Theoretical Article

Classification of biogenic carbonate rocks

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Abstract

All rocks formed by macroorganisms and microbes belong to bioliths, which are divided into macrobioliths and microbioliths. The macrobioliths are divided into the biolithites, i.e., reef rocks formed by macroorganisms, and the bioallolites composed of the skeletal grains and micrites formed by macroorganisms. The microbioliths are divided into calcimicroliths, ferromicroliths, mangamicroliths, and claymicroliths. The calcimicroliths are divided into microlithites (i.e., the reef rocks formed by microbes), microbialites, and the microallolites consisting of the grains formed from microlithites and microbialites and the micrites formed by microbes. The microlithite includes the framelite with a framework built by in situ skeletons of up-growing benthic microbes, bafflelite, and the filalite having a framework built by the in situ skeletons of soft filamentous microbes. Dendrolite is a specific kind of framelite. The microbialite includes stromatolite, laminate, thrombolite, crustolite, and oncolite.

Key words: **Bioliestone, framelite, bafflelite, filalite, crustolite, dendrolite, micromicrites.**

1 Introduction

Classification is an important content of the study of the rocks constituting the lithosphere or tectonic plates of the Earth. Rocks can be classified according to fabrics, compositions and origins. For example, according to their origin, all the rocks on Earth were divided into three types, igneous rocks, sedimentary rocks, and metamorphic rocks. The sedimentary rocks are divided into clastic rocks and carbonate rocks. The carbonate rocks can be divided according to their compositions, fabrics, and origins.

The first important classification of carbonate rocks was that by Folk (1959, 1962), in which, all carbonate rocks were divided into more than 22 types, according to their fabrics and compositions. In this classification, all reef rocks were placed under a collective name, **biolithite**. Also based on fabrics, a simpler classification of carbonate rocks was proposed by Dunham (1962), which is widely used. In

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Dunham's scheme, all reef rocks were under a new name, **boundstone**. Because of the progress of research on reef rocks, a classification of reef rocks was proposed (Embry and Klovan, 1971), in which, reef rocks were divided into **framestone**, **bafflestone**, and **bindstone**, and the rocks with big grains (diameter >2 mm) were divided into **rudstone** and **floatstone**. This scheme was revised by Wright (1992), who divided them into boundstone, framestone, and bafflestone, and defined five diagenetic rocks. During his studies on the widely distributed Middle and Upper Permian reefs built by calcisponges in southern China, Wu (1991, 1992) found a widely distributed reef rock characterized by sparse in situ reef-building sponges, and named it **prebafflestone**. In a later paper on the classification of carbonate rocks (Lokier and Junaibi, 2016), reef rocks were divided into bindstone (with organically -bound fabrics), framestone and boundstone (binding mode is not identifiable). These classifications have promoted the study of carbonate rocks. However, they did not include microbial rocks, that is, the rocks formed by microbes. The common kinds of microbial rocks include stromatolite (Kalkowsky, 1908), oncolite (Pia, 1927; Peryt, 1981), thrombolite (Aitken, 1967), and dendrolite (Riding, 1988). And an important classification of the microbial rocks was proposed by Riding (2000, 2011).

An integrated classification scheme to include all biogenic rocks formed by both macroorganisms and microbes is needed. Here such a scheme is proposed.

