Geochemically Distinct Oil Families in the Gudong Oilfield, Zhanhua Depression, Bohai Bay Basin, China

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1. INTRODUCTION

The Zhanhua Depression is one of the most petroliferous petroleum areas in the Bohai Bay Basin.† The Gudong Oilfield is a complex petroleum accumulation belt located in the northeast region of the Zhanhua Depression and in the south area of the Zhuangxi—Gudong buried—hill draping structural belt.‡ The Zhanhua Depression is a typical Tertiary rifted basin superimposed on a negative inverted basin developed during the Late Jurassic to Early Cretaceous. The Gudong Oilfield locates in the northeast region of the Zhanhua Depression and is surrounded by three sags: the Gunan Sag to the south, Wuhaozhuang Sag to the northwest, and Huanghekou Sag northeast (Figure 1c).§ However, source rocks in the Wuhaozhuang Sag are characterized by a shallow burial depth, low richness, and poor oil generation capacity.7 Previous geochemical studies have suggested that hydrocarbons in the Gudong Oilfield were derived from source rocks in the Gunan Sag and Huanghekou Sag.8 The Paleogene Shahejie (Es), Dongying (Ed), and Neogene Guantao (Ng) formations are the main oil-bearing strata that have been identified to date.2 The oil-bearing area covers 16.39 km², with proven oil reserves of 4619 × 10⁴ t.7 The major sedimentary facies in the Gudong Oilfield are lacustrine and deltaic deposits.8

The Gudong Oilfield is a complex hydrocarbon accumulation zone. The regional tectonic characteristics, the controlling factors of reservoir formation, and the type of reservoir have been well studied.2,7,9 However, the organic geochemical characteristics of crude oils in the Gudong Oilfield have not yet been investigated, and the differences between oils are unknown. Some oils exhibit different degrees of biodegradation, and the relationship between the distribution of biodegraded oils and their locations is unclear. This makes it more difficult to analyze the organic geochemical...
Oil correlation is a common application in petroleum. 

Table 1. Basic Information and Maturity-Related Geochemical Parameters for Oils from the Gudong Oilfield, Zhanhua Depression.

