Palaeontology

Lecture 3

The origin of life

What is life?

"a self-sustained chemical system capable of undergoing Darwinian evolution"

(this might be valid only for life on earth)

Essentials for life?

- Organic molecules for biological structures and processes
- A source of usable energy (e.g. sun or earth's heat)
- Liquid water as energy and information transporting medium

Factors that make Earth suitable for life

- The distance from the sun provides temperatures in the range where the water remains in liquid form.
- The temperature is constant for billion of years.
- Rotation allows all sides of the earth to have light and heat.
- The atmosphere absorbs and keeps the heat from the sun while it reflects part of the dangerous radiation in space.
- The magnetic field protects life from dangerous high energy particles and solar wind radiation.

Basic structure of life on earth

- All life forms on earth are based on the same set of molecular units and chemical reactions
- All earth life is carbon based
- Except carbon H, O, N and P also important
- Four types of molecules are essential for biological processes and structures

  proteins
  nucleic acids
  carbohydrates
  lipids

Life requires the following chemical elements

- Carbon
- Hydrogen
- Oxygen
- Nitrogen
- Posphorous
- Sulfur

All of them exist in the solar system

The four essential components of life

- Proteins - Amino acid chains. Proteins are the building blocks of the organisms, and the catalysts of chemical reactions.
- Nucleic Acids – The elements that transfer information and create "copies".
  DNA
  RNA
- Organic phosphorus compounds - Used to convert light or chemical fuel into energy needed for cell activities.
- Cell membranes to enclose all these elements within a cell and isolate them from the outside environment, creating a controlled semipermeable system.

Proteins

- The primary structural material of cells and thus of life
- Long chains (polymers) of amino acids
- Only 20 amino acids participate in the building of the major proteins of life

Nucleic acids

DNA (deoxyribonucleic acid)

RNA (ribonucleic acid)

The information-carrying and replicating components of life

DNA

- Long, double, helical chains
- Each side rail consists of alternating sugar, phosphate molecules and four different types of bases

