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Comparative Analysis of the Siliceous Source and Organic Matter Enrichment Mechanism of the Upper Ordovician–Lower Silurian Shale in the Upper-Lower Yangtze Area

Kun Zhang [1,2,3,4,5], Zhuo Li [1,2,*], Shu Jiang [5,6,*], Zhenxue Jiang [1,2,*], Ming Wen [1,2], Chengzao Jia [4], Yan Song [1,2,4], Weiwei Liu [7], Yizhou Huang [1,2], Xuelian Xie [8], Tianlin Liu [1,2], Pengfei Wang [9], Chang'an Shan [10] and Yinghui Wu [11]

1. State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, China; shandongzhangkun@126.com (K.Z.); mingw930331@163.com (M.W.); sya@petrochina.com.cn (Y.S.); ejeo33@163.com (Y.H.); 2015210204@student.cup.edu.cn (T.L.)
2. Unconventional Natural Gas Institute, China University of Petroleum, Beijing 102249, China
3. Unconventional Petroleum Collaborative Innovation Center, China University of Petroleum, Beijing 102249, China
4. Research Institute of Petroleum Exploration and Development, Beijing 100083, China; jiacz@petrochina.com.cn
5. Energy and Geoscience Institute, University of Utah, Salt Lake City, UT 84108, USA
6. Research Institute of Unconventional Oil & Gas and Renewable Energy, China University of Petroleum (East China), Qingdao 266580, China
7. Jiangxi Provincial Natural Gas Company, Ltd., Nanchang 330000, China; jxsg007@163.com
8. Guangzhou Marine Geological Survey, Guangzhou 510760, China; 15652635334@163.com
9. Geoscience Documentation Center, CGS, Beijing 100083, China; wpfupc725@outlook.com
10. School of Earth Sciences and Engineering, Xi'an Shiyou University, Xi'an 710065, China; shanca@xsyu.edu.cn
11. School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China; wuyinghui.wu@gmail.com

* Correspondence: lizhuopaper@163.com (Z.L.); sjiang@egi.utah.edu (S.J.); zhenxuejiangedu@126.com (Z.J.)

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Abstract: Organic matter is the material basis of hydrocarbon generation and the abundance of organic matter is a main factor of regional selection and evaluation in shale gas. Also the enrichment is influenced by sedimentary environments. Thus, it is important for the study on the geological factors controlling organic matter enrichment and further to provide scientific basis of regional selection and evaluation by organic matter enrichment area with analysis of the factors. In this paper, the Upper Ordovician–Lower Silurian shale from representative wells in the Upper-Lower Yangtze area is selected as the research object. The goal of this study is to quantitatively calculate the excess siliceous mineral content in shale siliceous minerals and determine the origin of excess silicon based on Al, Fe, and Mn elements; as well as to analyze the sedimentary organic matter enrichment mechanism based on the water body redox environment and bio-productivity. The results show that excess silicon from the Upper Ordovician–Lower Silurian shale in the Upper Yangtze area is biogenic and deposited in closed water bodies. On the one hand, the upper water body contains oxygen, which leads to higher bio-productivity. On the other hand, the lower water body has strong reducibility, which is conducive to sedimentary organic matter preservation. However, the excess silicon in the Upper Ordovician–Lower Silurian shale of the Lower Yangtze area is derived from hydrothermal solution. Hydrothermal activity can enhance the bottom water reducibility, and its nutrient elements can improve bio-productivity and enrich sedimentary organic matter. Therefore, the organic matter enrichment, which depends on the biological productivity and redox conditions, is controlled by the water closure in the Upper Yangtze and hydrothermal activities in the Lower

Yangtze respectively. It led to a conclusion that in the process of regional selection and evaluation of shale gas in the Late Ordovician–Early Silurian, it is favorable in the area of relatively strong closure, which is the center of cratonic depression, in the Upper Yangtze and in the hydrotherm-active area, which is the plate connection of the Lower Yangtze and the Cathaysian, in the Lower Yangtze.

Keywords: biogenic silicon; hydrothermal genesis silicon; closure; redox environment; bio-productivity

1. Introduction

Shale can provide important information for the study of palaeogeography, palaeo-depth, and paleoclimate, and it is an important sedimentary rock containing rich resources [1,2].

Since 2000, the exploration and exploitation of shale oil and gas has been successful in North America with the changes in exploration rationale and technology development [3–5]. China also contains vast shale gas resources [6–9]. In 2010, China National Petroleum Corporation drilled the first shale gas well, Wei 201 well, in the Weiyuan area of the southern Sichuan Basin. Subsequently, the preliminary commercial development of shale gas has been carried out successfully in the Weiyuan, Changning, Zhaotong, Fushun-Yongchuan, Fuling, and Ding Shan blocks [10–13]. Organic matter is the material basis of hydrocarbon generation in shale, and the organic pore it developed is the main space of shale gas enrichment. In addition, organic matter abundance is the one of the key factors in selected area evaluation of shale gas. The content of organic matter is influenced by abundance of sedimentary organic matter and degree of thermal evolution of organic matter. Under a certain degree of thermal evolution, the organic matter content today in shale is controlled by original abundance of sedimentary organic matter [14–18]. Therefore, it is vital for analyzing geological factors affecting the sedimentary organic matter abundance and studying the enrichment mechanism of organic matter to be solved [19,20].

