Biomarker distributions and depositional environments of continental source rocks in Sichuan Basin, SW China

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Abstract
In order to study the distributions of the biomarker of the continental source rocks in the Sichuan Basin, 71 source rock samples were collected from the Upper Triassic-Lower Jurassic strata in different regions. The n-alkanes, isoprenoids, terpane, sterane, sesquiterpenes, caranes and aromatics in the extracts were analyzed in detail. GC-MS analysis has been conducted to analyze the biomarker of the continental source rocks. The results of GC-MS analysis indicate that the Upper Triassic source rocks are high in the content of extended tricyclic terpanes, pristane, phytane, gammacerane, C₂₈ regular sterane and carotene. However, they are low in content of rearranged compounds. The ratio of Pr/Ph is less than 1, with the characteristics of tricyclic terpane C₂₁ > C₂₃. The Lower Jurassic source rocks are extremely low in content (even zero) of extended tricyclic terpanes, pristane, phytane, gammacerane, C₂₈ regular sterane and carotene, and high in content of rearranged compounds. The ratio of Pr/Ph is more than 1, with tricyclic terpane C₂₁ > C₂₃. These characteristics are still preserved after maturation. Moreover, during the sedimentation of the source rocks of T₃x²–T₃x³ members, the supply of continental plants was low (TAR < 1, with regular sterane C₂₇ > C₂₉, 1-MP/9-MP < 1). The source rocks of T₃x⁵ member were low in salinity (slightly low content of gammacerane and carotene), being different significantly from the other Upper Triassic source rocks. In addition, during the sedimentation of the source rocks of J₁dn Member, the supply of continental plants was also low (regular sterane C₂₇ > C₂₉, 1-MP/9-MP < 1), being quite different from that of J₁l member.
Through analysis of the difference in biomarkers, it is indicated that the sedimentary environment had changed from anoxic and brackish water during the Late Triassic to oxygen-rich and freshwater during the Early Jurassic in the Sichuan Basin. During this process, the types of organic matters had changed for several times.

**Keywords**
Biomarkers, source rock, sedimentary environment, continental facies, Triassic, Jurassic, Sichuan Basin

**Introduction**

Biomarkers, also known as molecular fossils, refer to the organic compounds derived from living organisms (Simoneit, 2004). Specifically, it refers to a specific compound with a certain stability during the process of geological evolution and records the special molecular structure information of the original biological parent material. Biomarkers exist widely in crude oil, source rock and coke pitch. Biomarkers are one of the most important geochemical tools in oil source correlation, which can provide the information about paleoenvironment, paleo-ecology and maturity of source rocks (Moldowan et al., 1986; Nytoft et al., 2020).

The Sichuan Basin is located in the south-western China, with an area of approximately \(18 \times 10^4 \text{km}^2\), between \(28^\circ\text{N} \text{ and } 32^\circ 40'\text{N}\) and \(102^\circ 30' \text{ to } 110^\circ\text{E} \) (Chen et al., 2014, 2016). Structurally, it belongs to the Upper Yangtze Plate. From Sinian to Quaternary, the strata are more than \(13,000 \text{ m}\) in thickness in this basin (Tong, 1990). The basin consists of five first-order oil and gas structural zones, including the paleo-tilted and middle-uplifted high-steep structural belt in the eastern Sichuan, paleo-depression and middle-uplifted lower structural zone in the southern Sichuan, paleo-uplifted and middle-tilted structural zone in the central Sichuan, low-steep structural zone in the middle and a new depression in the western Sichuan, and low-lying structural zone in the paleo-tilted and middle depression in the northern Sichuan (Lin et al., 2007).

The Sichuan Basin is one of the most important hydrocarbons-bearing basins in China, with multiple sedimentary cycles and several sets of source rocks. There are mainly two types of source rocks in the Sichuan Basin, namely marine and continental source rocks (Bai et al., 2010; Chen et al., 2016; Zhu et al., 2007). The marine source rocks are Late Sinian-Middle Triassic carbonate rocks which could be classified as five sets of source rocks, namely Z2d, ε1q, S1l, P1q and P2w in the (Xu et al., 2011). The continental source rocks are the Late Triassic clastic rocks, with six sets of source rocks, namely T3x1 (first member of the Xujiahe Formation), T3x2 (middle of the second member of the Xujiahe Formation), T3x3 (third member of the Xujiahe Formation), T3x5 (fifth member of the Xujiahe Formation) (Li et al., 2012), J1dn (Da’anzhai Formation) and J1l (Lianggaooshan Formation) in deposits (Figure 1) (Huang et al., 1996). According to the estimates by the company of PetroChina, \(4286.35 \times 10^{12} \text{ m}^3\) gas and \(3288.46 \times 10^8 \text{ t}\) oil have been generated from these source rocks, among which, 89.90% gas are generated from marine source rock, and all oil are generated from continental source rocks (Chen et al., 2014). Therefore, it is very important to study the continental source rocks in order to conduct the crude oil exploration in the Sichuan Basin.
The study on the biomarker of continental formations began in the 1980s in the Sichuan Basin. Tao (1988) conducted a systematic GC-MS analysis on the 10 black mudstone samples from the Upper Triassic strata in the western margin of the basin. Based on his analysis on terpane and sterane series compounds, Tao states that in the Sichuan Basin, epicontinental sea shelf-restricted facies deposited during the Early Late Triassic, but interior lacustrine facies deposited during the Middle-Late Triassic. The organic matter was at mature-high maturity stage. After that, the characteristics of biomarkers had been studied. By analyzing the distribution characteristics of biomarker, Li et al. (2015) and some other scholars had conducted the source-oil correlation for the Middle Jurassic oil sandstone in the north-western margin of the basin, the pyrobitumen in the Upper Triassic reservoirs in the Jiulongshan gas field in the north-western basin and the pyrobitumen in the reservoirs of the north-eastern Sichuan Basin, respectively. In addition, the study has been conducted about the sedimentary environment of the Late Triassic in the Sichuan Basin. It is generally believed that the marine environment was dominated during the early sedimentation stage of T₃ₓ₁, then changed into continental environment during the late sedimentation stage of T₃ₓ₁. After that, the seawater of Paleotethys entered into the Sichuan Basin. Some scholars, such as Luo (2011) believed...
that the marine sedimentary environment continued until T₃ₓ⁴. Shi (2012) considered that short-term local transgression occurred after the transition to continental deposition during the sedimentation of T₃ₓ¹. Zhang et al. (2012) discovered dinoflagellates in the source rocks of the Late Triassic Xujiahe Formation. It has been found that the biomarkers of the Late Triassic source rocks are different from that of the typical swamp facies source rocks. Therefore, a transgression had occurred in the Late Triassic.

Although extensive study has been conducted on the biomarkers of the continental source rocks in the Sichuan Basin (Lin, 2014; Shi et al., 2012; Yu et al., 2016), there are still some problems. Firstly, most studies are about the source rocks of the Late Triassic Formation, and only a few studies have been conducted on the Lower Jurassic source rocks. In addition, few studies have been conducted on the difference of biomarkers in these source rocks at different horizons. Secondly, as mentioned above, there are still many disputes about the sedimentary environment during the Late Triassic in Sichuan Basin. In addition, the analysis on the sedimentary environment during the Late Triassic through organic geochemistry study of the source rocks is not much, which is also a weak point in the present study. In this study, to address the two major weaknesses of the current study, the samples of the source rocks from the six layers of T₃ₓ¹, T₃ₓ², T₃ₓ³, T₃ₓ⁵, J₁dn and J₁l in Sichuan Basin have been collected, analysis about their biomarker distribution characteristics and the difference have been carried out, and biomarker distribution laws have been found out. The results of these study work can provide an important basis for the oil source correlation in the strata from the Upper Triassic to Lower Jurassic in Sichuan Basin. In addition, analysis about the main sedimentary environment of the source rocks from the Late Triassic to the Early Jurassic in Sichuan Basin has been conducted on the basis of the results of these study work, provide some understanding about sedimentary environment during this period from the organic geochemical aspects.