  Adenine

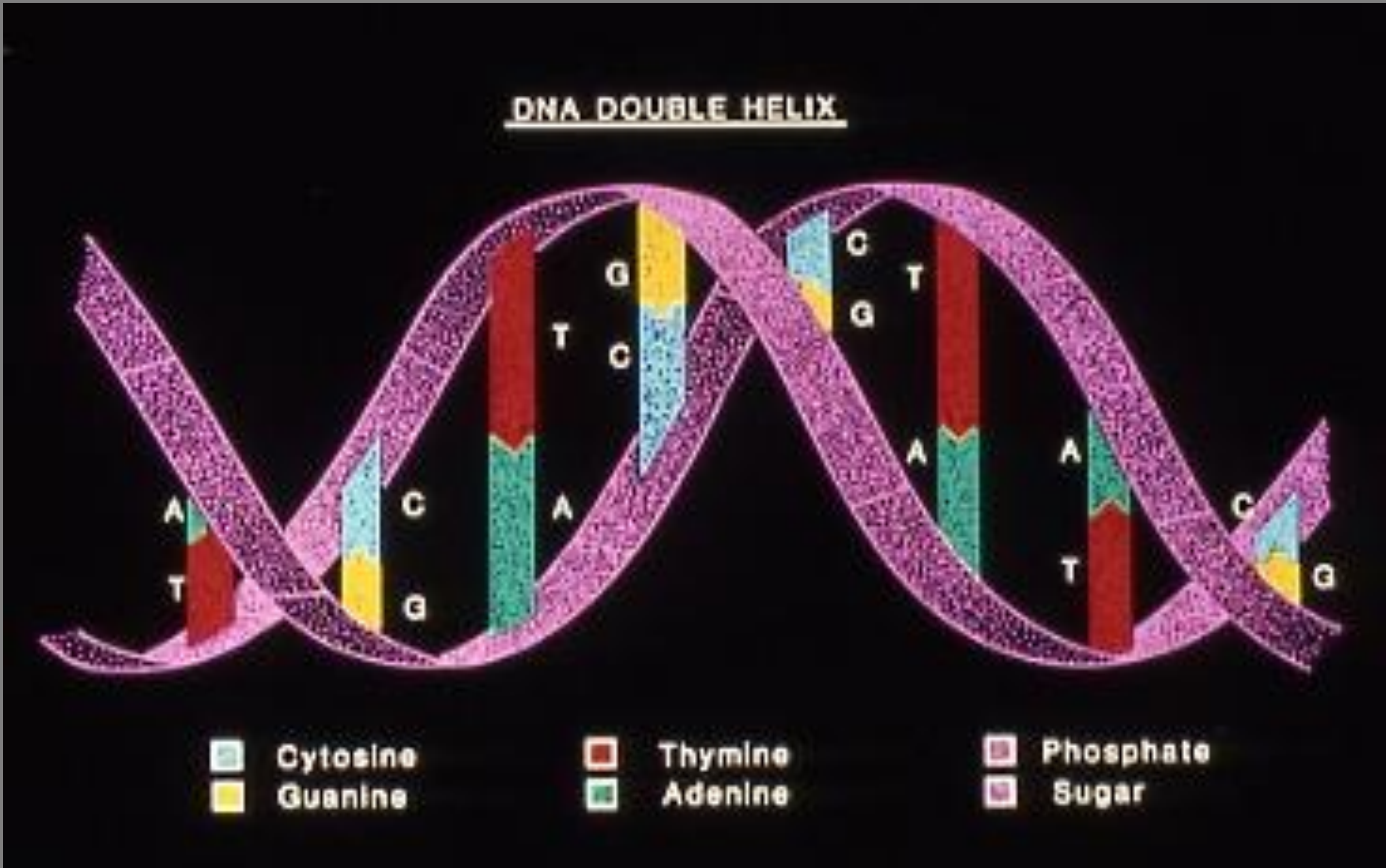
  Thymine

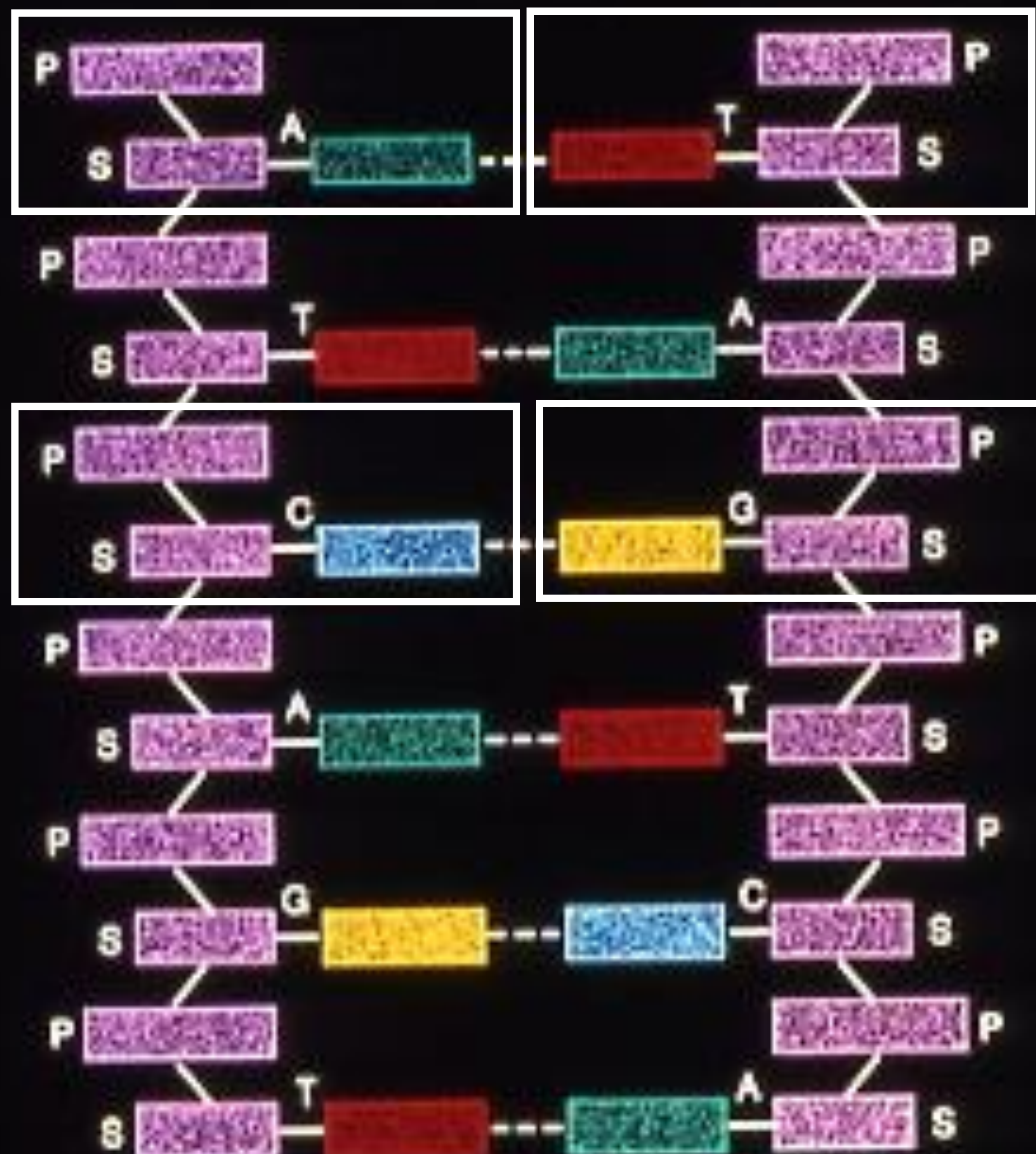
  Guanine

  Cytosine
- A nucleotide = base + sugar + phosphate
- Unique pairing of the nucleotide bases

  Adenine - Thymine

  Guanine - Cytosine

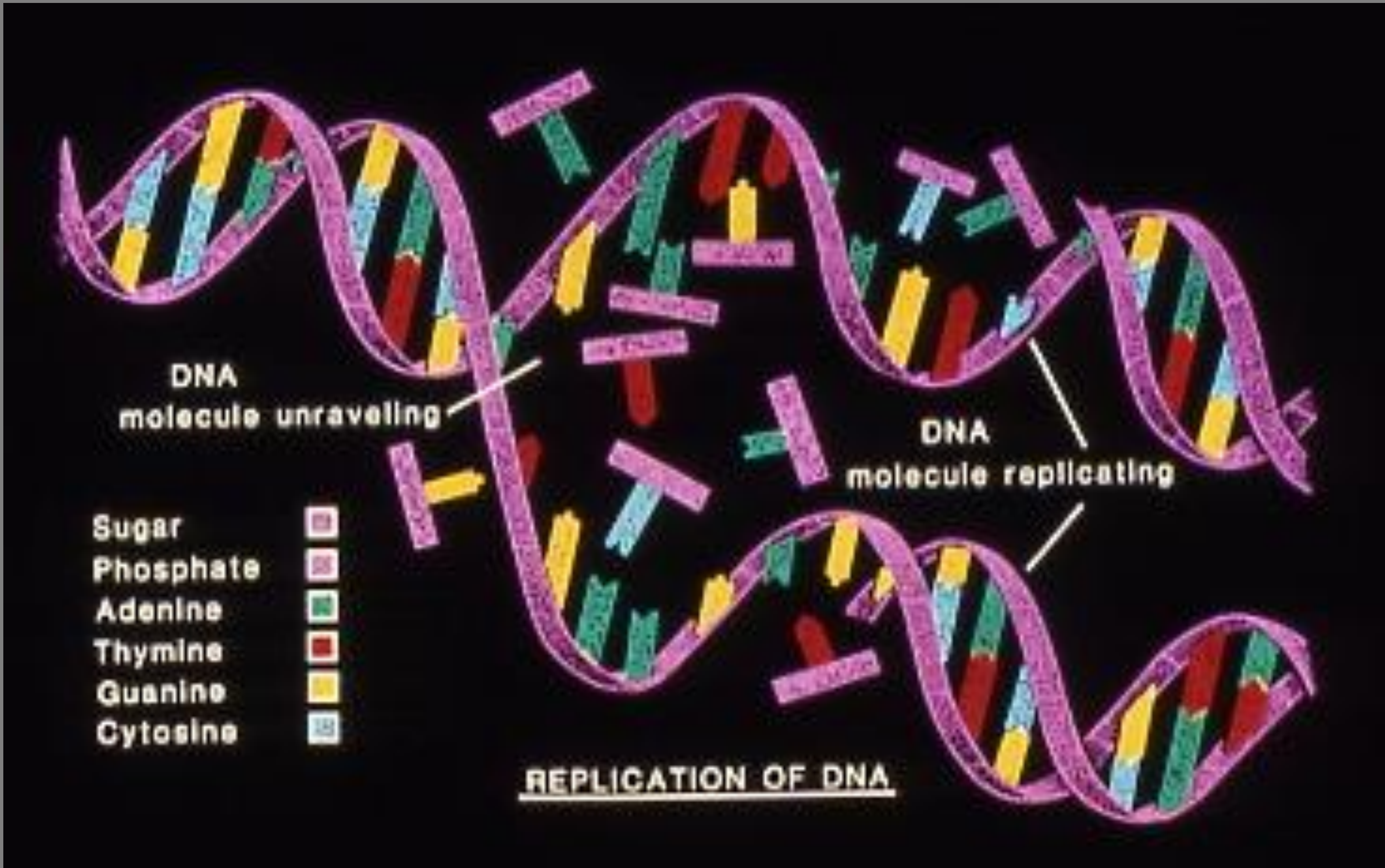

DNA DOUBLE HELIX
A
T
C
G
T
A
G
C
C
G
T
A
A
T
C
G
Cytosine
Guanine
Thymine
Adenine
Phosphate
Sugar



Sugar S
Phosphate P

Adenine A
Guanine G

Thymine T
Cytosine C


DNA
molecule unraveling
DNA
molecule replicating
Sugar
Phosphate
Adenine
Thymine
Guanine
Cytosine
REPLICATION OF DNA

RNA

- A single, long chain structure
- Each RNA chain consists of alternating sugar, phosphate molecules and four different types of bases

  Adenine

  Uracil

  Guanine

  Cytosine
- A sequence of three of these bases makes a codon, e.g. Guanine-Uracil-Adenine
- The total number of codons is 64

Differences between RNA and DNA

a. The base Uracil is present instead of Thymine

b. The sugar is of a different form (D-ribose instead of 2-deoxy-D-ribose)