A series of methods have been used to study the organic matter enrichment mechanism in marine shale deposition in the Yangtze area. Based on the data analysis of 30 outcrop sections and 12 wells in the study area—which are combined with lithology, elemental geochemistry, logging geophysics, and a paleontological phase marker—Zhang et al. [21] studied the Lower Silurian sedimentary environment, sedimentary evolution, and its influence on source rocks in the southeast Sichuan and northern Guizhou areas. Based on the outcrops and well drilling data, an isochronal stratigraphic framework—which was established based on specific graptolite zones and important markers, and combined with geological information such as lithofacies, paleontology, calcareous content, logging response characteristics, and geochemical characteristics—the Longmaxi Formation sedimentary microfacies were studied and the stratigraphic sequence, sedimentary evolution, and high-quality shale distribution characteristics were obtained [22]. Based on the sedimentary structure and combined with logging data, core description, and other data, Zhang et al. [23] studied the sequence stratigraphy and sedimentary facies of organic-rich shale in the Wufeng-Longmaxi Formation in the Jiaoshiba area of Fuling. According to the shale gas well data and typical sections of the Wufeng-Longmaxi Formation in Sichuan Basin, the sedimentary environment and shale thickness in different graptolite zones, as well as the shale plane distribution were analyzed, and the sedimentary environment, lithology, and thickness of the Wufeng-Longmaxi Formation characteristics were clarified [24].

Shale contains large silica contents and Holdaway and Clayton [25] defined the concept of excess silicon (i.e., siliceous minerals beyond the normal terrigenous clastic sources) and proposed a method to quantitatively calculate excess siliceous content. Wedepohl [26], Adachi et al. [27] proposed a method using the Al-Fe-Mn ternary plot to determine whether silicate minerals are derived from hydrothermal origins or biogenesis. In this paper, sedimentary environments of shale in the late Ordovician and early Silurian were studied in both Upper and Lower Yangtze via the siliceous mineral origins. The two methods are combined to quantitatively calculate whether there are excess siliceous minerals and excess siliceous mineral contents in shale siliceous minerals and determine the excess silicon origin using the Al-Fe-Mn ternary plot, which can help analyze the sedimentary organic matter enrichment mechanism, as well as compare the differences in sedimentary organic matter enrichment in the Late Ordovician–Early Silurian Upper and Lower Yangtze regions.

2. Geological Settings

2.1. Sedimentary and Stratum Characteristics

According to previous research [28–30], as shown in Figure 1, during the Cambrian to Silurian Periods the Yangtze and Cathaysian plates gradually converged and collided. The Upper Yangtze area was relatively wide and formed the cratonic depression basin after being pressed during the Late Ordovician–Early Silurian [31–33]. In contrast, the Lower Yangtze area was relatively long, narrow, and close to the junction of the Yangtze and Cathaysian plates and was crushed to form a foreland basin [34].

In this paper, the research goal is to identify a set of strata that was widely deposited in the Yangtze and Cathaysian plates in the Late Ordovician–Early Silurian. Due to its vast area, it has different names in different regions. The Late Ordovician sedimentary strata are called the Wufeng Formation in the Upper Yangtze region and the Xinkailing Formation in the Lower Yangtze region [6–9]. The Early Silurian depositional strata are called the Longmaxi Formation in the Upper Yangtze region and the Lishuwo Formation in Lower Yangtze region [34–36]. The focuses of this study are the Xinkailing Formation-no. 1 section of the Lishuwo Formation in the Lower Yangtze region and Wufeng Formation-no. 1 section of the Longmaxi Formation in the Upper Yangtze region. The Upper Ordovician–Lower Silurian shale lithology is characteristically dichotomized: the lower part of the Wufeng Formation-Xinkailing Formation and no. 1 section of the Longmaxi Formation-Lishuwo Formation are mainly black siliceous shale and gray-black calcareous sheet rock assemblages and the upper part of no. 1 section of the Longmaxi Formation-Lishuwo Formation is composed of gray-green to yellow-green shale, silty shale, and siltstone.

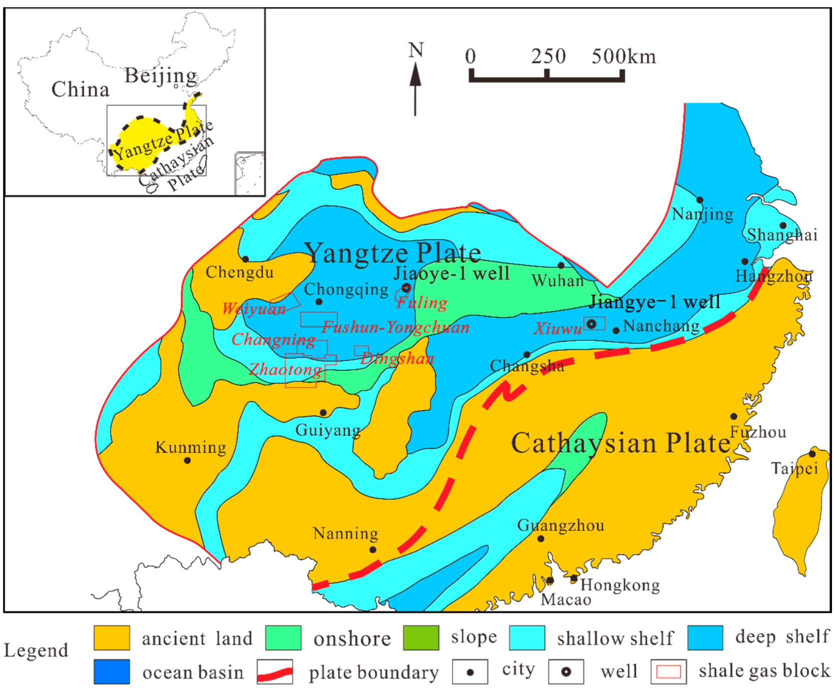

Figure 1. Sedimentary characteristics of the Late Ordovician–Early Silurian in southern China. Jiaoye-1 well is in the Upper Yangtze area and Jiangye-1 well is in the Lower Yangtze area.