**Samples and experiment**

Seventy-one core samples have been collected from six sets of strata, including the T₃ₓ¹, middle T₃ₓ², T₃ₓ³, T₃ₓ⁴, T₃ₓ⁵, J₁dn, and J₁l in the major sedimentary province of the continental source rocks in the Sichuan Basin. The samples were collected jointly by the company of PetroChina and Sinopec. In addition, the source rock samples exposed on the surface of Xuanhan County and Shizhu County in the eastern Sichuan region were also collected (the locations are shown in Figure 1). The bulk geochemical characteristics of these samples in are shown in Table 1.

In order to avoid the contamination of the samples by crude oil, drilling fluid, biologicals, etc., the outer surface of coring samples and field rock samples was cut off by using a cutter. Then, the samples were tapped into pieces with a diameter of 3 cm or less, and cleaned three times with distilled water. Finally, the samples were dried in an oven at temperature of 30°C after soaking twice in chloroform (2 hours each time), and the chloroform was blown off with pure nitrogen gas. The dried pieces were ground into powder by a rock grinder, and 300 g powdery samples with a mesh size of more than 100 meshes were sieved in a vibrating sieve. The crushed samples were Soxhlet extracted for 72 h with the solvent of CHCl₃ (99% purity). At the same time of extraction, copper foils were added for desulfurization. The extracted solution was concentrated to 50–70 ml using a rotary evaporator. The impurities were filtered off with a glass fiber paper and cotton
wool, and then concentrated with a nitrogen gas blower. When the solution was concentrated to 10–15 ml, it was transferred to a glass centrifuge tube in order to get rid of all of the CHCl₃ with a nitrogen blower. After 15 ml n-hexane (99.99% purity) was added and thoroughly dissolved, the glass centrifuge tube was placed in a centrifuge in order to make the asphaltene rapidly precipitated at a velocity of 3000 r/min. After de-asphalting of the rock extracts, they were separated with alumina and silica gel column chromatography. The saturated hydrocarbons were eluted with n-hexane, whereas the aromatic hydrocarbons were eluted with benzene.

The saturate fractions were used for the GC-MS analysis to obtain the distributions of n-alkanes, major isoprenoids, terpanes, steranes as well as other biomarkers. GC-MS analysis was conducted with an Agilent 6890 N/5975I gas chromatograph-mass. HP-5MS capillary column (30 m × 0.25 mm × 0.25 μm) was used for compounds separation. The oven temperature was held at 50°C for 1 min, followed by increasing to 100°C at 2°C/min, and then to 315°C at 3°C/min for 16.83 min. The injector was set at 300°C. Helium was used as carrier gas with a flow rate of 1.0 mL/min. The scanning range was set as 50–550 amu.

The aromatic fractions were used for the GC-MS analysis to obtain the distributions of Naphthalenes, biphenyls, fluorenes, phenanthrenes, dibenzothiophenes, etc. GC-MS analysis was conducted with an Agilent 6890 N/5973 gas chromatograph-mass. HP-5MS capillary column (60 m × 0.25 mm × 0.25 μm) was used for compounds separation. The oven temperature was held at 50°C for 1 min, followed by increasing to 150°C at 8°C/min, and then to 310°C at 4°C/min for 16.83 min. The injector was set at 290°C. Helium was used as carrier gas with a flow rate of 1.0 mL/min. The scanning range was set as 50–550 amu.

Table 1. Bulk geochemical characteristics of samples.

| Horizon | Sampling location | Depths (m) | TOC (%) | Ro (%) | Type of organic matter |
|---------|-------------------|------------|---------|--------|------------------------|
| T3x¹   | ZBC-, SMT-, CJ-, CX-, PLB-, BQ-, Lengshuixi, Huangtu | 1940.65–4746.50 | 0.97–2.12 | 1.83–2.57 | II₂–III |
| T3x²   | ZBC-, WXCR-, WC-, LGM-, PLB-, ZB-, M-, JS-, PLB-, DC-, AY-, BQ-, CX-, CQ-, CJ-, WJ- | 3398.02–4536.60 (or 0) | 1.17–9.01 | 1.71–2.10 | II₁–III |
| T3x³   | ZBC-, WXCR-, WC-, LGM-, PLB-, ZB-, M-, JS-, PLB-, DC-, AY-, BQ-, CX-, CQ-, CJ-, WJ-, Lengshuixi, Huangtu | 1796.33–4152.00 (or 0) | 0.97–5.11 | 1.16–1.92 | II₁–III |
| T3x⁵   | WXCR-, JS-, DC-, AY-, BQ-, CJ-, CX-, CQ-, Lengshuixi, Huangtu | 1885.50–3568.00 (or 0) | 1.09–2.50 | 1.21–1.51 | III |
| J1dn   | G-, X-, NC-, XHD-, TL-, PC-, YL-, ZB-, JS-, Lengshuixi, Huangtu | 1828.30–3241.6 (or 0) | 0.95–2.00 | 1.05–1.34 | I–III |
| J1l    | G-, X-, NC-, XHD-, TL-, PC-, YL-, ZB-, JS-, Lengshuixi, Huangtu | 1686.90–3291.60 (or 0) | 1.14–2.65 | 0.78–1.38 | II₂–III |
Results and discussion

After calculation, the characteristic parameters of biomarkers of continental source rocks in Sichuan Basin are shown in Figure 2.

*n-alkanes and isoprenoids*

The dominant peaks of the Upper Triassic are distributed mainly between \( n-C_{17} \) and \( n-C_{24} \), and the carbon number is distributed mostly between \( n-C_{12} \) and \( n-C_{30} \). The dominant peaks of the Lower Jurassic are mostly \( n-C_{21} \), and the carbon number is mostly distributed in \( n-C_{9} - n-C_{39} \) (Figure 3(a)). Compared with the Triassic, the Lower Jurassic is wider in carbon number distribution. The odd carbon number predominance index of \( n \)-alkanes (carbon predominance index (CPI) and odd-even predominance (OEP)) is used generally to evaluate the maturity of source rocks (Scalan and Smith, 1970). The CPI values of the extracts of the Upper Triassic and Lower Jurassic mudstone were all between 1.00 and 1.10 (the OEP values were all between 0.95 and 1.15) (Figure 2). Based on studies by Scalan and Smith (1970), CPI and OEP values are close to 1, indicating that all the samples are mature.

Bourbonniere and Meyers (1996) used the terrigenous/aquatic ratio (TAR = \([n-C_{27} + n-C_{29} + n-C_{31}] / [n-C_{15} + n-C_{17} + n-C_{19}]\)) to compare the ratio of continental and aquatic input. TAR is very susceptible to thermal maturation. In high-mature samples, macromolecules are easily broken into smaller molecules, resulting in the reduction of macromolecules and the enrichment of small molecules (Peters et al., 2005b). Therefore, the TAR value will decrease as the maturity increases. However, the TAR of the most of the upper Triassic samples ranges from 1.18 to 1.78, even up to 3.47. For the most mature T3x1 source rocks (\( R_o = 1.84 - 2.24\% \)), the TAR is 0.85–1.35. Only a few samples of T3x2–T3x3 have TAR < 1, and these samples are all from the yellow region as shown in Figure 3(c) (the middle segment of the western margin of the basin).

