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Crude-oil hydrocarbon composition characteristics and oil viscosity prediction in the northern Songliao Basin

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Crude oil hydrocarbon composition characteristics and oil viscosity prediction are important bases in petroleum exploration. A total of 54 oil/heavy-oil samples and 17 oil sands were analyzed and quantified using both comprehensive 2D gas chromatography (GC×GC) and comprehensive 2D gas chromatography/time-of-flight mass spectrometry (GC×GC/ TOFMS). The results show that crude oil in the West slope is mainly heavy oil and its hydrocarbon composition is characterized overall by paraffins > mono-aromatics > naphthenes > non-hydrocarbons > di-aromatics > tri-aromatics > tetra-aromatics. Aromatics are most abundant and non-hydrocarbons are least abundant, whilst content differences among paraffins, naphthenes, aromatics, and non-hydrocarbons are less than 15%. There are two types of heavy oil, secondary type and mixing type. Biodegradation is the main formation mechanism of heavy oil. Biodegradation levels cover light biodegradation, moderate biodegradation, and severe biodegradation. With increasing biodegradation, paraffin content decreases while contents of aromatics and non-hydrocarbons increase. In contrast, naphthene content increases first and then decreases with increasing biodegradation. In severe biodegradation stage, naphthenes decrease more quickly than aromatics and non-hydrocarbons. This provides a new method for studying oil/heavy-oil biodegradation mechanism and biodegradation resistance of different hydrocarbons at different biodegradation stages. In the Longhupao-Daan terrace and Qijia-Gulong depression, most crude oil is conventional oil. Its composition is dominated by paraffins with the lowest content of aromatics. In some casual oil wells from the Longhupao-Daan terrace, crude oil from Saertu oil reservoirs is moderately biodegraded whereas crude oil from Putaohua oil reservoir is lightly biodegraded. Chemical parameters using saturate hydrocarbons and aromatics are usually not suitable for determining organic type and thermal maturity of biodegraded oil, especially of moderately or severely biodegraded oil, whilst Ts/(Ts+Tm) ratio can be used to determine thermal maturity of both conventional crude oil and heavy oil.

Songliao Basin, crude-oil and heavy oil, hydrocarbon composition, comprehensive two-dimensional gas chromatography

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Crude oil is a complex and multi-component homogeneous mixture and is composed principally of hydrocarbons including paraffins, naphthenes, and aromatics with minor contents of non-hydrocarbons (e.g., nitrogen, sulfur, and oxygen compounds), resin, and asphaltene. Heavy oil is that with degassed oil viscosity greater than 100 mPa·s at subsurface temperature. Global heavy oil and bitumen sands resources are many times larger than conventional petroleum resources. Heavy oil and bitumen sands resources are rich in China and potential resources exceed 59.7×10^8 t (Hu

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et al., 2010), Heavy oil resources have become an important field in petroleum exploration. There are two main mechanisms forming heavy oil. One refers to primary heavy oil, which is immature oil generated by source rock at lower thermal maturity. The other refers to secondary heavy oil, which is crude oil that has been altered by biodegradation, oxidation due to water-washing and other physical chemistry processes. Chemical composition, especially hydrocarbon composition, of crude oil and heavy oil contains organic precursor, transformation products, and post-alteration information. Thus, crude oil hydrocarbon composition and oil viscosity characteristics are important parameters in understanding petroleum generation, maturation, migration, accumulation, preservation, oil-source correlation, post-alteration, and reservoir geochemistry in petroleum exploration.

To date, the northern Songliao Basin is one of major petroleum exploration fields for mid-shallow formation in the Songliao Basin. In the past decades, many oil/gas fields have been found, including Fulaerji oilfield, Pingyang oilfield, Taobao oilfield, Longhupao oilfield, Qijia oilfield, Alaxin gasfield, Erzhan gasfield, Baiyinnuole gasfield. Oil reservoir types are mainly about lithology and structural-lithology. Crude oil is mainly conventional oil and heavy oil. Heavy oil occurs mainly in the West slope. Petroleum geologists have studied oil generation, occurrence, and exploration potential in the northern Songliao Basin for several years (Lu et al., 1998, 2008; Lin et al., 2003; Wang et al., 2010; Xie et al., 2011). Feng et al. (2003) suggested that heavy oil in the West slope was formed mainly by oil biodegradation, on the basis of high temperature gas chromatography and biomarker analysis. Based on component analysis, gas chromatography, isotope analysis, mass spectrogram and etc., Zou et al. (2004) suggested that heavy oil in the West slope was the result of long-migration accompanying biodegradation and water-washing. Xiang et al. (2007) suggested that heavy oil above overpressure transition belts was formed mainly by oxidation due to water-washing from meteoric water infiltration and biodegradation, whereas heavy oil under overpressure transition belts was formed mainly by biodegradation. In transition belts, heavy oil was a mixture of biodegraded oil and non-biodegraded oil. In this paper, we use comprehensive two-dimensional gas chromatography (GC×GC) and comprehensive two-dimensional gas chromatography/time-of- flight mass spectrometry (GC×GC/TOFMS) to systematically study crude oil hydrocarbon compositional characteristics and distribution. There are three technological advancements in this paper: (1) crude oil/heavy oil can be directly analyzed to get hydrocarbon composition (paraffins, naphthenes, aromatics, non-hydrocarbons and etc.) thanks to high resolution, high peak capacity, and high sensitivity of GC×GC. Conventional group composition separation method cannot guarantee pristine compositional feature whereas the new method introduced here can avoid such deficiency and the associated analytical errors. The number of separated compounds is 15 times higher than that of one dimensional gas chromatography and the quantification is more accurate (Fryinger et al., 2001; Gregory et al., 2008; Mao et al., 2008). (2) 2D or 3D chromatography can be separated into several bands based on specific compound separation and qualification of GC×GC/TOFMS. In a 2D chromatogram, the lowest band represents paraffins that have the weakest polarity. Above the lowest band, there are naphthenes, mono-aromatics, di-aromatics, tri-aromatics, tetra-aromatics, and so on in order. In the same band, substituents with the same carbon number are arranged in line, whilst substituents with different carbon numbers are arranged in imbrication. The whole chromatogram can be divided into several different fields indicating different groups of compounds and the reliability of qualification is greatly improved (Schoenmakers et al., 2000; Adam et al., 2007; Mispelaar et al., 2005; Mao et al., 2008; Freitas et al., 2009; Wang et al., 2010), providing reliable indicators for studying crude oil/heavy oil hydrocarbon composition; (3) in this paper, GC×GC and GC×GC/TOFMS are first used in studying crude oil/heavy oil hydrocarbon composition and predicting oil viscosity of heavy oil from exploration wells.

1 Geological setting

The study area includes the West slope, Longhupao-Daan terrace, and Qijia-Gulong depression (Figure 1). The West slope consists of two secondary tectonic units (i.e., the Western overlapping zone and Taikang uplift zone) and is an east-dipping monoclinal structure. The Longhupao-Daan terrace is an N-S trending anticline with both flank dips slightly greater than 1° and is bounded on the west by the West slope and the first-order tectonic boundary of central depression. To its east is the Qijia-Gulong depression. Talaha oilfield is to the south and Qijia oilfield is to the north. The Qijia-Gulong depression is in the central depression and to its west is the Longhupao-Daan terrace. The Daqing plateau is to the east. From younger to older, the tectonic framework is similar and it is a monoclinal structure with the northwest higher than the southeast. The formation dips vary little and are well inherited.

The oil/gas fields of Xindian, Baiyinnuole, Alaxin, Erzhan, Jiangqiao, Fulaerji and etc. have been found in the West slope and the main oil/gas reservoirs are Saertu and Gaotaizi with petroleum mainly sourced from source rocks of the Qingshankou Fm. and Nenjiang Fm. (Feng et al., 2003; Xiang et al., 2005a, 2005b, 2007; Zou et al., 2004; Zhang et al., 2005; Sun et al., 2006; Zhu et al., 2006; Zhou et al., 2006, 2008; Zhao et al., 2006; Fu et al., 2007). The discovered petroleum resources are mainly heavy oil and natural gases in the West slope. In the Longhupao-Daan terrace, the discovered oilfields are Aogula oil field, Longhupao oilfield and etc. with main oil reservoirs of Saertu,

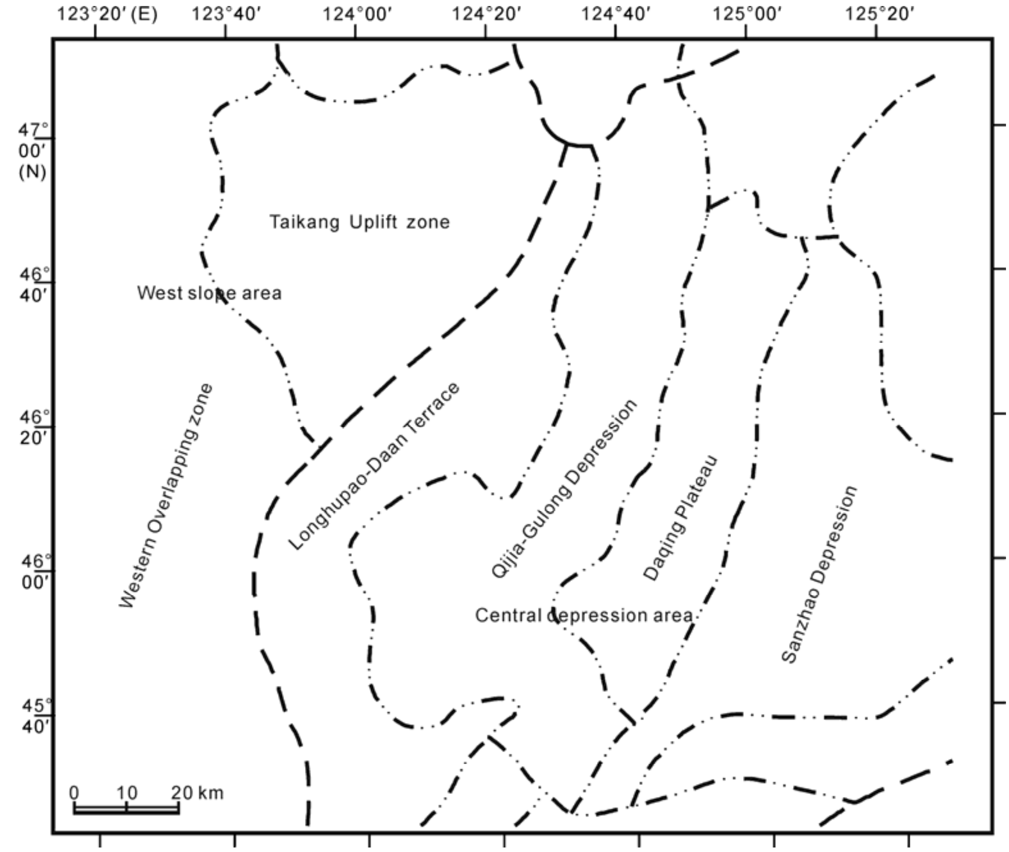

Figure 1 Structural map of the northern Songliao Basin.