| well | member | depth (m) | PMB | \( \delta^{13}C_{OIL} \) (%) | \( \delta^{13}C_{SAT} \) (%) | \( \delta^{13}C_{MIN} \) (%) | Pt/Ph | Tm/ Ts | C_{29}TArea/C_{29}H | C_{29}s | C_{29}H | C_{29}Ina | C_{29}H/(C_{29}H + C_{29}s) | MPI1 | MDR | %Rc |
|------|--------|-----------|-----|------------------|------------------|------------------|------|-------|-------------------|-------|-------|-------|-------------------------|-------|------|-----|
| GD571 | Ng | 1457–1458 | 2 | −26.7 | −28.4 | −26.2 | 1.25 | 1.16 | 0.14 | 0.57 | 0.45 | 0.41 | 0.44 | 1.98 | 0.66 |
| GD321 | Ng | 1353–1366 | 3 | −26.2 | −27.9 | −25.5 | 0.83 | 1.05 | 0.38 | 0.57 | 0.38 | 0.32 | 0.51 | 1.94 | 0.70 |
| GD40 | Ng | 1203–1209 | 4 | −26.1 | −27.5 | −25.7 | 1.29 | 0.48 | 0.58 | 0.43 | 0.39 | 0.64 | 2.01 | 0.79 |
| GD25 | Ng | 1625–1627 | 2 | −26.2 | −28.0 | −25.9 | 1.89 | 1.02 | 0.55 | 0.57 | 0.38 | 0.33 | 0.55 | 1.56 | 0.73 |
| GD32 | Ng | 1233–1245 | 3 | −26.2 | −27.5 | −25.5 | 0.99 | 1.02 | 0.43 | 0.57 | 0.40 | 0.33 | 0.25 | 0.89 | 0.55 |
| GD140 | Ng | 1410–1423 | 3 | −26.3 | −27.7 | −25.5 | 0.80 | 1.10 | 0.40 | 0.58 | 0.39 | 0.32 | 0.21 | 1.83 | 0.53 |
| GD39 | Ng | 1267–1269 | 4 | −26.2 | −27.5 | −25.6 | 1.01 | 0.39 | 0.57 | 0.39 | 0.32 | 0.51 | 2.58 | 0.71 |
| GD75 | Ng | 1301–1310 | 4 | −26.4 | −28.1 | −25.6 | 1.00 | 0.41 | 0.56 | 0.40 | 0.35 | 0.44 | 2.65 | 0.67 |
| GDQ1 | Ng | 1632–1645 | 3 | −26.1 | −26.6 | −25.8 | 2.31 | 1.05 | 0.48 | 0.56 | 0.39 | 0.34 | 0.61 | 1.29 | 0.77 |
| GD810 | Ng | 1376–1385 | 4 | −26.2 | −28.3 | −25.6 | 1.12 | 0.36 | 0.57 | 0.42 | 0.37 | 0.54 | 3.23 | 0.72 |
| GD7 | Ng | 1337–1351 | 4 | −26.4 | −27.8 | −25.4 | 1.08 | 0.22 | 0.57 | 0.41 | 0.35 | 0.51 | 1.21 | 0.71 |
| GD511 | Ng | 1368–1372 | 1 | −26.2 | −28.1 | −25.6 | 0.68 | 1.06 | 0.26 | 0.56 | 0.39 | 0.34 | 0.58 | 3.13 | 0.75 |
| GD28 | Ng | 1265–1275 | 2 | −26.6 | −28.3 | −25.9 | 1.23 | 0.93 | 0.57 | 0.57 | 0.38 | 0.35 | 0.63 | 1.74 | 0.78 |
| GDN39 | Es3 | 2967–2976 | 0 | −25.7 | −26.6 | −25.1 | 1.45 | 1.35 | 0.51 | 0.60 | 0.55 | 0.46 | 0.75 | 3.01 | 0.85 |
| GD282 | Es3 | 3592–3600 | 0 | −25.6 | −26.3 | −25.1 | 2.32 | 1.45 | 0.47 | 0.59 | 0.54 | 0.49 | 0.63 | 3.99 | 0.78 |
| GD2 | Es2 | 2828–2849 | 3 | −27.1 | −28.1 | −26.3 | 0.83 | 1.39 | 0.55 | 0.59 | 0.55 | 0.46 | 0.90 | 4.63 | 0.94 |
| GD59 | Es3 | 3297–3305 | 4 | −27.1 | −28.2 | −26.6 | 1.61 | 0.59 | 0.58 | 0.49 | 0.43 | 0.73 | 4.64 | 0.84 |
| GDN28 | Ng | 1285–1298 | 2 | −26.5 | −28.0 | −25.9 | 1.50 | 0.61 | 0.24 | 0.58 | 0.41 | 0.39 | 0.50 | 1.74 | 0.70 |
| GDN210 | Es2 | 2838–2844 | 3 | −26.2 | −27.9 | −25.6 | 0.33 | 0.57 | 0.19 | 0.58 | 0.40 | 0.37 | 0.60 | 3.01 | 0.76 |
| GDN27 | Ng | 1265–1275 | 2 | −26.6 | −28.3 | −25.9 | 1.23 | 0.59 | 0.25 | 0.58 | 0.40 | 0.39 | 0.53 | 1.96 | 0.72 |

