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ORIGINAL ARTICLE

Study on oil–source correlation by analyzing organic geochemistry characteristics: a case study of the Upper Triassic Yanchang Formation in the south of Ordos Basin, China

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Abstract In the south of the Ordos Basin, the oil source of the Upper Triassic Yanchang Formation is confused all the time, which affects further exploration. In this study, oil sources from the oil layers of Ch6, Ch8 and Ch9 are all analyzed and confirmed. Through their carbon isotope value and biomarkers, characteristics of crude oils from the Yanchang Formation are analyzed. Then, the oil–source relation is discussed, with the source rocks' features. Finally, the oil–source relation is calculated through cluster analysis. It is believed that the oils from the Yanchang Formation deposit in a similar redox environment, with weak oxidation–weak reduction, and have all entered maturity stage. Ch9 crude oil is more mature than crude oils from Ch6 and Ch8, and has more advanced plants and fewer algae. Gas chromatography (GC) and gas chromatography–mass spectrometry (GC–MS) analysis show that crude oils from Ch6 and Ch8 may come from Ch7, and Ch9 crude oil may not. Cluster analysis displays that crude oils from Ch6 and Ch8 have closer squared Euclidean distance with Ch7 source rocks than Ch9 crude oil does, indicating crude oils from Ch6 and Ch8 stem from Ch7 source rocks. And Ch9 crude oil has rather close squared Euclidean distance with Ch9 source rocks, illustrating Ch9 crude oil may be from Ch9 source rocks. This research may provide the theoretical basis for the next exploration deploy in the south of Ordos Basin.

Keywords Carbon isotope · Biomarker · Oil–source correlation · Cluster analysis · Yanchang Formation · Ordos Basin

1 Introduction

Oil–source correlation (in petroliferous basins) refers to the relation between crude oils and source rocks to confirm where gathered crude oils are from and to further predict the location of source rocks and reservoirs (Li 2000; Peng and Lü 2003; Cao et al. 2012). So far, oil–source correlation is studied mainly by geochemistry, including inorganic geochemistry and organic geochemistry. In inorganic geochemistry methods, trace elements are always used (Deng 1993; Jing et al. 2001). But, under the influence of their migration and secondary changes, there are still some limitations when applying them. Through organic geochemistry, oil–source correlation has been widely applied and favourable results have been achieved at present. Guo et al. (2006) discussed the oil source of the Yanan Formation in the southwest of the Ordos Basin and ensured that crude oils from Yanan Formation were from the Yanchang Formation. Bai et al. (2013b) studied the geochemical characteristics of crude oils and the oil–source correlation of the Yanchang Formation in the center of the Ordos Basin through biomarkers. However, previous studies (Meng et al. 2011; Bai et al. 2013b) often focus on qualitative analysis using carbon isotopes and biomarkers, leading to subjective judgments. Oil–source relation is hard to be identified accurately through spectrums of biomarkers in view of similar sedimentary environments. So it is necessary to combine some cluster analysis methods (Chang et al. 2004; Zhao et al. 2015) to deliver the verdict on the source of crude oils more accurately.

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The Ordos Basin is a large inner continental sedimentary basin in western China, with a huge oil resource potential in its Upper Triassic Yanchang Formation, developing two sets of source rocks (Ch7 and Ch9) (Duan et al. 2013). So far it can be confirmed that oil from the Ch7 oil layer is derived from Ch7 source rocks (Bai et al. 2013a; Zhao et al. 2014; Ren et al. 2014; Zhang et al. 2013; Zhao et al. 2012; Liang et al. 2011), while in other oil layers, the relation between the oil and source rocks has been controversial. Some scholars (Luo et al. 2010; Zhang et al. 2011) argued that oil from the whole Yanchang Formation is from Ch7 source rocks in the southwestern basin. However, other experts insisted that in the south central basin, oil from the Yanchang Formation stems from lower Ch9 source rocks, instead of Ch7 source rocks, and discussed the migration path before summarizing the different accumulation models with various reservoir cap assemblages (Duan et al. 2009; Zhang et al. 2008; Zhou et al. 2008). Given that they contain abundant fingerprint information, biomarkers can be applied to ascertain the oil–source correlation from 3 aspects: forming environment, kerogen type and maturation (Connan and Cassou 1980; Li et al. 1999; Duan et al. 2006). Consequently, by means of multiple parameters and spectrums of biomarkers, the oil–source relation can be discerned in previous research. Nonetheless, the similar geochemistry characteristics of Ch7 and Ch9 source rocks can still result in confused conclusion concerning oil source. Therefore, the issue of the oil–source relation needs to be further studied, which has significant meaning for further petroleum exploration of the Yanchang Formation.

In this paper, the crude oils geochemistry characteristics of the Yanchang Formation are analyzed primarily, including the crude oils carbon isotope value and their group compositions, *n*-alkanes and isoprenoids, steroid series and terpenoid series. Then, based on geochemistry characteristics and cluster analysis, the oil-resource correlation is conducted. After comprehensively judging the information, the sources of oil in different oil layers are finally proved.

2 Geological settings

Located in structural binding site of Midwestern China and consisting of six first-order tectonic units, Weibei Uplift, Yishan Slope, Yimeng Uplift, Jinxi Flexure Zone, Tianhuan Depression and Western Thrusted Zone (Fig. 1a), the Ordos Basin is the end product of movements affected from the Pacific plate and Tethyan oceanic crust after Indosinian movement (Wang 2011), which is one of the main basins developing hydrocarbon in China. The Yanchang Formation from the Upper Triassic, especially, is the most significant oil layer in the Ordos Basin in view of its abundant oil and gas reserves.

The Upper Triassic Yanchang Formation is divided into ten oil layers from top to bottom (Ch1 to Ch10), of which Ch9 and Ch7 are the main source rocks. The Ch9 oil layer develops 2 sets of fine source rocks at the top and bottom interlayered with dark gray and dark purple mudstones, siltstone and post stone. The Ch7 oil layer, in particular, was deposited 80–100 m in the deep lacustrine environment with a subsidence center near Fuxian (Duan et al. 2013), composing of dark gray mudstones and carbonaceous mudstone with thin siltstones at the top and charcoal grey mud, argillaceous siltstone and oil shale in the low part (Fig. 1b). Tilting to the northwest, the study area is situated in the transitional region between the Weibei Uplift and Yishan Slope, with an area of 1800 km^2 (Fig. 1a).

After the late Triassic, the area undergoes the formation and development period of tectonic evolution into a large inland basin of diverse sedimentation, receiving deposit of Triassic in the whole area (Yang and Deng 2013). Indosinian movement in the late Triassic and later Yanshan movement cause its unbalanced uplift, with various degrees of weathering denudation and deformation, resulting in the stratigraphic gaps from Ch6 oil layer to overlying Jurassic stratums and Ch1 and Ch2 oil layers to be universally missing from the southwestern area (Fig. 2). So far, industrial oil flows have been discovered in Ch6, Ch7, Ch8 and Ch9 oil layers.

3 Samples and analysis methods

In this study, 10 samples were collected from source rocks of Ch7 oil layer and 10 samples were collected from crude oil of Ch6, Ch8 and Ch9 oil layers in the study area, which were dispersedly located (Fig. 2).

