STROMATOLITES: THE SHAPE WE GIVE TO OUR VISION OF MARTIAN LIFE?

Tomaso R.R. Bontognali[1,2], Keyron Hickman-Lewis[3]

DOI: 10.2138/gselements.22.4.228

"Are we alone in the Universe?" This is a question that has occupied human thought for millennia, at least since the time of the early Greek philosophers, and likely even earlier. A concrete step toward answering it is the search for life through in situ exploration of planets and moons in our Solar System. Among potentially habitable worlds, Mars is relatively proximal, making it a compelling first target for astrobiology. But if life ever arose there, what kind of life might we find, and what would it look like?

AI-generated image (ChatGPT), prompted by authors.

Today, the Martian surface is considered hostile to life as we know it. Temperatures rarely exceed freezing, and the atmosphere is over 100 times thinner than Earth's, offering little protection from UV radiation and cosmic rays (Hassler et al. 2014; Martínez et al. 2017). These conditions desiccate and sterilise the surface, rendering it largely inhospitable; we thus have little expectation of finding indigenous living organisms at Mars' surface (Changela et al. 2021). Yet features like dry valleys, deltas, ancient lake basins, and water-formed minerals (carbonates and phyllosilicates, among others) suggest that between approximately 4.2 and 3.0 billion years ago (the Noachian–Hesperian periods), liquid water was stable at the surface of Mars (Carr and Head 2010). The conditions at this time may have resembled those of the early Earth.

For this reason, ongoing rover missions (*Curiosity*, *Perseverance*, *Zhurong*) and the upcoming ExoMars *Rosalind Franklin* mission target ancient rocks; they are not seeking living organisms but instead hope to find fossilised traces of past life (Vago et al. 2017; Farley et al. 2020). Expectations about the types of fossils that might be found in ancient Martian rocks rest on a simple assumption: that similar environmental conditions, given sufficient time, could have produced similar biological outcomes. Consequently, to guide our search for life on Mars, we look to Earth's oldest rocks and ask: what kinds of life do they preserve?

The answer, unfortunately, is "not much." The cellular fossil record of the early Archean is limited, thus far, to morphologically simple microorganisms, often with filamentous and spheroidal shapes (Javaux 2019). Were it not for their great age, these remains would hardly stir the imagination the way their younger, more charismatic descendants do, such as the Stegosaurs and Tyrannosaurs. Yet, in spite of their small size and morphological simplicity, one type of structure stands out, something that gives early life a visible form: intriguing laminated accretionary structures known as stromatolites.

Together with microbially induced sedimentary structures (Noffke et al. 2001), stromatolites, documented on Earth since at least ~3.5 billion years ago (van Kranendonk 2006), are among the few macroscopic morphological biosignatures that can be recognised with the naked eye in early Archean rocks. For this reason, one of the most hoped-for photographs for the science teams behind current robotic missions would be a Martian outcrop containing stromatolites. Coupled with geochemical data obtained on such structures, a mission might be able to build the hypothesis of having discovered a "potential biosignature" on Mars (Hickman-Lewis et al. 2023). At the time of writing, no compelling evidence for such structures has been observed in any image or other dataset returned from Mars.

Despite their great antiquity and occurrence throughout the ancient fossil record, some experts remain skeptical of the relevance of stromatolites for Mars astrobiology: many of the macroscopic microbial mats that form stromatolites are dominated by photosynthetic microorganisms, such as cyanobacteria, a relatively advanced metabolism that may never have had time to develop on Mars during its habitable period (see Nixon et al. 2013, for a review of alternative metabolic strategies). For this reason, the most compelling evidence for extraterrestrial life might ultimately come in the form of fossil organic molecules, as revealed by mass spectrometry analyses. And yet, it seems deeply human to long for something more tangible, a shape or a structure we can see with our own eyes, to fully grasp and emotionally connect with the significance of such a discovery.