Putaohua, Gaotaizi and Fuyang. The Qijia-Gulong depression is a long-term inherited deep-water depression and during the deposition of Qingshankou formation (K_2qn), a large volume of black lacustrine source rock has been developed. The Qingshankou and Nenjiang formations are the main source rock in the Songliao Basin, providing enough petroleum for oil/gas reservoirs of the Qijia-Gulong depression, Longhupao-Daan terrace, West slope, and Daqing plateau (Lin et al., 2003). In the Qijia-Gulong depression, Qijia oilfield, Jinten oilfield and etc. have been found with the main reservoirs of Saertu, Putaohua, Gaotaizi, and Fuyu.

2 Samples and experiment

2.1 Samples

A total of 54 oil/heavy oil samples (Table 1) and 17 oil sands from oil reservoirs of Saertu (S), Putaohua (P), Fuyu (F) and Yangdachengzi (Y) have been collected from the study area of northern Songliao Basin. In the West slope, the oil density, viscosity, freezing point, flash point, wax content, asphaltene content and resin content are 0.8466–0.9501 g/cm^3, 28.26–520.40 mPa·s, 3–33°C, 37–194°C, 10.0%–37.0%, 0.4%–3.4%, 14.4%–37.2%, respectively, whilst in the Longhupao-Daan terrace and Qijia-Gulong depression, they are 0.8138–0.9010 g/cm^3, 5.06–101.40 mPa·s, 8–41°C, 36–138°C, 13.0%–34.8%, 0.3%–8.6%, 2.6%–22.6%, respectively. Compared with oil form the Longhupao-Daan terrace and Qijia-Gulong depression, it is obvious that oil from the West slope is characterized by “four high, two low, and one moderate”, where “four high” means higher values of oil density, viscosity, resin content, and flash point, “two low” means values of freezing point and wax content are lower, and “one moderate” means asphaltene contents are moderate.

2.2 Experiment

2.2.1 Comprehensive two-dimensional gas chromatography

A LECO comprehensive two-dimensional gas chromatography (GC×GC) system was used, which consisted of an Agilent 7890A gas chromatography equipped with a LECO quad jet dual-stage thermal/cryogenic modulator, an FID detector and Agilent 7683B auto injector. Data acquisition and processing were performed using Chroma TOF software.

The primary GC column was DB-Petro (50 m×0.2 mm×0.5 μm film thickness). The primary oven temperature program was: 80°C (0.2 min) to 300°C at 2°C/min and the final temperature was maintained for 30 min.The secondary GC column was DB-17ht (2 m×0.1 mm×0.1 μm film thick-

Table 1 Oil physical characteristics in the northern Songliao Basin

Area	Well	Depth (m)	Reservoir	Density (g/cm^3)	Viscoity (mPa·s)	Freezing point (°C)	Flash point (°C)	Wax (%)	Asphaltene (%)	Resin (%)	Oil type
West slope	Fu701	471.2–481.4	S	0.9282	340.00	–	130	19.7	–	29.7	heavy oil
	Fu718	471.8–481.4	S	0.9230	308.20	4	156	22.4	/	34.1	heavy oil
	Jiang45	443.6–446.8	S	0.9292	330.00	19	37	15.6	3.4	43.5	heavy oil
	Jiang55	465.8–458.2	S	0.9258	298.50	–	148	17.7	1.5	34.5	heavy oil
	Jiang37	820.0–851.5	J	0.9501	141.00	23	–	–	2.8	–	heavy oil
	Jiang372	593.0–602.0	G	0.9243	159.60	6	109	10.0	4.0	22.9	heavy oil
	Jiang21	607.0–609.2	S	0.9200	300.00	–	/	16.8	0.4	37.2	heavy oil
	Jiang75	558.8–560.2	S	0.9157	240.00	13	165	14.3	2.0	36.0	heavy oil
	Du620	714.6–717.4	S	0.9242	398.80	3	154	24.5	2.3	34.1	heavy oil
	Du616	731.2–728.8	S	0.9117	202.30	–	178	19.7	1.4	27.4	heavy oil
	Du75	836.6–840.2	S	0.9332	450.00	–	–	–	–	–	heavy oil
	Du1-3	784.8–789.8	S	0.9132	120.00	–	122	37.0	2.6	19.3	heavy oil
	DuV-3	770.6–789.8	S	0.9146	211.10	–	100	21.4	0.9	21.7	heavy oil
	DuV-4	784.6–788.6	S	0.9200	520.40	10	194	25.6	1.0	26.5	heavy oil
	Lai65	662.4–664.4	S	0.9200	200.70	6	170	28.3	0.9	26.6	heavy oil
	Du52	872.4–866.0	G	–	222.40	11	–	21.0	–	33.4	heavy oil
	Du60	951.6–952.6	S	0.9217	340.20	–	–	–	–	–	heavy oil
	Du23	1178.0–1182.4	G	0.9111	141.00	4	130	22.8	2.2	20.6	heavy oil
	Du34	1212.4–1210.0	G	0.8957	79.87	32	80	26.2	1.5	15.9	conventional oil
	Du43	1070.0–1060.6	S	–	261.30	–	–	34.7	–	24.8	heavy oil
	Du20	1557.4–1533.3	G	0.8466	28.26	33	76	24.9	1.6	14.4	conventional oil
	Du22	1018.1–1015.6	S	–	330.31	17	–	28.8	–	23.8	heavy oil
	Du85	1451.0–1452.0	G	0.9013	264.09	–	–	–	–	–	heavy oil
Long-hupao-Daan terrace	Ha1	1232.4–1229.0	S	0.8934	78.60	8	124	22.2	0.7	19.8	conventional oil
	Ha10	1865.2–1844.6	P	0.8253	6.90	23	98	23.9	0.4	2.6	conventional oil
	Ha15	2269.0–1278.8	FY	0.8319	15.22	35	/	13.0	8.6	12.1	conventional oil
	Long124	1841.0–1858.6	S	0.8417	23.90	41	100	28.9	0.3	6.1	conventional oil
	Long23	2116.2–2272.6	FY	0.8445	33.50	35	105	31.8	0.8	5.4	conventional oil
	Long29	1987.2–1934.4	G	0.8539	21.10	36	60	30.7	0.9	12.6	conventional oil
	Long291	1915.4–1841.6	G	0.8726	35.20	32	74	23.2	1.8	16.0	conventional oil
	Ta20	1170.8–1172.2	S	0.8769	46.10	23	91	26.1	–	16.8	conventional oil
	Ta22	1340.6–1337.0	S	0.9010	101.40	15	100	25.2	3.8	21.5	heavy oil
	Ta23	1706.6–1708.6	G	0.8661	32.56	33	38	30.2	1.4	14.1	conventional oil
	Ta234	1934.6–2011.8	F	0.8623	45.20	36	40	27.0	2.7	12.5	conventional oil
	Ta251	1570.8–1772.6	P	0.8649	34.60	40	90	31.2	1.5	10.0	conventional oil
	Ta284	2074.0–2173.0	FY	0.8341	10.20	30	40	26.1	2.2	6.4	conventional oil
	Ta30	1882.0–1947.2	F	0.8504	17.44	32	59	29.9	2.5	8.1	conventional oil
	Ta301	1288.8–1289.6	S	0.8417	23.90	–	–	–	–	–	conventional oil
Qijai-Gulong depression	Jing51	1611.6–1613.8	S	0.8636	32.22	38	93	25.7	2.4	22.6	conventional oil
	Jing62	2017.8–2111.4	G	0.8497	40.19	38	44	34.8	6.7	19.5	conventional oil
	Jing88	1975.0–1977.0	S	0.8602	60.77	41	43	18.8	0.9	15.5	conventional oil
	Gu18	1966.6–1793.2	SP	0.8509	20.90	31	92	27.7	1.6	8.5	conventional oil
	Gu203	2324.0–2248.2	F	0.8639	26.73	35	68	20.8	0.9	12.3	conventional oil
	Gu22	1803.8–1802.8	S	0.8662	51.10	36	138	32.1	–	20.4	conventional oil
	Gu302	2179.4–2083.0	G	0.8523	16.30	32	81	25.2	1.5	11.6	conventional oil
	Gu702	1958.2–1991.2	G	0.8508	14.60	37	118	20.6	–	9.6	conventional oil
	Gu708	2136.6–2143.2	F	0.8638	24.28	37	–	–	–	–	conventional oil
	Gu96	1637.0–1634.5	S	0.8658	63.83	40	40	24.3	0.5	18.5	conventional oil
	Ying14	2230.8–2243.0	F	0.8313	12.64	37	36	28.3	1.7	3.0	conventional oil
	Ying15	1840.8–1777.2	S	0.8497	25.50	36	78	24.9	–	9.7	conventional oil
	Ying33	1882.6–1905.2	P	0.8138	5.06	34	39	21.0	0.8	13.1	conventional oil
	Ying39	2039.6–2042.4	G	0.8535	16.11	33	–	–	–	–	conventional oil
	Ying51	2021.0–1923.8	G	0.8331	8.85	26	62	23.4	0.4	6.4	conventional oil
	Ying62	1503.0–1495.8	S	0.8509	18.71	–	–	–	–	–	conventional oil

ness). The secondary oven temperature program was: 85°C (0.2 min) to 310°C at 2°C/min and the final temperature was maintained for 30min.The sample was injected at 300°C using split mode. The temperature for FID detector was 320°C. The supplementary gas for the detector was high purity helium. The modulation period was 10s with a 2.5 s hot pulse and 30°C modulator temperature offset higher than the primary oven temperature. The carrier gas is high purity helium and the flow rate was 1.8 mL/min. The flaming gas was hydrogen with the flow rate of 45 mL/min. The oxidant gas is air with the flow rate of 400 mL/min.

The qualification and quantification (area normalization method) were conducted on a comprehensive two-dimensional/time-of-flight mass spectrometry (GC×GC/TOFMS) system.