2.2. Tectonic Characteristics

The target of this research is the whole Yangtze area. Based on previous studies [31–33], the original continental crust in southern China was separated into two plates, the Yangtze plate and the Cathaysian, which were separated by oceanic basins in the early Middle Proterozoic. The Yangtze plate is a cratonic basin. In the Early Cambrian Period, both of these plates were extending. An ocean transgression occurred and deposited a set of organic-rich shale, which nearly covered the entire plate. Subsequently, the water body gradually became shallow. The lithology changed from fine-grained and silty shale to siltstone, sandstone, and other coarse-grained clastic rocks. During the Late Ordovician Period, this water body continued to shallow due to the crushing collision with the Cathaysian plate, and the sedimentary system was transformed from a clastic sedimentary system into a carbonate sedimentary system. During the Late Ordovician–Early Silurian Period, transgression occurred, and the sedimentary system changed again into a clastic sedimentary system. The oceanic basins between the two plates gradually subducted and collided with the Yangtze plate, and at the end of the Silurian Period, the Yangtze and Cathaysian plates finally integrated into one, the South China plate [34].

3. Samples, Experiments, and Data Sources

The Jiaoye-1 well is a key exploration well in the Upper Yangtze area, while the Jiangye-1 well is a key exploration well in the Lower Yangtze area, both of which have detailed well logging data, cores analysis data. Considering the wide range of marine deposit and strong shale homogeneity, research on the two representative wells can respectively reflect the sedimentary characteristics of shale in the Upper and Lower Yangtze regions. Therefore, in this study, we selected the Jiaoye-1 and Jiangye-1 wells as representative wells to analyze the organic matter enrichment mechanism of the Late Ordovician–Early Silurian shale in the Upper Yangtze and Lower Yangtze, respectively. A total organic carbon analyzer (OG-2000 V) was used to test the TOC (Total organic carbon) of 45 cores from the Wufeng Formation-no. 1 section of the Longmaxi Formation in Jiaoye-1 well and 42 cores from the Xinkailing Formation-no. 1 section of the Lishuwo Formation in Jiangye-1 well. In addition, Al, Fe, and Mn elemental analyses were performed using an X-ray fluorescence model (Axios-MAX) for 15 cuttings, which were sampled in every 5–6 m, from the Wufeng Formation-no. 1 section of the Longmaxi Formation in Jiaoye-1 well, and 91 cuttings, which were sampled in every 1–2 m, from the Xinkailing Formation-no.1 section of the Lishuwo Formation in Jiangye-1 well.

In this paper, the TOC content and Mo elemental test data of 21 core samples are also collected from the lower part of the Lower Ordovician Wufeng Formation–Lower Silurian no. 1 section of the Longmaxi Formation [37]. Also collected are excess barium (Ba_{XS}) data, which reflects the bio-productivity of the Upper Ordovician Xinkailing Formation–Lower Silurian no. 1 section of the Lishuwo Formation in the Jiangye-1 well [38,39], and excess zinc (Zn_{XS}) data, which reflects the bio-productivity of the Upper Ordovician Wufeng Formation–Lower Silurian Longmaxi Formation [37]. Finally, log data for U, Si, Al, and Th from two wells provided by the Schlumberger Corp. are also collected.

4. Results and Discussion

4.1. Redox Environment and Bio-Productivity Index

An elemental geochemical index is a common method used to determine depositional environments. Jones et al. [40] suggested that the U/Th values can reflect the redox conditions of the depositional environment through a whole rock sample analysis. In general, U/Th > 1.25 represents anoxic environments, U/Th values ranging from 0.75 to 1.25 are oxygen-depleted environments and U/Th < 0.75 represent oxidative environments. The contents of Zn and Ba are the most widely used to evaluate the productivity of ancient marine life. Zn and Ba elements come from both terrestrial and biological origins. Only Zn elements originating from biological effects are called Zn_{XS}, and these data are from Guo et al. [37]. Similarly, only the bio-derived Ba elements are called excess barium (Ba_{XS}), and these data are from Zhang et al. [38].

4.2. Analysis of the Sedimentary Organic Matter Enrichment Mechanism in the Upper Ordovician–Lower Silurian of Well Jiaoye-1

4.2.1. Calculation and Source Analysis of Excess Silicon

Jiaoye-1 well is in the Jiaoshiba block of the Upper Yangtze area, and the exploration target is the Upper Ordovician Wufeng Formation–Lower Silurian Longmaxi Formation. To accurately analyze the sedimentary organic matter enrichment mechanism, in this study, the concept of excess siliceous mineral content is introduced.

The siliceous sources are divided into three types, which are normal terrestrial detrital deposits, hydrothermal silicon in special cases and biogenic silicon [41–45]. Excess siliceous mineral content (abbreviated is Si_{ex}) refers to siliceous minerals except normal terrigenous clastic deposits and can be calculated using the formula

$$Si_{ex} = Si_s - [(Si/Al)_{bg} \times Al_s]$$

Si_s is the silicon element content in the sample, and Al_s is the aluminum element content of the sample; $(Si/Al)_{bg}$ is 3.11, which is the average content of shale [25].

Using this formula to calculate the excess siliceous mineral content from the Jiaoye-1 well in the Lower Ordovician Wufeng Formation–Lower Silurian no. 1 section of the Longmaxi Formation, the result is shown in Figure 2. The silicon minerals in the upper part of the no. 1 section of the Longmaxi Formation is derived from terrigenous detritus, whereas the lower part of the Wufeng Formation and Longmaxi Formation contain excess silicon. In the layers where excess siliceous minerals are present, the excess siliceous mineral content in half of the layers is between 0% and 5%, and the excess siliceous content in some layers is between 5% and 15% and even as high as 15% to 20%.

Wedepohl [26], Adachi et al. [27], and Yamamoto [46] proposed a method of using the Al-Fe-Mn ternary plot to determine whether siliceous minerals are derived from hydrothermal origin or biogenesis. In this paper, the element test values of Al, Fe, and Mn in the layers with excess siliceous minerals from the Jiaoye-1 well in the Lower Ordovician Wufeng Formation–Lower Silurian Longmaxi Formation are plotted in the triangular diagram. As shown in Figure 3, the numerical value is in the biogenesis area, which indicates that excess siliceous minerals are derived from biogenesis. Thus, the genetic diagram of silicon in the Lower Ordovician Wufeng Formation–Lower Silurian no. 1 section of the Longmaxi Formation in Jiaoye-1 well was accurately determined, which is shown in the middle part of Figure 3.