c. Single than double chain

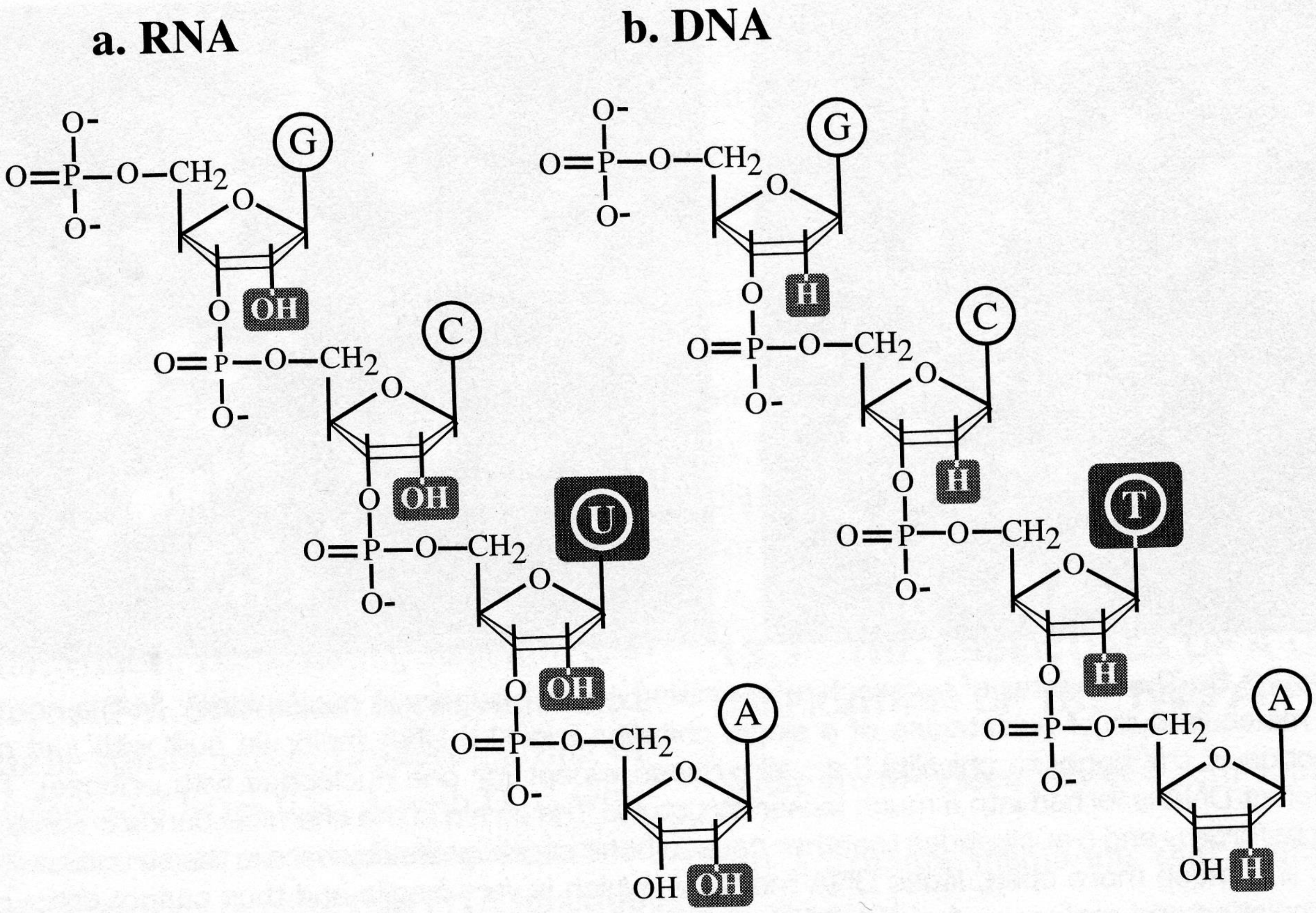
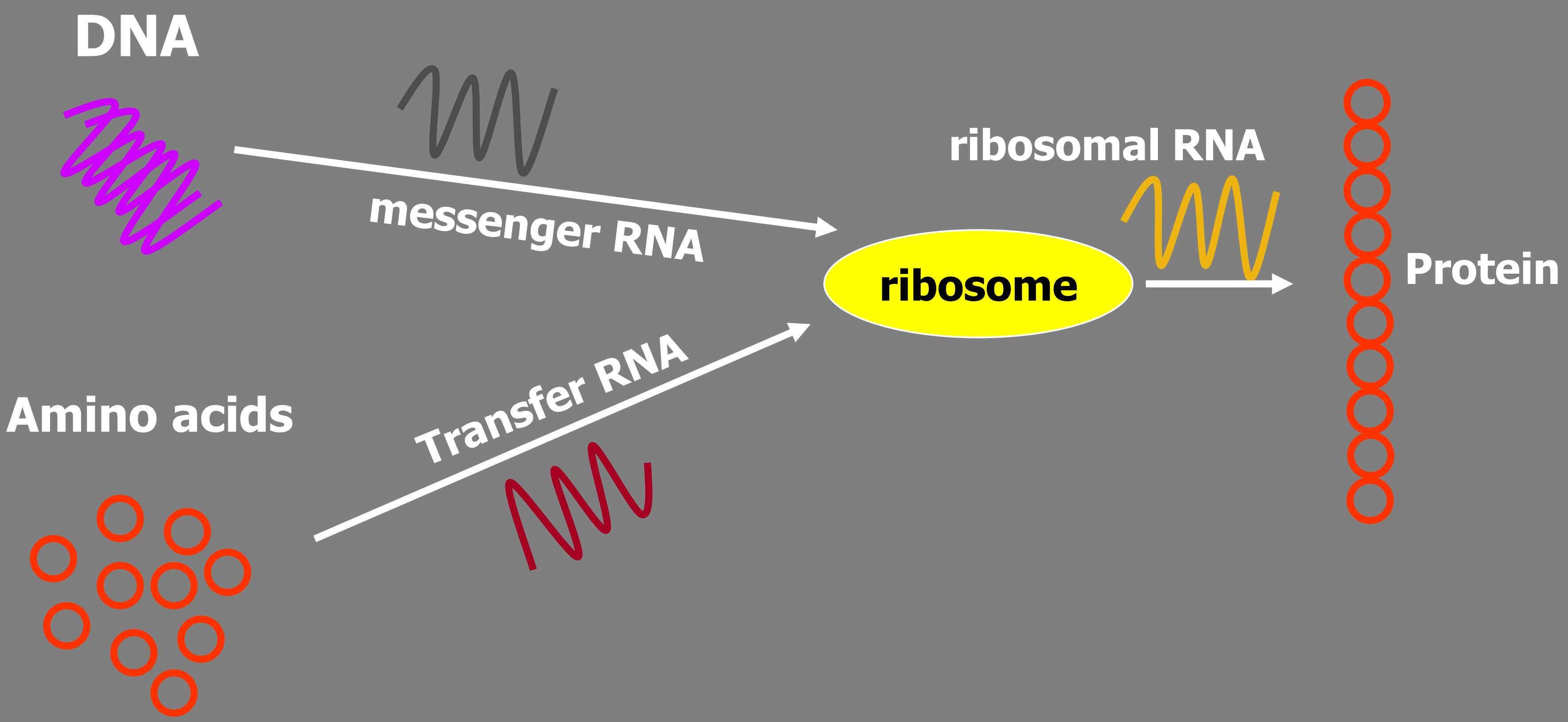


Figure 13.4. (a) Primary structure of the RNA molecule. Nucleotides are labeled within circles by the first letter of their name (for example, G for guanine). Other letters are elements (O for oxygen, P for phosphorus, etc.). Carbon atoms occupy the unlabeled vertices, in accordance with common chemical convention. The straight lines show *single* and *double* bonds, which reflect the number of electrons shared. (b) Structure of a DNA molecule. The differences between RNA and DNA are highlighted on the two structures.

Formation of proteins

- Protein synthesis is governed by DNA, through the intermediation of RNA, when DNA instead of replicating to form new DNA, transcribes RNA.
- Each codon codes for a specific amino acid, and thus a sequence of codons specifies a sequence of amino acids
- This amino acid sequence constitutes the synthesized protein

Formation of proteins (cont)



Formation of proteins (cont)

- The multi-role of RNA molecules indicate that RNA was central to the genesis of life
- DNA very specialized as a record of the genetic information of the individual organism and of certain structures in the cell
- DNA is a subsequent derived molecule
- Gene= a length of DNA with genetic information, expressed as a single protein
- Genetic code= the complete nucleotide sequence which determines the form and function of the organism's proteins
- All living organisms on earth use DNA and RNA

The cell

- The basic unit of living organisms
- All earth life is organised into cells (except viruses and virons)
- The cell structure provides a boundary (membrane) to separate the external from the internal environment where biochemical reactions occur and house DNA and RNA

Raw materials of life

- Early earth was rich in the building blocks of life (amino acids)
- Liquid water in stable oceans
- Atmosphere CH_4, NH_3, CO_2, CO, N_2, more complex molecules
- Source of amino acids terrestrial or external (extra terrestrial)

- The first organisms developed in an atmosphere with a minimum or no free oxygen. (Ororin, 1924)
- Therefore, the first organisms should have been anaerobic.
- Organic molecules could not be built into larger structures in a well-oxygenated environment. Oxygen would decompose (organic) the organic molecules.
- Due to lack of oxygen in the atmosphere, there was also no ozone (ozone layer) to protect the surface of the earth from dangerous and harmful ultraviolet radiation.

