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Research Status and Progress of Thrombolite

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Abstract

Microbial carbonate rocks are one of the earliest evidence of life on Earth, which record important information of the paleo-ocean and paleo-atmosphere. The study of different types of microbial carbonate rocks has important supplementary significance for the improvement of the classification of carbonate rocks, and also has important guiding significance for the study of the mechanism of carbonate rocks.

In this paper, the typical types of microbial rock in the Cambrian-Thrombolite as the object of` study, the type of thrombolite in the study area is divided, and the characteristics of various types of thrombolite are introduced in detail. In order to reveal the controlling factors of thrombolite formation, we summarize the previous research methods, the types of thrombolite symbiotic rocks and the types of microorganisms in thrombolite.

Keywords

Thrombolite; Microbolite; Carbonate rock; Epiphyton

1. Introduction

Since the birth of early life on Earth, its evolution has been closely related to the environment. The origin and evolution of life are significantly influenced by the environment. Meanwhile, life itself affects the surrounding environment through its own metabolic activities and biochemical activities. The obvious evolution of the atmosphere on Earth and the changes in Marine environmental conditions are obvious evidence that organisms influence and transform the surrounding environment (Shi et al., 2016). The earliest evidence of life discovered on Earth so far is also the organic serif layer in microbial rocks (Shi et al., 2016). Microbial rocks not only record important information about the ancient ocean and the ancient atmosphere (Wu et al., 2018), but also are important source rocks of hydrocarbons.

Thrombolite, as one of the main types of microbial rocks, have become another research hotspot of microbial carbonate rocks after stromatolites due to their special lithology, complex macroscopic morphology and controversial formation mechanism, and have received extensive attention from scholars at home and abroad.

The Cambrian Period represents the first episode of extensive cyanobacterial proliferation, during which abundant microbialites developed, with thrombolites being particularly predominant. As a classic type of microbialite, thrombolites primarily form through microbially-influenced calcification processes. Macroscopically, they are characterized by thrombolitic textures, though the irregular nature of these structures often manifests as patchy, columnar, and dendritic morphologies. In both domestic and international reported studies, the microbial constituents of thrombolites have predominantly been identified as Epiphyton, with other microbial types rarely observed. This study aims to conduct a comprehensive analysis of the types, microbial composition, and sedimentary characteristics of Cambrian thrombolites in Henan Province, to elucidate their depositional environment distribution patterns and spatiotemporal evolutionary trends, thus providing a foundational framework for investigating the genetic mechanisms of microbialite formation.

2. Definition of thrombolites

The earliest definition of thrombolites, proposed by Aitken (1967), describes them as "cryptalgal structures related to stromatolites but distinguished by a macroscopic clotted fabric instead of laminations". This original conceptualization highlights two critical aspects:

1.Macroscopic Morphological Continuity: Thrombolites share large-scale constructional similarities with stromatolites, including mound-shaped (domal), columnar, and stratiform architectures, suggesting overlapping genetic mechanisms in microbial mat development and sediment accretion.

2.Diagnostic Textural Criterion: Thrombolites are fundamentally differentiated from other microbial carbonates by their macroscopically visible clotted fabric (thrombolitic texture), characterized by irregular, non-layered aggregates of microbial micrite and sparite, which reflect stochastic microbial colonization rather than rhythmic laminae formation.

Thrombolitic limestone, characterized by its distinctive clotted and non-laminated fabric, was previously classified as bioturbated and modified stromatolites. A review of relevant literature reveals that existing descriptions of thrombolites' macroscopic complex structures lack systematic organization, with notable ambiguities persisting in the understanding of large- and medium-scale "clotted" structures. Regarding terminology, Soviet geologists historically grouped thrombolites with oncolites under the collective term "microphytolites". Du(1992) designated irregular spherical stromatolite-like structures as "patterned stones", while Chen(1993), through studying microbialites exhibiting clotted microstructures, proposed the translation "spotted grainstone" for thrombolites. These evolving terminological interpretations demonstrate that the conceptual understanding of thrombolites has undergone continuous refinement and expansion alongside research progress.

