Simulation of Gas Generation from the Paleogene Enping Formation in the Baiyun Sag in the Deepwater Area of the Pearl River Mouth Basin, the South China Sea

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ABSTRACT: The deepwater area of the Baiyun Sag is the primary region of deepwater oil and gas exploration in China. Since the breakthrough made in natural gas exploration in the structure of the LW3-1 gas field, explorers have given significant attention to the conditions and process of gas generation and to the accumulation and preservation of natural gas. The Paleogene Enping Formation provides one of the two sets of major source rocks in the Baiyun Sag. We selected three samples of source rocks from the Enping Formation, performed a thermocompression simulation experiment, calculated the hydrocarbon generation kinetic parameters, and simulated single-well gas generation to explore the process of gas generation in the gas-generating center of the Enping Formation in the Baiyun Sag. The major conclusions included the following: (1) The lacustrine dark mudstone and the carbonaceous mudstone from the Enping Formation in well HZ08-1-1 have hydrocarbon yields of 383.7 versus 307.3 kg/t of total organic carbon (TOC) and gas yields of 370.1 versus 302.9 kg/t of TOC. (2) The thermal evolution of the Enping Formation in the Baiyun Sag can be divided into three evolutionary stages. (3) Finally, the source rocks of the Enping Formation have a gas generation peak from approximately 17.5 to 8 Ma.

1. INTRODUCTION

The Baiyun Sag lies in a deepwater area of the continental slope in the northern South China Sea. This sag is the largest secondary tectonic unit of the Zhu II Depression in the Pearl River Mouth Basin. The Baiyun Sag has significant changes in water depth, ranging from 200 to 2800 m, and covers an area of approximately 15 000 km²† (Figure 1). The maximum residual thickness of the Paleogene strata is approximately 8000 m.‡,§ The deepwater area of the Baiyun Sag has been explored for more than 20 years.† Successful drilling was achieved in the PY30-1 gas field in the north slope of the Baiyun Sag, in the LW3-1 gas field in the main sag, and in a series of subsequent gas exploration targets.‡ These achievements have confirmed that the Baiyun Sag has enormous hydrocarbon generation potential and broad prospects for oil and gas exploration. Currently, the geological reserves of oil and gas found in the oil and gas region of the Baiyun Sag are composed of significantly more natural gas reserves than oil reserves. The proven natural gas reserves are approximately 2000 × 10⁹ m³, whereas the proven oil reserves are approximately 3500 × 10⁹ m³. These data have indicated that the exploration of natural gas should be the focus in the Baiyun Sag.‡ Studies on the gas generation of the source rocks are of great importance and can lay the foundation for an in-depth analysis of the rules governing natural gas accumulation and preservation. In the present study, we focused on the simulation of gas generation in the source rocks of the Enping Formation. On the basis of a thermocompression simulation experiment, we established the kinetic equation of the gas generation and analyzed the relevant processes to provide a reference for the study of the natural gas accumulation in the reservoirs.

2. GEOLOGICAL SETTING

2.1. Strata. The strata of the Baiyun Sag are chronologically composed of the Earlier Paleogene Shenhu Formation, the Paleogene Wenchang, Enping, and Zhuhai Formations, the Neogene Zhujiang, Hanjing, Yuehai, and Wanshan Formations, and the Quaternary stratum (Figure 2). The Shenhu and Wenchang Formations represent the deposition of the rift stage; the Enping Formation represents the deposition of the rift-depression stage; the Zhuhai Formation represents the deposition of the transition stage; and the Zhujiang, Hanjing, Yuehai, and Wanshan Formations, along with the Quaternary stratum, represent the deposition of the depression stage. According to He et al., the Paleocene Shenhu Formation is composed of brown and gray massive sandstone and volcanic debris, the Eocene Wenchang Formation is composed of semi-deep lacustrine sand–mudstone, the Lower Oligocene Enping Formation is composed of fluvial–lacustrine coal-bearing series, the Upper Oligocene Zhuhai Formation is composed of littoral–neritic sand–mudstone, the Lower Miocene Zhujiang Formation is composed of shore-shallow lacustrine sand–mudstone, the Middle Miocene Hanjiang Formation is composed of neritic mudstone, the Upper Miocene Yuehai Formation is composed of marine mudstone, the Pliocene Wanshan Formation is composed of neritic sand–mudstone with poor lithologic characteristics, and the Quaternary stratum is composed of unconsolidated sand layers with clay.§

