Pore characterization of marine-continental transitional shale in Permian Shanxi Formation of The Southern North China Basin

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Abstract
Organic-rich marine-continental transitional shale is widely developed in the Permian Shanxi Formation in the Southern North China Basin. In this study, shale samples from the southern and northern wells of the basin were characterized by X-ray diffraction, high-pressure mercury intrusion porosimetry, low-pressure gas adsorption (N₂ and CO₂) and argon ion polishing-field emissions scanning electron microscopy. The pore types and structures of shale micropores, mesopores and macropores are qualitatively described; their pore size distribution and volume are quantitatively characterized; and the influencing factors of the pore volume are analyzed. The results show that the marine-continental transitional shale pores exhibit an unbalanced multi-modal distribution with four peaks at 0.4–0.8 nm, 2–4 nm, 10–50 nm, and >10 μm. The mesopore volume is dominant, accounting for 40–70% of pores. The mesopores of the samples are slit-shaped pores and ink bottle-shaped pores. Since there is a desorption hysteresis loop on the N₂ adsorption-desorption curve, most of them belong to the H₄ type, and ye23-8 belongs to the mixed H₂ and H₄ type according to the IUPAC classification scheme. The slit-shaped pores are mainly interlayer pores and interparticle pores in clays, and the ink bottle-shaped pores are tiny dissolved pores and organic matter pores. Ro has negative correlation with the volumes of the mesopores and macropores, but it does not affect the volume of micropores. TOC has a positive correlation with the macropore and micropore volumes, and it has a negative correlation with mesopore volume. The relative contents of kaolinite and I/S have a positive correlation with the mesopore and macropore volumes. The relative content of illite has a negative correlation with...
the mesopore and macropore volumes. The relative content of chlorite has a negative correlation with the mesopore volume.

**Keywords**
Marine-continental transitional shale, pore characterization, gas adsorption, North China

**Introduction**

The exploration and development of shale gas in China have reached breakthroughs in recent years, and the marine shale gas in southern China has gained industrial production capacity (Jiang et al., 2016a; Zhang et al., 2004; Zou et al., 2010). Marine shales in southern China have favorable conditions such as high TOC, high Ro and overpressure. In addition to marine shale gas, marine-continental transitional shale gas also has certain exploration potential. In particular, the gas generation ability of marine-continental transitional coal measure strata has been widely recognized (Gong et al., 2018; Wang et al., 2019; Zhang et al., 2019; Zhao et al., 2018). Marine-continental transitional shale has the advantage of producing shale gas due to its high brittleness, its thin layers arranged into thick cumulative layers and its potential for microcrack development (Ren et al., 2007; Zhao et al., 2005). However, the reservoir characteristics and influencing factors of marine-continental transitional shale differ from those of marine shale and continental shale (Guo and Wang, 2019; Ma and Guo, 2019). Tang et al. (2016) added TOC to the lithofacies classification of shale, which helps to design optimization and increase production strategies. In the pore evolution of the marine-continental transitional shale, the contribution of pores formed by clay mineral transformation may be higher than that of organic matter (Chen et al., 2016). In addition, the highly mature type III organic matter in marine-continental transitional shale has fewer organic pores than marine shale (Liang et al., 2018). Therefore, the associated reservoir characteristics and development of marine-continental transitional shale need to be studied further.

High-pressure mercury intrusion porosimetry (MIP) is a classic method for measuring rock pore structures and pore volumes (Li, 2010; Shao et al., 2017). However, MIP can only describe the macropores (>50 nm) in shale. To describe the micropores (<2 nm) and mesopores (2–50 nm) in shale, scholars often use low-pressure gas adsorption. The most common method is N₂ adsorption, which can characterize pores with a pore size of 2–200 nm. Micropores can be calculated using CO₂ adsorption-desorption experiments because CO₂ can enter micropores with a minimum pore size of 0.35 nm (Sun et al., 2015; Yang et al., 2013). In this paper, the whole-aperture distribution of marine-continental transitional shale of the Permian Shanxi Formation in the Southern North China Basin is characterized by MIP and N₂/CO₂ adsorption. The pore type and pore structure of marine-continental transitional shale are analyzed by AIP-FESEM. Factors affecting the pore characteristics at various scales were studied from the perspectives of Ro, TOC and relative content of clays, which provide the foundation for understanding the characteristics of China’s marine-continental transitional shale reservoirs.
**Geological setting and samples**

