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Research Article

Influence of Organic Matter on Gas-Bearing Properties and Analysis of Sedimentary Mechanism of Organic Matter Enrichment: A Case Study on the Yangtze Region of Southern China during the Early Cambrian

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Shale gas exploration requires studies on the enrichment mechanism of sedimentary organic matter. The Lower Cambrian shale is taken as a study object to analyze the effect of organic matter on gas content using TOC content and porosity analyses, isothermal adsorption experiments, and FIB-HIM scanning electron microscopy observations. Then, we selected typical wells to determine the presence of excessive silica in the siliceous minerals by quantitative calculations. Besides, we analyzed the genesis of excessive siliceous minerals using elements including Al, Fe, and Mn, thus speculating the controlling factors of the redox environment and biological productivity. Results show that total organic carbon content controls the content of free and adsorbed gas, while shale gas mainly exists in organic pores and is developed in large numbers and with high roundness, showing the characteristics of "small pores inside big pores." In the Lower Yangtze region during the Early Cambrian, the excessive siliceous minerals were of hydrothermal origin, and there were frequent hydrothermal activities due to its closeness to plate boundaries. These activities can intensify the reducibility of the waterbody's bottom and improve the biological productivity on its surface, resulting in the enrichment of this matter. Most excessive silicon in this region is biogenic, while only a small part is of hydrothermal and biogenic mixed origin. The enclosed waterbody of the Upper Yangtze region was far from plate boundaries and close to the semiclosed "gulf," resulting in its delamination. The waterbody's surface was abundant with oxygen, thus increasing the biological productivity, while the high reducibility at the waterbody's bottom was conducive to preserving sedimentary organic matter.

1. Introduction

Since 2010, shale gas exploration in Sichuan and its surrounding areas has achieved great success with exploration concepts and technologies. PetroChina and Sinopec Group have conducted commercial exploitation in Weiyuan, Changning, Zhaotong, Fushun-Yongchuan, Fuling, Dingshan, Luzhou, Qijiang, Taiyang-Dazhai, Nanchuan, and other blocks [1–4]. Organic matter serves as the material basis on which shales generate hydrocarbon, and it provides shale gas with the main reservoir space and seepage channels. Open space in shale gas development areas can be used to build nature experience parks and caravan camps for hiking, trekking, sports tourism, outdoor sports, and other sporting events.

Exploring the enrichment pattern of sedimentary organic matter is becoming increasingly significant as the total organic carbon (TOC) content in shale is influenced by thermal evolution degrees and abundance of this matter. Many studies using different approaches have been conducted to analyze the mechanism [5–9]. Xia et al. utilized trace and rare Earth elements to prove that ascending currents facilitated organic matter enrichment. By studying strata of the Lower Cambrian Niutitang Formation (LCNF) in the upper reaches of the Yangtze region, southeast of Chongqing, they found that the formation was influenced by deep-sea hydrothermal fluids carried by oceanic currents [10]. After studying the lower boundary of the Cambrian series in the upper reaches of the Yangtze region, Zhang et al. concluded that the shales rich in organics in the shelf area are affected by seawater redox conditions. Organic matter can be better preserved in redox environments and, in the slope-basin area, its content in the organic-rich shales is mainly controlled by primary biological productivity. If organic matter is deposited under the same condition, this area is more abundant in organic matter than that in the shelf area [11]. Zhang et al. pointed out that shales were sediments of redox water conditions in the anoxic deep-sea environments on passive continental margins. Simultaneously, these shales were affected by ascending currents or hot water to a certain extent [12]. Findings by Qiu et al. show that volcanic ash has a relatively small influence on ocean regions with high productivity and promotes the organic matter's enrichment [13]. However, sedimentary waterbody's redox conditions (the change from rich oxygen and lean oxygen to hypoxia) are related closely to organic matter content and dominant in the enrichment of organic matter [14–17].

Recent technological advances and massive shale gas exploration have provided unprecedented data for studying the effect of organic matter on gas content as well as the enrichment pattern of organic matter sediments. Isothermal sorption experiments and FIB-HIM observations have provided new experimental methods for studying the effect of organic matter on gas content. Previous studies were mainly conducted on siliceous mineral genesis. The origin of siliceous minerals can be determined by Al-Fe-Mn triangular diagram that is proposed by Wedepohl, Holdaway and Clayton, Adachi et al., and Yamamoto [18–21]. Combining the two methods, this paper first quantitatively calculated whether there is excessive silicon in siliceous minerals in shales and then figured out its content. Furthermore, the origin of excess silicon was discovered, and the enrichment pattern of organic matter sediments was dissected. The organic matter sediments in the lower and upper reaches of the Yangtze region during the Early Cambrian are compared in this paper.

2. Geological Settings

2.1. Characteristics of Sedimentation and Strata. As researched previously [22–25], the Yangtze region consisted of paleocontinents, shallow deep shelves, continental slopes, and oceanic basins extending from northwest to southeast during the Early Cambrian. Correspondingly, the Cathaysian Plate was composed of the above from southeast to northwest, as shown in Figure 1. The waterbody is the deepest at the boundary of two plates and gets shallower in the direction of the ancient land on each side.

During the Early Cambrian period, a series of strata were vastly sedimented in both plates. To differentiate between them in the vast land, they are named variously (e.g., Wangyinpu Formation and Niutitang Formation in the lower course of Yangtze region and in its southeast part, resp.) in different areas. The target strata for exploring shale gas subsea in China are dark grey-black siliceous shales sediments rich in organics during the Early Cambrian period.

2.2. Tectonic Characteristics. This study involves the Lower and Upper Yangtze regions. Previous studies showed that, in the early Mesoproterozoic [24–26], the ocean basin divided South China's primitive continental crust into the Yangtze and Cathaysian Plates. Thereinto, the former refers to the Cratonic Basin. The two plates in tension experienced a massive transgression during the Early Cambrian period, depositing shales rich in organics that covered almost both plates. Subsequently, the waterbody grew shallower as the lithology transformed from fine and silty shales into siltstones, sandstones, and other coarse clastic rocks.

