Quality, hydrocarbon generation, and expulsion of the Eocene Enping Formation source rocks in the Wenchang Depression, western Pearl River Mouth Basin, South China Sea

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Abstract
Recently, increasing numbers of oil and gas reservoirs have been discovered in the Wenchang Depression, western Pearl River Mouth Basin, South China Sea, revealing prospects for hydrocarbon exploration. The Enping Formation (E3e) is a key target layer for the development of source rocks. However, previous work has only focused on lacustrine swamp source rocks of E3e in the Wenchang A Sag, without a systematic study of shallow lacustrine source rocks. In this study, the quality of E3e shallow lacustrine source rocks is reevaluated, and the hydrocarbon generation and expulsion characteristics are analyzed using relevant geological data and constructing a conceptual model. The results show that the E3e source rocks have greater thickness (50–600 m) and similar organic matter abundance (0.5–2.5%) compared with the E3e1 source rocks (50–500 m and 0.5–2.5%). On the whole, the E3e source rocks were deposited in the continental environment and are dominated by Type II and Type III kerogen. Meanwhile, the E3e source rocks of the Wenchang A Sag are in the stage of mature to over mature, while those of the Wenchang B Sag are in the stage of low mature. Vertically, the hydrocarbon generation...
potential of the $E_3e_2$ source rocks is greater than $E_3e_1$. Also, the cumulative hydrocarbon produc-
tion of steep slope in the Wenchang A Sag is larger than that in the Wenchang B Sag. In addition, the corre-
sponding vitrinite reflectances of hydrocarbon expulsion threshold and peak are 0.72 and 0.96%, respectively. Horizontally, four hydrocarbon generation and expulsion centers were mainly concentrated in different subsags of the Wenchang A and B Sags for $E_3e$. The maximum values of hydrocarbon generation and expulsion intensity for $E_3e_1$ are $1500 \times 10^4$ t/km$^2$ and $1000 \times 10^4$ t/km$^2$, respectively, while those for $E_3e_2$ are $1800 \times 10^4$ t/km$^2$ and $1200 \times 10^4$ t/km$^2$, respectively, with the expulsion efficiency of 75%.

Keywords
Geochemical parameters, hydrocarbon generation and expulsion, lacustrine source rocks, Pearl River Mouth basin, quality

Introduction
The Pearl River Mouth Basin is a Cenozoic hydrocarbon-rich basin in the northern part of South China Sea (Gong and Li, 1997; You et al., 2018). In this basin, the Wenchang Depression is an important part of the Zhu III Superdepression. In total, $1 \times 10^8$ m$^3$ of crude oil and more than $300 \times 10^8$ m$^3$ of natural gas have been found in the depression and its surrounding areas, demonstrating that the depression is an important oil and gas accu-
mulation area in the basin (Gong and Li, 2004; Kang and Feng, 2011; Xie et al., 2012). However, the proved reserves of oil and natural gas in the Wenchang Depression are only 13 and 5%, respectively, of the resources predicted by a basin simulation (Gan et al., 2009), likely due to the complex geological conditions leading to little prospecting and great dif-
ficulty in exploration.

The Wenchang Depression, primarily the Wenchang A and B Sags, consists of two sets of source rocks: the Wenchang Formation ($E_2w$) and $E_3e$ (Cui et al., 2009; Quan et al., 2015). A previous study divided the source rocks into three types: medium-deep lacustrine source rocks of $E_2w$ in the Wenchang A and B Sags, shallow lake source rocks of $E_2w$ distributed in an similar area to the former, and lacustrine swamp source rocks of $E_3e$ developed only in the Wenchang A Sag (Xie et al., 2012; Zhu et al., 1999). Medium-deep lacustrine source rocks of $E_2w$ are believed to be the main source rocks in the Wenchang Depression (Zhou et al., 2018), and its characteristics have been studied by predecessors. Other studies have shown that lacustrine swamp source rocks of $E_3e$ provide oil and gas for the formation of reservoirs in the Wenchang A Sag (Huang et al., 2007). Furthermore, the peak period of hydrocarbon expulsion is in early Miocene to Pliocene. The origin of the organic matter of $E_3e$ is considered to be mainly from the input of terrestrial plants and resin-rich compound, which is more likely to form natural gas and produce a small amount of light oil (Gan et al., 2009; Kang et al., 2011). However, some geologists have suggested that only a small area of lacustrine swamp source rock from $E_3e$ is distributed in the northern part of the Wenchang A Sag, while the central and southern parts are dominated by shallow lacus-
trine source rocks (Cheng et al., 2013a). In addition, the characteristics of crude oil drilled in the Wenchang 10–8 structure recently are quite different from those of $E_2w$, implying the possibility of generating hydrocarbons of $E_3e$ in the Wenchang A Sag (Lu et al., 2016).
The Wenchang B Sag has a smaller area than Wenchang A Sag, but dark mudstones of E3e were confirmed through the drilling data, indicating the possibility of generating oil and gas. However, previous studies of distribution, evaluation, hydrocarbon generation, and expulsion potential of the E3e source rocks have not been conducted in detail. In summary, reevaluation of the quality of shallow lacustrine source rocks is necessary.

By combining relevant geochemical parameters and experimental methods such as pyrolysis and chromatographic analysis, this study systematically evaluates four aspects of geological and geochemical characteristics in two sags: organic matter abundance, organic matter type, organic matter maturity, and molecular geochemical characteristics. Additionally, two other experimental methods, basin modeling and hydrocarbon generation potential method, were applied to evaluate the resource potential of source rocks in the Wenchang Depression. This study not only can analyze the hydrocarbon generation history of single wells but also establish a conceptual model of hydrocarbon generation and expulsion, with the aim of calculating the hydrocarbon expulsion intensity and quantities in the plane.

The evaluation of source rocks and the study of hydrocarbon generation and expulsion in the Wenchang Depression are beneficial for further exploration of reservoirs in the Zhu III Superdepression and provide an important reference for the rolling exploration and deployment of other similar exploration areas.