**Geological setting**

The Southern North China Basin is located in the Henan Province and Anhui Province of China, adjacent to the Tanlu Fault Zone in the east, the Qinling-Dabie Orogenic Belt in the south and the West-Hebei Uplifting Area in the west. It is a Mesozoic and Cenozoic superimposed basin that developed on the base of the North China Platform (Ju et al., 2015; Yu et al., 2005). The tectonic evolution of the basin is influenced by the Qinling-Dabie Orogenic Belt and the Tanlu Fault Zone. The basin direction is NWW, and the total area is approximately $1.5 \times 10^5 \text{km}^2$ (Figure 1).

The Southern North China Basin was part of the North China Craton Basin in the Late Paleozoic. Affected by the global sea level rise of the Late Carboniferous, the study area experienced the deposition of epicontinental sea sediments. Affected by the uplift of the Yinshan ancient land in the early Permian, the sea surface of the epicontinental sea retreated from the northwest to the southeast, and the study area began to evolve from the epicontinental sea basin to the continental basin (Ju et al., 2014; Li et al., 2017). In the Southern North China Basin, a set of sedimentary formations, dominated by marine-continental transitional facies, developed in the Permian Shanxi Formation (Peng, 1990; Tan et al., 2009). In the early stage, the tidal flats and peat swamps originated from the gradual withdrawal of seawater from the surface of the sea. The delta facies, which are dominated by rivers, were deposited in the late stage. In the early stage, the tidal flats and peat swamps originated from the gradual withdrawal of the sea surface from the epicontinental sea.

![Figure 1. Location and stratigraphy of the Southern North China Basin.](image)

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Experimental samples

The samples are from two exploration wells for shale gas in the Southern North China Basin (Figure 1). The ye23 well is located in the southeastern part of the basin, where the depth of the Shanxi Formation is 1405–1480 m. The ye31 well is located in the northern part of the basin, where the depth of the Shanxi Formation is 2670–2740 m. Both the wells formed the sedimentary deltas by marine regression in the Shanxi Formation (Yu et al., 2018). The kinds of sedimentary microfacies observed include desalinated lagoons, interdistributary bays, and marshes, which are dominated by the organic-rich shale with coal seams and sandstone.

The parameters related to the samples are shown in Table 1. The lithology of all samples is shale, and the kerogen is type III. The TOC test analysis is based on the national standard GB/T 19145–2003 of China, and the test instrument is a Leco carbon and sulfur analyzer. The Ro test is based on SY/T 5124–1995 “Measurement method for vitrinite reflectance in sedimentary rocks.” The microphotometer (MPV-SP) is used at an ambient temperature of 22°C and a relative humidity of 30%–32%. The microscope magnification is 125 times, the reflectance range is 0.1 to 10%, and the resolution is determined under the conditions of 0.01%. Due to the differences in sedimentary microfacies, the TOC differs such that the TOC of ye23-2 and ye31-1 is approximately 0.2%, the TOC of ye23-8 and ye31-2 is approximately 2.5% and the TOC of ye23-5 is approximately 4.7%. Due to the differences in burial depth, the Ro of the ye23 well samples is low, 0.94–1.14%, and the Ro of the ye31 well samples is higher, 3.2%.

Experimental methods

X-ray diffraction analysis

XRD can calculate the relative content of minerals (Chalmers and Bustin, 2008; Chalmers et al., 2012; Chen and Xiao, 2014; Wei et al., 2018). The samples were ground to powders and subjected to X-ray diffraction experiments using a D8 DISCOVER X-ray diffractometer at 24°C and 35% humidity (Clarkson et al., 2013). The relative content of minerals was estimated semiquantitatively using the main peak area corresponding to each mineral and corrected using the Lorentz polarization (Mastalerz et al., 2013).

High-pressure mercury intrusion porosimetry

MIP is a common method for testing the pore size distribution of rock. We used the Autopore IV9500 automatic mercury injection meter. The sample was ground into a
cylinder with a height of 10 mm and a diameter of 2–10 mm and placed in an oven. It was left at 110°C for 24 h to remove the water. The experimental principle is that the interfacial tension between different phases needs to be overcome when mercury is injected into the shale. Therefore, external pressure is required to force mercury into the shale, and the applied pressure depends on the capillary resistance of different pore sizes (Ross and Bustin, 2009). MIP can characterize macroporous (>50 nm) shale and has unique advantages in characterizing macroporous structures and connectivity (Chalmers et al., 2012; Cui et al., 2012; Sun and Guo, 2017). According to the Young-Dupre equation and the Washburn equation (Drummond and Israelachvili, 2002; Washburn, 1921), the relationship between the interfacial tension and the surface area can be obtained, and then the distribution of the surface area and pore volume of different pore sizes can be calculated.