Pr and Ph came from a variety of sources, such as paleo-bacteria, vitamin E, etc. (Goossens et al., 1984; Rowland, 1990). However, the most abundant sources were the chlorophyll a produced by photosynthesis and the phytol, which was generated by the breakup of the phytal side chain in the chlorophyll a and b in purple sulfur bacteria (Powell and McKirdy, 1973). The phytol is easily reduced to dihydrophytol under anoxic conditions and converts to phytane. Under oxy-rich conditions, phytol is easily oxidized to phytic acid, further decarboxylated to form terpenes, and finally converted to pristane (Rowland et al., 1990). Therefore, the content of Pr and Ph can be used to judge the redox conditions of the deposition environment. In addition, Pr/Ph, Pr/nC17 and Ph/nC18 are also often used as important parameters to determine the type of parent materials of organic matter and the sedimentary environment. In the extracts of the continental source rocks in the present study, the lowest value of Pr/Ph ratio appeared in T3x2 and T3x3 strata at the western margin of the basin, such as T3x2 of ZBC-1, T3x2 of WXC-3, T3x2 of WC-1, T3x3 of WJ-1, etc. with Pr/Ph ratio values in the range of 0.10 to 0.40. (Figure 2). The Pr/Ph ratio values of the Upper Triassic source rocks are distributed mostly between 0.3 and 1.1, whereas the Pr/Ph ratio values of the Lower Jurassic source rocks are distributed mostly between 1.4 and 2.1, i.e. the values are significantly larger than those of the Upper Triassic. Another feature is that the Pr/Ph ratio values of the source rocks increase gradually from the Upper Triassic T3x1 to the Lower Jurassic J1l (Figure 2). In addition, the Pr/nC17 and Ph/n-C18 ratio of the Upper Triassic are 0.36–1.02 and 0.34–1.57, respectively, significantly larger...
Figure 2. Parameters of the biomarks of the continental source rocks in the Sichuan Basin.
than that of the Lower Jurassic, which is 0.11–0.24 and 0.07–0.13 (Figure 2). The Pr/\(n\)-C\(_{17}\) and Ph/\(n\)-C\(_{18}\) values of Upper Triassic source rocks are significantly higher than those of the Lower Jurassic source rocks, indicating that there is more abundant chlorophyll source in the parent material of the Upper Triassic source rocks than in the Lower Jurassic source rocks.

Figure 3. Characteristics of the typical continental source rocks in the Sichuan Basin, \(n\)-alkanes, isoprenoids, terpanes and steranes. (Pr: pristane; Ph: phytane; TT: tricyclic terpanes; Ts: 18a-neohopanes; \(\alpha/\beta\): 17\(\alpha\), 21\(\beta\) hopanes; Diah: 17a-diahopanes; Erh: early-eluting rearranged hopanes; Ga: gammacerane; Mor: moretane). (a) \(m/z\) 85, \(m/z\) 191, \(m/z\) 217 Mass fragmentograms. (b) Mass spectrum of 30Erh. (c) Distribution characteristics of regular steranes in \(T_3x^2\)-\(T_3x^3\) source rocks in Sichuan Basin.
rocks (Figure 2). It also indicates that there are more autotrophic organisms in the Late Triassic than in the Early Jurassic. This organism may be a higher plant or an aquatic alga. It has been proved by lower Pr/n-C₁₇ and Ph/n-C₁₈ value of Lower Jurassic that during the Late Jurassic, the sedimentary environment was reduction environment, favourable for the existence of autotrophic organisms. Peters et al. (2005a) pointed out that when Pr/Ph is less than 0.8, the sedimentary environment is a typical reducing environment. When Pr/Ph is more than 3.0, the sedimentary environment is a typical oxidizing environment. The Pr/Ph ratios of most samples collected from T₃x¹ to T₃x₃ were less than 0.8, indicating a low-oxygen sedimentary environment. However, during the sedimentation period of T₃x⁵–J₁l, the oxygen content continued to rise, indicating a transitional environment of oxidative-reduction. The same phenomenon can be also seen in Figure 4, showing Pr/n-C₁₇ and Ph/n-C₁₈, the point group of T₃x¹–T₃x₃ falls into a reducing environment. Part of T₃x⁵ data points fall into a reducing environment and the remaining part fall in the transitional environment. All the point groups of J₁dn–J₁l fall into the transition zone. It should be noted that the Pr/Ph ratio decreases to the minimum value during the sedimentary period of T₃x² and T₃x₃, which may indicate that this region experienced an anoxic event during this period.

The Pr/Ph ratio value is also affected by the salinity of the sedimentary environment (Connan, 1974; Didyk et al., 1978). According to Schwark et al. (1998), Pr/Ph ratio shows a decreasing trend as salinity increases. Ten Haven et al. (1987) considers when Pr/Ph is less than 1, the sedimentary environment is a typical high salinity condition.

**Tricyclic terpanes**

The tricyclic terpane (TT) of the Upper Triassic is high in relative content. It can be clearly seen from Figure 3(a) that the TT/hopanes ratio of the Upper Triassic is significantly higher

![Figure 4. Pr/n-C₁₇–Ph/n-C₁₈ cross plot and variation trend of the Pr/Ph of the source rocks of T₃x¹–J₁l in the Sichuan Basin (part of the data is from Chen [2008]). (The area in the red frame is from figure in Connan and Cassou (1980)).](image-url)
than that of the Lower Jurassic. This may attribute to the fact that TT has better thermal stability than hopane, which is not prone to decompose (Farrimond et al., 1999; Peters et al., 1990). The maturity of Upper Triassic samples is higher than that of the Lower Jurassic. In most of the Upper Triassic source rock samples in the study area, the dominant peak of tricyclic terpane is 23TT, showing an ascending trend of 19TT < 20TT < 21TT < 23TT.

In contrast with the rocks of the Upper Triassic, the Lower Jurassic source rocks are extremely low in tricyclic terpane content. The dominant peak is 21TT, being the ‘middle convex type’ of 19TT < 20TT < 21TT > 23TT. Tricyclic terpane with a carbon number of more than 26 is rare (Figure 3(a)). There is no 28TT and 29TT extended tricyclic terpane. The content of 19TT is J1l > J1dn.