2.2.2 Comprehensive two-dimensional/time-of-flight mass spectrometry

A LECO comprehensive two-dimensional gas chromatography/time-of-flight mass spectrometry (GC×GC/TOFMS) system was used, which consisted of an Agilent 7890 gas chromatography equipped with a LECO dual-jet thermal modulator. The time-of-flight mass spectrometry was LECO Pegasus IV and the auto injector was by Agilent 7683B. Data acquisition and processing were performed using Chroma TOF software. The GC×GC conditions for GC×GC-TOFMS were the same as those for GC×GC given at section 2.2.1. Mass spectrometry conditions were: electron ionization mode at –70 eV, scan range at 40–520 u, ion source temperature 230°C, detector 1475 V, acquisition rate 100 spectra/s and acquisition delay period 11 min.

3 Experimental results

3.1 West slope

3.1.1 Hydrocarbon composition

As shown in Table 2 and Figure 2, heavy oil hydrocarbon composition in the West slope is characterized overall by paraffins > mono-aromatics > naphthenes > non-hydrocarbons > di-aromatics > tri-aromatics > tetra-aromatics with the highest content of aromatics and the lowest content of non-hydrocarbons, whereas content differences among paraffins, naphthenes, aromatics and non-hydrocarbons are less than 15%. Hydrocarbon composition of conventional crude oil is characterized overall by paraffins > non-hydrocarbons > naphthenes > mono-aromatics > di-aromatics > tri-aromatics > tetra-aromatics. Conventional crude oil is dominated by paraffins (>74%), whereas contents of naphthenes, aromatics and non-hydrocarbons are all less than 10%. Compared with conventional crude oil, heavy oil in the West slope has lower content of paraffins with higher contents of naphthenes, mono-aromatics, di-aromatics, tri-

Table 2 Hydrocarbon compositions of oils from the West slope[a)]

Well	Reservoir	Paraffin (%)	Naphthene (%)	Mono-aromatic (%)	Di-aromatic (%)	Tri-aromatic (%)	Tetra-aromatic (%)	Non-hydro-carbon (%)
Du1-3	S	34.38	30.13	13.95	1.88	0.58	0.90	18.18
Du22	S	21.98	22.82	27.03	2.75	1.59	0.94	22.89
Du43	S	16.02	18.69	30.71	4.52	2.05	1.19	26.83
Du60	S	20.58	22.37	25.06	3.39	2.59	1.54	24.49
Du616	S	19.80	30.77	27.09	5.91	2.03	1.10	13.30
Du620	S	30.28	25.27	12.17	2.94	0.73	0.76	27.87
Du75	S	9.62	21.55	32.95	4.55	1.67	0.64	29.02
DuV-3	S	46.84	23.99	13.66	4.86	0.46	0.46	9.73
DuV-4	S	16.26	23.37	29.69	1.85	0.62	0.81	27.41
Fu701	S	15.82	19.91	30.82	4.21	1.65	0.94	26.63
Fu718	S	22.43	22.65	22.98	3.95	1.36	0.90	25.73
Jiang21	S	24.34	24.11	15.65	0.64	0.24	0.24	34.78
Jiang45	S	9.93	17.53	31.65	4.09	1.79	1.11	33.90
Jiang55	S	12.71	24.50	30.13	4.71	2.22	1.12	24.62
Jiang75	S	24.75	23.66	28.73	2.02	1.11	2.05	17.69
Lai65	S	29.76	22.53	23.13	2.00	0.72	0.91	20.95
Jiang37	J	55.18	15.84	13.29	3.21	1.29	0.52	10.67
Jiang372	G	77.31	10.19	4.02	1.31	0.52	0.27	6.38
Du20	G	74.17	7.66	6.10	2.59	0.71	0.33	8.44
Du34	G	75.69	7.81	5.49	1.68	0.54	0.17	8.62
Du23	G	18.77	24.56	30.21	4.42	2.04	0.84	19.17
Du52	G	20.36	23.74	27.55	2.30	1.40	1.13	23.53
Du85	G	39.07	20.06	19.40	3.46	1.30	0.66	16.06

a) Samples of Du20 and Du34 are conventional crude oil whereas other samples are heavy oil.

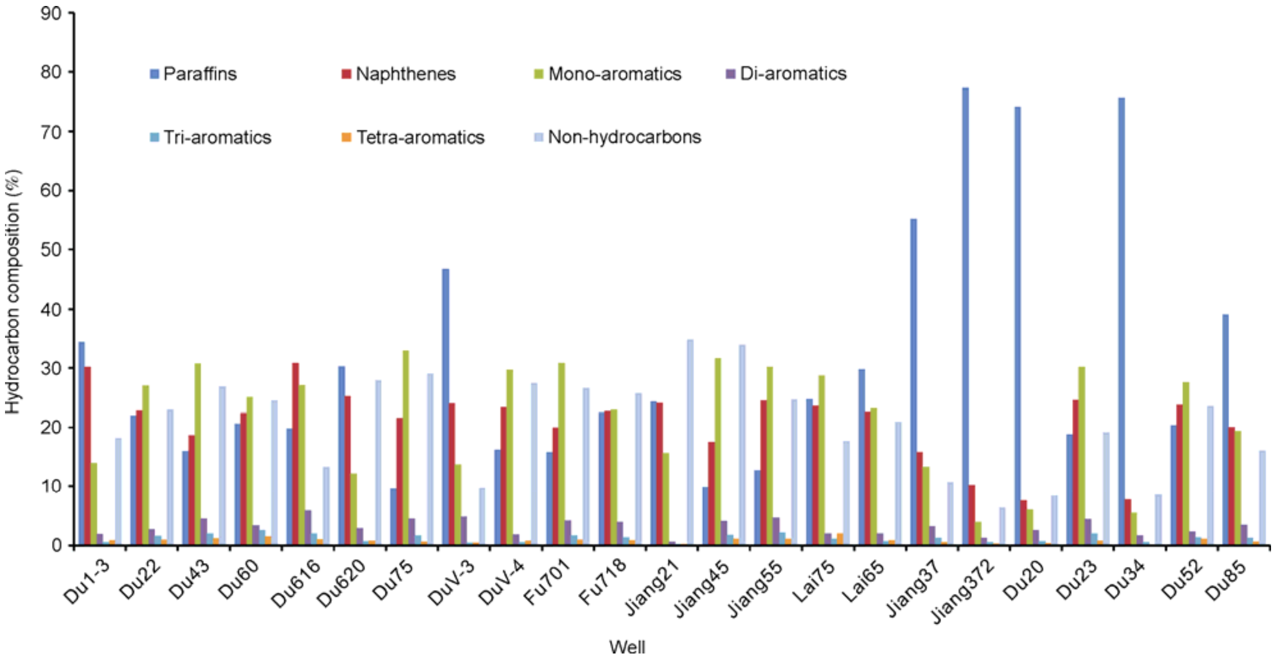

Figure 2 Hydrocarbon compositional distributions of heavy oils/crude oil from the West slope.

aromatics, tetra-aromatics and non-hydrocarbons. As paraffin content decreases, contents of naphthenes, mono-aromatics, di-aromatics, tri-aromatics, tetra-aromatics and non-hydrocarbons tend to increase.

3.1.2 Saturates and aromatics

As shown in Table 3, parameters indicated by saturate hydrocarbons of conventional crude oil in the West slope show that the crude oil is sapropelic mature oil, whereas such parameters indicated by heavy oil show that the heavy oil is sapropelic/humic oil, immature-low mature oil/mature oil.

As shown in Table 4, aromatic hydrocarbon parameters show that conventional crude oil from the West slope is mature oil, while heavy oil is immature-low mature oil or mature oil.

3.2 Longhupao-Daan terrace

3.2.1 Hydrocarbon composition

As shown in Figure 3, hydrocarbon composition of conventional crude oil from the Longhupao-Daan terrace is dominated by paraffin content and is characterized overall by paraffins > naphthenes > non-hydrocarbons > mono-aromatics > di-aromatics > tri-aromatics > tetra-aromatics with the highest content of paraffins and the lowest content of aromatics. Heavy oil (Saertu oil reservoir of well Ta22) is characterized by paraffins > naphthenes > nonhydrocarbons > mono-aromatics > di-aromatics > triaromatics > tetra-aromatics with the highest content of paraffins and the lowest content of non-hydrocarbons, whereas concentration differences among paraffins, naphthenes, aromatics, and non-hydrocarbons are less than 15%. Compared with hydrocarbon composition of conventional crude oil, heavy oil is characterized by lower content of paraffins and higher content of naphthenes, mono-aromatics, diaromatics, tri-aromatics, tetra-aromatics, and non-hydro- carbons.

3.2.2 Saturates and aromatics

Saturate hydrocarbon parameters of carbon number range, main peak carbon, OEP, Pr/Ph, Pr/nC_{17}, Ph/nC_{18}, ΣnC_{21}-/ΣnC_{22}+, nC_{21+22}/nC_{28+29} and Ts/(Ts+Tm) for conventional crude oil from the Longhupao-Daan terrace are nC_9–nC_{37}, nC_{17}–nC_{23}, 1.02–1.11, 1.02–1.40, 0.13–0.46, 0.10–0.42, 0.62–1.67, 1.50–1.92, 0.56–0.88, respectively, whilst for heavy oil from Saertu oil reservoir of well Ta22, they are nC_{10}–nC_{36}, nC_{29},1.46, 0.84, 0.66, 0.70, 0.56, respectively. Saturate hydrocarbon parameters show that conventional crude oil is sapropelic mature oil, whilst heavy oil is humic immature-low mature oil or mature oil.

Aromatic hydrocarbon parameters of MNR, ENR, MPR, MPI, DPR and DPI for conventional crude oil rare 1.19–2.05, 1.34–6.08, 0.85–2.20, 0.45–1.06, 1.70–2.87, 4.38–8.75, respectively, whilst parameters of MNR, ENR, MPR, MPI of heavy oil from Saertu oil reservoir of well Ta22 are 1.30, 1.88, 0.84, 0.57, respectively. Aromatic hydrocarbon parameters show that both conventional crude oil and heavy oil are mature oil.

