Research Article

Characteristics of Organic Macerals and Their Influence on Hydrocarbon Generation and Storage: A Case Study of Continental Shale of the Yanchang Formation from the Ordos Basin, China

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Organic macerals are the basic components of organic matter and play an important role in determining the hydrocarbon generation capacity of source rock. In this paper, organic geochemical analysis of shale in the Chang 7 member of the Yanchang Formation was carried out to evaluate the availability of source rock. The different organic macerals were effectively identified, and the differences in hydrocarbon generation and pore-forming capacities were discussed from two perspectives: microscopic pore development and macroscopic hydrocarbon generation through field emission scanning electron microscopy (FE-SEM) and energy-dispersive spectrum (EDS) analyses, methane isotherm adsorption, and on-site analysis of gas-bearing properties. The results show that the source rock of the Chang 7 member has a high abundance of organic matter and moderate thermal evolution and that the organic matter type is mainly type I. Based on the morphology of the organic matter and the element and pore development, four types of hydrogen-rich macerals, including sapropelite and exinite, and hydrogen-poor macerals, including vitrinite and inertinite, as well as the submacerals, algae, mineral asphalt matrix, sporophyte, resin, semifusinite, inertodetrinite, provitrinite, euvitrinite, and vitrodetrinite, can be identified through FE-SEM and EDS. A large number of honeycomb-shaped pores develop in sapropelite, and round-elliptical stomata develop in exinite, while vitrinite and inertinite do not develop organic matter pores. The hydrogen-rich maceral is the main component of organic macerals in the Chang 7 member of the Yanchang Formation. The weight percentage of carbon is low, so it has good hydrocarbon generation capacity, and the organic matter pores are developed and contribute 97% of the organic matter porosity, which is conducive to hydrocarbon generation and storage. The amount of hydrogen-poor maceral is low, and the weight percentage of carbon is low, and the organic matter pores are not developed, which is not conducive to hydrocarbon generation and storage.

1. Introduction

Organic maceral is a component of organic matter and has an important effect on hydrocarbon generation capacity [1, 2]. The method for identifying macerals in shale is derived from coal petrology, which involves complex sample preparation and uses transmitted light fluorescence to identify different macerals [3–5]. FE-SEM is an effective method to describe and analyze shale pore types and pore structure with simple sample preparation methods and high resolution.

Maceral is clearly visible under FE-SEM. Previous research used FE-SEM to effectively identify the organic maceral of the Shahezi Formation in the Songliao Basin, China, but did not detect the sapropelite and exinite, and the identification methods were not systematic [6]. The amount of research on continental shale is relatively low, and there is less research on the organic maceral of the Ordos Basin. Previous studies have shown that there is heterogeneity in the development of organic matter pores, but they have not studied its correlation with organic maceral [7, 8]. At present,

sapropelite and exinite are generally classified as hydrogen-rich macerals, which is an important support for organic matter in the generation of oil. The higher the content of hydrogen-rich macerals, the higher the hydrocarbon generation capacity will be, while vitrinite and inertinite are classified as hydrogen-poor macerals with low hydrocarbon generation capacity [9]. There is a lack of in-depth research on the difference in hydrocarbon generation and pore-forming capacities of different macerals.

The Ordos Basin is the second largest sedimentary basin in China, and the continental shale of the Chang 7 member of the Yanchang Formation is an important source rock in the region. In this paper, the research focused on Chang 7 shale samples, and FE-SEM combined with EDS methods was used to identify each organic maceral. The contribution of each maceral to the pore-forming capacity of organic matter and the relationship between macerals and hydrocarbon generation potential and gas content were studied. The relationship between organic maceral and hydrocarbon storage capacity was examined from both the microscopic and macroscopic perspectives. This research provides theoretical support for the in-depth understanding of the hydrocarbon generation capacity of organic matter and has a positive effect on the exploration and development of continental shale gas.