In the Ordovician, the waterbody continued becoming shallower due to the extrusion and collision of the Cathaysian Plate, and the sedimentary system transitioned from clastic rocks into carbonate rocks. However, a large-scale transgression occurred in the Upper Ordovician-Lower Silurian, causing this system to revert to clastic rocks, with organic-rich shales sedimented. The oceanic basin of both plates collided with the Yangtze Plate during the Cambrian-Silurian. When the Silurian period ended, the two plates merged to form the South China Plate.

3. Samples, Experiments, and Data Sources

We herein adopted samples taken from two wells and two sections, in which Well TX-1, Guizhou Taozichong outcrops, and Zhalagou outcrops were located in the upper reaches of the Yangtze region, and Well JY-2 was located in its lower reaches. Well TX-1 belongs to the Cen'gong shale gas block, and Well JY-2 belongs to the Xiuwu Basin. Well TX-1, Guizhou Taozichong outcrops, and Zhalagou outcrops are located near Guiyang in the Upper Yangtze region.

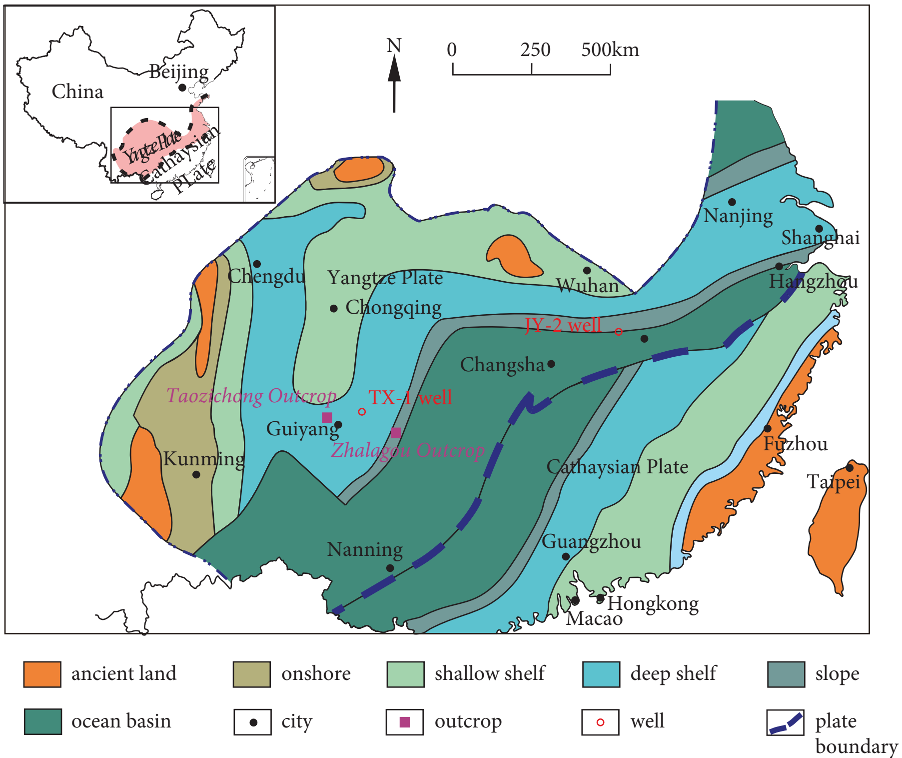


Figure 1: Sedimentary features of Early Cambrian South China (adapted from [17–20]).

Due to the relatively small variation of marine shales, this well and the two profiles are not far apart, so more data can be provided for the study of the organic matter enrichment mechanism of marine shales in the Upper Yangtze region.

Eighty key samples were collected from the LCNF's Well TX-1, among which 61 samples were analyzed using a Poro PDP-200 porosity tester for their shale porosity; 17 samples underwent isothermal adsorption experiment at 50°C using an isothermal adsorber model HPVA-200-4, and two samples were observed by FIB-HIM, that is, focused ion beam and helium ion microscopy, using a Zeiss Orion NanoFab. 75 and 61 core rock samples were taken from LCNF's Well JY-2 and LCNF's Well TX-1. A TOC analyzer (OG-2000V) was adopted to determine the TOC content of these samples. Besides, another 45 and 75 core samples were collected from the above wells, respectively. The elemental analyses for these samples, including Al, Fe, Mn, Ba, and Mo, were conducted by the X-ray Fluorescence Analyzer (Axios-MAX).

Zhang et al. reported TOC content of 37 samples as well as the Mo test data from the LCNF of Taozichong outcrops and Zhalagou outcrops in Guizhou [25]. The log data of Si, Al, U, and Th for the two aforementioned wells were collected from Schlumberger, with a logging interval of 0.125 m. Some data come from the literature of [27–31].

