Research Letter

Earth's oldest stromatolites in the 3.7 billion years old rocks from Greenland: evidence of benthic microbial communities

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Abstract

Stromatolites and laminite are record of benthic microbial communities. Here we report two stromatolites and one laminite we recognized from the published photos of the 3.7-billion-year old rocks in Isua, Greenland, which were used as the examples of structural folds in abiogenic laminated structures by previous researchers to argue against the interpretation of some conic structures as the earliest stromatolites by the earlier researchers. In order to help distinguish stromatolites from tectonic folds and laminites from abiogenic laminated rocks, here we propose three criteria for identifying stromatolites: (1) columnar, dome-like, and conic forms, (2) their axis are not in a convergent arrangement, and (3) their laminae are in dome-like or conic form, irregularly sinuous, often furcate, and merge in their lateral surface. According to these criteria, we reached the conclusion that the conic structures reported by the previous researchers are not stromatolites. Our recognition of these earliest microbialite rocks shows that the benthic microbial communities were present 3.7 billion years ago.

Key words: Stromatolite, microbialite, laminite, Isua, laminae.

1 Stromatolites as proofs of the earliest life on Earth

Search for the earliest life on Earth has always been one of the hottest topics in earth science research. Research of the earliest fossils, microbialites, and organic carbon are the three common methods for achieving this goal. Microbialites are the carbonate rocks formed by benthic microbial communities (Burne and Moore, 1987). There are many kinds of microbialites (Wu, 2022), and the kind that is the earliest recognized is stromatolites, which are columnar, domal, or conic carbonate structures with

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laminated internal fabrics formed by microbial mats.

2 Controversial on the earliest stromatolites on Earth

Before 2016, the known earliest stromatolites were those reported by Walter et al. (1980), from the 3.4-3.5 billion years old formation in the North Pole area, Western Australia. In 2016, Nutman et al. reported some conic structures in the 3.7-billion-year-old rock outcrops in Isua, Greenland (**Fig. 1**), interpreted them as stromatolites, and considered them the earliest life on Earth. This later discovery by Nutman et al. (2016) pushed the time of the first evidence of life on Earth more than 200 million years forward.

Nutman et al. (2016) presented four reasons for interpreting these conic structures as stromatolites: (1) The sediments between the adjacent conic structures indicate that these conic structures were above the seafloor; (2) the presence of low-temperature dolomite indicates the presence of microbial activity; (3) the rocks are sedimentary, not of hydrothermal origin from the geochemical analyses; and (4) they have a laminated internal fabric.

However, after reexamining these samples, based on three-dimensional morphological and geochemical studies, Allwood et al. (2018) suggested that the cone-like structures of Nutman et al. (2016) are possibly just an assemblage of deformation structures (**Fig. 2**) formed when the sediments were

