Update of Goal 1:

Determine if Life Ever Arose on Mars

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with inputs from many others

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March 18, 2010

Proposed Draft: Structure

1. Introductory material (background; rationale for priorities)

2. Statement of Objectives, Investigations, Sub-Investigations

   A. Search for evidence of ancient life

      → Habitability
      → Preservation potential
      → Life detection

      } Preferred order of execution, not priority; Life detection is highest priority, habitability & pp as "screening" investigations

   B. Search for evidence of extant life

      (Investigations analogous to A)

   C. Long-term evolution of habitability

3. Appendix

   → Detail on Life, Habitability, Biosignatures

Proposed Draft: Main Changes

1. Carbon objective reabsorbed into habitability, preservation potential & life detection objectives/investigations
   - ⟶ Carbon not de-prioritized; just appears in context
2. Separate objectives delineated for ancient & extant life
   - ⟶ Ancient currently prioritized over extant, but possibility to reassess
   - ⟶ Necessitates “sub-investigation” level to capture appropriate detail
3. Explicit inclusion of preservation potential investigations
   - ⟶ Habitability and PP as “screening” investigations
4. Modest updates to habitability and life detection at finest level of detail
5. Inclusion of appendix / level of detail / length

Habitability

Appears in two “modes”:

1. As a means to screen/prioritize potential landing sites or samples within a given landing site

   ⟶ Higher priority; Investigations A.1 & B.1

2. As a stand-alone research objective, focusing on long-term evolution as a function of planetary processes

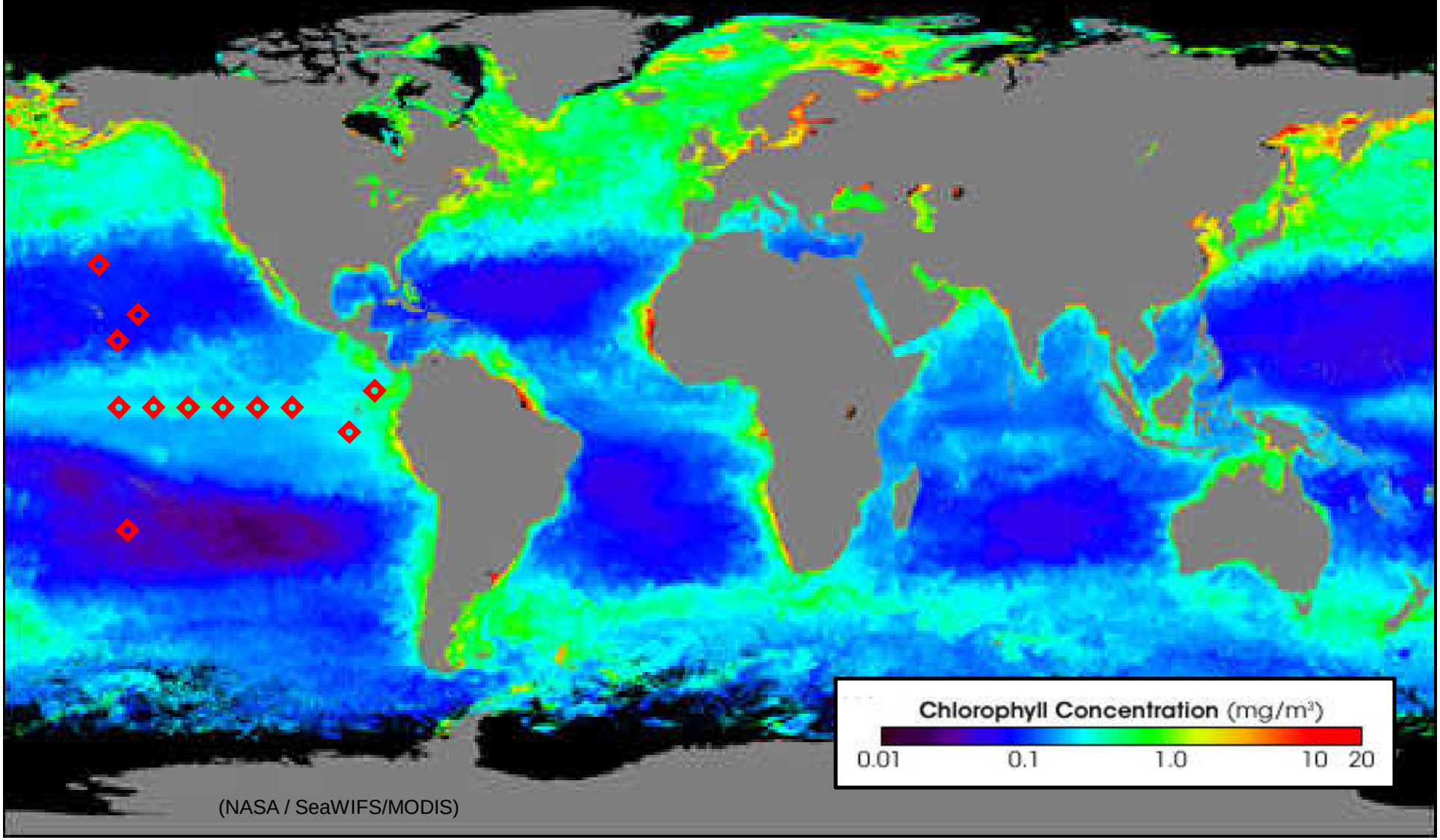
   ⟶ Secondary priority; Objective C (all Investigations)

Some observations about habitability . . .

(from the one place we can say something about the distribution of life in relation to its environment)

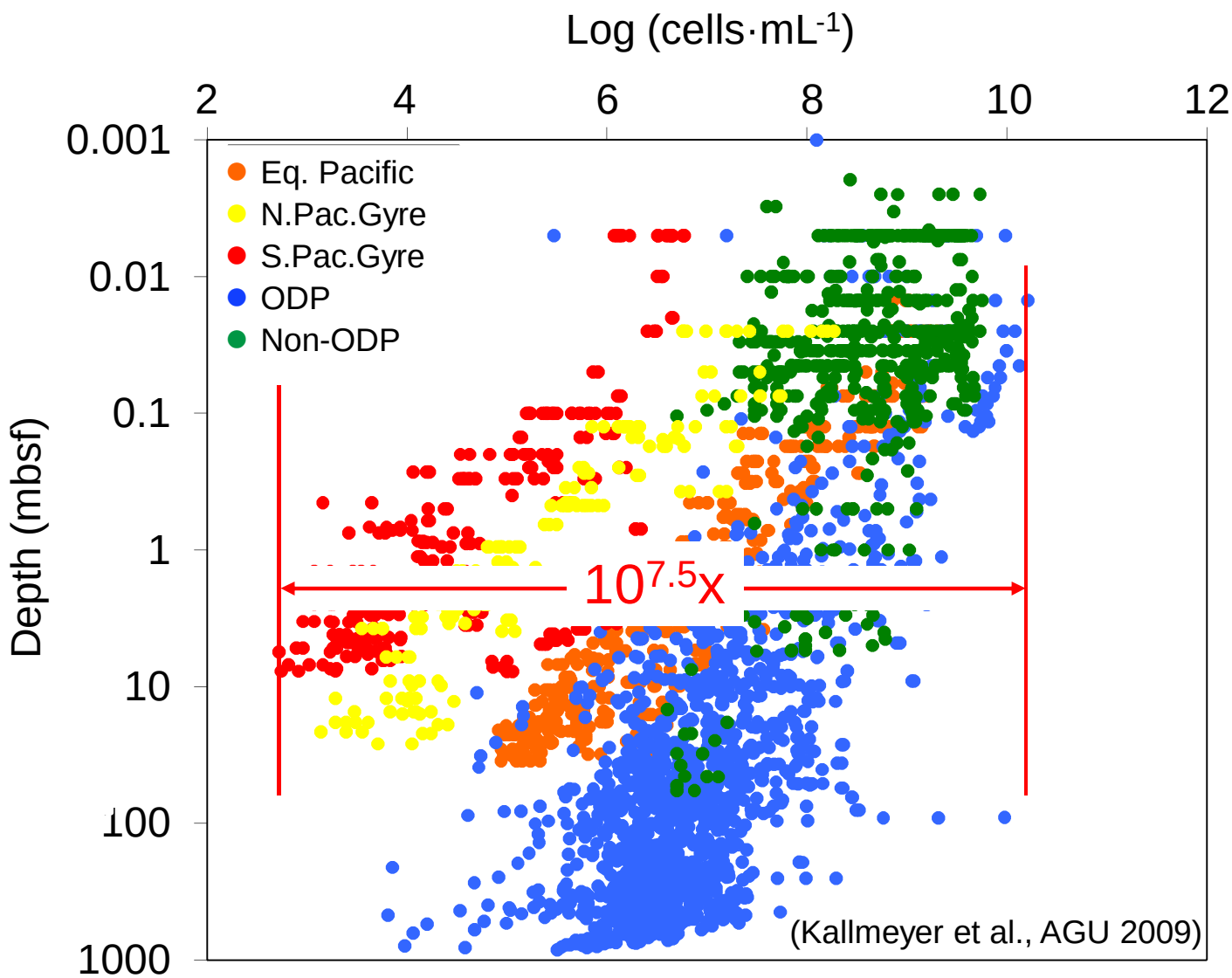
Biomass Density: African Land Cover

(Photosynthetic) Biomass Density: Ocean Surface



(NASA / SeaWIFS/MODIS)

Biomass Density: Pacific Ocean Sediments



Investigation A.1

Characterize prior habitability, with a focus on resolving more habitable versus less habitable sites

1. Establish overall geologic context.
2. Constrain prior water availability with respect to duration, extent, and chemical activity.
3. Constrain prior energy availability with respect to type (e.g., light, specific redox couples, etc.), chemical potential (e.g., Gibbs energy yield), and flux.
4. Constrain prior physicochemical environment, emphasizing temperature, pH, and water activity and chemical composition.
5. Constrain the abundance and characterize potential sources of bioessential elements.