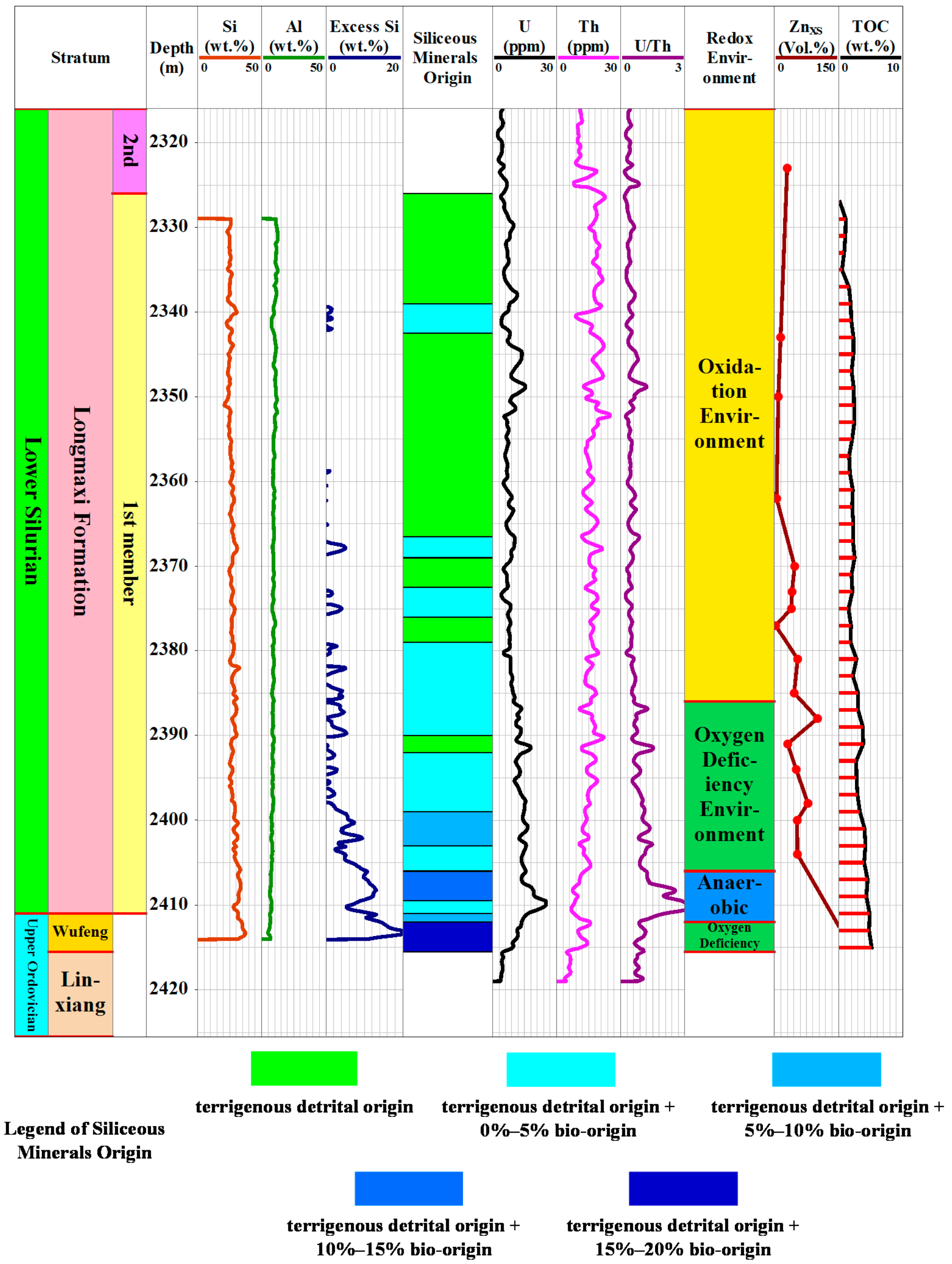

Figure 2. Excess silicon, redox environment, bio-productivity (Zn_{XS}), and TOC content of Jiaoye-1 well in the Upper Ordovician Wufeng Formation–Lower Silurian no. 1 section of the Longmaxi Formation in the Yangtze area. See Figure 1 for the well location.

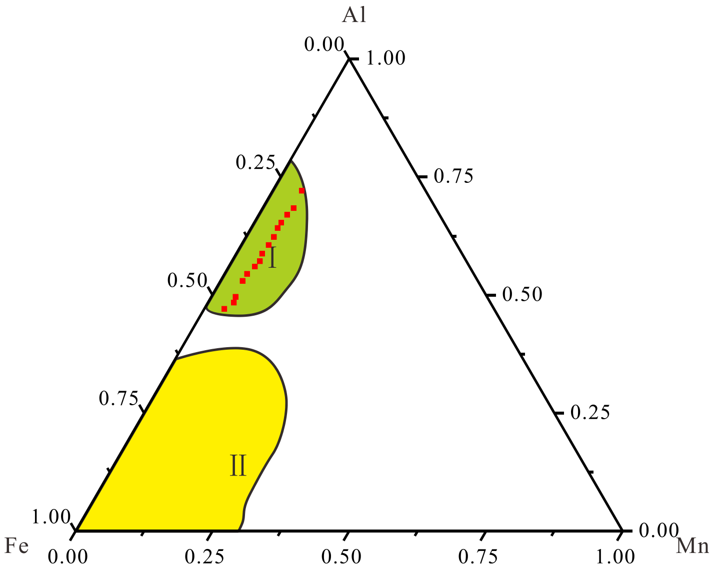

Figure 3. Through the Al-Fe-Mn ternary plot analysis, siliceous minerals from the Upper Ordovician Wufeng Formation–Lower Silurian no. 1 section of the Longmaxi Formation in Jiaoye-1 well contains excess siliceous minerals, which are derived from bio-origins. The base map is from Wedepohl [26], Adachi et al. [27], and Yamamoto [46]. See Figure 1 for the well location. I: bio-origin, II: hydrothermal origin.