2. Regional Geological Characteristics

The Ordos Basin is located in the central part of mainland China, in the western part of the North China Platform, spanning three provinces and two regions (Shanxi, Gansu, Ningxia, and Inner Mongolia). It is bounded by the Yellow River fault to the north, the Weihe River north margin fault to the south, Liupan Mountain and Yinchuan Basin to the west, and the Lishi fault zone with the Lvliang uplift to the east. The basin has experienced a series of complex tectonic movements such as Lvliang, Caledonian, Indosinian, and Yanshan, forming the geological features of the wide and gentle east and narrow west, the well-developed peripheral faults, and the simple structure in the basin [10, 11]. Based on the current structural morphology and basin evolution history, the basin can be divided into six tectonic units: the Yimeng uplift in the north, the Weibei uplift in the south, the western edge thrust belt in the west, the Jinxi folding belt in the east, and the Tianhuan depression and Yishan slope in the central region (Figure 1(a)) [12, 13]. The Triassic Yanchang Formation is one of the important oil-generating reservoirs in the basin. During the sedimentary period, the basin experienced a process of rapid development and then extinction, with the characteristics of the sedimentary evolution cycle. The continental sedimentary system of the river-lake-delta is widely developed. The Yanchang Formation can be divided into ten members from top to bottom. The upper part is composed of shale and thin siltstone, and the lower part is mainly composed of sand-shale interbeds (Figure 1(b)) [14]. In the Chang 7 member, the basin developed to its peak. The sedimentary facies were mainly deep lakes and semideep lakes, with developed organic-rich black shale and a small amount of siltstone and siltstone [15, 16].

3. Samples and Methodology

In this paper, a total of 410 shale samples from the Yanchang Formation were collected from shale gas wells of the Ordos Basin, China. Total organic content (TOC) analysis and rock pyrolysis were conducted on the 410 samples. TOC analysis was performed with a Leco CS230 carbon-sulfur analyzer. One gram of the sample was added to a crucible, and then the inorganic carbon was removed with dilute hydrochloric acid, and the sample was then rinsed with distilled water; the sample was then dried in an oven at 100°C for 12 h to perform TOC measurement. Rock-Eval analysis was carried out using an OGE-II rock pyrolyzer (RIPED, Beijing, China) under programmed heating processes. Then, the Tmax (the temperature at which the maximum number of hydrocarbons is generated) and other thermal parameters were obtained [17]. Vitrinite reflectance (Ro, %) values were identified using an MPM-80-type microspectrophotometer at a temperature of 25°C and a relative humidity of 65%. A total of 79 Ro data points were obtained. A total of 78 samples were used to quantify the organic maceral. Samples were crushed and sieved to a range size of 60~80 mesh, cemented with epoxy resin, and prepared into a 3 cm × 3 cm particle light sheet. According to the characteristics and the color, shape, and intensity of fluorescence under the Leica DM4500P polarizing microscope, the organic macerals were identified and the contents were analyzed by statistical methods.

A Zeiss Merlin field emission scanning electron microscope was used to examine samples at a temperature of 24°C and a relative humidity of 35%. Shale sections of 1 cm × 1 cm were Ar ion-milled to create an ultrasurface and then coated with carbon. The working voltage was set to 2 kV, and the working distance was 3~4 mm. The elemental composition of the mineral was determined using the EDAX ternary integrated system. Methane isotherm adsorption was measured using the FY-KT 1000 isotherm adsorption instrument at a temperature of 40°C and humidity of 2.12%. Samples were prepared by crushing and sieving to a size of 80 mesh and weighing, and 100 g portions were weighed out for moisture equilibrium treatment. The moisture equilibrium was processed for at least four days for each sample. After these pretreatments, samples were put into the apparatus for the isotherm adsorption test [18]. Eight pressure points were measured, and the time for each pressure point to reach equilibrium was not less than 12 hours. Then, the ideal gas equation of state was used to calculate the adsorption capacity of each point, and finally, the isotherm adsorption curve was obtained through regression. The total gas content was measured by on-site analysis using the gas-bearing experiment and the KD-III shale gas field analyzer developed by China University of Petroleum, Beijing.

