INTRODUCTION

Oil shale is an unconventional oil resource with large reserves. Its organic matter called kerogen can be converted into hydrocarbons through various heating processes. Since new discoveries for conventional oil and gas reservoirs have been declining steadily over the past few decades, rising energy demand has imposed increasing efforts in exploiting oil shale without causing extra contamination regardless of ex situ retorting or in situ development methods. Microwave heating, an efficient and environmental-friendly method, shows great potential in developing heavy oil, oil shale and oil sands. The viscosity of heavy oil could be irreversibly reduced by microwave heating in the presence of carbon nanoparticles. Bera and Babadagli...
confirmed the positive effect of microwave heating on the viscosity reduction of heavy oil.\(^8\) According to the development of oil shale, Yang proposed a microwave heating method with hydraulic fracturing for the in situ exploitation of oil shale.\(^9\) Moreover, lab experiments proved that oil shale could be efficiently transform into shale oil with high production and high quality under microwave irradiation. It only took 3 minutes for oil shale to reach approximately 1000°C under microwave heating in the existence of microwave absorbent conducted by Hascakir, showing the great function of microwave.\(^10\) Thermal transformation of oil shale during heating involves complex physical and chemical reactions. In recent years, there are many achievements to compare the similarities and differences between microwave heating and conventional heating by analyzing different outcomes,\(^11\) including heating rate,\(^12\) shale oil production and quality,\(^13\) gas volume, and composition.\(^14\)

Apart from above investigations, it’s also vital to study comprehensively the pore structure of oil shale during heating process which is playing an important role in the heat transfer and mass transport of its transformation products, particularly for the flow behavior of produced oil and gas during in situ development process.\(^15,16\) Many previous studies have focused on the effects of heating conditions (reaction temperature, heating rate and residence time) on the pore structure of oil shale under conventional heating. Schrodt and Ocampo found that during air combustion, the surface area of oil shale endured a drastic loss, accompanying with the increase of mesopores volume.\(^17\) Han et al investigated the evolution mechanism of pore structure at different residence time in a muffle furnace. The increase of the pore volume and specific surface area in the main combustion stage was attributed by the pore dilation within sample particles and the fragmentation of samples.\(^18\) Simultaneously, Han et al\(^19\) also studied the influence of reaction temperature on the pore structure by conducting the SEM experiment and SEM pictures showed large pore volume and specific surface area of oil shale after heat treatment. Moreover, micro CT was also applied as an efficient approach to quantify the pore structure of oil shale under conventional heating.\(^20,21\) However, there are limited investigations about the pore structure of oil shale under microwave irradiation, let alone the effects of microwave heating parameters on the pore distribution. Wang et al\(^22\) calculated the specific surface area and pore volume of oil shale based on BET measurement and BJH method, but they only took microwave heating temperature into account. Since the heating mechanism of microwave heating is different from heat conduction and thermal convection, output power has great impact on the heating rate and thus determines the creation of pore space. Also, heating time should be considered.

Fractal analysis has been widely used in many natural and social science fields and provides a new method to investigate the pore structure of rocks based on different testing methods, including SEM,\(^23\) mercury intrusion porosimetry,\(^24\) nuclear magnetic resonance,\(^25,26\) and gas adsorption/desorption methods.\(^26\) Among these methods, gas adsorption/desorption experiment is a convenient and reliable way to analyze the pore structure of rocks. Bai et al\(^27\) concluded that slow heating rate benefited the development of pores based on the nitrogen adsorption/desorption experiment and fractal analysis. Liu et al\(^28\) used fractal dimension calculated by nitrogen adsorption isotherms to investigate the pore structure of coal under microwave heating. In addition, Yang et al\(^29\) found the correlations between organic carbon content, clay minerals, pore structure parameter, and fractal dimension obtained from nitrogen adsorption data.

In this study, the effects of heating time (5, 10, 20, 30 minutes), reaction temperature (350, 450, 550, 650, 750°C) and output power (600, 800, 1000, 1200 W) on the heating behavior and pore structure of oil shale were examined using microwave heating method. The fractal theory was applied to calculate the fractal dimension of oil shale based on fractal Frenkel-Halsey-Hill (FHH) method. Moreover, the SEM experiment was conducted to confirm the results. These analysis methods as a workflow could efficiently reveal the pore structure of oil shale under microwave irradiation and support the application of microwave heating method on the development of oil shale.