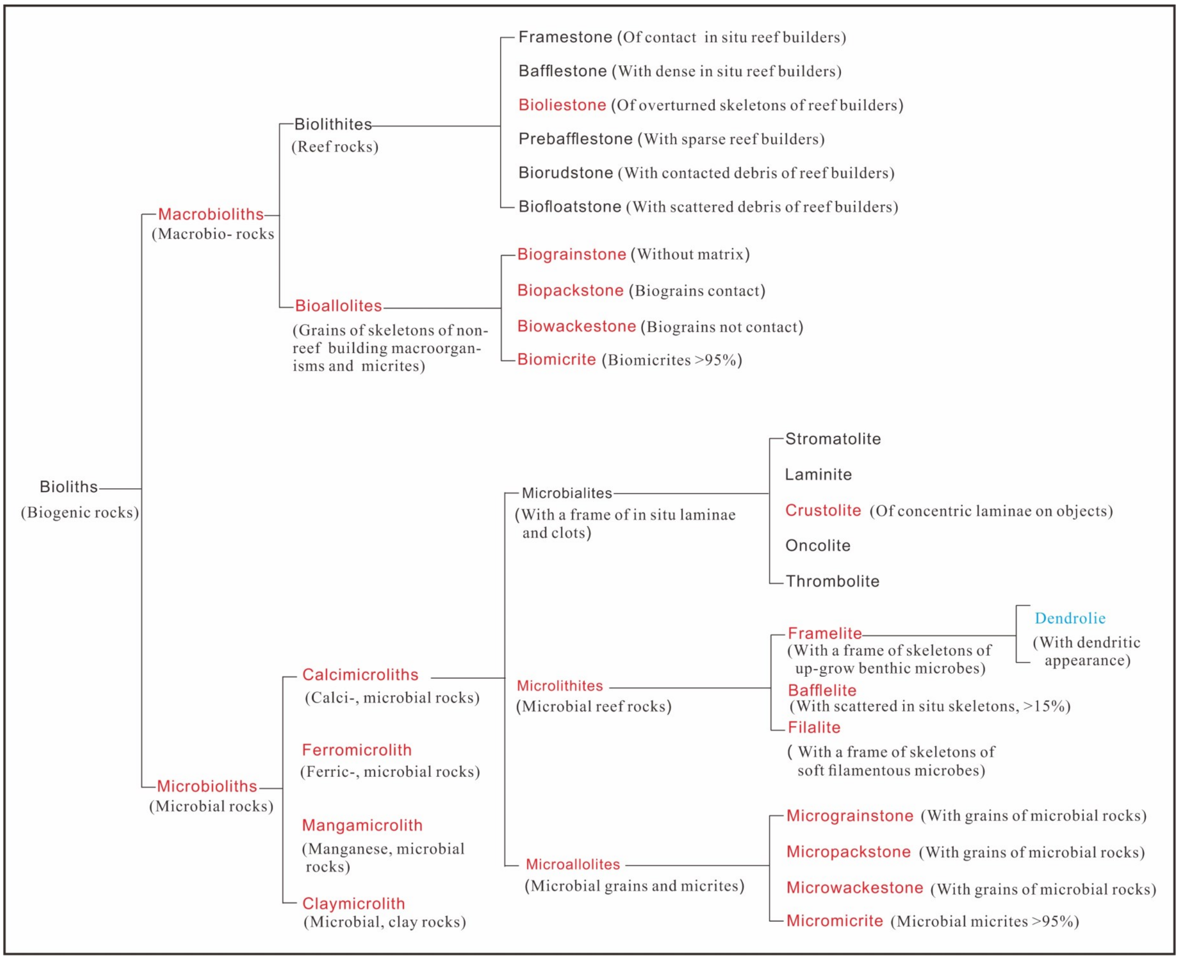

Fig. 1 Classification of bioliths. The new terms are in red color.

2 Classification of bioliths

Biogenic rocks, or bioliths (Wu, 2021), refer to the rocks formed by organisms. Bioliths can be classified at more than four levels. At the first level, bioliths are divided into the **macrobiolith** formed by macroorganisms and the **microbiolith** formed by microbes (Fig. 1). **Macrobiolith** is a new term, built by "macrobio"and "lith" (=rock). **Microbiolith** is a term that has been used (Kovalevskii et al., 1992; Melezhik and Fallick, 2010). Both **macrobiolith** and **Microbiolith** can be further divided.

(1) Macrobioliths

At the second level, based on their fabrics, macrobioliths can be divided into **biolithite** and **bioallolite**.

