectrometry (GC-MS) of the saturated fraction, and considering the geological characteristics of the study area, we define the identification characteristics of source rock affected by migrated hydrocarbons and establish the various patterns of influence that migrated hydrocarbons have on the source rock of the Fengcheng Formation in the southern Mahu Sag. The source rocks of the Fengcheng Formation are mostly fair to good, containing mainly Type II organic matter and being thermally mature enough to generate oil. Source rocks affected by migrated hydrocarbons exhibit relatively high hydrocarbon contents (S_1/TOC > 110 mg HC/g TOC, Extract/TOC > 30 %, HC: hydrocarbon), relatively low Rock-Eval T_{max} values, and relatively high tricyclic terpane contents with a descending and mountain-shaped distribution. Furthermore, biomarker composition parameters indicate a higher thermal maturity than in-situ source rocks. Through a comparison of the extract biomarker fingerprints of adjacent reservoirs and mudstones in different boreholes, three types of influence patterns of migrated hydrocarbons are identified: the edge-influence of thin sandstone-thick mudstone, the mixed-influence of sandstone-mudstone interbedded, and the full-influence of thick sandstone-thin mudstone. This finding reminds us that the influence of migrated hydrocarbons must be considered when evaluating source rocks and conducting oil-source correlation.

1. Introduction

The Mahu Sag, located in the Junggar Basin, is a significant oil and gas exploration region with abundant potential. The primary source rock in this sag is the Fengcheng Formation, which not only supplies the amount of oil and gas to various reservoirs such as the Carboniferous, Triassic, Jurassic, and Cretaceous but also is an essential oil and gas play (Qin et al., 2016; Zhi et al., 2021). Scholars have recently published a plethora of essential and new understanding, advances, and achievements regarding the tectonic, sedimentation, reservoir, and source rock of the Fengcheng Formation in Mahu Sag (Cao et al., 2015; Chen et al., 2016; Chen et al., 2017; Gao et al., 2018; Yu et al., 2018; Tang et al., 2021; Zhi et al., 2021; Dang et al., 2023). However, the influence of migrated hydrocarbons is not considered in oil-source correlation and source

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rock evaluation. Crude oils from more mature source rocks in deep sag may affect the source rock sample, resulting in not only a comparatively high Rock-Eval S_1 peak, production index (PI), and low T_{max} values (King et al., 2015; Li et al., 2018) but also changing the biomarker composition of source rock extract. Therefore, identifying and eliminating the influence of the migrated hydrocarbons on organic geochemical parameters is essential for source rock evaluation and oil-source correlation. The objective of this paper is to identify the characteristics of the Fengcheng Formation source rocks affected by migrated hydrocarbons and to summarize the influence patterns in the south of Mahu Sag using the data of TOC, Rock-Eval pyrolysis, and gas chromatography-mass spectrometry (GC-MS) of saturated hydrocarbon, along with the geological characteristics of the study area. The findings of this study contribute to the objectivity of source rock evaluation and oil-source correlation, especially in the context of near-source migration and accumulation or in the research of shale oil & gas.

2. Geologic setting

The Junggar Basin, China's second largest inland basin, is located in northwestern China, with an area of 1.3×10^5 km^2 (Fig. 1a) (Wang et al., 2000; Zhang and Zhang, 2006). The Mahu Sag, with an area of about 5×10^3 km^2, is located northwest of the Junggar Basin and has a structural pattern characterized by a monocline structure of 3°–5° to the southeast. It neighbors the Wu-xia thrust belts and Ke-bai thrust belts in the northwest, the Yingxi Sag, Sangequan Uplift, and Xiayan Uplift in the east, and the Dabasong Uplift in the southwest (Fig. 1b) (He et al., 2018; Su et al., 2020; Yu et al., 2021). The researched area of this paper is located in the south of Mahu Sag (Fig. 1a).

From bottom to top of the strata in Mahu Sag, there are recorded Carboniferous, Permian, Triassic, Jurassic, Cretaceous, Paleogene, Neogene, and Quaternary sediments (Fig. 1c). Multiple sets of regional unconformities develop among them (Fig. 1c). This paper focuses on the Fengcheng Formation, which was deposited in a lacustrine saltwater environment with complicated and changeable lithology, mainly consisting of sandy conglomerate, sandstone, mudstone, dolomite, tuffaceous mudstone, and volcanic rock. The Fengcheng Formation (referred to as P_1f) was divided into three members from top to bottom: Mbr 3, Mbr 2, and Mbr 1 (Fig. 2) (Yu et al., 2016; Feng, 2017; Ren et al., 2017), with Mbr 3 and Mbr 2 being the primary source rocks (Qin et al., 2016; Lei et al., 2017; Tang et al., 2021; You et al., 2021).

3. Samples and methods

A total of 60 mudstone samples in the Fengcheng Formation were collected from ten wells in the south of Mahu Sag: Well BBF (2 samples), Well MHCI (11 samples), Well MHBH (15 samples), Well MHZBE (10 samples), Well MHBF (1 sample), Well KBZG (14 samples), Well KBZD (2 samples), Well JLAG (1 sample), Well JLCD (1 sample) and Well BQB (3 samples) (Fig. 2). Total organic carbon (TOC) and Rock-Eval pyrolysis analyses were conducted on all samples. Twenty samples were performed solvent extraction, extract, and GC-MS of the saturated fraction. The GC-MS data of 24 crude oil samples and kerogen carbon isotope data from various formations were obtained from Xinjiang Oilfield Company.

3.1. Total organic carbon (TOC) and Rock-Eval pyrolysis

All the source rock samples were crushed and screened with an 80-mesh sieve to obtain powder samples. The TOC and Rock-Eval analysis of the rock powder samples were respectively performed on a LECO CS-230 carbon/sulfur analyzer and OGE-II rock pyrolyzer, which can chiefly obtain the data of total organic carbon (TOC, w.t.%), residual hydrocarbon (S_1, mg HC/g Rock), pyrolysis hydrocarbon (S_2, mg HC/g Rock), and the peak temperature of pyrolysis (T_{max}, °C). The S_1+S_2 (mg HC/g Rock), the production index [$PI=S_1/(S_1+S_2)$], the hydrogen index ($HI=S_2/TOC \times 100$, mg HC/g TOC), and the hydrocarbon index ($HCI=S_1/TOC \times 100$, mg HC/g TOC) and other parameters can be calculated using these experimental results.

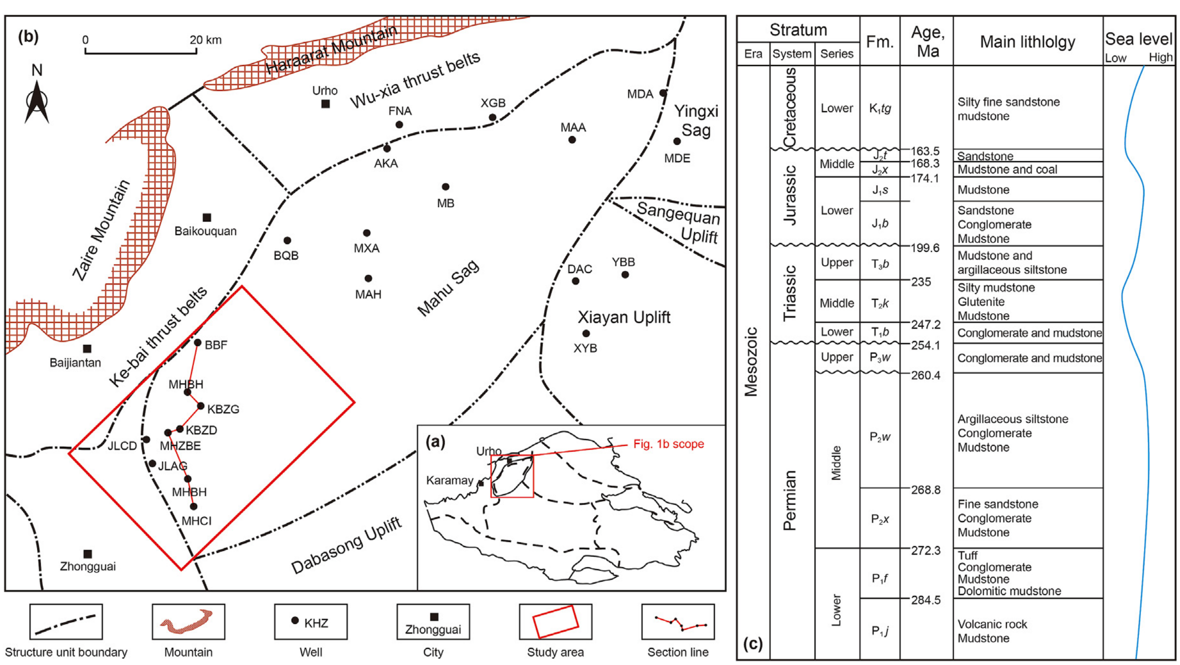

Fig. 1. (a) Location of the Mahu Sag in Junggar Basin. (b) Location of the wells and structural units of the Mahu Sag (The red polygon represents the study region). (c) Stratigraphic column of the Mahu Sag, the lithology of the Fengcheng Formation mainly includes tuffaceous sandstone, conglomerate, and mudstone (Ge, 2020). Fm. = Formation.

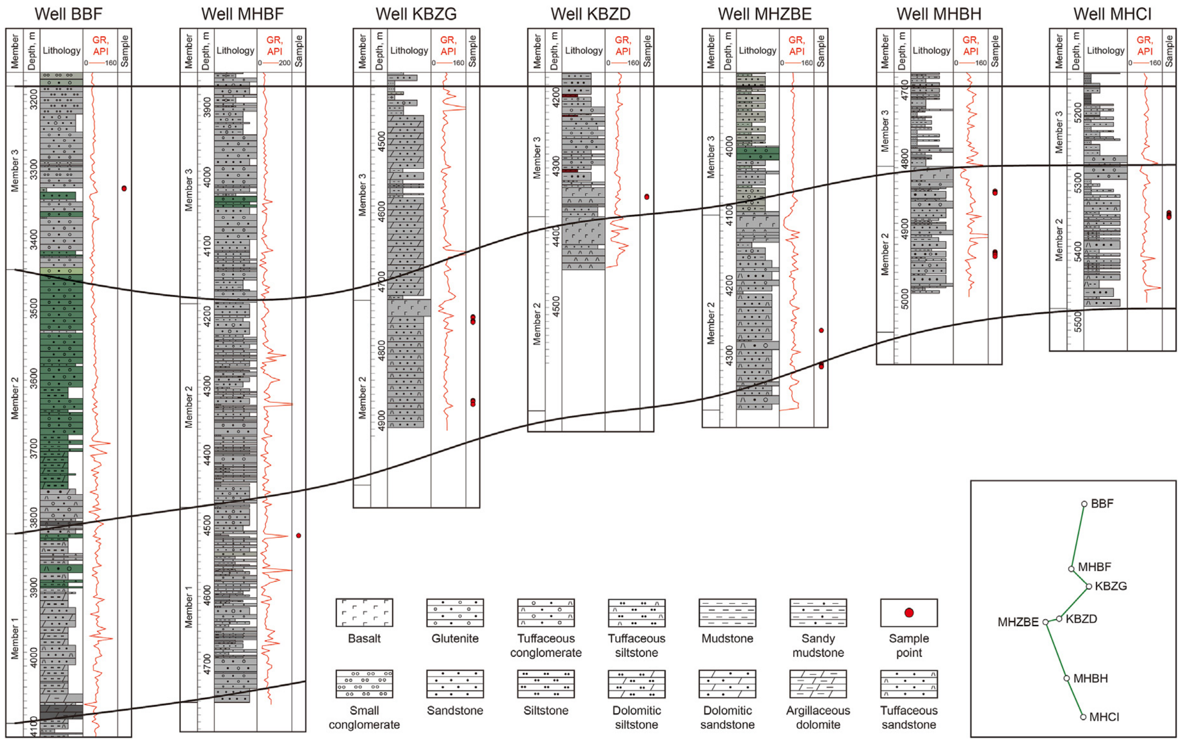

Fig. 2. Stratigraphic column and profile of Well BBF-Well MHBF-Well KBZG-Well KBZD-Well MHZBE-Well MHBH-Well MHCI of Mahu Sag in the northwest Junggar Basin. The red points in the figure indicate the positions of the source rock samples used in this paper.