The source rock samples were extracted with chloroform ($CHCl_3$) for 72 h. after being powdered under 80 mesh. Chloroform bitumen "A" analysis of source rocks were conducted by SY/T 5118-1995.

For group compositions analysis, 50 mg fractions of rock extracts or oils were analyzed, of which asphaltene was deposited with hexane. After solvent removal by rotary evaporation, the rock extracts or oils were fractionated using column chromatography (silica gel/alumina, 3:1) into saturates, aromatic and resins. The additive elution solvents were hexane, benzene and anhydrous alcohol. Analysis method was followed by SY/T 5119-2008.

For the carbon isotopic analysis of group compositions, chloroform bitumen "A" and crude oil, experiments were performed on MAT252, with 68 eV electron energy, 200 mass resolution, $<2 \times 10^{-6}$ Pa vacuum degree and

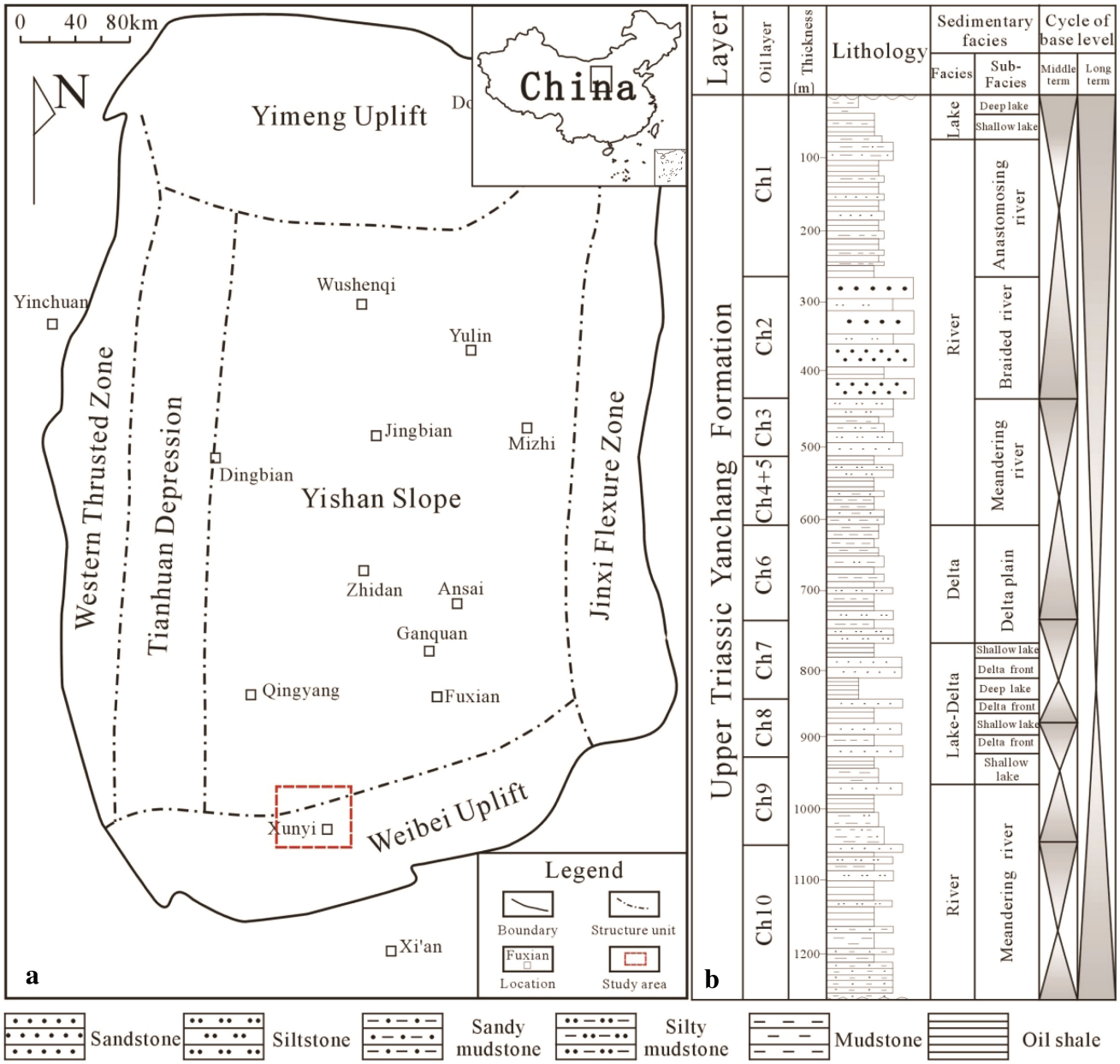

Fig. 1 **a** The geological map of Ordos Basin and location of studied section and **b** stratigraphic column of Upper Triassic Yanchang Formation (modified after Qiu et al. 2014)

0.8 mA emission current. The carbon isotope standard is the PDB standard, with less than ±0.3 ‰ test error.

The saturates of oils and extracts were tested by gas chromatography (GC) and gas chromatography–mass spectrometry (GC–MS) in Geochemistry Laboratory, China University of Petroleum. Gas chromatography (GC) analyses were conducted on an SHIMADZU GC-2010, under 26 °C indoor temperature and 50 % relative humidity, equipped with a 30 m × 0.25 mm × 0.25 μm HP-5 fused silica capillary column, with He as the carrier gas. Then the gas is boosted at the rate of 1.0 mL/min. The initial temperature of GC oven was kept at 100 °C. After 1 min, the temperature was increased to 300 °C at a rate of 4 °C/min, and then held at 300 °C for 25 min. The temperatures set for both the injector and FID were 300 °C. The testing standard was followed by GB/T 18340.5-2010.

Gas chromatography–mass spectrometry (GC–MS) analyses were performed on an Agilent 6890GC/5975i MS, under 26 °C indoor temperature and 50 % relative humidity, equipped with a 60 m × 0.25 mm × 0.25 μm HP-5MS fused silica capillary column, with He as the carrier gas. Then the gas is boosted at the rate of 1.0 mL/min. The initial temperature of GC oven was kept at 50 °C. After 1 min, the temperature was increased to 120 °C at a

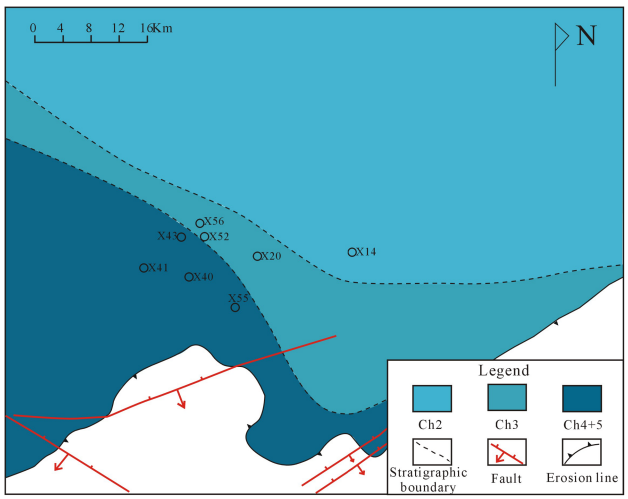

Fig. 2 Distribution of Yanchang Formation sedimentary strata before Jurassic in study area