Available data indicate that 19TT and 20TT are derived from continental higher plants (Preston and Edwards, 2000). With the increasing of carbon numbers, the content of the tricyclic terpane in coal decreases (Ekweozor et al., 1981; Hanson et al., 2000; Preston and Edwards, 2000). Only some J1l samples have the advantage of 19TT and 20TT, which indicate that continental plants have an absolute advantage only during the sedimentary period of J1l. The above points have also been confirmed by the distribution characteristics of TTs. In the organic matter of the marine or saline lacustrine facies, the dominant peak is 23TT, and compounds with 26TT are dominant (Peters and Moldowan, 1992; Zhu et al., 2015). In freshwater lacustrine source rocks and crude oils, the compounds with 21TT are dominant, indicating that the origins of the source rocks are aquatic and continental (Tao et al., 2015; Zhu et al., 2015). The 23TT is dominant in the Upper Triassic, and the 21TT is dominant in J1dn, with the characteristics of aquatic organism of saltwater lacustrine and freshwater lacustrine. A ternary diagram has been constructed for the source of 19TT–23TT (Figure 5). From this ternary diagram, the variation process from T3x1 to J1dn can be seen intuitively. As shown in Figure 5, the data points of the Upper Triassic are distributed mainly in the direction of salt-tolerant organic matter. These characteristics are obvious in T3x1 and T3x3 strata. The organic matter in the Lower Jurassic source rocks is dominated by freshwater organisms. The input of continental higher plant in J1l strata is much higher than that in J1dn strata. Therefore, based on the characteristics of tricyclic terpane, it can be inferred that, from the sedimentary period of T3x1 to the sedimentary period of J1l, the sedimentary environment changed from a high-salinity environment to continental freshwater lacustrines after the retreat of the seawater. During the sedimentary period of J1dn,

![Figure 5](image-url)

**Figure 5.** Ternary diagram of the tricyclic terpanes of the continental source rocks of the Sichuan Basin.
the sedimentary environment was continental freshwater lacustrines. During the sedimen-
tary period of J1l, the lacustrines shrank, resulting in increasing the input of the continental
higher plants.

In addition, in the Upper Triassic source rocks, 28TT and 29TT extended tricyclic ter-
pane is widespread. The extended tricyclic terpane index (ETR = [28TT + 29TT]/
[28TT + 29TT + Ts]) (Holba et al., 2001) ranged from 0.36 to 0.77. The ETR value of the
T3x5 member is significantly lower than that of the other horizons of the Upper Triassic. In
contrast, in the source rocks of the Lower Jurassic strata, except for the samples at the edge
of the basin, 28TT and 29TT extended tricyclic terpanes were not detected in most of the
Lower Jurassic samples. The ETR value is close to zero (Figure 2).

In a previous study, Holba et al. (2001) used extended tricyclic terpanes as age dis-
riminators. It is believed that by the extended tricyclic terpanes, the Triassic and Jurassic
can be distinguished effectively. In recent studies, some scholars proposed a challenge to
this point of view, contending that extended tricyclic terpane is an indicator for sedimen-
tary environment. Hao et al. (2009) indicate that ETR values are correlated positively with
GI and negatively with Pr/Ph ratio. Based on this point, it is believed that ETR and salinity are related closely with the oxygen content. Huang et al. (2017) argue that when
the value of ETR is over 0.67, the sedimentary environment is an upwelling sedimentary
environment, with marine characteristics. This study also points out that ETR value is not
irrefutable evidence for the division of marine and continental facies. In our study, the
range of ETR of T3x1–T3x3 samples ranges from 0.32 to 0.77, and the ETR of all the
samples from the western margin of the basin is over 0.67, indicating that in some areas at
the western margin of the basin, sedimentary environment was still affected by the marine
environment during the sedimentation period of T3x1–T3x3. The ETR values of T3x5–J1l
samples were less than 0.67, indicating that during the sedimentation period of T3x5–J1l,
the ocean had no influence on the sedimentation in this basin. In our study, it is also
observed that ETR was correlated positively with GI and negatively with Pr/Ph ratio
(Figure 6). This phenomenon can support the results of Hao et al. (2009). Accordingly,
the ETR values of the Upper Triassic were higher than those of the Lower Permian
(Figure 2). This indicates that the salinity during the Late Triassic was higher than that

![Figure 6. Correlation between the ETR and GI, ETR and Pr/Ph of T3x1–J1l source rocks.](image)
of the Early Jurassic, but the oxygen content during the Late Triassic was lower than that of the Early Jurassic.

Hopanes

There is abundant conventional hopane in the Upper Triassic source rock. The conventional hopane with a carbon number of 27 and 29–36 has been detected. On the \( m/z \) 191 map, \( 30\alpha\beta/h (C_{30}-17\alpha, 21\beta \text{hopane}) \) is the dominant peak. There are few rearranged hopanes, only a small amount of \( 27\text{Ts} (C_{27}-18a-\text{neohopanes}), \ 29\text{Ts} (C_{29}-18a-\text{neohopanes}) \) and an extremely small amount of \( 30\text{Diah} (C_{30}-17\alpha-\text{diahopanes}) \) \( (27\text{Ts}/Tm \leq 1; 29\text{Ts}/29\alpha\beta/h \leq 0.5; 30\text{Diah}/30\alpha\beta/h \leq 0.3) \) were detected (Figures 2 and 3(a)).

Different from the source rocks of the Upper Triassic, the source rocks of the Lower Jurassic are rich in rearranged hopanes. A total of three different series of rearranged hopanes, including \( 18a-\text{neohopanes} \) series (Ts), \( 17\alpha-\text{diahopanes} \) (Diah) and early-eluting rearranged hopanes series with unclear molecular structure (Erh) were detected in the extracts. Only two compounds, \( 27\text{Ts} \) and \( 29\text{Ts} \) were detected in the Ts series, but their content is very high \( (J_{1dn}: 27\text{Ts}/Tm = 0.84–21.90, 29\text{Ts}/C_{29}\text{-Hop} = 0.82–7.33; J_{1l}: \text{Ts}/Tm = 0.97–21.90, 29\text{Ts}/29\alpha\beta/h = 0.91–10.27) \) (Figure 2). The completed series of \( 27, 29–35 \) were detected in the Diah series and its content was often higher than normal hopane. In \( m/z \) 191 spectrum, the dominant peak was \( 30\text{Diah} \) instead of \( 30\alpha\beta/h \) \( (C_{30}-17\alpha, 21\beta \text{hopanes}) \) (Figure 3(a)). The \( 30\text{Diah}/30\alpha\beta/h \) ratio was up to 29.23. The Erhs (Early-eluting rearranged hopanes) carbon number is 29–34 (Figure 3(a)). The elution time of this series of compounds is far earlier than that of Diahs and \( \alpha\beta/h s \) (the peak time of the \( C_{30} \) homologue is between Ts and Tm, which is mistaken often for Tm). Figure 3(b) shows the mass spectrum of 30Erh. It can be seen that the peak of characteristic ion is not only \( m/z \) 191 but also \( m/z \) 365. This is quite different from the Diah series and the \( \alpha\beta/h \) series. It shows that the Erh series compounds have a unique special structure. The Erhs was first discovered by Telnaes et al. (1992) in the lacustrine crude oil of the Doseo Basin (Chad) and the Uinta Basin (Utah, U.S.A.). Later, Farrimond et al. (1994) also detected the same compound in the extract of the Jurassic black shale in northern Italy and named as “early-eluting rearranged hopane.” This name is also used by other scholars (Nytoft et al., 2006; Zhu et al., 2007). Farrimond et al. (1996) discovered “The \( 17\alpha\text{-diahopanes} \) and the early-eluting rearranged hopanes to closely covary” by principal component analysis (PCA), but the structure of the compounds is still unclear. Erhs were firstly discovered in the Sichuan Basin by Zhu et al. (2007) in the Jurassic crude oil in the central Sichuan. It was discovered in the source rocks of this area for the first time. In fact, in all the reports we find about Erhs (Farrimond et al., 1994; Jiang et al., 2016; Nytoft et al., 2006; Telnaes et al., 1992; Zhu et al., 2007), and Diahs always exist at the same time. In the samples where Erhs exists, Diah is always extremely abundant. Therefore, although the specific molecular structure of Erh is not clear at present, it can be speculated that Erhs may be a derivative of Diahs. Relatively speaking, the normal hopane of the Lower Jurassic is very low in content. Even in the source rocks of the \( J_{1l} \) Member in well XHD-9, only one \( 30\alpha\beta/h \) compound has been detected in normal hopane series. According to Volkman et al. (1983), diahopanes and neohopanes were sourced from the oxidation products of bacterial hopanoid, generated by the catalysis of an acid clay medium. It indicated that the sedimentary environment of the Lower Jurassic was a sub-oxidising to oxidising environment (Volkman et al., 1983). Although the molecular structure and geological significance of Erhs are still unclear, it has been clearly observed in this study that
Erh and Diah have covariability. This is consistent with the phenomena observed by Farrimond et al. (1996). Therefore, it can be speculated that the reasons for the formation of Erh and Diah may be the same, which also indicates the oxidation environment with high oxygen content. In addition, in the study of Telnaes et al. (1992) and Farrimond et al. (1994), no matter the organic matters came from the brackish lacustrine basin or from the freshwater lacustrine basin, both are rich in Erhs, with no obvious difference in the content. Therefore, it can be inferred that the Erhs value is not controlled by salinity.