3.3 Qijia-Gulong depression

3.3.1 Hydrocarbon composition

As shown in Figure 4, conventional crude oil hydrocarbon

Table 3 Saturate hydrocarbon parameters of oil from the West slope[a)]

Well	Main peak carbon	OEP	Pr/Ph	Pr/nC_{17}	Ph/nC_{18}	ΣnC_{21}-/ΣnC_{22}+	nC_{21+22}/nC_{28+29}	Ts/(Ts+Tm)
Du20	nC_{23}	1.13	1.17	0.20	0.16	1.08	1.82	0.71
Du34	nC_{23}	1.12	1.16	0.21	0.19	0.74	1.76	0.73
Du1-3	nC_{12}	1.23	1.14	0.19	0.18	1.76	0.49	0.56
Du22	nC_{26}	0.80	0.89	0.21	0.25	0.80	0.67	0.68
Du23	nC_{33}	1.49	0.53	0.34	0.45	0.68	1.04	0.72
Du43	nC_{33}	1.46	1.08	0.32	0.40	0.45	0.68	0.58
Du52	nC_{25}	1.10	0.92	0.17	0.19	0.81	1.00	0.72
Du60	nC_{12}	1.23	0.65	0.18	0.27	1.01	0.98	0.66
Du616	–	–	–	–	–	–	–	0.60
Du620	nC_{13}	0.99	1.40	0.24	0.22	4.54	2.72	0.67
Du75	nC_{18}	0.83	0.95	0.23	0.22	3.52	2.47	0.69
Du85	nC_{25}	1.08	1.06	3.12	2.57	0.18	0.60	0.79
DuV-3	nC_{13}	1.19	1.07	0.15	0.23	7.66	3.00	0.55
DuV-4	nC_{29}	1.42	0.86	0.26	0.30	0.23	0.54	0.63
Fu701	nC_{18}	0.93	0.58	0.16	0.29	1.11	1.04	0.72
Fu718	nC_{16}	0.83	0.57	0.18	0.19	1.25	1.91	0.65
Jiang21	nC_{19}	1.01	0.74	0.22	0.25	1.12	1.72	0.63
Jiang37	nC_{23}	1.18	1.09	0.30	0.27	0.85	1.61	0.75
Jiang372	nC_{23}	1.09	1.11	0.25	0.23	1.01	1.57	0.75
Jiang45	nC_{22}	0.95	0.82	0.16	0.19	0.69	1.37	0.75
Jiang55	nC_{30}	0.64	1.00	0.23	0.30	0.52	0.37	0.67
Jiang75	nC_{17}	1.02	1.19	0.48	0.46	0.83	1.81	0.75
Lai65	nC_{25}	1.59	0.90	1.41	1.39	0.28	0.85	0.74

a) Samples Du20 and Du34 are conventional oil whereas other samples are heavy oil.

Table 4 Aromatic hydrocarbon parameters of heavy oil and crude oil from the West slope[a)]

Well	MNR	ENR	MPR	MPI	DPR	DPI
Du20	1.28	2.01	1.05	0.55	1.98	4.24
Du34	1.32	2.23	1.12	0.57	2.11	4.56
Jiang372	1.03	2.45	0.77	0.49	1.77	5.11
Jiang37	0.95	3.84	0.76	0.61	2.05	3.95
DuV-3	1.91	3.16	2.11	0.89	9.74	2.83
Du85	1.31	1.76	0.83	0.57	1.91	5.22
Du1-3	1.96	3.22	1.10	0.72	–	–
Du620	1.73	3.04	1.35	0.67	1.19	4.51
Lai65	1.05	1.11	0.97	0.51	–	–
Jiang75	1.26	3.38	0.79	0.60	1.44	5.22
Jiang21	1.55	–	–	–	–	–
Fu718	1.53	2.52	0.22	0.18	1.21	6.47
Du22	1.25	–	0.75	0.47	0.79	7.20
Du60	1.32	1.66	1.09	0.63	1.89	5.39
Du52	1.37	2.95	1.13	0.74	0.90	10.99
Du616	1.05	2.40	0.89	0.58	–	–
Du23	1.31	2.45	0.78	0.61	2.26	5.18
DuV-4	1.31	–	–	–	–	–
Du43	–	–	0.90	0.61	1.32	4.11
Fu701	1.08	0.78	–	–	1.16	–
Jiang55	0.72	4.41	0.28	0.26	1.36	3.63
Jiang45	1.09	–	–	0.17	1.62	10.95
Du75	1.63	2.16	1.25	0.77	1.20	5.52

a) Samples Du20 and Du34 are conventional crude oil, whereas other samples are heavy oil; MNR=2-methylnaphthalene/1-methylnaphthalene, ENR=2-ethylnaphthalene/1-ethylnaphthalen, MPR=2-methylphenanthrene/1-methylphenanthrene, MPI=1.5*(2-methylphenanthrene + 3-methylphenanthrene)/(phenanthrene + 1-methylphenanthrene + 9-methylphenanthrene), DPR=(dimethylphenanthrene-3 + dimethylphenanthrene-4)/(dimethylphenanthrene-5 + dimethyl- phenanthrene-6), DPI=4*(dimethylphenanthrene-1 + dimethylphenanthrene-2 + dimethylphenanthrene-3 + dimethylphenanthrene-4)/(phenanthrene + dimethylphenanthrene-5 + dimethylphenanthrene-6 + dimethylphenanthrene-7).

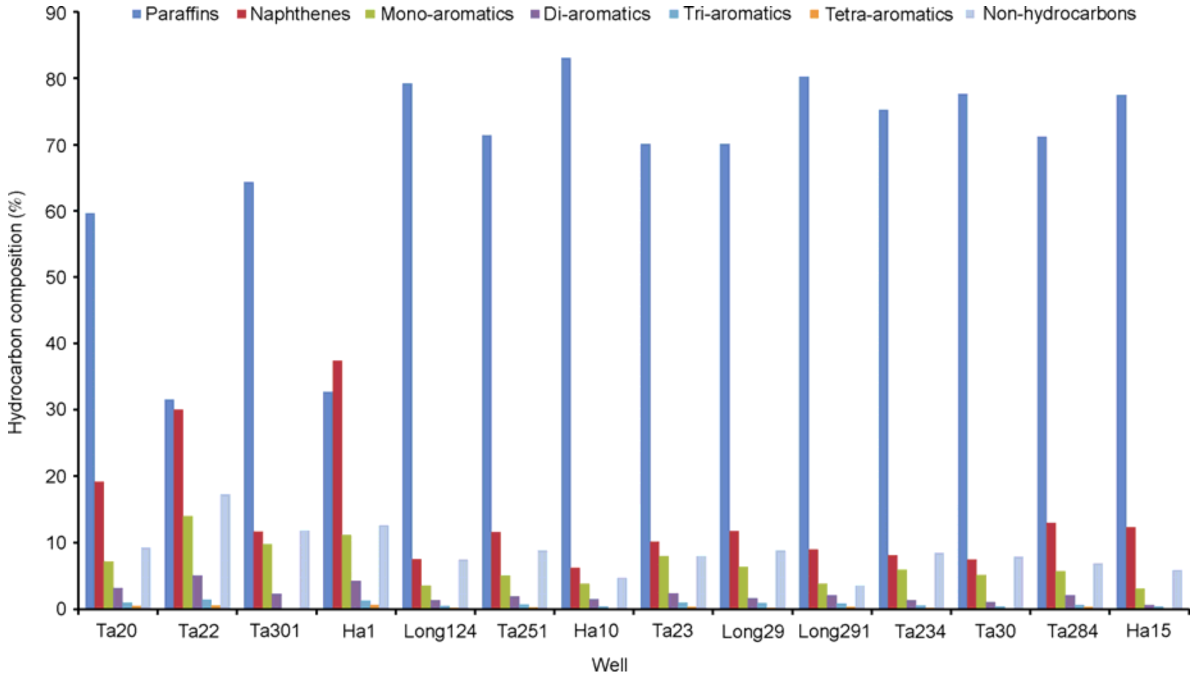

Figure 3 Hydrocarbon compositional distributions of oil from the Longhupao-Daan terrace.

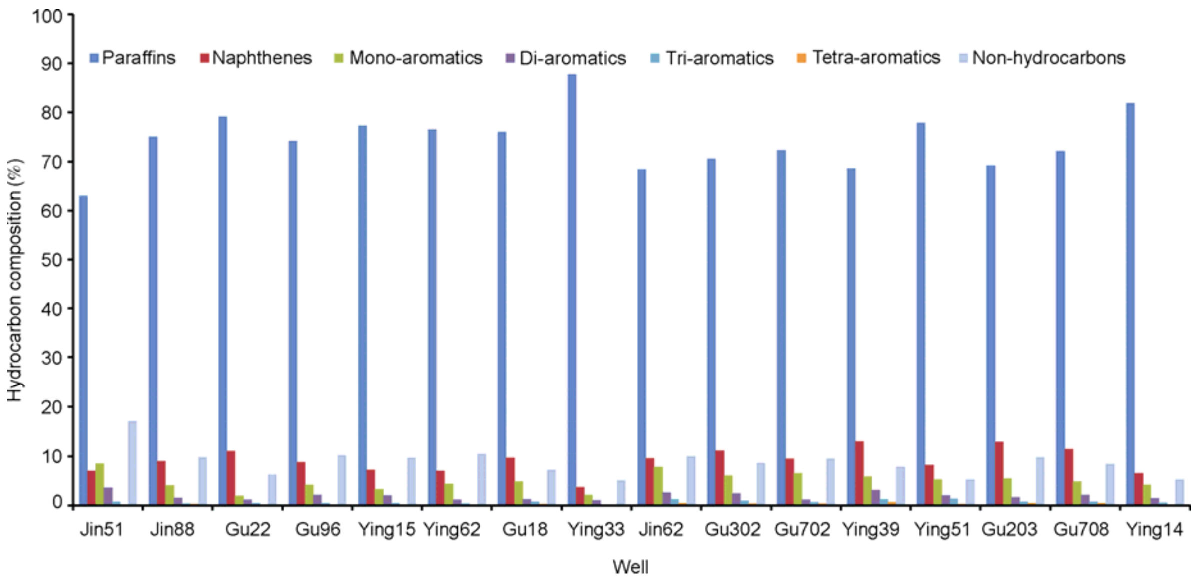

Figure 4 Hydrocarbon compositional distributions of crude oil from the Qijia-Gulong depression.

compositions of the Qijia-Gulong depression are characterized by paraffins > naphthenes > non-hydrocarbons > mono-aromatics > di-aromatics > tri-aromatics > tetra-aromatics with the highest content of paraffins and the lowest content of aromatics. Conventional crude oil is dominated by paraffin content.