Investigation B.1

Identify and characterize any presently habitable environments

1. Identify areas where liquid water presently exists, placing particular emphasis on reservoirs that are relatively extensive in space and time.
2. Establish general geologic context (e.g., rock-hosted aquifer or sub-ice reservoir; host rock type; etc.)
3. Identify and constrain the magnitude of possible energy sources (e.g., water-rock reactions, radiolysis) associated with occurrences of liquid water.
4. Assess the variation through time of physical and chemical conditions in such environments. Of particular importance are temperature, pH, and fluid composition.
5. Identify possible supplies of bioessential elements to these environments.

Objective C

Determine how the long-term evolution of Mars affected prebiotic chemistry and habitability

1. Characterize the evolution of the Martian hydrological cycle, emphasizing likely changes in the location and chemistry of liquid water reservoirs.
2. Constrain evolution in the geological, geochemical, and photochemical processes that control atmospheric, surface, and shallow crustal chemistry, particularly as it bears on provision of chemical energy and recycling and mobilization of bioessential elements.
3. Constrain the nature and abundance of possible energy sources as a function of changing water availability, geophysical and geochemical evolution, and evolving atmospheric and surface conditions.
4. Evaluate the presence and magnitude of oxidative or radiation hazards at the surface and in the shallow crust.

GOAL 1: LIFE

Preservation potential and life detection

- Objective A: Characterise past habitability and search for evidence of ancient life
- Objective B: Characterise present habitability and search for evidence of extant life

- Biosignatures
- Preservation
- Investigations for Mars

BIOSIGNATURES

Characteristics of life:

Cell components – complex organic molecules making up the different parts of cells

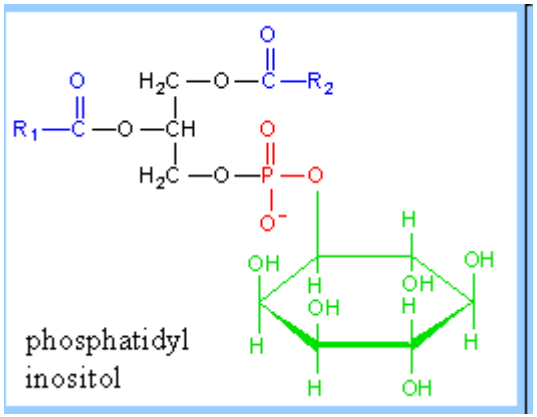
Metabolic activity – different strategies for living processes

Physical structures – cells →communities etc.

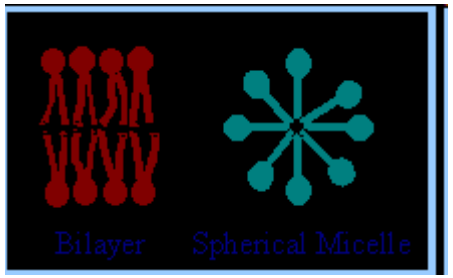
Biosignatures

Microbial components	Biosignature	Specific component or structure	
Cell components	***carbon molecules (kerogen)***	composition	Elemental, molecular (complex-degraded)
		structure	complexity (odd/even ratio)
			µ-structure

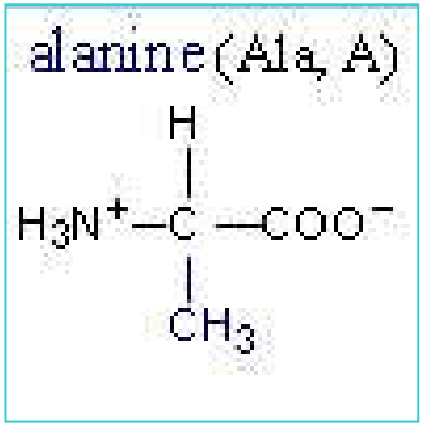
Composition:
- Complex molecules, e.g. lipids, proteins

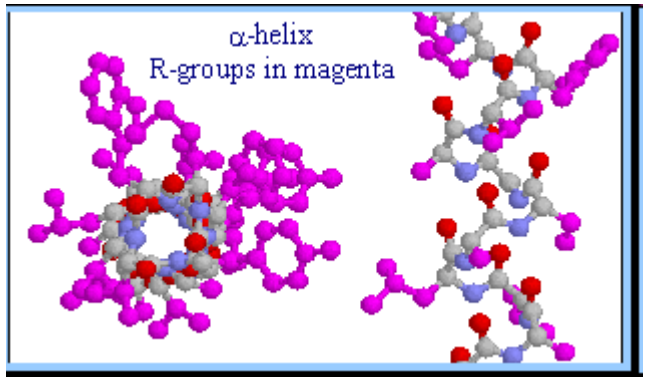


lipids

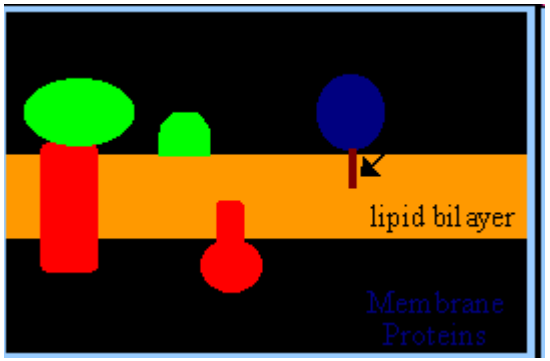


amino acids





proteins



Biosignatures

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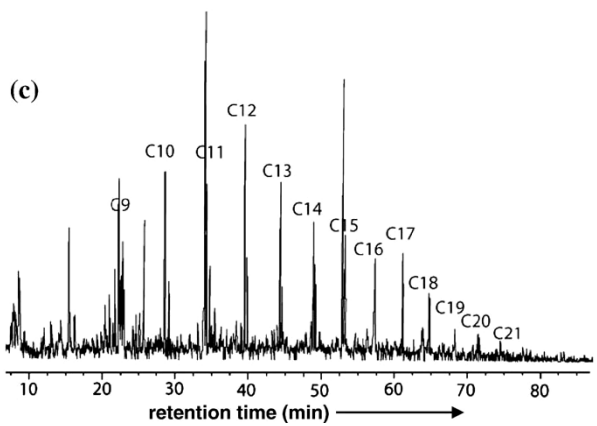
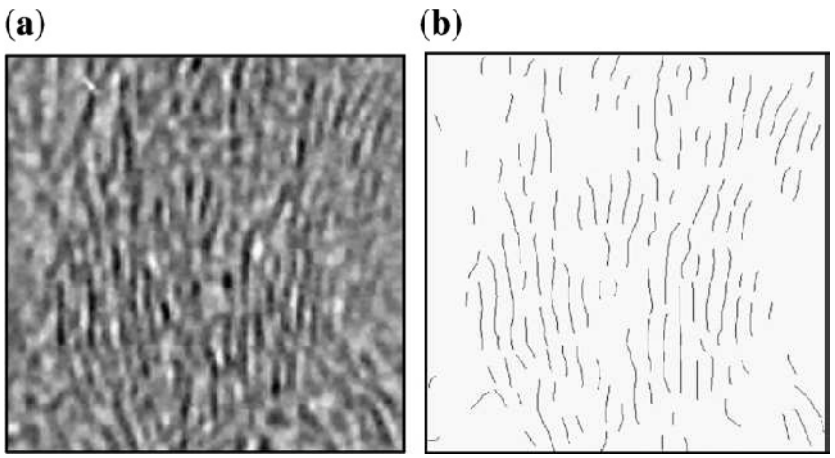
Cell components	***carbon molecules (kerogen)***	composition	Elemental, molecular (complex-degraded)
		structure	complexity (odd/even ratio)
			µ-structure

Composition:
- Complex molecules, e.g. lipids, proteins → degradation →kerogen



odd/even C numbers



1 nm leaflets = small aromatic molecules (edge on)

Derenne et al., 2008

Biosignatures

Microbial components	Biosignature	Specific component or structure	
Cell metabolic activity	***Elements***	Fractionated stable isotopes	C, O, S, N, P, Fe…
		concentration	Ni, Cu, Mn, Co, Mo, Se, V, Fe
	Biominerals/ microbial influence on minerals	direct precipitation biominerals (e.g.magnetite)	
		indirect precipitation biominerals (e.g.aragonite, dolomite)	
		Mineral composition	
		Mineral habit	
		Mineral dissolution	
		Mineral size	

Extant life

- Live/dead tests
- DNA staining
- Metabolic activity tests
- Transformation process rates
- ……..