4. Results

4.1. Organic Geochemistry

4.1.1. Om Richness. The abundance of organic matter is an important parameter for evaluating the quality of source

FIGURE 1: (a) The structural zones of the Ordos Basin. (b) The stratigraphic column of the Yanchang Formation in the Ordos Basin.

rocks, usually using TOC, chloroform pitch “A,” and hydrocarbon generation potential ($S_1 + S_2$). A total of 410 samples of the Chang 7 member in the Yanchang Formation were examined by TOC analysis and pyrolysis analysis. Statistics indicated that the TOC of the Chang 7 member shale was 0.2%~13%, with an average of 4.6% (Figure 2(a)); the content

of chloroform pitch “A” was 0.73%~1.75%, with an average of 1.26%; the amount of hydrocarbon generation potential was 0.6~30 mg/g, with an average of 12.9 mg/g, which had a good positive correlation with TOC, indicating that the shale of the Chang 7 member has good hydrocarbon generation potential (Figure 2(b)).

FIGURE 2: (a) The TOC frequency distribution. (b) The relationship between TOC and $S_1 + S_2$.

FIGURE 3: (a) Tmax-D crossplot. (b) Tmax-HI crossplot.

4.1.2. Om Type. The ability of source rock to generate hydrocarbon is not only related to the abundance of organic matter but also determined by the type of organic matter. Rock pyrolysis parameters can effectively classify the organic matter types mainly based on the crossplot of the pyrolysis parameters: maximum pyrolysis peak temperature (Tmax) and hydrogen index (HI) or degradation rate (D). Among the samples analyzed in this pyrolysis, D was 8%~43%, with an average of 24%. According to the Tmax- D crossplot (Figure 3(a)), the organic matter of Chang 7 shale was mainly type I with a small amount of type II₁; HI was 16~597 mg/g, with an average of 103 mg/g. According to the Tmax-HI crossplot (Figure 3(b)), the organic matter type was mainly type II. Most of the samples generate hydrocarbon that

migrates out of source rock, which leads to low HI, mostly less than 300 mg/g, and further affects the identification of organic matter types using the Tmax-HI crossplot. In summary, the organic matter type of the Chang 7 member in the Yanchang Formation is mainly type I, with a small amount of type II₁.

4.1.3. Thermal Maturity. The abundance and type of organic matter are the necessary basis components for source rock hydrocarbon generation, but maturity is the necessary condition for determining whether a large amount of hydrocarbon can be generated. Only when the oil generation window or the gas generation window is reached can a large amount of hydrocarbon be generated under the action of heat. At

FIGURE 4: (a) The Ro frequency distribution. (b) The Tmax frequency distribution of source rocks in the Chang 7 member.

FIGURE 5: The kerogen maceral triangulation in source rocks of the Chang 7 member in the Ordos Basin.

FIGURE 6: Characteristics of vitrinite under FE-SEM. (a) YY33, 1607.30 m, provitrinite. (b) YY33, 1622.80 m, euvitrinite. (c) YY34, 1396.37 m, vitrodetrinite. The EDS of the corresponding points are shown on the right.

present, the commonly used identification indexes are vitrinite reflectance (R_o) and maximum pyrolysis peak temperature (T_{max}). The analysis showed that the R_o was 0.82%~1.09%, with an average of 0.92% (Figure 4(a)); T_{max} was 349°C~462°C, with an average of 448°C (Figure 4(b)).

The Chang 7 shale is in the mature stage and mainly generates oil by kerogen pyrolysis.