4PMB: degree of biodegradation by Peters and Moldovan (1993). \( \delta^{13}C_{OIL} \) (%) is the stable carbon isotope ratios (%) for whole oil, saturate, and aromatic fractions, respectively; Tm = 17α(H)-trinorhopane; Ts = 18α(H)-trinorhopane; C_{29}TArea = 18α(H)-30-nor-18α(H)-30-norhopane, C_{29}TArea20S = C_{29}TArea20R = C_{29}TArea14α,17α(H)-stigmastane 20S, C_{29}TArea20R = C_{29}TArea14α,17α(H)-stigmastane 20R, C_{29}H/(C_{29}H + C_{29}s) = [C_{29}s,14β,17β(H)-stigmastane 20S] + [C_{29}s,14β,17β(H)-stigmastane 20R]; MP = methyl phenanthrene, MPI1 = 1.5 × (2-MP + 3-MP)/(P + 1-MP + 9-MP); %Re = 0.6MPI1 + 0.4; MDR = 4-MDBT/1-MDBT, DBT = dibenzothiophene.
shale, dolomite limestone, and bioastics.16 The third member of the Dongying (Ed) Formation was deposited in a weakly oxic to weakly reducing environment.16 The TOC contents of the Es1, Es2, and Ed members have been found to range from 0.33 to 9.19%, 0.11 to 2.67%, and 0.63 to 1.62%, respectively.16 The major organic input for the source rock in the Gunan Sag was microalgae.16 Source rocks in the Huanghekou Sag contain a large amount of terrestrial bio-inputs.16 The oils in the Gudong Oilfield have been charged at least twice.17 The first stage was in the Ed Formation; the petroleum accumulated during this stage underwent severe biodegradation.18 The reservoirs were severely destroyed by later tectonic movements, with only biodegradation products, resin, and asphaltene remaining.18 The late accumulation stage in the Minhuazhen Formation was important, from which the petroleum reserves mainly originated.7,18 During this stage, the reservoirs were severely destroyed by later tectonic events.17 The well locations of these samples are listed in Table 2. Selected Geochemical Parameters Used in Chemometric Methods.

3. SAMPLES AND METHODS

3.1. Samples. Twenty crude oil samples collected from different depths and reservoirs in Gudong Oilfield were investigated in this study. The oil samples were selected from a larger collection of samples; heavily biodegraded oils were excluded because the source-related and depositional environment-related biomarkers can be significantly affected by this secondary process. The well locations of these samples are shown in Figure 1c. Table 1 presents the corresponding geological and geochemical information (e.g., reservoir layer and depth) for these samples.

3.2. Laboratory Analyses. 3.2.1. GC Analysis. A Shimadzu 2010Plus gas chromatograph equipped with a flame ionization detector (FID) was used to analyze petroleum materials. The oven temperature was held at 40 °C for 5 min initially, then programmed to reach 295 °C at a rate of 4 °C/min, and held at 295 °C for 30 min finally. Helium was used as the carrier gas, and the flow rate was 1.0 mL/min.

