Concepts and frontiers of microbiopetrology

(Part 2 of the ppt for the plenary oral presentation by Ya-Sheng Wu for the 1st International Biopetrological Congress on September 23, 2023)

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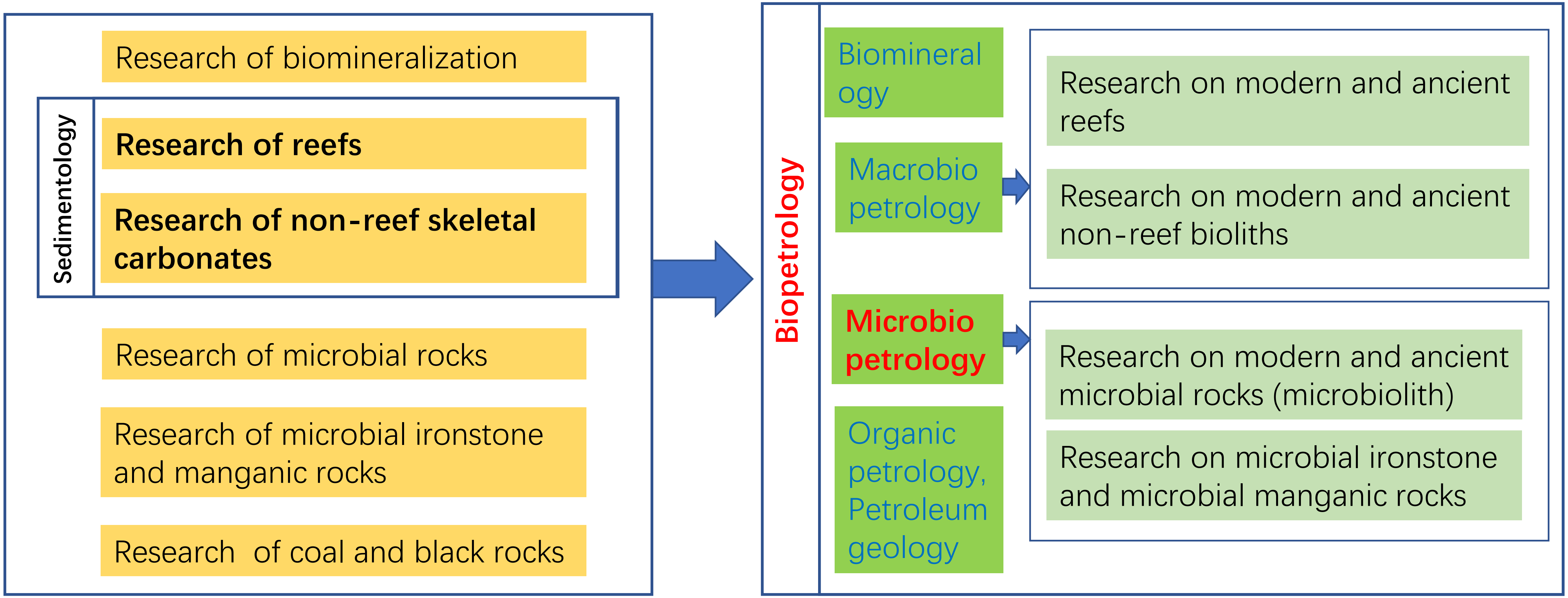
Key words: biolith, microbiolith → the second important → biogenic origin, amount → biopetrology, microbiopetrology → few research on microscopic fabric or nanoscopic fabric (not do, or cannot do) → mainly stromatolites, few thrombolites → no important impact on science or society → study on microfabrics and ultrafabrics → limitation of tools → evolution of microbiolith → inversion study → chemical composition reflects different minerals → tools → prior research fields of microbiopetrology

contents

Definition of biopetrology and microbiopetrology

A discipline to study the features, formation, environments of bioliths, and their significance in formation of mineral ores and petroleum reservoirs (Wu, 2022).



Undeveloped features of microbiopetrology

Microbiopetrolog is a young discipline, as seen from the following important events:

- In 1908, stromatolites were found,
- In 1967, thrombolites were found,
- In 1987, the term microbialite was proposed,
- In 2000, the classification of microbialites into 4 types was proposed (Riding, 2000),
- In 2022, a new classification of microbial rocks was proposed (Wu, 2022)

Microbiopetrology is in an undeveloped status, as seen from the following facts:

(1) There are few people engaged in research in microbiopetrology,
(2) There are few important research results in microbiopetrology,
(3) Its contribution to the society and science development is small.,
(4) It has not become an important and influential discipline.

The causes of the undeveloped status of microbiopetrology are as follows:

(1) Research on microbioliths was induced by curiosity instead of target to resolve big scientific problems such as evolution of life and Earth systems,

(2) Microbioliths are very complicated in formation and fabrics, and are difficult to study,

(3) Previous studies have a shortcoming: they paid main attention to macro- features of microbioliths, but little attention to their micro- features,

(4) The tools used in past and current studies are limitation: they do not have sufficient resolution.

Innovative ideas to promote microbiopetrology

(1) To study microbioliths for scientific and society development, not for curiosity,

(2) To recognize and classify microbioliths according to their macro- and microscopic fabrics,

(3) To focus study of microbioliths on their microscopic and nanoscopic features, especially on their original fabrics,

(4) To make inversion study on microbioliths so as to restore their original fabrics,

(5) To use dynamic thinking instead of static thinking in study of microbioliths,

(6) To apply the advances in microbiology, paleomicrobiology and experimental microbiology to the study of microbioliths,

(7) To combine the study of microbioliths with the study of evolution of Earth's systems.

Innovation in research method→significant research results→contribution to science and society development→increased impact of the discipline

Toward microscopic feature

Why to focus study of microbioliths on their microscopic and nanoscopic features

Microbioliths are formed by microbes.

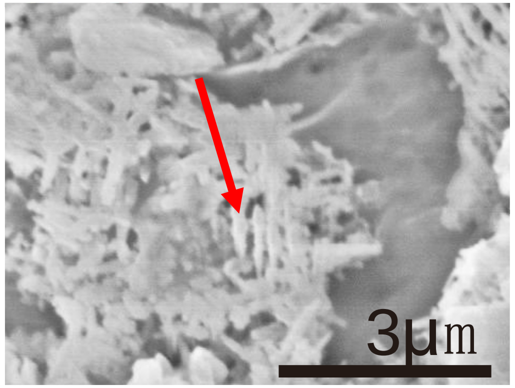
Microbes are small:

Groups	cyanobacteria	bacteria	archaea	fungi	virus
Range of diameter (μm)	1-70	0.20-1.25	0.1-15	2-30（<100）	0.01-0.3
Maximal length（μm)		8	200		0.45

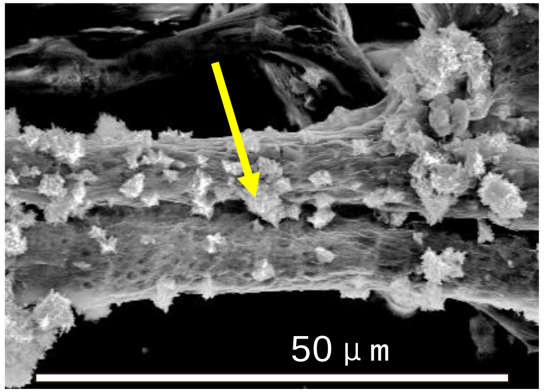
Concept 1: Microbioliths originally consist of fabric components of different grades.

Fabric components of microbioliths and their sizes

Single crystal	Micritic grain	Mineral crust (+mold hole)	proclot	Aggregation grain	miniclot（between original spaces） or minilaminae
Hundreds nm	Several microns	Several to tens microns	Tens microns	Tens to hundreds microns	Hundreds microns

