Geochemical Signatures and Controlling Factors of Rearranged Hopanes in Source Rocks and Oils from Representative Basins of China

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ABSTRACT: The origin and geochemical significance of the rearranged hopanes in hydrocarbon source rocks or crude oil have attracted extensive attention. Despite numerous studies, there is not yet a proper conclusion. Therefore, this paper discusses the formation conditions of such compounds and points out their geochemical significance in more detail using a remarkably broad range of source rocks and crude oils from four basins in China. Varying content of rearranged hopanes was found in a total of 19 source rocks and oils from the Ordos, Sichuan, and Tarim basins and the North China Block. Gas chromatography−mass spectrometry (GC−MS) in combination with X-ray diffraction (XRD) and conventional geochemical parameters was used for Pearson correlation analysis to reveal the enrichment mechanisms of rearranged hopanes in the studied rock and oil samples. The GC−MS and XRD results showed that the studied source rocks with high rearranged hopane contents are closely associated with the high abundance of quartz rather than that of clay. Furthermore, the present study reveals that anoxic lacustrine conditions are the primary controlling factors of relatively high abundance of rearranged hopanes in the studied rocks and oils, whereas thermal maturity and terrigenous organic matter input are the secondary factors.

1. INTRODUCTION

Rearranged hopanes are compounds with the same carbon framework as that of normal hopanes, whereas the position of the methyl side chain in rearranged hopanes differs from that in normal hopanes. A series of homologues has been identified in source rocks and oils, predominantly including 18α(H)-hopane series (C_{27} trinorhopane (Ts) and C_{29} norhopane (C_{29}Ts)), 17α(H)-diahopane series (C_{29}−C_{35} rearranged hopanes, with the C_{30} rearranged hopane as the main peak), 21-methyl-28-norhopane series, and C_{30} early-eluting rearranged hopane series (C_{30}E). Possible biological sources and formation environments of these rearranged hopanes have been widely discussed after their identification. Previous studies suggested that abundant rearranged hopanes are formed with sources of terrigenous organic matter, especially bacterially reworked higher plants or benthic red macroalgae and clay-induced mediator acidic catalysis under oxic and suboxic conditions, a brackish-to-freshwater environment or diagenesis, clay-catalyzed reactions in suboxic conditions, a suboxic brackish water environment, and an anoxic and brackish-saline environment. Thus, rearranged hopanes were used to interpret source inputs of bacterially reworked higher plants and/or depositional conditions of acidic clay catalysis in oxic−suboxic environments.

Surprisingly, few studies systematically reviewed the literature on the influence of the depositional environment on rearranged hopanes in rocks and oils in representative basins, although many source rocks and oils with the high abundance of rearranged hopanes were identified especially in the Ordos Basin, Sichuan Basin, North China Block, and Tarim Basin. Thus, this study set out to systematically investigate the influence of critical environmental factors on the occurrence of rearranged hopanes through a comparative study of source rocks and oils from the Ordos, Sichuan, and Tarim basins and the North China Block.

Received: September 19, 2020  
Accepted: November 2, 2020  
Published: November 12, 2020
2. GEOLOGICAL BACKGROUND

Rearranged hopanes are rich in source rocks or crude oils from the Ordos, Sichuan, and Tarim basins and the North China Block. Figure 1 displays the location of the study area within China.

2.1. The Ordos Basin. The source rocks used in this paper were partially selected from the Tongchuan area in the southern Ordos Basin, which is the second largest sedimentary basin in western China, covering up to ~250,000 km² of area.17 The Ordos Basin is bounded to the north by the Yinshan Mountains, to the south by the Qinling Mountains, to the west by the Liupanshan Mountains, and to the east by the Luliangshan east.15 This basin consists of six structural units: the Yimeng Uplift, Weibei Uplift, Tianhuan Depression, Shanbei Slope, Jinxi Flexural Fold Belt, and Western Edge Thrusting Belt.15 It is predominantly filled with Paleozoic, Mesozoic, and Cenozoic sediments with giant oil reservoirs concentrated in the Mesozoic fluvial–lacustrine deposits.25 The vast majority of the oil resources (~75%) among Mesozoic petroleum systems are discovered in the Upper Triassic Yanchang Formation.26 The Yanchang Formation consists of 10 bottom-up members (Chang 10 to Chang 1) based on the lithology and sequence stratigraphy.26 Particularly, sandstones in Chang 8 and 6 members are the primary oil reservoirs, whereas shales and siltstones in Chang 7 are recognized as the best source rock member for the Ordos Basin.27