Westall & Cavalazzi 2010

Biosignatures

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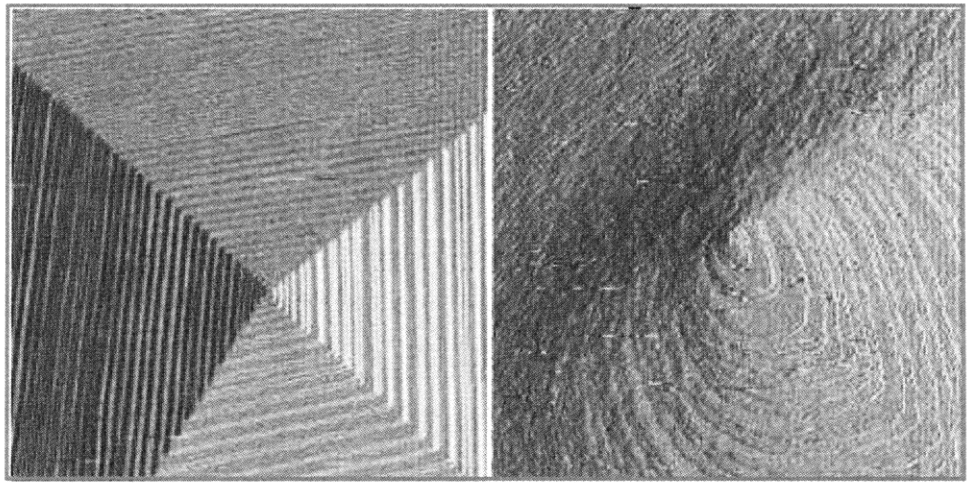
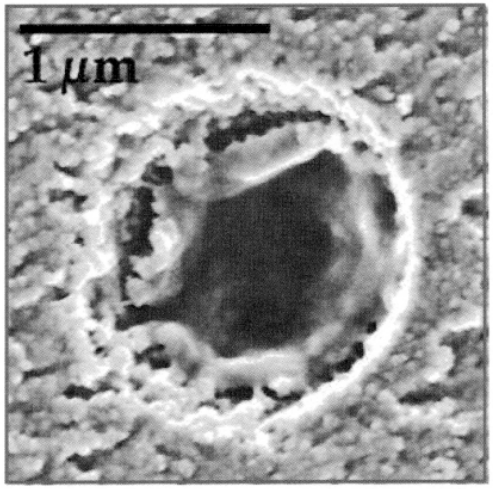


Crystal habit

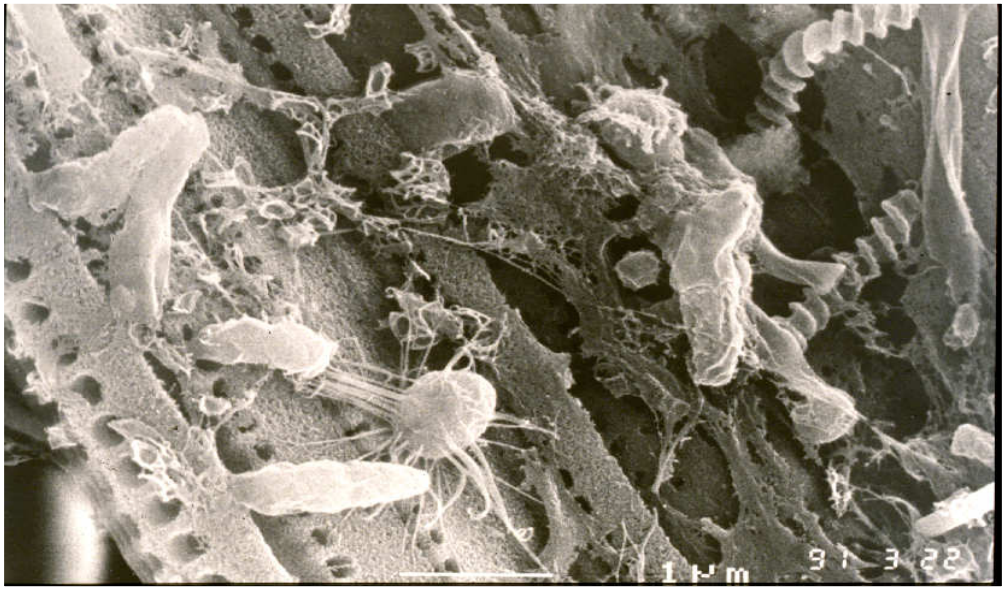
Banfield et al 2001

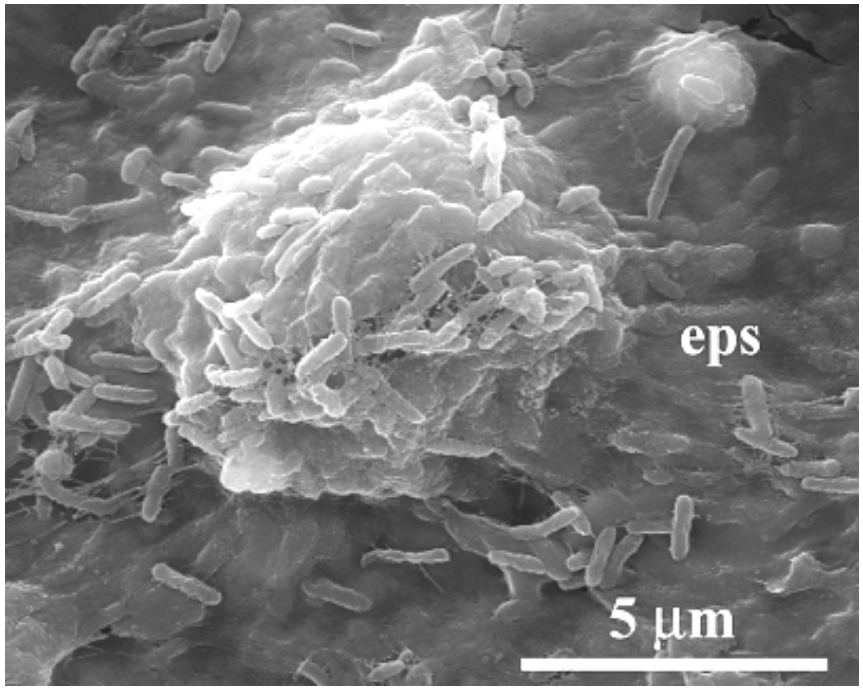


Microbial corrosion

Biosignatures

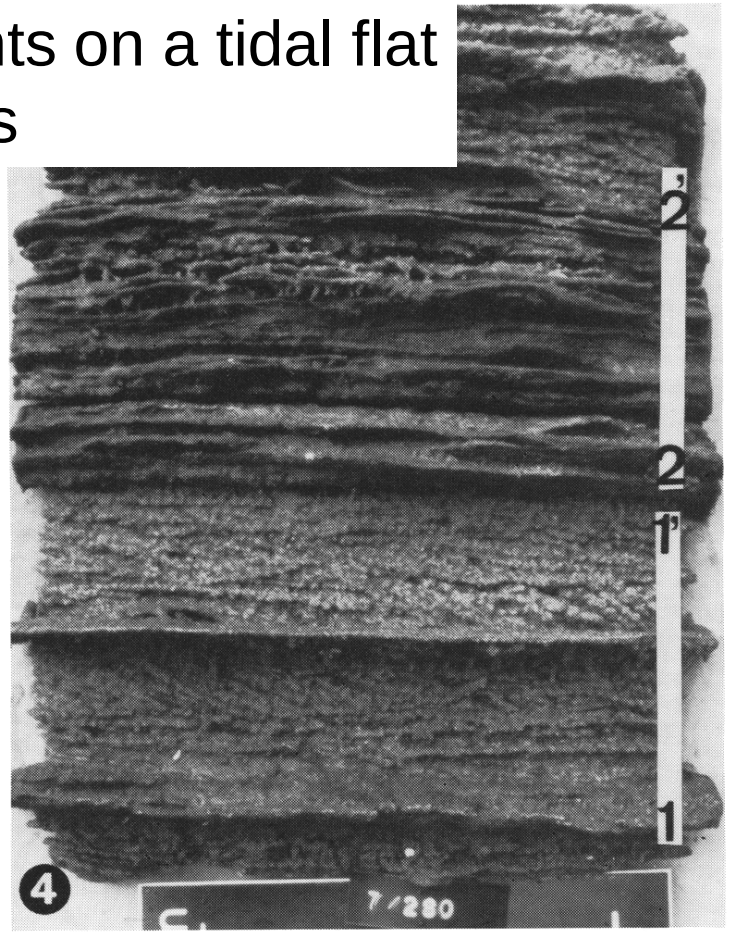
Microbial components	Biosignature	Specific component or structure	
Physical structures	***Fossil cells, colonies, mats***	Cells	
		Colonies	
		Biofilms/mats	
		stromatolites	
		MISS	
		clotted fabrics	

