Mineral crusts and mold holes in Martian rocks: Evidence of microbes on ancient Mars

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Abstract

Experimental studies and observations of modern microbialites in natural environments indicate that the metabolic action of some microbes can cause minerals to precipitate on their surface and form crusts enclosing the microbes. The holes left by degradation of died microbes are called mold holes. Mineral crusts and mold holes are widespread in present and ancient microbial rocks on Earth and are evidence of once presence of microbes. Structures similar to Earth's fossils and stromatolites and organic compounds have been found in previous studies on the photographs of Martian rocks taken by the Perseverance rover, suggesting that the Mars may have supported life. Based on an analysis of the photos by NASA's Perseverance rover in July 2022, of two drilling cores and a circular abraded surface at the Jezero crater area of Mars, this paper reports that the Martian rocks have dense mineral crusts and mold holes, suggesting that they were formed by microbial-induced precipitation, confirming the once presence of microbial communities on ancient Mars. Based on the size of the mold holes, the microbes that formed the rocks are probably cyanobacteria.

Key words: Mars, life, mineral crust, mold hole, microbialites, biolith, microbiolith

1. Introduction

Is there life on Mars? How do you look for evidence of life on Mars? There are four ways to determine if there is life on Mars: organic matter or organic compounds, fossils, microbial rocks, and miner-

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al crusts and mold holes. Some researchers have found structures similar to the algae, lichens, fungi and spores on Earth in shape in the images of Martian rock (Kaźmierczak, 2020; Rizzo, 2020; Elewa, 2021; Joseph et al., 2021; Latif et al., 2021; Rizzo et al., 2021); some found a variety of organic compounds in the lacustrine mudstone of Mars, which include aliphatic, aromatic and thiophene compounds (Eigenbrode et al., 2018; Heinz and Schulze-Makuch, 2020); and some found structures similar to tellurian microbial rocks in photographs of Martian rocks (Bianciardi et al., 2014, 2015; Noffke, 2015; Rizzo et al., 2015; Rizzo and Cantasano, 2016), suggesting that there is a high possibility of presence of life on Mars. To date, no research on whether there are mineral crusts and mold holes in Martian rocks have been carried out. The purpose of this paper is to look for evidence of mineral crusts and mold holes in photos of Martian rocks.

2. Mineral crusts and mold holes in terrestrial rocks

Organic matter is the compounds that make up living organisms, including proteins, amino acids, etc. Fossils are the remains, skeletons or bones, traces of activity, and so on left by organisms. A microbial skeleton is a structure made of minerals that is exactly in the same shape as a microbe. The rocks formed mainly by the action of microbes are called microbiolith (Wu, 2022).

There are many kinds of microbial rocks, and the most common two of them are stromatolites and thrombolites, both of which are identified mainly by shape and internal microfabrics. The most important characteristics of stromatolites are presence of micritic micro-laminae formed by microbial mats. The micro-laminae are usually several mm or sub-mm thick, arched upward, and have small bends and bifurcations (Wu and Jiang, 2022). The basic component unit of thrombolites is micritic miniclots, which are in irregular shape and composed of minerals several microns to sub-microns in size.

Mineral crusts are mineral envelops that encase microbes or the holes left by the microbes. Many microbes are enveloped in a transparent, gelatinous envelop called sheath. If the microbes are dense, their sheaths coalesce together to form a film-like structure called biofilm. Experimental studies and observations on microbes in modern natural environments show that under the condition of high pH value and high content of calcium ions and bicarbonate ions in water, the metabolic action of some genera and species of microbes can cause the pH value of their microenvironment to rise, which causes the precipitation of carbonate minerals on the sheath of the microbes, finally forming the mineral crusts enclosing the microbes. After the microbe dies and decay, a cavity called mold crust forms in the crust, which is in the same shape and size as the microbe. To date, studies have revealed that at least 8 cyanobacterial genera and 8 bacterial genera have an ability to form mineral crusts.

If microbes are dense, they form dense mineral crusts that connect to each other and make up one of the main types of microbial rock, thrombolite. If microbes are rare, the mineral crusts they form will disperse in sediments and may form other types of microbial rocks. Mineral crusts and mold holes are evidence of microbes. In addition, the types of the microbes can be inferred from the sizes and shapes of the mold holes.