3.2. Gas chromatography-mass spectrometry (GC-MS)

Soxhlet apparatus and chloroform as the solvent were used to obtain extract (bitumen) in 20 source rock powdered samples (approximately 100 g) for 72 h in a water bath (80 °C) (Tissot and Welte, 1984). Next, the fraction separation of 20 bitumen samples was performed by conventional column chromatography. Dissolve the asphaltene in excessive petroleum ether (*n*-hexane) for 24 h and filter to obtain insoluble asphaltene. Using a silica gel alumina chromatography column, the soluble residue was separated into saturated, aromatic hydrocarbon, and resin fractions with *n*-hexane, toluene, and toluene/methanol (1:1, v:v), respectively. Then, the thermo-Finnigan Trace-DSQ instrument was used to analyze GC-MS analysis for the saturated fractions. The initial oven temperature was maintained at 50 °C for 1 min and then heated to 120 °C at the rate of 20 °C/min, 250 °C at the rate of 4 °C/min, and 310 °C at the rate of 3 °C/min and maintain 30 min (Gao et al.,2017a, 2018).

3.3. Carbon isotope of kerogen and bitumen

The Soxhlet extraction method extracted all the powder samples of the Fengcheng Formation (< 0.2 mm), and the $\delta^{13}C$ of the extract was determined by the phosphoric acid method. The kerogen samples were obtained from the pre-extracted sample according to the China National Standard SY/T 5123–1995, and $\delta^{13}C$ kerogen was determined. The carbon isotope data of kerogen and asphaltene from other formations (including Lower Wuerhe Formation, Jiamuhe Formation, and Carboniferous) was obtained from Xinjiang Oilfield Company.

3.4. Organic petrography

Cut the core sample vertically, then polish it with a Buehler automatic grinding and polishing machine (EcoMet 250 with AutoMet 250). The prepared core samples were observed under the Leica microscope (DM6 M LIBS) with reflected and fluorescence lights and photographed and described to record the characteristics of the sample's microscopic components (Liu et al., 2017).

4. Results and discussion

4.1. Evaluation of source rock

The organic matter abundance, type, and thermal maturity of the source rock are usually assessed using TOC, Rock-Eval pyrolysis parameters, and chloroform extract content (Tissot and Welte, 1984; Waples, 1985; Peters, 1986; Peters and Cassa, 1994; Mukhopadhyay et al., 1995). The organic geochemical data of the Fengcheng Formation source rock samples can be found in Tables 1 and 2. The TOC contents and Rock-Eval S_1+S_2 values range from 0.10 to 2.01 % (average = 0.74 %) and 0.02–8.25 mg HC/g Rock (average = 2.42 mg HC/g Rock), respectively (Tables 1 and 2). As shown in Fig. 3a, the Fengcheng Formation source rocks are fair to excellent. The HI values of the source rocks fall in the range of 7.14–390.86 mg HC/g TOC with an average value of 169.48 mg HC/g TOC (Tables 1 and 2), indicating that there is mainly Type II$_2$ organic matter with a few Type III (Fig. 3b). This is further supported by the Rock-Eval S_2 values, which range from 0.01 to 7.27 mg HC/g Rock (average = 1.60 mg HC/g Rock). The Rock-Eval T_{max} and PI are usually used to determine the thermal maturity of source rocks (Tissot and Welte, 1984; Espitalié et al., 1985; Peters and Cassa, 1994; Hunt, 1996; Ghorri, 2001; Shalaby et al., 2012). The T_{max} and PI values of the Fengcheng Formation source rock samples change from 414 °C to 456 °C (average = 440 °C) and 0.05 to 0.67 (average = 0.34), respectively (Tables 1 and 2). The cross plots of T_{max} versus depth and T_{max} versus PI (Fig. 3c–d) indicate that most source rock samples are in the low mature to mature stage, with

Table 1
TOC and Rock-Eval pyrolysis data for the Fengcheng Formation source rock samples in the south of Mahu Sag.

Well	Depth, m	TOC, %	S_1, mg/g	S_2, mg/g	S_1+S_2, mg/g	PI	HI, mg/g	HCI, mg/g	T_{max}, °C	Extract, %	Extract/TOC, %	Affected
JLAG	3784.10	0.38	0.27	0.37	0.64	0.42	97.37	71.05	442	0.02	4.58	
JLCD	4340.00	0.64	1.50	1.97	3.47	0.43	307.81	234.38	/	0.46	71.44	✓
KBZD	4344.92	0.28	0.02	0.07	0.09	0.22	25.00	7.14	435	0.02	5.82	
KBZD	4346.40	1.17	0.41	3.95	4.36	0.09	337.61	35.04	434	0.26	21.80	
KBZG	4757.20	0.58	0.45	1.05	1.50	0.30	181.03	77.59	428	0.15	26.22	
KBZG	4856.40	1.40	1.73	3.14	4.87	0.36	224.29	123.57	426	0.46	33.09	✓
KBZG	4860.21	0.57	0.68	0.92	1.60	0.43	161.40	119.30	421	0.18	32.42	✓
MHZBE	4255.32	0.80	0.65	1.84	2.49	0.26	230.00	81.25	439	0.13	16.86	
MHZBE	4302.30	1.03	0.24	1.41	1.65	0.15	136.89	23.30	443	0.13	12.50	
MHZBE	4302.97	1.18	0.36	1.68	2.04	0.18	142.37	30.51	441	0.19	15.96	
MHBF	4513.50	0.81	0.48	1.43	1.91	0.25	176.54	59.26	450	0.14	17.00	
MHBH	4840.35	2.01	2.30	5.72	8.02	0.29	284.58	114.43	435	0.68	33.80	✓
MHBH	4842.00	1.10	1.93	2.73	4.66	0.41	248.18	175.45	432	0.42	37.89	✓
MHBH	4932.80	1.63	3.24	5.01	8.25	0.39	307.36	198.77	429	0.85	52.02	✓
MHBH	4937.05	1.88	1.46	5.87	7.33	0.20	312.23	77.66	435	0.47	24.85	
MHCI	5341.40	0.88	0.36	1.24	1.60	0.23	140.91	40.91	437	0.20	22.39	
MHCI	5342.06	0.44	0.16	0.44	0.60	0.27	100.00	36.36	437	0.09	20.91	
MHCI	5344.46	0.17	0.02	0.05	0.07	0.29	29.41	11.76	/	0.01	7.41	
MHCI	5344.40	1.18	0.85	1.91	2.76	0.31	161.86	72.03	433	0.33	27.60	
BQB	4287.55	0.38	0.10	0.43	0.53	0.19	113.16	26.32	445	0.02	4.05	
BQB	4293.72	0.13	0.09	0.05	0.14	0.64	38.46	69.23	439	0.01	4.62	
KBZG	4755.54	0.42	0.40	0.64	1.04	0.38	152.38	95.24	449	0.09	21.62	
KBZG	4855.14	1.18	1.72	3.18	4.90	0.35	269.49	145.76	431	0.49	41.71	✓
KBZG	4860.08	1.03	0.71	1.63	2.34	0.30	158.25	68.93	437	0.17	16.81	
MHBH	4842.73	1.32	2.97	3.50	6.47	0.46	265.15	225.00	442	0.53	39.99	✓
MHBH	4843.47	0.70	0.49	1.35	1.84	0.27	192.86	70.00	442	0.22	31.11	
MHBH	4842.30	1.27	2.50	2.97	5.47	0.46	233.86	196.85	442	0.49	38.74	✓
MHBH	4842.60	1.22	2.36	2.79	5.15	0.46	228.69	193.44	442	0.44	35.77	✓
MHBH	4843.40	0.70	0.89	1.66	2.55	0.35	237.14	127.14	441	0.24	34.29	✓
MHBH	4933.07	0.48	1.32	0.97	2.29	0.58	202.08	275.00	/	0.24	49.54	✓
MHBH	4934.20	0.92	3.81	2.77	6.58	0.58	301.09	414.13	414	0.79	85.98	✓
MHBH	4934.93	0.52	2.05	1.02	3.07	0.67	196.15	394.23	430	0.34	66.06	✓
MHBH	4935.94	1.52	1.75	3.92	5.67	0.31	257.89	115.13	444	0.44	29.16	✓
MHBH	4939.49	1.86	0.37	7.27	7.64	0.05	390.86	19.89	445	0.02	1.28	
KBZG	4749.16	0.20	0.07	0.10	0.17	0.41	50.00	35.00	453	0.01	6.75	
KBZG	4749.98	0.24	0.11	0.20	0.31	0.35	83.33	45.83	446	0.03	12.38	
KBZG	4750.61	0.19	0.08	0.14	0.22	0.36	73.68	42.11	456	0.01	7.21	
KBZG	4755.13	0.30	0.23	0.42	0.65	0.35	140.00	76.67	447	0.06	20.73	
KBZG	4755.66	0.52	0.50	0.89	1.39	0.36	171.15	96.15	449	0.13	24.04	
KBZG	4755.88	0.12	0.07	0.12	0.19	0.37	100.00	58.33	436	0.03	21.08	
KBZG	4854.74	0.16	0.17	0.14	0.31	0.55	87.50	106.25	/	0.04	24.00	
MHZBE	4305.17	0.14	0.01	0.01	0.02	0.50	7.14	7.14	441	/	/	
MHZBE	4305.45	0.52	0.21	0.79	1.00	0.21	151.92	40.38	446	/	/	
MHZBE	4305.84	0.20	0.03	0.09	0.12	0.25	45.00	15.00	447	/	/	
MHZBE	4306.21	0.46	0.08	0.31	0.39	0.21	67.39	17.39	451	/	/	
MHZBE	4306.40	0.76	0.13	0.91	1.04	0.13	119.74	17.11	447	/	/	
MHZBE	4306.66	1.02	0.28	2.55	2.83	0.10	250.00	27.45	447	/	/	
MHZBE	4306.92	1.03	0.36	2.88	3.24	0.11	279.61	34.95	445	/	/	
MHCI	5345.17	0.10	0.03	0.06	0.09	0.33	60.00	30.00	439	/	/	
MHCI	5345.75	0.19	0.14	0.19	0.33	0.42	100.00	73.68	435	/	/	
MHCI	5346.26	0.63	0.39	1.07	1.46	0.27	169.84	61.90	444	/	/	
MHCI	5346.49	0.40	0.28	0.68	0.96	0.29	170.00	70.00	442	/	/	
MHCI	5346.84	0.47	0.23	0.57	0.80	0.29	121.28	48.94	444	/	/	
MHCI	5347.81	0.40	0.29	0.47	0.76	0.38	117.50	72.50	441	/	/	
MHCI	5348.14	1.26	1.19	2.38	3.57	0.33	188.89	94.44	441	/	/	
BBF	3323.38	0.22	0.04	0.09	0.13	0.31	40.91	18.18	/	0.01	2.91	
BBF	3324.52	0.32	0.08	0.08	0.16	0.50	25.00	25.00	/	0.01	1.72	
KBZG	4755.44	0.55	0.62	1.02	1.64	0.38	185.45	112.73	448	0.15	27.45	✓
MHBH	4842.03	1.27	2.73	3.29	6.02	0.45	259.06	214.96	440	0.50	38.98	✓
BQB	4292.40	0.71	1.79	1.86	3.65	0.49	261.97	252.11	429	0.36	50.25	✓

Note: TOC: total organic carbon, w.t.%; S_1: residual hydrocarbon, mg HC/g Rock; S_2: pyrolysis hydrocarbon, mg HC/g Rock; S_1+S_2: hydrocarbon potential, mg HC/g Rock; PI: production index = $S_1/(S_1+S_2)$; HI: hydrogen index =(S_2/TOC) × 100, mg HC/g TOC; HCI: hydrocarbon index = (S_1/TOC) × 100, mg HC/g TOC; T_{max}: maximum peak temperature of Rock-Eval pyrolysis S_2, °C; Extract: chloroform extract, %; Extract/TOC, %; Affected: source rock affected by migrated hydrocarbons; /: no data.

sufficient thermal maturity for oil generation.

