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Molecular correlation of crude oils and oil components from reservoir rocks in the Tazhong and Tabei uplifts of the Tarim Basin, China

Shuang Yu [a], Changchun Pan [a,*], Jinji Wang [a], Xiaodong Jin [a], Lanlan Jiang [a], Dayong Liu [a], Xiuxiang Lü [b], Jianzhong Qin [c], Yixiong Qian [d], Yong Ding [d], Honghan Chen [e]

[a] *State Key Laboratory of Organic Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Wushan, Guangzhou 510640, China*
[b] *Basin & Reservoir Research Center, China University of Petroleum, Beijing 102249, China*
[c] *Wuxi Institute of Petroleum Geology, Sinopec, Wuxi, Jiangsu 214151, China*
[d] *Research Institute of Exploration and Development, Northwest Oil Company, Sinopec, Urumqi 830011, China*
[e] *Department of Petroleum Geology, Faculty of Earth Resources, China University of Geosciences, Wuhan 430074, China*

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ABSTRACT

Molecular data from a large set of source rock, crude oil and oil-containing reservoir rock samples from the Tarim Basin demonstrate multiple sources for the marine oils in the studied areas of this basin. Based on gammacerane/C_{31} hopane and $C_{28}/(C_{27} + C_{28} + C_{29})$ sterane ratios, three of the fifteen crude oils from the Tazhong Uplift correlate with Cambrian–Lower Ordovician source rocks, while the other crude oils from the Tazhong Uplift and all 39 crude oils from the Tahe oilfield in the Tabei Uplift correlate with Middle–Upper Ordovician source rocks. These two ratios further demonstrate that most of the free oils and nearly all of the adsorbed and inclusion oils in oil-containing reservoir rocks from the Tazhong Uplift correlate with Cambrian–Lower Ordovician source rocks, while the free and inclusion oils in oil-containing carbonates from the Tahe oilfield correlate mainly with Middle–Upper Ordovician source rocks. This result suggests that crude oils in the Tazhong Uplift are partly derived from the Cambrian–Lower Ordovician source rocks while those in the Ordovician carbonate reservoirs of Tahe oilfield are overwhelmingly derived from the Middle–Upper Ordovician source rocks.

The scatter of C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) and $C_{21}/(C_{21} + \Sigma C_{29})$ sterane ratios for the free and inclusion oils from oil-containing carbonates in the Tahe oilfield possibly reflects the subtle organofacies variations in the source rocks, implying that the Ordovician reservoirs in this oilfield are near the major source kitchen. In contrast, the close and positive relationship between these two ratios for oil components in the oil-containing reservoir rocks from the Tazhong Uplift implies that they are far from the major source kitchen.

1. Introduction

Numerous oil-source correlation studies have been performed in the Tarim Basin, yet the origins of the discovered oils in the cratonic region of this basin remain unresolved (e.g., Yang, 1991; Zhao et al., 1997; Hanson et al., 2000; Zhang et al., 2000, 2004, 2005; Sun et al., 2003; Wang and Xiao, 2004; Cai et al., 2009a,b; Pan and Liu, 2009; Li et al., 2010). The cratonic region covers most of the Tarim Basin, and the Tazhong and Tabei uplifts and Manjiaer Depression occupy a major part of the cratonic region (Fig. 1) (Zhang and Huang, 2005). Previous studies demonstrated that the main source rocks in the cratonic region of the Tarim Basin are within Cambrian and Ordovician strata (e.g. Gu et al., 1994; Zhang et al., 2000, 2004, 2005; Wang and Xiao, 2004). Some studies identified Cambrian–Lower Ordovician and Middle–Upper Ordovician source rocks and concluded that the marine oils from the Tazhong (central Tarim) and Tabei (northern Tarim) areas were derived overwhelmingly from the latter, based on the distributions of some age diagnostic biomarkers, such as 24-isopropylcholestanes, dinosteranes, triaromatic dinosteroids and 24-norcholestanes (e.g., Hanson et al., 2000; Zhang et al., 2000, 2002a,b, 2004; Zhang and Huang, 2005). The Cambrian–Lower Ordovician source rocks occur throughout most of the cratonic region of the Tarim Basin, generally deposited in evaporative lagoons and starved basins under strongly reducing environments (Gu et al., 1994; Zhang et al., 2004). The total organic carbon (TOC) contents of these source rock samples generally range from 1.2–2.3% (Zhang et al., 2004). However, they are generally overmature (>2.0% R_o; Zhang et al., 2004). The Middle–Upper Ordovician source rock samples, mainly within the Lianglitage Formation (O_{3l}), consist mainly of argillaceous limestones and marlstones deposited in shelf edge and slope environments. TOC values for 298 Middle–Upper Ordovician rock samples average 0.43%, with a maximum value of 6% (Zhang and

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* Corresponding author. Tel.: +86 20 85290183; fax: +86 20 85290706.
E-mail address: cpan@gig.ac.cn (C. Pan).

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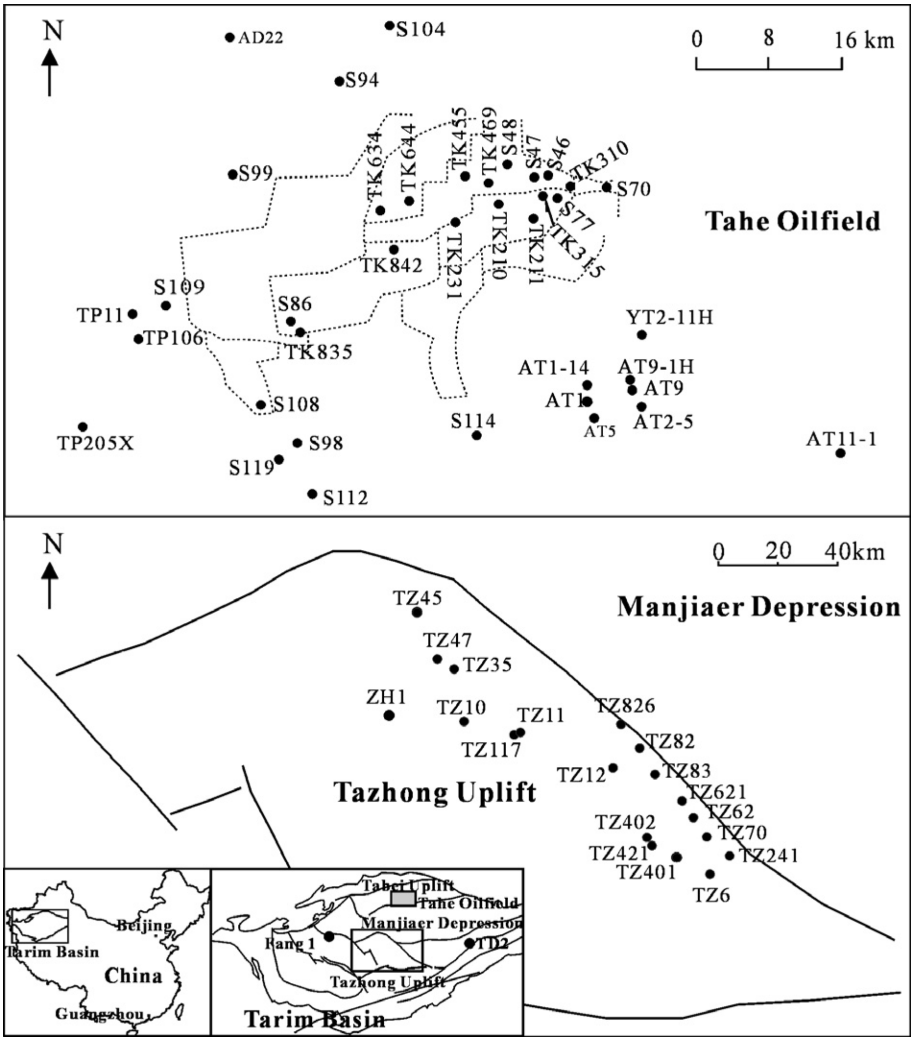

Fig. 1. Location map of the Tazhong Uplift, Tahe oilfield in the Tabei Uplift and the sampled wells.

Huang, 2005). These samples are mature to overmature with respect to oil generation (R_o 0.8–1.5%, Gu et al., 1994; Hanson et al., 2000; Zhang et al., 2000; Zhang and Huang, 2005).

The relatively low TOC values and limited thickness of the source rocks within the Middle–Upper Ordovician strata penetrated by boreholes appear to be inconsistent with the huge reserves of marine oil found in this basin. Other studies suggest that Cambrian–Lower Ordovician source rocks could account for most of these discovered oils (Zhao et al., 1997; He et al., 2002; Sun et al., 2003; Wang and Xiao, 2004; Cai et al., 2009a,b and references therein). Sun et al. (2003) concluded that the marine oils in the Tabei area were not derived from Middle–Upper Ordovician source rocks based on distributions of aryl isoprenoids in these marine oils and related asphaltenes. Recently, Cai et al. (2009a,b) demonstrated that the δ^{34}S values of kerogen decrease from the Cambrian, Lower Ordovician to Upper Ordovician source rocks in this basin, and suggested that non-biodegraded oils without associated H_2S may have originated from Cambrian–Lower Ordovician source rocks. Li et al. (2010) concluded that most of the oils in the Tazhong Uplift have a mixed origin and did not originate from Middle–Upper Ordovician strata alone based on biomarker compositions and δ^{13}C values of individual *n*-alkanes for 108 DST oils and some inclusion oils of reservoir rocks. Similar conclusions were drawn by Zhao et al. (2010) in a study of asphaltenes from a crude oil in an Ordovician carbonate reservoir in the Tazhong Uplift.

Routine oil-source correlation studies are mainly based on biomarker and carbon isotopic compositions of crude oil in reservoirs and residual oil from source rocks. Crude oils are mixtures of oil charges during the reservoir filling process. The Cambrian and Ordovician source kitchens for the major oil fields in the cratonic regions of the Tarim Basin have not been reached by boreholes because of the great depths. The source rock samples from the Cambrian and Ordovician strata reported in the literature are from outcrops in the border areas and/or cores from boreholes in uplifted parts of the basin (e.g., Zhang et al., 2000, 2004; Wang and Xiao, 2004; Cai et al., 2009a,b). Previous studies demonstrated that compositional analysis of oil-bearing fluid inclusions and sequential extraction of oil reservoir rocks are effective approaches to reveal molecular signatures of the initial oil charges (Karlsen et al., 1993; Wilhelms et al., 1996; George et al., 1997, 1998, 2004, 2008; Schwark et al., 1997; Jones and Macleod, 2000; Leythaeuser et al., 2000, 2007; Pan and Yang, 2000; Pan et al., 2000, 2003, 2005, 2007; Gong et al., 2007). Pan and Liu (2009) suggested that the initial oil charge originated from Cambrian–Lower Ordovician source rocks, while later oil charge was mainly derived from Middle–Upper Ordovician source rocks for the oil reservoirs in the Tazhong Uplift based on compositional analysis of oil-bearing fluid inclusions and sequential extraction of oil reservoir rocks for a small set of samples. In the present study, a large set of crude oil and reservoir rock samples from both the Tazhong Uplift and the Tahe

Table 1
Samples of source rocks, crude oils and oil-containing reservoir rocks from the Tarim basin in the present study.

	Strata	Depth (m)
Source rocks		
TD2-1	O1	4527.8
TD2-3	O1	4550.5
TD2-4	O1	4554.5
TD2-9	Cambrian	4768.5
TD2-10	Cambrian	4772.3
TD2-11	Cambrian	4917.5
TD2-12	Cambrian	4918.5
TD2-13	Cambrian	4920.0
Fang 1-2	Cambrian	4514.6
Crude oils in the Tazhong Uplift		
[a]TZ401O1	C1	3680–3780
TZ401O2	C3	3244–3308
TZ402O	C3	3259–3268
TZ421O	C3	3221–3223.5
[a]TZ11O	Silurian	4301–4307
[a]TZ117O	Silurian	4422.52–4436.12
[a]TZ47O	Silurian	4978.5–4986.0
[a]TZ45O	O3	6020–6150
[a]TZ82O	O3	5430–5487
[a]ZH1O	O3	5273.5–5349.5
TZ241O	O3	4618.47–4705.74
TZ62O	O3	4700.5–4758
TZ621O	O3	4851.1–4885
TZ83O	O3	5433–5441
TZ826O	O3	5468–5472
Crude oils from the Tahe oilfield in the Tabei Uplift		
GK3O	K1s	3739–3743
GK4XO	K1s	3764.4–3768.5
S3-6HO	K1bs	5055.2–5569.2
AT2-5O	T3h	4029–4033
AN1-1HO	T3h	4528–4614
DK19HO	T2a	4615–4730
S35CO	T2a	4451.5–4452.5
GK1O	T2a	4375–4625
AT9O	T2a	4244–4248
AT9-1HO	T2a	4608–4718
AT11-1O	T2a	4156–4160
TK239-1HO	T2a	4765–4886
AT1O	T	50,598
YT2-11HO	T	50,611
AT1-14XO	T	50,601
YT2-8XO	T	50,613
TK310O	C1k	5016.5–5018.5
S70O	C1k	5153.02–5167.5
S112O	O3l	6172.0–6189.0
TP106O	O2yj	6299–6365
TK118XO	O2yj	6231.2–6248.6
TK842O	O2yj	5528–5620
TP205XO	O2yj	6511–6531.6
TK210O1	O1y	5643.8–5680
TK210O2	O1-2y	5448.3–5560
TK211O	O1-2y	5430–5499.4
TK469O1	O1-2y	5548–5559.8
TK469O2	O1y	5562.0–5620
TK455O	O1-2y	5482.5–5548
S47O	O1-2y	5346–5497
S46O	O1-2y	5373.5–5454.4
S61CHO	O1-2y	5855.6–6020.5
TK231O	O2	5517.2–5585.1
TK315O	O1	5431.0–5498.0
S48O	O1	5363.0–5370.0
TK644O	O1	5565.4–5606.5
TK634O	O1	5567.0–5599.0
TK835O	O1-2	5765.0–5840.0
TK707O	O1	5708.0–5767.0
Oil-, tar-containing sandstones in the Tazhong Uplift		
[a]TZ401-1	C3	3245
[a]TZ401-2	C3	3433.80
TZ421-1	C3	3221.4
TZ421-2	C3	3226.2
TZ421-3	C3	3280.6
TZ402-5	C3	3246.6
TZ402-6	C3	3307
TZ402-7	C2	3583.9
continued		
TZ402-8	C2	3592.2
TZ402-9	C1	3630.1
ZH1-3	C	4438.5
ZH1-4	Devonian	4616.9
TZ47-3	Devonian	4400.80
[a]TZ47-6	Silurian	4992.20
[a]TZ11-1	Silurian	4310.5
[a]TZ11-2	Silurian	4411.2
[a]TZ11-5	Silurian	4459.70
TZ117-2	Silurian	4427.74
Oil-containing carbonates in the Tazhong Uplift		
[a]TZ45-1	O3	6058.70
[a]TZ45-2	O3	6068.20
TZ241-11	O3	4635.88
TZ241-12	O3	4663.7
TZ62-14	O3	4714.77
TZ62-15	O3	4737.75
TZ621-16	O3	4865.54
TZ621-17	O3	4879.46
TZ70-18	O3	4715.75
TZ70-19	O3	4895.8
TZ70-20	O3	4949.2
[a]TZ82-1	O3	5436.1
TZ82-21	O3	5450.04
TZ82-22	O3	5473.38
TZ826-23	O3	5665.02
TZ826-24	O3	5691.11
TZ826-25	O3	5739.63
TZ826-26	O3	5766.44
TZ83-27	O3	5218.38
TZ83-28	O3	5341.57
TZ83-29	O3	5448.52
Oil-containing sandstones from the Tahe oilfield		
AT9-1	T3h	4079.00
S77-1	C1kl	5147.71
S86-1	C1kl	5221.10
S98-1	C1b	5364.7
S99-1	C1kl	5317.16
S99-2	C1b	5847.94
S119-1	C1b	5293.1
S86-2	C1b	5460.00
S108-1	D3d	5411.3
S109-1	D3d	5723.6
TP11-1	D3d	5807.50
S108-2	S	5429.3
TP11-2	S1k	6043.94
S114-1	S1k	5427.50
Oil-containing carbonates from the Tahe oilfield		
S108-3	O3s	5862.4
TP11-3	O3s	6046.00
AT9-2	O3l	6325.90
S109-2	O3l	6120.1
AT5-1	O3q	6454.43
S86-4	O3	5681.60
S86-3	O2+3	5571.40
AT9-3	O2yj	6395.20
S112-1	O2yj	6353.5
S109-3	O2yj	6249.5
S99-3	O2yj	5924.60
S114-2	O2yj	6333.01
S114-3	O2yj	6384.10
AT5-2	O2yj	6481.50
AD22-1	O1−2y	6432.23
AD22-2	O1−2y	6485.28
S108-4	O1−2y	6114.5
S119-2	O1−2y	6330.1
S114-4	O1−2y	6457.21
S77-2	O1	5447.38
S77-3	O1	5586.66
S77-4	O1	5712.89
S94-1	O1	5955.4
S104-1	O1	6024.5
S104-2	O1	6097.01
S99-4	O1y	6184.05

[a] Samples that were reported in a previous study (Pan and Liu, 2009).

oilfield in the Tabei Uplift were analyzed to enhance understanding of the sources and filling processes of the major oil reservoirs in this basin. The Tahe oilfield is currently the largest field with proved in-place reserves up to 1.0 billion t. Based on geochemical data from this oilfield and others in this basin, a realistic estimate of the contributions from the source rocks within the Cambrian–Ordovician strata can be obtained.

2. Samples and experimental

2.1. Samples

Fifty-four crude oils, and 70 oil-containing sandstones and carbonates were studied (Table 1, Fig. 1). Of the 54 crude oils, 15 oils were collected from the Tazhong Uplift, including the seven

Table 2
The amounts of the total organic carbon (TOC) and extracted bitumen for source rocks within the Cambrian–Lower Ordovician strata in the Tarim Basin.