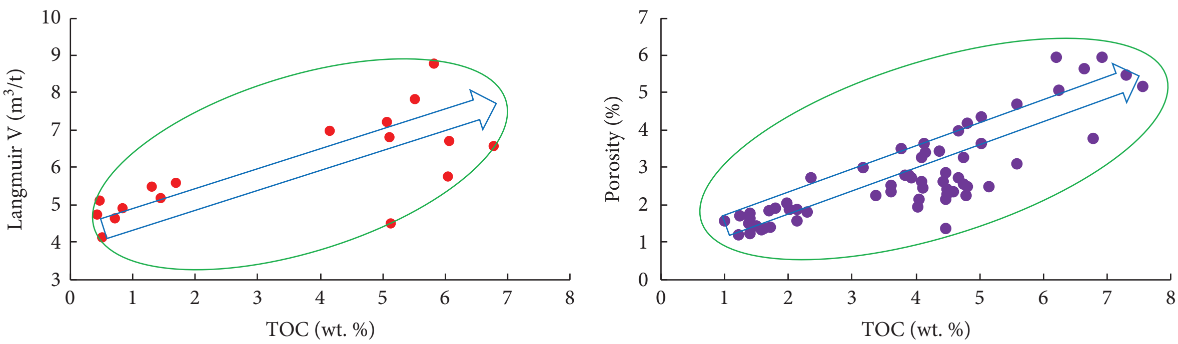
4. Results and Discussion

4.1. Impacts of Organic Matter on Gas Content

4.1.1. Relationship among TOC Content, Porosity, and Langmuir Volume. The Langmuir Volume (m^3/t) represents the maximum sorption capacity and physically denotes the adsorbed shale gas content at a specific temperature when methane adsorption saturates. The free gas is mainly correlated with porosity. The relationships between Langmuir Volume/core porosity and TOC content are shown in Figures 2(a) and 2(b), respectively. According to this figure, both the Langmuir Volume and core porosity have strong correlations with the TOC content, showing that the TOC content controls both the absorbed gas content and the free gas content, which are found to mainly exist in the organic matter pores.

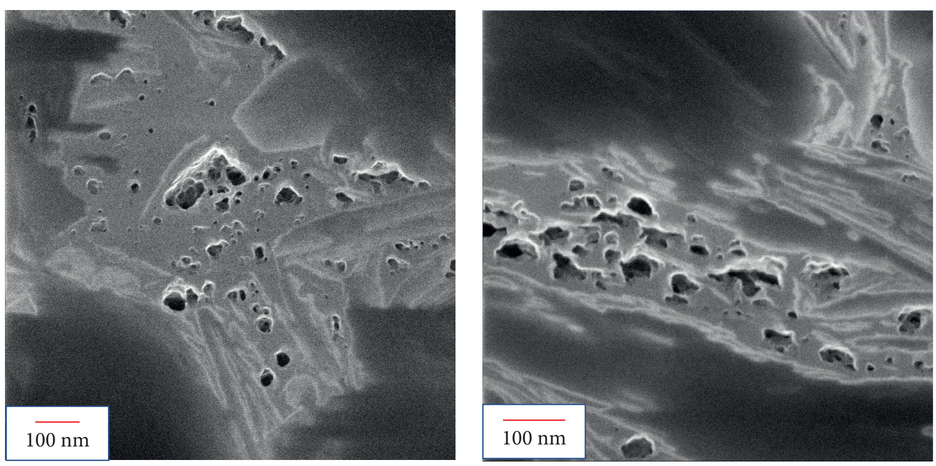
4.1.2. FIB-HIM Analysis of Organic Matter Pore Connectivity. The FIB-HIM images allow for the observation of pore interiors, resulting in a three-dimensional effect of a two-dimensional image. In the FIB-HIM images, as the molecular weight decreases, the greyscale composed by all shale materials increases, implying that the organic matter in the FIB-HIM images is lighter in color and has a lower greyscale than the inorganic minerals. According to Figures 3(a) and 3(b), the organic matter pores are well rounded and numerous, with a large number of tiny pores nested within large pores, which is similar to a honeycomb, providing them with excellent connectivity.

4.1.3. Significance of Conducting Analysis on the Sedimentary Mechanism of Organic Matter Enrichment. The aforementioned research shows that organic matter serves as both the material base for shale hydrocarbon generation and the main storage area and leakage channels for shale gas. The organic



(a) (b)

Figure 2: Relationship between Langmuir Volume and TOC content (a) and that between porosity and TOC content (b) for Well TX-1 of the Niutitang Formation in the Lower Cambrian. The well location is depicted in Figure 1.



(a) (b)

Figure 3: FIB-HIM images. (a) 1792 m, Well TX-1, LCNF. (b) 1801 m, Well TX-1, LCNF.

carbon (OC) content of modern shale is influenced by the abundance of primary organic matter sediments and the thermal evolution degree. When thermal evolution reaches a certain degree, the OC content of the modern shale is determined by the abundance of primary organic matter sediments. As a result, identifying factors that contribute to the abundance becomes crucial.

4.2. Index Selection for Redox Conditions and Bioproductivity

4.2.1. Selection of Redox Condition Indicators. A sedimentary condition is typically determined by elemental geochemical indexes. Jones and Manning analyzed the whole-rock samples and proposed that U/Th values reflect redox conditions of sedimentation. In general terms, A U/Th ratio exceeding 1.25 creates an anaerobic environment [32]; U/Th = 0.75–1.25 produces an oxygen-deficient environment; and U/Th less than 0.75 means an oxidative environment.

4.2.2. Selection of the Bioproductivity Indicators. The content of Ba and Mo each is widely adopted to demonstrate the paleooceanic productivity. The two elements originate from terrigenous sedimentation or biological action [33], and Ba that originates only from biotic sources is referred to as excess Ba (Ba_{xs}). The content is generally calculated by subtracting the terrigenous clastic Ba from the total content:

$$Ba_{xs} = \text{Basample} - Al_{sample}\left(\frac{Ba}{Al}\right)_{PAAS}, \tag{1}$$

where Ba_{sample} represents the total content of Ba and Al_{sample} represents that of Al in tested samples. PAAS refers to the standard Australian shale, and $(Ba/Al)_{PAAS}$ is the ratio of the two elements, namely, 7.7×10^{-3} [34].

Similarly, Mo derived solely from the biological action is referred to as excess Mo (Mo_{xs}). The estimated content can be figured by subtracting terrigenous clastic Mo from the total content.

$$Mo_{xs} = Mo_{sample} - Al_{sample}\left(\frac{Mo}{Al}\right)_{PAAS}, \tag{2}$$

where Mo_{sample} represents the total content of Mo and Al_{sample} represents that of Al. PAAS refers to the standard Australian shale, while $(Mo/\ Al)_{PAAS}$ is 1.086×10^{-5}, representing the ratio between the two elements in the same shale [34].