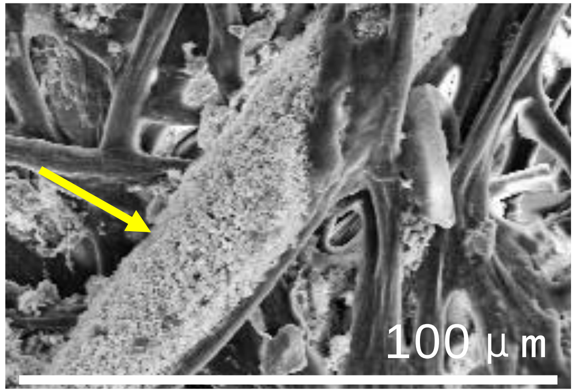


Single crystals

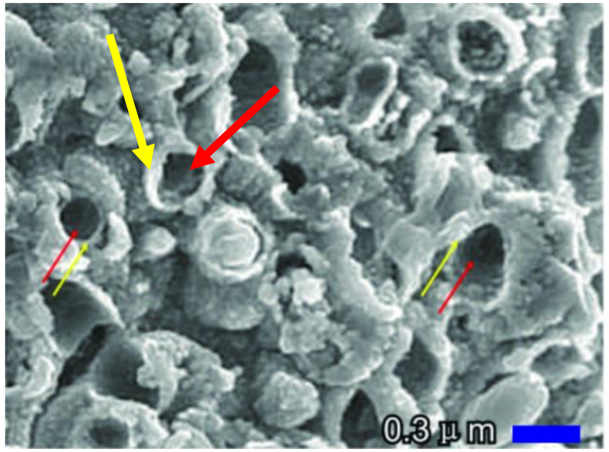


Micritic grains

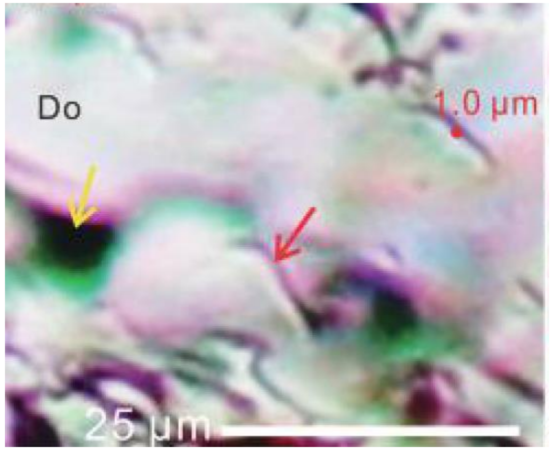
Micritic grains



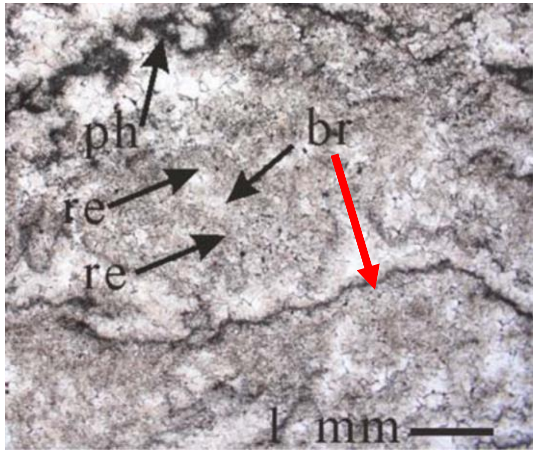
Mineral crusts



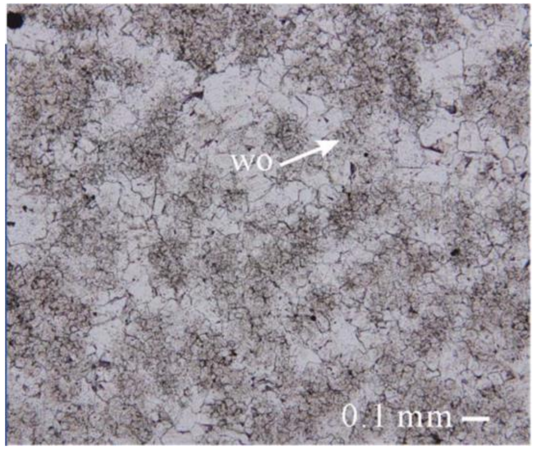
Mineral crusts (yellow arrow) and mold holes (red arrows) in an experiment (modified from Silva-Castro et al., 2015: 4f)



Mold holes (red arrows) in a Lower Cambrian Stage 3 dolostone sequence in Xinjiang, China



Minilaminae (black line, red arrow) in a stromatolite in a Lower Cambrian dolostone sequence in Xinjiang, China



Miniclots (in darker color, white arrow) in a thrombolite in a Lower Cambrian dolostone sequence in Xinjiang, China

Concept 2: Study of microbioliths should focus on their microscopic and nanoscopic features, because of two reasons: (1) microbes are small: most of them are smaller than 5 microns, and (2) fabric components of microbioliths are mostly smaller than 5 microns.

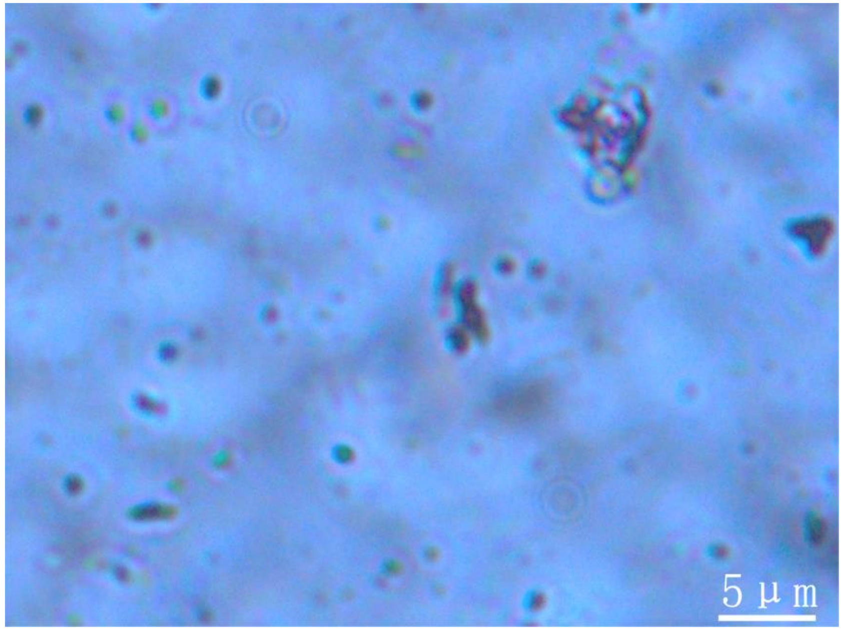
microscopic thrombolites = miniclots + original pores	macroscopic “clots” = thrombolite + secondary cavities, or = thrombolite + recrystallized patches
miniclots are tens to hundreds microns in size	“clots” are mm to cm in size

Recognition of microbioliths by macroscopic features is not supported by fabrics of microbioliths, and is easy to lead to incorrect results.

limitation of tools

The most widely used tool in the study of microbioliths is the optical microscope. Although the resolution of optical microscopes can theoretically reach 200 nanometers. In practice, however, their resolution in ordinary use is only 2 to 5 microns. Thus, the minerals and fossils less than 2 microns are generally difficult to distinguish under optical microscopes.

Most microbes, most microbial fossils and most fabric components of microbioliths are small than 2 microns, and thus cannot be seen under microscopes.



A photomicrograph of a thin section of a Precambrian metamorphic rock sample, taken by an Leica optical microscope

Advanced tools, such as electronic microscopes have much higher resolution. They make it possible to distinguish surface features less than 200 nanometers. However, they can be used to observe planar features, but not internal fabrics.

So, in the past and now, because most studies were performed with optical microscopes, the limitations of research tools prevent researchers from seeing most of the microfabric and nanofabrics of microbioliths, and the value and significance of the research results were greatly limited.

How can we break the bottleneck of micropetrology? It is necessary not only to have the idea of performing microscopic and nanoscopic study on microbioliths, but also to have powerful optical microscopes with high-resolution of less than 2 microns. If the two factors are ready, a new era of high-resolution research on microbioliths will come.

Toward the original

Why inversion study is needed to microbioliths?

Concept 3: All ancient microbioliths have evolved in fabric and composition.

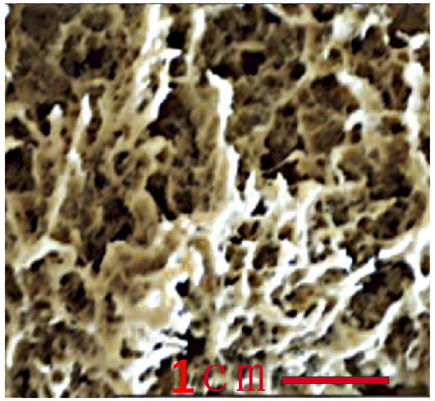
The evolution of microbioliths refers to the alteration in their fabric and composition caused by diagenesis.

Original microbioliths (original fabric and composition) → suffering various diagenetic processes → altered microbioliths (altered fabric and composition) → final microbioliths

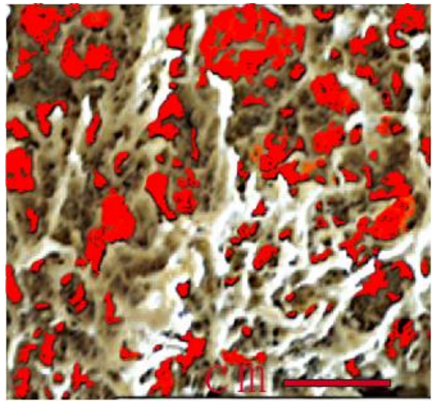
The main diagenetic processes that affect microbioliths include: (1) dolomitization, (2) cementation, precipitation of minerals in pores and cavities, (3) dissolution, forming pores and cavities, and (4) recrystallization.

Schematic diagram of evolution of ancient microbioliths:

Original fabric
An original thrombolite

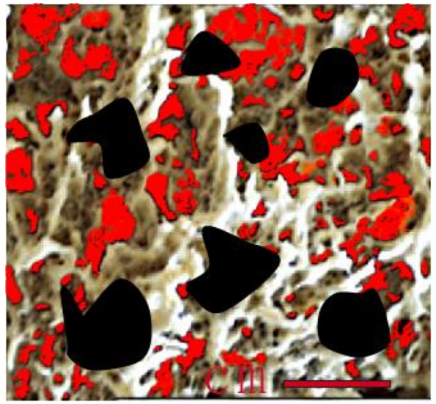


Altered thrombolite



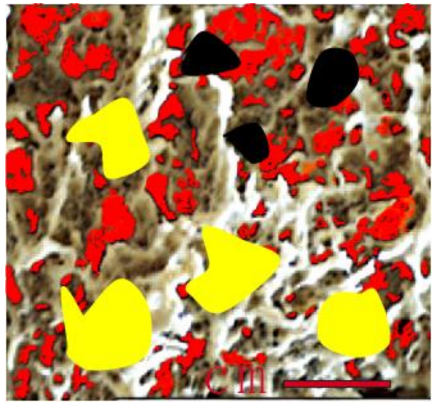
Red: cements in pores

Altered thrombolite



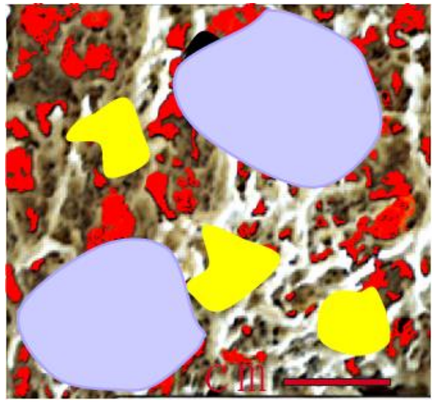
Black: dissolution pores

Altered thrombolite



Yellow: late cements

Final fabric
Final thrombolite



Grey: recrystallized patches

Concept 4: Evolution of minerals have occurred in almost all ancient microbioliths.