In addition, the content of Gammacerane is high in the T3x1–T3x3 source rocks (GI = 0.14–0.41) (GI = Gammacerane Index = Gammacerane/30αβh (Moldowan et al., 1985)), but decreases in the T3x5 member (GI = 0.11–0.19), being the lowest in the Lower Jurassic (GI = 0.01–0.16) (Figure 2). It is known that the gammacerane was sourced from the dehydration and hydrogenation of terahymanol (Ten Haven et al., 1989). The main source of terahymanol is bacterivorous ciliate that mainly lives in the chemocline (the interface between circulating water and non-circulating water) and the anaerobic environment at the bottom of the water (Mallory et al., 1963). Therefore, gammacerane can be used as an indicator of water stratification. Because the density stratification is common in high-salinity water, gammacerane is used generally as one of the markers of high-salinity sedimentary water. The study results of Moldowan et al. (1985), Philp et al. (1991) and Ma et al. (2015) indicate that the GI is usually less than 0.1 in freshwater lacustrines, less than 0.3 in mildly brackish water, 0.3–0.7 in brackish water, and greater than 0.7 in saline water. From this, it can be inferred that the sedimentary environment was brackish water during the depositional period of T3x1–T3x3 in the Late Triassic, mildly brackish water during the depositional period of T3x5, and changed into mildly brackish water to freshwater during the Early Jurassic. The GI increases gradual in this study from the Upper Triassic to the Lower Jurassic, which is consistent with the result of the salinity change as inferred from Pr/Ph.

Steranes

In this study, almost all regular sterane in the Upper Triassic samples exhibited the characteristics of C29 > C27. However, some samples in the T3x2–T3x3 layer exhibited different characteristics of C27 > C29. These samples were concentrated in the T3x2–T3x3 layer in the yellow area as shown in Figure 3(c) (the middle segment of the western margin of the basin). In the T3x2–T3x3 layer, C27 and C29 are almost the same in the wells near the yellow area, but C27 is obviously lower than C29 in the wells away from the yellow area. The C28 regular sterane accounts for 22–34% in C27–C29 regular sterane.

All the samples of the Lower Jurassic J1dn exhibit the characteristics of regular sterane C27 > C29, except those sampled from the basin margin, indicating that the organic matter of J1dn source rocks was sourced mainly from aquatic organisms. However, more than half of the samples of J1l source rocks exhibit the characteristics of regular sterane C27 < C29. Generally, the relative content of the C29 regular sterane in J1l source rocks is higher than that in J1dn source rocks (Figure 2). The C28 regular sterane of the Lower Jurassic is less than that of the Upper Triassic (Figure 2). Huang and Meinschein (1979) argued that the C27 regular sterane is of marine source, and the C29 regular decane is of continental source. However, this claim was quickly questioned. In fact, both C27 and C29 sterols (Brassell et al., 1981) existed in marine organisms, while abundant C27 sterane is also found in continental strata (Huang et al., 1987). Volkman (1986) pointed out that vascular plants and algae can also be used as major contributors to C29 sterols. The current accepted
statement for C_{27} regular sterane and C_{29} regular sterane is that C_{27} sterane is usually derived from lower aquatic organisms and algae, while C_{29} regular sterane is derived from algae and/or continental plants (Teng et al., 2019). In this study, most C_{29} regular sterane in the Upper Triassic samples demonstrated the presence of abundant continental plants or algae during the deposition of Late Triassic source rocks, during which, autotrophic organisms were dominated. This inference has been confirmed by the higher content of Pr and Ph in the Upper Triassic. In the source rock of J_1dn, the regular sterane C_{27} > C_{29} are dominated, indicating that sedimentary environment was not favourable for autotrophic organism during the sedimentation period of J_1dn, while at the interval of J_1l, C_{27} > C_{29} and C_{29} > C_{27} are almost the same, indicating that the autotrophic organism was dominated again (Figure 2). The content of the C_{28} regular sterane is significantly higher in the Upper Triassic source rocks than in the Lower Jurassic source rocks. Although there are no accepted conclusions about the source of C_{28} regular sterane, some studies suggest that it is likely to source from diatoms (Rampen et al., 2010). It indicates the algae bloomed during the Late Triassic epoch. In the Lower Jurassic source rocks, the content of C_{28} regular sterane is extremely low, indicating that algae decreased relatively during the Early Jurassic. On the premise that the depositional environment was algae reduction, the C_{27} regular sterane is dominated at J_1dn, indicating that higher plants decreased rapidly during this period, being favourable for the lower aquatic organisms.

The C_{27} diasterane/C_{27} regular sterane value of the Upper Triassic is between 0.04 and 0.25, but the C_{27} diasterane/C_{27} regular sterane value of the Lower Jurassic is 0.36–2.17 (Figure 2). Obviously, the diasterane content of the Lower Jurassic is higher than that of the Upper Triassic. In addition, the diasterane content of the J_1l strata is slightly higher than that of the J_1dn strata (Figures 2 and 3(a)). Previous studies have shown that diasterane is correlated with the sedimentary environment, diagenesis, maturity, and biodegradation (Moldowan et al., 1986; Sieskind et al., 1979). In our study, it is believed that the diasterane of the Lower Jurassic formed in a clay-rich sediment in an oxygen enrichment, acid-catalysed depositional environment (Baydjanova and George, 2019). Comparing the depositional period of the J_1l strata with the depositional period of the J_1dn strata, it can be seen that during the depositional period from J_1l to J_1dn strata, the lacustrine had shrank, and the water depth became shallower, with higher oxygen content. Consequently, the diasterane content was higher.

**Bicyclic sesquiterpenes**

In the m/z 123 mass chromatogram, the dominant peak of most samples is 8\beta-C_{16} drimane, followed by C_{15} drimane (C_{15} drimane/C_{16} drimane < 1). Sesquiterpenoids may be associated with resins (Noble and Alexander, 1989; Heppenheimer et al., 1992). Zhu et al. (1997) believe that the phenomenon of C_{16} drimane > C_{15} drimane occurs mostly in coal-measure-derived or inland-lacustrine-derived organic matter. In this study, all samples exhibited the characteristics of C_{16} drimane > C_{15} drimane, indicating the sedimentary environment was continental environment during the Late Triassic-Early Jurassic time.

