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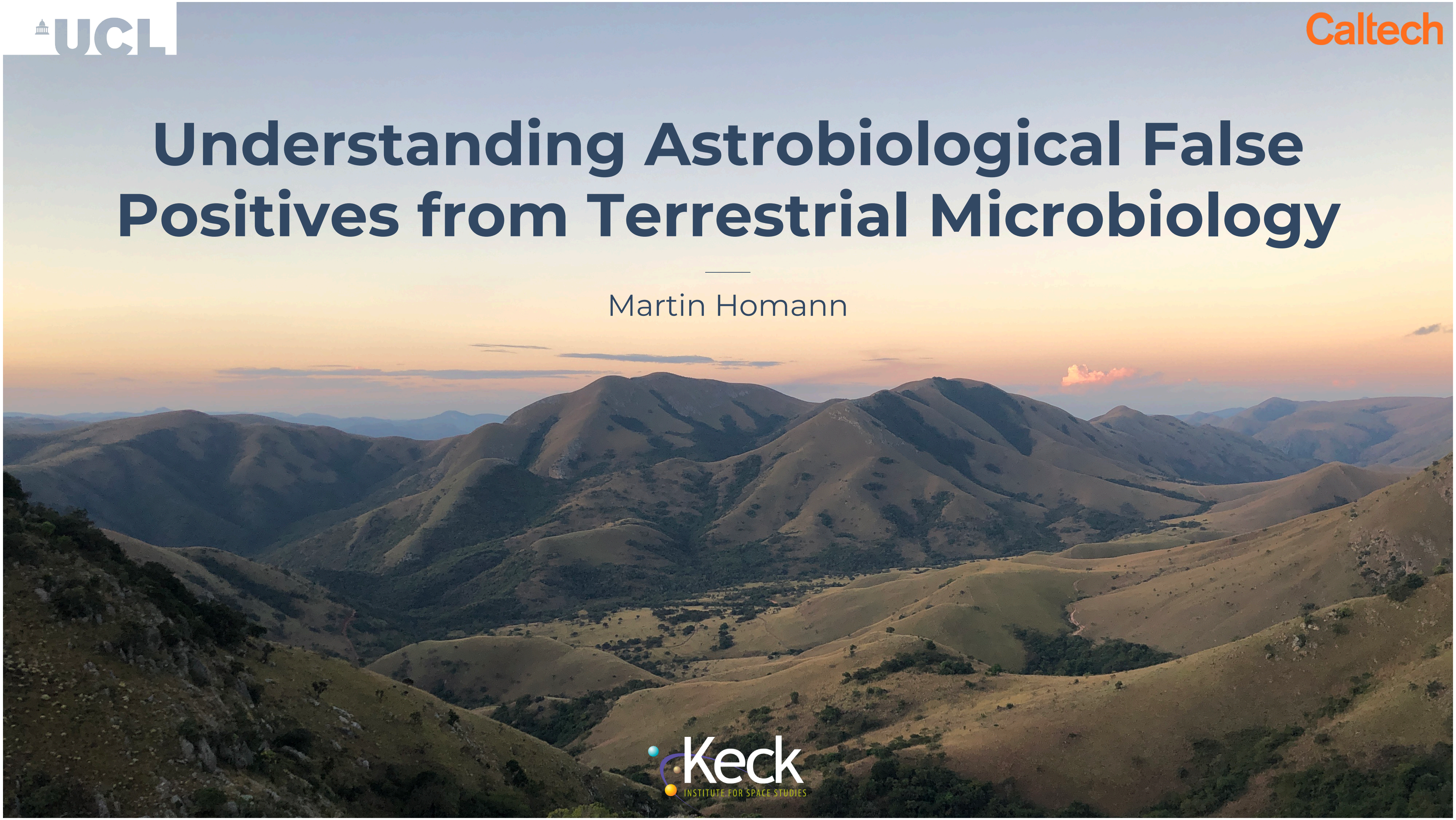
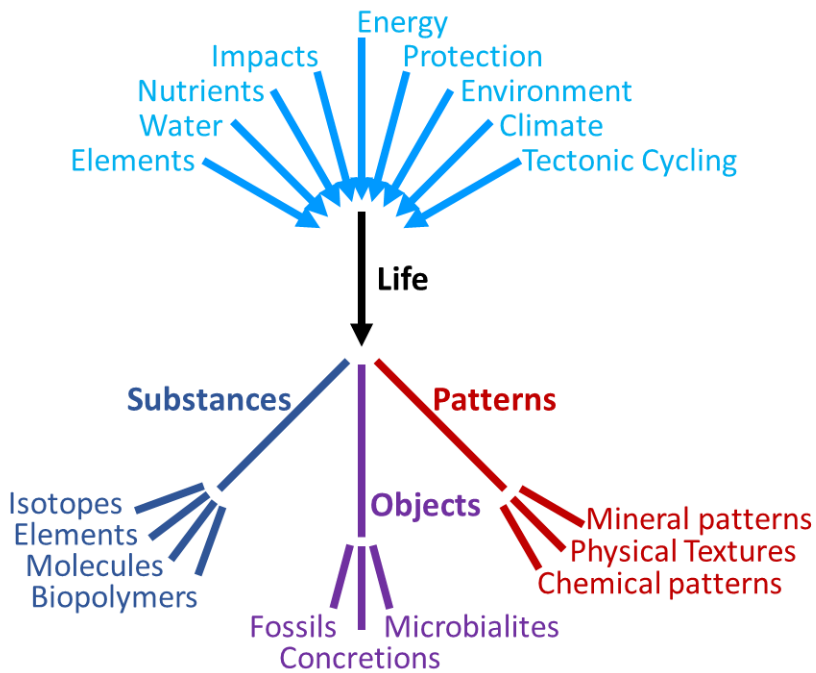
Understanding Astrobiological False Positives from Terrestrial Microbiology

Martin Homann



Keck INSTITUTE FOR SPACE STUDIES

Biosignatures in terrestrial and planetary contexts

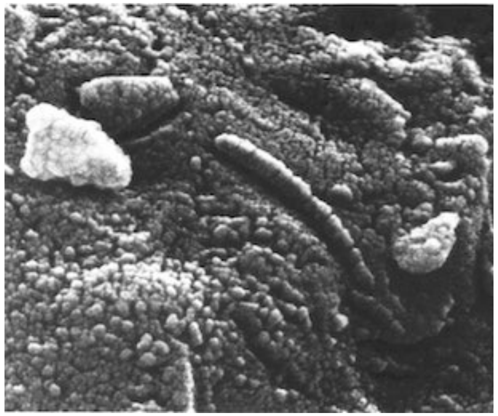


Chan et al, 2019

- **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

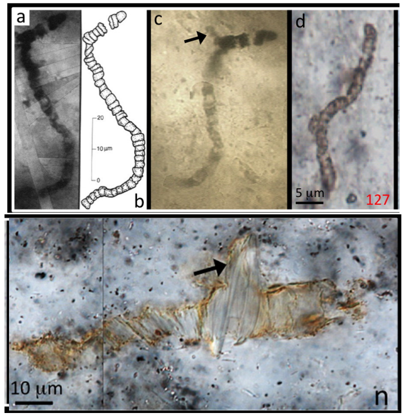
Allan Hills 8441 (4.09 Ga)



McKay, 1996: NASA

- Abiotic nanobacteria-like structures

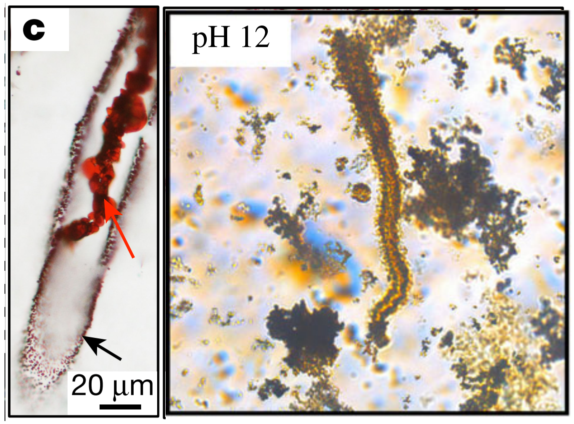
Apex filaments (3.5 Ga)



Schopf, 1993 Brasier et al., 2002 Wacey et al., 2015

- Mineral artefacts; sheets of phyllosilicates with carbonaceous coatings

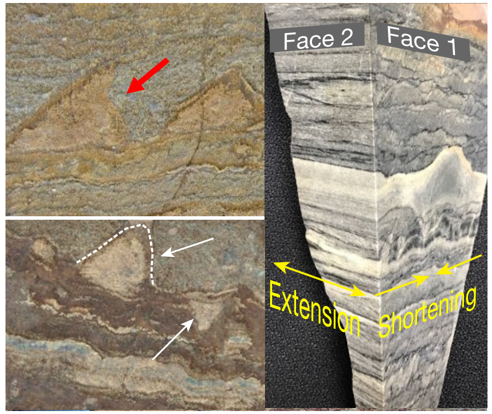
Hematite filaments (3.77 Ga)



Dodd et al., 2017 McMahon, 2019

- Possibly abiotic Fe-mineralized chemical gardens

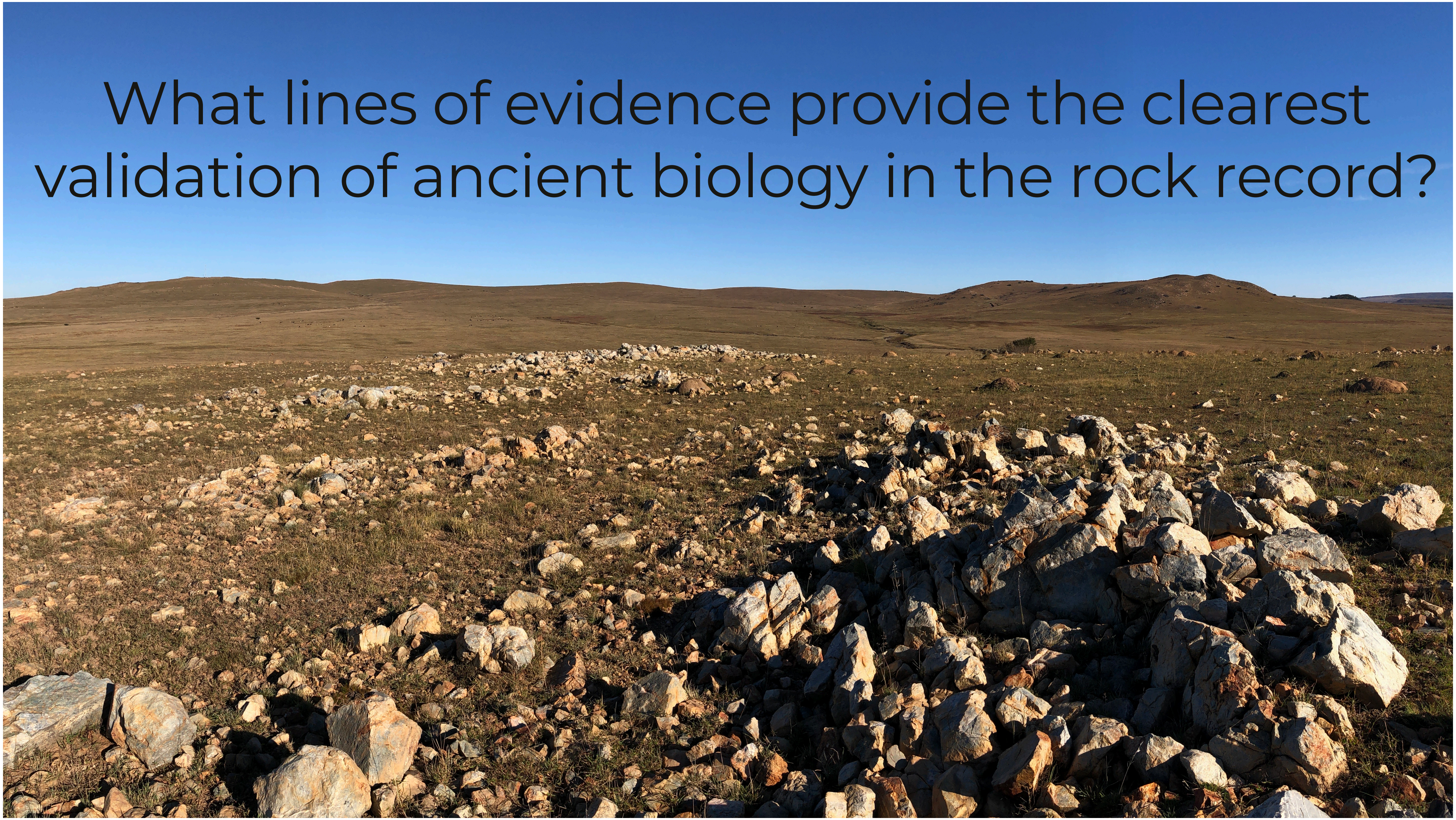
Stromatolites? (3.7 Ga)



Nutman et al., 2016 Allwood et al., 2018

- Probably products of structural deformation of layered rocks

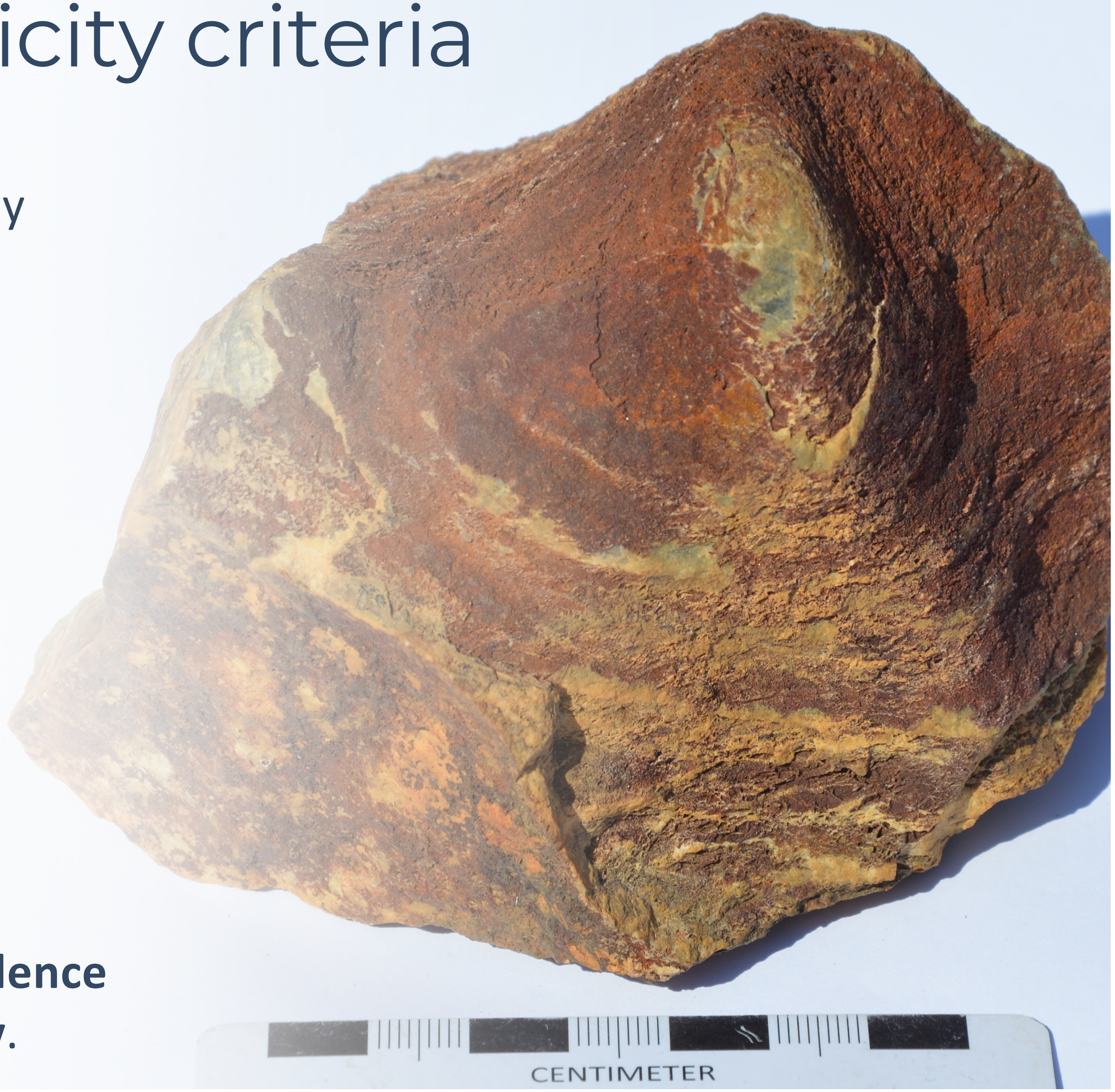
Morphological evidence alone is insufficient to determine the biogenicity of a lifelike structure.


