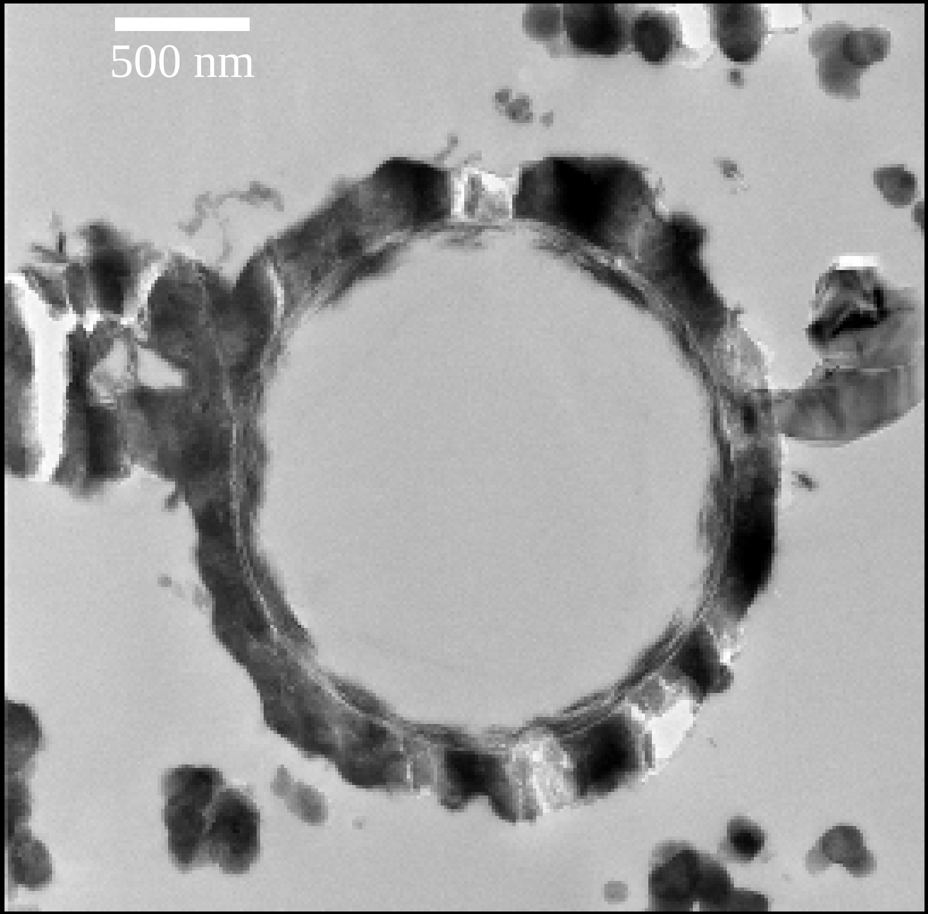
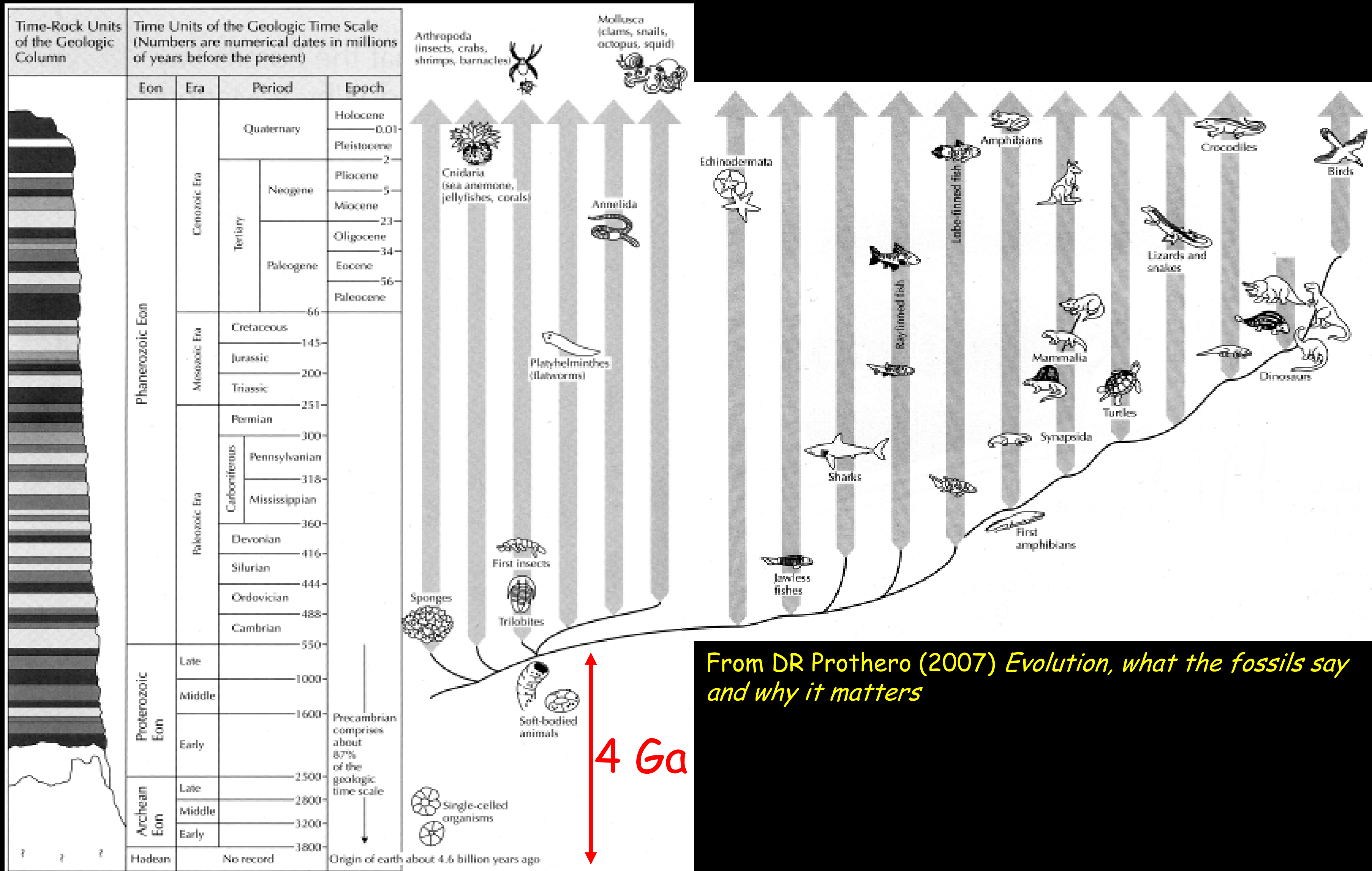
Early traces of life in the fossil record



Karim Benzerara

Institut de Minéralogie et de Physique des Milieux Condensés
CNRS & Univ. Pierre et Marie Curie

Paleontology has mostly focused on the study of life over the last 600 Myrs



From DR Prothero (2007) *Evolution, what the fossils say and why it matters*

We miss most of the life record (4 Ga), including the origins

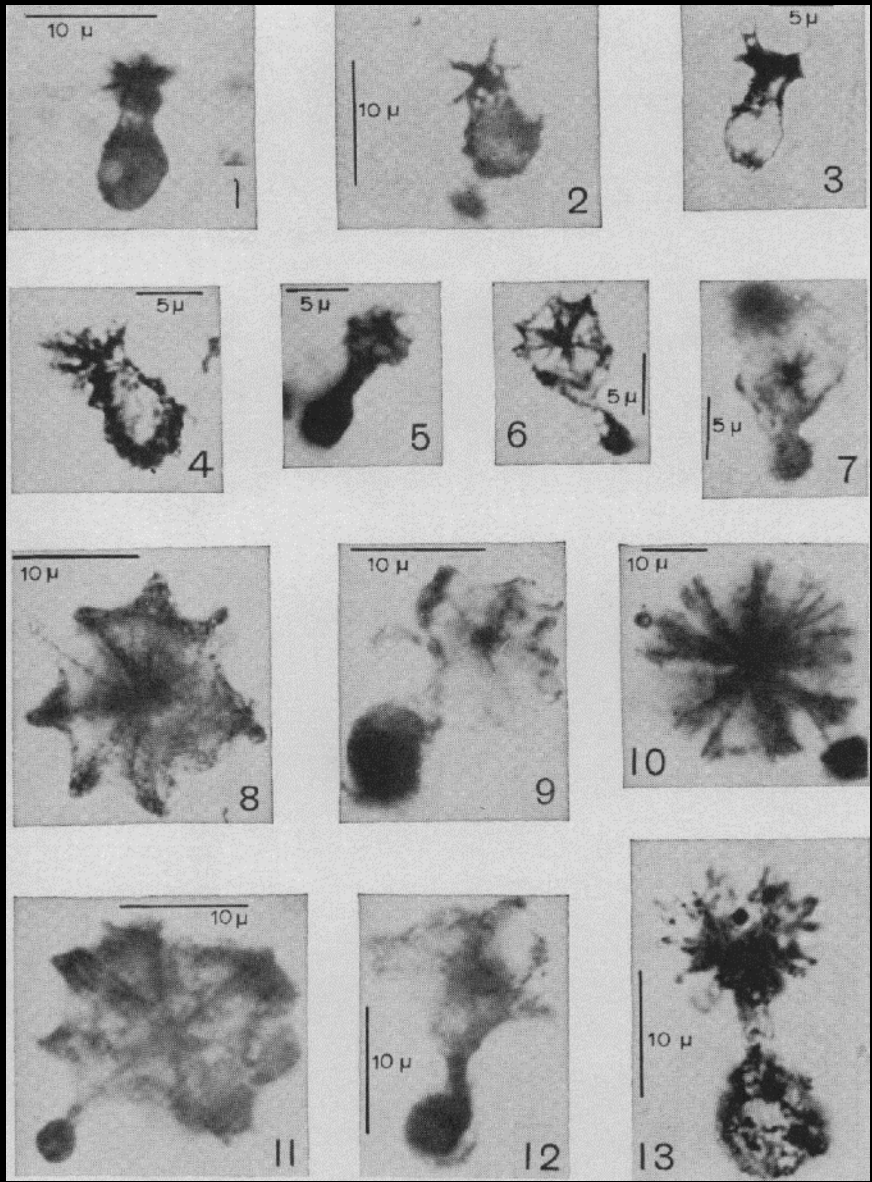
Organisms can leave obvious traces such as skeletons = fossils

T. rex, AMNH in New York

… Sometimes, even soft tissues can be fossilized

Archaeopteryx lithographica

More difficult for most ancient organisms: they were microbial

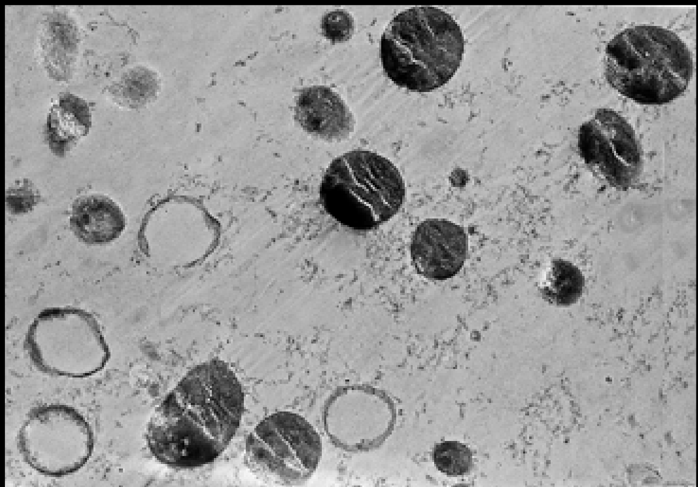


Fossil microorganisms in the Gunflint chert (Canada), ~1.9 Ga

Barghoorn and Tyler, 1965, Science

What is a fossil?

Trace of life preserved in the geological record



Experimentally fossilized bacteria
Benzerara et al. 2004

What is it composed of?

- ★ Microorganism itself (carbonaceous matter)
- ★ Replacement by minerals
- ★ Imprint of the microbe
- ★ Chemical transformations of the environment

How quick does it form?

Few days/weeks

How long is it preserved?

Billion years (?)

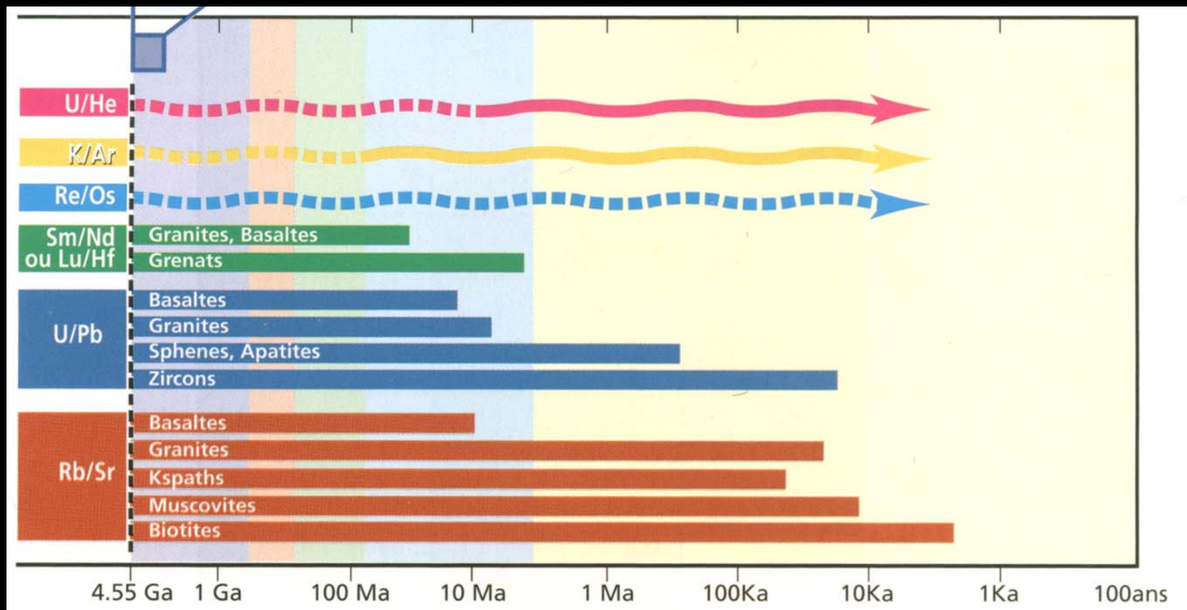
We need datations
e.g., Datation U/Pb on zircons

$^{238}U \rightarrow {}^{206}Pb + 8.{}^{4}He \qquad \lambda_{238} = 1.55125\times10^{-10}$ (4.5 Ga)

$$F = P\,(e^{\lambda t}-1) + F_0$$

$$^{206}Pb = {}^{238}U\,(e^{\lambda t}-1) + {}^{206}Pb_0$$

$$T=1/\lambda * \ln[({}^{206}Pb/{}^{238}U)+1]$$



Isotope Geology
C. Allègre

http://www.dailymotion.com/video/xclxo6_karim-benzerara-radiochronologie-ar_tech

Conditions at the surface of the Earth several billions years ago

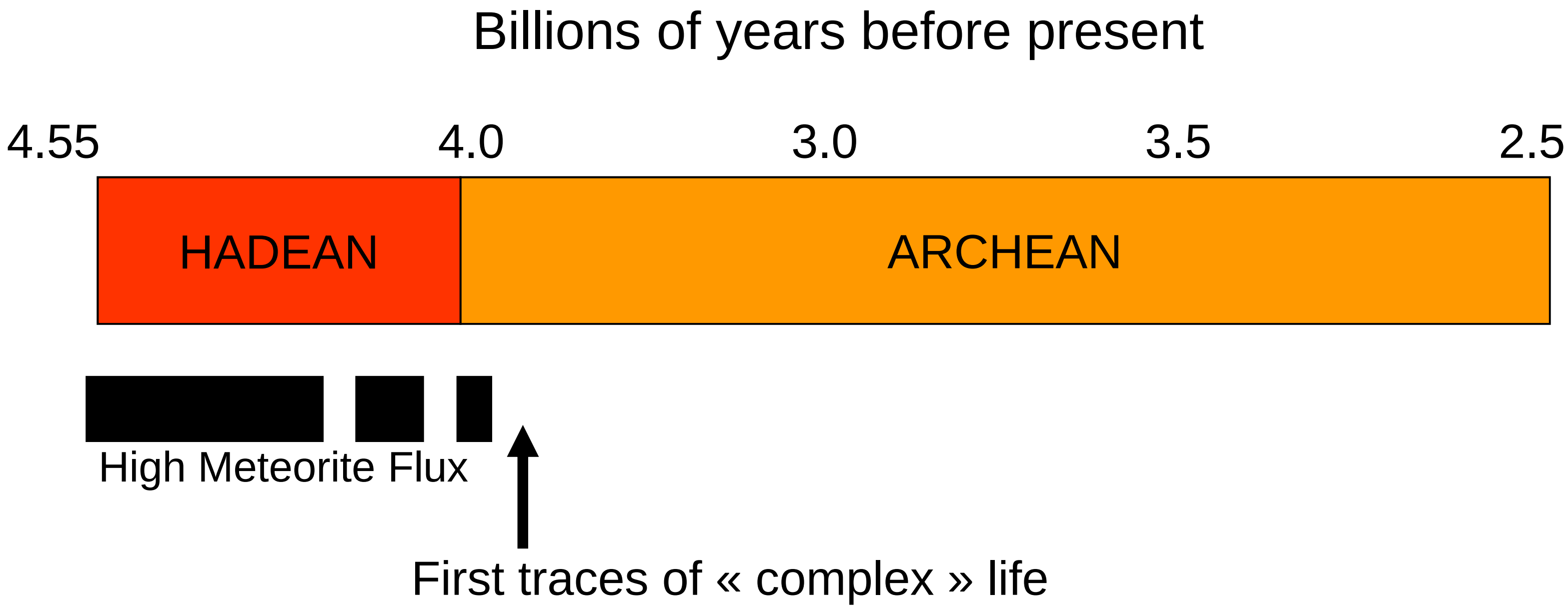
-Formation of the Earth : 4.55 Ga

- HADEAN: From 4.55 to 4 Ga. Intense meteoritic bombardment; vaporization of oceans and part of the crust but we start finding traces of oceans and crust at 4.4 Ga (Zircons).

- Archean, 4 – 2.5 Ga: Most ancient rocks; formation of most of the continental crust.

- Late Heavy Bombardment (4.1 to 3.8 Ga)
- Atmosphere: hardly any molecular oxygen (O_2)
- UV radiation (no ozone shield)
- Sun less luminous (20-30%)
- CO_2 and CH_4 -rich atmosphere
- Likely warm surface conditions (80° to 45°C) ?
- High rate of heat transfer from core to surface, possible thin crust, plate tectonics just being established
- Magnetic field by 3.2 Ga

When do the first traces of life appear in the geological record?



Current Paradigm: The Early Eden

= As soon as we find rocks, we find traces of life!