2.2. The Sichuan Basin. The source rocks used in this paper were partially selected from the Upper Permian Longtan Formation in the Eastern Sichuan Basin. This is a superimposed basin located in southwest China and undergoes multiple sedimentary cycles, covering up to ~230,000 km² of area.22 The Sichuan Basin consists of four basic structural units: the eastern depression, western depression, central uplift, and southern depression.28 It experienced two major tectonic movements, including early-phase passive continental margin tectonics from the Paleozoic to the Early Triassic and the late-phase foreland basin stage from the Late Triassic to the Eocene.22,29 Six hydrocarbon-rich strata, including Cambrian, Silurian, Carboniferous, Permian, Triassic, and Jurassic, have been found in the Sichuan Basin.22 Three major series of marine source rocks among the six strata are distributed in the Cambrian strata (C1j, C1n, and C1q), Longmaxi Formation (S1l), and Longtan Formation (P2l).30

2.3. The North China Block. The source rocks used in this paper were partially selected from Unit 3 of the Xiamaling Formation in the North China Block. This formation is predominantly distributed within the Yanliao Depression of the North China Block in latitudes of 10°–30°N.32 Recent zircon U–Pb dating of K-bentonite beds in this formation yields an age of 1368 ± 12 Ma,33,34 showing that it is formed during the Mesoproterozoic Era. It consists of six units (Unit 6 to Unit 1) from bottom to top, in total with a thickness of ~450 m.35 Unit 6 is mainly composed of cross-bedded sandstones and siltstones. Unit 5 is characterized by brown marlstones interbedded with laminated shales, organic-poor siltstones, and sandstones. Unit 4 consists mainly of alternating red and green mudstones and green sandy siltstones. The lithology of Unit 3 varies from bottom to top, with green siltstones at the bottom followed by interbedded black shales and chert in the middle, and black shales at the top. Unit 2 is characterized by thick black shales, and Unit 1 contains interbedded black and green shales.35,36

2.4. The Tarim Basin. The crude oils used in this paper were partially selected from the southwest depression in the Tarim Basin, which is located in northwestern China and one of the most petroliferous basins in this country, covering up to ~560,000 km² of area.37 This basin includes six first-order tectonic units, including the southwest depression, Kuqa Depression, Tazhong Uplift, Tabei Uplift, north depression,
The southwest depression currently has three major oil–gas fields, including the Kekeya oil field, Kedong gas field, and Akemomu gas field, with strata of promising hydrocarbon reservoirs concentrated in Neogene, Paleogene, Cretaceous, Carboniferous, Silurian, and Ordovician. The two main series of source rocks are marine carbonate rocks and mudstones in the Carboniferous-Lower Permian and lacustrine-swamp coal-bearing sandy mudstones in the Lower-Middle Jurassic.

### 3. SAMPLES AND ANALYTICAL METHODS

#### 3.1. Samples

In total, 19 source rock and oil samples were used in this paper. Two oil shales and two crude oils were used to illustrate the source rock and oil characteristics of this area. The samples are from the Ordos, Sichuan, and Tarim basins and the North China Block. Detailed sample data are listed in Table 1 and Figure 2.