3.2.2. Oil Fractionation and GC-MS Analysis. The crude oils were dissolved in excess n-hexane to remove asphaltenes, and the remainder was separated into saturates, aromatics, and resins by liquid chromatography on a column filled with silica/alumina (2:1 v/v). The selective ion monitoring (SIM) and full-scan detection were combined, and the scan range is 50 to 350 Da. The selected ions included m/z 191, 217, and 218. Gas chromatography–mass spectrometry (GC-MS) analyses of the saturates and aromatic fractions were performed on a Shimadzu QP2010 Ultra GC-MS instrument equipped with an HP-SMS (30 m x 0.25 mm i.d., 0.25 μm film thickness). Helium was used as the carrier gas at a constant flow rate of 1.0 mL/min. The temperature of GC oven was programmed to reach 200 °C from 50 °C and held for 2 min at 50 °C, then heated to 310 °C and held for 10 min at 310 °C. The electron ionization mode of MS was operated at 70 eV, and the ion-source temperature is 230 °C. The selective ion monitoring (SIM) and full-scan detection were combined, and the scan range is 50–550 Da. The selected ions included m/z 191, 217, and 218. Gas chromatography–mass spectrometry (GC-MS) analyses of the saturates and aromatic fractions were performed on a Shimadzu QP2010 Ultra GC-MS instrument equipped with an HP-SMS (30 m x 0.25 mm i.d., 0.25 μm film thickness). Helium was used as the carrier gas at a constant flow rate of 1.0 mL/min. The temperature of GC oven was programmed to reach 200 °C from 50 °C and held for 2 min at 50 °C, then heated to 310 °C and held for 10 min at 310 °C. The electron ionization mode of MS was operated at 70 eV, and the ion-source temperature is 230 °C. The selective ion monitoring (SIM) and full-scan detection were combined, and the scan range is 50–550 Da. The selected ions included m/z 191, 217, and 218. Gas chromatography–mass spectrometry (GC-MS) analyses of the saturates and aromatic fractions were performed on a Shimadzu QP2010 Ultra GC-MS instrument equipped with an HP-SMS (30 m x 0.25 mm i.d., 0.25 μm film thickness). Helium was used as the carrier gas at a constant flow rate of 1.0 mL/min. The temperature of GC oven was programmed to reach 200 °C from 50 °C and held for 2 min at 50 °C, then heated to 310 °C and held for 10 min at 310 °C. The electron ionization mode of MS was operated at 70 eV, and the ion-source temperature is 230 °C. The selective ion monitoring (SIM) and full-scan detection were combined, and the scan range is 50–550 Da. The selected ions included m/z 191, 217, and 218. Gas chromatography–mass spectrometry (GC-MS) analyses of the saturates and aromatic fractions were performed on a Shimadzu QP2010 Ultra GC-MS instrument equipped with an HP-SMS (30 m x 0.25 mm i.d., 0.25 μm film thickness). Helium was used as the carrier gas at a constant flow rate of 1.0 mL/min. The temperature of GC oven was programmed to reach 200 °C from 50 °C and held for 2 min at 50 °C, then heated to 310 °C and held for 10 min at 310 °C. The electron ionization mode of MS was operated at 70 eV, and the ion-source temperature is 230 °C. The selective ion monitoring (SIM) and full-scan detection were combined, and the scan range is 50–550 Da. The selected ions included m/z 191, 217, and 218. Gas chromatography–mass spectrometry (GC-MS) analyses of the saturates and aromatic fractions were performed on a Shimadzu QP2010 Ultra GC-MS instrument equipped with an HP-SMS (30 m x 0.25 mm i.d., 0.25 μm film thickness). Helium was used as the carrier gas at a constant flow rate of 1.0 mL/min. The temperature of GC oven was programmed to reach 200 °C from 50 °C and held for 2 min at 50 °C, then heated to 310 °C and held for 10 min at 310 °C. The electron ionization mode of MS was operated at 70 eV, and the ion-source temperature is 230 °C. The selective ion monitoring (SIM) and full-scan detection were combined, and the scan range is 50–550 Da. The selected ions included m/z 191, 217, and 218.
A working standard (black carbon) was measured to monitor the system. The temperature for reduction was 650 °C, and the temperature for oxidation was 950 °C. The stable carbon isotope values are reported in per mil (‰) relative to VPDB standard. Every sample was measured at least twice until the error was ≤0.5‰. The final stable carbon isotope results represent the averages of multiple runs.

3.3. Computational Methods. In this study, chemometric methods, including HCA and PCA, were applied to reveal the genetic relationship between the crude oil samples. The crude oil samples were divided into multiple classes using HCA; thus, samples within the same class exhibited the highest similarity, while samples in different classes showed significant differences.19,20 PCA can convert multiple indices into a few comprehensive indices that are independent of each other; however, the original information is unaffected.10,21 HCA from Pirouette software version 4.5 (Infometrix, Inc.) was setting: preprocessing = range scale, distance metric = euclidean, linkage method = incremental. PCA setting: preprocessing = range scale, maximum factors = 10, validation method = none, and row = none.

Thirteen source-related and depositional environment-related biomarker parameters, including C19/C23TT; C24Tet/C25TT; ETR \[ETR = (C_{28} + C_{29})/(C_{28} + C_{29} + T_{s}) \]; C35/C_{34}H; Ga/C_{35}H; steranes/hopanes (S/H); C_{30}4M/aαααα20R C_{29}H; TT/H \((\sum C_{19−30} TT/\sum C_{29−35} hopane)) \; C_{26}/C_{25}TT; C_{30}HR/C_{35}H; \; aαααα20R \; C_{32}%; \; aαααα20R \; C_{34}%; \; and \; aαααα20R \; C_{29}8% sterane ratios (compound symbols are described in the footnotes of Table 2), were used in HCA and PCA. Biomarkers that can be easily affected by secondary alterations (e.g., biodegradation and migration) were not employed. To avoid the influence of maturity on the classification, most maturity-related biomarkers, e.g., C_{29}20S/(20S + 20R), C_{29}β/ (αααα + ββββ), Ts/Tm ratios, and parameters, were excluded. In addition, the parameters with minimal values were not considered to achieve increased precision.