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2.2. Depositional Environment of the Enping Formation. During the deposition of the Enping Formation, low-lying areas were connected in the Baiyun Sag, forming the “Large Baiyun Lake”, with an expansion of the lake basin area. The primary provenance was in the northern part of the sag, and the delta system advanced toward the lake. The lowstand system tract of the Enping Formation was deposited in the initial rift—depression transformation stage. During this stage, the depression activity was not strong and the deposit thickness was not deep. The semi-deep lake covered a small area and was only developed at the basin center. The provenance primarily occurred from the northwest and the west, whereas small fan bodies were developed in the southern rift zone. During the deposition of the Enping lacustrine transgressive + highstand system tracts, the depression activity was strengthened and the lake basin area expanded to the rift zone surrounding the sag. The semi-deep lake was located in the central area of the basin, whereas the peripheral area was dominated by deltaic plain and primarily developed with the coal-measure source rocks; during this stage, the provenance was far away from the Baiyun Sag and sand bodies were only developed in the northwest of the Baiyun Sag. The source rocks of the Enping Formation of 200–1300 m thick were widely developed in most Baiyun Sag.

3. EXPERIMENTS AND METHODS

3.1. Thermocompression Simulation Experiment. The experimental apparatus primarily consisted of the following three parts: (1) The reaction kettle was a GCF-0.25L model manufactured by the Dalian Automatic Control Equipment Factory (Liaoning, China), with the design pressure of 19.6 MPa; (2) the temperature controller was a XMT-131 digital display regulator; and (3) the pyrolysis gas and gas condensate (also called light hydrocarbon) collection—separation system was composed of a liquid nitrogen-cooled liquid-receiving tube (to receive the gas condensate and water), an ice-cooled spiral condenser tube, and a graduated tube for the gas collection and measurement (Figure 3).

The simulation experiments were performed by individually heating the original samples at separate temperature levels. The original sample was used at each temperature level, and the simulation products were not separated from the reaction system, forming a closed system. The samples and deionized water were added to the reactor and then sealed.
To study the hydrocarbon generation of the lacustrine source rocks, rock samples from the Enping Formation were selected for the thermocompression simulation experiment. The simulated experimental conditions were set as follows: (1) simulation temperatures at 200, 250, 275, 300, 325, 350, 400, and 500 °C; because of the small sample size and high degree of thermal evolution (R0 value up to 1.0%) in well PY33-1-1, we only performed the simulation of these samples at six points for reference; (2) heating time of 24 h; (3) sample particle size of 5–10 mm, in favor of the organic maceral analysis and the reflectivity measurement of the whole rocks and the analysis of the hydrocarbon expulsion (80 g of samples for each temperature point); and (4) water addition at 10–20% of the sample weight.

### 3.2. Chemical Kinetic Equation Calibration Technology

To determine the chemical kinetic parameters for the oil- and gas-forming reactions of kerogen, we determined that the gas-forming process (KEG) was composed of a series of parallel first-order reactions. Each reaction has an activation energy $E_i$ and a frequency factor $A_i$, and an original gas generation potential of kerogen $X_{G0}$, where $i = 1, 2, \ldots, N$, as follows:

\[
\text{KEG}_i(X_{G0}) \rightarrow G_i(X)
\]

\[
\text{KEG}_j(X_{G0}) \rightarrow G_j(X)
\]

\[
\text{KEG}_k(X_{G0}) \rightarrow G_k(X)
\]

At time point $t$, the gas generation of the $i$th reaction is $X_i$ and is expressed according to the following equations:

\[
\frac{dX_i}{dt} = K_i(X_{io} - X_i)
\]

\[
K_i = A_i \exp\left(-\frac{E_i}{RT}\right)
\]

\[
i = 1, 2, 3, \ldots, N
\]

where $K_i$ is the $i$th gas-forming reaction rate constant of kerogen, $R$ is the gas constant ($1.987 \times 4.187 \text{ kJ mol}^{-1} \text{ K}^{-1}$), and $T$ is the absolute temperature (K).