(a) Biolithite

Biolithite is a term proposed by Folk (1962) to refer to "the undisturbed bioherm rocks", that is, reef rocks, which mainly consist of the in situ skeletons of macroorganisms. The firstly proposed classification of reef rocks includes the three types: **framestone**, **bafflestone**, and **bindstone** (Embry and Klovan, 1971). Although **bafflestone** was deleted by Wright (1992) and Lokier and Mariam (2016) from their classification schemes of reef rocks, according to our observation on the Upper and Middle Permian reefs in southern China, it is a common rock, and should be retained.

Based on his study on the Permian reefs in southern China, Wu found a common kind of rock characterized by sparse benthic reef-building sponge skeletons and another rock containing abundant wave-overturned sponge skeletons, and named them as **prebafflestone** (Wu, 1991, 1997) and **bioliestone** (Wu, 1998; Li et al., 2018; Liu et al., 2018), respectively.

Prebafflestone is similar to bafflestone in having scattered benthic reef-builders, and the difference between them is that the reef-builders are dense in the latter.

The key feature of **bioliestone** is that the reef-builders in this rock are mostly overturned because of the blow and agitation of the wave (Wu, 1998; Li et al., 2018; Liu et al., 2018). Additionally, the content of the overturned reef-builders should be greater than that of the in situ reef-builders, and the coverage of all reef-builders should be > 5%. Figure 2 shows two samples of calcisponge bioliestone respectively from the base and upper part of the Upper Permian calcisponge reef at Jiantianba, Lichuan, Hubei Province, southern China.

It is assumed that the bioliestone was formed in water that was not too stormy. If the wind and waves get stronger, the reef-builders will be broken to debris. There are a lot of gravels and sands of reef-building corals in the modern reefs in the South China Sea. Wu (1997) proposed to call the rocks consisting of the gravels and sands of reef-builders **biorudstone** (debris contact) or **biofloatstone** (debris not contact), two terms built by "bio" and "rudstone" and "bio" and "floatstone", respectively. Biorudstone and biofloatstone differ from the rudstone and floatstone defined by Embry and Klovan (1971) in that the gravels and sands in the former are mainly of reef-builders, but those in the latter can be of ahermatypic organisms.

In sum, biolithite includes framestone, bafflestone, prebafflestone, bioliestone, biorudstone, and biofloatstone.