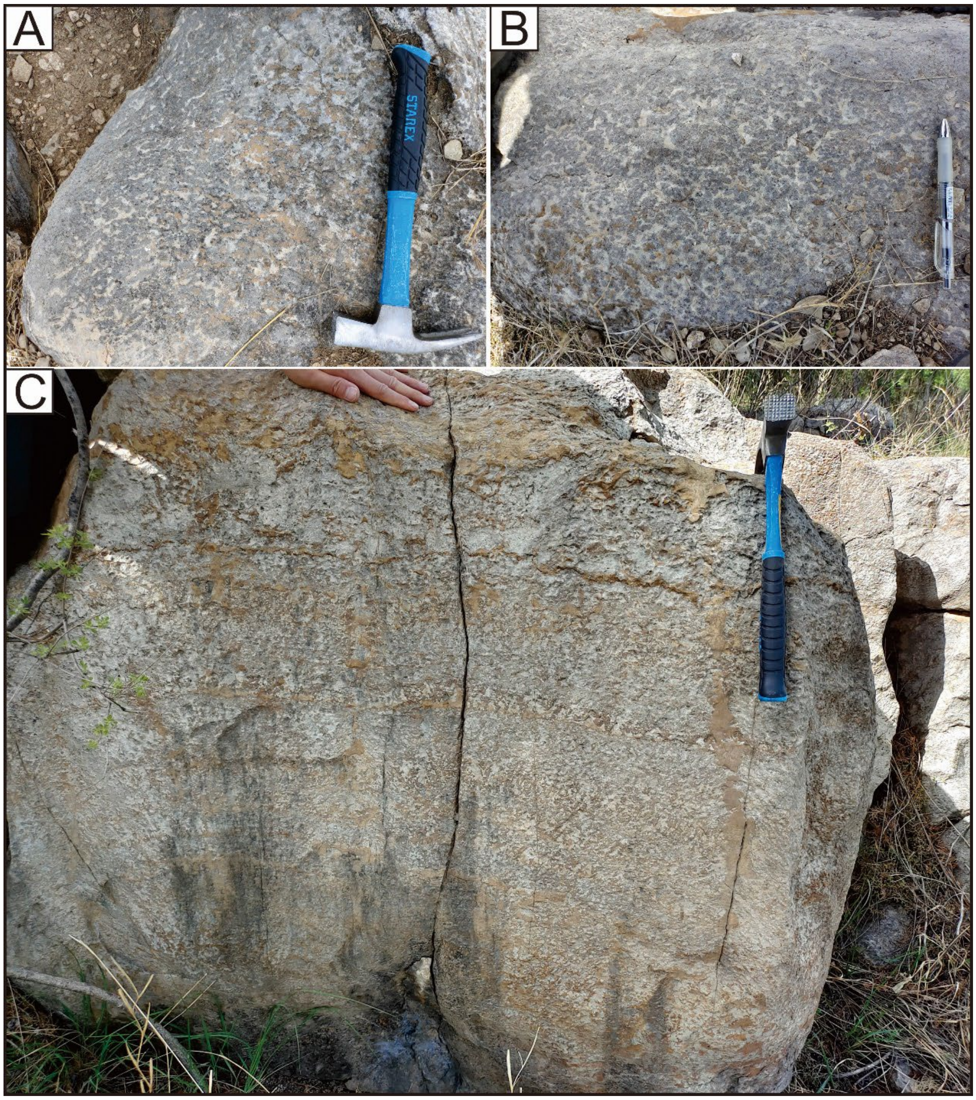

Fig. 1 Macroscopic characteristics of thrombolites

3. Classification of thrombolites

There is currently no standardized system established by domestic and international experts for the classification of thrombolites. The prevailing classification schemes primarily fall into two categories: the first categorizes thrombolites based on their formation mechanisms, while the second classifies them according to the morphological characteristics of thrombolitic clots observed in mesostructural features (Tab. 1). As products of microbial-environmental interactions, thrombolites' genesis is intrinsically associated with microbial activities, rendering classifications based on distinct formation mechanisms more scientifically rigorous. Although the morphological classification method has been widely adopted in thrombolite research, current descriptive protocols generally follow microbialite characterization principles that prioritize macro- to micro-scale observations. This approach predominantly focuses on macro-features while failing to incorporate critical microstructural characteristics into its classification framework.