OUTLINE

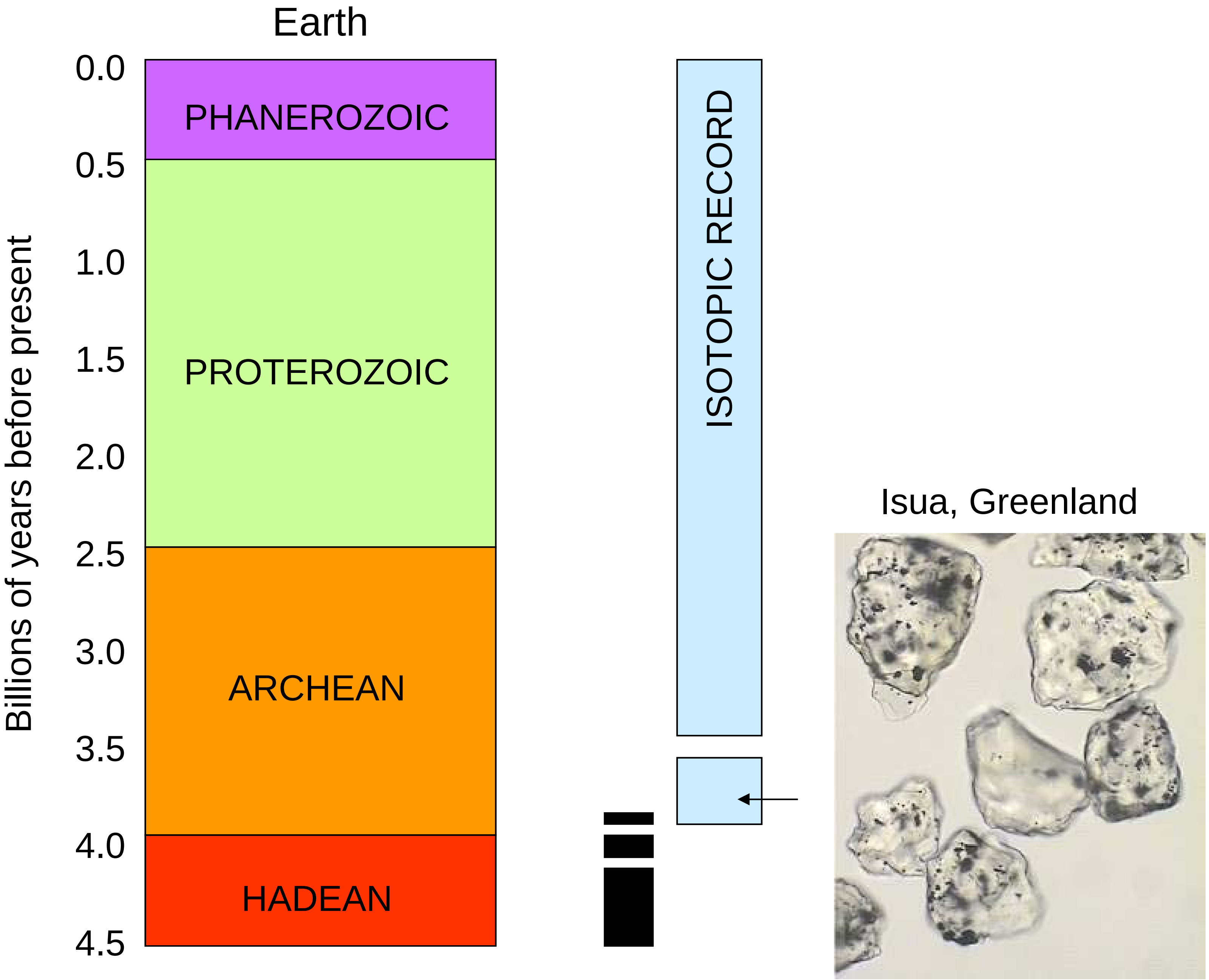
I. Review some of the oldest purported traces of life; what is it based on? Why are they debated

- ★ Chemical fossil – Isua, Greenland - 3.8 Ga
- ★ First microfossils – Pilbara, Australia - 3.5 Ga
- ★ Stromatolites – « everywhere » - 3.5-2.5 Ga

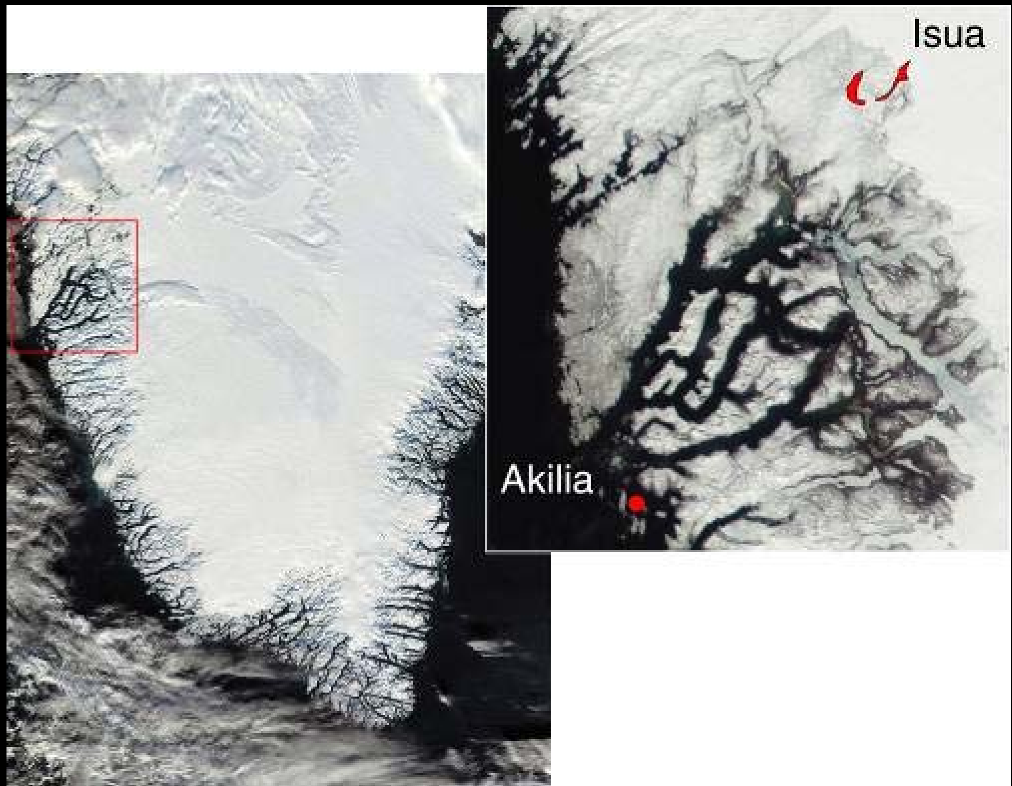
II. What are the perspectives?

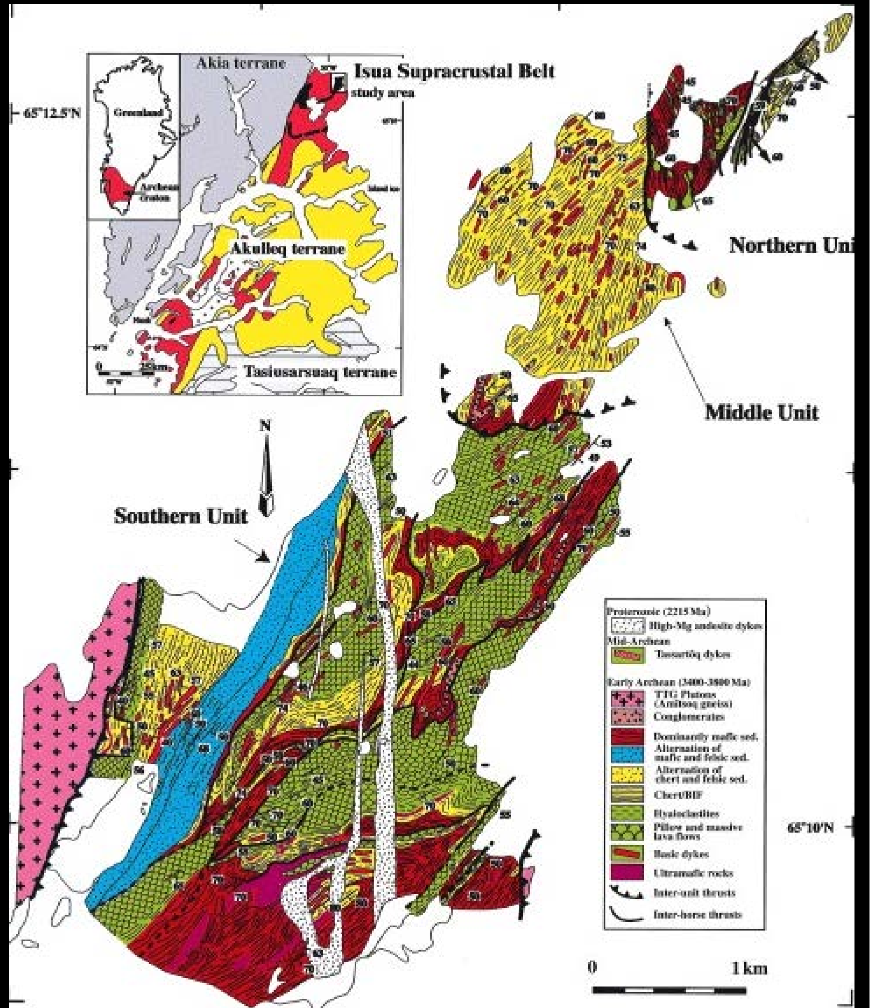
- ★ Can we predict what traces can be left in rocks by life?
- ★ Can we simulate aging over geological timescales?
- ★ How advanced analytical tools can help?

The oldest (chemical) traces of life ?



Akilia and Isua, Groënland (3,8 Ga)





Komiya et al (2004) Island Arc
Mojzsis et al (996) Nature

Isua : the oldest sedimentary rocks on Earth

Turbidites

Fe-rich sediments
(Banded Iron Formations)

Carbonates

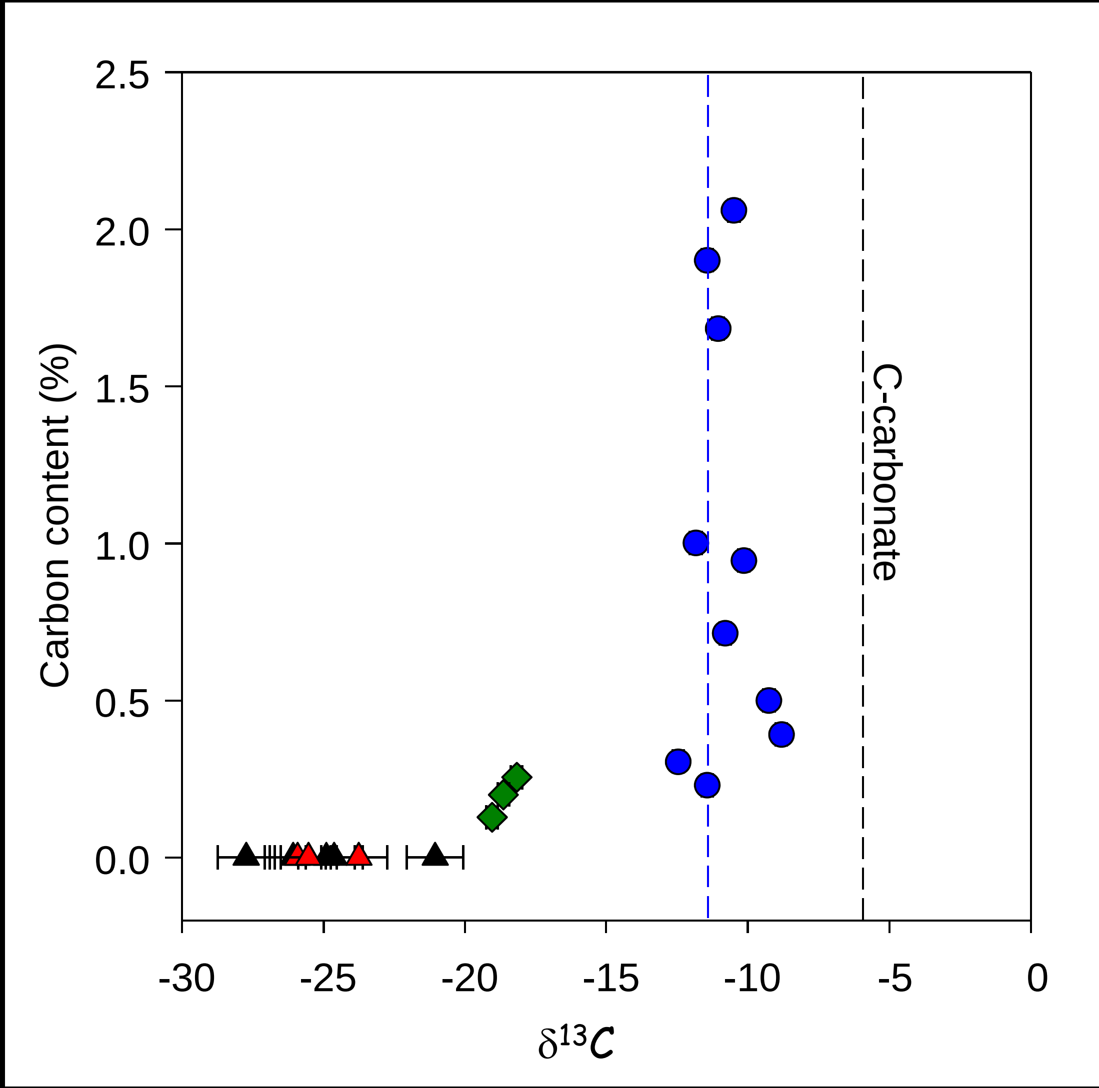
Some time after their formation in aqueous solutions, these rocks were buried and experienced an important heating and pressuring (metamorphism)

T= 550°C, P= 5 kbar

Courtesy of Mark Van Zuilen (IPGP)

There is reduced carbon (i.e., organic carbon) in these rocks and it has a particular isotopic composition

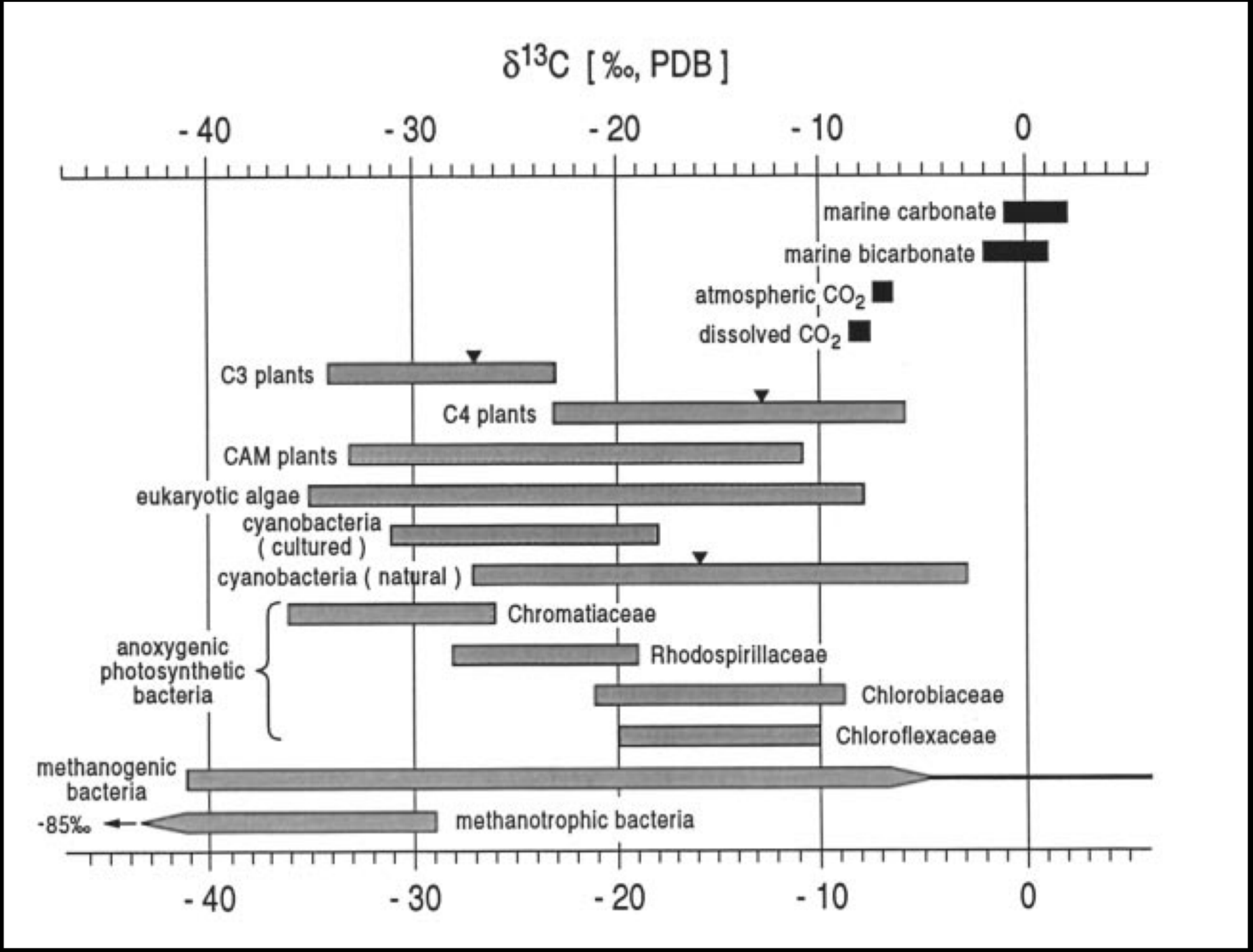
$$\delta^{13}C = \left(\frac{\left(\frac{^{13}C}{^{12}C}\right)_{sample} - \left(\frac{^{13}C}{^{12}C}\right)_{standard}}{\left(\frac{^{13}C}{^{12}C}\right)_{standard}} \right) * 1000$$



This organic carbon is light, i.e., relatively poor in ^{13}C: biological ?

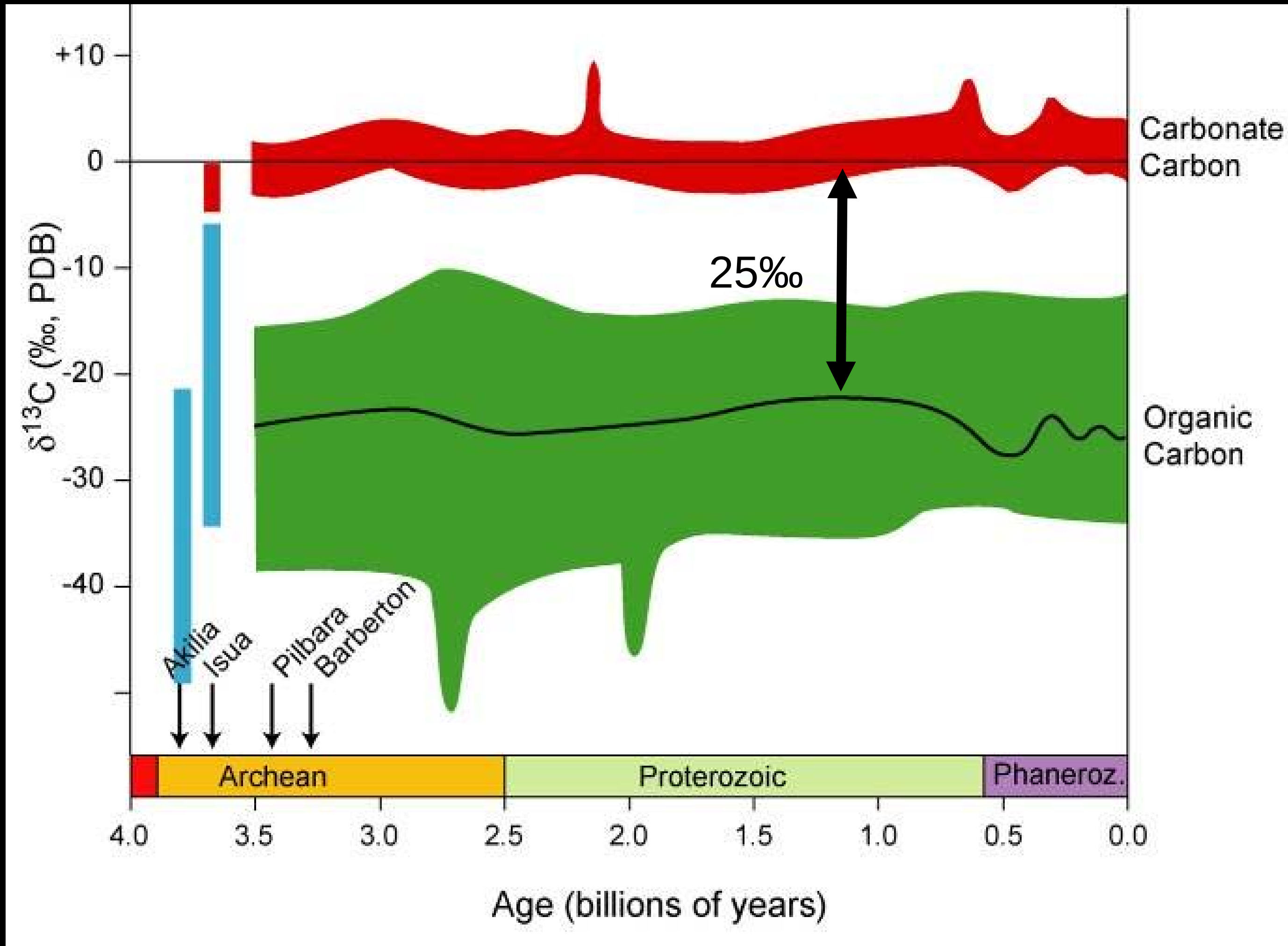
Courtesy of Mark Van Zuilen (IPGP)

Stable isotopes of carbon: good tracers of the origin of the molecules bearing it (?)