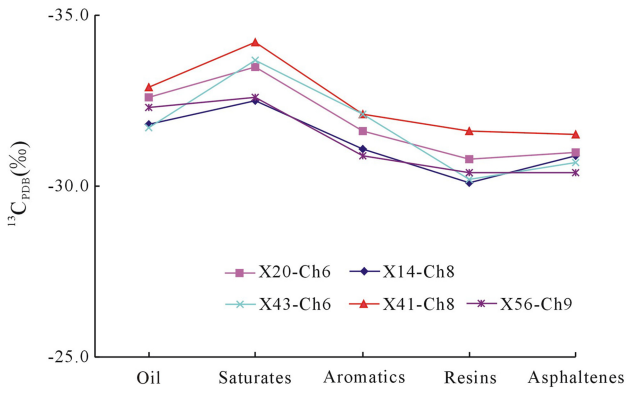

Fig. 3 Carbon isotopic distribution of crude oil samples and their group compositions in Yanchang Formation X20-Ch6 represents sample of Ch6 oil layer from X20 well and the rest are the same expression as this one

rate of 20 °C/min, and then held at 310 °C for 25 min. The testing standard was followed by GB/T 18606-2001.

4 Results and discussions

4.1 Geochemical characteristics of crude oil samples

Group compositions of crude oils are commonly affected by their source rocks sedimentary backgrounds, kerogen types, evolution degree, later modification and so on (Sofer 1984; Peters et al. 1996; Zhang and Xu 1992; Chen and Xu 1992; Shen 2002; Wang et al. 2005; Zhang 2006). On the condition of similar organic matter, high mature crude oils should have more hydrocarbon components and less polar components, compared with low mature crude oil (Chang 2004).

In terms of their carbon isotope value (from −32.9 ‰ to −31.7 ‰) and their group compositions (Table 1), crude oil samples from the Yanchang Formation have similar distribution characteristics (Fig. 3), such as depositing in similar environment, for example, fresh water or brackish water, possibly, and being dominated by type I kerogen.

The gas chromatogram of saturated hydrocarbon of crude oil samples from the Yanchang Formation also show similar distribution features, with nC_{15}–nC_{20} as the main peaks and approximate pristine and phytane (Fig. 4). Normally, the evolution degree becomes high as the odd–even predominance (OEP) approaches 1(Luo et al. 2015). The OEP of crude oil samples are in a narrow range from 1.04 to 1.12, with an average of 1.08, implying similar weak oxidation–weak reduction sedimentary conditions and mature characteristics. In addition, their kerogen types are mixed types dominated by algae, which is consistent with the conclusion of crude oil carbon isotope and group compositions analysis.

The distribution and content of phytane (Ph) and pristane (Pr) are related with the redox conditions (Li et al. 1999; Hanson et al. 2000; Peters et al. 1999). Under a strong reducing environment, phytol, the parent materials of phytane and pristane, would mainly transform into phytane; under a weak oxidizing environment, phytol would mainly transform into pristane (Meng et al. 2011). Therefore, the Pr/Ph ratio is a direct indicator used for judging the ancient redox environment. The Pr/Ph ratio of the Yanchang Formation crude oil samples are from 0.62 to 0.87, with an average of 0.76 (Table 2), revealing that there is a tiny discrepancy between them and a similar type of biological sources. According to the water oxidation

Table 1 Carbon isotopic value of crude oil samples and their group compositions in Yanchang Formation

Well	Oil layer	$\delta^{13}C_{PDB}$ (‰)	Group compositions $\delta^{13}C_{PDB}$ (‰)			
			Saturates	Aromatics	Resins	Asphaltenes
X20	Ch6	−32.6	−33.5	−31.6	−30.8	−31.0
X43	Ch 6	−31.7	−33.7	−32.1	−30.2	−30.7
X41	Ch 8	−32.9	−34.2	−32.1	−31.6	−31.5
X14	Ch8	−31.8	−32.5	−31.1	−30.1	−30.9
X56	Ch 9	−32.3	−32.6	−30.9	−30.4	−30.4

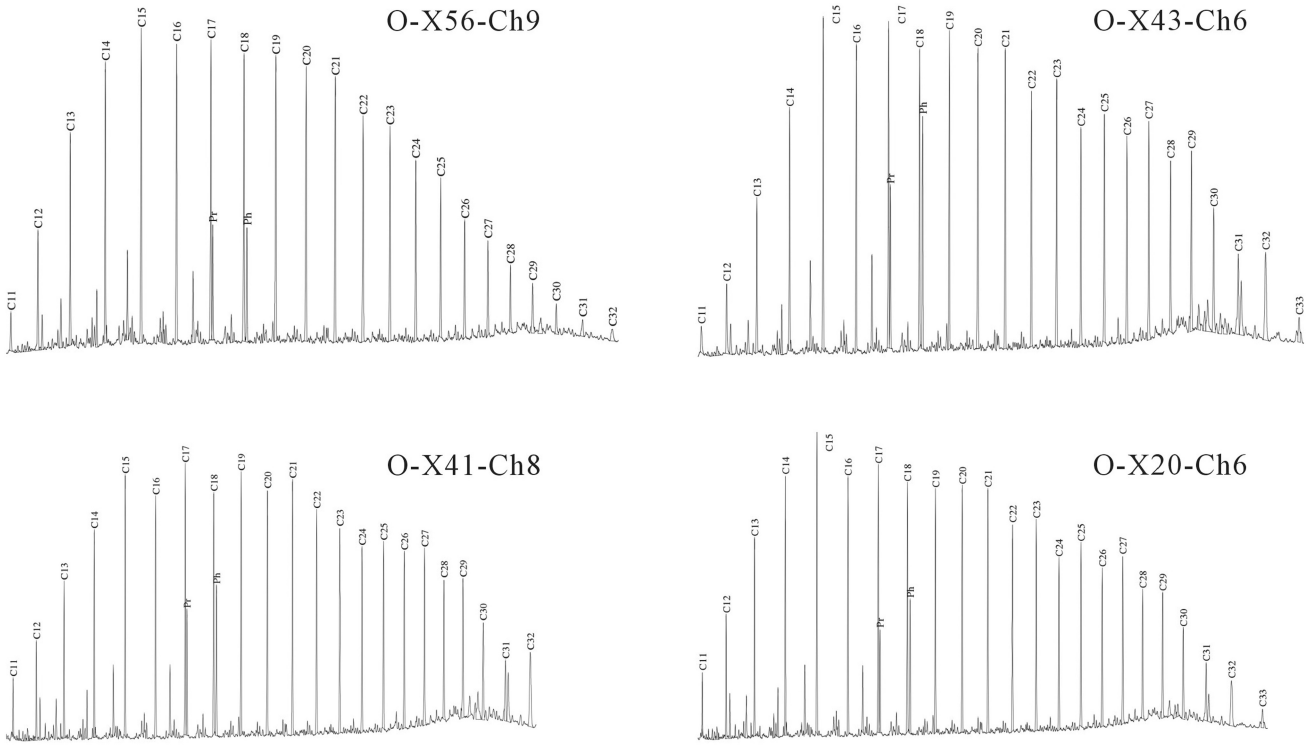

Fig. 4 Gas chromatogram of saturated hydrocarbon of crude oil samples in Yanchang Formation, O-X56-Ch9 represents crude oil sample of Ch9 oil layer from X56 well and the rest are the same expression as this one

reduction degree index proved by Haven (1987), the crude oil forming condition of Yanchang Formation is a weak oxidation–weak reduction environment. As can be seen from Fig. 5, the data of the crude oil samples projected to a relatively small region, illustrating that they may have similar parent materials.