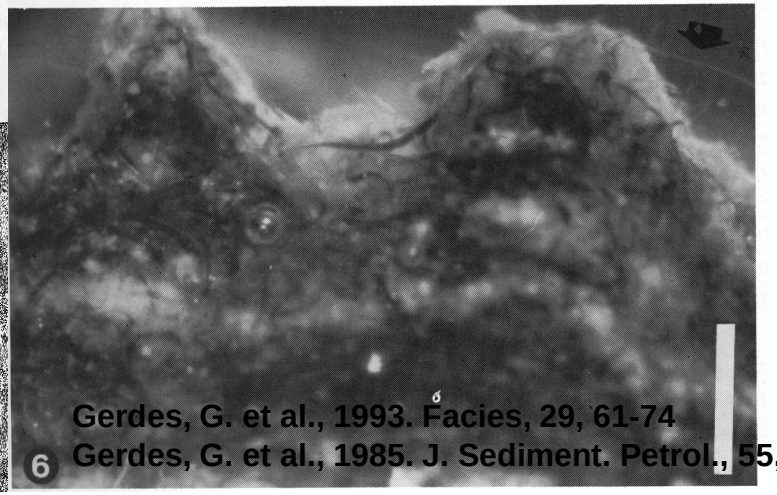




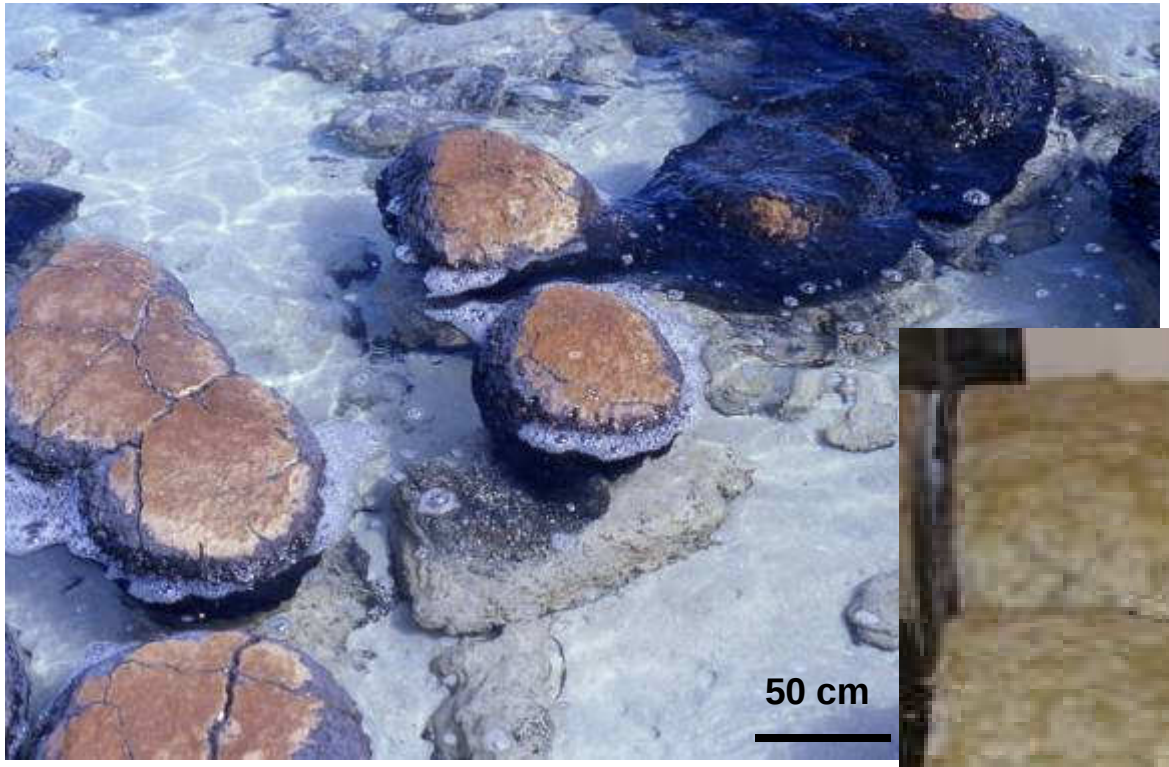
Westall et al., 2001

Modern biolaminated sediments on a tidal flat - Microbial mats





Gerdes, G. et al., 1993. Facies, 29, 61-74
Gerdes, G. et al., 1985. J. Sediment. Petrol., 55, 265-278



Modern stromatolites, Shark Bay, Australia

Biosignatures – past life

- **Problems with organic biosignatures:**
  - very old or metamorphosed kerogens consist of highly degraded molecules
  - younger contamination (terrestrial problem)

- **Problems with signatures of metabolic activity**
  - isotope fractionation by abiogenic processes (e.g. Fischer Tropsch synthesis of C with ~ -26‰)
  - abiogenic mineral precipitation
  - abiogenic leaching of elements (e.g. acid fumeroles)

- **Problems with physical structures:**
  - abiogenic minerals can imitate simple cellular structures
  - abiogenic sediment lamination

N.B. In many cases abiogenic and biogenic processes operate simultaneously

→ **Need a multi-scale, multidisciplinary approach**

Preservation of traces of life

➢**Preservation of organics**

- Chemical, radiolytic degradation
  → protection from oxidation (in presence of H_2O, FeIII minerals, H_2O_2)
  → protection from radiation (UV, ionising, radiolytic decay)

-Rapid racemization of chiral moelcules in presence of water

- Preservation through restructuring of molecules → resistant cross-linked macromolecules (aliphatic, aromatic)

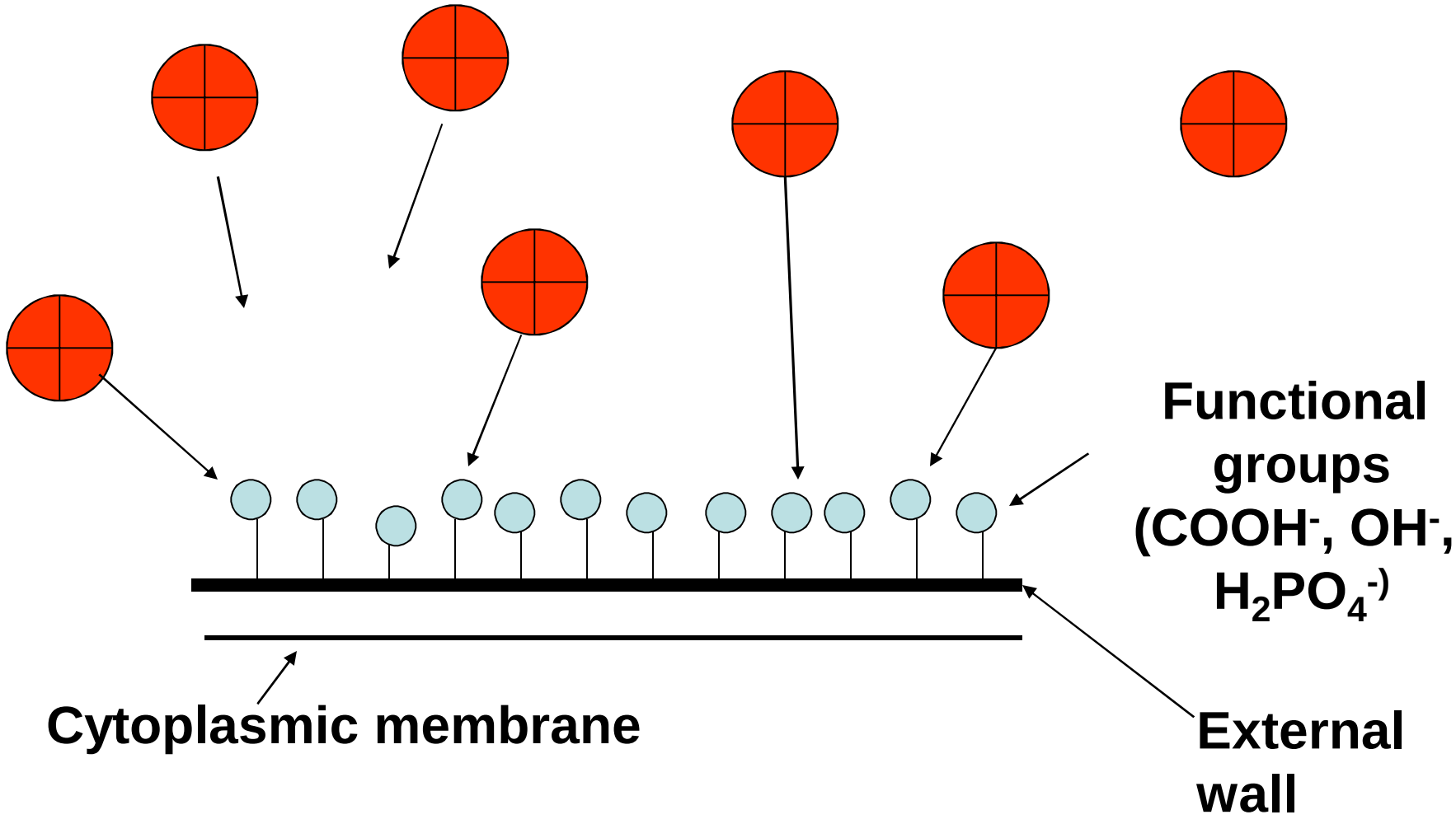
→ Encasing the organics in a protective (stable) mineral matrix