4.3. *Analysis of Mechanism of Organic Matter Sediments in the Lower Cambrian Well JY-2*

4.3.1. Calculation and Source Analysis of Excessive Siliceous Mineral Content. Well JY-2 lies in the shale gas block, Xiuwu Basin, in the lower course of the Yangtze region. The target stratum is Lower Cambrian Wangyinpu Formation (LCWF). With the goal of analyzing the sedimentation mechanism of an organic matter accurately, this study introduced the excessive siliceous mineral content (Si_{ex}) [35–39]. Silicon originates either from terrigenous clastic sedimentation in normal circumstances or from the hydrothermal and biogenic origins in special situations. Si_{ex} represents the siliceous minerals that would otherwise be derived from the sedimentation above.

The formula hereunder is used for the calculation of its content:

$$Si_{ex} = Si_s - \left[\left(\frac{Si}{Al} \right)_{bg} \times Al_s \right], \tag{3}$$

where Si_s and Al_s denote the content of Si and Al in samples, respectively. $(Si/Al)_{bg}$ or shale's average content is 3.11 [34].

The Si_{ex} content in Well JY-2 in the LCWF is calculated using the formula, and Figure 4 shows the result, indicating that the Si_{ex} is contained in most segments of the Wangyinpu Formation. Thereinto, half of them show the content of 10%–20%, while some show the value of 20%–30% or above.

The Al-Fe-Mn triangular graph, as put forward by Wedepohl, Holdaway and Clayton, Adachi et al., and Yamamoto, is used to identify whether the origin of siliceous minerals is hydrothermal or biogenic [18–21]. The test values of Al, Fe, and Mn in the segment containing Si_{ex} in Well JY-2 are plotted on a triangular graph in this paper. According to Figure 5, these values are primarily distributed over the hydrothermal origin area, demonstrating that Si_{ex} is formed due to this origin.

4.3.2. Effect of Hydrothermal Activities on Enrichment of Organic Matter Sediments. Previous studies have been carried out to study the closure of the waterbody in the Yangtze region, as shown in Figure 1. The results showed that the proximity of the Lower Cambrian Yangtze region to the open ocean basin led to weak closure of the waterbody, exerting a limited effect on sedimentary organic matter enrichment [38,39]. A great deal of silicon of hydrothermal origin formed in Well JY-2 is linked to the frequent tension activities on the Yangtze and Cathaysian Plates in the Lower Cambrian [18–21]. Its content demonstrates that the intensity of hydrothermal activities contributes to the presence of shale siliceous minerals. Furthermore, it influences the bioproductivity and the waterbody's redox conditions. Hence, the sedimentary organic matter abundance is influenced.

(1) Influence of Hydrothermal Activity on the Redox Environment. Sun et al. and Zhang et al. discovered that an anaerobic environment forms when the reduced acid hydrothermal fluids flow to the seafloor, helping to preserve organic matter [40–42]. The Lower Cambrian hydrothermal activities are well correlated with the water redox conditions in Xiuwu Basin. As shown in Figure 4, these activities frequently occur in Well JY-2 in the LCWF. In most cases, the U/Th value exceeds 1.25, indicating an anaerobic environment.

In the segments with high-intensity activities (LCWF's upper and lower areas), this value can range from 4 to 20, indicating that the waterbody is highly reducible. However, it is 1.25–4 when it comes to the segments with a lower intensity (Wangyinpu Formation's bottom and middle areas).

(2) Impact of Hydrothermal Activity on Paleoproductivity. A general assumption is that paleoproductivity has a strong influence on hydrothermal activities. Halbach et al. discovered more organisms with a higher activity intensity in the waterbody when they are closer to the hydrothermal area in Fiji Basin, based on an analysis of this area [43]. Compared with the ordinary ocean surface, the order of magnitude is 1–3 higher in this area.

Hydrothermal activities in Well JY-2 are also linked to the bioproductivity in the Lower Cambrian. Figure 4 depicts the frequent activities in the LCWF. The Ba_{xs} content here is higher than that in the overlying LCGF strata or in the underlying Upper Sinian Piyuancun Formation (USPF) strata.

(3) Impact of Hydrothermal Activity on the Shale TOC Content. This activity intensity has the potential to influence the water redox environment and bioproductivity and thus control the TOC content of the current shale. According to Figure 4, this content is as high as 10%–15% in the segments with high-intensity activities (Wangyinpu Formation's top and upper and lower parts in the Lower Cambrian). However, it reduces to 0.5%–5.5% in the segments with a lower intensity (the bottom and middle part of Wangyinpu Formation).

4.4. *Analysis on Sedimentary Characteristics of Well TX-1 in the Lower Cambrian*

4.4.1. Calculation and Source Analysis of Si_{ex}. Well TX-1 sits in the Cen'gong shale gas block, in the lower part of the Yangtze region. The LCNF is the target stratum. Similarly, the content of Si_{ex} is obtained using the formula. The results are shown in Figure 6. It can be speculated that Si_{ex} exists in Niutitang Formation, with content ranging from 10% to 20% in half of them and from 20% to 30% in others. Under certain circumstances, the value can even exceed 30%.

The siliceous mineral source in Well TX-1 in the LCWF is determined by the same method used for Niutitang Formation's Well JY-2. Al, Fe, and Mn values in the segment where Si_{ex} exists were determined in the test and cast onto the triangular graph, as shown in Figure 7. The results show that the silicon is mainly of biogenic origin, with a minor contribution from a mixed source.