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

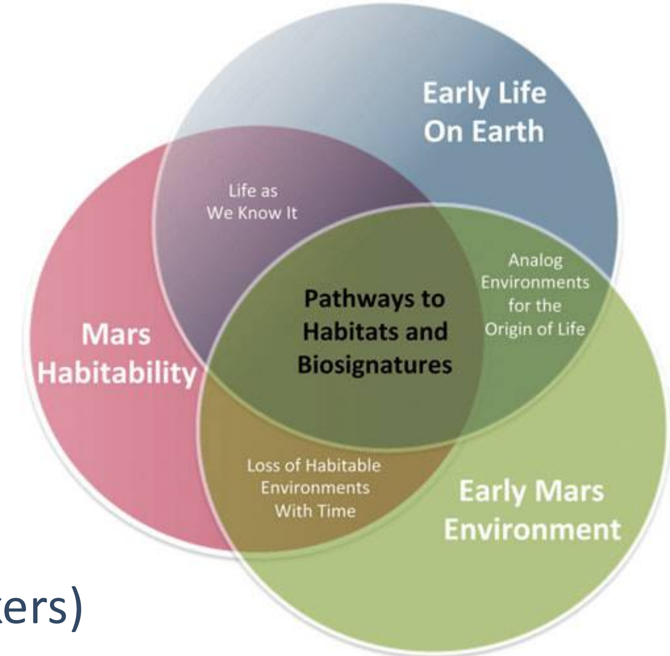
- Carbon-based and requiring a water solvent
- CHNOPS – key biogenic elements of life on Earth

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

Microbial mats

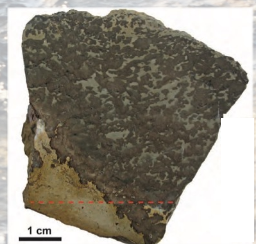
Laminated microbial communities; mainly bacteria and archaea

Biochemical sediments

↓

Microbialites

Stromatolites

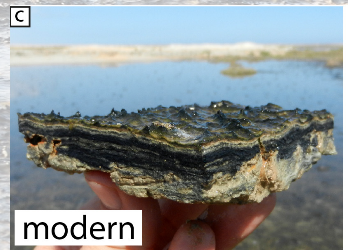


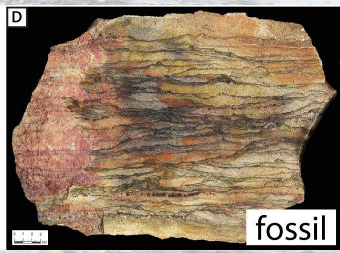
Thrombolites

Siliciclastic sediments

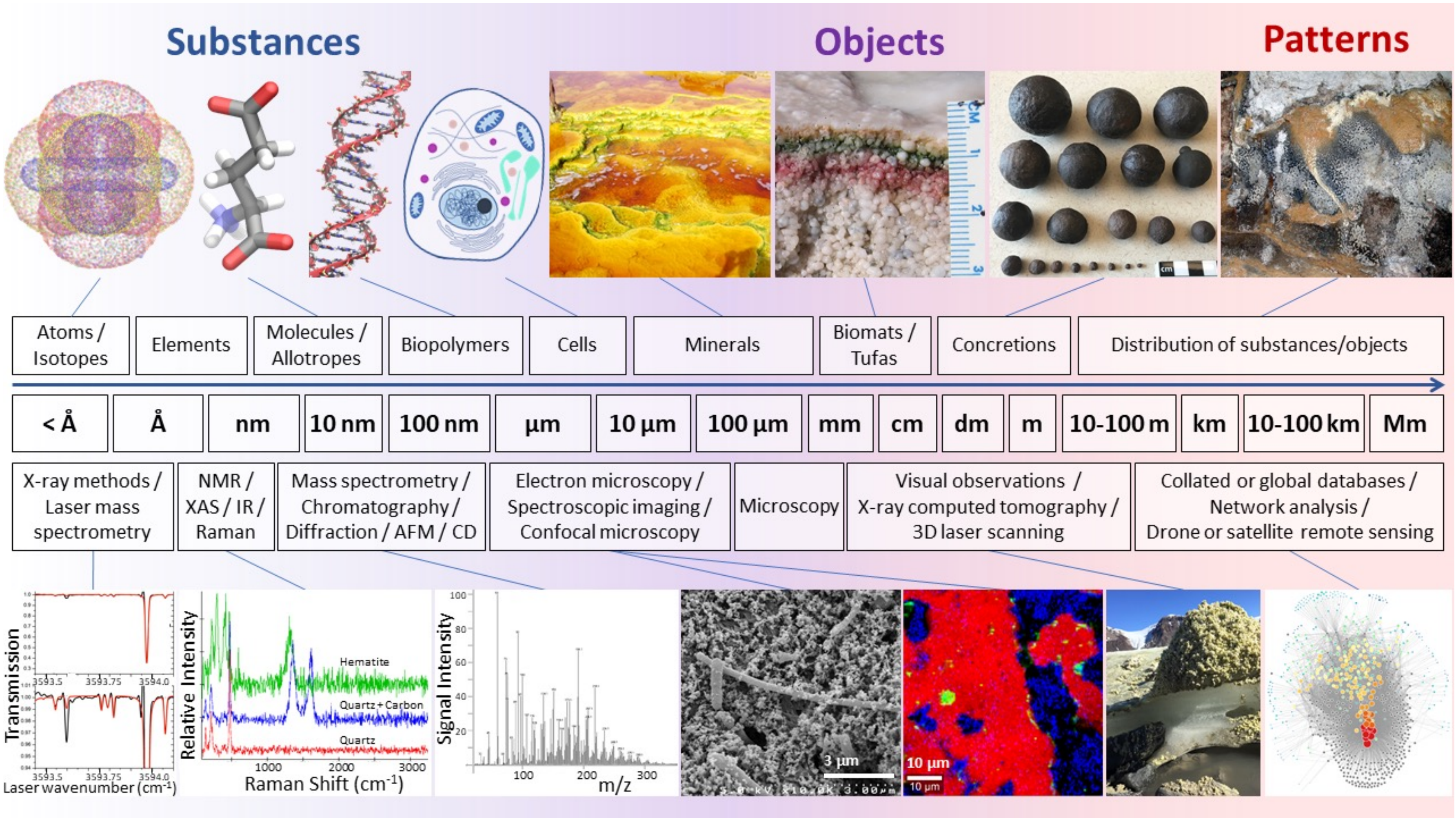
↓

Microbial mats



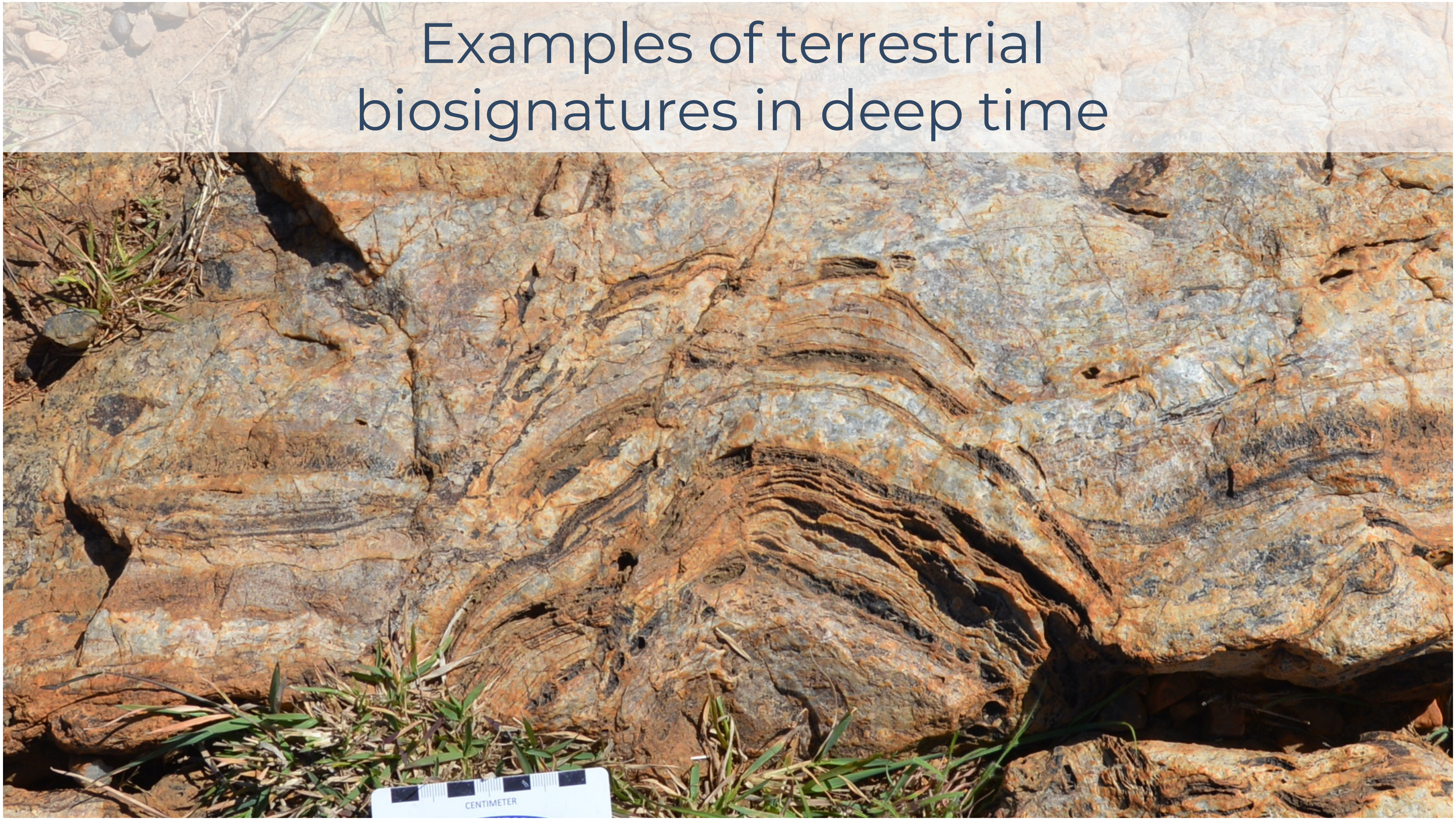


Biosignature and life detection methods

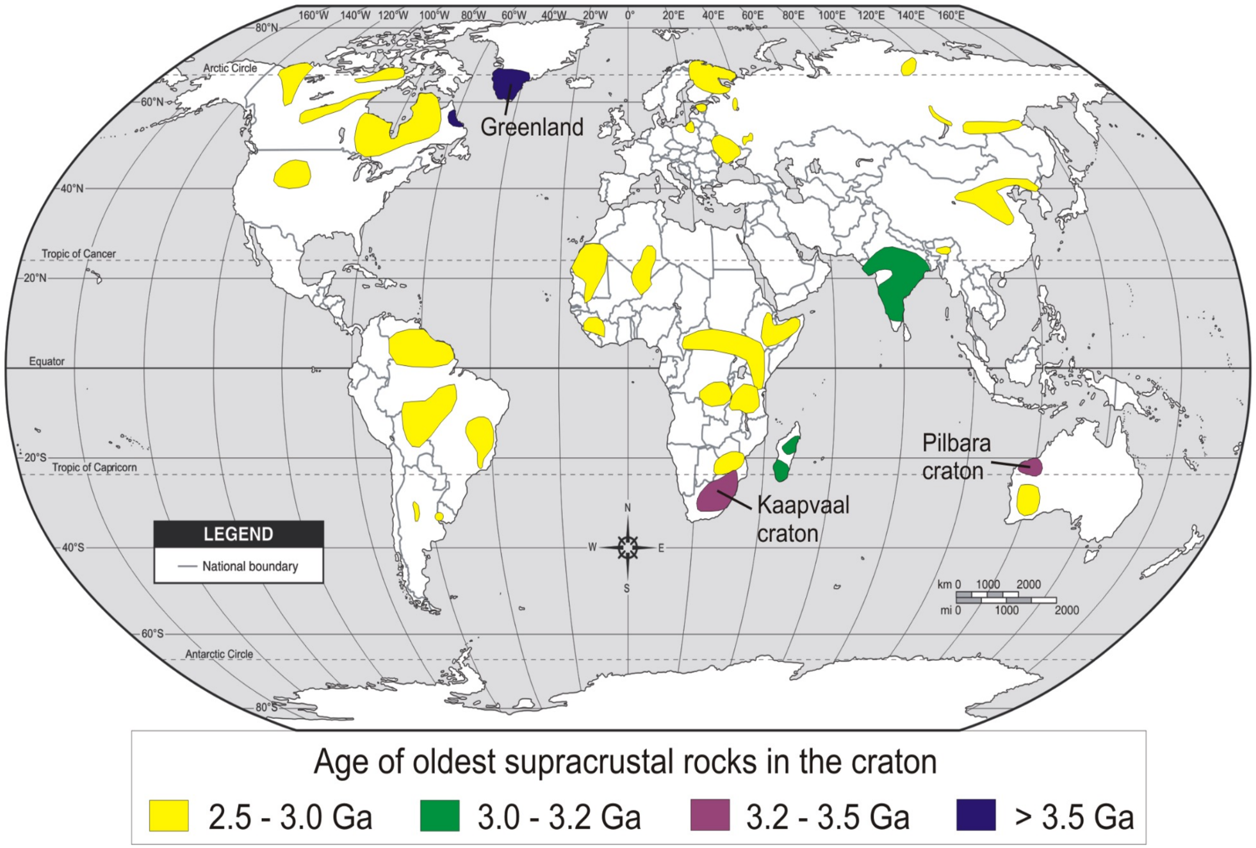


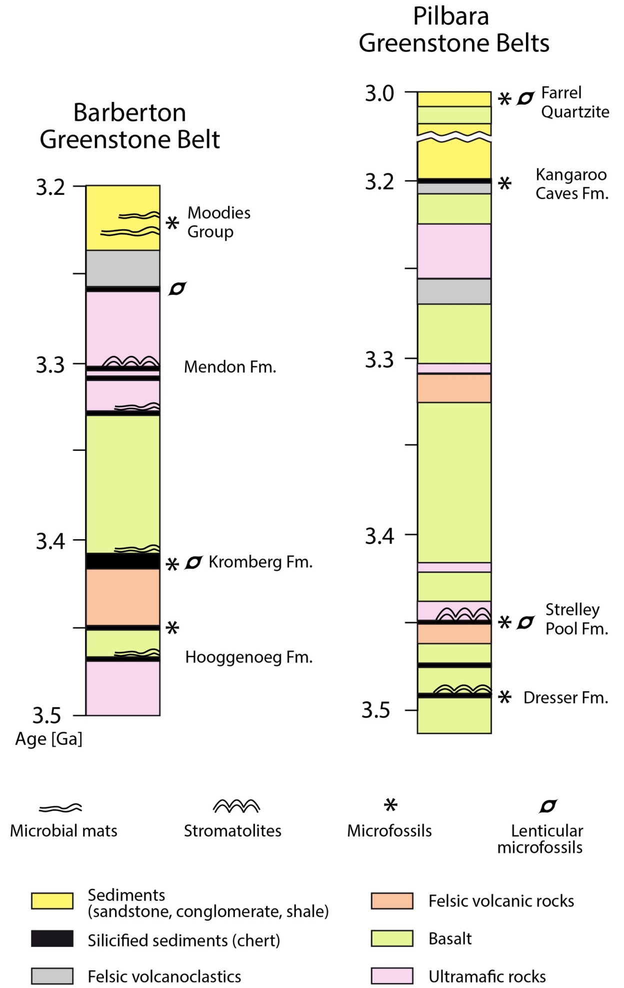
Chan et al, 2019

Examples of terrestrial biosignatures in deep time



Traces of early life in the Archean rock record



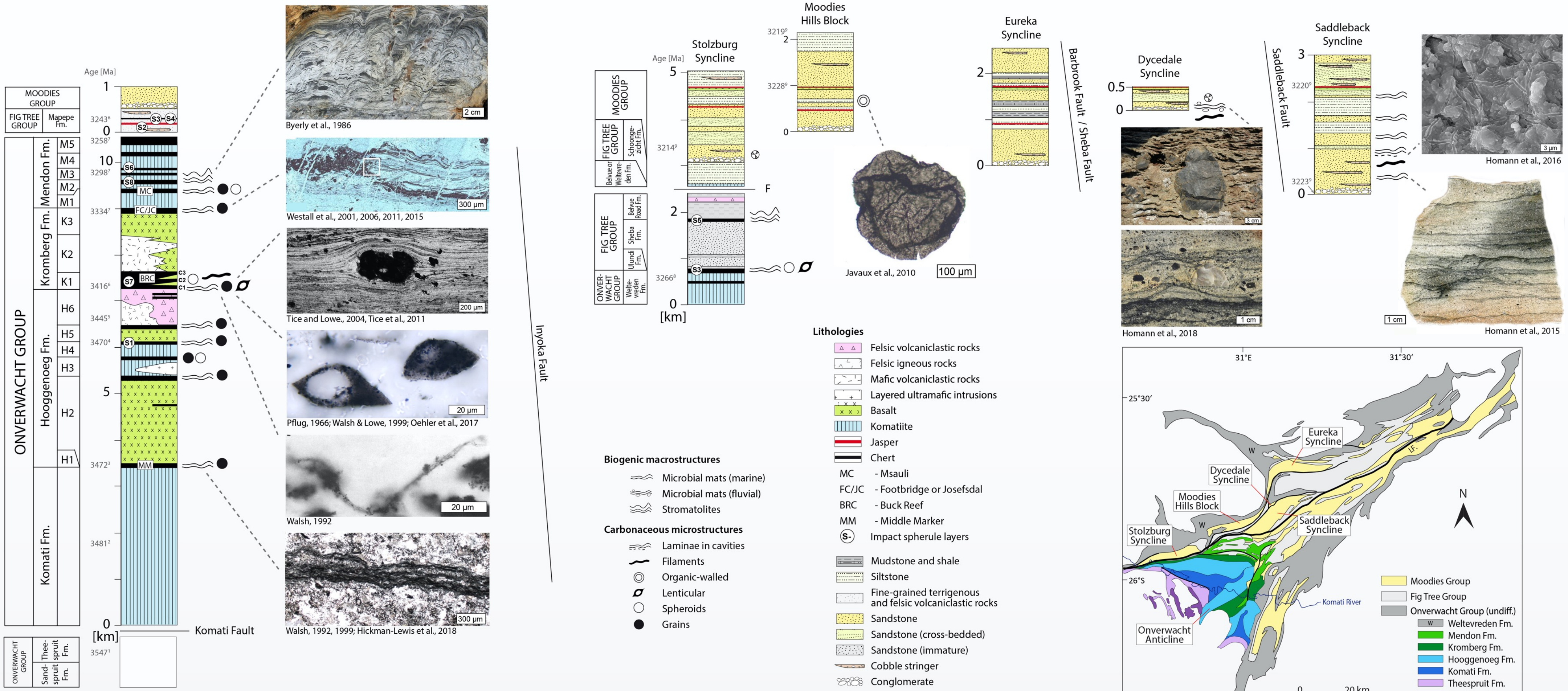


Wacey, 2009

Homann, 2019

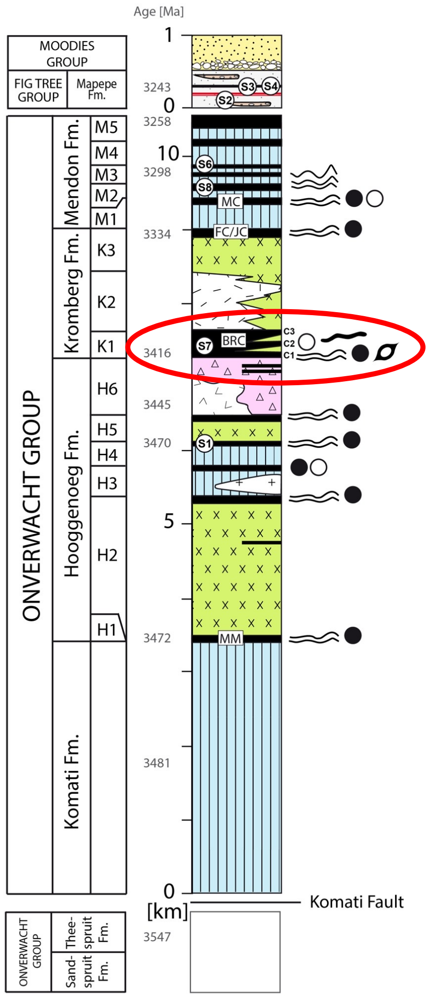
Barberton Greenstone Belt (BGB), South Africa