4.2.2. Effects of Water Closure on Sedimentary Organic Matter Enrichment

The relation between the Mo element and TOC content can reflect the closure degree of a water body [39,47,48]. According to the relative relationship between the Mo element and the TOC content obtained by previous studies [24,39]., the method of judging the closure of the water body can be shown in Figure 4. In the Figure 4, the pink region represents the strong water closure, the blue region represents the medium water closure, and the yellow region represents the weak water closure. There are 21 data points of Mo and TOC content from the lower part of the Wufeng Formation-No. 1 section of the Longmaxi Formation in Jiaoye-1 well are plotted. As shown in Figure 4, the data points are mostly in the area reflecting strong closure.

The conclusions of the closure analysis are consistent with the tectonic background of the Late Ordovician–Early Silurian. As shown in Figure 1, during the Late Ordovician–Early Silurian Period, the collision between the Yangtze and Cathaysian plates occurred and the organic-rich shale was deposited in the deep water shelf environment confined by ancient lands, which had poor connectivity with the external ocean, and resulted in a high degree of closure.

The closure of the water body is the reason for the difference in the redox environments and bio-productivity in the upper part of the Wufeng Formation–Longmaxi Formation. Cheng et al. [49] found that during the Late Ordovician–Early Silurian Period, stratification of water bodies occurred in the Upper Yangtze region. The upper part of water body was oxic and the lower part was suboxic. The oxic water body provided a supply for organisms to grow and reproduce which created a rich source of organic matter for sediments; depletion of oxygen in the lower water body prevented the decomposition of sedimentary organic matter, which is an advantage for the conservation of organic matter [49,50]. In the late Early Silurian, the bottom water gradually mixed with the warm water in the upper layer. As a result, the water temperature increased, and the anoxic oxygen environment was destroyed. In this case, the sedimentary organic matter was diluted, oxidized, and decomposed, and the organic matter abundance was reduced.

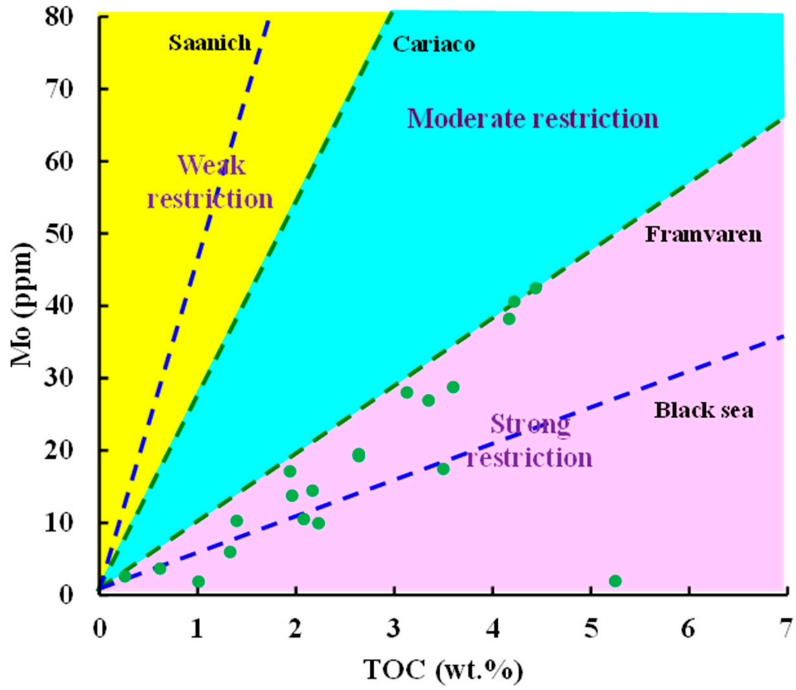

Figure 4. The Mo element and TOC content from the Upper Ordovician Wufeng Formation and Lower part of the Lower Silurian no. 1 section of the Longmaxi Formation in the Jiaoye-1 well. The base map is from Algeo and Lyons [47] and Zhang et al. [39]. See Figure 1 for the well location.

As shown in Figure 2, the data from Jiaoye-1 shows that due to the strong closure of the water body during the Early Ordovician–Early Silurian, the U/Th value characterizing the redox environment at the bottom of the water is approximately 3; the value in the upper part of the water body is reduced to 0.5, which indicates a change in the hypoxic environment to an oxygen-depleted environment and then further to an oxidizing environment, which means the closure of the water body was weaker. The change trend of excess zinc (Zn_{XS}) content is consistent with that of the biogenic silicon content, and both of them decrease gradually from bottom to top, which indicates that bio-productivity decreases with a decline in closure.

In the Late Ordovician–Early Silurian, the strongly closed water bodies led to higher bio-productivity and an anoxic-reduction environment. As a result, the TOC content in the lower part of the Wufeng Formation-no. 1 section of the Longmaxi Formation is 2–5% and then reduces to 0–2% in the upper part of the no. 1 section of the Longmaxi Formation as the closure of the water body weakened (Figure 2).

4.3. Analysis of the Sedimentary Organic Matter Enrichment Mechanism in the Upper Ordovician–Lower Silurian in the Jiangye-1 Well

4.3.1. Calculation and Source Analysis of Excess Silicon

The Jiangye-1 well is in the shale gas block of the Xiuwu Basin and the exploration target is the Upper Ordovician Xinkailing Formation–Lower Silurian no. 1 section of the Lishuwo Formation. Additionally, the amount of excess silicon is calculated according to the formula, which is shown in Figure 5. The silicon minerals in the upper part of the no. 1 section of the Lishuwo Formation are basically derived from terrigenous detritus with some layers containing a small amount of excess silicon content between 0~5%. However, in the lower part of the Xinkailing Formation and no. 1 section of the Lishuwo Formation, there is more excess silicon content, which is above 0–5% in most of the layers, between 5% and 15% in some layers and even up to 15–20%; this is similar to that in the Jiaoye-1 well in the Upper Ordovician Wufeng Formation–Lower Silurian Longmaxi Formation.

Using the same method to determine the origin of siliceous minerals in this paper, the element test values of Al, Fe, and Mn in layers with excess siliceous minerals from the Jiangye-1 well in the Upper Ordovician Xinkailing Formation–Lower Silurian no. 1 section of the Lishuwo Formation are placed in the triangular diagram. As shown in Figure 6, the numerical value is in the hydrothermal origin area, which indicates that excess siliceous minerals are derived from hydrothermal origin, which is different from the biogenic siliceous minerals of the Jiaoye-1 well in the Upper Ordovician Wufeng Formation–Lower Silurian Longmaxi Formation. Thus, the genetic diagram of silicon in the Lower Ordovician Xinkailing Formation–Lower Silurian no. 1 section of the Lishuwo Formation in Jiangye-1 well was accurately determined, which is shown in the middle part of Figure 5.

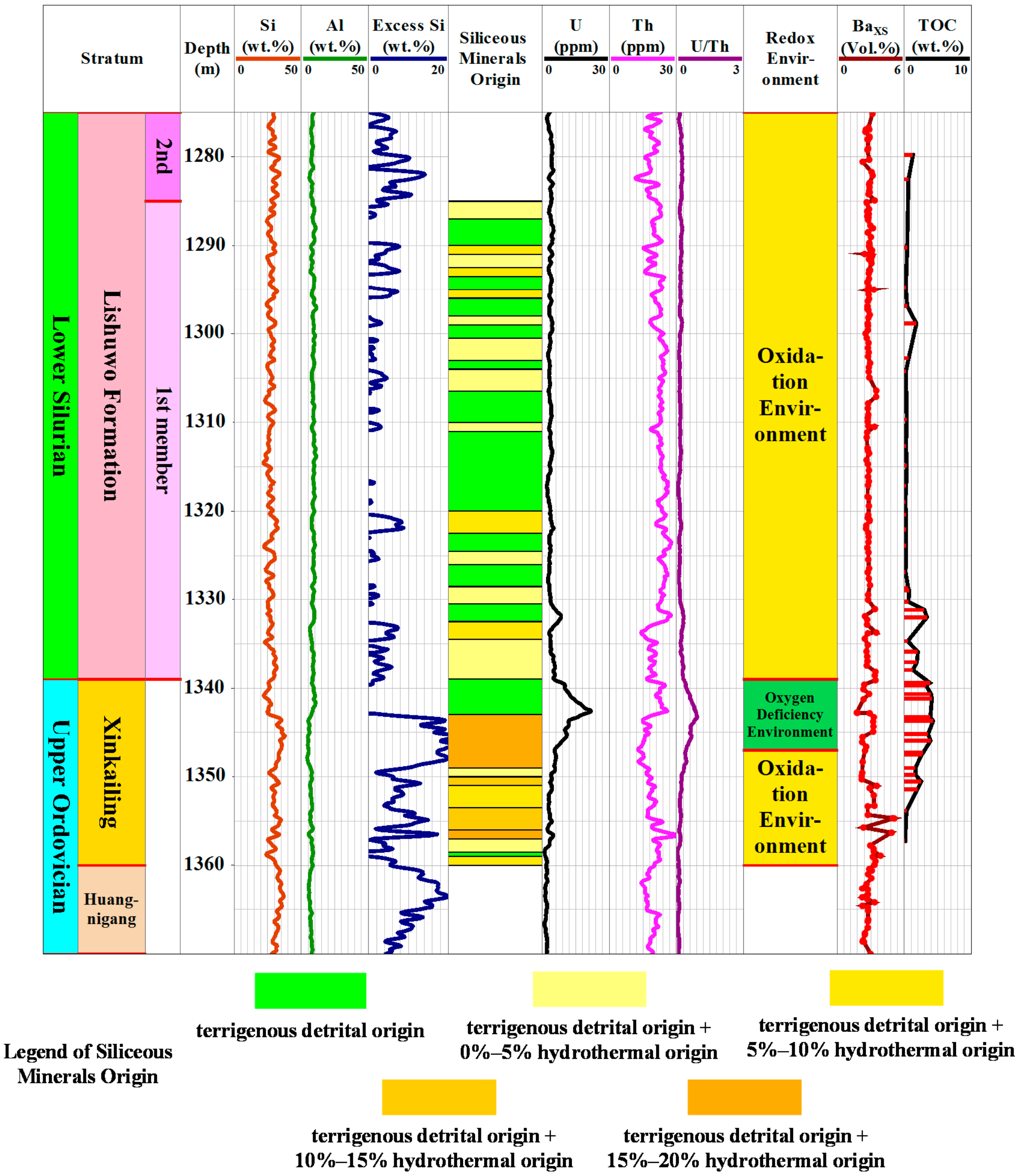

Figure 5. Excess silicon, redox environment, bio-productivity (Zn_{XS}), and TOC content of the Jiangye-1 well in the Upper Ordovician Xinkailing Formation–Lower Silurian no. 1 section of the Lishuwo Formation in the Yangtze area. See Figure 1 for the well location.

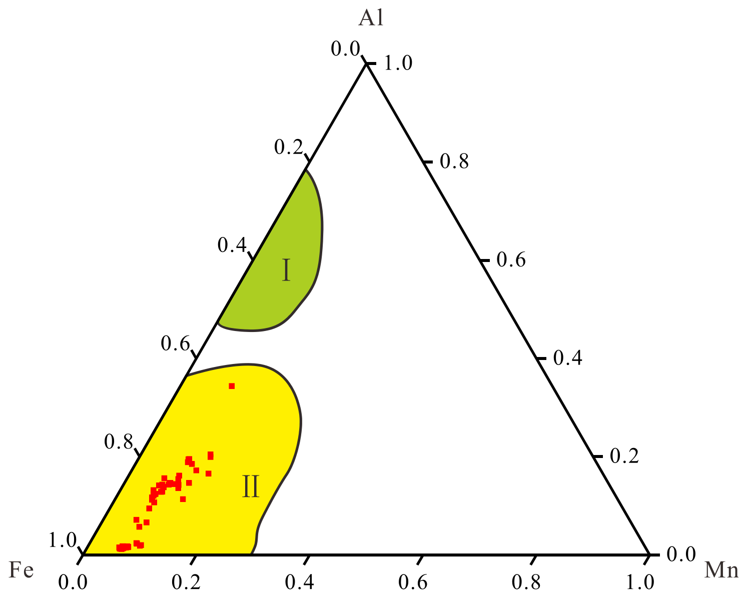

Figure 6. Through the Al-Fe-Mn ternary plot analysis, siliceous minerals from the Upper Ordovician Xinkailing Formation–Lower Silurian no. 1 section of the Lishuwo Formation in the Jiangye-1 well contain excess siliceous minerals, which are derived from hydrothermal origin. The base map is from Wedepohl [26], Adachi et al. [27] and Yamamoto [46]. See Figure 1 for the well location. I: bio-origin, II: hydrothermal origin.

4.3.2. Effects of Hydrothermal Activities on Sedimentary Organic Matter Enrichment

The existence of hydrothermal silicon in the Jiangye-1 well is related to the active compression between the Yangtze and Cathaysian plates during the Late Ordovician–Early Silurian [31–33,42]. The hydrothermal activities, formed siliceous minerals in shale, which had an impact on the redox conditions and bio-productivity of water bodies, and thus, this affected the abundance of sedimentary organic matter.

The research conducted by Sun et al. [51,52] and Zhang et al. [53] found that the reduced hydrothermal fluids went to the sea bottom to form an oxygen-deficient environment that was conducive to organic matter preservation. The redox conditions of the water body are also related to the hydrothermal activities in the Xiuwu Basin during the Late Ordovician–Early Silurian. Based on Figure 5, the hydrothermal genetic silicon content in the lower part of in the Lower Ordovician Xinkailing Formation–Lower Silurian no. 1 section of the Lishuwo Formation in the Jiangye-1 well ranged from 5% to 20%, which indicates frequent hydrothermal activities. This increases the redox index U/Th value up to 0.5 to 1 in some layers, which reflects the weak oxidation-oxygen poor environment. The silicon minerals from the most layers in upper part of the no. 1 section of the Lishuwo Formation is derived from terrigenous detritus, with some layers containing a small amount of excess silicon content between 0–5%. This indicates that the hydrothermal activity was weakened during the late depositional period of the Lishuwo Formation. The redox index U/Th is approximately 0–0.25 and the water body was strongly oxidizing.

It is generally accepted by many scholars that hydrothermal activities are closely related to paleoproductivity [38,54–57]. Halbach et al. [55] studied the hydrothermal activity in the Fiji Basin located in the southwestern Pacific and found that the closer to the hydrothermal activity zone, the greater the number and activities of organisms, and in the hydrothermal activities zone, the abundance of these organisms will be 1 to 3 orders of magnitude higher than in the normal ocean surface. Korzhinsky et al. [56] and McKibben et al. [57] thought that hydrothermal fluids could carry many rare elements on the surface of the crust, and these dissolved trace elements contain several essential nutrients (Si, N, P, Fe, and Zn) for marine life. In addition, trace elements existing in bodies of these organisms can be in the form of "sea snow" [56,57], which go into the seafloor after biological death and provide a source of organic enrichment for the source rocks.

Similarly, the bio-productivity in the Xiuwu Basin also has some correlation with hydrothermal activities during the Late Ordovician–Early Silurian. As shown in Figure 5, the hydrothermal activities in the lower part of the Xinkailing Formation and no. 1 section of the Lishuwo Formation were frequent. Among the layers with high silicon content, the content of excess barium (Ba_{XS}) used to characterize the bio-productivity was relatively higher than the upper part of the no. 1 section of the Lishuwo Formation with weak hydrothermal activities.

Active hydrothermal activities in the Late Ordovician–Early Silurian resulted in high bio-productivity and a weak oxidation-oxygen poor environment, which made the TOC content in the lower part of the present-day Xinkailing and Lishuwo Formations up to 2–4%, and then with the weakening of hydrothermal activities, the TOC content of the upper part of the no. 1 section of the Lishuwo Formation dropped below 2% (Figure 5).

4.4. Organic Matter Enrichment Mechanism in the Upper Ordovician–Lower Silurian Shale of the Upper-Lower Yangtze Area

4.4.1. The Upper Yangtze Area

As shown in Figure 7A, during the Late Ordovician–Early Silurian, a deep-shelf environment surrounded by ancient land in the Upper Yangtze region formed due to the convergence and collision between the Yangtze and Cathaysian plates in the Upper Yangtze area. These areas were not smoothly connected with the open sea, which caused a strong closure and stratification within the water body. The upper part of water body was oxic and the lower part was suboxic. The oxic water body provided a supply for organisms to grow and reproduce, which created a rich source of organic matter for sediments. Depletion of oxygen in the lower part of the water body prevented the decomposition of sedimentary organic matter, which is good for the organic matter enrichment from the upper part.

4.4.2. The Lower Yangtze Area

As shown in Figure 7B, the Lower Yangtze area was crushed to form the foreland basin with a certain water body depth due to the collision between the Yangtze and Cathaysian plates [34,58]. In addition, hydrothermal fluids rich in silicon, uranium and other mineral elements in the deep crust went into the bottom of the water along the junction of the two plates and entered the surface of the sea through upwelling. This was conductive to the growth of plankton, as well as the bio-productivity due to the nutrients carried by hydrothermal fluids. Also, the sedimentary organic matter was conserved, and all were an advantage for sedimentary organic matter enrichment.