**N₂ adsorption**

Since MIP cannot accurately characterize the mesopores, N₂ adsorption was used to characterize the structure and distribution of mesopores (2–50 nm) in shale (Ji et al., 2016). The Quadrasorb SI analyzer is used in the N₂ adsorption experiments. First, we grind the small samples into 20–50 mesh sizes. We purge the sample with pure N₂ and heat it until the mass remains the same. Experiments were performed using N₂ as the adsorbent at a temperature of 77.35 K. The principle of nitrogen adsorption is that when the temperature and pressure are constant, the gas molecules will reach the adsorption equilibrium on the surface of the shale. For this study, the adsorption amount is a function of the relative pressure (P/P₀). The surface area of the shale pores is analyzed based on the BET theory. The pore volume is calculated based on the input amount of liquid nitrogen under different relative pressures (P/P₀) and then calculated by the BJH model (Barrett et al., 1951).

**CO₂ adsorption**

MIP and N₂ adsorption can characterize mesopores and macropores in the shale (Kuila and Prasad, 2013). However, the characterization of micropores is nonexistent. We use CO₂ adsorption to describe micropores (<2 nm) (Jarvie et al., 2007; Ross and Bustin, 2008; Wang and Guo, 2019b). The NOVA4200e analyzer is used in this study. First, we grind small samples to 60–80 mesh size. We use pure CO₂ to purge the sample and heat it until the quality does not change. Experiments were performed using N₂ as the adsorbent at a temperature of 273.15 K. The principle of CO₂ adsorption is similar to that of N₂ adsorption, but the CO₂ molecules are smaller and can enter smaller pores.

**Results**

The mineral and clay contents of the samples are analyzed by XRD. The shale samples are characterized by XRD, MIP, N₂/CO₂ adsorption and AIP-FESEM. Macropores (>50 nm) of samples are characterized by MIP. Mesopores (2–50 nm) of samples are characterized by N₂ adsorption. Micropores (<2 nm) of samples are characterized by CO₂ adsorption. Pore types are identified and classified by AIP-FESEM.

The clay and mineral contents of each sample are shown in Table 2. The ye23 well sample has a high clay content of 52–81%. The ye31 well sample has a clay content of 44%–47%. The ye23-2 sample has the highest relative clay content of 81%. From the composition of clays, the most important components are the kaolinite, illite and illite-smectite mixed...
The ye23-2 and ye23-5 are mainly composed of kaolinite, whose relative content is close to 60%, followed by I/S, which accounts for 25%–32%. The ye23-8, ye31-1 and ye31-2 samples are mainly kaolinite and illite, with a relative content of kaolinite less than 40%, but the content of illite is high at 38–50%. The relative content of kaolinite is lower in samples with high thermal evolution, while the relative content of illite and chlorite is higher (Figure 2); this is because kaolinite is converted to illite in environments rich in K$^+$ with high thermal evolution and converted to chlorite in environments rich in Fe$^{2+}$ and Mg$^{2+}$ (Wang and Guo, 2019a).

Table 2. Relative content of clays and minerals of samples.

| Samples  | K  | C  | I  | S  | I/S | S%  |
|----------|----|----|----|----|-----|-----|
| ye23-2   | 57 | 6  | 5  | 0  | 32  | 25  |
| ye23-5   | 58 | 11 | 6  | 0  | 25  | 20  |
| ye23-8   | 34 | 12 | 38 | 0  | 16  | 10  |
| ye31-1   | 30 | 23 | 41 | 0  | 18  | 10  |
| ye31-2   | 25 | 17 | 50 | 0  | 8   | 10  |

