Journal of Petroleum Geology, Vol. 45(2), April 2022, pp 1 - 16

PROOF 2, 14.2.22

COMPOSITION OF LIGHT HYDROCARBONS IN JURASSIC TIGHT OILS IN THE CENTRAL SICHUAN BASIN, CHINA: ORIGIN AND SOURCE ROCK CORRELATION

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Crude oil reserves in tight Middle and Lower Jurassic reservoirs are of increasing exploration interest in the central Sichuan Basin, SW China. However, the origin of these "tight oils" is poorly understood. In this study, sixteen samples of light (C_4-C_{13}) oils/condensates from tight Middle and Lower Jurassic reservoir rocks were analysed using gas chromatography (GC) and isotope ratio mass spectrometry to investigate the oils' origin and to classify them into genetic families. The tight oils can be divided into two families. Family I oils occur in the Gongshanmiao oilfield where reservoir units comprise the Da'anzhai Member of the Lower Jurassic Ziliujing Formation, the Lower Jurassic Lianggaoshan Formation, and the First Member of the Middle Jurassic Shaximiao Formation. Family I oils are characterized by relatively low values of the methylcyclohexane (MCH) and cyclohexane (CH) indexes, low values of Mango's parameter K_2 for light hydrocarbon composition, and relatively negative $\delta^{13}C$ values ranging from -30.8‰ to -28.9‰. Family I oils are inferred to be self-sourced by lacustrine shales in the Da'anzhai Member and the Lianggaoshan Formation in the study area, both of which are rich in sapropelic organic matter. These source rocks also charged reservoirs in the First Member of Shaximiao Formation. By contrast, the newly discovered Family II oils, which occur at the Jinhua oilfield and the as-yet undeveloped Qiulin and Bajiaochang structures, are reservoired in the Second Member of Shaximiao Formation. Family II oils have higher values of the MCH index, CH index and Mango's K_2 parameter, and $\delta^{13}C$ values varying from -27.5‰ to -25.4‰. These oils have similar light hydrocarbon compositions and $\delta^{13}C$

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Key words: tight oil, oil family classification, light hydrocarbons, Shaximiao Formation, Central Sichuan Basin, Jurassic, source rocks, stable carbon isotope ratios, hierarchical cluster analysis.

values to oils derived from source rocks in the Upper Triassic Xujiahe Formation which contain dominantly humic organic matter. Family II oils are therefore inferred to be derived from the coaly mudstones in the Xujiahe Formation.

The different compositions of the tight oils in the First and Second Members of Shaximiao Formation appear to be controlled by the distribution and thickness of source rocks in the study area. Thus, the Gongshanmiao oilfield where Family I oils occur in the First Member is close to the depocentre of source rocks in the Da'anzhai Member and Lianggaoshan Formation. These source rocks are inferred to have charged the First Member reservoirs which may also be present in nearby oil- and gas-bearing structures such as Nanchong and Yingshan. By contrast, Family II oils occur in tight reservoirs in the Second Member in areas with thick successions of Upper Triassic Xujiahe Formation mudstone source rocks, such as the Jinhua oilfield. In areas where both source rocks are present such as the Zhongtaishan and Lianchi oilfields, Shaximiao Formation reservoirs appear to contain both Family I and Family II oils.

INTRODUCTION

"Tight oil" refers to oil resources stored in reservoir rocks such as tight (low permeability) sandstones and carbonates in close proximity to, and/or within the same formation as, the related source rocks (e.g. Jia *et al.*, 2012; Wu *et al.*, 2019; Cao *et al.*, 2017). Tight oils occur widely in China and commercial-sized tight oil reservoirs have been found in the Sichuan, Ordos, Junggar, Bohai Bay and Songliao Basins (Sun *et al.*, 2019; Song *et al.*, 2021).

The Sichuan Basin is located in the southwest of China (Fig.1). Since 1958, five tight oil fields (Gongshanmiao, Guihua, Jinhua, Lianchi and Zhongtaishan) have been discovered here and cumulative production exceeds 5 million tonnes (Li *et al.,* 2017). Data from several thousand wells in these fields have demonstrated that most of the production comes from tight reservoir intervals in the Lower Jurassic Da'anzhai Member of the Ziliujing Formation (J_1dn), the overlying Lianggaoshan Formation (J_1l), and the Middle Jurassic First Member of the Shaximiao Formation (J_2s^1) (Fig. 2). Lower and Middle Jurassic reservoir rocks at fields in the centre of the Sichuan Basin consist of a range of shallow-water lacustrine and associated fluvial and deltaic deposits including bioclastic limestones and fine-grained sandstones and siltstones (Pang *et al.,* 2018; Wang *et al.,* 2021).

The tight oil in the Lower Jurassic Da'anzhai Member appears to be self-sourced and to have been generated by organic-rich lacustrine shale source rocks present within the member itself. The tight Lianggaoshan Formation reservoir is likewise self-sourced by similar OM-rich dark mudstones (Chen *et al.*, 2014; Chen *et al.*, 2015; Yang *et al.*, 2016). In addition, the shale source rocks in these two units have generated the light oils which are reservoired in the Middle Jurassic First Member of the Shaximiao Formation (Li *et al.*, 2017; Lu *et al.*, 2021). Recent exploration efforts in the Qiulin and Bajiaochang areas near to the Gongshanmiao and Jinhua oilfields in the centre of the Sichuan Basin have led to the discovery of tight oils in the overlying Second Member of this formation (J_2s^2) (Huang *et al.*, 2021), although the origin of this oil remains unclear.

Light hydrocarbons (C_4-C_{13}), accounting for about 30% of normal oils, are important fractions of light crudes and condensates where they may be present in proportions of up to 90% (Wang *et al.*, 2008). Biomarkers in light oils and condensates are in general difficult to analyse because they are present in extremely low concentrations (Zhang *et al.*, 2005). Geochemical parameters specific to light hydrocarbons have therefore been widely used in oil family classifications of light oils and condensates, and also in oil-source correlations and studies of secondary alteration (including evaporative fractionation and biodegradation) (e.g Thompson, 1988; Cañipa-Morales *et al.*, 2003; Yang *et al.*, 2016; Chang *et al.*, 2018).

In the present study, Jurassic tight oils in the Central Sichuan Basin were classified into families on the basis of their light hydrocarbon compositions and stable carbon isotope ratios. The origin of the oil in the Middle Jurassic Shaximiao Formation was also investigated by correlation studies involving oils from the Upper Triassic Xujiahe Formation and oils from the Lower Jurassic Da'anzhai Member and Lianggaoshan Formation.

Geologic setting

Commercial reserves of tight oil occur in five oilfields in the central Sichuan Basin: Gongshanmiao, Guihua, Jinhua, Lianchi and Zhongtaishan (Fig. 1). In addition, a number of other oil- and gas-bearing structures have been discovered nearby such as Qiulin, Bajiaochang, Nanchong, Yingshan, and Longgang, indicating the potential for the development of tight oil resources in this area.

The stratigraphic column in the Sichuan Basin is composed of a Precambrian to Middle Triassic marine succession overlain by an Upper Triassic to Cenozoic interval dominated by terrigenous siliciclastic deposits (Li *et al.*, 2013). Hydrocarbon source rocks occur in the Upper Triassic Xujiahe Formation which can be divided into six members, numbered 1 through 6 (Fig. 2). Members 1, 3 and 5 consist of source rock intervals composed of coals and organic-rich mudstones, while Members 2, 4 and 6 comprise low-permeability sandstone reservoir units (Li *et al.*, 2013). The Xujiahe

