Understanding Astrobiological False Positives from Terrestrial Microbiology

Martin Homann
Biosignatures in terrestrial and planetary contexts

• **Objects, substances, and/or patterns** whose origin specifically require a biological agent (Des Marais et al. 2003).

• Candidate biosignatures are ranked by 3 criteria: **reliability, survivability, and detectability**.

• The usefulness of a biosignature comes not only from the probability of life having produced it, but also from the **improbability of non-biological processes** producing it (Mustard et al. 2013).
False positives and controversial biosignatures

- **Allan Hills 8441 (4.09 Ga)**
  - Abiotic nanobacteria-like structures

- **Apex filaments (3.5 Ga)**
  - Mineral artefacts; sheets of phyllosilicates with carbonaceous coatings

- **Hematite filaments (3.77 Ga)**
  - Possibly abiotic Fe-mineralized chemical gardens

- **Stromatolites? (3.7 Ga)**
  - Probably products of structural deformation of layered rocks

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Morphological evidence alone is insufficient to determine the biogenicity of a lifelike structure.
What lines of evidence provide the clearest validation of ancient biology in the rock record?
Biogenicity criteria

• Did the object form in a demonstrably habitable paleoenvironment?
• Is it assuredly endogenic and syngenetic to the host rock?
• Are morphology and biofabric consistent with a biotic origin?
• Is the chemical and isotopic composition distinctively life-like?

Multiple, independent lines of evidence are needed to establish biogenicity.
Fossil Biosignatures in Deep Time and Space

Life as we known it
- Carbon-based and requiring a water solvent
- CHNOPS – key biogenic elements of life on Earth

Where to look for?
- Archean sedimentary rock record: 4 – 2.5 Ga
- Lithified aquatic sediments: carbonates, cherts, ... sandstones

What to look for?
- Morphological biosignatures (biofabrics, microfossils)
- Chemical biosignatures (stable isotopes, biominerals, biomarkers)
- Traces of microbial life: microbial mats, biofilms, organic matter

Early diagenetic mineralization is key for preservation and survivability of biosignatures.
Microbial mats
Laminated microbial communities; mainly bacteria and archaea
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Laminated microbial communities; mainly bacteria and archaea

Biochemical sediments
↓
Microbialites
↓
Microbial mats

Siliciclastic sediments
↓
Microbial mats

Stromatolites
Thrombolites

Bahar Alouane, Tunisia
Biosignature and life detection methods

Substances
- Atoms / Isotopes
- Elements
- Molecules / Allotropes
- Biopolymers
- Cells
- Minerals
- Biomats / Tufas
- Concretions

Objects
- Distribution of substances / objects

Patterns

<table>
<thead>
<tr>
<th>Atoms / Isotopes</th>
<th>Elements</th>
<th>Molecules / Allotropes</th>
<th>Biopolymers</th>
<th>Cells</th>
<th>Minerals</th>
<th>Biomats / Tufas</th>
<th>Concretions</th>
<th>Distribution of substances / objects</th>
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</thead>
<tbody>
<tr>
<td>X-ray methods / Laser mass spectrometry</td>
<td>NMR / XAS / IR / Raman</td>
<td>Mass spectrometry / Chromatography / Diffraction / AFM / CD</td>
<td>Electron microscopy / Spectroscopic imaging / Confocal microscopy</td>
<td>Microscopy</td>
<td>Visual observations / X-ray computed tomography / 3D laser scanning</td>
<td>Collated or global databases / Network analysis / Drone or satellite remote sensing</td>
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</tr>
</tbody>
</table>

Chan et al, 2019
Examples of terrestrial biosignatures in deep time
Traces of early life in the Archean rock record
Barberton Greenstone Belt (BGB), South Africa
Evidence of early life in the BGB (3.5 – 3.2 Ga)
Traces of early life in the Buck Reef Chert

Stratigraphic thickness: 250 – 400m; exposed for nearly 50 km

- Black and white banded chert
- Silicified evaporites

Homann, 2019
Microbial mats in the 3.4 Ga Buck Reef Chert

Silicified mats draping carbonaceous grains

Eroded, rolled-up mat fragments indicate former cohesive consistency.