#### Table 1. Rock-Eval Data of the Source Rock Samples from the Ordos and Sichuan basins and the North China Block

| basin                  | formation                     | lithology | depth (m) | sample  | TOC   | S1    | S2    | PI    | T_{max} | S3    | HI    | OI    |
|------------------------|-------------------------------|-----------|-----------|---------|-------|-------|-------|-------|---------|-------|-------|-------|
| Ordos Basin            | Yanchang Formation/Chang 7   | oil shale | 13.08     | TNH-1.5 | 2.43  | 53.48 | 0.04  | 436   | 0.66    | 409   | 5     |
|                        | Yanchang Formation/Chang 7   | oil shale | 16.07     | TNH-3.4 | 3.58  | 74.91 | 0.05  | 433   | 1.01    | 466   | 6     |
| North China Block      | Xiamaling Formation/Unit 3   | oil shale | /        | gxhy    | 5.32  | 0.62  | 18.74 | 0.03  | 433     | 2.20  | 352   | 41    |
|                        | Xiamaling Formation/Unit 3   | oil shale | /        | dxhy    | 0.86  | 0.485 | 1.825 | 0.21  | 429     | 0.64  | 214   | 75.5  |
| Sichuan Basin          | Longtan Formation            | black shale | 328       | 10-VI-9 | 1.88  | 0.20  | 0.70  | 0.23  | 473     | 1.22  | 37    | 66    |
|                        | Longtan Formation            | black shale | 334.7     | 10-VI-31| 1.32  | 0.12  | 0.31  | 0.27  | 461     | 0.53  | 23    | 40    |
|                        | Longtan Formation            | black shale | 414.6     | 10-VI-50| 2.97  | 0.12  | 0.72  | 0.15  | 483     | 0.55  | 24    | 19    |
|                        | Longtan Formation            | black shale | 457       | 10-VI-56| 4.22  | 0.23  | 1.70  | 0.12  | 482     | 0.59  | 40    | 14    |

Figure 2. Mass spectrum (m/z 191) of the representative samples from the Ordos, Sichuan, and Tarim basins and the North China Block.
collected from the Ordos Basin, four black shales were gathered from eastern Sichuan Basin, two oil shales were collected from the Xiamaling Formation in the North China Block, and nine crude oils were selected from the southwest depression in the Tarim Basin.

3.2. Analytical Methods. All source rock samples were first ultrasonically cleaned using deionized water, then dried at 60 °C, and crushed into powder of 200 mesh. An IFP Rock-Eval 6 instrument was used to perform the pyrolysis analysis of the powdered samples. The powdered samples were initially heated to 300 °C in 3 mins to obtain the free hydrocarbon amount (S1) and then heated from 300 to 650 °C with a rate of 25 °C per minute to measure the remaining hydrocarbon generative potential (S 2). Furthermore, dissolved organic matter was obtained from powdered samples using a Soxhlet apparatus with dichloromethane/methanol in 93:7 v/v for 72 Table 2. Mineral Composition of the Source Rocks from the Ordos and Sichuan Basins and the North China Block

| basin            | sample  | quartz | feldspar | illite | chlorite | kaolinite | calcite | dolomite | high-Mg calcite | siderite | pyrite |
|------------------|---------|--------|----------|--------|----------|-----------|---------|----------|-----------------|----------|--------|
| Sichuan Basin    | 10-VI-9 | 14.7   | 9.6      | 10.1   | 15       | 0         | 15.2    | 8.3       | 15.3            | 11.8     | 0      |
|                  | 10-VI-31| 15     | 0        | 50.1   | 18.6     | 0         | 16.4    | 0         | 0               | 0        | 0      |
|                  | 10-VI-50| 6.6    | 0        | 47.5   | 0        | 42.8      | 0       | 0         | 0               | 0        | 3.1    |
|                  | 10-VI-56| 9.5    | 0        | 41.2   | 0        | 34.2      | 0       | 3.3       | 0               | 9.4      | 2.4    |
| North China Block| dxhy    | 81.1   | 0        | 18.9   | 0        | 0         | 0       | 0         | 0               | 0        | 0      |
|                  | gxhy    | 53.4   | 0        | 40.9   | 0        | 5.7       | 0       | 0         | 0               | 0        | 0      |
| Ordos Basin      | TNH1.5  | 19.5   | 21.6     | 37.8   | 15.6     | 0         | 0       | 0         | 0               | 0        | 5.6    |
|                  | TNH3.4  | 24.9   | 22       | 42.9   | 0        | 0         | 0       | 0         | 0               | 0        | 10.3   |