During the evolution of the steroid series, the regular steroids 14,17(H) are converted from a αα configuration to a ββ configuration, with the chiral carbon atoms converted from a R-biological configuration to a S-geological configuration (Huang et al. 1990; Mei 1980). So it is appropriate to research maturity by comparing the different configuration of the steroid series. $\alpha\alpha\alpha C_{29}20S/(20S + 20R)$ and $C_{29}\beta\beta/(\beta\beta + \alpha\alpha)$ increase with the raising of the degree of maturity, with a reaction equilibrium value of 0.52–0.55 and 0.67–0.71, respectively (Seifert and Moldowan 1986). The $\alpha\alpha\alpha C_{29}20S/(20S + 20R)$ and $C_{29}\beta\beta/(\beta\beta + \alpha\alpha)$ of the crude oil samples from the Yanchang Formation are in a range of 0.49–0.54 and 0.38–0.56, respectively, illustrating that the oils have been mature (Fig. 6) (Chen et al. 1998; Zhao 2007; Huang et al. 1990).

C_{27} and C_{28} regular steranes are mainly from lower aquatic organisms (e.g. various algae) and C_{29} regular sterane can be typically not only from algae, but also from advanced plants. Regular steranes in the mass chromatogram are normally distributed in the shapes of "V", "L" and reversed "L". The first two shapes show that lower aquatic organisms are involved during sedimentation, while reversed "L" means containing advanced plants (Bai et al. 2013b).

The mass chromatogram of steranes of Ch6 and Ch8 crude oil samples all distribute in a reversed "L" shape, which means their parent materials have advanced plants. And mass chromatogram of steranes of Ch9 crude oil sample distribute in a "V" shape, which means algae are dominated in its parent materials more than advanced plants, compared with Ch6 and Ch8 crude oil samples (Fig. 7). The Ch9 crude oil sample has the characteristics of Ts > Tm. However, Ch6 and Ch8 crude oil samples show Ts < Tm, which illustrates that the Ch9 crude oil sample is more mature than those of the Ch6 and Ch8 (Fig. 7).

The distribution of regular steranes of crude oil can provide its parent materials (Duan et al. 2006). The C_{29} regular steranes of the crude oil samples of the Yanchang Formation have a higher mean percentage of 42.36 %, compared with C_{27} and C_{28} regular steranes with relatively lower average percentages of 29.3 % and 28.34 %, respectively. A ternary diagram of C_{27}, C_{28} and C_{29} regular steranes compositions display that the parent materials of the crude oil samples of the Yanchang Formation are from mixed types, mainly lower aquatic organisms and terrestrial advanced plants (Fig. 8).

Table 2 Biomarker parameters of source rocks and crude oils in Yanchang Formation, Ordos Basin

Well	Oil layer	Sample type	1	2	3	4	5	6	7	8	9			10	11	12	13	14	15
											C_{27}	C_{28}	C_{29}						
X40	Ch7	Source rock	0.98	0.86	0.72	0.89	1.11	0.50	0.41	0.07	31.20	19.80	49.00	0.84	0.03	0.28	0.18	0.58	0.40
X40	Ch7	Source rock	1.54	1.70	0.75	0.59	1.21	0.48	0.43	0.05	31.90	18.50	49.60	2.03	0.02	0.52	0.19	0.58	0.30
X41	Ch7	Source rock	0.86	0.93	0.94	1.00	1.06	0.50	0.36	0.10	36.10	20.10	43.80	0.76	0.02	0.15	0.19	0.57	0.31
X41	Ch7	Source rock	2.02	0.90	0.35	0.48	1.08	0.50	0.36	0.06	32.70	22.60	44.70	1.02	0.01	0.21	0.09	0.57	0.79
X52	Ch7	Source rock	2.41	0.72	0.31	0.49	1.19	0.49	0.43	0.04	33.60	24.30	42.10	0.98	0.03	0.22	0.13	0.56	0.49
Z85[a]	Ch9	Source rock	1.32	1.18	0.22	0.14	0.98	0.48	0.43	0.21	37.90	25.10	37.00	1.34	0.26	0.01	0.10	0.59	1.02
X93[a]	Ch9	Source rock	1.38	2.91	0.53	0.17	1.05	0.49	0.50	0.66	38.90	21.80	39.30	1.35	0.12	0.21	0.13	0.59	1.50
X20	Ch6	Crude oil	1.27	0.76	0.41	0.58	1.12	0.53	0.46	0.02	28.00	29.10	42.90	0.58	0.04	0.19	0.10	0.54	0.29
X43	Ch6	Crude oil	1.09	0.62	0.50	0.88	1.08	0.49	0.38	0.02	27.50	28.10	44.40	0.58	0.03	0.32	0.12	0.56	0.49
X14	Ch8	Crude oil	1.38	0.77	0.35	0.48	1.04	0.54	0.52	0.03	29.30	26.20	44.50	0.60	0.05	0.22	0.10	0.53	0.30
X41	Ch8	Crude oil	1.11	0.77	0.49	0.67	1.06	0.51	0.46	0.01	26.20	29.20	44.60	0.59	0.03	0.19	0.11	0.55	0.24
X56	Ch9	Crude oil	2.12	0.87	0.34	0.41	1.09	0.50	0.56	0.06	35.50	29.10	35.40	0.78	0.13	0.57	0.09	0.47	0.46
X62[a]	Ch9	Crude oil	2.87	1.18	0.31	0.23	1.23	0.59	0.58	0.15	37.70	25.70	36.60	0.47	0.09	0.30	0.07	0.56	1.03

1, $\sum C_{21-}/\sum C_{22+}$; 2, Pr/Ph; 3, Pr/$nC_{17}$; 4, Ph/$nC_{18}$; 5, OEP; 6, ααα$C_{29}$sterane20S/(20S + 20R); 7, C_{29}steraneββ/(ββ + αα); 8, Diasteranes/regular steranes; 9, Regular steranes; 10, (C_{19} + C_{20})/C_{23}tricyclics; 11, C_{23}tricyclics/(C_{23}tricyclics + C_{30}hopance); 12, Regular steranes/hopance; 13, βα-C_{30}moretane/αβ-C_{30}hopance; 14 C_{31}hopance22S/(22S + 22R); 15 Ts/Tm

[a] Data cited are from Zhao et al. (2015). The wells are sited in northwest edge of the study area