3.3.2 *Saturates and aromatics*

Saturate hydrocarbon parameters of carbon number range, main peak carbon, OEP, Pr/Ph, Pr/nC_{17}, Ph/nC_{18}, ΣnC_{21}-/ΣnC_{22}+, nC_{21+22}/nC_{28+29} and Ts/(Ts+Tm) for conventional crude oil from the Qijia-Gulong depression are nC_9 to nC_{37}, nC_{13} to nC_{23}, 0.98–1.16, 0.78–1.49, 0.13–0.55, 0.12–0.60, 0.50–2.40, 0.74–2.08, 0.56–0.85, respectively. Saturate hydrocarbon parameters show that the oil is sapropelic mature oil.

Aromatic hydrocarbon parameters of MNR, ENR, MPR, MPI, DPR and DPI for conventional crude oil from Qijia-Gulong depression are 0.82–2.09, 0.99–5.89, 0.64–2.01, 0.45–0.98, 1.42–2.78, 3.35–5.36, respectively. Aromatic hydrocarbon parameters show that the oil is mature oil.

3.4 Hydrocarbon characteristic comparison of crude oil from the northern Songliao Basin and controlling factors

3.4.1 Hydrocarbon composition characteristic comparison of crude oil and controlling factors

Heavy oil from the West slope is different from heavy oil from the Longhupao depression in hydrocarbon composition. Heavy oil from the West slope is dominated by aromatic hydrocarbons and next by paraffins, whilst heavy oil from the Longhupao-Daan terrace is dominated by paraffins and next by naphthenes. The difference is caused by the biodegradation that will preferentially degrade normal alkanes and branched alkanes (Moldowan et al., 1979; Aeckersberg et al., 1991; Fritsche et al., 1992). At the severe biodegradation stage, naphthene biodegradation rate and extent are much higher than aromatics and non-hydrocarbons. The biodegradation extent of heavy oil from the West slope is much higher than that of crude oil from the Longhupao depression, resulting in heavy oil from the West slope dominated by aromatic content. Compared with conventional crude oil, heavy oil hydrocarbon composition is characterized by lower content of paraffins and higher content of naphthenes, aromatics and non-hydrocarbons. Heavy oil composition is controlled by both biodegradation extent and burial depth. Conventional crude oil from the northern Songliao Basin has similar hydrocarbon composition and it is dominated by paraffin content while concentration differences among naphthenes, aromatics and non-hydrocarbons are generally less than 5%. The crude oil is sourced mainly from the Qijia-Gulong depression in the central depression (Feng et al., 2003; Xiang et al., 2005a, 2005b, 2007; Zou et al., 2004; Zhang et al., 2005; Sun et al., 2006; Zhu et al., 2006; Zhou et al., 2006, 2008; Zhao et al., 2006; Fu et al., 2007). From the Qijia-Gulong depression to Longhupao-Daan terrace to West slope, there is a trend toward decreasing content of paraffins and increasing content of naphthenes, aromatics and non-hydrocarbon. Crude oil from the West slope occurs in shallower depth and it has migrated laterally upward for a long distance(Feng et al., 2003; Zou et al., 2004; Xiang et al., 2007), resulting in severe biodegradation. In contrast, crude oil from the Longhupao-Daan terrace has migrated laterally upward for a short distance and only rare oil is biodegraded, whereas crude oil from the Qijia-Gulong depression has not experienced any biodegradation. It is thus obvious that hydrocarbon composition of oil from the northern Songliao Basin has been affected by biodegradation, oxidation due to water-washing, burial depth, source rock and migration (Feng et al., 2003; Zou et al., 2004; Xiang et al., 2007).

3.4.2 Saturate and aromatic parameters comparison and controlling factors

Compared with conventional crude oil, saturate hydrocarbon parameters of heavy oil vary more widely. OEP value (0.80–1.59) and peak carbon number range (nC_{12}–nC_{33}) vary more widely because normal alkanes are selectively biodegraded by anaerobic/aerobic bacteria (Aeckersberg et al., 1991; Fritsche et al., 1992) or oil reservoirs have multiple oil charges. Due to preferential biodegradation of normal alkanes with low-molecular-weight, normal alkanes and branched alkanes (Moldowan et al., 1979), Pr/nC_{17} and Ph/nC_{18} ratios increase while Pr/Ph, $\sum C_{21}$-/$\sum C_{22}$+ (note that increasing ratios are caused by multiple oil charges) and C_{21+22}/C_{28+29} ratios decrease. Biodegradation has little impact on Ts and Tm, and during biodegradation Ts/(Ts+Tm) ratios remain nearly constant. Saturate hydrocarbon parameters of heavy oil show that it is sapropelic/humic type oil, immature-low mature oil or mature oil, whereas saturate hydrocarbon parameters of conventional crude oil show that it is sapropelic type mature oil. Such different interpretations are due to different biodegradation degrees of crude oil, implying that it should be careful when using saturate hydrocarbon parameters derived from GC×GC to determine source organic type and maturity of crude oil, especially those severely biodegraded. It seems that Ts/(Ts+Tm) ratio can be well used in determining maturity of both heavy oil and crude oil according to our results.

Compared with conventional crude oil, aromatic parameters of heavy oil vary more widely. Aromatic parameters of MNR, ENR, MPR, MPI, DPR and DPI show different increases or decreases and they are controlled by different biodegradation degrees of heavy oil from the West slope and by different biodegradation resistances of aromatic hydrocarbons. It thus should be careful when using aromatic parameters to determine oil maturity of biodegraded oil, especially those severe biodegraded.

Conventional crude oil from the northern Songliao Basin has similar saturate and aromatic composition. It is because the oil has not been biodegraded and it has sourced from the same source rocks.

4 Discussion

4.1 Hydrocarbon characteristics and composition distribution of heavy oil from the West slope with different geneses

Heavy oil in the West slope has two geneses (Feng et al., 2003). The first type is termed secondary type heavy oil and this type of heavy oil is formed by biodegradation, including oxidation due to water-washing. The second type is termed mixed type heavy oil and this type of heavy oil is formed by mixing of early-stage biodegraded oil and later-charged fresh oil.

4.1.1 Hydrocarbon characteristics and composition distribution of heavy oil from the West slope with different biodegradation degrees

GC×GC and GC×GC/TOFMS analysis shows that hopane has been affected either little or not at all by biodegradation and there are no 25-norhopanes present, indicating that the biodegradation level of crude oil from the West slope is below PM6 (Peter et al., 1993). Heavy oil biodegradation extent (e.g., light biodegradation, moderate biodegradation, and severe biodegradation) can be determined using normal alkanes/hopanes ratio, hydrocarbon compositions, spectrogram and etc.

As shown in Figure 5, in the 2D chromatogram of GC×GC for lightly biodegraded oil, signals for normal alkanes and branched alkanes such as pristane and phytane are complete and clear, whilst signals for naphthenes, aromatics and non-hydrocarbons are obscure. In the 3D chromatogram of GC×GC, signals for normal alkanes are strongest while signals for other compounds are weak. In the 1D chromatogram, signals for normal alkanes are strongest and complete with baseline nearly straight (Unresolved complex mixture, UCM content is very low). Generally, paraffin content is greater than 50%, naphthene content is less than 16%, mono-aromatic content is less than 13%, and non-hydrocarbon content is less than 11%. Steranes and hopanes have not been affected by biodegradation and normal alkanes/hopanes ratio is generally greater than 50. For lightly biodegraded oil, saturate hydrocarbon parameters of main peak carbon, OEP, Pr/Ph, Pr/nC_{17}, Ph/nC_{18}, ΣC_{21}-/ΣC_{22}+, C_{21+22}/C_{28+29} and aromatics have been little affected. Lightly biodegraded oil occurs mainly in the Gaotaizi and Saertu oil reservoirs of Taikang zone and the Jurassic reservoirs of Jiangqiao zone (e.g., heavy oil from well Jiang37 at depth of 820.0–851.5 m).

As shown in Figure 6, in the 2D chromatogram of GC×GC for moderately biodegraded oil, signals for normal alkanes with molecular-weight less than nC_{15} are obscure while signals for normal alkanes are slightly clear. Signals for branched alkanes such as pristane and phytane are complete but clear while signals for naphthenes, aromatics and non-hydrocarbons are slightly clear. In contrast, in the 3D chromatogram of GC×GC, signals for normal alkanes with molecular-weight greater than nC_{15} are strongest while signals for other compounds are weak. In the 1D chromatogram, signals for normal alkanes are strongest and indicate obvious biodegradation. Normal alkanes are relatively complete but with moderate baseline drift caused by higher content of UCM. Concentrations of paraffins, naphthenes, mono-aromatics and non-hydrocarbons are 50%–30%, 13%–31%, 12%–20% and 10%–28%, respectively. Steranes and hopanes have not been affected by biodegradation and normal alkanes/hopanes ratio ranges from 50 to 10. Saturate hydrocarbon parameters of main peak carbon, OEP, Pr/Ph, Pr/nC_{17}, Ph/nC_{18}, ΣC_{21}-/ΣC_{22}+ and C_{21+22}/C_{28+29} for moderately biodegraded oil have been affected much by biodegradation. The results show that main peak carbon number will increase, OEP value will increase or decrease, Pr/nC_{17} ratio will increase, Ph/nC_{18} ratio will increase, and ΣC_{21}-/ΣC_{22}+ ratio will decrease. Biodegradation has little impact on aromatic parameters for moderately biodegraded oil. It is

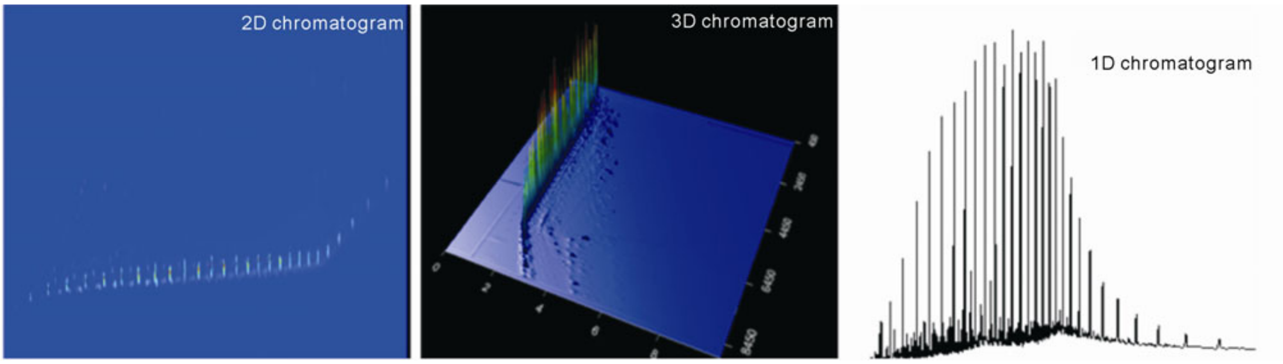

Figure 5 Chromatograms of lightly biodegraded oils.