4. RESULTS

4.1. Stable Carbon Isotope. The stable carbon isotope value (δ13C) of crude oil is mainly related to the depositional environment and the organic matter input of the source rocks, and is affected by isotope fractionation during thermal
The studied crude oils exhibited small variations with respect to the stable carbon isotope (δ13C) values. The δ13C values of the whole oils are within the range of −27.2 to −24.6‰ (Table 1). The δ13C values of the saturate and aromatic hydrocarbons range from −28.4 to −25.3‰ and from −26.7 to −23.8‰, respectively. These δ13C values indicate that the oils originated from lacustrine source rocks. In contrast, varying degrees of biodegradation are present in other oils, and n-alkanes are destroyed and contain significant unresolved complex mixture. The biodegradation extent is between level 0 and level 4.27 The hopanes, steranes, and aromatic fractions are well preserved and could be used to reveal the paleoenvironment, material sources of organic matter, and maturity of oils.

4.3. Biomarker Composition and Distribution. 4.3.1. Terpenoids. Terpenoid hydrocarbons were measured using m/z 191 mass chromatograms, and the terpane biomarker distributions for representative samples are shown in Figure 2b. The relative abundance of tricyclic terpanes (TT) is low, with C23TT being dominant, followed by C19TT or C21TT in the oil samples (Figure 2b). The ratios of C19/C23TT and C26/C25TT range from 0.21 to 0.58 and 1.02 to 1.36 (Table 2), respectively. The extended tricyclic terpane ratios (ETR) range from 0.12 to 0.29. Pentacyclic triterpane chromatograms occur in significant abundance and are dominated by 17α(H),21β(H) hopanes (C29H) in all samples; the C29R/C29H ratios vary from 0.21 to 0.35. In most samples, the relative abundance of C31−C35 homohopane generally decreases with increasing carbon member, while the relative intensities of C34H are slightly lower than those of C35H in samples GDN27 and GDN28. Gammacerane (Ga) is present in all samples, although the concentrations vary significantly. The ratios of C23H/C21H and Ga/C29H range from 0.53 to 1.05 and 0.04 to 0.32, respectively. 17α(H)-trinorhopane (Tm) and 18α(H)-trinorneohopane (Ts) show low relative abundances, and the Ts/Tm ratios range from 0.57 to 1.61 (Table 1, Figure 6b), thus indicating that there were significant differences among different source rock members in terms of the depositional environment and maturation.28

4.3.2. Steroids. The sterane mass chromatograms (m/z 217) for representative samples are shown in Figure 2c. In most samples, the concentrations of pregnanes and diasteranes are low relative to regular steranes. The distributions of C27ααα(20R), C28ααα(20R), and C29ααα(20R) regular steranes presented an asymmetric “V” type (Figure 2c). The relative abundance of C27−C29 regular steranes is calculated using the peak areas. The normalized relative abundances of %C27, %C28, and %C29 aaaa(20R) are 26−37, 10−32, and 35−53%, respectively. The C27/C29 aaaa(20R) ratios range from

Figure 4. Three-dimensional view of principal component analysis identifying oil genetics of the Gudong Oilfield. PC 1, PC2, and PC3 are principal components accounting for 81.1, 8.4, and 4.0% of the variance in the data, respectively.