Geological setting

The Pearl River Mouth Basin, located in the northeastern part of South China Sea, is approximately 800 km long from east to west and 100–360 km wide from north to south, covering an area of approximately 17.7 × 10^4 km^2 (Cui et al., 2009). The Pearl River Mouth Basin is divided into east and west parts by E113°10`. The eastern part of the basin includes Zhu I Superdepression, Zhu II Superdepression, Dongsha Uplift, and Panyu Uplift, while the western part is mainly composed of Zhu III Superdepression and Shenhu Uplift (Wang et al., 2017; Figure 1). The Zhu III Superdepression is further divided into seven tectonic units in the NE–SW direction by the secondary basement fault, namely, the Qionghai Depression and Yangjiang Depression in the north, the Qionghai Uplift and Yangjiang Low Uplift in the middle, and the Wenchang Depression, with the largest area and the deepest sedimentation in the south (the Wenchang A and B Sags are the main units discussed in this study) (Cheng et al., 2013b; Quan et al., 2015; Figure 1). Furthermore, the Wenchang 5, 6, 9, 10, and 14 subsags form the Wenchang A Sag, while the Wenchang B Sag is composed only of the Wenchang 19 subsag. In the section, due to the strong control of main faults, the Wenchang Depression is a haft-graben fault depression characterized by faulting in the south and overlapping in the north (Gong and Li, 1997, 2004). Also, the depression is divided into three different structural belts: steep slope, sag zone, and gentle slope.

Under the dual controls of crustal stretching and right-lateral strike-slip, the Zhu III Superdepression experienced three tectonic evolution stages: terrestrial fault lacustrine basin from Eocene to Early Oligocene (syn-rifting stage), fault depression basin from late Oligocene to Early Miocene (early postrifting stage), and depression basin since Middle Miocene (late postrifting stage) (Quan et al., 2019). As a result, the Zhu III Superdepression formed a typical double-layer structure similar to most Cenozoic fault basins in Eastern China.

As shown in Figure 2, the first stage (E2w and E3e), with thickness of 1800–3600 m, belongs to filling period of lakes in the rift and develops black mudstone, which is the main source rock of the depression (Zhang et al., 2009). The formation of E3e is composed of two
members: E3e1 and E3e2. The second stage (E3z and N1z2) consists mainly of sandstone with stratum thickness of 1500–2500 m, acting as excellent reservoirs. The third stage (N1z1, N1h, N1y, and N2w) is an open shallow sea environment with a thickness of 2000–3000 m, dominated by mudstone and forming a good regional seal stratum (You et al., 2018).

As a secondary tectonic unit, the Wenchang Depression has a similar sedimentary and tectonic evolutionary process to the entire Zhu III Superdepression (Cheng et al., 2013a; Quan et al., 2015).

Data and methods

Samples

A total of 55 mudstone samples were collected from eight wells drilled in the Wenchang Depression. Among all sampling wells, five are located in the Wenchang A Sag, and others

Figure 1. Location map of the Zhu III Superdepression and structural features in E3e1 Formation of the study area, Pearl River Mouth basin, South China Sea. The sampling wells are marked in black.
are distributed in the Wenchang B Sag. Through geochemical supplementation experiments on samples, a total of 183 data points were obtained for the analysis of source rocks. Additionally, more than 200 geochemical data points associated with source rocks, such as TOC and Ro, were obtained from previous studies by the Zhanjiang Branch of CNOOC China Ltd.
Labo(ratory) methods

To evaluate the potential of source rocks, three primarily geochemical analyses were performed: the determination of the total organic carbon (TOC) content, Rock–Eval pyrolysis, and vitrinite reflectance (Ro). A LECO CS-230 analyzer was used to measure TOC after removing carbonate with dilute hydrochloric acid at a concentration of 5% and washing the residue with distilled water. For the Rock–Eval pyrolysis measurements (Peters, 1986), an OGE-II instrument was employed. Using high purity helium gas as carrier gas, the sample was tested at a constant temperature of 300°C for 3 min, and the free hydrocarbon S1 was detected. Then, the temperature was raised to 600°C at a rate of 50°C/min, and the pyrolysis hydrocarbon S2 was detected at a constant temperature for 3 min (Tissot and Welte, 1984). Correspondingly, T_max was also obtained, which represents the maximum pyrolysis yield (Espitalié et al., 1977). An oil immersion lens and a Leica MPV Compact II reflected-light microscope were used to measure the mean random Ro, which could be acquired by averaging the histogram (Lee et al., 1997).

For the purpose of discussing depositional environment of source rocks, 28 samples from E3e1 and E3e2 were selected for gas chromatography (GC) analysis using an HP6890 chromatograph equipped with an HP-5MS fused silica column (30 m × 0.25 mm × 0.25 μm). The temperature was programmed to increase from 100 to 300°C at a rate of 4°C/min, with helium as carrier gas at a flow rate of 1 mL/min. Additionally, both the injector temperature and the FID detector temperature were 300°C.

Conceptual model of the hydrocarbon generation potential method

The hydrocarbon generation potential method proposed by Pang et al. (2005) (Figure 3) can calculate the hydrocarbon expulsion intensity and quantity through estimating the original hydrocarbon generation potential. The \(^{(S_1 + S_2)/TOC}\) is one of formulas commonly used in this method (Guo et al., 2013; Hu et al., 2018). The parameter S1 generally represents the extractable free hydrocarbon content when temperature is heated to not more than 300°C, and S2 represents the quantity of hydrocarbons generated by pyrolysis of kerogen and its related components (Peng et al., 2016). When oil and gas are not expelled, the greatest value is considered as the maximum hydrocarbon generation potential HCl_o (Guo et al., 2013; Hu et al., 2017b). The Ro value at the beginning of reduction represents the hydrocarbon expulsion threshold of source rocks, and the subsequent hydrocarbon generation potential can be called the residual hydrocarbon generation potential HCl_p (Hu et al., 2017a).

However, HCl_p can only represent current hydrocarbon generation potential rather than original. Therefore, the correction of HCl_p, which also can be called generation curve, is necessary. In general, organic carbon is mainly composed of effective and ineffective carbon (Bai et al., 2017). Effective carbon refers to that which can generate oil and gas given sufficient temperature and time. Ineffective carbon refers to the kerogen that cannot be converted into hydrocarbons, and the absolute content remains the same throughout the process of hydrocarbon generation and migration (Zheng et al., 2019). According to the principle of mass balance, the revised hydrocarbon generation potential can be acquired using equations (1) and (2)

\[
HCl_{pr} = HCl_o \times \delta
\]
where $\delta$ is the hydrocarbon generation recovery index and 0.83 is the average carbon content of hydrocarbons (Burnham, 1989).