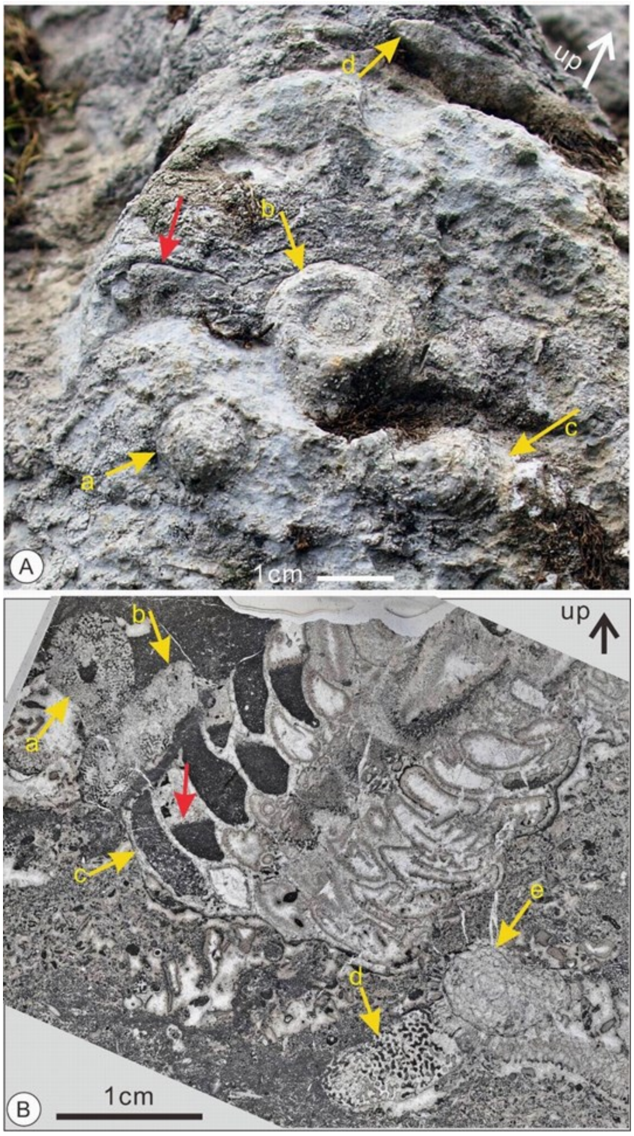

Fig. 2 Calcisponge **bioliestone** in the Upper Permian calcisponge reef in the Changxing Formation at Jiantianba, Lichuan, Hubei Province, southern China. **A**: An outcrop photo of the upper part of the reef. **Red arrow**: A fissure parallel to the beddings. **The white arrow**: The top surface of the bed is toward the upper right of the photo. **Yellow arrows**: Four columnar calcisponges parallel to the beddings represented by the fissure (Red arrow). **B**, Photomicrograph of the thin section labeled as JTBN-8-3A from the base of the reef. **Red arrow**: A geopetal structure, note the boundary between the white spars and the dark-colored micrites parallel to the beddings. **a**, **b**, and **d**: Columnar inozoan sponges. Sponge **a** and **e** are lying toward us. Sponges **b** and **d** are parallel to the photo. Sponge **c** is overturned.

(b) Bioallolite

Bioallolite is a new term built herein by "bio" , "allo"(=not in situ), and "lite"(=rock), to refer to the rocks mainly composed of the skeletons or skeletal debris of ahermatypic macroorganisms, and/or the micrites formed from calcified macroalgae.

The widely used terms grainstone, packstone, wackestone, and micrites were defined based on fabrics, not on their biogenesis or abiogenesis (Dunham, 1962), and do not belong to bioallolite. So, it is necessary to define four new terms, **biograinstone**, **biopackstone**, **biowackestone**, and **biomicrite,** to refer to the rock mainly composed of biogenic grains, the rock mainly composed of biogenic grains and micrites, the rock mainly composed of biogenic grains floating in biogenic micrites, and the rock mainly composed of the micrites formed from the disintegrating of calcified macroalgae, representatively.

The mound-like rock bodies mainly consisting of biogenic grains are called **bioclastic banks**, and those mainly consisting of biogenic micrites are called **biomicritic mounds**. If the origin of the micrites in a rock is uncertain, the rock cannot be placed in biolith.

The grainstone, packstone and wackestone in literature may be composed of both biogenic and abiogenic grains and micrites. A rock mainly composed of ooids is a grainstone. A rock mainly composed of crinoid grains is a biograinstone. If a rock is composed of both biogenic grains and abiogenic grains, its classification depends on the main grains.

(2) Microbioliths

Based on their mineral compositions, **microbioliths** are classified into **calcimicroliths, ferromicroliths, mangamicro-**

liths, and claymicroliths, which are mainly composed of the carbonate, ferric, manganese, and clay minerals formed by microbes, respectively.

The **calcimicroliths** can be further divided, according to their genesis and fabrics, into **microbialite**, **microlithite**, and **microallolite**.

(a) Microbialite

The term **microbialite** defined by Burne and Moore (1987) refers to the carbonate rocks formed by the activities of benthic microbial communities, and includes **stromatolite** (Kalkowsky, 1908), **laminite** (Aitken, 1967; Monty, 1976; Li et al., 2021), **crustolite**, **oncolite**, and **thrombolite** (Aitken, 1967). Aitken (1967) defined the term "laminite" for the planar laminated carbonate bodies formed by algal-mat activity.

It is redefined here that both **stromatolite** and **laminate** mainly consist of the dark-colored micritic laminae formed by the induced precipitation by microbes and the micritic laminae formed by the trapping of microbial mats.