Typically, T_{max} values enhance with increased depth, and PI values increase with increased T_{max}. However, the cross plots of T_{max} versus depth and T_{max} versus PI (Fig. 3c–d) reveal that some deeper samples of the Fengcheng Formation have low T_{max} values and a negative correlation between T_{max} and PI. This implies that lower T_{max} corresponds to higher PI values, suggesting that some source rock samples may be affected by migrated hydrocarbons or represent early generated hydrocarbons (Hakimi et al., 2010; Shalaby et al., 2012; Li et al., 2018). To objectively evaluate source rock, further research of these abnormal samples are required.

Table 2
The statistical data of TOC, Extract, Rock-Eval pyrolysis of source rock samples from the Fengcheng Formation in the south of Mahu Sag.

Index	Minimum	Maximum	Average	Sample No.
TOC, w.t.%	0.10	2.01	0.74	60
S_1, mg HC/g Rock	0.01	3.81	0.81	60
S_2, mg HC/g Rock	0.01	7.27	1.60	60
S_1+S_2, mg HC/g Rock	0.02	8.25	2.42	60
$S_1/(S_1+S_2)$	0.05	0.67	0.34	60
HI, mg HC/g TOC	7.14	390.86	169.48	60
HCI, mg HC/g TOC	7.14	414.13	95.34	60
T_{max}, °C	414	456	440	54
Extract, %	0.01	0.85	0.24	46
Extract/TOC, %	1.28	85.98	26.58	46

4.2. *Identification characteristics of migrated hydrocarbons influence*

The leading causes of abnormal low T_{max} values of source rock are the early generated hydrocarbon, the influence of migrated hydrocarbons, and maceral with abundant resinite. On the other hand, high T_{max} values result from mineral matrix conservation on hydrocarbons and igneous rock intrusion in source rocks (Zhang et al., 2006). The Rock-Eval pyrolysis parameters and organic petrology features suggest that the kerogen types of source rocks in the Fengcheng Formation are similar without any obvious abnormality (Fig. 3b). Furthermore, source rocks with abnormally low T_{max} values in the study area exhibit higher biomarker parameters indicating maturity, which rules out the influence of early generated hydrocarbon and maceral with abundant resinite. Therefore, the abnormally low T_{max} values and high PI values of the Fengcheng Formation source rocks in the south of Mahu Sag are mainly attributed to the influence of migrated hydrocarbons.

4.2.1. *Molecular composition of biomarkers*

Generally, relatively high S_1 (mg HC/g Rock) and low S_2 (mg HC/g Rock) coupled with depressed T_{max} (°C) can be utilized to identify between migrated and primary hydrocarbons (Hunt, 1996; Rabbani and Kamali, 2005; Ghorri and Haines, 2007). The amount and composition of hydrocarbon molecules in the source rock extract can be used to assess the influence of migrated hydrocarbons. The Rock-Eval T_{max} is commonly used as an indicator to determine the maturity of the source rock, with higher values indicating increased maturity of the source rock. Still, it is easily affected by other factors (Zhang et al., 2006). The biomarker isomerization parameters, such

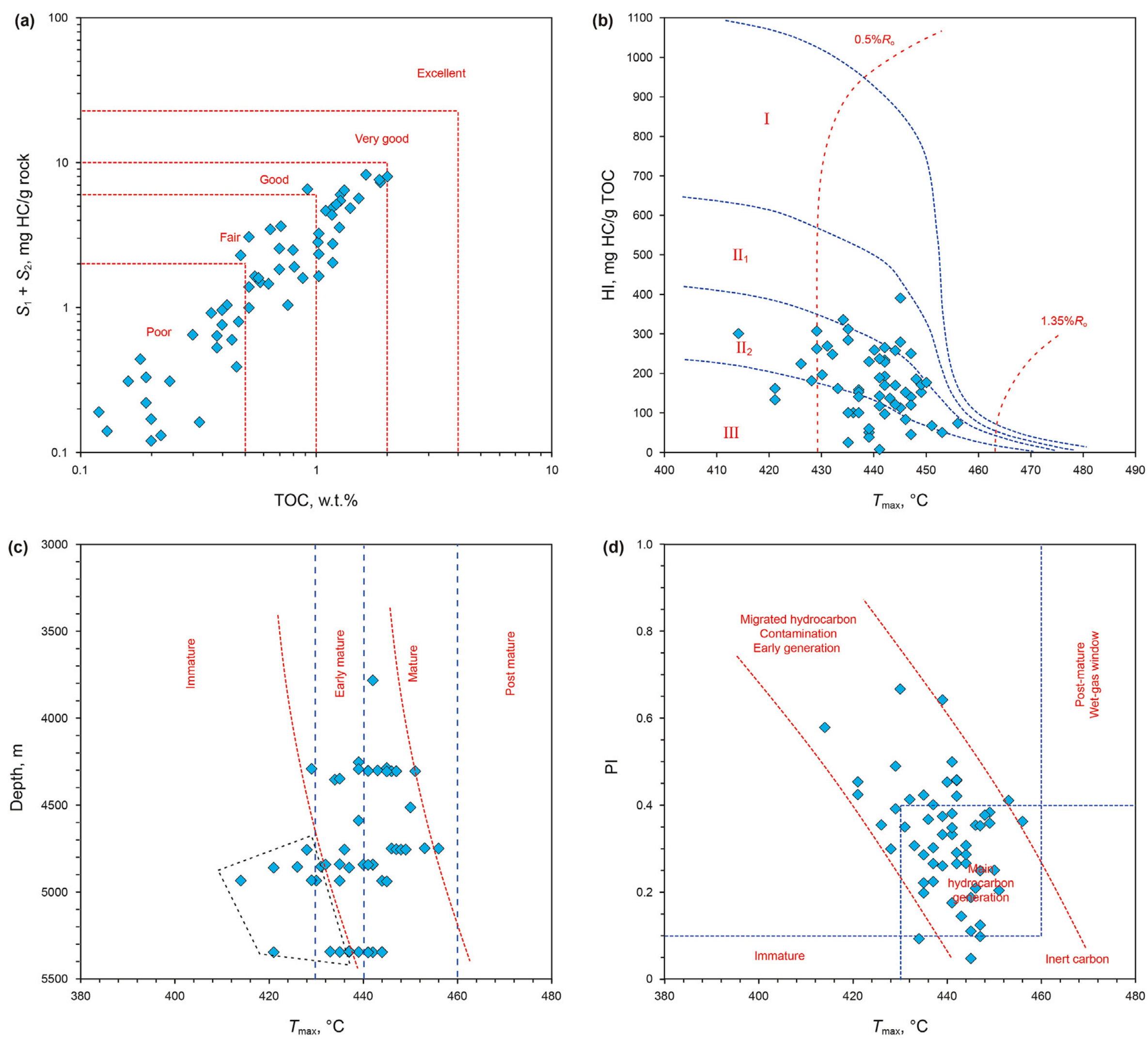

Fig. 3. Relationships between (a) Rock-Eval $S_1 + S_2$ and TOC, (b) HI and T_{max}, (c) Depth and TOC, (d) PI versus T_{max} of Fengcheng Formation source rock samples in the south of Mahu Sag. (Hakimi et al., 2010; Shalaby et al., 2012).

as ααα-20 S/(20S + 20R)-C_{29}-Sterane, ββ/(αα+ββ)-C_{29}-Sterane, and TT/(TT+17α-Hopane) ratio, are also considered to be effective maturity parameters (Seifert and Moldowan, 1978; Tissot and Welte, 1984; Peters and Cassa, 1994). The cross plots of the biomarker parameter versus T_{max} of source rock samples in the Fengcheng Formation (Fig. 4a–b) reveal that when the biomarker parameter values are smaller than the critical values (ββ/(αα+ββ)-C_{29}-Sterane ratio value is approximately 0.58, TT/(TT+17α-Hopane) ratio value is approximately 0.55), the T_{max} of the source rock gradually increases with increasing biomarker parameter values. When the biomarker parameter values exceed the critical value, the T_{max} value rapidly declines as the biomarker parameter values grow. At the same time, the cross plots between biomarker parameters and HCI (Fig. 4c–d) show that when biomarker parameter values are greater, the HCI values of source rock samples are high (HCI > 110 mg HC/g TOC) and rapidly rise with increasing biomarker parameter values. From the view of migration, these source rock samples with high HCI and low T_{max} values should be mainly related to migrated hydrocarbons. HCI and T_{max} values represent the amount of generated hydrocarbon and the temperature of the S_2 peak of pyrolytic hydrocarbon in the source rock, respectively. The migrated hydrocarbons enhance the generated hydrocarbons in source rocks, leading to a higher Rock-Eval S_1 value. Meanwhile, because heavier compounds in the migrated hydrocarbons can't evaporate immediately due to sorption at a lower temperature (< 300 °C, corresponding to S_1), these heavier hydrocarbons will be released as S_2 peak at the higher temperature (> 300 °C), which pulls S_2 peak temperature to the lower temperature side, leading to a decrease in T_{max} (Snowdon, 1995; Zhang et al., 2006; Romero-Sarmiento et al., 2016; Li et al., 2018). This means that the source rock samples with biomarkers maturity parameters higher than the critical values, higher HCI values, and lower T_{max} values of the Fengcheng Formation in Mahu Sag are affected by migrated hydrocarbons, while the samples with biomarker maturity parameters less than the critical value are not or rarely affected by migration hydrocarbon, and their T_{max} and HCI values increase slowly with the increased biomarker maturity parameters (Fig. 4).