## 2 | MATERIALS AND METHODS

### 2.1 | Materials

In this research, the oil shale samples were taken from Maoming, Guangdong Province, China. The raw oil shale was crushed and sieved to the particle size range of 20-24 mesh with standard sieves for microwave heating experiments. The characteristics of oil shale sample are shown in Tables 1 and 2. Furthermore, the Fischer assay analysis was conducted under anoxic conditions.

### 2.2 | Microwave heating experiment

Since oil shale is poor at absorbing microwave, it’s important to enhance the heating efficiency of oil shale under microwave irradiation. This could be achieved by adding chemical materials with high dielectric constant, such as carbon and metal nanoparticles.\(^30\) In this study, 0.1 wt% iron oxide nanoparticles dispersion was mixed with 20 g of raw oil samples to enhance the microwave heating efficiency. Under non isothermal condition, samples were irradiated in a homemade microwave apparatus shown in Figure 1. This unique experimental setup can bear up to 1200°C with a maximum output power of 1600 W at a frequency of 2450 MHz. The effects of microwave heating time, reaction temperature, and output
power on the heating behavior and pore structure of oil shale samples were analyzed. An armored thermocouple is used to measure the temperature of oil shale, and once the temperature reaches the set point, it would remain unchanged and fulfilled by the controlling system in the apparatus. Each group of oil shale samples after microwave heating was named and more information would be found in Table 3.

### 2.3 Testing methods

The pore structure of oil shale after microwave heating with different heating parameters was investigated based on the nitrogen adsorption/desorption experiment (ASAP 2460, Micromeritics, Norcross, GA, USA). Nitrogen, compared with methane and carbon dioxide, is not only cheap, but also is easy to be controlled when the relative pressure reaches saturated pressure. Nitrogen adsorption at 77.8 K was measured at the relative pressure of 0.1-0.995. The samples were degassed at 100°C for 6 h prior to the nitrogen adsorption measurement. After degassing of the oil shale samples, the glass tube was placed in the instrument and the measurements were performed. The specific surface area of samples was determined by applying Brunauer-Emmett-Teller (BET) method. Barrett-Joyner-Halenda (BJH) method was used to calculated the pore size distribution of samples via the desorption branch of the isotherms.

The fractal theory, a systematic approach to determine the surface irregularities of a heterogeneous material, may describe the porous structure of oil shale samples. According to the fractal theory, fractal dimension (D) describes the roughness of the material. The fractal dimension values range from 2 to 3 and higher fractal dimensions usually indicate a more complicated pore structure. In this work, the fractal dimension of oil shale samples is calculated by fractal Frenkel-Halsey-Hill (FHH) method using nitrogen adsorption data. FHH method is relative simple and convenient, and it requires only adsorption isotherms. Apart from calculating fractal dimension of oil shale, FHH method has widely been applied in determining fractal dimension of coals\(^{31}\) and shale gas.\(^{32}\) The equation is as follows\(^{33}\):

\[
\ln \frac{V}{V_0} = C + (D-3) \ln \left[ \frac{P_0}{P} \right]
\]

where \(P_0\) and \(P\) are the saturation and equilibrium pressure respectively, MPa. D is the fractal dimension. C is a characteristic constant. \(V_0\) and \(V\) are the volume of adsorbed gas volume at the pressures \(P_0\) and \(P\), respectively, ml.

| Mineral analysis (wt%) | Ultimate analysis (wt%) |
|------------------------|-------------------------|
| Clay                   | Hydrogen 2.7            |
| Quartz                 | Oxygen 5.38             |
| Potash feldspar        | Nitrogen 0.44           |
| Plagioclase            | Sulfur 1.01             |
| Calcite                | Total carbon 15.96      |
| Pyrite                 | Organic carbon 14.8     |

| Clay mineral analysis (wt%) | Proximate analysis (wt%) |
|-----------------------------|--------------------------|
| Illite and smectite         | Moisture 0.64            |
| mixed layer                 |                          |
| Illite                      | Volatile matter 75.5     |
| Kaolinite                   | Ash 18.66                |
| Chlorite                    | Fixed carbon 5.2         |

**TABLE 1** The characteristics of Maoming oil shale sample

**TABLE 2** Fisher assay analysis of Maoming oil shale

**FIGURE 1** Schematic diagram of the homemade microwave apparatus: (1) wave generator, (2) sample holder made from quartz glass, (3) digital display board, (4) thermocouple, (5) pressure gauge, (6) liquid receptor, (7) condensation loop device, (8) gas flow meter, and (9) vacuum bag
According to the fractal FHH model on the plot, D—3 can be derived from plotting of gas adsorption isotherm data in terms of \( \ln(\frac{V}{V_0}) \) versus \( \ln(\ln(\frac{P}{P_0})) \). The slope of the straight line should be equal to D—3.