The difference between $\text{HCl}_{\text{pr}}$ and $\text{HCl}_{\text{p}}$ is the hydrocarbon expulsion ratio through equation (3). The hydrocarbon expulsion rate can also be acquired through equation (4), which represents the corresponding variation of hydrocarbon expulsion ratio when $R_o$ increases by 0.1%. As shown in equation (5), the hydrocarbon expulsion efficiency is the percentage of hydrocarbon expulsion to total hydrocarbon generation

\[
\delta = \frac{1 - 0.83 \times \text{HCl}_{\text{p}}/1000}{1 - 0.83 \times \text{HCl}_{\text{o}}/1000}
\]  

\[
q_e(Z) = \text{HCl}_{\text{pr}} - \text{HCl}_{\text{p}}
\]  

\[
V_e = \frac{\Delta q_e(Z)}{\Delta R_o}
\]  

\[
R_e = \frac{q_e(Z)}{\text{HCl}_{\text{pr}}} \times 100
\]

where $q_e(Z)$ is the hydrocarbon expulsion ratio, measured in (mg HC)/(g TOC); $V_e$ is the hydrocarbon expulsion rate, measured in (mg HC/g TOC)/(0.1% $R_o$); and $R_e$ is the hydrocarbon expulsion efficiency, shown as percentages.
Through the above relevant indicators, we can calculate hydrocarbon generation and expulsion intensity of source rocks according to equations (6) and (7). Moreover, the amounts of hydrocarbons generated and expelled can be obtained from equations (8) and (9)

\[ I_g = \int_{R_{og}}^{R_o} 10 \times \text{HCl}_{pr} \times \rho \times h \times \text{TOC} \times dRo \]  

(6)

\[ I_e = \int_{R_{oe}}^{R_o} 10 \times q_e(Z) \times \rho \times h \times \text{TOC} \times dRo \]  

(7)

\[ Q_g = \int_{R_{og}}^{R_o} 10^5 \times \text{HCl}_{pr} \times \rho \times h \times A \times \text{TOC} \times dRo \]  

(8)

\[ Q_e = \int_{R_{oe}}^{R_o} 10^5 \times q_e(Z) \times \rho \times h \times A \times \text{TOC} \times dRo \]  

(9)

where \( I_g \) is the hydrocarbon generation intensity, measured in time per square kilometer; \( I_e \) is the hydrocarbon expulsion intensity, measured in time per square kilometer; \( Q_g \) is the amount of hydrocarbon generated, measured in t; \( Q_e \) is the amount of hydrocarbon expelled, measured in t; \( R_{og} \) is the vitrinite reflectance, expressed as percentages; \( R_{og} \) is the hydrocarbon generation threshold, measured in %; \( R_{oe} \) is the hydrocarbon expulsion threshold, measured in %; \( \rho \) is the density of source rocks, measured in gram per cubic centimeter; \( h \) is the thickness of source rocks, measured in meter; \( A \) is the area of source rocks, measured in square meter; and \( \text{TOC} \) is the TOC content, shown as percentages.

Results and discussion

Geochemical characteristics of the \( E_3e \) source rocks

Abundance of organic matter. The TOC content and the rock pyrolysis hydrocarbon potential (\( P_g = S_1 + S_2 \)), are indexes commonly used for evaluating the abundance of organic matter. Relevant experimental data are listed in Table 1. Combining geochemical data from earlier studies, Table 2 shows the overall statistical results. These data illustrate that the source rock quality of \( E_3e_1 \) is superior to that of \( E_3e_2 \), and the quality of the Wenchang A Sag is better than Wenchang B Sag.

In the Wenchang A Sag, the TOC contents of \( E_3e_1 \) have an average of 1.38%, ranging from 0.04 to 8.19%. The \( S_1 + S_2 \) values vary between 0.13 and 17.96 mg/g, with a mean value of 2.71 mg/g (Figure 4(a)). According to the evaluation criteria for source rocks in the oil and gas industry standard of the People’s Republic of China (Table 3), the \( E_3e_1 \) source rocks are regarded as fair to good source rocks. The \( E_3e_2 \) source rocks, whose quality is similar to \( E_3e_1 \), are slightly worse, with the average values of TOC content and \( S_1 + S_2 \) are 1.37% and 1.72 mg/g, respectively. In the Wenchang B Sag, the TOC content of \( E_3e_1 \) varies between 0.03 and 9.78%, with an average of 1.31%, and the \( S_1 + S_2 \) values range from 0.02 to 20.61 mg/g, with an average value of 2.70 mg/g. The \( E_3e_2 \) source rocks are of lesser quality, with mean values of the TOC content and \( S_1 + S_2 \) values of 0.60% and 1.17 mg/g, respectively (Figure 4(b)).
Table 1. Bulk geochemical results of the Rock–Eval pyrolysis, TOC determination and vitrinite reflectance (Ro) in the Wenchang Depression.