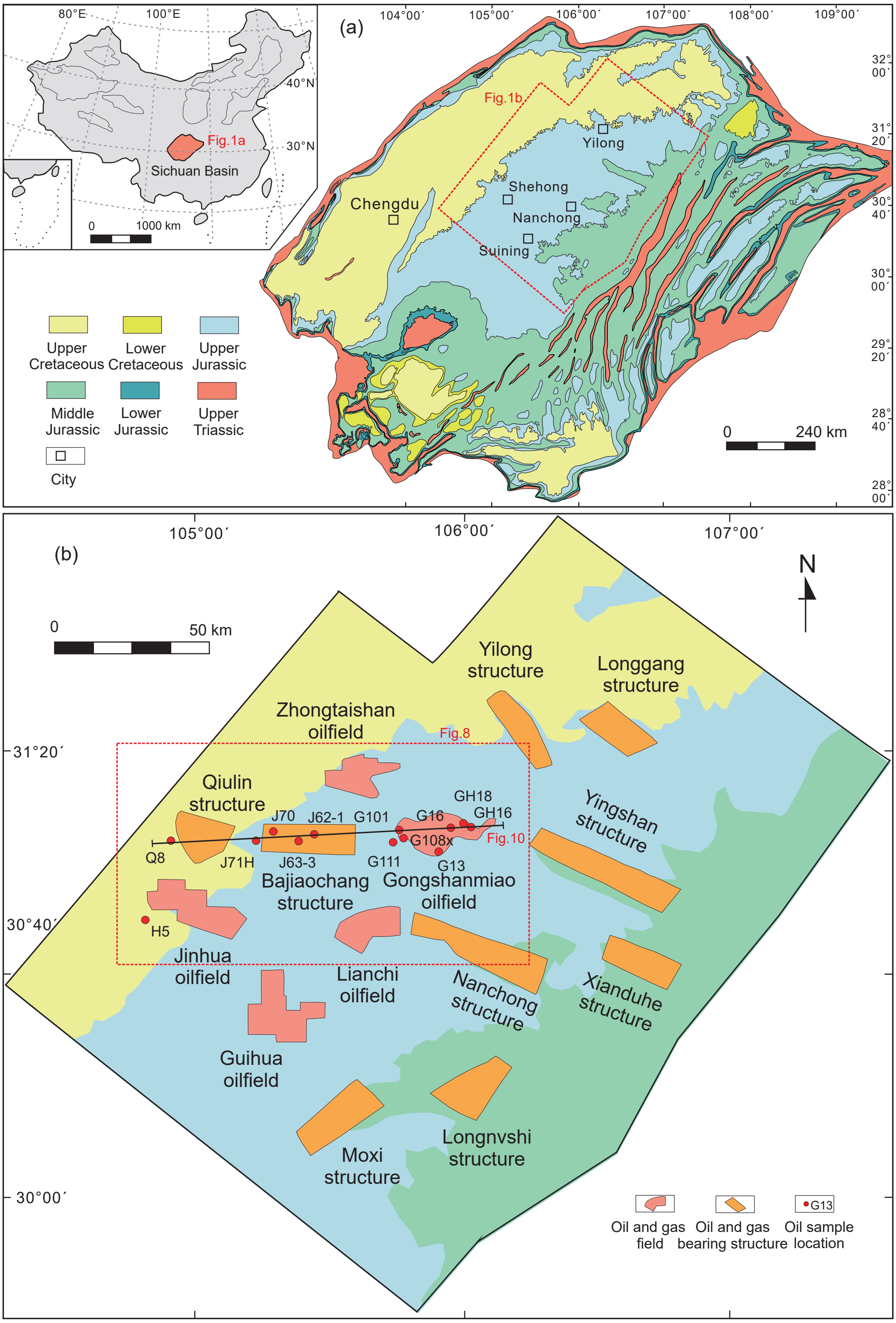

Fig. 1. (a) Generalised geological map of the Sichuan Basin, China (modified after Yang et *al.*, 2016). (b) Location map of the central Sichuan Basin (the boxed area in Fig. 1a) with Jurassic oil fields and oil- and gas-bearing structures; also shown is the profile of the section in Fig. 10.

Formation source rocks are more than 300 m thick in the west of the Sichuan Basin and have total organic carbon (TOC) contents of over 2.0% with a dominance of Type III kerogen (Dai, 2016).

The main source rocks in the centre of the basin consist of lacustrine shales in the Lower Jurassic Da'anzhai Member of the Ziliujing Formation and the directly overlying Lianggaoshan Formation. The Da'anzhai Member shales contain Type II kerogen, and have TOC and vitrinite reflectance (VR) values of 1.0-1.8% and 0.9-1.6 R_o% respectively (Yang *et al.*, 2016; Li *et al.*, 2017). The TOC and VR values of the mudstones in the Lianggaoshan Formation vary from 1.0 to 1.6% and 0.8 to 1.3 R_o%.

Jurassic oil-producing reservoir units in the centre of the Sichuan Basin include the Lower Jurassic Da'anzhai Member of the Ziliujing Formation and the directly-overlying Lianggaoshan Formation, together with the Middle Jurassic Shaximiao Formation (Fig. 2). Reservoir rocks in the Da'anzhai Member are primarily composed of shelly limestones, 10-30 m thick, which occur widely in the centre of the Sichuan Basin. Based on data provided by the Southwest Oil & Gas Field Company, PetroChina, the porosity of the limestones in the Da'anzhai Member ranges up to 6.8% with an average of 1.7% (see Chen *et al.,* 2015).

By contrast, the reservoirs in the Lianggaoshan Formation and the First Member of the Shaximiao Formation are dominated by fine-grained sandstones and siltstones with cumulative thicknesses ranging from 10 to 30m, and 50 to 200 m, respectively. The sandstone reservoir rocks in both the Lianggaoshan Formation and the First Member of the Shaximiao Formation are characterised by low average porosities and air permeabilities (< 4.2% and 0.49 mD respectively: Chen *et al.,* 2014; Li *et al.,* 2017).

The Second Member of the Shaximiao Formation has also recently been identified as a tight oil-producing reservoir interval in the Qiulin and Jinhua areas. Production rates from this unit can be high, and some wells such as QL-16 and QL-17 produce as much as 4.2 million cubic metres of gas with condensate per day (Huang *et al.*, 2021).

SAMPLES AND METHODS

Samples

Samples of light oils or condensates were collected from the Shaximiao Formation in the study area: six samples from the Second Member and three samples from the First Member. For comparison, five light oils from the Da'anzhai Member and Lianggaoshan Formation, and two condensates from the Xujiahe Formation, were also collected for analysis. Sample details are listed in Table 1. All the oils were collected at wellheads in the oil and gas fields studied (see well locations in Fig. 1). Sample temperature ranged from 20 to 28 °C. After collection, the oil samples were sealed and refrigerated to reduce volatilization of the light hydrocarbon fraction. Gas chromatography (GC) of the oil samples was then carried out promptly after sampling.

Methods

Gas chromatography

The gas chromatographic (GC) analysis used an Agilent 6890 apparatus equipped with a 50 m × 0.20 mm × 0.5 µm HP-PONA quartz capillary column. with high purity helium as the carrier gas at a constant flow rate of 1.0 mL/min. The initial oven temperature was held at 35 °C for 5 min followed by heating at 3 °C / min to 70 °C, then at 4.5 °C /min to 300 °C, with a final hold at 300 °C for 35min.

Stable carbon isotope analysis

Stable carbon isotope ratios of whole oils were analyzed with an isotope ratio mass spectrometer using carbon dioxide (CO_2) as a reference gas. This involved the combustion of oil to CO_2 in a FLASH 2000 EA reactor, and determination of the stable carbon isotope ratios using a Finnigan MAT 253 instrument. The measurement precision of carbon isotope ratios was within a range of -0.02‰ to +0.02‰ based on the Vienna PeeDee Belemnite (VPDB) standard.

All the samples were analyzed in the State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing.

RESULTS

Distribution of light hydrocarbons

A total of 26 C_4-C_7 light hydrocarbon compounds were detected in the oil samples from the Shaximiao Formation (Fig. 3) and consisted of alkanes (iso-alkanes and normal alkanes), cycloalkanes and light aromatics. As shown in Fig. 3, the condensates from the Second Member of the formation contain abundant cycloalkanes with methylcyclohexane as the main peak. By contrast, samples of light oils from the First Member are characterized by relatively high concentrations of *n*-alkanes. Aromatics (benzene and toluene) were almost below the detection limit in the First Member samples, but a relatively high abundance of aromatics was detected in the Second Member condensates.

In general, light hydrocarbons derived from source rocks with humic organic matter (OM) are relatively rich in isoalkanes and aromatics while those from source rocks with sapropelic OM have more abundant *n*-alkanes (Hu *et al.*, 1990; Chai *et al.*, 2020). The different compositions of the light hydrocarbons in the oil samples from the First and Second Member of Shaximiao Formation may therefore point to differences in the related source rock compositions.

