Earth’s earliest records of life

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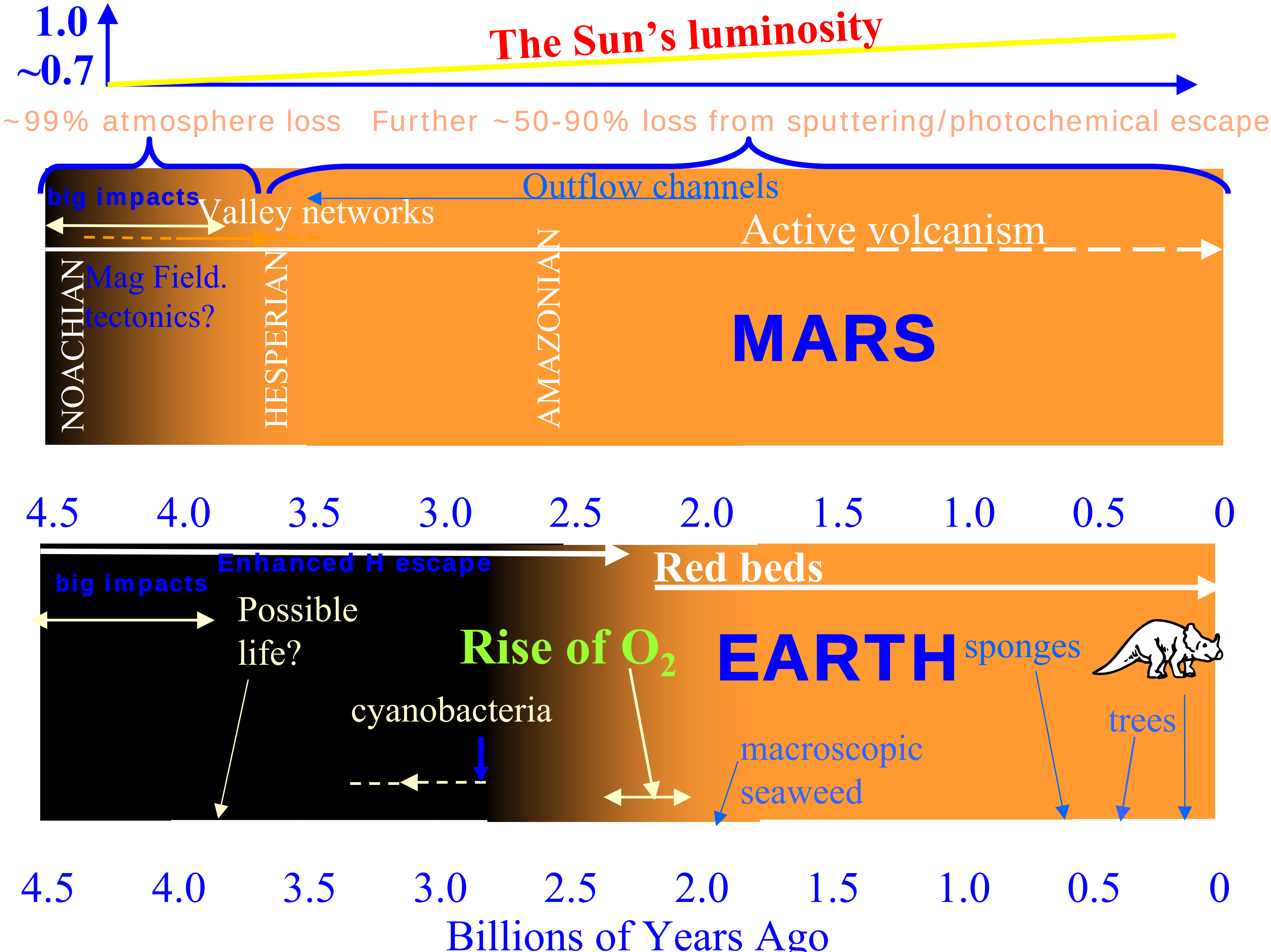
Early Earth versus Mars

Questions:

- **Was Mars inhabited early in its history?**
- **If so, are early Earth fossils and their habitats good analogues?**

Answer:

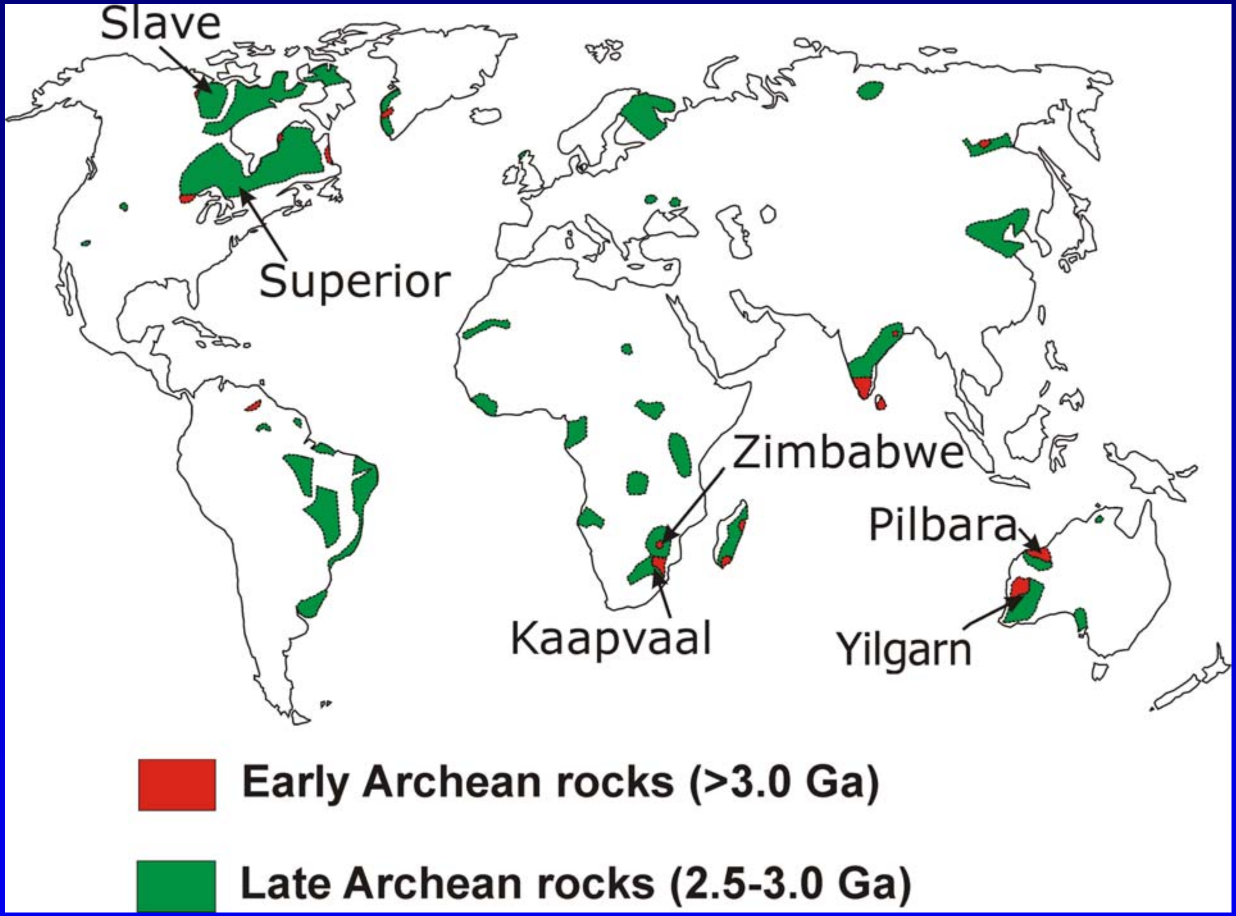
- **Assuming that Mars was inhabited, early Earth fossils are their best available analogue, and anything else is speculation.**


1.0
~0.7
The Sun's luminosity
~99% atmosphere loss
Further ~50-90% loss from sputtering/photochemical escape
big impacts
Valley networks
Outflow channels
Active volcanism
Mag Field.
tectonics?
NOACHIAN
HESPERIAN
AMAZONIAN
MARS
4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0
Enhanced H escape
big impacts
Red beds
Possible
life?
Rise of O2
EARTH
sponges
cyanobacteria
trees
macroscopic
seaweed
4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0
Billions of Years Ago

This talk

- Review the types of fossil evidence for the earliest life on Earth, with some examples
- Discuss the geological settings where they occur
- Consider how they can be preserved or destroyed
- Present the sorts of prior information needed in order to find them

Early Earth Rocks

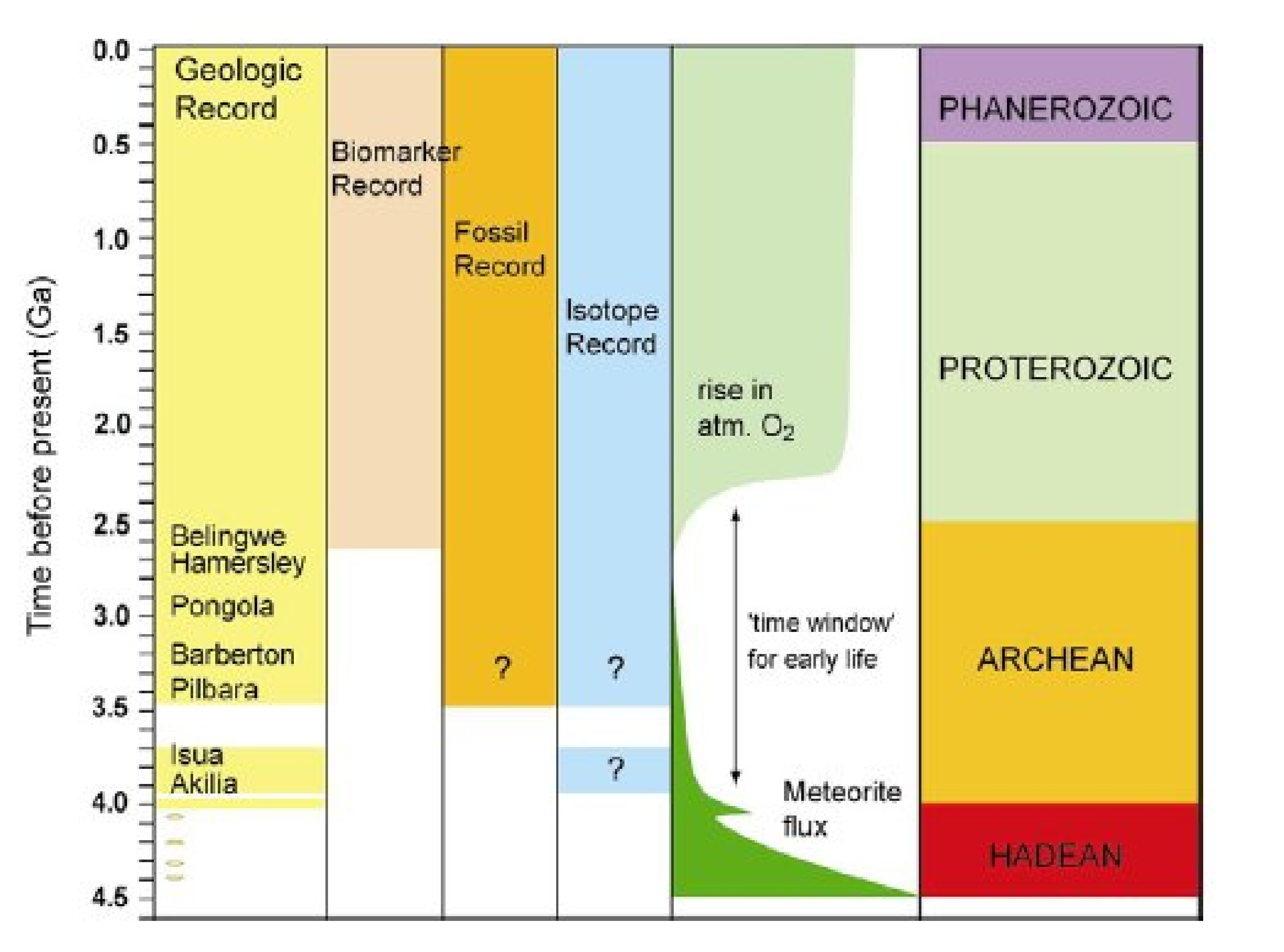


Distribution of Archean rocks

Problem: Old rocks are rare on Earth, mostly poorly preserved because of metamorphism, deformation and inadequate exposure, and so signs of primordial life are hard to find and even more difficult to interpret