4.2. Organic Macerals. The kerogen organic macerals play an important role in classifying organic matter types and

FIGURE 7: Characteristics of inertinite under FE-SEM. (a) YY33, 1622.8 m, semifusinite. (b) YY33, 1622.8 m, semifusinite. (c) YY33, 1622.8 m, inertodetrinite and microfracture. The EDS of the corresponding points are shown on the right.

revealing the hydrocarbon generation potential of source rock. There are various names and classification methods for organic maceral [19, 20]. This article refers to the Chinese standard SY/T 6414 to classify maceral. Through identification and quantitative analysis of macerals of 78 shale samples from the Chang 7 member, it was found that the organic

matter was composed of sapropelite, exinite, vitrinite, and inertinite. The relative percentage content of sapropelite was 16.2%~98.6%, with an average of 77.9%, indicating that it mainly accepted the input of organic matter such as planktonic algae and lower microorganisms; the relative percentage content of exinite was 1.2%~16%, with an average of

FIGURE 8: Characteristics of exinite under FE-SEM. (a) YY33, 1622.8 m, sporophyte. (b) YY33, 1622.8 m, sporophyte. (c) YY33, 1622.8 m, resin. The EDS of the corresponding points are shown on the right.

7.2%; the relative percentage of vitrinite was 0.2%~81.1%, with an average of 13.8%; the relative percentage of inertinite was 0.4%~8.9%, with an average of 1.0%. The kerogen maceral triangulation showed that sapropelite is the main component of the Chang 7 shale kerogen, and the organic matter was mainly type I (Figure 5).

4.2.1. Vitrinite. Vitrinite is the product of humification and gelation of the wood fiber tissue of higher plants [21]. Vitrinite has a darker color, smooth surface, and uniform texture, is enriched in bands or clumps, and generally does not develop pores under FE-SEM. Due to the difference in the degree of gelation, the cell structure of the original plant is

FIGURE 9: Characteristics of sapropelite under FE-SEM. (a) YY33, 1622.8 m, algae. (b) YY33, 1622.8 m, algae. (c) YY7, 1153.35 m, amorphous organic matter. The EDS of the corresponding points are shown on the right.

preserved differently. Based on this, vitrinite can be subdivided into provitrinite, euvitrinite, and vitrodetrinite. Provitrinite can be clearly observed under the electron microscope in the cell wall and cell cavity structure of the original plant. The cell wall often deforms and bends under compaction, and the cell cavity becomes different in shape

due to pressure, which is oval or arc-shaped. The interior is often filled with inorganic minerals (Figure 6(a)). The cell structure of the primitive plants of euvitrinite is not visible under strong gelation. The results showed that the euvitrinite of the Chang 7 member is mainly matrix vitrinites, which have smooth surfaces, dense texture, rich shapes, and bands

TABLE 1: Main identification features of organic macerals under FE-SEM for Chang 7 shale in the Ordos Basin.

Maceral	Submaceral	Characteristics under FE-SEM	EDS
Vitrinite	Provitrinite	Visible cell structure, distorted cell wall, cell cavity filled with inorganic minerals, undeveloped pore	C: 80%~90%
	Euovitrinite	Invisible cell structure, banded and cloddy, undeveloped pore	O: <10%
	Vitrodetrinite	Obvious protrusions, fragmentary with sharp edges, undeveloped pore	
Inertinite	Semifusinite	Swelling cell wall, combined with the surrounding matrix tightly, cell cavity filled with minerals, ribbon-shaped, underdeveloped pore	C: 80%~90%
	Inertodetrinite	Invisible cell structure, fragmentary with angular, arc-shaped, or other morphologies, transverse microcracks developed	O: >10%
Exinite	Sporophyte	Ellipsoidal, worm-like, and irregular shapes, cluster distribution round-elliptical large pores developed	C: 60%~70%
	Resin	Elliptical or irregular without cell structure, flat surface, circular-elliptical large pores developed	O: >10%
Sapropelite	Algae	Various shapes, cluster distribution, uneven surface, jagged edges, honeycomb-shaped pores developed	C: 40%~60%
	Mineral asphalt matrix	No fixed shape, unclear outline, mixed with inorganic minerals, large honeycomb pores developed	O: >10%

