Abstract

For the sake of explaining the organic geochemical characteristics of the hydrocarbon source rocks (SRs) around Karamay, such as thermal maturity (TM) (evidences from the temperature of maximum pyrolysis yield (Tmax), the Carbon Preference Index (CPI) and Odd to Even Preference (OEP) values, the C30 M/H versus Tm/Ts, the C29 \( \beta \beta / (\beta \beta + \alpha \alpha) \) versus C29 20 S/ (20 S + 20 R)), hydrocarbon potential (HP) (evidences from total organic carbon (TOC) and rock pyrolysis (RP)), organic matter (OM) source input (evidences from n-Alkane distribution, the relative quantity of C27-C28-C29 steranes, the \((C_{19} + C_{20})/C_{23}\) tricyclic terpane (TT), and the Terrigenous/aquatic ratio (TAR)) as well as paleoenvironment (evidences from the pristane/phytane (Pr/Ph) and the Gammacerane index), and in order to analyze the biodegradation degree and source of oil sand (OS) oil, 55 core samples of SRs in all were selected to measure TOC and RP. 14 core samples of SRs and 3 OS samples were selected for gas chromatography–mass spectrometry (GC-MS) analysis. 11 core samples of SRs and 3 OS samples were used for organic carbon isotope (OCI) analysis. The results indicate that except the SR from Fengcheng formation \((P1_f)\) which is in the stage of high or over evolution, the other SRs are in mature stage. OM type of Carboniferous (C) SRs are type II kerogen, with the largest abundance. OM type of the SRs in
Wuerhe formation (P2w) and Jiamuhe formation (P1j) are type III kerogen with good and medium OM abundances. Almost all SRs were formed in the reduction environment of high salinity, and the main OM source input is the lower aquatic plants. Karamay formation (T2k) and Badaowan formation (J1b) oil sands (OSs) around Karamay have undergone serious biodegradation. It is suggested that OS oil are mainly from P1f SRs (evidences from the tricyclic terpanes (TT), triarysteranes, pregnane, homopregnane and OCI).

**Keywords**
Oil-source correlation, biodegradation, organic geochemical characteristics, oil sands, source rocks, surroundings of Karamay

**Introduction**
Junggar basin is the basin with the most abundant OS resources in China. OS is mainly distributed in the northwest edge of the basin from Kebai fault zone to Wuxia fault zone. The OSs, which are mainly found in Middle Triassic T2k, Upper Jurassic J1b and Cretaceous Tugulu group, have such characteristics: there are many oil-bearing sand layers (3–14 layers); the thicknesses are large (1.5–26.15m), and the oil contents are high (3%–18%). Among them, the geological resources of OS with burial depth of 0–100 m are 5.1 × 10^8 t, and the recoverable resources are 3.43 × 10^8 t; the geological resources of OS with burial depth of 100–500 m are 9.2 × 10^8 t, and the recoverable resources are 5.52 × 10^8 t. However, exploring and developing OS resources in this area has not been paid enough attention to. It was not until 2012 that China’s first barrel of OS oil was processed and produced from the OS in Wuerhe area in the north of Karamay. In 2013, PetroChina and the local government jointly established Xinjiang Jingobi OS Mine Development Company and built development project of OS mine in Wuerhe area.

Analyzing the geochemical characteristics of OS oil can solve the source problem of OS oil and provide help for exploring and developing OS resources efficiently. However, the distribution of OSs in the surface and near surface environment is inevitably affected by biodegradation, and then some commonly used oil source contrast biomarkers are consumed, which makes it difficult to study the source of OS oil. Firstly, the degree of biodegradation of OS oil should be judged according to the geochemical characteristics. Volkman et al. (1983), Connan (1984), Williams et al. (1986), Wenger et al. (2002), Bao et al. (2007), Larter et al. (2012) sequenced the biomarkers of anti-biodegradation ability from weak to strong based on the experiment and crude oil sample analysis: n-Alkane, i-Alkane, isoprenoid alkane, bicyclic sesquiterpene alkane, hopane (25-norhopanes formed after degradation), sterane, hopane (25-norhopanes not formed after degradation), rearranged sterane, aromatic sterane and porphyrin. Peters and Moldowan (1993) classified the degree of biodegradation into 10 levels. Secondly, different oil source comparison methods are selected according to the degree of biodegradation. For crude oil subject to slight biodegradation, the method of comparison of chromatographic characteristics of saturated hydrocarbon in crude oil and SR extract can be applied, which includes the distribution features of n-Alkane and i-Alkane, the main peak carbon number of n-Alkane, odd and even dominant values, pristane/phytane (Pr/Ph), etc. For crude oil with medium biodegradation degree, such as
n-Alkane, i-Alkane and isoprene alkanes, which have been modified by microorganisms, the geochemical characteristics of steranes and hopanes can be used for comparison (Peters and Moldowan, 1993). The commonly used parameters include: the Gammacerane index (Ga/C₃₀H = Gammacerane/17αβ C₃₀hopane) reflecting the sedimentary environment of the SRs, the relative contents of C₂₇-C₂₈-C₂₉ steranes reflecting the type of the SRs, the C₂₉ 2₀ S/(2₀ S + 2₀ R) steranes, the C₂₉ β/β ((α + β)/(α + β)) steranes, the C₂₉M/C₂₉H (C₂₉ moretane/norhopane) and the C₃₁ 2₂ S/(2₂ S + 2₂ R) representing the maturity, etc. For crude oil which have suffered from serious biodegradation and whose steroids and hopane have been damaged to different degrees, aromatic steroids (such as triarysteranes) with stronger biodegradation ability can be used for oil source comparison (Seifert et al., 1984). TT and pregnane + homopregnanne have strong anti-biodegradation ability, which is also a good method for oil source comparison of severely biodegradable crude oil (Anders and Robinson, 1971; Li et al., 2012; Peters et al., 2007; Reed, 1977; Wang et al., 2008). In addition, OCI is often used for oil source comparison. For light biodegradation crude oil, the carbon isotopes of n-Alkane can be used for oil source comparison. For medium biodegradation crude oil, the carbon isotopes of terpenes can be used for oil source comparison. For serious biodegradation crude oil, the carbon isotopes of the whole oil are generally used for oil source comparison (Atlas, 1981; Kennicutt, 1988; Stahl, 1980).

**Geological setting**

Karamay is located near the Kebai fault zone and the southwest edge of Mahu Sag. The faults and stratigraphic unconformities have been developed a lot (Figure 1). Through these faults and unconformities, the oil and gas generated by the SRs in Mahu Sag migrated to the sand of Triassic, Jurassic and Cretaceous near Karamay, and then was thickened and degraded by microorganisms, finally forming OSs.

There are four sets of strata that can be used as SRs in Mahu Sag (Figure 2(a)): the C SRs, the P₁j SRs, the P₁f SRs and the P₂w SRs (Chen et al., 2016; Feng et al., 2019, 2020a, 2020b; Tao et al., 2016). Under the tectonic background of continuous compression, Mahu Sag in period C was transformed from ocean to land environment, and its SRs were mainly tuffs and mudstones (Zhou et al., 2019). The SRs of Permian were all formed in lacustrine environment, in which the P₁j of Early Permian was volcanic lacustrine environment, with the SRs being mainly mudstones, argillaceous siltstones and tuffs; the P₁f of Early Permian was in profundal and limited lacustrine environment, and the SRs were mudstones and argillaceous dolomites; in the period of P₂w of Middle Permian, the lake water became shallow, and the SRs were mainly mudstones deposited under the shallow lake environment. Tao et al. (2016), Yu et al. (2018a, 2018b), Zhang et al. (2018), Feng et al. (2020a, 2020b) thought that the P₁j SRs were deposited in the alkali lake environment, with a wide distribution area, good type and large abundance of organic matter. Now they are primarily in the stage of mature evolution and are the best SRs in the region. For example, the crude oil in the sand conglomerate reservoir of Baikouquan formation of Triassic in Mahu Sag primarily came from the P₁j SRs (Feng et al., 2019; Liu et al., 2016). Did the OS oil around Karamay mainly come from the P₁j SRs? At present, there is no research work in this area.