	TOC (%)	Bitumen (mg/g TOC)		TOC (%)	Bitumen (mg/g TOC)
TD2-1	1.54	6.71	TD2-11	2.41	1.45
TD2-3	2.99	0.42	TD2-12	3.42	1.30
TD2-4	2.97	0.77	TD2-13	1.63	1.25
TD2-9	1.06	13.70	Fang 1-2	0.80	5.79
TD2-10	0.81	7.05			

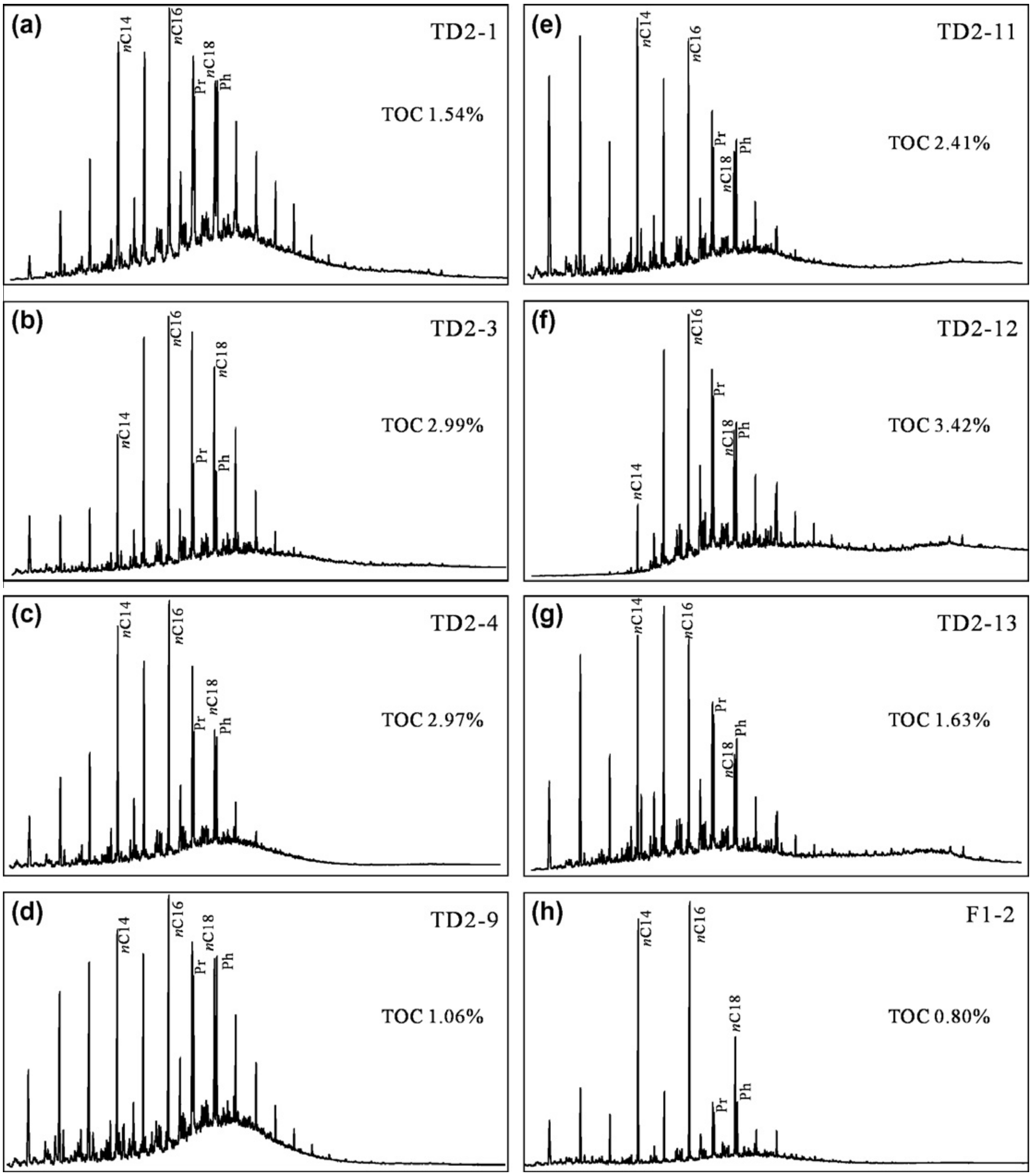

Fig. 2. Partial gas chromatograms of the selected source rocks within the Cambrian–Lower Ordovician strata from wells TD2 and Fang 1.

Table 3
Selected molecular parameters.

	Pr/ n-C_{17}	Ph/ n-C_{18}	Pr/ Ph	T/ (T + H)	Ts/ Tm	G/ $C_{31}H$	$C_{28}DH$/ $C_{29}H$	$C_{29}DH$/ $C_{30}H$	C_{21}/ ($C_{21} + \Sigma C_{29}$)	D/ (D + R)	$C_{27}/\Sigma C_{27-29}$	$C_{28}/\Sigma C_{27-29}$	$C_{29}/\Sigma C_{27-29}$
Source rocks from Wells TD2 and Fang 1													
TD2-1	0.50	0.95	0.68	0.33	0.65	0.45	0.33	0.11	0.37	0.16	0.30	0.35	0.35
TD2-3	0.44	0.54	1.02	0.49	0.65	0.22	0.35	0.11	0.38	0.20	0.29	0.37	0.34
TD2-4	0.67	1.08	1.01	0.69	0.69	0.22	0.39	0.13	0.65	0.22	0.24	0.37	0.39
TD2-9	0.77	1.08	0.83	0.56	0.86	0.57	0.47	0.16	0.55	0.18	0.29	0.32	0.40
TD2-10	0.84	1.57	0.73	0.84	0.88	0.41	0.78	0.24	0.81	0.35	0.37	0.32	0.31
TD2-11	0.92	1.30	0.92	0.40	0.67	0.30	0.40	0.13	0.38	0.17	0.28	0.33	0.39
TD2-12	1.01	1.31	1.17	0.22	0.66	0.45	0.30	0.12	0.21	0.16	0.31	0.30	0.40
TD2-13	1.02	1.37	1.16	0.11	0.75	0.46	0.33	0.10	0.11	0.12	0.30	0.32	0.38
Fang 1-2	0.96	0.53	0.78	0.70	0.89	0.47	0.92	0.31	0.51	0.27	0.37	0.34	0.29
Crude oils from the Tazhong Uplift (C, S)													
[a]TZ401O1	0.29	0.38	0.95	0.88	1.05	0.09	0.20	0.07	0.69	0.49	0.28	0.11	0.61
TZ401O2	0.28	0.33	1.14	0.69	0.73	0.11	1.40	0.48	0.40	0.42	0.27	0.10	0.63
TZ402O	0.26	0.36	0.87	0.68	0.82	0.16	1.27	0.41	0.41	0.51	0.19	0.17	0.64
TZ421O	0.27	0.32	1.10	0.72	0.88	0.10	1.00	0.33	0.47	0.51	0.26	0.15	0.60
[a]TZ11O	0.40	0.54	1.07	0.19	0.52	0.70	0.09	0.03	0.08	0.12	0.24	0.33	0.43
[a]TZ117O	0.33	0.47	0.87	0.82	0.76	0.08	0.12	0.07	0.58	0.33	0.34	0.12	0.54
[a]TZ47O	0.32	0.41	0.98	0.80	0.79	0.10	0.20	0.12	0.51	0.41	0.29	0.17	0.54
Crude oils from the Tazhong Uplift (O3)													
[a]TZ45O	0.33	0.44	0.97	0.93	5.27	0.18	0.10	0.06	0.66	0.46	0.42	0.15	0.44
[a]TZ82O	0.25	0.34	0.95	0.90	2.44	0.12	0.06	0.03	0.67	0.44	0.53	0.08	0.39
[a]ZH1O	0.30	0.41	0.90	0.80	1.02	0.09	0.00	0.00	0.40	0.40	0.30	0.11	0.59
TZ241O	0.26	0.30	1.04	0.50	1.01	0.05	2.02	0.73	0.30	0.55	0.32	0.11	0.57
TZ62O	0.35	0.42	1.01	0.31	0.62	0.31	0.42	0.18	0.20	0.22	0.26	0.28	0.45
TZ621O	0.25	0.30	0.89	0.57	1.03	0.11	0.17	0.09	0.36	0.46	0.30	0.14	0.55
TZ83O	0.36	0.40	1.11	0.42	2.02	0.03	0.34	0.14	0.41	0.47	0.33	0.14	0.53
TZ826O	0.30	0.38	0.99	0.42	1.12	0.33	0.63	0.20	0.30	0.29	0.36	0.28	0.35
Crude oils from the Tahe oilfield in the Tabei Uplift (K, T, C)													
GK3O	0.26	0.17	1.94	0.52	0.98	0.19	0.55	0.14	0.32	0.29	0.30	0.15	0.55
GK4XO	0.28	0.20	1.76	0.49	0.97	0.17	0.60	0.17	0.29	0.31	0.28	0.17	0.55
S3-6HO	0.18	0.08	2.50	0.28	1.39	0.16	0.07	0.16	0.20	0.43	0.13	0.14	0.73
AT2-5O	0.33	0.40	1.00	0.57	0.86	0.13	0.19	0.10	0.25	0.26	0.36	0.13	0.51
AN1-1HO	0.34	0.46	0.87	0.61	0.84	0.10	0.14	0.10	0.32	0.30	0.36	0.14	0.50
DK19HO	0.36	0.44	1.01	0.44	0.50	0.13	0.32	0.13	0.18	0.21	0.30	0.14	0.57
S35CO	0.35	0.45	0.91	0.55	0.61	0.13	0.32	0.11	0.25	0.25	0.32	0.14	0.54
GK1O	0.37	0.45	1.12	0.77	1.06	0.09	0.15	0.08	0.41	0.38	0.33	0.13	0.54
AT9O	0.33	0.38	1.13	0.55	0.75	0.14	0.22	0.10	0.23	0.27	0.33	0.12	0.55
AT9-1HO	0.39	0.47	1.23	0.74	0.64	0.07	0.31	0.13	0.40	0.24	0.38	0.13	0.49
AT11-1O	0.36	0.44	1.08	0.56	0.62	0.13	0.49	0.17	0.25	0.26	0.33	0.14	0.53
TK239-1HO	0.35	0.44	0.97	0.57	0.91	0.10	0.12	0.06	0.29	0.28	0.32	0.13	0.55
AT1O	0.35	0.43	1.05	0.53	0.62	0.15	0.26	0.12	0.22	0.26	0.30	0.16	0.54
YT2-11HO	0.34	0.44	0.87	0.50	0.54	0.14	0.31	0.11	0.21	0.24	0.29	0.11	0.59
AT1-14XO	0.35	0.43	0.96	0.50	0.59	0.13	0.28	0.11	0.21	0.25	0.33	0.13	0.54
YT2-8XO	0.34	0.44	0.84	0.53	0.62	0.11	0.27	0.10	0.23	0.25	0.33	0.14	0.53
TK310O	0.37	0.46	0.95	0.60	1.02	0.11	0.10	0.07	0.24	0.31	0.35	0.12	0.53
S70O	0.36	0.47	0.87	0.63	0.94	0.11	0.07	0.05	0.29	0.29	0.36	0.12	0.52
Crude oils from the Tahe oilfield in the Tabei Uplift (O)													
S112O	0.38	0.52	0.83	0.76	1.92	0.10	0.28	0.14	0.31	0.28	0.29	0.15	0.56
TP106O	0.50	0.72	0.80	0.46	0.58	0.13	0.45	0.16	0.16	0.21	0.31	0.13	0.56
TK118XO	0.35	0.46	0.92	0.80	2.06	0.12	0.32	0.18	0.32	0.35	0.36	0.12	0.52
TK842O	0.41	0.56	0.91	0.52	0.44	0.13	0.26	0.11	0.21	0.23	0.32	0.14	0.54
TP205XO	0.37	0.48	0.92	0.49	1.12	0.12	0.13	0.06	0.19	0.28	0.33	0.12	0.55
TK210O1	0.42	0.58	0.79	0.66	0.38	0.16	0.49	0.20	0.33	0.24	0.32	0.12	0.56
TK210O2	0.45	0.62	0.83	0.45	0.38	0.16	0.38	0.13	0.17	0.21	0.22	0.15	0.64
TK211O	0.43	0.59	0.86	0.48	0.42	0.15	0.40	0.15	0.19	0.22	0.28	0.12	0.59
TK469O1	0.43	0.59	0.84	0.54	0.42	0.14	0.44	0.18	0.22	0.23	0.29	0.13	0.58
TK469O2	0.46	0.63	0.80	0.42	0.40	0.17	0.39	0.13	0.15	0.20	0.19	0.15	0.66
TK455O	0.41	0.55	1.01	0.48	0.38	0.14	0.43	0.16	0.19	0.21	0.29	0.14	0.57
S47O	0.40	0.53	0.94	0.48	0.47	0.13	0.27	0.10	0.19	0.22	0.30	0.13	0.57
S46O	0.41	0.54	0.89	0.52	0.57	0.11	0.25	0.09	0.22	0.24	0.35	0.11	0.54
S61CHO	0.39	0.54	0.84	0.53	0.55	0.09	0.13	0.05	0.23	0.22	0.32	0.13	0.56
TK231O	0.43	0.60	0.81	0.45	0.44	0.12	0.26	0.09	0.19	0.22	0.22	0.13	0.66
TK315O	0.45	0.62	0.79	0.44	0.44	0.11	0.27	0.10	0.18	0.21	0.23	0.16	0.61
S48O	0.49	0.68	0.79	0.43	0.41	0.11	0.34	0.12	0.18	0.21	0.19	0.17	0.63
TK644O	0.46	0.64	0.78	0.47	0.41	0.15	0.37	0.12	0.18	0.22	0.20	0.15	0.65
TK634O	0.47	0.65	0.86	0.46	0.39	0.15	0.38	0.13	0.17	0.20	0.21	0.17	0.63
TK835O	0.43	0.61	0.81	0.41	0.43	0.14	0.17	0.06	0.16	0.23	0.20	0.16	0.64
TK707O	0.62	0.87	0.78	0.50	0.51	0.11	0.14	0.05	0.23	0.22	0.20	0.20	0.60
Oil-, tar-containing sandstones from the Tazhong Uplift (Group A)													
TZ421-1a	1.13	0.99	0.81	0.91	0.57	0.47	0.65	0.23	0.71	0.32	0.22	0.33	0.45
TZ421-1b1	0.62	0.91	0.97	0.61	1.05	0.46	0.30	0.09	0.32	0.17	0.24	0.27	0.49

(*continued on next page*)

Table 3 (*continued*)

	Pr/ n-C_{17}	Ph/ n-C_{18}	Pr/ Ph	T/ (T + H)	Ts/ Tm	G/ $C_{31}H$	$C_{28}DH$/ $C_{29}H$	$C_{29}DH$/ $C_{30}H$	C_{21}/ (C_{21} + ΣC_{29})	D/ (D + R)	$C_{27}/\Sigma C_{27-29}$	$C_{28}/\Sigma C_{27-29}$	$C_{29}/\Sigma C_{27-29}$
TZ421-1b2	1.00	1.05	1.68	0.33	1.22	0.45	0.19	0.08	0.14	0.19	0.20	0.31	0.49
TZ421-1c1	0.46	0.57	1.16	0.16	0.79	0.49	0.20	0.07	0.08	0.15	0.25	0.29	0.45
TZ421-1c2	0.70	0.66	1.73	0.21	1.04	0.52	0.22	0.06	0.12	0.19	0.25	0.31	0.44
TZ421-2a	1.11	0.99	0.64	0.92	0.34	0.62	0.57	0.21	0.70	0.31	0.16	0.35	0.50
TZ421-2b1	0.91	0.88	0.65	0.88	0.51	0.54	0.52	0.20	0.50	0.32	0.14	0.34	0.52
TZ421-2b2	0.89	0.92	0.92	0.55	0.92	0.45	0.23	0.08	0.31	0.17	0.22	0.32	0.46
TZ421-3a	0.93	0.87	0.80	0.92	0.49	0.55	0.74	0.27	0.75	0.35	0.19	0.33	0.48
TZ421-3b1	0.75	0.83	0.94	0.68	1.33	0.40	0.34	0.13	0.42	0.27	0.19	0.33	0.48
TZ421-3b2	0.70	0.80	0.87	0.69	0.66	0.40	0.29	0.12	0.44	0.19	0.21	0.31	0.48
TZ421-3c1	0.49	0.56	0.92	0.34	1.11	0.43	0.23	0.07	0.20	0.22	0.22	0.31	0.47
TZ421-3c2	0.57	0.59	1.07	0.37	0.95	0.47	0.35	0.10	0.22	0.21	0.20	0.32	0.48
TZ402-6a	1.01	0.72	1.04	0.50	1.04	0.32	0.60	0.15	0.30	0.27	0.31	0.29	0.40
TZ402-6b	0.49	0.62	1.12	0.33	1.13	0.38	0.42	0.11	0.17	0.27	0.23	0.29	0.48
TZ402-6c	0.48	0.51	1.36	0.22	1.11	0.41	0.30	0.08	0.14	0.23	0.25	0.31	0.44
TZ402-7a	0.85	0.70	1.36	0.33	1.23	0.37	0.24	0.06	0.21	0.19	0.30	0.27	0.43
TZ402-7b1	0.55	0.61	1.34	0.29	1.17	0.46	0.35	0.09	0.17	0.22	0.23	0.34	0.43
TZ402-7b2	0.57	0.81	1.43	0.26	1.06	0.45	0.26	0.05	0.12	0.20	0.23	0.32	0.45
TZ402-7c1	0.56	0.51	1.79	0.14	0.70	0.43	0.15	0.04	0.10	0.20	0.21	0.34	0.45
TZ402-7c2	0.74	0.58	1.76	0.22	0.95	0.42	0.24	0.07	0.12	0.26	0.21	0.30	0.49
TZ402-8a	1.32	0.71	1.02	0.67	0.96	0.30	0.99	0.28	0.44	0.31	0.29	0.28	0.43
TZ402-8b	1.93	0.90	1.42	0.34	1.06	0.42	0.48	0.12	0.15	0.20	0.25	0.27	0.47
TZ402-8c	0.57	0.62	1.22	0.33	1.16	0.36	0.44	0.10	0.20	0.22	0.29	0.27	0.44
TZ402-9a	2.37	1.76	1.37	0.56	0.99	0.25	1.00	0.24	0.37	0.30	0.27	0.26	0.47
TZ402-9b	0.35	0.31	1.07	0.34	1.27	0.32	0.62	0.18	0.17	0.31	0.21	0.28	0.51
TZ402-9c	0.39	0.46	1.42	0.26	1.07	0.39	0.29	0.08	0.22	0.25	0.26	0.30	0.44
ZH1-3a	0.94	1.07	0.79	0.60	1.13	0.32	0.37	0.20	0.55	0.23	0.36	0.29	0.35
ZH1-3b1	0.75	0.93	1.14	0.27	0.95	0.22	0.26	0.12	0.14	0.21	0.31	0.29	0.40
ZH1-3b2	0.65	0.70	1.27	0.32	1.27	0.25	0.23	0.13	0.18	0.20	0.30	0.33	0.37
ZH1-3c1	0.55	0.82	0.91	0.14	1.01	0.46	0.11	0.06	0.03	0.13	0.23	0.34	0.43
ZH1-3c2	0.57	0.78	0.94	0.43	1.08	0.38	0.11	0.05	0.29	0.13	0.24	0.31	0.44
[a]TZ47-6a	0.44	0.47	0.82	0.37	0.55	0.31	0.19	0.11	0.12	0.15	0.23	0.30	0.47
[a]TZ47-6b1	0.71	0.71	1.74	0.33	0.83	0.25	0.23	0.12	0.16	0.22	0.27	0.30	0.43
TZ47-6b2	0.74	0.83	1.53	0.46	1.03	0.23	0.17	0.08	0.19	0.25	0.25	0.36	0.39
[a]TZ47-6c1	0.63	0.48	1.87	0.59	0.71	0.17	0.15	0.07	0.32	0.20	0.40	0.20	0.40
TZ47-6c2	0.50	0.31	2.23	0.54	0.77	0.21	0.12	0.08	0.18	0.20	0.29	0.26	0.45
TZ117-2a	0.78	0.88	0.85	0.86	1.00	0.48	0.31	0.13	0.63	0.25	0.31	0.34	0.35
TZ117-2b1	0.84	0.83	1.25	0.19	1.21	0.33	0.24	0.11	0.10	0.22	0.30	0.31	0.39
TZ117-2b2	0.79	0.89	1.23	0.42	1.47	0.41	0.18	0.10	0.35	0.30	0.35	0.25	0.40
TZ117-2c1	0.55	0.68	1.13	0.30	0.60	0.47	0.14	0.06	0.12	0.15	0.37	0.30	0.33
TZ117-2c2	0.52	0.80	1.06	0.18	0.95	0.40	0.12	0.06	0.04	0.13	0.27	0.29	0.44
Oil-, tar-containing sandstones from the Tazhong Uplift (Group B)													
[a]TZ401-1a	0.53	0.54	0.51	0.81	0.96	0.13	0.72	0.31	0.52	0.33	0.34	0.16	0.50
[a]TZ401-1b1	0.32	0.32	0.85	0.22	1.02	0.28	0.32	0.14	0.13	0.20	0.35	0.30	0.35
TZ401-1b2	0.30	0.26	0.88	0.43	1.12	0.25	0.41	0.15	0.26	0.26	0.32	0.28	0.40
[a]TZ401-1c1	0.33	0.36	0.97	0.52	0.91	0.35	0.31	0.12	0.28	0.24	0.36	0.31	0.33
TZ401-1c2	0.39	0.47	1.02	0.26	0.89	0.40	0.16	0.06	0.12	0.16	0.23	0.34	0.43
[a]TZ401-2a	0.79	0.56	0.32	0.83	0.96	0.15	0.78	0.35	0.52	0.31	0.40	0.14	0.46
[a]TZ401-2b1	0.28	0.35	0.76	0.39	0.96	0.26	0.44	0.16	0.22	0.25	0.32	0.29	0.39
TZ401-2b2	0.44	0.50	1.00	0.52	1.05	0.22	0.65	0.17	0.31	0.24	0.41	0.26	0.33
[a]TZ401-2c1	0.64	0.84	0.91	0.21	0.78	0.40	0.14	0.06	0.06	0.13	0.24	0.30	0.46
TZ401-2c2	1.02	1.45	0.82	0.35	0.81	0.37	0.27	0.09	0.20	0.18	0.34	0.31	0.35
TZ402-5a	0.92	0.72	0.91	0.66	0.92	0.20	1.13	0.39	0.32	0.34	0.31	0.15	0.54
TZ402-5b	0.32	0.33	1.28	0.35	1.11	0.43	0.39	0.11	0.19	0.24	0.23	0.28	0.49
TZ402-5c	0.42	0.46	1.38	0.28	1.19	0.30	0.48	0.11	0.18	0.19	0.33	0.24	0.43
ZH1-4a	0.98	1.40	0.84	0.49	2.45	0.10	0.07	0.03	0.69	0.31	0.32	0.23	0.45
ZH1-4c1	0.67	0.96	1.03	0.27	1.06	0.30	0.16	0.08	0.11	0.14	0.41	0.28	0.31
ZH1-4c2	0.62	0.80	0.98	0.19	1.13	0.35	0.10	0.05	0.04	0.13	0.24	0.31	0.44
TZ47-3a	0.59	1.14	0.60	0.22	0.75	0.10	0.06	0.05	0.13	0.31	0.16	0.17	0.67
TZ47-3b2	0.72	0.80	1.25	0.31	1.13	0.18	0.18	0.08	0.23	0.33	0.28	0.26	0.46
TZ47-3c1	0.82	0.83	1.21	0.28	1.04	0.17	0.12	0.06	0.18	0.27	0.32	0.27	0.41
TZ47-3c2	0.61	0.74	1.18	0.24	0.71	0.16	0.09	0.05	0.13	0.26	0.28	0.25	0.47
[a]TZ11-1a	0.34	0.32	1.05	0.44	0.91	0.17	0.17	0.06	0.38	0.21	0.29	0.16	0.55
[a]TZ11-1b1	0.58	0.46	1.28	0.42	0.90	0.15	0.20	0.10	0.27	0.17	0.28	0.21	0.51
TZ11-1b2	0.61	0.31	1.20	0.43	0.87	0.17	0.21	0.09	0.28	0.18	0.33	0.23	0.44
[a]TZ11-1c1	0.63	0.80	1.04	0.54	0.99	0.20	0.21	0.09	0.38	0.18	0.38	0.24	0.38
TZ11-1c2	0.61	0.68	1.28	0.34	0.96	0.28	0.16	0.06	0.11	0.14	0.26	0.29	0.45
[a]TZ11-2a				0.51	0.57	0.10	0.10	0.04	0.24	0.26	0.36	0.19	0.46
[a]TZ11-2b2	0.78	1.07	1.38	0.61	0.64	0.15	0.15	0.08	0.36	0.26	0.35	0.25	0.40
TZ11-2c1	0.73	0.85	1.28	0.36	0.79	0.28	0.14	0.06	0.14	0.20	0.25	0.29	0.46
[a]TZ11-2c2	0.59	0.85	0.97	0.44	0.70	0.27	0.13	0.06	0.20	0.20	0.28	0.26	0.45
[a]TZ11-5a	0.70	0.81	0.47	0.71	0.72	0.09	0.10	0.07	0.37	0.28	0.36	0.13	0.51
[a]TZ11-5b1	0.46	0.48	1.11	0.40	0.93	0.20	0.22	0.12	0.18	0.24	0.34	0.27	0.39
TZ11-5b2	0.42	0.42	0.93	0.48	0.78	0.18	0.20	0.10	0.20	0.26	0.34	0.25	0.41
[a]TZ11-5c1	0.48	0.50	1.07	0.27	0.92	0.38	0.09	0.05	0.08	0.15	0.25	0.32	0.44