Terrestrial origin

The atmospheric “soup” was exposed to

a. Ultraviolet light
b. Electrical discharges of lightning bolts
c. Volcanic activity

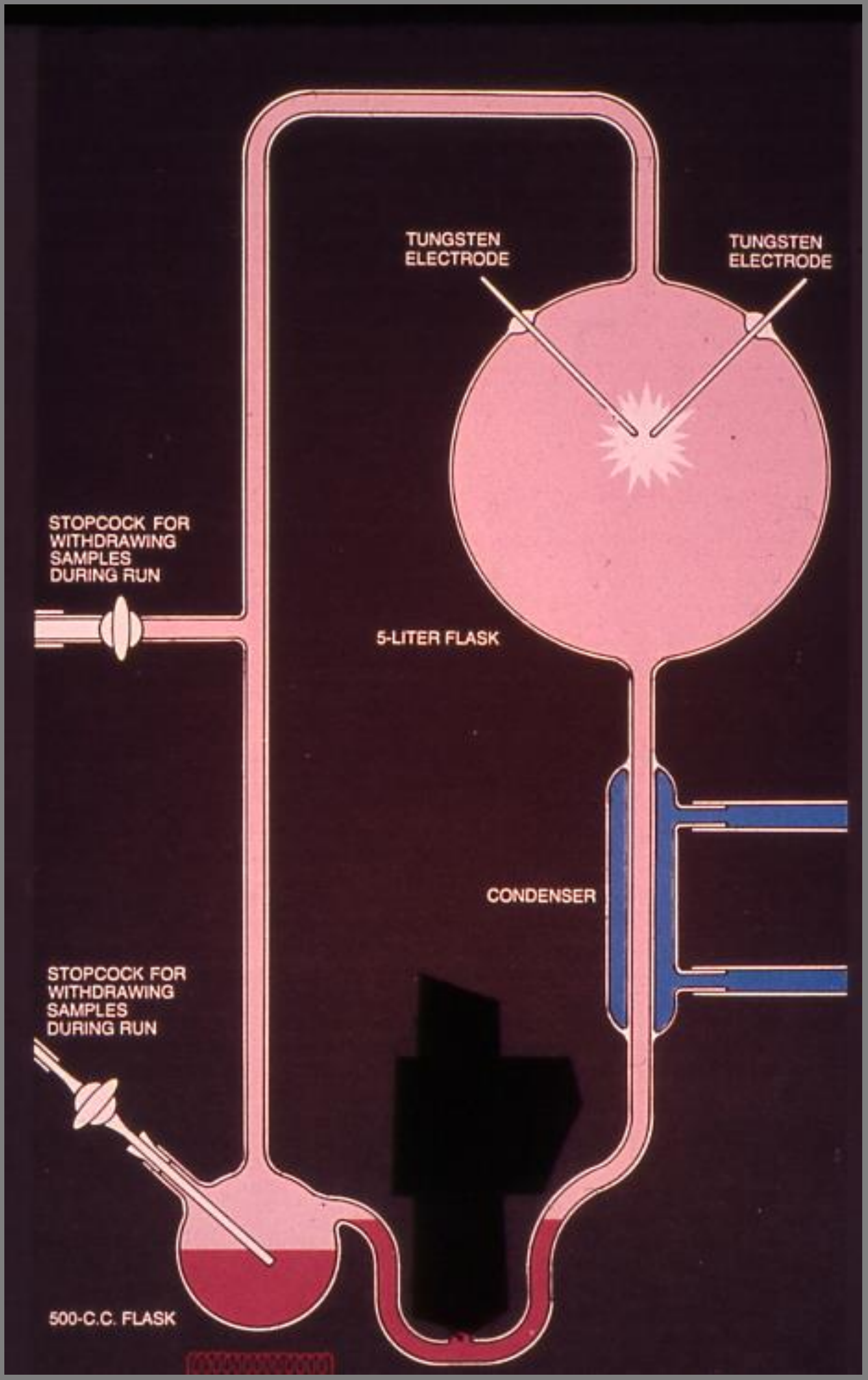
This could provide the synthesis of more complex organic groups

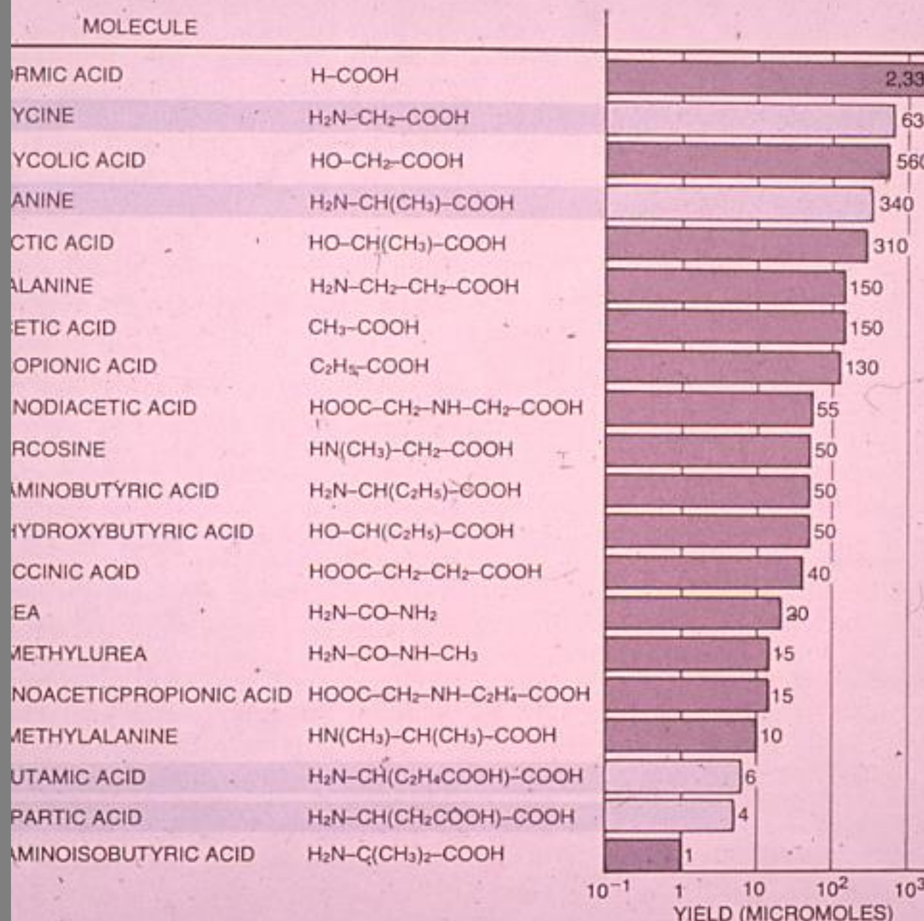
Miller-Urey (1953)

- Atmosphere rich in NH_3, CH_4, little CO_2
- water
- Spark discharges (lightning)

↓

Amino acids


TUNGSTEN ELECTRODE
TUNGSTEN ELECTRODE
STOPCOCK FOR WITHDRAWING SAMPLES DURING RUN
5-LITER FLASK
CONDENSER
STOPCOCK FOR WITHDRAWING SAMPLES DURING RUN
500-C.C. FLASK


MOLECULE
RMIC ACID H–COOH 2,330
YCINE H₂N–CH₂–COOH 630
YCOLIC ACID HO–CH₂–COOH 560
ANINE H₂N–CH(CH₃)–COOH 340
CTIC ACID HO–CH(CH₃)–COOH 310
ALANINE H₂N–CH₂–CH₂–COOH 150
ETIC ACID CH₃–COOH 150
OPIONIC ACID C₂H₅–COOH 130
NODIACETIC ACID HOOC–CH₂–NH–CH₂–COOH 55
RCOSINE HN(CH₃)–CH₂–COOH 50
AMINOBUTYRIC ACID H₂N–CH(C₂H₅)–COOH 50
HYDROXYBUTYRIC ACID HO–CH(C₂H₅)–COOH 50
CCINIC ACID HOOC–CH₂–CH₂–COOH 40
EA H₂N–CO–NH₂ 20
METHYLUREA H₂N–CO–NH–CH₃ 15
NOACETICPROPIONIC ACID HOOC–CH₂–NH–C₂H₄–COOH 15
METHYLALANINE HN(CH₃)–CH(CH₃)–COOH 10
UTAMIC ACID H₂N–CH(C₂H₄COOH)–COOH 6
PARTIC ACID H₂N–CH(CH₂COOH)–COOH 4
AMINOISOBUTYRIC ACID H₂N–C(CH₃)₂–COOH 1
10⁻¹ 1 10 10² 10³
YIELD (MICROMOLES)

However problems arose

a. Models and geochemical data suggest that CO2 the dominant gas in early atmosphere
b. Methane and ammonia less in early atmosphere, thus H less
c. Gas mixture in experiment quite different from early atmosphere

Extraterrestrial origin

- Comets, meteorites, interstellar dust have organic molecules and amino acids

e.g. Murchison meteorite. Fell in 1969 over Murchison, Australia. Classified as a carbonaceous chondrite (C 0.5-5%, Water 12%). Of cometary origin. Todate, more than 92 different amino acids identified, of which only 19 are found on earth.