Stable carbon isotope ratios

The stable carbon isotope composition of a crude oil is mainly controlled by the source rock, and is therefore widely used in oil family classifications and oil-source correlation studies (Galimov, 2006; Zhu, 2001; Zhu *et al.*, 2017). In general, crude oils whose carbon isotope values differ by more than 2~3‰ are believed to be derived from different source rocks (Peters *et al.*, 2005). The $\delta^{13}C$ values of oils from the Xujiahe

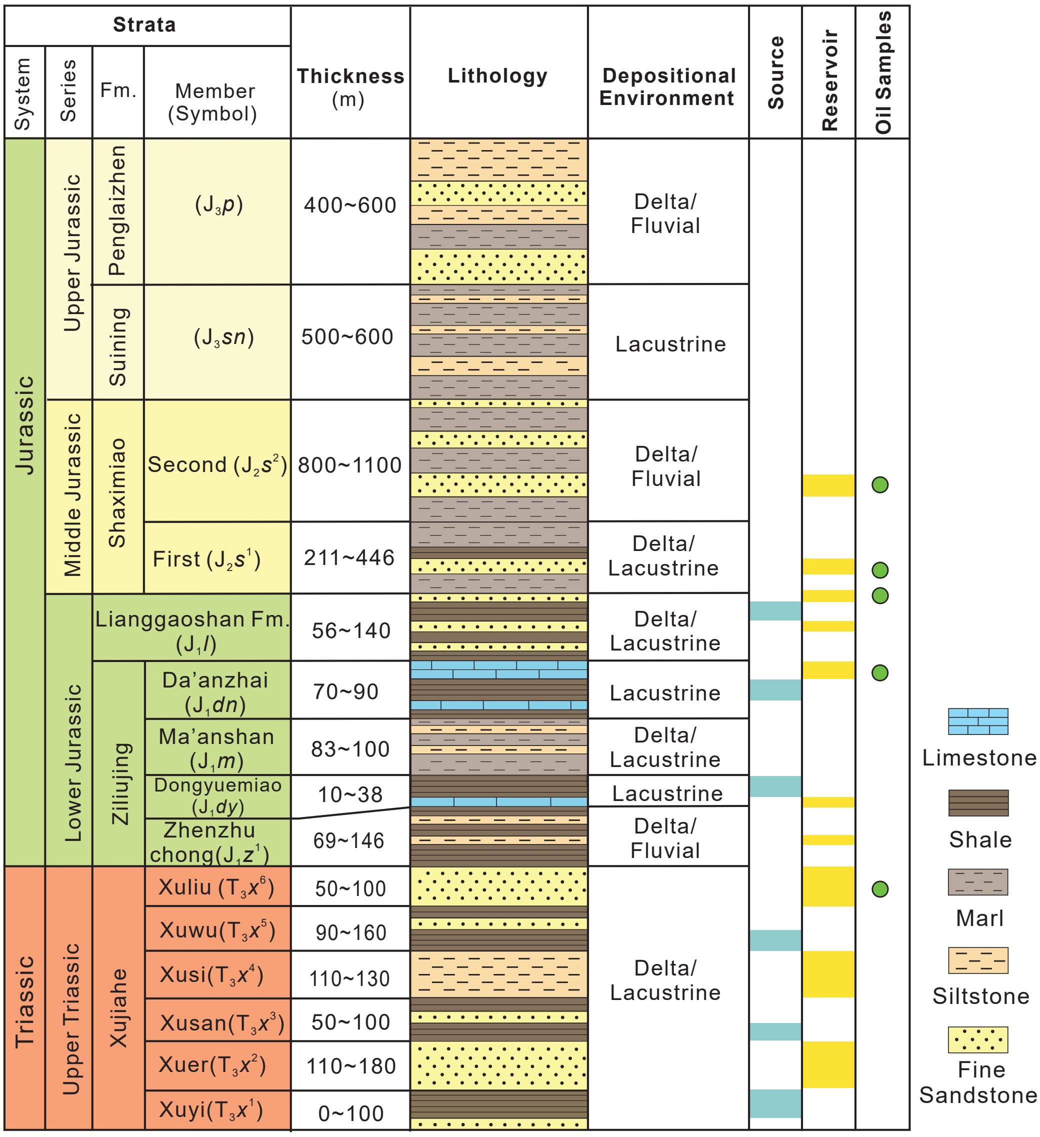

Fig. 2 Lithostratigraphic column for the Triassic-Jurassic succession in the central Sichuan Basin, showing formation thicknesses and lithologies, and abbreviations used in this paper.

Formation and Da'anzhai Member vary from -26.2‰ to -25.8‰, and from -30.7‰ to -30.1‰, respectively (Table 1). The $\delta^{13}C$ values of crude oil samples from the Shaximiao Formation range from -30.6‰ to -25.4‰, implying that the oils may be derived from different source rocks.

DISCUSSION

Distinguishing oils from the First and Second Members of the Shaximiao Formation based on their content of light hydrocarbons

(i) Methylcyclohexane and cyclohexane content

Light hydrocarbon fractions with six-membered ring structures in oil and gas, such as methylcyclohexane, are mainly formed from six-membered oxygen-containing ring structures in plant lignin and cellulose (Leythaeuser *et al.*, 1979; Hu *et al.*, 1990; Chai *et al.*, 2020). Hence, the relative contents of these fractions in an oil sample can be used to assess the contribution of humic organic matter in the related source rocks (Obermajer *et al.*, 2000). The methylcyclohexane (MCH) index and cyclohexane (CH) index are widely applied to indicate the organic matter type in a related source rock (e.g. Hu *et al.*, 1990). Light hydrocarbons derived from humic kerogen usually show a relatively high content of methylcyclohexane and cyclohexane, with values of the MCH and CH indexes >52% and 29%, respectively. However, light hydrocarbons derived from sapropelic kerogen have MCH and CH index values <52% and 29%, respectively (Hu *et al.*, 1990; Yang *et al.*, 2016).

The MCH and CH indexes in the light oils from the First Member of the Shaximiao Formation have values similar to those of oil samples from the Lower Jurassic Da'anzhai Member and Lianggaoshan Formation, with values of 46.9-50.0% and 25.5-29.0%, respectively. By contrast, both of these indexes for oil samples from

Table 1 Light hydrocarbon parameters and stable carbon isotope values for the oils from the central Sichuan Basin.

No.	Well	Strata	Area	Type	$3\text{-}MC_5/nC_6$	$2\text{-}MC_6/nC_7$	$nC_7/MCyC_6$	K_1	K_2	Heptane values	Isoheptane values	MCH Index	CH Index	$\delta^{13}C$ (‰)
1	G16	J_2s^1	Gongshanmiao	Light oil	0.21	0.18	0.77	1.01	0.11	27.85	1.25	50.21	29.00	-30.6
2	GH16	J_2s^1	Gongshanmiao	Light oil	0.18	0.18	0.91	1.03	0.10	32.06	1.82	46.93	25.50	-30.4
3	GH18	J_2s^1	Gongshanmiao	Light oil	0.19	0.19	0.89	1.03	0.15	30.94	1.74	47.13	25.60	-30.4
4	G101	J_1l	Gongshanmiao	Light oil	0.16	0.15	0.98	1.04	0.16	32.54	1.48	44.93	28.48	-30.8
5	G13	J_1l	Gongshanmiao	Light oil	0.17	0.16	0.99	1.06	0.17	32.11	1.50	44.59	27.14	-30.8
6	G108X	J_1dn	Gongshanmiao	Light oil	0.16	0.16	0.92	1.04	0.14	31.01	1.45	46.30	28.49	-30.7
7	G111	J_1dn	Gongshanmiao	Light oil	0.19	0.20	0.71	1.07	0.15	27.59	1.66	52.43	32.52	-30.1
8	J94	J_1dn	Bajiaochang	Light oil	0.22	0.22	0.95	1.12	0.21	30.10	1.72	44.94	29.17	-30.6
9	JN17	T_3x	Jinhua	Condensate	0.48	0.56	0.15	1.23	0.14	7.72	0.93	74.47	55.77	-26.2
10	JN2	T_3x	Jinhua	Condensate	0.45	0.47	0.14	1.14	0.20	8.18	0.91	76.19	59.14	-25.8
11	H5	J_2s^2	Jinhua	Condensate	0.38	0.41	0.27	1.13	0.20	13.78	1.57	69.51	51.87	-25.9
12	Q8	J_2s^2	Qiulin	Condensate	0.38	0.41	0.39	1.14	0.26	15.82	1.67	61.62	56.03	-26.6
13	J62-1	J_2s^2	Bajiaochang	Condensate	0.19	0.18	1.14	1.08	0.27	36.28	2.84	43.16	29.10	-28.9
14	J70	J_2s^2	Bajiaochang	Condensate	0.30	0.33	0.43	1.11	0.28	19.42	4.03	65.14	56.73	-25.6
15	J63-3	J_2s^2	Bajiaochang	Condensate	0.33	0.37	0.50	1.11	0.25	19.36	1.95	58.08	53.35	-25.4
16	J71H	J_2s^2	Bajiaochang	Condensate	0.33	0.35	0.34	1.12	0.27	16.58	2.31	67.98	54.51	-27.5