Table 3 (*continued*)

	Pr/ n-C_{17}	Ph/ n-C_{18}	Pr/ Ph	T/ (T + H)	Ts/ Tm	G/ $C_{31}H$	$C_{28}DH$/ $C_{29}H$	$C_{29}DH$/ $C_{30}H$	C_{21}/ (C_{21} + ΣC_{29})	D/ (D + R)	$C_{27}/\Sigma C_{27-29}$	$C_{28}/\Sigma C_{27-29}$	$C_{29}/\Sigma C_{27-29}$
TZ11-5c2	0.42	0.34	1.30	0.24	1.11	0.36	0.11	0.06	0.06	0.17	0.20	0.36	0.44
Oil-containing carbonates from the Tazhong Uplift													
[a]TZ45-1a	0.78	0.17	0.84	0.78	1.26	0.20	0.20	0.14	0.50	0.33	0.33	0.33	0.34
[a]TZ45-1c1	0.55	0.45	1.02	0.34	1.50	0.32	0.11	0.08	0.10	0.19	0.26	0.32	0.42
TZ45-1c2	0.54	0.46	0.95	0.34	1.46	0.35	0.14	0.07	0.09	0.20	0.27	0.33	0.40
[a]TZ45-2a	0.62	0.22	1.09	0.84	3.30	0.21	0.22	0.08	0.73	0.34	0.29	0.33	0.38
[a]TZ45-2c1	0.42	0.40	0.92	0.32	2.47	0.27	0.11	0.07	0.13	0.21	0.32	0.31	0.37
TZ45-2c2	0.41	0.37	0.96	0.29	2.70	0.21	0.13	0.07	0.11	0.24	0.27	0.33	0.40
TZ241-11a	0.40	0.35	0.99	0.29	1.44	0.33	1.55	0.37	0.13	0.32	0.31	0.31	0.38
TZ241-11c1	0.32	0.37	0.97	0.14	3.63	0.40	0.35	0.10	0.08	0.25	0.23	0.27	0.50
TZ241-11c2	0.33	0.43	0.88	0.15	3.38	0.43	0.50	0.11	0.05	0.25	0.17	0.34	0.49
TZ241-12a	0.35	0.34	0.82	0.36	1.27	0.26	0.53	0.19	0.13	0.36	0.28	0.28	0.44
TZ241-12c	0.26	0.30	0.78	0.19	1.22	0.41	0.34	0.13	0.07	0.19	0.17	0.36	0.46
TZ62-14a	0.48	0.61	0.98	0.36	0.74	0.13	0.13	0.07	0.19	0.35	0.25	0.22	0.53
TZ62-14c1	0.45	0.61	0.95	0.21	0.80	0.13	0.11	0.05	0.17	0.28	0.24	0.27	0.50
TZ62-14c2	0.40	0.54	0.81	0.18	0.81	0.15	0.07	0.04	0.13	0.33	0.17	0.32	0.51
TZ62-15a	0.59	0.59	0.53	0.37	0.79	0.16	0.18	0.09	0.26	0.38	0.30	0.28	0.42
TZ62-15c1	0.54	0.64	0.97	0.16	0.92	0.33	0.25	0.09	0.09	0.21	0.21	0.31	0.47
TZ62-15c2	0.50	0.60	0.72	0.24	0.88	0.28	0.15	0.07	0.14	0.32	0.22	0.28	0.50
TZ621-16a	0.90	0.87	1.01	0.40	0.89	0.37	0.39	0.13	0.22	0.25	0.36	0.28	0.36
TZ621-16c1	0.55	0.76	1.36	0.14	1.05	0.22	0.11	0.05	0.14	0.23	0.22	0.28	0.50
TZ621-16c2	0.48	0.66	1.07	0.10	1.05	0.28	0.13	0.05	0.07	0.18	0.17	0.33	0.50
TZ621-17a	0.56	0.59	0.93	0.36	0.83	0.24	0.15	0.07	0.23	0.34	0.32	0.27	0.40
TZ621-17c1	0.40	0.49	0.99	0.21	0.92	0.20	0.13	0.06	0.13	0.28	0.19	0.25	0.56
TZ621-17c2	0.41	0.50	0.92	0.18	0.88	0.20	0.11	0.06	0.14	0.28	0.20	0.30	0.50
TZ70-18a	0.69	0.63	0.78	0.33	0.87	0.27	0.34	0.10	0.23	0.34	0.35	0.33	0.33
TZ70-18c	0.39	0.50	0.85	0.28	0.89	0.24	0.26	0.10	0.16	0.25	0.26	0.27	0.47
TZ70-19a	0.67	0.67	0.94	0.29	1.52	0.28	0.44	0.16	0.18	0.28	0.26	0.33	0.40
TZ70-19c1	0.40	0.46	1.27	0.11	2.76	0.28	0.18	0.09	0.08	0.22	0.18	0.29	0.53
TZ70-19c2	0.26	0.32	0.85	0.08	2.80	0.27	0.20	0.11	0.04	0.24	0.14	0.27	0.58
TZ70-20a	0.76	0.74	0.98	0.34	1.28	0.34	0.27	0.11	0.23	0.26	0.26	0.31	0.43
TZ70-20c	0.44	0.46	1.25	0.12	2.87	0.36	0.19	0.08	0.08	0.21	0.18	0.31	0.51
[a]TZ82-1a	0.38	0.46	0.57	0.72	1.93	0.25	0.23	0.10	0.47	0.36	0.37	0.28	0.35
[a]TZ82-1c1	0.33	0.41	0.86	0.39	2.82	0.35	0.25	0.11	0.15	0.24	0.30	0.30	0.40
TZ82-1c2	0.33	0.42	0.81	0.37	2.81	0.36	0.15	0.07	0.14	0.25	0.27	0.30	0.43
TZ82-21a	0.56	0.70	1.33	0.17	1.11	0.37	0.37	0.14	0.08	0.28	0.36	0.28	0.36
TZ82-21c	0.30	0.34	1.17	0.07	1.80	0.46	0.22	0.10	0.04	0.12	0.31	0.28	0.41
TZ82-22a	0.49	0.61	0.98	0.67	2.56	0.20	0.42	0.15	0.31	0.45	0.34	0.27	0.39
TZ82-22c	0.33	0.41	0.87	0.27	4.74	0.48	0.34	0.09	0.16	0.31	0.18	0.34	0.47
TZ826-23a	0.43	0.55	0.41	0.66	3.42	0.16	1.14	0.52	0.34	0.44	0.34	0.31	0.35
TZ826-23c	0.43	0.46	0.98	0.19	1.26	0.44	0.22	0.09	0.11	0.25	0.20	0.31	0.49
TZ826-24a	0.48	0.52	0.82	0.52	3.21	0.17	0.87	0.39	0.23	0.41	0.29	0.33	0.38
TZ826-24c1	0.44	0.54	1.24	0.21	1.87	0.48	0.28	0.10	0.08	0.23	0.18	0.35	0.47
TZ826-24c2	0.35	0.45	0.96	0.21	2.15	0.38	0.39	0.14	0.09	0.31	0.19	0.32	0.49
TZ826-25a	0.58	0.62	1.01	0.26	1.71	0.42	1.04	0.39	0.26	0.33	0.31	0.33	0.36
TZ826-25c1	0.21	0.23	1.22	0.14	3.80	0.39	0.14	0.06	0.05	0.18	0.17	0.34	0.49
TZ826-25c2	0.29	0.35	1.09	0.11	2.66	0.51	0.16	0.06	0.03	0.15	0.16	0.34	0.50
TZ826-26a	0.76	0.81	0.87	0.19	1.57	0.42	0.73	0.30	0.13	0.28	0.34	0.31	0.35
TZ826-26c	0.45	0.65	1.22	0.13	1.34	0.39	0.25	0.08	0.07	0.21	0.16	0.31	0.53
TZ83-27a	0.78	0.87	1.26	0.50	1.57	0.27	0.26	0.09	0.53	0.27	0.26	0.32	0.42
TZ83-27c	0.32	0.34	1.05	0.10	2.89	0.33	0.21	0.10	0.07	0.21	0.16	0.32	0.52
TZ83-28a	1.05	0.92	1.18	0.53	1.07	0.52	0.53	0.19	0.48	0.30	0.35	0.29	0.36
TZ83-28c	0.37	0.44	1.30	0.22	2.43	0.36	0.21	0.08	0.12	0.23	0.17	0.33	0.50
TZ83-29a	0.43	0.41	1.65	0.49	1.22	0.31	0.71	0.20	0.38	0.27	0.29	0.33	0.38
TZ83-29c1	0.50	0.62	1.34	0.09	1.32	0.49	0.03	0.02	0.03	0.13	0.20	0.34	0.46
TZ83-29c2	0.33	0.41	1.16	0.12	2.48	0.31	0.35	0.08	0.07	0.19	0.15	0.32	0.54
Oil-containing sandstones from the Tahe oilfield in the Tabei Uplift													
AT9-1a	0.78	1.06	0.63	0.20	0.29	0.51	0.38	0.28	0.09	0.16	0.09	0.28	0.62
AT9-1b1	0.44	0.65	1.30	0.18	0.41	0.37	0.27	0.18	0.10	0.18	0.16	0.28	0.56
AT9-1b2	0.76	1.08	1.30	0.11	0.36	0.35	0.24	0.21	0.06	0.19	0.12	0.21	0.66
AT9-1c1	0.50	0.53	1.81	0.11	1.32	0.23	0.06	0.04	0.05	0.16	0.29	0.26	0.45
AT9-1c2	0.64	0.62	2.52	0.15	1.35	0.16	0.06	0.03	0.06	0.21	0.28	0.29	0.43
S77-1a	0.66	0.76	0.77	0.54	0.67	0.44	0.19	0.07	0.17	0.13	0.30	0.32	0.38
S77-1b1	0.64	0.77	0.97	0.24	0.88	0.34	0.15	0.07	0.12	0.20	0.29	0.29	0.42
S77-1b2	0.42	0.63	1.03	0.32	0.95	0.34	0.12	0.07	0.15	0.20	0.28	0.32	0.41
S77-1c1	0.48	0.64	1.46	0.08	1.23	0.36	0.06	0.03	0.04	0.15	0.26	0.27	0.47
S77-1c2	0.57	0.45	2.40	0.10	1.40	0.15	0.05	0.03	0.05	0.19	0.33	0.28	0.39
S86-1a	0.43	0.56	0.48	0.60	0.91	0.14	0.20	0.07	0.25	0.27	0.29	0.17	0.54
S86-1b1	0.37	0.58	0.69	0.49	0.98	0.18	0.18	0.06	0.18	0.25	0.28	0.19	0.54
S86-1b2	0.45	0.58	0.75	0.51	0.91	0.17	0.17	0.07	0.18	0.27	0.26	0.19	0.56
S86-1c1	0.57	0.61	1.36	0.14	1.48	0.20	0.08	0.04	0.06	0.18	0.33	0.26	0.41
S86-1c2	0.33	0.60	1.55	0.16	1.42	0.19	0.06	0.04	0.08	0.20	0.33	0.28	0.40
S99-1a	0.43	0.58	0.50	0.53	0.52	0.14	0.33	0.11	0.23	0.25	0.27	0.12	0.61

(*continued on next page*)

Table 3 (*continued*)