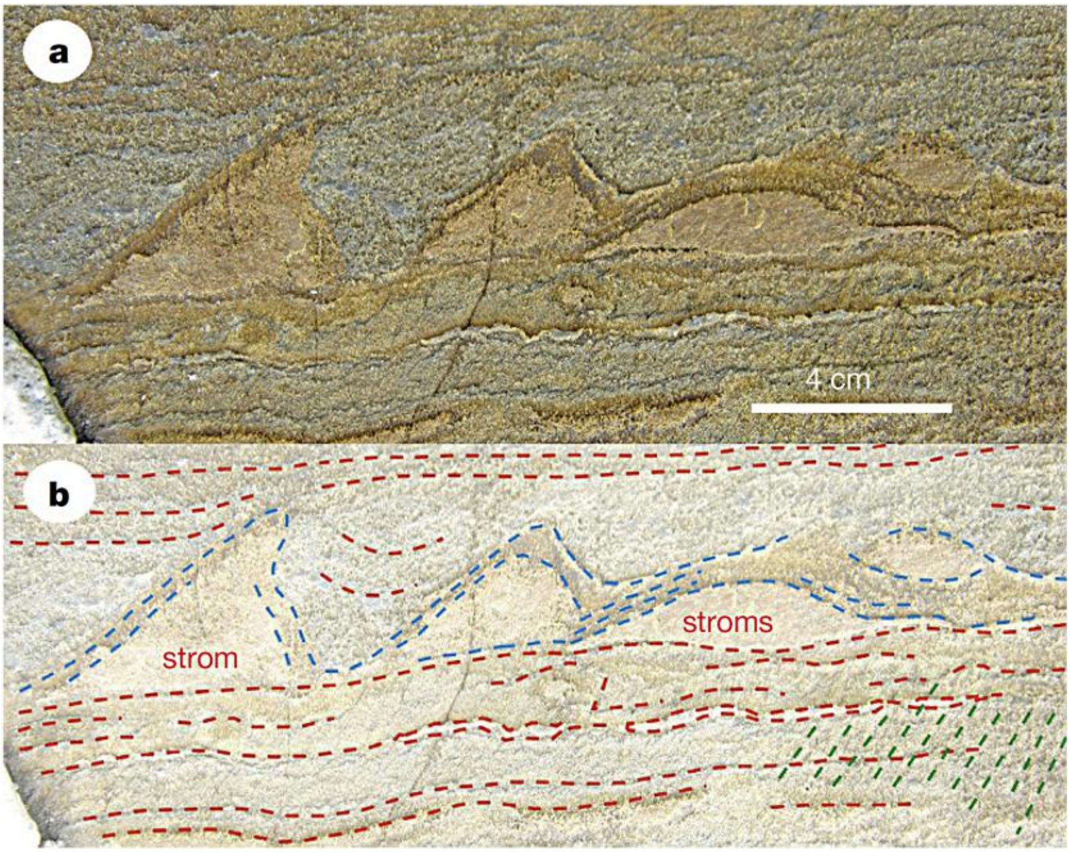

Fig. 1 The conic structures in Isua, Greenland interpreted as stromatolites by Nutman et al. (2016). (Modified from Figure 1 of Nutman et al. (2016)). The original legend: Image is inverted because layering is overturned in a fold. b, Interpretation of a, with isolated stromatolite (strom) and aggregate of stromatolites (stroms). Locally, lamination is preserved in the stromatolites (blue lines). Layering in the overlying sediment (red lines) onlaps onto the stromatolite sides. A weak tectonic foliation is indicated (green lines).