Evidence of early life in the BGB (3.5 – 3.2 Ga)



Homann, 2019

Traces of early life in the Buck Reef Chert



Homann, 2019

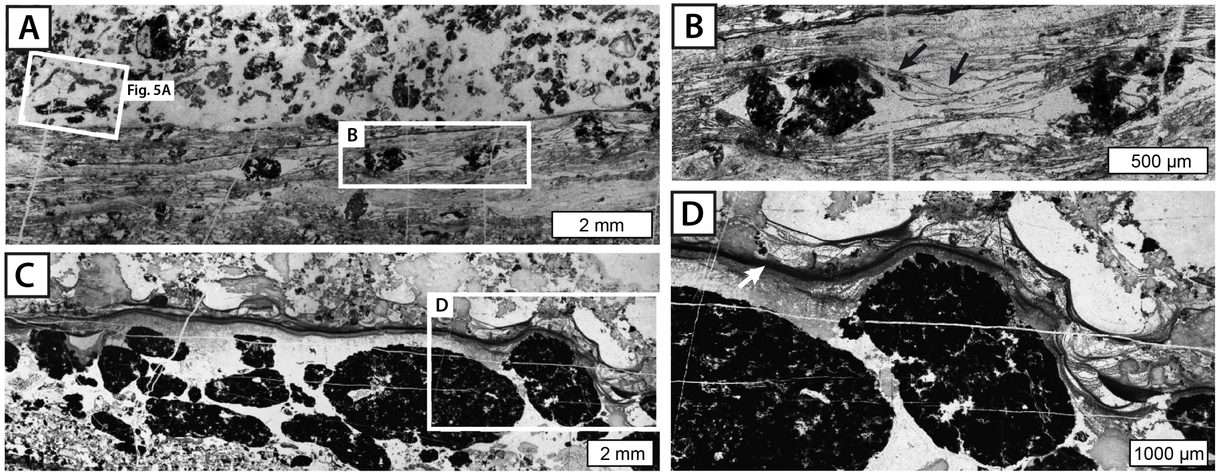
Stratigraphic thickness: 250 – 400m; exposed for nearly 50 km

Black and white banded chert

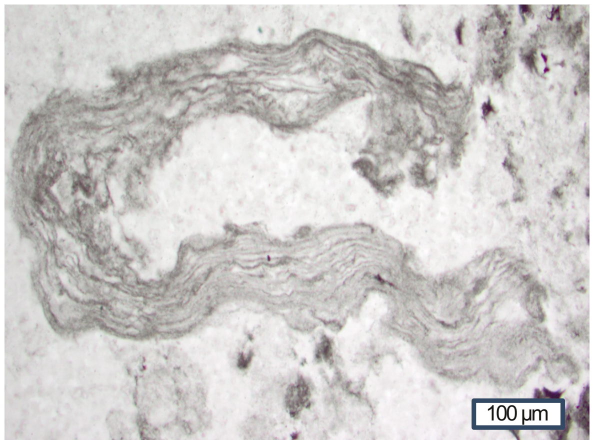
Silicified evaporites

Microbial mats in the 3.4 Ga Buck Reef Chert

Silicified mats draping carbonaceous grains

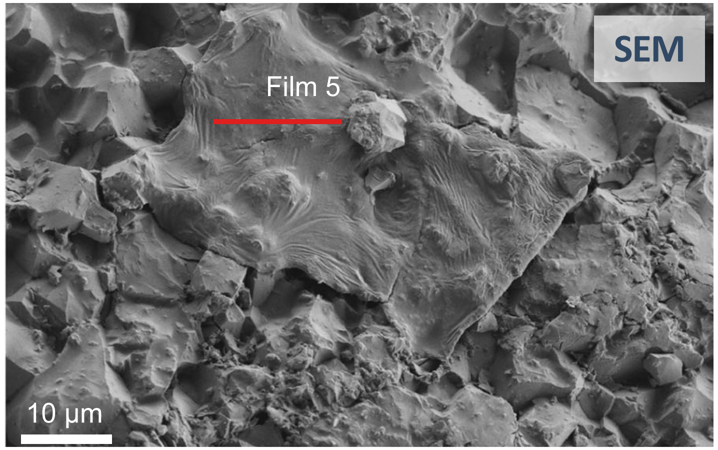


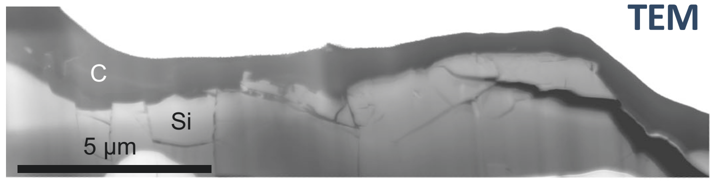
Tice and Lowe et al., 2004; Tice, 2009

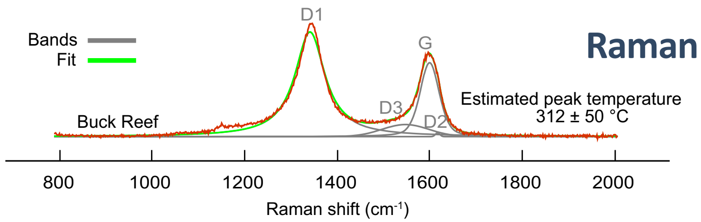


Eroded, rolled-up mat fragments indicate former cohesive consistency.

Carbonaceous biofilms



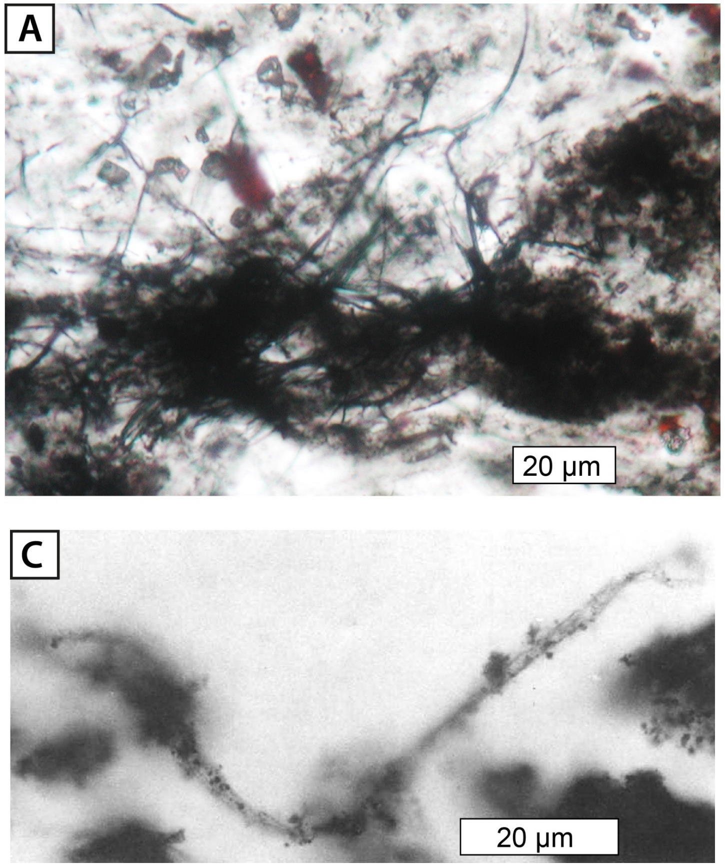




Alleon et al., 2021

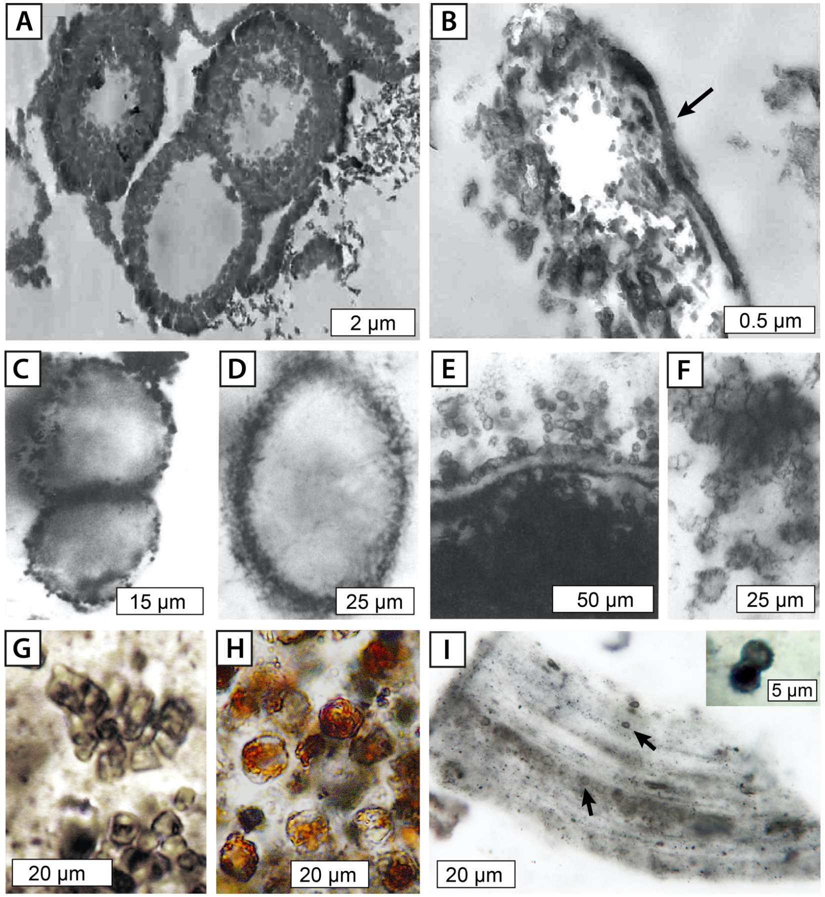
Microstructures of (non)biogenic origin

Filamentous structures



Walsh 1992; 2000

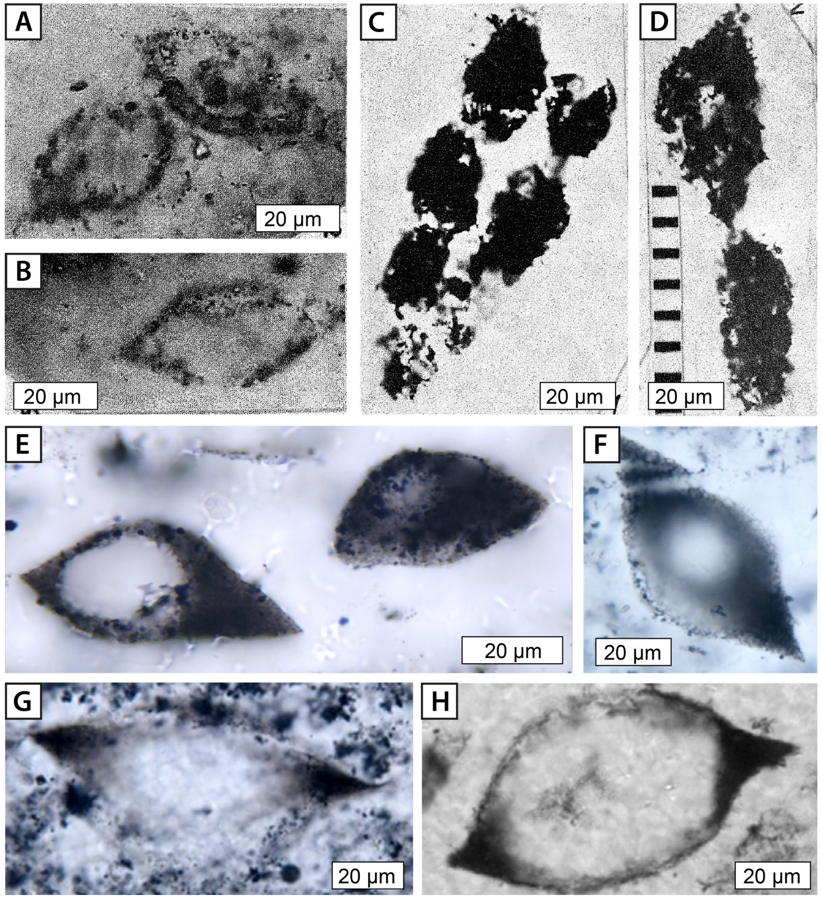
Spheroidal structures



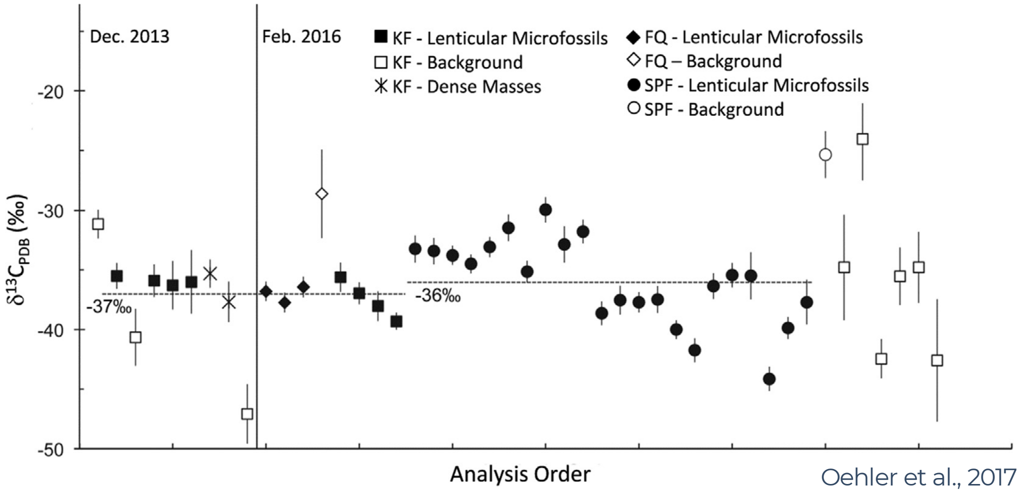
Glikson et al. (2008); Walsh (1992); Kremer and Kazmierczak (2017); Knoll and Barghoorn, 1977

Microfossils in the 3.4 Ga Buck Reef Chert

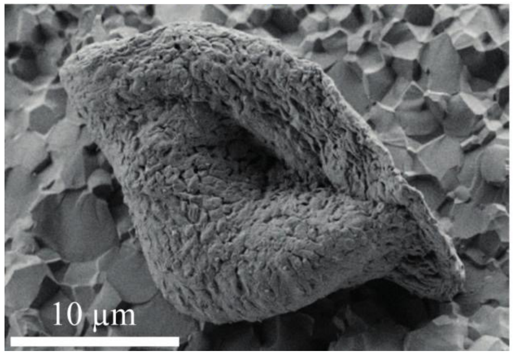
Lenticular microfossils



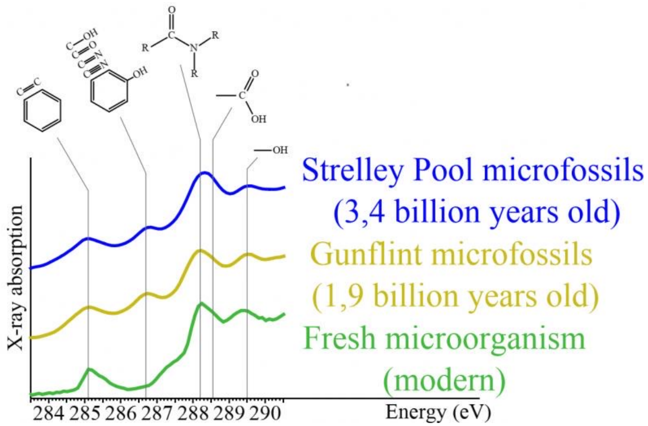
Pflug, 1966; Walsh 1992; Oehler et al., 2017