	Pr/ n-C_{17}	Ph/ n-C_{18}	Pr/ Ph	T/ (T + H)	Ts/ Tm	G/ $C_{31}H$	$C_{28}DH$/ $C_{29}H$	$C_{29}DH$/ $C_{30}H$	C_{21}/ $(C_{21} + \Sigma C_{29})$	D/ (D + R)	$C_{27}/\Sigma C_{27-29}$	$C_{28}/\Sigma C_{27-29}$	$C_{29}/\Sigma C_{27-29}$
S99-1b1	0.57	0.64	1.20	0.37	0.78	0.20	0.22	0.08	0.14	0.24	0.27	0.19	0.55
S99-1b2	0.62	1.06	1.14	0.28	0.86	0.28	0.24	0.06	0.15	0.21	0.25	0.25	0.50
S99-1c1	0.65	0.92	1.10	0.12	1.28	0.28	0.07	0.03	0.07	0.17	0.29	0.26	0.45
S99-1c2	0.61	0.91	1.16	0.16	1.48	0.20	0.07	0.04	0.08	0.21	0.34	0.26	0.40
S98a	0.89	1.34	0.64	0.54	0.61	0.13	0.19	0.07	0.18	0.25	0.29	0.14	0.57
S98b1	0.44	0.46	1.54	0.31	0.93	0.23	0.17	0.07	0.14	0.25	0.27	0.20	0.53
S98b2	0.40	0.76	1.13	0.41	1.00	0.20	0.16	0.07	0.17	0.22	0.31	0.17	0.52
S98c1	0.60	0.68	1.53	0.13	1.42	0.20	0.07	0.04	0.08	0.20	0.29	0.29	0.42
S98c2	0.58	0.83	1.27	0.10	1.02	0.32	0.07	0.03	0.06	0.18	0.27	0.26	0.47
S99-2a	0.52	0.72	0.63	0.56	0.44	0.21	0.85	0.29	0.23	0.24	0.20	0.14	0.66
S99-2b1	0.29	0.77	0.90	0.51	0.71	0.26	0.33	0.10	0.34	0.24	0.28	0.24	0.48
S99-2b2	0.64	0.87	1.27	0.29	0.83	0.20	0.33	0.10	0.18	0.23	0.29	0.22	0.49
S99-2c1	0.60	0.58	1.71	0.22	1.05	0.19	0.18	0.06	0.12	0.22	0.26	0.26	0.48
S99-2c2	0.47	0.51	1.65	0.23	1.17	0.23	0.16	0.05	0.11	0.21	0.27	0.23	0.50
S119-1a	0.74	1.14	0.49	0.60	0.59	0.15	0.20	0.08	0.26	0.27	0.26	0.15	0.59
S119-1b	0.33	1.08	0.83	0.53	0.80	0.20	0.17	0.06	0.31	0.26	0.32	0.20	0.48
S119-1c	0.74	0.99	0.96	0.40	0.86	0.19	0.12	0.04	0.16	0.24	0.26	0.22	0.52
S86-2a	0.43	0.58	0.58	0.53	0.78	0.13	0.16	0.05	0.26	0.26	0.22	0.18	0.60
S86-2c1	0.39	0.52	0.84	0.53	1.33	0.12	0.17	0.06	0.21	0.29	0.27	0.17	0.56
S86-2c2	0.44	0.58	0.85	0.56	1.01	0.15	0.23	0.08	0.24	0.30	0.30	0.18	0.53
S108-1a	0.49	0.59	0.66	0.55	0.64	0.16	0.28	0.09	0.21	0.28	0.27	0.14	0.59
S108-1b1	0.45	0.65	1.22	0.49	1.01	0.19	0.25	0.07	0.22	0.25	0.29	0.19	0.53
S108-1b2	0.50	0.68	1.11	0.42	0.81	0.20	0.21	0.06	0.17	0.24	0.26	0.20	0.54
S108-1c1	0.41	0.49	1.21	0.25	0.83	0.25	0.12	0.04	0.14	0.21	0.26	0.21	0.53
S108-1c2	0.61	0.59	1.50	0.14	0.99	0.24	0.09	0.03	0.09	0.19	0.24	0.26	0.51
S109-1a	0.75	1.00	0.69	0.80	1.03	0.33	0.30	0.12	0.63	0.30	0.38	0.30	0.32
S109-1b1	0.53	0.58	1.41	0.17	1.14	0.30	0.18	0.03	0.10	0.21	0.26	0.29	0.45
S109-1b2	0.58	0.90	1.17	0.23	1.15	0.29	0.14	0.06	0.18	0.24	0.28	0.30	0.42
S109-1c1	0.63	0.78	1.50	0.12	1.29	0.23	0.06	0.03	0.08	0.18	0.30	0.28	0.43
S109-1c2	0.54	0.61	1.57	0.10	1.34	0.28	0.07	0.03	0.04	0.18	0.30	0.26	0.44
TP11-1a	0.54	0.69	0.77	0.63	0.79	0.30	2.64	0.85	0.19	0.19	0.09	0.20	0.71
TP11-1b1	0.49	0.64	1.31	0.47	1.07	0.27	0.95	0.29	0.25	0.24	0.23	0.25	0.52
TP11-1b2	0.49	0.66	1.29	0.36	0.94	0.28	0.65	0.14	0.18	0.20	0.28	0.22	0.50
TP11-1c1	0.46	0.50	1.29	0.18	1.22	0.26	0.30	0.09	0.10	0.19	0.24	0.26	0.50
TP11-1c2	0.43	0.39	1.57	0.25	1.56	0.20	0.30	0.10	0.10	0.19	0.33	0.27	0.40
S108-2a	0.49	0.61	0.64	0.52	0.57	0.15	0.34	0.11	0.17	0.26	0.27	0.13	0.60
S108-2b1	0.37	0.68	1.11	0.42	0.94	0.27	0.22	0.10	0.17	0.23	0.27	0.23	0.50
S108-2b2	0.51	0.75	1.11	0.47	0.74	0.20	0.26	0.10	0.21	0.26	0.31	0.16	0.53
S108-2c1	0.51	0.51	1.33	0.19	1.09	0.16	0.10	0.04	0.13	0.22	0.25	0.25	0.50
S108-2c2	0.51	0.61	1.13	0.26	1.02	0.20	0.12	0.04	0.18	0.23	0.26	0.24	0.50
TP11-2a	0.71	0.94	0.76	0.45	0.65	0.14	0.11	0.05	0.16	0.24	0.27	0.18	0.55
TP11-2b1	0.52	0.61	1.58	0.24	0.75	0.20	0.11	0.05	0.15	0.27	0.28	0.22	0.50
TP11-2b2	0.34	0.74	1.02	0.42	0.82	0.20	0.09	0.04	0.28	0.23	0.35	0.22	0.44
TP11-2c1	0.68	0.78	1.15	0.36	1.20	0.18	0.21	0.05	0.16	0.20	0.47	0.23	0.30
TP11-2c2	0.65	0.73	1.18	0.33	1.14	0.14	0.06	0.08	0.11	0.21	0.28	0.24	0.48
S114-1a	0.64	0.74	0.97	0.56	0.74	0.20	0.16	0.08	0.16	0.26	0.29	0.13	0.58
S114-1b1	0.43	0.52	1.42	0.55	1.25	0.20	0.17	0.07	0.12	0.26	0.24	0.17	0.59
S114-1b2	0.40	0.57	1.33	0.53	1.18	0.29	0.14	0.08	0.13	0.28	0.24	0.17	0.60
S114-1c1	0.46	0.61	1.45	0.29	0.97	0.31	0.09	0.04	0.17	0.21	0.30	0.25	0.45
S114-1c2	0.54	0.60	1.44	0.17	1.16	0.26	0.06	0.03	0.10	0.18	0.29	0.26	0.45
Oil-containing carbonates from the Tahe oilfield in the Tabei Uplift													
S108-3a	0.54	0.65	0.47	0.55	0.83	0.14	0.21	0.07	0.17	0.27	0.27	0.16	0.56
S108-3c	0.48	0.62	0.84	0.28	0.57	0.09	0.08	0.03	0.16	0.24	0.27	0.16	0.56
TP11-3a	0.82	1.12	0.65	0.30	0.54	0.13	0.07	0.03	0.09	0.23	0.22	0.17	0.60
TP11-3c	0.38	0.77	0.82	0.40	0.95	0.14	0.08	0.03	0.27	0.25	0.33	0.19	0.48
AT9-2a	0.53	0.58	0.73	0.57	1.57	0.31	0.19	0.08	0.17	0.32	0.26	0.30	0.44
AT9-2c1	0.53	0.60	0.87	0.60	2.03	0.24	0.09	0.06	0.20	0.38	0.24	0.25	0.52
AT9-2c2	0.52	0.60	0.90	0.62	3.39	0.27	0.07	0.05	0.18	0.37	0.30	0.20	0.50
S109-2a	0.72	0.93	0.78	0.71	1.00	0.32	0.35	0.11	0.56	0.28	0.30	0.31	0.39
S109-2c	0.32	0.61	0.98	0.15	0.79	0.12	0.05	0.01	0.19	0.22	0.23	0.19	0.58
AT5-1a	0.37	0.45	0.82	0.67	2.13	0.21	0.29	0.17	0.29	0.35	0.26	0.22	0.52
AT5-1c1	0.37	0.40	0.60	0.16	2.05	0.16	0.21	0.11	0.03	0.34	0.15	0.22	0.62
AT5-1c2	0.41	0.46	0.63	0.18	0.83	0.25	0.19	0.07	0.07	0.22	0.27	0.19	0.54
S86-4a	0.46	0.57	0.85	0.39	0.80	0.29	0.16	0.07	0.30	0.17	0.30	0.27	0.43
S86-4c1	0.37	0.49	1.01	0.11	0.98	0.08	0.03	0.02	0.33	0.17	0.48	0.14	0.39
S86-4c2	0.37	0.54	0.99	0.16	1.08	0.10	0.04	0.02	0.41	0.19	0.49	0.13	0.38
S86-3a	0.57	0.69	0.57	0.43	0.67	0.15	0.17	0.06	0.11	0.27	0.17	0.19	0.65
S86-3c1	0.54	0.71	0.92	0.35	0.90	0.16	0.14	0.05	0.10	0.27	0.20	0.15	0.65
S86-3c2	0.37	0.58	1.01	0.46	1.18	0.17	0.15	0.05	0.17	0.28	0.22	0.16	0.62
AT9-3a	0.38	0.48	0.68	0.09	1.79	0.13	0.08	0.03	0.14	0.23	0.18	0.24	0.58
AT9-3c1	0.18	0.24	0.84	0.13	2.03	0.09	0.05	0.02	0.28	0.35	0.23	0.18	0.60
AT9-3c2	0.19	0.25	0.82	0.11	2.04	0.10	0.05	0.03	0.22	0.24	0.28	0.20	0.53
S112-1a	0.45	0.57	0.49	0.50	1.68	0.24	0.20	0.11	0.14	0.27	0.18	0.24	0.57
S112-1c	0.34	0.46	0.94	0.20	0.83	0.08	0.06	0.02	0.25	0.23	0.26	0.16	0.58

Table 3 (*continued*)

	Pr/ n-C_{17}	Ph/ n-C_{18}	Pr/ Ph	T/ (T + H)	Ts/ Tm	G/ $C_{31}H$	$C_{28}DH$/ $C_{29}H$	$C_{29}DH$/ $C_{30}H$	C_{21}/ $(C_{21} + \Sigma C_{29})$	D/ (D + R)	$C_{27}/\Sigma C_{27-29}$	$C_{28}/\Sigma C_{27-29}$	$C_{29}/\Sigma C_{27-29}$
S109-3a	0.86	1.10	0.56	0.42	0.63	0.16	0.42	0.15	0.15	0.22	0.21	0.18	0.61
S109-3c1	0.58	0.83	0.58	0.41	0.59	0.13	0.40	0.14	0.16	0.22	0.26	0.19	0.56
S109-3c2	0.58	0.88	0.46	0.46	0.60	0.13	0.39	0.14	0.18	0.21	0.29	0.18	0.53
S99-3a	0.46	0.60	0.89	0.53	0.52	0.22	0.75	0.24	0.18	0.21	0.25	0.25	0.50
S99-3c1	0.44	0.80	0.77	0.50	0.64	0.19	0.60	0.21	0.20	0.25	0.27	0.18	0.55
S99-3c2	0.44	0.80	0.77	0.49	0.75	0.21	0.58	0.18	0.21	0.24	0.30	0.18	0.51
S114-2a	0.50	0.64	0.54	0.39	0.83	0.14	0.10	0.04	0.15	0.25	0.23	0.28	0.50
S114-2c1	0.41	0.58	0.70	0.36	0.84	0.10	0.09	0.04	0.20	0.26	0.36	0.12	0.51
S114-2c2	0.46	0.62	0.70	0.27	0.80	0.07	0.07	0.03	0.12	0.24	0.27	0.16	0.57
S114-3a	0.58	0.83	0.50	0.31	0.74	0.10	0.05	0.02	0.13	0.16	0.33	0.14	0.53
S114-3c1	0.29	0.46	0.67	0.11	0.72	0.07	0.02	0.01	0.13	0.18	0.23	0.17	0.60
S114-3c2	0.27	0.47	0.60	0.09	0.74	0.06	0.02	0.01	0.14	0.18	0.20	0.11	0.69
AT5-2a	0.53	0.87	0.55	0.39	0.77	0.14	0.09	0.04	0.29	0.22	0.23	0.14	0.63
AT5-2c	0.29	0.37	0.85	0.35	2.62	0.14	0.14	0.06	0.28	0.32	0.27	0.16	0.57
AD22-1a	0.46	0.51	0.80	0.18	0.74	0.10	0.19	0.05	0.16	0.22	0.19	0.17	0.64
AD22-1c1	0.20	0.27	0.76	0.10	0.63	0.06	0.05	0.02	0.19	0.22	0.26	0.16	0.58
AD22-1c2	0.22	0.33	0.69	0.08	0.62	0.05	0.05	0.01	0.16	0.21	0.23	0.13	0.64
AD22-2a	0.26	0.33	0.73	0.19	0.68	0.14	0.27	0.07	0.23	0.31	0.20	0.13	0.67
AD22-2c1	0.15	0.21	0.74	0.17	0.60	0.11	0.18	0.06	0.29	0.30	0.26	0.15	0.60
AD22-2c2	0.15	0.21	0.75	0.19	0.64	0.12	0.18	0.06	0.29	0.33	0.22	0.22	0.56
S108-4a	0.42	0.56	0.61	0.05	1.03	0.08	0.02	0.01	0.15	0.20	0.20	0.12	0.68
S108-4c1	0.16	0.21	0.79	0.02	0.43	0.06	0.01	0.01	0.11	0.14	0.15	0.11	0.74
S108-4c2	0.15	0.22	0.68	0.03	0.42	0.03	0.04	0.01	0.14	0.13	0.16	0.11	0.73
S119-2a	0.67	0.87	0.52	0.20	1.28	0.10	0.05	0.01	0.18	0.24	0.23	0.17	0.60
S119-2c	0.24	0.34	0.80	0.09	1.18	0.08	0.02	0.02	0.29	0.24	0.32	0.13	0.55
S114-4a	0.53	0.82	0.57	0.46	0.79	0.11	0.03	0.02	0.23	0.17	0.30	0.16	0.55
S114-4c1	0.23	0.34	0.69	0.14	0.93	0.07	0.04	0.02	0.19	0.17	0.23	0.18	0.59
S114-4c2	0.22	0.33	0.66	0.14	0.96	0.07	0.10	0.02	0.21	0.19	0.24	0.15	0.62
S77-2a	0.53	0.63	0.70	0.46	0.45	0.15	0.22	0.08	0.19	0.21	0.25	0.20	0.55
S77-2c1	0.39	0.60	1.09	0.26	0.59	0.10	0.06	0.02	0.32	0.21	0.34	0.18	0.48
S77-2c2	0.28	0.64	0.67	0.33	0.63	0.11	0.14	0.04	0.19	0.22	0.30	0.19	0.51
S77-3a	0.72	0.98	0.42	0.34	0.35	0.11	0.03	0.02	0.13	0.16	0.28	0.13	0.59
S77-3c1	0.42	0.72	0.58	0.20	0.31	0.05	0.02	0.02	0.14	0.17	0.30	0.15	0.55
S77-3c2	0.39	0.66	0.48	0.19	0.35	0.05	0.02	0.01	0.11	0.14	0.30	0.16	0.54
S77-4a	0.78	1.21	0.42	0.13	0.60	0.09	0.03	0.01	0.08	0.12	0.23	0.23	0.55
S77-4c1	0.29	0.49	0.59	0.07	0.42	0.05	0.01	0.01	0.11	0.14	0.23	0.15	0.62
S77-4c2	0.30	0.48	0.65	0.08	0.43	0.07	0.02	0.01	0.12	0.13	0.22	0.17	0.62
S94-1a	0.72	1.06	0.63	0.51	1.00	0.23	1.22	0.50	0.13	0.21	0.22	0.17	0.61
S94-1c	0.31	0.46	0.64	0.32	0.41	0.09	0.47	0.15	0.16	0.22	0.25	0.15	0.60
S104-1a	0.58	0.78	0.62	0.38	0.61	0.19	1.47	0.38	0.25	0.29	0.20	0.16	0.63
S104-1c	0.41	0.56	0.77	0.16	0.49	0.10	0.41	0.10	0.19	0.25	0.23	0.15	0.62
S104-2a	0.65	0.83	0.69	0.45	0.58	0.36	2.57	0.57	0.27	0.23	0.22	0.19	0.60
S104-2c1	0.29	0.62	0.82	0.22	0.52	0.12	0.63	0.11	0.30	0.26	0.27	0.18	0.55
S104-2c2	0.42	0.53	0.89	0.17	0.49	0.13	0.61	0.10	0.26	0.24	0.28	0.18	0.55
S99-4a	0.88	1.23	0.59	0.34	0.63	0.22	0.48	0.12	0.17	0.24	0.25	0.26	0.48
S99-4c	0.18	0.24	0.70	0.04	0.57	0.08	0.02	0.01	0.15	0.17	0.23	0.18	0.59

T/(T + H): C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} hopane); G/C_{31}H: gammacerane/C_{31} hopanes (R + S); C_{28}DH/C_{29}H: C_{28} 25-norhopane/C_{29} hopane; C_{29}DH/C_{30}H: C_{29} 25-norhopane/C_{30} hopane; $C_{21}/(C_{21} + \Sigma C_{29})$: $C_{21}/(C_{21} + \Sigma C_{29})$ steranes; D/(D + R): C_{27} diasteranes/(C_{27} diasteranes + C_{27} regular steranes); $C_{27}/\Sigma C_{27-29}$: $C_{27}/(C_{27} + C_{28} + C_{29})$ steranes (ααα20R); $C_{28}/\Sigma C_{27-29}$: $C_{28}/(C_{27} + C_{28} + C_{29})$ steranes (ααα20R); $C_{29}/\Sigma C_{27-29}$: $C_{29}/(C_{27} + C_{28} + C_{29})$ steranes (ααα20R); 25-norhopanes were measured on the m/z 177 mass chromatograms, all other terpanes were measured on the m/z 191 mass chromatograms, and steranes were measured on the m/z 217 mass chromatograms.

[a] Data that were reported previously (Pan and Liu, 2009).

reported previously (Pan and Liu, 2009). The other 39 oils were collected from the Tahe oilfield in the Tabei Uplift. Of the 70 oil-containing reservoir rocks, 30 were collected from the boreholes in the Tazhong Uplift, including the nine reported previously. The other 40 samples were collected from the Tahe oilfield in the Tabei Uplift. In addition, 24 source rocks within the Sinian-Ordovician strata were collected and systematically analyzed. However, only nine samples with TOC ⩾0.80% were reported in this paper, which were collected from Cambrian–Lower Ordovician strata in wells TD2 and Fang 1 (Table 1, Fig. 1).

2.2. Total organic carbon (TOC) and bitumen extraction of source rock cores

The source rock cores were first cleaned and then ground into powder (about 200 mesh). A small aliquot of powder was taken from each sample for measurement of TOC using a Leco-200 analyzer. The remaining powdered samples (about 100 g each) were Soxhlet extracted with dichloromethane:methanol (DCM:MeOH 93:7 v:v) for 72 h to obtain the source rock extracts (bitumens).

2.3. Sequential extraction of the oil-containing sandstone cores

Each core was crushed and disintegrated gently to obtain isolated grains. The individual grains were sieved to obtain the 0.10–0.30 mm size fraction, which appeared to be single grains when examined microscopically. If the amount of the grains for a sample was over 120 g, the sample was divided into two parts. Samples weighting 60–100 g were Soxhlet extracted with DCM:MeOH (93:7 v:v) for 72 h. For duplicate samples, the resultant extracts were combined. The first extract is considered to be free oil. In the tables and figures the free oil sample code carries the suffix "a". The extracted grains were further treated with HCl to remove carbonate minerals. After acid treatment, the grains were Soxhlet extracted again with DCM:MeOH (93:7 v:v) for 72 h and the extract is considered to be adsorbed oil. In the tables and figures the adsorbed oil sample code carries the suffix “b”. After the second extraction, the grains were treated with chromic acid ($K_2Cr_2O_7$:H_2SO_4) for 12 h to oxidize residual, external organic matter. Following chromic acid digestion, the grains were Soxhlet extracted for a third time (DCM:MeOH; 72 h) to fully remove any remaining oil components (e.g., aliphatic components trapped in asphaltenes but liberated during reaction with chromic acid). This extract was not analyzed. The fully cleaned grains were dry ground to powder for 3 min using a grinding machine to liberate oil-bearing fluid inclusions, and then Soxhlet extracted (DCM:MeOH; 72 h) to obtain the inclusion oil. In the tables and figures the inclusion oil carries the suffix “c” to the sample code. Before grinding the cleaned grains, about 50 g silica gel (80–100 mesh), which was organic matter free was placed in a cleaned container and ground into powder to completely remove any remaining organic matter on the surfaces of the “cleaned” container and grinding setup.

2.4. Sequential extraction of carbonate cores

Each of the carbonate cores was crushed and sieved to obtain the 0.10–0.30 mm size fraction. If the amount of the grains for a sample was >120 g, a duplicate was prepared. Samples weighting 60–100 g were Soxhlet extracted with DCM:MeOH (93:7 v:v) for 72 h. For duplicate samples, the extracts were combined. The first extract is considered to be free oil. The grain fractions were further treated with H_2O_2 (12 h) to oxidize residual external organic matter. Subsequently, the grains were Soxhlet extracted again (72 h) to remove residual oil components. The fully cleaned grains were treated with HCl to remove carbonate minerals and liberate oil-bearing fluid inclusions. The residue was finally extracted with DCM:MeOH (72 h) to obtain the inclusion oil. No absorbed oil components were obtained from any of the carbonate samples.