and clumps (Figure 6(b)). Vitrodetrinite is the detrital particles of vitrinite, mainly derived from peat-decomposed plants. The cell structure of the plant is not visible under FE-SEM, but the protrusions are obvious, often in the shape of bones and sharp edges (Figure 6(c)). EDS showed that the weight percentage of carbon in vitrinite was generally 80~90%, and the weight percentage of oxygen was generally less than 10%. Vitrinite is formed in a reducing environment and therefore has a low oxygen weight percentage [22].

4.2.2. Inertinite. Inertinite is formed by the carbonization of higher plants [23]. It is gray-black under FE-SEM, usually grid-like, ribbon-like, clump-like, and angular. The submacerals observed in samples are mainly semifusinite and inertodetrinite. Semifusinite is a component between fusinite and provitrinite. The cell wall swells strongly, and it is combined tightly with the surrounding matrix. The cell cavity is compressed and becomes smaller, filled with minerals. Semifusinite is ribbon-shaped, with underdeveloped pores (Figures 7(a) and 7(b)). Inertodetrinite is the fragments of fusinite, semifusinite, and sclerotinite. The cell structure of plants is not visible. It is gray-black, with angular, arc-shaped, and other morphologies, and it can develop transverse microcracks (Figure 7(c)). It is difficult to distinguish between vitrinite and inertinite under FE-SEM.

Inertinite and vitrinite have similar shapes and structures, which are not easy to distinguish under FE-SEM, but the two can be effectively identified with the help of EDS. EDS showed that the weight percentage of carbon in inertinite was generally 80%~90%, which was similar to vitrinite, but the weight percentage of oxygen was generally greater than 10%, which was significantly higher than vitrinite. This was mainly because the inertinite was formed in an oxidation environment, and the vitrinite was formed in a reducing environment, so the weight percentage of oxygen in inertinite was higher than that in vitrinite [22]. In addition, the inertinite had a higher protrusion, which is also an effective way to distinguish it from vitrinite.

4.2.3. Exinite. Exinite is derived from stable organs or metabolites in higher plants, such as resin and essential oil. It has good chemical stability and is not damaged by biochemical processes, so it is a good hydrocarbon generation material [21]. It had a high brightness under FE-SEM. Two submacerals, sporophyte and resin, were mainly observed in samples. Sporophyte is derived from the reproductive organs of plants and can be divided into macrospores (>0.1 mm) and microspores (<0.1 mm) according to their morphological size. Most of the microspores observed under FE-SEM have ellipsoidal, worm-like, and irregular shapes, with low-medium protrusions, often distributed in groups, with round-elliptical large pores (Figures 8(a) and 8(b)). The resin is mainly formed by plant waxes, resins, and lipids and is generally regarded as a good hydrocarbon generation material. The surface was flat, the inside is uniform, and the shape was elliptical or irregular without cell structure, and there were circular-elliptical large pores (Figure 8(c)).

Previous studies have shown that the combination of organic matter and inorganic minerals is more likely to lead to the formation of organic matter pores [24]. Compared with other inorganic minerals, clay minerals are more likely to catalyze the formation of gaseous hydrocarbons [25]. In the process of hydrocarbon expulsion and pore generation, affected by the catalysis of clay minerals, the EDS of the organic matter showed inorganic mineral elements such as Al, K, Mg, and Si. The weight percentage of carbon was found to be generally 60 to 70%, and the weight percentage of oxygen generally exceeded 10%. The influencing factors that control the development of organic matter pores are complicated. The hydrocarbon generated and organic acids may also be involved. This area requires needs further study to elucidate the mechanism.