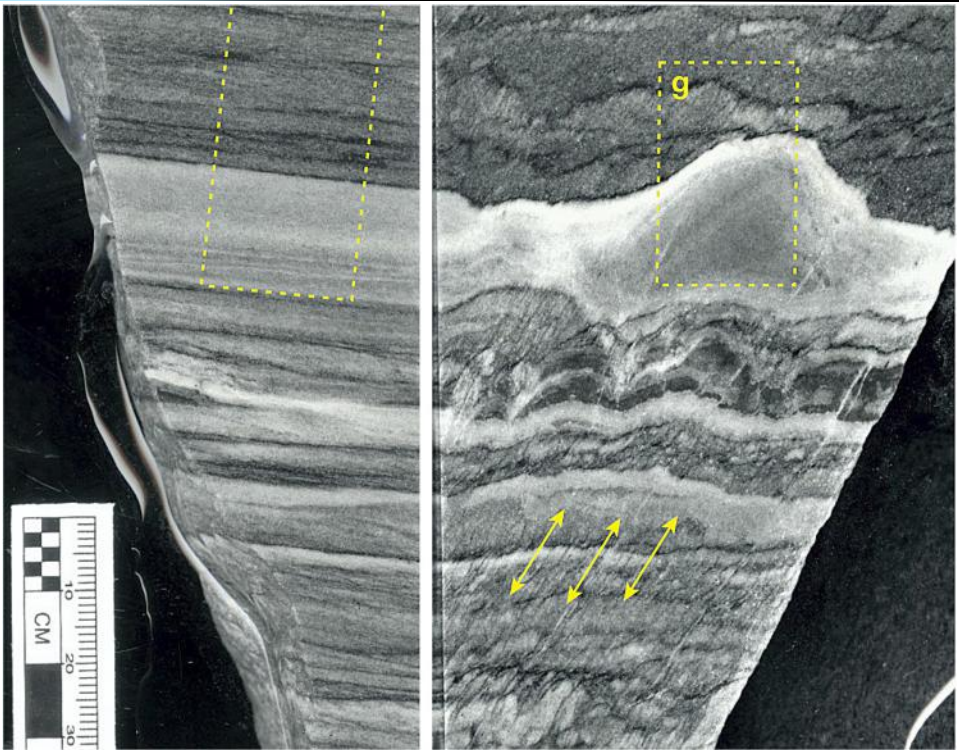

Fig. 2 Modified from Fig 1-b, c of Allwood et al. (2018). The original legend: Fig. 1 Putative stromatolites of Greenland. b–c, Sample from site A. b, Face 2 shows even, parallel layering. c, Face 1 shows irregularly layered fabric with planar discontinuities (arrows in c) and convex-up features.

buried and not formed by microbial activity. Our examination seems also supporting Allwood et al. (2018)'s suggestion that the sample pictures presented by Nutman et al. (2016) may not be stromatolite. We reached this conclusion from these five points: (1) The conic structures of their samples have bent top ends, their shape is not that of typical stromatolites because no stromatolite has a curved top; (2) the conic structures in the sample are tilted in the same direction, which is a typical feature of ripple marks or microscopic folds formed by tectonic compression; (3) though deposits formed between the cones indicate that they are structures protruding from the seafloor, they could also be the result of non-microbial activities, such as wave ripples; (4) their conic structures do not have any of the typical internal laminated fabrics of stromatolites; and (5) the low-temperature dolomite and geochemical composition may also have an alternative explanation.

Nutman et al. (2019) defended their interpretation of the cones as stromatolites with release of more geochemical data, which, in our opinion, is not sufficient to support their argument for biogenic origin of the conic structures. In addition, Zawaski et al. (2020) also disputed the biogenic origin of the conic structures of Nutman et al. (2016), based on the photos (**Fig. 3**) of the outcrop 10 m from the conic structures of Nutman et al. (2016). We agree that the centimeters to decimeter bending of the laminated rock in Figure 3 of Zawaski et al. (2020) is more like folds formed by tectonic compression and are not stromatolites, because they have fold axes (red dash line) inclining in similar directions and in a convergent pattern (red arrows representing the compression direction of tectonic stress). However, the millimeter-scale irregular curvature of the laminae is similar to that of stromatolites.

As a reply to the negation of Zawaski et al. (2020), Nutman et al. (2021) provided some 3D CT images of the rock lamination of Nutman et al. (2016), as evidence of biogenic origin. However, in our opinion, the laminae in the 3-D images do not have the features of stromatolitic laminae because they