| Well name | Depth (m) | Formation | S$_1$ (mg/g) | S$_2$ (mg/g) | T$_{max}$ ($^\circ$C) | TOC (%) | HI (mg/g) | Ro (%) |
|-----------|-----------|-----------|--------------|--------------|------------------|--------|----------|--------|
| WC6-A     | 3814      | E$_3$e$_1$| 0.13         | 0.28         | 446              | 0.53   | 53       | 0.91   |
| WC6-A     | 3822      | E$_3$e$_1$| 0.16         | 0.35         | 451              | 0.60   | 58       |        |
| WC6-A     | 3828      | E$_3$e$_1$| 0.24         | 0.51         | 448              | 1.10   | 46       | 0.92   |
| WC6-A     | 3844      | E$_3$e$_1$| 0.16         | 0.3          | 446              | 0.56   | 53       | 0.92   |
| WC6-A     | 3902      | E$_3$e$_1$| 0.21         | 0.62         | 456              | 0.84   | 74       | 0.95   |
| WC6-A     | 3964      | E$_3$e$_1$| 0.25         | 0.44         | 448              | 0.73   | 60       |        |
| WC6-A     | 3978      | E$_3$e$_1$| 0.18         | 0.32         | 449              | 0.69   | 46       |        |
| WC6-A     | 3999      | E$_3$e$_1$| 0.29         | 0.66         | 456              | 1.05   | 63       |        |
| WC6-A     | 4008      | E$_3$e$_1$| 0.28         | 0.69         | 459              | 0.98   | 70       |        |
| WC6-A     | 4013      | E$_3$e$_1$| 0.22         | 0.43         | 462              | 0.71   | 61       | 1.02   |
| WC6-A     | 4018      | E$_3$e$_1$| 0.25         | 0.43         | 455              | 0.83   | 52       | 1.02   |
| WC6-A     | 4038      | E$_3$e$_1$| 0.29         | 0.64         | 459              | 0.97   | 66       | 1.04   |
| WC6-A     | 4040      | E$_3$e$_1$| 0.24         | 0.63         | 457              | 0.86   | 75       |        |
| WC6-A     | 4046      | E$_3$e$_1$| 0.17         | 0.34         | 470              | 0.72   | 47       |        |
| WC6-A     | 4082      | E$_3$e$_1$| 0.32         | 0.91         | 464              | 1.38   | 66       | 1.06   |
| WC6-A     | 4104      | E$_3$e$_1$| 0.35         | 0.96         | 461              | 1.32   | 73       |        |
| WC6-A     | 4116      | E$_3$e$_1$| 0.68         | 2.06         | 464              | 2.78   | 74       | 1.07   |
| WC6-A     | 4136      | E$_3$e$_1$| 0.36         | 0.82         | 464              | 1.50   | 55       | 1.07   |
| WC9-D     | 3746      | E$_3$e$_1$| 1.39         | 4.7          | 446              | 2.21   | 213      | 0.86   |
| WC9-D     | 3754      | E$_3$e$_1$| 1.31         | 4.09         | 445              | 2.03   | 201      |        |
| WC9-D     | 3765      | E$_3$e$_1$| 1.05         | 3.4          | 447              | 1.74   | 196      |        |
| WC9-D     | 3768      | E$_3$e$_1$| 1.41         | 4.13         | 446              | 2.33   | 177      |        |
| WC9-D     | 3778      | E$_3$e$_1$| 1.24         | 3.04         | 445              | 1.61   | 189      |        |
| WC9-D     | 3788      | E$_3$e$_1$| 1.01         | 2.99         | 445              | 1.94   | 154      | 0.91   |
| WC9-D     | 3798      | E$_3$e$_1$| 0.73         | 2.7          | 381              | 1.38   | 196      |        |
| WC9-D     | 3804      | E$_3$e$_1$| 0.87         | 2.53         | 444              | 1.35   | 187      |        |
| WC9-D     | 3804.5    | E$_3$e$_1$| 0.93         | 2.56         | 444              | 1.42   | 181      |        |
| WC10-B    | 3452      | E$_3$e$_1$| 0.44         | 1.05         | 434              | 1.84   | 57       |        |
| WC10-B    | 3490      | E$_3$e$_1$| 0.22         | 0.61         | 440              | 0.84   | 73       | 0.72   |
| WC10-B    | 3600      | E$_3$e$_1$| 0.55         | 2.2          | 444              | 2.26   | 97       | 0.75   |
| WC10-B    | 3610      | E$_3$e$_1$| 0.76         | 3.6          | 444              | 2.89   | 125      |        |
| WC10-B    | 3688      | E$_3$e$_1$| 0.29         | 0.93         | 444              | 1.05   | 88       |        |
| WC11-A    | 4308      | E$_3$e$_1$| 0.59         | 1.1          | 366              | 0.26   | 425      | 0.84   |
| WC11-A    | 4506      | E$_3$e$_1$| 1.19         | 2.74         | 369              | 1.72   | 160      |        |
| WC11-A    | 4507      | E$_3$e$_1$| 1.24         | 2.99         | 371              | 1.72   | 174      |        |
| WC2-A     | 3266      | E$_3$e$_2$| 0.3          | 1.24         | 446              | 0.97   | 128      | 0.8    |
| WC2-A     | 3344.5    | E$_3$e$_2$| 0.63         | 1            | 445              | 1.17   | 86       |        |
| WC2-A     | 3357.5    | E$_3$e$_2$| 1.26         | 3.28         | 453              | 2.97   | 110      | 0.82   |
| WC2-A     | 3375.5    | E$_3$e$_2$| 1.19         | 8.29         | 437              | 2.42   | 343      |        |
| WC2-A     | 3402.5    | E$_3$e$_2$| 1.01         | 2.98         | 430              | 1.87   | 152      | 0.85   |
| WC19-B    | 1897.5    | E$_3$e$_1$| 0.73         | 11.66        | 433              | 3.71   | 314      |        |
| WC19-B    | 1915.5    | E$_3$e$_1$| 1.17         | 19.44        | 431              | 7.31   | 266      |        |
| WC19-B    | 1927.5    | E$_3$e$_1$| 1.27         | 16.31        | 431              | 5.90   | 277      |        |
| WC19-B    | 1963.5    | E$_3$e$_1$| 1.24         | 10.94        | 432              | 3.86   | 283      |        |
| WC19-B    | 1990.5    | E$_3$e$_1$| 0.82         | 9.67         | 431              | 3.54   | 273      |        |

(continued)
All relevant parameters indicate that the E3e1 source rocks in the Wenchang B Sag are fair to good source rocks, and the quality of E3e2 source rocks is poor. Additionally, chloroform bitumen “A” is also an indicator of organic matter abundance, and the estimation standard is listed in Table 3. Taking the Wenchang A Sag as an example, the chloroform bitumen “A” of E3e1 source rocks is 0.006–1.565%, whereas the value of E3e2 is less, varying between 0.015 and 0.21% (Figure 4(c)). The average values of E3e1 and E3e2 are 0.178 and 0.086%, respectively, which are consistent with previous results (Figure 4(d)).

By studying the sedimentary facies, seismic inversion results, and TOC measured data, Figure 5(a) and (b) shows the distribution of TOC content for the E3e1 and E3e2 source rocks in the Wenchang Depression. In E3e1, the greatest TOC value is the Wenchang 10 subsag, with a maximum value of 2.5% or more, followed by the Wenchang 6 and 9 subsags. Furthermore, the area with high TOC content is greater on north and south, smaller in the center. Additionally, the Wenchang 14 subsag has the lowest TOC value of only 0.5%. In the Wenchang B Sag, the highest TOC content is the Wenchang 19 subsag, the value of which is approximately 2.0%.

Table 2. Geochemical attributes of different areas in the Wenchang Depression.

| Formation | TOC | S1 + S2 | TOC | S1 + S2 |
|-----------|-----|---------|-----|---------|
| WC19-B    | 0.04–8.19 | 164 | 0.03–9.78 | 111 |
| WC19-C    | 0.31–7.27 | 96 | 0.02–4.19 | 81 |

In the table, $0.04–8.19_{(1.38)}$ is minimum–maximum mean.
and 19 subsags have the highest TOC values, with maximum values of 2.5% or more, followed by the Wenchang 9 and 14 subsags, with maximum values exceeding 2.0%. The lowest is the Wenchang 10 subsag, with TOC values less than 2.0%, and the trend is greater on east and west, smaller in the center. Comparing two members of E3e, the distribution of TOC values resembles the thickness of source rocks, which is affected by the movement of sedimentary center.