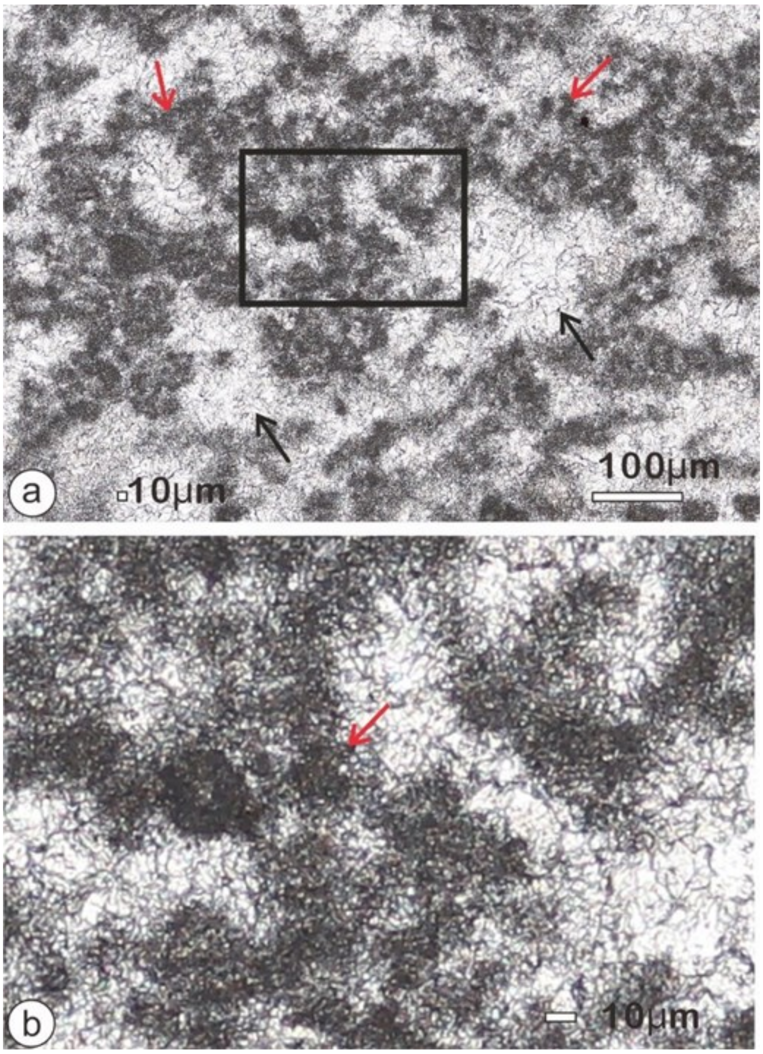

Fig. 3 Photomicrographs of the thin section of a thrombolite in the Middle Ordovician at Taoqupo reservoir, Yaoxian, Shaanxi Province, China, showing the reticulate miniclotted fabric built by the dark-colored reticulate micritic miniclots (red arrows) and the light-colored bright patches (black arrows). **b**: The enlargement of the area within the black square in **a**.

Laminites are very common in the early Cambrian dolostone succession in the Tarim Basin, Xinjiang, China (Li et al., 2021; Wu et al., 2021).

The new term "**crustolite**" is defined here to refer to the rocks consisting of the microbial micritic laminae encrusting on some objects such as the in situ skeletons of benthic animals such as inozoan calcisponges (Wu, 1991; Li et al., 2018; Liu et al., 2018). This rock is common in the Middle Ordovician limestone sequences in Shaanxi Province, China and in the Middle and Upper Permian reefs in southern China.

Oncolite is an old term (Pia, 1927; Peryt, 1981; Burne and Moore, 1987; Wu et al., 2018) referring to the rock composed of oncoids, a kind of spherical structures with microscopic concentric laminated inner fabric. It forms in a slightly turbulent water by the microbial mats encrusting some kind of cores, such as debris of rocks or shells.

Thrombolite was defined as "characterized by a **macroscopic** clotted fabric" (Aitken, 1967, p. 1164; Riding, 2011, p. 641). Here it is redefined to refer to the rock with a miniclotted microfabric, i.e., having a framework built by dark-colored micritic **miniclots**. Figure 3 shows the reticulate miniclotted fabric of a thrombolite limestone in the Middle Ordovician at Taoqupo reservoir, Yaoxian, Shaanxi Province, China. Although **leiolite** was defined as an internally aphanitic microbialite (Braga et al., 1995; Riding, 2011), I suggest to abolish it, because, if it has no fabric, how can it be recognized as a biolith.