Carbonaceous biofilms

Estimated peak temperature: 312 ± 50 °C

Bands Fit

D1 D2 D3

Buck Reef

Raman shift (cm⁻¹)

800 1000 1200 1400 1600 1800 2000

Tice and Lowe et al., 2004; Tice, 2009

Alleon et al., 2021
Microstructures of (non)biogenic origin

Filamentous structures

Spheroidal structures

Walsh 1992; 2000

Glikson et al. (2008); Walsh (1992); Kremer and Kazmierczak (2017); Knoll and Barghoorn, 1977
Microfossils in the 3.4 Ga Buck Reef Chert

Lenticular microfossils

Table 1

<table>
<thead>
<tr>
<th>Formation (analysis years)</th>
<th>Structure</th>
<th># of analyses/# of structures</th>
<th>Range of (d_{13}C) values (‰)</th>
<th>Weighted mean (d_{13}C) values (‰)</th>
<th>MSWD</th>
<th>Weighted SD (‰)</th>
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<tbody>
<tr>
<td>KF (2013, 2016)</td>
<td>Lenticular forms</td>
<td>8/5</td>
<td>-39.3 to -35.5</td>
<td>-37.3 ± 0.4</td>
<td>2.0</td>
<td>1.6</td>
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<td>Dense masses</td>
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<td>-37.7; -35.3</td>
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<td>Background</td>
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<td>-36.4 ± 0.7</td>
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<td>6.6</td>
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<td>Lenticular forms</td>
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<td>Lenticular forms</td>
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<td>-44.1 to -30.0</td>
<td>-36.1 ± 0.2</td>
<td>12.4</td>
<td>3.0</td>
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<tr>
<td></td>
<td>Background</td>
<td>1</td>
<td>-25.3</td>
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</tbody>
</table>

Pflug, 1966; Walsh 1992; Oehler et al., 2017

Oehler et al., 2017

Alleon et al., 2018

Strelley Pool microfossils (3.4 billion years old)

Gunflint microfossils (1.9 billion years old)

Fresh microorganism (modern)
Possible stromatolites in ~3.3 Ga cherts

- Stratigraphic thickness: 1 - 20 cm within a 5 m thick chert layer
- Scattered outcrops for >10 km along strike
Stromatolites or silicious sinter deposits?

- Domal to pseudo columnar growth morphologies
- Crinkly, carbonaceous laminations contain Mg-Bo-Cr tourmaline
- Mineralization was likely driven by boron-rich hydrothermal fluids (Byerly et al., 1986; Lowe and Byerly, 2015)
Organic Carbon isotopes and Raman spectroscopy

- $\delta^{13}C_{\text{org}}$ values range between -34.5‰ and -22.1‰ (n=16)
- consistent with biogenic origin

- Raman spectroscopy confirms presence of mature carbon
- $T_{\text{peak}}$: 440°C
El Tatio geothermal field, Chile
Microbial mats and evaporative silicification in hot spring silica sinters
Silica deposits on Mars with features resembling hot spring biosignatures at El Tatio in Chile

Steven W. Ruff & Jack D. Farmer

Home Plate silica

El Tatio

![Image](https://example.com/image1.jpg)

![Image](https://example.com/image2.jpg)

![Image](https://example.com/image3.jpg)

![Image](https://example.com/image4.jpg)

![Image](https://example.com/image5.jpg)

![Image](https://example.com/image6.jpg)

![Image](https://example.com/image7.jpg)

![Image](https://example.com/image8.jpg)

![Image](https://example.com/image9.jpg)

![Image](https://example.com/image10.jpg)

![Graph](https://example.com/graph1.png)

![Graph](https://example.com/graph2.png)