In order to analyze the source of OS oil around Karamay, it is necessary to analyze the geochemical characteristics of OS oil. OS samples come from the top of T₂k and the bottom of J₁b in Tuziakne Ditch, northwest Karamay (Figures 1 and 2(b)). The T₂k and J₁b in this
Figure 1. Locations of the study wells where the SRs come from (The relationship between the samples and the wells is shown in Tables 1 to 3) and the sections.

Figure 2. Stratigraphic columns (a and b), sections and OS samples, by referring Tao et al. (2016), Liu et al. (2016), Mao et al. (2020), Wang et al. (2020) and Feng et al. (2019, 2020a).
area are in unconformity contact. Their sedimentary environments are all braided river
delta, and the OSs are mainly coarse sandstones (Figure 2(b)). Due to long-term exposure
to the surface, the sandstones have been subject to weathering and the densities are reduced
(Figure 2). Among them, the OS oil must have undergone a strong biodegradation, which
brings difficulties to the study of the source of OS oil. It is necessary to comprehensively
analyze the geochemical characteristics of OS oil and make a comparative study of oil
sources on the basis of evaluating the degree of biodegradation.

**Sampling and methodology**

A total of 55 core samples of SRs (8 in the study area and 47 in the north of the study area)
were selected for TOC and RP measurement (Figure 1 and Table 1). 14 core samples of SRs
and 3 OS samples were selected for the GC-MS analysis of aliphatic hydrocarbons and
aromatic hydrocarbons (Figure 1 and Table 2). 11 core samples of SRs and 3 OS samples
were selected for OCI analysis (Figure 1 and Table 3).

TOC was tested by the LECO cs-230 analyzer. The OGE–II oil evaluation station was
used for RP experiment. Soxhlet apparatus was used to separate aliphatic hydrocarbons and
aromatic hydrocarbons, and then GC-MS analysis was carried out. See Feng et al. (2020a)
for the process of these experiments.

The carbon isotopic compositions of SR extracts and OS oil were measured by the
Finngen-MAT252 Mass Spectrometer. The process was as follows: firstly, CCl4 was used
to dissolve the sample; then the sample was burned at 800°C; then it was reduced at 250°C;
and finally, it was measured after being cooled by liquid nitrogen. The error range of stable
carbon isotope composition is ±0.1 ‰, and the output standard of δ13C value is V-PDB.

**Results**

**Characteristics of SRs**

TOC and RP results of SRs can reflect the abundance, type and maturity of organic matter.
Of the SR samples for TOC and RP experiments, 8 samples from the study area and 47
samples from the north of the study area are selected for supplement and comparison.
Among these SR samples, the TOC from C is the highest (average TOC = 2.91%, standard
deviation (SD) = 1.46%), followed by the TOC of P2w (average TOC = 2.83%, SD = 0.46%)
and P1j (average TOC = 1.66%, SD = 0.1%), and the TOC of P1f is the lowest, with the
TOC value being 0.84% (Table 1 and Figure 3). The average values of S1 + S2 from large to
small are: the C SRs (average S1 + S2 = 2.48 mg HC/g rock, SD = 1.59 mg HC/g rock), the
P2w SRs (average S1 + S2 = 0.78 mg HC/g rock, SD = 0.51 mg HC/g rock), the P1j SRs
(average S1 + S2 = 0.10 mg HC/g rock, SD = 0.08 mg HC/g rock) and the S1 + S2 of P1f
SRs is 0.09 mg HC/g rock (Table 1 and Figure 3). By comparing the TOC and S1 + S2 of
the SRs of different strata in the study area, it is found that the trend of the two are the
same. Comparing the TOC and S1 + S2 values of 47 samples in the north of the study area, it
is found that: for the C SRs, the TOC values of the SR samples from the study area and the
north of the study area are similar, while the S1 + S2 values of the SR samples from the study
area are slightly larger; for the P1j SRs, the TOC values of the SR samples from the study
area are slightly larger, while the S1 + S2 values are relatively smaller; for the P1f SRs, the
TOC values and S1 + S2 values of the SR samples from the study area are significantly
Table 1. TOC and RP results of the SRs in the study area and the northern part of the study area.

| Region            | Well | Sample No. | Depth (m) | Formation | Lithology            | TOC (%) | $S_1$ (mg/g) | $S_2$ (mg/g) | $S_1 + S_2$ (mg/g) | HI (mg/g) | $T_{max}$ (°C) |
|-------------------|------|------------|-----------|-----------|-----------------------|---------|--------------|--------------|--------------------|-----------|----------------|
| Other areas       | Ac1  |            | 2         | P$_2$w    | Mudstone              | 0.28    | 0.08         | 0.18         | 0.26               | 63.25     | 566            |
| of Mahu Sag       | Ac1  |            | 3         | P$_2$w    | Mudstone              | 0.52    | 0.04         | 0.06         | 0.1                | 11.6      | 444            |
|                   | Ac1  |            | 5         | P$_2$w    | Mudstone              | 0.84    | 0.08         | 0.19         | 0.27               | 22.61     | 292            |
|                   | Ac1  |            | 6         | P$_2$w    | Mudstone              | 0.19    | 0.04         | 0.08         | 0.12               | 42.11     | 329            |
|                   | Ac1  |            | 7         | P$_2$w    | Mudstone              | 1.06    | 0.08         | 0.06         | 0.14               | 5.68      | 567            |
|                   | Ac1  |            | 9         | P$_2$w    | Mudstone              | 7.9     | 0.12         | 0.18         | 0.3                | 2.28      | 298            |
|                   | Ac1  |            | 10        | P$_2$w    | Mudstone              | 1.62    | 0.05         | 0.07         | 0.12               | 4.32      | 474            |
|                   | Ac1  |            | 11        | P$_3$w    | Mudstone              | 1.7     | 0.42         | 0.35         | 0.77               | 20.64     | 446            |
|                   | Ac1  |            | 12        | P$_2$w    | Mudstone              | 1.19    | 0.10         | 0.14         | 0.24               | 11.81     | 424            |
|                   | Ac1  |            | 13        | P$_2$w    | Mudstone              | 1.92    | 0.18         | 0.22         | 0.4                | 11.48     | 532            |
|                   | Ac1  |            | 14        | P$_2$w    | Mudstone              | 1.52    | 0.03         | 0.02         | 0.05               | 1.32      | 412            |
|                   | Ac1  |            | 15        | P$_2$w    | Mudstone              | 1.72    | 0.09         | 0.13         | 0.22               | 7.57      | 413            |
|                   | Ac1  |            | 16        | P$_3$w    | Argillaceous siltstone | 1.62  | 0.69         | 0.51         | 1.2                | 31.41     | 386            |
|                   | Fc1  |            | 17        | P$_1$j    | Argillaceous siltstone | 0.44  | 0.05         | 0.06         | 0.11               | 13.73     | 424            |
|                   | Fc1  |            | 18        | P$_1$j    | Argillaceous siltstone | 0.64  | 0.03         | 0.04         | 0.07               | 6.26      | 307            |
|                   | Fc1  |            | 19        | P$_1$j    | Argillaceous siltstone | 2.27  | 0.25         | 1.08         | 1.33               | 47.49     | 441            |
|                   | Fc1  |            | 20        | P$_1$j    | Argillaceous siltstone | 0.79  | 0.08         | 0.13         | 0.21               | 16.41     | 382            |
|                   | Fc1  |            | 21        | P$_1$j    | Argillaceous siltstone | 0.68  | 0.05         | 0.09         | 0.14               | 13.22     | 472            |
|                   | Fc1  |            | 22        | P$_1$j    | Mudstone              | 1.64    | 0.06         | 0.21         | 0.27               | 12.8      | 515            |
|                   | X76  |            | 25        | P$_1$j    | Argillaceous siltstone | 0.49  | 0.16         | 0.15         | 0.31               | 30.69     | 424            |
|                   | X76  |            | 26        | P$_1$j    | Argillaceous siltstone | 0.92  | 0.15         | 0.3          | 0.45               | 32.67     | 454            |
|                   | X76  |            | 27        | P$_1$j    | Mudstone              | 0.52    | 0.09         | 0.14         | 0.23               | 27.07     | 523            |
|                   | X76  |            | 28        | P$_1$j    | Mudstone              | 0.3     | 0.12         | 0.15         | 0.27               | 50.27     | 311            |
|                   | Fn1  |            | 30        | P$_1$f    | Argillaceous dolomite | 3.41   | 0.36         | 8.37         | 8.73               | 245.2     | 449            |
|                   | Fn1  |            | 32        | P$_1$f    | Mudstone              | 1.85    | 0.31         | 3.46         | 3.77               | 186.9     | 449            |
|                   | Fn1  |            | 33        | P$_1$f    | Argillaceous dolomite | 2.07   | 0.39         | 2.06         | 2.45               | 99.45     | 446            |
|                   | Fn1  |            | 34        | P$_1$f    | Mudstone              | 1.09    | 0.3          | 0.61         | 0.91               | 55.73     | 443            |
|                   | Fn1  |            | 37        | P$_1$f    | Mudstone              | 1.45    | 0.37         | 1.66         | 2.03               | 114.8     | 447            |
|                   | Fn1  |            | 39        | P$_1$f    | Mudstone              | 2.56    | 0.59         | 7.29         | 7.88               | 284.8     | 460            |
|                   | Fn1  |            | 41        | P$_1$f    | Mudstone              | 0.87    | 0.91         | 0.93         | 1.84               | 106.8     | 436            |
|                   | Fn1  |            | 43        | P$_1$f    | Argillaceous dolomite | 0.82   | 0.46         | 0.53         | 0.99               | 64.62     | 394            |