➢ **Preservation of metabolic signatures – in rocks**
- Metamorphism (thermal) → lighter isotopes
- Dissolution/destruction of signatures preserved in minerals

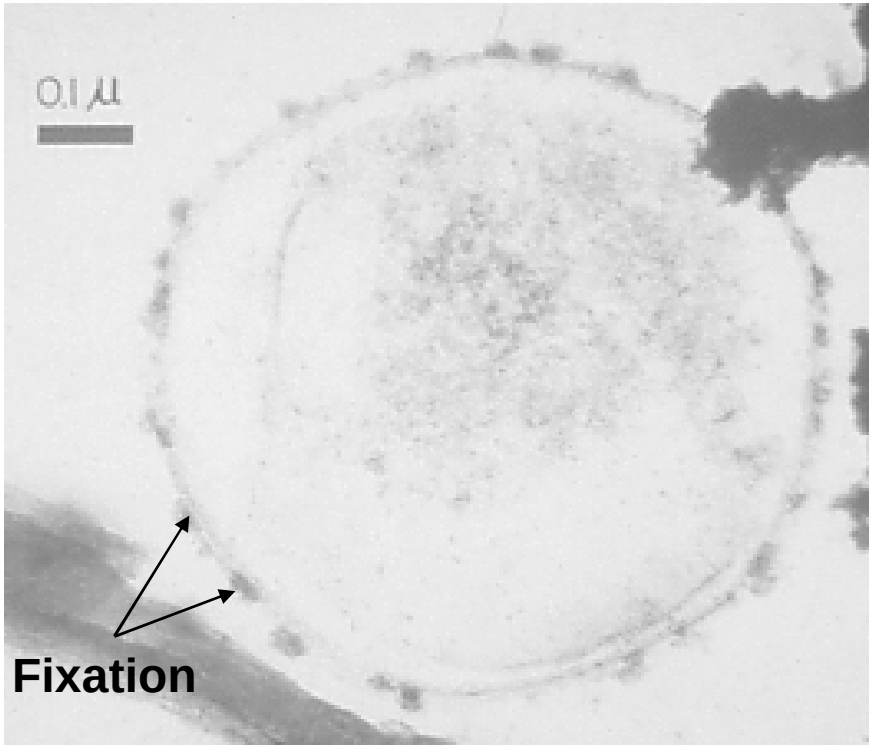
➢ **Preservation of soft-bodied microorganisms**
- Rapid fossilisation/burial for preservation of cellular structures

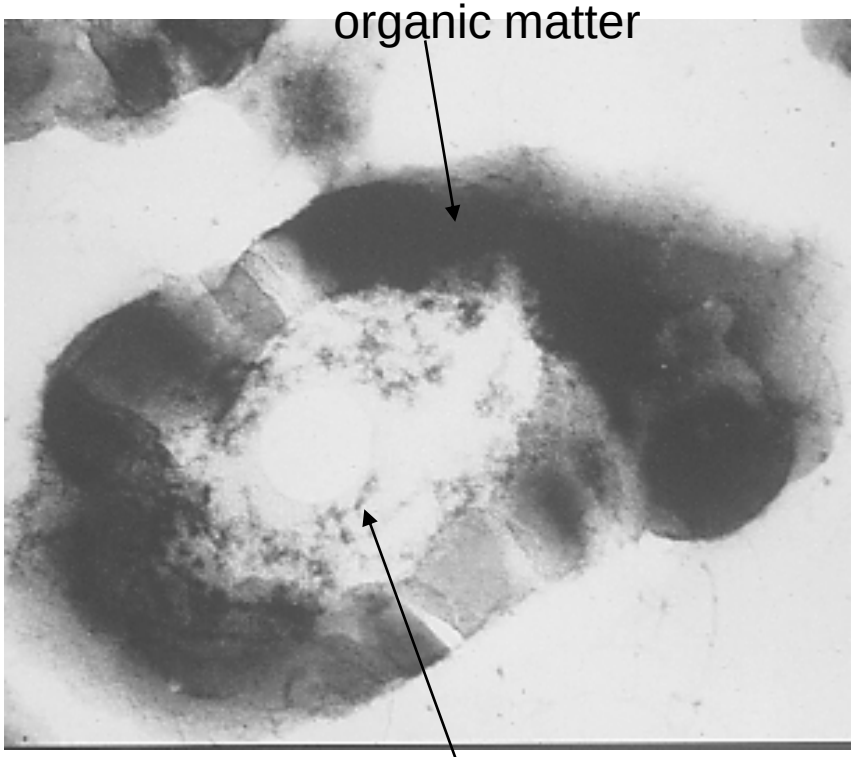
The fossilisation of bacteria

Fixation of ions (SiO^{2-}, $Ca^{2+}CO_3^{2-}$….) to functional groups in the organic substrate