Figure 3. Cross plots of the content of rearranged hopanes and selected minerals, showing the possible connection between the rearranged hopanes and the quartz instead of clay minerals. (a) Clay content (%) versus C29Ts/C29 hopane; (b) clay content (%) versus C30*/C29 hopane; (c) quartz content (%) versus C29Ts/C29 hopane; (d) quartz content (%) versus C30*/C29 hopane; (e) quartz content/clay content versus C29Ts/C29 hopane; and (f) quartz content/clay content versus C30*/C29 hopane.
Multiple biomarker proxies were used in the statistical analysis, and biomarker parameters was determined using SPSS 22.0. The correlation coefficient between the rearranged hopanes and other saturated biomarker parameters was determined using SPSS 22.0. Various parameters were calculated using the following formulas:

\[ R = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}} \]

where \( R \) is the correlation coefficient, \( x \) and \( y \) are the values of the two variables, and \( \bar{x} \) and \( \bar{y} \) are their respective means.

### Table 3. Selected Biomarker Ratios of Source Rocks and Crude Oils from the Ordos, Sichuan, and Tarim basins and the North China Block

| basin          | formation/member | lithology | sample       | R1  | R2  | R3  | R4  | R5  | R6  | R7  | R8  | R9  | R10 | R11 | R12 |
|----------------|------------------|-----------|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Ordos Basin    | Yanchang/Chang 7 | oil shale | TNH3.4       | 0.74| 0.14| 0.58| 0.12| 0.26| 1.17| 0.16| 0.05| 0.32| 25.24| 28.79| 45.98 |
| Ordos Basin    | Yanchang/Chang 7 | oil shale | TNH5.5       | 0.67| 0.19| 0.66| 0.13| 0.19| 1.27| 0.13| 0.06| 0.33| 29.42| 17.21| 53.36 |
| Sichuan Basin  | Longtan Formation/P1 | black shale | 10-VI-9 | 0.67| 0.21| 0.42| 0.15| 0.22| 0.75| 0.19| 0.08| 0.38| 27.68| 23.77| 48.55 |
| Sichuan Basin  | Longtan Formation/P1 | black shale | 10-VI-31 | 0.64| 0.30| 0.65| 0.16| 0.21| 0.61| 0.38| 0.18| 0.48| 33.62| 25.24| 41.15 |
| Sichuan Basin  | Longtan Formation/P1 | black shale | 10-VI-50 | 0.56| 0.37| 0.65| 0.18| 0.15| 0.81| 0.31| 0.11| 0.41| 32.57| 25.30| 42.13 |
| Sichuan Basin  | Longtan Formation/P1 | black shale | 10-VI-56 | 0.85| 0.28| 0.66| 0.16| 0.21| 0.67| 0.27| 0.09| 0.43| 31.36| 24.36| 44.28 |
| North China Block | Xialong Formation/Unit 3 | oil shale | ghby | 0.63| 0.34| 0.55| 0.26| 2.54| 0.86| 0.56| 0.40| 0.29| 24.92| 29.36| 45.72 |
| North China Block | Xialong Formation/Unit 3 | oil shale | dhby | 0.63| 0.89| 0.48| 0.23| 2.36| 0.48| 0.97| 0.53| 0.35| 17.70| 20.48| 61.83 |
| Ordos basin    | /                 | crude oil | h31 | 0.57| 2.82| 0.46| 0.13| 0.24| 1.69| 0.67| 0.26| 0.53| 19.80| 34.14| 46.06 |
| Ordos basin    | /                 | crude oil | C18 | 0.85| 0.33| 0.77| 0.15| 0.19| 1.15| 0.46| 0.12| 0.46| 24.15| 27.13| 48.72 |
| Ordos basin    | /                 | crude oil | K101| 1.31| 0.51| 1.09| 0.29| 0.49| 0.96| 0.27| 0.14| 0.44| 21.25| 26.87| 51.88 |
| Tarim basin    | N1                | crude oil | K20 | 1.15| 0.73| 2.36| 0.25| 1.25| 2.26| 0.96| 1.70| 0.60| 23.64| 19.49| 56.87 |
| Tarim basin    | N1                | crude oil | K10 | 1.49| 2.43| 0.54| 0.15| 0.86| 0.92| 0.14| 0.13| 0.51| 9.90| 34.40| 55.70 |
| Tarim basin    | N1                | crude oil | K709| 1.16| 0.49| 4.74| 0.32| 1.09| 1.75| 1.39| 1.80| 0.62| 20.94| 34.04| 45.02 |
| Tarim basin    | K2                | crude oil | Kd1 | 1.19| 0.45| 0.97| 0.28| 0.93| 0.82| 1.27| 0.94| 0.59| 11.93| 32.41| 55.66 |
| Tarim basin    | K2                | crude oil | K103| 1.12| 0.86| 1.41| 0.41| 0.73| 1.21| 1.56| 1.98| 0.56| 13.23| 33.53| 53.24 |
| Tarim basin    | N1                | crude oil | K2  | 1.12| 0.42| 2.53| 0.77| 0.98| 1.31| 1.63| 3.27| 0.63| 14.42| 35.72| 49.86 |
| Tarim basin    | N1                | crude oil | K20 | 1.52| 0.62| 0.49| 0.29| 0.36| 0.89| 0.31| 0.22| 0.48| 25.17| 24.36| 50.07 |