Note: $K_1 = (2\text{-}MC_6+2,3\text{-}DMC_5)/(3\text{-}MC_6+2,4\text{-}DMC_5)$; $K_2 = (2,2\text{-}DMC_5+2,3\text{-}DMC_5+2,4\text{-}DMC_5+3,3\text{-}DMC_5+3\text{-}EC_5+2,2,3\text{-}TMC_4)/(2\text{-}MC_6 + 3\text{-}MC_6 + 1,1\text{-}DMCyC_5 + 1,c3\text{-}DMCyC_5 + 1,t3\text{-}DMCyC_5)$; Heptane Value = $nC_7 \times 100/(CyC_6 + 2\text{-}MC_6 + 1,1\text{-}DMCyC_5 + 3\text{-}MC_6 + 1,c3\text{-}DMCyC_5 + 1,t3\text{-}DMCyC_5 + 1,t2\text{-}DMCyC_5 + nC_7 + MCyC_6)$; Isoheptane Value = $(2\text{-}MC_6 + 3\text{-}MC_6)/(1,c3\text{-}DMCyC_5 + 1,t3\text{-}DMCyC_5 + 1,t2\text{-}DMCyC_5)$; MCH Index = $MCyC_6 \times 100/(nC_7 + MCyC_6 + 1,1\text{-}DMCyC_5 + 1,c3\text{-}DMCyC_5 + 1,t3\text{-}DMCyC_5 + 1,t2\text{-}DMCyC_5)$; CH index = $CyC_6 \times 100/(nC_6 + CyC_6 + MCyC_5)$

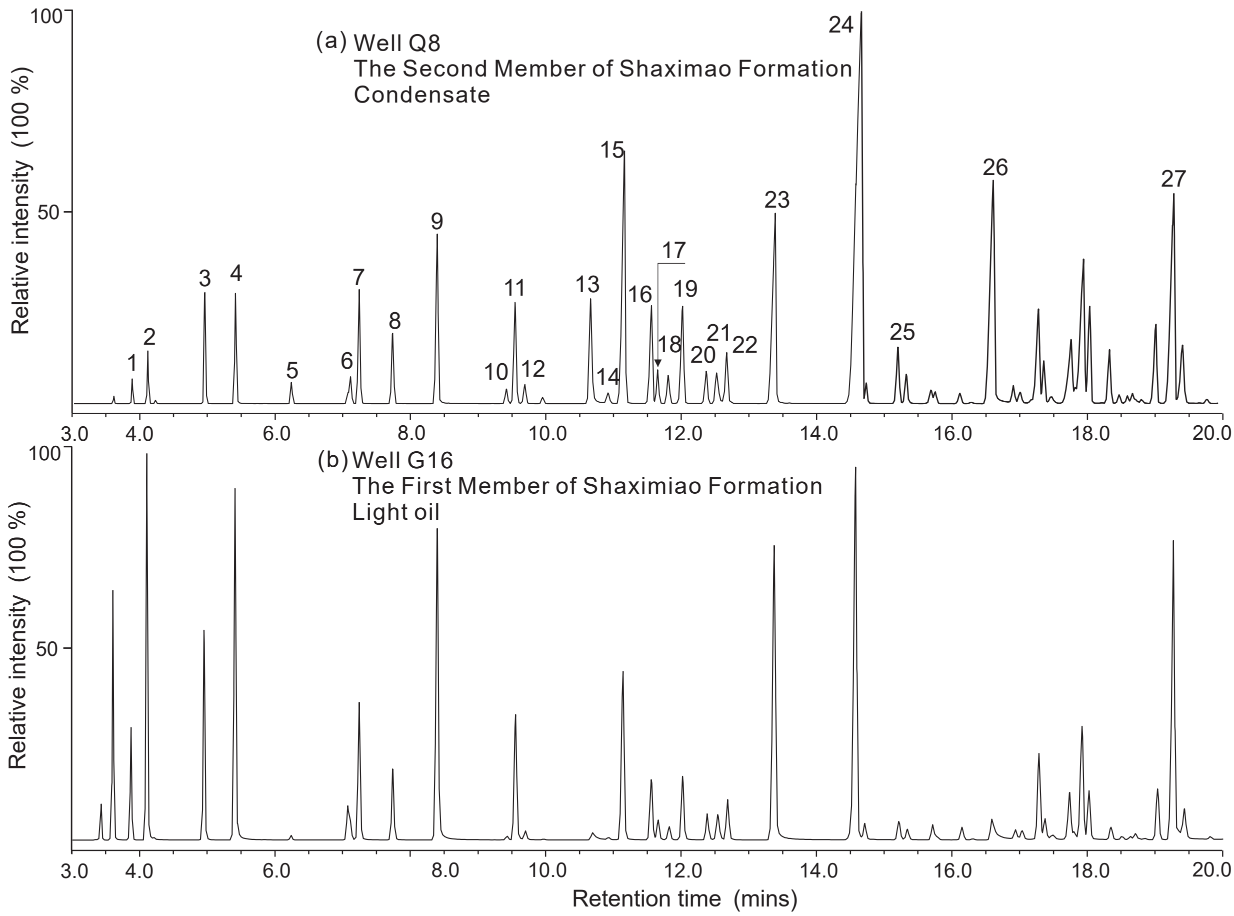

Fig. 3. Representative gas chromatograms of condensate and light oil samples from the Shaximiao Formation from wells in the center of the Sichuan Basin.
1: iso-butane (*i*C_4); 2: *n*-butane (*n*C_4); 3. isopentane (*i*C_5); 4: *n*-pentane (*n*C_5); 5: dimethylpentane (2,2-DMC_4); 6: cyclopentane (CyC_5); 7: 2-methylpentane(2-MC_5); 8: 3-methylpentane (3-MC_5); 9: *n*-hexane (*n*C_6); 10: 2,2-dimethylpentane (2,2-DMC_5); 11: methylcyclopentane (MCyC_5); 12: 2,4-dimethylpentane (2,4-DMC_5); 13: benzene (Benz); 14: 3,3-dimethylpentane (3,3-DMC_5); 15: cyclohexane (CyC_6); 16: 2-methylhexane (2-MC_6); 17: 2,3-dimethylpentane (2,3-DMC_5); 18: 1,1-dimethylcyclopentane (1,1-DMCyC_5); 19: 3-methylhexane (3-MC_6); 20: 1,cis-3-dimethylcyclopentane (1,c3-DMCyC_5); 21: 1,trans-3-dimethylcyclopentane (1,t3-DMCyC_5); 22: 1,trans-2-dimethylcyclopentane (1,t2-DMCyC_5); 23:*n*-heptane (*n*C_7); 24: methylcyclohexane (MCyC_6); 25: ethylcyclopentane (ECyC_5); 26: toluene (Tol); 27: octane (*n*C_8).

Second Member of the Shaximiao Formation (except for that from well J62-1) are much higher (Table 1), suggesting a relatively greater contribution of humic organic matter in the corresponding source rocks. The higher MCH and CH contents of the oils in the Second Member of the Shaximiao Formation are shown on a ternary diagram of *n*-hexane (*n*C_6), cyclohexane (CyC_6) and methylcyclopentane (MCyC_5) (Fig. 4a). This diagram shows that the oils in the First and Second Members of the Shaximiao Formation in the study area can clearly be distinguished from each other.

The relative percentages of methylcyclohexane (MCyC_6), *n*-heptane (*n*C_7) and dimethylcyclopentanes (DMCyC_5) for oil samples from the First and Second Members of the Shaximiao Formation were also plotted in a ternary diagram (Fig. 4b, after Hu *et al.*, 1990; Huang *et al.,* 2022). The diagram shows that the oil samples from the Second Member (except for that from well J62-1) plot in the same field as the condensates from the Upper Triassic Xujiahe Formation; these oils and condensates have high contents of methylcyclohexane. By contrast, the oil samples from the First Member show characteristics similar to the oils from the Lower Jurassic Da'anzhai Member and Lianggaoshan Formation (Fig. 4b). These oils have lower contents of methylcyclohexane.

Figs 4a and b show that the oil sample from the Second Member of the Shaximiao Formation from the J62-1 well on the Bajiaochang structure plots in the same field as the light oils from the First Member. The oil is relatively rich in *n*-hexane (Fig. 4a) and *n*-heptane (Fig. 4b) with a relatively low methylcyclohexane content. The distribution of C_6 and C_7 hydrocarbons in oils from the First and Second Members of the Shaximiao Formation therefore shows the complexity of the oil's origin in the study area.