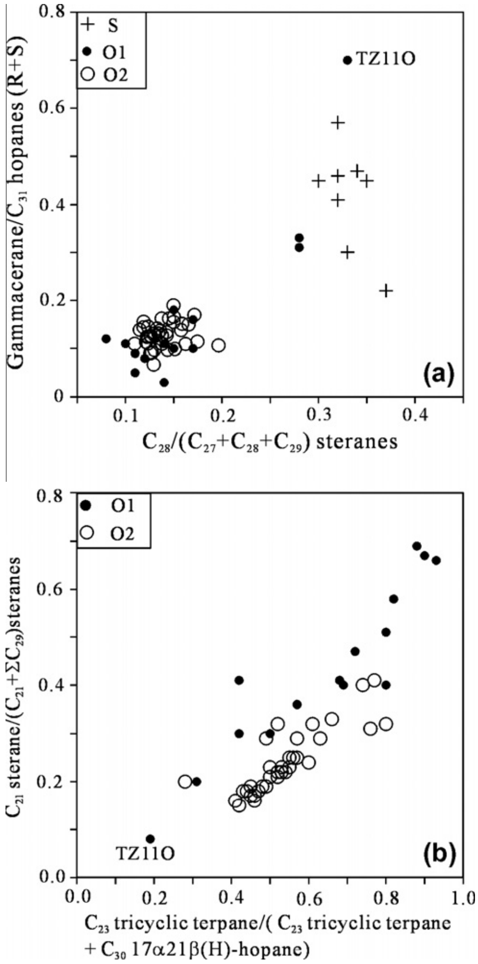

Fig. 3. Crossplots of the ratios of $C_{28}/(C_{27} + C_{28} + C_{29})$ steranes versus gammacerane/C_{31} hopanes (a) and C_{23}-tricyclic terpane/(C_{23}-tricyclic terpane + C_{30}-17α(H)-hopane) versus $C_{21}/(C_{21} + \Sigma C_{29})$ steranes (b) for the source rocks and crude oils. S: the Cambrian–Lower Ordovician source rocks; O1: crude oils from the Tazhong Uplift; O2: crude oils from the Tahe oilfield in the Tabei Uplift.

2.5. Oil fractionation

The oil samples were deasphaltened using a 40× excess of hexane. The extracts from the source rocks and the free, adsorbed and inclusion oils from the reservoir rocks were first diluted with about 1 ml or less of DCM and were then deasphaltened using a 40× excess of hexane. All the deasphaltened samples were fractionated on a silica:alumina column using hexane, benzene and methanol as eluants to yield the saturated, aromatic and resin fractions, respectively.

2.6. GC and GC–MS analyses

Gas chromatographic (GC) analysis of the saturated fractions from the crude oils and source and reservoir rocks was performed on a HP6890 GC fitted with a 30 m × 0.32 mm i.d. HP-5 column with a film thickness of 0.25 μm and using nitrogen carrier gas. A constant flow mode and flame ionization detector were employed. The GC oven temperature was held initially at 70 °C for 5 min, ramped from 70–290 °C at 4 °C/min, and then held at 290 °C for 30 min. After GC analysis, the saturated fractions were further treated with urea adduction to separate *n*-alkanes and iso- and cyclic alkanes. Gas chromatographic–mass spectrometric (GC–MS) analysis of iso- and cyclic alkane fractions for the source rocks and the crude oils and reservoir rocks from the Tazhong Uplift was carried

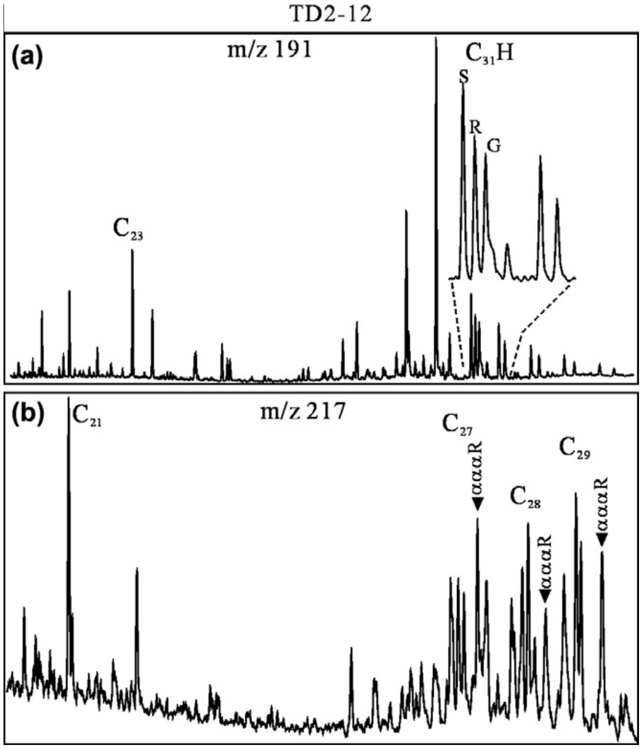

Fig. 4. Terpane (*m*/*z* 191) and sterane (*m*/*z* 217) mass chromatograms of source rock TD2-12 from the Cambrian strata in (a), C_{23} = C_{23} tricyclic terpane; $C_{31}H$ = C_{31}17α(H),21β(H)-homohopanes (22S and 22R); G: gammacerane.

out using a Micromass Platform II quadrupole mass spectrometer interfaced to a HP5890 GC while that for the crude oils and reservoir rocks from the Tahe oilfield in the Tabei Uplift was carried out using a Thermal Scientific DSQ II quadrupole mass spectrometer interfaced to a Trace GC ULTRA. The latter analysis was performed one year after the former. Both the HP5890 GC and Trace GC ULTRA were fitted with a 30 m × 0.25 mm i.d. HP-5MS column with a film thickness of 0.25 μm and using helium carrier gas. A constant flow mode was used. The mass spectrometer was operated in electron impact (EI) mode at 70 eV. The GC oven temperature was initially held at 80 °C for 2 min, ramped from 80–180 °C at 8 °C/min, from 180–290 °C at 2 °C/min, and then held at 290 °C for 20 min.

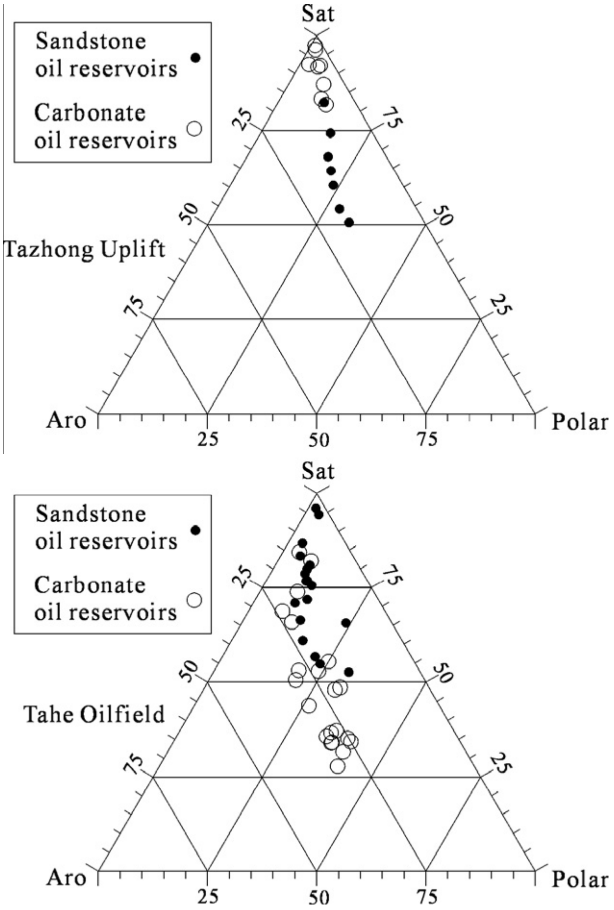

Fig. 5. Ternary diagrams of saturated, aromatic and polar composition of the crude oils from the Tazhong Uplift and the Tahe oilfield in the Tabei Uplift.

Table 4
Gross composition of the crude oils (%).

	Sat	Aro	Res	Asp
Crude oils from the Tazhong Uplift (C, S)				
[a]TZ401O1	74.31	9.63	5.79	10.27
TZ401O2	54.17	17.65	12.01	16.18
TZ402O	60.47	15.90	10.06	13.57
TZ421O	50.56	17.29	19.33	12.83
[a]TZ11O	82.27	7.12	4.60	6.01
[a]TZ117O	64.28	14.55	4.67	16.51
[a]TZ47O	68.07	13.33	2.32	16.28
Crude oils from the Tazhong Uplift (O3)				
[a]TZ45O	96.22	2.15	0.63	1.00
[a]TZ82O	97.32	1.67	0.26	0.75
[a]ZH1O	92.36	5.56	1.47	0.61
TZ241O	92.08	3.12	2.35	2.45
TZ62O	81.72	6.99	5.91	5.38
TZ621O	83.23	7.28	5.70	3.80
TZ83O	87.08	4.85	5.69	2.38
TZ826O	91.67	3.86	4.16	0.31
Crude oils from the Tahe oilfield (K, T, C)				
GK3O	65.59	10.49	2.13	21.79
GK4XO	75.60	13.35	3.68	7.36
S3-6HO	86.82	9.84	1.58	1.76
AT2-5O	76.91	13.71	4.48	4.89
AN1-1HO	81.01	11.07	3.03	4.89
DK19HO	54.80	21.82	6.05	17.34
S35CO	52.58	16.38	4.81	26.24
GK1O	94.34	2.33	1.69	1.64
AT9O	76.71	14.04	3.24	6.02
AT9-1HO	96.03	2.16	0.60	1.21
AT11-1O	71.82	16.24	4.86	7.08
TK239-1HO	78.72	13.31	3.06	4.91
AT1O	70.90	19.49	6.78	2.82
YT2-11HO	56.72	22.01	6.38	14.90
AT1-14XO	60.96	22.71	8.37	7.97
YT2-8XO	66.33	20.56	5.38	7.73
TK310O	83.44	12.01	2.67	1.88
S70O	79.90	12.28	2.27	5.56
Crude oils from the Tahe oilfield (O)				
S112O	82.12	10.23	2.74	4.91
TP106O	52.90	23.15	5.34	18.61
TK118XO	84.44	11.78	2.62	1.17
TK842O	55.45	19.55	7.71	17.29
TP205XO	73.89	17.47	4.49	4.15
TK210O1	27.88	31.25	14.42	26.44
TK210O2	34.35	25.00	12.85	27.80
TK211O	34.04	29.66	10.82	25.48
TK469O1	35.74	29.87	12.36	22.02
TK469O2	36.73	28.34	10.08	24.84
TK455O	34.19	29.41	9.93	26.47
S47O	68.72	23.49	7.16	0.63
S46O	53.09	27.57	10.29	9.05
S61CHO	65.85	22.77	6.56	4.83
TK231O	48.06	21.79	11.30	18.84
TK315O	50.58	29.51	8.10	11.81
S48O	35.24	25.26	10.76	28.73
TK644O	37.27	26.85	11.17	24.70
TK634O	31.71	28.11	13.70	26.48
TK835O	48.67	20.31	10.20	20.82
TK707O	43.91	29.83	9.45	16.81

Sat: saturates; Aro: aromatics; Res: resins; Asp: asphaltenes.

[a] Data that were reported previously (Pan and Liu, 2009).

3. Results

3.1. Source rocks

3.1.1. Amounts of total organic carbon and extracted bitumen

The total organic carbon (TOC) contents and amounts of the extracted bitumen are listed in Table 2. For the eight samples from TD2-1 to TD2-13 within Cambrian–Lower Ordovician strata from the TD2 well, TOC values range from 0.81–3.42%, and the amounts of the extracted bitumen range from 0.77–13.70 mg/g TOC. For sample Fang 1-2 from Cambrian strata in the Fang 1 well, the TOC value and the amount of extracted bitumen are 0.80% and 5.79 mg/g TOC, respectively.

3.1.2. n-Alkanes and isoprenoids

The gas chromatograms of seven rocks from the TD2 well with TOC >1% and rock Fang 1-2 from the Fang 1 well with TOC 0.80% are shown in Fig. 2. The source rocks from Cambrian–Lower Ordovician strata generally show an even/odd predominance of *n*-alkanes for carbon numbers <18. However, rocks TD2-3 and TD2-12 with TOC values 2.99% and 3.42%, respectively, do not exhibit a clear even/odd predominance (Fig. 2b and g). This result may be partly due to the heavy loss of short *n*-alkanes by evaporation.

The ratios of pristane (Pr)/*n*-C_{17}, phytane (Ph)/*n*-C_{18} and Pr/Ph of source rocks are shown in Table 3. For the eight rocks within the Cambrian–Lower Ordovician strata from the TD2 well, these three ratios range from 0.44–1.02, 0.54–1.57 and 0.68–1.17, respectively. For sample Fang 1-2 from Cambrian strata in the Fang 1 well, these three ratios are 0.96, 0.53 and 0.78, respectively.

3.1.3. Terpanes and steranes

The selected terpane and sterane parameters for the source rocks are presented in Table 3 and Fig. 3. All nine samples within the Cambrian–Lower Ordovician strata from TD2 and Fang 1 well contain relatively high amounts of gammacerane and C_{28} regular steranes with the ratios of gammacerane/C_{31} hopanes and C_{28}/(C_{27} + C_{28} + C_{29}) steranes ranging 0.22–0.57 and 0.29–0.40, respectively (Fig. 3a). Terpane (*m*/*z* 191) and sterane (*m*/*z* 217) mass chromatograms of sample TD2-12, a representative of these nine source rocks are shown in Fig. 4.

3.2. Crude oils

3.2.1. Gross compositions

The gross compositions of the oils from the Tazhong Uplift and the Tahe oilfield in the Tabei Uplift are shown in Table 4 and Fig. 5. For the 15 oils from the Tazhong Uplift, including the seven reported previously (Pan and Liu, 2009), the amounts of saturates, aromatics, resins and asphaltenes range from 50.56–97.32%, 1.67–17.65%, 0.26–19.33% and 0.61–16.51%, respectively. The eight oils from the Ordovician oil columns generally contain a higher amounts of saturates and lower amounts of the other fractions than the seven samples from the Carboniferous and Silurian oil columns (Table 4, Fig. 5a). For the 39 oils from the Tahe oilfield, the amounts of saturates, aromatics, resins and asphaltenes range from

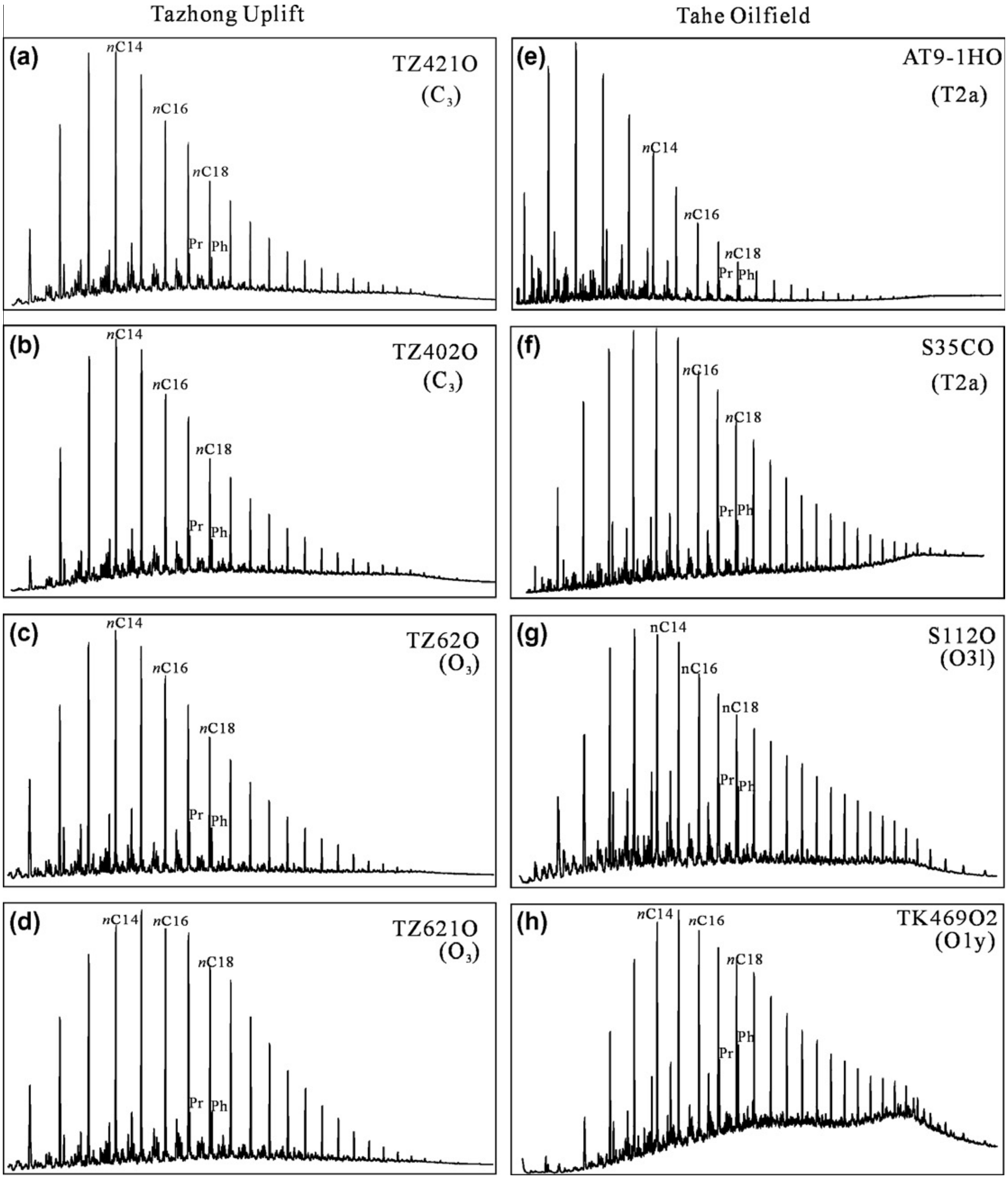

Fig. 6. Partial gas chromatograms of the selected crude oils from the Tazhong Uplift (left) and the Tahe oilfield in the Tabei Uplift.

27.88–96.03%, 2.16–29.87%, 0.60–14.42% and 1.21–28.73%, respectively. The 21 oils from the Ordovician carbonate reservoirs contain less saturates and more of the other fractions than the 18 samples from the Cretaceous, Triassic and Carboniferous sandstone reservoirs (Table 4, Fig. 5b), in contrast to the oils from the Tazhong Uplift. In addition, gross compositions vary substantially more for oils from the Tahe oilfield than the Tazhong Uplift.