The No. 1 and No. 2 peak in Figure 7(a) are 9\alpha-4, 4, 8, 8, 9-pentamethyldecalin and 8\beta-4, 4, 8, 9, 9-pentamethyldecalin. They have different methyl replacement pattern from drimanes, and are the rearranged compounds of drimanes (Ji et al., 2016; Zhu et al., 1997). The content of rearranged drimanes is high in the Lower Jurassic strata, generally higher than that of C_{15} drimane, but lower than that of C_{16} drimane, even as high as 2.25 times of that of...
C\textsubscript{15} drimane. However, in the Upper Triassic strata, the content of rearranged drimanes is usually lower than that of C\textsubscript{15} drimane. Similar with diahopanes and diasteranes in origin, in bicyclic sesquiterpenes, the rearranged mechanism of C\textsubscript{15}, rearranged drimane, is similar to that of rearranged decane (Alexander et al., 1984), requiring the catalysis of acidic clay minerals and a high-oxygen environment. Correspondingly, the C\textsubscript{15} rearranged drimane content is higher in the Lower Jurassic than in the Upper Triassic, which is consistent with the rearranged decane content, being higher in the Lower Jurassic than in the Upper Triassic.

**Carotanes**

The first batch of identified biomarkers is β-carotane, and its precursor, β-carotene, is believed to be derived from salt-tolerant algae (Avron and Ben-Amotz, 1992; Fu et al., 1990). The presence of β-carotane implies high salinity. β-carotane and γ-carotane were detected obviously in all samples of T\textsubscript{3x1}–T\textsubscript{3x3} source rocks. Obviously, it has been proved by the distribution characteristic of β-carotane in the continental source rocks of the Sichuan Basin that salinity was high during the sedimentary period of T\textsubscript{3x1}–T\textsubscript{3x3}. The content is lower in T\textsubscript{3x5} than in the other strata of the Upper Triassic, indicating that during the sedimentary period of T\textsubscript{3x5}, the salinity decreased. However, in the samples of the Jurassic source rocks, this series of compounds is extremely low in content or is hardly

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Mass fragmentograms (m/z 123 and m/z 125) of the continental source rocks of the Sichuan Basin. (1 = 9\textsubscript{β}-4, 4, 8, 8, 9-pentamethyl decalin; 2 = 8\textsubscript{β}-4, 4, 8, 9-pentamethyl decalin.). (a) m/z 123 mass fragmentograms. (b) m/z 125 mass fragmentograms.
detected (Figure 7(b)). This indicates that during the Early Jurassic, the sedimentary environment turned into a low-salinity environment, which is in good agreement with the salinity change derived from other parameters. The carbon skeleton of β-carotane may be preserved in an anoxic sedimentary environment (Peters et al., 2005a). Therefore, an anoxic sedimentary environment is a significant indicator for the formation of a large quantity of β-carotane. The distribution of β-carotane in T₃x¹–J₁dn also indicates that the oxygen content increased gradually from the Late Triassic to Early Jurassic.

**Aromatic hydrocarbons**

**Phenanthrene series.** The phenanthrene series is aromatic hydrocarbon compound, with the highest content, and has been detected in this study. In addition to phenanthrene, there are abundant methyl phenanthrenes (MPs), dimethyl phenanthrenes (DMPs) and trimethyl phenanthrenes (TMPs). The contents of 2-MP and 3-MP in the source rocks of T₃x¹–T₃x³ layer are higher than that in the source rocks of T₃x⁵ layer and Lower Jurassic. The content of 1-MP is similar with that of 9-MP in all the T₃x¹–T₃x⁵ layer, except in J₁dn, the content of 9-MP is significantly higher than that of 1-MP and in J₁j, the content of 1-MP is significantly higher than that of 9-MP (Figure 8). In addition to be used to estimate the maturity of organic matter, the methyl phenanthrenes (MPs) series compounds can reflect the type of parent material of organic matter. 1-MP is predominant in continental crude oil, most of which is from type III parent material (Heppenheimer et al., 1992). We try to apply this idea to the source rock, and find that during the sedimentation of J₁j horizon, the environment was favourable for 1-MP, which is an evidence that the depositional environment was favourable for continental plant (Figure 2). 9-MP is usually derived from the parent material of type I-II (Isaksen, 1991). Song et al. (2007) believed that 9-MP is related to tetracyclic compounds similar to the carbon skeleton in sterane. The source rocks of the J₁dn layer are characterized by 9-MP > 1-MP, indicating that aquatic organisms were dominated during the sedimentary period of J₁dn. It is clearly indicated by the close proximity of 9-MP to 1-MP in most of the Upper Triassic samples that in addition to a large number of continental plant inputs, there are also aquatic organisms that are not inferior to continental plants in the Late Triassic (Figure 2).

**‘Three fluorenes’ series.** The three fluorenes series refers to three types of compounds with similar structures, including fluorene (F), dibenzothiophene (SF or DBT), and dibenzofuran (OF or DBF). Many scholars believe that they are derived from the same substance. The α carbon atom of fluorene is active and can be replaced by O and S atoms in the oxidising and reducing environment, forming dibenzofuran and dibenzothiophene (Asif et al., 2009; Lalonde et al., 1987). Therefore, it is often used to determine the oxygen content and sedimentary environment (Asif and Wenger, 2019; Asif et al., 2009). It can be observed from the total ion-current profile of the aromatic hydrocarbons that the content of the three fluorenes series compounds is also detected. The three fluorenes series refers to three types of compounds with similar structures, including fluorene (F), dibenzothiophene (SF or DBT), and dibenzofuran (OF or DBF). In the Upper Triassic source rocks, the relative content of dibenzothiophene is high, but the relative content of dibenzofuran is extremely low, with the distribution characteristics of SF > F > OF. However, in the Lower Jurassic source rocks, the relative content of is higher than that of SF, with the characteristics of F > OF > SF (Figure 8).
In the Upper Triassic source rocks, the relative content of dibenzothiophene is high, but the relative content of dibenzofuran is extremely low, showing the distribution characteristics of \( SF > F > OF \). However, in the Lower Jurassic source rocks, the relative dibenzofuran content is higher than that of dibenzothiophene. This difference indicates that the sedimentary environment during the Early Jurassic was more oxidised than that of the Late Triassic. The source rocks of \( J_{1l} \) are more abundant in fluorene than that of \( J_{1dn} \). After numerous experiments, the F-SF-OF triangle plot has been used to distinguish sedimentary environments (Zhang et al., 2012).

As shown in Figure 9, most of the Upper Triassic points fall on the area of the marine/saline lacustrine source rocks. The points of the two samples of the Lower Jurassic \( J_{1dn} \) fall...
on the boundary between the coal measure and freshwater lacustrine source rocks. The points of the two samples of J1,l fall completely on the area of the coal measure source rocks. This confirms that the interpretation chart can be used to identify the sedimentary environment effectively. It should be noted that the thermal stability of dibenzofurans is much lower than that of fluorene and dibenzothiophene (Radke et al., 2000). Therefore, the sedimentary environment can only be determined accurately by using the three fluorines series at the oil window stage (Zhu et al., 2015). However, in the current study, there are certain deviations in the position of the Upper Triassic samples in the figure, and can be determined accurately only if combined with the other parameters.