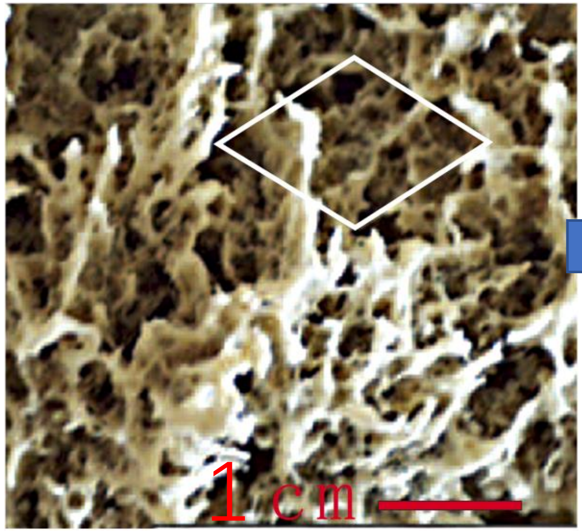
Evolution of minerals happened in different ways. A common way is as follows:

Nanoscopic calcite/aragonite mineral → micritic calcite/aragonite mineral → micritic dolomite → powder-crystalline dolomite → fine-crystalline dolomite → medium-crystalline dolomite → coarse-crystalline dolomite

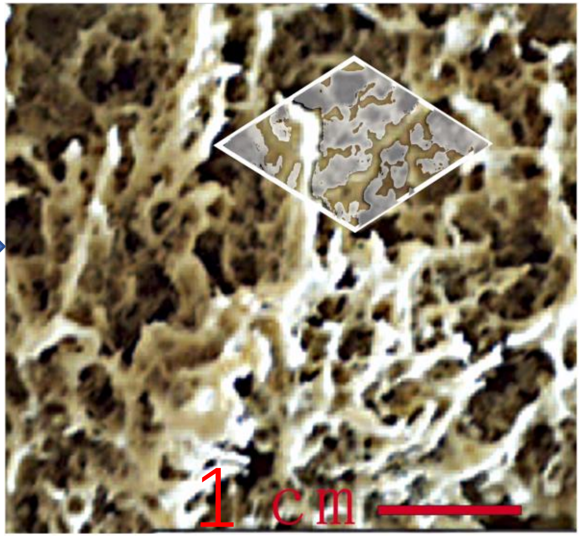
Concept 5: Most dolomitization are essentially growth of poikilitic dolomites in pores of existing microbioliths.

Dolomitization is actually growth of the numerous parts of each larger dolomite crystal in the pores of the existing rock, forming the larger dolomite crystal with the precursor rock as inclusions. The smallest mineral component of microbioliths is rod-like nanoscopic calcite, and the smallest dolomites are generally several microns in size.

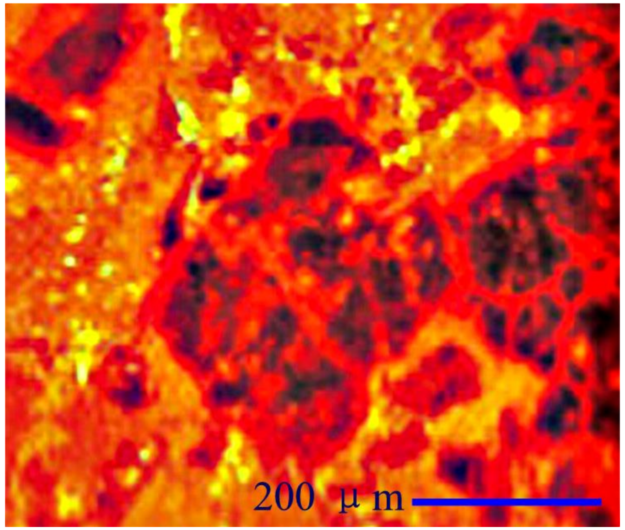
Schematic diagram of showing formation of a large dolomite crystal in a thrombolite:



An original thrombolite with a lot of pores (in dark color). Modified from Arp, 2012



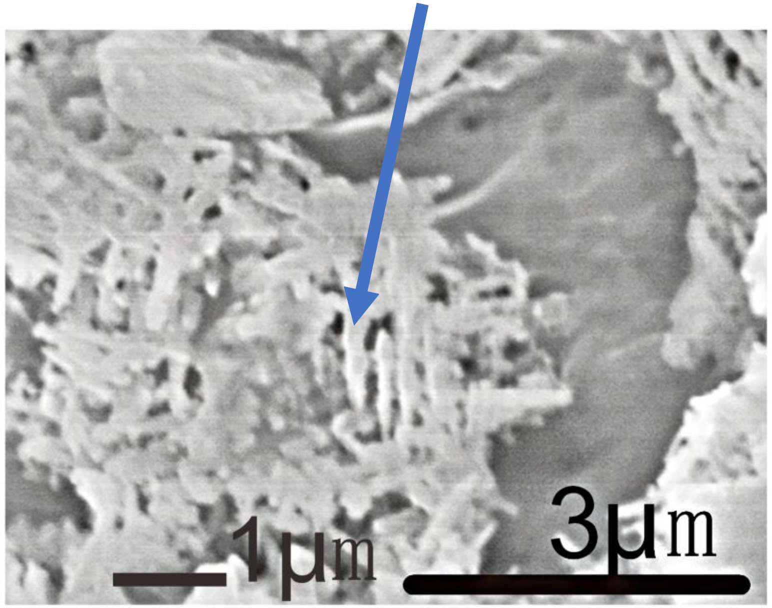
A imaginary rhombic poikilitic dolomite in the thrombolite



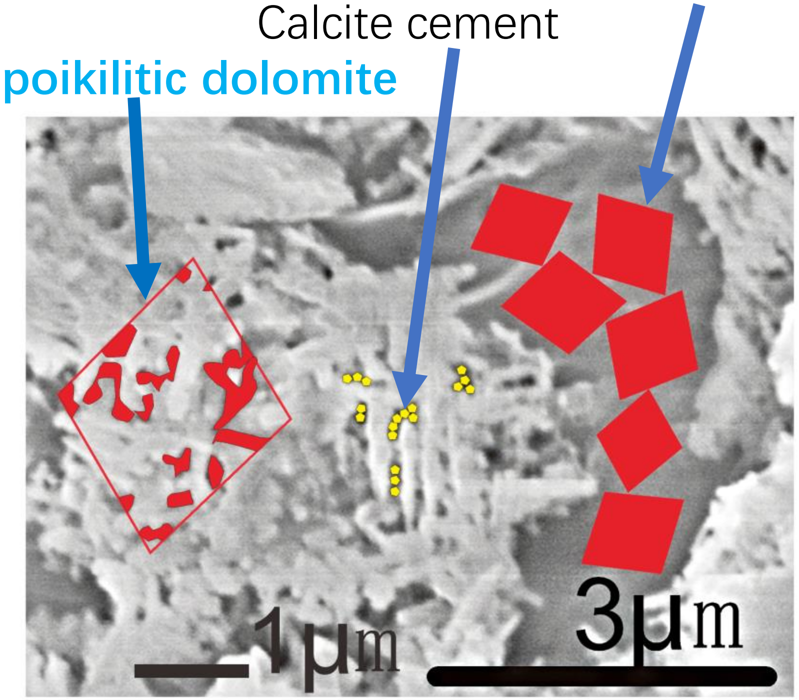
A few rhombic dolomite with inclusions of existing rock. Cambrian, North China. Modified from Bai et al., 2023, fig. 4

Concept 6: Poikilitic Recrystallization of Dolomites Recrystallization of dolostone is actually growth of the numerous parts of each larger dolomite crystal in the pores between the preexisting smaller dolomite crystals, forming the larger dolomite crystal with the preexisting smaller dolomites as inclusions.

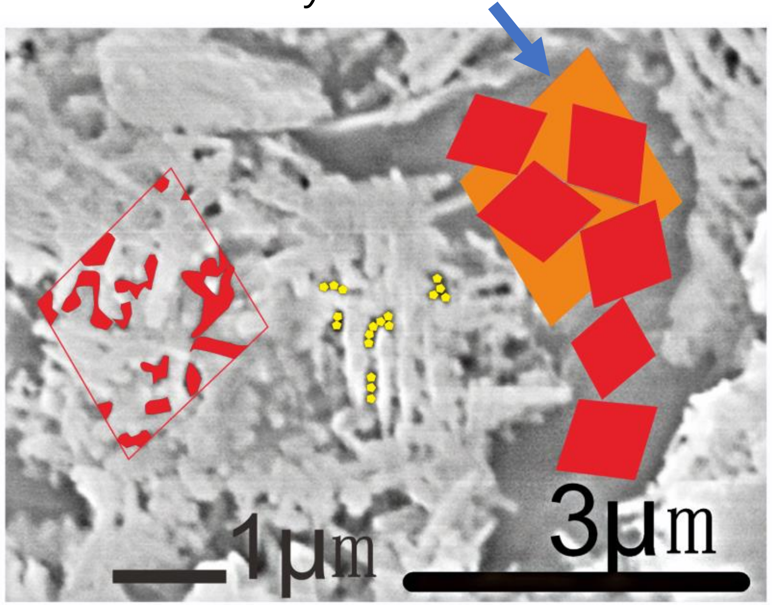
Schematic diagram showing the evolution of a microbiolith:



A micritic calcite grain consisting of rod-like carbonate crystals formed in an experiment (Wu et al., 2021)



A poikilitic dolomite, some calcite cement, and several clean dolomite formed in the grain. All imaginary.



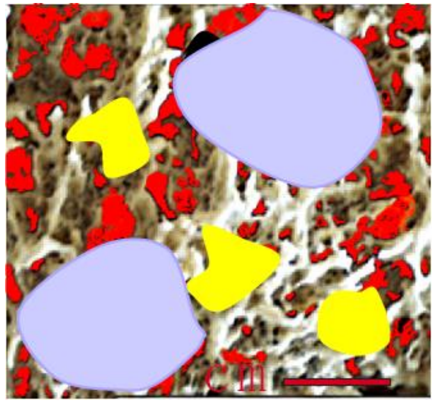
A imaginary large **poikilitic** dolomite (in yellow color) with inclusions of preexisting dolomites

Concept 7: Because evolution of fabric and composition is present in all ancient microbioliths, inversion study is needed to all ancient microbioliths, so as to restore their original fabrics and compositions.

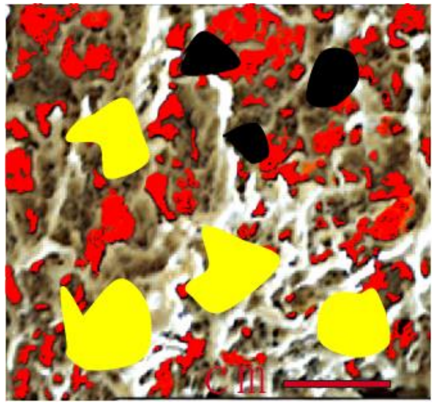
Concept 8: Inversion study of microbioliths refers to recognition of the minerals in the pores of original microbioliths and restoration of the original fabric and composition.