3.2.2. *n*-Alkanes and isoprenoids

For all 54 oils from the Tazhong Uplift and Tahe oilfield in the Tabei Uplift, including the seven samples previously reported (Pan and Liu, 2009), the distribution patterns of *n*-alkanes are very similar, although the gross compositions differ substantially. Gas chromatograms of the eight selected oils are shown in Fig. 6. All of the oils lack an odd/even predominance and the amounts of *n*-alkanes decrease very smoothly with carbon number, demonstrating that these *n*-alkanes have experienced extensive cracking (e.g., Kissin, 1987), which occurred in the source rocks prior to expulsion or/and in the reservoir rocks. For the 15 oils from the Tazhong Uplift, the ratios Pr/n-C_{17}, Ph/n-C_{18} and Pr/Ph range from 0.25–0.40, 0.30–0.54 and 0.87–1.14, respectively (Table 3). Among the 18 oils from the Cretaceous, Triassic and Carboniferous sandstone reservoirs in the Tahe oilfield, oils GK3O and GK4XO have relatively low Ph/n-C_{18} ratios, 0.17 and 0.20, respectively, and high Pr/Ph ratios, 1.94 and 1.76, respectively. The values of Pr/n-C_{17} for the two oils are 0.26 and 0.28, respectively, similar to those of the oils in the Tazhong Uplift. Oil S3-6HO has low ratios of Pr/n-C_{17} and Ph/n-C_{18}, 0.18 and 0.08, respectively, and a high Pr/Ph ratio of 2.50, compared with oils in the Tazhong Uplift. The remaining 15 oils have Pr/n-C_{17}, Ph/n-C_{18} and Pr/Ph ratios ranging from 0.33–0.39, 0.38–0.47 and 0.84–1.23, respectively, similar to oils in the Tazhong Uplift (Table 3). The 21 oils from the Ordovician carbonate reservoirs in the Tahe oilfield have relatively high ratios of Pr/n-C_{17}, Ph/n-C_{18}, ranging from 0.37–0.62 and 0.46–0.87, respectively, but a similar Pr/Ph ratio, ranging from 0.78–1.01, compared with oils from the Tazhong Uplift (Table 3).

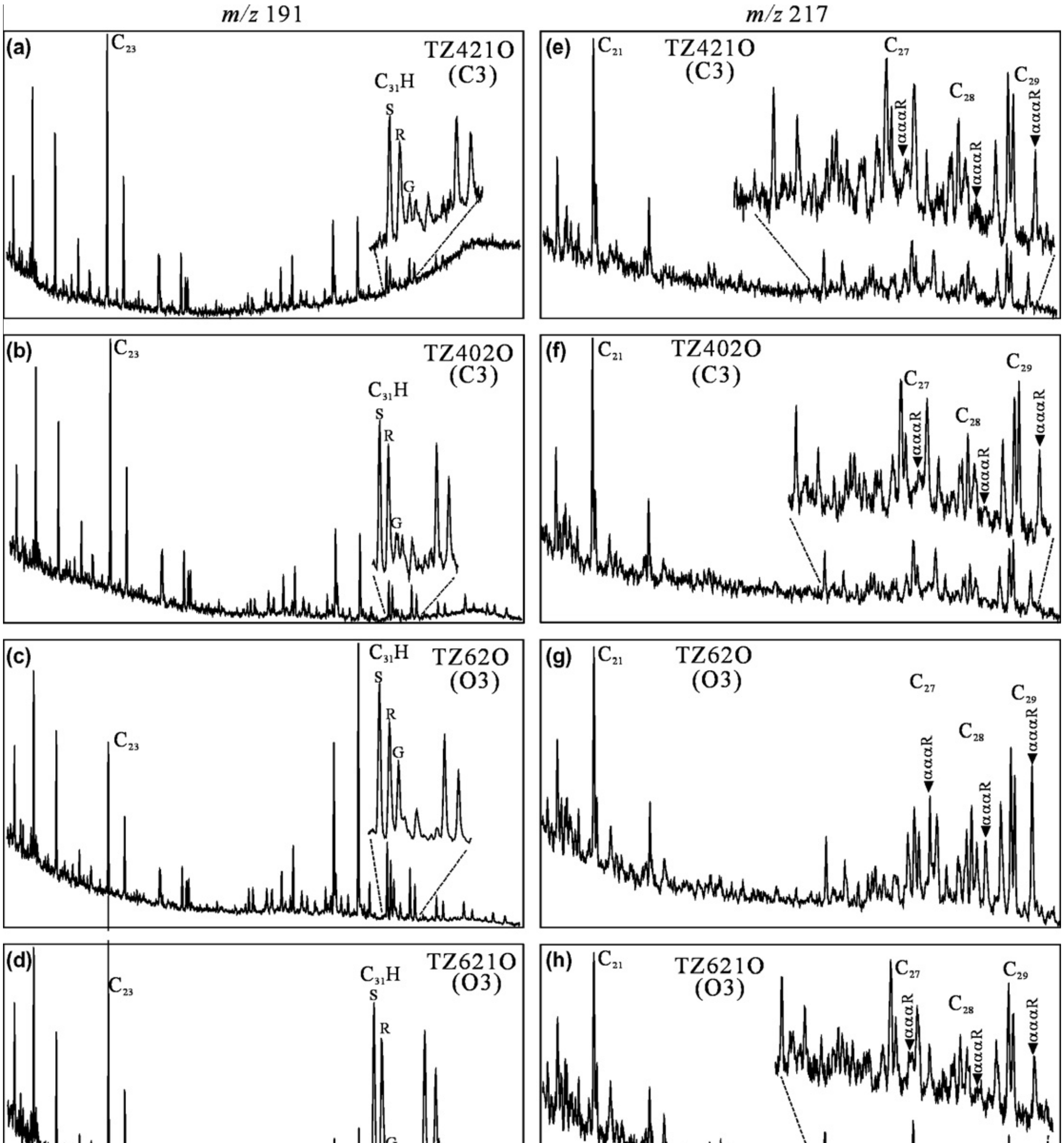

Fig. 7. Terpane (*m*/*z* 191) and sterane (*m*/*z* 217) mass chromatograms of the selected crude oils from the Tazhong Uplift. Peak identifications are as in Fig. 4.

3.2.3. Terpanes and steranes

Selected terpane and sterane parameters for all of the oils from the Tazhong Uplift and Tahe oilfield in the Tabei Uplift, including the seven reported previously (Pan and Liu, 2009), are listed in Table 3. The *m*/*z* 191 and *m*/*z* 217 mass chromatograms of eight selected oils are shown in Figs. 7 and 8.

Of the 15 oils in the Tazhong Uplift, oils TZ11O, TZ62O and TZ826O have high relative concentrations of gammacerane and C_{28} regular steranes, with the ratios of gammacerane/C_{31} hopanes and $C_{28}/(C_{27} + C_{28} + C_{29})$ steranes ranging from 0.31–0.70 and 0.28–0.33, respectively, while the other oils have low relative concentrations of these two compounds with the ratios ranging from 0.03–0.18 and 0.08–0.17, respectively (Table 3, Fig. 3a). The ratios of C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) and $C_{21}/(C_{21} + \Sigma C_{29})$ steranes vary substantially among the fifteen oils, ranging from 0.19–0.93 and 0.08–0.69, respectively (Table 3, Fig. 3b).

All 39 oils from the Tahe oilfield have low relative concentrations of gammacerane and C_{28} regular steranes, with the ratios of gammacerane/C_{31} hopanes and $C_{28}/(C_{27} + C_{28} + C_{29})$ steranes ranging 0.07–0.19 and 0.11–0.20, respectively, in very narrow intervals (Table 3, Fig. 3a). The ratios of C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) and $C_{21}/(C_{21} + \Sigma C_{29})$ steranes of the 39 oils are between 0.28–0.80 and 0.15–0.41, respectively, in ranges much smaller than those for oils from the Tazhong Uplift (Table 3, Fig. 3b).

3.3. Oil-containing reservoir rocks

The variations in gross composition among the free oil, adsorbed oil and inclusion oil of the oil-bearing sandstones and carbonates are similar to those described previously (e.g., Pan and Liu, 2009). The ratios of Pr/*n*-C_{17}, Ph/*n*-C_{18} and Pr/Ph for free oil in the reservoir rocks are substantially influenced by evaporation

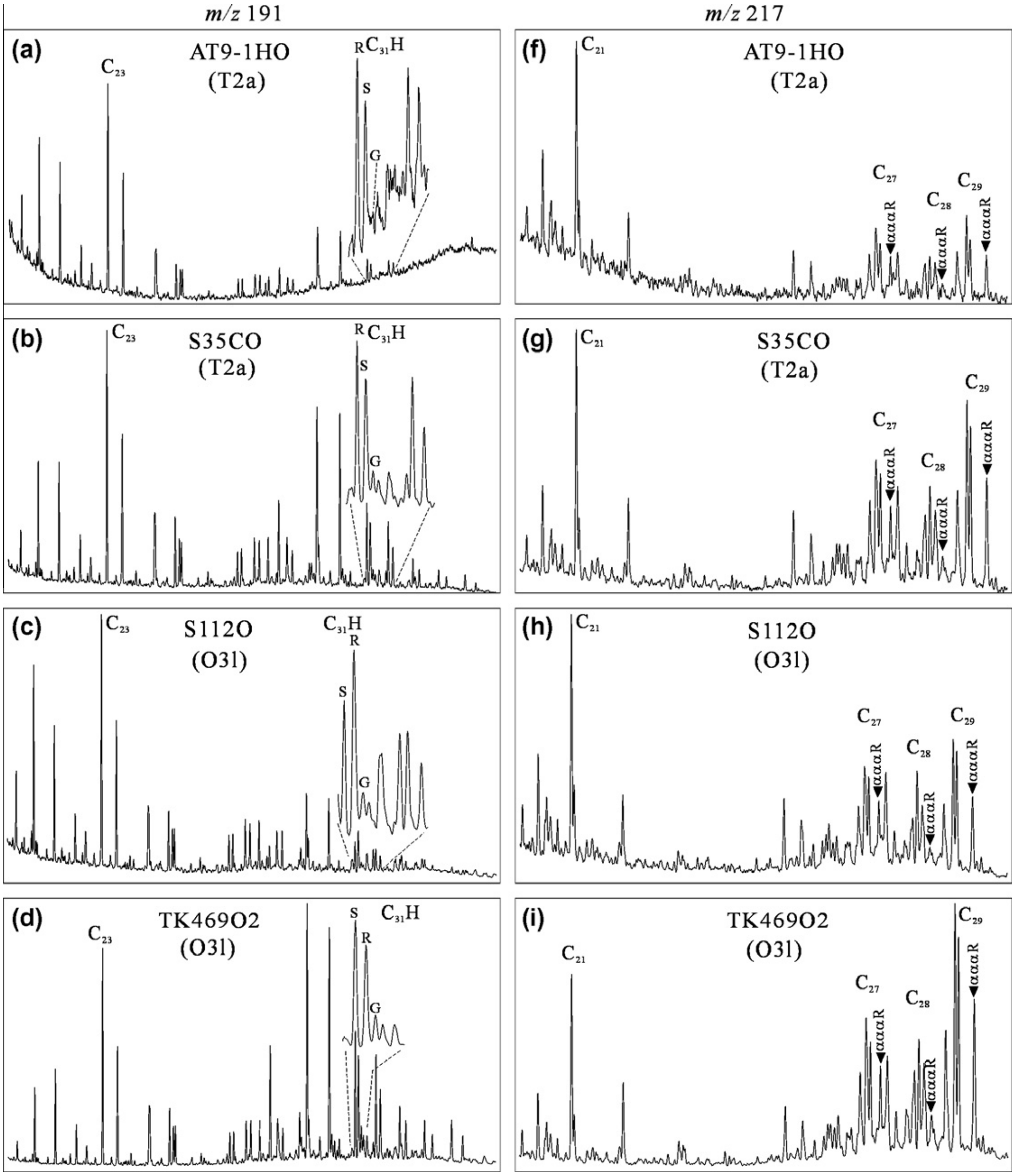

Fig. 8. Terpane (*m*/*z* 191) and sterane (*m*/*z* 217) mass chromatograms of the selected crude oils from the Tahe oilfield in the Tabei Uplift. Peak identifications are as in Fig. 4.

during core storage. In this paper, only terpane and sterane parameters for the reservoir rocks are discussed.

3.3.1. Reservoir rocks in the Tazhong Uplift

The terpane and sterane parameters for 18 oil- and tar-containing sandstones from the carboniferous and Silurian strata in the Tazhong Uplift are listed in Table 3. Six of these samples (TZ401-1, TZ401-2, TZ47-6, TZ11-1, TZ11-2 and TZ11-5) were reported previously (Pan and Liu, 2009). However, the duplicate samples of adsorbed oil and inclusion oil for these six samples were not reported in the previous paper. In addition, tar-containing sandstones of TZ401-3 and TZ401-4 reported previously, are not included in the present study because terpanes and steranes in these two samples were severely biodegraded.

The 18 oil- and tar-containing sandstones can be classified into two groups. Group A contains ten samples and Group B contains the other eight samples. For Group A, all of the free, adsorbed and inclusion oils have relatively high amounts of gammacerane and C_{28} steranes. The ratios of gammacerane/C_{31} hopanes and $C_{28}/(C_{27}+C_{28}+C_{29})$ steranes range from 0.25–0.62 and 0.26–0.35 for the free oils, 0.22–0.54 and 0.27–0.36 for the adsorbed oils and their duplicates, and 0.17–0.52 and 0.20–0.34, respectively, for the inclusion oils and their duplicates (Table 3, Fig. 9a). For Group B, the free oils have relatively low amounts of gammacerane and C_{28} steranes. However, the relative amounts of these two compounds increase significantly from the free oil, to the adsorbed oil, to the inclusion oil for each sample. The ratios of gammacerane/C_{31} hopanes and $C_{28}/(C_{27}+C_{28}+C_{29})$ steranes range from 0.09–0.17 and 0.13–0.23 for the free oils, 0.15–0.28 and 0.21–0.30 for the adsorbed oils and their duplicates, and 0.16–0.40 and 0.24–0.36, respectively, for the inclusion oils and their duplicates (Table 3, Fig. 9a).

For all 18 oil- and tar-containing sandstones, the ratios C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) and $C_{21}/(C_{21}+\Sigma C_{29})$ steranes generally decrease from the free oil, to the adsorbed oil, to the inclusion oil (Table 3, Fig. 10a). These two ratios range from 0.22–0.92 and 0.12–0.75 for the free oils, 0.19–0.88 and 0.10–0.50 for the adsorbed oils and their duplicates, and 0.14–0.59 and 0.03–0.38, respectively, for the inclusion oils and their duplicates. Gas chromatograms and m/z 191 and m/z 217 mass chromatograms of the free, adsorbed and inclusion oils for samples TZ421-2 and TZ402-5, representatives of Groups A and B, respectively, are in Figs. 11 and 12.

Of the 21 oil-containing carbonates from the Ordovician strata in the Tazhong Uplift, three samples (TZ45-1, TZ45-2 and TZ82-1) were reported previously. However, the duplicates of the inclusion oils for the three samples were not reported in the previous paper (Pan and Liu, 2009). For nearly all of the 21carbonates, the free and inclusion oils and their duplicates have relatively high amounts of gammacerane and C_{28} steranes, with the ratios of gammacerane/C_{31} hopanes and $C_{28}/(C_{27}+C_{28}+C_{29})$ steranes ranging from 0.13–0.49 and 0.22–0.36, respectively. In comparison with the eight crude oils from the Ordovician carbonate reservoirs in the Tazhong Uplift, all oil components from these carbonate rocks are substantially different from six of the eight oils while similar to the other two oils based on these two ratios (Table 3, Fig. 9b). For all of these carbonates, the ratios of C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) and $C_{21}/(C_{21}+\Sigma C_{29})$

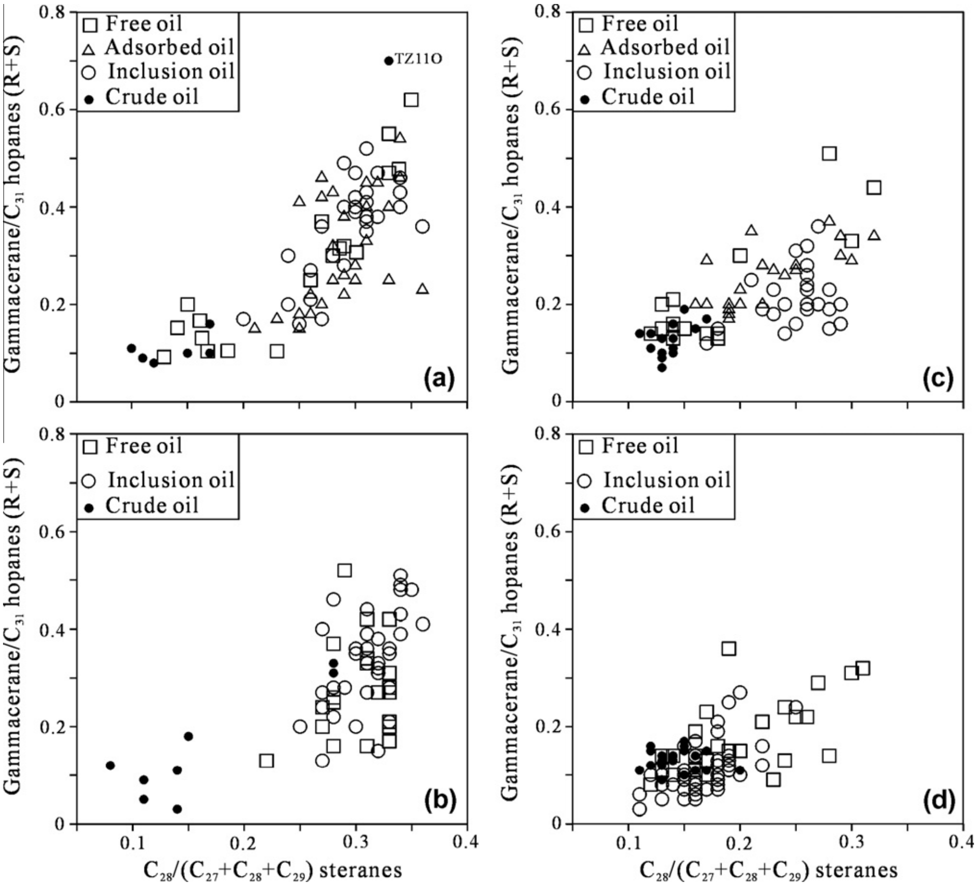

Fig. 9. Plot of the ratios of $C_{28}/(C_{27}+C_{28}+C_{29})$ steranes versus gammacerane/C_{31} hopanes for the crude oils and the free, adsorbed and inclusion oils in the reservoir rocks. (a) Crude oils and sandstones from the Carboniferous and Silurian sandstone reservoirs in the Tazhong Uplift; (b) crude oils and carbonates from the Ordovician carbonate reservoirs in the Tazhong Uplift; (c) crude oils and sandstones from the Cretaceous–Silurian sandstone reservoirs in the Tahe oilfield; (d) crude oils and carbonates from the Ordovician carbonate reservoirs in the Tahe oilfield.

steranes are significantly higher for the free oils than their corresponding inclusion oils and duplicates. These two ratios range from 0.19–0.84 and 0.08–0.73 for the free oils, and 0.07–0.39 and 0.03–0.17 for the inclusion oils and duplicates (Table 3, Fig. 10b). Chromatograms and *m*/*z* 191 and *m*/*z* 217 mass chromatograms of the free and inclusion oils for TZ621–16, a representative of these 21 carbonates, are in Fig. 13.