Moreover, in order to further investigate the pore structure of oil shale and validate the analysis results, SEM experiment was conducted to observe oil shale samples before and after microwave heating. Firstly, particle samples were prepared to be conductive by surface treatment. After being sputter-coated with gold, the samples were placed in the vacuum chamber of scanning electron microscope (Quanta 450, FEI Company, Fremont, CA, USA) with maximum magnification lenses of 100 000×. Specifically, the observation was based on two directions of pictures. One direction obtained by taking the pictures perpendicular to the bedding plane is used to investigate the surface morphology of the samples and another direction acquired by taking the pictures parallel to the bedding plane makes it possible to study the internal pore structure of the samples.

3 | RESULTS AND DISCUSSION

3.1 | Heating behavior under microwave treatment

Microwave heating is different from other conventional heating methods that we are familiar with. The temperature distributions for each sample with different heating parameters are shown in Figures 2 and 3. For different heating time, fast heating rate was achieved by microwave heating at an output power of 800 W and it took approximately 10 minutes for oil shale to reach 550°C at which oil shale could completely transformed into oil and gas.\(^{34}\) As a result, M1 and M2 sample could be successfully under thermal decomposition. Within 10 minutes, M3 sample could arrive at more than 500°C, but M4 sample did not reached 250°C within 5 minutes and only liquid water turned into steam shown in Figure 2B. In Figure 3A, curves show similar trend due to the same output power level and 20 minutes were sufficient for all oil shale samples to reach the required temperature. However, for M7 and M8 sample, oil shale could not completely transform into oil and gas due to the low set temperature. When it comes to different output power, Figure 3B shows the great difference in heating rate under microwave heating. Higher output power leaded to faster heating rate, because output power determined the movements of molecules which was consistent with the investigation by Hong et al.\(^{35}\) For M11 sample, it only took 5 minutes to reach 550°C, showing the great ability of microwave in reducing energy usage. For convention heating, it usually takes 60 minutes to reach 550°C, accompanying with high energy consumption.\(^{36}\) Since the heating behavior of oil shale plays a vital role in influencing transformation process, it’s essential to figure out the temperature difference.

| Oil shale number | Output power, W | Heating time, min | Reaction temperature, °C |
|------------------|-----------------|-------------------|-------------------------|
| M1               | 800             | 30                | 750                     |
| M2               | 800             | 20                | 750                     |
| M3               | 800             | 10                | 750                     |
| M4               | 800             | 5                 | 750                     |
| M5               | 800             | 20                | 650                     |
| M6               | 800             | 20                | 550                     |
| M7               | 800             | 20                | 450                     |
| M8               | 800             | 20                | 350                     |
| M9               | 600             | 20                | 750                     |
| M10              | 1000            | 20                | 750                     |
| M11              | 1200            | 20                | 750                     |

\(\text{TABLE 3} \) Microwave heating information based on different heating parameters

[FIGURE 2] Temperature distribution of oil shale samples under microwave heating: A, oil shale samples under different heating time and B, temperature distribution of oil shale sample M4
FIGURE 3 Temperature distribution of oil shale samples under microwave heating: A, under different reaction temperature and B, under different output power

FIGURE 4 Adsorption/desorption isotherms of raw oil shale and samples with different heating parameters: A, under different heating time, B, under different reaction temperature and C, under different output power
of each sample by applying different heating parameters and thus further analyze the pore structure.

### 3.2 Analysis of nitrogen adsorption/desorption experiment

The nitrogen adsorption/desorption isotherms of raw oil shale and samples after microwave heating with different heating parameters were analyzed and shown in Figure 4. The isotherms were similar and exhibited a reverse S shape. Based on the classification method proposed by the IUPAC, these isotherms shown in Figure 4 belong to type II isotherm. Generally, the shape of isotherms varies with the relative pressure 0-0.5 and 0.5-1. At the relative pressure below 0.5, the adsorption isotherm was essentially coincident with the desorption isotherm, indicating that the nitrogen gas molecule first adsorbed on the surface of micro pores whose pore size was slightly larger than that of gas molecule. As the relative pressure increased, the isotherms quickly increased and the hysteresis loop occurred, demonstrating that the monolayer adsorption evolved into multilayer adsorption and the nitrogen gas molecule showed capillary condensation. When the isotherms were at extremely high relative pressure ($P/P_0 > 0.8$), the adsorption branches ascended sharply. This result indicated that there were certain amount of mesopores and macropores in the oil shale samples.

