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Study on the Main Controlling Factors of the Early Ordovician Stromatolites Development in Liujiachang Area of Songzi City

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Abstract

The Early Ordovician stromatolites in the study area are mainly exposed at the bottom and middle and lower parts of the Second Member of Nanjinguan Formation, the top of the Fourth Member of Nanjinguan Formation, the middle of the Second Member of Fenxiang Formation and the bottom of the First Member of Honghuayuan Formation. In order to find out the controlling factors of Lower Ordovician stromatolites development in the study area, the analysis data of carbon, oxygen isotope samples, macro element samples as well as their variation characteristics are studied and then combined them with previous research results, which is eventually beneficial for reaching the conclusion: sea level change is one of the main factors controlling the formation of stromatolites. There are five sea level change cycles in the Early Ordovician period. The analysis of sea level change and accommodation space variation characteristics show that when the growth rate of the accommodation space is approximately equal to that of carbonate, the circulation of seawater is well, and the amount of light and oxygen is sufficient, so that the cyanobacteria organism can be multiplied in large quantities. The growth and development provide favorable conditions, and favorable conditions are provided for the growth and development of stromatolites; The peak changes in CaO content and CaO/MgO ratio indicate that the formation period of stromatolites is arid climate environment with high water temperature and large evaporation. Prokaryote reproduction is suitable for the environments with high seawater cleanliness. When the amount of land-based debris injected into the sea increases, the turbidity of water will lead to a large number of deaths of algae microorganisms that form stromatolites, and the stromatolitic microbial mats cannot be preserved. In addition, the growth and predation of macro-organisms play a restrictive role in the development of stromatolite-forming micro-organisms blue-green algae. According to the actual situation of the development of the laminated rocks in the study area, what is the dominant function in the formation and decline of stromatolites between the evolution of metazoans and changing environments is discussed in the study.

Keywords

Stromatolite, Main Controlling Factor, Formation, The Early Ordovician

1. Introduction

The meaning of stromatolites has long been controversial. Regarding the cause of formation of stromatolites, there are two kinds of statements about the meaning of stromatolites: organic statements and inorganic statements. Organic statements are represented by Awramik and Chang Yuguang (2013). Stromatolites are a kind of microbial rocks. They are a special biological sedimentary structure formed by capturing, binding or promoting mineral deposits caused by the growth and metabolic activities of cyanobacteria, algae and other microorganisms living in shallow sea environments. The most prominent feature is the striation structure with alternating light and shade [1]. The inorganic theory is represented by Tang Dongjie (2012) and others. It refers to the fact that some stromatolites are recognized as a kind of submarine carbonate deposit under specific marine living conditions due to the lack of evidence of some microbial fossils [2].

The study of stromatolites has a long history in China. In the 1920s, Grabau (1922) first introduced Walcott's concept of stromatolites. With the discovery of stromatolites in Precambrian strata, the potential value of stromatolites is slowly being explored [3]. For the study of Ordovician stromatolites in China, Du Rulin *et al.* (1993) and Cao Ruiji *et al.* (1987, 1993) conducted a comprehensive and in-depth study of early Paleozoic stromatolites reefs in North China [4]. Jiang Liping, Wang Jianpo and others (2014) studied on the structural characteristics of the lower Ordovician stromatolites in Shitai, South Anhui Province and discussed the interference of biological, physical and chemical factors on the stromatolites [5]. The study of Ordovician stromatolites by Hu Bin *et al.* (2014) in Jiaozuo Area, northwestern Henan Province enriched the environmental characterization of stromatolites and the exploration significance of Ordovician source rocks [6]. At present, the study of stromatolites by geologists in China is still concentrated on Proterozoic, with a small amount in Cenozoic and modern times, while the study of Ordovician stromatolites in Paleozoic is very little. There is little research on the Ordovician stromatolites in the study area. Therefore, it is believed that the further study of the early Ordovician stromatolites in Liujiachang Area, Songzi Cith, Hubei Province is of great significance of the characterization of the main controlling factors of the rich stromatolites, and can also be used to indicate the paleoclimate. Through the reconstruction of the paleoenvironment, it provides further understanding of the early Ordovician climate and certain guiding significance for the study of environmental changes.

2. The Regional Geological Background of Liujiachang Area

Liujiachang Town is located in the southwest margin of Songzi City in Hubei Province. On the geotectonics, it experiences the influence of Indosinian period to Yanshanian period multi-stage tectonic movements. The Sinian to Tertiary systems in the area are widely developed and belong to the middle section of Yangtze stable landmass. In the ancient geographical position, Liujiachang Area is located in the middle Yangtze carbonate platform. The lower Ordovician profile in the area is continuously exposed, with widespread stromatolite development and good exposure. It has good similarity with the standard profile of Huanghua Field of Ordovician in Yangtze platform. In the ancient geographical position, Liujiachang Area is located in the middle Yangtze carbonate platform. Liujiachang Town is located in the southwest margin of Songzi City in Hubei Province. On the geotectonics, it experiences the influence of Indosinian to Yanshanian multi-stage tectonic movements. The Sinian to Tertiary systems in the area are widely developed and belong to the middle section of Yangtze stable landmass. In the ancient geographical position, Liujiachang Area is located in the middle Yangtze carbonate platform (**Figure 1**). The lower Ordovician profile in the area is continuously exposed with widespread stromatolite development and good exposure. It has good similarity with the standard profile of Huanghua Field of Ordovician in Yangtze platform.