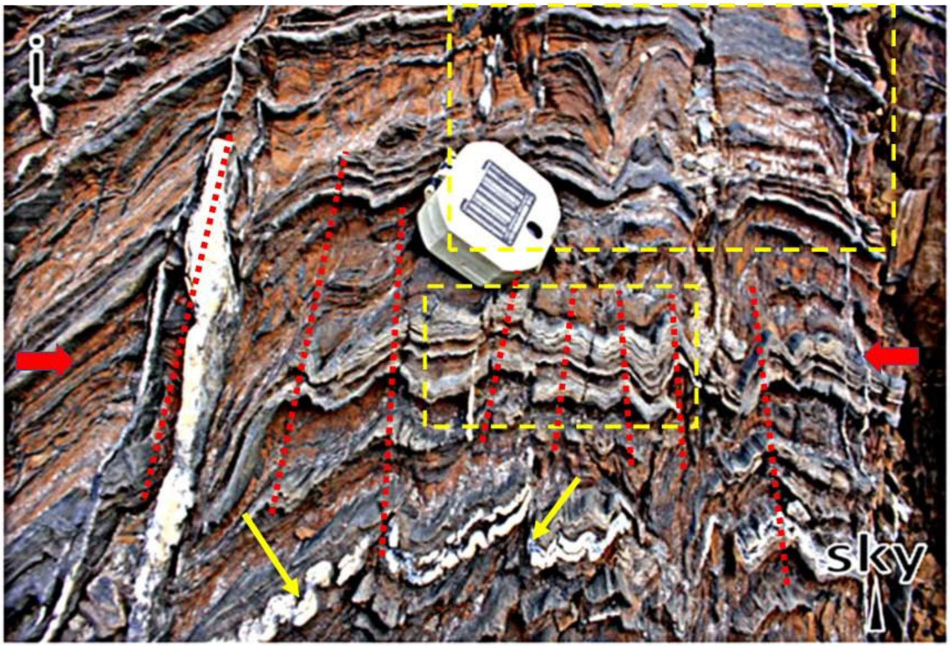

Fig. 3 Modified from Fig. 3-I of Zawaski et al. (2020), with the white compass as a scale. The original legend: (i) Centimeter to decimeter-scale folding of layered calc-silicate schist containing local quartzite and quartz-rich schist layers (~10 m south of Site A; ~8 cm wide compass for scale). Here we recognized at least four rows of small structural folds with axis in the positions of the red lines, with small shear structure (the left red dot line), the sausage structure (yellow arrows). The red arrows reflect the directions of the structural compression.

are straight, and do not have the characteristic tiny curvature of stromatolites. They may be the abiotic beddings of the sedimentary clastic rocks, instead of the lamination of stromatolites originated from microbial mats.

3 Criteria for identifying stromatolites

Because of the significance of stromatolites for studying the origin of the life on Earth, there is a need for us to have clear criteria for identifying stromatolites. Stromatolites are defined as laminated rocks formed by benthic microbes (Riding, 2011). There are two kinds of commonly seen stromatolites: trapping and calcified stromatolites formed through the trapping of sediments and the calcification of the microbial mats, respectively. All calcified stromatolites and some trapping stromatolites have a framework consisting of the irregularly superposed laminae formed by calcification of successive microbial mats. The interspaces between the laminae consist of cavities, sediment fills such as micrites or lime intraclasts, and calcite cements.

The laminae originally consist of dense biogenic micrites, and are dark in color in thin sections. If they are silicified in early diagenetic periods, they become more resistant to weathering and often form embossments on outcrops (**Fig. 4**). The sediments or cements in between the laminae are light in color. The alternation of the bands of dark laminae of microbial mat origin and those of sediments or cements is regarded as a key feature of stromatolites. Since the sedimentary rocks formed in deep water or still water can have beddings similar to the lamination of stromatolites, understanding the difference between the laminated sediments and laminae of stromatolites will help distinguish stromatolites from the small folds formed in laminated sedimentary rocks.

Based on our observations, the main features of stromatolites include: (1) columnar, dome-like, and conic form, (2) mostly perpendicular to the seafloor (**Fig. 4**), and (3) consisting of dark micritic laminae consisting of micron to nanometer-sized calcite crystals formed by calcification of microbial mats. The micritic laminae of stromatolites are generally in convex-up, dome-like or conic form (**Fig.**