(b) Microlithite

The new term **microlithite** is built by"microbio" and "lithite" (=reef rock), to refer to the rocks that have a framework built by the in situ skeletons of microbes. The microbial skeletons in this rock have regular shape, and can be identified into biological or paleontological genera or species. This rock includes at least three subtypes, **framelite, bafflelite,** and **filalite**. The new term **framelite** is built by "frame" and "lite" (=rock), referring to the rocks having a framework built by the in situ skeletons of up-growing benthic microbes. Typical representatives of this rock are *Epiphyton* framelite and *Renalcis* framelite.

Dendrolite belongs to framelite, because, according to its definition (Riding, 1988, 1991), dendrolite is a kind of microbial rock characterized by the macroscopic dendritic appearance on outcrop or hand samples that formed by calcified microbes such as *Epiphyton*. It is a specific kind of framelite.

The **framelite** in the Zhangxia Formation of the Cambrian Series 3 in Jinan, Shandong Province,

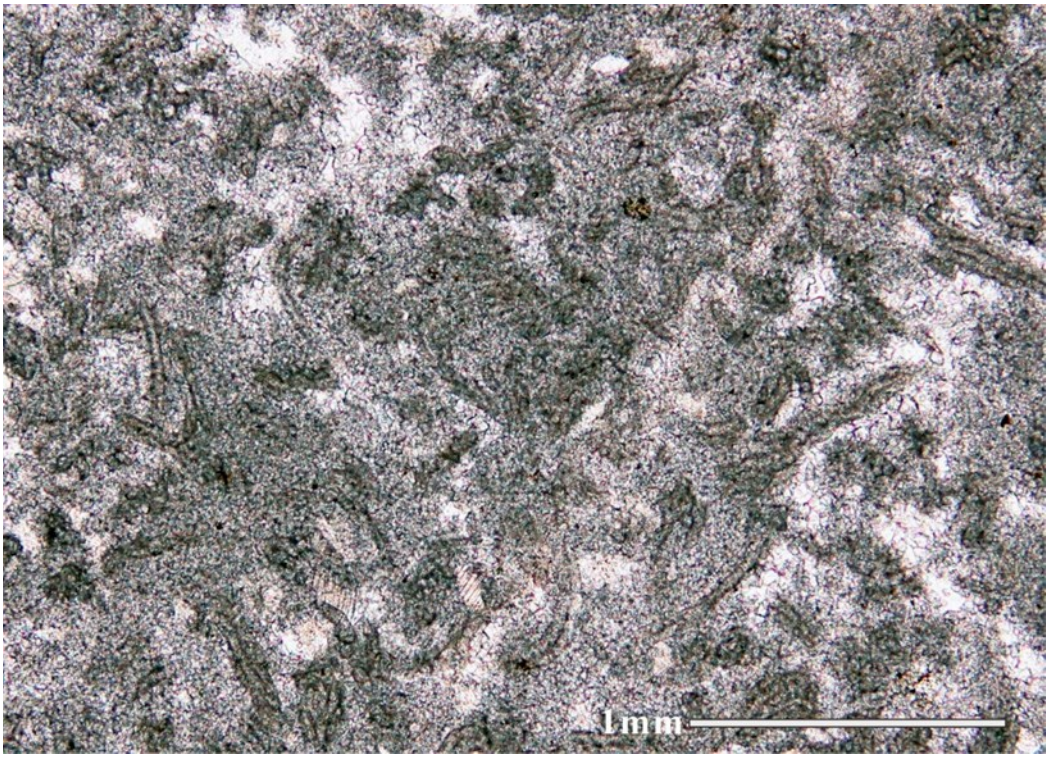

Fig. 4 Photomicrograph of the thin section of a filalite in the Lower Cambrian Stage 2 sequence at Sugaitblak, Aksu, Xinjiang, China, with a framework built by the in situ filamentous skeletons of microbes (probably *Girvanella*).