Figure 5. Factor loading of the selected biomarker variables.
The ratios of C30-4M to C29 regular steranes (C30-4M/steranes) were found in all samples with varying abundance. The ratios of C30-4M to C29 regular steranes (C30-4M/steranes) range from 0.21 to 0.99 (Table 2), reflecting a varying contribution of microalgae.29 As maturity-related parameters, the C2920S/(20S + 20R) and C29ββ/(αα + ββ) ratios range from 0.38 to 0.55 and 0.32 to 0.49, respectively, thereby indicating that the oil samples were generated during the early-mature—mature stage.27

4.4. Oil—Oil Correlation Based on Chemometrics. The geochemical characteristics of the oil samples exhibited considerable variation because they originated from different source rocks. To improve our understanding of the genetic relationships among the crude oil samples, chemometric methods were applied to classify them and extract the leading factors.19 Chemometric methods can improve the calculation accuracy of genetic relationships by extracting useful information from a large amount of geochemical data.30

HCA of 13 source-related and depositional environment-related parameters produced a dendrogram that roughly classified the crude oil samples. An oil family is defined as a group of oils from source rocks deposited in a similar environment and with similar organic matter input.19 The oils were divided into three families with a similarity coefficient of 0.55 (Figure 3). The scores plot of PCA represents the best classification of samples from n-dimensional space into two-dimensional or three-dimensional space by extracting the relationship between parameters.10,21 Based on the score plot for the samples, we obtained their classification. In addition, based on the correlation coefficient between the principal component (PC) and each variable parameter, we determined the main controlling variables.31 As shown in Figure 4, the PCA scores and loading plots were employed to select the biomarker parameters obtained from all oil biomarker data from the Gudong Oilfield. The results showed that PC1, PC2, and PC3 accounted for 81.1, 8.4, and 4.0% of the total variance in the original dataset, respectively. The oil samples from the Gudong Oilfield were classified into three families on the scores plot of PCA, which was consistent with the HCA results. As shown in Figure 5, the loading on PC1 is dominated by a positive correlation with the ratios of S/H and C29H-4M/aaa20R C29 sterane. These parameters are mainly related to the organic matter input of source rocks. The loadings on PC2 mainly exhibit a positive correlation with the ETR and C35/C34H ratios, which are associated with the depositional environment of source rocks.

5. DISCUSSION

5.1. Geochemical Characterization of Oil Families. 5.1.1. Thermal Maturity. The thermal maturity of these oils was assessed by the saturate and aromatic biomarker parameters. Previous studies demonstrated that the C33S/(S + R) homohopane ratio is highly specific for immature to early oil generation.10,23 The values are within the range of 0.56—0.60, which are close to the equilibrium values (0.57—0.62), thus suggesting that the oil samples are mature. However, the commonly used maturity parameters, i.e., C29 20S/(20S + 20R) and C29 ββ/(αα + ββ) steranes,27 indicate that the maturity of family II is higher than that of family I and family III. This is supported by the fact that the ratios of C29 20S/(20S + 20R) and C29 ββ/(αα + ββ) of family II (0.49—0.55 and 0.43—0.49, respectively, Figure 6a) are higher than those of family I (0.38—0.45 and 0.32—0.41, respectively) and family III (0.40—0.41 and 0.37—0.39, respectively). The aromatic biomarker parameters of dibenzothiophene (DBT) isomers and alkyl phenanthrenes (MP) can also be used to evaluate maturity.33 As shown in Figure 6c, the MDR (4-MDBT/1-MDBT) and methyl phenanthrene indicates (MPI 1) values range from 3.01 to 4.64 and from 0.63 to 0.90, respectively. These exceeded those of family I and III, thus agreeing with variation trend of the ratios of C2520S/(20S + 20R) and C25ββ/(αα + ββ) steranes. The equivalent vitrinite reflectance (%Rc = 0.6 × MPI 1 + 0.4) values are between 0.53 and 0.94, which indicates that all of the oil samples are at the mature stage.23,32 However, the maturity of family II (%Rc range from 0.78 to 0.85) is higher than that of family I (%Rc range from 0.53 to 0.79) and family III (%Rc range from 0.72 to 0.76). The maturity of oil can also be reflected by hopane parameters, for example, the Ts/Tm and C29Ts/C29 hopane ratios both increase with maturity.23,33 Family II has higher Ts/Tm and C29Ts/C29 hopane ratios (1.35—1.61 and 0.47—0.59, respec-
tively, Figure 6b) in comparison to family I. However, for family III, the Ts/Tm and C<sub>29</sub>Ts/C<sub>29</sub> hopane ratios are abnormally low (0.57 – 0.61 and 0.19 – 0.25, respectively). The reversal of the Ts/Tm and C<sub>29</sub>Ts/C<sub>29</sub> hopane ratios might be associated with the depositional environment and some specific lithologies, for instance, carbonates or evaporitic source rocks.33