For carbonate rocks, the minerals formed in different diagenetic stages are generally in the same color under microscopes. But, they should have difference in chemical composition, such as contents of major elements and trace elements, and in isotope compositions of some elements. Thus, they can be distinguished by chemical compositions. To distinguish the different minerals will make it possible to differ the later-formed minerals from the original microbiolithic components.

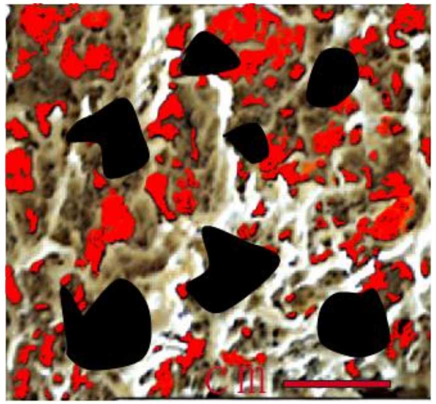
Schematic diagram illustrating inversion study of ancient microbioliths:



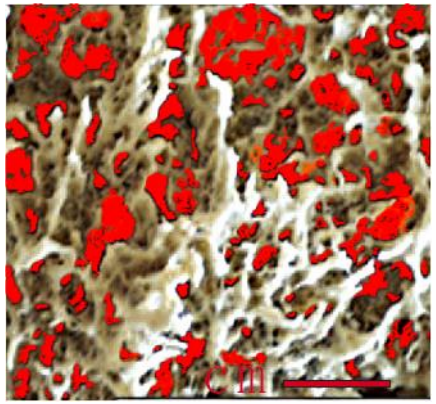
An imaginary final thrombolite with recrystallized patches (grey), later cements (yellow) and early cements (red)



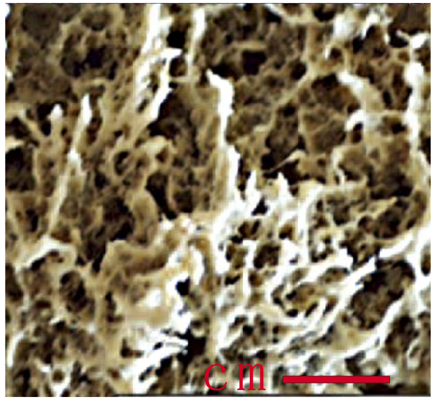
In step 1, the recrystallized patches were recognized



In step 2, the later cements were recognized



In step 3, the early cements were recognized

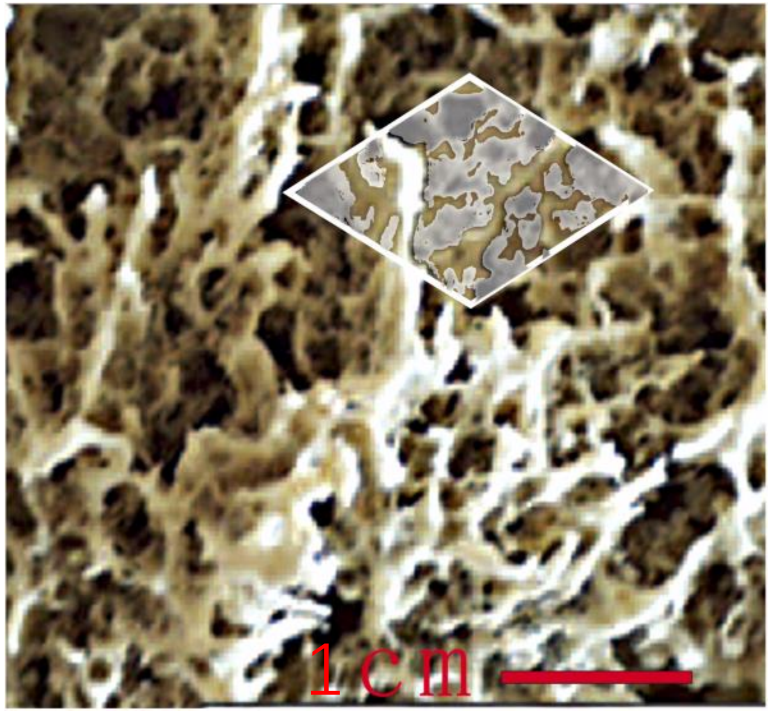


Finally, the original thrombolite were restored

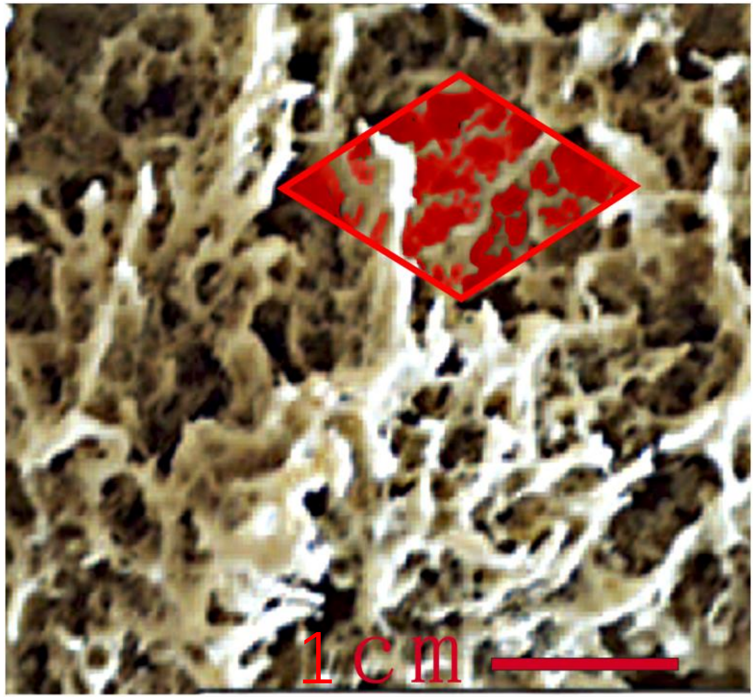
An example of inversion study of minerals:

coarse-crystalline dolomite → medium-crystalline dolomite → fine-crystalline dolomite → powder-crystalline dolomite → micritic dolomite → micritic calcite or aragonite → nanoscopic calcite or aragonite

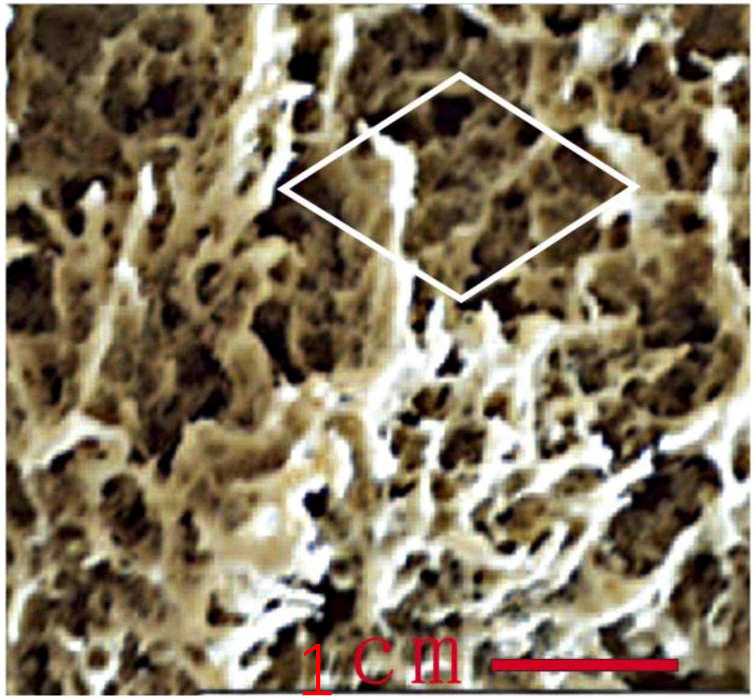
Schematic diagram showing inversion study of a large dolomite crystal:



A large rhombic dolomite consisting of the original minerals and secondary mineral parts in the same color, in an ancient microbiolith



The secondary mineral parts are different from the original microbiolith in composition, and can be distinguished