Schidlowski, Precambrian Research, 2001

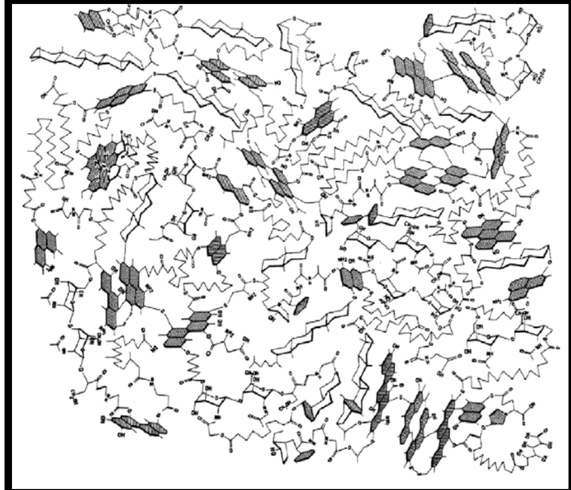
$\delta^{13}C$ of organic carbon constant since 3.8 Ga



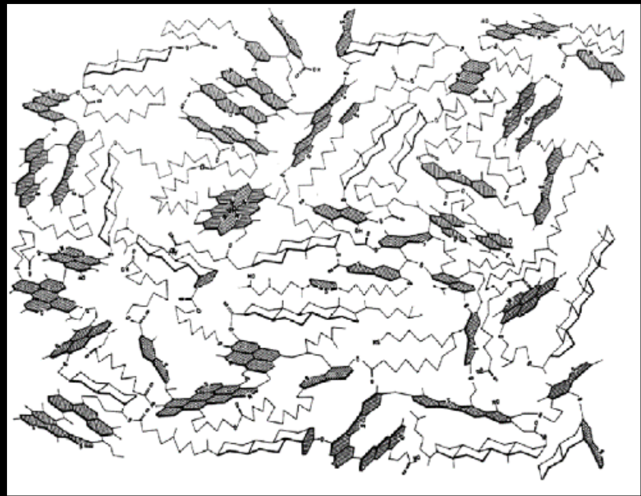
One interpretation:
Amount of organic carbon constant since 3.8 Ga
-25 ‰ = oxygenic photosynthesis (Schidlowski et al. 1987)

Transformation of organic carbon upon aging (with increasing T and P)

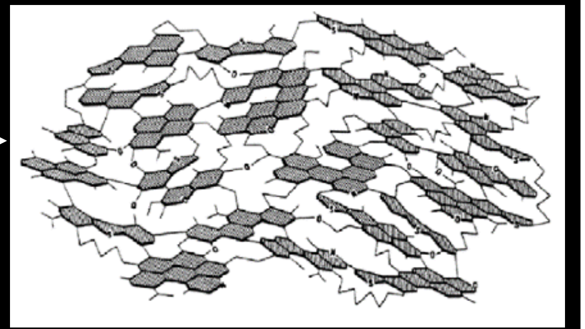
H/C=1.34; O/C=0.196

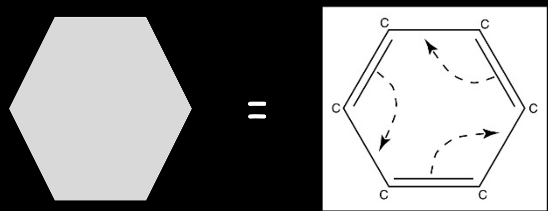


H/C=1.25; O/C=0.089

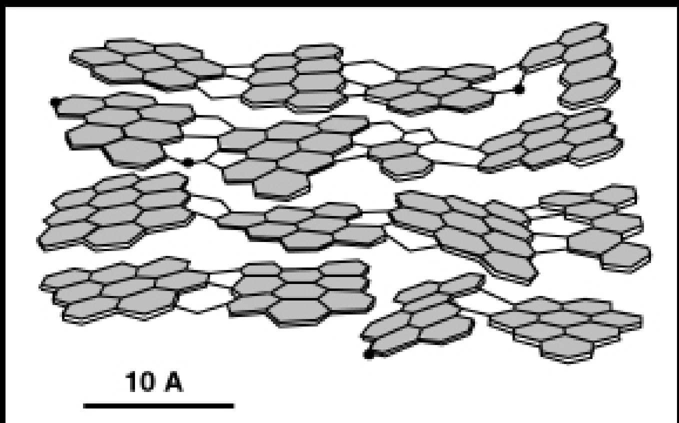


H/C=0.73; O/C=0.026

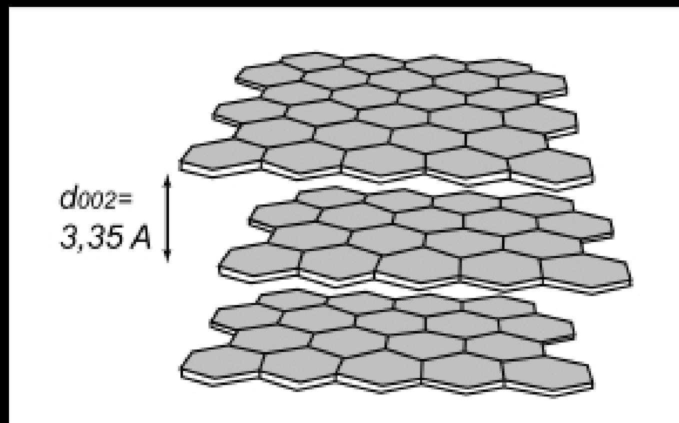




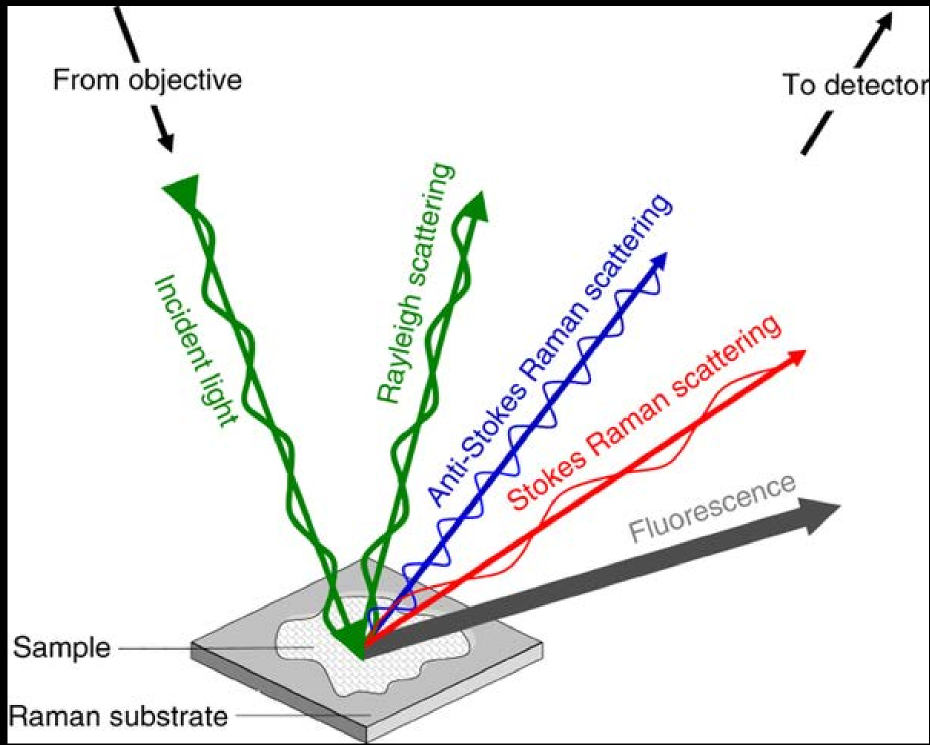
disordered carbonaceous material



graphite



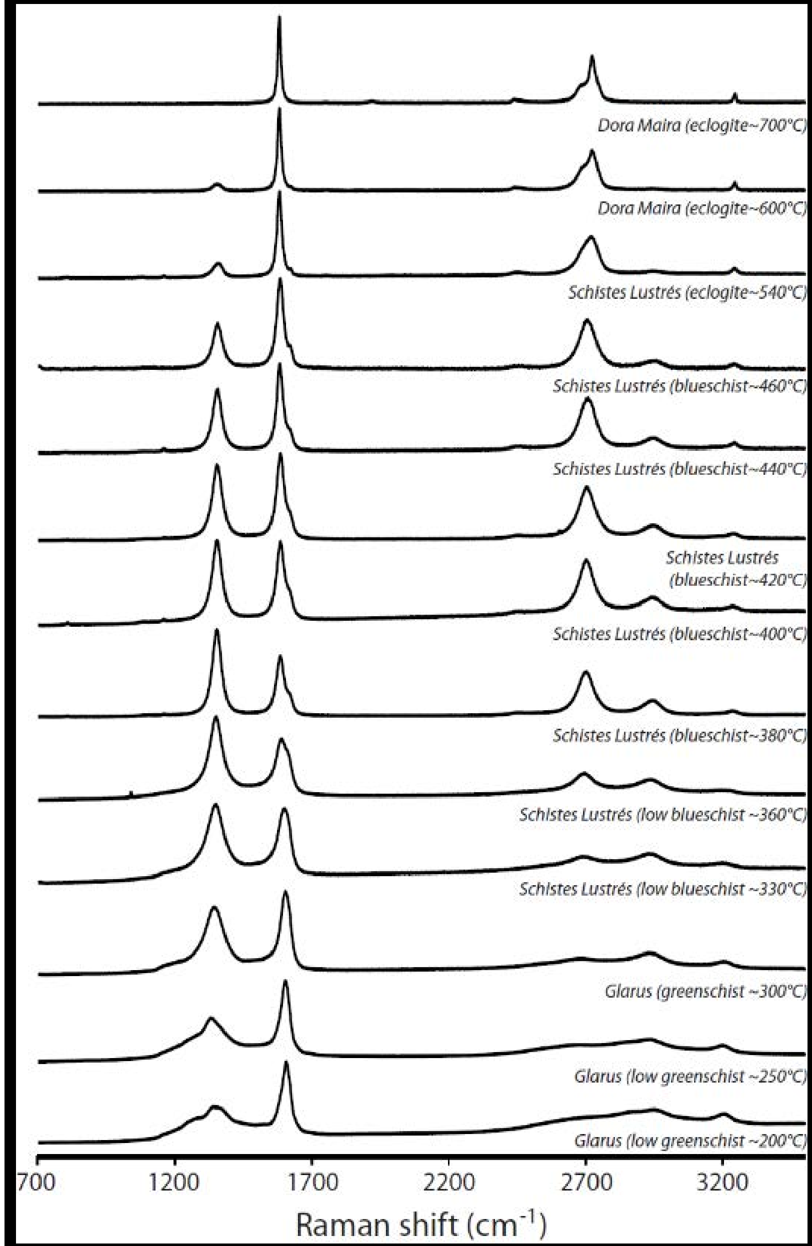
Use of Raman spectroscopy to study carbonaceous matter

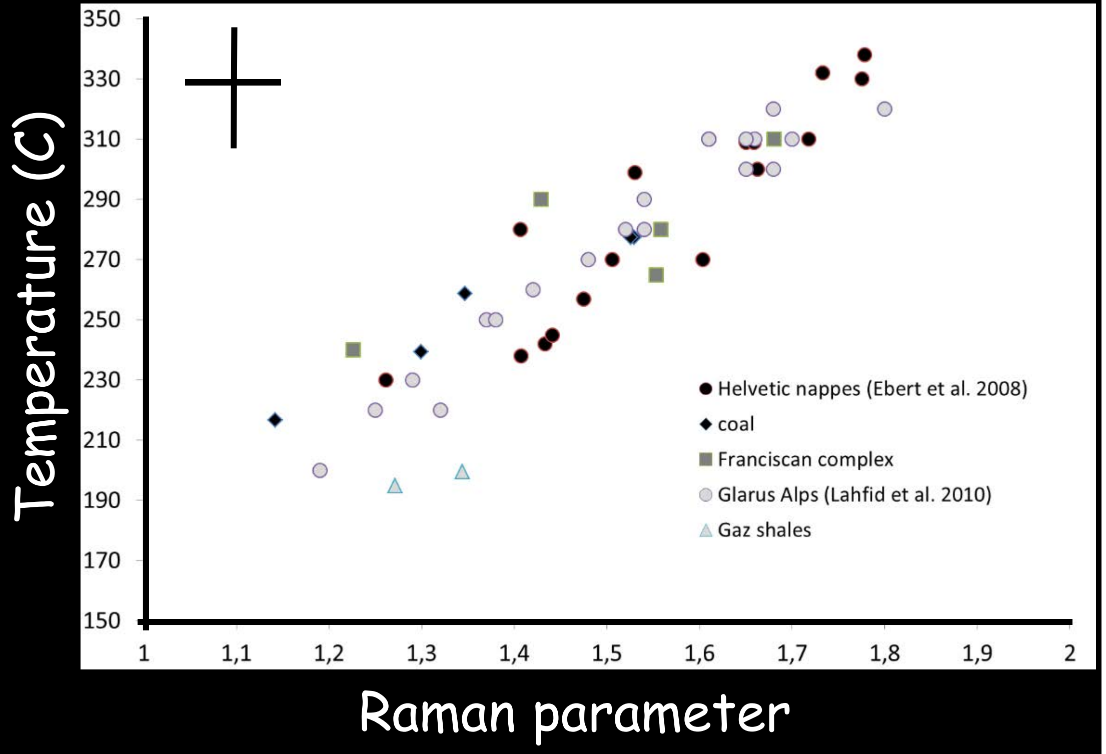


Inelastic scattering of light
Vibrational frequencies are characteristic of chemical bonds in a specific molecule; Information about degree of cristallinity

e.g., Beyssac and Lazzeri (2012) Application of Raman spectroscopy to the study of graphitic carbons in the Earth Sciences. EMU Notes in Mineralogy, 12, 415-454.

Studying carbonaceous matter by Raman as a measure of thermal maturity

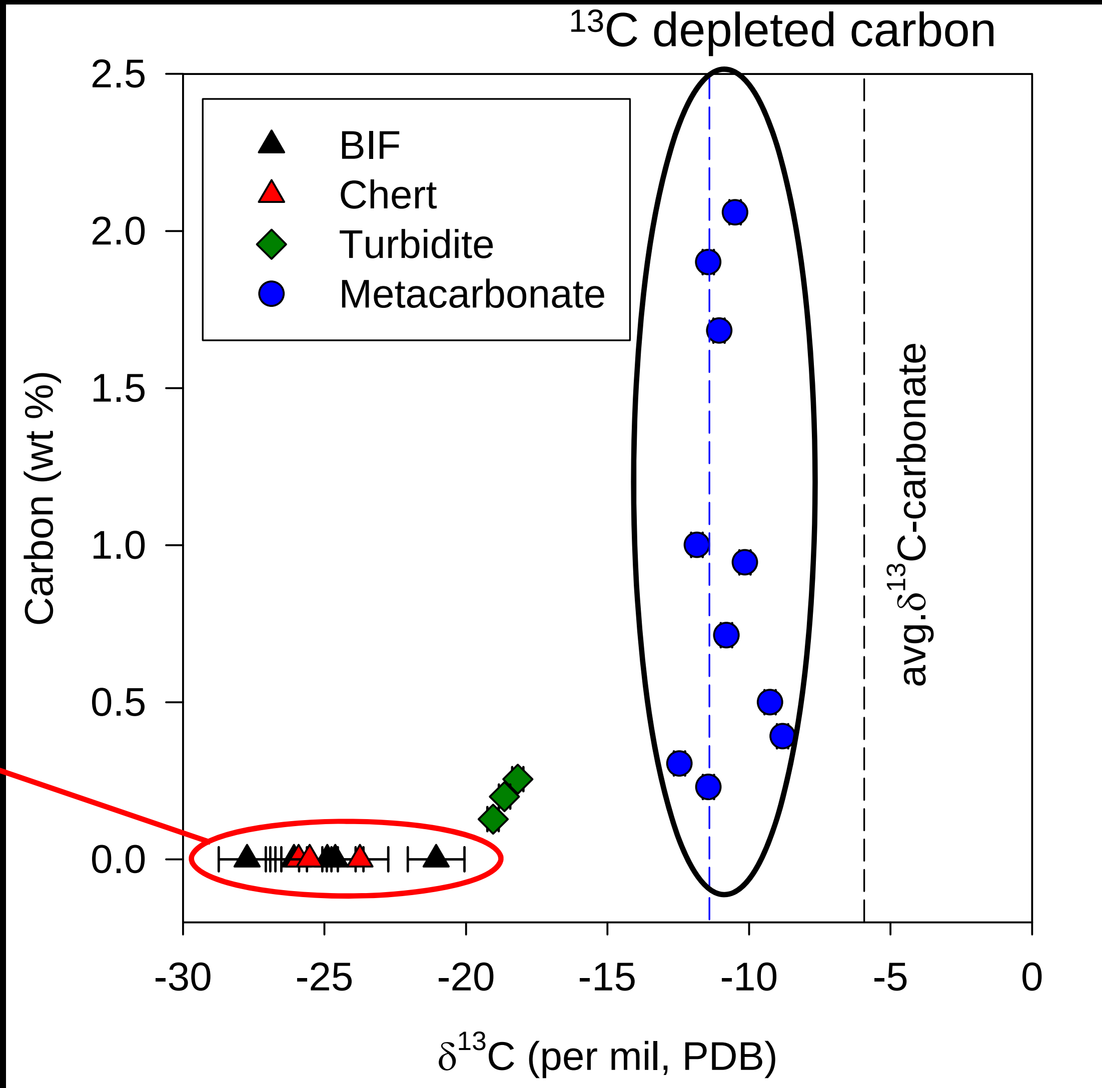




Beyssac et al (2002; 2003)

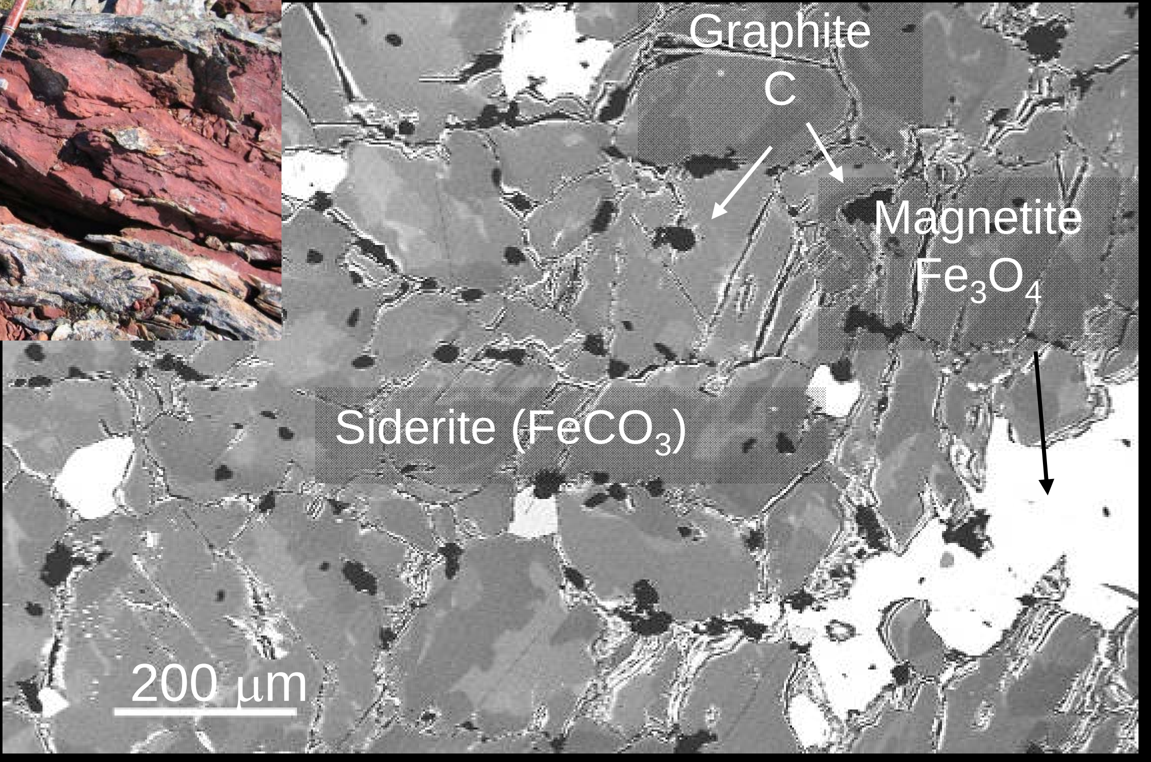
Raman study of organic carbon in Isua rocks

Non-metamophosed carbon
= Modern contamination



Organic carbon production by thermal decomposition of Fe-carbonates in Isua rocks

Van Zuilen et al. (Nature, 2002)