5.1.2. Sources of Organic Matter. The relative amounts of C<sub>27</sub>−C<sub>29</sub> regular steranes are commonly employed to provide information on organic facies and organic matter input.34 In general, C<sub>27</sub>, C<sub>28</sub> and C<sub>29</sub> sterols are associated with zooplankton, phytoplankton, and higher plants, respectively;23,35,36 however, brown algae and many species of green algae can also generate C<sub>29</sub> sterols.37 The average C<sub>27</sub>/C<sub>29</sub> sterane ratios are low in family I and family II (average at 0.79 and 0.70, respectively). For family III, the C<sub>27</sub>/C<sub>29</sub> sterane ratios are relatively high (0.88 – 1.01).

The high abundance of C<sub>19</sub>TT and C<sub>24</sub> tetracyclic terpane (C<sub>24</sub>Tet) can indicate the input of terrigenous organic matter.23,38 The oil samples in family I exhibited low ratios of C<sub>19</sub>/C<sub>23</sub>TT (0.09 – 0.24) and C<sub>24</sub>Tet/C<sub>26</sub>TT (0.56 – 1.03, average of 0.69, Figure 7a). Oils in family II are characterized by relatively high ratios of C<sub>19</sub>/C<sub>25</sub>TT (0.42 – 0.58) and C<sub>24</sub>Tet/C<sub>26</sub>TT (0.89 – 1.15). Further, C<sub>30</sub>−4M steranes are prominent in some special microalgae such as prymnesiophyte algae.29 A low S/H ratio is more indicative of terrigenous and/or microbially reworked organic matter.38–40 As shown in Figure 7b, the S/H and C<sub>30</sub>−4M/aaa20R C<sub>29</sub> sterane ratios in family I are relatively high, in the ranges of 0.38 – 0.45 and 0.66 – 0.99, respectively. The S/H values of family II and family III are lower than that of family I (average of 0.25 and 0.26, respectively). The C<sub>30</sub>−4M/aaa20R C<sub>29</sub> ratios of family II (0.21 – 0.65) are lower than those of family I and family III (0.73 – 0.88). Collectively, these parameters suggest that microalgae are the dominant organic matter source for the source rock of oils in family I, and that C<sub>29</sub> steranes are possibly from brown algae or special types of green algae. For family II, parameters suggest a large contribution of terrigenous organic matter input and lower contribution of microalgae to the source rock. For family III, microalgae (especially zooplankton algae) make a large contribution to the organic matter of the source rock.36

5.1.3. Depositional Environment. All three families can be inferred to be derived from lacustrine source rocks, as supported by high C<sub>26</sub>/C<sub>25</sub>TT (1.02 – 1.36) and low C<sub>31</sub>R/C<sub>30</sub>H (0.21 – 0.28) ratios.23 High abundance of gammacerane is usually associated with a high salinity or strong water column stratification.41,42 The Ga/C<sub>30</sub>H ratios are between 0.04 and 0.32 (Table 2, Figure 8a), which suggests variable water conditions of the source rocks. The salinity (or water column stratification) of the source rock for family I (Ga/C<sub>30</sub>H ratios range from 0.18 to 0.32) is higher than those of family II and family III (Ga/C<sub>30</sub>H ratios are in the ranges of 0.04 – 0.13 and 0.09 – 0.17, respectively). The ETR can be used to reflect the salinity during sediment deposition.23,43 The ETR values of the three families were 0.22 – 0.29, 0.14 – 0.18, and 0.12 – 0.15, respectively, showing the same variation tendency as the Ga/C<sub>30</sub>H ratios, indicating that the salinity of the source rock for
diagnostic characteristics of the source rocks are listed in Table 3.