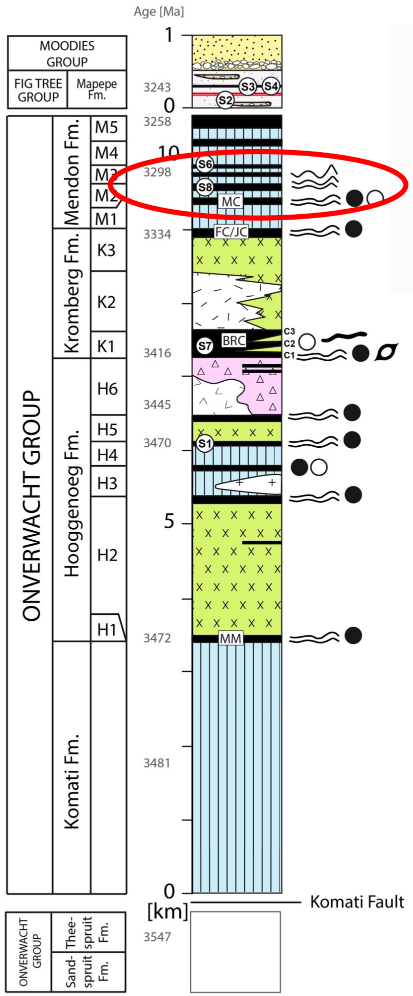
Oehler et al., 2017



Alleon et al., 2018



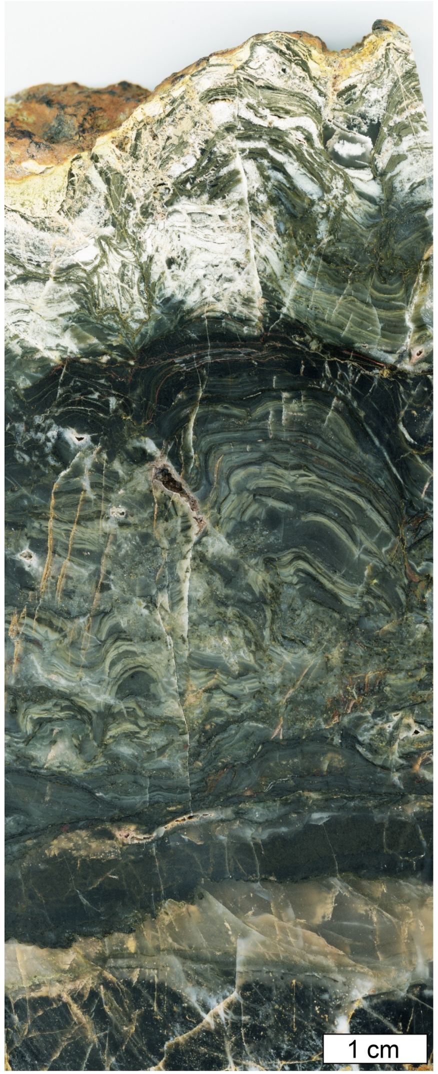
Possible stromatolites in ~3.3 Ga cherts

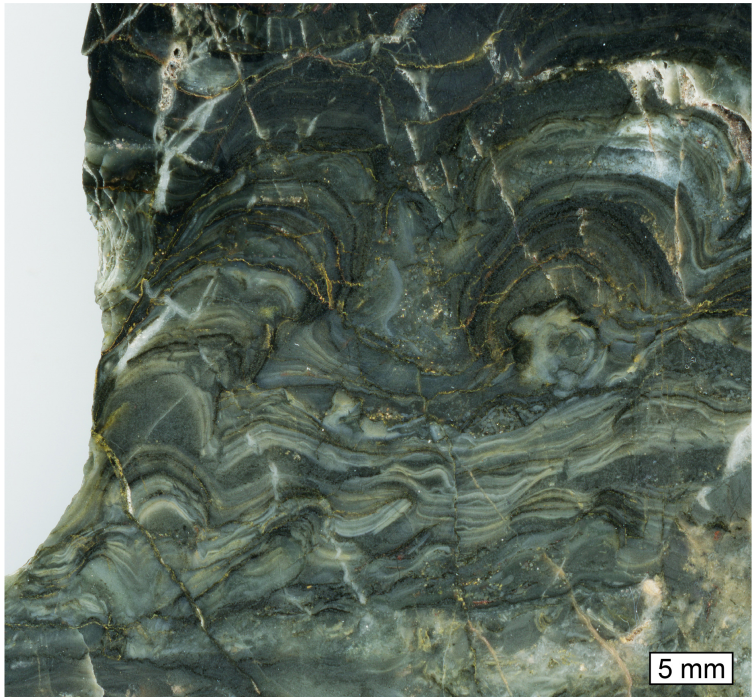


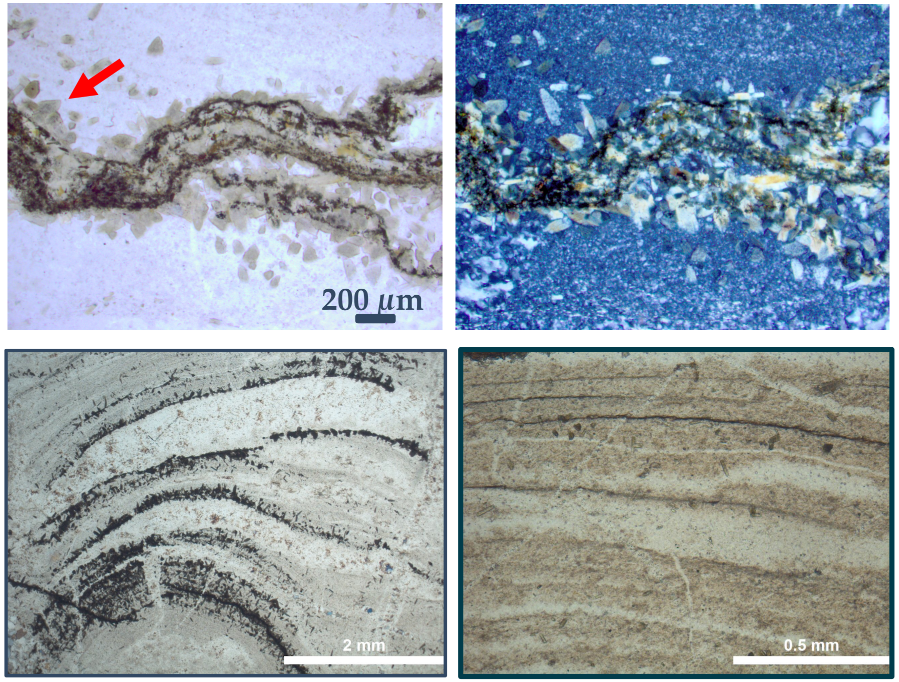
- Stratigraphic thickness: 1 - 20 cm within a 5 m thick chert layer
- Scattered outcrops for >10 km along strike

Stromatolites or silicious sinter deposits?

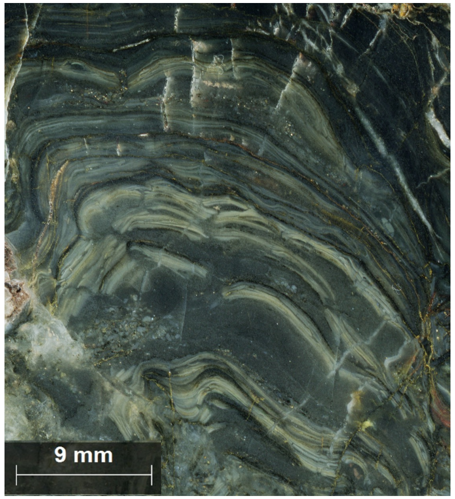
- Domal to pseudo columnar growth morphologies
- Crinkly, carbonaceous laminations contain Mg-Bo-Cr tourmaline
- Mineralization was likely driven by boron-rich hydrothermal fluids (Byerly et al., 1986; Lowe and Byerly, 2015)

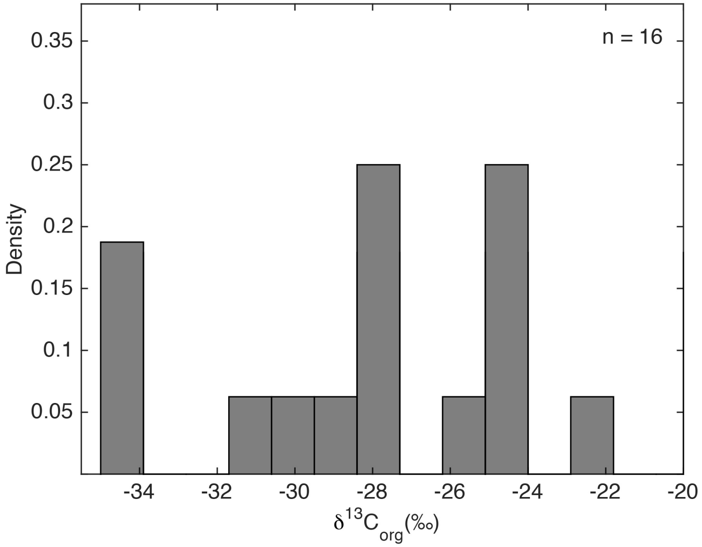




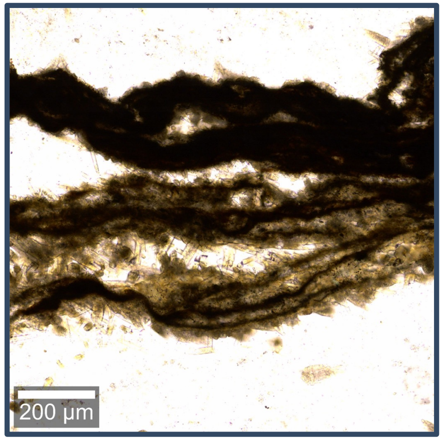


Organic Carbon isotopes and Raman spectroscopy

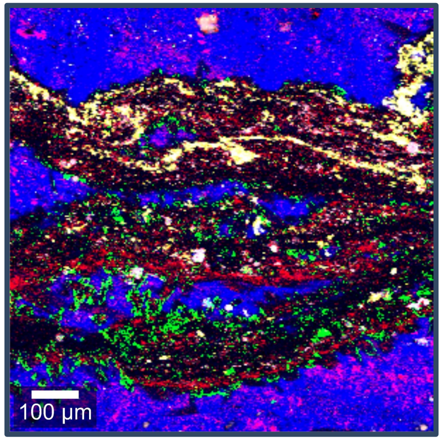


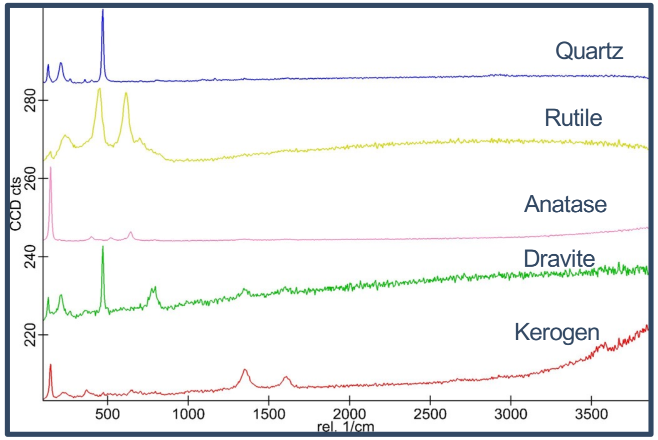


- $\delta^{13}C_{org}$ values range between -34.5‰ and -22.1‰ (n=16)
- consistent with biogenic origin



Alice Hawkins, 2022, MSc thesis



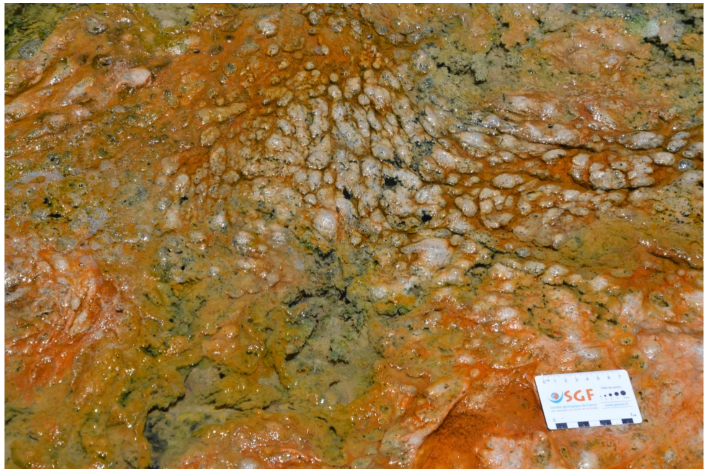


- Raman spectroscopy confirms presence of mature carbon
- T_{peak}: 440°C


El Tatio geothermal field, Chile

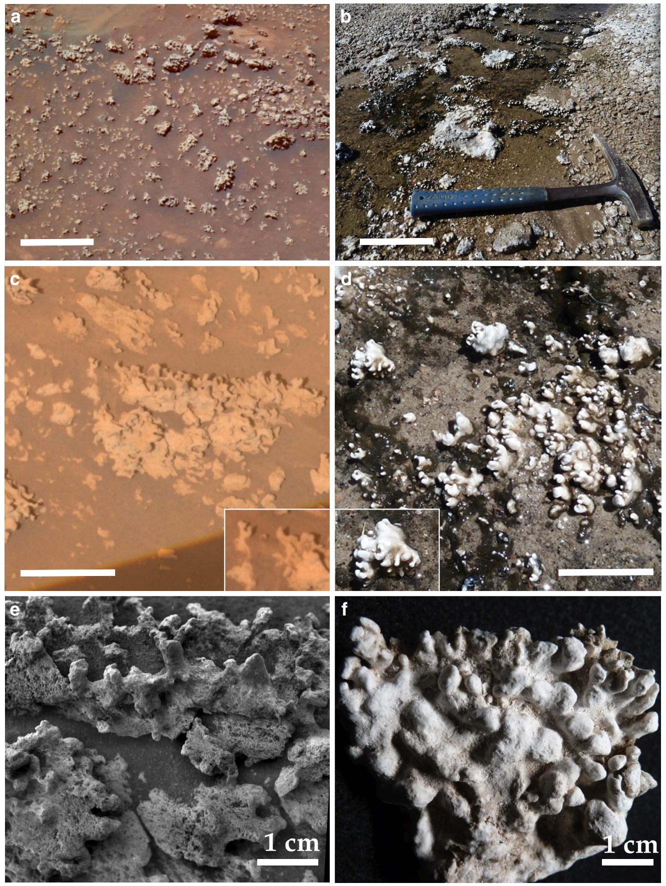
Microbial mats and evaporative silicification in hot spring silica sinters

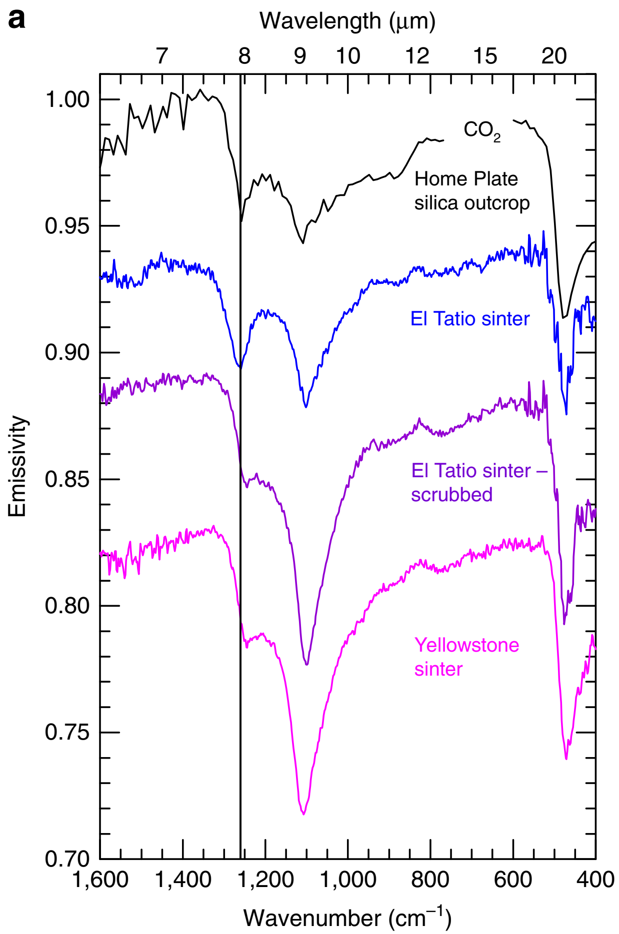



Silica deposits on Mars with features resembling hot spring biosignatures at El Tatio in Chile

Steven W. Ruff[1] & Jack D. Farmer[1]





Ruff and Farmer, 2016

Silica deposits on Mars with features resembling hot spring biosignatures at El Tatio in Chile