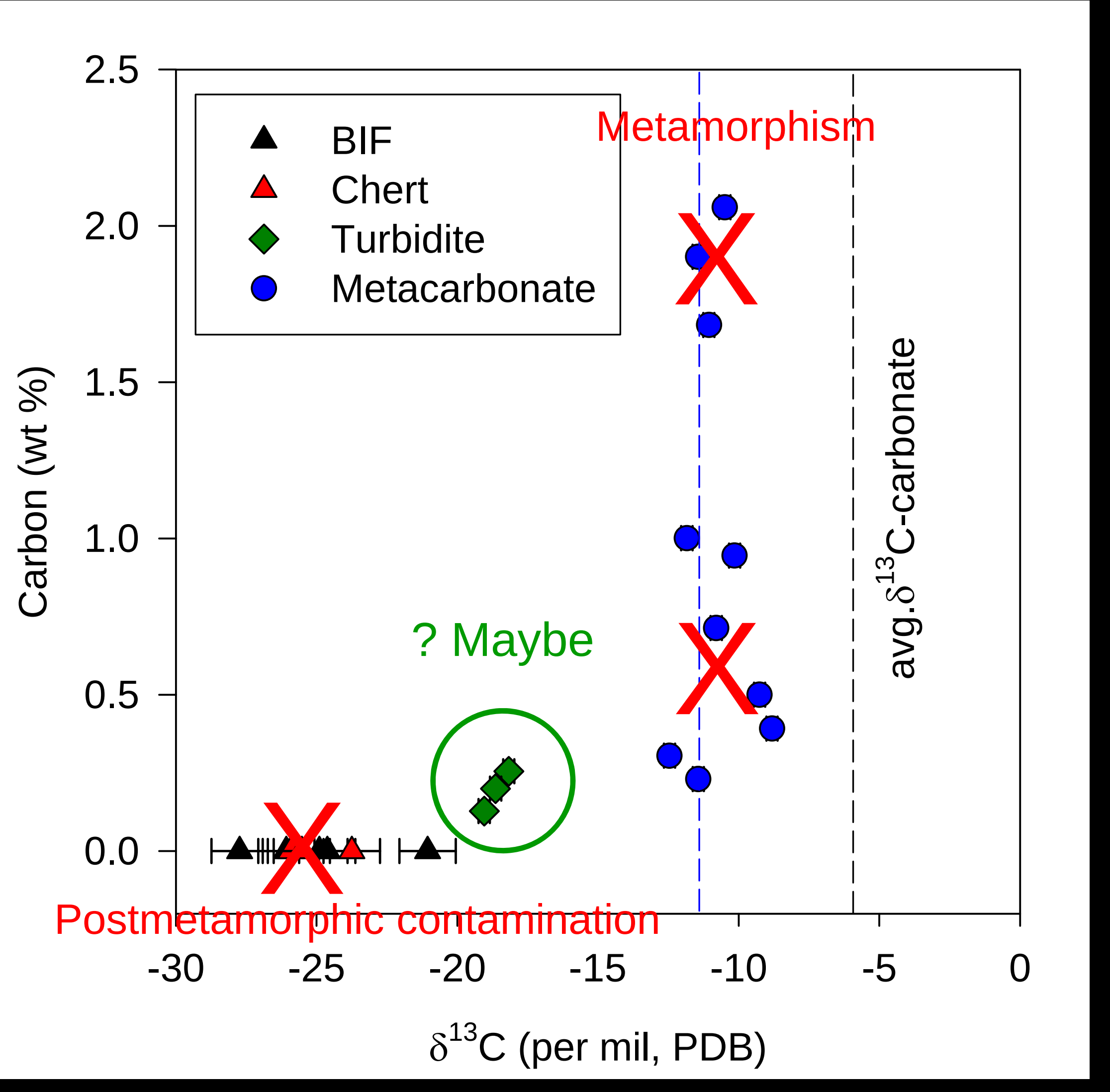
Thermal decomposition:
T= 550°C
P= 5 kBar

siderite magnetite graphite

$$6\ FeCO_3 = 2\ Fe_3O_4 + 5CO_2 + C$$

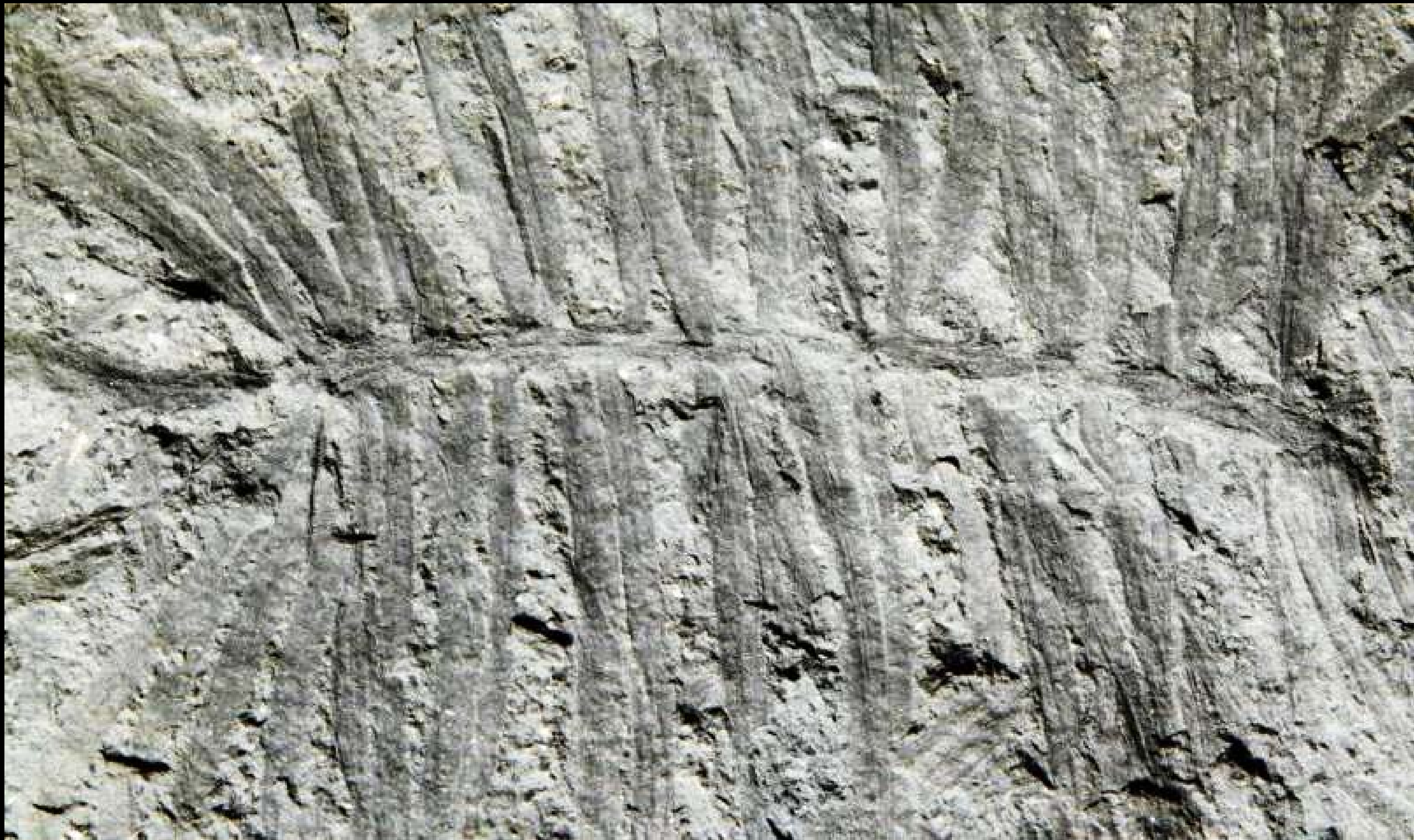
⇒ Isotopic fractionation of carbon

Summary



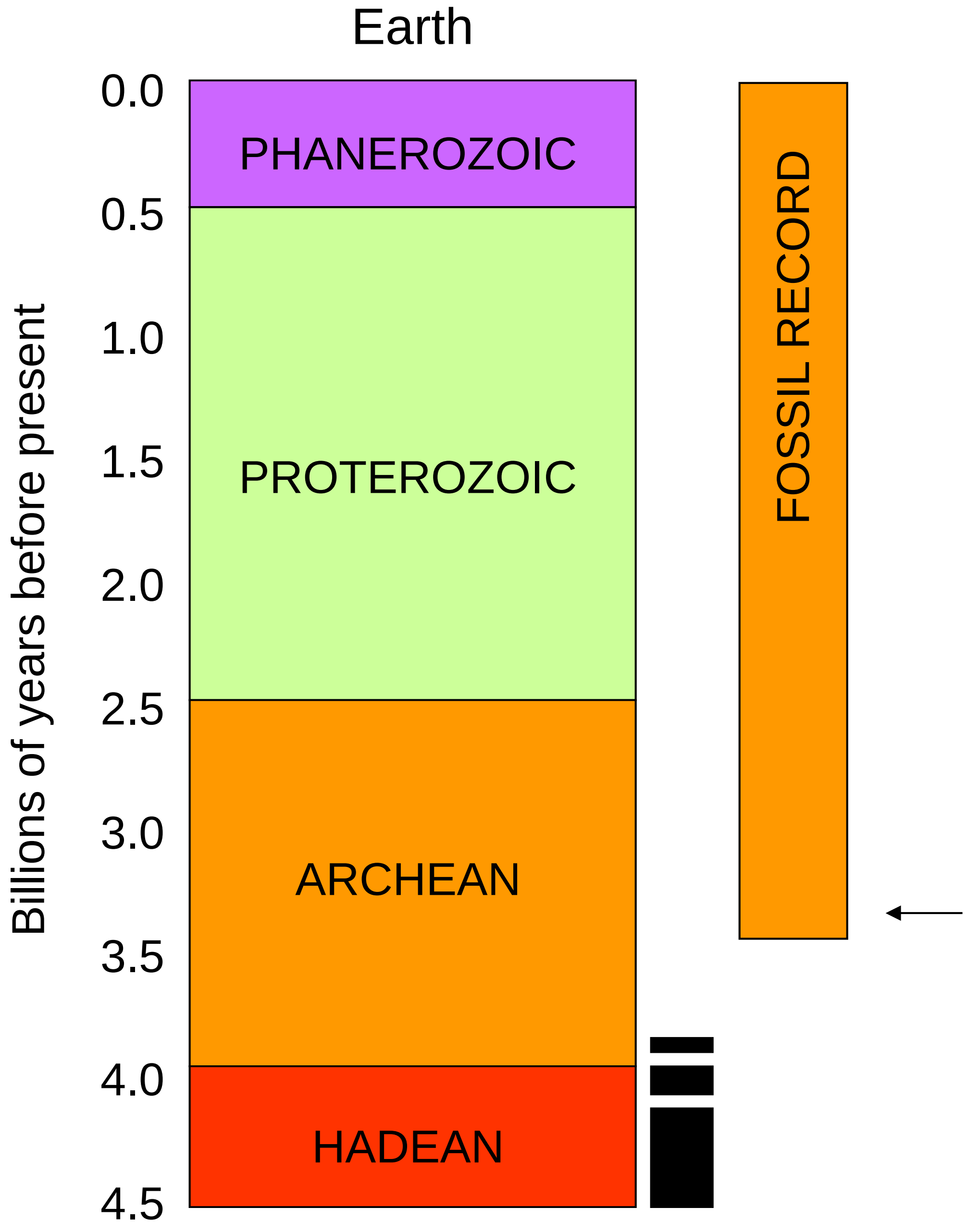
BIF
Chert
Turbidite
Metacarbonate
Metamorphism
? Maybe
Postmetamorphic contamination
avg.δ13C-carbonate
Carbon (wt %)
δ13C (per mil, PDB)
2.5
2.0
1.5
1.0
0.5
0.0
-30
-25
-20
-15
-10
-5
0

Yet, some fossils can be preserved in relatively highly metamorphosed rocks même de haut grade

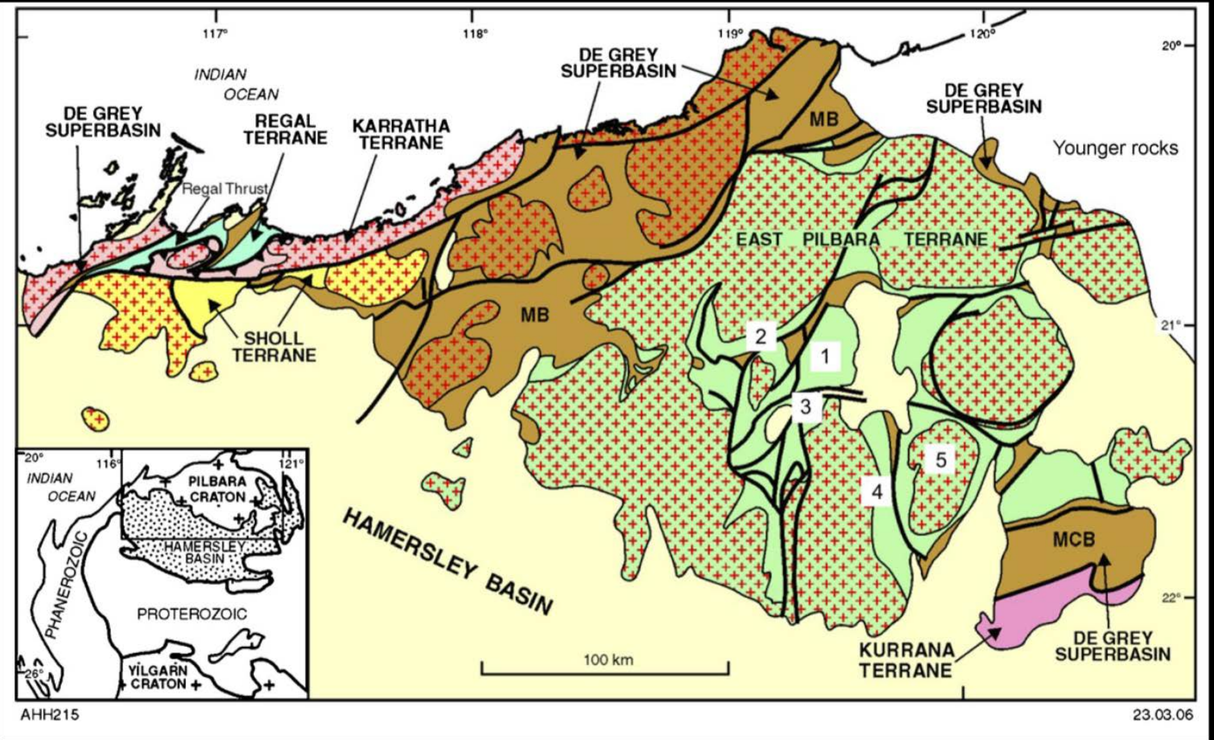


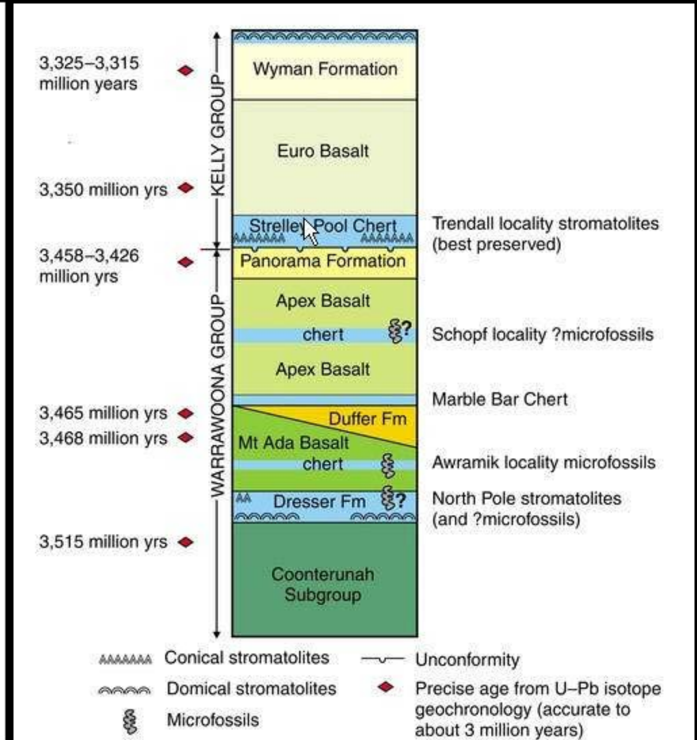
Fossil of a fern-like plant mixed with minerals indicative of metamorphic conditions: >15km, 360°C (New Zealand) Galvez et al. (2012) *Geobiology*

The oldest microfossils? (Australie, 3.465 Ga) ?



First microfossils at 3.47 Ga in Apex chert, Pilbara (Australia)





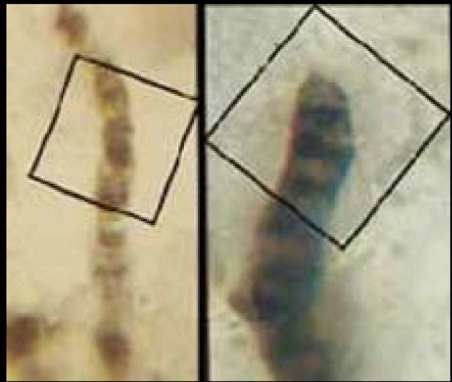
Allwood et al. (2007) Prec Res

Observation of dark filaments in silica-rich rocks (cherts)

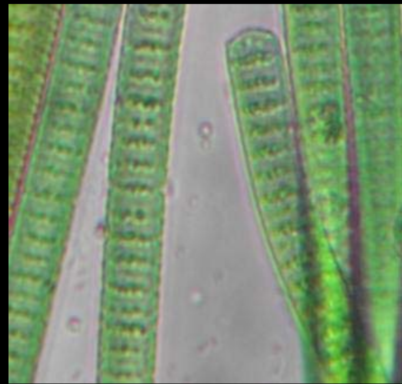
Schopf et Packer, 1987; Schopf et al., 2002

1st interpretation: microfossils

Morphology: Simple, unbranched filaments with septation: look like chains of cells



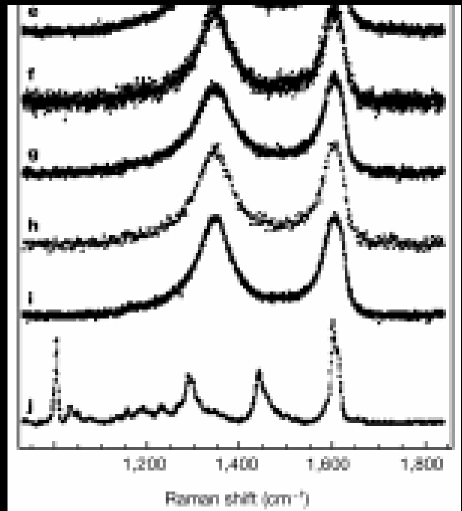
Morphology ⟷



Filaments, Australia, 3.5 Ga

Modern cyanobacteria

Chemical composition: Reduced carbon



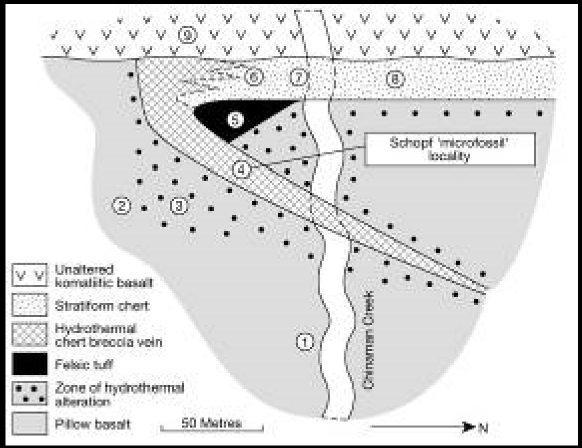
Paleoenvironment: Sedimentary (shallow water) environment

Schopf et Packer, 1987; Schopf et al., 2002

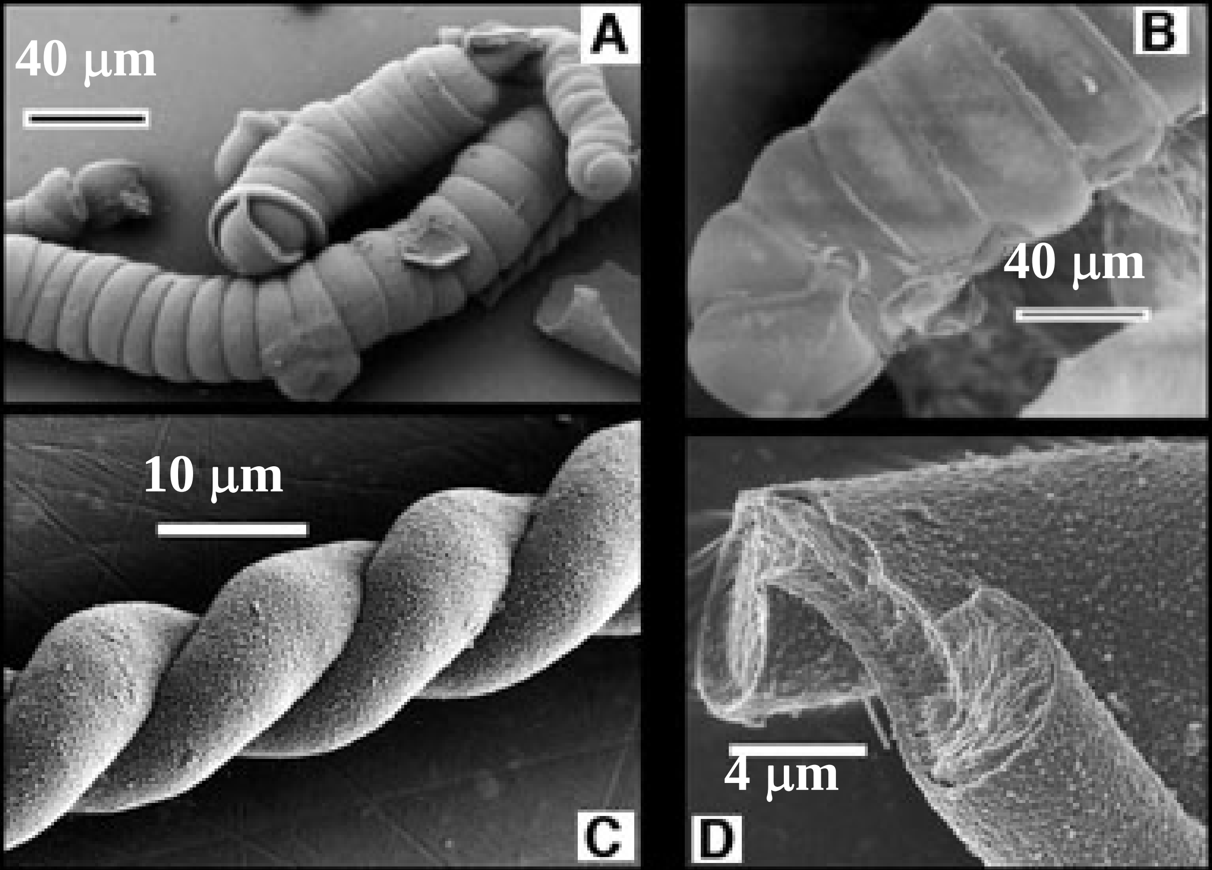
2^{nd} interpretation: abiotic objects

Brasier et al. (Nature, 2002), Garcia-Ruiz et al. (Science, 2003)