Analysis of comet Hyatuke has shown a very similar chemical makeup

- Origin of comets: the Oort cloud

Chirality-handedness

- Amino acids and other organic molecules, show two different versions (enantiomers), left- and right-handed
- Handedness of biological molecules plays a role in their functionality

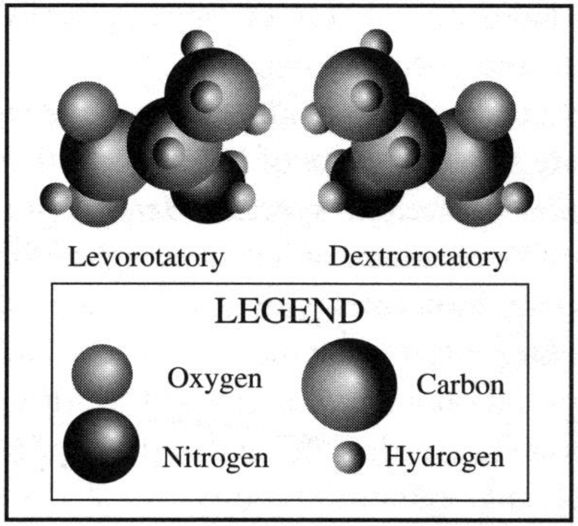


Figure 13.1. Left- and right-handed enantiomers of the amino acid alanine. The left-handed type is referred to as *levorotary* or L-alanine; the right-handed is *dextrorotary*, or D-alanine.

Chirality-handedness (cont)

- Proteins constructed from left-handed amino acids
- RNA-DNA utilize only right-handed sugars
- Organisms cannot utilize right-handed amino acids and left-handed sugars
- Nonbiological amino acids (meteorites, Miller-Urey experiments) roughly an equal mixture of left- and right handed molecules
- Polymers such as proteins do not prefer particular handedness
- So, how could a particular handedness can be selected by prebiological chemistry?

- Either from terrestrial or extraterrestrial origin organic molecules present in early earth
- If life started on earth, oceans are the most likely place
- Origin of life

a. Vesicle model
b. RNA world

Vesicle model

- Catalysis
- Biological catalysts=enzymes
- Autocatalysis

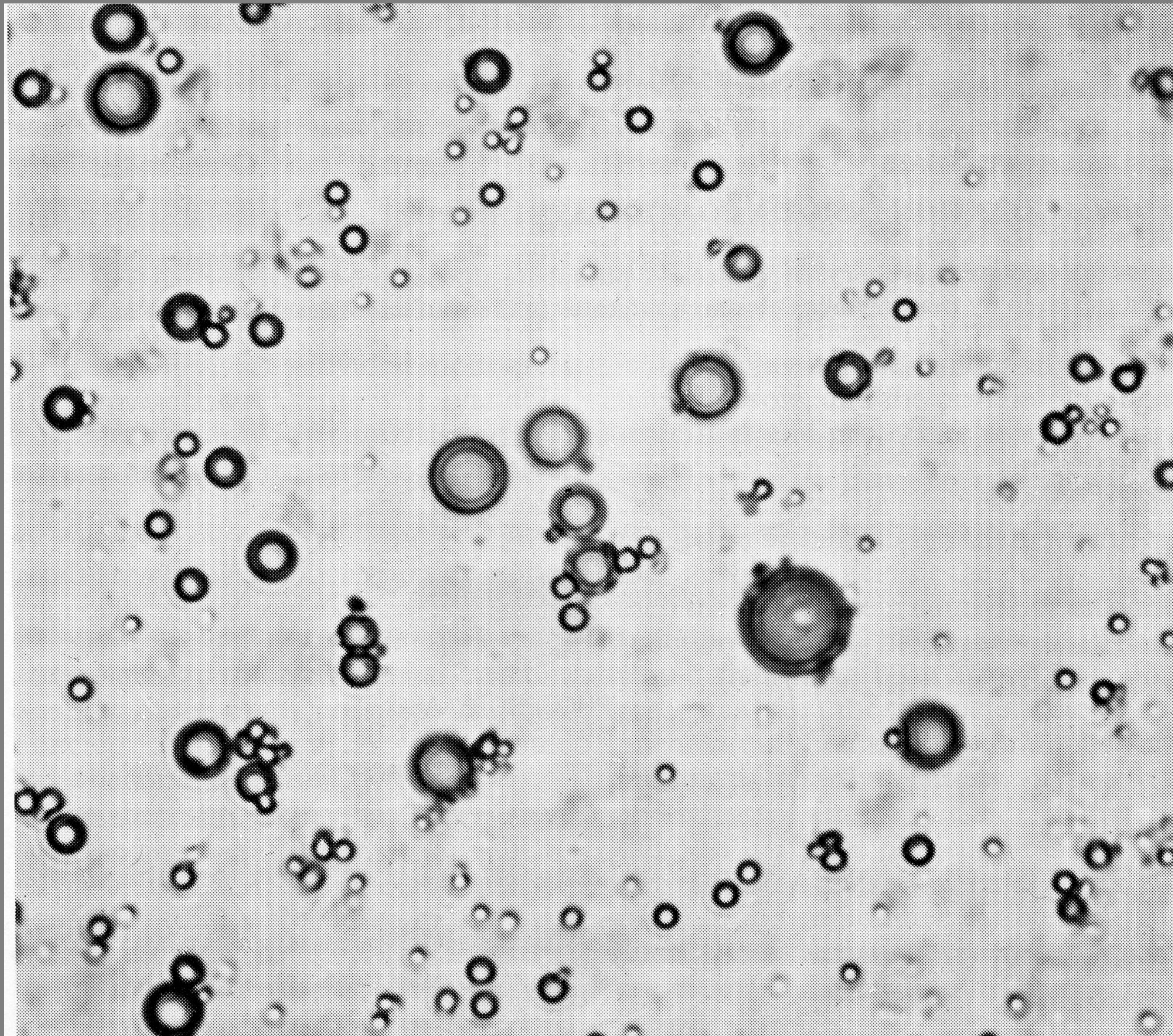
a. Continuous supply of reactants
b. Source of energy

Vesicle model (cont)