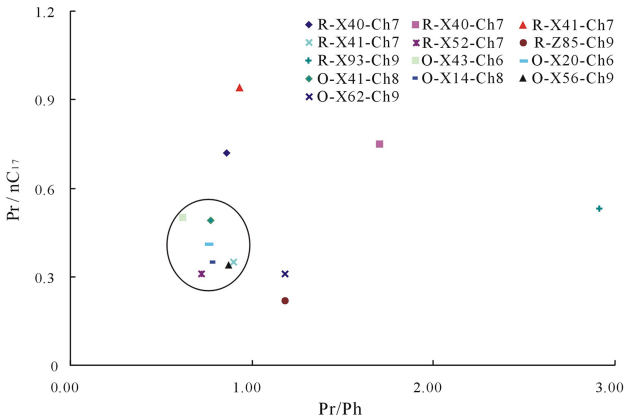

Fig. 5 Cross plots of Pr/nC_{17} versus Pr/Ph rations in the studied crude oil samples and source rock samples in Yanchang Formation, R-X40-Ch7 represents source rock sample of Ch7 oil layer from X40 well and the rest are the same expression as this one

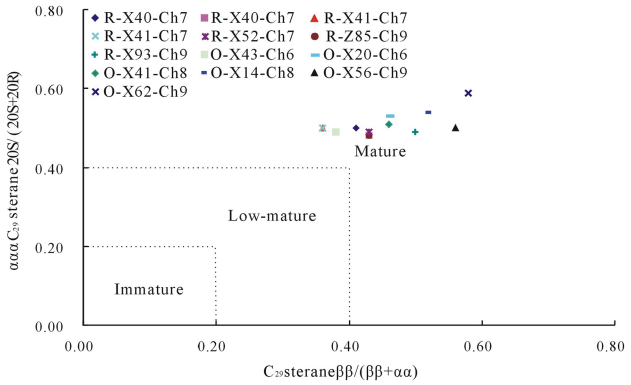

Fig. 6 Cross plot of αααC_{29}sterane20S/(20S + 20R) versus C_{29}steraneββ/(αα + ββ) rations in studied crude oil samples and source rock samples in Yanchang Formation

In the terpenoid series, hopanoids are transformed from a biological configuration of ββ-C_{30} hopanes to a geological configuration of αβ-C_{30} hopanes and from 22R to 22S in the evolution process (Mei 1980). Thus, βα-C_{30} moretane/αβ-C_{30} hopanes and C_{31}homohopane 22S/(22S + 22R) can be indicators for judging the maturity of crude oil. βα-C_{30} moretane/αβ-C_{30} hopanes and C_{31}homohopane 22S/(22S + 22R) are from 0.09 to 0.12 and from 0.47 to 0.56, with an average of 0.10 and 0.53, respectively (Table 2), which means a similar forming environment and mature characteristics to the crude oil samples of the Yanchang Formation.

4.2 Oil–source correlation

4.2.1 Geochemical characteristics of source rock samples

The carbon isotope value is always used to discern the tiny fluctuated variation of the $\delta^{13}C$ in organic matters. The carbon isotope value of crude oil, its group compositions and chloroform bitumen "A" can be formed to diverse tendency lines, ascertaining an oil–source relation between crude oils and source rocks (Li et al. 2000).

The carbon isotope value of chloroform bitumen "A" and the group compositions of source rock samples in Ch7 have approximative distributions, implying their similar sedimentary environment and parent materials, and the carbon isotope value of chloroform bitumen "A" is from

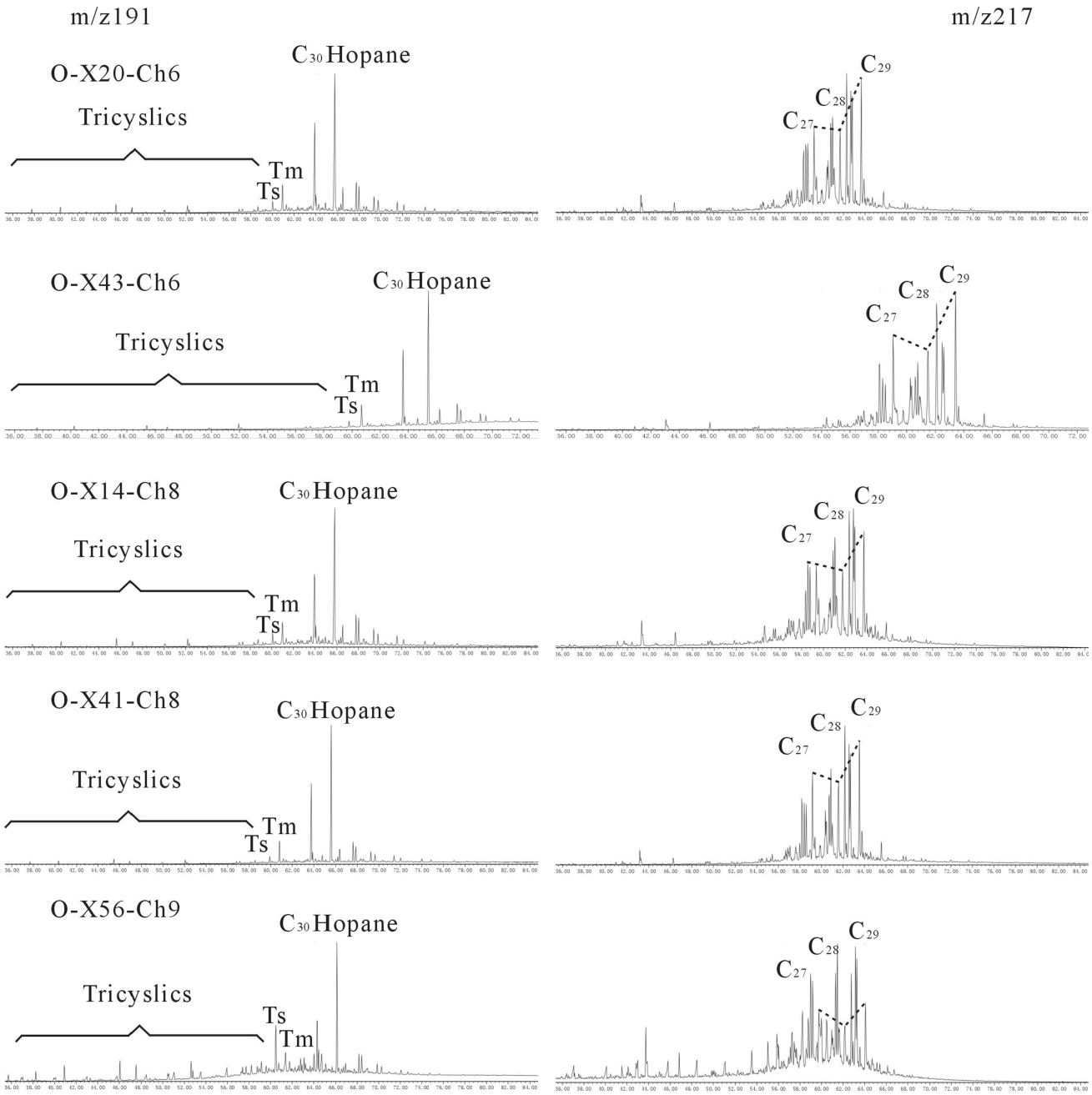

Fig. 7 Mass chromatogram of hopanes (m/z 191) and steranes (m/z 217) of crude oil samples in Yanchang Formation

−32.0 ‰ to −27.9 ‰ with an average of −29.7 ‰ (equivalent to Ro = 0.7 %–0.8 %).