Although all the hysteresis loops of the oil shale samples are similar, there are also distinctions. For example, in Figure 4B, as the reaction temperature increases, the hysteresis loop increases initially and then decreases again. This phenomenon could be explained by the evolution of pore structure during microwave irradiation. Specifically, the effect of pore shadowing (small pores blocking the pathway of large pores to the vapor phase) corresponding to the hysteresis loop is strengthened initially and then weakened with increasing reaction temperature. Since the heating mechanism of microwave heating is different from heat convection and heat conduction, more analysis would be done in the following investigations.

### 3.3 Change of pore structure during microwave irradiation

The evolution of pore structure of oil shale during microwave irradiation could provide useful seepage channels for the produced oil and gas transportation. This would significantly benefit the production of the reaction zone for the in situ exploitation of oil shale under microwave heating. Figure 5

![Graphs](image)

**FIGURE 5** The variations in specific surface area, cumulative pore volume and average pore diameter: A, D, under different heating time, B, E, under different reaction temperature, C, F, under different output power
describes the influence of heating time on the specific surface area and cumulative pore volume of samples. Under extremely short heating time (5 minutes), oil shale only reached approximately 250°C which was below the transformation temperature of oil shale. Water played an important role in affecting the pore structure, forming the jet flow pressure on the pores due to the evaporation of the water. This effect of jet flow caused by microwave heating was more significant than that leaded by conventional heating, because water with high dielectric constant resulting in high absorption of microwave energy could be quickly vaporized. Therefore, three kinds of data (specific surface area, cumulative pore volume, and average pore diameter) shown in Figure 5 were all increased at first especially for the average pore diameter. For 10 minutes, pore volume and average pore diameter underwent a sharp reduction. Oil products could not be discharged completely out of the heating system within 10 minutes and thus blocked the pores through condensation when the temperature was cooled down. As the heating time reached 30 minutes, specific surface area, cumulative pore volume, and average pore diameter rapidly dramatically increased to 24.625 m²/g, 0.105 mL/g, and 18.61 nm, respectively. This result was consistent with the results by Bai et al. Many investigations studied the influence of reaction temperature on the pore structure of oil shale under conventional heating. Although under 750°C the specific surface area and average pore diameter decrease shown in Figure 5B and E high reaction temperature is also responsible for the development of pores. This outcome may be due to the complex chemical and physical reactions under extreme high temperature. Figure 5C and F demonstrate that it’s difficult to find the linear relationship between the analysis data and output power. With output power ranging from 600 to 1200 W, all oil shale samples successfully transformed into shale oil and gas. On the one hand, relative low heating rate benefited the discharge of volatiles from the internal structure, because the tendency of secondary reactions was subject to the temperature of oil shale particles contacting the volatiles. On the other hand, the jet flow pressure induced by the intense steam and volatiles was more significant with faster heating rate, which was accomplished by using higher output power. Moreover, microwave has the ability to generate thermal stress in the rocks. Specifically, there was huge difference between the raw oil shale and irradiated samples in terms of specific surface area and pore
distribution. The evolution mechanism of pore structure during microwave heating resulted from the comprehensive factors. Firstly, with increasing temperature and heating time, the decomposition of kerogen is significantly responsible for the formation of pore structure. Then, the jet flow pressure of the steam and volatiles also benefits the increase of pore volume, but this effect is severe at relative low temperature. Furthermore, thermal stress caused by the selective heating of microwave would induce micro fractures. High output power can enhance this effect but also would promote secondary reactions, resulting in the blockage of pores. At last, complicated physical and chemical reactions under microwave irradiation especially at high reaction temperature are also a factor.