The GC-MS diagram, cross plots of biomarker parameters, and data on the biomarker molecular composition of the source rock samples saturated fraction from the Fengcheng Formation in the south of Mahu Sag (Figs. 5 and 6, Table 3) indicate that the characteristics of source rock samples are similar, mainly including the rising type content of C_{27}-C_{28}-C_{29} regular sterane and the apparent

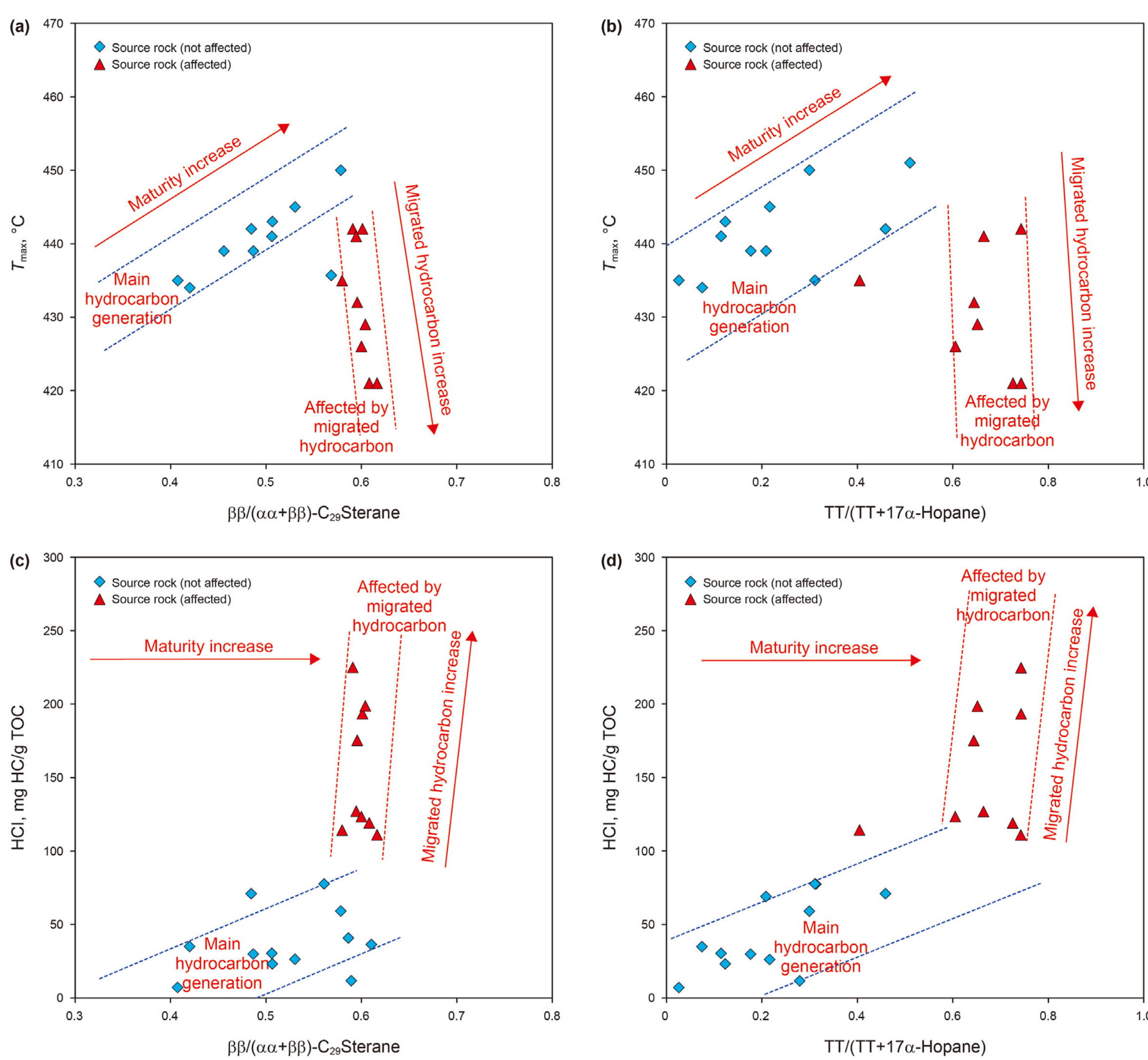

Fig. 4. Cross plots of Rock-Eval pyrolysis parameters and maturity parameters of the Fengcheng Formation source rocks affected by migrated hydrocarbons in the south of Mahu Sag. (a) T_{max} versus ββ/(αα+ββ)-C_{29}-Sterane; (b) T_{max} versus TT/(TT+17α-Hopane); (c) HCI versus ββ/(αα+ββ)-C_{29}-Sterane; (d) HCI versus TT/(TT+17α-Hopane).

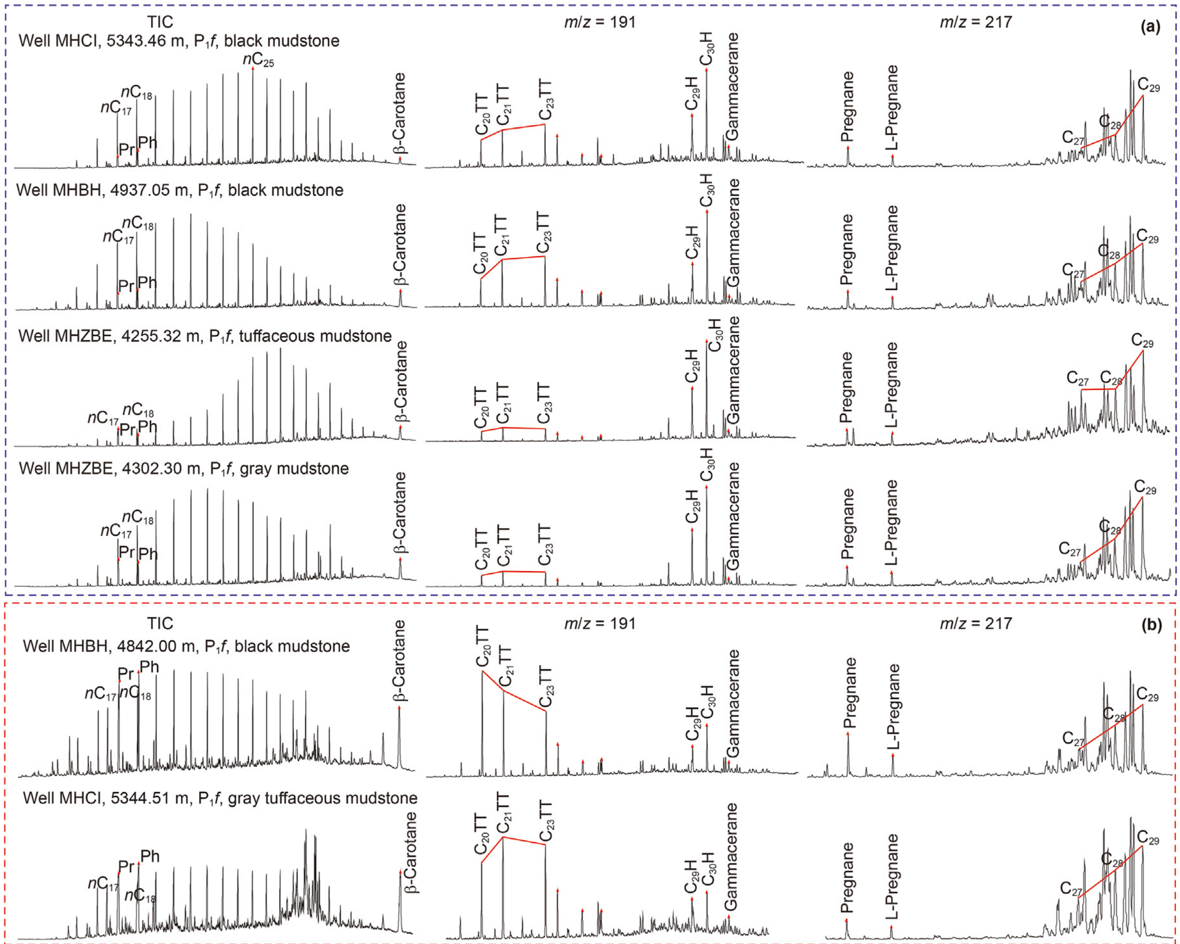

Fig. 5. Gas chromatography-mass spectrometry (GC-MS) of the saturated fraction of the Fengcheng Formation source rock samples in the southern Mahu Sag. (a) low content of tricyclic terpane and not affected by migrated hydrocarbons; (b) high content of tricyclic terpane and affected by migrated hydrocarbons.

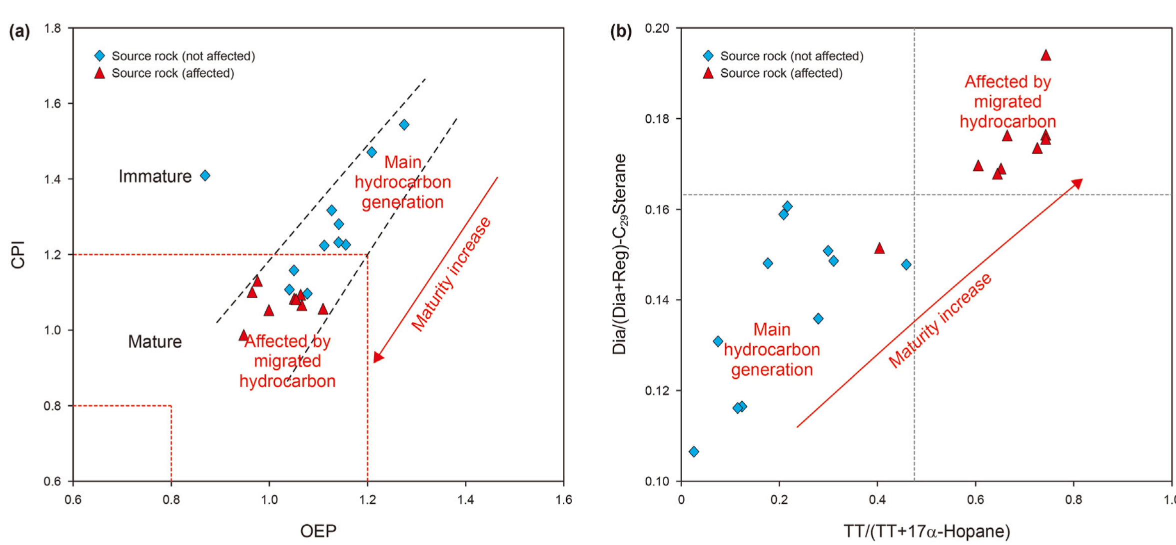

Fig. 6. Relationships between (a) OEP and CPI, (b) TT/(TT+17α-Hopane) and Dia/(Dia + Reg)-C_{29}-Sterane of Fengcheng Formation source rock samples in the south of Mahu Sag.

gammacerane content, suggesting similarities in organic matter type and sedimentary environment (Fig. 5a–b). However, further analysis reveals significant differences in the relative contents of tricyclic terpane, the ratio of Dia/(Dia + Reg)-C_{29}-Sterane, the distribution patterns of C_{20}, C_{21}, and C_{23} tricyclic terpane, as well as the OEP and CPI values of source rock affected by migrated hydrocarbons compared to those of normal source rock (Figs. 5 and 6). The source rock samples affected by migrated hydrocarbons are

Table 3
Saturated hydrocarbon biomarker parameters of the Fengcheng Formation source rock samples in the southern Mahu Sag.