(continued)
| Region   | Well | Sample No. | Depth (m) | Fmation    | Lithology         | TOC (%) | $S_1$ (mg/g) | $S_2$ (mg/g) | $S_1 + S_2$ (mg/g) | HI (mg/g) | $T_{max}$ (°C) |
|----------|------|------------|-----------|------------|-------------------|---------|-------------|-------------|---------------------|-----------|---------------|
| Fn1      | 45   | 4252       | P1f       | Mudstone   | 0.85              | 0.49    | 0.53        | 1.02        | 62.67               | 386       |
| Fn1      | 46   | 4320       | P1f       | Argillaceous dolomite | 3.35              | 0.27    | 2.33        | 2.6         | 69.56               | 449       |
| Fn1      | 47   | 4327       | P1f       | Argillaceous dolomite | 9.57              | 0.56    | 1.06        | 1.62        | 11.08               | 449       |
| Fn1      | 48   | 4338       | P1f       | Argillaceous dolomite | 7.39              | 0.3     | 1.91        | 2.21        | 25.84               | 446       |
| Fn1      | 49   | 4340       | P1f       | Argillaceous dolomite | 3.78              | 0.18    | 5.37        | 5.55        | 142.1               | 452       |
| Fn1      | 50   | 4358       | P1f       | Argillaceous dolomite | 3.13              | 1.02    | 1.42        | 2.44        | 45.4                | 433       |
| Bz7      | 51   | 745        | C         | Tuff       | 19.4              | 0.31    | 0.31        | 0.62        | 1.6                 | 414       |
| Bz7      | 52   | 913        | C         | Tuff       | 20.7              | 0.02    | 0.04        | 0.06        | 0.19                | 546       |
| Bz7      | 53   | 1097       | C         | Tuff       | 1.24              | 0.14    | 0.18        | 0.32        | 14.49               | 521       |
| Bz7      | 54   | 1108       | C         | Tuff       | 1.3               | 0.07    | 0.12        | 0.19        | 9.24                | 395       |
| Bz7      | 55   | 1289       | C         | Tuff       | 3.88              | 0.12    | 0.27        | 0.39        | 6.96                | 436       |
| Bz7      | 56   | 1421       | C         | Tuff       | 0.91              | 0.06    | 0.15        | 0.21        | 16.4                | 433       |
| Bz7      | 57   | 1433       | C         | Tuff       | 1.49              | 0.08    | 0.16        | 0.24        | 10.77               | 448       |
| Bz7      | 58   | 1997       | C         | Tuff       | 3.62              | 0.17    | 0.24        | 0.41        | 6.64                | 389       |
| Bz7      | 59   | 2269       | C         | Tuff       | 2.82              | 0.11    | 0.3         | 0.41        | 10.63               | 289       |
| Bz7      | 60   | 2336       | C         | Tuff       | 1.57              | 0.1     | 0.18        | 0.28        | 11.49               | 400       |
| Surroundings of Karamay | K80 | 67       | 4202      | P2w       | Silty mudstone   | 2.19    | 0.08        | 0.19        | 0.27                | 8.67      | 439           |
| Surroundings of Karamay | K80 | 68       | 4216      | P2w       | Mudstone         | 3.47    | 0.31        | 0.98        | 1.29                | 28.23     | 455           |
| Mh16     | 70   | 4382       | P1f       | Mudstone   | 0.84              | 0.03    | 0.06        | 0.09        | 7.17                | 512       |
| K302     | 76   | 4156       | P1j       | Silty mudstone | 1.56              | 0.07    | 0.1         | 0.17        | 6.4                 | 444       |
| K302     | 79   | 4311       | P1j       | Mudstone   | 1.76              | 0.01    | 0.01        | 0.02        | 0.57                | 398       |
| K022     | 80   | 2661       | C         | Tuffaceous mudstone | 2.39              | 0.72    | 3           | 3.72        | 125.6               | 446       |
| Jl24     | 81   | 2720       | C         | Tuffaceous mudstone | 4.9               | 0.11    | 3.38        | 3.49        | 68.91               | 441       |
| Jl24     | 82   | 2778       | C         | Tuffaceous mudstone | 1.44              | 0.09    | 0.14        | 0.23        | 9.76                | 317       |
| Sample no. | Depth (m) | Fm. | Lithology | n-Alkanes | Tepanes (m/z 191) | Steranes (m/z 217) |
|------------|-----------|-----|-----------|-----------|-------------------|-------------------|
| Mh6 62 | 3772 | P2w | Mudstone | 1.69 0.43 1.28 | 1.07 0.51 | 1.93 0.46 0.27 | 0.19 0.18 0.56 | 36.80 33.38 29.83 | 0.42 0.35 | 0.36 0.28 |
| Mh6 63 | 3773 | P2w | Mudstone | 2.00 0.52 1.13 | 1.08 0.97 | 0.53 0.54 | 1.00 0.71 0.25 | 0.15 0.15 0.53 | 45.69 31.15 23.16 | 0.39 0.41 | 0.43 0.36 |
| K80 66 | 4084 | P2w | Silty mudstone | 0.23 0.08 1.11 | 1.18 0.93 | 0.32 0.41 | 1.84 0.35 0.29 | 0.14 0.19 0.63 | 3.41 46.72 49.87 | 0.48 0.41 | 0.53 0.46 |
| K80 67 | 4201.5 | P2w | Silty mudstone | 0.13 0.04 1.50 | 1.24 0.98 | 0.37 0.48 | 0.97 0.05 0.36 | 0.13 0.20 0.62 | 2.26 48.17 49.57 | 0.46 0.45 | 0.42 0.36 |
| K80 68 | 4215.8 | P2w | Mudstone | 3.08 1.49 | 1.04 0.55 | 0.69 1.03 | 0.29 0.73 | 0.53 0.65 | 0.13 0.12 0.58 | 17.53 45.35 37.12 | 0.43 0.47 | 0.51 0.48 |
| Mh16 70 | 3482 | P2f | Mudstone | 4.08 0.48 1.12 | 1.07 0.77 | 0.62 0.97 | 2.36 0.67 0.24 | 0.15 0.15 0.55 | 43.88 27.17 28.95 | 0.43 0.38 | 0.47 0.42 |
| K82 71 | 4084.3 | P2f | Tuffaceous mudstone | 0.15 0.03 | 1.33 1.28 | 0.94 0.49 | 0.70 4.15 | 0.57 0.58 | 0.43 0.08 0.42 | 0.47 31.40 40.88 | 0.38 0.41 | 0.44 0.37 |
| K302 76 | 4156 | P2j | Silty mudstone | 0.88 0.50 | 1.30 1.10 | 0.91 0.61 | 1.07 0.31 | 0.28 0.14 | 0.17 0.55 | 38.08 31.98 29.94 | 0.43 0.37 | 0.46 0.40 |
| K302 78 | 4232.6 | P2j | Mudstone | 4.30 0.36 | 1.42 1.20 | 1.07 1.16 | 0.51 0.73 | 0.51 0.83 | 0.15 0.15 0.65 | 6.13 42.55 49.32 | 0.50 0.38 | 0.46 0.41 |
| K302 79 | 4310.6 | P2j | Tuffaceous mudstone | 1.77 0.60 | 1.09 1.07 | 0.72 0.35 | 0.43 0.75 | 0.16 0.33 | 0.14 0.24 0.65 | 4.85 46.48 48.67 | 0.46 0.43 | 0.49 0.40 |
| J124 81 | 2720 | C | Tuffaceous mudstone | 3.08 1.52 | 3.12 3.14 | 0.55 0.92 | 2.03 0.56 | 0.32 0.11 0.85 | 0.10 0.25 0.36 | 86.78 10.79 2.43 | 0.16 0.36 | 0.49 0.45 |
| J124 82 | 2778 | C | Tuffaceous mudstone | 0.21 0.11 | 1.18 1.11 | 1.31 0.51 | 0.71 2.92 | 0.70 0.22 | 0.16 0.12 | 0.61 18.66 40.80 | 40.54 0.47 | 0.37 0.38 |
| J110 83 | 3002.5 | C | Tuffaceous mudstone | 1.52 0.55 | 1.11 1.06 | 0.72 0.32 | 0.39 0.80 | 0.46 | 0.40 0.14 | 0.20 0.48 | 13.54 41.55 44.91 | 0.48 0.49 | 0.46 0.45 |