The key feature of mineral crusts is that they all have a mold hole inside. Although in many cases the mold holes have been filled by organic remains or later-formed minerals, the boundary between the mineral crusts and the filling materials can be identified if their compositions are different. The spaces between mineral crusts are likely to be filled by later-formed minerals. Mineral crusts can be recognized if the mineral filling the space between them is different from them in composition or fabrics. In most cases, because the minerals making up mineral crusts are very fine, often nano-sized, and are highly reflective on rock surface, they are usually in lighter color on outcrops or rock sample surface.

The coarser minerals between crusts have higher light transmittance and strong light absorption, tending to be dark on outcrops or rock sample surface. The identification of mineral crusts is easier when the mold holes and the interspaces between mineral crusts are not filled.

In the case of relatively dense microbes, the thickness of the mineral crusts of microbes is not uniform, generally being only a few to dozens of microns. The size and shape of the mold holes depend on the types of the microbes that form them. According to research, the cyanobacteria on Earth that can form mineral crusts are usually in filamentous, spherical, and capsule-like shapes. Most cyanobacteria have a diameter between 1 μm to 50 μm, a few filamentous cyanobacteria have a very small diameter, only several hundred nanometers. The bacteria that can form mineral crusts are small, in spherical or capsule-like shape, generally < 1 μm in diameter and < 3 μm in length. According to our experiments, some filamentous green algae can also form mineral crusts and mold holes. Most of these filamentous green algae are several tens of microns in diameter. According to studies, the mold holes in the stromatolites of Hamelin, Shark Bay, Australia have a diameter of 125-250 μm, while the mold holes in the modern stromatolites and thrombolites in Highborne Cay, Bahamas have a diameter ranging 23-46 μm (Wu et al., 2021).

Because mineral crusts and mold holes are small, they can only be observed under a powerful microscope or by a scanning electron microscope. For modern microbes, their three-dimensional shapes can be directly observed. However, the mineral crusts and mold holes in microbial rocks cannot be separated from the rocks, and their three-dimensional shapes cannot be directly observed. Their 2-D shapes can be observed on outcrops of rocks, slabs and from thin sections. The two-dimensional cross-sections of the mold holes of small globular microbes are circular. The cross sections of the mold holes of the capsule-like microbes are round, and their oblique and longitudinal sections are elliptical. The transverse sections of the mold holes of filamentous microbes are rounded, their longitudinal sections are curved and tubular, and their oblique sections are oval.

Mineral crusts enveloping the bases of the filamentous green algae were observed in a mineralization experiment we performed in 2021 (Fig. 1). Wormlike mold holes and calcite crusts are present in the smooth surface of a modern stromatolite specimen from Hamelin Pool, Shark Bay, Australia (Fig. 2a, b), with the mold holes mostly 160-170 μm in diameter, and the mineral crusts mostly 130-160 μm in thickness. The smooth surface of a Mesoproterozoic stromatolite stone at Beijing West Railway Station shows very clear mineral crusts and mold holes (Fig. 2c, d). The mold holes are generally wormlike, with a diameter of 70-140 μm, and the thickness of the mineral crusts varies greatly, generally 70-100 μm. The diameter of the filamentous mold holes in a Cambrian microbialite in Xinjiang, China is only 1-1.5 μm (Wu et al., 2021).

Although before the concept of mineral crusts and mold holes was proposed (Wu et al., 2021), the existence of mineral crusts and mold holes had not been recognized in the study of microbial rocks, we can still recognize mineral crusts and mold holes from the photos of modern and ancient microbial rocks. For examples, the minerals formed in the bacterial mineralization experiment by Silva-Castro et al. (2015) are composed of bacterial mineral crusts (Fig. 2e), and the diameters of the mold holes are generally < 0.3 μm, and their length generally < 1 μm， while the thickness of the mineral crusts is generally only 0.03 μm. The thickness of the mineral crusts and diameter of the mold holes in a modern travertine sample are only 0.4 μm, 0.6 μm, respectively (Dupraz et al., 2009). A modern microbialite (thrombolite) sample from a modern lake in Kiribati show dense mold holes that are generally less than 15 μm in diameter (Arp et al., 2012). The diameter of the mold holes in a Mesoproterozoic stromatolite sample from Fangshan, Beijing is generally 0.4-0.9 μm (Tang et al., 2013).