Figure 3 shows the variation of the mercury intrusion-extrusion volume with the pressure of the samples, and the curves can be divided into two categories. One category corresponds to the ye23-2, ye23-5, ye31-1 and ye31-2 samples, which have two inflection points and a wide hysteresis loop. When the pressure is less than 0.1 MPa, the volume of mercury intrusions rapidly increases. This stage mainly corresponds to macropores with a diameter larger than 10 μm, which proves that the macropore volume in this range is relatively high. When the pressure is between 0.1 and 60 MPa, the curve becomes gentle, and the mercury intrusion volume is small, which proves that the pore volume corresponding to the pressure range

Figure 2. Relative contents of minerals and the TOC and Ro of samples.
When the pressure is higher than 60 MPa, the volume of mercury intrusion rises again rapidly. This phase corresponds to the mesopores with a pore diameter of less than 50 nm, which proves that the mesopores of the shale are relatively developed. The other category corresponds to the ye23-8 sample, which has only one inflection point at 0.1 MPa and a narrow hysteresis loop. When the pressure is higher than 0.1 MPa, the volume of mercury intrusions changes from the rapid rise to the slow rise and it is limited, which proves that the mesopores are not developed.

The above phenomenon can also be demonstrated by the rate of change in pore volume (Figure 4), and the mesoporous development of ye23-8 is the least favorable of all the samples studied. The mesopores of ye23-2, ye31-2 and ye31-1 are more developed, and
the ye23-5 macropores are very developed. This also explains why the total volume of mercury in ye23-5 is significantly higher than in other samples. It is speculated that the macropore development of ye23-5 is related to the high content of siderite. The precipitation and dissolution of siderite lead to the development of macropores.

The N₂ adsorption-desorption curves of the samples (Figure 5) show that each curve forms an adsorption hysteresis loop at high pressures, indicating capillary condensation in the shale pores (Sun and Guo, 2017). N₂ adsorption has similar results to MIP, and the samples can be divided into two categories according to the shapes of the adsorption-desorption curves (Sing, 1982). One category corresponds to the ye23-2, ye23-5, ye31-1 and ye31-2 samples. Their adsorption curves are generally concave because the interactions between the sample pores and the nitrogen molecules are less than the interactions between the molecules inside the pores. When \( P/P_0 \) is less than 0.4, the adsorption and desorption curves are basically coincident. When \( P/P_0 \) is between 0.4 and 0.8, the adsorption curve rises gently. When \( P/P_0 \) is higher than 0.8, the adsorption curve rises rapidly. According to the IUPAC classification, this type of hysteresis loop corresponds to the H₄ type, indicating that it has narrow-slit-shaped pores and that there is no adsorption limit in the higher relative pressure range. The other category corresponds to the ye23-8 sample. The main difference is that the adsorption volume does not rise rapidly when \( P/P_0 \) is higher than 0.8, the adsorption hysteresis loop is narrow and there is a plateau at the beginning of the desorption curve. The type of adsorption hysteresis loop of ye23-8 corresponds to the mixed type of H₂ and H₄, which proves that there are ink bottle-like shaped pores.

Figure 6 shows the pore distribution curve calculated by the BJH model. The pore distribution of ye23-8 is significantly different than that of the other samples. The pore distribution of ye23-8 has no peak, and the pore size decreases from 2 nm to 100 nm. It is obvious that 10-100 nm pore volume of ye23-8 is significantly smaller than other samples. The other samples have two peaks, which are in the range of 2–4 nm and 20–40 nm. Among them, the ye23-2 mesopores are the most developed, and the distribution is relatively uniform.
The mesopore volume showed a decreasing trend with the pore diameter, which proves that the pores are not developed. The other samples have two peaks, which are in the range of 2–4 nm and 20–40 nm. Among them, ye23-2 has the largest mesopore volume and a relatively uniform distribution.

Figure 7 shows the micropore distribution and cumulative pore volume based on the CO2 adsorption results. The micropores of the samples are mainly distributed in the range of 0.45–0.65 nm and 0.8–1 nm. The micropores of ye23-2, ye23-8 and ye31-2 are relatively large, and the micropores of ye23-5 and ye31-1 are relatively small.

**Discussion**

**Whole-aperture distribution characteristics**

Table 3 lists the micropore (<2 nm), mesopore (2–50 nm) and macropore (>50 nm) volumes and proportions of samples. The results show that the main contributor to the marine-continental transitional shale pores is the mesopores, which account for 40%–70% of pores, followed by macropores, which account for 20–%50%, and the lowest is micropores, which account for 7%–18%. In particular, the ye23-5 sample is dominated by macropores, which have high TOC and low Ro values. Since the sample is geographically close to the coal seam and has a high quartz content, its high brittleness causes microcracks to develop. XRD measured the presence of abundant siderite (Table 2), and many of the siderite-filled pores and dissolved pores were observed by AIP-FESEM. The reason for the development of macropores of ye23-5 is closely related to fluid activity.