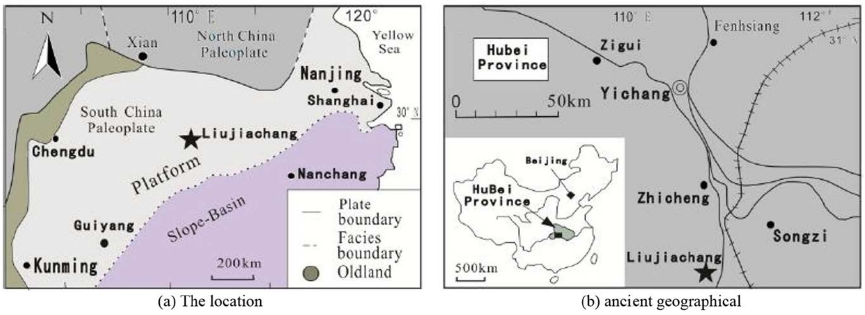

Figure 1. The location and ancient geographical map of Liujiachang area.

3. Early Ordovician Stromatolite Type and Its Stratigraphic Distribution in Liujiachang Area

The section of Liujiachang Area in Songzi City is 390 m thick in the early Ordovician. There are five stromatolitic limestones in the early Ordovician strata, of which three are exposed in the Nanjinguan Formation and one in Fenxiang Formation and the Honghuayuan Formation. The specific exposure and distribution characteristics are analyzed as follows:

3.1. The Type and Distribution of Stromatolites in Nanjinguan Formation

The Nanjinguan Formation in Liujiachang Section of Songzi is rich in lithologic types, with sandy limestone, bioclastic limestone, dolomite and shale, 3 stromatolites are exposed. The formation is divided into 4 sections. A set of gray medium-thick sandy limestone, bioclastic limestone and shale are developed in the First Member of Nanjinguan Formation, where trilobite, conodont and brachiopod *Nanorthis* sp. Fossils are induced.

The Second Member of Nanjinguan Formation is mainly composed of grayish white medium-thick sand bioclastic limestone and grayish yellow thin banded micritic limestone and banded calcareous mudstone interbedded with columnar and wavy stromatolites. The first stromatolite is exposed at the bottom of the second section and is about 2.7 - 3.2 m thick. There exists a thick layer, massive wavy laminated limestone. In the transverse direction, there are small clumps of sand or dust in the dark layer. A large number of clumps can be observed at the trough between the dark layer and the adjacent wavy layer, ranging in size from 1.5 - 6 cm. In addition, sand and biological debris can also be seen. The bright and dark grain layers show different characteristics. The dark grain layers are mostly irregular dark gray bands, while the bright grain layers are mostly gray discontinuously irregular bands. The interval between the bright and dark grain layers is obvious, and in general the bright layer is slightly larger than the dark layer. The second part of the stromatolite is exposed in the lower part of the Second Section of Nanjinguan Formation. The thick gray layer—massive columnar laminated limestone is about 2.5 - 2.9 m thick. The columnar stromatolite is composed of a plurality of columnar bodies stacked vertically and bent upward independently. The transverse sections of the columnar bodies are mostly circular, oval and irregular oval, etc. the diameter is 8 - 50 cm, and the height is 40 - 180 cm. Fenxiang Formation consists of a set of yellow-green shale, gray to light gray medium-thick layer of gravelly sand limestone and algal reef limestone. The lower part of the second section is developed with gray thick layer—massive wavy laminated limestone, which is about 7.5 - 8.2 m thick. The bottom is light gray bright crystal sand debris and bioclastic limestone, and the top is yellow mudstone. In the transverse direction, the striation layer mostly shows regular undulations, with a wavelength of 5 - 40 cm, mainly about 15 cm, with a wave height of 1 - 15 cm and mainly about 5 cm.

3.2. The Type and Distribution of Stromatolites in Fenxiang Formation

Fenxiang Formation consists of a set of yellow-green shale, gray to light gray medium-thick layer of gravelly sand limestone and algal reef limestone. The lower part of the second section is developed with gray thick layer—massive wavy laminated limestone, which is about 7.5 - 8.2 m thick. The bottom is light gray bright crystal sand debris and bioclastic limestone, and the top is yellow mudstone. In the transverse direction, the striation layer mostly shows regular undulations, with a wavelength of 5 - 40 cm, mainly about 15 cm, with a wave height of 1 - 15 cm and mainly about 5 cm. The sub-township formation consists of a set of yellow-green shale, gray to light gray medium-thick layer of gravelly sand limestone and algal reef limestone. The lower part of the second section is developed with gray thick layer-massive wavy laminated limestone, which is about 7.5 - 8.2 m thick. The bottom is light gray bright crystal sand debris and bioclastic limestone, and the top is yellow mudstone. In the transverse direction, the striation layer mostly shows regular undulations, with a wavelength of 5 - 40 cm, mainly about 15 cm, with a wave height of 1 - 15 cm and mainly about 5 cm.