Influence of maturity on the distribution of biomarkers

Besides the type of the parent material and sedimentary environments, the maturity is also one of the important factors affecting the distribution of biomarkers in source rocks. As to this, extensive study has been conducted by previous scholars. Therefore, before analyzing the sedimentary environment and types of the parent material through biomarkers, it is necessary to discuss firstly about the influence of maturity on these biomarkers. Fortunately, in this study, most of the biomarker parameters which are influenced easily by maturity seem to be counter-empirical in relation to Ro. For example, due to the high thermal stability of diasterane, the ratio of diasterane/regular sterane usually increases with the increasing in maturity (Peters et al., 1990). However, in this study, it is found that the samples with lower maturity had a significantly higher diasterane/regular sterane value than the samples with higher maturity. It is quite different from previous studies. Such special phenomena also occurred on parameters such as Ts/Tm, Pr/n-C17, Ph/n-C18, and Pr/Ph (Figure 10). This seems to indicate that the influence of maturity on the distribution of biomarkers is relatively small compared with the influence of sedimentary environment and parent material type on the distribution of biomarkers in these samples. For example, the input of continental higher plants was large in quantity during the Late Triassic (Zhang et al. 2012).

Figure 9. Ternary diagram of the three fluorines series of the continental source rocks of the Sichuan Basin. (I: Limestone source rocks; II: Saline lacustrine/marine source rocks; III: Freshwater lacustrine source rocks; IV: Coal measure source rocks). (Zhang et al. 2012).
et al. (2012) believed that a salt-tolerant mangrove forest grew around high-salinity waters during the Late Triassic, and a large amount of chlorophyll a had been brought into the water, resulting in the accumulation of a large amount of chlorophyll a. Therefore, the Upper Triassic source rocks are high in Pr/n-C_{17} and Ph/n-C_{18} values. Although maturity has decreased the value of Pr/n-C_{17} and Ph/n-C_{18}, the influence of the organic matter sources is also great. It is believed that due to the significant difference in the sedimentary environment and organic matter sources of T3x\textsuperscript{1}–J_{1}l, the parameters of Ts/Tm, Pr/n-C_{17}, Ph/n-C_{18}, Pr/Ph, and diasterane/sterane differ greatly. The thermal maturity at the late stage was not enough to reverse these differences. Therefore, it is concluded that thermal maturity is not

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Correlation between the bio-standard parameters and Ro of T3x\textsuperscript{1}–J_{1}l source rocks.}
\end{figure}
the most important reason for the distribution of isoprenoids and rearranged compounds in the T3x1–J1 formation; the sedimentary environment and organic matter sources play an important role. Therefore, it can be seen that for most samples, although the higher Ro values indicate the high maturity of organic matter, the distribution characteristics of the biomarkers can still be used to speculate parent types of the source rock and sedimentary environments.

Change process of the sedimentary environment of the source rocks from the Late Triassic to the Early Jurassic

The geological significance represented by the change characteristics of the important parameters in Figure 2 has been summarized in Table 2. On the basis of this, the changing process in the sedimentary environment of the source rocks and input of organic matter during the depositional period from T3x1 to J1l in Sichuan basin can be analyzed. It can be seen from Figure 2 that TOC of Lower Jurassic source rock is lower than that of Upper Triassic source rock. This indicates that the source of organic matter in the Early Jurassic was smaller than that in Late Triassic. However, due to the different rates of reduction of continental higher plants and aquatic organisms, the types of organic matter in different strata are different.

T3x1. T3x1 is divided into two sub-members, namely Ma’antang and Xiaotangzi. At present, it is generally believed that in Sichuan basin, the Ma’antang sub-member is still marine facies. There is evidence indicated that the depositional period of Ma’antang corresponded to the anoxic event of global ocean at the end of the Carney period (Li et al., 2014). The sedimentation of Xiaotangzi sub-member was converted into continental environment (Lin, 2014). All the samples of the source rocks from the T3x1 horizon in this study are from the Xiaotang sub-member. The results of the analysis show several common characteristic, with high TAR, high Pr and Ph, regular sterane C29>C27, and 1-MP/9-M ratio is close to 1, which proved that there was abundant input of continental high plant during the depositional period of the source rocks of Xiaotang sub-member. However, at the same time, it has been proved by the low Pr/Ph ratio, high GI, 23TT dominance, high ETR, high carrot alkanes, and low content of rearranged compounds that T3x1 was deposited in anoxic and brackish water sedimentary environment. We believe that the reason for anoxic environment may be due to the subsequent influence of anoxic events during the depositional period of Ma’antang (Deng et al., 2018), while the brackish water body may be inherited directly from the seawater. Through the above evidence, it is strongly proved that the sedimentary environment of the source rocks in this period is already continental, but inherited the characteristics of some marine sedimentary environments.

T3x2–T3x3. At the interval of T3x2–T3x3, the biomarkers of most samples are generally similar to these of T3x1. This indicates that in most of the basins, the sedimentary environments during the depositional period of T3x2–T3x3 were similar to those of the T3x1 period—with abundant input of continental high plant, in brackish water anoxic sedimentary environment. The difference is that at the mid-section of the western margin of the basin, some changes had occurred. The samples taken from this area are characterized by the low values of TAR, regular sterane C27>C29, 1-MP < 9-M and extremely low values of Pr/Ph, which indicates this fact that the input of continental high plant was low and the oxygen content
Table 2. Geological significance of the biomarker compounds of the terrestrial source rocks in different horizons in the Sichuan Basin.

| Formation of source rocks | Isoprenoid Alkenes | Tricyclic terpanes Rearranged hopanes | Gamacerane (quantitative, with reference range) | Regular steranes | Rearranged steranes | Carotanes | 'Three fluorene' series | Rearranged drimane |
|--------------------------|--------------------|-------------------------------------|---------------------------------------------|-----------------|-------------------|-----------|------------------------|-------------------|
| J1                       | High Pr/Ph, low Pr/ nC17, and Ph/ nC18 | High C19 and C20, C21 > C23; ETR = 0 | High content | The main content of GI: 0.04–0.16 | C29 > C27 dominant, with minor C27 > C29 | High content | no | Data point group is located in the coal measure source rock area |
|                          | Low salt and oxygen rich | Freshwater aquatic organisms + terrestrial higher plant input | Oxygen rich | Mildly brackish water to freshwater | Terrestrial higher plants advantage (occasional aquatic organism advantage) | Oxygen rich | Low salinity | Abundant input of higher plant |
| J1dn                     | High Pr/Ph, low Pr/ nC17, and Ph/ nC18 | C21 > C23; ETR = 0 | High content | The main content of GI: 0.10–0.16 | C27 > C29 | High content | no | Data point group is located in coal measure source rock area, but close to the freshwater lake area |
|                          | Low salt and oxygen rich | Freshwater aquatic organisms | Oxygen rich | Mildly brackish water to freshwater | Aquatic organism advantage | Oxygen rich | Low salinity | Continental freshwater lake |
| T3x3                     | Low Pr/Ph, high Pr/nC17, and Ph/nC18 | \( C_{21} < C_{23} \) and \( C_{21} > C_{23} \) are co-existent; ETR = 0.42–0.52 | Low content | GI = 0.14–0.19 | C29 > C27 | Low content | No data | Low content |
|                          | Saltwater anoxic and low salt oxygen rich + terrestrial higher plant input | Salt-tolerant organisms mixed with freshwater organisms | Anoxic | Mildly brackish water | Terrestrial higher plants advantage | Anoxic | Salinity higher than J1dn–J1l, but lower than T3x3–T3x3 |
| T3x3                     | Low Pr/Ph, high Pr/nC17, and Ph/nC18 | \( C_{21} < C_{23} \); ETR = 0.53–0.77 | Low content | The main content of GI: 0.29–0.39 | C29 > C27 dominant, C27 > C29 and C27 > C29 | Low content | High content | The data point group is located in salt |
|                          | Low content | High content | Low content | | | | | |