**Note:** R1 = pristane/phytane; R2 = gammacerane/C31 22R hopane; R3 = C35S/C34S homohopanes; R4 = C31 22R/C30C hopanes; R5 = C19/C23 tricyclic terpane; R6 = C27/C25 tricyclic terpane; R7 = 18αt-30-norneohopane/C29 hopane; R8 = 17αt-diahopane (C29*-C29 hopane); R9 = C29 steranes (ββ)/(αααα + ββββ); R10 = %C27 sterane, %C28 sterane, %C29 sterane, %C30 sterane, %C27 sterane, %C28 sterane, %C29 sterane, %C30 sterane, and %C31 sterane. For any further information on these selected parameters, please refer to the study by Peters et al.13

### 4. RESULTS AND DISCUSSION

#### 4.1. Geochemical Features of Source Rocks

As shown in Table 1, there is a wide variation in the Rock-Eval data of eight rocks from the Ordos Basin, North China Block, and Sichuan Basin. The total organic carbon (TOC) content of the studied rocks ranges from 13.08 to 16.07 wt %, 0.86 to 5.32 wt %, and 1.32 to 4.22 wt %, respectively. The hydrocarbon genetic potentials (S1 + S2) of these source rocks fall in the ranges of 14.32 to 16.07 wt %, 0.86 to 12.37 wt %, and 1.32 to 4.22 wt %, respectively. The hydrocarbon potential, as determined by the hydrogen index, of the studied rocks ranges from 23.64 to 19.49 wt %, 34.40 to 55.70 wt %, and 13.08 to 16.07 wt %, respectively. The hydrogen index of these rocks ranges from 23.64 to 19.49 wt %, and HI values of samples from Songliao Basin are good source rocks, whereas source rocks from the Sichuan Basin have relatively a low hydrocarbon generation potential.

Hydrogen index (HI) of sample dhby indicates Type II/III, while HI values of samples from Songliao and Sichuan basins indicate Type II and Type IV, respectively.