Figure 8 shows the detailed pore size distribution of each marine-continental transitional shale sample. The macropore data are derived from MIP, the mesopore data are derived from N2 adsorption and the micropore data are derived from CO2 adsorption. The results show that the marine-continental transitional shale pores exhibit an unbalanced multimodal distribution with four peaks of 0.4–0.8 nm, 2–4 nm, 10–50 nm, and >10 μm.
Factors affecting the porosity of marine-continental transitional shale

The influencing factors of pores have always been the focus of sedimentologists and explorers. The factors affecting pores are very complex, but essentially they are affected by sedimentation, tectonic evolution and diagenesis. The pore types of shale can be divided into four types: intergranular pores, intragranular pores, organic matter pores and microcracks.
Figure 8. Whole-aperture distribution characteristics of shale samples.
Organic matter pores refer to tiny pores developed in organic matter that are formed during the burial and thermal evolution of organic matter, and they are widely distributed in kerogen in shale. The organic pores are a minimum size < 1 nm and can be up to 1 µm, which varies greatly depending on the degree of thermal evolution (Bao et al., 2015; Bu et al., 2015). However, we did not find organic matter pores of 1 µm in the samples, and the maximum diameter of organic pores was less than 300 nm, which may be related to kerogen type (Figure 9(a) and (b)).

The intergranular pores can be divided into rigid intergranular pores and intergranular pores in clays, which are residual primary pores that have gradually decreased in size due to compaction. The rigid intergranular pores are generally relatively large macropores located between the quartz particles, iron particles or iron and clay, with a pore diameter of 0.1–5 µm (Figure 9(c) and (d)). Intergranular pores in clays are also generally macropores and are pores located between the clay minerals; they are often narrow or irregularly shaped, with a pore diameter larger than 50 nm (Figure 9(e)). Intergranular pores in clays are developed in large quantities in the shales.

Figure 9. Schematic diagram of the diameter distribution of different pore types and AIP-FESEM photographs of samples. (a) Tiny OM pores in ye23-2 sample; (b) A lot of OM pores in ye23-8 sample; (c) Pyrite is filled in pores in the ye23-5 sample; (d) Intergranular pores between quartz and clays in ye23-5 sample; (e) Interlayer pores and intergranular pores in clays in ye23-2 sample; (f) Huge dissolved pores of pyrite frambords in ye23-5 sample; (g) Tiny dissolution pores in the quartz in ye23-8 sample; (h) Short microcrack in ye23-2 sample; (i) Long microcrack in ye23-8 sample.
Intragranular pores mainly include dissolved pores and interlayer pores in clays. Dissolved pore is similar to organic pore, but it is formed in the inorganic mineral particle, which is formed by the dissolution of mineral particles by the acidic or alkaline fluids. Dissolved pore can be large or small, but the pore diameter is larger than 20 nm, belonging to mesopores or macropores. The ye23-5 sample exhibits many dissolved pores of siderite, which may be the reason why it has many macropores (Figure 9(f) and (g)). Interlayer pores in clays are narrow-plate pores between flaky clay mineral aggregates. For example, in the process of dehydration of I/S to illite, the spacing of its own layered silicate framework becomes larger, so that the interlayer pores are developed. Interlayer pores in clays are widely distributed in shale samples and appear as slits in two dimensions. They are often extended in three dimensions and connected with other pores. These pores are important seepage channels for shale gas. The pore diameter is 10–500 nm, belonging to mesopores or macropores (Figure 9(e) and (g)).

Microcracks are formed by the nonstructural genesis, such as clay mineral dehydration or hydrocarbon pressurization. High contents of quartz and TOC or thin shale formations are favorable for the formation of microcracks. Therefore, the microcracks in the marine-continental transitional shale are very developed. The microcracks extend in an irregular line and can cut through the particles. The width is 100–500 nm, and the length is up to 20 μm, which plays an important role in improving the physical properties of shale (Figure 9(h) and (i)).