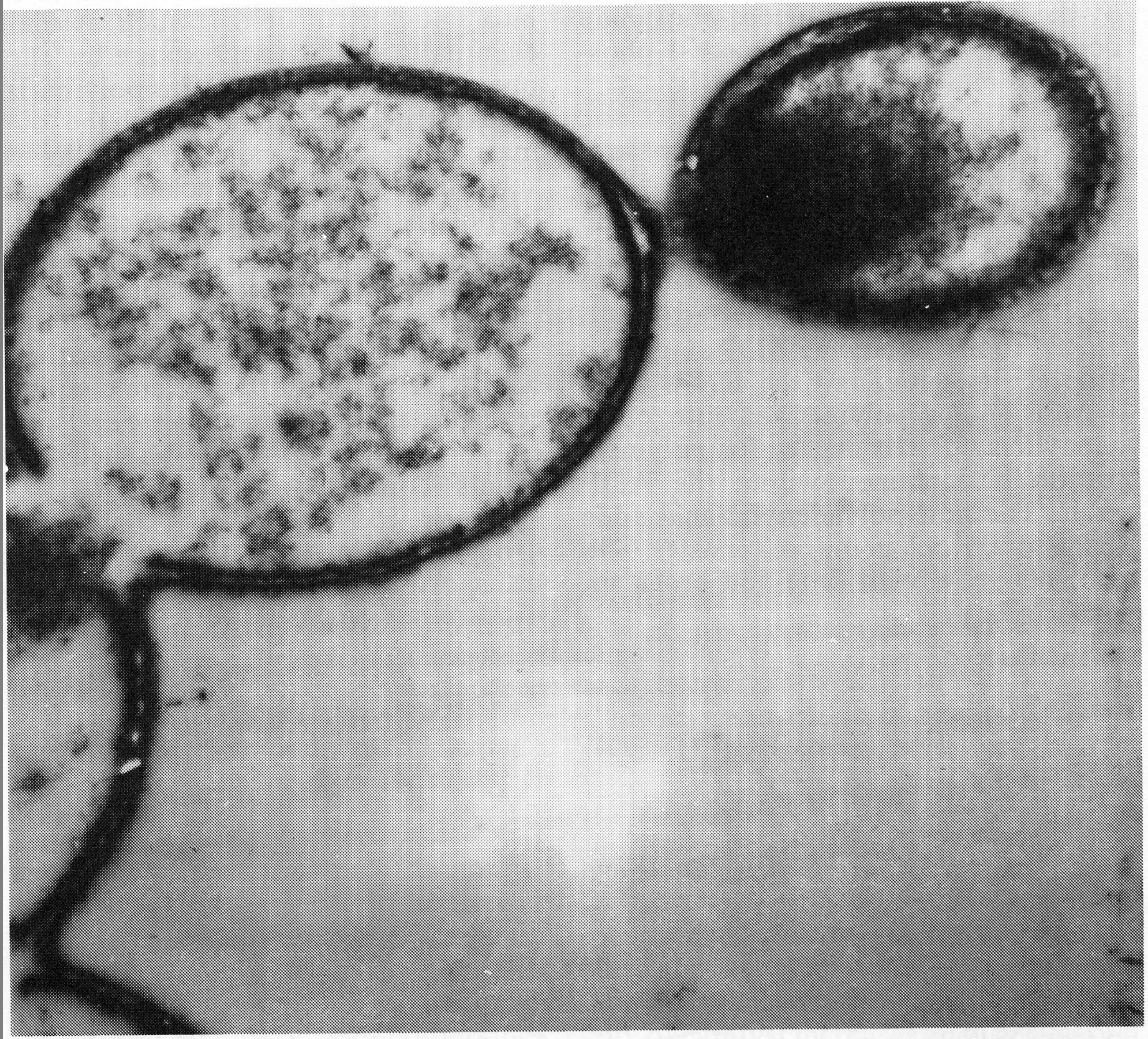
- Autocatalysis brought increased complexity to organic molecules, proteins and other structures formed
- Isolated system, allowing though energy and reactants to be pumped in and products to be removed
- In aqueous medium, certain simple molecules form bilayer membranes, e.g. lipids which can be produced abiologically
- Thus vesicles (microspheres or coacervates) could be formed

Hot water solutions of vesicles will cool to form microspheres, microscopic spheres (bubbles) that have many characteristics of living cells:

- External wall as “film" (lipid)
- Capable of osmotic reduction and enlargement
- Separation into two daughter microspheres
- Concentrate in lines to form laminae like some bacteria
- Movement of internal parts like living cells



ANOTHER KIND OF MICROSPHEROIDAL AGGREGATE, studied by Sidney W. Fox of the University of Miami, forms from "thermal proteinoid," a polymer produced by heating dry mixtures of amino acids to moderate temperatures. Under suitable conditions thermal proteinoid will form microspheres several micrometers in diameter, which grow slowly and eventually bud. The microspheres seem to have a two-layer membrane suggestive of that in bacteria.



COACERVATES, polymer-rich colloidal droplets, have been studied in the Moscow laboratory of A. I. Oparin because of their conjectural resemblance to prebiological entities. These coacervates are droplets formed in an aqueous solution of protamine and polyadenylic acid. Oparin has found that droplets survive longer if they can carry out polymerization reactions.

The RNA world

- RNA came before DNA
- RNA can act as catalyst
- At the very early stages of life on earth, RNA the reproductive as well as the catalytic molecule

How RNA could have been synthesized?

- The nucleic acid bases can be produced by nonbiological means
- Although not clear, the random attachment of the phosphate to a ribose sugar possible
- The problem is the synthesis of the ribose with the right chirality, where an enzyme (and thus protein) is needed
- But enzymes cannot be made without RNA

How RNA could have been synthesized?

- Possibly clay minerals concentrated ribose
- Organic molecules attached on clay minerals form organised structures
- Clay is helpful in polymerizing proteins and nucleic acids
- Oceans, hence clays
- Ribose can be formed

Still problem with chirality

a. Precursor molecule
b. Selection of a particular chirality

However

- Efforts to synthesize nucleotides have been unsuccessful
- Amino acids (and thus proteins) are easy to synthesize
- Nucleotides without a double helix are extremely unstable

Proteins first

- Proteins easy to built (amino acids)
- Proteins stored genetic information
- Short polypeptides (long chain amino acids) in experiments have catalysed the formation of their own copy
- RNA came later as a by product of metabolism
- Thus proto-life was probably built of proteins not nucleic acids

a. The formation of autocatalytic vesicles
b. Production of polymers of a dominantly single chirality (sugars, amino acids)
c. In this system, production of RNA, DNA was possible (or other nucleic acid)
d. Nucleic acids in vesicles, became coupled to reproduce

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Where was the first life formed?

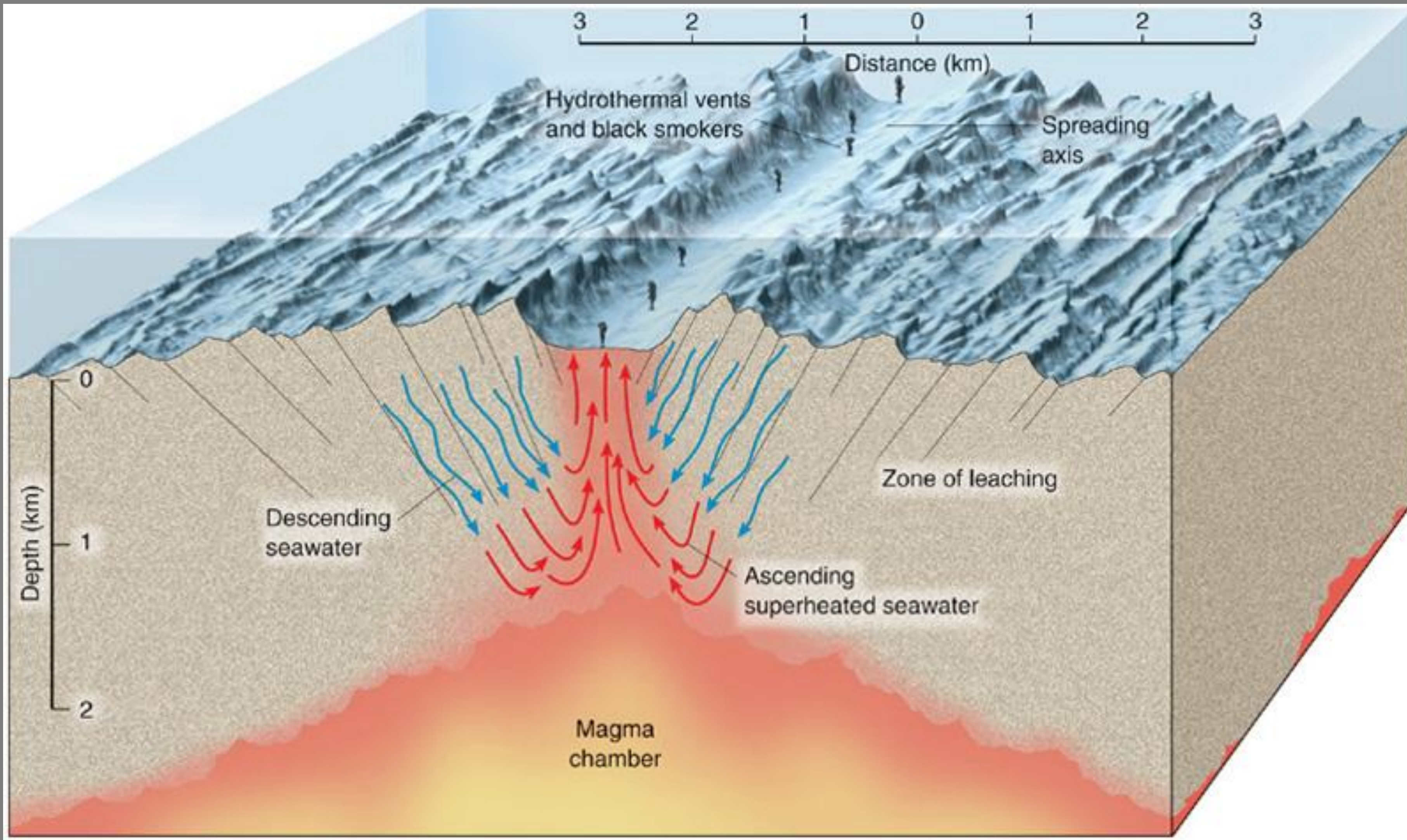
- The first life avoided ultraviolet radiation living either:
  Deep under the water
  Below the surface of the rocks

  Life most likely began at sea, perhaps in areas where it was related to underwater hydrothermal vents and "smokers".