#### 4.2. Distribution of Rearranged Hopanes

Three series of rearranged hopanes were identified in studied rock and oil samples from the North China Block and Sichuan, Ordos, and Tarim basins, in accordance with the relative retention time, C19TT/C23TT, C26TT/C25TT, %C27 sterane, %C28 sterane, %C29 sterane, and %C30 sterane. For any further information on these selected parameters, please refer to the study by Peters et al.13
mass spectral feature, peak sequence, and identification standards from prior research.\textsuperscript{5,16,23,31} Compounds of rearranged hopane series contain the 18\(\alpha\)(H)-neohopane series (Ts and C\textsubscript{29}Ts), the 17\(\alpha\)(H)-dihopane series (C\textsubscript{29} and C\textsubscript{30} rearranged hopanes), and the early-eluting rearranged hopane series (C\textsubscript{30} early-eluting rearranged hopane or 30E) (Figure 2). All of the samples show a strong dominance of 18\(\alpha\)(H)-neohopane and 17\(\alpha\)(H)-dihopane series. The early-eluting rearranged hopane series (30E) is detected only in a small number of samples from the Tarim Basin and North China Block. Thus, two biomarker parameters of rearranged hopanes, including C\textsubscript{29}Ts/C\textsubscript{29} hopane and C\textsubscript{30}/C\textsubscript{30} hopane, were mainly discussed in this paper.

4.3. Relationship between Clay Minerals and Rearranged Hopanes. XRD results of bulk samples show that the rock samples are principally composed of quartz, feldspar, illite, chlorite, kaolinite, calcite, dolomite, high-Mg calcite, siderite, and pyrite (Table 2). Great differences in mineral composition exist among samples from different regions. For example, quartz is dominant in two rock samples from the Xiamaling Formation. In contrast, illite is predominant in other samples from the Ordos and Sichuan basins.

The total content of clay minerals in all the source rocks ranges from 18.9 to 90.3\%, with a mean value of 52.7\%. Clay minerals are mainly illite, chlorite, and kaolinite. The relative abundance of rearranged hopanes is unlikely linked to the content of clay minerals, as suggested by a little correlation between the C\textsubscript{29}Ts/C\textsubscript{29} hopane or C\textsubscript{30}/C\textsubscript{30} hopane ratio and clay mineral content (Figure 3a,b). This is against the conventional wisdom that the rearranged hopanes are likely catalyzed by clay minerals.\textsuperscript{3,13} This phenomenon corroborates the findings of source rocks in the Songliao Basin and Yabulai Basin.\textsuperscript{18,44} Contrary to the clay content, a strong positive relationship between the relative concentration of rearranged hopanes and quartz was observed (Figure 3c,d). This may mean the quartz content in source rocks plays an essential role in the generation of rearranged hopanes.

4.4. Relationship between Rearranged Hopanes and Other Biomarkers. Biomarker compounds in rock extracts and oils are controlled by the sources and depositional environments of organic matter in sediments, whereas thermal maturity reflects the degree of thermally driven reactions that sedimentary organic material was converted to petroleum.\textsuperscript{13} Therefore, Pearson correlation analysis (PCA) of source-, depositional environment-, and maturity-related biomarker parameters was used to examine the relationship between these biomarkers and the relative abundance of rearranged hopanes. PCA is a multivariate statistical method that improves the interpretation of geochemical data and widely applied in many disciplines.\textsuperscript{45–48}