In summary, the diameter of the mold holes in modern microbialites on Earth is 15-170 μm, and the thickness of the mineral crusts ranges 130-160 μm. The diameter of the mold holes in the ancient microbialites on Earth is 0.4-140 μm, and the thickness of the mineral crusts is 70-100 μm.

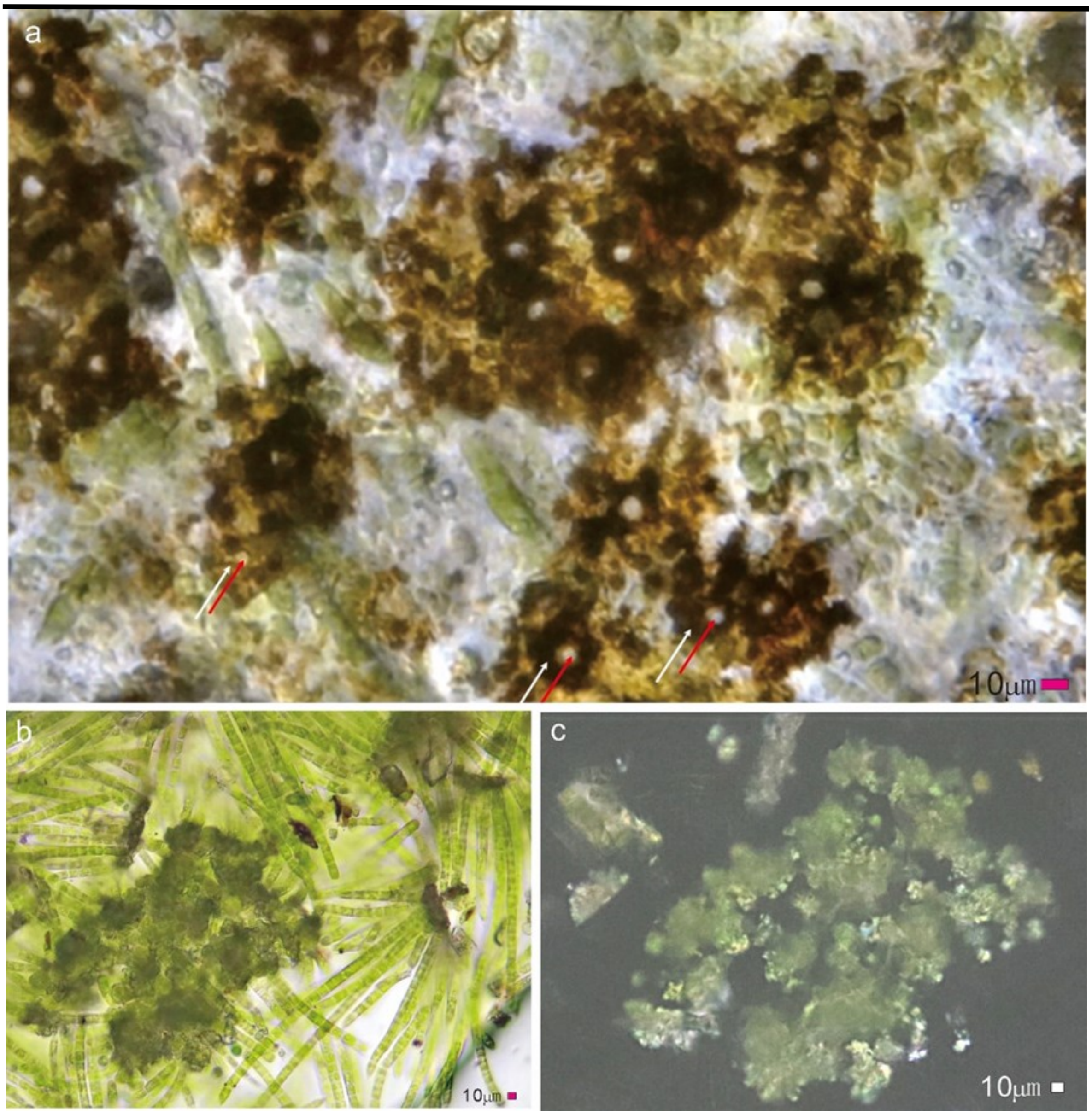

Fig. 1 Mineral crusts and mold holes formed by the filamentous green alga *Uronema elongatum* in a culture experiment. a: A photo taken from the bottom of the petri dish, showing the mineral crusts in yellow color that began to form on the bases of the filaments due to biologically induced forming the brown mineral crusts enveloping them. The green alga *Uronema elongatum* is in green color, and the rounded mold holes in white color. b: A photo of the up surface of the petri dish, showing the green filaments of *Uronema elongatum* and the dark calcite particles. c: Enlargement of a part of the minerals in photo b, under orthonormal polarizing microscope, showing the high white interference color characteristic of calcite.

This picture was taken from the bottom of a petri dish, showing the bases of the filaments of the green alga. The green filaments grow perpendicular to the petri dish. The brown mineral crusts in this photo have white circular mold holes left by the disappeared filaments. According to their morphological features, the green algal filaments belong to *Uronema elongatum*.