Although the mesostructures of thrombolites are closely linked to depositional environments, their distribution patterns are not universally consistent. For instance, dendritic and reticular thrombolites typically form in low-energy aquatic environments, whereas patchy and columnar thrombolites develop in high-energy settings (Qi et al., 2014; Tang, 2013). However, exceptions exist. For example, patchy thrombolites at the Permian-Triassic boundary in Guizhou, China, occur in low-energy environments, while dendritic and grid-like structures are found in high-energy conditions. The diversity of thrombolitic mesostructures across different geological periods and strata underscores the variability in their depositional environments and formative processes, suggesting that classification based solely on mesostructural features inadequately explains their genesis. Concurrently, increasing attention has been directed toward the calcareous microbial components and microstructural characteristics of thrombolites. Variations in microbial community morphology may critically influence mesostructural modifications, growth patterns, and spatial distribution of thrombolites. Ultra-microstructural observations, including radiated fibrous calcite and calcified EPS remnants with spherical or honeycomb textures, indicate that thrombolites likely originate from complex calcification processes within multi-layered biofilms of microbial mats (Mei et al., 2019). These findings highlight the essential role of microstructural features in both identifying thrombolites and elucidating their formation mechanisms.

Thrombolites frequently exhibit abundant Epiphyton and Girvanella, with distinct macrostructural differences observed in thrombolitic limestones formed by different cyanobacterial communities. Based on microbial community types in the study area, thrombolites can be classified into Girvanella-dominated thrombolites and Epiphyton-dominated thrombolites. Further subdivision integrates mesostructural clot characteristics: Girvanella-dominated thrombolites are categorized into columnar Girvanella thrombolites and patchy Girvanella thrombolites, while Epiphyton-dominated thrombolites are subdivided into patchy Epiphyton thrombolites and dendritic Epiphyton thrombolites.

Tab. 1 Classification of thrombolites(Modified after Du , 1992)

class	subclass	group
thrombolites	porous thrombolite	Vesicularites; Vesicularia; Conjerta
	clotted thrombolite	Vermiculites; Glebosites; Nubecularites; Hiceroglyphites
	web-like thrombolite	Maecovella

4. Microbial communities within Cambrian thrombolites

The microbialites of the Cambrian Period primarily consist of oncolites, thrombolites, and stromatolites, among which thrombolites have been most extensively studied. Thrombolites originated as early as the Paleoproterozoic Era in Canada, experienced widespread development during the late Cambrian, and began to decline in the early Ordovician. During the Cambrian Period, thrombolites were predominantly distributed in the North China, South China, and Tarim Basin regions of China. In addition to these regions, significant occurrences have also been documented in Siberia, Australia, the United States, and northern Spain.

Microorganisms, as one of the most widely distributed life forms on Earth, are characterized by their remarkable diversity, potent metabolic capabilities, and rapid reproduction rates, exhibiting extensive distribution and colossal biomass in natural environments. Microbialites predominantly comprise photosynthetic prokaryotes (e.g., cyanobacteria), eukaryotic microalgae (including brown algae, red algae, and diatoms), and chemoautotrophic/heterotrophic microorganisms such as sulfur bacteria. Numerous studies on microbial components within thrombolites have identified Epiphyton, Girvanella, and Renalcis as the dominant taxa (Qi et al., 2014; Chen et al., 2014; Gao et al., 1998), with subsidiary occurrences of Kordephyton, Bija, Tartninia, Renalcis, Amgaina, Razumovskia, Actinophycus, Bacinella, and Lithocodium reported in specific regions.

5. Girvanella

Girvanella is filamentous, with a calcareous, circular and tubular filament that is unbranched. The filaments can appear individually and are often irregularly intertwined. Girvanella has the following characteristics: it is curved, tubular, with a uniform diameter, and has a calcified thick shell. The outer diameter ranges from several micrometers to dozens of micrometers, the tube wall is thin, and it is microcrystalline in nature. The geological periods during which Girvanella has appeared globally are mainly concentrated in the Cambrian, Devonian, and the end of the Permian. In recent years, a large number of microbial carbonate rocks containing Girvanella have been reported, including thrombolites, oncolites, stromatolites, giant oolites, etc., and obvious Girvanella filaments can be observed inside these rocks, indicating that Girvanella has played an important role in the formation of microbial carbonate rocks (Chang et al., 2014; Dai et al., 2014).