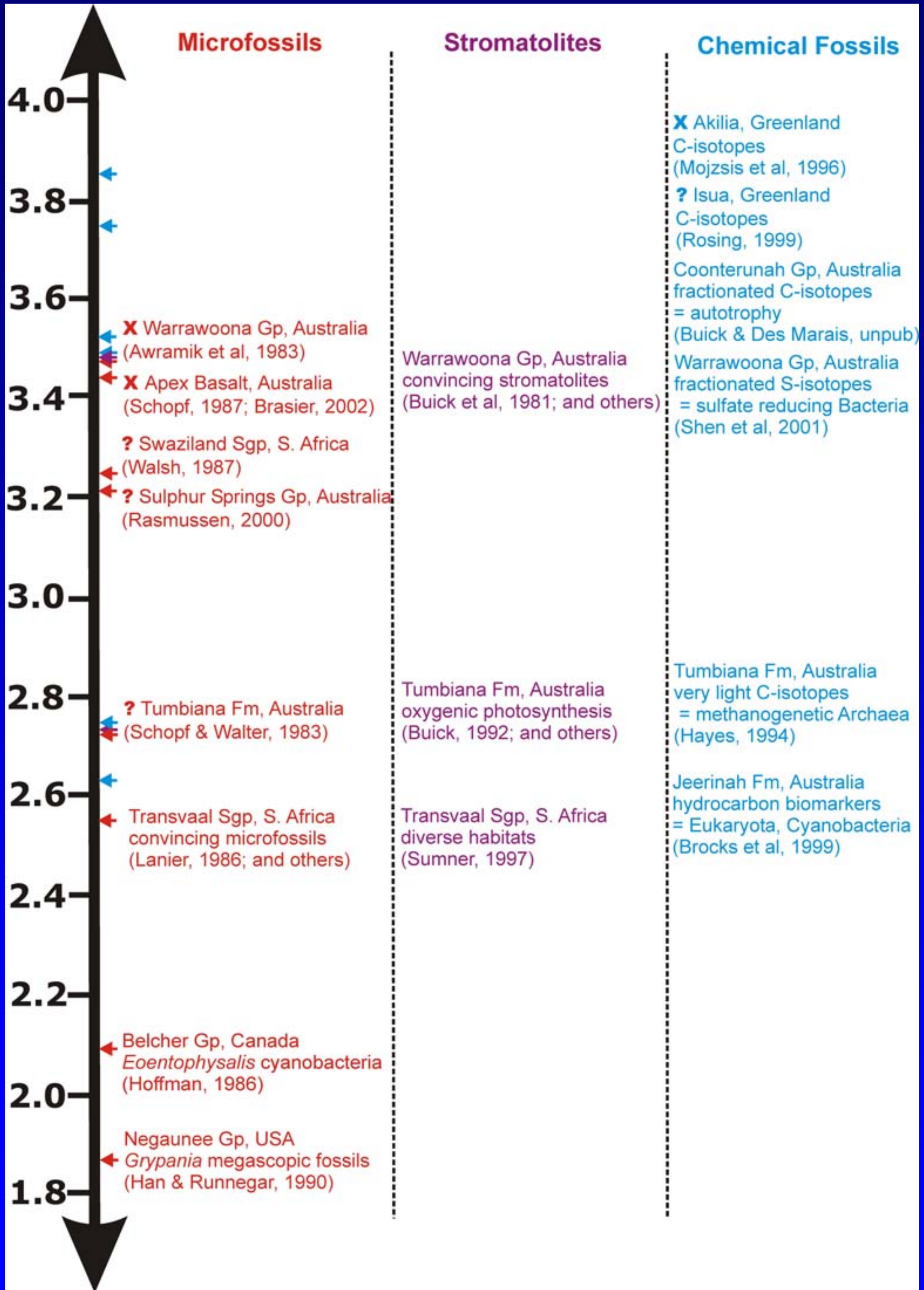
Early Earth

- Only a few significant Archean fossil localities



Archean Fossil Record

- Archean has a fairly diverse but quite controversial fossil record
- Doubts about age or biogenicity

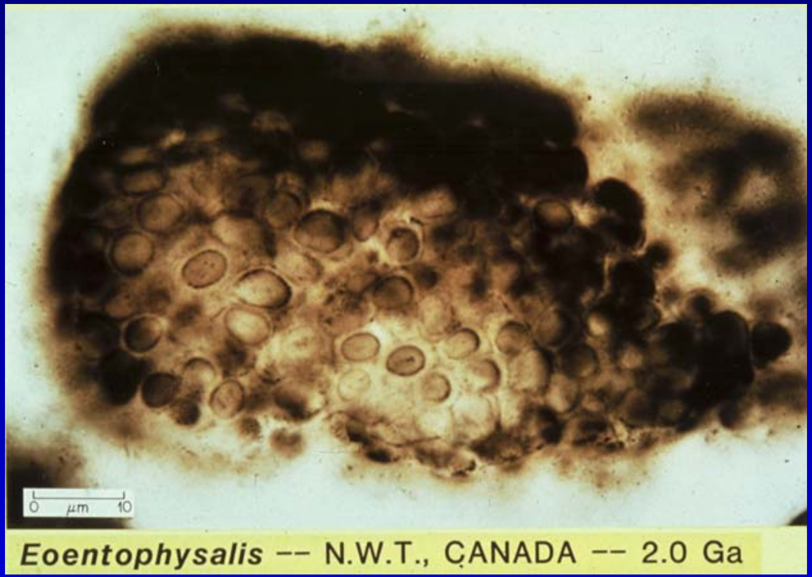


Types of evidence of early life

- MICROFOSSILS: preserved remains of microbial bodies (*body fossils*)
- STROMATOLITES, ONCOLITES, MISS : preserved remains of microbial activities (*trace fossils*)
- BIOMARKERS: preserved remains of microbial molecules (*molecular fossils*)
- ISOTOPES: preserved relics of microbial metabolism (*atomic fossils*)
- BIOMINERALS: preserved remains of microbial mineralization (*no certain biominerals known from the Archean*)
- BIOALTERATION: preserved remains of microbial remineralization (*recently discovered in Archean rocks*)

Microfossils

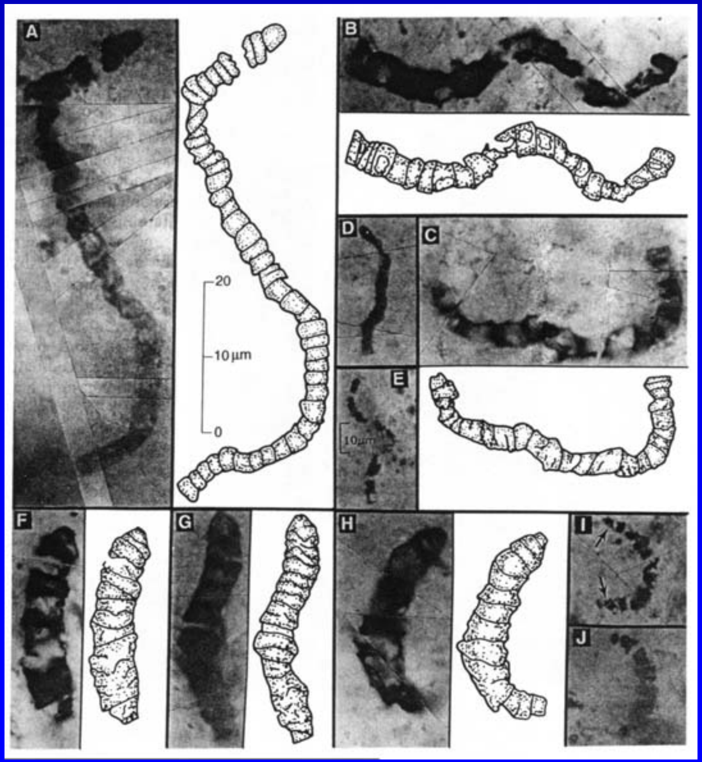
- microbial cell walls and extracellular sheaths made up of resistant polymers
- mostly preserved where rapid entombment in microcrystalline quartz
- often not diagnostic of biological relationships as most are small and simple
- usually signs of behavior are needed before biological origin is certain
- contamination (*younger fossils in older rocks*) is a common problem

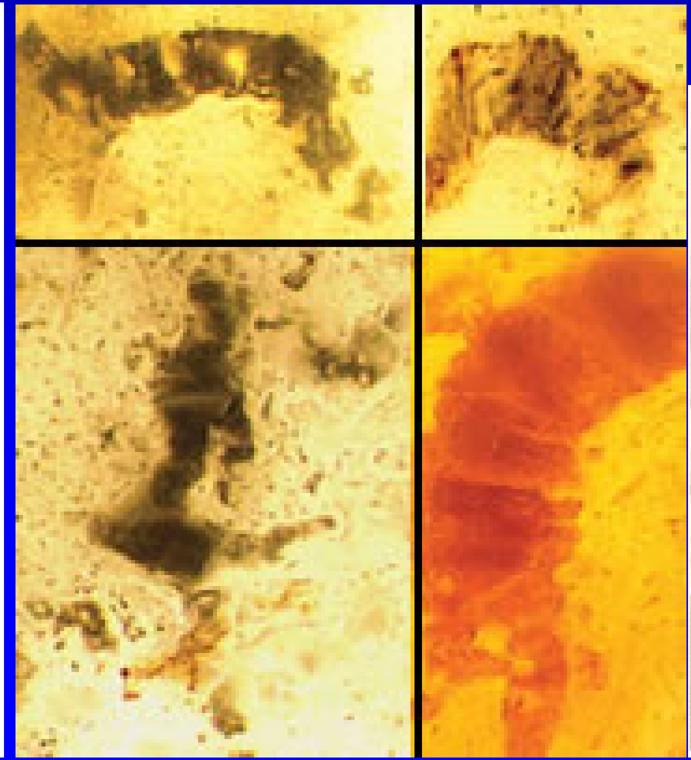


Proterozoic cyanobacterial microfossils

Oldest microfossils?

- ~3.45 billion years, Marble Bar, northwest Australia
- carbonaceous microstructures with apparent cellular organization
- surrounded by greenschist facies (>350°C) rocks
- <u>pale (unmetamorphosed) in vein (contamination)?</u>





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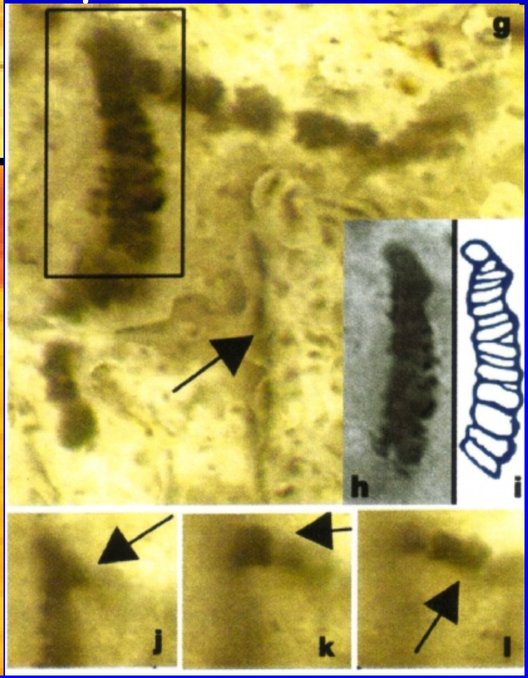
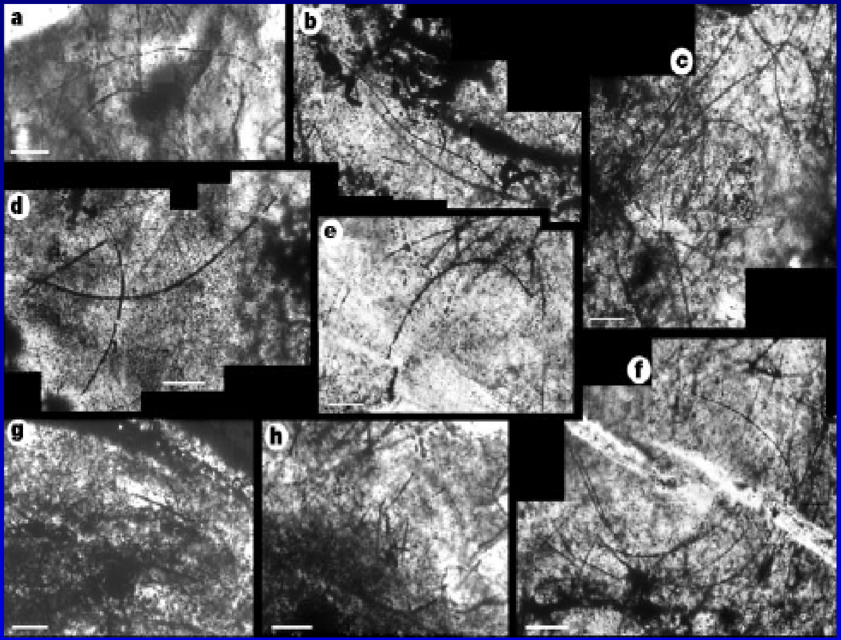
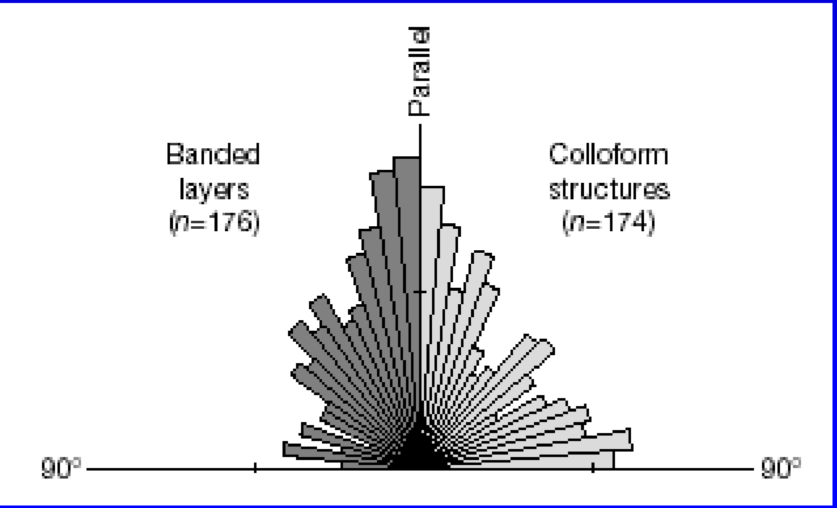


Oldest microfossils?

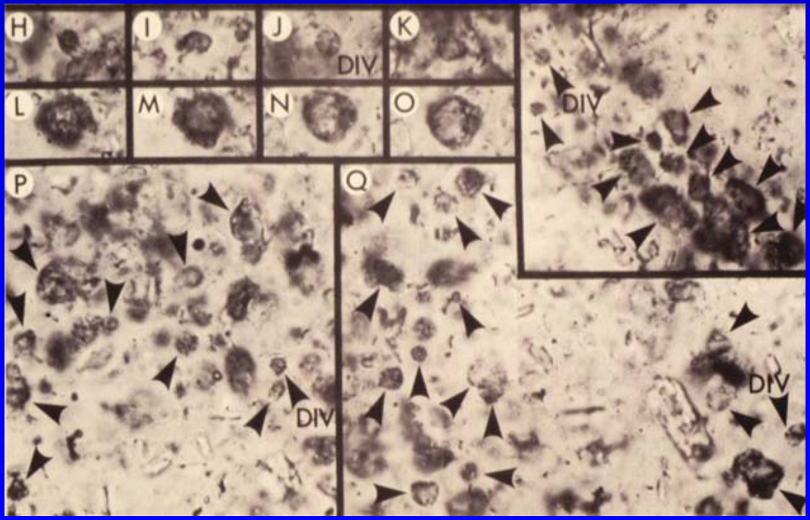
- 3.23 billion years, Sulphur Springs, northwest Australia
- pyritic filaments in subsurface hydro-thermal metal deposit, oriented in different directions on substrates
- <u>possibly behavior but no cellular organization</u>





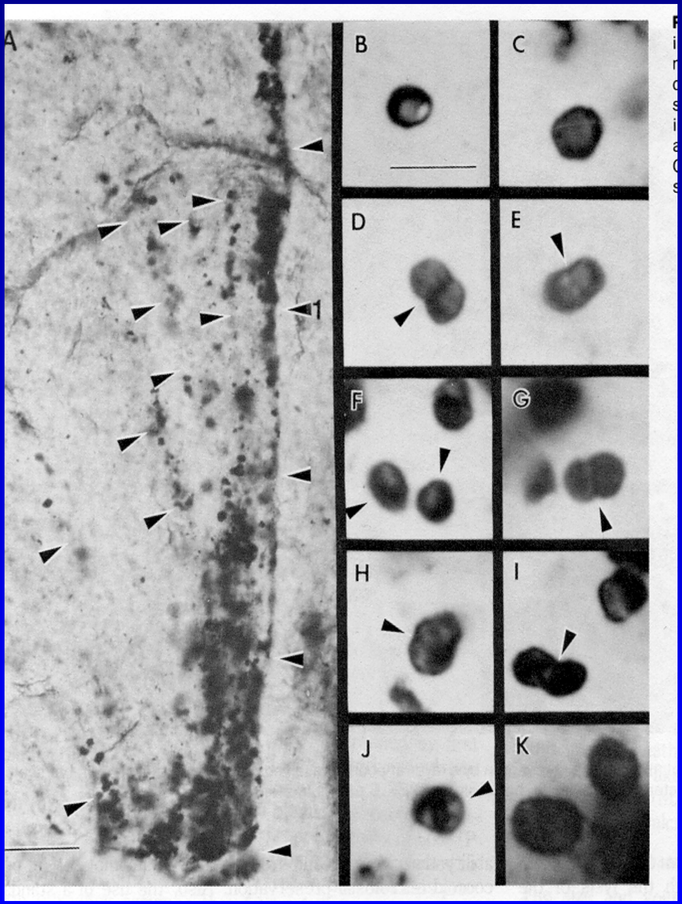
Oldest microfossils?