Reinterpretation of geological setting: → Hydrothermal environment



Abiotic processes can form similar filament morphologies



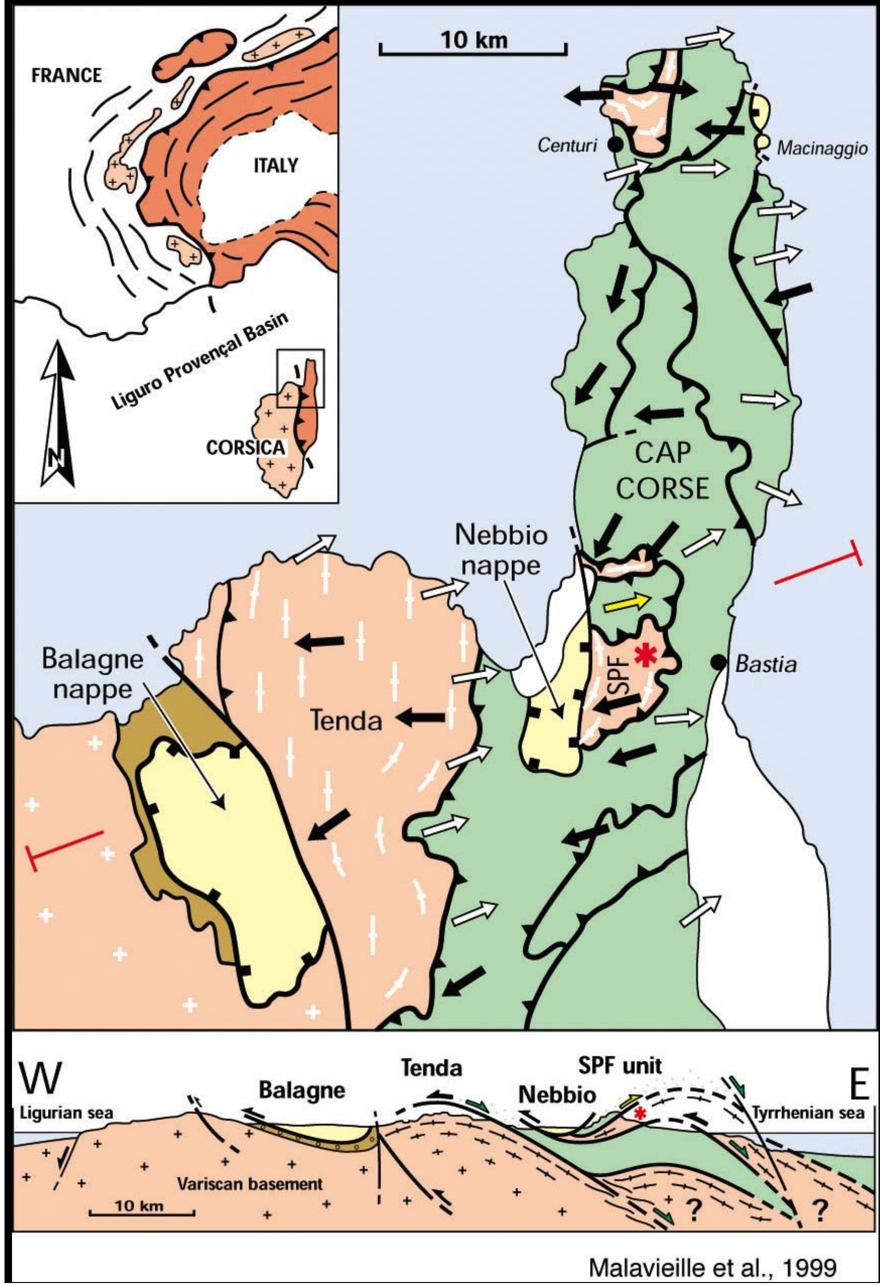
Garcia-Ruiz et al. (2003)

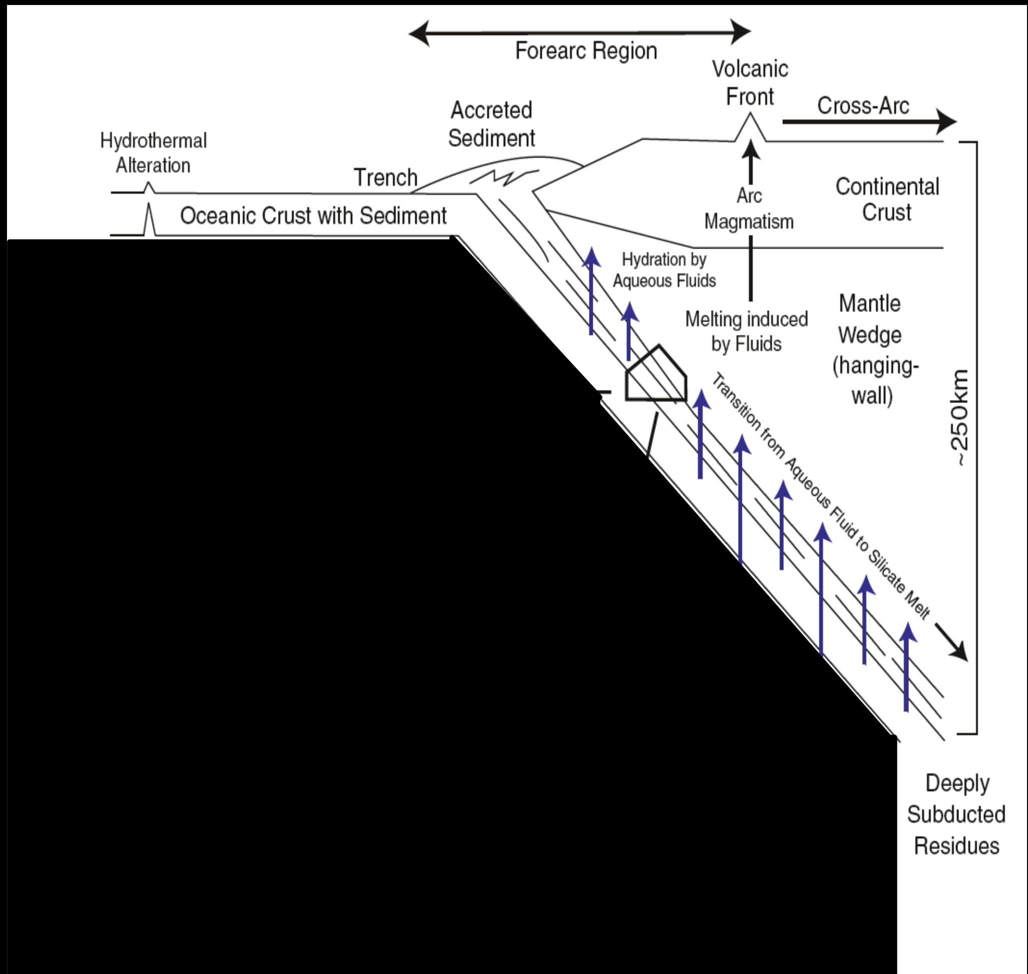
→ Abiotic synthesis of segmented filaments

Barium salt + sodium silicate

ambient T and P, pH from 8.5 to 11.

Abiotic processes can form reduced carbon e.g., massive formation of abiotic reduced carbon in Corsica



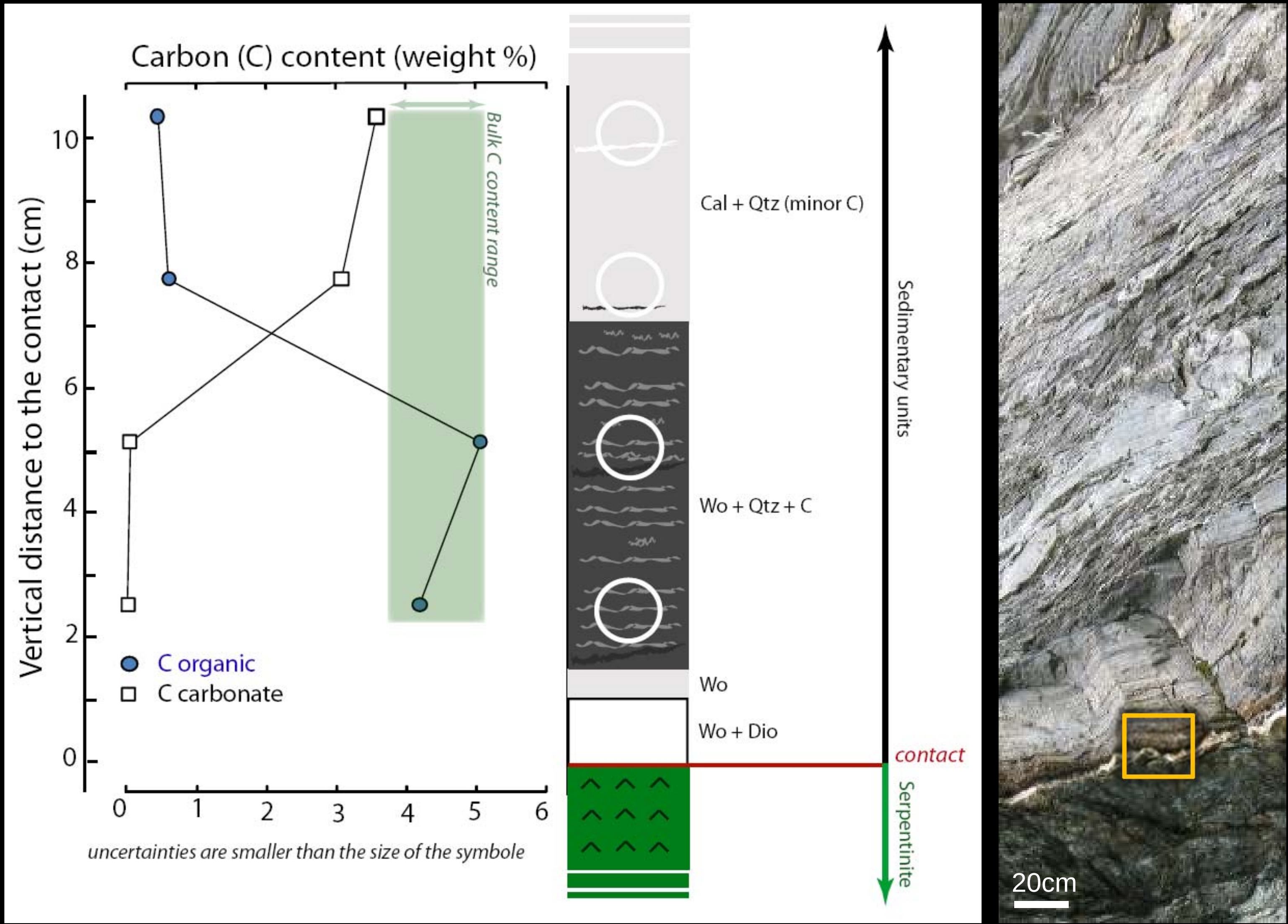


Galvez et al. Nature Geoscience (2013)


APPELLATION PATRIMONIO CONTRÔLÉE

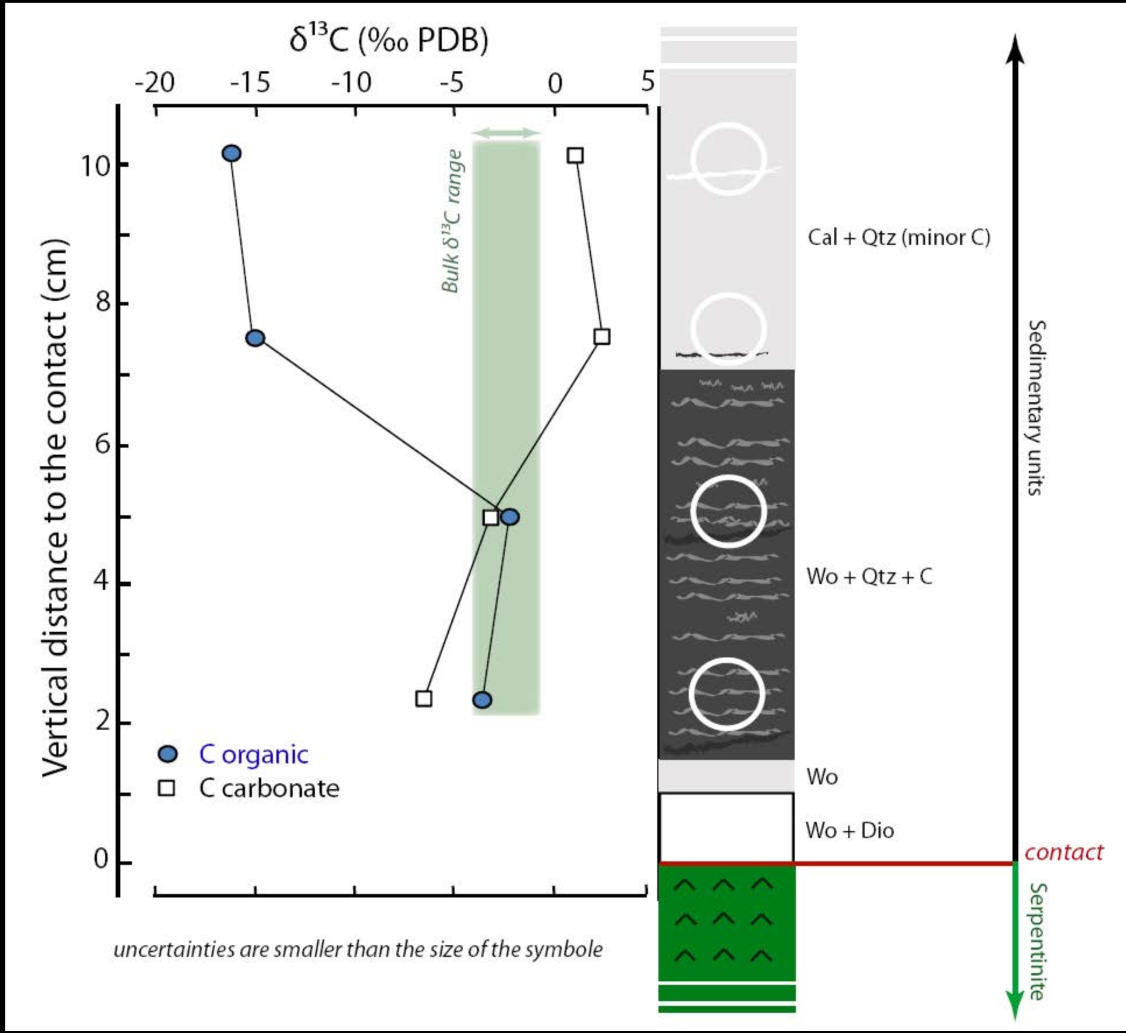
Mineralogical and chemical analyses of the rocks show that reduced carbon comes from the reduction of C in carbonates

$$CaCO_3 + SiO_2 + 2H_2 = CaSiO_3 + C + 2H_2O$$



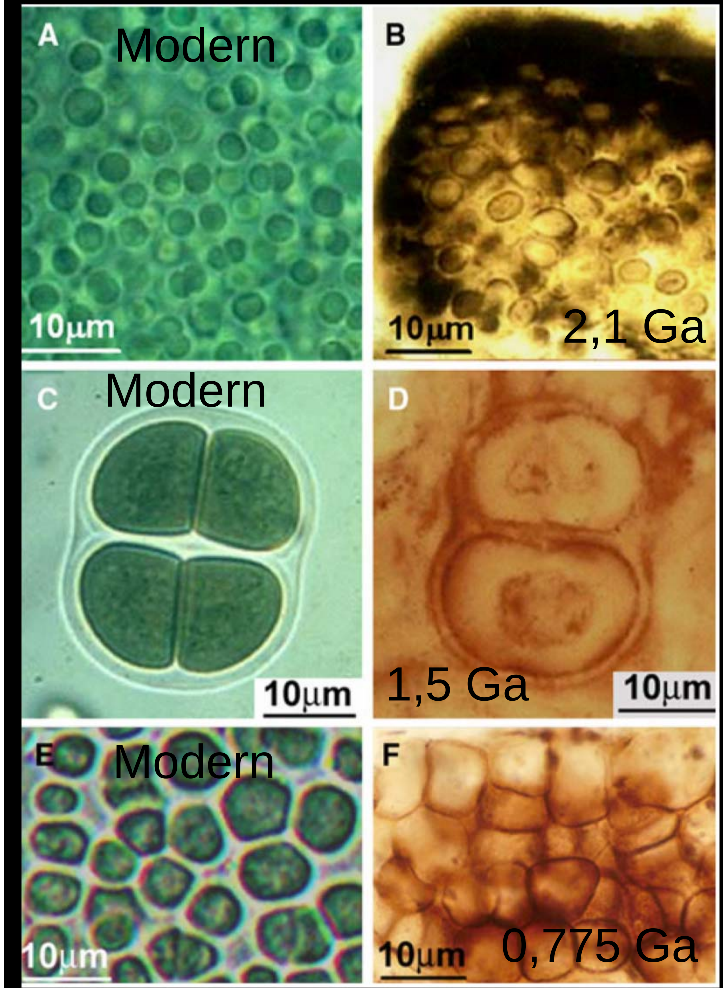
Reduced C ≠ biological

Carbon isotopes provide a signature about abiotic origin?