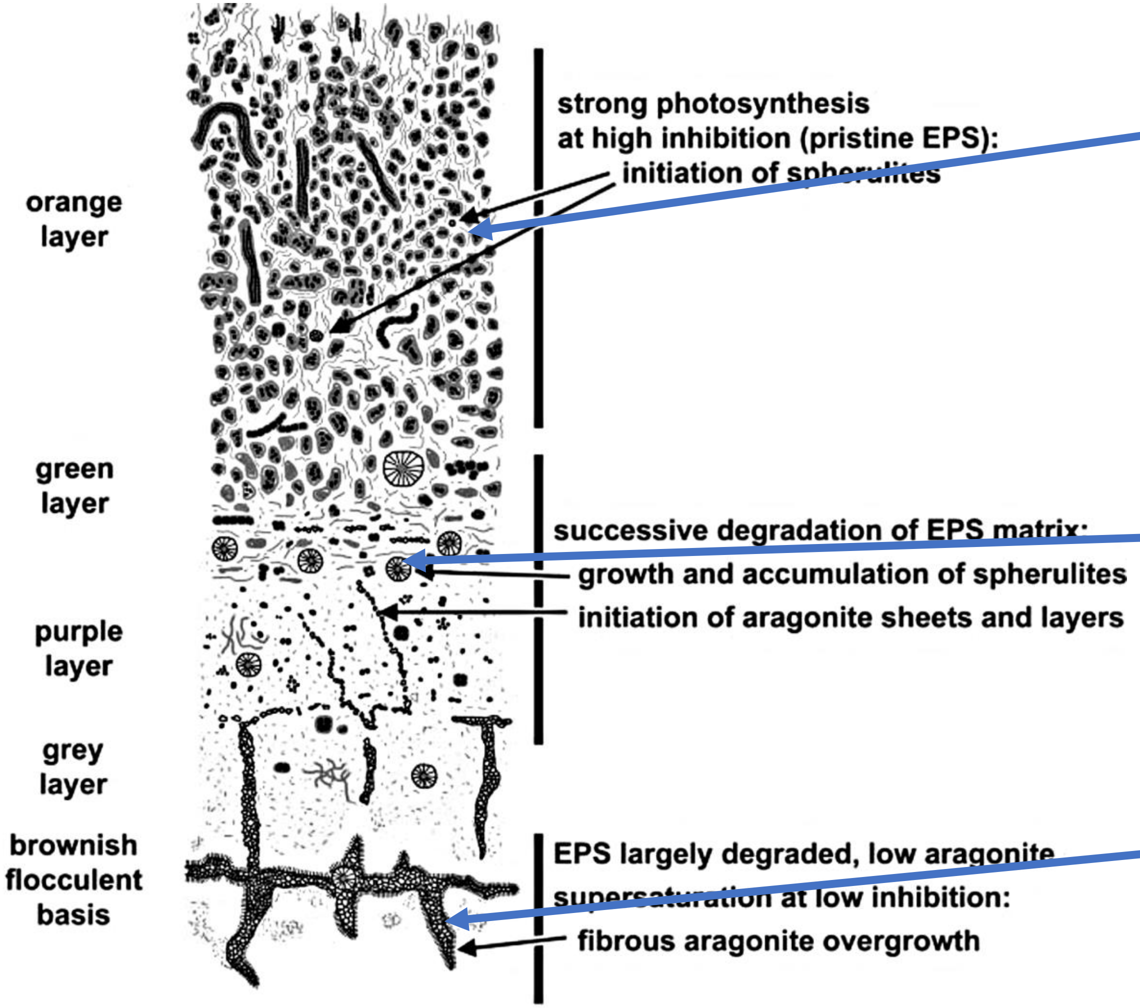


Then, the outline of the original minerals can be determined.

The objective of study of microbioliths is not to satisfy curiosity but to restore their original fabrics and paleo-communities, and determine the paleooceanic conditions. If these goals are not reached, the study is not really accomplished.

To see the passed

Concept 9: The microbialites beneath the present microbial mats are not formed now but were formed in the past by some disappeared microbial mats. So, dynamic thinking is needed in study of modern microbioliths.



Interpretation by me

Some minerals are forming.

The carbonates were formed by the EPS that are degrading.

The thrombolite was formed by some disappeared microbial mats.

(A model diagram of formation of thrombolite in a modern lake by Arp (2012)

Frontiers of microbiopetrology

1. **To construct a microfabric-community-environment (MCE) database of bioliths**

   Different environments host different microbial communities and may form microbioliths with different microfabrics. Each record in MCE database should consist of the microfabric, the microbial community forming it, and the main environmental conditions controlling the community.

1. **To construct a microbe-morphology-environment (MME) database of extant microbes**

   Each extant microbial species lives in one or several specific environments, and may have different morphologies adapted to different environments.

   Each record in MME database should consist of the species name, its morphology, and the main features of its environment. The records should be obtained from research on microbes in present-day natural environments or from experiments. Therefore, the establishment of MME database should be based on research results in microbiology and experimental microbiology.

3. To perform research on all carbonate rocks, ironstones including BIFs, and manganic rocks on the Earth

Especially, to conduct inversion study on them and study on their microscopic and nanoscopic fabrics, to find the microbioliths, based on restored original microfabrics, to restore their paleo-communities, and to determine their paleoenvironments, based on their mold holes, MME database, MCE database, and geochemical analyses.

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Chinese version:

微生物岩石学研究的创新方向

——首届国际生物岩石学大会之大会口头报告PPT的第二部分

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报 告 提 纲

1. 生物岩石学和微生物岩石学定义
2. 微生物岩石学的现状
3. 促进微生物岩石学的创新思维
4. 聚焦于微生物岩石的显微特征

6. 以确定微生物岩石的原始结构为目标
7. 用动态思维研究现代微生物岩石
8. 微生物岩石学的前沿研究领域

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生物岩石学和微生物岩石学定义

生物岩石学是研究生物形成岩石的作用、过程、产物、与生物演化、地球演化、资源和环境的关系的一门新兴交叉学科，它整合了以往的生物矿化作用研究、生物礁研究、非礁碳酸盐岩研究、微生物岩石研究、微生物型金属矿产研究等几个领域的研究（Wu, 2022，吴亚生，2023）。

- 生物矿化作用研究
- 现代和古代生物礁研究
- 现代和古代非礁相碳酸盐岩研究
- 现代和古代微生物岩石研究
- 微生物成因铁质岩、锰质岩研究
- 煤、黑色岩研究

→

生物岩石学

- 生物矿化作用学
- 宏生物岩石学
  - 生物礁学：生物礁研究
  - 非礁相碳酸盐岩研究（以前归在**沉积学**）
- **微生物岩石学**
  - 现代和古代微生物岩石研究
  - 微生物成因铁质岩、锰质岩研究
- 有机岩石学、油气地质学

微生物岩石学学科现状

学科历史短：

1908 发现叠层石

1967 发现凝块石

1987 定义微生物岩

2000 微生物岩分成4类（Riding, 2000)

2022 微生物岩石分为12类(Wu, 2022)

学科影响小：

研究的人数少

有重大影响的成果少

对经济和社会的贡献小

学科的社会认知度低

没有形成一个有影响力的学科（以前一部分归在沉积岩、一部分没有归属）

微生物岩石学学科发展缓慢的原因至少包括以下几个方面：

(1) 对微生物岩的研究是出于好奇心，而不是为了解决生命和地球系统进化等重大科学问题，

(2) 微生物岩的结构和结构非常复杂，很难研究，

(3) 以往的研究主要关注微生物岩的宏观特征，而对其微观特征关注较少;

(4) 在过去和现在的研究中使用的工具是有局限性的:它们没有足够的分辨率。

微生物岩石学研究的思想、方法创新

- ◆ 好奇心驱动的研究；
- ◆ 宏观特征和中观特征识别微生物岩石；
- ◆ 宏观和中观特征对微生物岩石分类；
- ◆ 只做有限的微观研究；
- ◆ 未开展反演研究；
- ◆ 研究工具有很大局限性；
- ◆ 与微生物学、古微生物学和实验微生物学结合少；
- ◆ 延伸和拓展研究几乎未开展

- ◆ 从好奇心驱动的研究，转变为解决大科学问题的研究；
- ◆ 中观特征+微观特征 识别微生物岩石；
- ◆ 中观特征+微观特征 对微生物岩石分类 ；
- ◆ 微观、超微观特征作为研究的关键内容；
- ◆ 反演研究作为主要研究内容之一；
- ◆ 开展研究工具创新；
- ◆ 非常重视与微生物学、古微生物学和实验微生物学的结合；
- ◆ 把微生物岩石学研究融合到地球科学研究的大系统中去

思想和方法创新→产出重要或重大成果→提升对科学和社会的贡献能力→成为有影响的学科

——把研究重点放到显微特征上

Why显微和超微尺度？

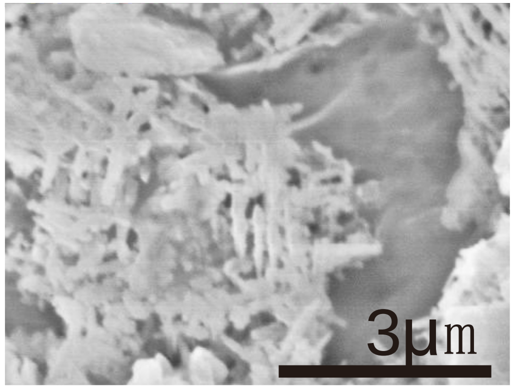
微生物很小：

微生物类别	蓝藻	细菌	古菌	真菌	病毒
直径范围 (μm)	0.5-70	**0.20-1.25**	0.1-15	2-30（<100）	0.01-0.3
最大长度 (nm)		8	200		0.45

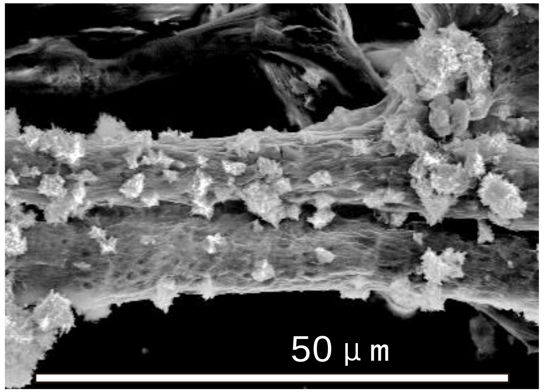
概念1： 微生物岩石由不同级别的微小结构单元组成。

结构组成单元的类型和大小

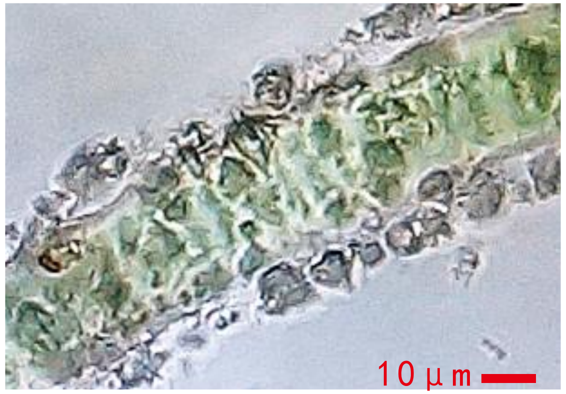
	单晶	泥晶颗粒	矿物壳（+模孔）	基本凝块	集合体颗粒	显微凝块（自然孔隙之间的）或显微纹层
直径或宽度（微米）	<1	<6	0.5-70	几十	几十~几百	几百



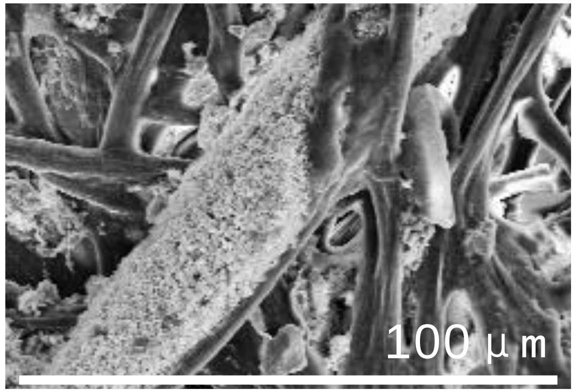
单晶 (Wu et al., 2021)