4.2.4. Sapropelite. Sapropelite is the product of saprofication of lower aquatic organisms, such as algae [21]. Similar to exinite, it is a hydrogen-rich and oxygen-poor maceral in the source rock, which tends to generate oil. It is an excellent

FIGURE 10: Schematic diagram of the Phi of each maceral extracted using the IPP software.

hydrocarbon generation material and the main component of the Chang 7 kerogen organic maceral. The color was lighter under FE-SEM. Two submacerals, algae and amorphous organic matter, were mainly observed in samples. Algae are the remains of single-celled or multicelled lower aquatic organisms and an important part of the hydrocarbon generation maceral. The algae had various shapes, with the characteristics of cluster distribution, uneven surface, and honeycomb-shaped pores, and the edges were often jagged under FE-SEM (Figures 9(a) and 9(b)).

Amorphous sapropelite mainly appears in the form of a mineral asphalt matrix, which is a composite of organic matter and inorganic minerals. The results showed that the mineral asphalt matrix of the Chang 7 member accounted for the absolute proportion of organic matter, with an average of more than 50%, and plays an important role in hydrocarbon generation and the evaluation of source rock. The mineral asphalt matrix had no fixed shape, an unclear outline, was

TABLE 2: The contribution of each maceral to the organic matter pores of the Chang 7 member.

Organic maceral	Weight percentage (%)	Average Phi (%)	Contribution	Percentage contribution (%)
Sapropelite	77.94	25.8	0.20109	94.96
Exinite	7.23	6.2	0.00448	2.12
Vitrinite	13.77	4.4	0.00606	2.86
Inertinite	1.06	1.1	0.00012	0.06

mixed with inorganic minerals, and developed a large number of honeycomb pores (Figure 9(c)). The sapropelite was affected by the catalysis of clay minerals during the hydrocarbon generation process. The EDS showed inorganic mineral elements such as K, Na, Mg, Al, and Si, and the weight percentage of carbon was low, generally 40~60%, and the weight

FIGURE 11: Relationships between macerals and TOC and $S_1 + S_2$.

percentage of oxygen generally exceeded 10%. The higher the weight percentage of carbon, the worse the hydrocarbon generation potential. Sapropelite had the best hydrocarbon generation potential, followed by exinite, vitrinite had a poor hydrocarbon generation potential, and inertinite had the worst generation potential.

4.2.5. Synthetic Discrimination of Organic Macerals. Based on FE-SEM and EDS, the organic macerals can effectively be identified by their morphology and elemental composition. Sapropelite and exinite had higher brightnesses, and the organic matter pores were developed. Sapropelite developed honeycomb-shaped pores, and exinite developed round-elliptical large pores. EDS showed that the oxygen of the two is greater than 10%. The carbon of sapropelite was 40%~60%, while that of exinite was 60%~70%. Vitrinite and inertinite were dark with undeveloped organic matter pores under FE-SEM. EDS showed that the carbon of the above was 80%~90%. The oxygen of vitrinite was less than 10%, while that of inertinite was greater than 10%. The higher protrusion of inertinite was also an effective auxiliary method to distinguish it from vitrinite. The identification method of each submaceral is shown in Table 1.

5. Discussion

5.1. Control of Organic Matter Porosity by Macerals. It is assumed that the organic matter pores in the shale are evenly

distributed, and the plane porosity of the entire space (Φ) on any organic matter section is equal. Therefore, the sample can be used to deduce the organic matter porosity through several scanning electron microscope pictures. The pore parameters were extracted using the Image-Pro Plus (IPP) software. First, the target area was selected; then, an appropriate gray value was set to divide the pore and matrix; and finally, the required parameters were selected. This study used Φ as the analysis parameter. Prior studies have done a lot of research on the methods to calculate organic matter porosity [26, 27]; the calculation formula is as follows:

$$\varphi_{\text{org}} = \varphi_s \times \frac{\omega_{\text{TOC}}}{100} \times \frac{\rho_s}{\rho_{\text{org}}} \times 100\%, \quad (1)$$

where φ_{org} , φ_s , and ω_{TOC} are the organic matter porosity, plane porosity of the entire space, and the weight percentage of organic matter, respectively; ρ_s represents the shale density, which is 2.6 g/cm³; and ρ_{org} represents the density of organic matter, which is 1.2 g/cm³.