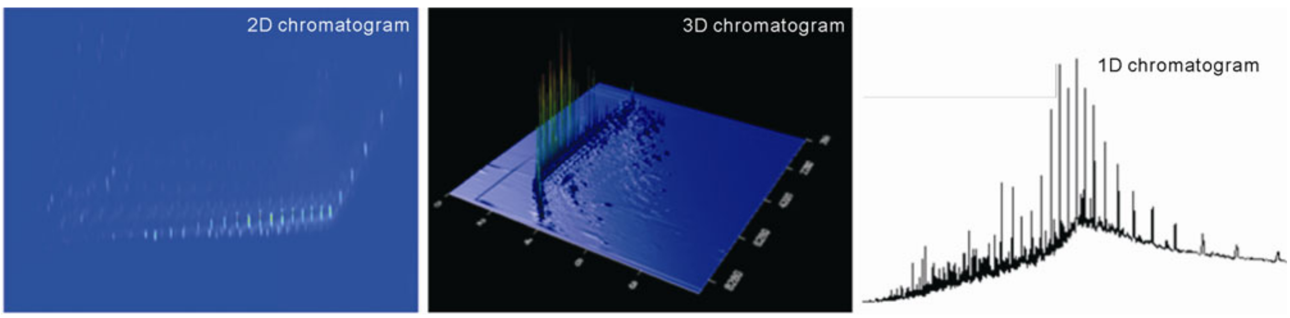

Figure 6 Chromatograms of moderately biodegraded oil.

thus not supposed to use saturate hydrocarbon and aromatic parameters to study maturity, source organic type and oil-source of moderately biodegraded oil. Moderately biodegraded oil occurs mainly in the Gaotaizi and Saertu oil reservoirs of Jiangqiao and Taikang zones (e.g., heavy oil in the well Du85 at depth between 1451.0–1452.0 m, Gaotaizi oil reservoir).

As shown in Figure 7, in the 2D chromatogram of GC×GC for severely biodegraded oil, signals are obscure for normal alkanes, slightly clear for branched alkanes such as pristane and phytane, and clearer for naphthenes, aromatics and non-hydrocarbons. In contrast, in the 3D chromatogram of GC×GC, signals for normal alkanes, naphthenes, aromatics and non-hydrocarbons are different. In the 1D chromatogram, many normal alkanes are lost with severe baseline drift due to high content of UCM. Paraffin content is generally less than 30%, whereas contents of naphthenes, mono-aromatics and non-hydrocarbons are 18%–31%, 16%–33%, and 13%–35%, respectively. Steranes and hopanes have been affected little by biodegradation and normal alkanes/hopanes ratio is less than 10. Saturate hydrocarbon parameters of main peak carbon, OEP, Pr/Ph, Pr/nC_{17}, Ph/nC_{18}, ΣC_{21}-/ΣC_{22}+ and C_{21+22}/C_{28+29} have been greatly affected by biodegradation. The results show that main peak carbon number will increase, OEP value will increase or decrease, Pr/nC_{17} ratio will increase, Ph/nC_{18} ratio will increase, and ΣC_{21}-/ΣC_{22}+ ratio will decrease. Biodegradation has little impact on aromatic parameters for severely biodegraded oil. It is thus not supposed to use saturate hydrocarbon and aromatic parameters to study maturity, source organic type and oil-source of severely biodegraded oil. Severely biodegraded oil occurs mainly in the Saertu and Gaotaizi oil reservoirs of Jiangqiao and Fulaerji zones (e.g., heavy oil in the well Fu701 at depth of 471.2–481.4 m, Saertu oil reservoir; heavy oil in the well Jiang45 at depth of 443.6–446.8m, Saertu oil reservoir; heavy oil in the well Du23 at depth of 1178.0–1182.4 m, Gaotaizi oil reservoir).

Biodegradation-genetic heavy oil is the result of selective biodegradation of normal alkanes, branched alkanes and etc., leading to greater oil density and viscosity. As biodegradation extent increases, paraffin content decreases while aromatics and non-hydrocarbon contents tend to increase. As to naphthene, its content tends to increase first and then decrease and the turnover occurs when contents of paraffins, aromatics, naphthenes and non-hydrocarbons are about 30%, 26%, 24%, 20%, respectively. It is obvious that during oil biodegradation, different groups of hydrocarbons have different biodegradation resistances. The severe biodegradation stage is started when paraffin content is less than 30%. The biodegradation rate of naphthenes is significantly higher than that of both aromatics and non-hydrocarbons, and relative content of naphthenes tends to decrease while aromatics and non-hydrocarbon contents tend to increase. Biodegradation is a common geological process in the West slope and is the main cause of heavy oil.

4.1.2 Hydrocarbon characteristics and composition distribution of mixing-genetic heavy oil from the West slope

Based on GC×GC, mass spectrometry, chromatograms, viscosity, resin content, asphaltene content and flash point in combination with other researches (Dallam, 2001; Feng et al., 2003), mixing-genetic heavy oil is a mixture of biodegraded oil and light hydrocarbons from oil evaporative fractionation or a mixture of biodegraded oil and non-biodegraded oil.

As shown in Figure 8, in the 2D chromatogram of GC×GC for heavy oil, which is a mixture of biodegraded oil and light hydrocarbons from evaporative fractionation, signals are clear for normal alkanes with molecular-weight less than nC_{15} and are obscure for normal alkanes with molecular-weight greater than nC_{15}, branched alkanes such as pristane and phytane, naphthenes, aromatics and non-hydrocarbons. Signals for normal alkanes with molecular-weight less than nC_{15} are strongest whereas signals for other compounds are slightly weaker, indicating that the heavy oil is a mixture of moderately biodegraded oil and light hydrocarbons. In the 1D chromatogram, the heavy oil is dominated by normal alkanes with molecular-weight less than nC_{20} and with baseline drifted, indicating that the heavy oil is dominated by light hydrocarbons with higher content of UCM. Generally, concentrations of paraffins, naphthenes,

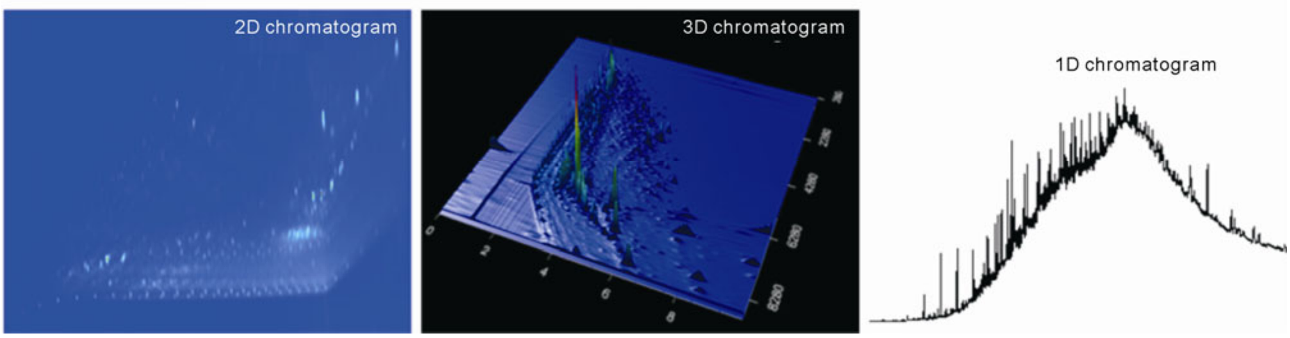

Figure 7 Chromatograms of severely biodegraded oil.

mono-aromatics and non-hydrocarbons are 50%–30%, 20%–30%, 12%–15% and 10%–20%, respectively. Saturate hydrocarbon parameters mainly reflect characteristics of subsequently charged light hydrocarbons from evaporative fractionation, whilst aromatic parameters show characteristics of heavy oil. Dallam suggested that oil with anomalously higher content of gasoline-range compounds from the West Sak oilfield of Alaska is due to filling of gasoline-range fraction to biodegraded oil reservoirs (Dallam, 2001). High oil viscosity, resin content, asphaltene content, and flash point show that the oil has been biodegraded. Such mixing-genetic heavy oil occurs mainly in the Saertu reservoirs of Jiangqiao zone (e.g., Saertu oil reservoir in the well Du1-3 at depth between 784.8–789.8 m; Saertu oil reservoir in the well DuV-3 at depth of 770.6–789.8 m).

As shown in Figure 9, in the 2D chromatogram of GC×GC for heavy oil that is a mixture of biodegraded oil and non-biodegraded oil, signals are clear for normal alkanes and are slightly obscure for branched alkanes such as pristane and phytane, naphthenes, aromatics and non-hydrocarbons. In the 3D chromatogram of GC×GC, signals for normal alkanes are strongest while signals for other compounds are slightly weaker, indicating that the oil is a mixture of biodegraded oil and non-biodegraded oil. In the 1D chromatogram, signals for normal alkanes are strongest and complete but with baseline drifted, indicating that the heavy oil is composed of conventional oil and UCM. Generally, paraffin content is greater than 60% while contents of naphthenes, mono-aromatic and non-hydrocarbon are less than 15%, 10% and 11%, respectively. Saturate hydrocarbon parameters display characteristics of subsequently charged non-biodegraded oil. In contrast, high viscosity, high resin content, high asphaltene content, and high flash point are characteristics of biodegraded oil. Such mixing-genetic heavy oil occurs mainly in the Gaotaizi oil reservoirs of Jiangqiao zone (e.g., heavy oil in the well Jiang372 at the depth of 593.0−602.0 m, Gaotaizi oil reservoir).