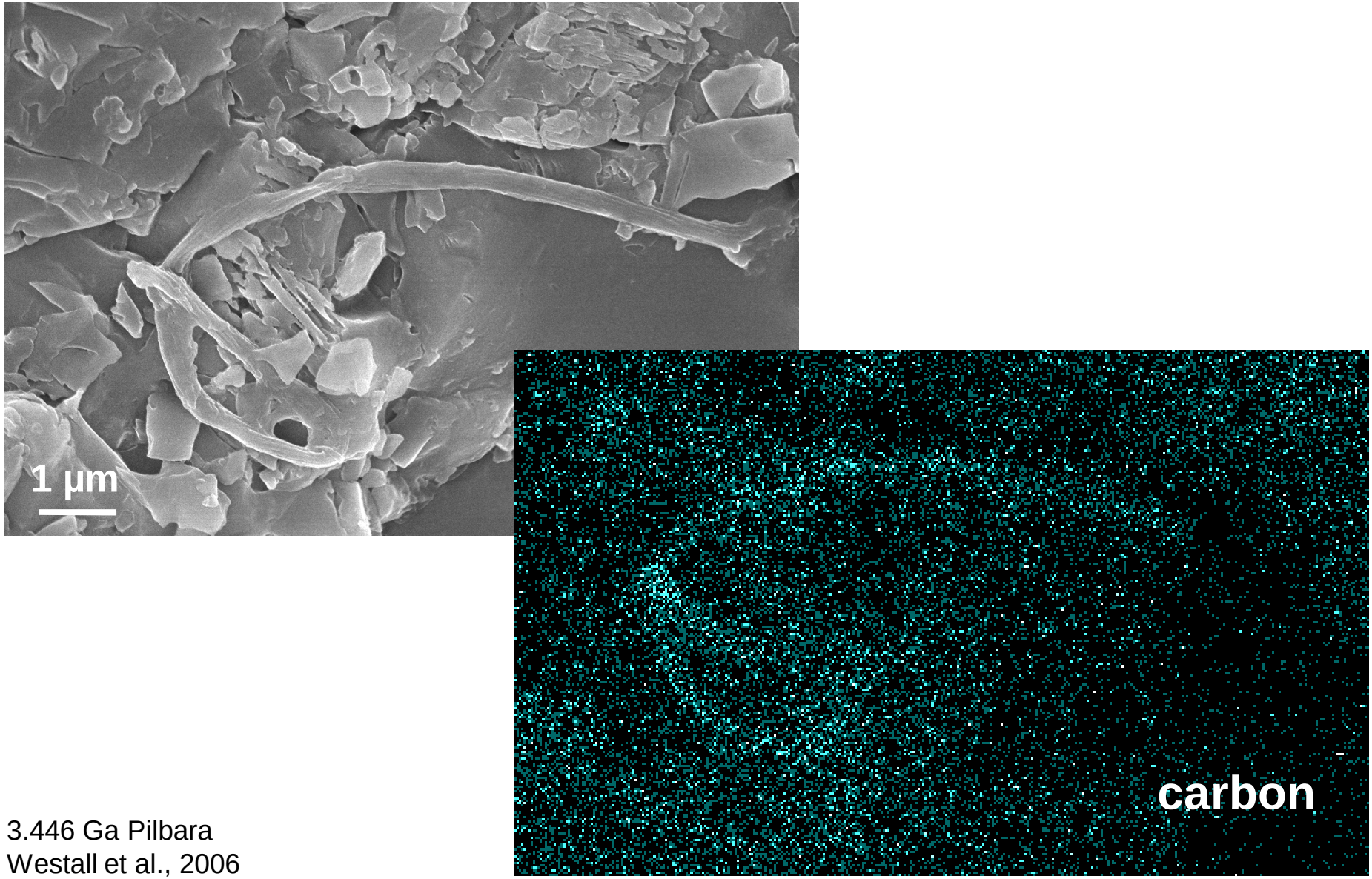
Fossilisation of bacteria





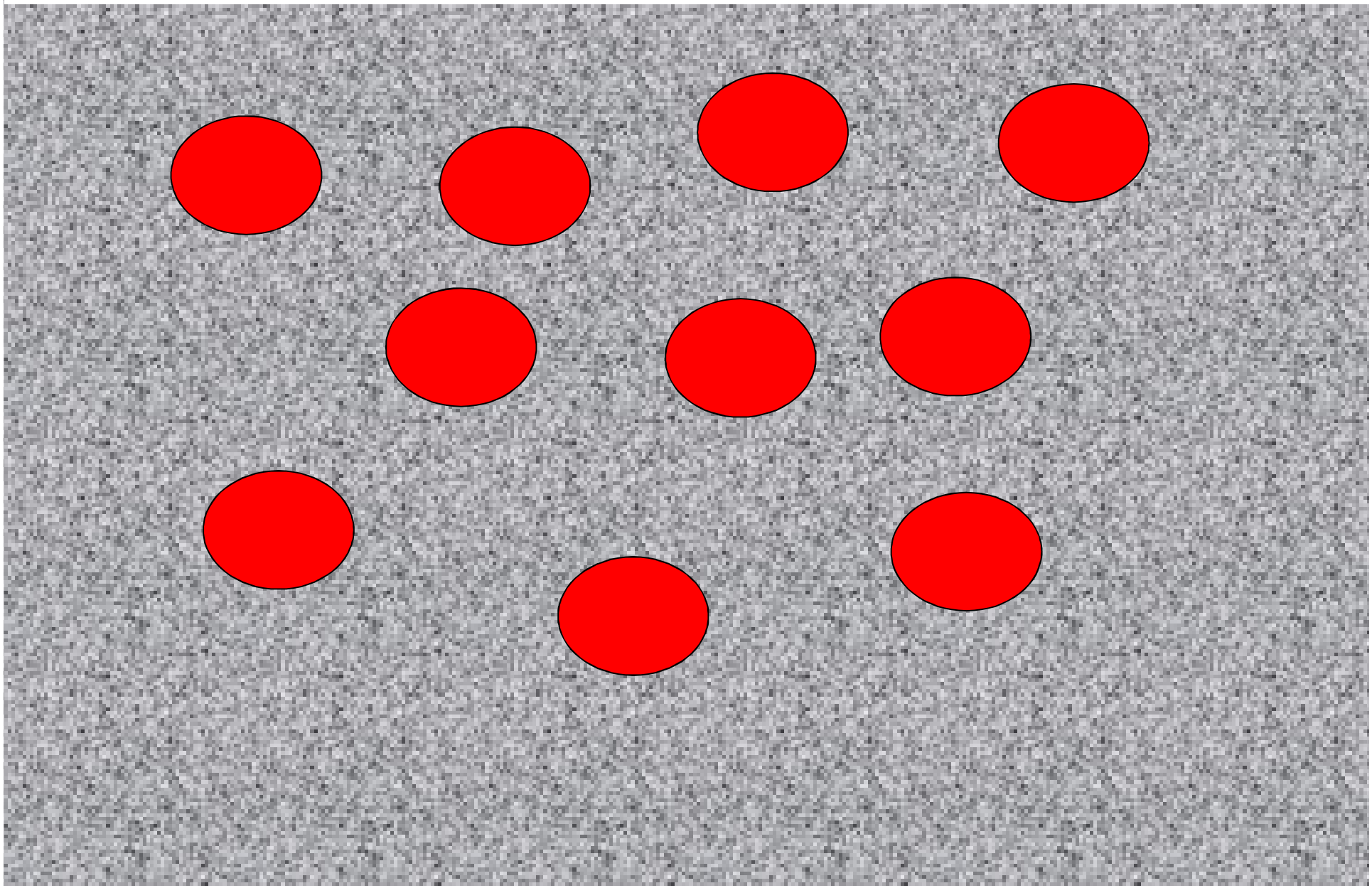
Westall et al., 1995

Fossilised microbial filament (carbonaceous)



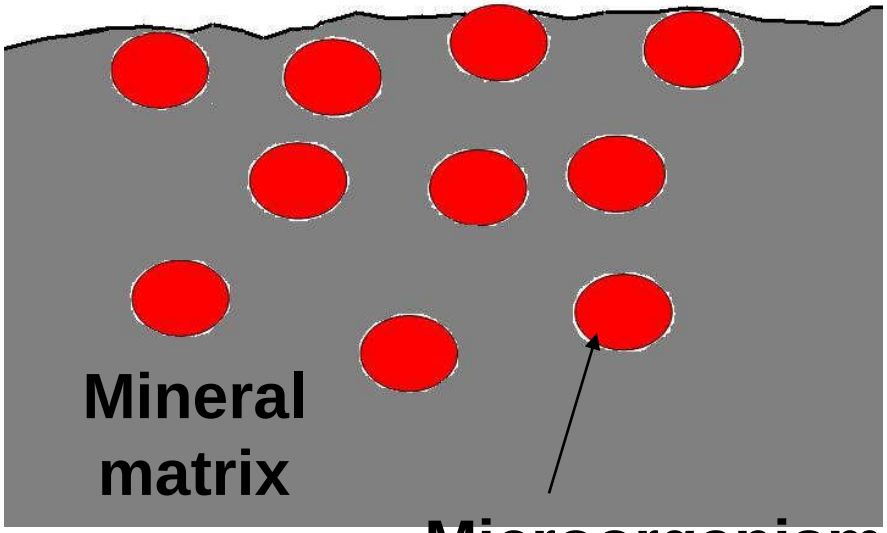
3.446 Ga Pilbara
Westall et al., 2006

Schematic representation of fossilised coccoidal microorganisms in a mineral matrix