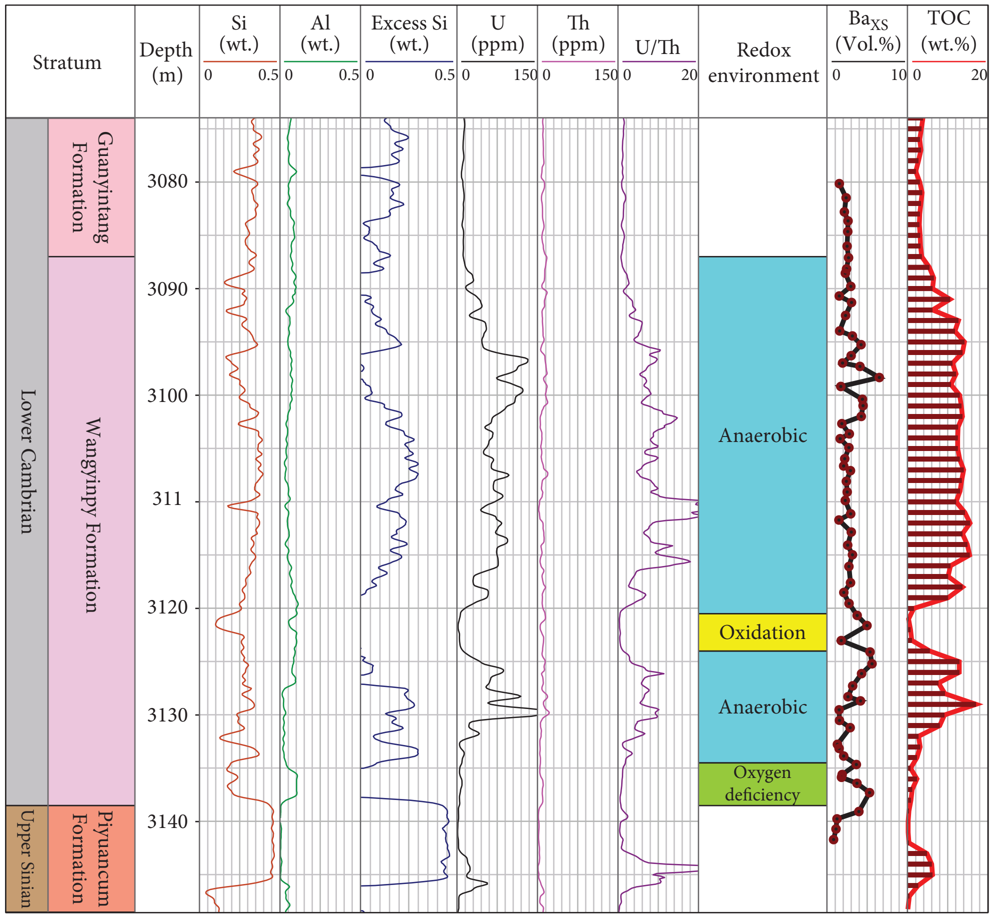


Figure 4: Si_{ex}, U/Th (index for redox environment), Ba_{xs} (index for bioproductivity), and TOC content in Well JY-2 in the LCWF of the lower reaches of Yangtze region. The location of Well JY-2 is depicted in Figure 1.

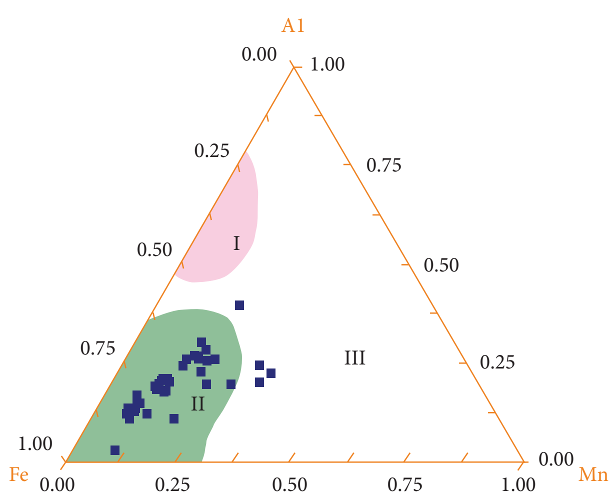


Figure 5: The Al-Fe-Mn triangular graph is adopted to demonstrate the source of siliceous minerals in Well JY-2's Si_{ex} segment in the LCWF. Si_{ex} is discovered to be hydrothermal in origin. The location of Well JY-2 is shown in Figure 1. I indicates bioorigin; II indicates hydrothermal origin; and III indicates mixed origin.