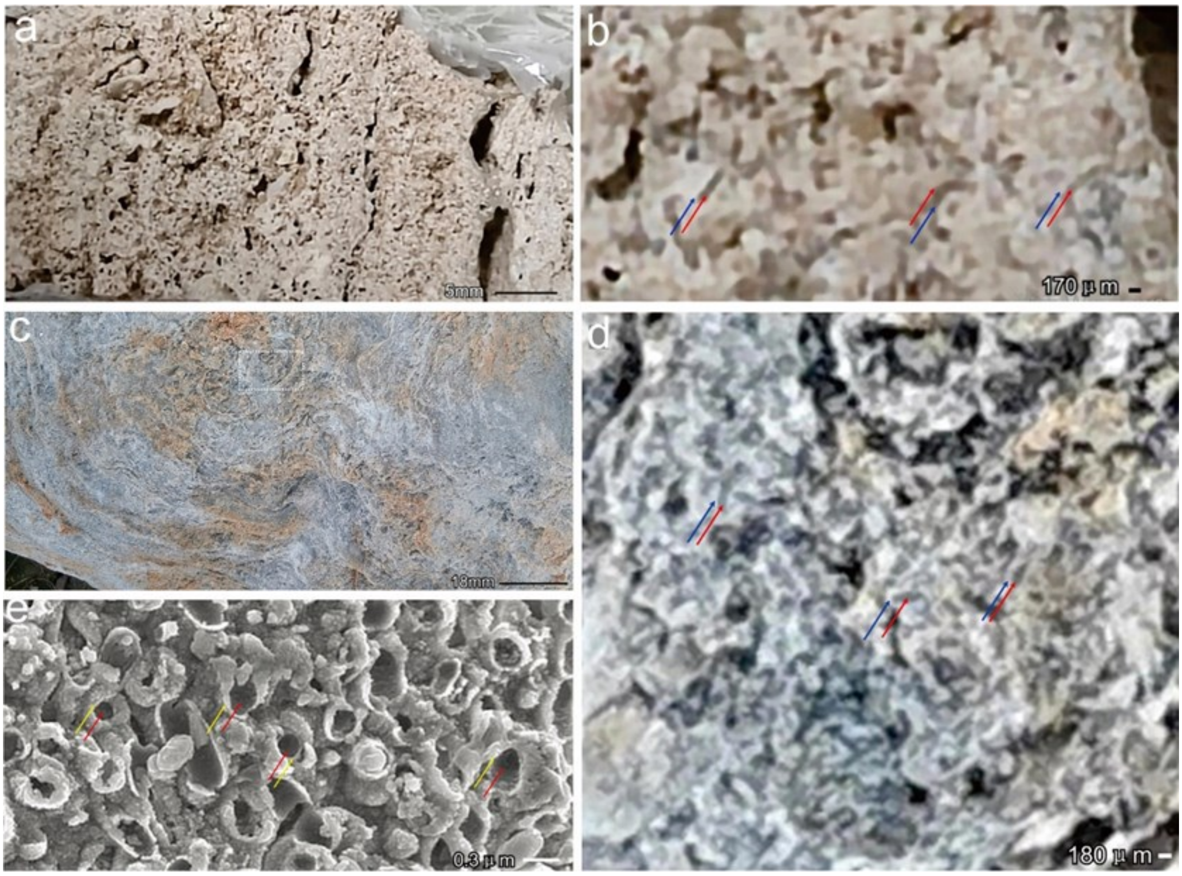

Fig. 2 Pictures of some modern and ancient microbial rocks consisting of dense mineral crusts and mold holes. a: A photograph of the smooth surface of a modern microbialite specimen from Shark Bay, Australia, showing two laterally stretching holes with a thickness of less than 3 mm. The nearly horizontal holes make the rock look like a stromatolite, but its microfabric makes it look more like a thrombolite. b: A local magnification of figure a. The rock consists of dense mineral crusts and mold holes, the mineral crusts are in pale yellow color, and the mold holes are dark, in wormlike or nearly round shape. c: A stromatolite having laminated fabric (Mobile phone photo 2022-10, IMG_20211206_105111, Beijing West Railway Station). The thickness of a single lamina is 6-9 mm. d: The enlargement of the white box in the middle of photo c, with dense mineral crusts and mold holes. The mineral crusts are grayish yellow to grayish white in color, forming a network; The mold holes are dark, in gray color, and in wormlike, capsule-like and spot-like shapes. e: The mineral crusts and mold holes formed in a bacterial mineralization experiment, modified from Fig. 4f of Silva-Castro et al. (2015). The mineral crusts formed in the culture of *Bacillus* and *Branchbacillus* consist of calcite and aragonite, in capsule-like shape, and are very thin.

3. Mineral crusts and mold holes in Martian rock

In this paper the photos of two drilling cores and one circular polished surface of the Martian rock, taken by NASA's Perseverance rover on July 6 and 11, 2022, were downloaded from the NASA’s website and studied. The rock is in the Jezero crater and belongs to an ancient river delta facies, consisting of sediments transported from source rocks hundreds of miles away. The polished surface was made by NASA's Perseverance rover on the rock of Skinner Ridge in the Jezero crater of Mars on July 21, 2022.

After we enlarged the three photos on the computer, we saw dense mineral crusts and mold holes (Fig. 3a, c, e). However, due to the low pixel, the photos are not clear enough. After the sharpness of the photos was raised, clearer mineral crusts and mold holes could be seen in the adjusted photos (Fig. 3b, d and f).

Photo 3b consists entirely of dense mineral crusts and mold holes. The mineral crusts are generally white in color and 90-150 μm in thickness. Most mold holes are nearly spherical in shape, and a few are worm-shaped, with a diameter range of 90-180 μm. The thickness of the mineral crusts and the diameter of the mold holes are similar to those of the modern stromatolites in Hamelin pool, Shark Bay, Australia and the Mesoproterozoic stromatolites in Beijing West Railway Station.

The drilling core in photo 3d also has dense mineral crusts, which are generally white in color, and the mold holes are mostly filled with materials. Some mold hole filling is dark or black due to the presence of iron or organic matter. The thickness of the mineral crusts and the diameters of the mold holes are about 180 μm.

Photo 3f is the polished surface of the Martian rock at Jezero crater area. It has dense mineral crusts and molds. The crusts have a thickness of approximately 170-180 μm. Most mold holes have been filled with gray or black material (possibly organic matter), are nearly spherical or worm-shaped in shape, and are about 180 μm in diameter. Some of the black matter may be organic matter.