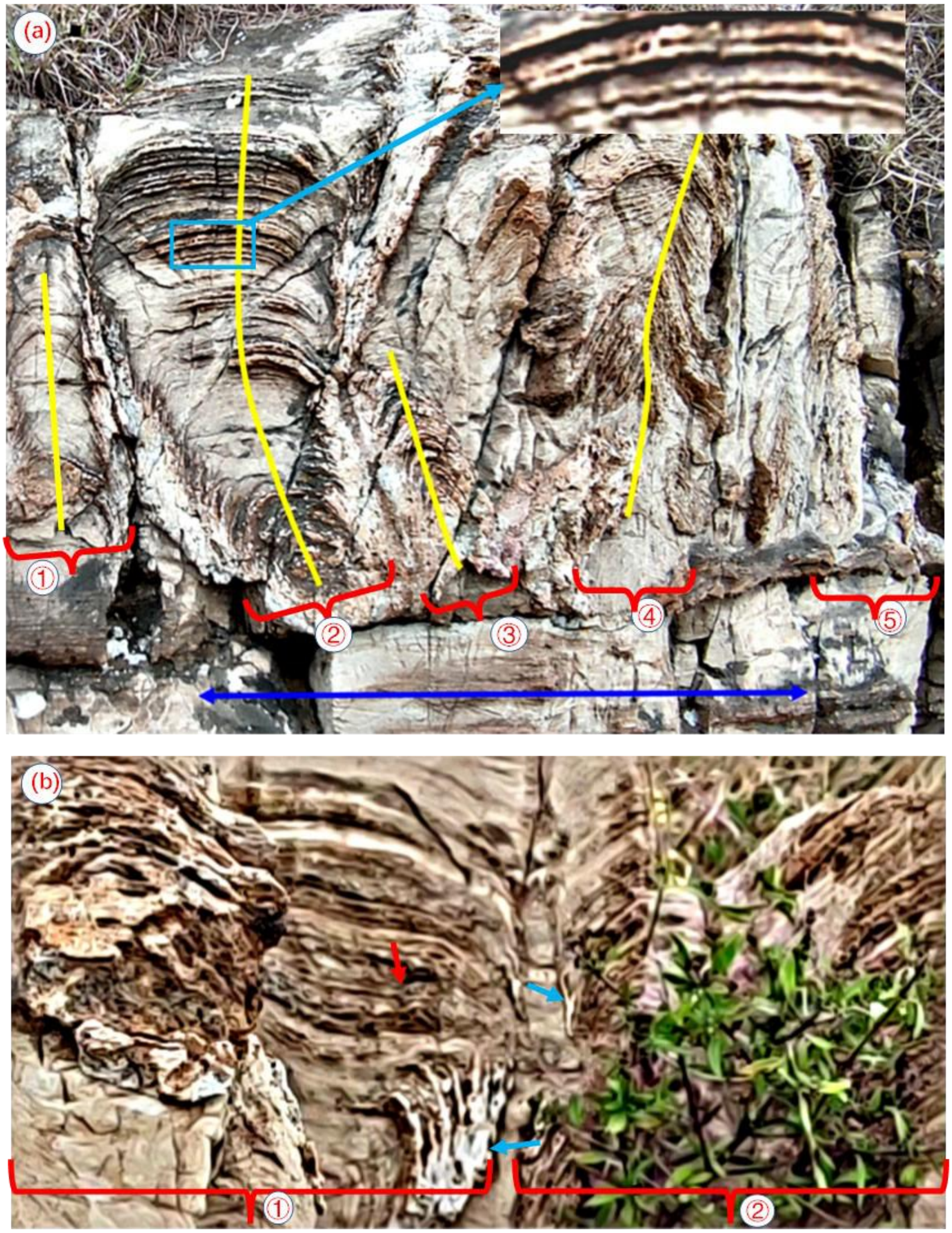

Fig. 4 Some stromatolites (“1” to “5” in (a) and (b)) in the Mesoproterozoic Gaoyuzhuang Formation dolostones on the outskirts of Shijiazhuang, Hebei Province, China. (a): showing the dome-like laminae in the left three stromatolites, and the conic and tent-like laminae in the right stromatolite, and the stromatolite axis (yellow lines) that are not parallel to each other and generally bent (the blue line parallel the seafloor); (b) showing that the laminae merged in the lateral surface of stromatolite “2” (blue arrow), and they merged and formed net-like fabric in stromatolite “1” (blue arrow). The insert in (a) shows the laminae are irregularly sinuous and uneven in thickness.