4.2 Hydrocarbon characteristics and distribution of oil from different oil reservoirs of the Longhupao-Daan terrace

Based on hydrocarbon compositional characteristics, there are three types of oil in the Longhupao-Daan terrace. The first type is termed moderately biodegraded oil, which contains low content of paraffins (<50%), high content of naphthenes (>30%), high content of aromatics (>15%) and high content of non-hydrocarbons (>12%), mainly occurring in Saertu oil reservoir (e.g., heavy oil in the Saertu oil reservoir of well Ta22). The second type is termed lightly biodegraded oil, which contains high content of paraffins (>50%), slightly high content of naphthenes (11%–20%), slightly high content of aromatics (8%–13%), and slightly high content of non-hydrocarbons (8%–11%) , mainly occurring in the Saertu oil reservoir or Putaohua oil reservoir (e.g., crude oil in the Saertu oil reservoir of well Ta20 and crude oil in the Putaohua oil reservoir of well Ta251). The third type is termed non-biodegraded oil, which contains high content of paraffins (>70%), low content of naphthenes (<%12), low content of aromatics (11%), and slightly high content of non-hydrocarbons (<9%), mainly occurring in the

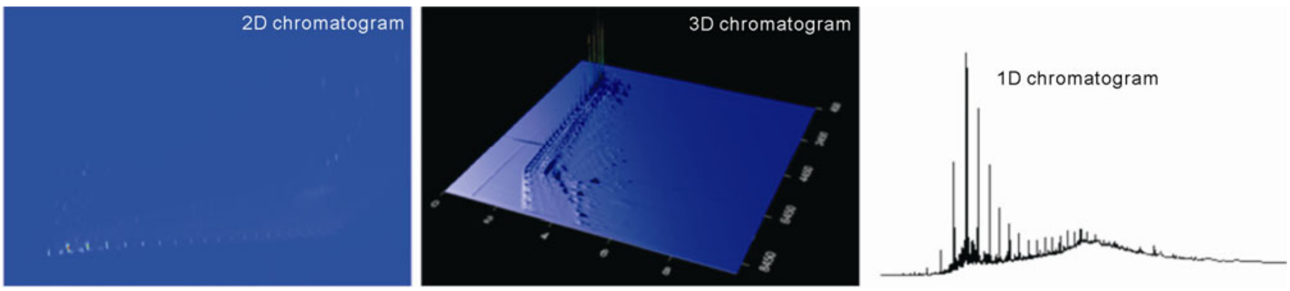

Figure 8 Chromatograms of a mixing-type heavy oil of biodegraded oils and evaporative fraction.

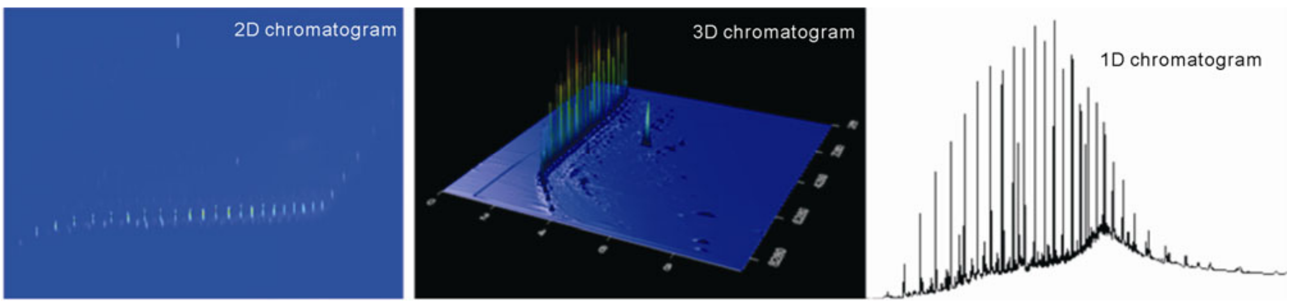

Figure 9 Chromatograms of a mixing-type heavy oil of biodegraded oil and non-biodegraded oil.

Gaotaizi oil reservoir or Fuyang oil reservoir (e.g., wells Ta23, T284, Long29, Long23). Note that crude oil in the Saertu oil reservoir and Putaohua oil reservoir has been biodegraded more or less and biodegradation is closely related to heavy oil and secondary microbial methane. Thus, natural gas from oil biodegradation and heavy oil are important resources in the Longhupao-Daan terrace in future exploration.

As shown in Figure 10, oil from different oil reservoirs in the Longhupao-Daan terrace has different characteristics of chromatogram. Both 2D chromatogram of GC×GC and 1D chromatogram show that heavy oil in the Saertu oil reservoir of well Ta20 has high content of paraffins, slightly high contents of naphthenes and aromatics, and low content of non-hydrocarbons, and they have been lightly biodegraded. Heavy oil in the well Ta22 has slightly high content of paraffins, naphthenes, aromatics, non-hydrocarbons and UCM, and they have been moderately biodegraded. Crude oil in the Putaohua oil reservoir of well Ta 251 has lost all normal alkanes with molecular-weight less than nC_{15} due to biodegradation and it has been lightly biodegraded. Crude oil in the Gaotaizi oil reservoir of well Ta23 and Fuyang oil reservoir of well Ta284 is dominated by paraffins and has not been biodegraded. Compared with 1D chromatogram, 2D chromatogram of GC×GC has an advantage in studying oil biodegradation and hydrocarbon composition. For example, crude oil in the well Ta22 shows obscure characteristics of biodegradation in the 1D chromatogram while it shows obvious biodegradation characteristics in the 2D chromatogram of GC×GC.

4.3 Oil viscosity prediction and distribution in the northern Songliao Basin

4.3.1 Oil viscosity prediction and characteristics in the northern Songliao Basin

Oil viscosity prediction for oil sands is important for petroleum exploration, heavy oil test and development programme. Multiple correlation analysis using hydrocarbon

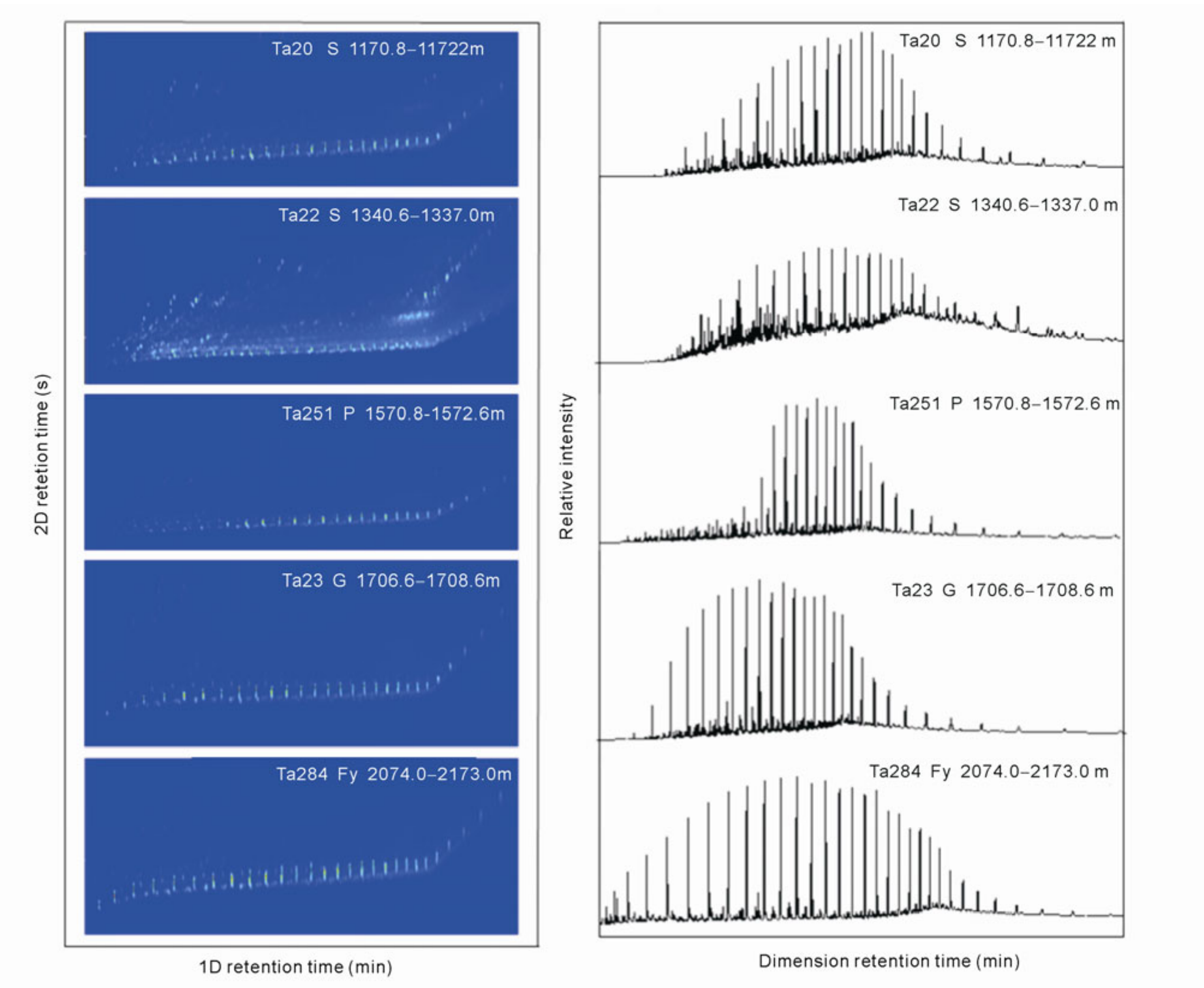

Figure 10 Chromatograms of crude oil from the Longhupao-Daan terrace.

composition derived from GC×GC was used to get weighted coefficients for each group of compounds. An oil viscosity index (Iv) was introduced and it was formulated as Iv=8.7855×non-hydroarbons + 1.9715×aromatics + 1.2422× naphthenes–0.8293×paraffins. As shown in Figure 11, a relationship between oil viscosity and oil viscosity has been established. The relationship can be used to predict oil viscosity of oil sands.