(continued)
| Formation of source rocks | Isoprenoid Alkenes | Tricyclic terpanes | Rearranged hopanes | Rearranged steranes | Carotanes | 'Three fluorene' series | Rearranged drimane |
|--------------------------|--------------------|-------------------|-------------------|-------------------|----------|----------------------|------------------|
| **Geological interpretation** | Saltwater anoxic and low salt oxygen rich + terrestrial higher plant input | Salt-tolerant organisms | Anoxic | Brackish water | Terrestrial higher plant advantage (accompanied by local transgression) | Anoxic | Salt lake | Anoxic |
| **T$_{3x}^2$ Compound characteristics** | Low Pr/Ph, high Pr/nC$_{17}$, and Ph/nC$_{18}$ | C$_{21} < $C$_{23}$; ETR = 0.36–0.76 | Low content | The main content of GI: 0.19–0.32, significantly fluctuating | C$_{29} > $C$_{27}$ dominant, C$_{29} > $C$_{27}$ and C$_{27} > $C$_{29}$ co-existent in Western Sichuan | Low content | The data point group is located in salt lake area. SF takes advantage | Low content |
| **Geological interpretation** | Saltwater anoxic and low salt oxygen rich + terrestrial higher plant input | Salt-tolerant organisms | Anoxic | Brackish water to mildly brackish water | Terrestrial higher plant advantage (accompanied by local transgression) | Anoxic | Salt lake | Anoxic |
| **T$_{3x}^1$ Compound characteristics** | Low Pr/Ph, high Pr/nC$_{17}$, and Ph/nC$_{18}$ | C$_{21} < $C$_{23}$; ETR = 0.62–0.78 | Low content | The main content of GI: 0.30–0.38 | C$_{29} > $C$_{27}$ | Low content | The data point group is located in salt lake area. SF takes advantage | Low content |
| **Geological interpretation** | Saltwater anoxic and low salt oxygen rich + terrestrial higher plant input | Salt-tolerant organisms | Anoxic | Brackish water | Terrestrial higher plant advantage | Anoxic | Salt lake | Anoxic |
was also low during the depositional period of these source rocks. During the depositional period of T₃ₓ₂–T₃ₓ₃, the sedimentary environments had a tendency to transform into marine facies in this region. Shi (2012) believed that local transgressions occurred after the period of T₃ₓ₁ in Sichuan Basin, and this study seems to support this point. It should be emphasized that if the transgression occurred really, its scope was only limited to a small area in the western margin of the basin. In other regions of the basin, the input of continental high plant was high, and we cannot consider the whole basin as marine facies.

T₃ₓ₅. Both the rising in value of Pr/Ph and the intersection maps of Pr/n-C₁₇–Ph/n-C₁₈ show that the oxygen content rose again during this period, indicating that the Sichuan basin had gradually recovered from the global anoxic event at the end of the Carney period. Different from the point of view of some researchers in the past that the waters of the whole Sichuan Basin had been salty during the Late Triassic, in this study, gammacerane and carotene in the source rocks of this horizon have been reduced significantly, indicating that the waters have been gradually desalinated during this period.

At the same time, no evidence of transgression was found in the samples from this horizon. All these seem to suggest that during the sedimentary period of T₃ₓ₅, the Sichuan basin had been completely removed from the influence of the ocean, and gradually recovered from the global anoxic event at the end of the Carney period.

J₁dn. During the Early Jurassic, the sedimentation had been converted from the foreland basin into the Craton basin sediment in the study area. The sedimentary period of J₁dn was the weakest extensional period in the Early Jurassic, with the most stable activity in the orogenic belt. The depression rate of the whole basin was much larger than the accumulation rate of the continental debris, leading to the formation of the largest lake basin in the Early Jurassic in Sichuan Basin. It is fully proved by the abundance of rearranged compounds, the low values of GI, low ETR and high Pr/Ph ratios that during this depositional period, the sedimentary environment was a typical environment with rich oxygen, acidic and freshwater. Due to the rapid expansion of water bodies during this period, the input of continental plants reduced further, resulting in a favourable condition for lower organisms. It should be noted that during this depositional period, both the amount of aquatic and continental high plants has significantly reduced compared to the Late Triassic. However, the reducing rate of continental plants was faster. The evidence is that in some areas, the content of Pr and Ph decreases, and the TAR, the C₂₈ regular sterane and TOC also decrease, with the value of the 1-MP/9-MP ratio less than 1. All these have proved that during this period, freshwater lacustrine sedimentation was dominated, during which the contribution of aquatic organisms was great.

J₁l. Compared with J₁dn, the content of rearranged compounds and Pr/Ph ratio was higher, proving that the oxygen content during this depositional period was higher. The salinity was reduced further. Although C₂₉ regular sterane regained the dominance, and the relative content of 19TT and 20TT was high, the content of Pr and Ph is the same with that of J₁dn. This seems to indicate that due to the shrinking of water body, the quantity of lower aquatic organisms reduced, and the continental plants were dominated. But the contribution of continental plants may not increase substantially. The evidence is that the value of Pr and Ph has no great change, and the values of 19TT, 20TT and TAR have increased. The arid conditions of the Middle Jurassic seem to be began in this period.
Conclusions

1. The distributions of biomarkers are different in the Upper Triassic and Lower Jurassic source rocks. The biomarkers of Upper Triassic source rocks are higher in the content of extended tricyclic terpanes, carane, pristane and phytane. The Lower Jurassic source rocks are rich in rearrangement compounds. This difference can be used to distinguish effectively the Upper Triassic and the Lower Jurassic source rocks.

2. It is indicated through the analysis of typical characteristic parameters of biomarkers that the Upper Triassic source rocks are sourced from aquatic organisms and continental plants in the Sichuan Basin. Algae were dominated in aquatic organisms. During the sedimentary period of T3x2–T3x3, aquatic organisms were dominated in the western margin of the basin, resulting in large amount of input of continental plants. The organic matter of the J1dn Member of the Lower Jurassic source rocks was sourced mainly from bacteria and algae, while the organic matter of the J1l Member source rocks was mainly sourced from continental plants.

3. Through the study of the environmental characteristic parameters of biomarkers, it is indicated that the source rocks of the T3x1–T3x3 Member of the Upper Triassic were deposited in anoxic and brackish water sedimentary environment in the Sichuan Basin. Transgression might occur locally during the depositional period of T3x2–T3x3. The source rocks of T3x5 Member were deposited in the mildly brackish water and weak oxidation-weak reduction environment, while the source rocks of Upper Jurassic were deposited mainly in an oxygen-rich, mildly brackish water-freshwater sedimentary environment.

4. The sedimentary environment analyzed in this study is only the sedimentary environment of the source rocks of the corresponding horizons. The paleo-deposited environment of the entire horizon cannot be restored by relying only on biomarkers. Furthermore, due to the technical limitations, no further analysis has been done on the newly discovered early-eluting rearranged series compounds. These are the limitations of this study, and also the focus of future research.

Highlights

- The biomarkers of the Upper Triassic source rocks are different from that of the Lower Jurassic source rocks.
- The sedimentary environment of Upper Triassic source rocks was brackish water reducing environment.
- During the sedimentation of the Upper Triassic source rocks, small-scale transgression occurred.
- The sedimentary environment of the Early Jurassic was oxidising freshwater lacustrine environment.

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