In summary, micropores of shale are organic matter pores. The shale mesopores are mainly organic pores, interlayer pores in clays and dissolved pores. Macropores of shale are dominated by the intergranular pores, dissolved pores and microcracks (Figure 9).

According to the relationship between Ro, TOC and pore volume (Figure 10), the mesopore and total pore volumes of marine-continental transitional shale decrease with increasing Ro, while the micropore volumes remain basically unchanged. Thermal evolution does not result in a dramatic increase of organic matter pore (mainly micropores) volumes for type III kerogen, which is different from marine shale. The volumes of intergranular and intragranular pores (mainly mesopores and macropores) decrease with the increasing thermal evolution and enhancing compaction. Therefore, the possible improvements of high-mature marine-continental transitional shale reservoirs are the development of dissolved pores and microfractures, such as the ye23-5 sample. Macropores are positively correlated with TOC, and mesopores are negatively correlated with TOC, which is also different from

![Figure 10](image-url). Relationship between the pore volumes and the Ro and TOC of samples.
the marine shale. The addition of continental organic matter and debris increases the macropore volumes, and the inorganic mineral dissolved pores and intergranular pores also increase the macropores.

According to the relationship between the mesopore volumes, macropore volumes and the relative content of clay (Figure 11), the content of kaolinite is positively correlated with the macropore volumes, which is related to the high content of kaolinite in the early stage of diagenesis. With the increase of thermal evolution, kaolinite is transformed to chlorite, I/S and illite. Illite content has a negative correlation with the mesopore and macropore volumes because illite is the final product of diagenesis. I/S is positively correlated with the mesopore volumes because the pore size of the interlayer pore in clays inside I/S is mainly mesopores. In addition, chlorite content appears to have a weakly negative correlation with mesopore volumes.

The five shale samples are typical samples with suitable differences selected by us. Whether SEM, N2/CO2 adsorption or MIP, different samples have their own characteristics. However, due to the insufficient number of samples, the relationship between pore characteristics and various factors needs further research and more sample support.

**Conclusion**

1. Marine-continental transitional shale pores of the Southern North China Basin exhibit an unbalanced multimodal distribution in pore sizes with four peaks at 0.4–0.8 nm, 2–4 nm, 10–50 nm, and >10 μm. The mesopore volume is dominant, accounting for 40–70%. In particular, the macropores of the ye23-5 sample dominate due to the filling and dissolution of the siderite, which caused the development of the dissolved pores and microcracks.

2. There is a desorption hysteresis loop on the N2 adsorption-desorption curve belonging to the H4 type of curve, which proves that the mesopores are mainly narrow-slit-shaped pores. In particular, ye23-8 belongs to the mixed type of H2 and H4, so it also has ink bottle-like shaped pores, which are confirmed in the AIP-FESEM photograph to be tiny dissolved pores and organic matter pores.

3. Due to the poor ability of type III kerogen to produce organic matter pores, the contribution of organic matter pores of marine-continental transitional shale is limited. The
mesopore and total pore volumes of marine-continental transitional shale decrease with increasing Ro. Macropores are positively correlated with TOC, and the mesopores are negatively correlated with TOC. The relationship between micropores and Ro and TOC is unclear.

4. The content of kaolinite is positively correlated with the macropore volumes. Chlorite has a negative correlation with the mesopore volumes, but I/S is positively correlated with the mesopore volumes. Illite has a negative correlation with the mesopore and macropore volumes.

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Appendix

Notation

| Notation | Description                                      |
|----------|--------------------------------------------------|
| XRD      | X-ray diffraction                                |
| MIP      | high-pressure mercury intrusion porosimetry     |
| AIP-FESEM| argon ion polishing-field emissions scanning electron microscopy |
| IUPAC    | international union of pure and applied chemistry|
| BET      | Brunauer, Emmett and Teller equation            |
| BJH      | Barrett, Joyner and Halenda method              |
| OM       | organic matter                                   |
| Ro       | vitrinite reflectance, %                         |
| TOC      | total organic carbon content, %                  |
| K        | kaolinite                                        |
| C        | chlorite                                         |
| I        | illite                                           |
| S        | smectite                                         |
| I/S      | illite-smectitemixed layer                       |
| S%       | smectite content, wt.%                           |
| P/P₀     | relative pressures, ratio of equilibrium pressure (P) to saturated vapor pressure (P₀) |