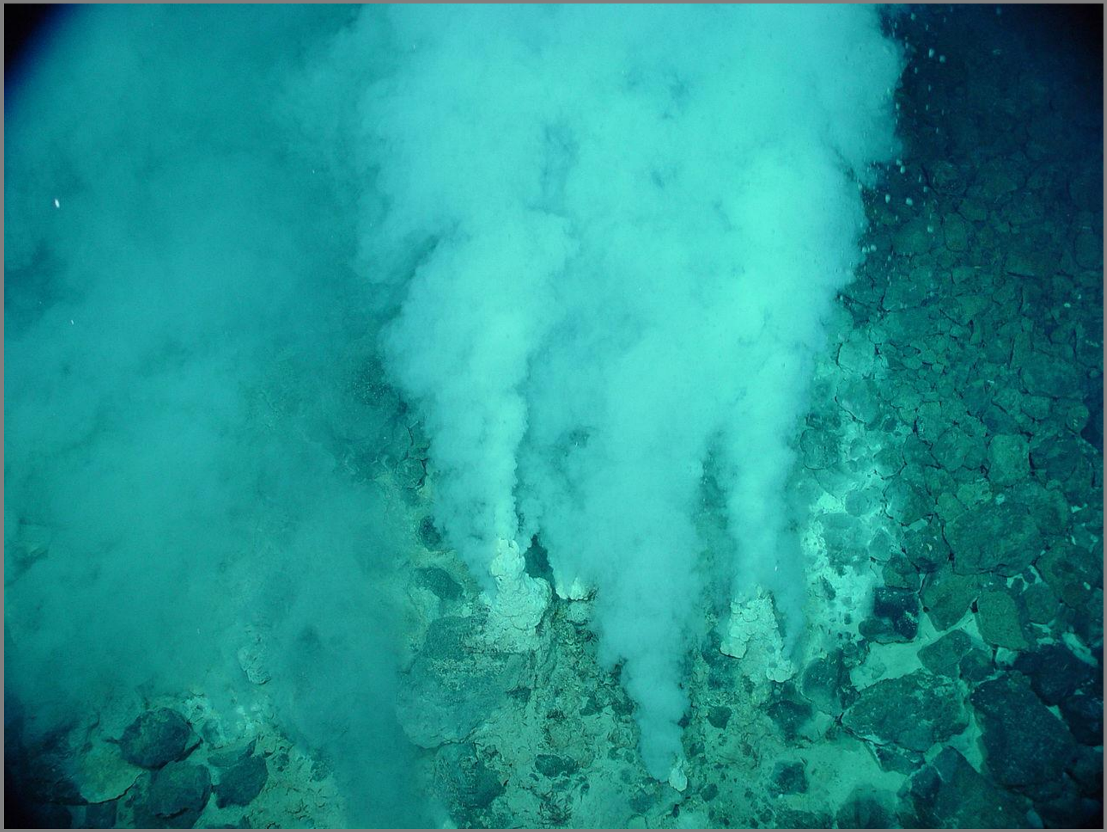
Που σχηματίστηκε η πρώτη ζωή;

- Η πρώτη ζωή απέφυγε την υπεριώδη ακτινοβολία ζώντας:
  - Βαθειά κάτω από το νερό
  - Κάτω από την επιφάνεια των πετρωμάτων

- Η ζωή το πιο πιθανό ξεκίνησε στη θάλασσα, ίσως σε περιοχές όπου σχετίζονταν με υποθαλάσσια υδροθερμικά πεδία και «καπνίστρες».


3 2 1 0 1 2 3
Distance (km)
Hydrothermal vents
and black smokers
Spreading
axis
0
1
2
Depth (km)
Zone of leaching
Descending
seawater
Ascending
superheated seawater
Magma
chamber

«Vents»



Temperatures>100ºC.

Evidence of creating life at sea in hydrothermal vents

1. The sea contains salts needed for health and development.
2. Water is the world's solvent, capable of dissolving organic compounds, creating a rich "broth" or primordial "soup".
3. The ocean currents mix these compounds, making possible the collisions between molecules, and combining them into larger organic molecules.

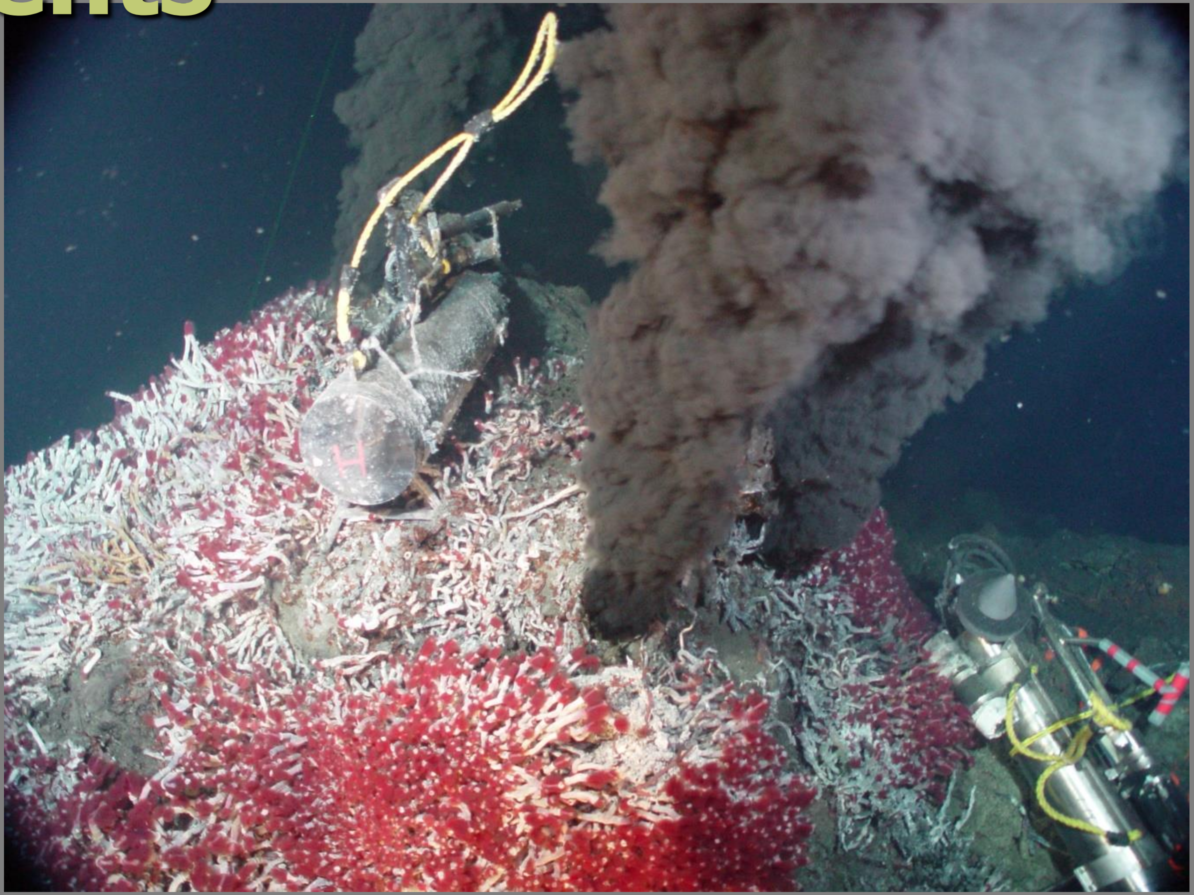
Evidence of creating life at sea in hydrothermal vents

4. Microbes in hydrothermal vents are hyperthermophilic and grow in sea water at temperatures above boiling (100 ° C).
5. These microbes get energy from chemosynthesis, without light, instead of photosynthesis.
6. Hyperthermophils are Archaeobacteria, with different DNA from bacteria.