1. Waxiness index = \( \sum n-C_{21-30} / \sum n-C_{15-20} \)
2. TAR = \( (n-C_{37} + n-C_{39} + n-C_{41}) / (n-C_{15} + n-C_{17} + n-C_{19}) \)
3. OEP = \( (n-C_{27} + 6 \times n-C_{29} + 4 \times n-C_{30}) / (4 \times n-C_{28} + 4 \times n-C_{30}) \)
4. CPI = 0.5 \( \times [(n-C_{21} + n-C_{23} + n-C_{25} + n-C_{27} + n-C_{29}) + (n-C_{23} + n-C_{25} + n-C_{27} + n-C_{29} + n-C_{31})] / (n-C_{22} + n-C_{24} + n-C_{26} + n-C_{28} + n-C_{30}) \)
5. Pr/Ph = pristine/phytane
6. Pr/n-C_{17} = pristine/n-C_{17}
7. Ph/n-C_{18} = phytane/n-C_{18}
8. \( (C_{19} + C_{20}) / C_{23} \) TT
9. Ts/Tm
10. Gal/C_{30} = Gammacerane/17\alpha / \beta C_{30} hpane
11. C_{29}M/C_{29}H = C_{29} moretane/norhopane
12. C_{29}M/C_{30}H = C_{30} moretane/hopane
13. 22S/(22S + 22R)
14. C_{29} = C_{27} + C_{28} + C_{29} + C_{30} + C_{31}
15. \( C_{29} = C_{27} + C_{28} + C_{29} + C_{30} + C_{31} \)
16. \( C_{29} = C_{27} + C_{28} + C_{29} + C_{30} + C_{31} \)
17. \( C_{29} = 20S/(20S + 20R) \)
18. \( C_{29} = 20S/(20S + 20R) \)
smaller; for the $P_{2w}$ SRs, the TOC and $S_1 + S_2$ values of the SR samples from the study area are slightly higher.

Hydrogen index (HI) and temperature of maximum pyrolysis yield ($T_{\text{max}}$) are of great significance to determine the type and maturity of organic matter in SRs. Among the SR samples in the study area, the average value of HI of samples from C is the largest, which is $68.10 \text{ mg HC/g TOC}$, and its range is also large, being between $9.76$ and $125.64 \text{ mg HC/g TOC}$; the average HI value from $P_{2w}$ is the second largest, being $18.45 \text{ mg HC/g TOC}$; the average HI value from $P_{1f}$ is $7.17 \text{ mg HC/g TOC}$; the lowest average value of HI is $3.49 \text{ mg HC/g TOC}$, which is from $P_{1j}$ (Table 1). The highest $T_{\text{max}}$ is $512^\circ \text{C}$ from $P_{1f}$; the second highest is $447^\circ \text{C}$ from $P_{2w}$ (ranging from $439^\circ \text{C}$ to $455^\circ \text{C}$); the $T_{\text{max}}$ from $P_{1f}$ is ranging from $398^\circ \text{C}$ to $444^\circ \text{C}$ (average $= 421^\circ \text{C}$); the $T_{\text{max}}$ from C is ranging from $317^\circ \text{C}$ to $446^\circ \text{C}$ (average $= 401^\circ \text{C}$) (Table 1).

**Table 3.** The $\delta^{13} \text{C}$ values of the representative SR and OS samples.

| Well   | Sample no. | Depth   | Fm. | Lithology       | $\delta^{13} \text{C} (\%o)$ |
|--------|------------|---------|-----|-----------------|-------------------------------|
| Mh6    | 61         | 3700.3  | $P_{2w}$ | Mudstone    | $-28.45$                     |
| Mh6    | 64         | 3838.4  | $P_{2w}$ | Mudstone    | $-28.69$                     |
| Mh6    | 65         | 3847    | $P_{2w}$ | Mudstone    | $-25.59$                     |
| K80    | 68         | 4215.8  | $P_{2w}$ | Mudstone    | $-29.71$                     |
| K82    | 69         | 3856    | $P_{2w}$ | Mudstone    | $-28.46$                     |
| K82    | 72         | 4088.5  | $P_{1f}$ | Tuffaceous mudstone | $-30.05$                     |
| J117   | 73         | 3786    | $P_{1j}$ | Silty mudstone | $-28.80$                     |
| K302   | 74         | 3993    | $P_{1j}$ | Mudstone    | $-29.85$                     |
| K302   | 75         | 4154.6  | $P_{1j}$ | Silty mudstone | $-29.42$                     |
| K302   | 77         | 4231.8  | $P_{1j}$ | Silty mudstone | $-28.71$                     |
| K302   | 79         | 4310.6  | $P_{1j}$ | Mudstone    | $-28.18$                     |
| Oil sand | YS-1       | /       | $T_{2k}$ | Sandstone   | $-29.97$                     |
| Oil sand | YS-2       | /       | $J_{1b}$ | Sandstone   | $-30.89$                     |
| Oil sand | YS-3       | /       | $J_{1b}$ | Sandstone   | $-30.28$                     |