When the experiment adopts a constant heating rate ($D$), then the following expression is applied:

\[
\frac{dT}{dt} = D, \quad \text{that is,} \quad \frac{dt}{D}
\]

From eqs 1–4, we can obtain the following expression:

\[
\frac{dX_i}{X_{G0} - X_i} = A_i \exp\left(-\frac{E_i}{RT}\right) dt
\]

\[
X_i = X_{G0} \left(1 - \exp\left(-\int_{T_0}^{T} \frac{A_i}{D} \exp\left(-\frac{E_i}{RT}\right) dT\right)\right)
\]

The total amount of gas generation of $N$ parallel reactions is expressed according to the following equation:

\[
X = \sum_{i=1}^{N} X_i = \sum_{i=1}^{N} \left(1 - \exp\left(-\int_{T_0}^{T} \frac{A_i}{D} \exp\left(-\frac{E_i}{RT}\right) dT\right)\right)
\]

The iterative method was used to determine the chemical kinetic parameters ($E_i$, $A_i$, and $X_{G0}$) for the $N$ parallel first-order reactions. This approach enables the best fitting of the theoretical gas yield of kerogen calculated using eq 7 and the simulated gas yield of kerogen at each temperature point. The calculation can be accomplished using two-dimensional basin modeling software. Figure 4 shows the hydrocarbon conversion rate (%) at the $A_i$ value of 6.02 × 10²/s according to different $E_i$ values (45–59, 61, 63, and 65 kcal/mol). In the fitting process, the parameters $E_i$, $A_i$, and $X_{G0}$ can be adjusted to achieve the best results.

### 3.3. Samples

Three samples were selected to represent the different types of source rocks from the Enping Formation (see Figure 1 for sampling locations).

The Enping Formation was drilled in the PY33-1-1 well (located in Figure 1) in the Baiyun Sag, revealing that shallow lacustrine and swamp source rocks are well-developed in this sag. The geochemical analysis showed that these source rocks feature substantially varying organic carbon content (1.12–56.18%), a high hydrocarbon generation potential (0.56–97.47 mg/g), a low hydrogen index value [50–300 mg/g of total organic carbon (TOC)], partial humic-type organic matter, with a Pr/Ph value of 1.6–5.9, and a substantially varied depositional environment. Today, the major source rocks of the Enping Formation are in a highly mature stage of thermal evolution. A dark mudstone sample from well PY33-1-1 (interval 4270–4460) represents debris, with a larger span of depth, types II and III kerogen, 1% TOC, and a R0 value of up to 1.0%. These rocks have undergone strong hydrocarbon generation, and their experimental simulation data are only used for reference.

The dark mudstone (interval 3367–3385 m) and the carbonaceous mudstone (interval 3352–3358 m) of the Enping Formation from well HZ08-1-1 (Zhu I Depression; see Figure 1 for sampling locations) contain types II and III kerogen, respectively. In terms of the depositional environment, the samples from well HZ08-1-1 represent shallow...
yield was 307.3 kg/t of TOC, and the highest gas yield was 302.9 kg/t of TOC. The $R_o$ value of the main gas generation phase ranged from 0.87 to 2.5%.

The coal-measure source rock from the Enping Formation in well PY33-1-1 (4270–4460 m, selected debris) contains 1% TOC. The simulation experimental data are given in Table 3. Because of the small sample size, the simulation experiment was conducted at only six temperature points ranging from 250 to 500 °C. The highest hydrocarbon yield was 167.25 kg/t of TOC, and the highest gas yield was 156.25 kg/t of TOC. The $R_o$ value of the main gas generation phase ranged from 1.0 to 2.0%. Because the original sample features the thermal evolution at a degree of approximately 1.0%, this type of source rock has hydrocarbon generation in a late stage.

5. DISCUSSION


Well PY35-2-1 (located in Figure 1) was taken as the simulation model, in which the Enping Formation is buried at moderate depths of 4976.54–6424.12 m (according to the interpretation of the drilling and seismic data). The hydrocarbon generation kinetic parameters of kerogen in the source rocks were adjusted using the Basin Mod 1D software and then used for the simulation of the hydrocarbon generation. The numerical simulation results were compared to the thermocompression simulation experimental data. After the best fit of the results was achieved, $E_r$, $A_r$, and $X_{IG}$ could be obtained for the source rocks of the Enping Formation.