Well Jiang77 and well Jiang84 are in the Taikang uplift zone of West slope and they are 1.0 km apart. Crude oil from oil sands was sampled using conventional physical method. Hydrocarbon compositions have been derived from GC×GC analysis. As shown in Table 5, contents of paraffins, naphthenes, aromatics and non-hydrocarbons of oil from oil sands of well Jiang77 are 14.73%–22.72%, 15.52%–31.17%, 24.57%–33.73%, 19.84%–37.21%, respectively. Contents of paraffins, naphthenes, aromatics and non-hydrocarbons of oil from oil sands of well Jiang 84 range from 2.20%–17.31%, 10.30%–30.95%, 29.43%–46.25%, 22.06%–50.71%, respectively. It seems that the crude oil is characterized by high content of aromatics or non-hydrocarbons and low content of paraffins. Hydrocarbon composition of oil from oil sands is vertically heterogeneous. The Saertu oil-bearing interval at 573.31−579.37m of well Jiang77 was interpreted as a productive oil layer. By steam soaking technique, the interval produced no water and its daily heavy oil production was 51.84 t. The produced heavy oil has not been oxidized by water-washing and its hydrocarbon composition is controlled mainly by biodegradation. The Saertu oil-bearing interval at 578.29–581.09 m of well Jiang84 was interpreted as an oil layer and its daily heavy oil production was 0.56t without producing any water applying steam soaking technique. The hydrocarbon composition of produced oil is controlled mainly by biodegradation. In contrast, the Gaotaizi oil-bearing interval at 594.61–598.01 m was interpreted as oil-water layer according to both geological logging and wireline logging. The produced heavy oil has been oxidized by water-washing. Under aerobic and eutrophic conditions, oil biodegradation rate is faster (Jobson et al., 1972). For the heavy oil, contents of paraffins and naphthenes are less than 4.33% and 14.51%, respectively, while contents of aromatics and non-hydrocarbons are greater than 82.23%. Thus, both biodegradation degree and secondary alteration extent for Gaotaizi oil reservoir are much higher than those for Saertu oil reservoir, corroborating that at the severe biodegradation stage, naphthene biodegradation rate and extent are much higher than aromatics and non-hydrocarbons.

As shown in Table 5, the predicted oil viscosity for the Saertu oil reservoir (573.31–579.37 m) of well Jiang77 is 280.62 mPa·s in average, which is close to 290.16 mPa·s for crude oil from oil production test with the relative deviation of 3.34%. The predicted oil viscosity for the Saertu oil reservoir (578.29–581.09 m) of well Jiang84 is 319.38 mPa.s in average, which is close to 303.82 mPa·s for crude oil from oil production test with the relative deviation of

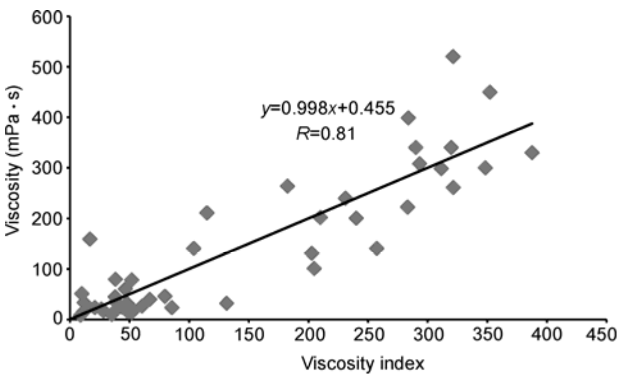

Figure 11 Cross plot of oil viscosity index (Iv) versus oil viscosity.

Table 5 Hydrocarbon composition and oil viscosity of crude oil from oil sands

Well	Depth (m)	Reservoir	Paraffin (%)	Naphthene (%)	Aromatics (%)	Non-hydrocarbon (%)	Iv	Predicted viscosity (mPa·s)	Averaged viscosity (mPa·s)	Oil viscosity of testing oils (mPa·s)
Jiang77	537.31	S	22.05	15.52	25.22	37.21	377.62	377.32	358.69	untest
	537.61		17.63	24.17	27.36	30.84	340.29	340.06		
	573.31	S	15.40	31.17	30.23	23.20	289.37	289.25	280.62	290.16
	574.91		22.72	25.42	32.02	19.84	250.17	250.12		
	577.87		14.73	27.14	33.20	24.93	305.98	305.82		
	579.37		18.65	22.69	36.79	21.87	277.39	277.29		
	585.48	S	21.91	24.42	24.57	29.09	316.21	316.00	307.15	untest
	593.28		15.71	26.41	33.73	24.15	298.45	298.30		
Jiang84	578.29	S	13.82	27.74	29.72	28.72	333.91	333.70	319.38	303.82
	579.59		13.38	26.09	29.43	31.10	352.56	352.31		
	580.49		14.58	28.10	30.97	26.35	315.37	315.19		
	581.09		17.31	30.95	29.68	22.06	276.41	276.32		
	594.61	G	3.12	11.60	34.57	50.71	525.49	524.89	476.76	untest
	595.41		2.35	14.50	40.34	42.81	471.70	471.21		
	596.41		4.32	13.44	41.66	40.58	451.76	451.31		
	597.41		2.65	11.92	42.61	42.82	472.81	472.32		
	598.01		2.20	10.30	46.25	41.25	464.55	464.08		

4.99%. The viscosity of crude oil from Saertu oil formation (537.31–593.28 m) of well Jiang77 ranges from 250.12 to 377.32 mPa·s with an average of 306.77 mPa.s. The viscosity of crude oil from Saertu oil formation (578.29–581.09 m) of well Jiang84 ranges from 276.32 to 352.31 mPa·s with an average of 319.38 mPa·s. The viscosity of crude oil from the Gaotaizi oil reservoir (594.61–598.01 m) of well Jiang84 ranges from 451.31 to 524.89 mPa·s with an average of 476.76 mPa·s. It is evident that oil viscosity for the Gaotaizi oil reservoir is significantly higher than that for the Saertu oil reservoir. In the two wells, oil viscosity is vertically heterogeneous while it is more or less horizontally homogenous (315.49 and 319.38 mPa·s in average, respectively).

4.3.2 Oil viscosity distribution in the northern Songliao Basin

As shown in Tables 1 and 5, oil viscosity in the northern Songliao Basin ranges from 5.06 to 520.40 mPa·s, covering conventional crude oil and heavy oil. Crude oil discovered in Qijia-Gulong depression occurs in Saertu, Putaohua, Gaotaizi and Fuyu oil reservoirs and it is conventional crude oil. Crude oil discovered in the Longhupao-Daan terrace occurs in Saertu, Gaotaizi, Fuyu and Yangdachengzi oil reservoirs and most is conventional crude oil with heavy oil only in the Saertu oil reservoir of well Ta22. Crude oil discovered in the West slope occurs in Saertu and Gaotaizi oil reservoirs and most oil found in Saertu oil reservoir is heavy oil, whilst only crude oil from the Gaotaizi oil reservoir of well Du34 and Du20 is conventional crude oil. From Qijia-Gulong to Longhupao to West slope, oil viscosity tends to increase. Vertically, from shallower to deeper, oil viscosity overall tends to decrease. Generally, oil viscosity is highest in Saertu oil reservoir while lowest in Putaohua oil reservoir. Oil viscosity's spatial distribution is controlled by biodegradation, oxidation due to water-washing, source rock.

5 Conclusions

(1) From the Qijia-Gulong depression to Longhupao-Daan terrace to West slope in the northern Songliao Basin, paraffin content in crude oil decreases while contents of naphthenes, aromatics and non-hydrocarbons increase. Oil viscosity increases overall westward. There is no heavy oil discovered in the Qijia-Gulong depression. Only rare wells contain heavy oil in the Longhupao-Daan terrace, whereas crude oil in the West slope is mainly heavy oil. From shallower to deeper, oil viscosity decreases overall with the highest oil viscosity in Saertu oil reservoir and the lowest in Putaohua oil reservoir.

(2) Oil biodegradation extent can be effectively determined by geochemical parameters of paraffins, naphthenes, aromatics, non-hydrocarbons, normal alkanes/hopanes and etc. no biodegraded oil has been found in the Qijia-Gulong depression whereas in the Longhupao-Daan terrace, some crude oil from Saertu oil reservoir is moderately biodegraded and some crude oil from Putaohua oil reservoir is lightly biodegraded. In the West slope, there is mainly heavy oil due to biodegradation and water-washing. There are two types of heavy oil, including secondary type and mixing type. The secondary type of heavy oil is formed from oil biodegradation and oxidation due to water-washing and the mixing type of heavy oil is formed from mixing of early biodegraded oil and evaporative fractions or non-biodegraded oil. Biodegradation is the main cause of heavy oil. Lightly biodegraded oil contains 60%–50% paraffins, whilst contents of naphthene, mono-aromatics and non-hydrocarbons are less than 16%, 13% and 11%, respectively. Moderately biodegraded oil contains 50%–30% paraffins, whilst contents of naphthenes, mono-aromatics and non-hydrocarbons are 13%–31%, 12%–20%, and 10%–28%, respectively. Severely biodegraded oil contains less than 30% paraffins, whilst contents of naphthenes, mono-aromatics and non-hydrocarbons are 18%–31%, 16%–33% and 13%–35%, respectively.

Crude oil in the Saertu oil reservoir of well Jiang77 and Jiang84 in the West slope is severely biodegraded oil. Hydrocarbon composition and oil viscosity are similar for heavy oil and they are vertically heterogeneous and slightly homogeneous horizontally. Crude oil from Gaotaizi oil reservoir is heavy oil that has been severely biodegraded and oxidized by water-washing. The heavy oil contains less than 4.5% paraffins, less than 14.5% naphthenes, greater than 35% aromatics and greater than 41% non-hydrocarbons. The oil viscosity of the heavy oil is higher than that of crude oil from Saertu reservoir. Compared with oil from Saertu oil reservoir, oil from Gaotaizi oil reservoir has experienced more severe biodegradation and post-alteration.

(3) As biodegradation degree increases, paraffin content of crude oil and heavy oil in the northern Songliao Basin decreases while contents of aromatics and non-hydrocarbon increase. In contrast, naphthene content tends to increase first and then decrease as biodegradation increases. At the severe biodegradation stage when contents of paraffins, naphthenes, aromatics and non-hydrocarbons are 30%, 24%, 26% and 20%, respectively, naphthene biodegradation rate and extent are significantly greater than aromatics and non-hydrocarbons. Biodegradation has a great impact on saturate hydrocarbon parameters of oil and has impact on aromatic parameters. Thus, parameters of saturate hydrocarbon and aromatics cannot really reflect source organic type and maturity of heavy oil, especially those moderately or severely biodegraded. Ts/(Ts+Tm) ratio can effectively indicate thermal maturity of heavy oil and crude oil.

(4) Hydrocarbon composition and oil viscosity of oil from the northern Songliao Basin are controlled by biodegradation, oxidation due to water-washing, burial depth, source rock and etc. Saertu and Gaotaizi reservoirs are the main heavy oil exploration targets in the West slope while

Gaotaizi reservoir is one of conventional crude oil exploration targets. Natural gas from oil biodegradation is an important resource in the West slope and exploration of associated gas reservoirs is an important field for shallow-depth exploration. The Qijia-Gulong depression and Longhupao-Daan terrace are focused on for conventional crude oil exploration. Exploration of heavy oil and natural gas from oil biodegradation in the Longhupao-Daan terrace is an important field in the future.

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