Using the shale sample of 1622.8 m of YY33 as an example, the results of extracting the Φ of each maceral under FE-SEM through the IPP software are shown in Figure 10. The Φ of sapropelite was 20%~40%; the Φ of exinite was 5%~10%; the Φ of vitrinite was 2%~5%; the Φ of inertinite was <2%. According to the formula, the organic porosity of the sample was 0.97%.

FIGURE 12: Continued.

FIGURE 12: EDS of different macerals. (a) YY34, 1388.97 m, sapropelite. (b) YY8, 1451.04 m, exinite. (c) YY12, 1624.29 m, vitrinite. (d) YY13, 1206.44 m, inertinite. The EDS of the corresponding points are shown on the right.

The organic matter porosity of the Chang 7 shale samples was calculated to be between 0.44% and 1.06%, and the contribution to the total porosity was about 11% to 47%, accounting for an average of 26%. Limited by the accuracy of the software, pores smaller than 5 nm were not included, so the actual organic matter porosity should be greater. As mentioned above, observations under FE-SEM found that there were great differences in the degree of organic matter pore development of different macerals. The hydrogen-rich macerals sapropelite and exinite developed large organic matter pores, while the organic matter pores of hydrogen-poor macerals vitrinite and inertinite were relatively under-developed, and the content of each maceral was different, which contributed to the different degrees of organic matter porosity. Therefore, in order to quantitatively evaluate the contribution of each maceral to the organic matter porosity, the contribution of each maceral was calculated by using the mass percentage and the average Phi (a certain maceral contribution = mass percentage $\times$ average Phi). It can be seen from Table 2 that the sapropelite provided the most organic matter pores, with a contribution percentage of 94.96%, while the inertinite provided almost no organic matter pores, with the lowest contribution of 0.06%.

5.2. Relationship between Macerals and Potential Hydrocarbon Generation. Different macerals have different capacities of hydrocarbon generation. Generally speaking, the higher the content of hydrogen-rich sapropelite and exinite, the better the capacity of hydrocarbon generation. The relative content of hydrogen-rich macerals was positively correlated with TOC and $S_1 + S_2$ (Figures 11(a) and 11(b)), which indicated that the hydrogen-rich macerals are the favorable hydrocarbon-generating macerals of Chang 7 shale. There was no obvious correlation between hydrogen-poor macerals and TOC and $S_1 + S_2$ (Figures 11(c) and 11(d)), indicating that the capacity for hydrocarbon generation is weak and that inertinite is the maceral with the lowest capacity for hydrocarbon generation. The relative content of hydrogen-poor macerals in the Chang 7 shale was relatively

low and had little influence on the capacity for hydrocarbon generation of the shale.

The carbon and hydrogen contents of organic matter are usually used to judge the hydrocarbon generation potential. The higher the weight percentage of carbon and the lower the weight percentage of hydrogen, the lower the hydrocarbon generation potential. As the EDS can only measure the weight percentage of carbon, the measured carbon level was used to judge the difference in hydrocarbon generation potential of each maceral. Using the EDS of each maceral of some samples as examples, the weight percentage of carbon in the sapropelite was 40%~60% (Figure 12(a)); the weight percentage of carbon in the exinite was 60%~70% (Figure 12(b)); the weight percentage of carbon measured in the vitrinite was 80%~90% (Figure 12(c)); the weight percentages of carbon in inertinite and vitrinite were similar, ranging from 85% to 90% (Figure 12(d)). It can be seen from sapropelite, exinite, vitrinite, and inertinite that the weight percentage of carbon increases successively, indicating that the hydrocarbon generation potential is successively worsened. This is consistent with the previous research results [6, 28].