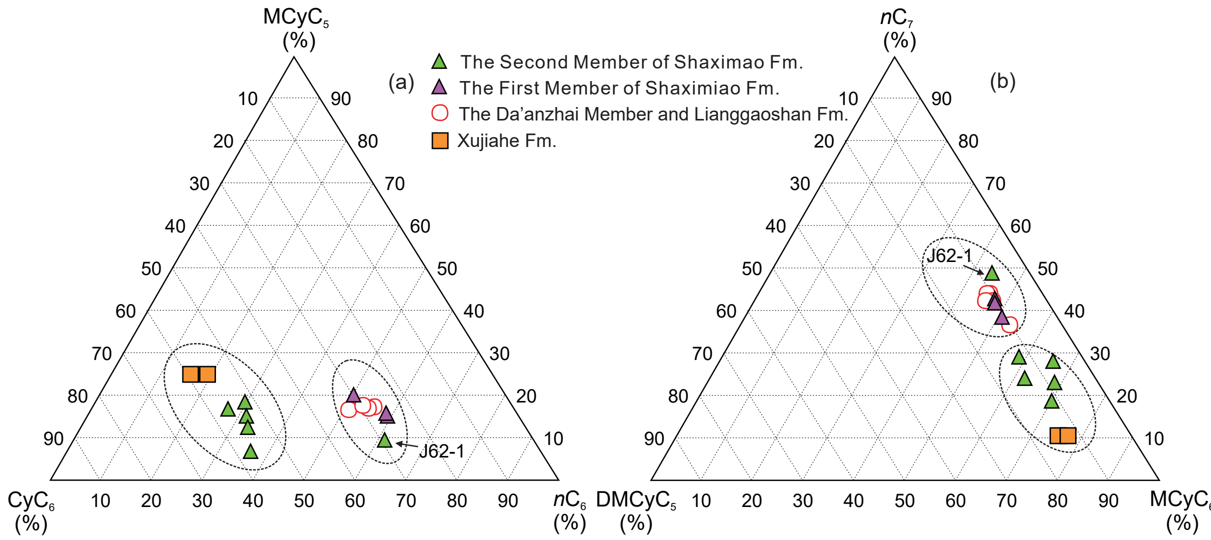

Fig. 4. Triangular plots of: (a) *n*-hexane (*n*C_6), cyclohexane (CyC_6) and methylcyclopentane ($MCyC_5$); and (b) methylcyclohexane ($MCyC_6$), *n*-heptane (*n*C_7) and dimethylcyclopentanes ($DMCyC_5$) for oil samples from the centre of the Sichuan Basin (after Hu *et al*., 1990). Two groups of oils can clearly be distinguished.

(ii) Mango's parameters K_1 and K_2

On the basis of the light hydrocarbon compositions of 2000 oil samples, Mango (1987) found that K_1, the ratio of (2-MC_6+2, 3-DMC_5) to (3-MC_6+2, 4-DMC_5), varied little around a value of 1.0. However, subsequent investigations indicated that K_1 for oils from Sabine Parish, Louisiana and from the Midland Basin, Texas, varied moderately with average values of 1.09 and 0.786, respectively (Mango, 1990). ten Haven (1996) reported that the average value of K_1 for 500 oils from Southeast Asia was 1.07 but found that the value was as high as 1.67 for oils from the Northwest Basin, Argentina.

The K_1 value may vary for oils derived from a different source (Mango, 1997). Tight oils from Lower and Middle Jurassic reservoir units in the centre of the Sichuan Basin have K_1 values ranging from 1.01 to 1.14 (Table 1). Oils from the Second Member of the Shaximiao Formation (except for the sample from well J62-1) show K_1 values similar those of oils from the Upper Triassic Xujiahe Formation, ranging from 1.11 to 1.14. However, K_1 values for oils from the First Member are lower, between 1.01 and 1.03, and are closer to the values of the oils from the Da'anzhai Member and Lianggaoshan Formation.

The conventional view is that the thermal cracking of kerogen is the dominant process for the generation of light hydrocarbons (e.g. Martin *et al*., 1963). But this theory does not explain the lack of variation in K_1 values for oils with different maturities or which are derived from different source rocks. A steady-state catalytic kinetic scheme of C_7 hydrocarbons was therefore suggested to explain the origin of light hydrocarbons in petroleum by Mango (1987), and another ratio (K_2) was proposed, based on this scheme (Mango, 1990; Mango, 1994).

Mango *(ibid.)* defined $K_2 = P_3/(P_2 + N_2)$, where P_2 = 2-methylhexane (MC_6) + 3-MC_6, P_3 = 2,2-dimethylpentane (DMC_5) + 2,4-DMC_5 + 3,3-DMC_5 + 2,3-DMC_5 + 3-ethylpentane (EC_5) + 2,2,3- trimethylpentane (TMB), and N_2= 1,1-dimethylcyclopentane ($DMCyC_5$) + 1,c3-$DMCyC_5$ + 1,t3-$DMCyC_5$. In general and in common with K_1, oils from same source rock should have similar K_2 values.

K_2 values of the oils from the First Memberof the Shaximiao Formation from the study area are lower than K_2 values for oils from the Second Member, with averages of 0.12 and 0.26 respectively (Table 1). Samples of oils from the First and Second Members can clearly be distinguished in a plot of P_2+N_2 versus P_3 (Fig. 5a).

Zhang *et al.* (2005) found that, owing to the presence of relatively high contents of methylcyclohexane and toluene, terrigenous oils from the Tarim Basin could be distinguished from marine oils in a plot of ($MCyC_6$ + Tol) versus (P_3 + P_2 + N_2). This cross-plot can also be used to divide the analysed oil samples from the central Sichuan Basin (Fig. 5b). In general, methylcyclohexane and toluene are more abundant in oil and gas derived from source rocks containing humic organic matter (Hu *et al*., 2014). As shown in Fig. 5b, the contents of methylcyclohexane and toluene in oils from the Xujiahe Formation oils and the Second Member of Shaximiao Formation (except for the sample from Well J62-1) are higher than those in oils from the Da'anzhai Member and Lianggaoshan Formation and the First Member of the Shaximiao Formation, and accounts for more than 50% of the C_7 light hydrocarbons. Therefore, the light hydrocarbons in oils from the Second Member of the Shaximiao Formation and the Xujiahe Formation are interpreted mostly to be derived from source rocks containing humic OM; while those in oils from the

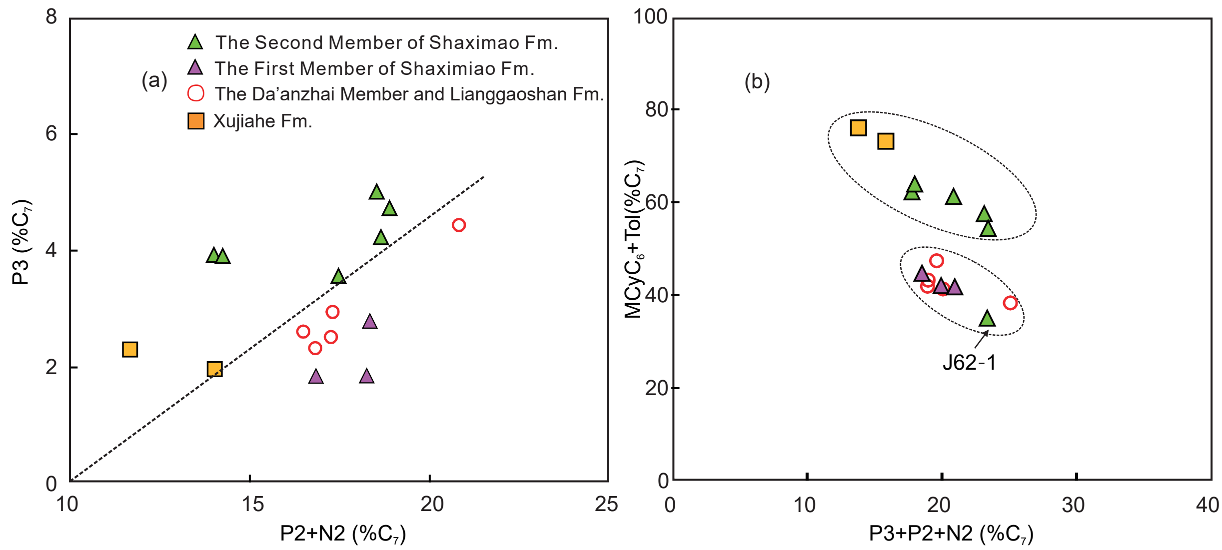

Fig. 5. Cross plots of: (a) P_3 versus (P_2 + N_2); and (b) ($MCyC_6$+Tol) versus (P_3+P_2+N_2), showing the presence of two main oil types in the study area. Note: P_2 = 2-MC_6 + 3-MC_6; P_3 = 2,2-DMC_5 + 2,4-DMC_5+3,3-DMC_5 + 2,3-DMC_5+ 3-EC_5 + 2,2,3-TMB; N_2= 1,1-$DMCyC_5$ + 1,c3-$DMCyC_5$ + 1,t3-$DMCyC_5$.