- **~3.2 billion years, Swaziland Supergroup, South Africa**
- kerogen filaments and spheres
- some possibly dividing
- but no complex behavior (e.g. mat formation, preferential orientation, colonial habit)



Oldest microfossils

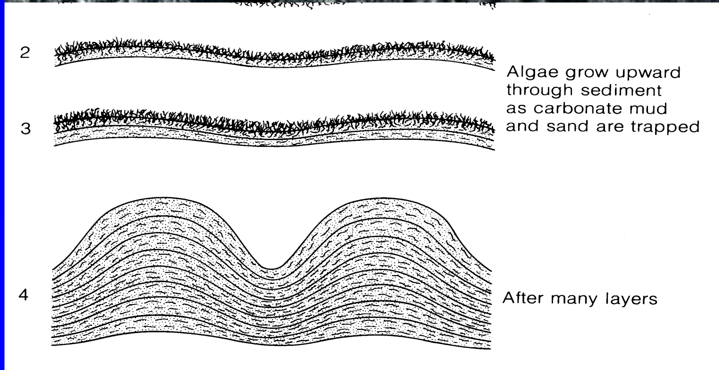
- **~2.6 billion years, Transvaal Supergroup, South Africa**
- dividing cells and matting filaments in stromatolites
- clear evidence of cellularity, complex behavior, interaction with surrounding environment



Stromatolites

- layered sediment mounds accreted by microbial growth, movement or metabolism
- display convex-upward doming with layers thickening over flexure crests
- microbial mats baffle currents causing grain deposition, trap sediment by overgrowth, or precipitate carbonate during photosynthesis
- modern stromatolites formed by cyanobacteria, diatoms, green algae where animals are scarce
- many abiotic mimics; e.g. stalagmites, folds

Shark Bay, Australia



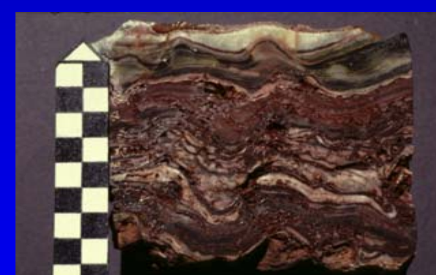
Other trace fossils

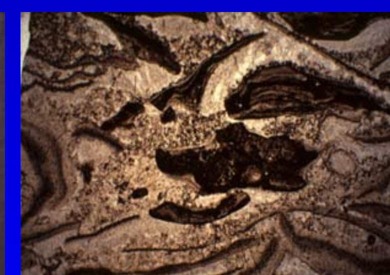
- Oncolites: like stromatolites but concentric microbial lamination around a lithic nucleus

- Microbially-Induced Sedimentary Structures (MISS): surface features on sands and muds from ephemeral biofilm binding

Oldest stromatolites?

- **3.47 billion years, North Pole, Australia**
- **stromatolites with domical structure, layers thickening over flexure crests, alternate layers kerogen-rich and -poor, fragments eroded from apex**
- **very probably biogenic but absence of microfabric with palimpsests of microbes makes proving it difficult**

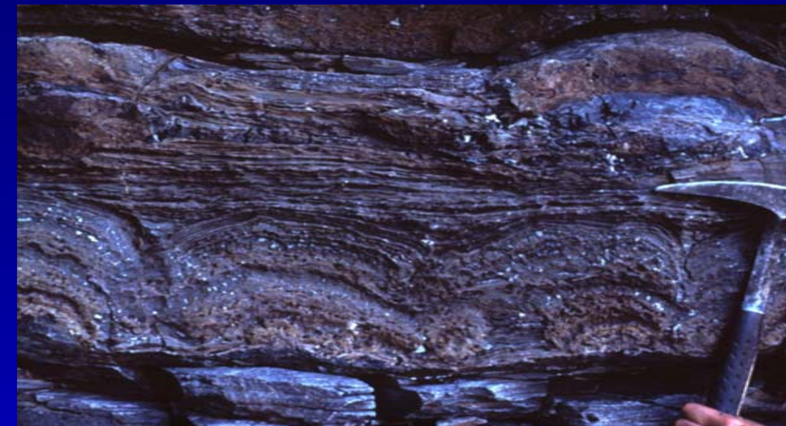


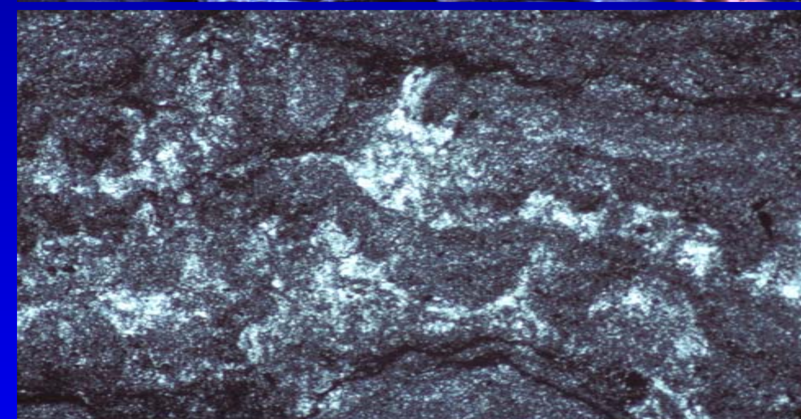


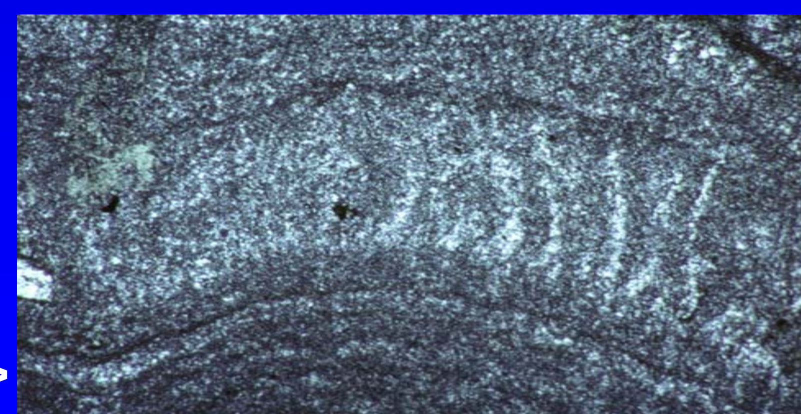
↑1cm eroded flakes with kerogenous layering

Oldest stromatolites

- 2.72 billion years ago: clearly biogenic stromatolites in Tumbiana Formation, northwest Australia
- Show relics of tufted (middle) and erect (bottom) microbial filaments
- Implies oxygenic photosynthesis because stromatolites grew in sulfur-poor lakes on basalt, where reactants for other metabolisms are absent







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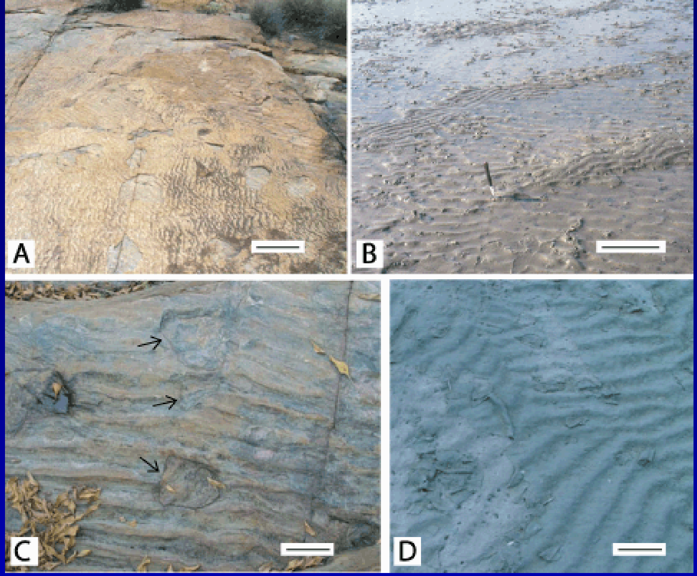
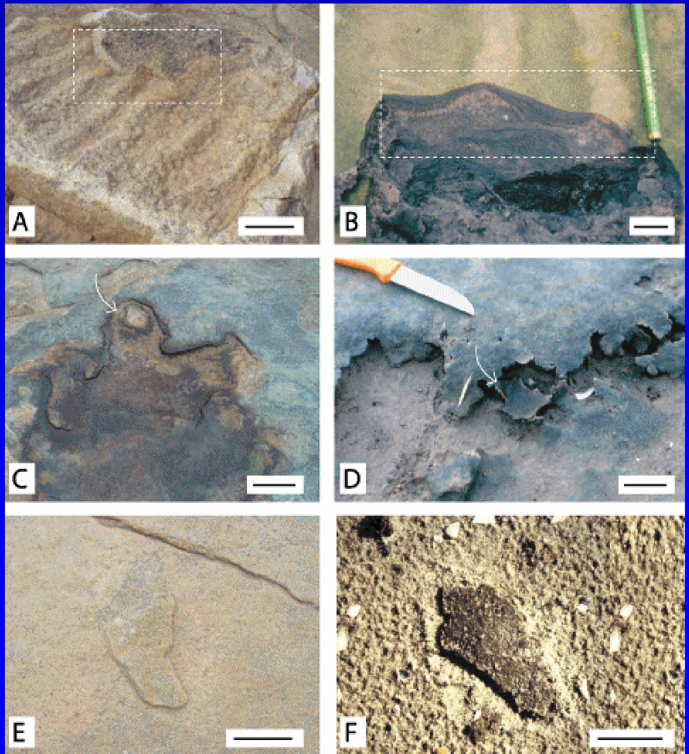
Oldest trace fossils

- No certain oncolites known from Archean
- Diverse MISS known from ~3.2 Ga Moodies Group, ~3.0 Ga Pongola Group in South Africa
- Include multi-directional ripples stabilized by biofilm (*above*), eroded and fragmented superficial biofilms (*below*), gas-domes, tufted biofilm palimpsests etc



Archean **Modern**

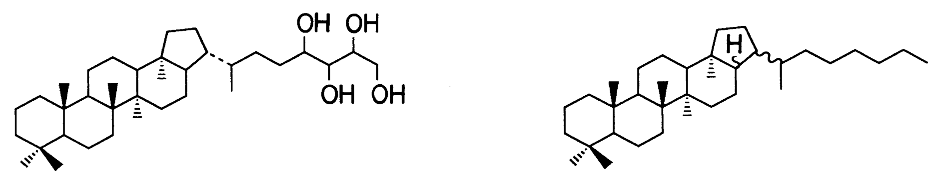


Biomarker Molecules

- hydrocarbon molecules from photosynthetic pigments and membrane rigidifiers
- found in oil and kerogen (non-crystalline, highly aromatic, insoluble organic matter)
- no functional groups or multiple bonds, just carbon skeleton but recognizable if complex
- concentrations minute at T > 200ºC
- easily contaminated by ancient petroleum, modern organic fluids, laboratory waste, diesel fumes

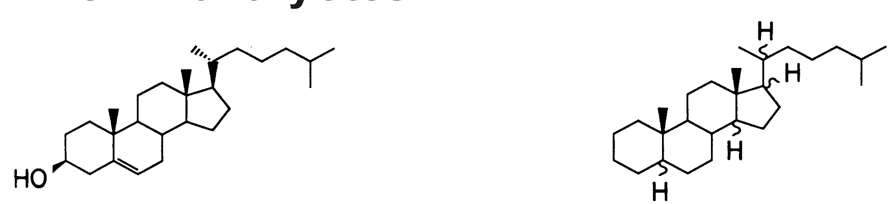
Biomolecules **Geomolecules**

Acyclic isoprenoids from pigments and Archaea



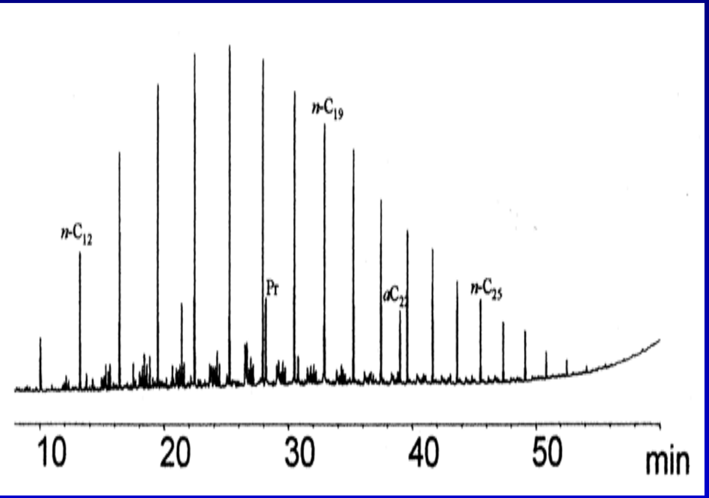
Hopanepolyol and hopane from Bacteria

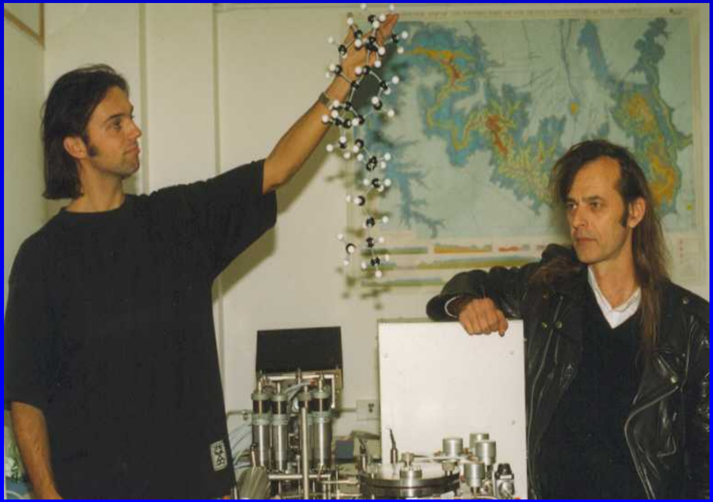
Sterol (cholesterol), sterane (cholestane) from Eukaryotes



Oldest molecular fossils?