5.3. Control of Gas Content by Macerals. Macerals are an important factor affecting the capacity of hydrocarbon generation of organic matter, and they also control the gas content of shale reservoirs. At present, there are few studies on the effect of maceral content on shale adsorption capacity. The adsorption gas content measured by the methane isotherm adsorption experiment was a comprehensive reflection of gas adsorption on the surface of organic matter and inorganic minerals. In order to accurately analyze the adsorption volume of organic matter, assuming that methane molecules are uniformly adsorbed on the surface of organic and inorganic matter pores, the adsorption volume of organic matter was calculated according to the proportion of organic matter pores out of the total pores.

According to the statistical analysis of the relationship between the macerals of Chang 7 shale in the Yanchang

FIGURE 13: Relationships between macerals and adsorbed gas.

FIGURE 14: Relationships between macerals and total gas content.

Formation and the adsorption amount of organic matter, there was no significant correlation between the hydrogen-poor macerals and the adsorption amount of organic matter (Figure 13(a)). There was also a positive correlation between the hydrogen-rich macerals and the adsorption amount of organic matter (Figure 13(b)). A large number of organic matter pores are developed in hydrogen-rich macerals, which provide more surface area and more adsorption sites for gas, so the adsorption capacity is increased. However, the organic matter pores of hydrogen-poor macerals are not developed, so they are not conducive to gas adsorption.

Shale gas is the product of kerogen evolution and mainly exists in shale pores in free and adsorbed states. According to the statistical analysis of the relationship between macerals and total gas content in Chang 7 shale of the Yanchang Formation, there was no obvious correlation between hydrogen-poor macerals and total gas content (Figure 14(a)). The hydrogen-rich macerals were positively correlated with the total gas content (Figure 14(b)). Hydrogen-rich macerals have a good capacity for hydrocarbon generation, which can generate a lot of shale gas and develop more organic matter pores, providing space for the occurrence of shale gas. However, the hydrogen-poor macerals have a worse capacity for hydrocarbon generation, the organic matter pores are not developed, and the content of hydrogen-poor macerals in

Chang 7 shale was low, so it had no obvious contribution to the total gas content.

6. Conclusion

Based on our studies, the following conclusions can be drawn:

- (1) FE-SEM and EDS can effectively identify the various macerals. Based on the morphology and elements of the organic matter of the Chang 7 member, the synthetic discrimination method of organic macerals was established. Sapropelite was mainly composed of the mineral asphalt matrix, followed by algae; exinite was composed of sporophyte and resin; vitrinite had a small amount of provitrinite, euvitrinite, and vitrodetrinite; inertinite was composed of semifusinite and inertodetrinite.
- (2) The sapropelite developed a large number of honeycomb pores, and the exinite developed round-elliptical stomata; a small amount of organic matter pores and microfractures were seen in vitrinite and inertinite. Further calculations showed that the sapropelite provides the most organic matter pores,

with a contribution percentage of 94.96%, and the inertinite provides almost no organic matter pores, with a contribution percentage of 0.06%

- (3) The EDS showed that the weight percentage of carbon increases successively in the order of sapropelite, exinite, vitrinite, and inertinite, which indicates that the hydrogen-rich macerals have a better hydrocarbon generation capacity, and the hydrogen-poor macerals have a lower hydrocarbon generation capacity. The hydrogen-rich macerals have a positive correlation with the organic matter adsorption gas volume and total gas content, while the hydrogen-poor macerals have no obvious correlation. Sapropelite and exinite are conducive to the generation of shale gas and develop rich organic matter pores. They can provide space for shale gas reservoirs. Vitrinite and inertinite do not develop organic matter pores and are not conducive to the generation and storage of hydrocarbons

Data Availability

The data used to support the study is available within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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