5.1.1. Kinetic Parameters for the Hydrocarbon Generation of the Low-Maturity Dark Mudstone from Well HZ08-1-1.

Figure 5 compares the results of the numerical simulation of the gas generation and the data of the thermocompression simulation for the dark mudstone from well HZ08-1-1. At the temperature of 400 °C for the thermocompression simulation (equivalent to a $R_o$ value of 1.65%), the gas yield of the numerical simulation is slightly high, and at the temperature of 500 °C for the thermocompression simulation (equivalent to a $R_o$ value of 3.13%), the gas yield of the numerical simulation is slightly low. Overall, the results show a good fit. The obtained kinetic parameters for the hydrocarbon generation ($E_r$, $X_{IG}$, and the oil cracking parameters) are given in Table 4 and Figure 6. The $E_r$ values are distributed over the range of 49.5–64 kcal/mol. The $X_{IG}$ values generally exhibit a normal distribution, with the highest levels of 8–15% corresponding to the $E_r$ values of 52–59 kcal/mol.

5.1.2. Carbonaceous Shale Hydrocarbon Kinetic Parameters from the Low-Maturity Sample of Well HZ08-1-1.

Figure 7 compares the results of the numerical simulation of the gas

![Figure 4. Relationship between the hydrocarbon conversion rate and the thermal evolution with different activation energies.](image-url)
The overall fitting of the results is satisfactory, and the obtained kinetic parameters ($E_i$, $A_i$, and $X_{IG}$) are listed in Table 5 and Figure 8. The $E_i$ values are distributed over the range of 46–66 kcal/mol. The $X_{IG}$ values show a skewed distribution, with the highest levels of 8–12% corresponding to the $E_i$ values of 56–64 kcal/mol.

**Table 4. List of the Chemical Kinetic Parameters for the Dark Mudstone from Well HZ08-1-1**

<table>
<thead>
<tr>
<th>$X_{IG}$ (0–1)</th>
<th>$E_i$ (kcal/mol)</th>
<th>$A_i$ ($s^{-1}$)</th>
<th>$X_{IG}$ (0–1)</th>
<th>$E_i$ (kcal/mol)</th>
<th>$A_i$ ($s^{-1}$)</th>
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<td>0.005</td>
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<td>0.02</td>
<td>53</td>
<td>$1.91 \times 10^{15}$</td>
</tr>
<tr>
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<td>50</td>
<td>$1.91 \times 10^{15}$</td>
<td>0.15</td>
<td>54</td>
<td>$1.91 \times 10^{15}$</td>
</tr>
<tr>
<td>0.01</td>
<td>50.5</td>
<td>$1.91 \times 10^{15}$</td>
<td>0.3</td>
<td>55</td>
<td>$1.91 \times 10^{15}$</td>
</tr>
<tr>
<td>0.04</td>
<td>51</td>
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<td>0.32</td>
<td>56</td>
<td>$1.91 \times 10^{15}$</td>
</tr>
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<td>57</td>
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<tr>
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<td>53</td>
<td>$1.91 \times 10^{15}$</td>
<td>0.05</td>
<td>59</td>
<td>$1.91 \times 10^{15}$</td>
</tr>
<tr>
<td>0.15</td>
<td>54</td>
<td>$1.91 \times 10^{15}$</td>
<td>0.11</td>
<td>60</td>
<td>$1.91 \times 10^{15}$</td>
</tr>
<tr>
<td>0.15</td>
<td>55</td>
<td>$1.91 \times 10^{15}$</td>
<td>0.02</td>
<td>62</td>
<td>$1.91 \times 10^{15}$</td>
</tr>
<tr>
<td>0.115</td>
<td>56</td>
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<td>0.02</td>
<td>63</td>
<td>$1.91 \times 10^{15}$</td>
</tr>
<tr>
<td>0.1</td>
<td>58</td>
<td>$1.91 \times 10^{15}$</td>
<td>0.01</td>
<td>64</td>
<td>$1.91 \times 10^{15}$</td>
</tr>
</tbody>
</table>

*E_i* activation energy; $A_i$ frequency factor; $X_{IG}$ the original gas generation potential of kerogen, where $i = 1, 2, ..., N$. 

Generation and the data of the thermocompression simulation for the carbonaceous mudstone from well HZ08-1-1. The overall fitting of the results is satisfactory, and the obtained kinetic parameters ($E_i$, $A_i$, and the oil cracking parameters) are listed in Table 5 and Figure 8. The $E_i$ values are distributed over the range of 46–66 kcal/mol. The $X_{IG}$ values show a skewed distribution, with the highest levels of 8–12% corresponding to the $E_i$ values of 56–64 kcal/mol.
5.2. Gas Generation Analysis. Well PY35-2-1 in the central sag was used as an example to analyze the thermal evolution and the gas generation of the Enping Formation in the Baiyun Sag.  