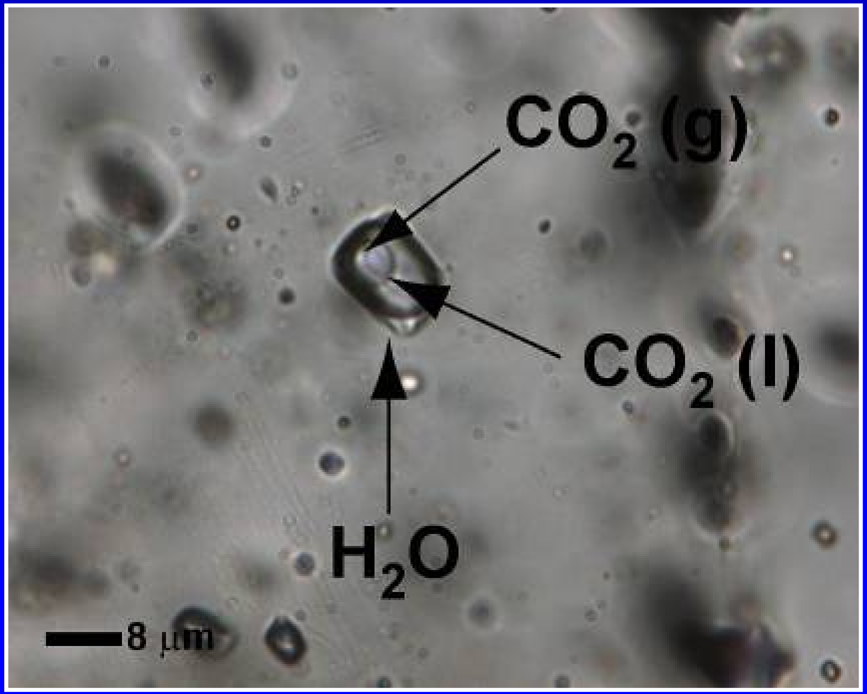
- 2.69 Ga Jeerinah kerogen
- yields hopanes - Bacteria
- $>C_{31}$ 2α-methylhopanes - photosynthetic cyanobacteria producing oxygen
- diverse steranes including cholestane – Eukaryotes
- Jochen Brocks thinks they are contaminants, but many unique features inexplicable by younger origin
- suggests all 3 domains of life were extant by late Archean, including complex eukaryotic cells

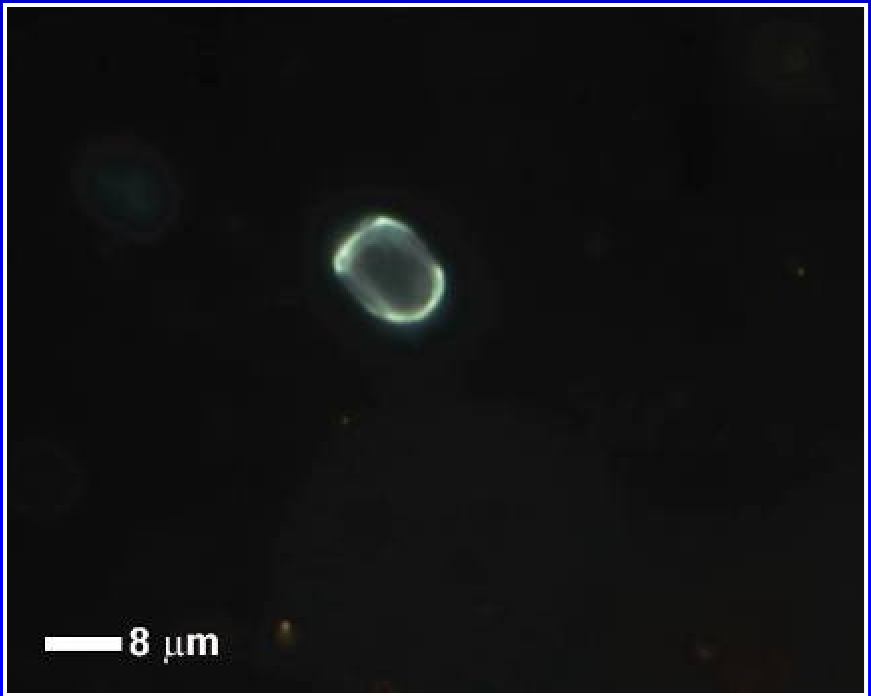




Oldest molecular fossils

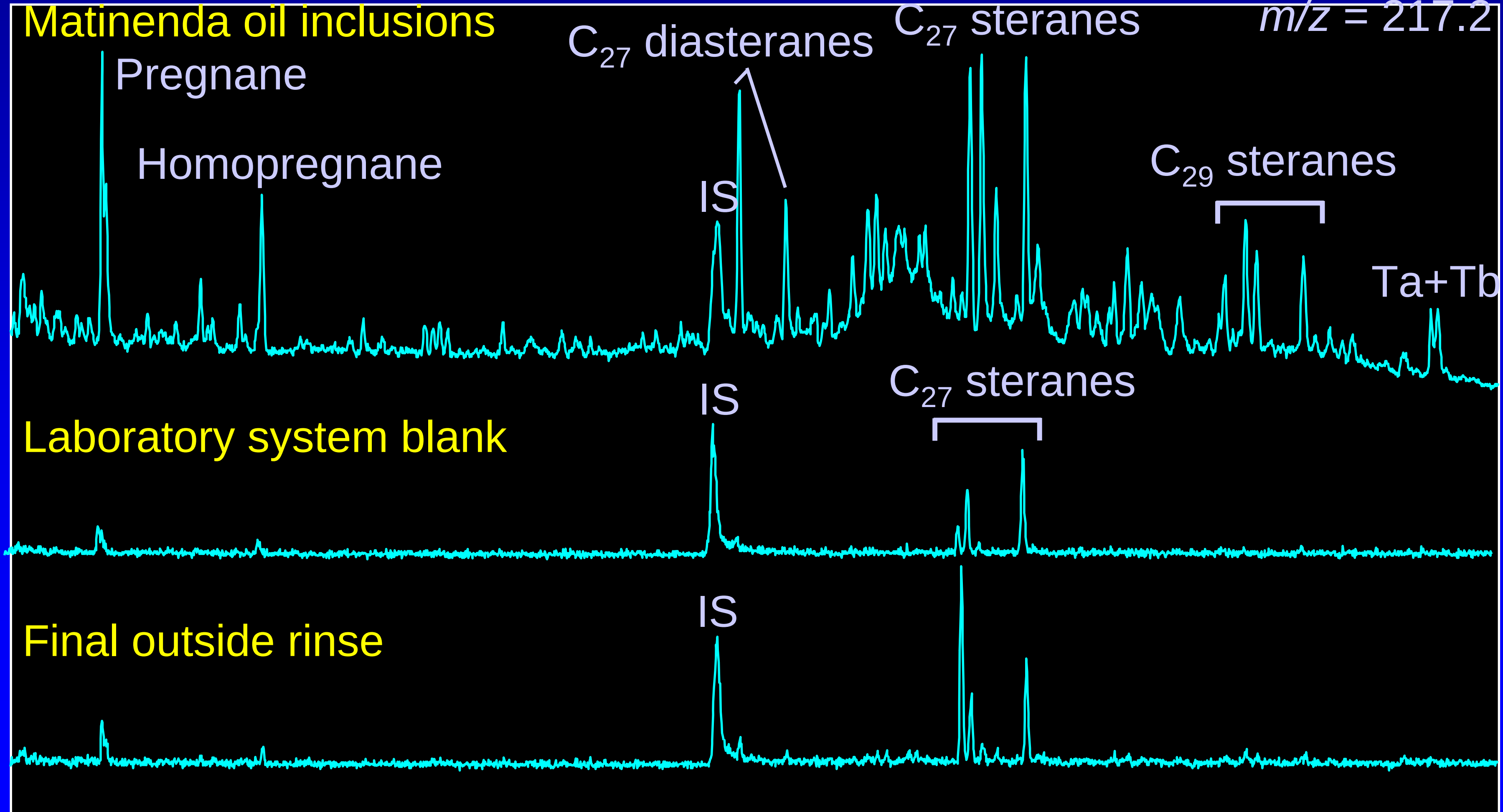
- Fluid inclusions within quartz grains in the ~2.45 billion year old Matinenda Formation, Canada
- Contain oil as a fluorescing rim to the carbonic and aqueous phases filling the inclusion
- Inclusions were trapped before their host rock was metamorphosed at ~2.2 billion years ago





Oldest molecular fossils

- Matinenda fluid inclusion oil show peaks above background, so clearly indigenous
- contain diverse and abundant steranes
- C_{27} steranes: contaminants in system blank; others indigenous; diversity indicates eukaryotic source



Isotopic Fractionations

- microbial metabolism fractionates the stable isotopes of carbon ($\delta^{13}C$), sulfur ($\delta^{34}S$) and nitrogen ($\delta^{15}N$)
- biotic fractionations are much larger than abiotic at low temperatures and pressures
- isotopic evidence trapped in minerals survives thermal and mechanical trauma well
- need isotopic ratios of reactant and product to be sure of biogenic origin

Carbon Isotopes

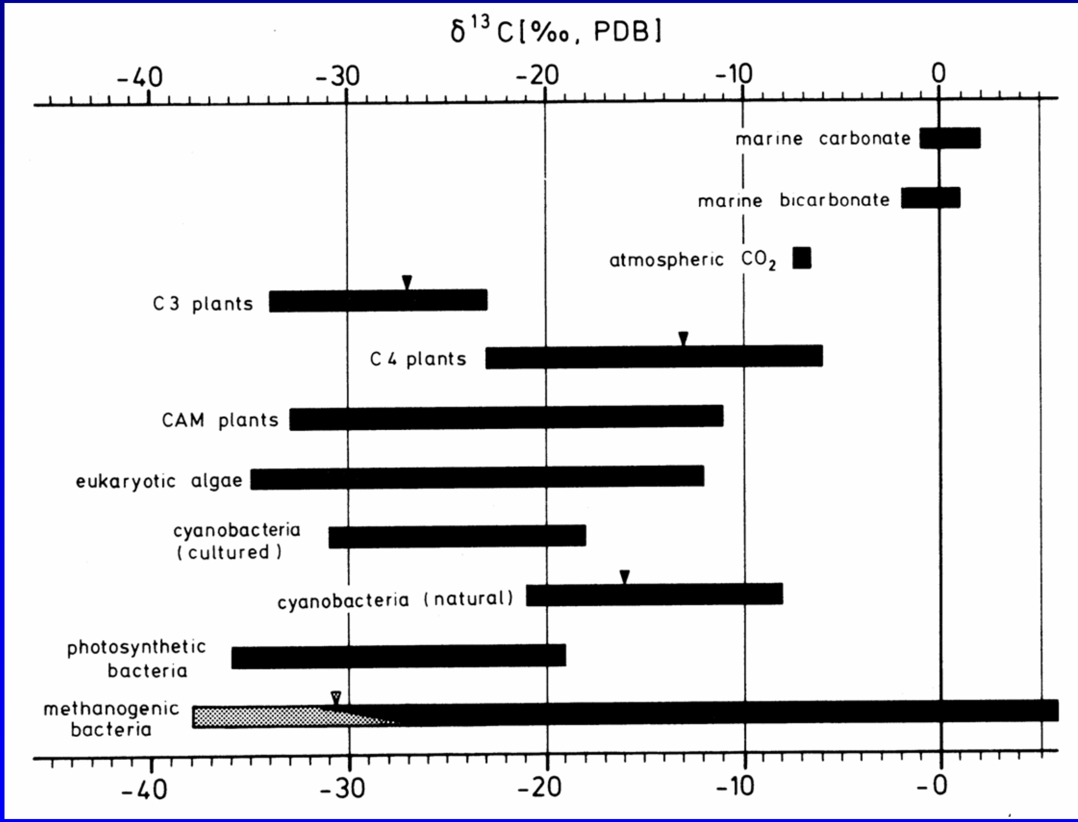
- 2 stable isotopes of carbon: ^{12}C, ^{13}C
- ^{12}C forms bonds that need slightly less energy to break
- Molecules with ^{12}C are slightly lighter
- These factors induce "fractionations" – discrepancies between the isotopic ratios in reactant and product
- Isotopic ratios expressed by "delta notation"

$$\delta^{13}C = \left[\frac{\left({}^{13}C/{}^{12}C\right)_{\text{sample}}}{\left({}^{13}C/{}^{12}C\right)_{\text{standard}}} - 1 \right] \times 10^{3} \left[‰,\ \text{PDB}\right]$$

- Fractionations between reactant and product expressed as "epsilon notation" e.g. $\varepsilon = \delta$ carbonate – δ organic
- "Life is lazy", so biological reactions strongly favor the light isotope