Well	Depth, m	Pr/Ph	Pr/n-C_{17}	Pr/n-C_{18}	CPI	OEP	GI	Ts/Tm	20S, %	ββ, %	TT, %	Dia, %	Affected
MHBH	4842.60	1.28	1.81	1.73	1.13	0.98	0.28	0.12	0.47	0.60	0.74	0.18	✓
MHBH	4842.73	1.05	1.58	1.71	1.10	0.96	0.34	0.33	0.46	0.59	0.74	0.19	✓
MHBH	4843.40	1.23	1.79	1.64	1.08	1.05	0.27	0.20	0.47	0.59	0.66	0.18	✓
MHBH	4932.80	0.72	0.91	1.20	1.09	1.06	0.23	0.21	0.46	0.60	0.65	0.17	✓
MHBH	4842.00	1.05	1.64	1.64	0.99	0.95	0.22	0.10	0.47	0.60	0.64	0.17	✓
MHBH	4840.35	1.13	1.34	1.31	1.07	1.07	0.21	0.03	0.46	0.58	0.40	0.15	✓
KBZG	4856.40	0.81	1.50	2.05	1.08	1.05	0.35	0.13	0.46	0.60	0.61	0.17	✓
KBZG	4860.21	0.80	1.25	1.62	1.05	1.00	0.28	0.19	0.46	0.61	0.73	0.17	✓
MHCI	5347.37	0.89	1.42	1.81	1.06	1.11	0.40	0.46	0.45	0.62	0.74	0.18	✓
MHBF	4513.50	1.42	1.23	0.93	1.10	1.08	0.07	0.08	0.48	0.58	0.30	0.15	
KBZD	4346.40	1.63	2.48	1.58	1.47	1.21	/	0.41	0.55	0.42	0.07	0.13	
KBZD	4344.92	0.88	0.26	0.19	1.54	1.27	0.09	0.46	0.54	0.41	0.03	0.11	
JLAG	3784.10	1.35	0.94	1.06	1.41	0.87	0.86	0.27	0.45	0.48	0.46	0.15	
MHZBE	4302.30	1.26	1.00	0.66	1.23	1.16	0.07	0.27	0.47	0.51	0.12	0.12	
MHZBE	4302.97	1.20	1.00	0.67	1.16	1.05	0.19	0.30	0.47	0.51	0.11	0.12	
MHBF	4588.80	0.88	0.56	0.57	1.23	1.14	0.13	0.57	0.42	0.49	0.18	0.15	
MHBH	4937.05	0.87	0.34	0.37	1.11	1.04	0.09	0.28	0.50	0.56	0.31	0.15	
BQB	4287.55	1.09	0.98	0.88	1.32	1.13	0.18	0.14	0.46	0.53	0.22	0.16	
BQB	4293.72	1.08	0.84	1.00	1.28	1.14	0.47	0.19	0.44	0.46	0.21	0.16	
MHCI	5344.46	0.78	0.34	0.40	1.22	1.11	0.16	1.06	0.44	0.59	0.28	0.14	

Note: Pr/Ph: the ratio of pristine and phytane; Pr/n-C_{17}: Pristane/C_{17} n-alkane; Pr/n-C_{18}: Phytane/C_{18} n-alkane; CPI: carbon preference index = $[(C_{25}+C_{27}+C_{29}+C_{31}+C_{33})/(C_{24}+C_{26}+C_{28}+C_{30}+C_{32})+(C_{25}+C_{27}+C_{29}+C_{31}+C_{33})/(C_{26}+C_{28}+C_{30}+C_{32}+C_{34})]/2$; OEP: odd-even predominance = $(C_{23}+6\times C_{25}+C_{27})/(4\times C_{24}+4\times C_{26})$; GI: Gammacerane/$C_{30}$-Hopane; Ts/Tm: 18a(H)-22,29,30-trisnorneohopane/ 17a(H)-22,29,30-trisnorhopane; 20S: 20S/(20R + 20S)-$\alpha\alpha\alpha$-C_{29}-Sterane; ββ: ββ/(ββ+αα)-C_{29}-Sterane; TT/(TT+17α-Hopane): TT = $(C_{20}TT + C_{21}TT + C_{23}TT)/3$; Dia/(Dia + Reg)-$C_{29}$-Sterane (Dia: Diasteranes, Reg: regular steranes); Affected: source rock affected by migrated hydrocarbons; /: no data.

characterized by that the tricyclic terpane relative contents are higher than that of hopanes, the distribution patterns of C_{20}, C_{21}, and C_{23} tricyclic terpane are mostly mountain-shaped and descending types, and OEP and CPI have low values ranging from 0.95 to 1.11 (average = 1.03) and 0.99 to 1.13 (average = 1.07), respectively (Figs. 5b and 6, Table 3). Whereas the source rock not affected by migrated hydrocarbons has the following characteristics: the relative content of tricyclic terpane is low, the distribution pattern of C_{20}, C_{21}, and C_{23} tricyclic terpane content is primarily ascending, the OEP and CPI values are relatively high, ranging from 0.87 to 1.27 (average = 1.11) and 1.1 to 1.54 (average = 1.28), respectively (Figs. 5a and 6, Table 3). These characteristics suggest that source rock samples affected by migrated hydrocarbons have relatively high thermal maturity (Seifert and Moldowan, 1978). In addition, the source rocks affected by migrated hydrocarbons have high Pr/Ph, Pr/n-C_{17}, and Pr/n-C_{18} values (Table 3).

4.2.2. TOC and Rock-Eval pyrolysis

The S_1/TOC > 100 mg HC/g TOC usually indicates that there is a large amount of free oil in the source rock sample (Behar et al., 2003; Jarvie, 2012), and S_1/TOC > 150 mg HC/g TOC reveals that the source rock samples affected by migrated hydrocarbons (Li et al., 2018). The previous threshold, though, might change depending on the geological setting. According to the principle of hydrocarbon generation and expulsion of source rock, when hydrocarbon expulsion does not occur in the source rock, the amount of generated hydrocarbon (equal to S_1 or extract) grows with the increasing TOC content, and when the amount of generated hydrocarbons is sufficient for the saturated adsorption of the source rock itself, the source rock starts to expel hydrocarbons. S_1 is currently equal to the amount of residual hydrocarbons and will not increase. When there is no hydrocarbon expulsion in the source rock, the maximum slope between S_1 and TOC represents the maximum relative amount of generated hydrocarbon (S_1/TOC). The samples over the maximum relative generated hydrocarbon may be affected by migrated hydrocarbons (Gao et al., 2012, Gao et al., 2017b). The organic matter type and thermal maturity of the source rock of the Fengcheng Formation in the south of Mahu Sag are similar according to the Rock-Eval parameters and may be identified using this method. Fig. 7 shows the cross plots of S_1 and extract versus TOC of the Fengcheng Formation source rock. When the TOC content is lower than 0.48 w.t.%, the maximum of the S_1/TOC ratio values is approximately 1.1, and the maximum of the extract/TOC ratio values is 0.3. When the TOC content exceeds 0.48 w.t.%, some source rock samples fall in the area above the isocline of 1.1 of S_1/TOC ratio and 0.3 of extract/TOC ratio values. These source rock samples should be affected by migrated hydrocarbons according to the characteristics of organic geochemical and hydrocarbon generation and expulsion (Fig. 7). Therefore, S_1/TOC > 110 mg HC/g TOC and extract/TOC > 0.3 can be used to identify the source rock affected by migrated hydrocarbons, which is consistent with the identification boundary reflected by the biomarker parameters (HCI > 110 mg HC/g TOC) (Fig. 4).

In the diagrams of the Extract/TOC ratio and HCI versus Rock-Eval T_{max} (Fig. 8a–b), the source rock samples affected by migrated hydrocarbons have lower T_{max} values (ranging from 414 °C to 448 °C; average: 434 °C) compared to the source rock samples not affected by migrated hydrocarbons (varying from 428 °C to 456 °C; average: 442 °C). Meantime, source rock samples affected by migrated hydrocarbons have higher HCI and extract/TOC values (HCI > 110 mg HC/g TOC and extract/TOC > 30%), which further indicates that the source rocks affected by migrated hydrocarbons in the Fengcheng Formation are characterized by high HCI (> 110 mg HC/g TOC), extract/TOC (> 30%), and low T_{max} values. The cross plots of HI versus TOC and Rock-Eval T_{max} (Fig. 8c–d) reveal that the source rock not affected by migrated hydrocarbons has a broader range of HI values (from 7.14 to 390.00 mg HC/g TOC, average = 135.00 mg HC/g TOC), while the source rock affected by migrated hydrocarbons has a narrower range of HI values (from 133.00 to 308.00 mg HC/g TOC, average = 236.00 mg HC/g TOC) and relatively higher. This can be attributed to the fact that once the hydrocarbon generation capacity of the source rock reaches a specific threshold, its wettability changes to oil-wet, making it more susceptible to being affected by migrated hydrocarbons.

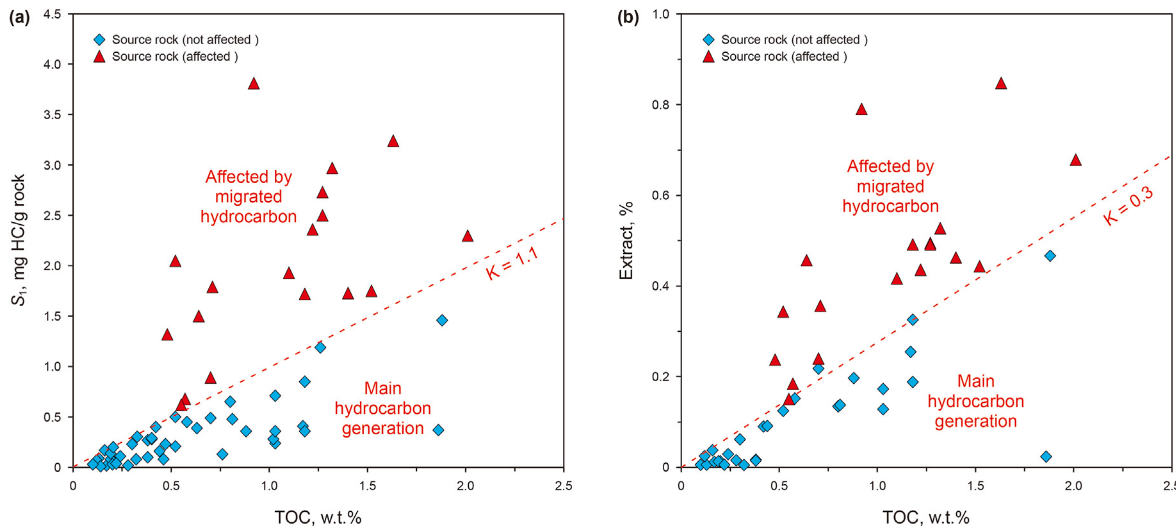

Fig. 7. Cross plots for Rock-Eval pyrolysis parameters identification of source rocks affected by migrated hydrocarbons in the Fengcheng Formation, southern Mahu Sag (Gao et al., 2017b; Li et al., 2018). (a) Rock-Eval S_1 versus TOC; (b) Extract versus TOC. The isocline of 1.1 of S_1/TOC ratio and 0.3 of Extract/TOC ratio (red line) is the maximum relative hydrocarbon generating quantity. The source rocks affected by migrated hydrocarbons fall in the area above the isocline.