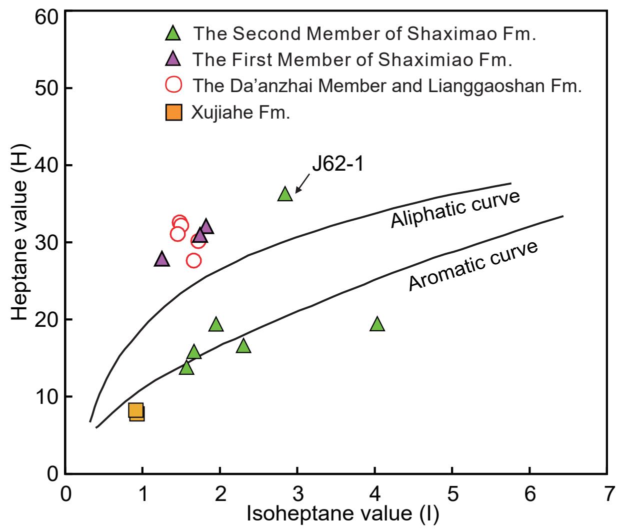

Fig. 6. Cross plot of isoheptane and heptane values for oil samples from the study area (after Thompson, 1983). Oil samples which plot near or above the aliphatic curve are derived from source rocks containing aliphatic kerogen; oils plotting near or below the aromatic curve are derived from source rocks containing mainly humic kerogen.

Da'anzhai Member, Lianggaoshan Formation and the First Member of the Shaximiao Formation were derived from a different source kitchen.

(iii) Heptane and isoheptane

The heptane and isoheptane values were proposed in early studies to evaluate the palaeotemperatures experienced by argillaceous sediments during their burial history, based on the light hydrocarbon compositions of subsurface sediment samples from different depths (Thompson, 1979). The heptane value = $nC_7 \times 100$ / (CyC_6 + 2-MC_6+1, 1-$DMCyC_5$ + 3-MC_6 + 1,c3-$DMCyC_5$ + 1,t3-$DMCyC_5$ + 1,t2-$DMCyC_5$ + $MCyC_6$ + nC_7); while the isoheptane value = (2-MC_6 + 3-MC_6) / (1,c3-$DMCyC_5$ + 1,t3-$DMCyC_5$ +1, t2-$DMCyC_5$). Thompson (1983) showed that the heptane and isoheptane values of oils have a close relationship with the kerogen types of the associated source rocks A cross-plot of these values may therefore provide a way to classify the kerogen type (Wang *et al.*, 2010).

On such a plot (Fig. 6), the three oil samples from the First Member of the Shaximiao Formation and the five light oil samples from the Da'anzhai Member and Lianggaoshan Formation analysed plot in the zone above the aliphatic curve, implying that these oils were derived from source rocks containing sapropelic kerogen. In contrast, the majority of the oils from the Second Member of Shaximiao Formation and from the Xujiahe Formation plot in an area adjacent to the aromatic curve, indicating these oils were derived from

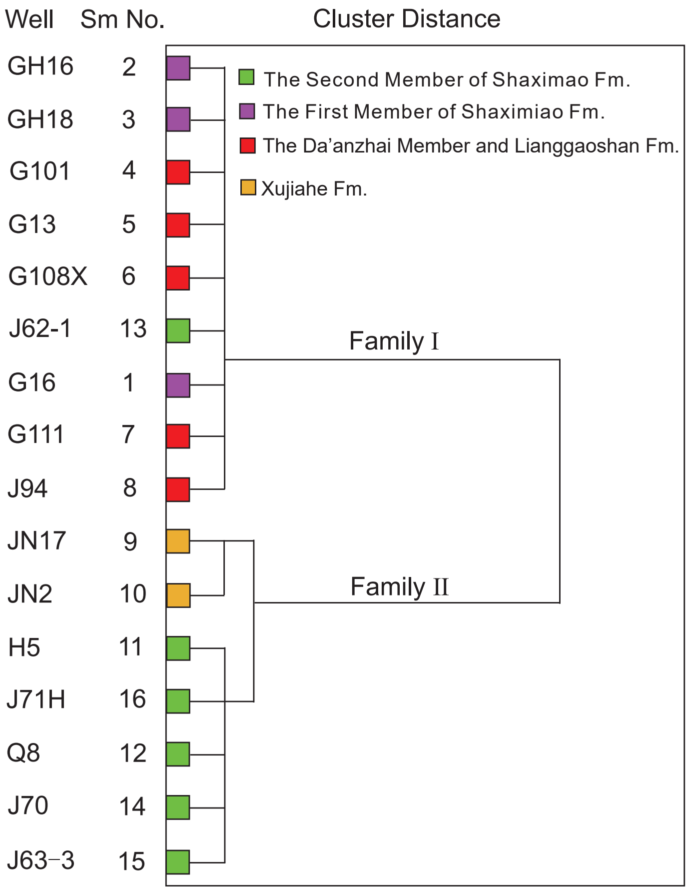

Fig. 7. Hierarchical cluster analysis using selected light hydrocarbon parameters and stable carbon isotope values showing the results of oi family classification. Note: No., sample number; selected parameters are shown in Table 1.

humic kerogen. The well J62-1 oil sample plots close to the oils from the First Member of the Shaximiao Formation and is distinct from the other oils from the Second Member of the Shaximiao Formation.

Stable carbon isotope compositions

Stable carbon isotope compositions have widely been applied to determine the genetic relationships between source rocks and oils (Peters *et al.*, 2005). In general, crude oils generated from sapropelic kerogen commonly exhibit relatively low $\delta^{13}C$ values, below -28.0‰; while $\delta^{13}C$ values for oils originating from humic kerogen are usually less negative than -28.0‰ (Fu *et al.*, 2019; Shen *et al.*, 1998; Chung *et al.*, 1992).

In the oils from study area, the carbon isotope compositions of samples of the oil from the Upper Triassic Xujiahe Formation are significantly less negative than those of oil samples from the Da'anzhai Member and Lianggaoshan Formation (Table 1; see also Chen *et al.*, 2013). The Xujiahe Formation samples have $\delta^{13}C$ values ranging from -26.2‰ to -25.8‰, and are therefore interpreted to have been generated from source rocks dominated by humic organic matter. In contrast, the oils from the Da'anzhai Member and Lianggaoshan Formation with $\delta^{13}C$~-30‰ (Table 1) are interpreted to be derived from source rocks in the Da'anzhai Member and Lianggaoshan Formation which contain sapropelic kerogen.

The oil samples from the Shaximiao Formation can be divided into two groups, using a stable carbon isotope ratio of -28.0‰ as a dividing line. The majority of oil samples from the Second Member of the formation have $\delta^{13}C$ values ranging from -27.5‰ to -25.4‰ (Table 1), closely similar to those of the oils from the Xujiahe Formation, indicating that they are derived from humic-rich Xujiahe Formation source rocks. However, the $\delta^{13}C$ values of oils from the First Member of the formation, and of the oil sample from the Second Member from well J62-1, are more negative than -28.0‰, similar to the oils from the Lower Jurassic Da'anzhai Member and Lianggaoshan Formation which are derived from sapropelic source rocks.