**Figure 3.** TOC and $S_1 + S_2$ values of the SRs in the study area and the north of the study area.
**Aliphatic hydrocarbons characteristics**

The m/z 85 mass chromatograms (MCs) can reflect the \( n \)-Alkane distributions. The \( n \)-Alkane distribution of C SRs includes two types (Table 2 and Figure 4): the first type is pre unimodal, and the main peak carbon is \( n \)-C\(_{16} \), for example, Sample 82. Low waxiness index (WI) (0.21) and Terrigenous/aquatic ratio (TAR) (0.11) indicate that the low molecular weight (MW) \( n \)-Alkane is dominant, and low Odd to Even Preference (OEP) (1.18) as well as Carbon Preference Index (CPI) (1.11) values indicate that there is no obvious odd carbon number predominance. The second type is post unimodal, and the main peak carbon is \( n \)-C\(_{23} \). For example, Samples 80 and 83. High waxiness index (1.77 and 1.52) and TAR (0.60 and 0.55) indicate that the high molecular weight \( n \)-Alkane is dominant, and low OEP (1.09 and 1.11) and CPI (1.07 and 1.06) values indicate that there is no obvious odd carbon number predominance (OCNP).

The \( n \)-Alkane distribution of P\(_{3j} \) SRs includes two types (Table 2 and Figure 4): the first type is pre unimodal, and the main peak carbon is \( n \)-C\(_{16} \) or \( n \)-C\(_{17} \), for example, Samples 76 and 79. Low WI (0.15 and 0.36) and TAR (0.03 and 0.14) indicate that the low MW \( n \)-Alkane is dominant, and low OEP (1.33 and 1.20) and CPI (1.28 and 1.07) values indicate that there is no obvious OCNP. The second type is bimodal, and the main peak carbons are \( n \)-C\(_{18} \) and \( n \)-C\(_{25} \). For example, Sample 78. Low WI (0.88) and TAR (0.50) indicate that the low MW \( n \)-Alkane is dominant, and low OEP (1.30) and CPI (1.10) value indicates that there is no obvious OCNP.

The \( n \)-Alkane distribution of P\(_{3f} \) SRs also includes two types (Table 2 and Figure 4): the first type is pre unimodal, and the main peak carbon is \( n \)-C\(_{17} \), for example, Sample 71. Low WI (0.48) and TAR (0.21) indicate that the low MW \( n \)-Alkane is dominant; low OEP (1.12) and CPI (1.07) values indicate that there is no obvious OCNP. The second type is post unimodal, and the main peak carbon is \( n \)-C\(_{25} \), for example, Sample 70. High WI (3.08) and TAR (1.49) indicate that the high MW \( n \)-Alkane is dominant; low OEP (1.04) and CPI (1.07) values indicate that there is no obvious OCNP. Different from other SR samples, the m/z 85 MCs baseline of Sample 70 slightly uplifted, indicating that it suffered slight microbial degradation and some unresolved complex mixture (UCM) were formed.

The \( n \)-Alkane distribution of P\(_{2w} \) SRs also includes two types (Table 2 and Figure 4): the first type is pre unimodal, and the main peak carbon is \( n \)-C\(_{17} \), for example, Samples 67 and 68. Low WI (0.23 and 0.13) and TAR (0.08 and 0.04) indicate that the low MW \( n \)-Alkane is dominant; low OEP (1.11 and 1.50) and CPI (1.18 and 1.24) values indicate that there is no obvious OCNP. The second type is bimodal, and the main peak carbon is \( n \)-C\(_{16} \) or \( n \)-C\(_{17} \) and \( n \)-C\(_{25} \) or \( n \)-C\(_{27} \), for example, Samples 62, 63 and 66, in which the low WI (0.60 and 1.00) and TAR (0.43 and 0.52) of Samples 63 and 66 show that the low MW \( n \)-Alkane is dominant; the high WI (1.69) and TAR (0.77) of Sample 62 show that the high MW \( n \)-Alkane is dominant. These samples all have low OEP (1.13–1.50) and CPI (1.08–1.23) values, indicating that there is no obvious OCNP.

The m/z 85 MCs of the three OS samples all showed obvious baseline uplift, indicating that they all suffered from strong biodegradation (Figure 4).

Pr/Ph ratio can reflect the redox conditions of sedimentary environment. The Pr/Ph ratios in the study area range from 0.55 to 4.04 (Table 2). There are four samples with Pr/Ph ratios greater than 1, including Samples 62, 63, 79 and 82. The Pr/Ph ratio of Sample 62 is the largest, which is 4.04. The Pr/\( n \)-C\(_{17} \) ratio of Sample 62 is also the largest, which is
The Pr/\textit{n}-C\textsubscript{17} ratios of the other samples are 0.32 – 0.92 (Table 2). The Ph/\textit{n}-C\textsubscript{18} ratios of all the SR samples are 0.39 – 2.03 (Table 2).

The distribution of TT can be seen from m/z 191 MCs of aliphatic hydrocarbons (Figure 5). According to the relative content (RC), four types can be classified: for Type 1, the C\textsubscript{20} TT has the largest relative content (Figure 5), for example, Samples 63, 71, 76 and 82. The relative contents of C\textsubscript{23} TT are the highest for the other three types. Among them, the samples with the relative contents of C\textsubscript{20} TT greater than C\textsubscript{21} TT (such as Samples 68

Figure 4. The m/z 85 MCs of the representative SR and OS samples.
and 78) are classified into Type 2 (Figure 5); the samples with the relative contents of C_{20} TT less than C_{21} TT and the relative contents of C_{24} TT greater than C_{21} TT (such as Samples 70 and YS-2) are classified into Type 3 (Figure 5); the samples with the relative contents of C_{20} TT less than C_{21} TT and the relative contents of C_{24} TT less than C_{21} TT (such as Sample 80) are classified into Type 4 (Figure 5). The (C_{19} + C_{20})/C_{23} TT ratio can reflect the OM’s source and the depositional paleo-environment (Bohacs et al., 2000;
Peters et al., 2008; Tao et al., 2015). The ratios from $P_{2w}$ and $P_{1f}$ samples are the most similar, 0.96–1.93 (average $= 1.34$, SD $= 0.45$) and 0.29–2.36 (average $= 1.33$, SD $= 1.04$), respectively; the ratios from $P_{1j}$ samples are the largest, ranging from 1.07 to 4.15 (average $= 2.35$, SD $= 1.31$); the ratios from C samples are the smallest, ranging from 0.52 to 2.92 (average $= 1.26$, SD $= 0.96$) (Table 2).

Hopanes evolved from the bacteriohopanepolyols precursors which came from the bacterial membranes (Peters et al., 2005). The m/z 191 MCs of aliphatic hydrocarbons also show the distribution characteristics of hopane (Figure 5). C$_{30}$ $\alpha\beta$ hopane (C$_{30}$H), C$_{29}$ $\alpha\beta$ hopane (C$_{29}$H), C$_{31}$H to C$_{35}$H of all SR samples can be detected, and the relative contents gradually decrease. Almost all samples’ 22S isomers of C$_{31}$H to C$_{35}$H are more enriched than 22R isomers. Relevant parameters of hopane have also been calculated (Table 2), including the C$_{29}$M/C$_{29}$H ratio, the C$_{30}$M/C$_{30}$H ratio, the Gammacerane index, the Ts/Tm and the 17$\alpha\beta$ C$_{31}$22S/(22 S + 22 R) value. It is difficult to distinguish the hopane in the OS samples, but C$_{29}$H can still be detected (Figure 5).