To be specific, two source rock samples from the X40 well possess higher carbon isotope values of chloroform bitumen "A" than other samples, which may be caused by the different properties of their parent materials. This can also explain the anisotropism of the source rock samples.

Comparing Fig. 3 with 9, crude oil samples from the Yanchang Formation almost have the same tendency lines with Ch7 source rock samples (Table 3), reflecting that there may be close relationship among them.

During the degradation of it, kerogen would be full of heavier $\delta^{13}C$. The values of $\delta^{13}C$ normally decrease with the reducing polarity of each group composition, showing characteristics of asphaltenes > resins > aromatics > saturates (Zhang 2006). However, thermal maturation and migration have an effect on the carbon isotope of each group composition, so it is reasonable to consider other biomarkers in association with the oil–source correlation.

Saturated hydrocarbon mass chromatograms of Ch7 source rock samples uniformly show a single peak type with C_{15} and C_{19} as the main peak and no obvious odd–

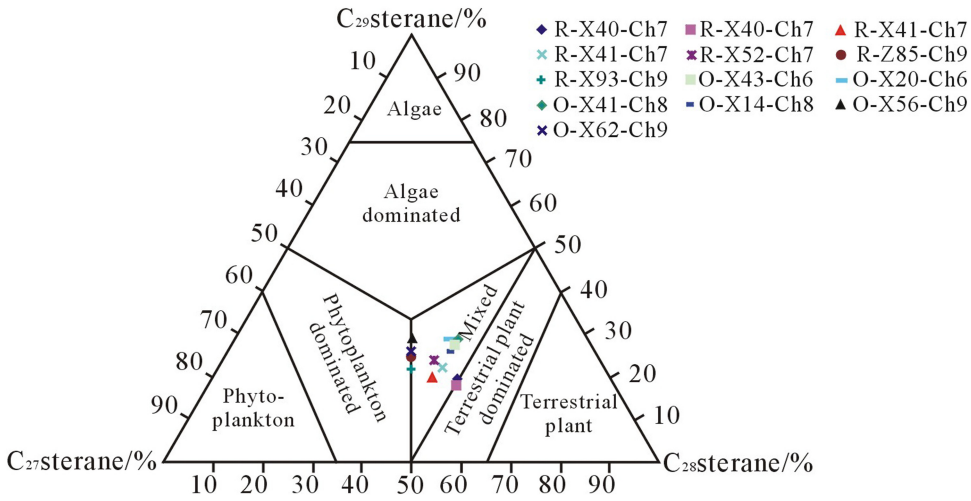

Fig. 8 Ternary diagram of C_{27}, C_{28} and C_{29} sterane compositions in crude oil samples and source rock samples in Yanchang Formation, and the base map is from Zhao et al. (2015)

even predominance (Fig. 10), reflecting that their configurations are close to each other with plenty of algae input. But there are still differences among the source rock samples' sedimentary environments. Ch7 source rock samples from the X40 well have a higher oxidation degree than other samples with Pr/Ph = 1.70 (Fig. 5). One of the source rock samples from the X41 well is closely related to Ch6 crude oil from the X20 well and the X43 well, Ch8 crude oil from the X14 well and the X41 well and Ch9 crude oil from the X59 well, indicating they may have the same consanguinity, while source rock samples from the X40 well are far from crude oil samples, reflecting rather far relation among them (Fig. 5).

Regular steranes of Ch7 source rock samples have the similar reversed "L" shape distribution with crude oil samples from Ch6 and Ch8, suggesting crude oil may come from Ch7 source rocks (Fig. 11). However, Ch9 crude oil samples with a "V" distribution may not stem from Ch7 source rocks.

At the same time, C_{31}hopanes22S/(22S + 22R) versus Diasteranes/regular steranes shows that crude oil samples

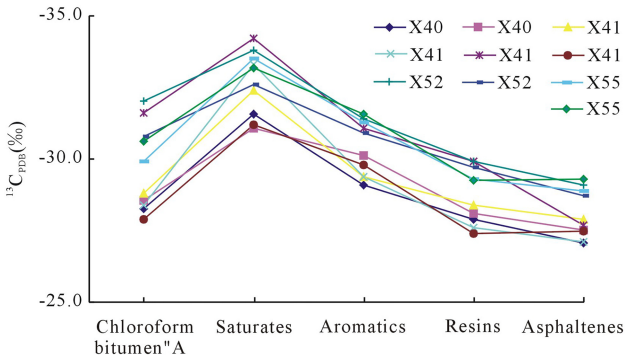

Fig. 9 Carbon isotope distribution of chloroform bitumen "A" and group components of Ch7 source rock samples

of Ch6 and Ch8 and Ch7 source rock samples are distributed in a small region with a short distance of Ch9 crude oil sample, which possibly implies crude oils from Ch6 and Ch8, instead of Ch9 crude oil, may stem from Ch7 source rocks (Fig. 12).

The C_{31}homohopane22S/(22S + 22R) of about 0.60 attains equilibrium at the beginning of the oil window (Waples and Machihara 1991). C_{31}homohopane22S/(22S + 22R) of Ch7 source rock samples are in range of 0.56–0.58 with an average of 0.57, implying that they have almost approached the oil window.

However, because of axis scales, Fig. 12 can only declare a possible relation between the crude oil samples and source rock samples. Distances among samples would diminish when the axis scales enlarged, so it can only distinguish the possibility.

4.2.2 Oil–source correlation cluster analysis

In conventional figures concerning oil–source correlations, oil–source relations are always influenced by axis scales. If the axis scales turn large, data casted into the figure are proved to have better relevance with minor distance. On the contrary, worse relevance among samples can be determined with small axis scales. Therefore, more analysis should be conducted to explore the relations of crude oil and source rocks.

For subtler research of oil–source correlations, more sensitive parameters and more accurate calculation methods should be used for analysis. Using relative Euclidean distance and the dendrogram of cluster analysis theory, correlations and attributes among samples can be clearly perceived. The basic logic of cluster analysis is to classify the similarity level of statistic value one by one, according to the affinity relationship diagram (Zhu et al. 2000).