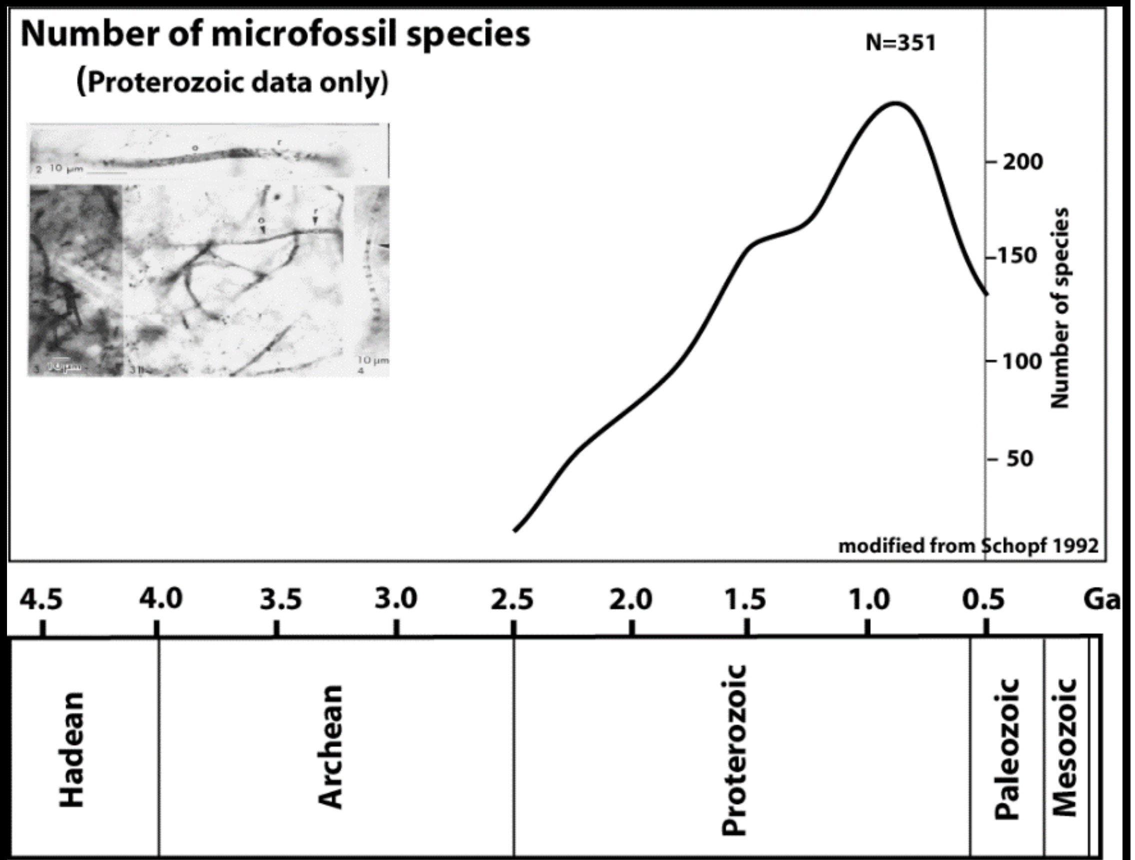


Here yes, but in other cases there might be some issues: isotopic reequilibration with other co-existing C species during metamorphism; isotopic fractionation due to some metamorphic reactions (see before)

Younger undisputed occurrences of microfossils do exist though

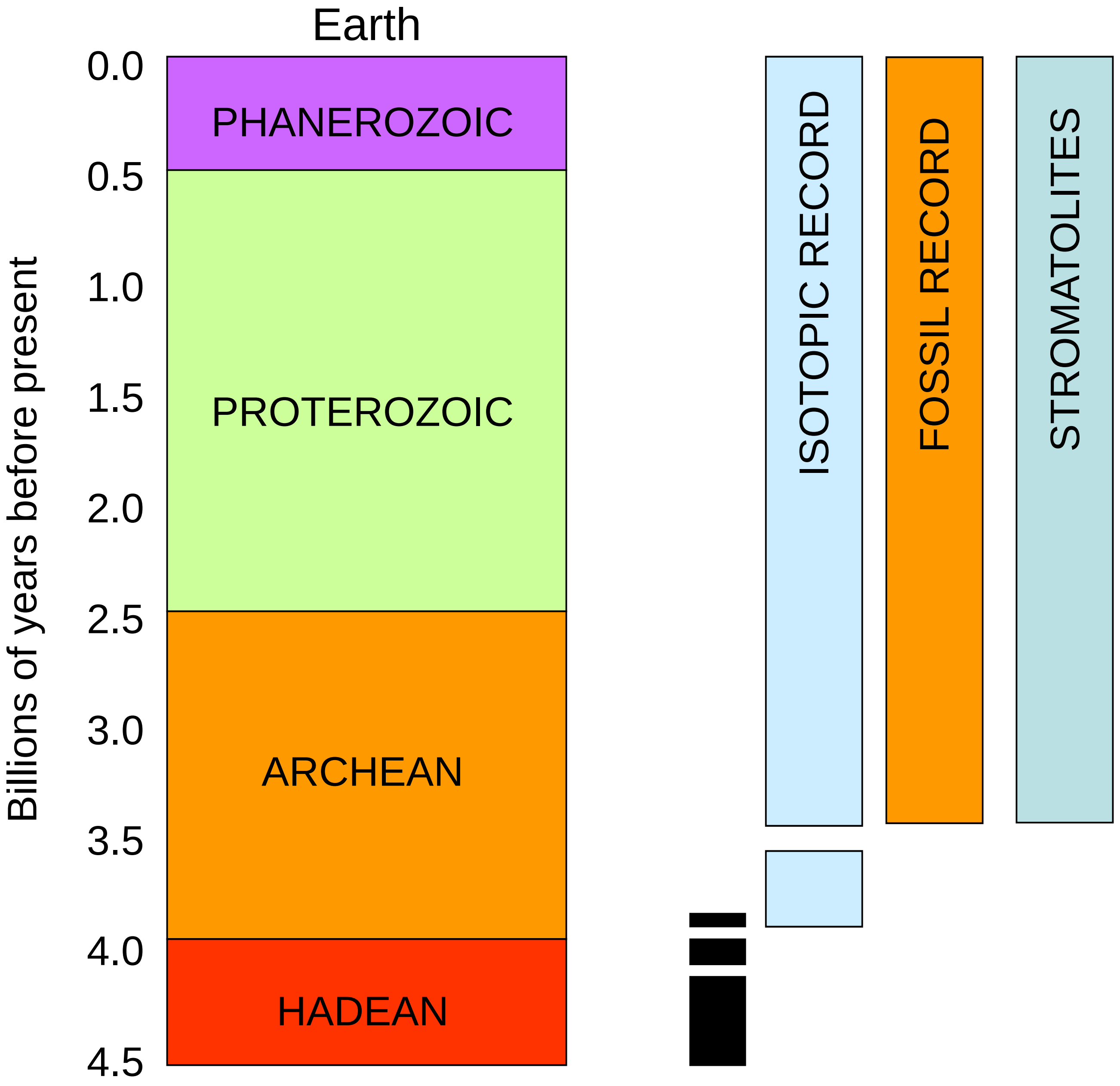


From Schopf (2011)



From Schopf 1992

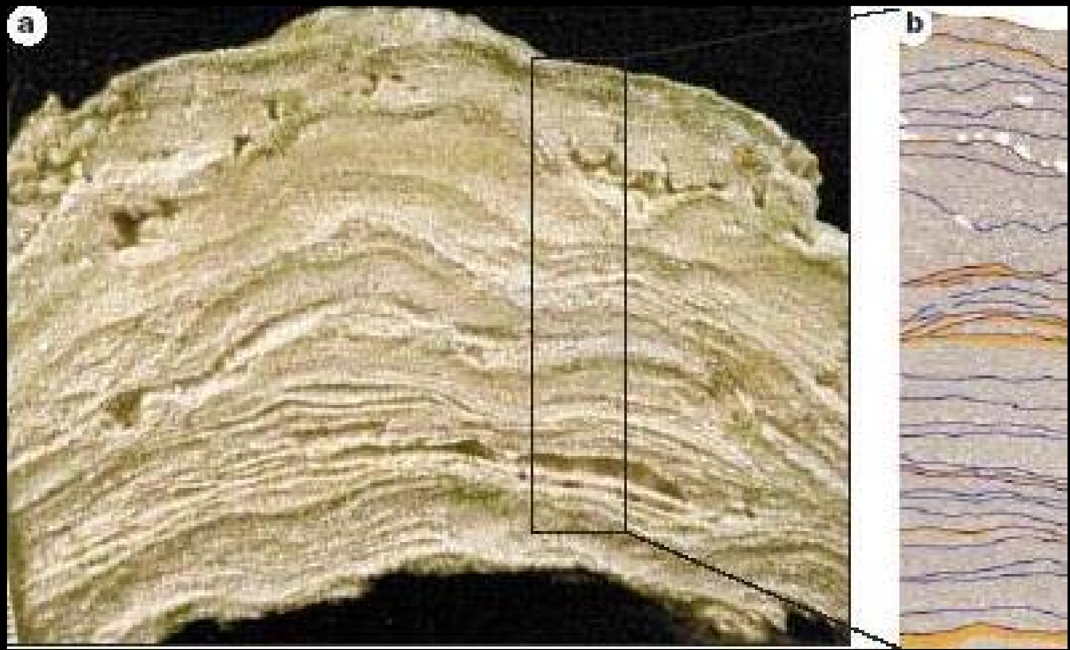
The oldest rocks formed by life?



Stromatolites: a record of Early life (?)

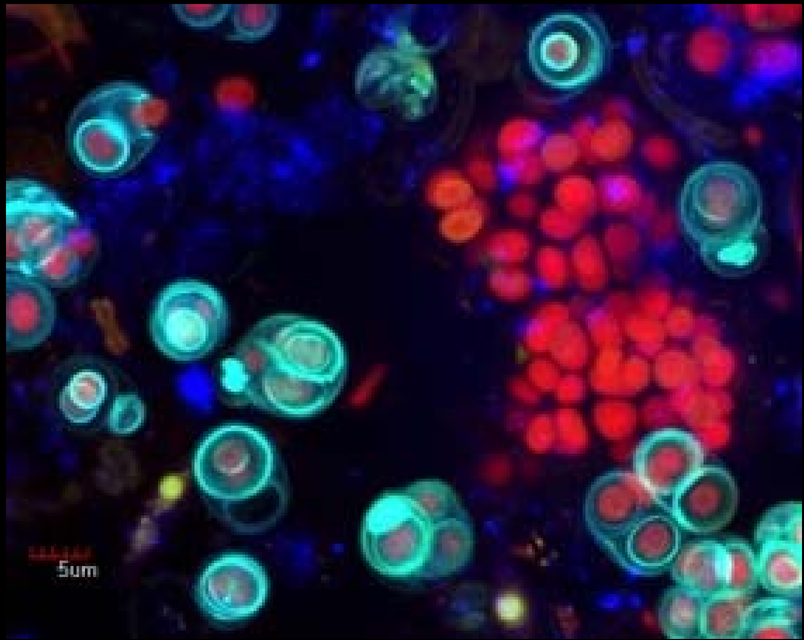
Descriptive definition

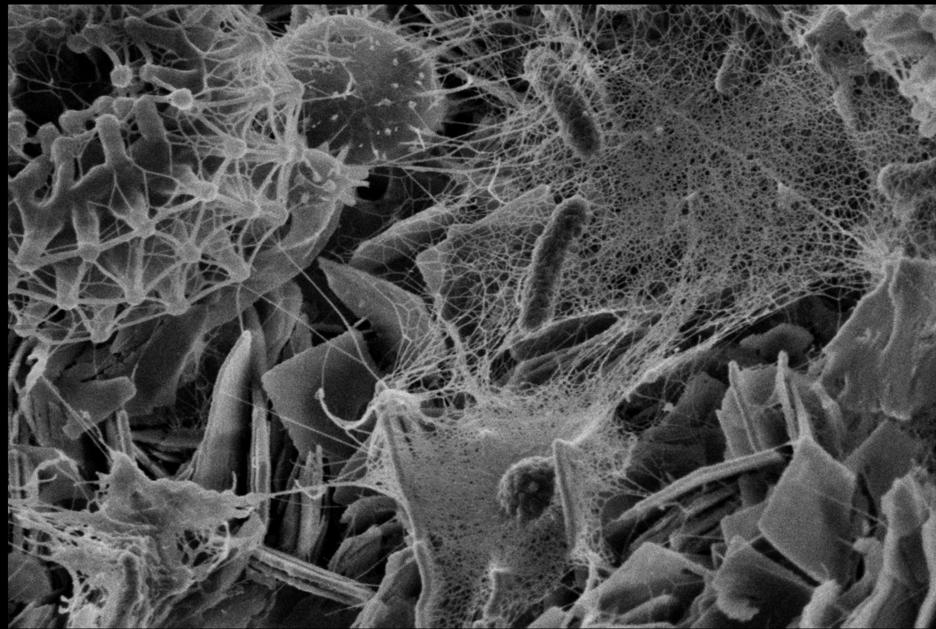
Laminated sedimentary rock often composed of carbonates forming from a point or a limited surface (e.g., Semikhatov et al., 1979). Stromatolites can have various morphologies.



Modern stromatolite from Bahamas
[Reid et al. 2000 Nature 989-992]

Modern stromatolites are inhabited by a huge diversity of microbes, including Cyanobacteria
(e.g. Lopez-Garcia et al., 2005)

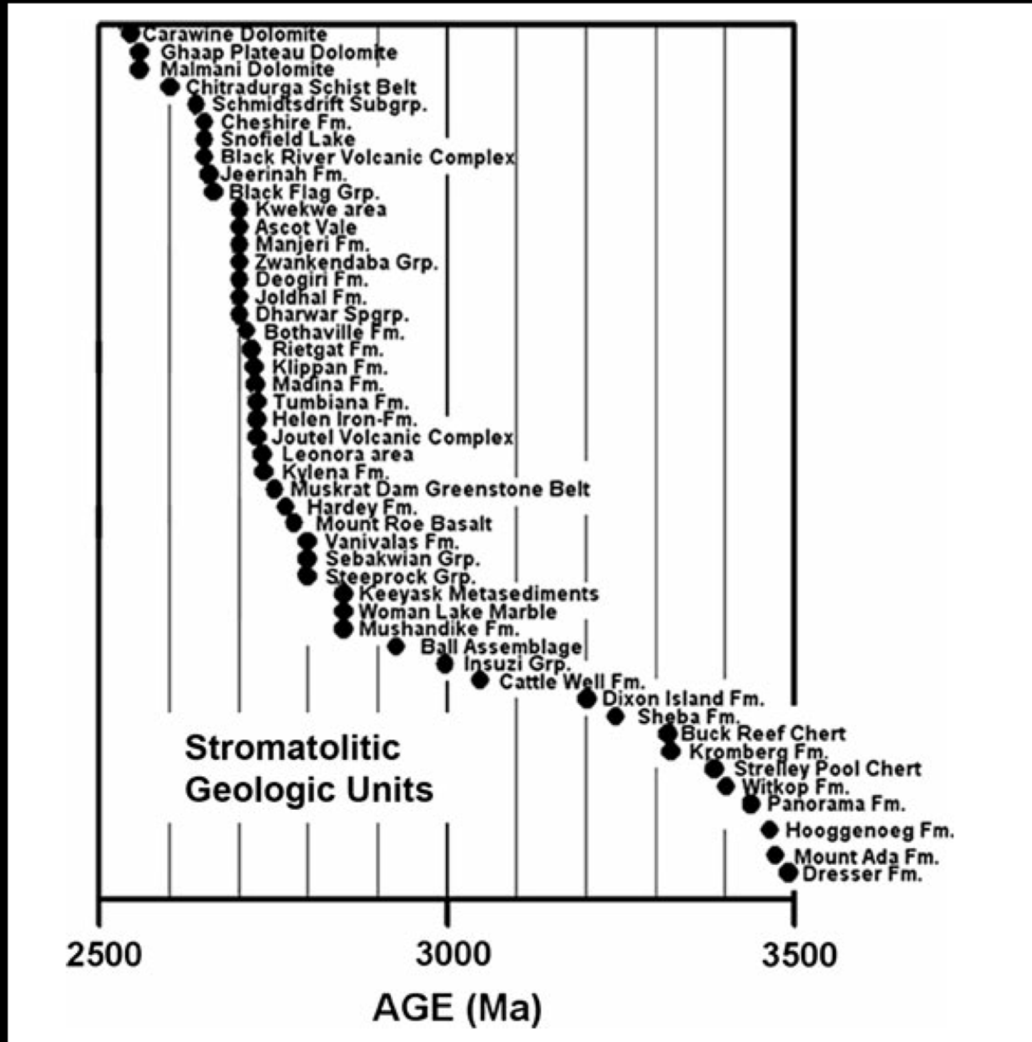




Formation of stromatolites (??)
Photosynthesis:

Precipitation $Ca^{2+} + 2HCO_3^- \rightleftharpoons \underline{CaCO_3} + H_2O + \overline{CO_2}$

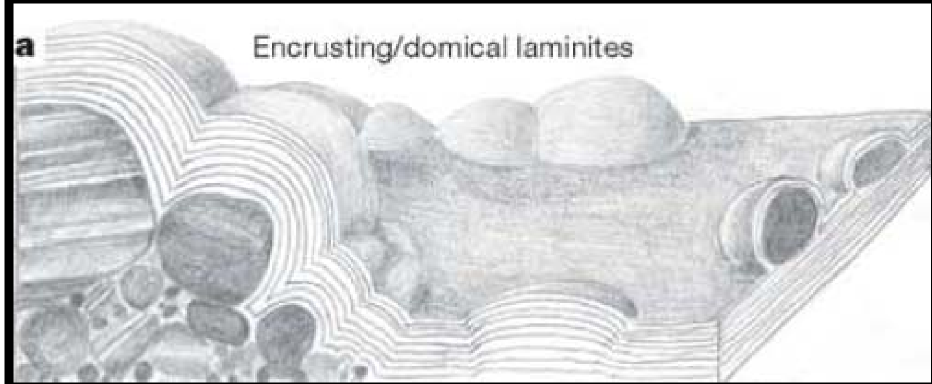
Numerous ancient microbialites since 3.5 Ga



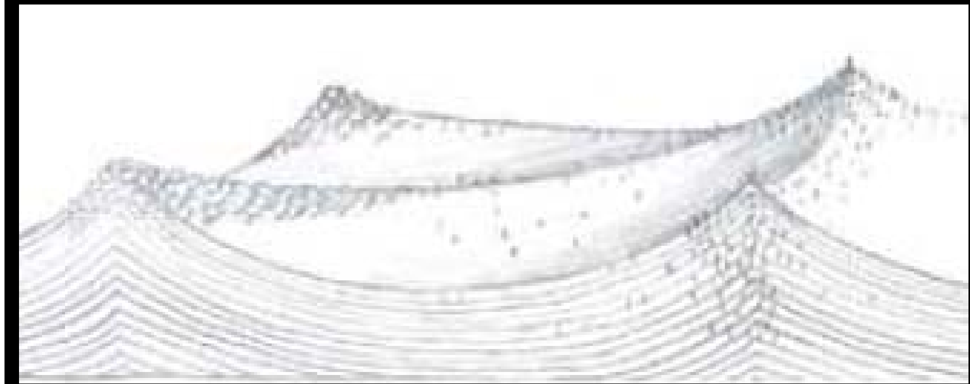
From Schopf 2011

Morphological diversity in 3.5 Ga old stromatolites in Australia

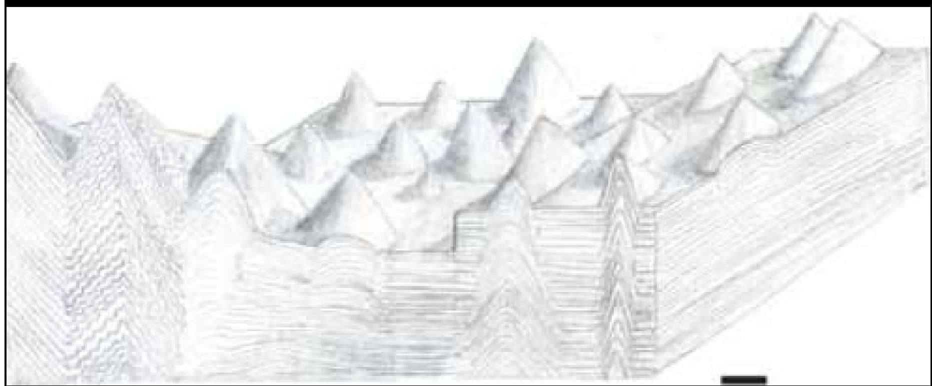
Encrusting/domical laminites

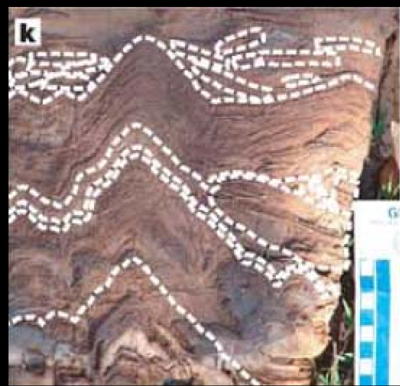


Crests



Cones





Allwood et al. (2006) Nature

BUT…

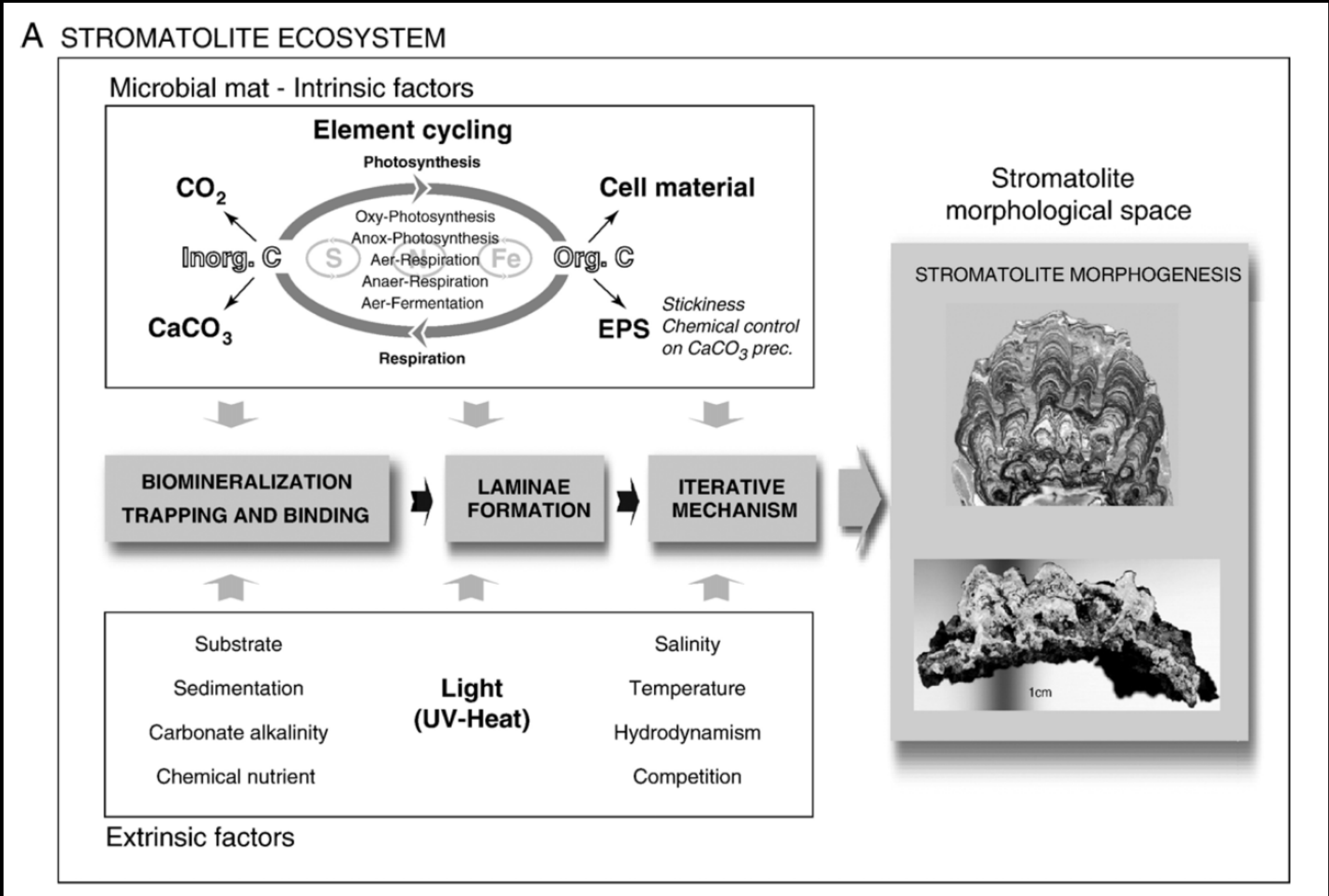
★ No potential microfossil detected in Archean stromatolites