Twelve biomarker parameters as variables were selected to perform the PCA through SPSS statistical software (Table 3). For convenience, only two biomarker ratios of rearranged hopanes with other geochemical parameters were selected (Table 4 and Figure 4). Results of the PCA show that the two series of rearranged hopanes are well correlated with each other (R\(^2 = 0.9\)), probably indicating that they were produced by the same source.\textsuperscript{13,16} Also, correlation coefficients between the C\textsubscript{29}Ts/C\textsubscript{29} hopane and other biomarker parameters decreased as follows: C\textsubscript{35}R/H (R\(^2 = 0.87\)) > C\textsubscript{35S}/C\textsubscript{34S} (R\(^2 = 0.73\)) > C\textsubscript{29} \(\beta\beta\)/(\(\alpha\alpha\) + \(\beta\beta\)) (R\(^2 = 0.63\)) > %C\textsubscript{27} \(\alpha\alpha\alpha\) R (R\(^2 = 0.50\)) > C\textsubscript{26TT}/C\textsubscript{25TT} (R\(^2 = 0.47\)) > %C\textsubscript{28} \(\alpha\alpha\alpha\) R (R\(^2 = 0.43\)) > C\textsubscript{19TT}/C\textsubscript{23TT} (R\(^2 = 0.31\)).

The PCA results suggest that those rock and oil samples with high rearranged hopane abundance are predominantly associated with the C\textsubscript{35}R/H and C\textsubscript{35S}/C\textsubscript{34S} ratios followed by the C\textsubscript{29} \(\beta\beta\)/(\(\alpha\alpha\) + \(\beta\beta\)), %C\textsubscript{27} \(\alpha\alpha\alpha\) R, and %C\textsubscript{28} \(\alpha\alpha\alpha\) R ratios and lastly the C\textsubscript{26TT}/C\textsubscript{25TT} and C\textsubscript{19TT}/C\textsubscript{23TT} ratios. C\textsubscript{35S}/C\textsubscript{34S} ratios are commonly used to reflect redox conditions,\textsuperscript{49} whereas high values of the C\textsubscript{35}R/C\textsubscript{30} hopane and C\textsubscript{26TT}/C\textsubscript{25TT} ratios are closely related to the lacustrine source rocks.\textsuperscript{13,50} These data may indicate that anoxic lacustrine conditions are favorable to generate high concentration of rearranged hopanes. Moreover, the two rearranged hopane ratios are positively correlated with the C\textsubscript{29} \(\beta\beta\)/(\(\alpha\alpha\) + \(\beta\beta\)) sterane ratio, likely indicating that relatively high thermal maturity is also one of the major determinants to generate high abundance of rearranged hopanes.\textsuperscript{3} Moreover, %C\textsubscript{27} \(\alpha\alpha\alpha\) R and C\textsubscript{19TT}/C\textsubscript{23TT} are negatively and positively correlated with the relative abundance of rearranged hopanes, respectively. There is a poor correlation between the rearranged hopanes and %C\textsubscript{28} \(\alpha\alpha\alpha\) R. The results show the rearranged hopanes to be related to lacustrine organic matter input.

In a word, the high concentration of rearranged hopanes in the studied rock and oil samples from the Songliao, Ordos, and Tarim basins and the North China Block may be principally related to the anoxic lacustrine environment and likely related

![](https://dx.doi.org/10.1021/acsomega.0c04615)
to thermal maturity and terrigenous organic matter input, in terms of the correlation coefficient.

5. CONCLUSIONS
This paper proposed the controlling factors on relatively high abundance of rearranged hopanes in the studied rocks and oils from the Sichuan, Ordos, Tarim basins and the North China Block using multiple techniques. On the one hand, the rearranged hopane ratios are positively correlated with the content of quartz rather than that of clay. This is against the conventional wisdom that the rearranged hopanes are likely catalyzed by clay minerals. On the other hand, the correlation results of this systematical study of rocks and oils from representative basins in China show that the key controlling factor on the generation of abundant rearranged hopanes is the anoxic lacustrine environment. Lastly, PCA is a statistical method that can improve the interpretation of geochemical data through considering the effects of multiple parameters simultaneously. Thus, the method of this study may be applied into similar research studies in other sedimentary basins.

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Notes
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■ ACKNOWLEDGMENTS
This work was supported by the Doctoral Research Initiation Project of Guangdong Ocean University (Grant nos. R20030 and R17001), National Science Foundation of China (Grant no. 41602139), and the Special Financial Aid for Talents of Guangdong Ocean University (Grant no. 002026002004).

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