The distribution of steranes and diasteranes are shown in m/z 217 MCs. In this study, C$_{27}$ $\alpha\alpha\alpha$ 20 R cholestanes, C$_{28}$ $\alpha\alpha\alpha$ 20 R cholestanes and C$_{29}$ $\alpha\alpha\alpha$ 20 R cholestanes exhibit two types of distribution (Figure 6): upward type distribution, including Samples 68 and 80; “V” type distribution, including Samples 63, 71, 70, 76, 78 and 82. The relative content of regular steranes in SRs is significantly higher than that of diasteranes. The average percentage of relative content of C$_{27}$-C$_{28}$-C$_{29}$ regular steranes in SR samples gradually increase. Among them, C$_{27}$ regular steranes are 3.41% - 86.78% (average $= 27.71\%$, SD $= 22.75\%$); C$_{28}$ regular steranes are 10.79% - 48.17% (average $= 35.34\%$, SD $= 10.96\%$); C$_{29}$ regular steranes are 2.43% - 62.14% (average $= 36.96\%$, SD $= 14.96\%$) (Table 2). For the SRs, the C$_{29}$ 20S/(20S + 20 R) sterane ratios are 0.16 – 0.50 and the C$_{29}$ $\beta\beta/ \beta\beta + \alpha\alpha$ sterane ratios are 0.31 – 0.49 (Table 2). The relative content of regular steranes in OS samples is low, and some of them have been consumed (Figure 6). There are also two distribution characteristics of $\beta\beta\alpha$ pregnane, $\alpha\beta$ pregnane and homopregnane in SR and OS samples (Figure 6): inverted “V” type distribution includes all SR samples except Sample 70, and descending type distribution includes all OS samples and SR Sample 70.

**Characteristics of triarysteranes**

Triarysteranes in aromatic hydrocarbons have strong anti-biodegradation ability, which is of great significance to the oil source comparison of severely degraded crude oil. The distribution characteristics of triarysteranes can be seen from the m/z 231 MCs of aromatic hydrocarbons (Figure 7). Triarysteranes in SRs are easy to identify, with two types: the first type has the largest relative content of C$_{26}$20R + C$_{27}$20S, and the representative samples include Samples 70, 76 and 80 from $P_{1f}$, $P_{1j}$ and C; the second type has the largest relative content of C$_{28}$20S, and the representative sample is Sample 68 from $P_{2w}$. For the OS samples, triarysteranes of Sample YS-2 from J$_{1b}$ can be identified, which is similar to the first type; only a small amount of triarysteranes of Sample YS-3 from J$_{1b}$ can be identified; triarysteranes cannot be identified in Sample YS-1 from T$_{2k}$ (Figure 7).

**Characteristics of OCI**

The OCI of the extracts from the SRs in the study area are similar (Table 3). The distribution of $\delta^{13}C$ is between $-30.05\%$ and $-25.59\%$. Among them, the OCI of the SRs from $P_{1f}$
are the lightest, and δ\(^{13}\)C is −30.05‰; the OCI of the SRs from P\(_j\) are lighter, and δ\(^{13}\)C is between −29.85‰ and −28.18‰ (average = −28.99‰, SD = 0.58‰); the OCI of the SRs from P\(_w\) are the heaviest, and δ\(^{13}\)C is from −29.71‰ to −25.59‰ (average = −28.18‰, SD = 1.38‰); the OCI of the SRs from C are not measured. The OCI of OSs is very light, and δ\(^{13}\)C is between −30.89‰ and −29.97‰ (average = −30.38‰, SD = 0.38‰).
Organic geochemical characteristics of SRs

TM of SRs. The TM of SRs can be estimated by some parameters from RP and aliphatic hydrocarbon (Flannery and George, 2014; George et al., 1994, 1997; Geršlová et al., 2015; Luo et al., 2016a, 2016b, 2017; Peters et al., 2005).

HI and Tmax can reflect the TM of SRs (Peters and Cassa, 1994). It can be seen from Figure 8 that the OM of P\textsubscript{1f} SR is in the stage of high-over maturity evolution, and that of P\textsubscript{2w} and P\textsubscript{1j} SRs are in the stage of maturity evolution (excluding Sample 79 from P\textsubscript{1j}, because its S\textsubscript{2} value is very small, being only 0.01 mg HC/g Rock, and the corresponding Tmax is not credible), while most of the OM of C SRs are in maturity evolution stage (Samples 80 and 81), and a few are in immaturity stage (Sample 82). Comparing the SR samples in the north of the study area (Figure 8), it is found that the TM of OM in C SRs in the study area is higher, and the TM of OM in P\textsubscript{1f} SR is significantly higher, and the TM of OM in P\textsubscript{2w} SRs is concentrated in the mature stage. At the same time, the CPI and OEP values of almost all the samples are low (Table 2), which indicates that the TM is high.

Figure 7. The m/z 231 MCs of the representative SR and OS samples, displaying the distribution of triarysteranes.
With the increase of the TM, \( \frac{C_{30M}}{C_{30H}} \) in hopanes decreases gradually, while \( \frac{T_s}{T_m} \) increases gradually (Peters et al., 2005). As shown in Figure 9, the SR samples in the study area drop in the zone of pre material to early material. Compared with Tmax, the TM reflected by \( \frac{C_{30M}}{C_{30H}} \) and \( \frac{T_s}{T_m} \) is slightly lower.

The \( \frac{C_{29}^{20S}}{(20S + 20R)} \) and \( \frac{C_{29}^{bb}}{(bb + aa)} \) can reflect the TM of OM (Peters et al., 2005). With the increase of the TM, the \( C_{29}^{20S} \) has gradually increased compared with \( C_{29}^{20R} \) (equilibrium point \( \frac{C_{29}^{20S}}{(20S + 20R)} = 0.52 - 0.55 \)) and the \( C_{29}^{bb} \) has gradually increased compared with \( C_{29}^{aa} \) (equilibrium point \( \frac{C_{29}^{bb}}{(bb + aa)} = 0.67 - 0.71 \)) (Seifert and Moldowan, 1978). From Figure 10, all the SR samples are in the mature stage.

In conclusion, almost all the SR samples are in mature TM stage, while only 70 samples from \( P_{1f} \) are in high-over mature TM stage and 82 samples from C are in immature TM stage.

**OM and sedimentary paleoenvironment of SRs.** The relative content of Pr and Ph can reflect the redox conditions of the ancient water body when the SR was deposited (Powell and
Mckirdy, 1973). Didyk et al. (1978), Peters et al. (2005) thought that if Pr/Ph is less than 1.0, the environment was in reduction conditions; if Pr/Ph is greater than 3.0, the environment was in oxidation conditions. It can be seen from Figure 11 that only Pr/Ph of Sample 62 from P2w is greater than 3.0, which reflected oxidation environment, and all the other samples’ Pr/Ph values are around 1, indicating reduction environment. Consistent with the redox conditions of ancient water reflected by Pr/Ph (Figure 12), Pr/n-C17 and Ph/n-C18 also indicate that Sample 62 belonged to oxidation environment and all the other samples belonged to reduction environment (Peters et al., 1999).

The SRs deposited in high salinity water have high Gammacerane content (Damsté et al., 1995). It can be seen from Table 2 and Figure 11 that almost all SR samples have the characteristics of high Gammacerane index, which indicates that they were formed in the environment of saliency qualified water column with reduction. Only Sample 81 from C and Sample 62 from P2w have low Gammacerane indexes (Table 2 and Figure 11).
The relative contents of C\textsubscript{27}, C\textsubscript{28} and C\textsubscript{29} steranes can indicate the input of OM. If the OM is from higher plants, the relative content of C\textsubscript{29} sterane is higher (Huang and Meinschein, 1979). Otherwise, the indicator OM mainly comes from the prokaryotic organizations (Isaken, 1991). According to the relative contents of C\textsubscript{27}, C\textsubscript{28} and C\textsubscript{29} steranes, most of the SR samples in the study area can be divided into two types (Figure 13): Type 1 has low relative content of C\textsubscript{27} sterane, while the relative contents of C\textsubscript{28} and C\textsubscript{29} steranes are similar, and this type of samples fall into the terrestrial zone; Type 2 has similar relative contents of C\textsubscript{27}, C\textsubscript{28} and C\textsubscript{29} steranes, and this type of samples fall into the marine zone. Except for the C sedimentary period, the study area was a transitional environment of land and sea, and the P\textsubscript{2w}, P\textsubscript{1f} and P\textsubscript{1j} sedimentary periods were all lake environments. Combined with the characteristics of high Ga content, it is considered that the lake was a salt water

Figure 12. Plot of Pr/n-C\textsubscript{17} versus Ph/n-C\textsubscript{18} can reflect the paleosedimentary environment of the SRs.