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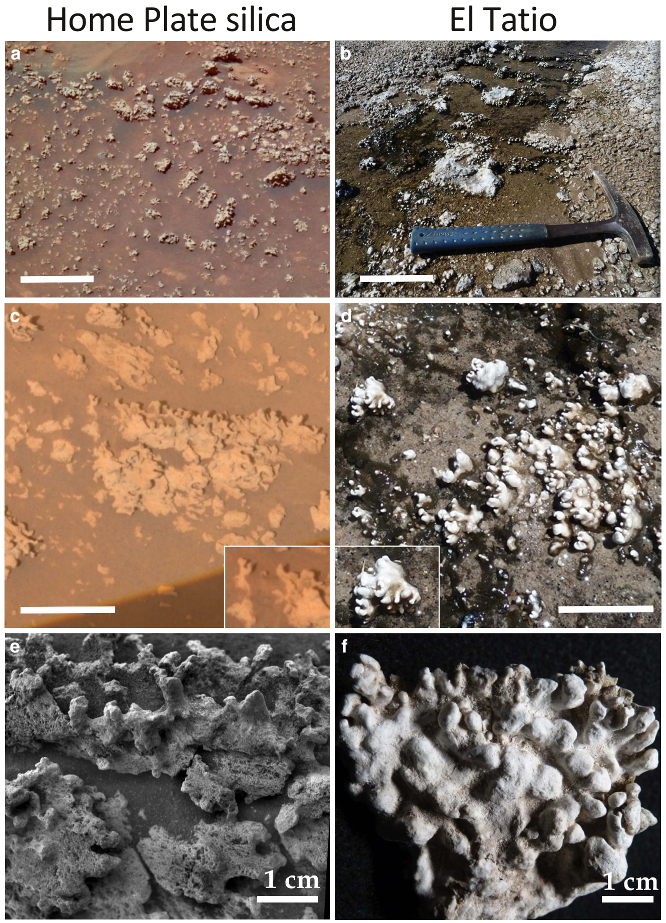
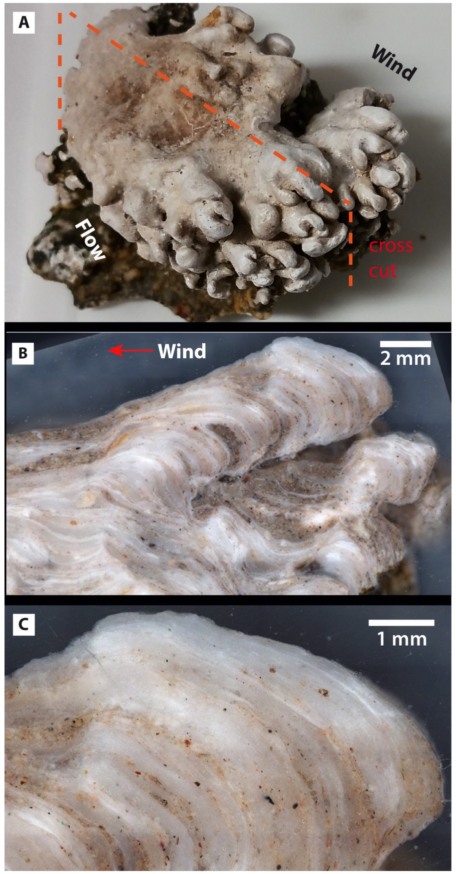
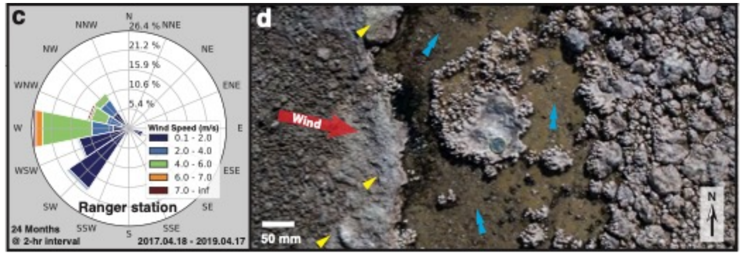


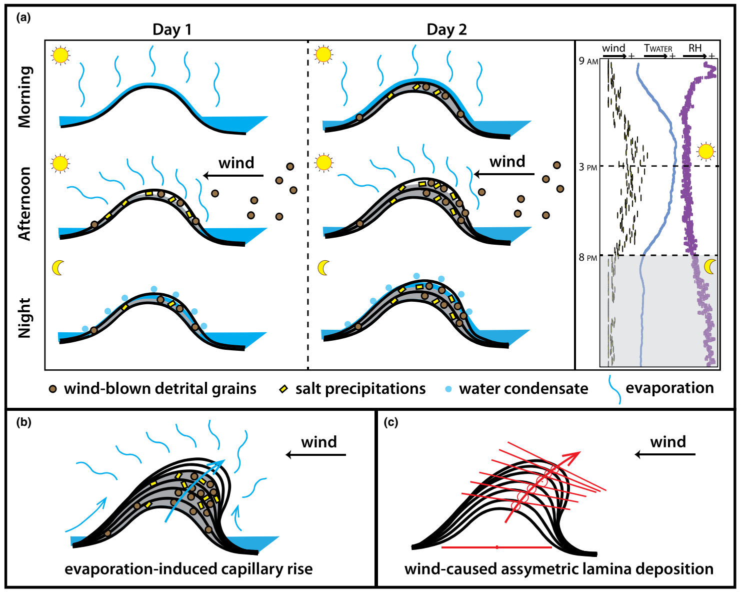
Ruff and Farmer, 2016

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

Jian Gong[1,2] | Carolina Munoz-Saez[3] | Dylan T. Wilmeth[1,4] | Kimberly D. Myers[1] | Martin Homann[5] | Gernot Arp[6] | John R. Skok[7] | Mark A. van Zuilen[1]







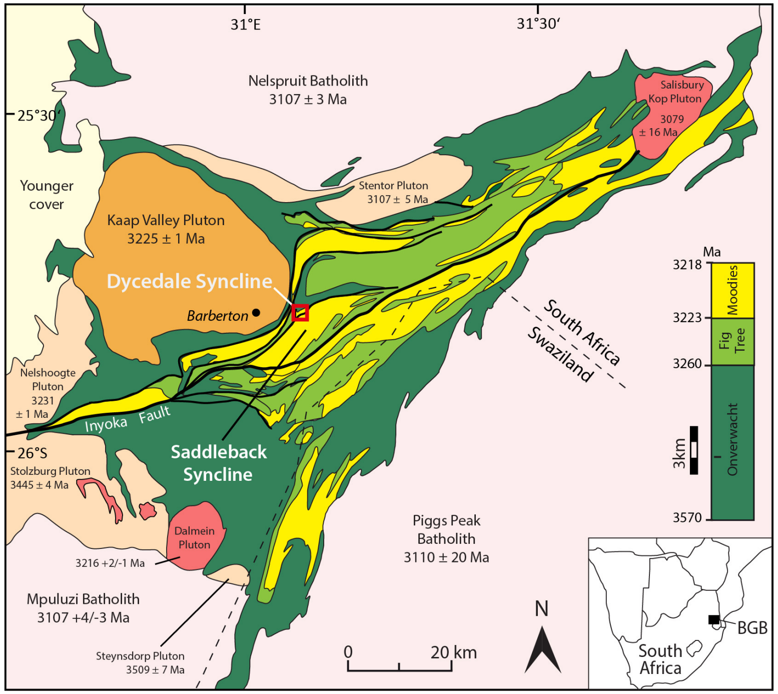
Gong et al., 2021

Microbial mats in the 3.22 Ga old Moodies Group

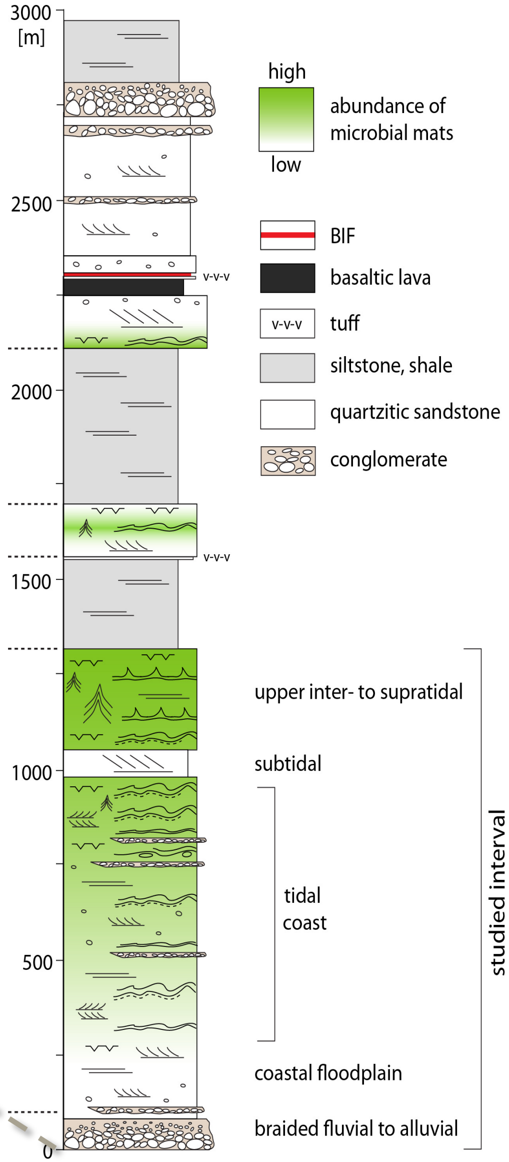
Homann, 2019

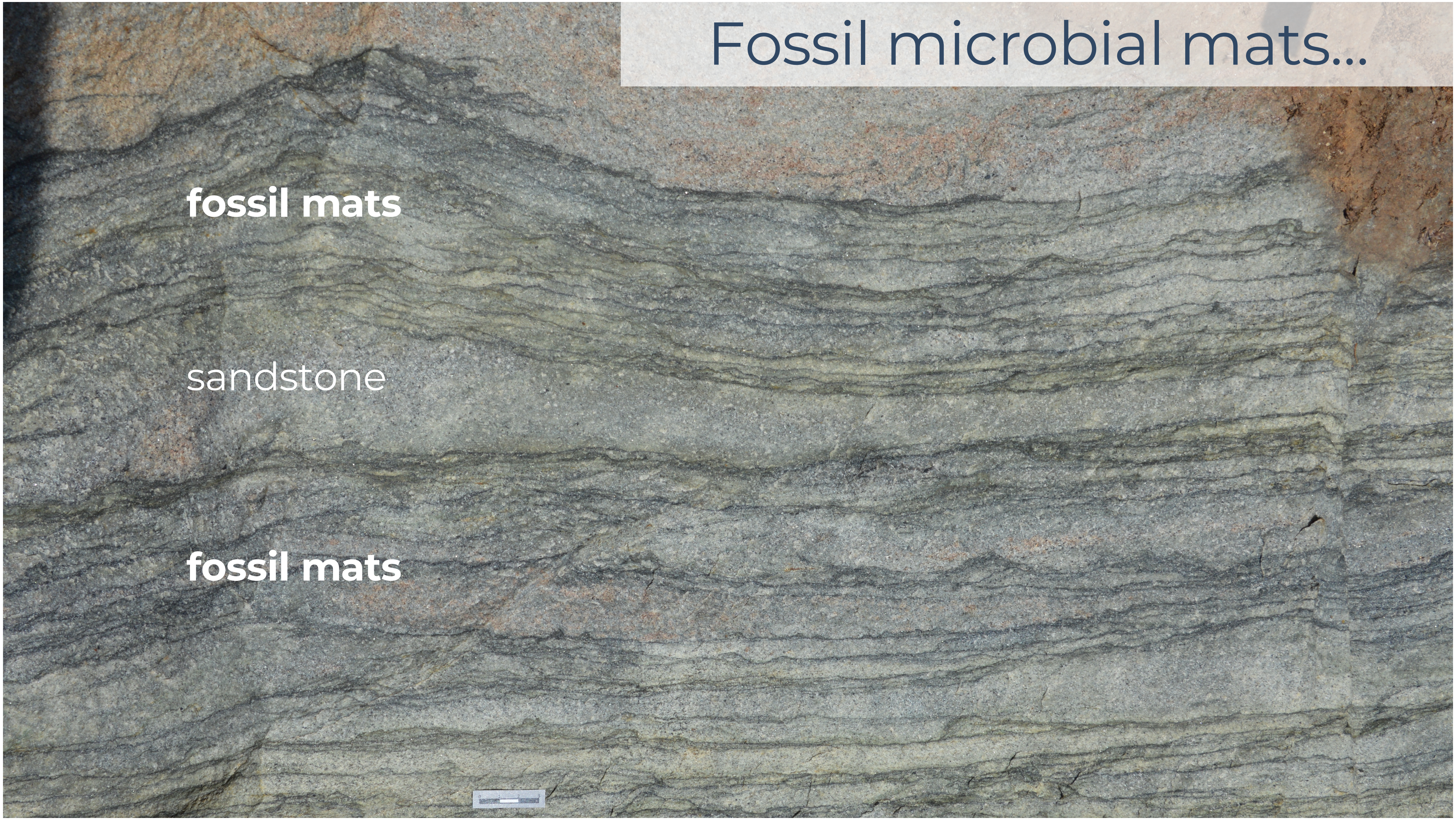
The 3.22 Ga Moodies Group

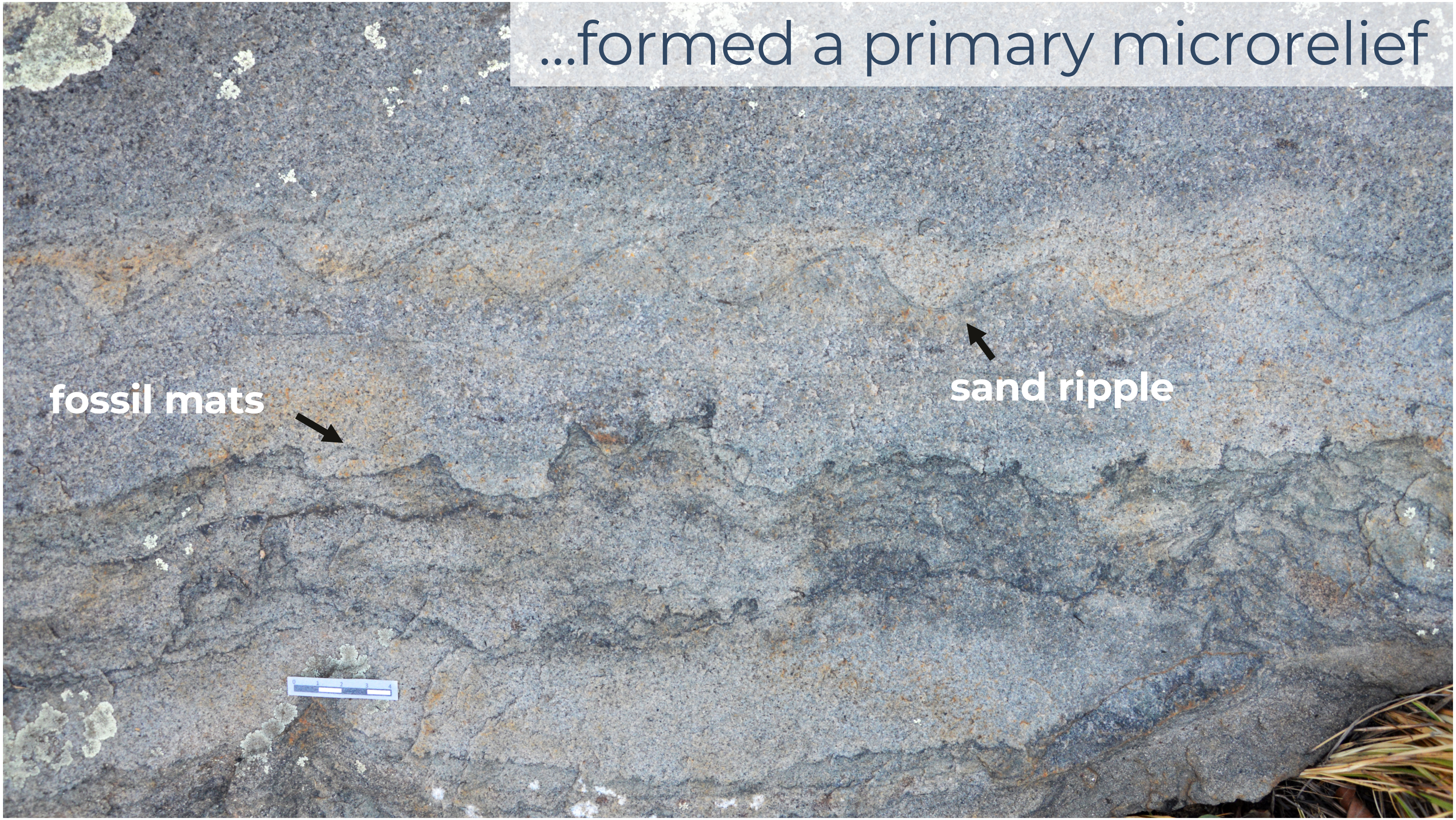
- Earth's oldest well-preserved continental to marine transition
- Very-high-resolution record (3.6 km deposited over 1 to 14 Myr)
- Paleoenvironment: alluvial to deltaic settings, with a dominance of coastal plains and tidal deltas