China has a framework built by the branching calcified microbe *Epiphyton*. It was used as an example of dendrolite by Riding (2000, Fig. 13), but was described as a framestone by Lee et al. (2014, Fig. 9), and was described as thrombolite by Yan et al. (2017). Since the term framestone was defined for the biolithite formed by macroorganisms, it is better to avoid using it for microbial reef rocks. The disagreement over the assignment of this rock indicates the need to revise the old classification.

Bafflelite is characterized by abundant scattered in situ skeletons of upgrowing benthic microbes in the matrix of micrites and other deposits. The content of the skeletons should be >15%.

Filalite is a new term built by “fila” (=filamentous) and “lite” (= rock), referring to the rock having a framework built by the skeletons of soft filamentous microbes. Figure 4 is a filalite from the Lower Cambrian sequence at Sugaitblak, Aksu, Xinjiang, China.

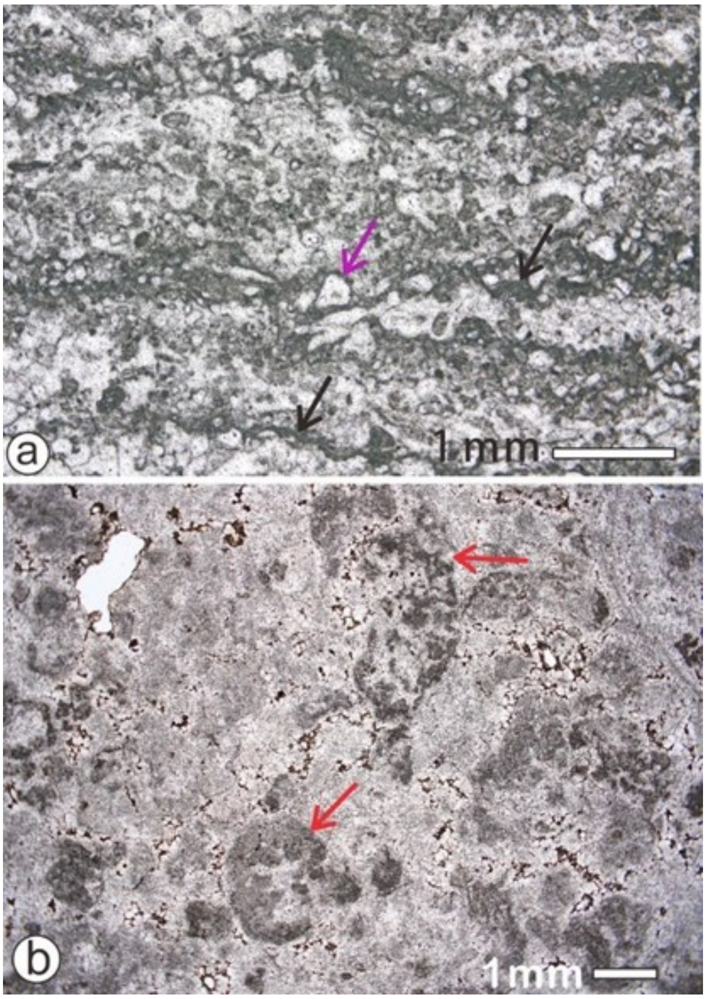

Fig. 5 Photomicrographs of two microallolites. **a**: The laminated micrograinstone in the Qigebulake Formation of the terminal Ediacaran at Sugaitblak, Aksu, Xinjiang, China, consisting of dark-colored thin laminae dominated by micrites and lighter-colored thicker layers dominated by grains formed from the thin laminae. The grains are white because of internal recrystallization. **b**: Fine-silty dolomite of *Renalcis* micrograinstone in the Cambrian Stage 3 at Sugaitblak, Aksu, Xinjiang, China, consisting of debris of *Renalcis* (red arrows).