Acid etching

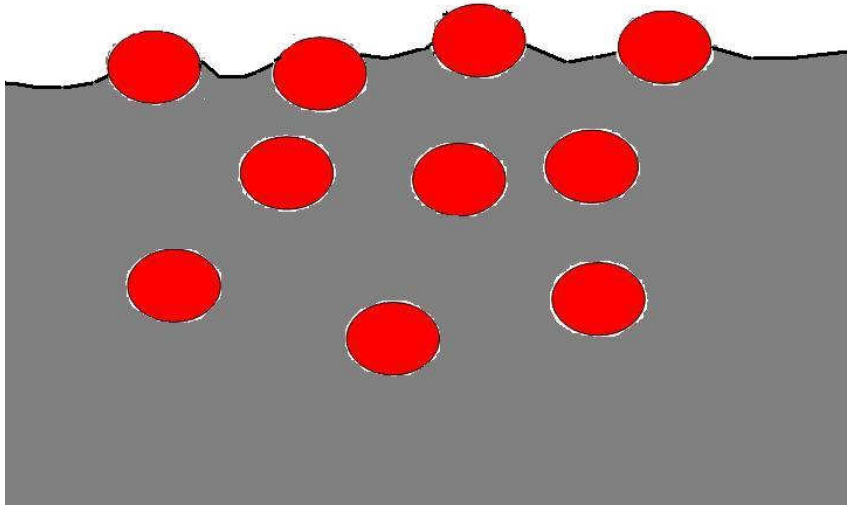
Rock surface



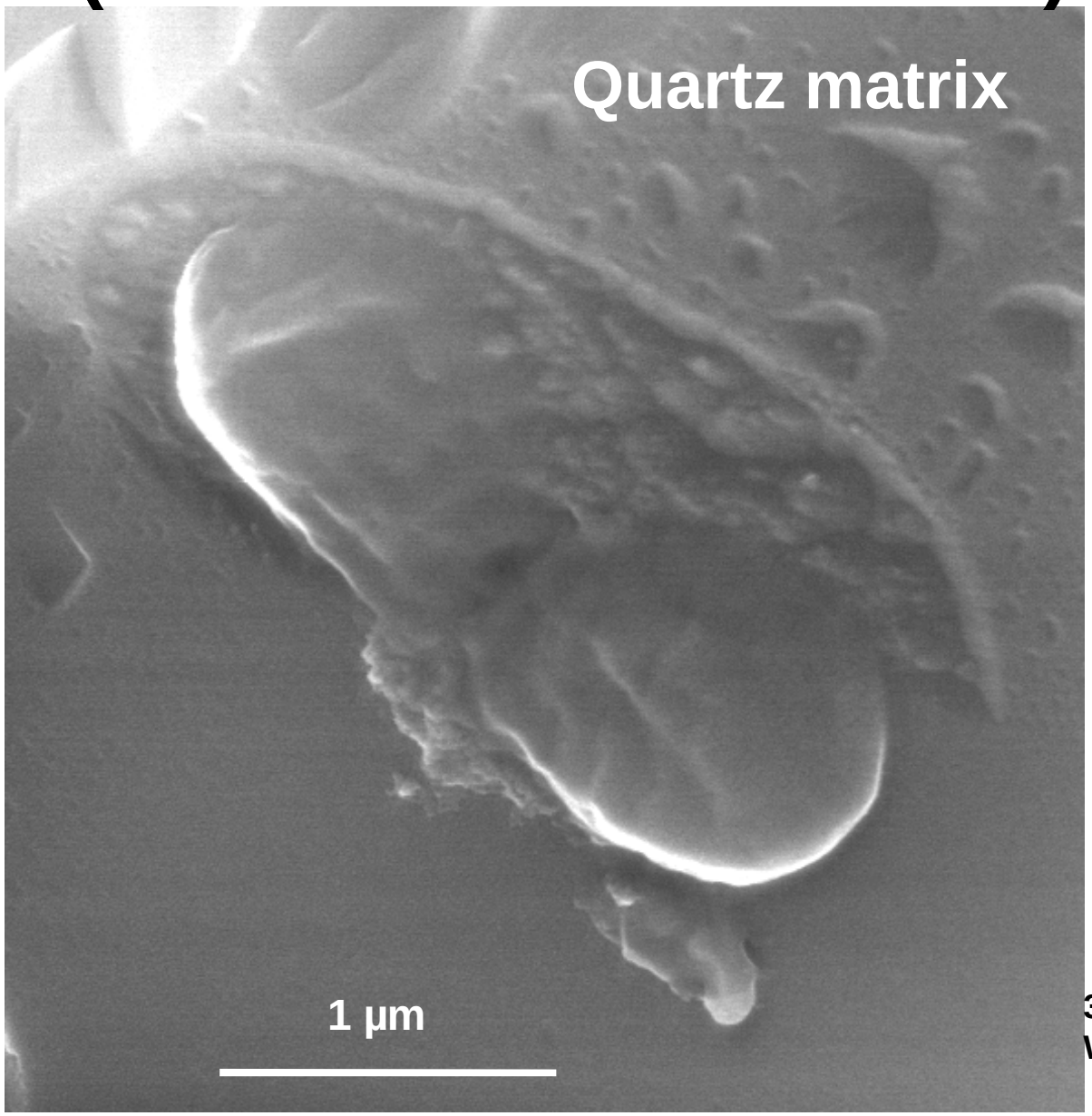
Microorganism
(=organic C plus
mineral coating)

BEFORE

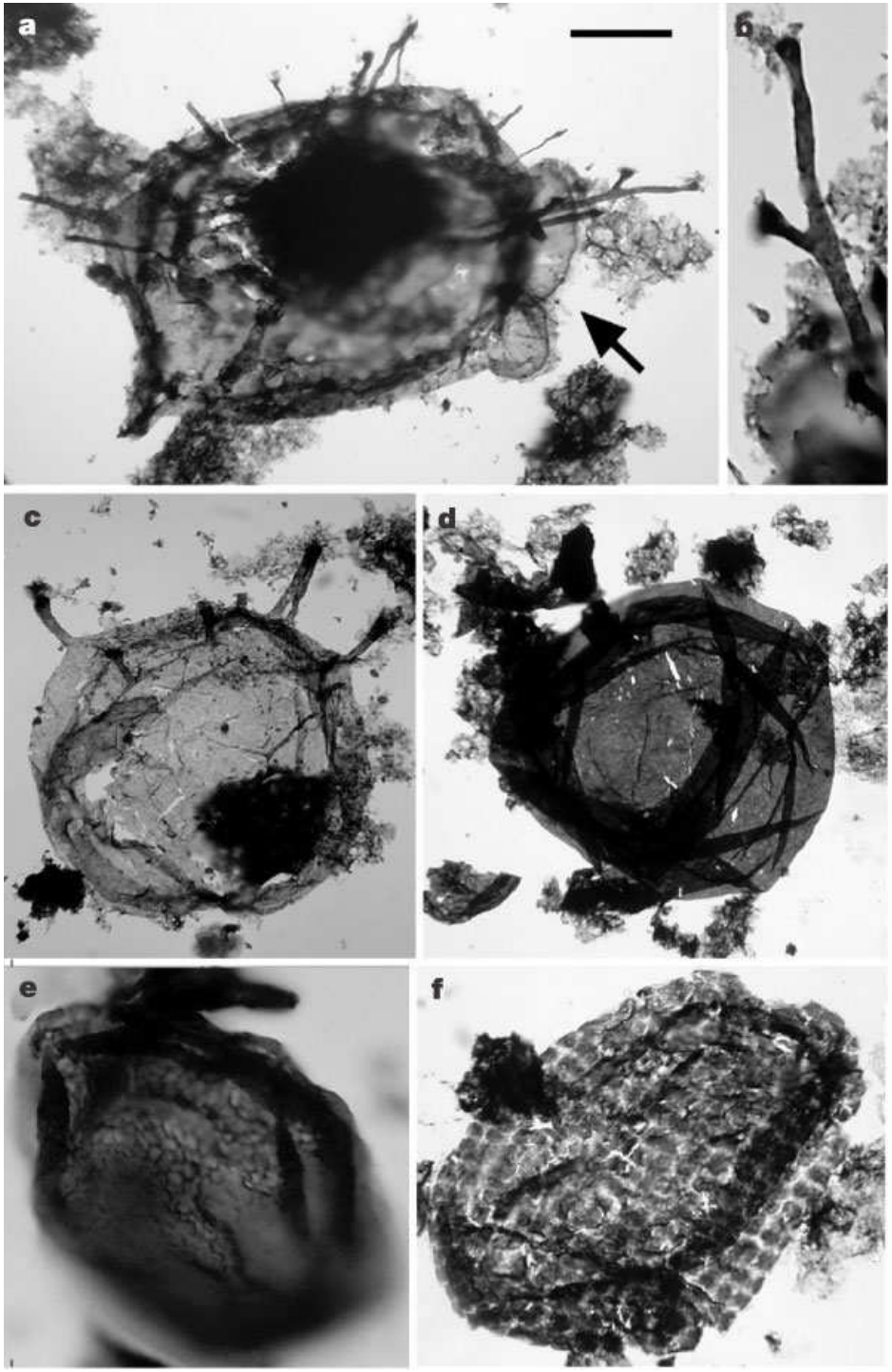
AFTER



Dividing coccoids (observation with HR-SEM)