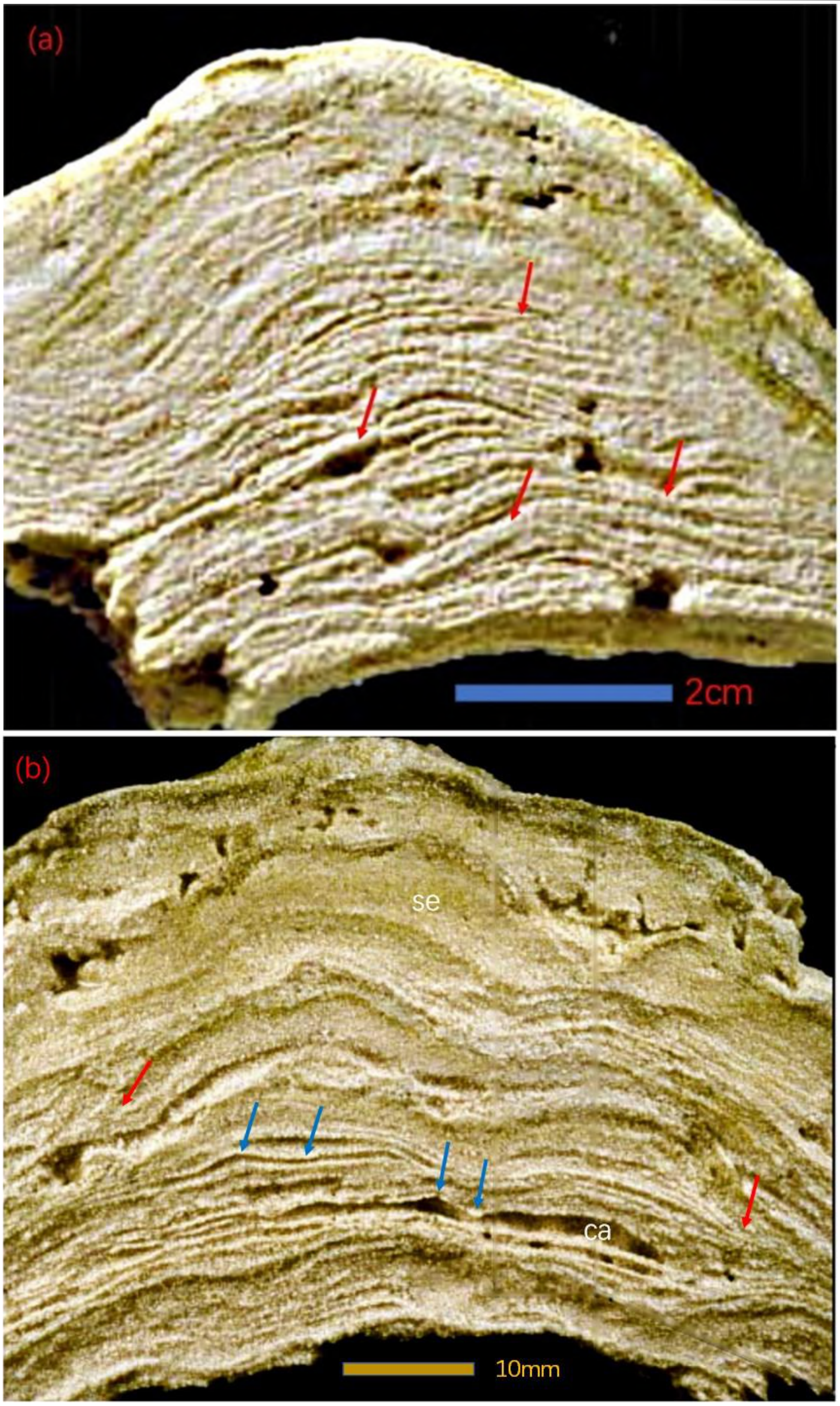

Fig. 5 Vertical section of two modern stromatolites from the shallow subtidal seawater, Highborne Cay, Bahamas (from Reid et al. (2000), with raised sharpness), showing the convex-up, dome-like micritic laminae (blue arrows) formed by calcification of microbial mats are irregularly sinuous, uneven in thickness, and have furcation and merging (red arrows). The interspaces between the micritic laminae are lime intraclastic sediments (se) or empty (ca).

4), are rugged, and often bifurcate (**Figs. 4, 5**) and merge on the lateral surface of stromatolites (**Fig. 4**). These features can be used to distinguish stromatolites from tectonic folds and deformation structures of laminated sedimentary rocks. The interspace between the micritic laminae consist of sediments, cements, and microscopic cavities.