★ Laminated carbonate deposits can possibly form through abiotic processes (numerical models combining sedimentation, diffusion, abiotic precipitation + noise…)

→ Grotzinger et al. (1996):

Questioning the biogenicity of some of the Archean stromatolites

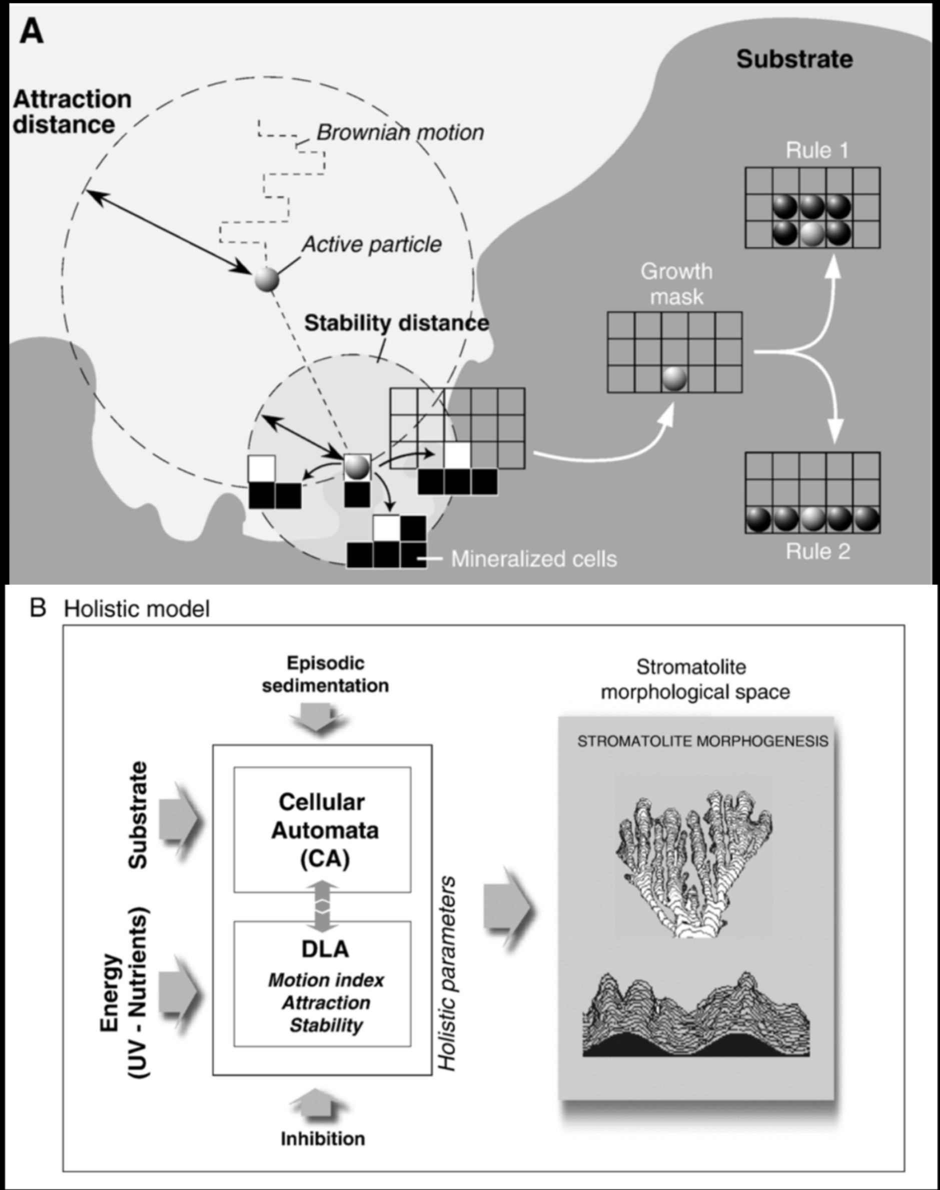
Is macroscopic morphology a biosignature?
What controls morphogenesis? By biological processes at the micro-/nano-scale?

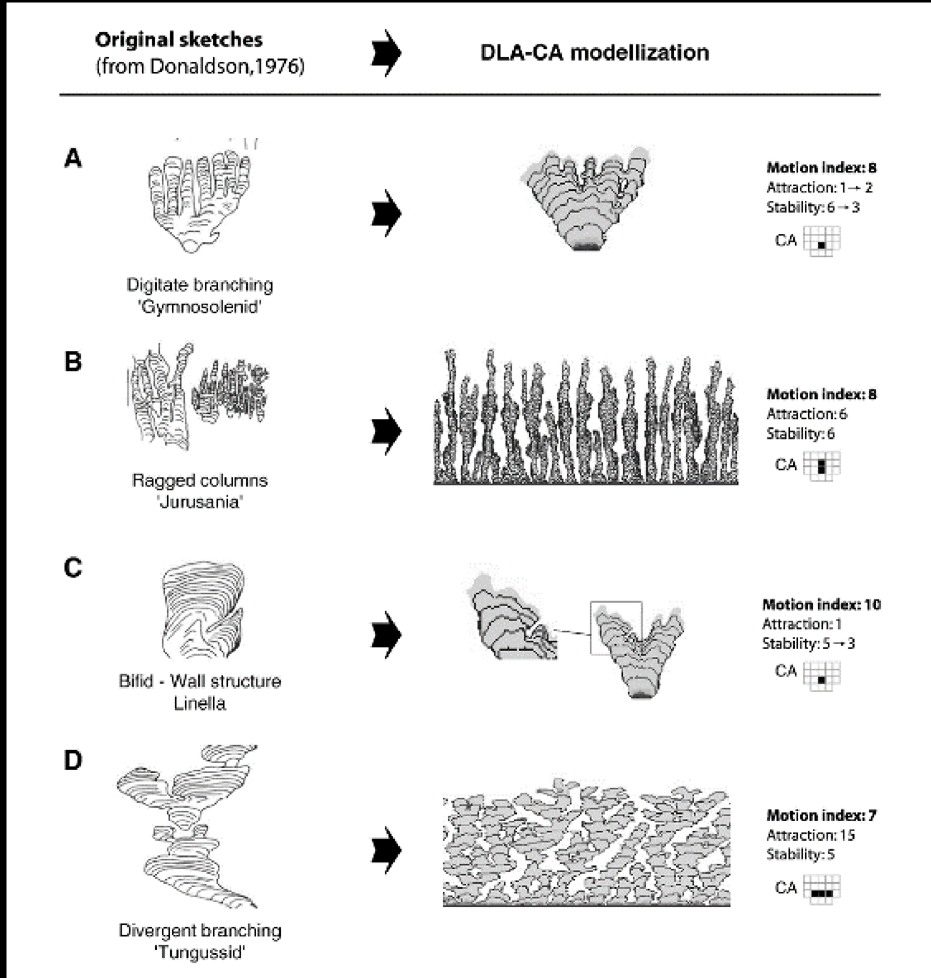


Dupraz C et al (2006) Translation of energy into morphology: Simulation of stromatolite morphospace using a stochastic model Sed. Geol. 185: 185-203

Simulation of stromatolite morphogenesis

e.g., combination of diffusion limited aggregation with cellular automata





Summary: What are the challenges for finding traces of life?

Objects are small/simple: potential confusion with abiotic objects

Some geological processes form objects similar to fossils

Aging of rocks (Temp, Pressure) can erase traces of life

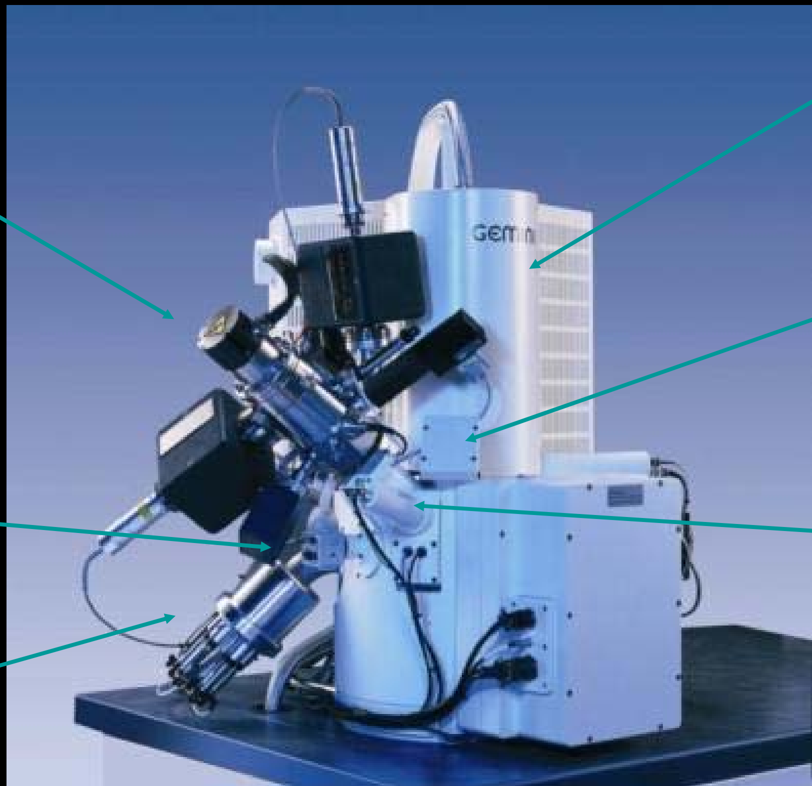
It is difficult/impossible to date directly a fossil. Does it have the same age as the enclosing rocks?

2. Perspectives: How to go further

Improved characterization at the micro-/nano-scale

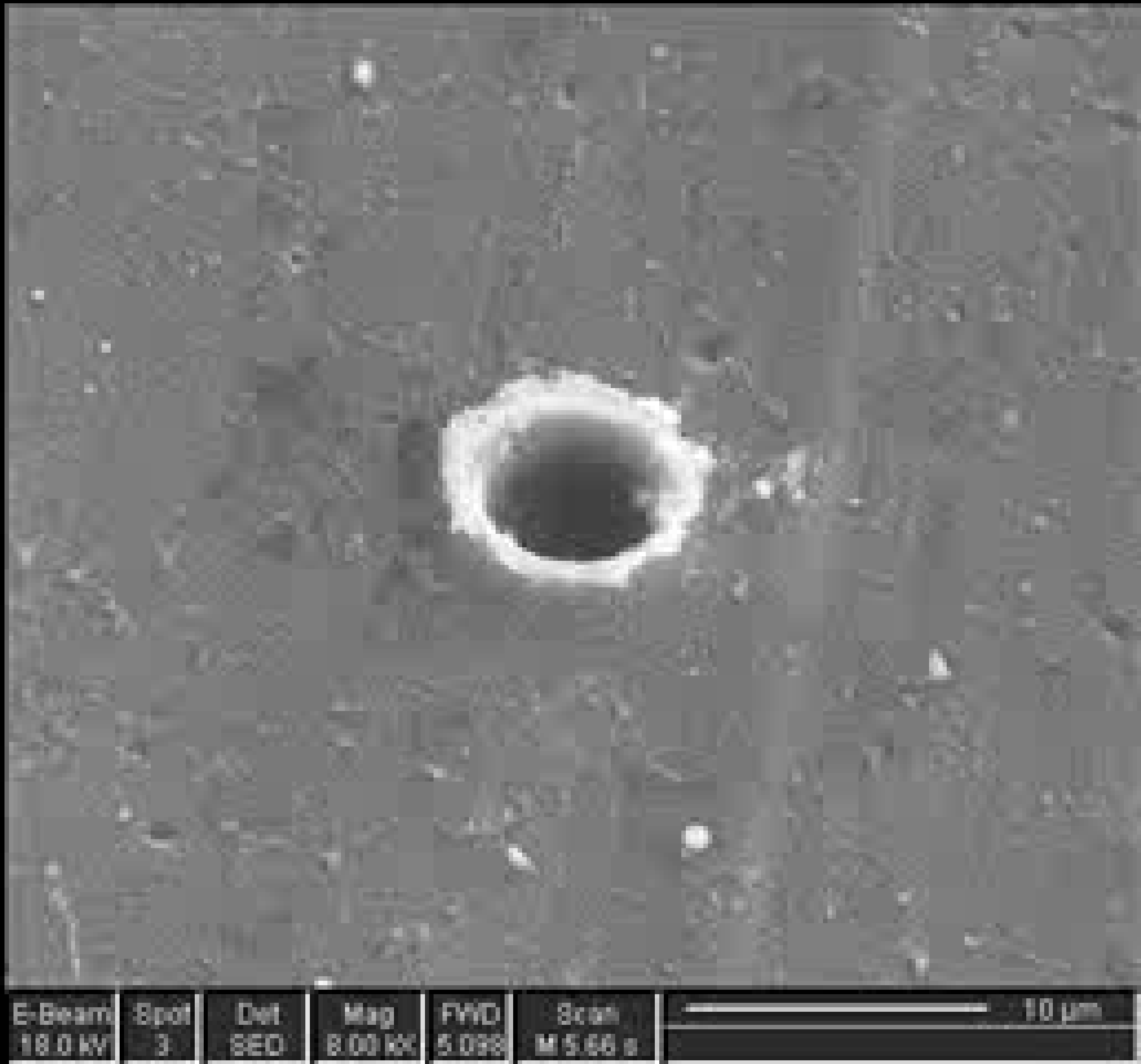
Analytical issue

Preparation of micro-sample by Focused Ion Beam milling

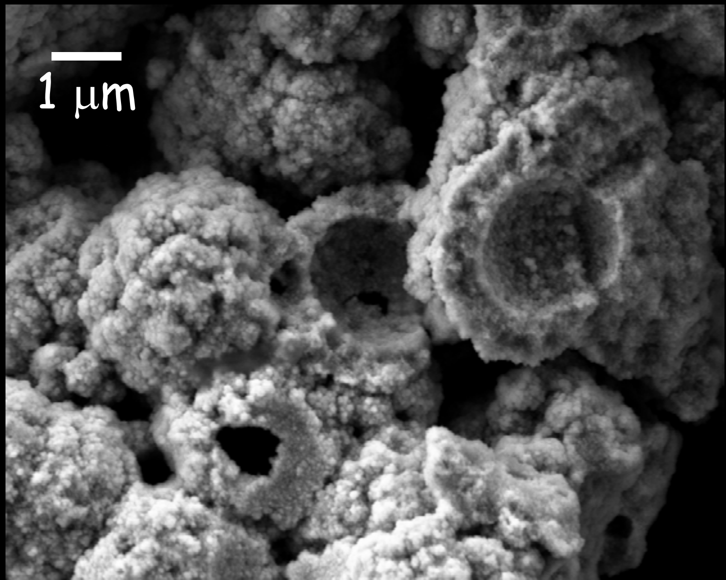


★ FIB = SEM+ ion gun (Ga^+ in general)

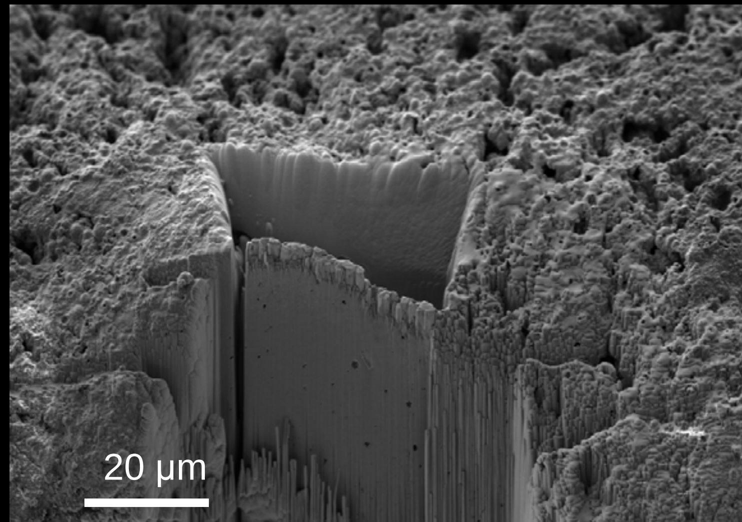
How does it work ?