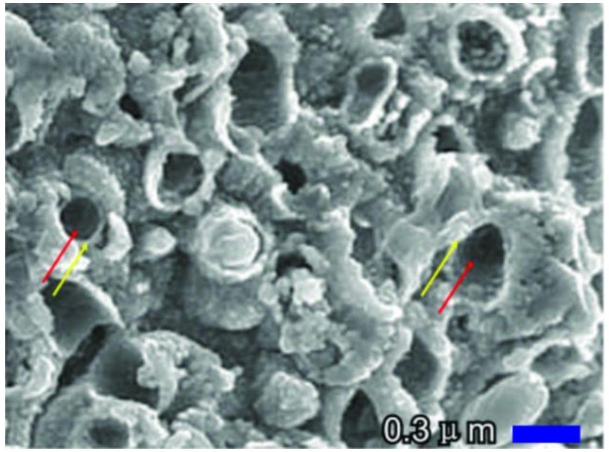
泥晶颗粒 (Wu et al., 2021)



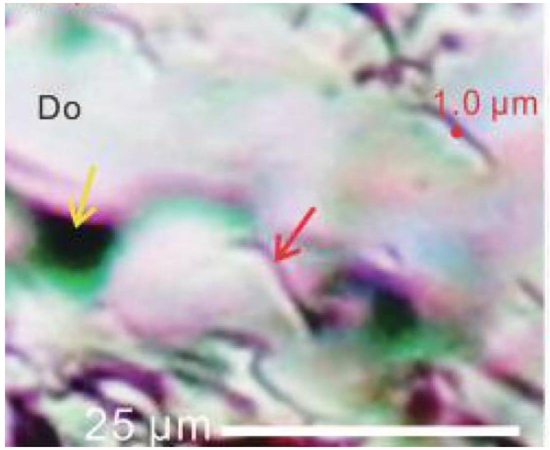
泥晶颗粒 (Wu et al., 2021)



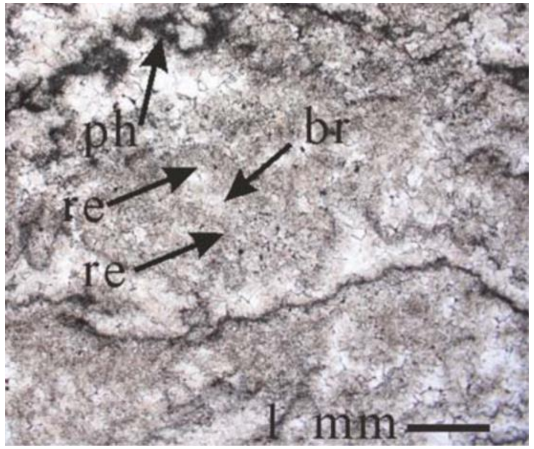
矿物壳 (Wu et al., 2021)



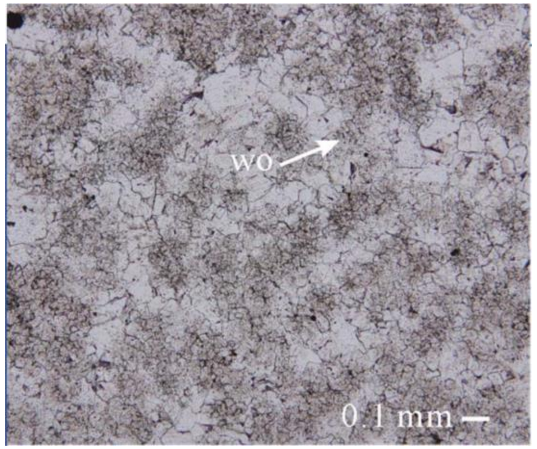
矿物壳 (黄色箭头) 和模孔 (红色箭头) (照片修改自 Silva-Castro et al., 2015: 4f)



模孔 (红色箭头)， 新疆阿克苏下寒武统第三阶肖尔布拉克组云质微生物岩。(Wu et al., 2021)



微纹层 （黑色线状) 新疆阿克苏下寒武统第三阶肖尔布拉克组云质层纹石。(Li et al., 2021)



微凝块 （暗色） 新疆阿克苏下寒武统第三阶肖尔布拉克组云质凝块石。(Li et al., 2021)

概念 2: 由于（1）形成微生物岩石的微生物一般都很小，（2）组成微生物岩石的结构单元都很小，因此，微生物岩石学研究需要聚焦于其微米和纳米尺度的结构特征。

显微尺度的凝块石 = 显微凝块+未填满的自然孔隙	中观尺度的凝块石 = 凝块石+溶蚀空洞或大的自然孔洞或重结晶形成的斑块
几十~几百微米尺度的	cm尺度的

根据宏观特征识别微生物岩石不为微生物岩石的结构特征支持，容易导致错误结果。

工具的局限性

研究微生物岩最广泛使用的工具是光学显微镜。虽然光学显微镜的分辨率理论上可以达到200纳米。然而，在日程实际使用中，它们的分辨率只有2到5微米。因此，在光学显微镜下，小于2微米的矿物和化石通常难以看见。大多数微生物化石、大多数微生物岩结构成分都小于2微米，因此在一般光学显微镜下无法看到。

先进的工具，如电子显微镜的分辨率要高得多。它们使观察小于1微米的表面特征成为可能。然而，它们只可以用于观察平面起伏特征，却不能用于观察内部结构。

因此，在过去和现在，由于大多数研究都是在光学显微镜下进行的，研究工具的局限性使研究人员无法看到微生物岩的大部分微米结构和纳米结构，研究结果的价值和意义受到了很大的限制。

如何打破微生物岩石学的瓶颈?不仅要有对微生物岩石进行微米级和纳米级研究的意识，而且要有分辨率达到2微米或更小的光学显微镜。如果这两个因素都准备好了，那么，对微生物岩石进行高分辨率研究的新时代就会到来。

——以确定原始结构为目标

为什么需要对微生物岩石开展反演研究?

概念3: 所有微生物岩石都发生了结构和成分的演变。

微生物岩石的演化：指其结构和成分因成岩作用而发生的改变。

原始微生物岩石（原始结构和成分）→ 不同时期的各种成岩作用改造 → 改变了的微生物岩石 (非原始结构和成分的) → 最终的微生物岩石（最终的结构和成分）

影响微生物岩石的成岩作用主要包括：（1）白云石化作用，（2）胶结作用，指孔隙和孔洞中矿物的结晶，（3）溶蚀作用，形成溶蚀孔洞，（4）重结晶作用。

古代微生物岩石演化示意图:

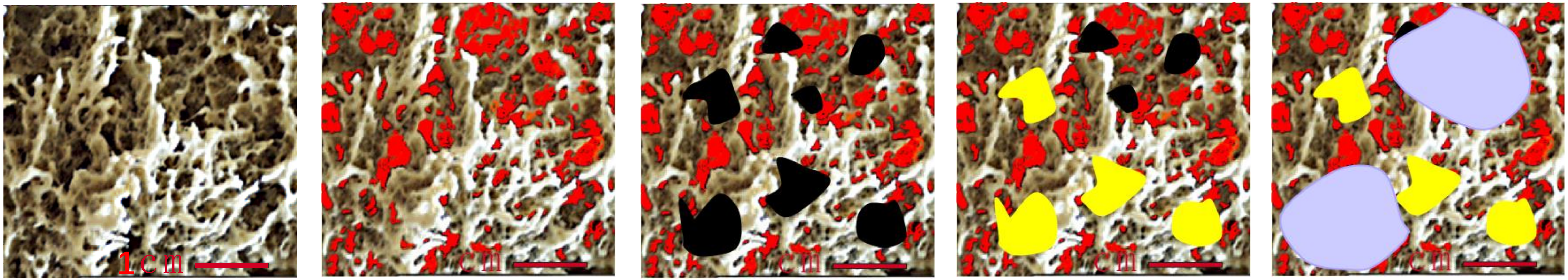
原始结构
原始的凝块石

改变了的凝块石

进一步改变的凝块石

再改变了的凝块石

最终的结构
最终的凝块石



红色：孔隙中的胶结物

黑色：溶蚀形成的孔洞

黄色：晚期形成的胶结物

灰色：重结晶形成的斑块

概念 4: 几乎所有的古代微生物岩石都发生了矿物的演化。

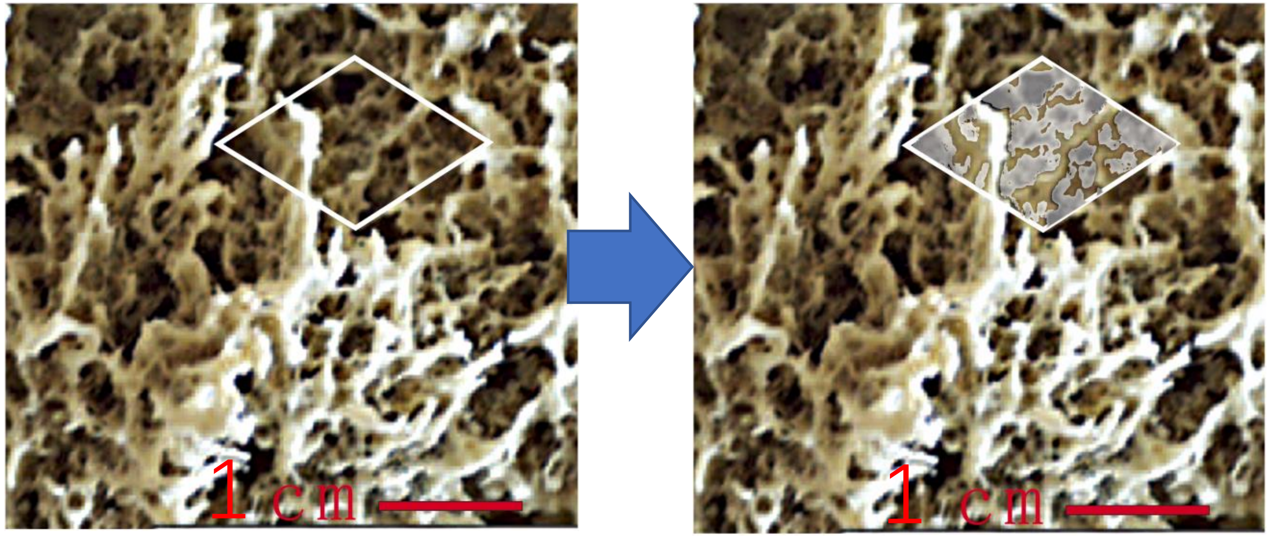
古代微生物岩石的矿物演化方式多种多样，以下是一种发生在中国新疆阿克苏下寒武统第三阶云质微生物岩石中的演化方式：

几百纳米大小的方解石或文石 → 数微米大小的方解石或文石 → 泥晶白云石 → 粉晶白云石 → 细晶白云石 → 中晶白云石 → 粗晶白云石

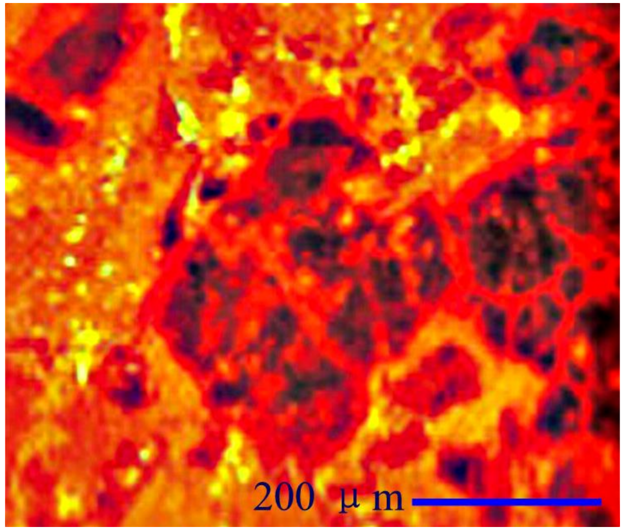
概念 5: 大多数的白云石化作用实际上是包晶白云石在已有岩石的孔隙中生长的过程。包晶——包含有其它物质的晶体。

白云石化实际上是较大的白云石晶体的各个部分在先前存在的岩石的孔隙中生长，形成较大的白云石晶体的过程；以前的岩石成为包裹体。微生物岩石最小的结构成分为棒状、几百纳米大小的方解石，最小的白云石一般为几微米大小。

一个白云石大晶体形成的示意图：



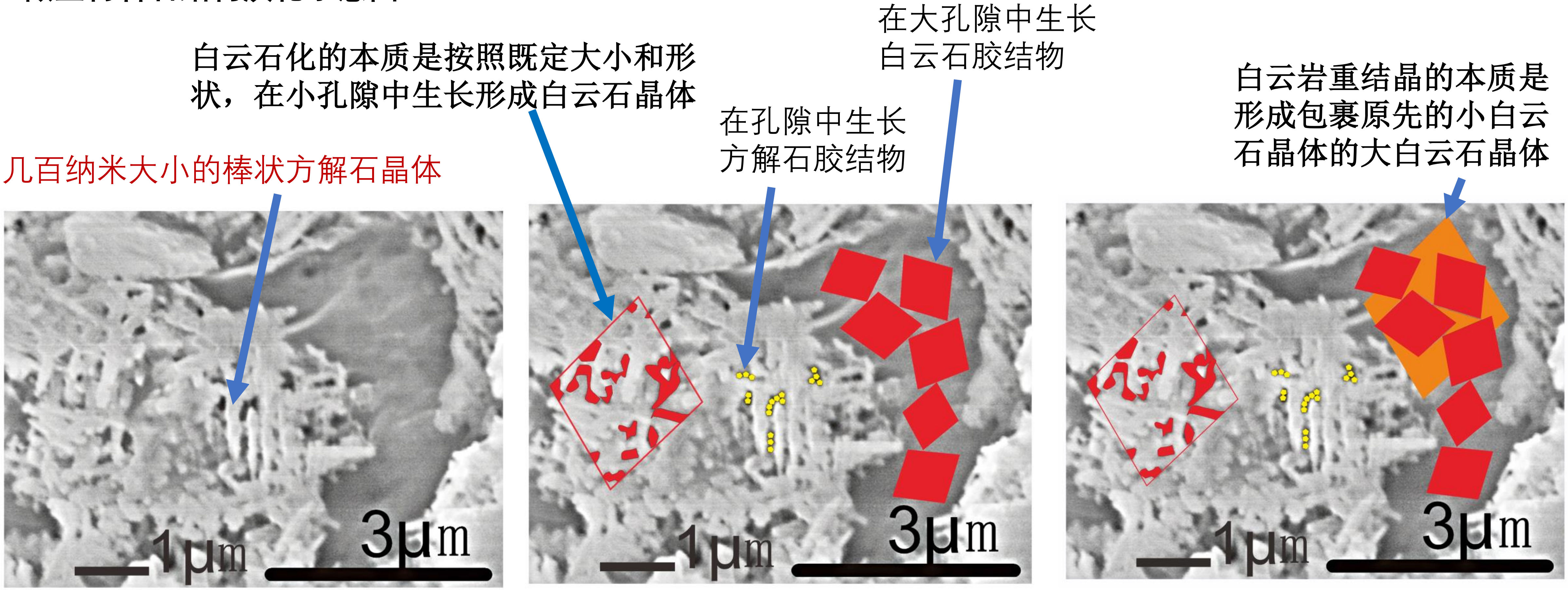
修改自 Arp, 2012



白云岩阴极发光照片。几个大的菱形白云石晶体内部有原岩的包体。照片修改自 Bai et al., 2023, fig. 4

概念 6：白云石重结晶作用实际上是大白云石晶体的各个部分在已有的小白云石晶体之间的空隙中生长，形成大白云石晶体的过程；先前的小白云石晶体将成为包裹体。

微生物岩石结构演化示意图：



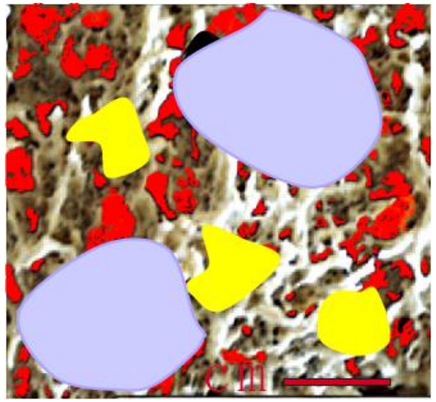
(Wu et al., 2021)

概念 7: 由于所有的古代微生物岩石都发生了结构和组成的演化，因此，需要对所有的古代微生物石岩进行反演研究，以恢复它们的原始结构和组成。

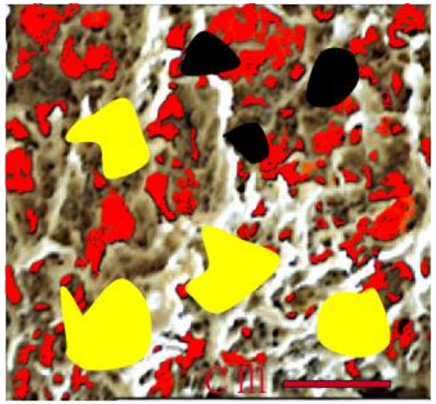
概念 8: 微生物岩的反演研究指通过识别原始微生物岩石孔隙中的矿物，从而恢复其原始结构和组成的研究。

对于碳酸盐岩而言，不同成岩阶段形成的矿物在显微镜下通常呈现相同的颜色。但是，它们在化学组成上，如主量元素和微量元素的含量，以及某些元素的同位素组成上应该有差异。因此，它们可以通过化学成分来区分。把不同的矿物区分开来，就有可能把后来形成的矿物与原来的岩石区别开来。

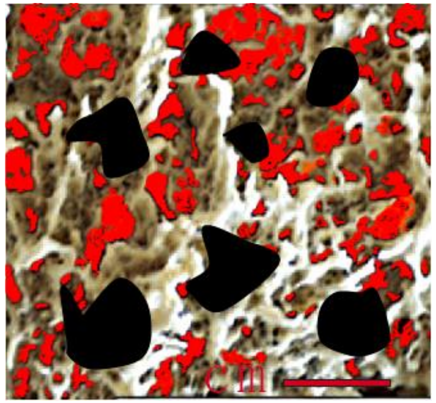
微生物岩石反演研究示意图:



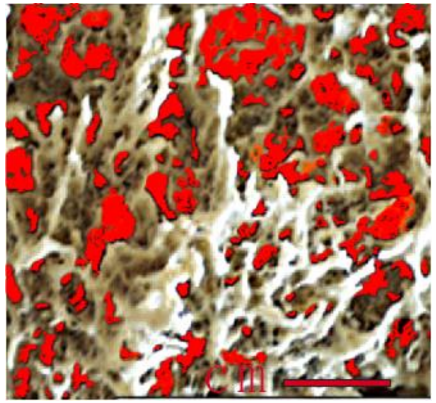
最终的岩石



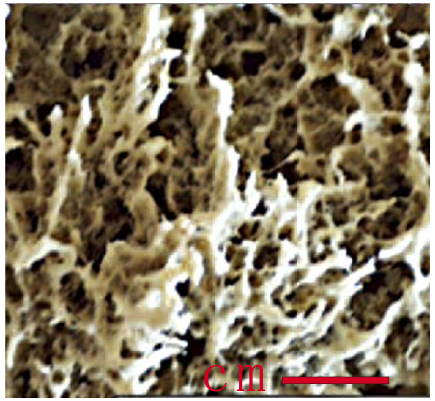
识别出重结晶形成的斑块



识别出晚期形成的充填溶洞的胶结物



识别出早期形成的胶结物

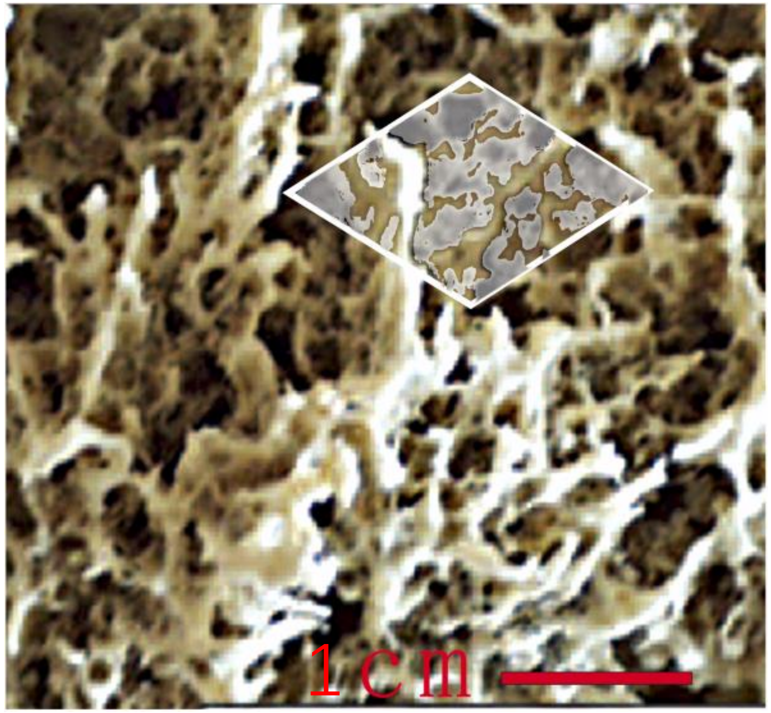


初始的岩石

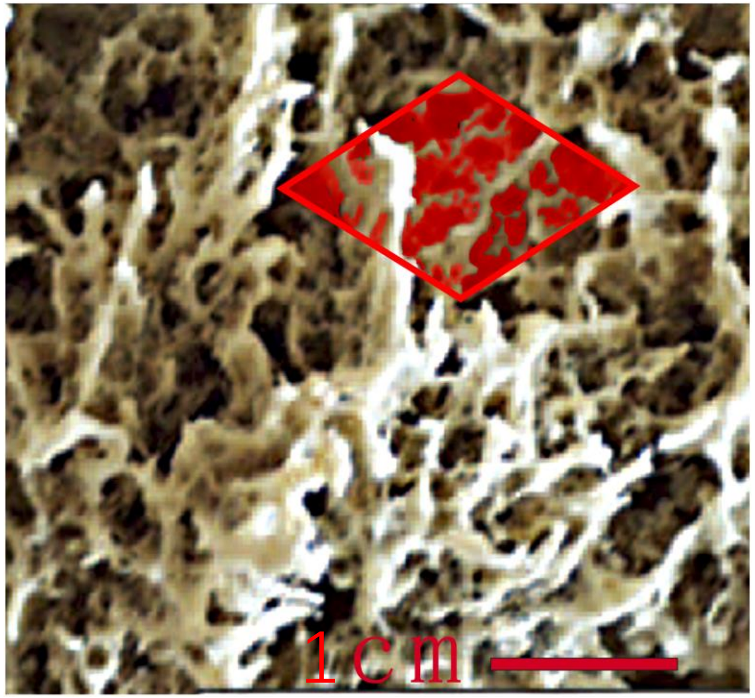
古代微生物岩石的矿物反演研究举例:

粗晶白云石 → 中晶白云石 → 细晶白云石 → 粉晶白云石 → 泥晶白云石 → 泥晶方解石或文石 → 纳米级方解石或白云石

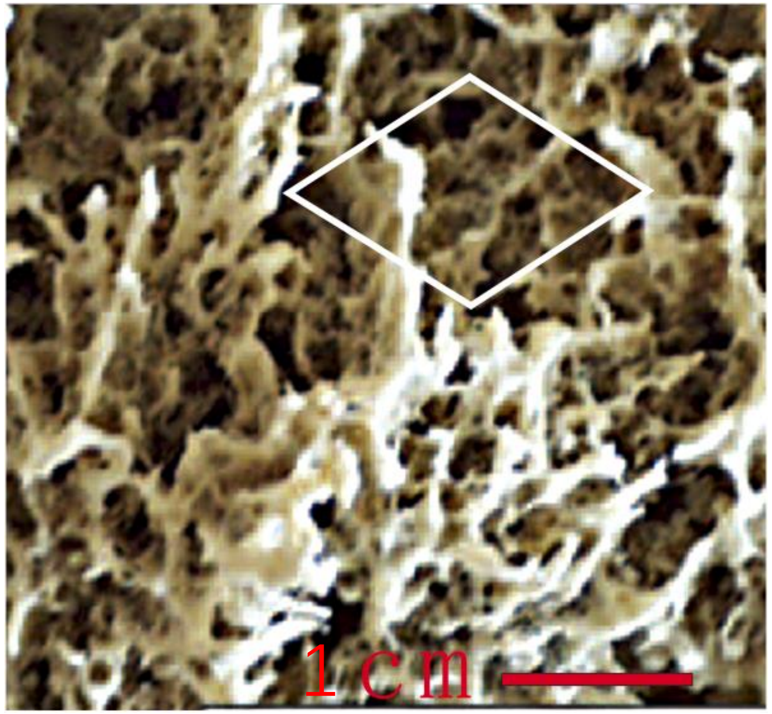
一个大白云石晶体的反演研究示意图:



一个大白云石晶体，由原始方解石矿物和在其间孔隙中生长的白云石分体共同组成



通过成分的不同，识别出构成白云石晶体的各个分体（红色）

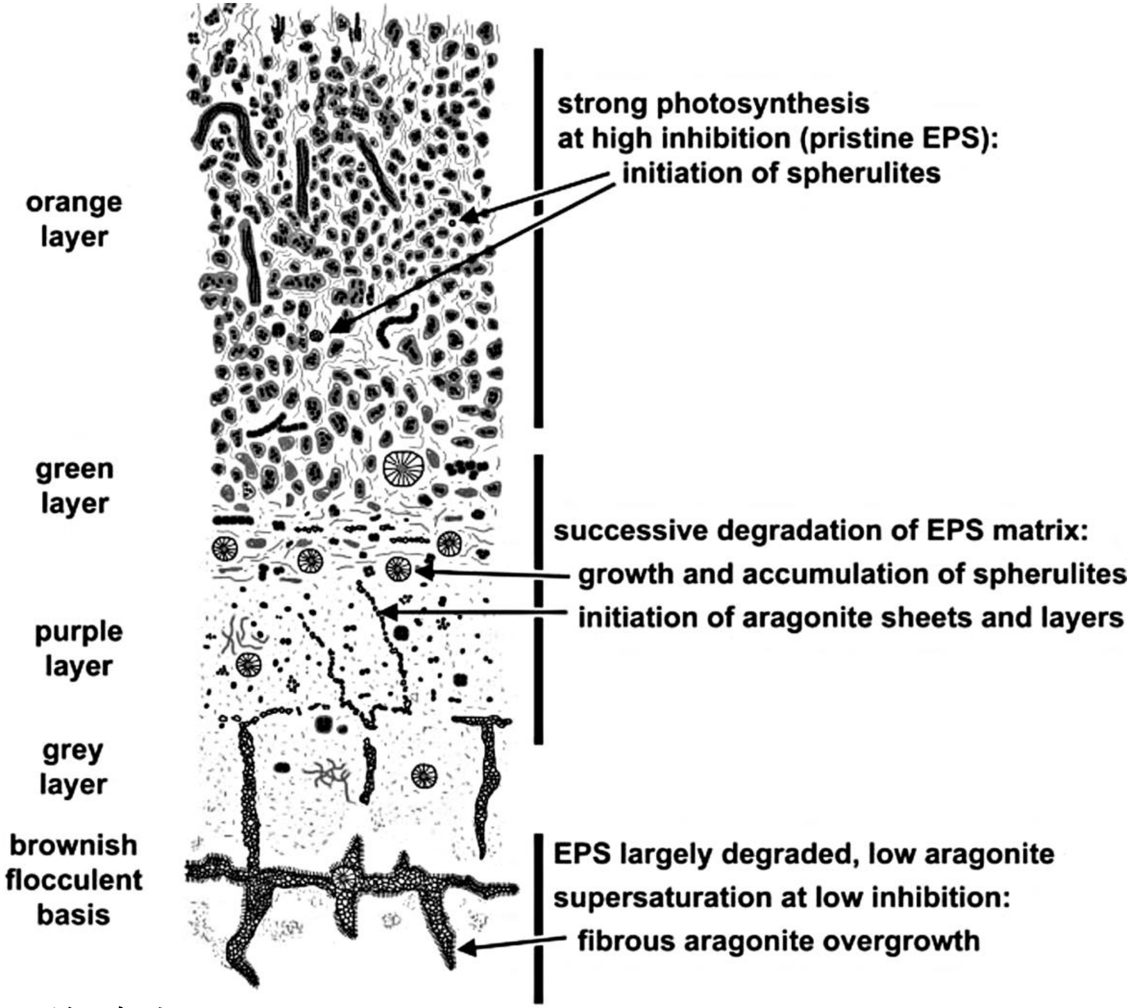


于是，可以识别出原始的结构

研究微生物岩的目的不是为了满足好奇心，而是为了恢复原始结构，恢复古群落和古环境条件。如果没有达到这些目标，研究就没有真正完成。

——用动态思维研究现代微生物岩石

概念 9：现今微生物席之下的微生物岩石不是其上的微生物席形成的，而是由已经消失的微生物席形成的。



(修改自Arp, 2012)

吴亚生此处的解释

有很少的矿物在形成

形成球状矿物的微生物席降解殆尽

形成这种微生物岩石的微生物席已经消失了

微生物岩石学的前沿研究领域

(1) 构建“显微结构-古群落-古环境”三位一体的微生物岩石数据库

不同环境有不同的微生物群落，可以形成不同结构的微生物岩石。该数据库的每一条记录由微生物岩石显微结构、形成这种结构的微生物群落、以及控制这种群落的主环境因素三位一体的数据组成。

(2) 建设“微生物-形态-环境”三位一体的现代微生物数据库

每种现生微生物物种可能生活在一到几种特定环境，可能有适应不同环境的不同形态。

该数据库的每一条记录由微生物种名、微生物的形态、以及其生活环境的主要特征构成。该数据库的数据应当来自对现代自然环境的微生物的研究，以及微生物实验研究，即要基于现代微生物学和实验微生物学的研究成果。

(3) 对各个时代的碳酸盐岩、铁质岩、锰质岩开展全面、系统的研究

特别要开展反演研究和显微结构、超微结构的研究，发现微生物岩石，重建古群落和古环境。

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