On microscopic and ultramicroscopic scales, the micritic laminae of stromatolites consist of mold holes and crusts or proclots (Wu et al., 2021). The mold holes are the spaces left by the decomposition of the microbes in the microbial mats that form the stromatolitic laminae, and are originally in the same sizes and shapes as the microbes. The crusts consist of the micron to nanometer-sized minerals enveloping the microbes and formed by induced calcification. Proclots are the micrites in between adjacent mold holes, and are formed by the precipitation induced by microbes.

4 Recognition of stromatolites in the Greenland 3.7 billion years old rocks

Since the conic-structures described by Nutman et al. (2016) do not have the typical form and internal fabrics of stromatolites stated above, we agree with Allwood et al. (2018), and Zawaski et al. (2020) that they probably are not stromatolites. In our Figure 3, which is modified from the Fig. 3-i of Zawaski et al. (2020) with raised contrast and sharpness, we found that in the centimeter to decimeter-scale folding of the layered calc-silicate schist, it contains local quartzite and quartz-rich schist layers (~10 m south of Site A; ~8 cm wide compass for scale). Zawaski et al. (2020) used this photo to show they are actually structural folds and not stromatolites. Because the arrangement of the axis of the small conic structures (red do lines) are in a convergent pattern, we agree with them that they are small structural folds, not stromatolites.

This negation, however, does not mean that there is no stromatolite in the 3.7 billion years old rocks of Isua, Greenland. After we made a detailed observation on the upper right part of Figure 3, we found the presence of typical features of stromatolites in two structures (**Fig. 6(b):** within the red dot lines). The axis of the two structures are different from those of the folds (red dot lines of Fig. 3) and there are convex-down laminae between the two structures (“6”, meaning that the two structures were above the seafloor. The laminae are in dome-like or conic form (Fig. 6: “1”, “2”), being irregularly sinuous (“4”), with furcation (“3”) and merging (“5”), and are not continuous between the two structures.

The five features mentioned above indicate the two structures are stromatolites, instead of folds. In addition, since the laminae in the surrounding area of the two stromatolites are irregularly sinuous in microscopic scale, they belong to another microbialite type, laminite (Wu, 2022), a kind of sheetlike microbialite with the same internal fabric as stromatolites. The laminae of laminite are also formed by microbial mats. The two stromatolites are distributed in a laminite.

5 The difference between stromatolites and small structural folds

Based on our past studies, we propose the following three criteria that might help in differentiating stromatolites from small structural folds of laminated sedimentary rocks: (1) The axis of small folds are generally straight, often inclines to the same direction, and the folds form convergent patterns, while the axis of stromatolites are roughly perpendicular to the seafloor and can be bent; (2) The laminae of adjacent small structural folds are connected to each other, while the laminae of adjacent stromatolites are not connected to each other in most cases; and (3) The laminae of stromatolites merge on their lateral surfaces, while small folds do not.