Two drilling core photographs and one polished surface photograph of the ancient deltaic facies rock at the Jezero crater consist of dense mineral crusts and mold holes, and the thickness of the mineral crusts and the diameters of the mold holes are similar to the mineral crusts and mold holes in the modern and ancient stromatolites on Earth, confirming the presence of mineral crusts and mold holes in Martian rocks, which suggests that the Martian rocks studied here were formed by the mineral precipitation induced by the microbial mats in ancient Mars. This finding supports the previous assumption that microbes once existed on Mars. The microbial communities of modern stromatolites in Shark Bay, Australia is mainly composed of cyanobacteria (Collins and Jahnert, 2014). The Martian mold holes are similar to the mold holes in the tellurian microbialites studied here, indicating that the ancient microbial communities in the ancient volcanic crater lake on Mars are dominated by cyanobacteria.

The mineral crusts are noodle-like in shape, slightly raised above the surrounding, in yellowish color, being dense, and are about 170~180μm in thickness. The mold holes are usually filled with dark or black materials, most of which are wormlike in shape, but a few are dot-like, generally having a diameter of about 180 μm. The black components may be organic matter, most likely asphalt. The yellow components may be carbonate minerals with iron.

4. Conclusions

Two images of drilling cores and one image of in-situ polished rock surface at the Jezero crater area on Mars have dense mineral crusts and mold holes. The mineral crusts are generally white in color. Most of the mold holes are filled with dark minerals, but a few are filled with black materials, or are not filled. The mold holes are generally rounded or wormlike in shape. The diameter of the mold holes and the thickness of the mineral crusts are generally 90-180μm. The dense mineral crusts and mold holes indicate that the rock at the Jezero crater area of Mars were formed by microbes. The similarity of the Martian mold holes to those in the tellurian microbialites in size indicates that the Martian microbes of the drilling cores and polishing surface are dominated by cyanobacteria.