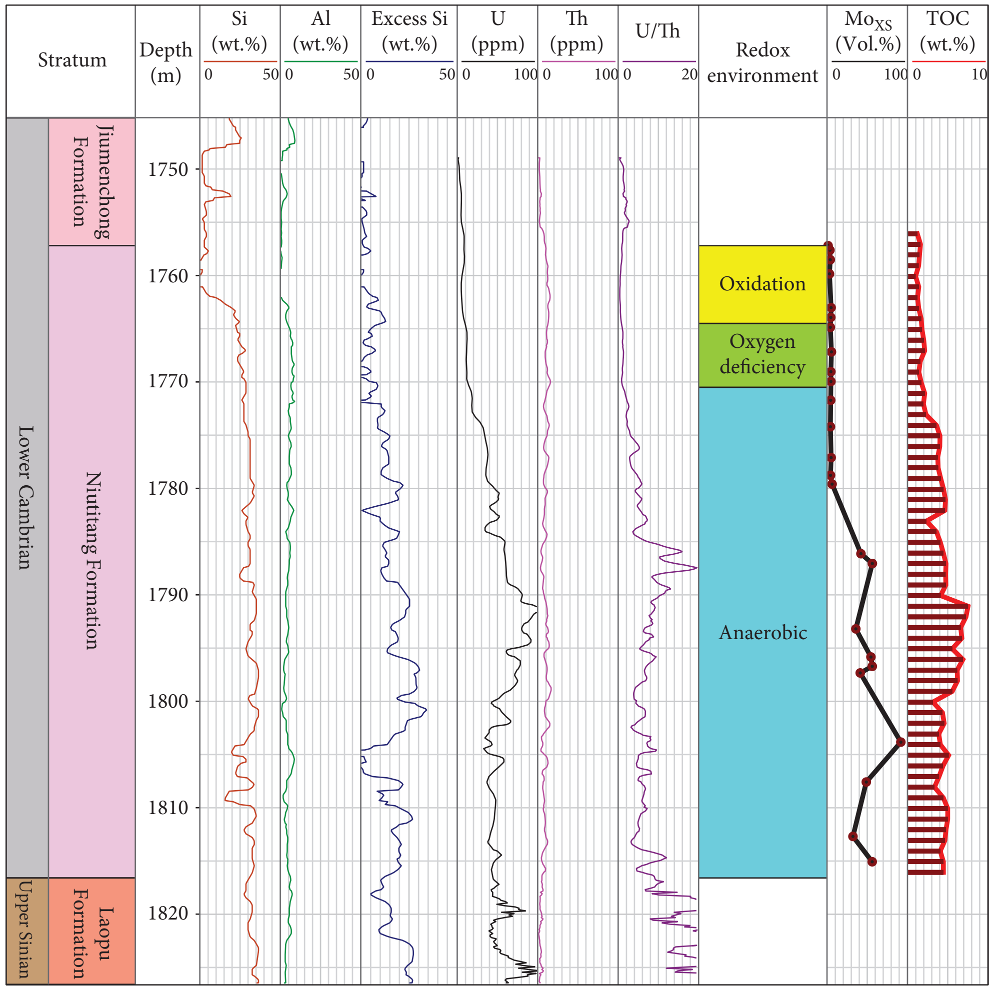


Figure 6: The content of Si_{ex}, U/Th (index for redox environment), Ba_{xs} (index for bioproductivity), and TOC of Well TX-1 in the LCNF in the Yangtze region. The location of Well TX-1 is depicted in Figure 1.

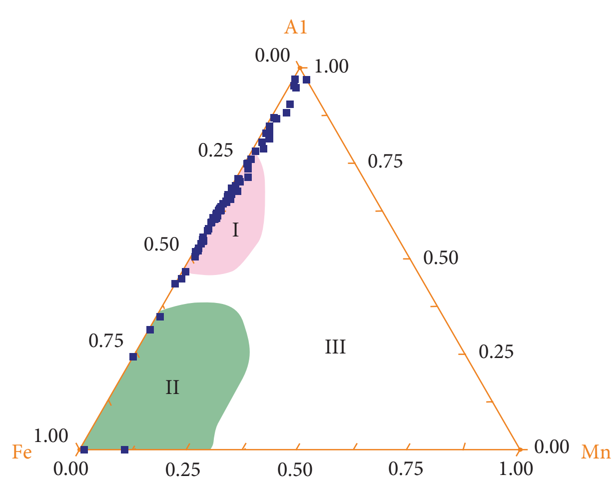


Figure 7: The Al-Fe-Mn triangular graph is adopted to explore the source of siliceous minerals in the Si_{ex} segment in Well TX-1 in the LCNF. The location of Well TX-1 is shown in Figure 1. I indicates bioorigin; II indicates hydrothermal origin; and III indicates mixed origin.

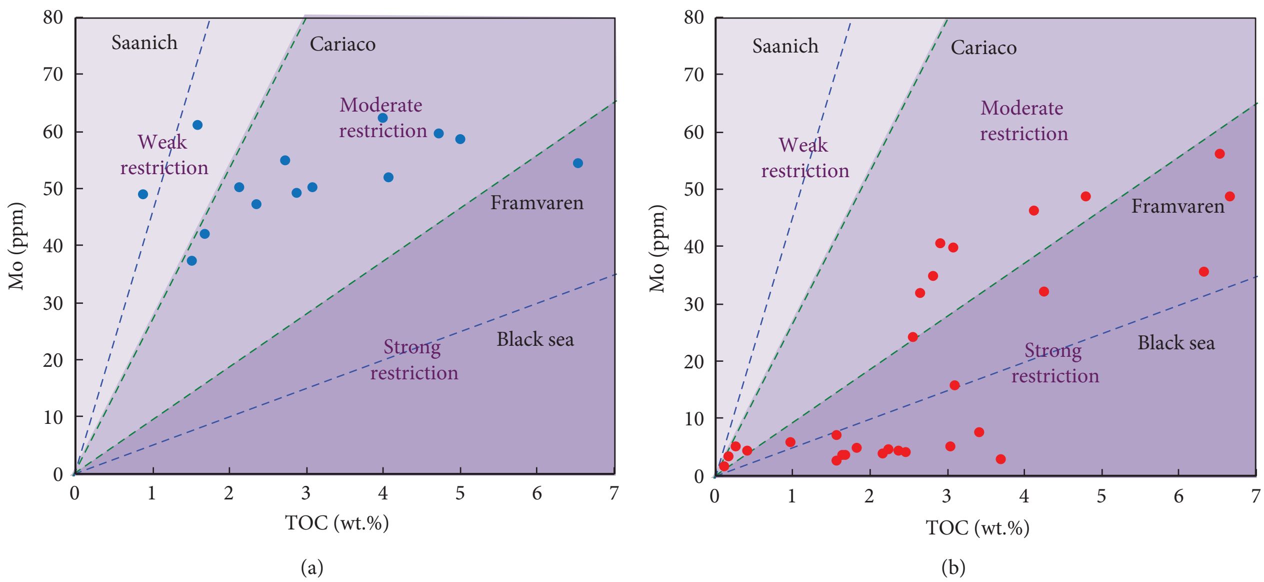


Figure 8: Well TX-1 in the Early Cambrian and nearby Taozichong outcrops, Zhalagou outcrops Mo-TOC content, and their relationship with waterbody closure. The Upper Niutitang Formation (a) and the Lower Niutitang Formation (b) during the sedimentary period.