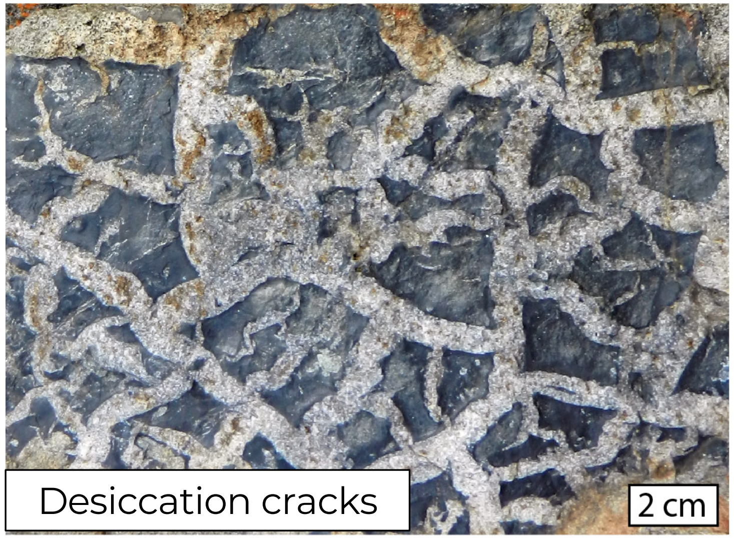
Homann et al., 2015; 2016

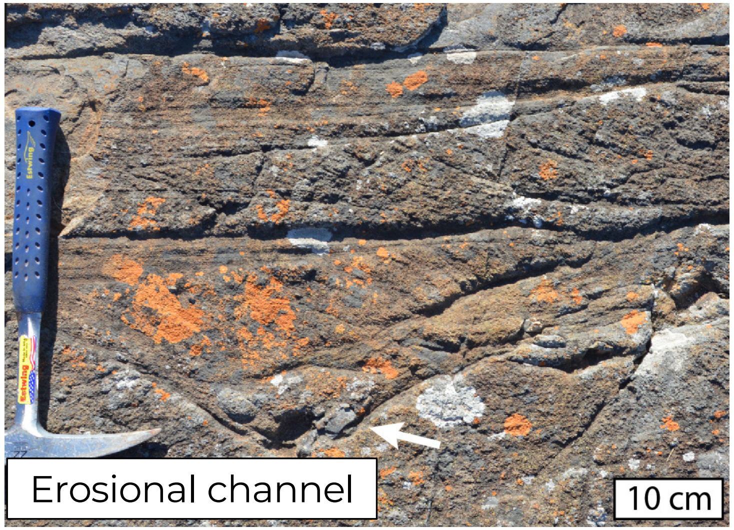



Fossil microbial mats...
fossil mats
sandstone
fossil mats

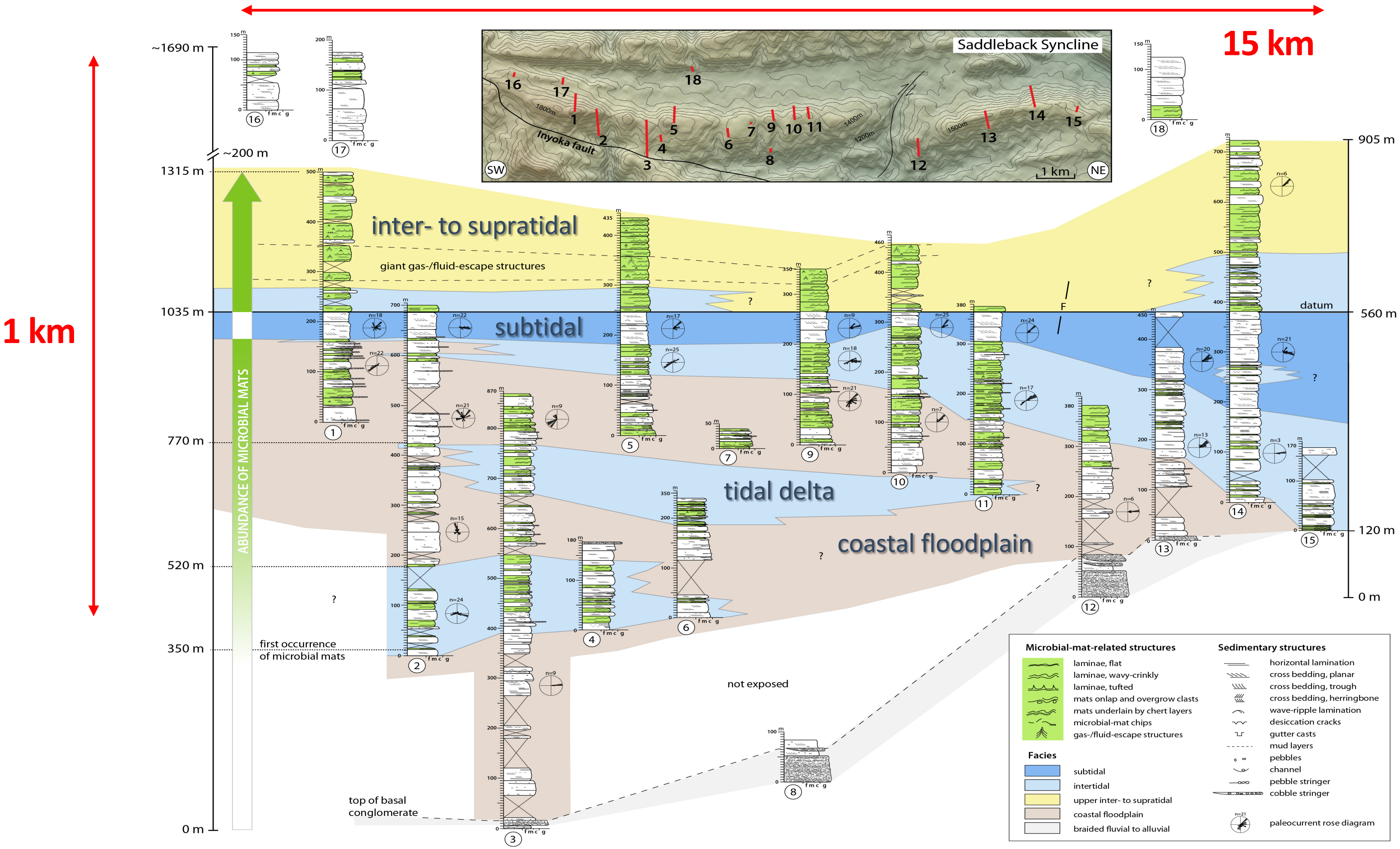

...formed a primary microrelief
fossil mats
sand ripple

Exceptionally well-preserved sedimentary structures



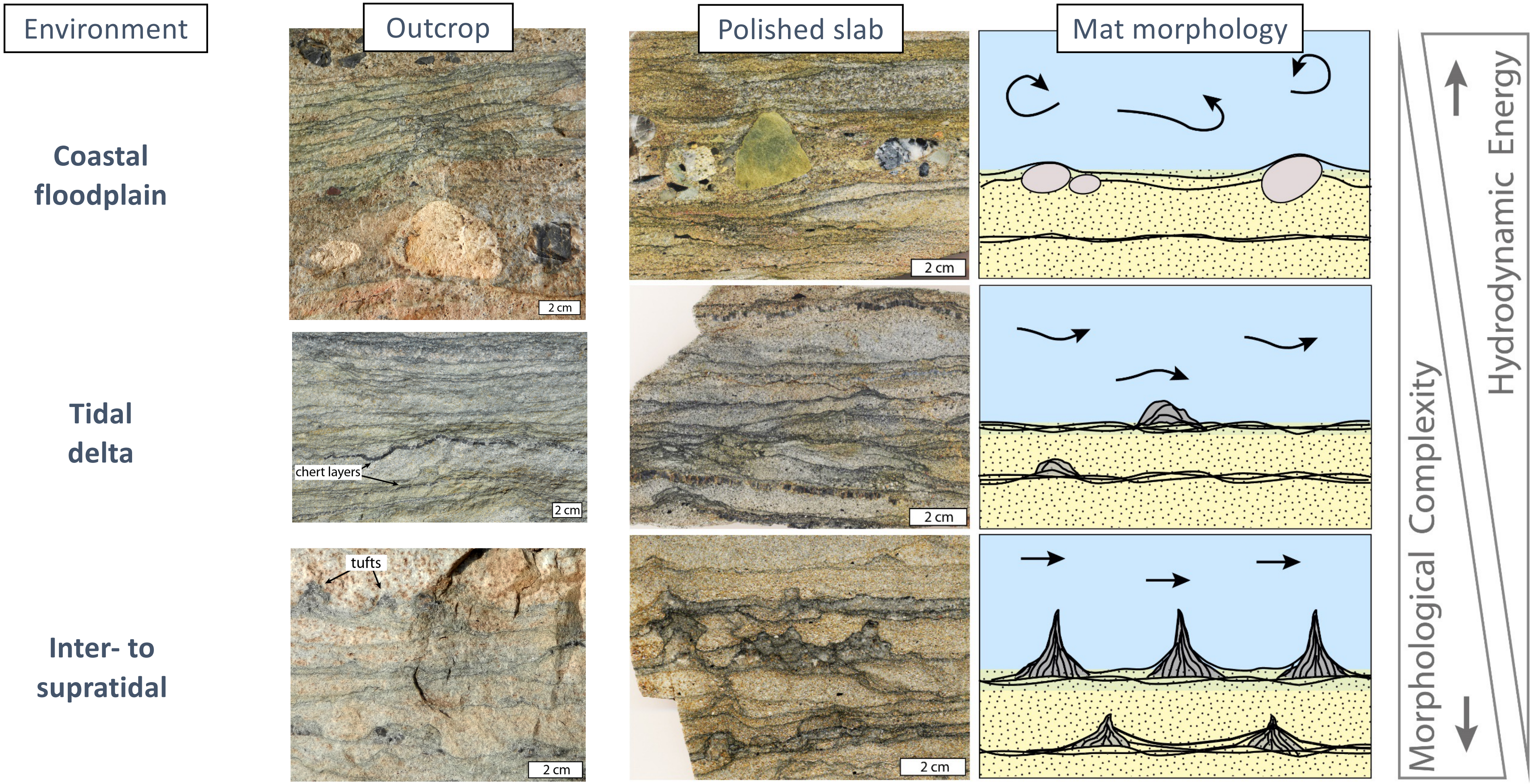


Stratigraphic correlation and depositional facies



Homann et al., 2015

Morphological adaptation to different hydrodynamic settings

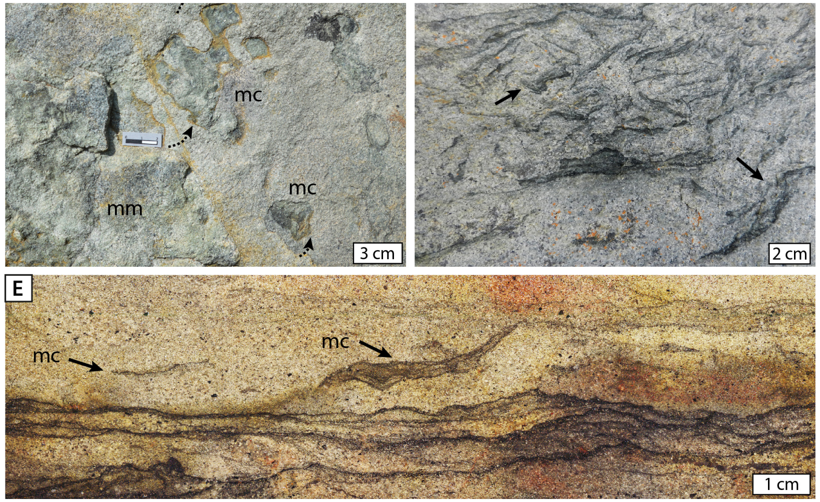


Homann et al., 2015

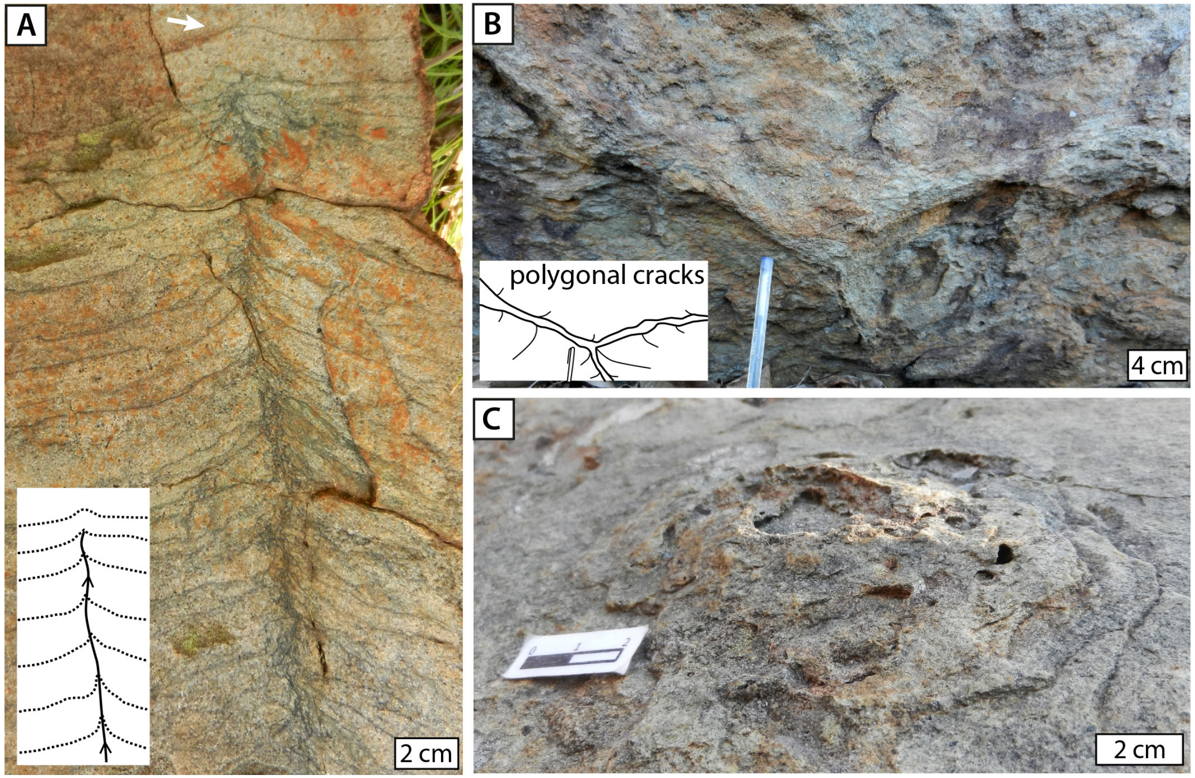
Microbially induced sedimentary structures