6. Epiphyton

Epiphyton is composed of dense and branched radiating clusters of thalli. The diameter of a single branch is usually 40-80 μm. The spaces between the branches are generally filled with micritic calcite, and the branches typically grow upright and bifurcate upwards. According to its morphology, it can be classified into shrub-like and chamber-like (cluster-like) types. Among them, the shrub-like Epiphyton colonies usually grow in a shrub-like pattern. The Epiphyton branches are micritic branches with dichotomous branching, having a diameter of 50-60 μm. The branch-

es are relatively long, but they are not continuous and are often interrupted by microcrystalline or spar calcite. The chamber-like (cluster-like) Epiphyton colonies usually appear as aggregates of round or ellipsoidal pellets. The branches mainly exhibit dichotomous branching, are relatively thin, with a diameter of 30-40 μm, and are relatively short. In the longitudinal section, it is fan-shaped, and the branches grow gradually in a radial pattern from the inside to the outside.
By conducting statistics on the Epiphyton preserved in the geological period, it has been found that Epiphyton and archaeocyathids often coexisted with each other in the early and middle Cambrian period. Thereafter, it sporadically appeared in the Early Ordovician, Silurian, Late Devonian, and Triassic periods.

7. Renalcis

Renalcis is an elliptical or reniform chambered cyanobacterium. Since Renalcis and Epiphyton often appeared together during the geological period and were preserved as reef-building frameworks in microbialites or microbial reefs, many scholars have confused Renalcis with the chambered Epiphyton. The differences between the two are as follows: obvious bifurcated branches can be seen in the chambered Epiphyton, and the diameter of a single chamber is relatively large, while the diameter of a single chambered Renalcis is small and there is no obvious bifurcation. The wall of the elliptical sphere is relatively thick, and the interior is filled with lime mud; the diameter of a single chamber is 30-50 μm, and there is no obvious internal structural formation. According to the community morphology, it can be classified into agglomerated, septate dendritic, chambered, saccular, and transitional types between two different shapes.

8. Formation mechanism of thrombolites

At present, the formation mechanisms of thrombolites mainly involve the following three aspects:
1.Thrombolites are considered to be stromatolites that are formed as a result of being disrupted by bioturbation, bioturbation burrows, and boring activities. This situation was relatively common at the end of the Precambrian and during the Paleozoic era.
2.Some thrombolites are the products of primary microbial calcification and agglutination. They mainly develop in the subtidal zone and appear in the forms of columns, mounds, layers, and thick-layered crusts (Riding, 1991, 2000).
3.Thrombolites may represent a eukaryotic structure (Feldmann et al., 1998), and some agglutinated thrombolites from the Late Miocene may support this understanding.

9. Deficiencies in the study of thrombolites:

1.Thrombolites are characterized by macroscopic clots and are distinguished from stromatolites. However, due to the complexity of their formation mechanisms and the diversity of their occurrence characteristics, specific definitions and explanations have not been provided for their classification and clot structures since the concept was proposed. This has led many scholars to mistakenly call other uneven structures in rocks "clots", and has also caused chaos in the classification of thrombolitic rocks. What kind of structure can be defined as a thrombolite? What kind of classification system can better contribute to the study of thrombolitic rocks? It is necessary to supplement and explain them on the basis of previous studies.

2.There is a diverse range of microbial types in thrombolites. A large number of studies show that the research on the types of thrombolite microorganisms mainly focuses on Epiphyton, and there is no in-depth research on other microorganisms. Different microorganisms can all form clot structures with similar mesoscopic structures. What controls this similarity? In addition to Epiphyton, what is the relationship between other cyanobacteria and the environment and the multi-level structures of thrombolites, as well as the influence of the EPS structures of other cyanobacteria, the calcification process, and their relationship with the structures of thrombolites?

3.Thrombolites are widely distributed in the Cambrian period. What are the spatial distribution characteristics of thrombolites? And what are the factors that control the spatial distribution of thrombolites in different areas?

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