**Figure 4.** Organic matter abundance of the E3e source rocks: (a) \(S_1 + S_2\) versus TOC; (b) \(S_1 + S_2\) versus TOC; (c) chloroform bitumen “A” versus TOC; (d) \(S_1 + S_2\) versus chloroform bitumen “A.” The E3e1(A) and E3e2(A) samples are from the Wenchang A Sag, and the E3e1(B) and E3e2(B) samples are from the Wenchang B Sag.

| Table 3. Classification standard for organic matter abundance of source rocks (SY/T 5735–1995). |
|---------------------------------------------------------------|
| **Indexes** | **Source rock types** | **Non** | **Poor** | **Fair** | **Good** | **Excellent** |
| TOC (%) | \(<0.4\) | 0.4–0.6 | 0.6–1.0 | 1.0–2.0 | \(>2.0\) |
| Chloroform bitumen “A” (%) | \(<0.015\) | 0.015–0.05 | 0.05–0.1 | 0.1–0.2 | \(>0.2\) |
| \(S_1 + S_2\) (mg/g) | \(<2\) | 2–6 | 6–20 | \(>20\) |
Types of organic matter. To distinguish the types of organic matter, the hydrogen index (HI) and oxygen index (OI) are widely adopted. The sample points of E3e have different characteristics in two regions. Most sample points of the Wenchang A Sag are located near the curve with a Ro value of 1.35%, indicating high maturity (Figure 6(a)). However, in the
Wenchang B Sag, the sample points are mainly in the immature to mature stage, as indicated by their location near the curve with a Ro value of 0.5% (Figure 6(b)).

In addition, the HI values of E3e1 in the Wenchang A Sag are between 33.62 and 424.87 mg HC/g TOC, with a mean value of 110.94 mg HC/g TOC, while the values of
E3e2 range from 42.16 to 342.7 mg HC/g TOC, with an average of 122.14 mg HC/g TOC (Figure 6(a)). From Figure 6(c), the average values of OI for E3e1 and E3e2 are 67.99 and 90.93 mg CO2/g TOC, respectively. These data show that the E3e source rocks are dominated by (approximately 96%) Type II and Type III kerogen. The HI values of E3e1 and E3e2 in the Wenchang B Sag are 37.9–396.47 and 26.37–269.02 mg HC/g TOC, respectively, with average values of 177.01 and 173.07 mg HC/g TOC (Figure 6(b)). Moreover, most relevant data indicate that 60–65% of samples in the Wenchang B Sag are Type II kerogen, but some sample points have lower HI values, indicating Type III kerogen. According to Figure 6(d), the mean values of OI for E3e1 and E3e2 in the Wenchang B Sag are 79.53 and 59.5 mg CO2/g TOC, respectively, proving that the primary kerogen is Type II. In general, the source rocks of the Wenchang Depression are dominated by Type II and Type III kerogen.

Thermal maturity of organic matter. Vitrinite reflectance (Ro) and the highest pyrolysis peak temperature (Tmax) are important parameters used to evaluate the thermal evolution of source rocks. In this paper, the minimum Ro value of 0.5% is considered as the hydrocarbon generation threshold (Espitalié, 1985; Tissot and Welte, 1984), with a Tmax value of 430°C (Barker, 1974; Sykes and Snowden, 2002).

Wang et al. (2017) proposed that geothermal gradients of different structural zones in the Wenchang A Sag are different. Due to the development of mudstone in the sedimentary center and its low thermal conductivity, the average geothermal gradients increase from the center of depression to the edge, and the value changes from 32.8 to 36.7°C. Comparing the data in Table 1, the Tmax value of 3452–3688 m in well WC10-B is 434–444°C, while the value of 4308–4507 m in well WC11-A is as low as 366–371°C. This is related to the fact that well WC10-B is located on steep slope and well WC11-A is close to the center of depression. In short, we need to discuss thermal maturity of different tectonic zones in the Wenchang A and B Sags separately.

The experimental data are distributed in three structural zones of the Wenchang A Sag, while the Wenchang B sag is concentrated in the steep slope. Figure 7(a) and (b) shows that the Ro values of different zones in Wenchang Depression all have a linear relationship with depth, and the R^2 values are all greater than 0.7, which indicates a good correlation. The Ro values of steep slope in the Wenchang A Sag range from 0.67 to 1.1%, and those in the Wenchang B Sag vary between 0.42 and 1.1%, illustrating that the former have entered the stage of maturity and the latter have only entered low-maturity stage. The wells analyzed in the Wenchang A Sag are from the central and northern areas, while the wells tested in the Wenchang B Sag are only from shallower position on south. Although the well data are limited to the steep slope in the Wenchang B Sag, source rocks in the sag zone can be inferred to have higher maturity according to the relation between the buried depth and Ro. Additionally, the relevant formulas are useful for studying the distribution of organic matter maturity on the plane. For another parameter, Tmax, the range in the Wenchang A Sag is 366–470°C, within which much oil and gas can be generated (Table 1). In addition, the Tmax values in the Wenchang B Sag span from 424 to 441°C, showing that source rocks mainly produce low-maturity oil.

Based on the comprehensive analysis of structural contour map (Figure 1) and Ro-depth relationship (Figure 7(a) and (b)), Figure 8(a) and (b) shows the distribution of vitrinite reflectance in E3e1 and E3e2, indicating that the organic matter maturity of source rocks in two sags is significantly different. As a whole, the organic matter maturity in the Wenchang
Depression was gradually increasing from periphery to the center. The highest Ro value of the E3e1 source rocks in the Wenchang A Sag was mostly 1.0–1.2%, and some areas in the Wenchang 9 subsag even reached 1.4%. Therefore, the Wenchang A Sag was in the mature stage and produced large amount of oil and gas. Additionally, it shows high values for E3e2 in the Wenchang 6, 9, and 10 subsags, the maximum Ro value greater than 1.4%, suggesting that the whole region was at a high maturity stage. In the Wenchang B Sag, the maximum Ro value in the Wenchang 19 subsag is 0.6–0.8%, and source rocks were in the low-maturity to maturity stage. In short, the maturity of the E3e2 source rocks is superior to E3e1, and the maturity of the Wenchang A Sag is higher than Wenchang B Sag.