Figure 13. The relative contents of C\textsubscript{27}-C\textsubscript{28}-C\textsubscript{29} steranes.
lake with high salinity. Therefore, the relative contents of C\textsubscript{27}, C\textsubscript{28} and C\textsubscript{29} steranes in the SR formed in the salt water lake may be similar to that in the marine environment. Two samples are totally different from the other samples (Table 2 and Figure 13): one is Sample 62 from P\textsubscript{2w}, with the relative content of C\textsubscript{29} sterane being significantly higher than the relative contents of C\textsubscript{27} and C\textsubscript{28} steranes, so it is speculated that a large proportion of its OM was terrigenous higher plants; the other one is Sample 81 from C, with the relative content of C\textsubscript{27} sterane being significantly higher than the relative contents of C\textsubscript{28} and C\textsubscript{29} steranes, and the OM is mainly aquatic plankton.

The (C\textsubscript{19} + C\textsubscript{20})/C\textsubscript{23} TT and the TAR can also reflect the input of OM (Bourbonniere and Meyers, 1996; Meyers, 1997; Peters & Moldowan, 1993; Tao et al., 2015). The ratio of (C\textsubscript{19} + C\textsubscript{20})/C\textsubscript{23} TT and the TAR are small for most SRs in the study area, which also indicate that the amount of terrestrial OM is small (Table 2 and Figure 14). In contrast, Sample 70 from P\textsubscript{1f} and Sample 81 from C have the same feature of high TAR, indicating the input of higher plants (Table 2 and Figure 14). However, the degradation of Sample 70 may affect the distribution of n-Alkanes, and the OM input results reflected by the TAR and C\textsubscript{27}-C\textsubscript{28}-C\textsubscript{29} steranes of Sample 81 contradict each other.

In conclusion, almost all the samples are formed in water with high salinity and reduction environment, and terrestrial higher plants are not the main input of OM. Sample 62 from P\textsubscript{2w} and Sample 81 from C are totally different from the other samples. Among them, Sample 62 has relatively high content of C\textsubscript{29} sterane, and its n-Alkanes have bimodal characteristics, with the high molecular weight of n-Alkanes content being large, which indicates that the OM has a large proportion of terrestrial higher plants, combined with the characteristics of low Ga content and high Pr/Ph. It is speculated that Sample 62 was deposited in the freshwater oxidation environment near the lake estuary. For Sample 81, the relative content of C\textsubscript{27} sterane is high, but the high molecular weight of n-Alkane is high (TAR value is large); the contribution of terrestrial higher plants may be large, and the content of Ga is also low, while Pr/Ph is less than 1, indicating that Sample 81 might be in an environment of freshwater deep-water lake.

**Hydrocarbon generating capacity of SRs.** According to the Tmax of RP test and some parameters from hopane and sterane (Table 2 and Figure 8 to 10), except for one sample of P\textsubscript{1f} which is in the stage of high - over TM, the other SRs are in the mature stage. According to the RP

![Figure 14. TAR versus (C\textsubscript{19} + C\textsubscript{20})/C\textsubscript{23} TT shows the contributions of the OM input.](image-url)
results, the kerogen type of C SRs is the best, which is type II; the kerogen type of P1j and P3w SRs is type III; however, the thermal evolution of P1f is too high to judge the kerogen type. According to the n-Alkane distribution (Figure 4) and the elative quantity of C27-C28-C29 steranes (Figure 13), the SRs of all strata have the input of terrigenous higher plants, but terrigenous higher plants are not the main source of OM. According to the TAR (Figure 14), the terrestrial higher plants’ contribution to Sample 62 of P2w and Sample 81 of C is obvious.

According to TOC and S1+S2 (Figure 3), the OM abundance of C SRs is the largest, reaching good to excellent level; the OM abundance of P2w SRs is large, reaching good level; the OM abundance of P1j SRs is moderate level; the OM abundance of P1f SR is the least, possibly affected by its high TM.

According to the Pr/Ph (Figure 11 and Table 2) value, the Gammacerane index (Figure 11 and Table 2) and the Pr/n-C17 versus Ph/n-C18 (Figure 12) value, it is believed that almost all the samples were formed in the water body of high salinity and reduction environment, while the Pr/Ph value of Sample 62 from P2w is greater than 3, and the Gammacerane content is low, which was fresh water oxidation environment. The Gammacerane content of Sample 81 from C is also very low, which is speculated to be fresh water environment.

Finally, the SRs of C are considered the best; the P2w SRs are good, and the P1j SRs are medium. Although P1f SR has a high TM and has been subjected to biodegradation, it is considered that the hydrocarbon generation capacity of P1f SRs were also very good in the reservoir forming period, compared with the north of the study area.

**Biodegradation degree of OS oil**

Biodegradation of crude oil is a step-by-step process. Through experiments and analysis of crude oil samples, Volkman et al. (1983); Williams et al. (1986); Wenger et al. (2002); Larter et al. (2012) have sequenced the biomarkers of anti-biodegradation ability from weak to strong: n-Alkane, i-Alkane, isoprenoid alkane, bicyclic sesquiterpene alkane, hopane (25 - norhopanes formed after degradation), sterane, hopane (25 - norhopanes not formed after degradation), rearranged sterane, aromatic sterane and porphyrin.

The m/z 85 MCs of aliphatic hydrocarbon reflect the n-Alkane distributions. It can be seen that the baseline of m/z 85 MCs of the three OS oil samples has obvious uplift (Figure 4). It shows that n-Alkane has been strongly biodegraded and a large number of UCM has been formed.

From the m/z 191 MCs of aliphatic hydrocarbon, the distribution characteristics of hopane and TT can be seen (Figure 5). The baselines of m/z 191 MCs of the three OS oil samples in the distribution range of hopanes are significantly raised, and C30H to C35H and 25 - norhopanes could not be detected, but C29H and Ga could be detected. On the one hand, it shows that the OS oil has experienced strong biodegradation, and hopanes are destroyed due to degradation (Bennett et al., 2006; Rullkötter and Wendisch, 1982; Seifert et al., 1984; Wang et al., 2010; Wenger et al., 2002); on the other hand, it shows that C29H and Ga have stronger anti-biodegradation ability than C30H to C35H and 25 - norhopanes. C19TT to C25TT of Sample YS-2 can be detected, but that of Sample YS-3 and Sample YS-1 cannot be detected. This shows that the biodegradation of Sample YS-3 and Sample YS-1 is more serious than that of Sample YS-2.
The distribution characteristics of regular steranes, diasteranes and pregnanes in OS oil can be seen from m/z 217 MCs of aliphatic hydrocarbons (Figure 6). In the distribution range of regular steranes and diasteranes, the baseline has obvious uplift. Compared with the SR samples without biodegradation, regular steranes are more difficult to identify and their relative contents are significantly reduced, which indicates that regular steranes have been subject to obvious biodegradation. Compared with C$_{27}$-C$_{28}$-C$_{29}$ regular steranes, the relative contents of diasteranes in the three OS samples did not increase significantly, which indicates that diasteranes may also have been subject to biodegradation. The pregnane and homopregnane of the three OS samples can be detected well, which shows that the anti-biodegradation ability of pregnane and homopregnane is better than that of regular steranes and diasteranes. Compared with the TT of Sample YS-3 and Sample YS-1, it can be inferred that the anti-biodegradation ability of pregnane and homopregnane is better than that of TT.