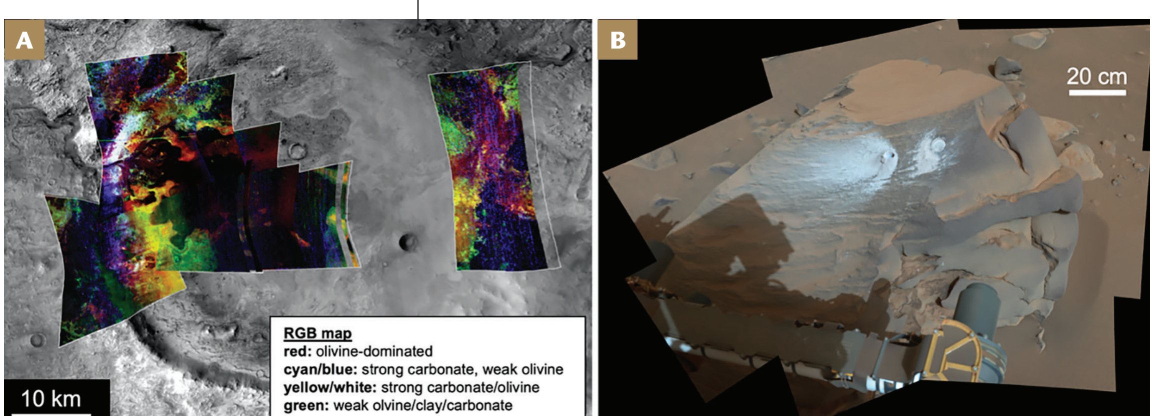

FIGURE 1 The carbonate-bearing Jezero crater marginal unit. (**A**) Photogeological map showing compositional diversity in carbonate-bearing lithologies around the margins of Jezero crater. ADWPTED FROM HORGAN ET AL. (2020). (**B**) Bunsen Peak, a locality along the western margin of Jezero crater at which the Comet Geyser core sample was collected by the *Perseverance* rover. This rock sample is carbonate-bearing and considered to have among the highest organic biosignature preservation potential of the samples collected to date by the rover. CREDIT: NASA/JPL-CALTECH/ASU/MSSS.

1 Space Exploration Institute
Fbg de l'Hôpital 68
2000 Neuchâtel, Switzerland

2 University of Basel
Klingelbergstrasse 27
4056 Basel, Switzerland

3 School of Natural Sciences
Birkbeck, University of London
Malet Street, Bloomsbury
London, WC1E 7HX. UK

Thus far, one locality considered promising for the presence of stromatolites, the carbonates on the margins of Jezero Crater (Fig. 1), has been explored; however, despite its interpretation as a potential lakeshore carbonate deposit (Horgan et al. 2020), no morphological biosignatures of relevance to stromatolites have been detected (Williford et al. 2025). A new opportunity may arise in the coming years with the *Rosalind Franklin* rover, which will attempt to land in a previously unexplored region of Mars where abundant surface water likely once existed (the phyllosilicate-rich Oxia Planum; Vago et al. 2017). A sample return mission would also offer opportunities to detect putative microbial biosignatures in Martian sedimentary rocks using high-resolution, high-sensitivity microscopic and geochemical techniques in terrestrial laboratories (Herd et al. 2025).

Only time will tell whether life ever existed on Mars, and perhaps, even before we learn whether Mars was ever inhabited, our expectations of what extraterrestrial life might look like will already have evolved. But for now, we continue to dream of Martian stromatolites.

REFERENCES

Carr MH, Head III JW (2010) Geologic history of Mars. Earth and Planetary Science Letters 294: 185-203, doi: 10.1016/j.epsl.2009.06.042

Changela HG and 37 coauthors (2021) Mars: new insights and unresolved questions. International Journal of Astrobiology 20: 394-426, doi: 10.1017/S1473550421000276

Farley KA and 29 coauthors (2020) Mars 2020 mission overview. Space Science Reviews 216: 142, doi: 10.1007/s11214-020-00762-y

Hassler DM and 447 coauthors (2014) Mars' surface radiation environment measured with the Mars Science Laboratory's Curiosity Rover. Science 343: 6169, doi: 10.1126/science.1244797

Herd CDK and 13 coauthors (2025) Sampling Mars: geologic context and preliminary characterization of samples collected by the NASA Mars 2020 Perseverance rover mission. Proceedings of the National Academy of Science 122: e2404255121, doi: 10.1073/pnas.2404255121

Hickman-Lewis K and 11 coauthors (2023) Advanced two- and three-dimensional insights into Earth's oldest stromatolites (ca. 3.5 Ga): prospects for the search for life on Mars. Geology 51: 33-38, doi: 10.1130/g50390.1

Horgan BNH, Anderson RB, Dromart G, Amador ES, Rice MS (2020) The mineral diversity of Jezero crater: evidence for possible lacustrine carbonates on Mars. Icarus 339: 113526, doi: 10.1016/j.icarus.2019.113526

Javaux, EJ (2019) Challenges in evidencing the earliest traces of life. Nature 572 : 451-460, doi: 10.1038/s41586-019-1436-4

Martínez GM and 15 coauthors (2017) The modern near-surface Martian climate: a review of in-situ meteorological data from Viking to Curiosity. Space Science Reviews 212: 295-338, doi: 10.1007/s11214-017-0360-x

Nixon SL, Cousins CR, Cockell CS (2013) Plausible microbial metabolisms on Mars. Astronomy & Geophysics 54: 1.13-1.16, doi: 10.1093/astrogeo/ats034

Noffke N, Gerdes G, Klenke T, Krumbein WE (2001) Microbially induced sedimentary structures--a new category within the classification of primary sedimentary structures: PERSPECTIVES. Journal of Sedimentary Research 71: 649-656, doi: 10.1007/978-3-642-11274-4_1004

Vago JL and 74 coauthors (2017) Habitability on early Mars and the search for biosignatures with the ExoMars Rover. Astrobiology 17: 471-510, doi: 10.1089/ast.2016.1533

Van Kranendonk MJ (2006) Volcanic degassing, hydrothermal circulation and the flourishing of early life on Earth: a review of the evidence from c. 3490-3240 Ma rocks of the Pilbara Supergroup, Pilbara Craton, Western Australia. Earth-Science Reviews 74: 197-240, doi: 10.1016/j.earscirev.2005.09.005

Williford KH and 74 coauthors (2025) Carbonated ultramafic igneous rocks in Jezero crater, Mars. Science 380: eadu8264, doi: 10.1126/science.adu8264