**Molecular geochemical characteristics.** Pr/Ph is commonly used as an indicator for determining the redox degree of organic paleo-environment (Bendoraitis et al., 1962; Brooks et al., 1969; Powell and Mckirdy, 1973). In general, a ratio of Pr/Ph below 1.0 indicates reducing environment, and a higher Pr/Ph ratio (above 3.0) reflects oxic environment, which is common in the sediments of rivers, coastal marshes, and shallow lakes (Didyk et al., 1978; Ten Haven et al., 1987). Figure 9(a) shows that more than 50% of samples in both E3e1 and E3e2 were in weak oxidation state, while 28.1 and 22.2% of samples were in strong oxidation state, respectively. Therefore, areas near sampling wells of E3e are dominated by oxidation, and the degree of E3e1 is higher than that of E3e2. Moreover, Pr/nC17 and Ph/nC18 can be used to identify depositional environment and thermal maturity. As shown in Figure 9(b), the average values of Pr/nC17 and Ph/nC18 are 0.90 and 0.33, respectively, for E3e1. In addition, the corresponding values for E3e2 are 0.72 and 0.29, respectively. Thus, the source rocks of E3e
Figure 8. Ro contour of source rocks in the Wenchang Depression: (a) the top of the \( E_3e_1 \) source rocks; and (b) the top of the \( E_3e_2 \) source rocks (values in %).
are mainly deposited in the continental environment, and the degree of thermal evolution in E3e2 is higher than E3e1.

Carbon preference index (CPI) and odd–even preference (OEP) acquired by GC are used to evaluate the maturity of organic matter in different depositional environments (Peters and Moldowan, 1993). The CPI and OEP values in the Wenchang A Sag are 1.108 and 1.031 on average, respectively, illustrating that samples are in the mature stage (Figure 9(c)). In addition, the mean values of those in the Wenchang B Sag are 1.740 and 1.559, respectively, suggesting that samples are in the immature to low mature stage. This is also related to the fact that samples are located on steep slope, and it can be speculated that source rocks in the sag zone are already in the mature stage.

Figure 9. The depositional environment of the E3e source rocks in the Wenchang Depression: (a) histograms of the Pr/Ph values; (b) variation in Pr/nC17 with Ph/nC18 for mudstone samples; (c) CPI versus OEP; (d) carbon number distribution of different typical wells. The E3e1(A) and E3e2(A) samples are from the Wenchang A Sag, and the E3e1(B) and E3e2(B) samples are from the Wenchang B Sag.

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n-Alkanes are the main components of saturated hydrocarbon fractions, and the distribution of high carbon number hydrocarbons (>nC23) indicates the input of terrestrial organic matter, while medium relative molecular mass hydrocarbons (nC15-nC21) indicate that the sources are aquatic organisms such as algae (Gelpi et al., 1970;
Peters et al., 2005). Figure 9(d) shows that the carbon number is nC13-nC40, and hydrocarbons are dominated by high carbon number, which reflects that the origin is terrestrial organic plants. However, the distribution of n-alkane varies from different wells. The main carbon peaks of well WC19-F in the Wenchang B Sag are nC17-nC19 and nC27-nC33 with double peaks, which reflects a mixture of terrestrial plants and aquatic organisms. Also, the curve of this well is jagged, but the curves of WC10-B and WC11-A in the Wenchang A Sag are smooth, indicating that the maturity of the latter is higher. From the main peak carbon number of well WC10-B, we can know that organic matter is derived from terrestrial organisms. But the main carbon peaks of well WC11-A are nC16-nC20, which indicates aquatic organism inputs. In previous studies (Cheng et al., 2013b), the T/C30H value of this well is 0.13–0.19, and the ratio of $\sum$C30-4MST/C29ST is between 0.3 and 0.4, which also shows the contribution of aquatic organisms. Therefore, this result may be due to the fact that the well is near the middle-deep lacustrine facies, rather than the high maturity of organic matter.

Huang and Meinschein (1979) used the relative concentrations of C27, C28, and C29 regular steranes to determine depositional environment. Higher plants are the main organisms on land, and relatively simple planktons are the main aquatic organisms, which is the difference between terrestrial and marine environments. In general, aquatic organisms are rich in C27 sterane, and terrestrial plants are richer in C29 sterane compared to C27 and C28 steranes (Moldowan et al., 1985; Peters et al., 2005; Volkman, 1986). According to Figure 10, the content of C29 sterane is 41% on average, ranging from 27 to 53%, whereas the content of C27 sterane is less, averaging only 29%. These results suggest that terrestrial plants contribute more to the organic matter in E3e than aquatic organisms, supporting the conclusion that it is dominant by terrestrial environment.

![Figure 10](image-url)

**Figure 10.** Ternary plot of $\alpha\alpha\alpha\alpha$-C27R, $\alpha\alpha\alpha\alpha$-C28R, and $\alpha\alpha\alpha\alpha$-C29R steranes for mudstone samples. The E3e1(A) and E3e2(A) indicate the Wenchang A Sag samples, and the E3e1(B) and E3e2(B) indicate the Wenchang B Sag samples.
Thickness and distribution of the $E_{3e}$ source rocks

Gao et al. (2013) and Wang et al. (2015) proposed that the TOC content, residual HCl, and conversion rate of hydrocarbon generation (“A”/TOC) should all be considered when analyzing the effectiveness of source rocks. For the same set of source rocks with similar characteristics, the variability in the amount of saturated hydrocarbons should be within a limited range. The amount of hydrocarbons will increase with increasing organic carbon content; thus, when the corresponding hydrocarbon generation meets the adsorption, the excess hydrocarbons will be expelled from source rocks. Simultaneously, the line of the residual hydrocarbons will deviate from the normal correlation trend. Therefore, the inflection point of residual hydrocarbon content is the lower limit of the organic carbon content for effective source rocks.

Figure 11(a) and (b) shows the variation of the residual hydrocarbon content and hydrocarbon generation conversion rate for the source rocks of $E_{3e}$ in the Wenchang Depression. The HCl and “A”/TOC values of source rocks both increase with increasing TOC when the TOC content is less than 1.1 or 0.9%, respectively, indicating that the hydrocarbons are not saturated. When the TOC content is greater than 1.1 or 0.9%, respectively, the HCl and “A”/TOC values begin to decrease with increasing TOC content, indicating that oil and gas generated are saturated and begin to be expelled. Therefore, comprehensively considering the distribution of sample points and the variation degree of the curve in two plates, the lower limit of the organic carbon content to discriminate effective source rocks is 1.0%.

Based on the effective source rocks of single wells, thickness variation and distribution could be analyzed with sedimentary facies analysis and seismic inversion. Figure 12(a) and (b) shows the distribution area of TOC $>1.0\%$, which demonstrate that source rocks of $E_{3e1}$ and $E_{3e2}$ are widely distributed in the Wenchang Depression. The thicknesses of the Wenchang 6 subsag, the southwestern of the Wenchang 9 subsag, and the Wenchang 10 and 14 subsags of $E_{3e1}$ are higher than other regions in the Wenchang A Sag. Among them, the maximum value is located in the Wenchang 10 subsag, with the thickness reaching 500 m, and the greatest thickness in the other three areas is only 300 m.