From the m/z 231 MCs of aromatic hydrocarbons, the distribution characteristics of triarysteranes can be seen (Figure 7). Triarysteranes can be identified well in Sample YS-2, which shows that the biodegradation degree of triarysteranes is light. Some triarysteranes can be identified in Sample YS-3, which indicates that triarysteranes have been biodegraded. Triarysteranes could not be detected in Sample YS-1, which indicates that all triarysteranes have been consumed by biodegradation. It can be seen that the biodegradation order of the three samples from weak to strong is Sample YS-2, Sample YS-3 and Sample YS-1. By comparing the pregnane, homopregnane and triarysteranes of Sample YS-1, it is concluded that the anti-biodegradation ability of pregnane and homopregnane is stronger. By comparing the TT and triarysteranes of Sample YS-2, it is concluded that triarysteranes have stronger anti-biodegradation ability.

In a word, regular steranes, hopanes (no 25 - norhopanes formed after degradation) and diasteranes of Sample YS-2 have been biodegraded obviously, while TT, triarylosanes, pregnane and homopregnane have no obvious biodegradation; regular steranes, hopanes (no 25 - norhopanes formed after degradation), diasteranes and TT of Sample YS-3 have been biodegraded obviously, while triarylosanes have suffered slight biodegradation, and pregnane as well as homopregnane had no obvious biodegradation; regular steranes, hopanes (no 25 - norhopanes formed after degradation), diasteranes, TT and tricyclic of Sample YS-1 have been biodegraded obviously, while pregnane and homopregnane have suffered slight biodegradation.

On the one hand, the recognition shows that the degree of biodegradation of all OSs are very serious, and the order of biodegradation can be further identified from weak to strong as Sample YS-2, Sample YS-3 and Sample YS-1. On the other hand, it shows that the order of biomarker compounds with complete anti-biodegradation ability from weak to strong is speculated as: n-Alkane, i-Alkane, isoprenoid alkane, bicyclic sesquiterpene alkane, hopane (25 - norhopanes formed after degradation), sterane, hopane (25 - norhopanes not formed after degradation), rearranged sterane, TT, aromatic sterane, pregnane and homopregnane.

**Source of OS oil**

According to the degree of biodegradation, the relative contents of TT, aromatic sterane, pregnane and homopregnane can be used to analyze the source of OS oil. Bost et al. (2001) thought that in TT, except C$_{20}$TT, the lower the carbon number, the easier the
biodegradation. However, according to the distribution characteristics of TT in SRs and OS Sample YS-2 (Figure 5), the relative content of C\textsubscript{20}TT is lower than that of C\textsubscript{21}TT in severely biodegradable OS Sample YS-2, which is significantly different from most of the non-biodegradable SRs except for Samples 70 and 80, which shows that the TT distribution characteristics are mainly controlled by the source of crude oil and can be used for oil source comparison. The TT distribution of Sample YS-2 is similar to that of SR Sample 70 from P\textsubscript{1f}. The OS oil may come from the SRs of P\textsubscript{1f}. According to the distribution characteristics of pregnane and homopregnane in SRs and all OSs (Figure 6), the distribution characteristics of pregnane and homopregnane in Samples YS-2, YS-3 and YS-1 are similar, and they are only similar to those of SR Sample 70 from P\textsubscript{1f}. According to the distribution characteristics of triarysteranes in SRs and OS Sample YS-2 (Figure 7), the distribution characteristics of triarysteranes in OS Sample YS-2 are similar to those of SR Sample 70 from P\textsubscript{1f}, SR Sample 76 from P\textsubscript{j} and SR Sample 80 from C. Based on the above biomarkers, it is considered that the OS oil may mainly come from P\textsubscript{1f} SRs.

The OCI can further determine the source of OS oil. The biodegradation experiment of crude oil has shown that (Atlas, 1981; Kennicutt, 1988; Stahl, 1980) light carbon isotope \(^{12}\text{C}\) was preferentially used by microorganisms, resulting in the enrichment of heavy carbon isotope \(^{13}\text{C}\) by residual saturated hydrocarbon. The addition of microbial degradation products resulted in the enrichment of light carbon isotope \(^{12}\text{C}\) by non-hydrocarbon and asphaltene, with almost no change in aromatics \(\delta^{13}\text{C}\) value, but little change in total oil \(\delta^{13}\text{C}\) value. In the process of biodegradation, the transfer of organic acid and carbon dioxide may be beneficial to the enrichment of heavy isotope \(^{13}\text{C}\). Only the total oil carbon isotope \(\delta^{13}\text{C}\) values of the SR samples from P\textsubscript{2w}, P\textsubscript{1f} as well as P\textsubscript{j} and the three OS samples were measured (Table 3). Due to the lack of samples, the results of previous carbon isotope tests of the SRs in the adjacent area were supplemented (Chen et al., 2016) (Figure 15). It is found that the \(\delta^{13}\text{C}\) values of P\textsubscript{2w}, P\textsubscript{1f} in the study area are similar to those measured by predecessors, while the \(\delta^{13}\text{C}\) values of P\textsubscript{j} in the study area are obviously lighter. The \(\delta^{13}\text{C}\) values of the three OS samples are almost the same, indicating that they were from the same SR. These values are all distributed in the OCI range of P\textsubscript{1f} SRs, and they are obviously lighter than the OCI values of P\textsubscript{2w} and P\textsubscript{j} SRs. This further proves that the OS oil came from P\textsubscript{1f} SRs. However, considering the carbon isotope fraction during the process of kerogen thermal degradation and hydrocarbon generation, this does not mean that P\textsubscript{2w} and P\textsubscript{j} SRs have no contribution.

Figure 15. The \(\delta^{13}\text{C}\) values of other region are from Chen et al. (2016).
Conclusions

According to the organic geochemical characteristics of the SR samples from P\textsubscript{2w}, P\textsubscript{1f}, P\textsubscript{1j}, and C around Karamay: P\textsubscript{1f} SR is in high - over mature stage now, and the others are in the mature stage; C SRs are of Type \textit{II} kerogen with the largest OM abundance, and the P\textsubscript{2w} and P\textsubscript{1j} SRs are of Type \textit{III} kerogen with the good and medium OM abundances; besides, a few of P\textsubscript{2w} and C SRs were formed in the fresh water oxidation and reduction environment respectively. All the SRs were formed in the water body of high salinity reduction environment.

According to the biomarker characteristics of OS samples from T\textsubscript{2k} and J\textsubscript{1b} around Karamay, it is concluded that all OSs have experienced a very serious biodegradation, and the biodegradation order from weak to strong is Sample YS-2, Sample YS-3 and Sample YS-1. It is speculated that the complete biomarker sequence of anti-biodegradation ability is: \textit{n-}Alkane, \textit{i-}Alkane, isoprene like alkane, bicyclic sesquiterpene alkane, hopane (25 - norhopanes formed after degradation), sterane, hopane (no 25 - norhopanes formed after degradation), diasterane, tricyclic terpanes, aromatic sterane, pregnane and homopregnane.

The biomarker characteristics of the OS oil samples in the surrounding area of Karamay are similar to those of the P\textsubscript{1f} SR samples. The OCI of the OS oil samples, which is distributed in the OCI range of the P\textsubscript{1f} SRs, is obviously lighter than the OCI of the SRs of P\textsubscript{2w} and P\textsubscript{1j}. It is speculated that the OS oil mainly comes from the P\textsubscript{1f} SRs.

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