3.3.2. Reservoir rocks from the Tahe oilfield in the Tabei Uplift

Selected molecular parameters for the 14 oil-containing sandstones from the Tahe oilfield are shown in Table 3. The ratios gammacerane/C_{31} hopanes and $C_{28}/(C_{27} + C_{28} + C_{29})$ steranes range from 0.13–0.51 and 0.12–0.32 for the free oils, 0.17–0.37 and 0.16–0.32 for the adsorbed oils and duplicates, and 0.12–0.36 and 0.17–0.29, respectively, for the inclusion oils and duplicates. For 10 of the 14 sandstones, these two ratios are low for the free oils, ranging from 0.13–0.21 and 0.12–0.18, respectively, and generally increase from the free oils, through the adsorbed oils and duplicates, to the inclusion oils and duplicates (Fig. 9c). The ratios C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) and $C_{21}/(C_{21} + \Sigma C_{29})$ steranes for the free oil S109-1a are relatively high, 0.80 and 0.63, respectively. However, they are substantially lower for the other free oils and all the adsorbed and inclusion oils and duplicates among the 14 sandstones, ranging from 0.08–0.60 and 0.04–0.26, respectively (Fig. 10c). Gas chromatograms and *m*/*z* 191 and *m*/*z* 217 mass chromatograms of the free, adsorbed and inclusion oils for S99-1, a representative of these 14 sandstones, are in Fig. 14.

For the 26 oil-containing carbonates, the ratios of gammacerane/C_{31} hopanes and $C_{28}/(C_{27} + C_{28} + C_{29})$ steranes are similar between the free oils and the corresponding inclusion oils and their duplicates (Fig. 9d). For some samples, these two ratios even vary in a reversed trend, decreasing from the free oils to the corresponding inclusion oils and their duplicates. The differences of the two ratios among all of the free and inclusion oils and their duplicates among the 26 carbonates and the 21 crude oils from the carbonate reservoirs in the Tahe oilfield are small compared with those for the reservoir rocks and crude oils from the Tazhong Uplift (Fig. 9a, b and d). There are no clear trends for the two ratios C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) and $C_{21}/(C_{21} + \Sigma C_{29})$ steranes from the free oils to the corresponding inclusion oils and their duplicates for these carbonates, unlike results from the Tazhong Uplift (Fig. 10b and d). Gas chromatograms and *m*/*z* 191 and *m*/*z* 217 mass chromatograms of the free and inclusion oils for S77-3, a representative of the 26 carbonates from the Tahe oilfield, are in Fig. 15.

4. Discussion

4.1. Sources and maturities of crude oils and oil components in reservoir rocks from the Tazhong Uplift

Three of the 15 oils, one from the Silurian sandstone reservoir and the other two from Upper Ordovician carbonate reservoirs, have relatively high values of gammacerane/C_{31} hopanes and C_{28}/

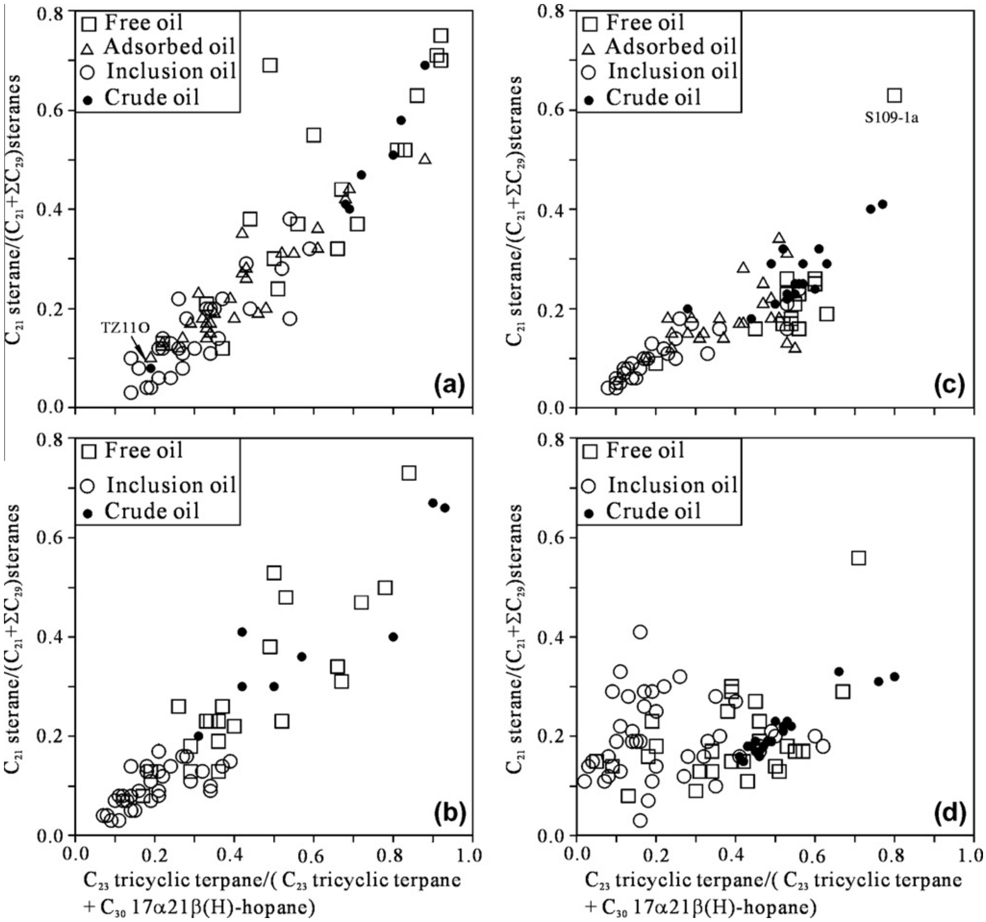

Fig. 10. Plot of the ratios of C_{23}-tricyclic terpane/(C_{23}-tricyclic terpane + C_{30}-17α(H)-hopane) versus $C_{21}/(C_{21} + \Sigma C_{29})$ steranes. (a) Crude oils and sandstones from the Carboniferous and Silurian sandstone reservoirs in the Tazhong Uplift; (b) crude oils and carbonates from the Ordovician carbonate reservoirs in the Tazhong Uplift; (c) crude oils and sandstones from the Cretaceous–Silurian sandstone reservoirs in the Tahe oilfield; (d) crude oils and carbonates from the Ordovician carbonate reservoirs in the Tahe oilfield.

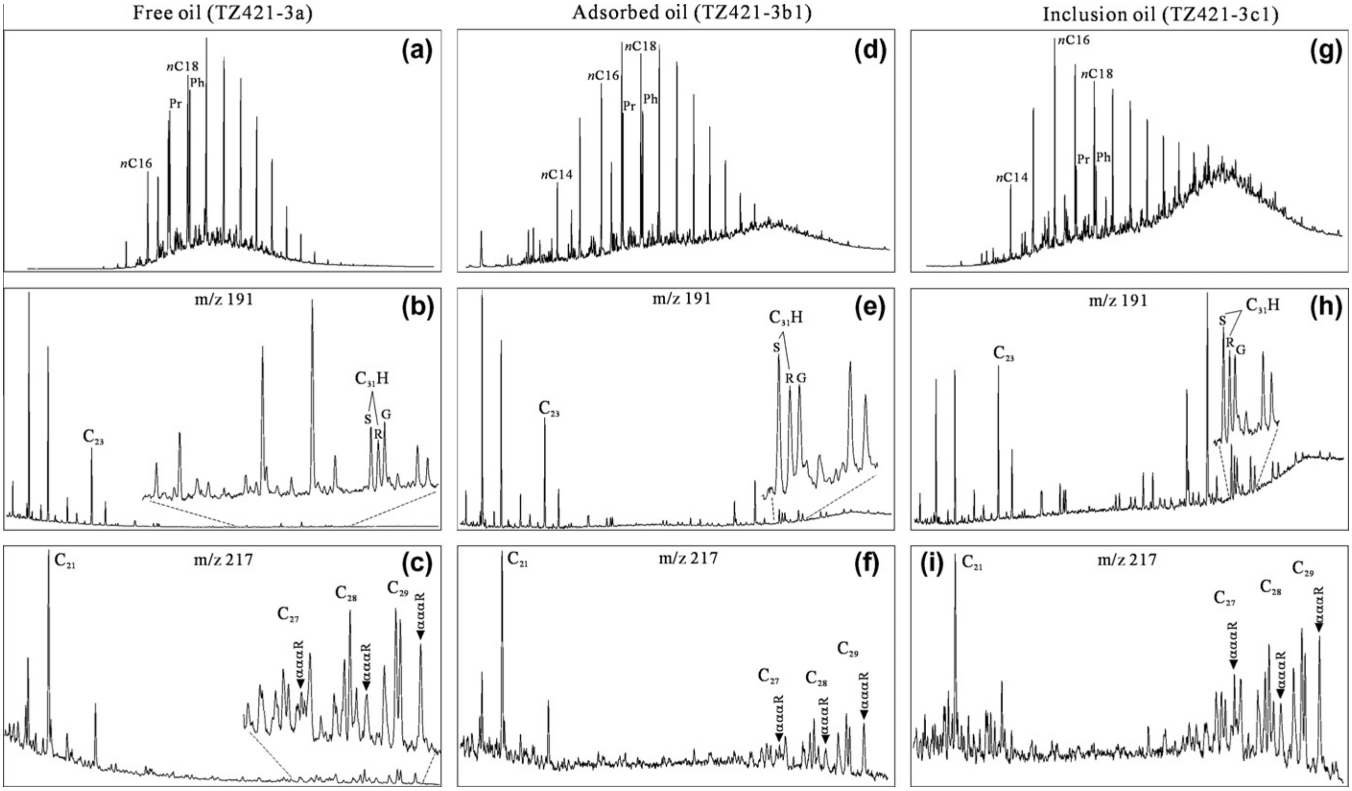

Fig. 11. Gas chromatograms and *m*/*z* 191 and *m*/*z* 217 mass chromatograms of oil-containing sandstone sample TZ421-3 from the Tazhong Uplift. (a–c) Free oil; (d–f) adsorbed oil; (g–i) inclusion oil; peak identifications are in Fig. 4.

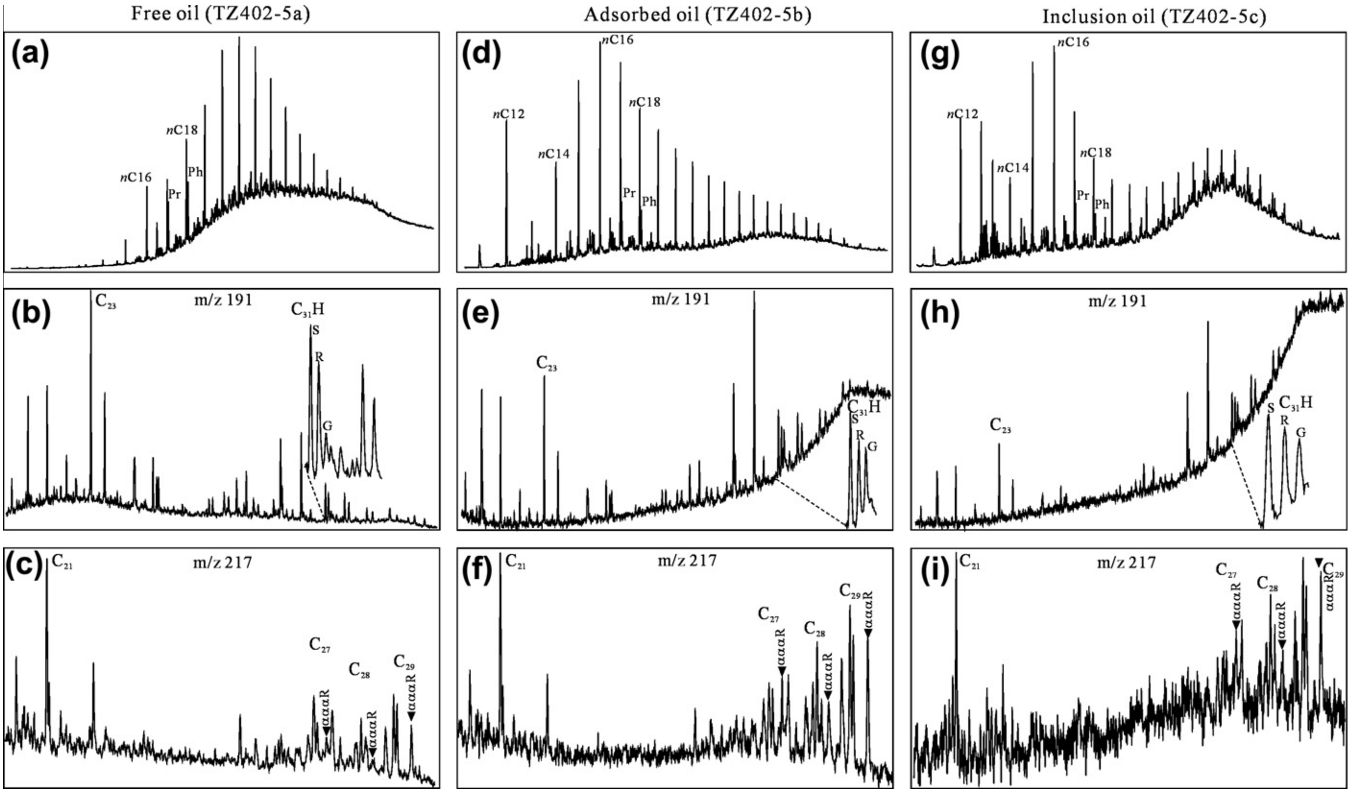

Fig. 12. Gas chromatograms and *m*/*z* 191 and *m*/*z* 217 mass chromatograms of oil-containing sandstone sample TZ402-5 from the Tazhong Uplift. (a–c) Free oil; (d–f) Adsorbed oil; (g–i) inclusion oil; peak identifications are in Fig. 4.

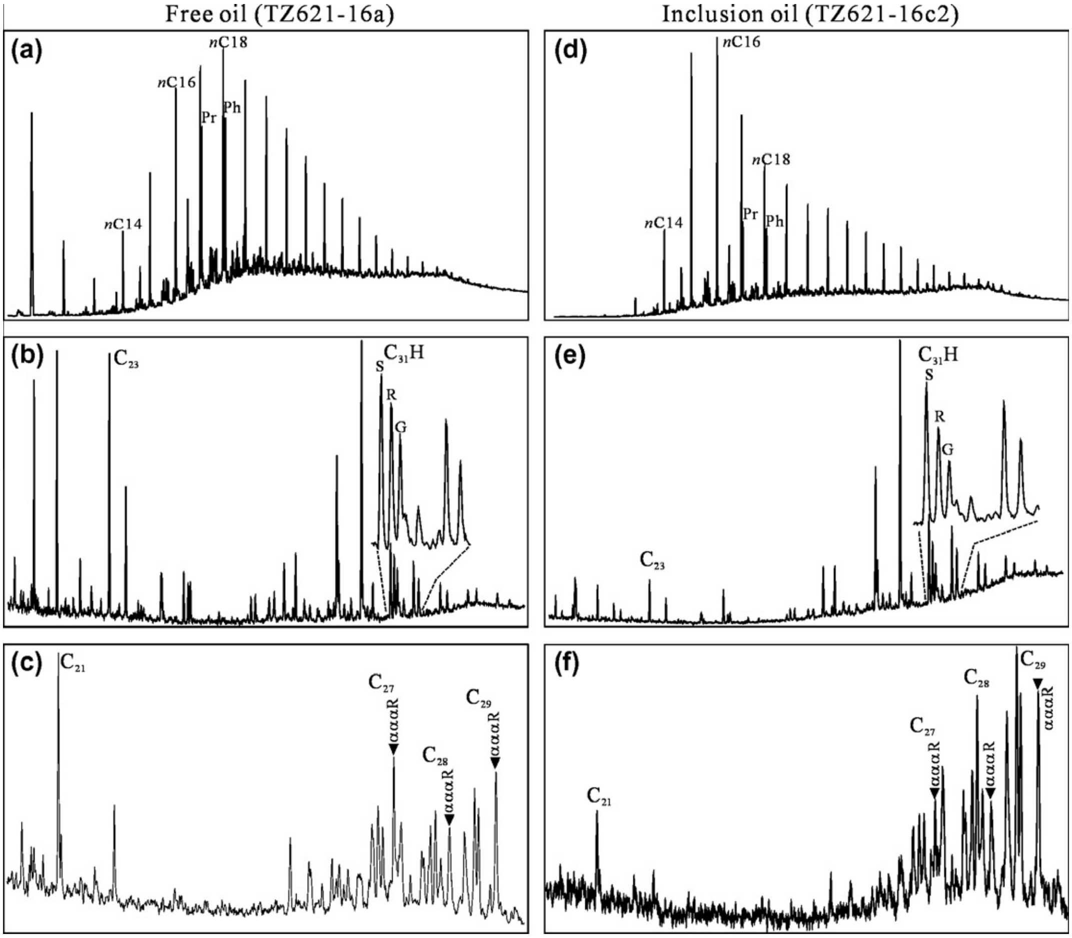

Fig. 13. Gas chromatograms and m/z 191 and m/z 217 mass chromatograms of oil-containing carbonate sample TZ621-16 from the Tazhong Uplift. (a–c) Free oil; (d–f) inclusion oil; peak identifications are in Fig. 4.

$(C_{27} + C_{28} + C_{29})$ sterane ratios and correlate with Cambrian–Lower Ordovician source rocks (Fig. 3a). The other 12 oils have relatively low values for these two ratios, differing from Cambrian–Lower Ordovician source rocks (Fig. 3a). Numerous studies have documented that source rocks within the Lianglitage Formation (O_{3l}) of Late Ordovician age are characterized with low relative concentrations of gammacerane and C_{28} steranes (e.g., Hanson et al., 2000; Zhang et al., 2002a,b, 2004; Wang and Xiao, 2004; Cai et al., 2009a,b; Li et al., 2010). Therefore, these 12 oils correlate with source rocks of Lianglitage Formation (O_{3l}). For the Group A oil- and tar-containing sandstones (10 samples, Table 3) and nearly all of the 21 oil-containing carbonates, the free, adsorbed and inclusion oils have relatively high values for these two ratios and therefore correlate with the Cambrian–Lower Ordovician source rocks. For the Group B oil- and tar-containing sandstones (eight samples, Table 3), the free oils have relatively low values for these two ratios and correlate with source rocks within the Lianglitage Formation (O_{3l}), while the adsorbed and inclusion oils have relatively high values of these two ratios and correlate with the Cambrian–Lower Ordovician source rocks. These results suggest that the initial oil charge for the Group B sandstones originated from Cambrian–Lower Ordovician source rocks, while the later oil charge originated from source rocks similar to those within the Lianglitage Formation, consistent with our previous study (Pan and Liu, 2009).

There are two interpretations for the substantial difference of these two ratios between most crude oils and the free, adsorbed and inclusion oils of reservoir rocks: (1) biomarkers in the initial oil charge were diluted by those in the later oil charge; and (2) when the initial oils entered the reservoirs most reservoir rocks had relatively high porosity and permeability due to shallow burial. Therefore, initial oils entered most reservoir rocks. In contrast, when later oils entered the reservoirs most reservoir rocks had low porosity and permeability due to deep burial. Therefore, the later oils only entered limited reservoir rocks with relatively high porosity and permeability. All oil samples in the present study and previous studies by others are DST oils, which came from the reservoir intervals with relatively high porosity and permeability.