Shrinkage cracks

Mat fragments

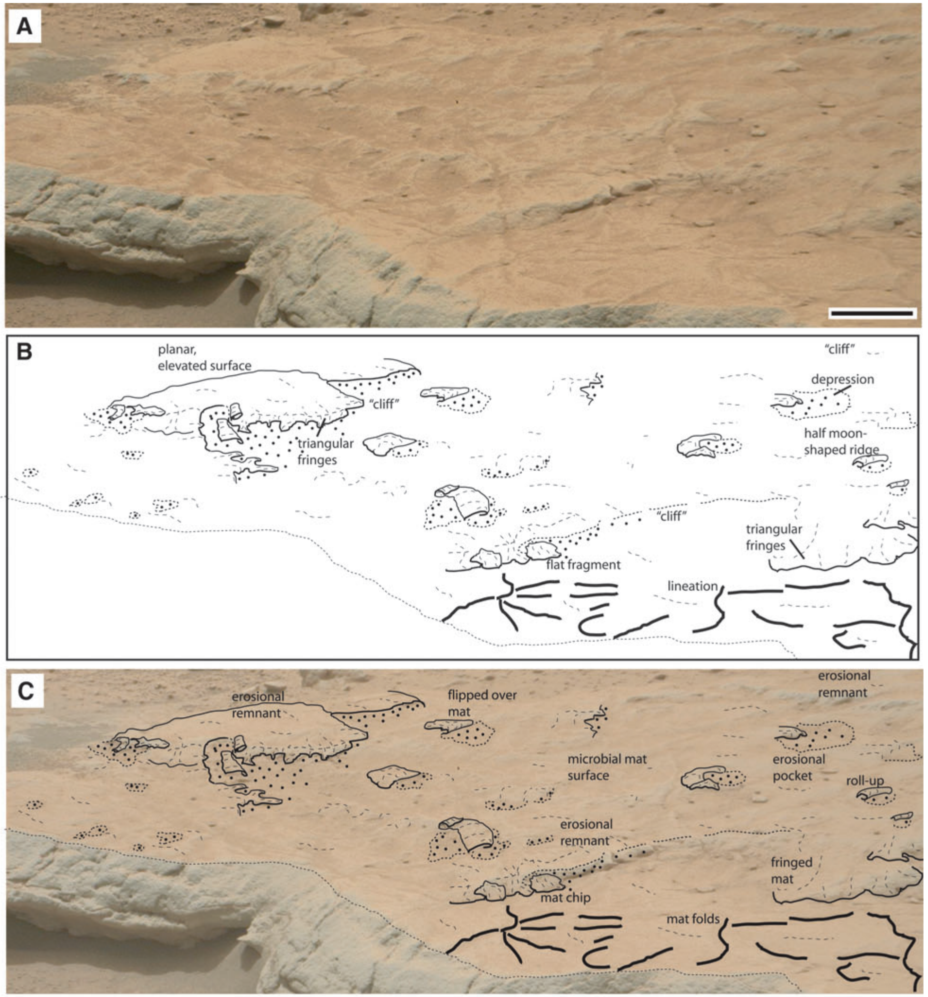


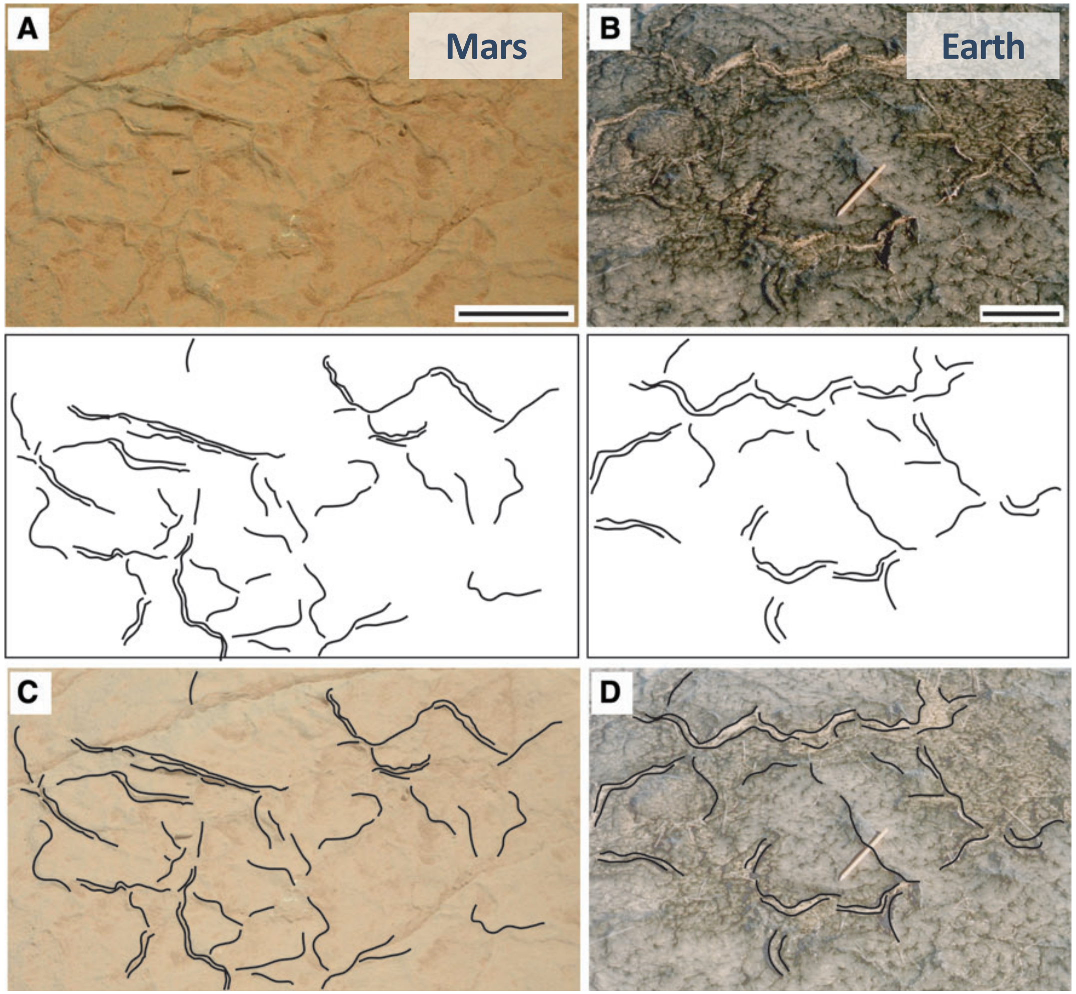
Fluid-escape structures



Homann et al., 2015

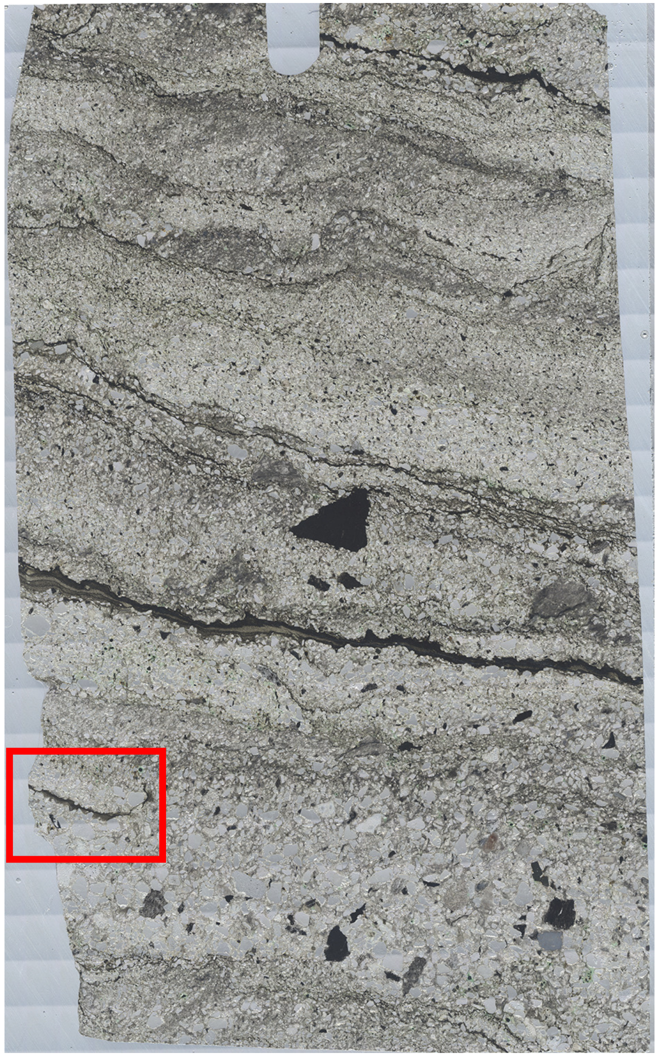
Microbially induced sedimentary structures on Mars?

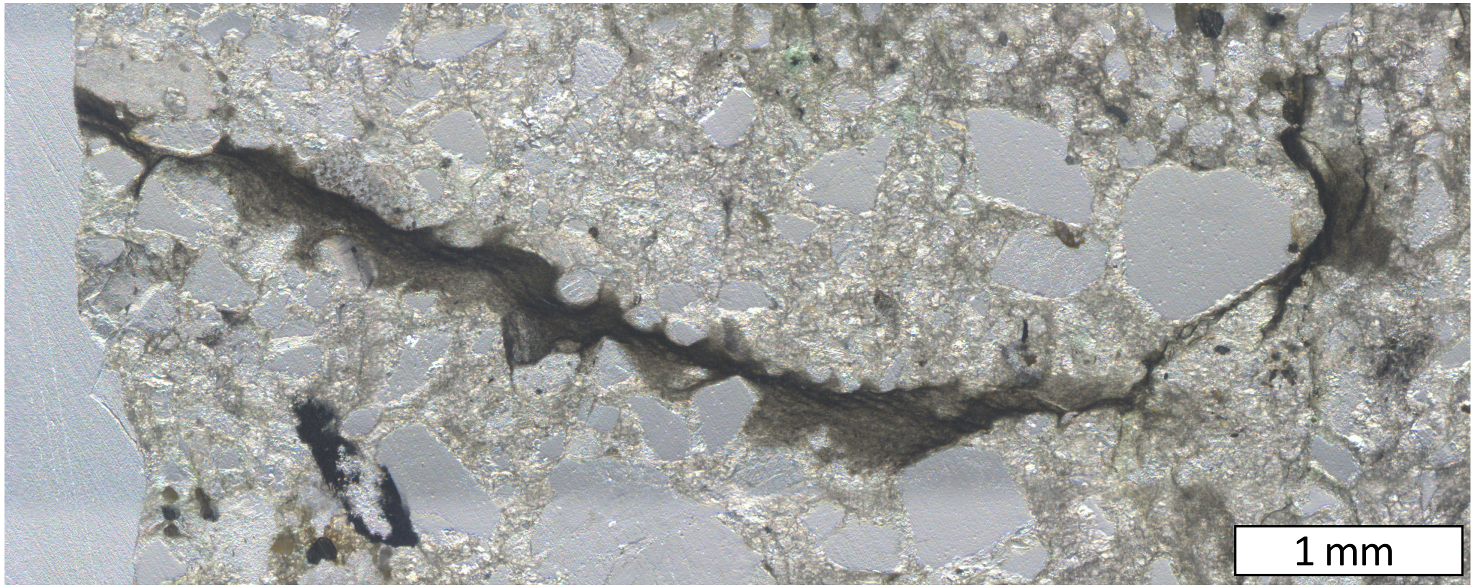


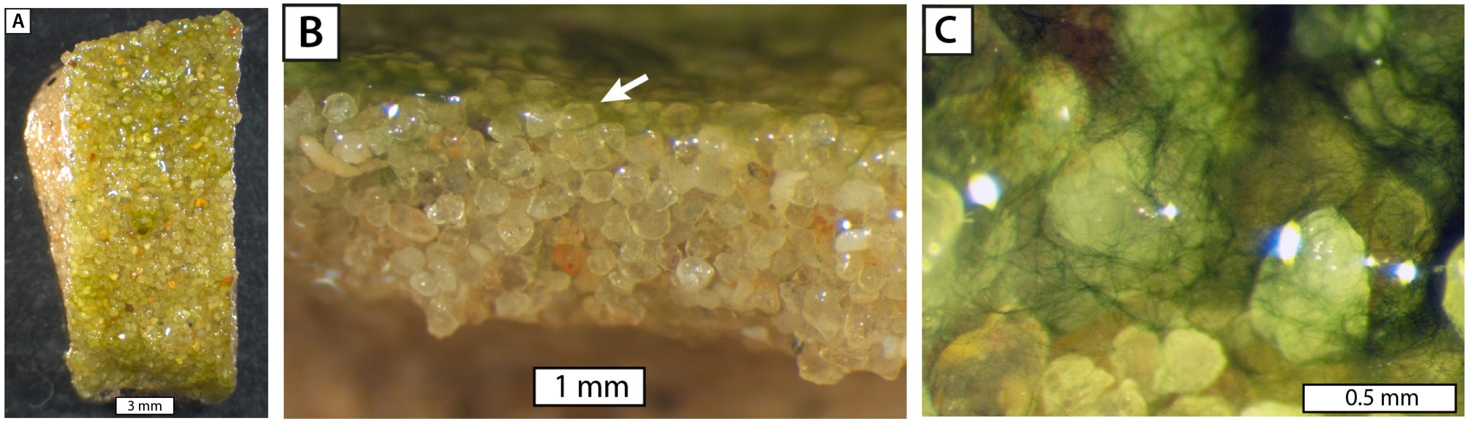


Noffke, 2015

Fossil mats are preserved as organic-rich laminations

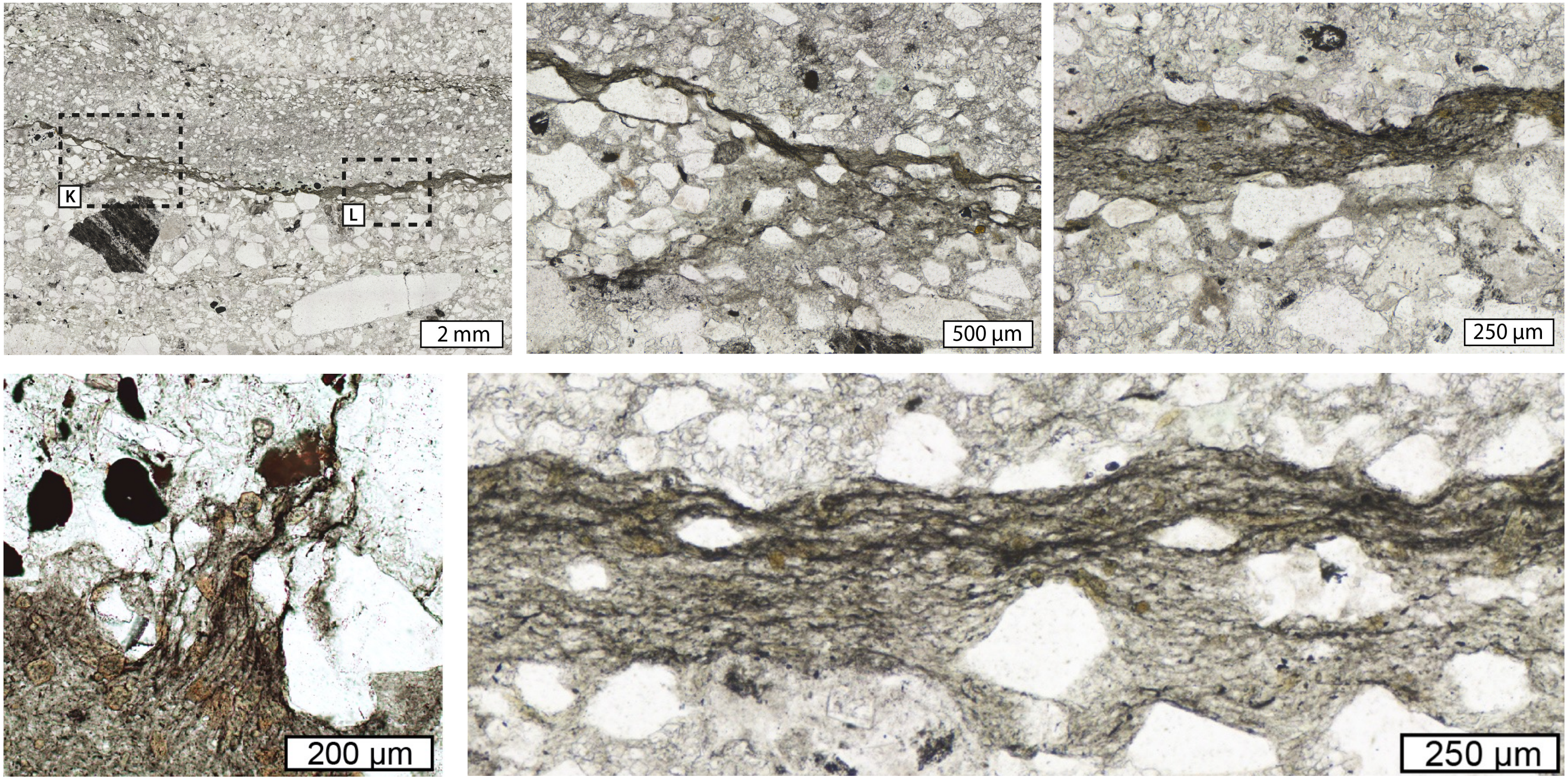




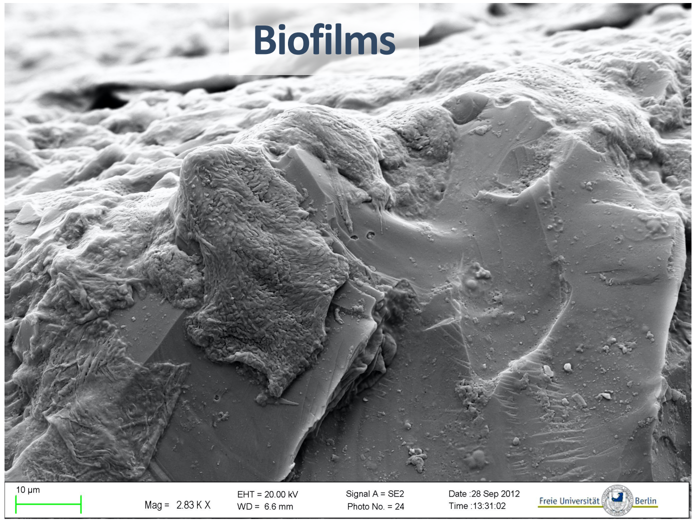


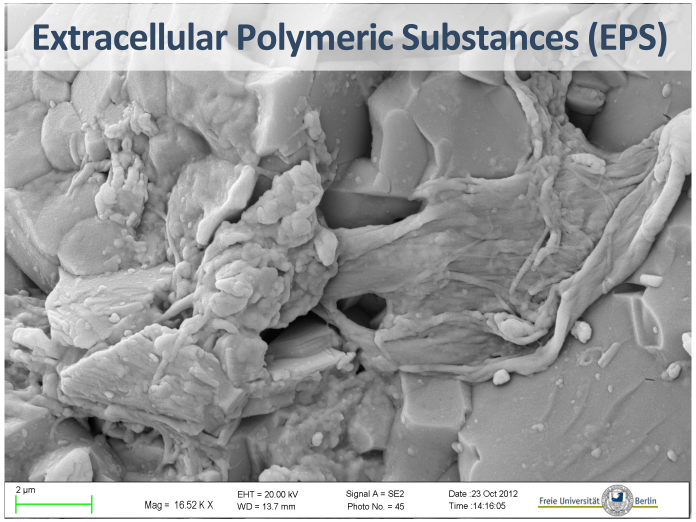
Homann, 2016

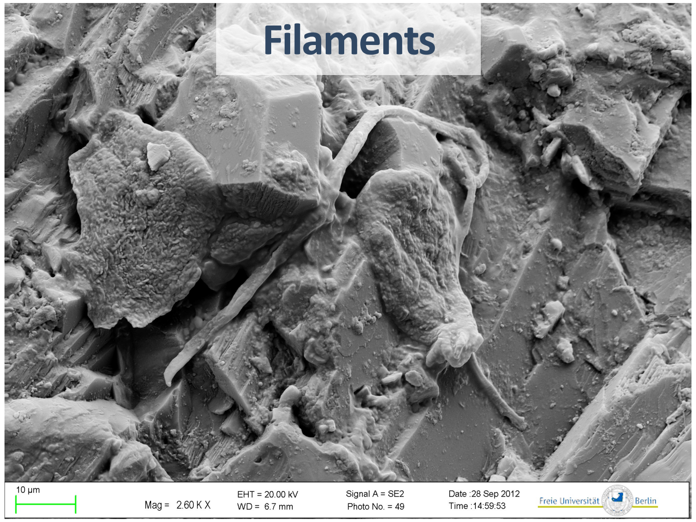
Laminae composed of filamentous microstructures