However, the thicknesses of the Wenchang 9 and 19 subsags are relatively small, ranging from 50 to 200 m. In addition, the thickness of $E_{3e2}$ in the Wenchang 5 subsag is 50–600 m, followed by the Wenchang 14 subsag, with the maximum thickness is 350 m. Then, the Wenchang 9 subsag, with the maximum thickness exceeding 300 m, has two sedimentary centers in the northeast and southwest. Last, the source rocks of the Wenchang 10 and 19 subsags are mainly in the center of respective subsags, distributed between 50 and 250 m. The comparison shows that the thickness of $E_{3e2}$ is greater than that of $E_{3e1}$. Overall, the trends in two members are the same, that is, the values increase gradually from the periphery of depression to the center. In the different periods of the Wenchang A Sag, the development of source rocks underwent a great change. For example, the Wenchang 5, 9, and 14 subsags are the most favorable areas of $E_{3e2}$. However, in $E_{3e1}$, the sedimentary center of the Wenchang 5 subsag moved to the Wenchang 6 and 10 subsags, rendering them more favorable areas of source rocks. In addition, two sedimentary centers of the Wenchang 9 subsag moved to the south and north, respectively. Also, the distribution area of the Wenchang 14 subsag was enlarged, while that of the Wenchang 19 subsag was diminished.

Hydrocarbon generation and expulsion characteristics of the $E_{3e}$ source rocks

Burial history and hydrocarbon generation history of single wells. This study uses the single well simulation submodule (BasinMod 1 D) in the PRA Basin Simulation Software to establish
burial history models. The data required for basin simulation mainly include geological age, lithology, thickness of source rocks, and its covered strata, as well as thermal history of sedimentary basin (Yalcin, 1991; Yalcin et al., 1997). The stratigraphic framework used in this paper is provided by CNOOC Zhanjiang Branch, and the heat flow in the depression is 61–65 mW/m². Well WC9-D is located on steep slope in the southern part of the Wenchang A Sag, and well WC19-D is also located on the same tectonic zone in the eastern part of the Wenchang B Sag. So, the differences of burial time and hydrocarbon generation characteristics in steep slope of two sags can be compared.

According to Deng et al. (2012), the stratum of the Wenchang A Sag is dominated by sedimentation during the evolution process, with basically no uplift and denudation. In the center of the Wenchang B Sag and north of the Wenchang C Sag, the formation was reversed due to local compression. However, the former appears as thinning of stratigraphic deposits, while the latter shows partial erosion. WC19-D is located in the south of the Wenchang B Sag and far from the Wenchang C Sag. So, it can be seen that this well has not been denuded combining geological stratification data. In well WC9-D, when the temperature increased to 100°C, the E₃e₁ source rocks entered the low-mature stage in N₁z₁ Formation. Additionally, the mature stage producing a large amount of hydrocarbons at a temperature of 113°C was in N₁y Formation (Figure 13(a)). The evolutionary time of the E₃e₂ source rocks is similar to E₃e₁, while the temperature is relatively lower. In contrast with the Wenchang A Sag, tectonic inversion delayed the hydrocarbon generation time of the Wenchang B Sag, and the temperatures were lower. Taking well WC19-D as an example, the E₃e₁ source rocks only entered the low-maturity stage in N₁y Formation at a temperature of 94°C (Figure 13(b)). Moreover, the low-maturity stage of the E₃e₂ source rocks was in N₁z₁ Formation. In short, Wenchang A Sag has higher maturity and produced more hydrocarbons than Wenchang B Sag.

According to the relevant geochemical indicators, such as TOC and HI, the E₃e₂ source rocks have greater hydrocarbon generation potential compared with E₃e₁. Therefore, the
Figure 12. Thickness distribution of source rocks in the Wenchang Depression: (a) the E₃e₁ source rocks; and (b) the E₃e₂ source rocks (values in meters).
The hydrocarbon generation rate of the \( E_{3e2} \) source rocks in two typical single wells was the focus of analysis. Figure 14(a) through (d) explains the generation rate of oil and gas in each period. Well WC9-D began to produce hydrocarbons in \( E_{3z1} \) Formation. The hydrocarbon generation rate first increased and then decreased over time, reaching the peak of hydrocarbon generation in \( N_{1y} \) Formation. At present, the hydrocarbon generation is at a slower rate. The maximum rates of oil and gas generation per organic carbon in well WC9-D are 25 and 5 (mg HC/g TOC)/Ma, respectively (Figure 14(a) and (c)). By adding the hydrocarbons generated in each period, the cumulative oil and gas production rates per unit mass of organic carbon are 158 and 30 mg HC/g TOC, respectively (Figure 15(a)). The hydrocarbon generation rate of well WC19-D has been increasing since oil and gas generation began in \( N_{1z2} \) Formation. Just before \( N_{2w} \), the value first increased slowly and then began to increase rapidly. Currently, the hydrocarbon generation rate is high. Using the same calculation method, the cumulative oil and gas production rates per unit mass of organic carbon are 100 and 18 mg HC/g TOC, respectively (Figure 15(b)). The maximum value of oil generation rate in WC19-D is similar to that in WC9-D (Figure 14(a) and (b)), and the maximum gas generation rate has the same conclusion (Figure 14(c) and (d)).

**Hydrocarbon generation and expulsion models of the \( E_{3e} \) source rocks.** The center of the Wenchang Depression developed abnormally high pressure in \( E_{3e} \) and had similar geothermal gradients in two members of two sags (Wang et al., 2017). In addition, the source rocks are all considered as fair to good and mainly Type II and Type III kerogen. And the characteristics of single-well hydrocarbon generation are also similar. Only organic maturity of the Wenchang A and B Sags are different, which can be reflected by hydrocarbon generation and expulsion model. Therefore, the two members of Enping Formation in the entire Wenchang depression can be modeled uniformly. The remaining hydrocarbon generation potential index \( HCIP \) and equation (1) were used to draw the envelope curve of 100 \times \( (S_1 + S_2) / TOC \) and calculate the original hydrocarbon generation ratio \( HCI_{or} \) (Figure 16(a)). As shown in Figure 16(b) and (c), the hydrocarbon expulsion ratio \( q_e(Z) \) and hydrocarbon expulsion rate \( V_e \) were obtained by equations (3) and (4), respectively. Finally, using equation (5), the hydrocarbon expulsion efficiency could be acquired.
Figure 14. Oil and gas generation rates of the E₃e₂ source rocks in various periods: (a) oil generation rate from well WC9-D in the Wenchang A Sag; (b) oil generation rate from well WC19-D in the Wenchang B Sag; (c) gas generation rate from well WC9-D in the Wenchang A Sag; (d) gas generation rate from well WC19-D in the Wenchang B Sag.