Carbon isotope fractionations

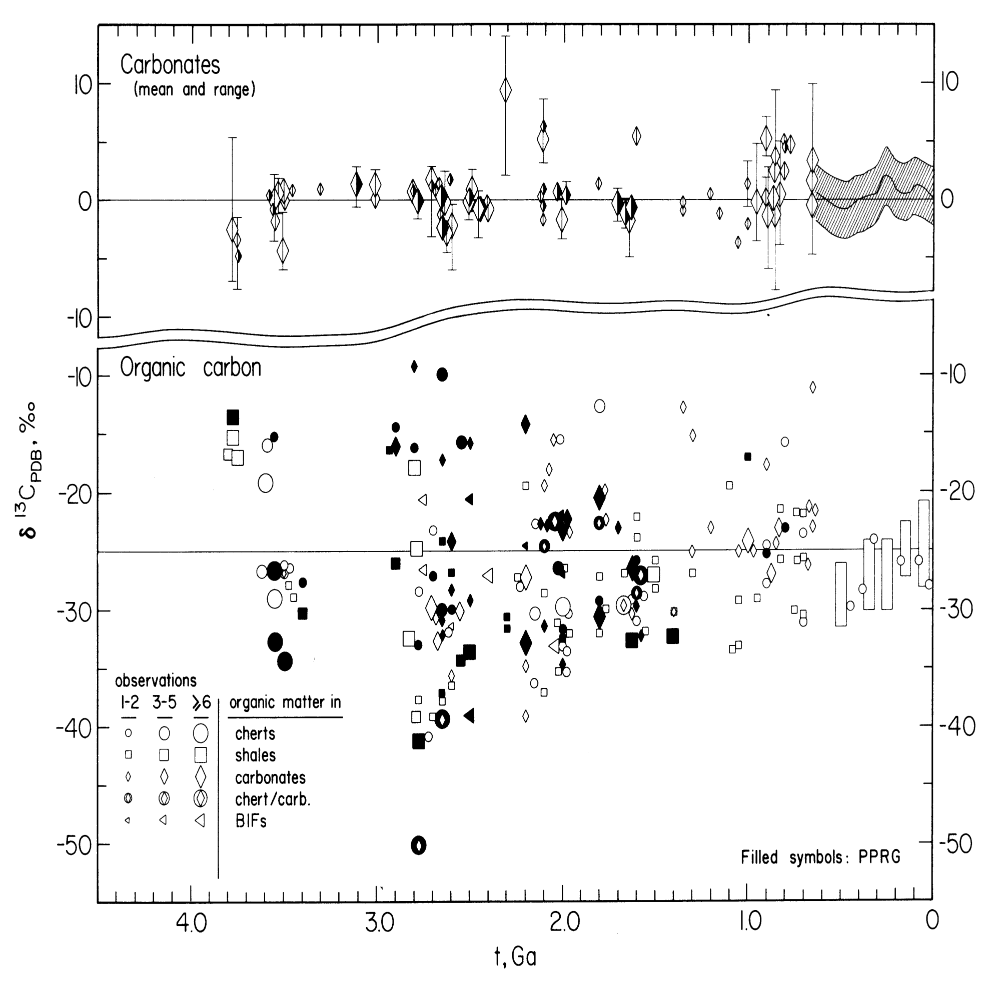
- Different metabolisms fractionate differently
- Fractionation range varies according to ecological conditions
- Thus rarely diagnostic of specific metabolism
- Can be diagnostic of autotrophic carbon-fixation if both reactant and product are preserved showing full fractionation



C-isotope evidence of metabolism

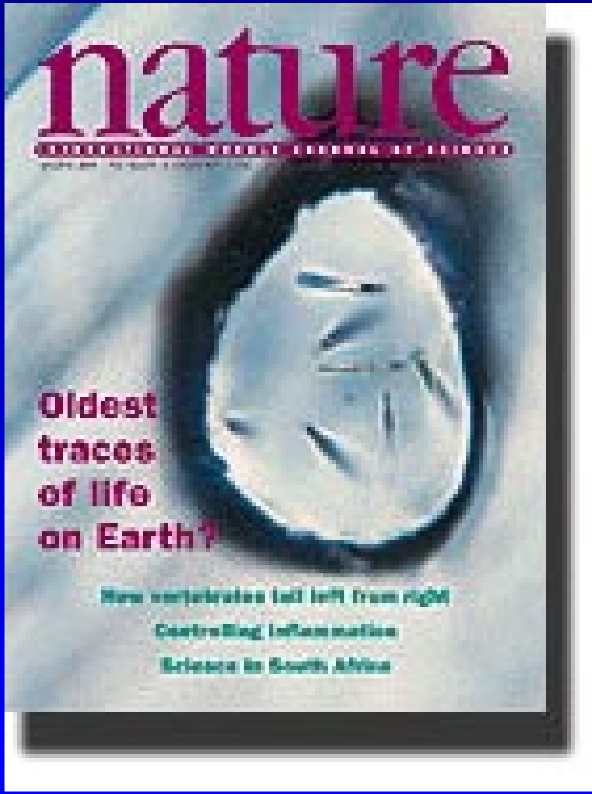
$\delta^{13}C_{organic}$ indicates methanogenesis (maybe also methanotrophy) if < -40‰

- clear evidence from 2.8-2.6 billion years in non-marine Fortescue Group & marine Hamersley Group, Australia
- <u>shows early evolution of Archaea</u>, one of the 3 fundamental domains of life



Oldest Evidence of Life?

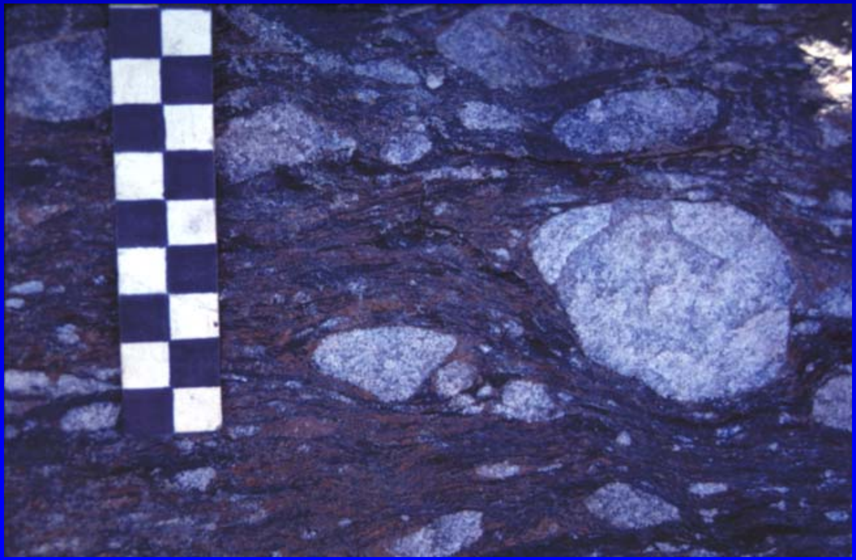
- **~3.85 billion years, Akilia, Greenland**
- Alleged to contain graphite with light $\delta^{13}C$ (-45 to -20‰) in apatite grains in ferruginous quartzite
- Interpreted as biological isotope fractionation
- Difficult to replicate this finding
- Uncertain that rock was sedimentary
- Some doubts about age (apatite crystals hosting graphite are ~1.6 Ga)
- Without sedimentary carbonate, unclear that isotopic fractionation is of biological magnitude, or if it shows consistency expected of biology



Biogenic graphite? in apatite from Akilia

Oldest Evidence of Life?

- **~3.8 billion years, Isua, Greenland**
- graphite with light $\delta^{13}C$ (-20‰) in metamorphosed shale, consistent with biological fractionation during autotrophy
- <u>no sedimentary carbonates (only metamorphic) to determine extent of fractionation, so cant prove biological origin</u>

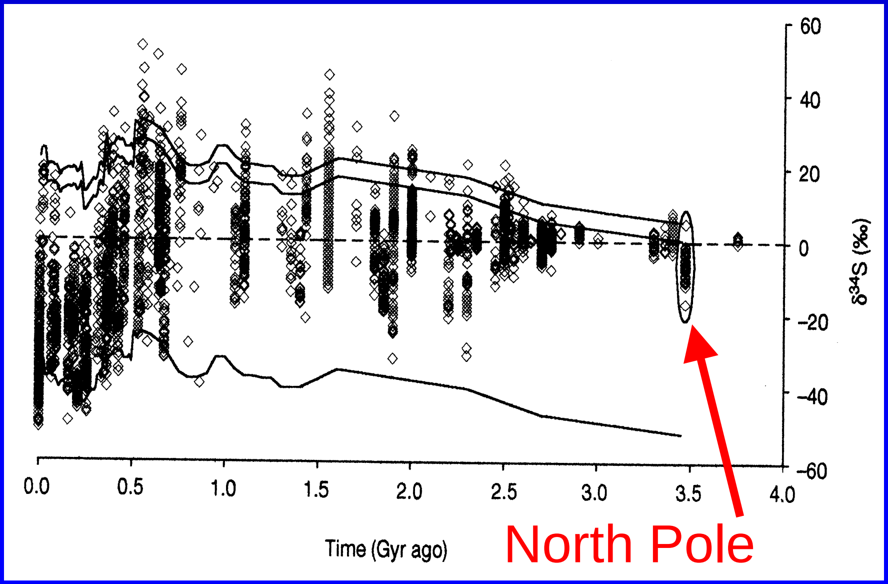


Isua meta-conglomerate showing sedimentary origin

~3.8 billion year old graphitic metasediments, Isua, Greenland

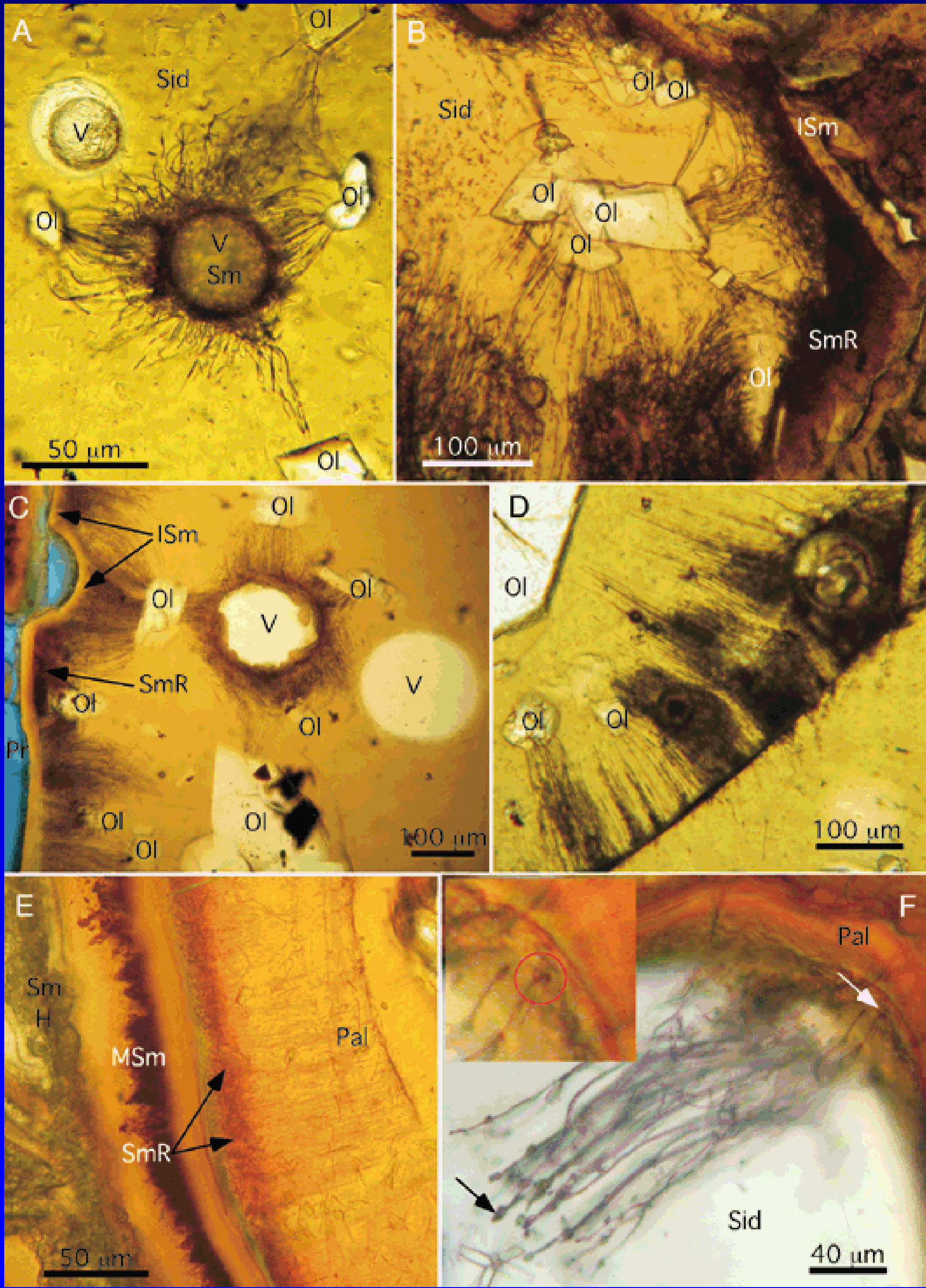
S-isotope evidence of metabolism?