(c) Microallolites

Microallolite is a new term built by “microbio” , “allo” (=not in situ) and “lite” (=rock), referring to the rock consisting of the grains formed from microlithites or / and microbialites, or of the grains and the micrites formed by benthic and planktonic microbes, or of the micrites.

In a similar way to bioallolites, the **microallolites** can be divided into **micrograinstone**, **micropackstone**, **microwackestone**, and **micromicrites**. The four new terms refer to the rocks composed of the **microbial grains** formed from microbialites and microlithites and / or the microbial micrites formed from the induced precipitation by microbes. The micrograinstone consists of only microbial grains, lacking micrites (Fig. 5). The micropackstone consists of contact microbial grains, with a micritic matrix. The microwackestone consists of microbial micrites and the scattered microbial grains (content of grains >5%). The micromicrite consists of microbial micrites (content of micrites >95%). Figure 5 is a laminated micrograinstone and a *Renalcis* micrograinstone.

The ferromicroliths, mangamicroliths, and claymicroliths can be classified in a way similar to the calcimicroliths.

(3) About dolomitic bioliths

Generally, bioliths are originally composed of calcite or / and aragonite minerals. However, many ancient bioliths have been altered to dolostones. Then, how to name these rocks? It is suggested here to add “dolo” to the front of the rock names in Figure 1. For example, if a *Renalcis* micrograinstone is composed of fine dolomites, it can be named a *Renalcis* fine dolomicrograinstone.

(4) About hybrid rocks

The term hybrid rock refers to the rocks composed of two or more kinds of components such as siliciclastics, carbonate cement, ooids, stromatolitic laminae, and skeletal grains. Hybrid rocks are common, although only a few researchers have paid attention to them. Riding (1988), Riding and Virgone (2020) have made in-depth analyses on the classification and nomenclature of hybrid rocks. Their schemes are useful when hybrid rocks are encountered.

(5) Microscopic vs macroscopic recognition of bioliths

It is important to point out that the recognition of biolithites need to be conducted on outcrops, since many reef-builders are big. Some corals can grow to more than 1 m in diameter. On the other hand, most microbioliths must be recognized according to microscopic fabrics, although microbialites were previously defined according to macroscopic fabrics (Riding, 2011).

3 Conclusions

Identification of bioliths is a primary step in the study of bioliths, and is conducted on the basis of definitions. Although all classification schemes are subjective, a comprehensive and logical classification can help the identification of bioliths. The new classification scheme proposed here is based on my observation and consideration of the biogenic rocks I have investigated and on my reading from the important literature by previous researchers, is a well-meant quest, and needs to be supplemented and improved in the future.

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Comment by Giorgio Bianciardi:

An interesting approach for a well-developed attempt at a new classification that allows a better analysis and understanding of a biopetrological sample under examination.

Comment by Fritz Neuweiler:

This is a very technical manuscript introducing a great number of new terms. I would prefer a more simple, practice-oriented approach.

Ya-Sheng Wu's Reply to Fritz Neuweiler :

Thank you very much! Actually, the reason why the classification is complicated is that the rocks are complicated, as exampled by the hybrid types proposed by Riding and Virgone (2020) and many transitional types that have not been included in the scheme.

Comments by Bob Burne:

I suggest that it would be best for you to make reference to Potonié's classification of non-combustable "biolithen". However, I would note that the term "Biolith" is a German term the translates into English as "Biolite" .

Reply by Ya-Sheng Wu:

Thank you very much! I searched articles with “biolith” and “biolite”, and found that the former has one meaning, that is, biogenic rocks, and was widely used, but the latter has more than one meanings. So, I prefer to use the former**.**

Innovation scored by: Wyn Hughes, Santanu Banerjee, Yue-Feng Shen, Hong-Wei Kuang, Hua-Xiao Yan, Fritz Neuweiler, Giorgio Bianciardi.

Innovation score (0-5): (5+5+3+5+5+1.5+5)/=4.2

Detailed reviewed by: Hua-Xiao Yan, Bogusław Kołodziej, Santanu Banerjee, Hong-Wei Kuang, Feng Zhang.

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