3.42 Ga Barberton
Westall, 2010



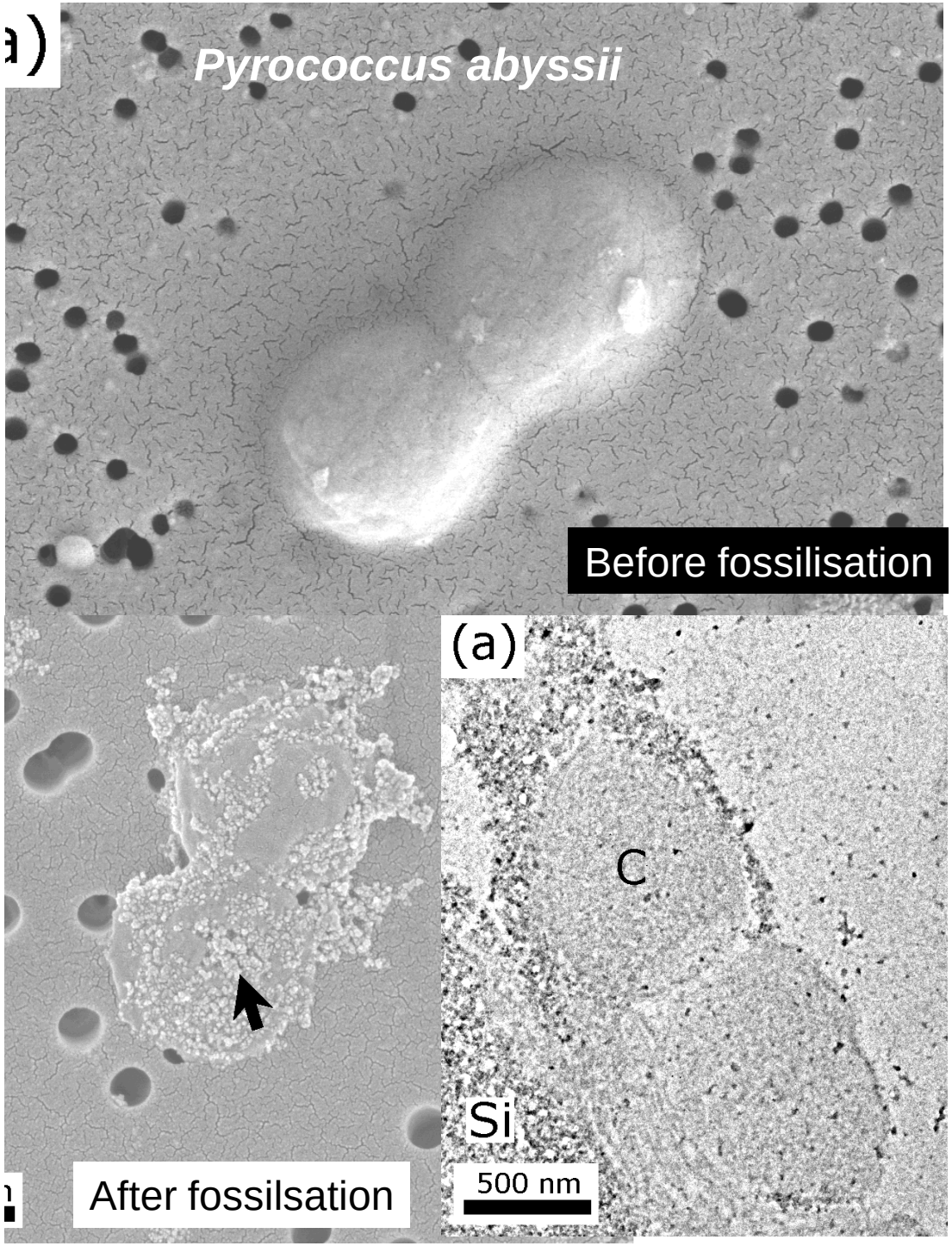
Compressed carbonaceous fossils preserved in fine grained sediments

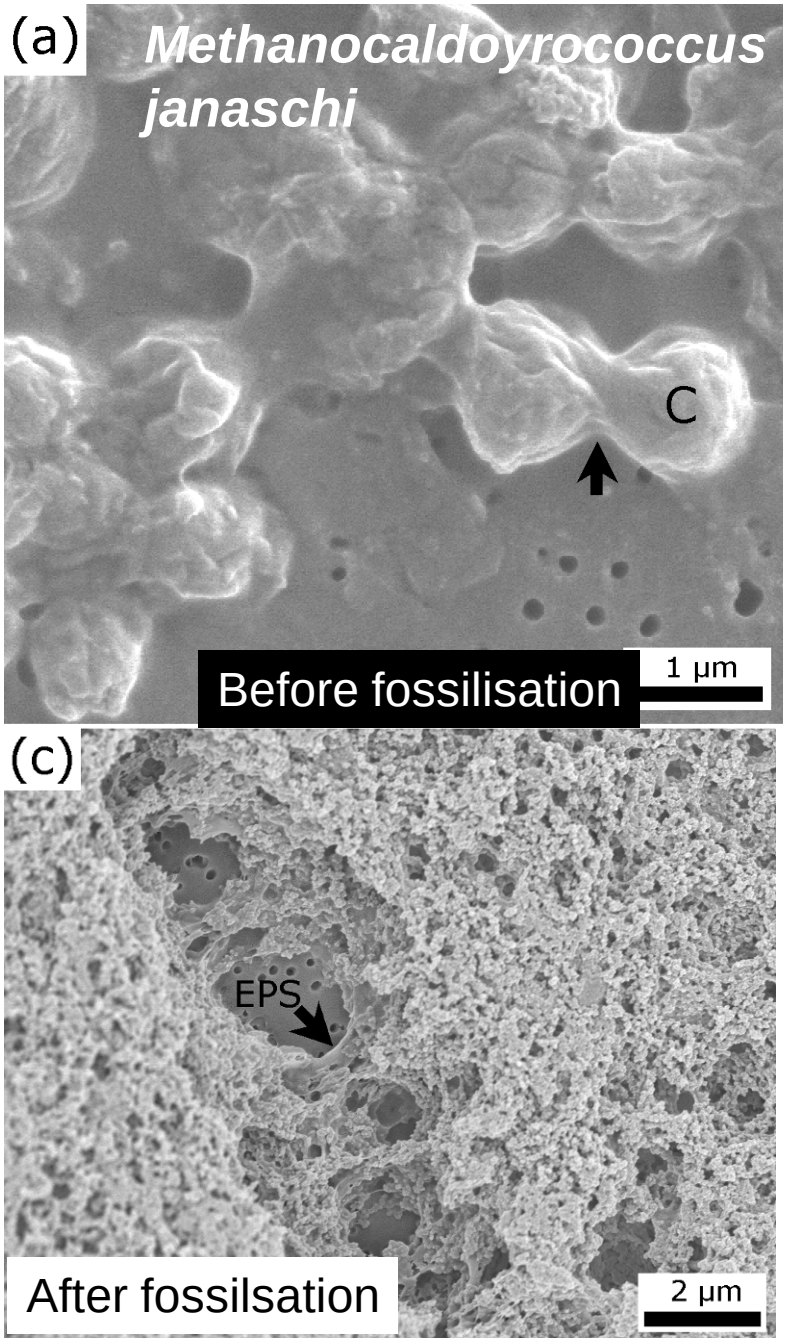
Javaux et al., 2001

Preservation of ancient traces of life

- The organisms need to be rapidly preserved
  --> Rapid fossilisation/burial for soft bodied structures

- Not all organisms in a community are preserved/can be preserved
  → Chemoorganotrophs use dead organisms a carbon source, *i.e.* organisms are degraded before they can be preserved
  → Some microbes lyse very rapidly before they can be fossilised
  e.g. thermophilic Archaea
  Pyrococcus abyssii
  Methanocaldococcus janaschi





Orange et al., 2009

Preservation of ancient traces of life

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- Not all organisms in a community are preserved/can be preserved
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  → Some microbes lyse very rapidly before they can be fossilised

- The sediments/rocks with which the fossilised microorganisms are associated need to be preserved from:
  - excessive metamorphism (maximum lower greenschist < 250℃)
  - plate tectonic destruction of the crust
  - erosion

- The fossiliferous rocks need to be exposed sufficiently for study

GOAL 1: INVESTIGATIONS

GLOBAL INVESTIGATION STRATEGY

1. Context
- field context
- hand specimen/thin section study
  → environment of formation = habitability
- diagenetic/metamorphic history of the host rocks

2. Biosignatures
- organic
- metabolic
- physical

3. Interpretation
- biogenicity
- information about the microorganisms
  - metabolic strategies
  - interaction with the environment

GOAL 1: INVESTIGATIONS

- Objective A: Characterise past habitability and search for evidence of ancient life

3. Search for evidence of ancient life in environments having high combined potential for prior habitability and preservation of biosignatures

3.1. Characterise organic chemistry, including where possible stable isotope composition and stereochemical information. Characterise co-occurring concentrations of possible bio-essential elements.

3.2. Seek evidence of possibly biogenic physical structures from microscopic (micron scale) to macroscopic (meter scale), combining morphological, mineralogical, and chemical information where possible.

3. 3. Seek evidence of past conduct of metabolism, including: stable isotope composition of prospective metabolites: mineral or other indicators of prior chemical gradients: localised concentrations or depletions of potential metabolites (especially biominerals: and evidence of catalysis in sluggish

GOAL 1: INVESTIGATIONS

- Objective B: Characterise present habitability and search for evidence of extant life

3. Search for evidence of ancient life in environments having high combined potential for prior habitability and preservation of biosignatures

3.1. Seek evidence for ongoing metabolism in the form of rapid catalysis of chemically sluggish reactions, stable isotope fractionation, and strong chemical gradients. Seek biogenic gases, which have potential to migrate from potentially habitable deep subsurface environments to surface environments where they may be accessibme to remote or *in situ* characterisation.

3.2. Characterise organic chemistry and co-occurring concentrations of bioessential elements, including stable isotopic composition and stereochemistry. Analayses may includ but should not be limited to known molecular biomarkers of terrestrial life, such as membrane lipids, proteins, nucleic acid polymers, and complex carbohydrates.

3. 3. Seek evidence of organic and mineral structures or assemblages that may be associated with life. Seek evidence of mineral transformations bearing evidence of biological catalysis (e.g. depletion of possibly bio-essential elements in mineral surfaces