3.3. The Type and Distribution of Stromatolites in Honghuayuan Formation

The Honghuayuan Formation is characterized by the development of reef limestone. At the bottom of the formation, there is a gray thick layer—massive stromatolite calcathaium limestone, about 2.2 - 2.5 m thick, with light gray bright crystal bioclastic limestone at the bottom and yellow mudstone at the top. The stromatolites in this layer mainly exist in the form of algal laminae. They can grow in separate laminae wrapped with each other or around caladium. Generally speaking, the stromatolites of the Honghuayuanare Formation are mostly blocky or mound-shaped. In the transverse direction, the stromatolites of Honghuayuan are irregularly wavy with uneven peaks, with a wavelength of about 6 - 10 cm and a wave height of 5 - 15 cm. The striations are usually wrapped. A small amount of biological debris and sand debris can be seen between the striations.

4. The Main Controlling Factors for the Growth and Development of Stromatolite

There are many factors that affect the growth and development of stromatolites. This paper holds that the main controlling factors for the growth and development of stromatolites are "external factors"—sedimentary environment and "internal factors"—macro biological effects. The influence of sedimentary environmental factors is mainly manifested in salinity, temperature, changes of ancient sea level, sequence control and terrigenous debris.

4.1. Sedimentary Environment

4.1.1. Sea Level Change and Sequence Control

Sea level changes greatly change some environmental factors such as water depth, water energy and oxygen content. Each sea level change cycle includes different types of sequence changes. Therefore, sequence is one of the decisive factors for the formation of stromatolites, which directly controls the accommodation space. When the growth rate of the accommodation space is approximately equal to the accumulation rate of carbonate, the circulation of seawater is good and the amount of light and oxygen is sufficient, thus causing the blue fungus organisms to multiply in large quantities and providing favorable conditions for the growth and development of stromatolites [7]; Stromatolites occur near the sequence boundary, in the low system tract and in the high system tract (**Figure 2**). According to this distribution feature of stromatolites, the study area is divided into five sea level change cycles of the Early Ordovician Nanjinguan Formation, the sub-township formation and the Honghuayuan Formation. The first cycle occurs in the First and Second Sections of Nanjinguan Formation, the second cycle occurs in the Third and Fourth Sections of Nanjinguan Formation, the third cycle occurs in the First Section of the Fenxiang Formation, the fourth cycle occurs in the Second Section of the Fenxiang Formation and the fifth cycle occurf in the First and Second Sections of the Honghuayuan Formation. The above sea level change characteristics are described as follows:

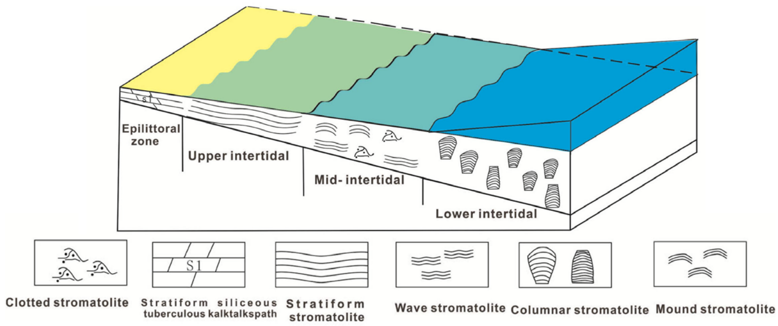

Figure 2. The sedimentary pattern of stromatolites.

Cycle I corresponds to the First and Second Sections of the Nanjinguan Formation. Due to this sea level rise, a set of brilliant arenaceous limestone, bioclastic limestone, shale and argillaceous limestone sedimentary assemblages are developed at the early and middle stages of the Nanjinguan Formation. The system tract is dominated by retrogradation-aggradation sub-sequence stacking. There are several secondary sea level cycles during this period. During the period of high sea level, the growth rate of the accommodation space slows down and gradually stabilizes and is equal to the deposition rate of sediments. The seawater gradually becomes shallow and circularly stable, and light is sufficient, thus causing the blue fungus organisms to multiply in large quantities and form large wavy to columnar stromatolites.

Cycle II corresponds to the Third and Fourth Sections of Nanjinguan Formation. The second sea level cycle occur in the study area in the late period of Nanjinguan Formation. During the sea level rise period, an aggradation-progradation type sedimentary quasi-sequence characterized by tuff, granular limestone and dolomitic limestone is formed. During the period of high system tract, the growth rate of accommodation space slows down and the sea water is unstable and limited. Dolomitic sandy limestone with large cross bedding is developed. Some microbes are abundant in water and small stromatolites are formed.

Cycle III corresponds to the First Segment of the Fenxiang Formation, due to the slow rise in sea level, the growth rate of the accommodation space is slowed down, the seawater energy is relatively high, and several sets of bright grain grey rock formations are developed. The development mode of the sub-sequence in the high system tract transits from retrogradation to aggradation accumulation. When the growth rate of the accommodation space is slowed down to approximately the same rate as that of carbonate accumulation, the seawater circulation is good and stable, the oxygen content and light in the water body are sufficient, and a large number of macrofossils such as brachiopods and trilobites are developed, at the same time, cyanobacteria and algae are bonded to capture sediments to form nucleatemicrobial rock deposits under high energy conditions.

Cycle IV occurs in the Second Member of Fenxiang Formation. During the sea level rise period, due to the large rise of the sea surface, a relatively thick shale deposit is formed in the study area, in which widely distributed biological fossils such as floating graptolite *Dictyonema*, brachiopods and trilobites are developed. During the period of high water level, accompanied by several sub-level sea level changes, a number of granular limestone and shale subsequence rhymes are superimposed. At the early stage of high water level, the growth rate of accommodation space is slowed down and gradually stabilized and is nearly equal to the deposition rate of sediment. Seawater gradually becomes shallower and circulates well, and light s very sufficient, as a result, blue fungus organisms are massively propagated and forms large wavy to columnar stromatolites. At the bottom of the red garden formation at the late stage of high water level, wavy stromatolites and bottle basket reefs are also formed.

Cycle V occurs in the First and Second Sections of the Honghuayuan Formation and enters the early stage of the Honghuayuan Formation and still maintains the state of high sea level at the end of the sub-village stage. A relatively rapid rise in sea level occurs immediately after the event. During the period, accompanied by several sub-level sea level changes, a number of shales are superimposed with sub-sequence rhythms of granulite limestone, bottle basket stone and other macro reef limestone. With the gradual decline of sea level, the expansion rate of the accommodation space is close to the deposition rate of sediments, a balanced carbonate deposit is formed, which provides favorable conditions for the growth of cyanobacteria.

4.1.2. Paleosalinity

Stromatolites widely existed in various water environments in Precambrian, but declines rapidly after entering Phanerozoic. After studying modern marine stromatolites such as the Bahamas, Shark Bay in Australia, and Sabkha stromatolites in Kuwait, Riding and Pentecost pointed out that the salinity of water was one of the important factors affecting the sharp decrease of stromatolites after Precambrian. This conclusion based on the study of modern marine stromatolites is still of guiding significance to the study of stromatolites in geological history [8].

Epstein and Mayada (EP stein and Maya da, 1953) established the basic principle of using $\delta^{18}O$ to calculate paleosalinity, and pointed out that $\delta^{18}O$ would also increase with the increase of salinity. Claydon and Dickens (1959) pointed out that carbon isotope in carbonate rocks was also related to salinity. Keith and Weber (1964) combined $\delta^{18}O$ and $\delta^{13}C$ to indicate the paleosalinity and put forward equations to distinguish marine facies and freshwater carbonate rocks $Z = 2.048(\delta^{13}C + 50) + 0.498(\delta^{18}O + 50)$ (δ standard is PDB) [9]. In order to verify the reliability of this formula for the determination of paleosalinity, a correlation analysis is made between *Z* value and $\delta^{18}O$ and *Z* value and $\delta^{13}C$ in the study area. The correlation analysis shows that the correlation coefficient between *Z* value and $\delta^{18}O$ is 0.3241, and the correlation coefficient between *Z* value and $\delta^{13}C$ is 0.975 (**Figure 3**). These analysis results indicate that the *Z* value of the early Ordovician in the study area mainly reflects the relationship with $\delta^{13}C$, so *Z* value is not suitable for reflecting paleosalinity information [10] [11]. In addition to the carbon and oxygen isotopes analyzed earlier, which can be used to characterize the paleosalinity, the ratio of characteristic elements in sediment is also indicative of the paleosalinity. For example, Sr/Ba (**Figure 4**). Generally, Sr/Ba mainly reflects the salinity of water, the higher the ratio is, the greater the salinity is, which reflects the hot and dry climate. The lower the ratio is, the smaller the salinity is, which reflects the low temperature and humid climate.

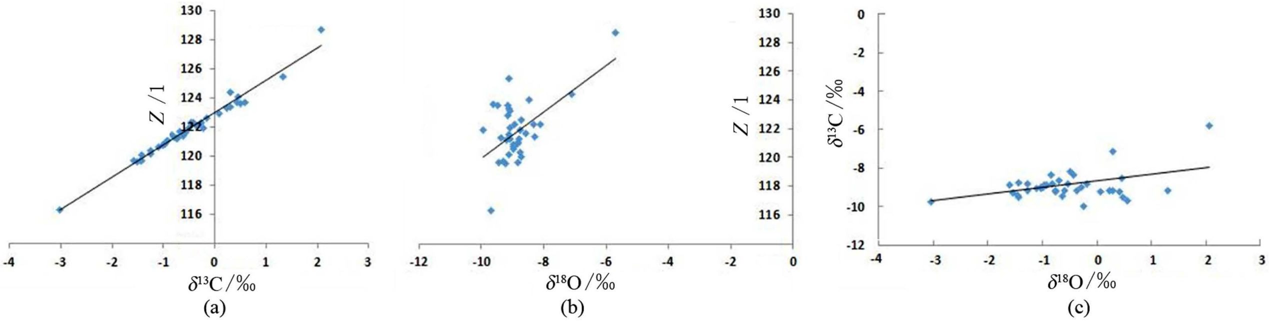

Figure 3. The correlation analysis of carbon-oxygen isotope and *Z* Value in Early Ordovician carbonate of Liujiachang Area.

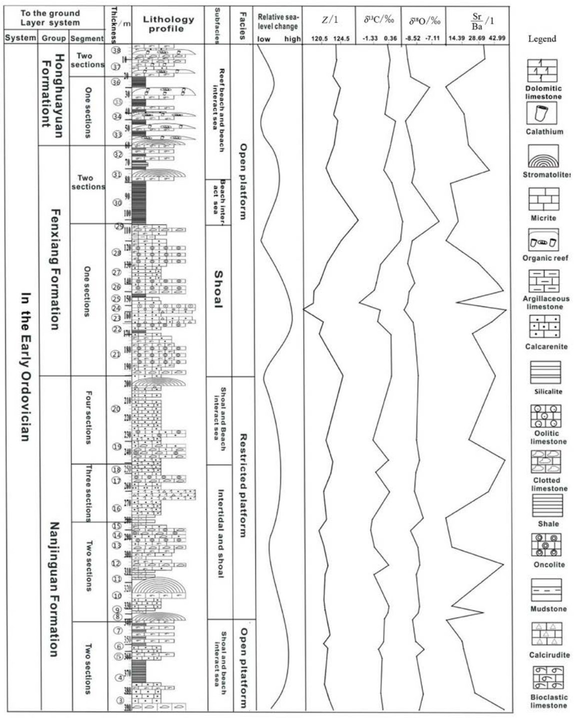

Figure 4. The sedimentary histogram and vertical variation of isotope and trace elements in Early Ordovician of Liujiachang.

4.1.3. Ancient Temperature

Modern stromatolites are mostly distributed in tropical and subtropical regions, such as Nevada, California and the Bahamas. Temperature is another important factor controlling the photosynthesis of blue-green algae. Wang Ziqiang (1982) cultured and observed modern stromatolites indoors, when the highest temperature was higher than 15˚C, cyanobacteria began to grow [12]. Zhu Shixing *et al.* (1993) believed that the distribution of algae mats in Yantian was controlled by factors such as temperature and water depth [6]. These all reflect that temperature affects the formation of stromatolites by affecting the growth and development of micro-organisms that form stromatolites.

Oxides CaO and MgO in seawater are derived from geochemical process products in seawater. CaO/MgO content is mainly related to the evaporation rate, which is closely related to climate. Hot and dry weather conditions promote the evaporation of sea (lake) water and accelerate precipitation of CaO [13]. From the line chart of CaO content and CaO/MgO values in the study area (**Figure 5**), it can be seen that both CaO content and CaO/MgO values in the exposed area of stromatolite peak, indicating that stromatolite is mainly formed in arid climate environment with high water temperature and large evaporation capacity.

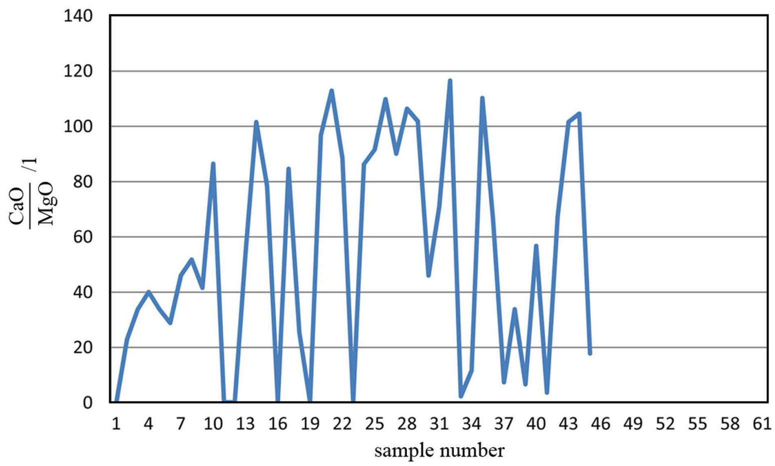

Figure 5. The variation of CaO/MgO values in the study area.

4.1.4. Terrigenous Debris

Oxides of some terrigenous debris such as SiO_2, Al_2O_3, Fe_2O_3, MnO, TiO_2 and P_2O_5 can reflect the amount of terrigenous debris injected into the sea at the same time to some extent. The influence of terrigenous debris on the growth of stromatolite-forming bacteria and algae was the fundamental cause of the influence of terrigenous debris on stromatolite formation [14] [15]. The content of these oxides is basically the lowest among the stromatolites in the study area, geochemical analysis and comparison shows that the stromatolites have lower SiO_2, Al_2O_3, Fe_2O_3, MnO, TiO_2 and P_2O_5 content compared with other contemporaneous rocks (**Table 1**), indicating that the stromatolites in the study area are formed in clean water environment where the amount of continental debris injected is quite a bit. Because prokaryotes are suitable for the environments where seawater is relatively clean, water turbidity caused by the increase in the amount of land-based debris injected into the sea induces large number of deaths of algae microorganisms that form stromatolites and thus the stromatolites microbial mats cannot be preserved. This also reflects that the amount of land-based debris injected greatly affects the growth and development of stromatolites.

Table 1. The comparison of terrigenous debris content in stromatolite and ordinary limestone in the study area.

Lithology of sample	mass fraction/%					
	SiO_2	Al_2O_3	Fe_2O_3	MnO	TiO_2	P_2O_5
Stromatolites	2.53	0.05	0.48	0.36	0.02	0.01
Argillaceous banded limestone	17.62	0.27	5.49	2.37	0.03	0.01
Bioclastic limestone	9.04	0.14	2.66	1.19	0.09	0.18
Dolomitic limestone	2.23	0.04	0.21	0.16	0.00	0.01

4.2. Metazoan Effect

Zhang Yuandong, Zhan Renbin, *et al.* (2009) proposed that since the great radiation of Ordovician organisms, especially after the middle Ordovician, the number of phytophagous gastropods, sea urchins, ostracods, etc. has increased significantly. They mainly feed on marine micro-organisms. At the same time, some gastropods, trilobites, ostracods, etc. that feed on marine sedimentary soft mud continued to multiply in large quantities [16]. Cao Ruiji and others found the stromatolites in the Neoproterozoic Shijiachong Formation, leaving obvious "scars" similar to those caused by drilling holes and herbivores [17]. Ge Jingyan (2017) believed that early Ordovician micro-organisms were gradually replaced by metazoan organisms and algae gradually disappeared [18]. Based on the evidence that the stromatolites flourishes at the end of the early Ordovician and the number of stromatolites decreases greatly in the middle Ordovician, it can be inferred that macro-organism plays a restrictive role in the development of the micro-organism blue-green algae that formed stromatolites. The effect of macro-organism on the growth and development of stromatolites fundamentally affects the growth and development of stromatolite-forming microorganisms. The specific effect is illustrated by the biological evolution of the Early Ordovician sub-township formation and the Nanjingguan Formation. The middle and upper parts of the Fenxiang Formation are developed with Termadocian reef [19], with 1 community group and 4 community zones (Table 2).

4.2.1. Gastropods

When *Batostoma* community zone I evolves to *Caladium*-blue green algae community zone, *Archaeoscyphia*, which depends on filtering food from flowing water, is difficult to flourish in *Calathium*-blue green algae community due to the weak circulation of water, and the decrease in the number of filtering food organisms also weakens the filtering food function, thus being more beneficial to the prosperity of micro-organisms blue green algae. Gastropods, which widely exist in the two community zones, destroy the drilling of *Calathium* and also destroy the blue-green algae that are linked to and wound with *Calathium*, thus affecting their adsorption and adhesion to external stucco and carbonate sediments, which is also not conducive to the formation of stromatolites.

Table 2. The Early Ordovician biocommunity evolution and distribution in Liujiachang Area (quoted from Xiao Chuantao *et al.*, 1994; Cheng Jun *et al.*, 2017).

<table>
<tr><td rowspan="7">Songzi Hubei</td><td colspan="2">Fenxiang Formation</td></tr>
<tr><td colspan="2">Community Batostoma Community Ⅰ—Calathium-blue-green algae Community zone—Archaeoscyphia Community zone—Batostoma Community zone II

Community Batostoma Community zone II, Archaeoscyphia Community zone, Calathium-blue-green algae Community zone, Batostoma Community zone II</td></tr>
<tr><td colspan="2">Honghuayuan Formation</td></tr>
<tr><td>One sections</td><td>Two sections</td></tr>
<tr><td>Sea Lily barrier reef—Algae-Calathium bonding-Barrier reef—Bryozoa barrier reef</td><td>Calathium bonding-barrier reef</td></tr>
<tr><td colspan="2">Nanjinguan Formation</td></tr>
<tr><td colspan="2">Pelmatozoan community, Pelmatozoan-Crustacean Cyanobacteria, Pelmatozoan-Silicified Sponge-Cyanobacteria community, echinoderm-blue-green algae community</td></tr>
</table>

4.2.2. Archaeoscyphia

When the *Calathium*-blue-green algae community zone-*Archaeoscyphia* (ancient pot sponge) community zone evolves, as the water body gradually deepens, the light and oxygen decrease, the content of blue-green algae also decreases correspondingly, the water body circulation state becomes better, the *Archaeoscyphia* increases greatly, and the amount of caladium decreases greatly. Because the ecological function and the ecological environment of *Calathium* are similar to that of *Archaeoscyphia*, this largely indicates that they are participating in the formation of food chain and competing for living space or living space. The blue-green algae with the main ecological function of linking and winding *Calathium* will lose the object of clinging and winding as the number of *Calathium* is greatly reduced, and "sinking in the water bottom" cannot be exposed to sufficient light and photosynthesis is limited. This series of factors will affect the number of blue-green algae.

4.2.3. Bryozoa

At the first stage of Honghuayuan Formation, the sea lily barrier reef is mainly developed in the early stage. In the middle stage of the sea level rise, the number of sea lilies decreases sharply, and the number of *Calathium* and blue green algae increases correspondingly. At this time, the algae—*Calathium* bonding—barrier reef is mainly formed, and a certain scale of stromatolite is developed. At the second stage of the Honghuayuan Formation, the bryozoa is added, while the number of blue green algae is obviously reduced. At this time, the biological reef is mainly bottle basket worm—bryozoa barrier reef, and the stromatolite is hardly developed. The number of marine filter food animals in bryozoa increases. Because bryozoa is often fixed on algae [20], the dense growth and non-uniform distribution of shells in the research area have greatly suppressed the living space of blue-green algae. At this time, the area is in a relatively deep water environment. These two main reasons lead to the large-scale development of blue-green algae in the area. Only a small amount of blue-green algae cannot bond to form stromatolites. Finally, bryozoon and the bottle basket worms jointly build reefs to form Calathium-bryozoa barrier reef.

4.2.4. Echinoderm

A large number of echinoderm fossils, *i.e.* crinoid stems, are found in the strata of the First and Second members of the Nanjinguan Formation in the study area, and the distribution of crinoid stem in the Second Member of Nanjinguan Formation is higher than that in the First Member of Nanjinguan Formation. In the strata of the Second Member of the Nanjinguan Formation with a large number of crinoid stem, wave and columnar stromatolites also happened to develop, and crinoid also often formed reefs together with blue-green algae [21]. According to the individual and community ecology, the reefs of the Nanjinguan Formation in the study area were divided into four major biological communities (**Table 2**) [22] in *Pelmatozoan* community and *Pelmatozoan*-Crustacean Cyanobacteria, *Pelmatozoan*-Silicified Sponge-Cyanobacteria community, although the abundance of crinoid and blue-green algae has changed, the ecological functions of the two are basically stable. According to the preserved state of the root of the crinoid stem, it can be seen that its function is to grow firmly in situ and resist waves. The lower microorganism cyanobacteria are mostly striated and grown around the crinoids, their ecological function is to wrap barrier organisms, the two together form a relatively solid anti-wave framework, which helps to form large-scale reefs and provides a stable foundation for the development and evolution of communities.

5. Discussion

Stromatolites, like other organisms, have experienced an evolutionary pattern from simple to complex pattern in geological history, from local development to the peak of development and then gradually decline. However, due to the limitation of the distribution of stromatolites fossils and the uncertainty of metazoan origin [23], the attenuation of stromatolites in a certain period of time has brought uncertainty. There are generally two tendencies to explain the reasons for the attenuation of stromatolites: the tendency of metazoan mechanism of action and the tendency of sedimentary environment reform mechanism.

At present, the research on the relationship between microbial rocks and metazoan is also a hot field in the world. Some scholars believe that the decline of stromatolite in geological history has a certain relationship with metazoan action [22]. Metazoan action includes: eating, drilling, supporting, etc. Xiao Chuantao and Cao Juan discovered a large number of blue fungus microbial fossils *Girvanella* [24] [25] in the stromatolites of the Honghuayuan Formation. They found echinoderm that jointly built reefs. With the prosperity of echinoderm, such stromatolites gradually decreased, which was in line with the viewpoint [26] [27] that prosperity of metabenthos caused the decline of microbial rocks. With the prosperity of metazoan benthic animals, bacteria and algae microorganisms that form stromatolites are continuously filtered and eaten and drilled to cause the destruction of stromatolites. Reid *et al.* found a large number of traces of internal laminae destroyed and preserved in laminae by creatures such as clams and sponges in modern stromatolites [28]. Cao Ruiji *et al.* found biological boreholes and scars left by herbivores' destruction in stromatolites of Neoproterozoic Shijiachong Formation, Maqiao Area of Baokang County, Hubei Province [29], these all illustrate the reduction in the longitudinal distribution of stromatolites and the disturbance of filtering food of metazoan flora to the formation of stromatolites.

Some scholars also questioned that stromatolites, like other organisms, also depend on the surrounding ecological environment during their development. Through isotopic age determination of strata in which stromatolites are distributed, relative abundance determination of metazoan and corresponding database analysis, metazoan experienced at least five mass extinctions in the Phanerozoic, among which only the number of stromatolite morphological species in the late Devonian and late Permian showed a rebound phenomenon, while no geological record of stromatolite morphology and increase in number appeared after the three mass extinctions in the late Ordovician, late Triassic and late Cretaceous [23]. During the Cambrian period, the proliferation of microbial carbonates is coincided with the radiation of metazoan, which contradicts the viewpoint that metazoan competition significantly restricts the development of microbial carbonates or stromatolites. Based on the study of the environmental and resource variables in the stromatolite layer around the coast of southern Africa, the result shows that there is no obvious relationship between the biomass or composition of stromatolite microalgae and the metazoan community occupying the stroma. This result shows that invertebrates may rely on other primary producers as food resources, such as macroalgae. This indicates that the benthic community may have limited direct grazing effect on stroma and will not hinder the formation of structure [30]. Metazoan prosperity is not the only reason for the scarcity of microorganisms. Other factors that appears in the Cambrian period [31] [32], such as the decrease in calcium carbonate concentration in seawater [33] and changes in nutrient availability [34] may also contribute to the decline in the number of metazoan.

In this study area, the Echinodermata has not only fixation barrier effect, but also food filtering effect. During the transition period from the First Section of

Nanjinguan to the Second Section of Nanjinguan, the abundance of sea lilies and cyanobacteria show a growth pattern of "eliminating each other". In the First Section of Nanjinguan Formation, the abundance of sea lilies is much larger than that of stromatolites, while in the Second Section of Nanjinguan Formation, the number of stromatolites has recovered and started to form a large number of reefs. In view of this special situation, the following analysis is carried out: both the fixation barrier and the filtering effect of echinoderms with handles belong to metazoan, which disturbs the growth of stromatolites to a certain extent. Through the analysis and comparison of the corresponding major trace element indexes of the First and Second Sections of Nanjinguan Formation, the relative enrichment degree of Na and Sr/Ba in the First to Fourth Sections is higher than that in the Fifth to Eleventh Sections (**Table 3**), which shows that the salinity of the First Section of the Nanjinguan Formation is higher than that of the Second Section of the Nanjinguan Formation, Na is an important indicator of seawater salinity [35], the high value represents the dry-hot climate, and the low value represents the wet-warm climate, which is consistent with the indication meaning of Sr/Ba in **Table 1**. Based on the sea level change cycle of the Second and Second sections of Nanjinguan (**Table 1**), it is not difficult to find that the sea level from the First Section to the Second Section of Nanjinguan is slowly falling and tends to be stable. The salinity of seawater also rises with the decline of sea level. At this time, the salinity is suitable for the growth of stromatolites, instead inhibiting the growth of metazoan. To sum up, the changes in the abundance of stromatolites are the result of the comprehensive action of metazoan and ecological environment. Compared with metazoan, the influence of ecological environment on stromatolites is more obvious.

Table 3. The distribution of main trace elements in Nanjinguan Formation of Liujiachang Area (ug/g).

Sample number	Position	mass fraction/%			Sr/Ba
		Na	Sr	Ba	
LO1s-3-TO	One sections (Nanjinguan Formation)	0.05	262.63	4.89	53.67
LO1n-4-TO		0.05	226.90	4.37	51.97
LO1n-5-TO		0.06	325.65	11.22	29.03
LO1n-7-TO		0.07	348.27	22.57	15.43
LO1n-7-WC2		0.10	368.36	281.56	0.24
LO1n-8-TO	Two sections (Nanjinguan Formation)	0.07	355.77	24.37	14.60
LO1n-9-TO		0.09	263.02	128.95	2.04
LO1n-10-TO		0.05	381.31	11.63	32.79
LO1n-11-TO		0.07	467.29	74	6.31
LO1n-12-TO		0.06	299.40	5.61	53.41
LO1n-13-TO		0.05	338.49	6.65	50.87
LO1n-14-TO		0.06	306.68	25.87	11.86

6. Conclusions

Based on the previous research results, this paper discusses the main controlling factors of the lower Ordovician stromatolite development in the study area by combining the analysis data of carbon and oxygen isotope samples, trace and major element samples and their variation characteristics, and obtains the following conclusions and understandings.

1) Sea level change is one of the main factors controlling the formation of stromatolites. There are five sea level change cycles during the early Ordovician period. The change of sea level directly controls the accommodation space. When the growth rate of accommodation space is approximately equal to the accumulation rate of carbonate, the seawater circulates well and the light and oxygen are sufficient, thus causing the blue fungus organisms to multiply in large quantities and providing favorable conditions for the growth and development of stromatolites.

2) Analysis of the correlation between C and O isotopes and Z values of carbonate rocks in the study area and Sr/Ba vertical change map show that the laminated limestone is exposed in the high Sr/Ba area, *i.e.* the growth and development of the laminated limestone in the study area is in the high salinity area.

3) The exposed area of stromatolite shows peaks in the CaO content table and the CaO/MgO value line chart in the study area, indicating that the formation period of stromatolite is a dry climate environment with high water temperature and large evaporation.

4) Prokaryotes are suitable for environments where seawater is relatively clean. When the amount of land-based debris injected into the sea increases, the turbid water induces a large number of death of algae microorganisms that form stromatolites; thus the stromatolites microbial mats cannot be preserved.

5) The growth and predation of macro-organisms play a restrictive role in the development of micro-organisms blue-green algae that form stromatolites. This is mainly reflected in the drilling and destruction of gastropods, the competition for living space between organisms with similar living habits, and the feeding of filter-feeding organisms on micro -organisms.

6) Through the analysis and comparison of the growth of stromatolites in the study area, and the comprehensive analysis of macro-animal effect and the influence of ecological environment on stromatolites, it is revealed that the influence of ecological environment in the study area should be significantly different from that of metazoan.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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