4.4.2. The Influence of Waterbody Closure Degree on Enrichment of the Organic Matter Sediments

(1) Determination of the Waterbody Closure Degree. As shown in Figure 7, Lower Cambrian shales in the Well TX-1 are mainly biogenic silica, and a small portion of them is silica of mixed biogenic and hydrothermal origin, which implies that the hydrothermal activity was weak in the Upper Yangtze region during the Early Cambrian, and hydrothermal activity did not play an important role in the enrichment of sedimentary organic matter in this region. The Mo and TOC contents reflect the closure degree of the waterbody [44–47]. Algeo and Lyons and Zhang et al. cast the statistics of 64 Lower Cambrian series, including Well TX-1, the Taozichong outcrops, and the Zhalagou outcrops nearby onto the block, respectively [48]. According to Figure 8, the statistics of the Lower Niutitang Formation were mostly concentrated in highly closed areas (Figure 8(b)), whereas those of the upper part were mostly concentrated in medium-closed counterparts (Figure 8(a)).

The analyses and conclusions of closure and hydrothermal activities were consistent with the structural background of the Early Cambrian area of the upper part of the Yangtze region. The Yangtze and Cathaysian Plates were separate from each other in the Early Cambrian, as shown in Figure 1. Well TX-1 and its periphery were located at the deep-water continental of the Upper Yangtze region, which were farther from the ancient land. However, the areas were close to the half-closed "gulf" surrounded by the shallow-water shelf and, therefore, had a relatively high closure. Besides, Well TX-1 and its periphery were distant from the convergence between the Yangtze Cathaysian Plates. Therefore, hydrothermal activities there were less intense.

(2) Influence of Waterbody Closure Degree on Redox Environment and Biological Productivity. Waterbody closure serves as the major cause of the distinction in the redox conditions and bioproductivity in the upper part of the Yangtze region and the LCNF. According to Cheng et al., when layering occurs in highly closed water, the upper part becomes oxic while the lower part becomes suboxic [48]. The upper water contained sufficient oxygen that promoted plankton propagation and growth, offering plenty of organic matter for the sedimentation [49–54]. Suboxic slowed the breakdown of organic matter sediments in lower parts, which facilitates the preservation of organic matter. Under low closure degrees, on the other hand, the bottom water gradually converges with the warm water at the top, damaging the original environment [24,55–59]. Meanwhile, there was less sedimentary organic matter with lower abundance as they further underwent dilution and oxidative decomposition [60–63].

According to the analysis of Well TX-1's statistics in Figure 6, the waterbody closure of the Lower Niutitang Formation was strong during the sedimentary period, characterizing high U/Th values (4~20) in the lower part of the redox environment where the water had strong reducibility. As the height rose, the value decreased to 0~4, showing the conversion from oxygen-deficient to the oxygen-lean environment and eventually oxidizing environment. Meanwhile, Mo_{xs}, the index characterizing bioproductivity, decreased as heights increased. This was also true for the excess siliceous mineral content.

(3) Influence of Waterbody Closure Degree on the TOC Content. The level of closure influences water's redox environment and bioproductivity, further affecting the TOC content in shales. According to Figure 6, TOC content could amount to 3%~7.5% in the Lower LCNF, where waterbody