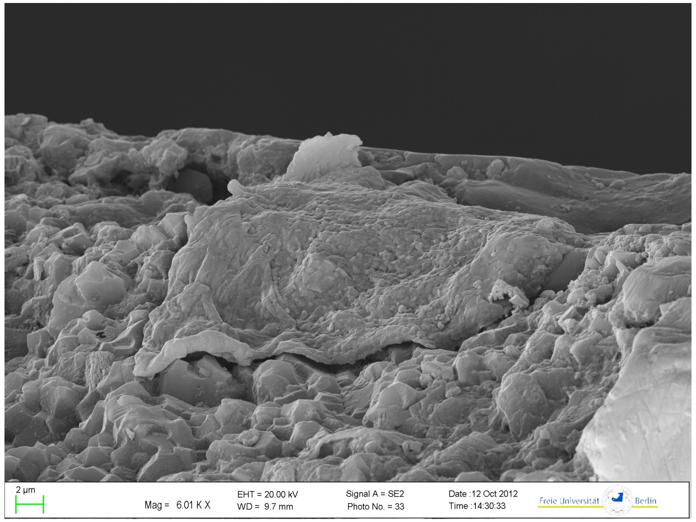


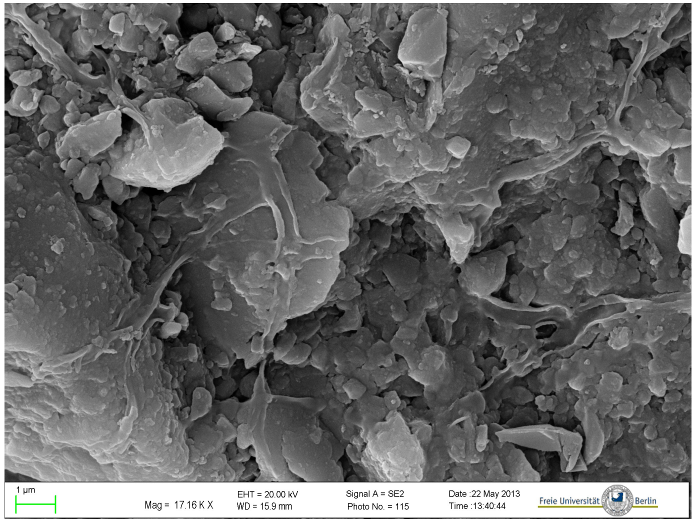
Scanning electron microscopy analysis

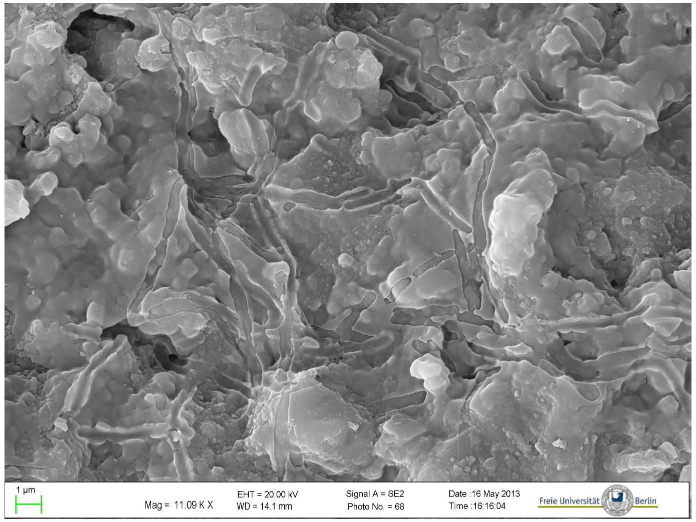






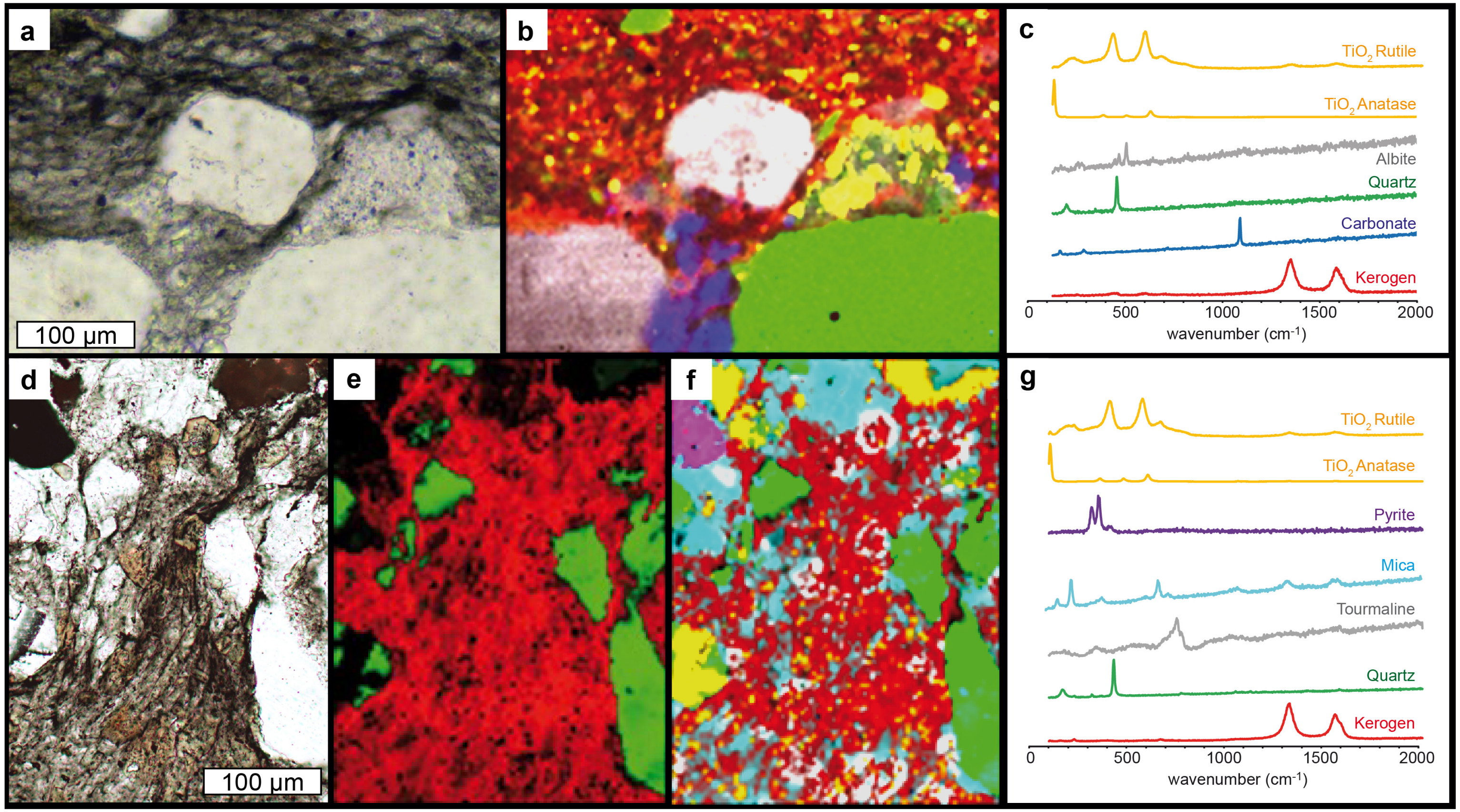






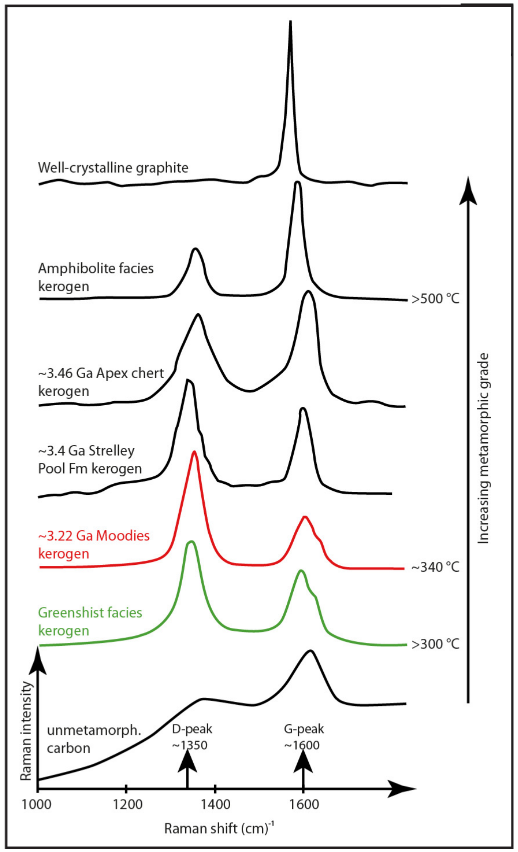
Raman analysis confirms:

(1) Carbonaceous composition of the laminae



Homann et al., 2018

(2) Syngenicity of the kerogen



mod. after Wacey, 2009

Comparison of marine and fluvial mats

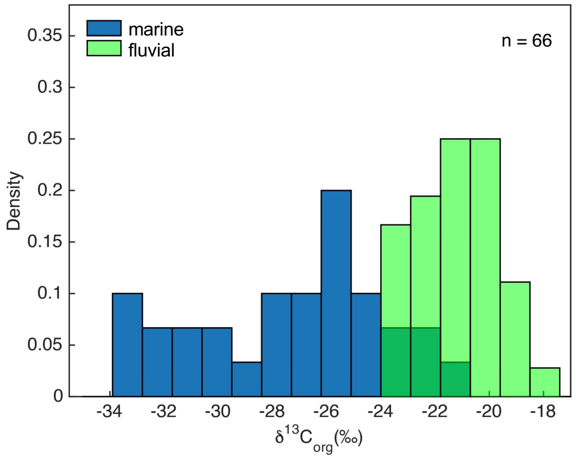
Marine facies

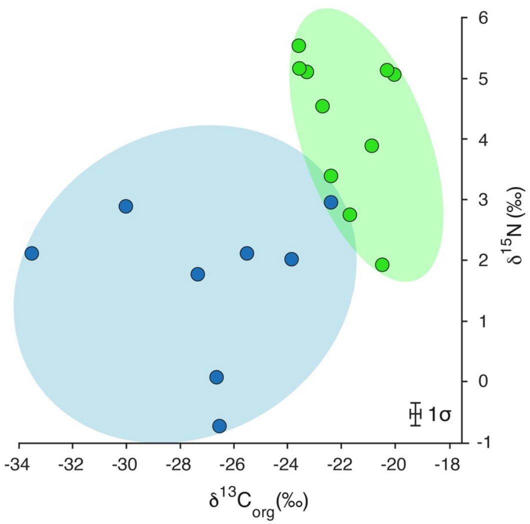
- Interbedded with medium- to coarse-grained sandstones
- Crinkly and tufted growth morphologies

Fluvial facies

- Interbedded with pebbly sandstones and conglomerates
- Mostly planar and generally thicker mats

Organic carbon and nitrogen isotope analysis





Fluvial mats: $-24 < \delta^{13}C < -18‰$

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

Marine mats: $-34 < \delta^{13}C < -21‰$

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

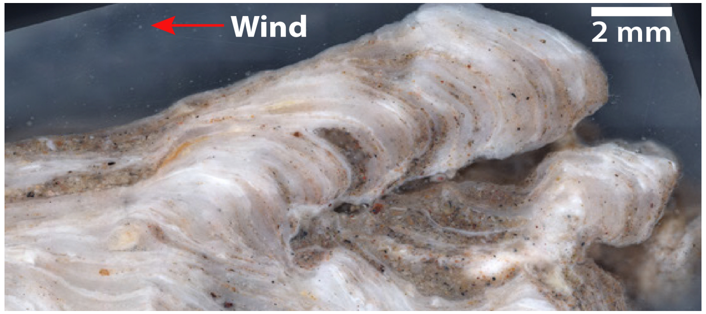
Fluvial mats: $+2 < \delta^{15}N < +5‰$

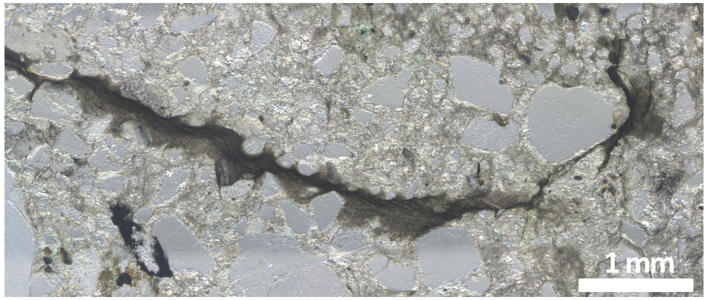
Marine mats: $0 < \delta^{15}N < +3‰$

- Biological mechanisms that produce biomass with $\delta^{15}N > +2‰$:
  1) Partial assimilation of ammonium (NH_4^+)
  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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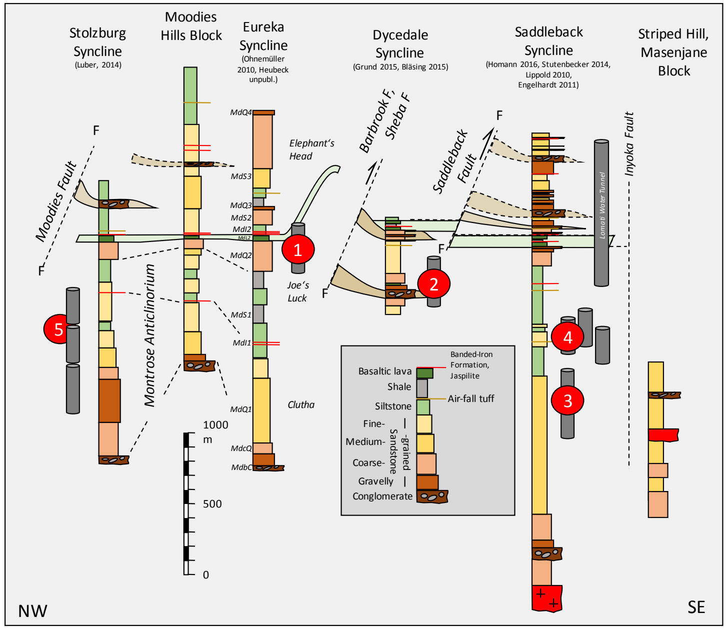
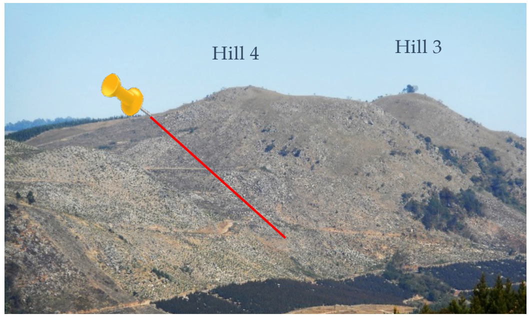
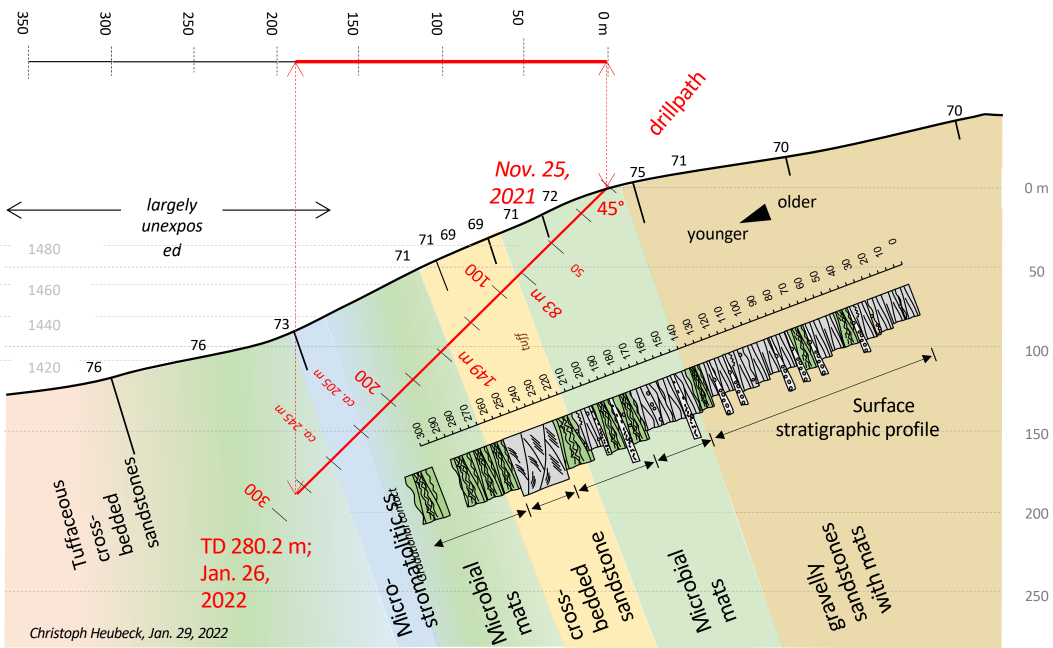
ICDP drilling project: Barberton Archean Surface Environments

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



ICDP drilling project BASE





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

Drill core diameter: