Calcified Biofilms from Cambrian Oolitic Limestones in China

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Abstract: Calcified biofilms are preserved as thin micritic coatings in the Cambrian oolitic limestone of two sections in North and South China. Standard petrographic examination revealed that the biofilms were developed during the early diageneric stage immediately after the freshly deposited ooids, proceeding in the continuous sequence of depositional processes. The biofilm outlines are highly irregular, with steep sides, tower-like structures and overhanging projections; the internal fabric of the biofilms is composed of roughly laminated micrite aggregates with channel-like structures. Biofilms exhibit a strong fluorescent reaction. Detailed SEM examination suggests that the biofilms are biotically dominated by cyanobacteria. Our study demonstrates that microbial colonies, such as biofilms, can develop on ooid cortices and influence the formation and microstructures of those ooids.

Key words: geobiology, ooids, micrite, cyanobacteria, Cambrian, Hubei and Shaanxi provinces

1 Introduction

Biofilms are generally defined as submillimetric coatings in benthic systems formed by complex communities of microorganisms growing in a matrix of extracellular polymeric substances (EPS) (Wimpenny, 2000; Hall-Stoodley et al., 2004; Branda et al., 2005). They are formed by various microbes, such as archaeans, bacteria, eukaryotic algae, fungi, and protozoans, and thrive in a diverse range of modern and ancient ecosystems (Costerton et al., 1995; Costerton and Stoodley, 2003; Denkhaus et al., 2007). Biofilms are capable of forming organic and mineral deposits by interaction between the substrates, water bodies, and the atmosphere, thus they have preservation potential, and can be recognized in ancient rocks (Riding, 2002). The discovery of a variety of morphologies of silicified and phosphatized biofilms in Archean rocks from South Africa and Australia (Hofmann et al., 1999; Westall et al., 2001; Westall et al., 2003), respectively, indicates that biofilms were present on Earth at least 3.5 billion years ago.

Studies on carbonate sediments also provide evidence that it is feasible for the calcification of biofilms in carbonate sedimentary environments (Riding, 2002). In situ experiments mimicking the natural process of low-Mg calcite precipitation illustrated that biofilms played a substantial role in low-Mg calcite ooid cortex formation in the early stage of ooid formation (Plee et al., 2008). Their experiment bridged the gap between field observations and laboratory experiments, and confirmed the point of view that microbes and their metabolic activities promoted the genesis of cortical layers in ooids (Buczynski and Chafetz, 1991; Folk, 1993; Gerdies et al., 1994; Knorre and Krumbein, 2000; Folk and Lynch, 2001; Plee et al., 2008; Liu and Zhang, 2012).

In this paper, a detailed study of calcified biofilms from China, which were formed during the earliest diageneric stage, is coupled with microfacies analyses of the oolitic limestone to elucidate the formation processes of biofilms in this case.

2 Materials and Methods

2.1 Localities and stratigraphy

The samples were collected from two localities, the Wangjiaping section in the Three-Gorge area of Hubei Province, South China, and the Tushan section of the Hancheng area in Shaanxi Province, North China (Fig. 1).

Stratigraphic studies have been carried out at the Wangjiaping section for decades (Wang et al., 1987; Zhang and Hua, 2005). It has been suggested as a Cambrian standard section in China (Wang et al., 1987). The Lower Cambrian here is subdivided into four units including in ascending order, the Shuijingtuo Formation, Shipai Formation, Tianhebian Formation, and Shilongdong
Formation (Fig. 1). The oolitic limestone samples were collected from the bottom of the Tianheban Formation, which is dominated by banded argillaceous limestone.

Cambrian strata of the North China Platform are well developed in the Hancheng area, especially in the Tushan section. The Cambrian here is dominated by platform carbonate facies (Luo, 2002), and subdivided into six lithological units in ascending order termed the Huoshan Formation, Mantou Formation, Maozhuang Formation, Xuzhuang Formation, Zhangxia Formation, and Sanshanzi Formation (Fig. 1). The study materials come from the uppermost oolitic limestone of the Xuzhuang Formation, which is composed of argillaceous limestones interbedded with oolitic limestone and silty shales.

2.2 Methods

Oolitic limestones were systematically sampled in outcrops of the two studied localities. Determination of microfacies and microstructures are based on the study of polished slabs and thin sections under polarizing microscope. The Scanning Electron Microscope (SEM) and the UV fluorescence microscope were used to investigate surface morphology and the detailed characteristics of the calcified biofilms. All analyses were carried out at the State Key Laboratory of Continental Dynamics, Northwest University, Xi’an, China.

3 Results

3.1 Petrographic examination

Standard petrographic examination revealed that sample materials from Wangjiaping section were mostly unaffected by diagenetic processes. Major constituents are ooids and calcite cements except for a small amount of peloids and skeletal grains. There are three types of ooids including concentric, radial and micritic ooids. The size of ooids varies with ooid type: concentric ooids (1.0–2.0 mm in diameter) are relatively larger in size than radial ooids (0.5–1.0 mm in diameter); and micritic ooids are 0.3–2.0 mm in diameter. The nuclei of the ooids are mainly peloids and fragments of skeletal grains. The mixture of ooid types and ooid sizes indicates that the ooids were reworked by the current. The occurrence of reworked ooids also reflects changes in environmental conditions. On the other hand, our studies showed that there were three types of calcite cement filling the interstitial spaces including circumgranular cements (shown in Fig. 2b), gravitational cements (shown in Figs 2a, b, c), and equant spar calcite cement (shown in Figs 2b, c).

Petrographic characteristics of ooids from the Tushan section are very different. Microscopic examination revealed that the concentric ooids were the major ooid...
type accounting for 90% of the grains, and that they were cemented by the gravitational and equant spar calcite cements (Fig. 2d). However, the samples were deeply transformed by dolomitization, which changed the original rock fabric.

3.2 Microscope and SEM studies
Calcified biofilms are represented as thin micrite coatings on the ooid cortices of the samples with three-dimensional structures (Fig. 2). The size and outer shape of the biofilms vary. As shown in the microscope images, the narrow biofilm is less than 200 μm in diameter and looks like a strumae (struma - Latin, singular), whereas the larger ones are millimeters in size and with the outer shape of a lump. The external surfaces of the biofilms are smooth but highly irregular, with steep sides and
overhanging projections (Fig. 2d). The internal fabric is composed of rounded micrite aggregates approximately 10–20 μm in diameter (Fig. 3). It is worth noting that there are some black objects preserved in the interior of the biofilm and around the periphery, but they are different in mineral composition. The black areas within the biofilm are composed of dolomircite and represent channel-like structures (Figs 2d, e, f), whereas the black objects dotted around the periphery of the biofilms are pyrite crystals (Figs. 3a, b).

SEM examination revealed that the microfabric of the biofilms is different from that of the ooid cortices. The latter are composed of carbonate laminae consisting of radially arranged calcite crystals whose long axes are perpendicular to the surface of the laminae; however, the calcified biofilms are composed of roughly laminated micrite (Fig. 3c). In addition, SEM examination also revealed a tubular structure, with an external diameter of 20 μm, delimited by a well-defined micritic wall in transverse section (Fig. 3d). A similar structure has been reported as Girvanella, a filamentous cyanobacterium, from the same materials by Liu and Zhang (2012). The thickness of the tube wall is about 2 μm, and the internal cavity is filled with micrite. Furthermore, the fluorescence microscope examination of these biofilms showed a strong fluorescence reaction (Fig. 4).

4 Discussion

Biofilms are ubiquitous in modern aquatic environments (Costerton et al., 1995; Costerton and Stoodley, 2003). They can be preserved by mineral precipitation during their formation (Toporski et al., 2002), and have an extraordinarily long fossil record. Biofilms are documented as fossils in rocks throughout the 3.5 Ga-old fossil record of life on Earth (Westall et al., 2000). Fossil biofilms in ancient rocks are described as smooth, ropyl-textured, bedding plane films (Westall et al., 2003), or as thin micrite veneers from a variety of crypts in the Phanerozoic limestones (Riding, 2002).

In this study, the micrite coatings preserved in the oolitic limestone are considered to be calcified biofilms. The specific morphologies and architectural characteristics show the different origin of the calcified biofilms from the ooids and cements. The roughly laminated arrangement of micritic particles in the biofilms is similar to the laminated textures of fine-grained limestone with microtextures produced by bacteria in laboratory experiments (Flügel, 2004). In comparison with modern uncalkified biofilms, the internal channel-like architectures of the biofilms are considered to be water conduits or uncolonized nutrient-poor spaces (Fig. 2d). During the accretion of the biofilms, the characteristic architecture such as the irregular shapes, steep sides and overhanging projections was formed (Fig. 2d).

Microfacies analysis indicates that the ooids from the Wangjiawan section were reworked prior to final consolidation. The enrichment of the concentric ooids identifies that they were deposited at the very beginning in a high-energy environment, and then this proceeded in the early diagenesis stage when water energy reduced, which was characterized by the appearance of the circumgranular cements (Fig. 2b). Subsequently, the ooids were redeposited when the water energy changed again, and this formed the final reworked ooids. Finally, the sediments proceeded to the final diagenesis stage, which resulted in the consolidation of the oolitic limestone. The calcified biofilms were formed during the early diagenetic stage immediately after the freshly deposited ooids proceeding in the continuous sequence of depositional processes (Fig. 5).

A variety of microbes including archaea, bacteria, euarcheotic algae, fungi, and protozoa can produce biofilms. Of these microorganisms, cyanobacteria are the most abundant and considered as an important contributor to the formation of biofilms (Noflijke, 2010); they are recognized for their ability to occupy diverse aquatic and terrestrial habitats, produce organic compounds, and stabilize sediments (Reitner and Thiel, 2011; Chen and Lee, 2014). Detailed SEM examination on calcified biofilms showed that cyanobacteria were involved in their formation (Fig. 3d), and thus it is suggested that these biofilms are biotically dominated by cyanobacteria.

An idealized formation and disintegration of a biofilm in a natural environment includes the attachment of planktonic cells, the quick production of EPS, biofilm maturation, and the disintegration (dispersal) of the biofilms (Stoodley et al., 2002). However, it is quite different when comes to the geological records. The stages of attachment of cells and the production of EPS have not been discerned in our samples. The maturation stage, in which biofilms are more like simple conical structures in shape (Fig. 2a), sees the growth of cells and aggregation into microcolonies; it is facilitated by the adhesion sites of the first colonizers and the production of EPS (Denkhaus et al., 2007), which is occupied by a loosely organized glycocalyx rather than by bacterial cells (Geesy et al., 1994). Within a further development, the size of the biofilms becomes much larger, and the shape is much more irregular (Figs 2b, c). Then these biofilms gradually step into a stage of disintegration. In this stage, the biological structures of the biofilms are more stable. The thick amalgamated masses become smooth, but generally with considerable surface roughness. The internal channel-
Fig. 3. Details of the internal fabric of the calcified biofilms from oolitic limestone of the Wangjiawang section. The biofilms are composed of laminated micrite aggregates (a–c), which differ from the cortices that consist of radially arranged crystals (c). The tubular object preserved in the biofilm is a fragment of *Girvanella* delimited by a well-defined micritic wall in transverse section (dashed circle in d). Note the pyrite particles dotted around the periphery of the biofilms (dark-colored minerals in a–b).

Fig. 4. Fluorescence photographs of calcified biofilms from oolitic limestone of the Wangjiawang section. Note the tower-like structure (ts) in b.

like structures promote the migration of fluid around the microcolonies, facilitating nutrient delivery and waste removal. The dispersal stage is characterized by the detachment of cells, and even of portions of the biofilms into the surrounding environment. The overhanging projections are the most likely parts of the biofilms to be ripped off and transported by a current until redeposited again (Fig. 2d).
5 Conclusions

Biofilms are part of an epibenthic ecosystem on earth and have a significant influence on the biogeochemical cycle and mineral precipitates. Biofilms can be mineralized during their formation, which increases the possibility of fossilization. In this first description of calcified biofilms from Cambrian oolitic limestone in China, our studies indicate that there is compelling evidence for the presence of calcified biofilms on the cortices of the ooids, such as the specific morphologies and architectural characteristics, the strong fluorescent reaction, and the presence of cyanobacteria. The development of biofilms on the ooid cortices reveals a low hydrodynamic condition conducive to the growth of microbes. It is also demonstrated that microbial communities, such as biofilm and microbial mat, can be involved in the formation of ooids.

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References


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