Statistical grouping

The genetic relationships between crude oils from the centre of the Sichuan Basin were investigated by hierarchical cluster analysis (HCA) which is widely utilized for oil family classification (e.g. Mashhadi *et al.*, 2015; Xiao *et al.*, 2019; Fu *et al.,* 2019; Yandarbiev *et al.*, 2021). The cluster distance in the HCA, which represents the genetic similarity, was calculated from selected source-related light hydrocarbon parameters

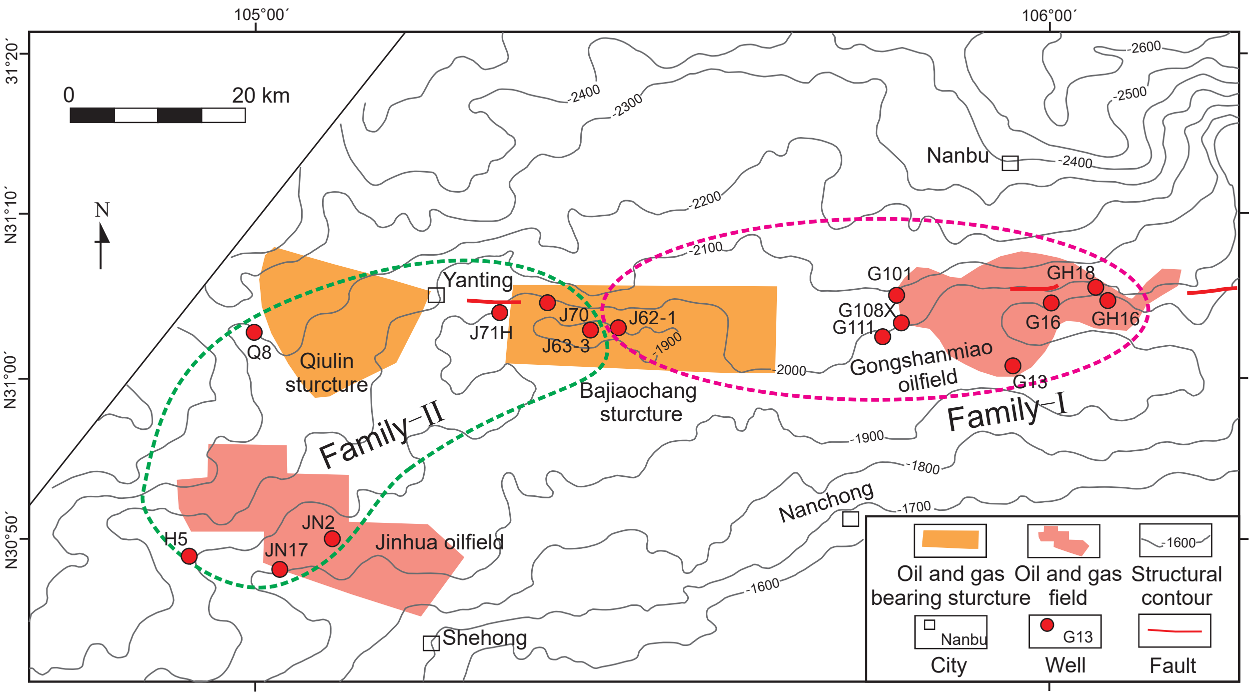

Fig. 8. Map of the centre of the Sichuan Basin showing the distribution of the two oil families proposed in this study. Structure contours (metres) show the depth to the base of the Shaximiao Formation in the study area.

and stable carbon isotope values (Table 1). According to the HCA, oils from the study area can be divided into two oil families which are referred to here as Families I and II (Fig. 7).

Family I oils include the oils from the Da'anzhai Member and Lianggaoshan Formation, the oil from the First Member of the Shaximiao Formation, and the oil from Second Member from well J62-1. Oils in this family are present in the area around the Gongshanmiao oilfield and the eastern part of the Bajiaochang structure (Fig. 8). The light hydrocarbon parameters and carbon isotope composition indicate that Family I oils are derived from source rocks dominated by sapropelic kerogen. In previous studies, oils from the Da'anzhai Member and Lianggaoshan Formation in the study area were demonstrated to be self-sourced by dark lacustrine mudstones within these units (Lu *et al.*, 2021). Family I oils are therefore likely to be derived from source rocks in the Da'anzhai Member and Lianggaoshan Formation.

The newly identified Family II oils include oils in the Upper Triassic the Xujiahe Formation and the majority of the oils in the Second Member of the Shaximiao Formation (Fig. 7). These oils occur in the Jinhua oilfield, the Qiulin structure and the west of the Bajiaochang structure (Fig. 8). The oils in the Upper Triassic Xujiahe Formation are typical coal-related oils and are believed to be self-sourced from humic source rocks in the study area (Tang *et al.*, 2011; Dai, 2016). Therefore the Family II oils, including those from the Second Member of the Shaximiao Formation (with the exception of that from well J62-1) may also be derived from Xujiahe Formation coaly source rocks. The discovery of the newly identified Family II oils indicates that the Upper Triassic Xujiahe Formation comprises an important source of the oil in Jurassic tight reservoirs in the central Sichuan Basin, in addition to the Lower-Middle Jurassic source rocks which have previously been identified.

Exploration potential for tight oil in the Shaximiao Formation

The Upper Triassic Xujiahe Formation mudstones and the lacustrine mudstones in the Lower Jurassic Da'anzhai Member and Lianggaoshan Formation are source rocks for tight oil in the Central Sichuan Basin. The Xujiahe Formation mudstones were deposited in delta-front to shallow lacustrine conditions and are widespread in the basin (Wang *et al.,* 2021). Source rock intervals primarily occur in Members 3 and 5 of the formation whose thickness decreases from west to east in the study area. Thus, Xujiahe Formation source rocks are around 400 m thick at the Qiulin structure (Fig. 9a) but only about 200 m thick at the Gongshanmiao oilfield to the east (Dai, 2016).

By contrast, the depocentres of the Lower Jurassic Da'anzhai Member and Lianggaoshan Formation are located in the centre of the Sichuan Basin and their thickness decreases to the west (Fig. 9b). Thus, their cumulative thickness is about 100 m around the Gongshanmiao oilfield but less than 40 m at the Qiulin structure (Yang *et al.*, 2016).

As demonstrated above, Family I oils occur mainly in the area around the Gongshanmiao oilfield (Fig.

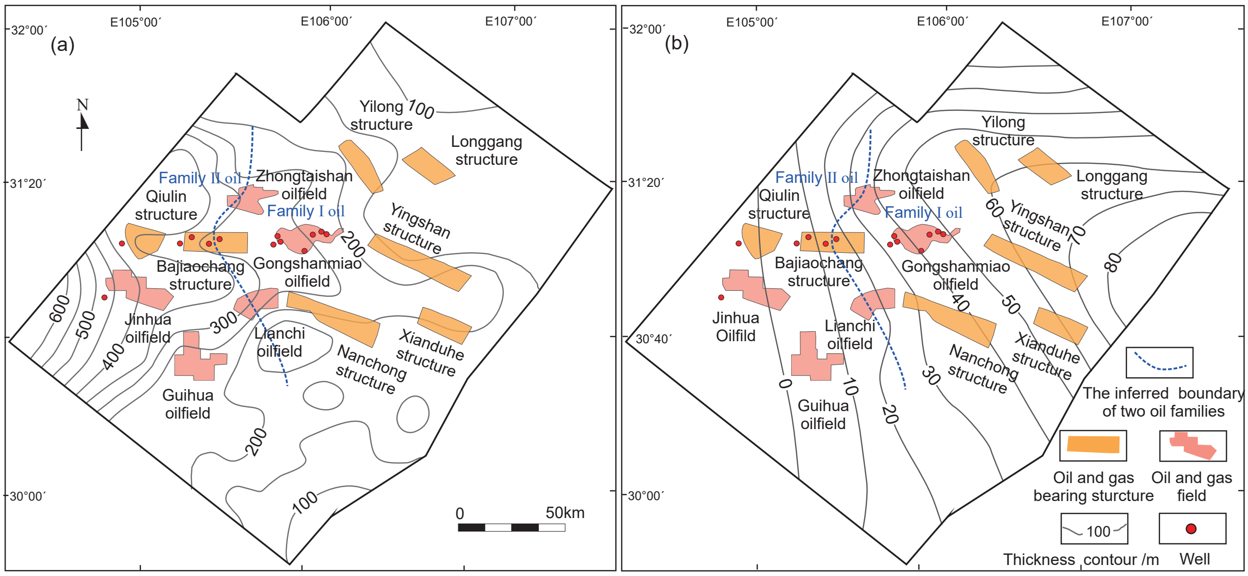

Fig. 9. Maps of the central Sichuan Basin showing the thickness (contours in metres) of source rock intervals in (a) the Upper Triassic Xujiahe Formation and (b) the Lower Jurassic Lianggaoshan Formation. Coloured polygons show oil and gas fields (pink) and oil- and gas-bearing structures (orange). The boundary between the two oil families (blue dashed line) is speculative and is based on oil-oil correlations and the thickness of the respective source rocks.

10). In this area, source rocks in the Lower Jurassic Da'anzhai Member and Lianggaoshan Formation are at their thickest (Fig. 9a). By contrast, Family II oils are primarily located in the area around the Jinhua oilfield and Qiulin structure to the west (Fig. 10), near the depocentre of the Upper Triassic source rocks (Fig. 9b). The Bajiaochang structure is located in the inferred transitional zone between these two areas (Fig. 9), and both Family I and Family II oils are present here (Fig. 10).