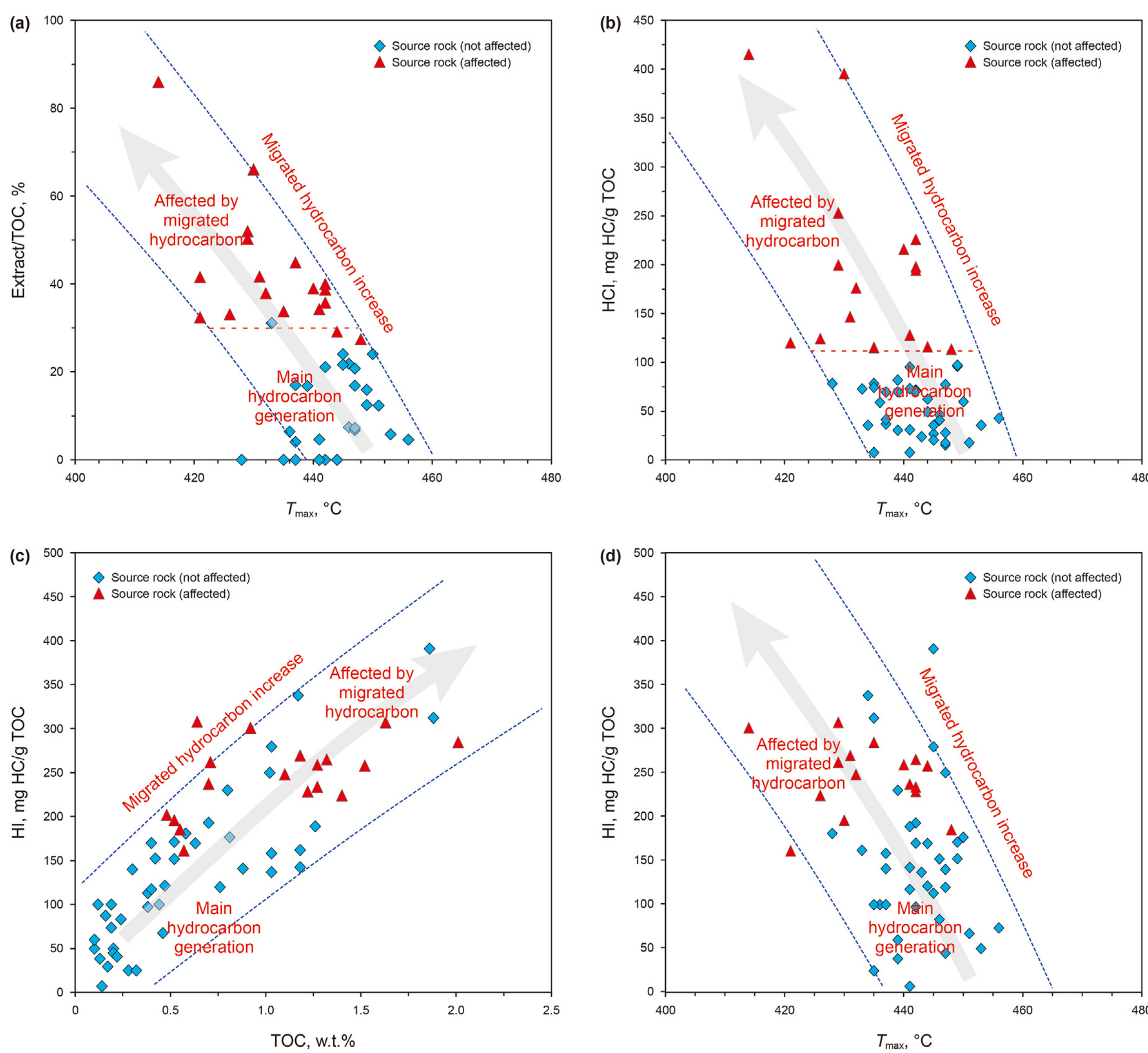

Fig. 8. Cross plots of (a) Extract/TOC versus T_{max}, (b) HCI versus T_{max}, (c) HI versus TOC, and (d) HI versus T_{max} of the Fengcheng Formation source rock samples in the south of Mahu Sag.

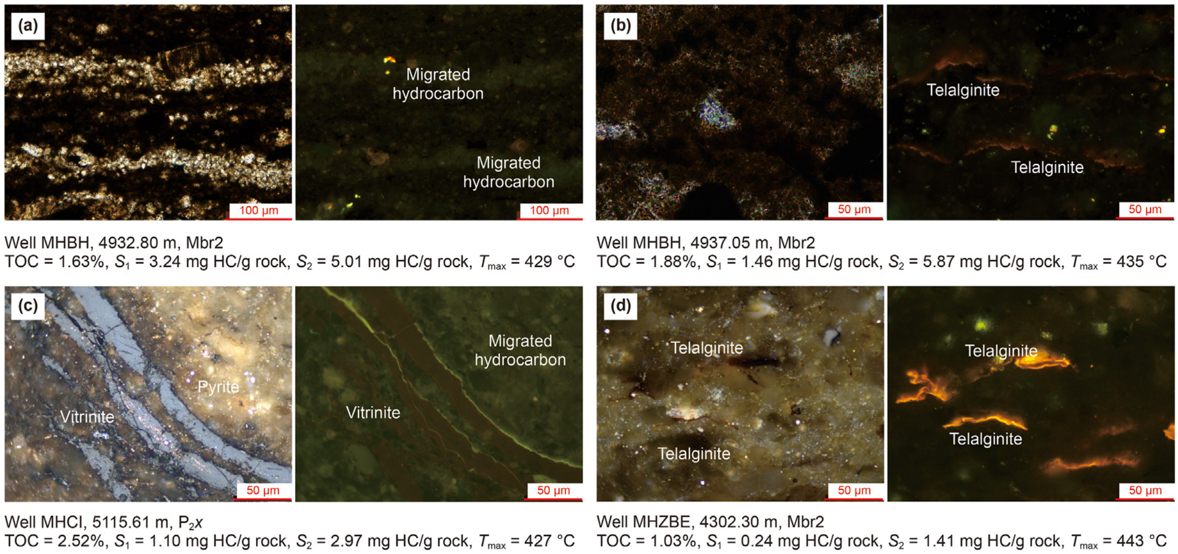

Fig. 9. Organic petrological characteristics of the Fengcheng Formation source rock samples in the south of Mahu Sag, Junggar Basin. (a) Well MHBH, 4932.85 m, P_1f_2, black mudstone, transmitted light and fluorescence; (b) Well MHBH, 4937.05 m, P_1f_2, black mudstone, transmitted light and fluorescence; (c) Well MHCI, 5115.61 m, P_2x, black carbonaceous mudstone, reflected light, fluorescence; (d) Well MHZBE, 4302.30 m, P_1f_2, gray mudstone, reflected light, fluorescence.

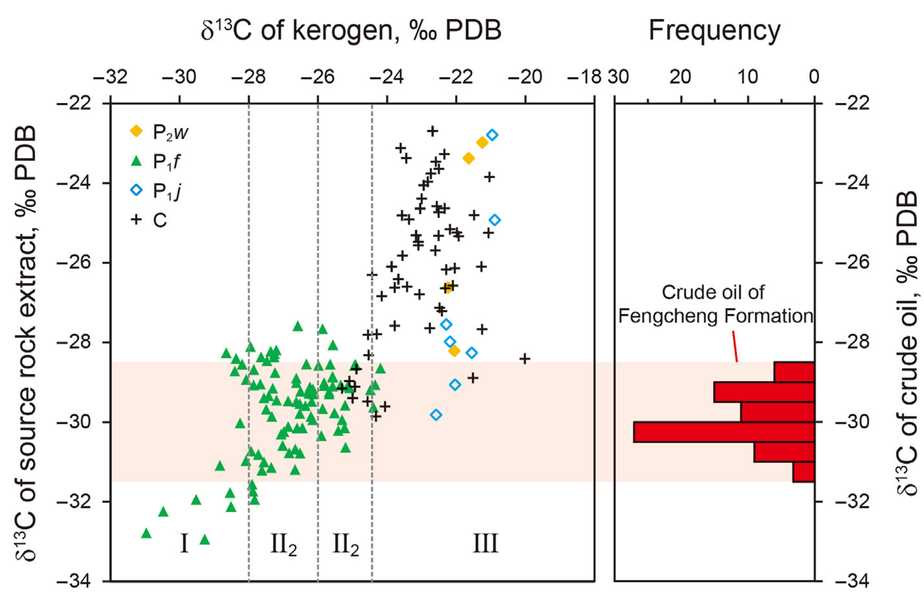

Fig. 10. Cross plot of kerogen carbon isotope and extract carbon isotope of the source rocks in different formations of Mahu Sag, and frequency distribution map of carbon isotope in the Fengcheng Formation, the Northwest Junggar Basin (modified from Dang et al., 2023).

4.2.3. Petrological of source rocks

The fluorescence characteristics of organic petrology can also serve as indirect evidence to prove that source rock is affected by migrated hydrocarbons. However, its usage is limited due to the complexity of preparing the organic petrology sample and the diverse influencing factors. Fig. 9 depicts the organic petrology characteristics of the Fengcheng Formation source rock samples in the south of Mahu Sag. Some of these samples exhibit strong yellow-green fluorescence in the dolomite interlayer and matrix, along with high S_1 and low T_{max} values. This observation aligns with the previously identified characteristics of source rock affected by migrated hydrocarbons (Fig. 9a–c). On the other hand, certain source rock samples have yellowish-brown fluorescent telalginite (Cao et al., 2015; Liu et al., 2020; Zhi et al., 2021) with low S_1 and high T_{max} values (Fig. 9a–c), but the fluorescence in the matrix is weak. This suggests that these source rock samples are rarely affected by migrated hydrocarbons. While the fluorescence characteristics of source rock petrology can help identify the influence of migrated hydrocarbons, this method is associated with significant uncertainty. Therefore, it can be used as an auxiliary method to identify source rock affected by migrated hydrocarbons.

4.3. Origin of migrated hydrocarbons

Numerous research achievements have been on the origin of crude oil in the Fengcheng Formation of Mahu Sag (Wang and Kang, 2001; Cao et al., 2005, 2006; Huang et al., 2016; Chen et al., 2017). The source rock in Mahu Sag is primarily found in the Carboniferous, Jimuhe, Fengcheng, and Lower Wuerhe formations (Wang and Kang, 2001). Fig. 10 illustrates that the kerogen and bitumen

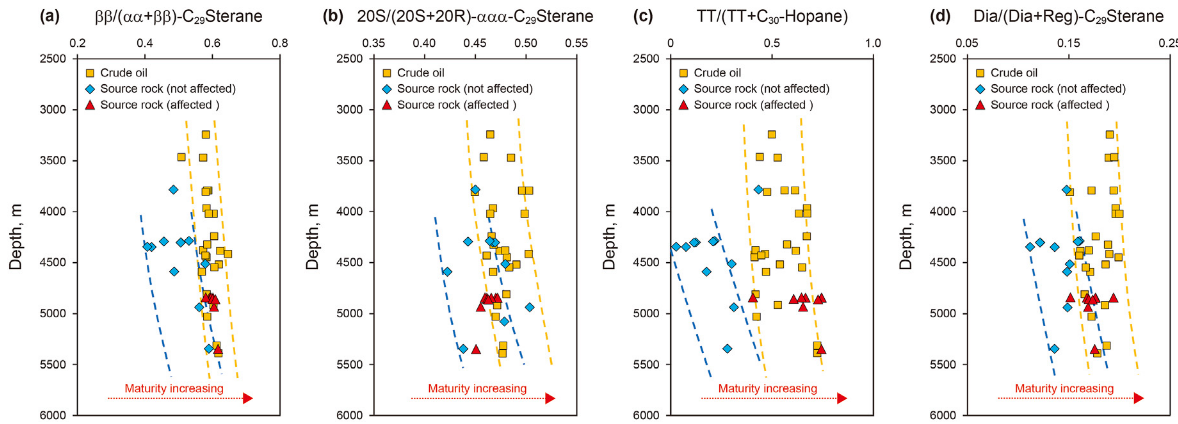

Fig. 11. Comparison plot of oil-source maturity parameters of the Fengcheng Formation in the south of Mahu Sag. (a) ββ/(αα+ββ)-C_{29}-Sterane versus Depth, (b) the 20S/(20S + 20R)-ααα-C_{29}-Sterane versus Depth, (c) TT/(TT+17α-Hopane) versus Depth, and (d) Dia/(Dia + Reg)-C_{29}-Sterane versus Depth (Dia: Diasteranes, Reg: regular steranes). The maturity of crude oil is higher than that of in-situ source rock at the same depth, and the maturity of source rock affected by migrated hydrocarbons is between them.