Previous studies demonstrated that the ratios of C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) and $C_{21}/(C_{21} + \Sigma C_{29})$ steranes are effective parameters indicating the oil maturities within the medium to high levels (R_o%: 1.0–1.3) (van Graas, 1990; Peters and Moldowan, 1993; Pan and Yang, 2000; Pan et al., 2003). For the seven oils from the Carboniferous and Silurian sandstone reservoirs, six oils have relatively high values for these two ratios (Fig. 10a), demonstrating high maturity. Only oil TZ11O has relatively low values for these two ratios (Fig. 10a). However, the exceptionally high abundances of terpanes and steranes in this oil demonstrate that it was contaminated by oil components from the Silurian tar-containing sandstones (Pan and Liu, 2009). For the eight oils from Ordovician carbonate reservoirs, these two ratios vary from medium to high values (Fig. 10b). Because all 15 oils have similar distributions of n-alkanes, consistent with extensively cracking (e.g., Kissin, 1987), we believe that these oils originated from source rocks within the peak to late oil generation stage. The variations of these two ratios generally

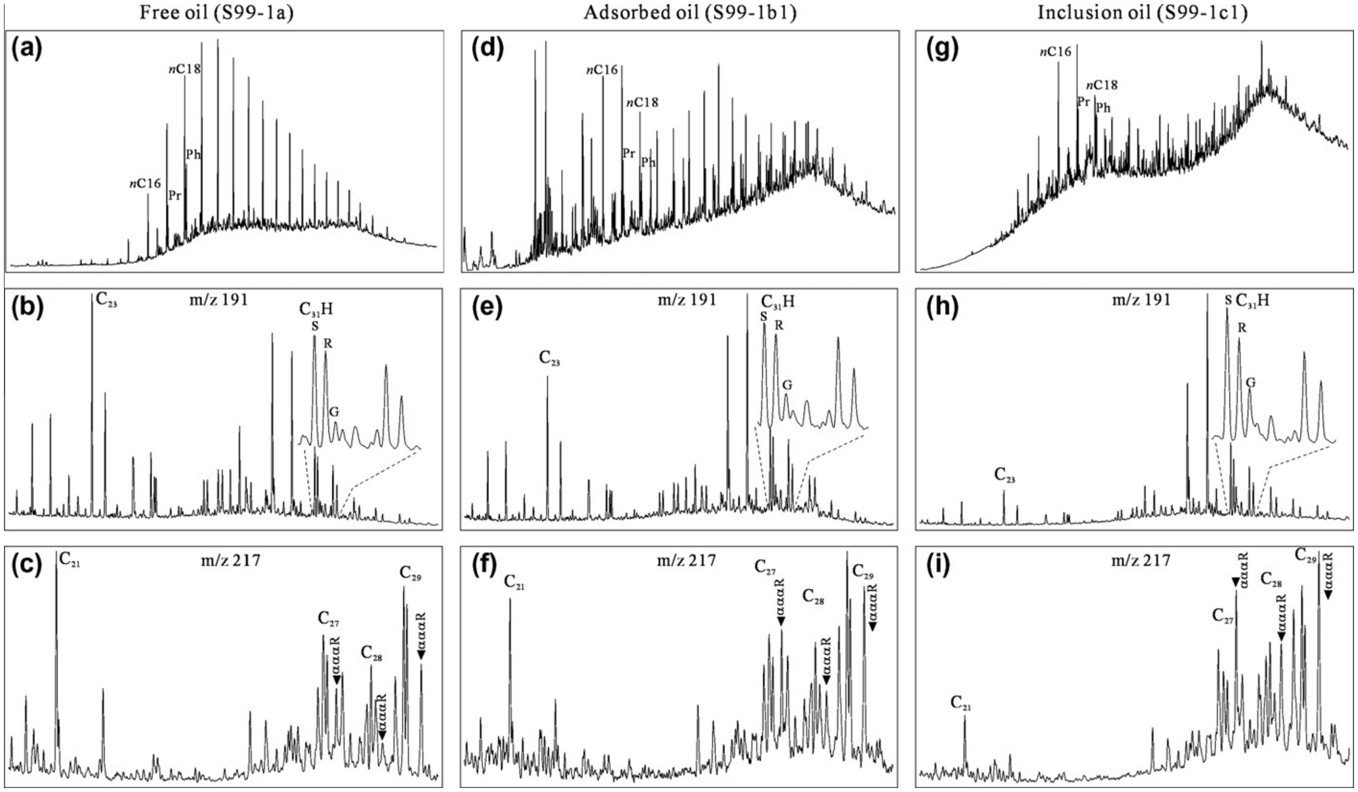

Fig. 14. Gas chromatograms and m/z 191 and m/z 217 mass chromatograms of oil-containing sandstone sample S99-1 from the Tahe oilfield. (a–c) Free oil; (d–f) adsorbed oil; (g–i) inclusion oil; peak identifications are in Fig. 4.

decrease from free oil, through adsorbed oil, to inclusion oil for each of the oil- and tar-containing sandstones and from free oil to inclusion oil for each of the oil-containing carbonates, demonstrating that the maturities of the charged oils increased during filling of the reservoirs in the Tazhong Uplift. Based on these two ratios, the maturities of the 15 crude oils are generally similar to those of the free oils of oil- and tar-containing sandstones and the carbonates (Fig. 10a and b). In addition, the maturity ranges appear to be similar between the free oils of the oil-containing sandstones and carbonates and between the inclusion oils in these two types of reservoir rocks (Fig. 10a and b).

4.2. Sources and maturities of the crude oils and oil components in reservoir rocks from the Tahe oilfield in the Tabei Uplift

All 39 oils from the Tahe oilfield have low values of gammacerane/C_{31} hopanes and $C_{28}/(C_{27} + C_{28} + C_{29})$ steranes and correlate with the source rocks within the Lianglitage Formation (O_{3l}) (Fig. 3a). For the 14 oil-containing sandstones, four free oils and most adsorbed and inclusion oils have relatively high values of these two ratios compared with the crude oils from the sandstone reservoirs (Fig. 9c), possibly demonstrating that the charged oils for the sandstone reservoirs are partly derived from Cambrian–Lower Ordovician source rocks. For the 26 oil-containing carbonates, the free and inclusion oils generally have low values of these two ratios with very few exceptions, and correlate with source rocks within the Lianglitage Formation (Fig. 9d). This result demonstrates that oils in the carbonate reservoirs were mainly derived from source rocks similar to those within the Lianglitage Formation with very minor contributions from Cambrian–Lower Ordovician source rocks.

The 39 oils from the Tahe oilfield generally have medium values of C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) and $C_{21}/(C_{21} + \Sigma C_{29})$ sterane ratios (Table 3, Fig. 10c and d), demonstrating that these oils are mainly generated during the peak oil generation stage (R_o% 0.9–1.2). These two ratios appear to be related to the gross compositions of the oils, i.e., higher contents of the saturate hydrocarbon fraction correspond to higher values of the two ratios (Tables 3 and 4). However, although the variations in gross compositions are substantially greater for oils from the Tahe oilfield than the Tazhong Uplift (Fig. 5), the ranges of these two ratios are much smaller for the former than the latter (Figs. 3b and 10). The oils with low content of saturates are actually mixtures of biodegraded and non-biodegraded oil components (e.g. Wang et al., 2008; Pan and Liu, 2009). The oils from the Tahe oilfield, especially from the carbonate reservoirs, have relatively higher proportions of biodegraded oil components than do the oils from the Tazhong Uplift because the former have less saturates than the latter (Fig. 5).

For the 14 oil-containing sandstones, maturity generally decreases from the free oil to adsorbed oil to inclusion oil based on the two ratios (Fig. 10c). The free and adsorbed oils have similar or lower maturities than those for crude oils from the sandstone reservoirs, except the free oil S109-1a with a maturity relatively higher than that of the crude oils. The inclusion oils have maturities generally lower than crude oils. For the 26 oil-containing carbonates, the free oils have C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) ratio similar to or lower than the analyzed oils from the carbonate reservoirs, while the inclusion oils have generally lower values of the ratio than the crude oils (Fig. 10d). However, the free and inclusion oils, especially the latter, have $C_{21}/(C_{21} + \Sigma C_{29})$ sterane ratio that varies irregularly with C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) ratio (Fig. 10d). Nevertheless, we believe that for these oil-containing carbonates the free oils have similar and/or lower maturities, while the inclusion oils have lower maturities than the crude oils from the carbonate reservoirs.

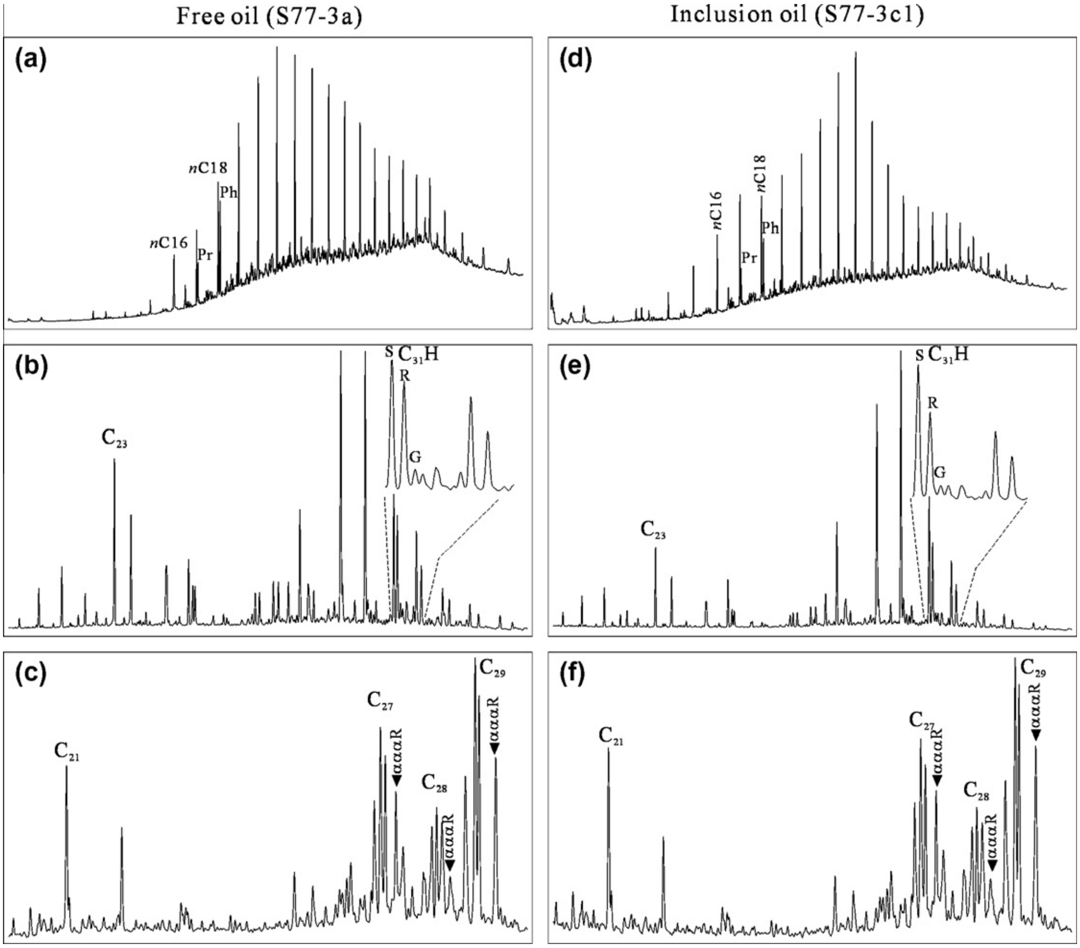

Fig. 15. Gas chromatograms and m/z 191 and m/z 217 mass chromatograms of oil-containing carbonate sample S77-3 from the Tahe oilfield. (a–c) Free oil; (d–f) inclusion oil; peak identifications are as in Fig. 4.

4.3. Major sources for the marine oils

Previous studies demonstrated that the marine oils in the Tarim Basin have high relative concentrations of 24-isopropylcholestanes and low relative concentrations of dinosteranes, triaromatic dinosteroids and 24-norcholestanes, and correlate with extracts of Middle–Upper Ordovician source rocks, but are strikingly different from extracts from Cambrian source rocks (Hanson et al., 2000; Zhang et al., 2000, 2002a,b, 2004). Therefore, the authors of those studies concluded that these marine oils originated from Middle–Upper Ordovician rather than Cambrian source rocks. Later studies further demonstrated that the Cambrian–Lower Ordovician source rocks have high relative concentrations of gammacerane and C_{28} regular steranes compared with the Middle–Upper Ordovician source rocks and the marine oils (Zhang et al., 2002a,b, 2004; Wang and Xiao, 2004, and references therein; Cai et al., 2009a,b; Jia et al., 2010; Li et al., 2010). The samples of Middle–Upper Ordovician source rocks in these previous studies are mainly from the Lianglitage Formation, which was previously determined to be of Middle–Late Ordovician (O_{2+3}), but currently of Late Ordovician (O_{3l}) age. The molecular data for source rocks and crude oils in the present study are consistent with these previous studies (Table 3, Fig. 3a). However, the Middle–Upper Ordovician source rocks penetrated by boreholes contain little organic carbon and have limited volume (e.g., Cai et al., 2009a,b). Therefore, these source rocks appear to be inconsistent with the huge petroleum resources that have been found (Cai et al. (2009a,b) and references therein).

Pan and Liu (2009) presented a contamination model for the formation of oil reservoirs in the Tazhong Uplift. They suggested that both the initial and later oil charges originated mainly from Cambrian–Lower Ordovician source rocks, but the later oil charge was contaminated by oil components from the Silurian tar sandstones and the Middle–Upper Ordovician source rocks based on the molecular data for the free, adsorbed and inclusion oils in the reservoir rocks. Contamination has been documented in previous studies (e.g., Li et al., 2000; Curiale, 2002). This model can be used to interpret the molecular data of the crude oils and reservoir rocks from the Tazhong Uplift in the present study. The molecular signatures of most free oils and nearly all of the adsorbed and inclusion oils for the reservoir rocks are similar to the Cambrian–Lower Ordovician source rocks, but differ substantially from the main crude oils and the Middle–Upper Ordovician source rocks (Fig. 9a and b). However, this contamination model cannot be used to explain the analytical data for crude oils and reservoir rocks from the Tahe oilfield where the molecular signatures of most free and inclusion oils in the carbonate reservoir rocks are similar to the crude oils and the Middle–Upper Ordovician source rocks, but differ from the Cambrian–Lower Ordovician source rocks (Fig. 9d). The crude oils in the Tahe oilfield are the mixtures of biodegraded and non-biodegraded oils (e.g., Wang et al., 2008). The terpanes and steranes in these oils have been concentrated. Although the crude oils vary substantially in gross composition, they have very similar terpane and sterane distributions, which reflect the molecular signatures of the main source rocks.

Tahe oilfield is the largest field found in this basin, and two thirds of the oil reserves in the Tahe oilfield occur in Ordovician carbonate reservoirs. In addition, the Silurian tar sandstones widely occur in the Tazhong and Tabei uplift and the original oil reserves for these tar sandstones are estimated up to 0.86 billion t (Jiang et al., 2008). Previous studies demonstrated that most of the Silurian tar sandstones correlate with the normal marine oils and the Middle–Upper Ordovician source rocks based on molecular and carbon isotopic data (e.g., Hanson et al., 2000; Zhang et al., 2000; Pan and Liu, 2009; Jia et al., 2010). Therefore, a major part of the marine oils in this basin originated from Middle–Upper Ordovician source rocks, which have low gammacerane/C_{31} hopanes and $C_{28}/(C_{27} + C_{28} + C_{29})$ sterane ratios. Although the Middle–Upper Ordovician source rocks penetrated by boreholes have relatively low TOC and limited thickness, thick source rocks with high TOC and molecular composition similar to the source rocks in the Lianglitage Formation could occur in the Manjaer Depression between the Tazhong and Tabei uplifts. These source rocks need not necessarily lie within the Lianglitage Formation (O_{3l}) and are possibly within the Upper–Middle Ordovician, or even the older strata. However, they are expected to be younger than the Cambrian–Lower Ordovician source rocks because oils from them entered the reservoirs later than those from the Cambrian–Lower Ordovician source rocks based on the molecular data for the reservoir rocks from the Tazhong Uplift and some sandstones from the Tahe oilfield.

It is strange that the C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) and $C_{21}/(C_{21} + \Sigma C_{29})$ sterane ratios vary irregularly for the Ordovician oil-containing carbonates in Tahe oilfield, while they correlate with each other for the Triassic-Silurian sandstones from the Tahe oilfield and both the oil-containing carbonates and sandstones from the Tazhong Uplift (Fig. 10). One possible interpretation of this phenomenon is that the values of these two ratios in the Ordovician carbonates from the Tahe oilfield reflect the subtle organofacies variations in the major source rocks. These two ratios are influenced by both maturity and facies (e.g., Peters and Moldowan, 1993; Peters et al., 2005). If oils with the subtle facies differences migrated long distances, they might be mixed. As a result, these two ratios vary regularly and have a close relationship with each other for these mixed oils. The data for these two ratios may imply that the Ordovician carbonate reservoirs in the Tahe oilfield are close to the major source kitchen, while the oil reservoirs in the Tazhong Uplift are far from the major source kitchen. For the Tahe oilfield, the filling process may be different between the sandstone and carbonate reservoirs. Oil may charge the carbonate reservoirs first, and then migrate into the sandstone reservoirs, or the migration routes for oils charging the sandstone and carbonate reservoirs may be different.

Inclusion oils are mainly trapped by minerals during initial filling of a reservoir unit (e.g., George et al., 1997; Pan et al., 2000). The inclusion oils in the carbonates from the Tahe oilfield have C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) and $C_{21}/(C_{21} + \Sigma C_{29})$ sterane ratios that vary irregularly and substantially, indicating that the initial oils were not fully homogenized during the early filling process of the reservoirs. The free oils in these carbonates may include oil components in open pores and closed pores, which were released when the rock samples were crushed into small grains (Pan and Liu, 2009). Therefore, the free oils are usually different in molecular composition from the crude oils even within the same depth interval. The crude oils from the carbonate reservoirs in the Tahe oilfield are mainly in caves, which formed during multiple karstifications (e.g., Wang et al., 2008), and therefore, they are much more homogenized in molecular composition than those from the sandstone reservoirs in this field and the carbonate and sandstone reservoirs in the Tazhong Uplift (Fig. 10).

5. Conclusions

(1) Three of the 15 crude oils from the Tazhong Uplift correlate with Cambrian–Lower Ordovician source rocks, while the other crude oils from the Tazhong Uplift and all 39 crude oils from the Tahe oilfield in the Tabei Uplift correlate with Middle–Upper Ordovician source rocks based on the relative concentrations of gammacerane and C_{28} steranes.

(2) Most of the free oils and nearly all of the adsorbed and inclusion oils from oil-containing reservoir rocks in the Tazhong Uplift correlate with Cambrian–Lower Ordovician source rocks, demonstrating that the initial oil charge originated from these older source rocks. In contrast, the free and inclusion oils from oil-containing carbonates in the Tahe oilfield correlate with Middle–Upper Ordovician source rocks with very few exceptions. This result suggests that both the initial and later oil charges mainly originated from these younger source rocks. However, the effective source kitchens that contain these younger source rocks have not yet been drilled.

(3) The scatter of C_{23} tricyclic terpane/(C_{23} tricyclic terpane + C_{30} 17α,21β(H)-hopane) and $C_{21}/(C_{21} + \Sigma C_{29})$ sterane ratios for the free and inclusion oils from the oil-containing carbonates in the Tahe oilfield possibly reflects subtle organofacies variations in the source rocks, implying that the Ordovician reservoirs in this oilfield are close to the major source kitchen. In contrast, the close and positive relationship between these two ratios for the oil-containing reservoir rocks from the Tazhong Uplift implies these oil reservoirs are far from the major source kitchen.

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