Table 3 Carbon isotopic value of Ch7 source rock samples and their group compositions

Well	Chloroform bitumen "A" $\delta^{13}C_{PDB}$ (‰)	Group compositions $\delta^{13}C_{PDB}$ (‰)			
		Saturates	Aromatics	Resins	Asphaltenes
X40	−28.3	−31.6	−29.1	−27.9	−27.1
X40	−28.5	−31.1	−30.1	−28.1	−27.5
X41	−28.8	−32.4	−29.4	−28.4	−27.9
X41	−28.4	−33.3	−29.4	−27.6	−27.1
X41	−31.6	−34.2	−31.1	−29.9	−27.7
X41	−27.9	−31.2	−29.8	−27.4	−27.5
X52	−32.0	−33.8	−31.4	−29.9	−29.1
X52	−30.8	−32.6	−30.9	−29.7	−28.7
X55	−29.9	−33.5	−31.3	−29.3	−28.9
X55	−30.6	−33.2	−31.6	−29.3	−29.3

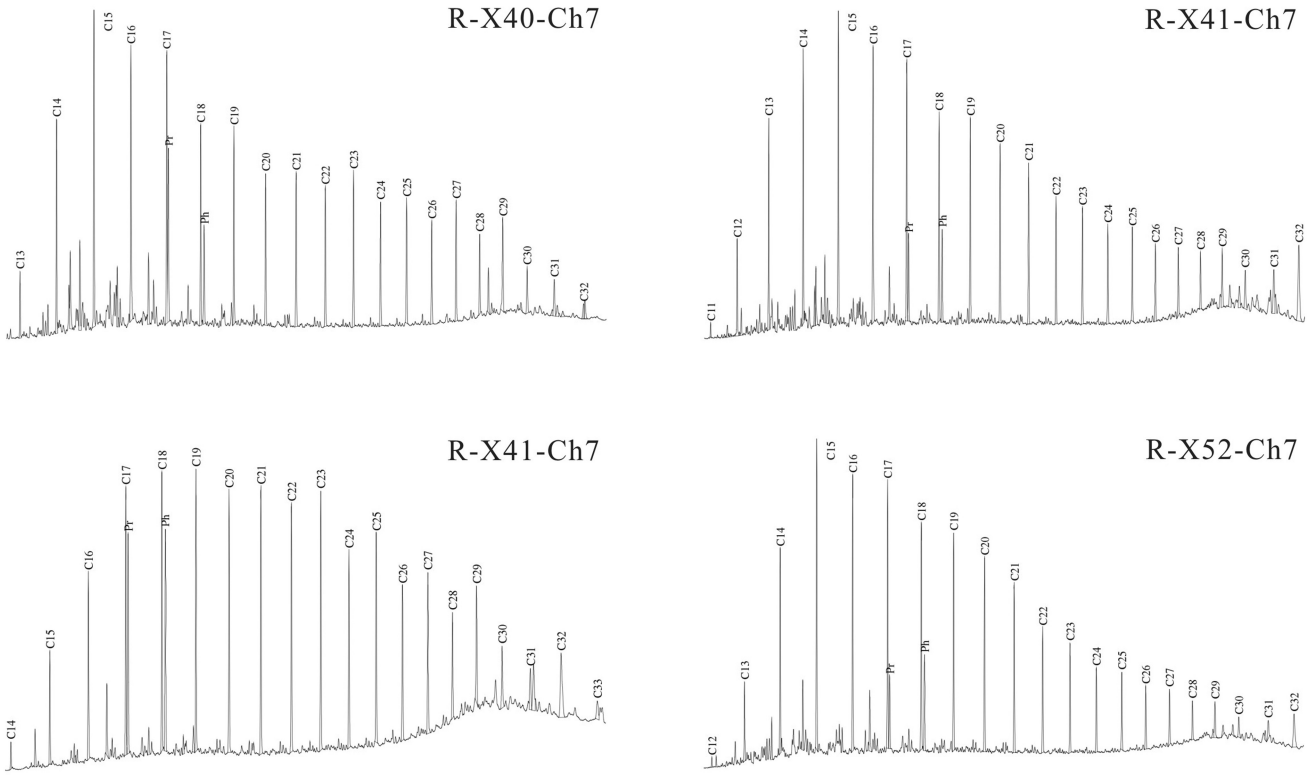

Fig. 10 Staturated hydrocarbon mass chromatogram of Ch7 source rock samples

By using the hierarchical clustering method, the crude oil samples of Ch6, Ch8 and Ch9 and source rock samples of Ch7 and Ch9 (Zhao et al. 2015) are calculated by 17 parameters (Table 4). Correlations among crude oil samples of Ch6 from the X20 well and the X43 well and Ch8 from the X14 well and the X41 well are preferable (Fig. 13), which illustrate that they come from the same source rocks. All the source rock samples from Ch7 have good correlations (Fig. 13), demonstrating that the paleoenvironment of the sedimentary period has little difference in the study area, with higher correlations.

Compared with those of Ch9 from the Z85 well and X93, source rock samples of Ch7 have good correlations with the crude oil samples of Ch6 and Ch8, which explains