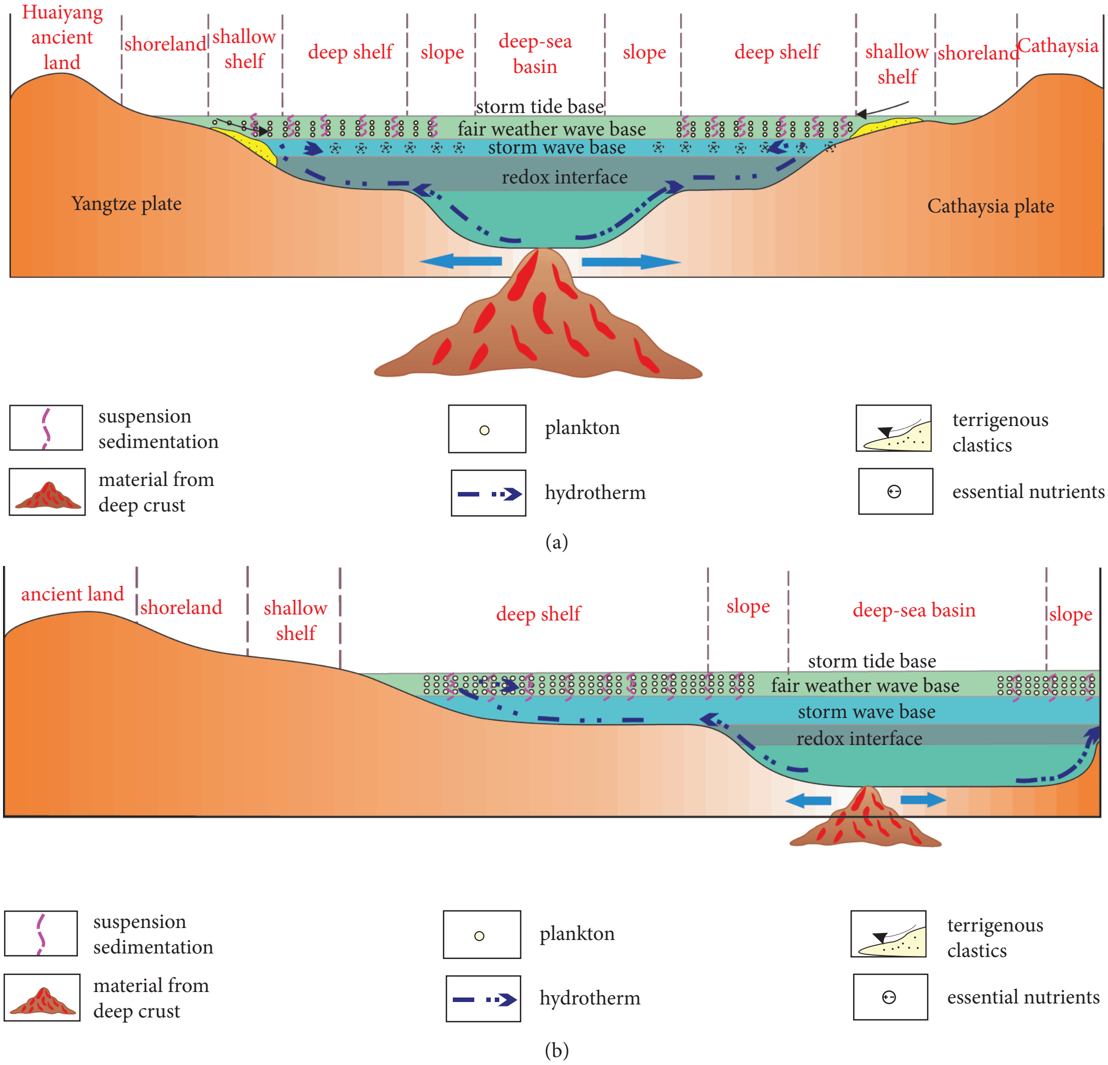


Figure 9: Enrichment patterns of organic matter sediments of the Lower Yangtze (a) and Upper Yangtze (b) during the Early Cambrian (adapted from [64–66]).

closure was strong, while, in the Upper LCNF, the content was lower with weak waterbody closure, ranging from 1% to 2%.

4.5. Enrichment Patterns of Organic Matter Sediments in the Lower and Upper Yangtze Areas in the Early Cambrian

4.5.1. The Lower Yangtze Region in the Early Cambrian. According to Figure 9(a), in the Early Cambrian, the hydrothermal fluids with nutrition from the deep crust moved into the Oceanic Basin in the Lower Yangtze region because of extension tectonics of the Yangtze and Cathaysian Plates. The upwelling current brought fluids to the continental area in the end. For one thing, the hydrothermal fluids were mixed with nutritive salt-rich surface water, promoting plankton propagation and growth and enhancing bioproductivity. The fluids at the bottom of the waterbody, for another, created a reducible environment, thus facilitating the preservation of organic matter in the primitive sediment. Both were beneficial to sediment enrichment.

4.5.2. The Upper Yangtze Region in the Early Cambrian. The Early Cambrian Upper Yangtze region was located far from the convergence of the Yangtze and the Cathaysian Plates, as shown in Figure 9(b). As a result, hydrothermal activities there were weaker than those in the lower counterpart. The deep-water continent in the Upper Yangtze Area neared the half-closed "gulf" surrounded by the shallow-water continent. As a result, the waterbody became more sealed off, and layering occurred in the Lower Niutitang Formation. On the top, the abundant oxygen promoted planktons' fast propagation. At the bottom, the hypoxic reduction environment was conducive to preserving the organic matter sediments from the upper layers, facilitating its enrichment. In the Upper Niutitang Formation, the waterbody was less enclosed during the sedimentary period, and thereby the water from different layers mixed up, resulting in the bioproductivity decrease. Furthermore, the reducibility of the waterbody at the bottom also decreased, which impeded the conservation of the sedimentary organic matter.

5. Conclusions

The Lower Cambrian marine shales in South China's Yangtze region were studied in this paper. The influences of organic matter on gas content and the enrichment patterns of organic matter sediments are studied in Well JY-2 in the Lower Yangtze Region of LCWF and Well TX-1 in the Upper Yangtze region of LCNF. The conclusions are as follows:

(1) The TOC content of shales controls the free and adsorbed gas contents. The primary source of shale gas is organic pores. The pore development of organic matter is high in number and roundness, with "small pores nesting in the large pores" and good connectivity.

(2) In the Lower Cambrian shales of the lower reaches of the Yangtze region, other than the common continental clastic origin, the rest of siliceous minerals are hydrothermal originally. Hydrothermal activities were common in the lower reaches of the Yangtze region near the confluence of the Yangtze and Cathaysian Plates. These activities increased the reducibility of the waterbody's bottom and the bioproductivity of its surface, further facilitating the enrichment of the organic matter sediments.

(3) In the Upper counterpart, besides the continental clastic origin, most of the siliceous minerals were formed through biological activities, with only a few having both biological and hydrothermal origins. The Upper Yangtze region was far from the convergence of the Yangtze and Cathaysian Plates and was close to the half-closed "gulf" surrounded by the shallow-water shelf. Relatively strong waterbody closure gave rise to the layering phenomenon. There was sufficient oxygen on the top, leading to high bioproductivity, while the reducibility was strong at the bottom, promoting the sedimentation of the organic matter.

Data Availability

Some of the data are contained in a published source cited in the references. All the data in this paper are accessible to the readers.

Additional Points

Highlights. (1) The TOC content controls the free and adsorbed gas contents. The shale gas mainly occurs in organic pores and is developed in large numbers, with "small pores nesting in big pores," showing the characteristics of high roundness and good connectivity. (2) Lower Yangtze region's closeness to plate boundaries induced intensive hydrothermal activities in the Early Cambrian period, thus affecting organic matter's enrichment. (3) Upper Yangtze region was farther from plate boundaries but close to the semiclosed "gulf." Thus, the enclosed waterbody played the leading role in organic matter's enrichment, while hydrothermal activities were the secondary influencing factor.

Conflicts of Interest

The authors declare that there are no conflicts of interest with respect to the results of this paper.

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