- indicates sulfate reduction if $\varepsilon^{34}S_{sulfate\text{-}sulfide}$ > 10‰
- clear record back to ~2.7 billion years
- single older record (3.47 billion years, North Pole)
- no evidence of hydrothermal origin (pyrite on internal growth faces of barite crystals, formerly gypsum
- <u>shows early evolution of respiration</u>, but low ocean sulfate



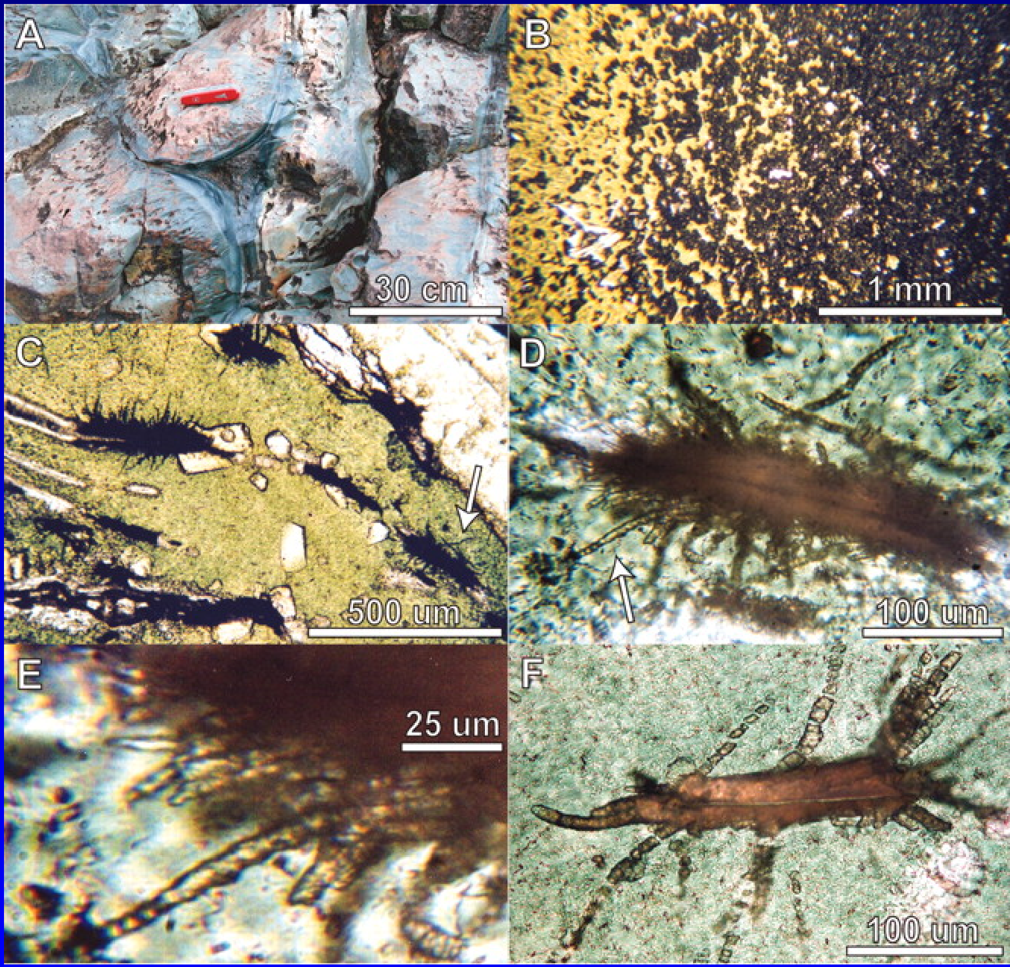
Biolateration

- Occurs where microbes etch or dissolve minerals
- Best known in carbonates, but also in basaltic glass, sulfides
- May form surface pits, granular texture or invasive tubules
- Tubules with complex morphology (branching, distinct opening or teminal geometry, preferential orientation towards particular minerals) can be discriminated from abiotic chemical alteration



Archean bioalteration

- Known from ~3.4 Ga pillowed basalts from Pilbara, Australia and Kaapvaal, South Africa
- Need very low metamorphic grade or else destroyed by recrystallization
- Hard to prove biogenicity unless internal organic carbon, preferential orientation towards particular minerals



Microtubules in chloritized volcanic glass, Kaapvaal Craton

Where do Archean fossils occur?

- Almost exclusively in sedimentary rocks (bioalteration in basalts are exception)
- Mostly in carbonates (silicified?), but also sulfate evaporites, clastic sediments (sandstones, shales), rarely in tuffs
- Preferentially found in fine-grained sediments
- Only known from aqueous settings (marine, lakes) but not from rivers, ephemeral water bodies
- Largely preserved in reducing environments
- Stable tectonic settings distal from point sources of heat or pressure (volcanoes, orogenies or impact craters)
- In areas of active erosion

What do you need to find them?

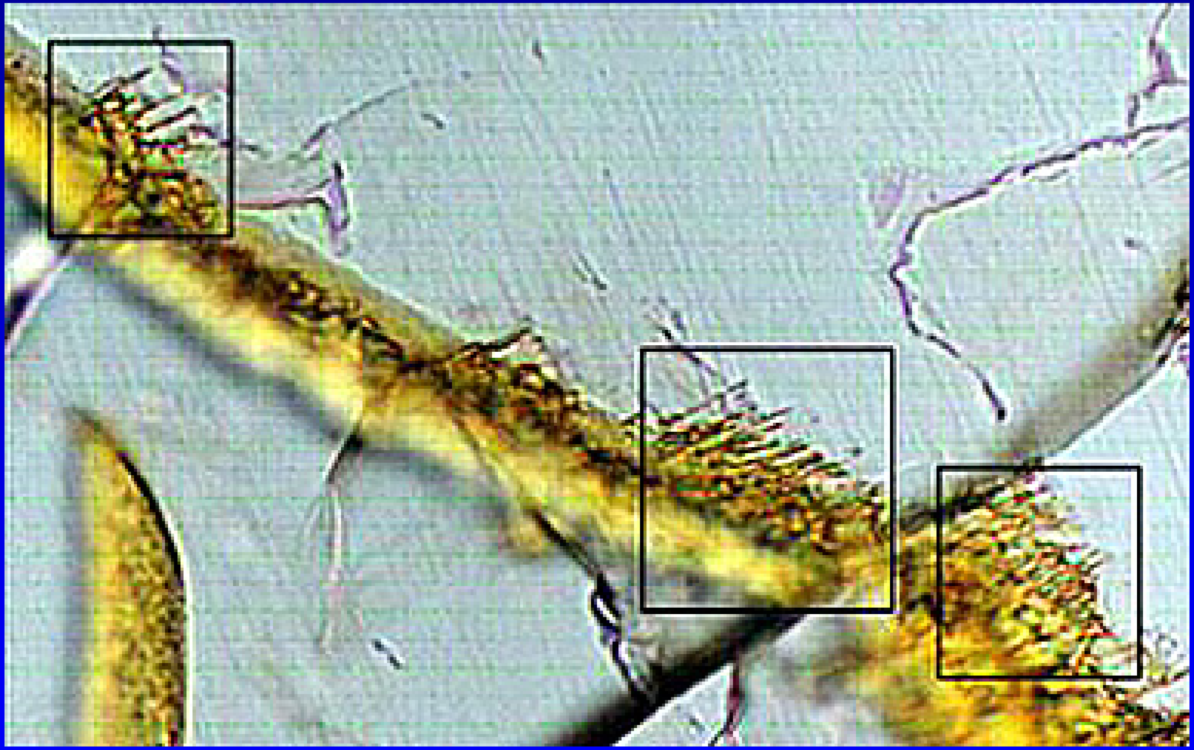
- Thorough mineralogical and lithological information
- Full stratigraphic history
- Good geochronology
- Complete post-depositional paragenesis (diagenesis, metamorphism, deformation)
- Recent geomorphological evolution
- A diverse suite of analytical techniques (macro-imaging, microscopy, whole-rock geochemistry, organic geochemistry, isotopic geochemistry)
- A whole lot of luck!!

Where would I go to find them on Mars?

- Somewhere with diverse sedimentary rocks
- Somewhere with long-lived water bodies
- Somewhere with rapid lithification (evaporative or hydrothermal settings)
- Somewhere with fine grain-size
- Somewhere with little evidence of oxidation or acidic alteration
- Somewhere with little subsequent disturbance
- Somewhere only recently exposed
- Somewhere with well-understood basic geology

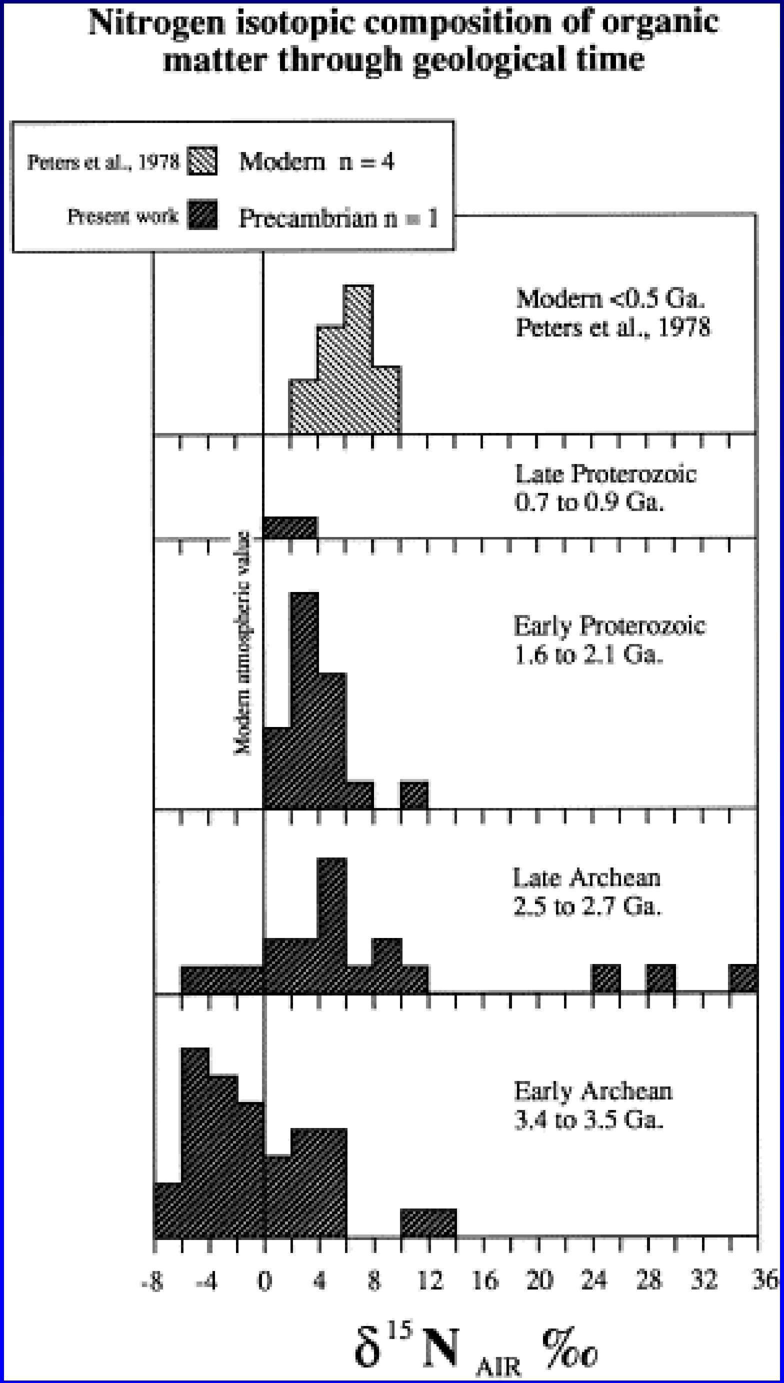

Early Mars?

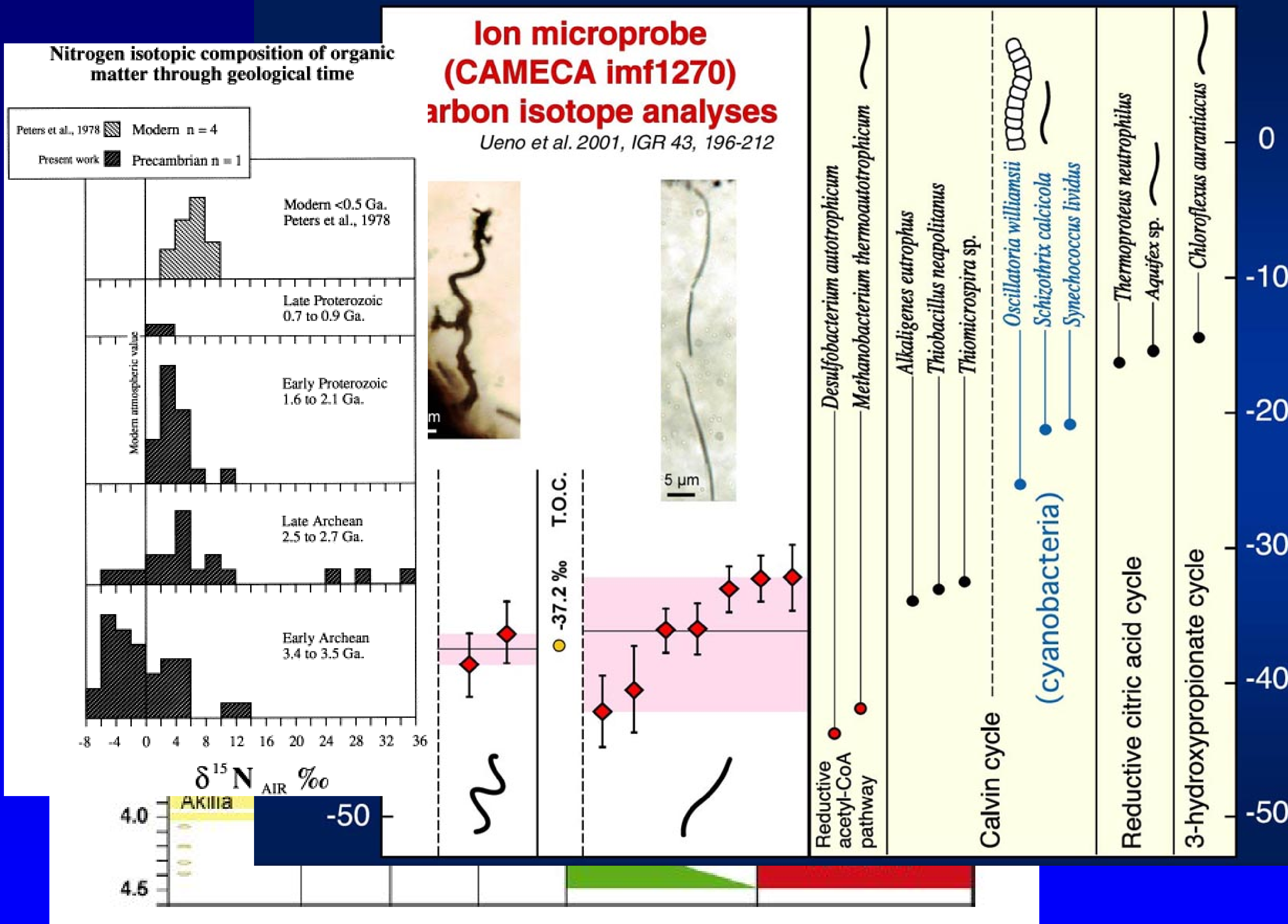
- Nakhla



Nitrogen isotopes

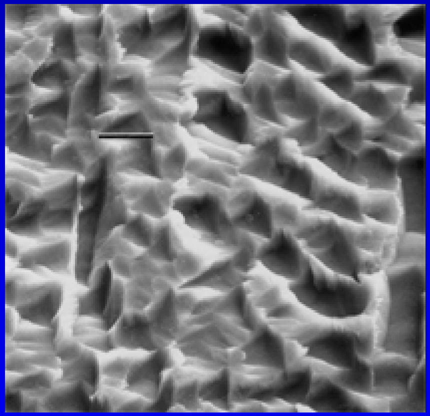
- Positively fractionated $\delta^{15}N$ in organic matter by denitrification
- No strong evidence until early Proterozoic, perhaps in late Archean