The structure model of rock pores defines the micropore (<2 nm), mesopore (2-50 nm), and macropore (>50 nm). Figure 6 shows significant peaks at 4 nm and relative small peak around 20-50 nm for the samples after microwave heating, demonstrating the most of the pore volume corresponds to mesopores. For raw oil shale, the peak around 6-20 nm is also evident as shown in Figure 6A. As with the microwave heating process was underway, micropores formed at first. Then a large amount of mesopores at 4 nm were induced, and the mesopores also changed to macropores. For Figure 6B, reaction temperature also influences the pore distribution. At 350°C, only a small part of oil shale started to decompose. The removal of the water in the blind and closed pores is dominantly responsible for the increase of the pore size. For M8 sample, the number of mesopores with an average pore diameter ranging from 5 to 20 nm is the largest in the Figure 6B. Between 350 and 550°C, oil shale was under transformation. As the temperature increased, both of the specific surface area and cumulative pore volume increased thanks to the decomposition of the kerogen. At 450°C, although the number of the mesopores reduced to some extent, the number of macropores contributed to the average pore diameter increasing from 19.61 nm to 24.45 nm. Above 550°C, the peak value at 4 nm increased remarkably corresponding to the reduction of the average pore diameter. This result was consistent with the research done by Wang et al.22 Figure 6C shows that with increasing microwave power level, the shape of curves
is very similar. It can be seen that the higher output power level is, the higher peak at will be 4 nm. For microwave heating, oil shale samples would not be heated from exterior to interior but be irradiated volumetrically. When volatiles were quickly released from oil shale internal structure, it was easy to build up a high internal pressure within sample particles. This would open and link the adjacent pores, leading to large pore volume. Furthermore, output power determines the intensity of molecular motion and thus controls the heating rate of targeted material. Fast heating rate accelerates the transformation of oil shale but also induces the secondary reactions between the volatiles and hot solid shale. Liquid products would be trapped by the solid shale, resulting in the blockage of large pores. Consequently, the largest cumulative pore volume and average pore diameter were obtained by the output power of 600 W.

The above analysis indicated that evolution mechanism of pore structure of oil shale under microwave heating should be a comprehensive result from the factors including the transformation of kerogen, the jet flow pressure of the steam and volatiles, the thermal stress induced by microwave, complex reactions as well as different heating parameters.

3.4 Fractal dimension of pore structure

The FHH plots of oil shale samples are shown in Figure 7. There are two distinct linear segments at the $P/P_0$ intervals of 0-0.5 (region one) and 0.5-1 (region two). In region one, the solid-gas interactions were mainly controlled by van der Waals forces. In region two, the liquid-gas surface tension was dominant. As a result, the fractal dimension of oil shale samples should be calculated by two regions and defined as $D_1$ and $D_2$, respectively. $D_1$ may represent the surface roughness and surface morphology while $D_2$ may reflect the space roughness and pore structure of the oil shale samples. In Figure 7, the data in two regions shows good fits and related coefficients are higher than 0.9. The FHH plots of other samples were similar and more details could be found in the Supporting Information.

The relationship between fractal dimension and heating time is pictured in Figure 8A. There is no significant correlation between $D_1$ and $D_2$, suggesting that they represent two different fractal dimensions of samples. During microwave heating, the formation of volatiles leaded to pore volume increment. However, if the volatiles could not be discharged efficiently, some pores would be jammed due to the condensation
Simultaneously, surface became smoother resulting in the decrease of $D_1$ value within 10 minutes. As the transformation of kerogen and the discharge of volatiles were completed, both $D_1$ and $D_2$ values were enhanced, though longer residence time slightly increased the fractal dimension. A good correlation between fractal dimension and reaction temperature is shown in Figure 8B. Except for raw oil shale, samples after microwave heating under higher reaction temperature always yield greater $D_1$ and $D_2$ values. With the transformation of oil shale, more pore volume in terms of mesopores and macropores were created and micro fractures were also induced by microwave irradiation. Oil shale containing a larger number of multiple pores definitely had greater $D_1$ and $D_2$. However, fast heating rate acquired by microwave heating promoted the secondary reactions between volatiles and solid shale with increasing reaction temperature, leading to more blocked pores with smaller average pore diameter. As a result, the creation of more mesopores with small pore diameter proved by Figure 6B signifies a more complicated pore structure.\textsuperscript{41} When it comes to the effect of output power, there are two main aspects. The first is that higher power level leads to faster heating rate, creating more pore volume due to the sharp increase of internal pressure. Moreover, selective heating characteristic of microwave heating makes it possible to induce micro fractures because of the thermal stress within the matrix. This aspect is responsible for the increase of $D_1$ and $D_2$ values shown in Figure 8C. On the contrary, high temperature was detrimental to the discharge of the products. The accumulation of the volatile matter in the pores smoothed the surface and decreased $D_1$ value. However, the impact of the first aspect outweighed the second aspect, and therefore the values of $D_1$ and $D_2$ continue to rise until output power reaches 1000 W shown in Figure 8C.

Because $D_1$ and $D_2$ may reflect pore surface fractal dimension and represent pore structure fractal dimension, respectively, efforts were taken to verify if there were correlation between specific surface area and $D_1$, the relationship between cumulative pore volume and $D_2$, and the regularity between average pore diameter and $D_2$. A good linear relationship between the specific surface area and $D_1$ is clearly observed in Figure 9A. Oil shale samples with higher

![Figure 9](image-url)
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specific surface area resulted in higher $D_1$ value and rougher surface. In Figure 9B and C there is no obvious relationship between cumulative pore volume and $D_2$ while a linear trend can be observed between the average pore diameter and $D_2$, which may be caused by the unique heating mechanism of microwave. Take an example of the effect of output power. It took 8 and 10 minutes to reach 750°C for 1000 and 1200 W respectively. The two samples were under fast heating rare and thus endured the blockage of pores, leading to the reduction of average pore diameter and the increase of $D_2$ value. However, microwave heating is capable of inducing more pores and micro fractures. This phenomenon would be more significant with higher output power level. As a result, the cumulative pore volume obtained by 1200 W was more than that acquired by 1000 W. So in Figure 6C, the phenomenon that the peak value at 4 nm is the highest for 1200 W is the result of jammed mesopores as well as the induced mesopores. From the analysis above, it is proved that the application of fractal dimension on the pore structure of oil shale under microwave heating is reliable.

3.5 | SEM analysis

Since the surface morphology and pore structure of oil shale samples characterized by fractal dimension were both evolved and developed during microwave heating, the SEM images of oil shale samples were also investigated. In order to better distinguish the characteristic of $D_1$ and $D_2$, images obtained by taking pictures parallel and perpendicular to the bedding plane are both shown in Figure 10. Specifically, it is more appropriate to examine the surface roughness based on taking the pictures perpendicular to the bedding plane. Moreover, pictures taken parallel to the bedding plane may reliably reflect the internal structure.

In Figure 10A and B raw oil shale and M8 sample both have very smooth surface as shown by a relative low fractal dimension $D_1$. At the reaction temperature of 350°C, there are evident large pores with multiple diameters from Figure 10B on the right. When it comes to the Figure 10C and D both samples’ surfaces are rough and complex according to the great fractal dimension $D_1$. In addition, high temperature complicated the pore structure and high output power accelerated the formation of jammed pores. Accordingly, M11 sample had relative higher fractal dimension $D_1 = 2.624$, $D_2 = 2.517$ but contained a large number of pores with small diameter.

4 | CONCLUSIONS

This paper presented the effects of microwave heating parameters on the heating behavior, surface morphology and
pore structure of oil shale. Eleven oil shale samples were irradiated at 2.45 GHz with different heating time, reaction temperature and output power. Nitrogen adsorption/desorption experiment was conducted to determine the specific surface area, cumulative pore volume and average pore diameter of particle samples. Fractal dimension D1 and D2 calculated based on the Frenkel-Halsey-Hill model were used to investigate the pore structure of oil shale, and SEM analysis was applied to verify the conclusions.

Heating distribution results showed that high output power greatly enhanced the heating rate which was a key factor influencing the pore structure. The shape of pores changed into mesopores with small diameter with increasing output power and reaction temperature because of the internal pressure caused by the steam and volatiles and thermal stress within matrix induced by microwave. Moreover, microwave heating time was responsible for the transformation of kerogen and thus affected the pore structure. Correspondingly, the fractal dimension D1 and D2 reflecting the surface roughness and pore space roughness of oil shale, respectively, also varied with different heating parameters. However, a positive correlation between specific surface area and D1, and a negative correlation between average pore volume and D2 were observed, verifying the fractal theory on the pore structure of oil shale under microwave heating. Microwave has the ability to induce micro pores and fractures, resulting in the no connection between fractal dimension and cumulative pore volume. Moreover, the SEM images obtained by taking the pictures parallel and perpendicular to the bedding plane were consistent with the above results.

Above analysis will significantly benefit the application of microwave on the development of oil shale no matter for the ex situ or in situ exploitation methods. More investigations on the flow behavior of oil shale and the effect of external pressure should be considered to promote the knowledge of transformation and evolution mechanisms.

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AUTHOR CONTRIBUTIONS

Jingyi Zhu and Zhaozhong Yang conceived and designed the study. Jingyi Zhu and Nailu Wang performed the experiments. Jingyi Zhu and Min Jia analyzed the data. Jingyi Zhu wrote the paper. Jingyi Zhu, Zhaozhong Yang and Xiaogang Li reviewed and edited the manuscript. All authors read and approve the manuscript.

COMPETING INTEREST

The authors declare no competing financial interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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