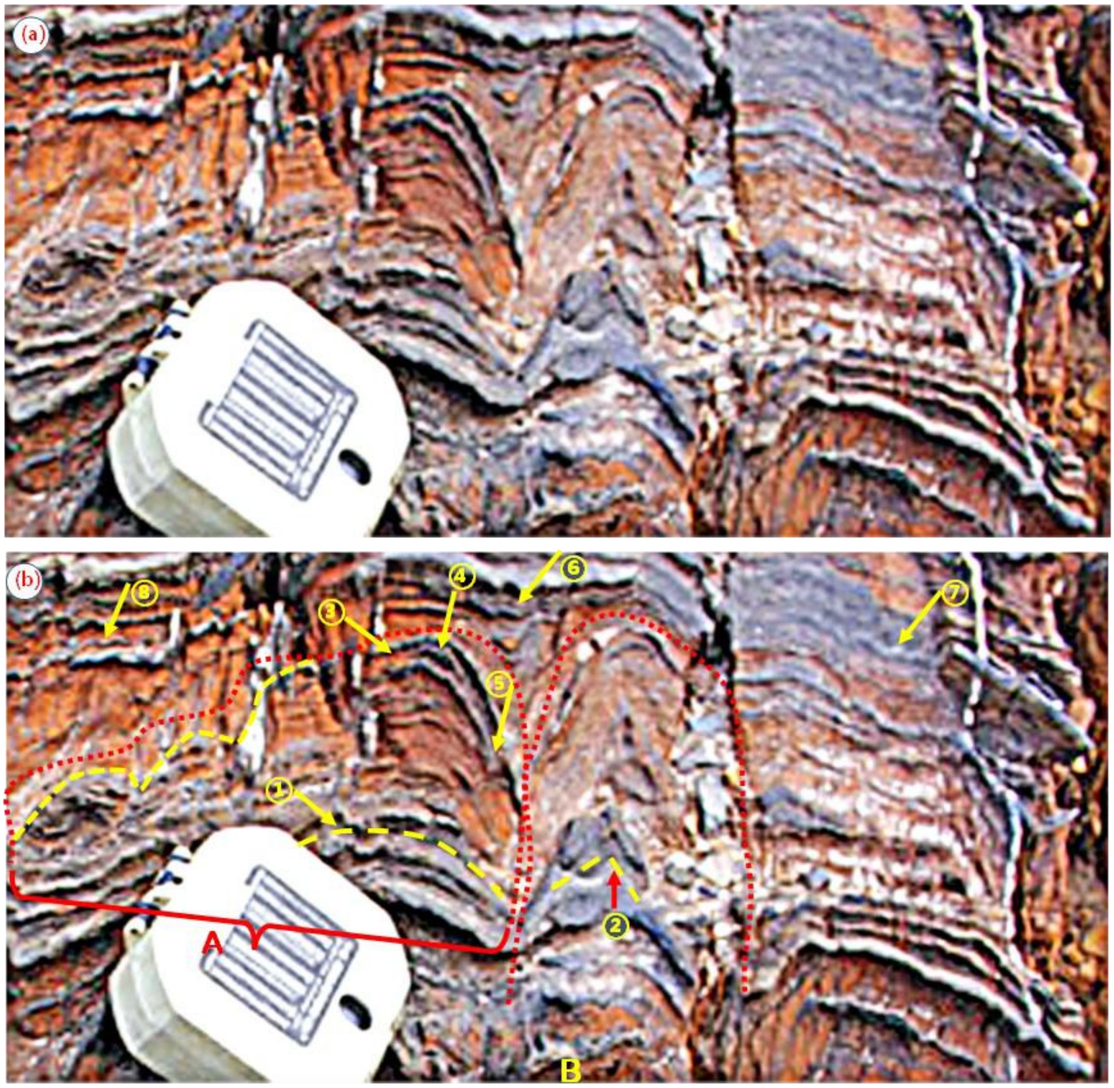

Fig. 6 Enlargement of the up yellow box in Fig. 3, with raised sharpness and contrast. Two stromatolites (A, B) with five typical stromatolitic features: “1” : The dome-like laminae; “2”: The conic laminae; “3”: The furcated laminae; “4”: The sinuous laminae; “5”: The merged laminae in the lateral surface of them; “6”: The downward convex laminae in between them indicating they were reliefs at the seafloor; “7”: The irregularly sinuous laminae indicate they belong to a laminite, another common type of microbialite; “8”: The irregularly sinuous laminae of the laminite covering the stromatolites.

6 Conclusions

The conic structures from the 3.7 billion year old rocks in Isua, Greenland, reported in Nutman et al. (2016), lack the stromatolitic forms and laminae, and are not stromatolites in our opinion. In this study, however, we found two typical stromatolites with the forms and internal fabrics typically characteristic of stromatolites from the folded 3.7 Ga laminated rock reported by the later researchers, which is ten meters from the outcrop studied by Nutman et al. (2016). Therefore, we think benthic microbes existed on Earth 3.7 billion years ago.

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