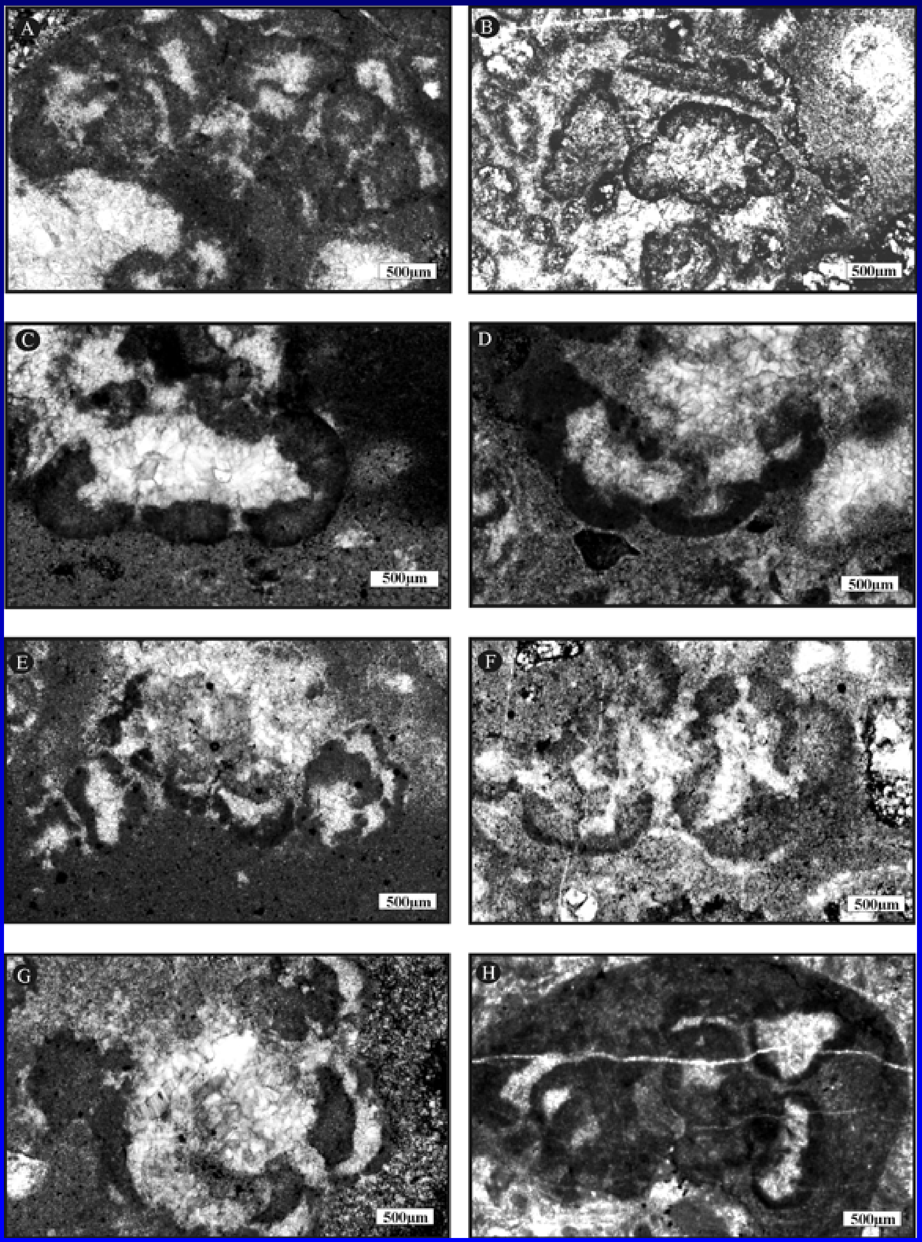




Nitrogen isotopic composition of organic matter through geological time
Peters et al., 1978 Modern n = 4
Present work Precambrian n = 1
Modern <0.5 Ga. Peters et al., 1978
Late Proterozoic 0.7 to 0.9 Ga.
Early Proterozoic 1.6 to 2.1 Ga.
Late Archean 2.5 to 2.7 Ga.
Early Archean 3.4 to 3.5 Ga.
Modern atmospheric value
-8 -4 0 4 8 12 16 20 24 28 32 36
δ15N AIR ‰
Ion microprobe (CAMECA imf1270)
arbon isotope analyses
Ueno et al. 2001, IGR 43, 196-212
5 µm
T.O.C.
-37.2 ‰
Desulfobacterium autotrophicum
Methanobacterium thermoautotrophicum
Reductive acetyl-CoA pathway
Alkaligenes eutrophus
Thiobacillus neapolitanus
Thiomicrospira sp.
Oscillatoria williamsii
Schizothrix calcicola
Synechococcus lividus
(cyanobacteria)
Calvin cycle
Thermoproteus neutrophilus
Aquifex sp.
Reductive citric acid cycle
Chloroflexus aurantiacus
3-hydroxypropionate cycle
0
-10
-20
-30
-40
-50
Akilia
4.0
4.5

- Pyrite corrosion
  Sulfolobus

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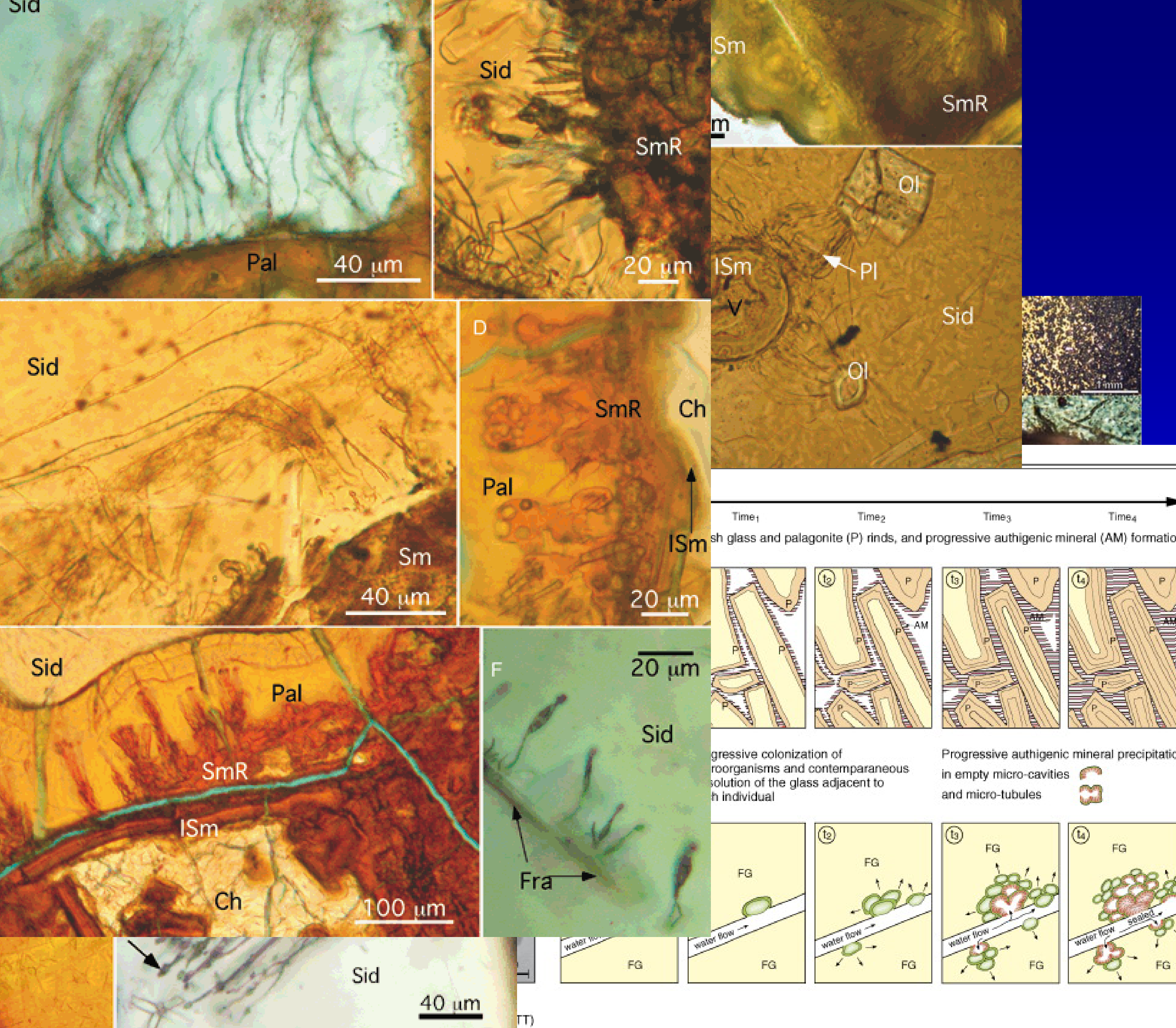

Sid
Pal
40 μm
Sid
SmR
20 μm
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SmR
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Sid
Sm
40 μm
D
SmR
Ch
Pal
ISm
20 μm
Time1
Time2
Time3
Time4
sh glass and palagonite (P) rinds, and progressive authigenic mineral (AM) formation
P
AM
Sid
Pal
SmR
ISm
Ch
100 μm
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20 μm
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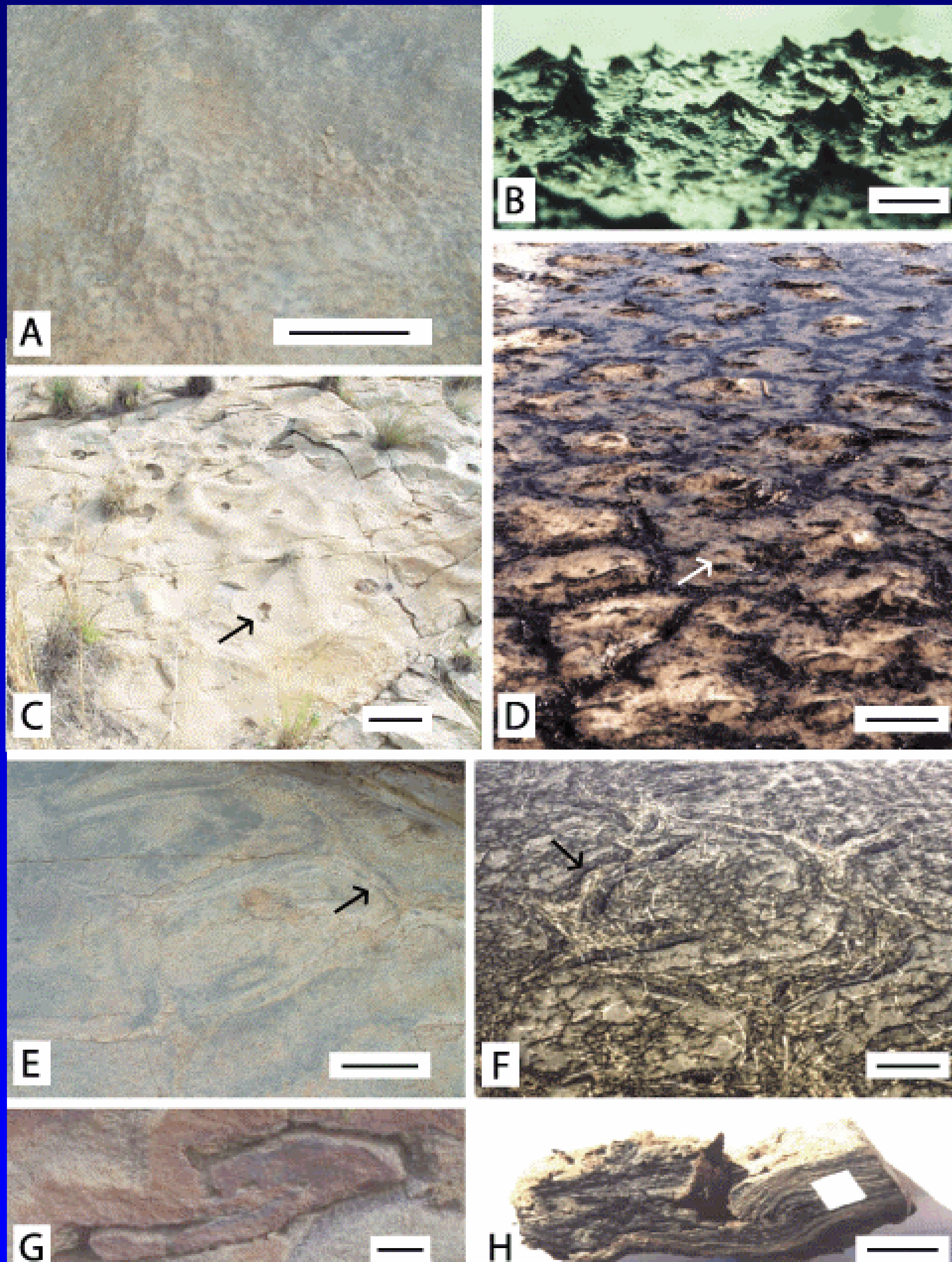
Fra
gressive colonization of
roorganisms and contemparaneous
solution of the glass adjacent to
h individual
Progressive authigenic mineral precipitation
in empty micro-cavities
and micro-tubules
FG
water flow
sealed
Sid
40 μm
TT)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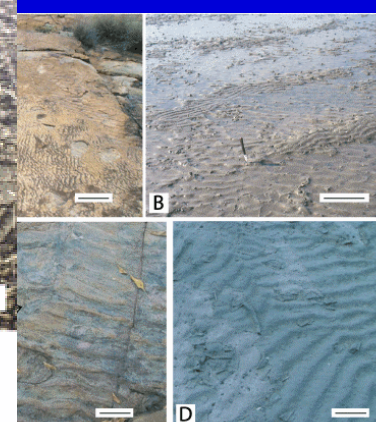
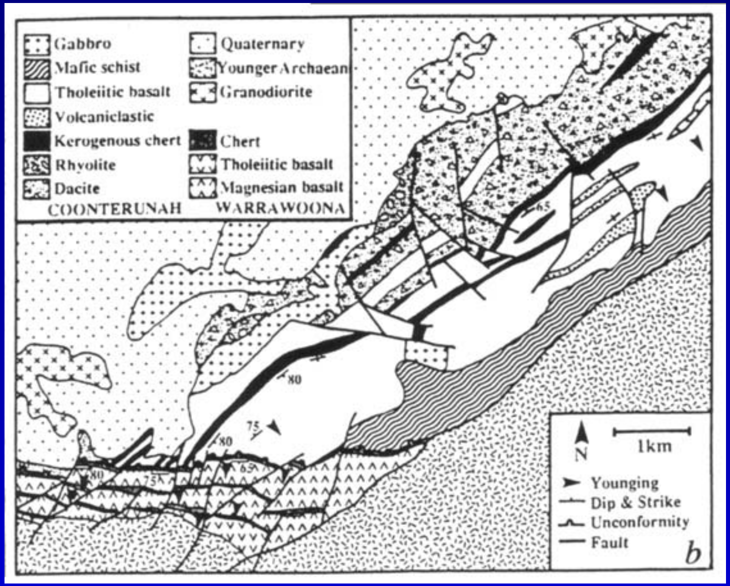

B
D

Oldest evidence of life?