5.2.1. Thermal History Analysis. Since the Eocene, the Baiyun Sag has undergone the following three evolutionary stages: the Paleocene to Early Oligocene rift stage (49−30 Ma), the Late Oligocene transition stage (30−23.8 Ma), and the Early Miocene to the present depression stage (23.8−present; Figure 2). The corresponding terrestrial heat flow evolved from a typical rift basin to a passive continental margin. The terrestrial heat flow value gradually increased from low to high levels, peaking during the most intense expansion of the passive continental margin (the depositional period of the Zhujiang Formation in the late Early Miocene), and then experienced thermal cooling (the present terrestrial heat flow in well PY35-2-1 up to 77 W/m²). According to this trend, the thermal history (Figure 10) can be simulated on the basis of the burial history and the measured $R_o$ values (the data are from the nearby exploratory well; Figure 9). 

Because of its significant thickness (approximately 1447.58 m), we simulated the thermal evolution and the hydrocarbon generation of the Enping Formation at three burial points (top, middle, and bottom). The burial depths at the top, middle, and bottom points are 4976.54, 5595.66, and 6424.12 m, respectively (Table 6). 

The mature stage of the Enping Formation varies at different depths (Table 6 and Figure 11). The bottom Enping Formation 

<table>
<thead>
<tr>
<th>Table 5. List of the Chemical Kinetic Parameters for the Carbonaceous Mudstone of the Enping Formation from Well HZ08-1-1$^a$</th>
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<tr>
<td>hydrocarbon generation of kerogen</td>
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<tr>
<td>$X_{gi}$ (0–1)</td>
</tr>
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<td>0.02</td>
</tr>
<tr>
<td>0.03</td>
</tr>
<tr>
<td>0.04</td>
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<td>0.05</td>
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<td>0.03</td>
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<td>0.04</td>
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<tr>
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<td>0.11</td>
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<tr>
<td>0.11</td>
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<tr>
<td>0.12</td>
</tr>
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</tr>
<tr>
<td>0.04</td>
</tr>
<tr>
<td>0.01</td>
</tr>
</tbody>
</table>

$^a$ $E_i$, activation energy; $A_i$, frequency factor; and $X_{gi}$, the original gas generation potential of kerogen, where $i = 1, 2, ..., N$. 

Figure 7. Comparison of the numerical simulation results of the gas generation and the thermocompression simulation data for the carbonaceous mudstone from well HZ08-1-1.

Figure 8. Distribution of the activation energy and the hydrocarbon generation potential for the carbonaceous mudstone of the Enping Formation in well HZ08-1-1.

Figure 9. Relationship between the $R_o$ value and the burial depth at the nearby well PY35-2-1 located in Figure 1.
began to mature ($R_o = 0.5\%$) in 29.5 Ma (the late depositional period of the Enping Formation; 30 Ma); it entered the mature stage ($R_o = 0.7\%$) in 23 Ma (the late depositional period of the Zhuhai Formation; 23.8 Ma), the highly mature stage ($R_o = 1.0\%$) in 16.8 Ma (the late depositional period of the Zhujiang Formation; 16.5 Ma), and the overmature stage ($R_o = 1.3\%$) in 15.29 Ma (the beginning of the depositional period of the Hanjiang Formation). The thermal evolution entered the dry gas stage ($R_o > 2.0\%$) in 12.2 Ma (the mid-late depositional period of the Hanjiang Formation; 12.5 Ma). The middle Enping Formation began to mature in 23.2 Ma (the mid-late depositional period of the Zhuhai Formation; 23.8 Ma), the highly mature stage ($R_o = 1.0\%$) in 16.8 Ma (the late depositional period of the Hanjiang Formation; 16.5 Ma), and the overmature stage ($R_o = 1.3\%$) in 15.29 Ma (the beginning of the depositional period of the Hanjiang Formation). The thermal evolution entered the dry gas stage ($R_o > 2.0\%$) in 12.2 Ma (the mid-late depositional period of the Hanjiang Formation). The middle Enping Formation began to mature in 23.2 Ma (the mid-late depositional period of the Zhuhai Formation; 23.8 Ma), the highly mature stage ($R_o = 1.0\%$) in 16.8 Ma (the late depositional period of the Hanjiang Formation; 16.5 Ma), and the overmature stage ($R_o = 1.3\%$) in 15.29 Ma (the beginning of the depositional period of the Hanjiang Formation). The thermal evolution entered the dry gas stage ($R_o > 2.0\%$) in 12.2 Ma (the mid-late depositional period of the Hanjiang Formation). The middle Enping Formation began to mature in 23.2 Ma (the mid-late depositional period of the Zhuhai Formation; 23.8 Ma), the highly mature stage ($R_o = 1.0\%$) in 16.8 Ma (the late depositional period of the Hanjiang Formation; 16.5 Ma), and the overmature stage ($R_o = 1.3\%$) in 15.29 Ma (the beginning of the depositional period of the Hanjiang Formation). The thermal evolution entered the dry gas stage ($R_o > 2.0\%$) in 12.2 Ma (the mid-late depositional period of the Hanjiang Formation).