Table 4
Saturated hydrocarbon biomarker parameters of the Fengcheng Formation crude oil in the south of Mahu Sag.

Well	Depth, m	Type	Pr/Ph	Pr/n-C_{17}	Pr/n-C_{18}	OEP	CPI	20S, %	ββ, %	TT, %	Dia, %
JLAG	3793	oil	1.13	0.90	0.92	1.04	1.10	0.50	0.59	0.56	0.17
JLAG	3793	oil	1.20	0.98	1.01	1.04	1.14	0.50	0.58	0.61	0.19
JLCD	3245	oil	0.99	1.01	1.11	1.10	1.10	0.46	0.58	0.50	0.19
JLCE	4519	oil	1.32	0.72	0.61	1.08	1.17	0.49	0.62	0.54	0.19
JLDI	4591.5	oil	1.13	0.67	0.67	1.12	1.16	0.47	0.57	0.47	0.17
JLEA	4416	oil	1.26	0.40	0.32	1.13	1.20	0.50	0.65	0.47	0.19
JLEA	4448	oil	1.31	0.40	0.33	1.11	1.18	0.48	0.58	0.41	0.20
JLEE	5030	oil	1.16	0.86	0.82	1.09	1.15	0.47	0.58	0.42	0.17
KHZ	4385	oil	1.43	0.67	0.53	1.13	1.15	0.47	0.62	0.62	0.16
KHAA	3807	oil	1.01	1.05	1.19	1.04	1.11	0.45	0.58	0.48	0.15
KHBA	3470	oil	1.05	1.05	1.19	1.04	1.15	0.49	0.57	0.53	0.19
KHIA	4242	oil	1.02	1.01	1.11	1.03	1.06	0.47	0.61	0.67	0.18
KBZD	4379.5	oil	1.27	1.18	1.16	1.07	1.18	0.48	0.57	0.42	0.17
MHAE	3967	oil	1.07	0.86	0.95	1.02	1.09	0.47	0.58	0.67	0.20
MHAF	4430.5	oil	1.03	1.20	1.31	1.00	1.03	0.46	0.58	0.45	0.16
MHBF	4548.5	oil	0.99	1.02	1.21	1.08	1.09	0.48	0.61	0.65	0.17
MHBF	4323	oil	0.89	1.00	1.24	1.06	1.09	0.47	0.58	0.57	0.19
MHBH	4810.5	oil	1.23	0.87	0.79	1.06	1.10	0.48	0.58	0.42	0.17
MHBH	4916.5	oil	0.95	0.85	1.00	1.05	1.12	0.47	0.60	0.53	0.19
MHCI	5314.5	oil	1.35	0.70	0.60	1.05	1.10	0.48	0.61	0.72	0.19
MHCI	5389.5	oil	1.12	0.91	0.89	1.04	1.04	0.48	0.62	0.72	0.18
MHG	4021	oil	1.04	1.09	1.29	1.01	1.09	0.50	0.60	0.63	0.20
MHG	4021	oil	1.03	1.12	1.35	1.01	1.11	0.46	0.59	0.67	0.20
MHH	3465	oil	0.98	0.87	0.98	1.01	1.13	0.46	0.51	0.44	0.19

Note: Pr/Ph: the ratio of pristine and phytane; Pr/n-C_{17}: Pristane/C_{17} n-alkane; Pr/n-C_{18}: Phytane/C_{18} n-alkane; OEP: odd-even predominance = (C_{23} + 6 × C_{25} + C_{27})/(4 × C_{24}+4 × C_{26}); CPI: carbon preference index = [(C_{25} + C_{27} + C_{29} + C_{31} + C_{33})/(C_{24} + C_{26} + C_{28} + C_{30} + C_{32}) + (C_{25} + C_{27} + C_{29} + C_{31} + C_{33})/(C_{26} + C_{28} + C_{30} + C_{32} + C_{34})]/2; 20S: 20S/(20R + 20S)-ααα-C_{29}-Sterane; ββ: ββ/(ββ+αα)-C_{29}-Sterane; TT(%): TT/(TT+17α-Hopane): TT = (C_{20}TT + C_{21}TT + C_{23}TT)/3; Dia: Dia/(Dia + Reg)-C_{29}-Sterane (Dia: Diasteranes, Reg: regular steranes).

carbon isotope values in the Fengcheng Formation source rock samples range from −30.96 ‰ to −24.19 ‰ and −32.94 ‰ to −27.58 ‰, respectively. In contrast, the carbon isotope values in other layers vary from −25.3 ‰ to −20.01 ‰ and −29.82 ‰ to −22.79 ‰. The carbon isotope values of crude oil in the Fengcheng Formation range between −31.22 ‰ and −28.6 ‰, which closely resemble those of the source rock extract in the Fengcheng Formation (Fig. 10). Previous research indicates that the carbon isotope fractionation of kerogen during the later stage of hydrocarbon generation is within 3 ‰ (Chen et al., 2016; Du, 2020). Consequently, it is believed that the crude oil in the Fengcheng Formation primarily originated from the Fengcheng Formation source rock itself.

Fig. 11 and Table 4 illustrate the relationship between the biomarker parameters of crude oil and source rock concerning the depth of the Fengcheng Formation. The data indicate that the maturity of crude oil is higher compared to in-situ source rock samples that have not been affected by migrated hydrocarbons. The maturity of source rock affected by migrated hydrocarbons lies between in-situ source rock and crude oil samples, with most samples exhibiting maturity levels closer to crude oil. These observations suggest that the crude oil in the study area mainly came from a source rock with higher thermal maturity located in the deep sag, and the in-situ source rock samples display lower thermal maturity, while some high-maturity source rock samples were mainly affected by migrated hydrocarbons with higher thermal maturity from the inner sag.

4.4. *Geologic pattern of migrated hydrocarbons influence and significance*

The distribution of source rocks affected by migrated hydrocarbons in the Fengcheng Formation of Mahu Sag follows specific

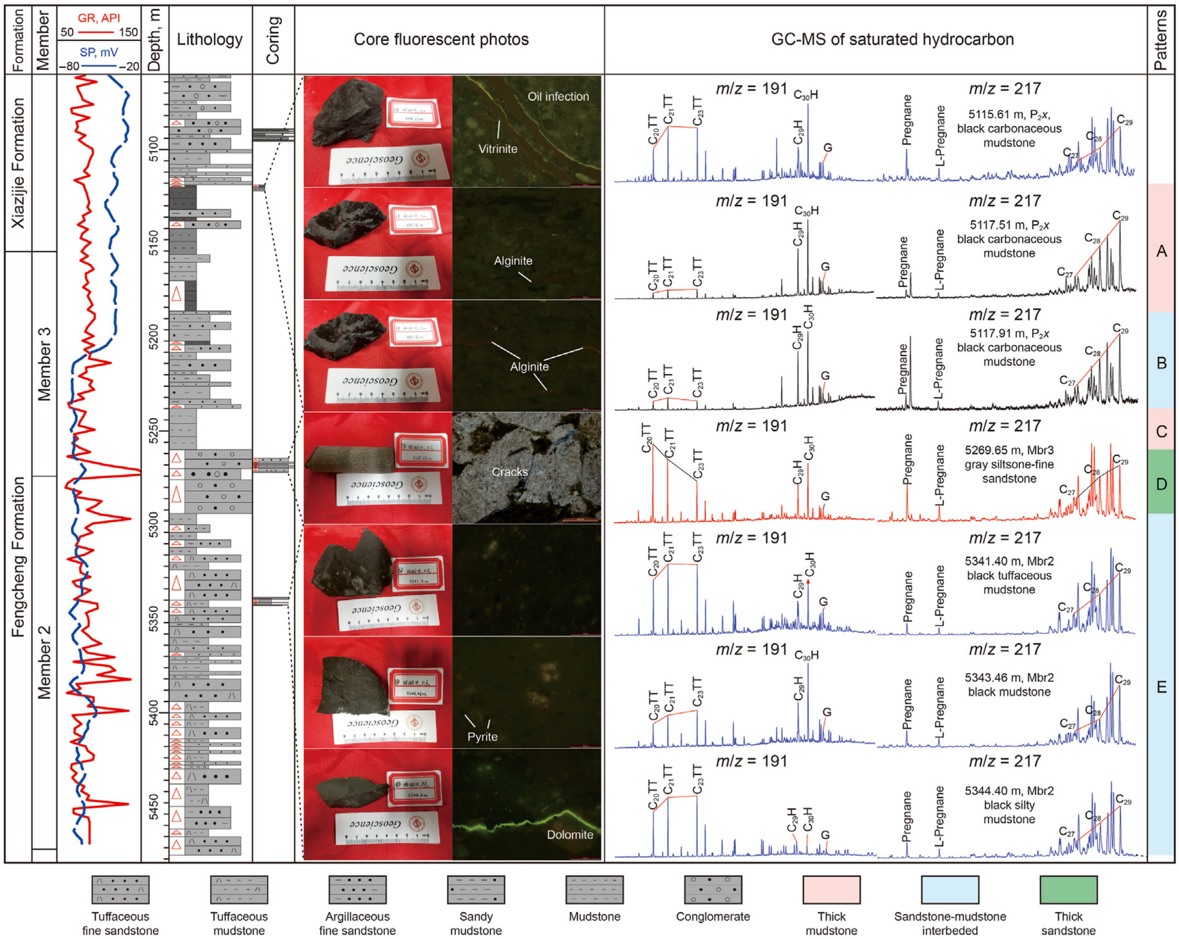

Fig. 12. Comprehensive column of lithologic assemblage and extraction GC-MS characteristics of the Fengcheng Formation in well MHCI in the south of Mahu Sag. A and C members are thick mudstones with a high maturity of extract close to sandstone and low maturity of extract far from sandstone, B and E members are sandstone-mudstone interbedded with a wide range of extract maturity, and D member is thick sandstone with high maturity of extract. (Red: crude oil biomarkers with high maturity; Blue: biomarkers of extracts from source rock affected by migrated hydrocarbons, with medium maturity; Black: biomarkers of extracts from source rock not affected by migrated hydrocarbons, low maturity.)

rules. Fig. 12 presents a comprehensive column depicting lithology, organic petrology, and biomarker characteristics of the Fengcheng Formation's source rock in well MHCI. It can be observed that thick mudstone is developed in members A and C, while sandstone-mudstone interbedding is developed in members B and E. Additionally, member D is characterized by the presence of thick sandstone. The extract of thick mudstone in Member A can represent the in-situ source rock samples, and its maturity is lower than that of other samples, indicating that other samples are affected by migrated hydrocarbons.