Based on the above studies, it can be concluded that the degree of water closure has controlled the redox environment and the biological productivity of the water body in the upper Yangtze region, which further affected the abundance of the organic matter. Thus, in the Upper Yangtze area, the favorable area for exploration is located in the central part of the cratonic basin with strong water closure; in the Lower Yangtze area, the favorable area is close to the junction between the Yangtze plate and the Cathaysian plate, in which the hydrothermal activities were active.

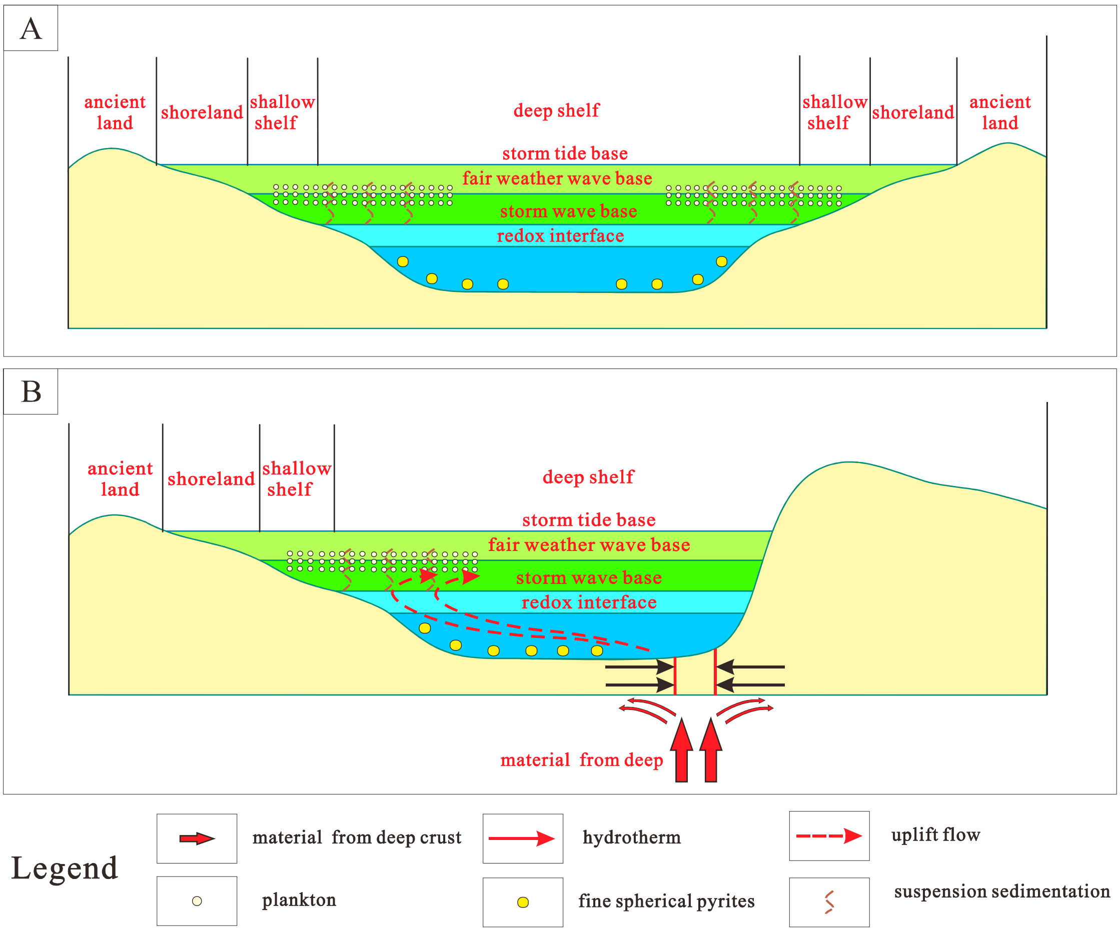

Figure 7. Organic matter enrichment pattern of the Upper Ordovician–Lower Silurian shale in the Upper-Lower Yangtze area. The Upper Yangtze area (**A**) and Lower Yangtze area (**B**).

5. Conclusions

In this paper, the Upper Ordovician–Lower Silurian marine shale strata in the Yangtze area of southern China are selected for study. Representative wells, Jiaoye-1 and Jiangye-1, are selected in the Upper and Lower Yangtze regions, respectively. Through TOC content testing, elemental analysis of cuttings, and the collected elemental well logging data, the following conclusions can be drawn regarding the organic matter enrichment mechanism:

(1) Excess siliceous minerals of the Upper Ordovician–Lower Silurian shale in the Upper Yangtze area are biogenic, while they are derived from hydrothermal origin in the Lower Yangtze area. The content of both areas decreases gradually from the bottom to the upper layers.

(2) The water closure of the Wufeng Formation and the lower part of the no. 1 section of the Longmaxi Formation in the Upper Yangtze area was relatively strong, which is consistent with the regional tectonic setting. The strong closure of the water body could lead to seawater stratification. As a result, the biological productivity of the seawater surface and the reducibility in the bottom of the seawater was enhanced, which is beneficial for the preservation of sedimentary organic matter. The water closure in the upper part of the no. 1 section of the Longmaxi Formation gradually weakened, which results in a decrease of organic matter content in the shale.

(3) Hydrothermal activities in the Xinkailing Formation and the lower part of the no. 1 section of the Lishuwo Formation in the Lower Yangtze area were active. Hydrothermal activities can enhance the reduction of the water body bottom, which promotes the increase of biological productivity and results in sedimentary organic matter enrichment. During the upper sedimentary period of the no. 1 section of the Lishuwo Formation, the hydrothermal activities weakened, which resulted in a decrease in the shale organic matter content.

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