When primarily considering the thermal evolution characteristics of the middle Enping Formation, the thermal history of the source rocks can be divided into the following three stages: the mature stage during the deposition of the Zhuhai Formation, the highly mature stage during the deposition of the Hanjiang Formation, and the overmature to dry gas stage during the deposition of the Yuehai–Wanshan Formation (Figure 11).

5.2.2. Gas Generation Analysis. The established hydrocarbon generation kinetic equations of the dark mudstone and the carbonaceous mudstone from the Enping Formation were used to simulate the gas generation based on the simulation results of the thermal evolution. The gas yield and the generation rate of the two types of source rocks were simulated for the bottom, middle, and top of the Enping Formation (Figure 12).

Figure 12a shows that the primary gas generation stage of the dark mudstone in the bottom Enping Formation is 26–14.5 Ma, with a gas generation peak in 16.0 Ma. Figure 12b shows that the primary gas generation stage of the carbonaceous mudstone in the bottom Enping Formation is 26–14.5 Ma, with a gas generation peak in 16.0 Ma. Figure 12c shows that the primary gas generation stage of the dark mudstone in the middle Enping Formation is 17–10 Ma, with a gas generation peak in 14.0 Ma. Figure 12d shows that the primary gas generation stage of the carbonaceous mudstone in the middle Enping Formation is 17–10 Ma, with a gas generation peak in 14.5 Ma. Figure 12e shows that the primary gas generation stage of the dark mudstone in the top Enping Formation is 15–8.5 Ma, with a gas generation peak in 13.0 Ma.
Figure 12f shows that the primary gas generation stage of the carbonaceous mudstone in the top Enping Formation is 14.5–0 Ma, with a gas generation peak at the present.

Figure 13 illustrates the changes in the gas generation rate of the dark mudstone and the carbonaceous mudstone at the three positions (bottom, middle, and top of the Enping Formation) over time. The cumulative data indicate that the dark mudstone has its gas generation peak in 17.5–10 Ma, whereas the carbonaceous mudstone has its peak in 17–8 Ma. The latter had a relatively strong gas generation after 5 Ma,
whereas the former had a weak gas generation during the same period.

6. CONCLUSION

In this study, we calculated gas generation kinetic parameters and simulated single-well gas generation based on a thermocompression simulation experiment for the Paleogene Enping Formation source rocks. The primary conclusions are as follows: (1) In the Enping Formation, the dark mudstone has an earlier hydrocarbon generation and a higher hydrocarbon yield than the carbonaceous mudstone by the thermocompression simulation. (2) The chemical kinetic equations for the source rocks of the Enping Formation were obtained and solved using the thermocompression simulation and the basin modeling techniques. The dark mudstone has an activation energy of 49.5–64 kcal/mol, exhibiting a normal distribution. The carbonaceous mudstone has an activation energy of 46–66 kcal/mol, showing a skewed distribution of the hydrocarbon generation potential. (3) In terms of the thermal evolution characteristics at the well point PY35-2-1, the Enping Formation in the Baiyun Sag can be divided into the following three evolutionary stages: the mature stage during the deposition of the Zhujiang Formation, the highly mature stage during the deposition of the Hanjiang Formation, and the overmature to dry gas stage during the deposition of the Yuehai–Wanshan Formation. (4) With regard to the hydrocarbon generation rate, the dark mudstone has a hydrocarbon generation peak from 17.5 to 10 Ma, whereas the carbonaceous mudstone has its peak from 17 to 8 Ma. The latter maintains strong hydrocarbon generation from 5 Ma to the present, but the former has weak hydrocarbon generation during the same period.

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Notes
The authors declare no competing financial interest.

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