The extent and thickness of Middle Permian source rocks has been found to be an important factor controlling the distribution of crude oil in Permian tight dolomite reservoir rocks in the Junggar Basin, NW China (Kuang *et al.,* 2012). Likewise in the Ordos Basin, Song *et al.* (2021) found that tight oil mainly occurs in reservoirs in the Chang 6 and 8 Members of the Triassic Yanchang Formation in locations near to thick source rocks in the Chang 7 Member. The results of the present study similarly show that the extent and thickness of source rocks appears to be an important factor controlling the distribution of tight oil in the Shaximiao Formation in the central Sichuan Basin.

Tight-oil producing Shaximiao Formation reservoir rocks occur in the Gongshanmiao oilfield and in the Bajiaochang and Qiulin structures (Fig. 10). The same reservoir rocks may also occur in other oilfields and structures where there is a similar source rock distribution such as the Guihua, Lianchi, Zhongtaishan fields and the Nanchong, Yingshan and Longgang structures (Fig. 9). Although oil and gas exploration targetting the Shaximiao Formation in the central Sichuan Basin is still in its preliminary stages, many oil- and gas-bearing structures await further development.

Seismic interpretations indicate that a large-scale fault connecting coaly Upper Triassic Xujiahe Formation source rocks with reservoirs in the Shaximiao Formation occurs at the Bajiaochang structure (Fault J1: Fig. 10). However similar faults are not present at the Jinhua and Qiulin structures (Wang *et al.*, 2021).

Previous studies have suggested that Middle Jurassic fluvial sandbodies in the Second Member of the Shaximiao Formation may serve as important carrier beds for the lateral migration of oil and gas (Huang *et al.*, 2021). The results of this study support this migration model, since a range of compositional parameters such as the toluene content vary markedly from the Bajiaochang structure to the Qiulin-Jinhua structures. As toluene is easily soluble in water, the content of toluene in oils decreases with increasing migration distance, and the Tol/nC_7 ratio has therefore been widely used for tracing oil and gas migration (e.g. Hu *et al.*, 2018). The Tol/nC_7 ratios of oils from the Second Member of the Shaximiao Formation from the Bajiaochang structure (except for that from well J62-1) and from the Qiulin-Jinhua structures range from 0.86 to 1.16 and 0.51 to 1.06, respectively; in general this indicates an overall filling direction from the Bajiaochang to the Qiulin-Jinhua structures (Fig. 10).

The ratio of (2-MC_5+3-MC_5)/nC_6 can also be used as a migration parameter (Hu *et al.*, 2018). Values for oils from the Bajiaochang structure are lower than those for oils from the Qiulin-Jinhua structures, with averages of 0.83 and 0.98, respectively. This

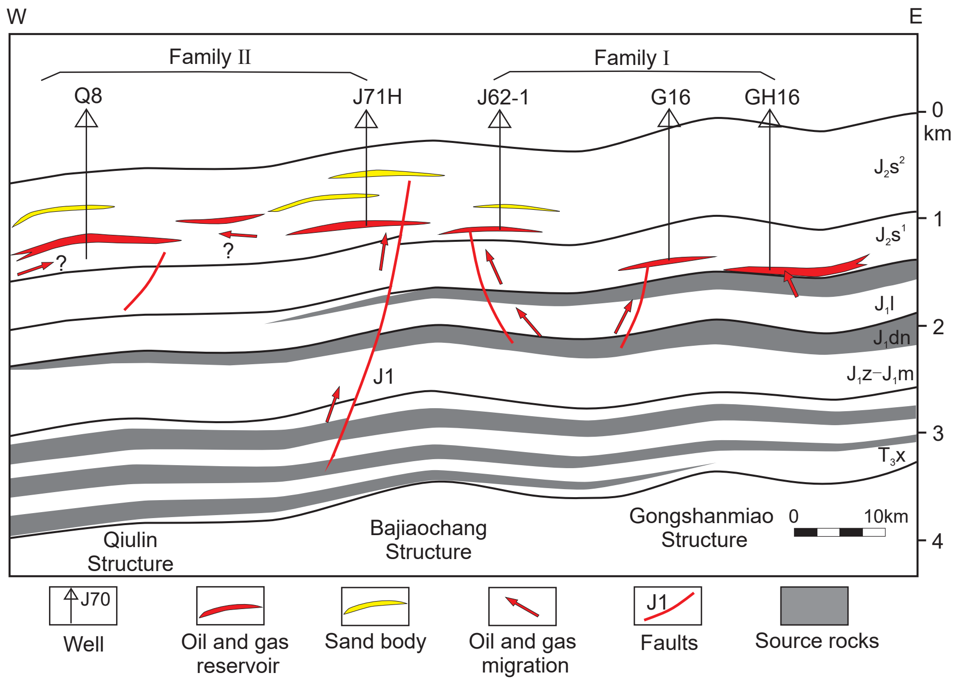

Fig. 10. Cartoon west-east cross section showing the accumulation of the Family I and II two tight oils in the First and Second Members of the Shaximiao Formation. Profile line in Fig. 1b.

also implies that oils in the Qiulin-Jinhua structure may have experienced longer distance migration. However, the Shaximiao Formation was deposited in a deltaic to lacustrine environment, and delta-front and subaqueous channel sands extend widely from the west to the centre of the Sichuan Basin (Huang *et al.*, 2021). Thus the oils from the Second Member of the Shaximiao Formation in the Qiulin-Jinhua structure may also have migrated from the depocentre of the Xujiahe Formation in the west of the Sichuan Basin (Fig. 10). Although the migration pathway of oils in the study area requires further investigation, the distribution of source rocks appears to be a crucial factor controlling the distribution of tight oils in the Shaximiao Formation.

CONCLUSIONS

Tight oils from Lower and Middle Jurassic reservoir rocks in the central Sichuan Basin, SW China, were classified into two oil families by hierarchical cluster analysis based on compositional analyses of light (C_4-C_{13}) hydrocarbons and stable carbon isotope ratios:

Family I oils were present in tight reservoir rocks in the Da'anzhai Member of the Ziliujing Formation, the Lianggaoshan Formation, and the First Member of the Shaximiao Formation. These oils have relatively low values of the methylcyclohexane and cyclohexane indexes, low values of Mango's parameter K_2 for light hydrocarbon composition, and relatively negative $\delta^{13}C$ values (between -30.8‰ and -28.9‰). Family I oils are interpreted to be derived from source rocks containing mainly sapropelic organic matter. Previous studies have demonstrated that the oils from the Da'anzhai Member and Lianggaoshan Formation are self-sourced from organic-rich lacustrine mudstones in these units which are therefore inferred to be the probably source rocks for all the Family I oils.

Newly identified Family II oils have higher values of the methylcyclohexane and cyclohexane indexes and higher values of Mango's K_2 parameter. $\delta^{13}C$ values were less negative than those of Family I oils and ranged from -27.5‰ to -25.4‰. Family II oils were present in tight reservoir rocks in the Second Member of the Shaximiao Formation. The oils have similar compositions and $\delta^{13}C$ values to self-sourced oils from coaly mudstones in the Upper Triassic Xujiahe Formation. Family II oils were therefore inferred to have been generated by Xujiahe Formation source rocks.

Family I oils occur in the First Member of Shaximiao Formation in the Gongshanmiao oilfield in the east of the study area, a region where there are thick source rock intervals in the Da'anzhai Member and Lianggaoshan Formation. By contrast, Family II oils occur in the Second Member of the Shaximiao Formation primarily in the west of the study area, for example at Jinhua and Qiulin, near the depocentre of the Upper Triassic Xujiahe Formation. In intermediate areas such as the Zhongtaishan and Lianchi oilfields, the Shaximiao Formation reservoirs may contain oils derived from source rocks in both the Xujiahe Formation and in the Da'anzhai Member and Lianggaoshan Formation.

In the study area in the central Sichuan Basin, the distribution of oils in Lower and Middle Jurassic tight reservoirs is therefore primarily controlled by the extent, thickness and type of source rocks.

ACKNOWLEDGEMENTS

This work was funded by the National Natural Science Foundation of China (Grant No. 41972148) and the Foundation of the State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing (No. PRP/open-1803). The authors would like to thank Lei Zhu and Shengbao Shi for assistance with the GC analyses. They are grateful to the Southwest Oil & Gas Field Company of the CNPC for permission to publish this paper. They thank two anonymous reviewers for their constructive comments and suggestions on the manuscript, and JPG editorial staff for help with the English language presentation.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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