Ruff and Farmer, 2016
Silica deposits on Mars with features resembling hot spring biosignatures at El Tatio in Chile

Morphogenesis of digitate structures in hot spring silica sinters of the El Tatio geothermal field, Chile

Steven W. Ruff & Jack D. Farmer

Ruff and Farmer, 2016

Gong et al., 2021
Microbial mats in the 3.22 Ga old Moodies Group
The 3.22 Ga Moodies Group

- Earth’s oldest well-preserved continental to marine transition
- Very-high-resolution record (3.6 km deposited over 1 to 14 Myr)
- Paleoenvironment: alluvial to deltaic settings, with a dominance of coastal plains and tidal deltas

Homann et al., 2015; 2016
Fossil microbial mats...
Exceptionally well-preserved sedimentary structures

- Desiccation cracks
- Herringbone cross-bedding
- Ripples
- Erosional channel
- Foresets in underwater dunes
Stratigraphic correlation and depositional facies

Homann et al., 2015
Morphological adaptation to different hydrodynamic settings

Environment

Coastal floodplain

Tidal delta

Inter- to supratidal

Outcrop

Polished slab

Mat morphology

Homann et al., 2015
Microbially induced sedimentary structures

Shrinkage cracks

Mat fragments

Fluid-escape structures

Homann et al., 2015
Microbially induced sedimentary structures on Mars?

Some of the early cracks would have ''healed'' when water temporarily flooded the surface and the microbial mat reestablished growth on top of the early cracks. However, once the water level dropped for an extended period of time, the microbial mat would have desiccated and left only the next generation of desiccation cracks to be preserved.

6. Lithofacies of the Gillespie Lake Member

A panoramic view of a Gillespie Lake Member outcrop higher in the stratigraphic section shows rocks exposed along a very gentle slope (Fig. 9). The rocky surface was dissected by decimeter-scale channels that defined elevated and isolated meter-sized fragments of the outcrop. The elevated fragments display three types of morphologies and are distinguished here as facies: (i) Facies 1—planar surfaces (''plateaus'') that appear in the Mastcam photographs as having a light brown color; (ii) Facies 2—slightly irregular though overall planar plateaus that appear in the images to be gray in color (note that the plateaus of Facies 2 are morphologically higher than those of Facies 1); and (iii) Facies 3—round-tipped, conical shaped elevations (''knobs'') that are dark gray in color.

The geomorphology of the surface of the outcrop shown in the Mastcam panorama of Fig. 9 includes three flat depressions (marked L1, L2, and L3) surrounded by gentle rims. Facies 1 forms the bottom of the depressions, each of which is surrounded by the flat-topped plateaus (R) of Facies 2. Facies 3 constitutes the highest points (K) of the surface of Rock Bed 2 of the 3.7 Ga Gillespie Lake Member, Mars (A) and (C), with cracks on the surface of a modern microbial mat photographed at Bahar Alouane, Tunisia (B) and (D). The sketches document the location of the structures shown in the photographs. (A) The cracks on the martian rock bed surface are characterized by two parallel elevated edges; within some of the cracks, the sediment beneath the upper layer of the rock bed is exposed. Some cracks appear only as elevated ridges, and there is no crack opening preserved. (B) The cracks in the modern microbial mat are defined by two parallel elevated edges. The pencil in the photograph crosses a crack that is not open and, instead, appears as a small ridge. (C and D) The overlays assist in the identification of the structures on the rock bed surfaces that are shown in the photographs. Scales ca. 15 cm. Color images available online at www.liebertonline.com/ast

Noffke, 2015
Fossil mats are preserved as organic-rich laminations
Laminae composed of filamentous microstructures
Scanning electron microscopy analysis

Biofilms

Extracellular Polymeric Substances (EPS)

Filaments
Raman analysis confirms:

(1) Carbonaceous composition of the laminae

(2) Syngenicity of the kerogen

Homann et al., 2018

mod. after Wacey, 2009
Comparison of marine and fluvial mats

Marine facies
- Interbedded with medium- to coarse-grained sandstones
- Crinkly and tufted growth morphologies