The extract from the thick sandstone at the top of Mbr 2 of Fengcheng Fm (D member) is characterized by a high relative content of tricyclic terpane with a descending type of C_{20}, C_{21}, and C_{23} tricyclic terpane distribution. It also exhibits a high sterane isomerization parameter, such as the $\beta\beta/(\beta\beta+\alpha\alpha)$-$C_{29}$-Sterane ratio (Fig. 12). These findings indicate that the crude oil primarily originates from a source rock with higher maturity in the deep sag. On the other hand, the extract from the source rock in the thin sandstone-mudstone interbedded (E member) shows ascending and mountain-shaped types of C_{20}, C_{21}, and C_{23} tricyclic terpane distribution. The relative content of tricyclic terpane and sterane isomerization parameters falls between the D and A members. This suggests that the extract has contributions from in-situ source rocks and deep sag source rocks. This can be attributed to the thick sandstone acting as a good carrier layer, primarily containing highly mature crude oil from the deep sag. In contrast, the thin sandstone-mudstone interbed has limited migration capacity and is weakly influenced by migrated hydrocarbons. Member A is a thick mudstone that overlies the thick sandstone. The organic petrology and GC-MS analysis of the source rock extract, which is adjacent to the sandstone (Fig. 12), reveals that the relative content of tricyclic terpane and the sterane isomerization parameter of the source rock located far away from the sandstone are lower and that of close to the sandstone is high. In addition, the organic petrological analysis indicates the presence of yellow-green high maturity characteristics of crude oil influence. This phenomenon suggests that the source rock near the thick sandstone is more susceptible to the influence of migrated hydrocarbons.

As shown in Fig. 13, the upper part of Mbr 2 of the Fengcheng Formation primarily consists of many permeable layers (basalt and sandstone) with thin mudstone (F and H member). In the lower part, there are thin interbedded sandstone and mudstone (G and I members). The source rock extract near the thick sandstone exhibits a high relative content of tricyclic terpane, with a predominance of descending type distribution of C_{20}, C_{21}, and C_{23} tricyclic terpane, indicating a significantly high maturity. These terpanes mainly originate from deeply source rocks with high maturity in the deep sag. In addition, the source rock extract in the sandstone-mudstone interbedded demonstrates a relatively low relative content of tricyclic terpane. The distribution of C_{20}, C_{21}, and C_{23}

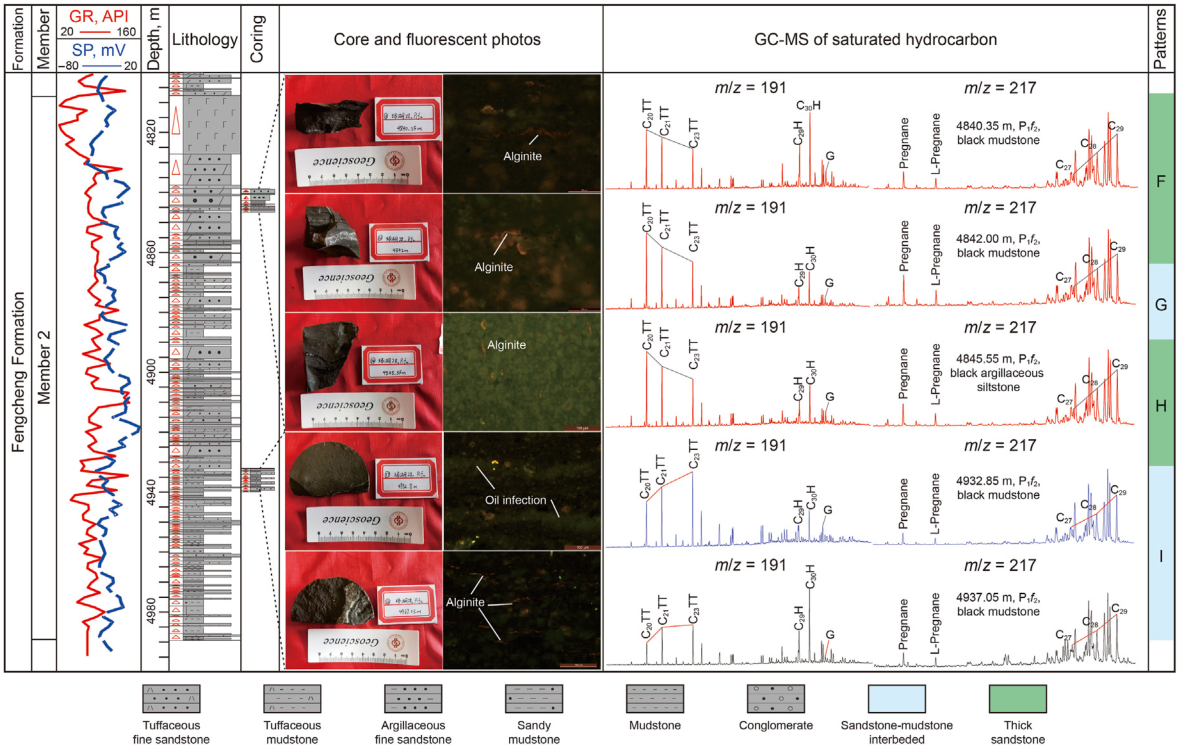

Fig. 13. Comprehensive histogram of lithologic assemblage and extraction GC-MS characteristics of the Fengcheng Formation in well MHBH in the south of Mahu Sag. F and H members are thick sandstone with a high maturity of extract, and G and I members are sandstone-mudstone interbedded with a wide range of extract maturity.

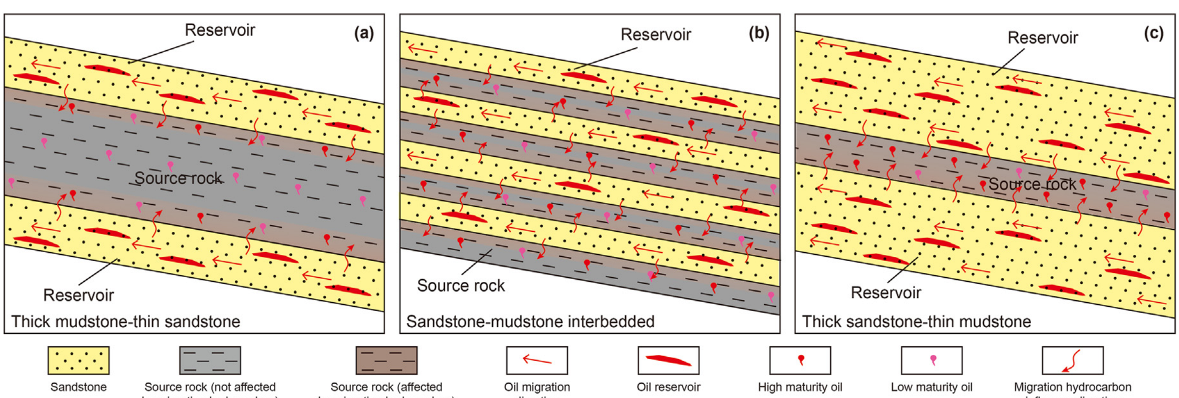

Fig. 14. Patterns of source rock affected by migrated hydrocarbons of the Fengcheng Formation in the south of Mahu Sag. (a) Thick mudstone-thin sandstone pattern; (b) sandstone-mudstone interbedded pattern; (c) thick sandstone-thin mudstone pattern. The red shadow represents the zone affected by the migrated hydrocarbons.

tricyclic terpane is ascending, mainly from an in-situ source rock with a minor contribution from the deeper source rock. These characteristics further highlight that the influence of migrated hydrocarbons on the source rock is primarily associated with the thickness of the sandstone and its distance to the sandstone.

Further research shows that the influence degree of migrated hydrocarbons in the study area is closely related to the lithologic combination. Based on the distribution characteristics of migrated hydrocarbons in existing wells, three patterns of migrated hydrocarbons influence in the study area have been identified (Fig. 14). The first pattern, depicted in Fig. 14a, is the edge-influence of thin sandstone-thick mudstone. This pattern is mainly observed at the top of the Mbr 3 of the Fengcheng Formation. It is characterized by the high maturity of the sandstone and adjacent mudstone extracts, while the mudstone extract further away from the sandstone shows lower maturity. The influence scope of this pattern is relatively small, but it can easily affect the overlying mudstone. The second pattern, shown in Fig. 14b, is the mixed-influence of sandstone-mudstone interbedded. It is primarily distributed at the bottom of the Mbr 2 of the Fengcheng Formation. Due to the limited migration ability of thin sandstone, the extract in this pattern contains contributions from both in-situ source rock and a small amount of migrated hydrocarbons. The third pattern, illustrated in Fig. 14c, is the full-influence of thick sandstone and thin mudstone. It is mainly found at the top of the Mbr 2 of the Fengcheng Formation. The thick sandstone acts as a good transport layer, facilitating the migration of hydrocarbons, which significantly influence the adjacent mudstone, resulting in a high maturity of the extract.

The study on the characteristics of source rocks in the Fengcheng Formation highlights the importance of identifying source rocks affected by migrated hydrocarbons. This identification is crucial for source rocks evaluation and the oil-sources correlation. Failure to identify source rocks affected by migrated hydrocarbons can lead to limited maturity evaluation of source rocks in the Fengcheng Formation and difficulties in determining the maturity of in-situ source rocks during the oil-sources correlation process. This achievement significantly enhances the objectivity of oil-source correlation and source rock evaluation, especially in the context of near-source migration and accumulation or in shale oil & gas research, because source rocks are highly susceptible to the influence of migrated hydrocarbons, it has a broader significance of promotion.

5. Conclusions

The source rocks of the Fengcheng Formation are chiefly fair to excellent in quality, containing Type II organic matter and being at a thermal mature stage for oil generation. However, some deeper source rocks have lower T_{max} values and relatively higher PI values due to the influence of migrated hydrocarbons.

The source rocks affected by migrated hydrocarbons can be identified by their relatively high hydrocarbon content (S_1/TOC > 110 mg HC/g TOC, Extract/TOC > 30 %), lower Rock-Eval T_{max} values, higher thermal maturity parameters of biomarkers (the ββ/(αα+ββ)-C_{29}-Sterane is approximately 0.58, the TT/(TT+17α-hopane) is approximately 0.55), and the presence of C_{20}, C_{21}, and C_{23} TT with a descending and mountain-shaped distribution. These migrated hydrocarbons mainly came from the Fengcheng Formation source rocks with high maturity in the deeper sag.

The characteristics of migrated hydrocarbons' influence in the study area are closely related to the geological lithologic combination. Through a comparison of the extract biomarker fingerprints of adjacent reservoirs and mudstones in different boreholes, three types of influence patterns of migrated hydrocarbons are identified: the edge-influence of thin sandstone-thick mudstone, the mixed-influence of sandstone-mudstone interbedded, and the full-influence of thick sandstone-thin mudstone.

This research aims to identify and eliminate the influence of migrated hydrocarbons on the geochemical parameters of the source rocks in oil-source correlation and source rock evaluation, especially in the context of near-source migration and accumulation or in shale oil & gas research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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