In the Huanghekou Sag, the Es3 source rocks were deposited under suboxic condition in a brackish water environment. The Pr/Ph and Ga/C30H ratios vary from 1.23 to 1.52 and from 0.11 to 0.64, respectively, and the relative abundance of C30-4M steranes is high,16 thus corresponding to oils in family I. The widespread family I oils appear to indicate that a substantial portion of the oils in the Gudong Oilfield originate from the Es3 source rocks. The Ed source rocks were deposited in an oxic freshwater environment, and the relative abundance of C30-4M steranes is lower than that of the Es3 source rocks.16

Family II presents the same characteristics as the Ed source rock. The Pr/Ph and Ga/C30H ratios of the Es3 source rock are similar to those of the Es3 member, but the relative abundance of C30-4M steranes is high,15 and no oil samples in this study correspond to the Es3 member. In the Gunan Sag, the Es3 member has high Pr/Ph ratios (0.88–2.00) but a low relative abundance of C30-4M steranes and low Ga/C30H ratios (0.07–0.12),16 which indicate a freshwater–brackish reducing environment. The source rocks of oil samples in family III are similar to the Es3 member. The Es3 source rocks were deposited in a brackish–saline reducing environment. The Pr/Ph and Ga/C30H ratios range from 0.26 to 0.89 and from 0.46 to 0.96, respectively.2,6 The C2920S/(20S + 20R) ratios were between 0.14 and 0.28, thereby implying an immature to early-mature stage. None of the oil samples in this study originated from this member. The Es3 source rocks in the Huanghekou Sag and the Es3 source rocks in the Gunan Sag have limited contribution to oils in the Gudong Oilfield.

6. CONCLUSIONS

Chemometric analysis of 13 source-related and depositional environment-related parameters for 20 crude oil samples from the Gudong Oilfield revealed that they generally fell into three families. The organic geochemical characteristics of the oil families indicate that the oils all originated from lacustrine source rocks, although the thermal maturity, organic matter sources, and depositional environment of their source rocks differ. Family I was from the source rock deposited under suboxic conditions in a brackish water environment, with microalgae having been the dominant source of organic matter. The inferred source rock is the Es3 source rock in the Huanghekou Sag, and a substantial portion of the oils in the Gudong Oilfield originated from the source rock. The source rock of family II was deposited in a weakly oxidizing environment with a large amount of terrigenous organic input. It is probable that the source rock is Ed member in the Huanghekou Sag. For family III, the Es3 member in the Gunan Sag is the most likely source. Oils in family III were deposited under a weakly reducing environment with microalgae (especially zooplankton algae) providing the organic matter input. All of the crude oil samples are at the mature stage.

Table 3. Diagnostic Characteristics of the Source Rocks for the Gudong Oilfield

| Sag      | member | Pr/Ph | Ga/C30H | C2920S/(20S + 20R) | 4M-C29/C29 steranes |
|----------|--------|-------|---------|--------------------|---------------------|
| Gunan    | Es1    | 0.26–0.89 | 0.46–0.96 | 0.12–0.79 | 0.14–0.28 | 0.03–0.11 |
|          | Es3    | 0.88–2.00 | 0.07–0.12 | 0.86–1.97 | 0.46–0.57 | 0.08–0.22 |
|          | Ed     | 2.20–3.04 | 0.03–0.08 | 0.23–0.89 | 0.36–0.51 | 0.05–0.14 |
| Huanghekou | Es1    | 1.23–1.52 | 0.11–0.64 | 0.47–1.65 | 0.33–0.41 | 0.15–0.25 |
|          | Es3    | 1.32–1.83 | 0.04–0.10 | 0.89–1.95 | 0.39–0.68 | 0.15–0.56 |
however, the maturity of family II is higher than those of family I and family III.

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Notes

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