Figure 15. Cumulative hydrocarbon production of oil and gas of the E₃e₂ source rocks: (a) well WC9-D in the Wenchang A Sag; (b) well WC19-D in the Wenchang B Sag.
For the hydrocarbon expulsion mode of the E3e source rocks in the Wenchang Depression (Figure 16), the source rocks entered the hydrocarbon expulsion threshold when the corresponding vitrinite reflectance (Ro) was 0.72% (Figure 16(a)). The hydrocarbon expulsion ratio increased rapidly in the early stage and slowly in the later stage (Figure 16(b)). When the Ro value reached 0.96%, the hydrocarbon expulsion rate of source rocks reached a maximum of 60 mg/g (100 m) and then decreased with the thermal maturity (Figure 16(c)). Analysis of the hydrocarbon expulsion efficiency curve reveals that the maximum value is as high as 75% (Figure 16(d)).

**Hydrocarbon generation and expulsion intensity.** Taking Ro equal to 0.5 and 0.72% as the standard for the hydrocarbon generation and expulsion threshold, respectively, the cumulative hydrocarbon generation and expulsion intensity of E3e1 and E3e2 source rocks can be obtained. Figures 17 and 18 show that the hydrocarbon generation and expulsion centers correspond to the spatial distributions of source rocks (equations (6) and (7)).

The hydrocarbon generation and expulsion centers of the E3e1 source rocks are mainly concentrated in the Wenchang 6, 9, and 10 subsags of the Wenchang A Sag. In terms of hydrocarbon generation intensity, the Wenchang 10 subsag is the greatest, with a value of $1500 \times 10^4$ t/km$^2$, followed by the Wenchang 6 and 9 subsags, with a value of $600 \times 10^4$ t/km$^2$. For hydrocarbon expulsion intensity, the Wenchang 10 subsag also has the largest value of $1000 \times 10^4$ t/km$^2$. The expulsion intensity of the Wenchang 6 and 9 subsags is $400 \times 10^4$ t/km$^2$, with no significant difference. The ability of hydrocarbon generation and expulsion in the Wenchang 19 subsag is weak, and its corresponding values are $300 \times 10^4$ and $200 \times 10^4$ t/km$^2$, respectively. The hydrocarbon generation and expulsion centers of the E3e2 source rocks are mainly concentrated in the Wenchang 5, 9, 10, and 14 subsags in the Wenchang A Sag, and the Wenchang 19 subsag in the Wenchang B Sag. The hydrocarbon generation and expulsion intensity of the Wenchang 5 subsag are the greatest, $1800 \times 10^4$ and $1200 \times 10^4$ t/km$^2$, respectively, followed by Wenchang 9 subsag with values of $900 \times 10^4$ and $600 \times 10^4$ t/km$^2$, respectively. The Wenchang 14 and 19 subsags, the characteristics of
Figure 17. Recent hydrocarbon generation intensity of source rocks in the Wenchang Depression: (a) the $E_3e_1$ source rocks; (b) the $E_3e_2$ source rocks (contour values in $\times 10^4$ t/km$^2$).
Figure 18. Recent hydrocarbon expulsion intensity of source rocks in the Wenchang Depression: (a) the E3e1 source rocks; (b) the E3e2 source rocks (contour values in $10^4$ t/km$^2$).
which are similar, have the lowest values of $600 \times 10^4$ and $400 \times 10^4$ t/km$^2$, respectively. In summary, the relevant values are greater in E$_{3e2}$.

We used equations (8) and (9) to calculate the cumulative amounts of hydrocarbon generation and expulsion. The total amounts of generated and expelled hydrocarbon are $32.43 \times 10^8$ tons and $24.32 \times 10^8$ tons, respectively, for E$_{3e1}$; $44.24 \times 10^8$ tons and $33.18 \times 10^8$ tons, respectively, for E$_{3e2}$. The hydrocarbon expulsion and retention efficiencies are 75% and 25%, respectively. The oil and gas produced in E$_{3e1}$ is mainly from the Wenchang A sag, and those in E$_{3e2}$ are jointly contributed by the Wenchang A and B Sags, which indicates that there are abundant resources of the E$_{3e}$ source rocks in the Wenchang Depression.

**Conclusions**

1. The source rocks of E$_{3e}$ were deposited in the continental environment where terrestrial plants were the primary source of organic matter. The thickness of the E$_{3e1}$ source rocks is 50–500 m, slightly thinner than E$_{3e2}$, and both members are widely distributed in the Wenchang Depression. In contrast, the E$_{3e1}$ and Wenchang A Sag have greater organic matter abundance, but the entire depression is dominated by Type II and Type III kerogen. The E$_{3e}$ source rocks of the Wenchang A Sag are in the mature to over mature stages, while those of the Wenchang B Sag are in the low-mature stages.

2. Vertically, single wells of the same structural belts in the Wenchang A and B Sags, such as steep slope, have similar maximum of oil and gas generation rates. However, the former has a higher maturity, an earlier maturity time, and greater cumulative hydrocarbon generation rate. Additionally, the Ro value that entered the hydrocarbon expulsion threshold was 0.72%, and the corresponding value of hydrocarbon expulsion peak was 0.96%.

3. Horizontally, the hydrocarbon generation and expulsion amounts are $32.43 \times 10^8$ tons and $24.32 \times 10^8$ tons, respectively, for E$_{3e1}$, and those for E$_{3e2}$ are $44.24 \times 10^8$ tons and $33.18 \times 10^8$ tons, respectively, with the expulsion efficiency for both is 75%. Four hydrocarbon generation and expulsion centers existed in both members, which mainly focused on the Wenchang 9 and 10 subsags in the Wenchang A Sag and the Wenchang 19 subsag in the Wenchang B Sag. In addition, the Wenchang A Sag is still generating and expelling a large amount of oil and gas in the Wenchang 6 subsag of E$_{3e1}$ and Wenchang 5 and 14 subsags of E$_{3e2}$. The maximum values of the hydrocarbon generation and expulsion intensity are $1500 \times 10^4$ t/km$^2$ and $1000 \times 10^4$ t/km$^2$, respectively, for E$_{3e1}$, and those for E$_{3e2}$ are $1800 \times 10^4$ t/km$^2$ and $1200 \times 10^4$ t/km$^2$, respectively.

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