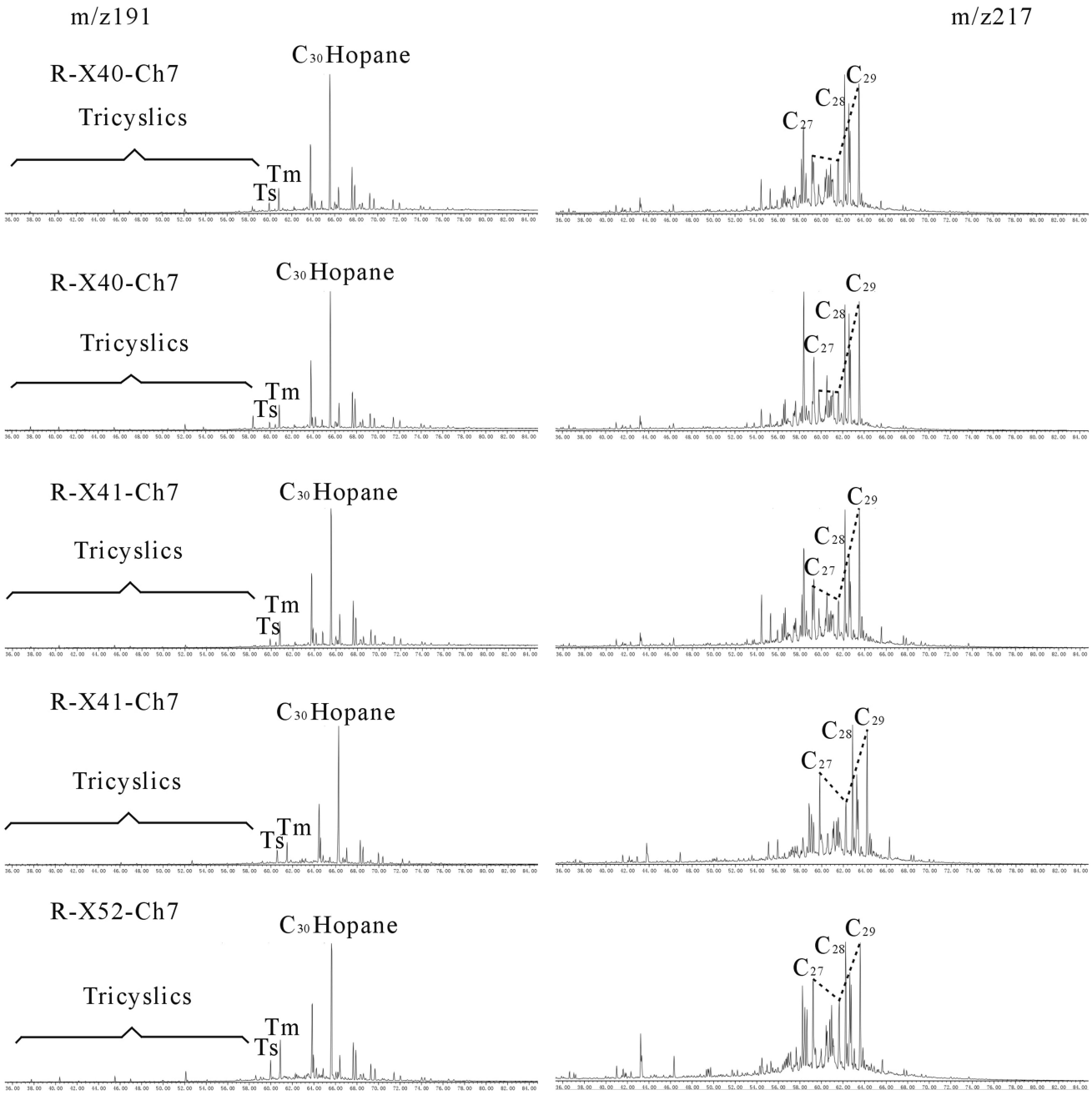

Fig. 11 Mass chromatogram of hopanes (m/z 191) and steranes (m/z 217) of Ch7 source rock samples

the fact that oil of Ch6 and Ch8 originate from Ch7 source rocks. Ch9 source rock sample from the Z85 well have 0.003-squared Euclidean distance (Table 4) with crude Ch9 oil sample from the X62, which means Ch9 oil is likely from Ch9 source rocks. And, Ch9 crude oil of the X56 well has worse relation with Ch7 source rocks, which shows that Ch9 crude oil doesn't come from Ch7 source rocks in the study area.

5 Conclusions

Crude oils and their group compositions from the Yanchang Formation have similar carbon isotopic values (−32.9 ‰ to −31.7 ‰), indicating they have similar parent materials (mainly algae) and forming environments. The biomarker parameters [OEP, Pr/Ph, regular steranes, $\alpha\alpha\alpha C_{29}$sterane20S/(20S + 20R), C_{29}sterane$\beta\beta/(\beta\beta + \alpha\alpha)$,

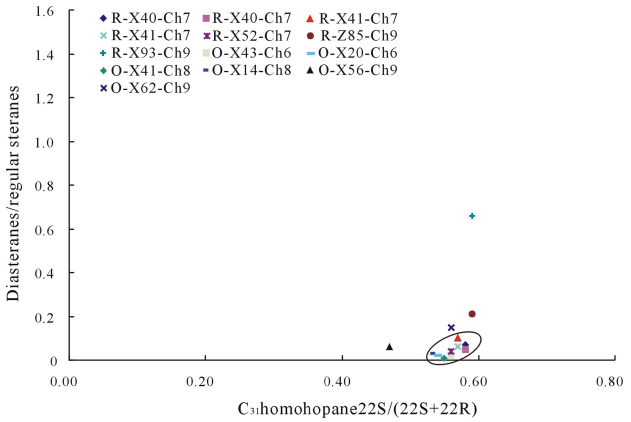

Fig. 12 Cross plot of C_{31}homohopane 22S/(22S + 22R) versus Diasteranes/regular steranes rations in studied crude oil samples and source rock samples in Yanchang Formation

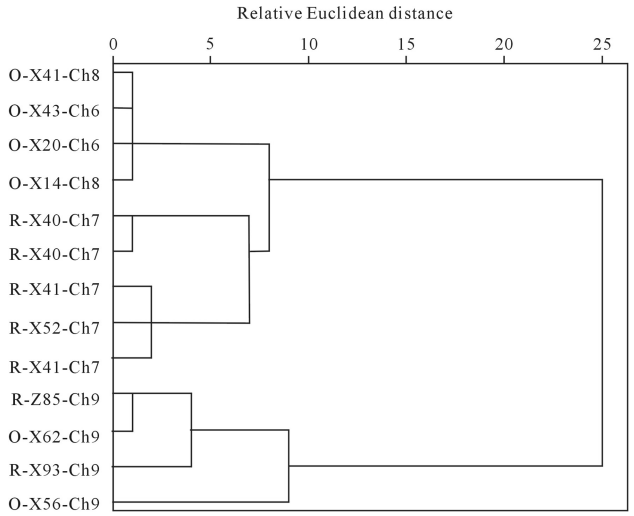

Fig. 13 Cluster analysis of biomarker parameters in the studied crude oil samples and source rock samples in study area

C_{31}hopance22S/(22S + 22R) etc.] of the crude oils from the Yanchang Formation reflect that the oils have already entered the maturity stage and were deposited in a weak oxidation–weak reduction sedimentary environment.

According to the ratios and distribution characteristics of the biomarkers, the crude oils of Ch6 and Ch8 in study area, rather than Ch9 crude oil, are from Ch7 source rocks,. Ch9 crude oil may not come from Ch7 source rocks. By cluster analysis, crude oils of Ch6 and Ch8 have rather closer squared Euclidean distance with Ch7 source rocks, which means they do actually come from Ch7 source rocks. Ch9 crude oil has a further squared Euclidean distance with Ch7 source rocks, with a closer squared Euclidean distance with Ch9 source rocks, implying that Ch9 oil may stem from Ch9 source rocks.

Table 4 Squared Euclidean distance between the studied samples in Yanchang Formation, Ordos Basin

Sample number	Squared Euclidean distance												
	R-X40-Ch7	R-X40-Ch7	R-X41-Ch7	R-X41-Ch7	R-X52-Ch7	R-Z85-Ch9	R-X93-Ch9	O-X14-Ch8	O-X20-Ch6	O-X41-Ch8	O-X43-Ch6	O-X56-Ch9	O-X62-Ch9
R-X40-Ch7	0.000												
R-X40-Ch7	0.002	0.000											
R-X41-Ch7	0.112	0.121	0.000										
R-X41-Ch7	0.057	0.076	0.032	0.000									
R-X52-Ch7	0.171	0.201	0.046	0.025	0.000								
R-Z85-Ch9	0.610	0.646	0.224	0.295	0.148	0.000							
R-X93-Ch9	0.459	0.471	0.120	0.217	0.124	0.039	0.000						
O-X14-Ch8	0.102	0.142	0.133	0.034	0.058	0.375	0.349	0.000					
O-X20-Ch6	0.227	0.284	0.234	0.107	0.094	0.371	0.404	0.020	0.000				
O-X41-Ch8	0.195	0.251	0.285	0.129	0.153	0.523	0.536	0.024	0.010	0.000			
O-X43-Ch6	0.157	0.208	0.217	0.085	0.106	0.448	0.450	0.006	0.005	0.000	0.000		
O-X56-Ch9	0.934	1.000	0.494	0.519	0.301	0.076	0.225	0.519	0.429	0.604	0.550	0.000	
O-X62-Ch9	0.649	0.689	0.257	0.317	0.159	0.003	0.061	0.389	0.376	0.531	0.459	0.058	0.000

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