Fluvial facies
- Interbedded with pebbly sandstones and conglomerates
- Mostly planar and generally thicker mats
Organic carbon and nitrogen isotope analysis

**Fluvial mats:** 
-24 < δ¹³C < -18‰

- consistent with autotrophic carbon fixation via the *Calvin-Benson cycle*

**Marine mats:** 
-34 < δ¹³C < -21‰

- best explained with carbon fixation via *Wood–Ljungdahl pathway*, which includes methanogens and sulfate reducers

**Fluvial mats:** 
+2 < δ¹⁵N < +5‰

**Marine mats:** 
0 < δ¹⁵N < +3‰

- Biological mechanisms that produce biomass with δ¹⁵N > +2‰:
  1) Partial assimilation of ammonium (NH₄⁺)
  2) Partial nitrification
  3) Partial denitrification

Homann et al., 2018
Summary

- Multiple, independent lines of evidence are needed to establish biogenicity; morphology alone is not enough.

- Early diagenetic mineralization is key for the preservation and survivability of biosignatures.

- Silicified microbial mats are some of the most robust evidence for early life on Earth.
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ICDP drilling project: Barberton Archean Surface Environments

- 7 months of drilling: Nov. 2021 to June 2022
- 8 drill cores from 5 sites: 3131m in total

Table 2 - BASE drill site data

<table>
<thead>
<tr>
<th>Site Nr.</th>
<th>Name</th>
<th>horizontal length (m)</th>
<th>along-drillhole length (MD, m)</th>
<th>TVD of hole (m)*</th>
<th>cored strat. thickness (m)*</th>
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<tbody>
<tr>
<td>1</td>
<td>Elephant’s Kloof</td>
<td>350</td>
<td>400</td>
<td>285</td>
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<tr>
<td>2</td>
<td>Dycedale Syncline</td>
<td>370</td>
<td>450</td>
<td>350</td>
<td>420</td>
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<tr>
<td>3</td>
<td>Microbial mats</td>
<td>280</td>
<td>450</td>
<td>205</td>
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<td>4-1</td>
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<td>400</td>
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<td>base</td>
<td>380</td>
<td>450</td>
<td>300</td>
<td>370</td>
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</tbody>
</table>

* assuming 45° wellpath inclination

Fig. 2. Schematic stratigraphic columns of the Moodies Group, showing architecture of the Moodies Group and correlation of sections (modified after Heubeck et al., 2016). Note position of the Lomari water tunnel.

Eureka Syncline (Ohnemüller 2010, Heubeck unpubl.)
Stolzburg Syncline (Luber, 2014)
Dycedale Syncline (Grund 2015, Bläsing 2015)
Moodies Hills Block
Montrose Anticlinorium
Conglomerate Gravelly Coarse Medium Fine Siltstone Air-fall tuff Banded Iron Formation, Jaspilite Basaltic lava-grained Sandstone Shale

Head: Luck Clutha MdbC MdcQ MdQ1 MdS1 Md L2 MdI2 MdS2 MdQ3 MdS3 MdQ4 MdI1

Inyoka Fault Stripe Hill, Masenjane Block

Christoph Heubeck
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Nic Beukes
Takeshi Kakegawa
Stefan Lalonde
Mike Tice
M.V. Kranendonk
ICDP drilling project BASE

Site 3 (Saddleback Syncline): Post-drill geological cross section

Drill core diameter: 6.1 cm

Mars 2020
1.3 cm

Christoph Haucke, Jan. 20, 2022

Hill 3
Hill 4

TD 280.2 m; Jan. 26, 2022

Nov. 25, 2021

largely unexposed

Microstromatolitic sands
Gradational contact
Tuffaceous cross-bedded sandstones

Gravelly sandstones with microbial mats

Microbial mats

Drill core diameter: 6.1 cm

6.1 cm

1.3 cm

Microbial mats