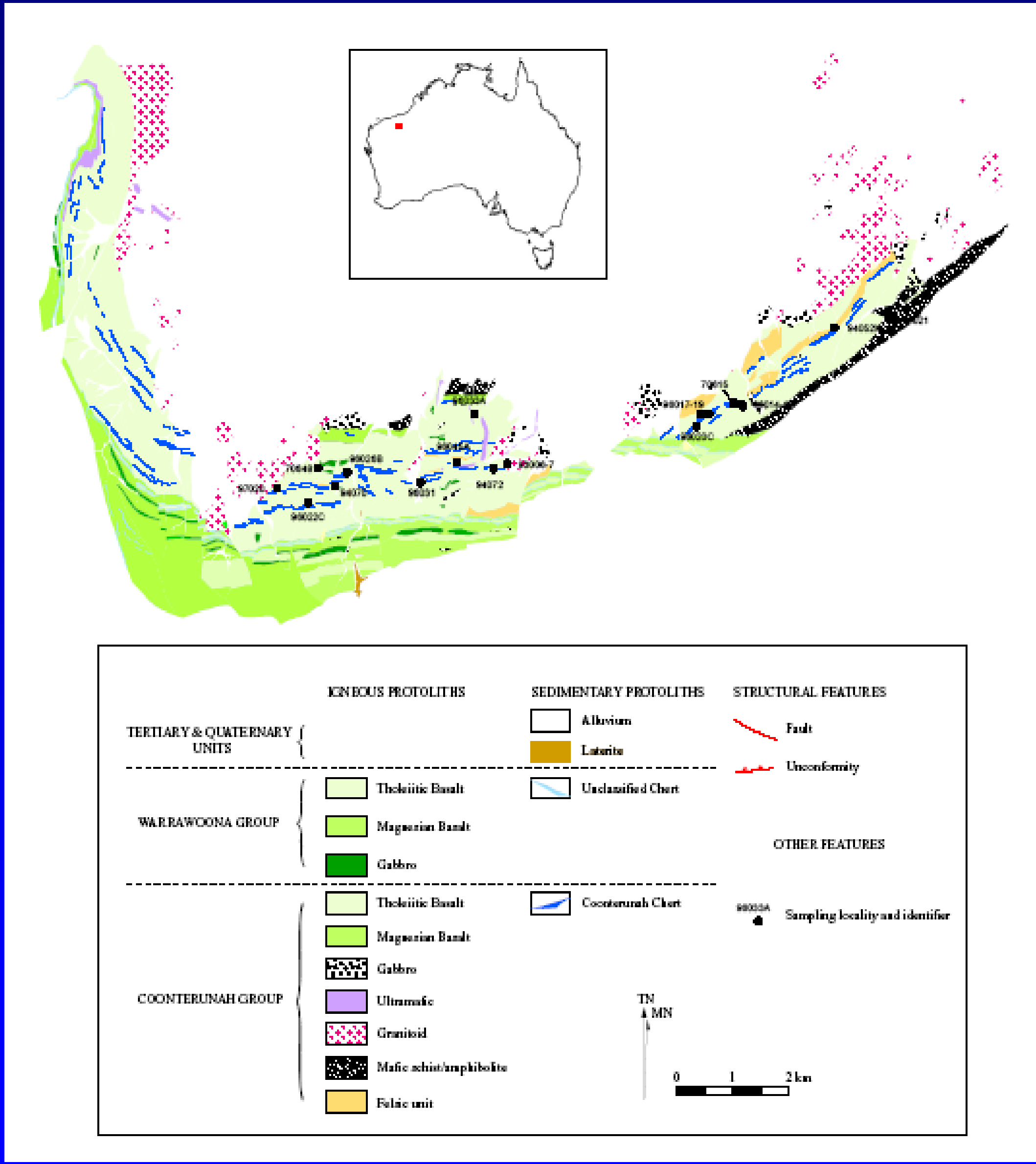
- Coonterunah Group, northwest Australia - 3.52 billion years
- Oldest low-grade (sub-amphibolite facies) rocks on Earth
- Mostly minimally deformed (only tilting and block faulting)
- Unconformably underlies the Warrawoona Group, previously thought to be the oldest low-grade rocks on Earth
- Therefore a good place to go looking for C-isotope evidence of autotrophy



Angular unconformity between Coonterunah-Warrawoona cherts

Coonterunah Group

- 5km of stratigraphy
- 75km strike length
- Units mostly continuous
- Broad regional folding
- Metamorphic grade increases into western fold and towards granite
- Deep-water marine depositional environment (no current structures)
- Distal to land (no coarse terrigenous clastic sediments)



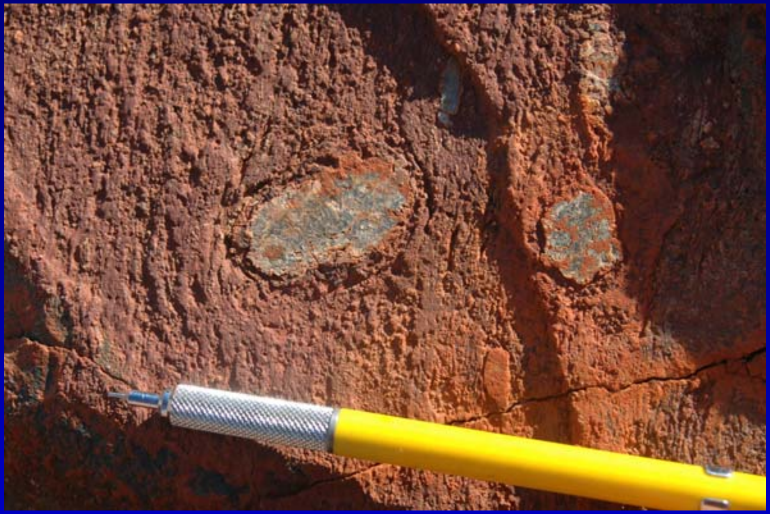
Coonterunah basalts

- Bulk of Coonterunah stratigraphy is basalt
- Mostly tholeiitic, but magnesian and komatiitic in places
- Mostly massive, but extensive pillowed horizons and some amygdaloidal units
- Some felsic volcanics (rhyolites & dacites) interbedded, massive or autobrecciated

Pillowed magnesian basalt from base of Coonterunah Group

Coonterunah tuffs

- Several metres of tuff underlie carbonate
- Conglomeratic at base, fining upwards to mud
- Basaltic in composition
- Some carbonate matrix to conglomerate, but elsewhere slightly silicified
- Indicates that carbonate was not formed after deposition



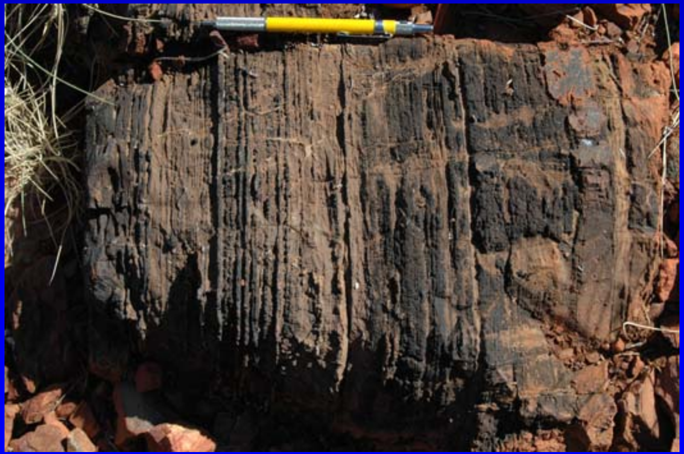
Conglomeratic basal tuff

Slightly silicified sandy tuff

Coonterunah carbonates

- One carbonate horizon
- Only 32 cm thick
- Can be traced along strike for 5 km
- Plane-laminated at 1 mm scale
- Inter-laminae of magnetite
- Composed of ferroan calcite
- No detrital component
- No sedimentary structures indicating current activity
- Not metamorphic or metasomatic

Pure ferroan calcite



Ferroan calcite interlayered with magnetite

Coonterunah chert

- Chert overlies carbonate bed and comprises bulk of Coonterunah sediment
- Alternating 1cm laminae of microcrystalline quartz and magnetite-grunerite-kerogen
- Rare siderite and pyrite laminae
- No traction current structures
- Resembles Fe-poor banded iron formation

Magnetite – quartz laminated chert

Oldest Evidence of Life?

- Cant say what type of C-fixation (oxygenic photosynthesis, anoxygenic photosynthesis, chemoautotrophy etc.) because fractionation is not diagnostically light or heavy
- But definitely evidence of life!

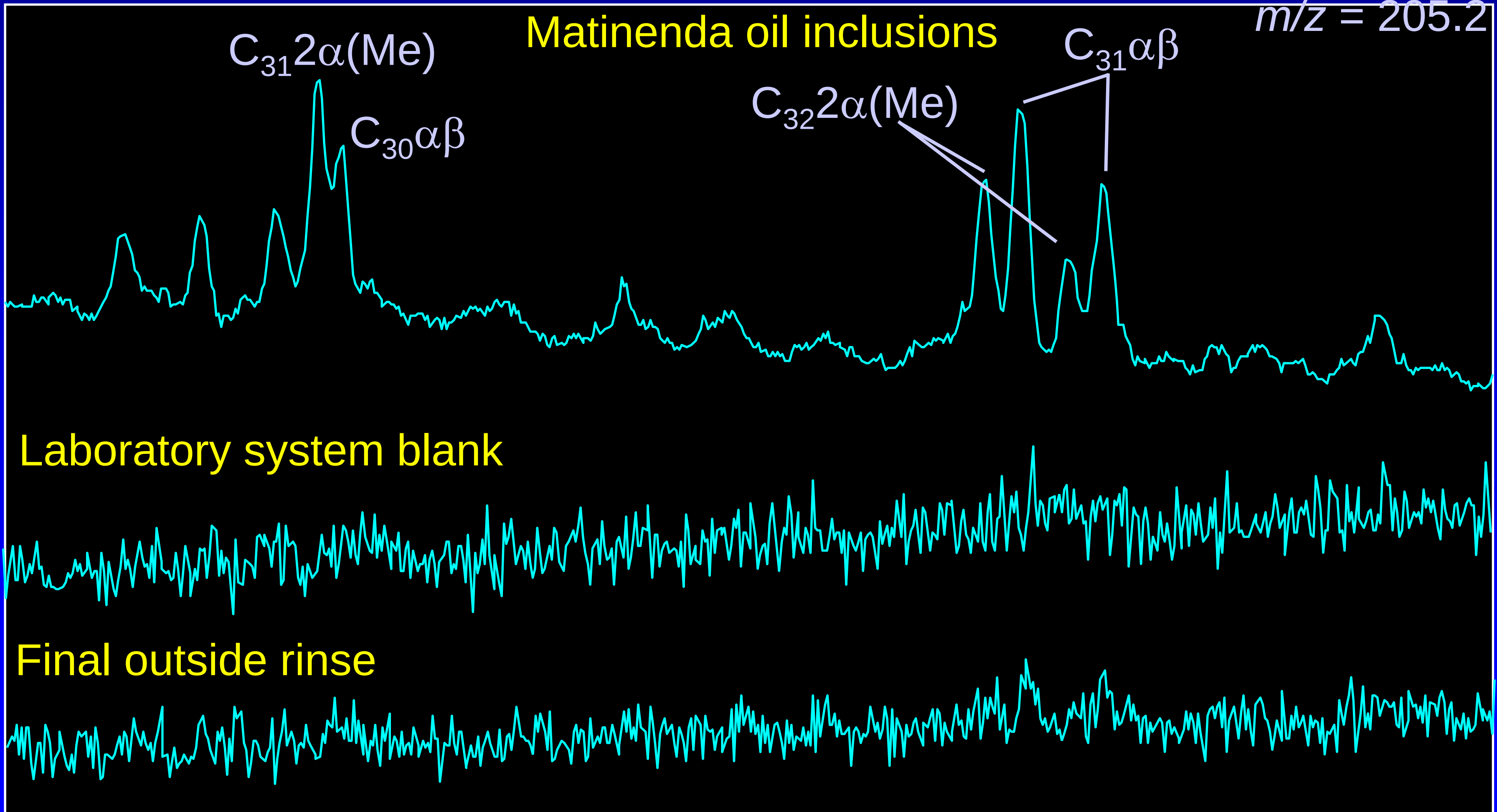
- Could be argued that this is oldest indisputable evidence for life on Earth (and in the Universe)

- Older light $\delta^{13}C_{organic}$ from ~3.8 Ga rocks at Akilia and Isua, Greenland don't have co-existing sedimentary $\delta^{13}C_{carb}$

- Coonterunah data more robust because isotopes on both sides of the carbon-fixation reaction are preserved

Oldest molecular fossils

- Matinenda biomarkers show peaks above background, so clearly indigenous
- Abundant >C_{31} 2α-methylhopanes are derived from cyanobacteria



Life in the Archean

- Can place dates on the "Tree of Life" based on the Archean fossil record
- Shows most microbial evolution occurred early including Eukaryote lineage
- Earth has been inhabited since almost the start of the geologic record
- Life probably appeared rapidly – didn't take billions of years
- May mean that it evolves easily given the right conditions
- Widely distributed in the Universe?