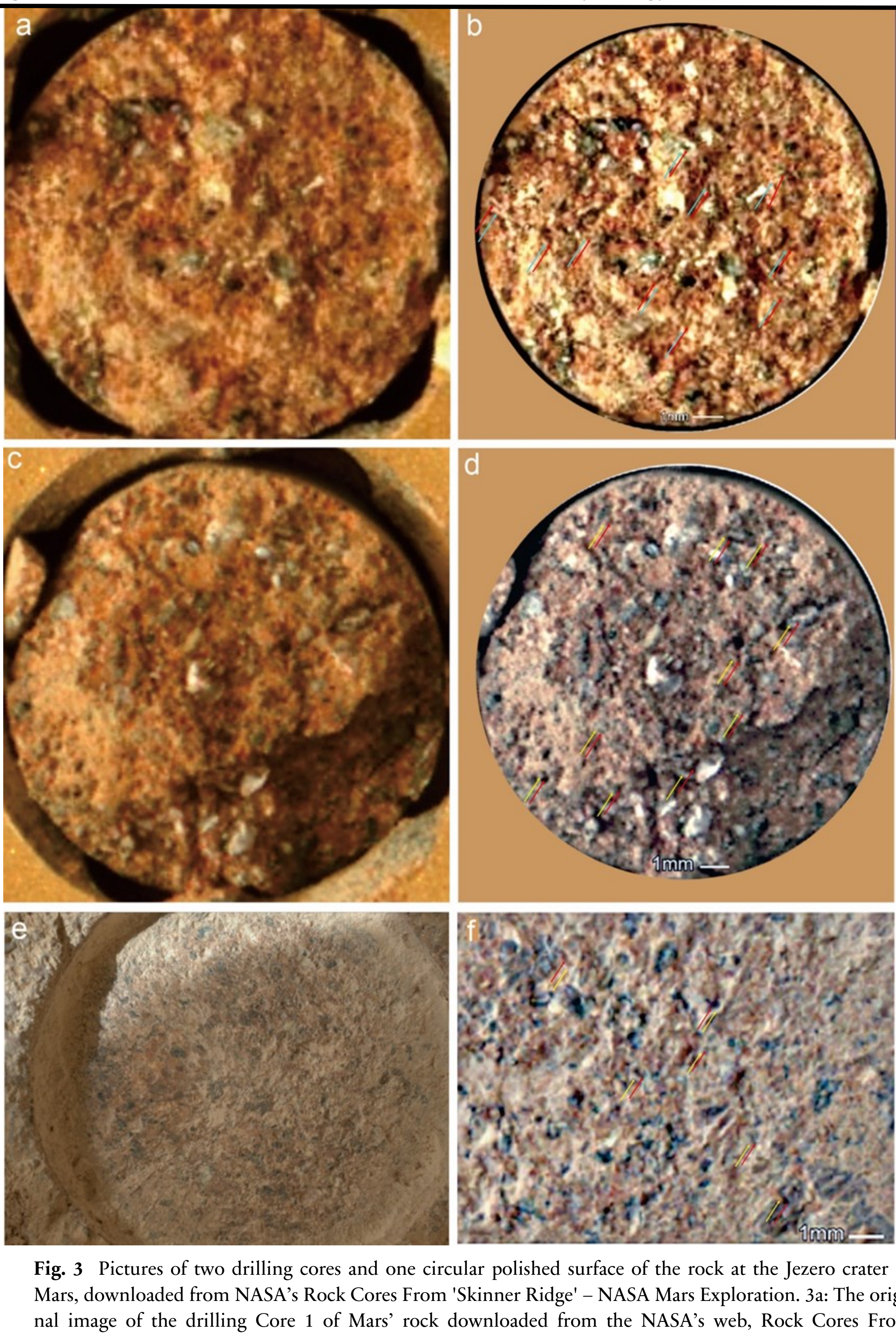

Fig. 3 Pictures of two drilling cores and one circular polished surface of the rock at the Jezero crater of Mars, downloaded from NASA's Rock Cores From 'Skinner Ridge' – NASA Mars Exploration. 3a: The original image of the drilling Core 1 of Mars' rock downloaded from the NASA's web, Rock Cores From 'Skinner Ridge' – NASA Mars Exploration, untreated except for cutting edges, showing dense mineral crusts and mold holes. The diameter of the cylindrical core is 10 mm. 3b: It is from Figure 3a with sharpness improved, consisting of dense mineral crusts (blue arrow) and mold holes (red arrow). The mineral crusts are in a white-yellow-mixed color, noodle-like in shape, with a uniform thickness, forming a network; The mold

holes are dark in color, most rounded in shape, with some in worm-like shape. The mineral crust thickness ranges generally 90-150 μm. The diameter of the mold holes generally ranges 90-180 μm. 3c: It was downloaded from Rock Cores From 'Skinner Ridge' – NASA Mars Exploration, and is the original image of the drilling core 2 collected from the bedrock in the Jezero crater on Mars. It consists of dense mineral crusts and mold holes, but most of them are unclear. The drilling core is 14 mm wide. 3d: It is from photo 3c with increased sharpness. It consists of dense mineral crusts (indicated by yellow arrows) and mold holes (indicated by red arrows). The mineral crusts are noodle-like in shape, forming a network, in a white-black-mixed color, and was contaminated with yellow muds, and are about 180 μm in thickness. The mold holes are dark in color, mostly dotlike in shape, with a few in long shape. Their diameters are generally 180 μm. The dark part of the mineral crusts probably contain iron. 3e: It was downloaded from Two Abrasion Patches From Perseverance at Jezero Delta-NASA Mars Exploration, and is the original image of the circular polished surface of the rock outcrop in the Jezero crater area on Mars, taken on June 29, 2022, with many mold holes, but not clear. The photo width is 57mm. 3f: It was from the photo 3a with a increased sharpness, showing dense mineral crusts (indicated by the yellow arrows) and mold holes (indicated by the red arrows), with some areas without mineral crusts and mold holes, in a generally yellow but not white color, which is different from Figure 3a and 3c.

5. Research methods

On July 6, 2022, NASA's Mars' Perseverance rover drilled two chalk-sized cores from the rocks in the Jezero crater area of Mars and ground a 5.7cm-wide circular polished surface. The rover took pictures of the two cores and the polished surface, and put them on NASA's open website making them open to public. We downloaded the three photos, and found dense mineral crusts and mold holes in them. Only their sharpness was slightly increased, no other change was made on them. The mineral crusts and mold holes were measured, and were compared with those in modern and ancient microbial rocks on Earth.

6. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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