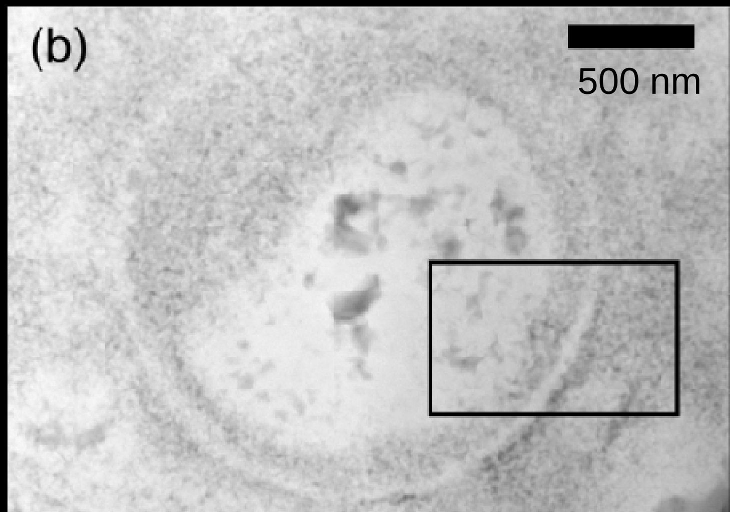


FIB milling to prepare an ultrathin sections for TEM analyses



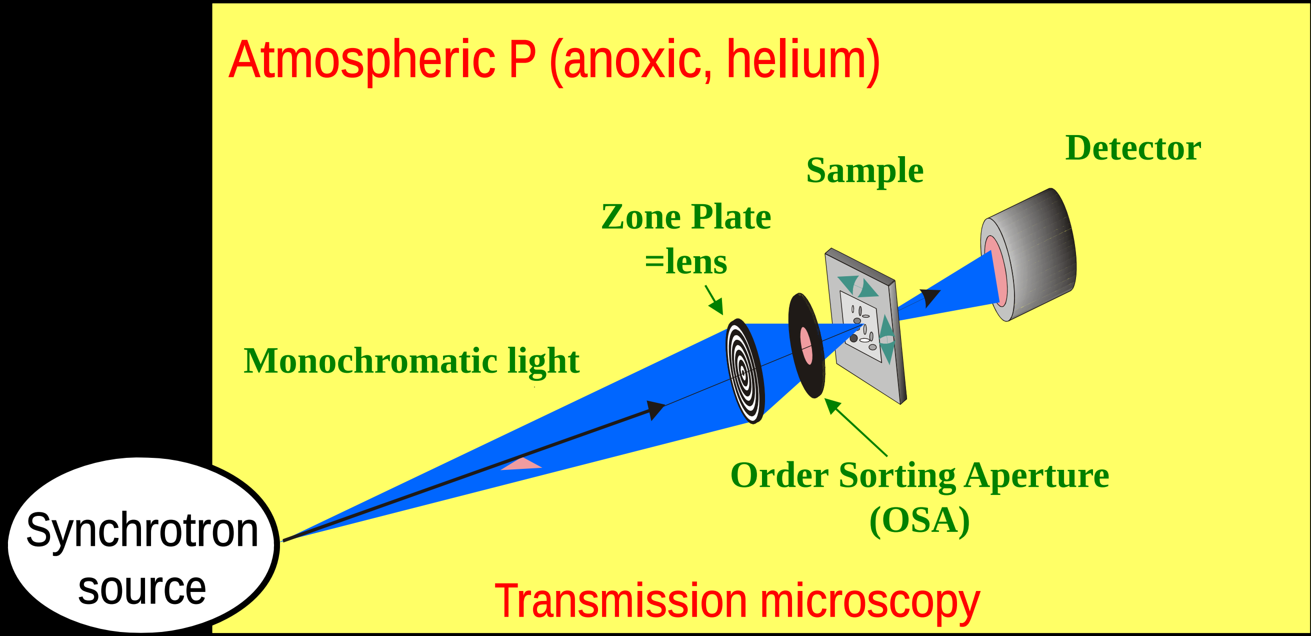
Sectioning

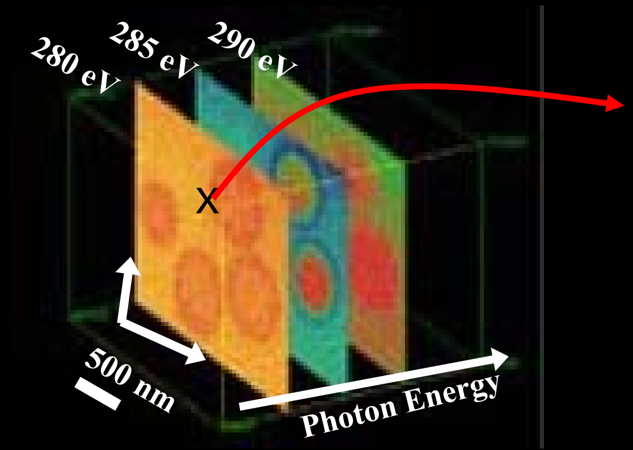




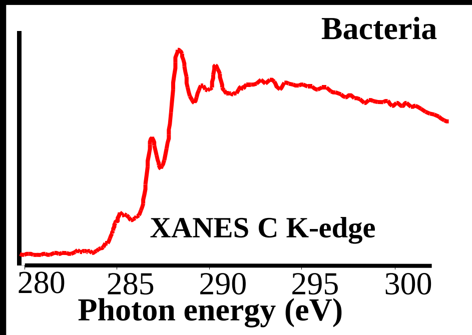
Scanning Transmission X-ray Microscopy (STXM)

Berkeley, Saskatoon, Villigen





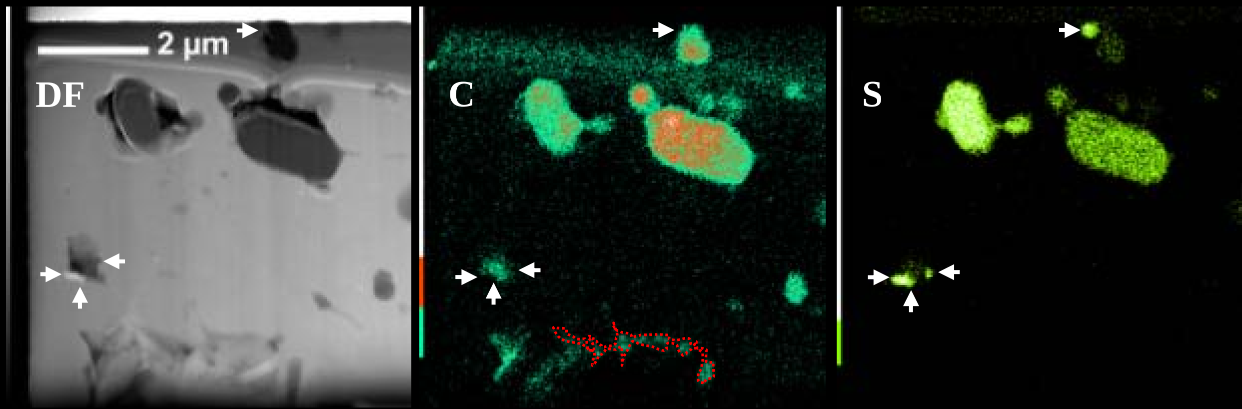
X-ray Absorption Near Edge Spectroscopy (XANES)

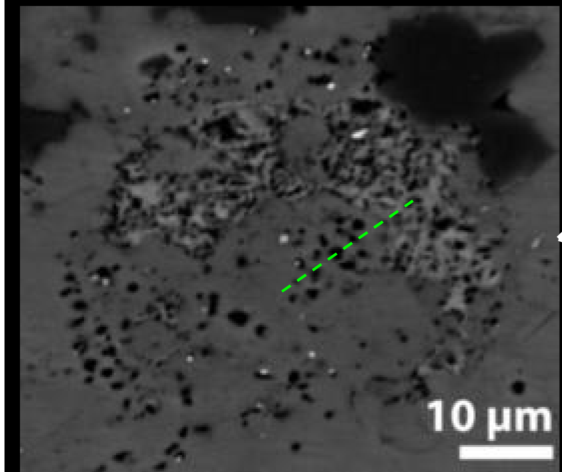


Imaging w. 25 nm resolution

Ca & C speciation at 25 nm resolution

Speciation of C in micron-scale organic globules in 2.7 Ga rocks

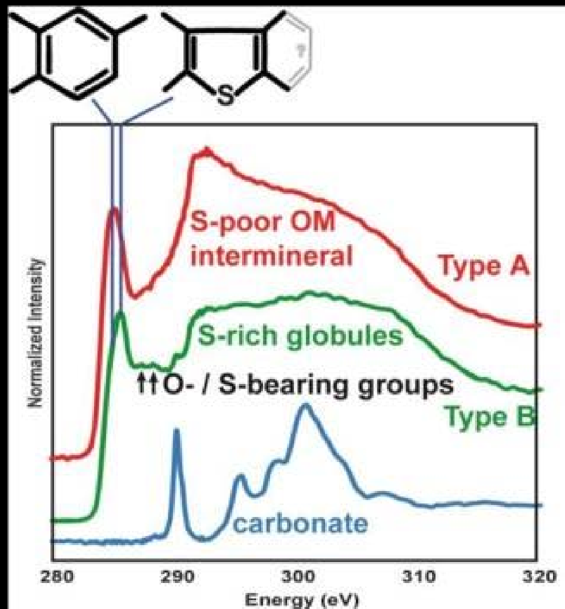




Polished section (SEM)

TEM

STXM (XANES)

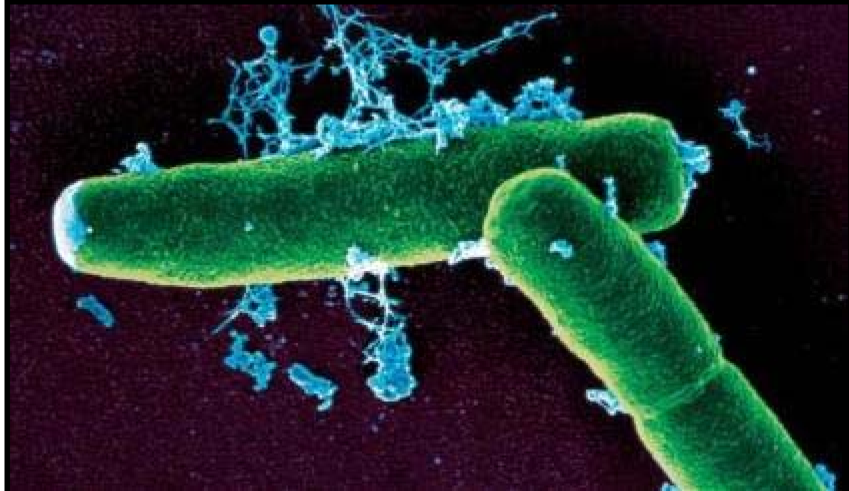


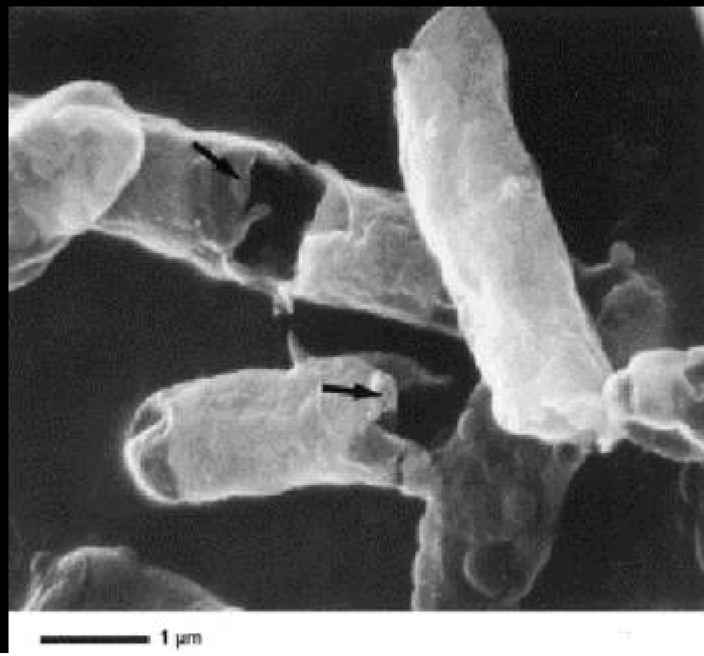
Lepot et al. (2009) Geochim. Cosmochim Acta
See also Alleon et al (2016) in Nature Comm

2. Perspectives: How to go further

Better understand fossilization processes of bacteria, and how they can be preserved over geological time

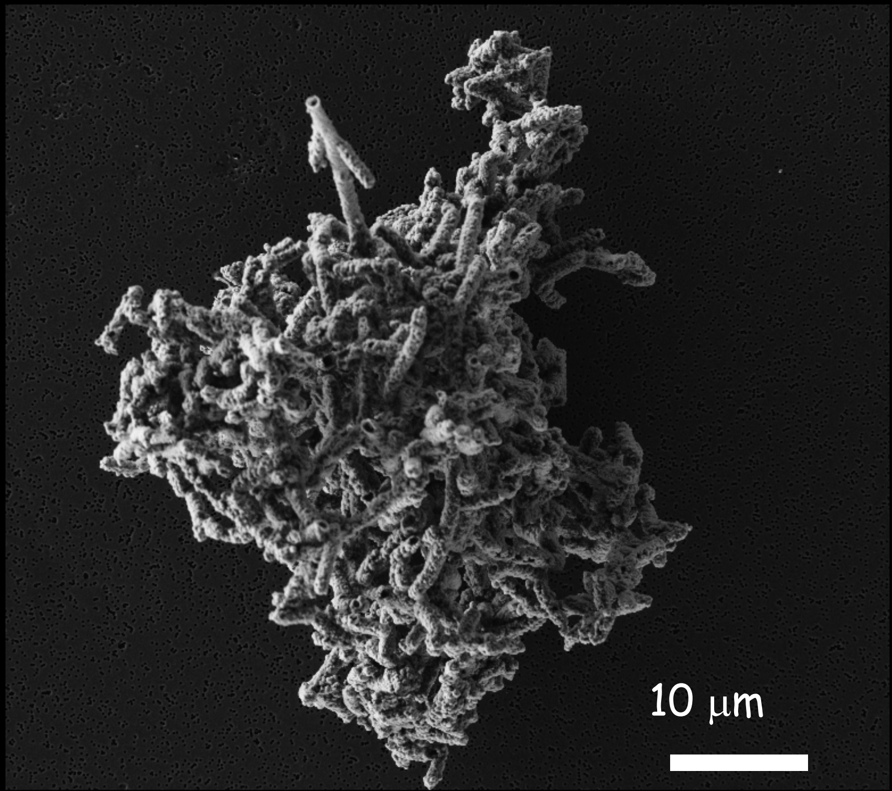
Cell structures degrade very fast after cell death…

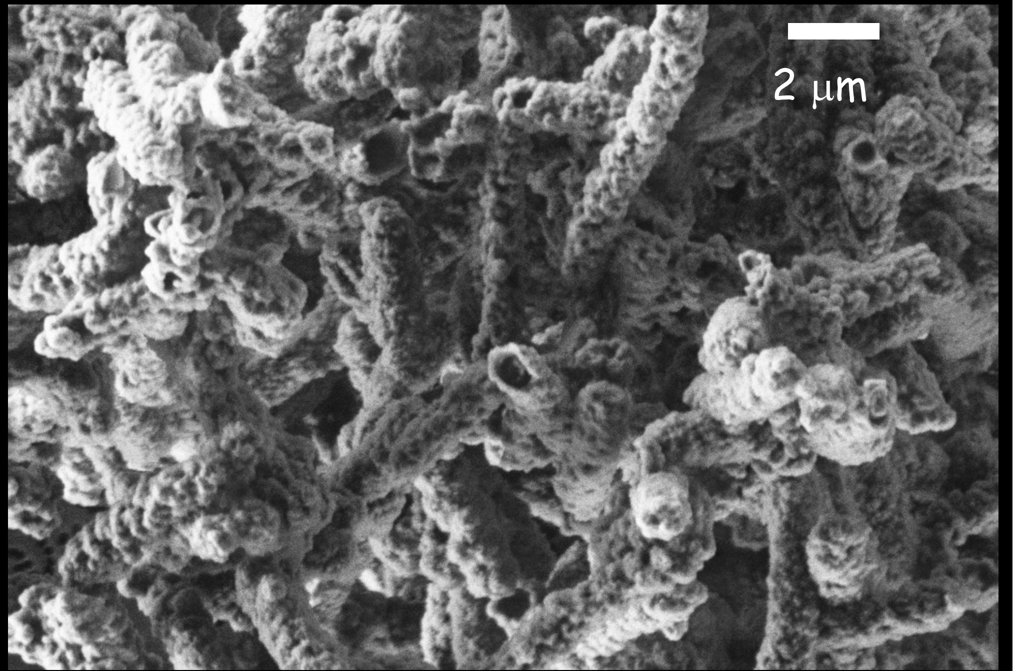




In a few hours/days

Better preserved if encrustation by minerals

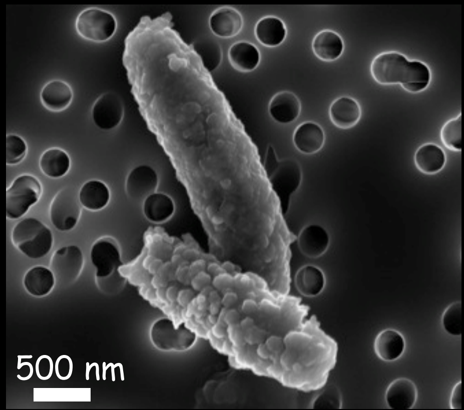




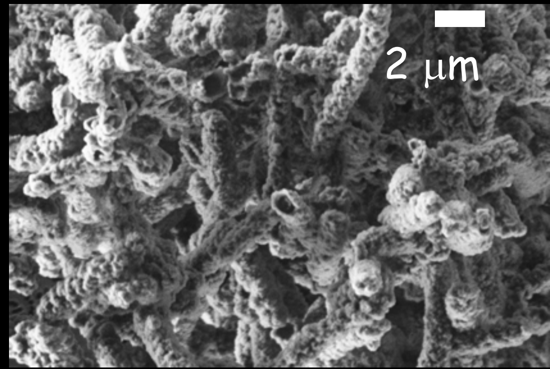
Cosmidis et al (2015) Frontiers in Earth Science

Mutants of E. coli self-encrusting completely in less than 2 days by calcium phosphates

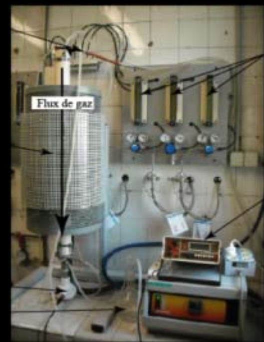
Experimental fossilization of bacteria



Precipitation of cells by Ca-phosphates



Heating, pressuring,



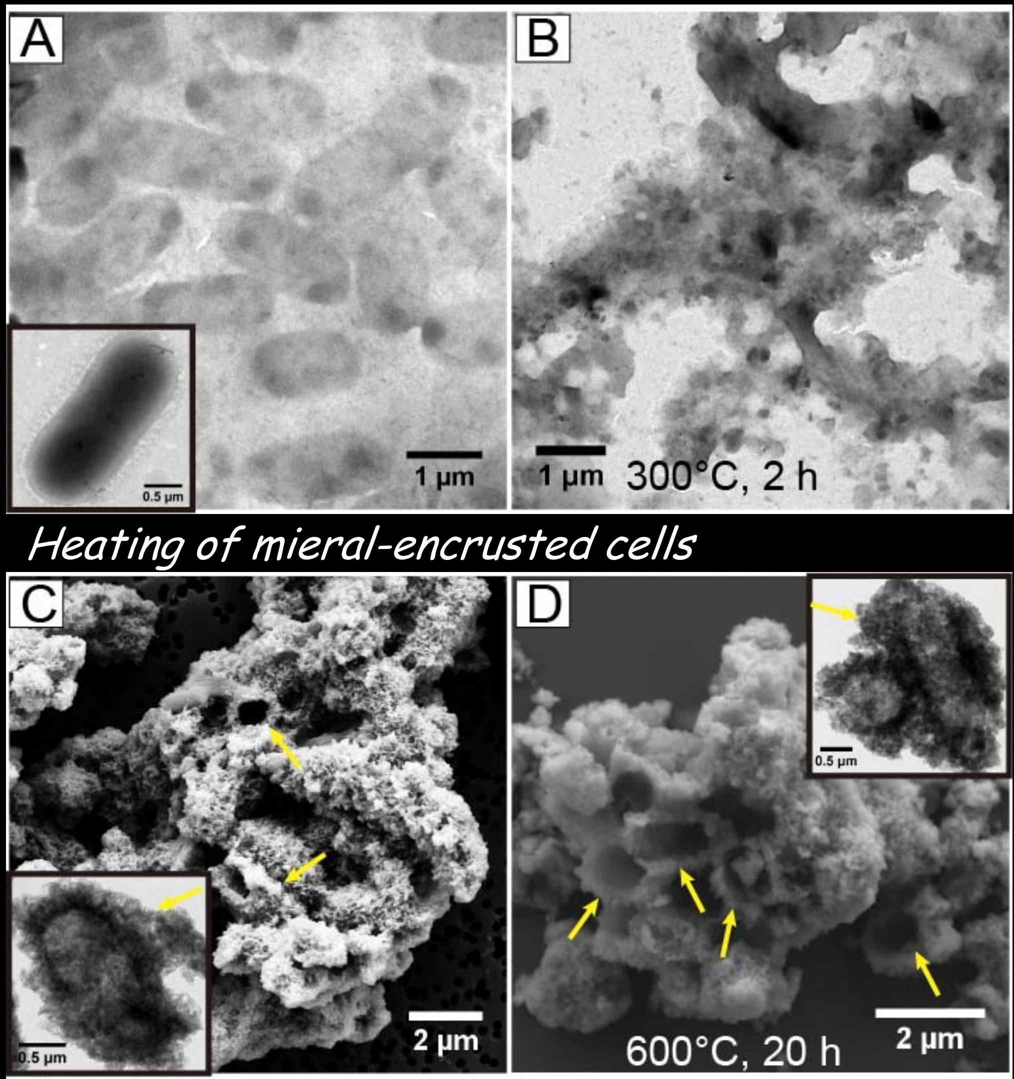
Li et al. (2013) Chemical Geology, 359, 49-69

Hypothesis: follows an Arrhenius law,

i.e. high temperature and short duration = long duration at moderate temperature

Heating of non mineral-encrusted bacteria

Heating of mieral-encrusted cells



Li et al. (2014) EPSL

Conclusions

Investigation of the oldest traces of life requires the study of old rocks

These rocks and therefore traces of life have been transformed by aging (temperature, pressure…)

Discriminating biological from abiological is sometimes a challenge

The use of cutting edge analytical techniques, including spectroscopies, microscopies is necessary

Simulation of fossilization in the laboratory may be possible but limitations of this approach need to be better understood

Interpretation of ancient traces requires a good knowledge of modern microorganisms, which yet needs further knowledge (the present is the key to the past)

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Difficiles à reconnaitre et souvent contestés :

Cf. « La quête des toutes premières traces de vie »
La Recherche, Février 2013.

Les microorganismes peuvent être fossilisés. Cela ne signifie pas que tout ce que l'on voit est un fossile de microorganisme!