Organisms living around vents

Crabs and polychaete worms

Organisms living around vents



Polychaete worms.

Evolution of first life

- The first cells had to be created and formed under anoxic conditions (in the absence of free oxygen); they were probably anaerobic bacteria or archaeobacteria.
- Some of the first organisms became photosynthetic, probably due to a lack of raw materials for energy. So, using the energy of the sun, they made their own raw materials for energy (Autotrophs). Photosynthesis was an advantage given by this adaptation.

  Oxygen was a "waste" (by-product) of photosynthesis.

"Side effects" of the accumulation of oxygen in the atmosphere

- Ozone layer formation that absorbs harmful ultraviolet radiation, and protects the primitive and fragile forms of life.
- The formation of iron layers stops.
- Oxidation of iron and formation of the first red layers.
- Development of aerobic metabolism. It uses oxygen to turn the food into energy.
- Development of eukaryotic cells that could withstand oxygen in the atmosphere.

Older signs of life

They appear in sedimentary rocks of the Archaic era.

Microscopic microscopic prokaryotic organisms.

Chemical fossils

Stromatolites

Laminae with algae

Molecular fossils

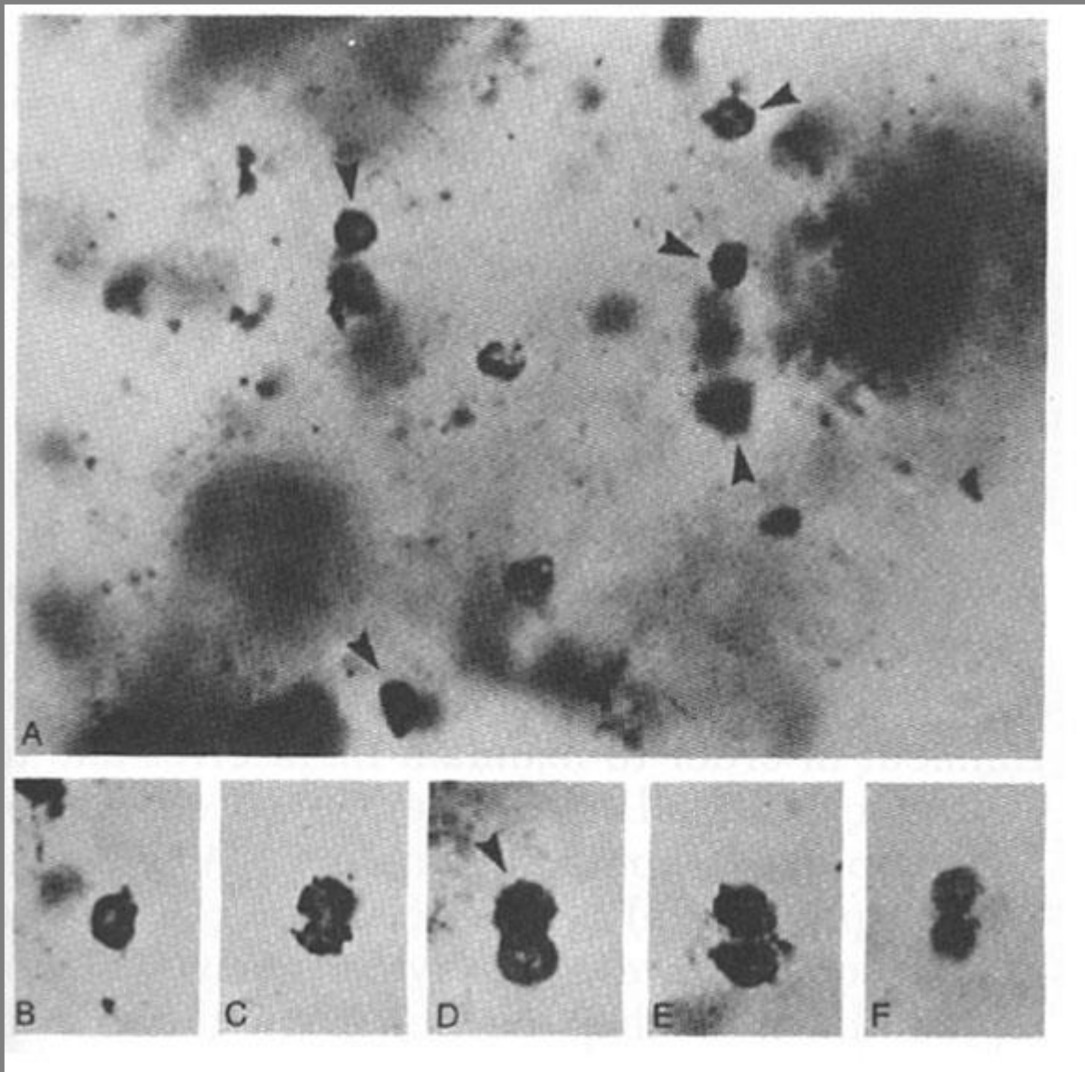
Earliest microfossils

Until two years ago

- 3500 my
- W. Australia
- Cyanobacteria, surprisingly advanced

↓

Photosynthesis had already started


A
B
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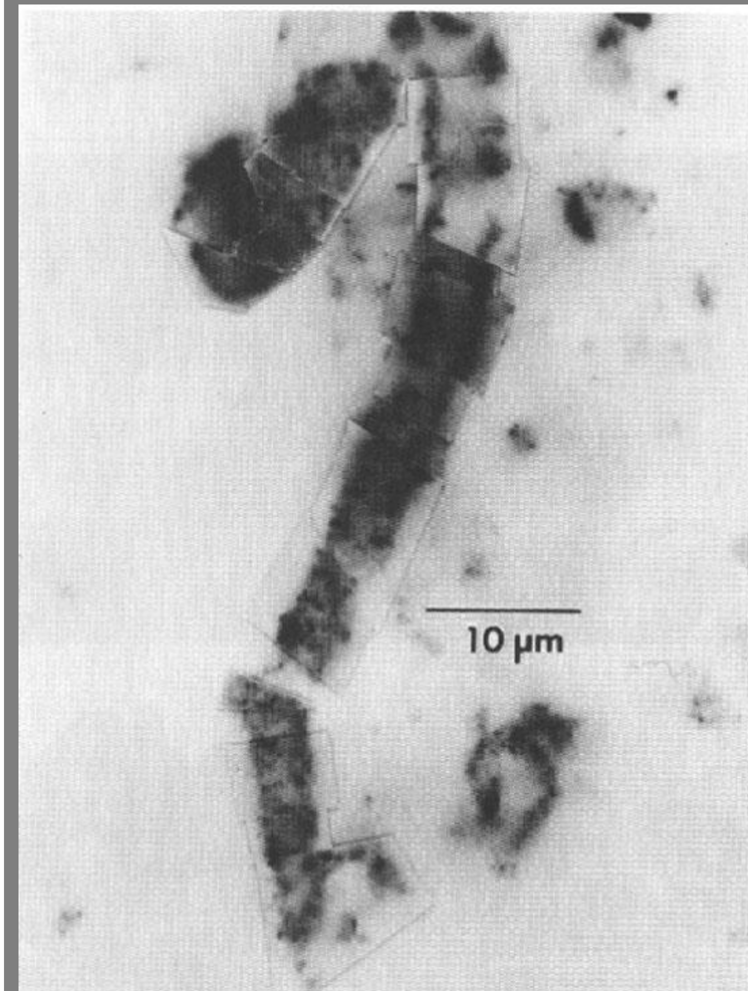
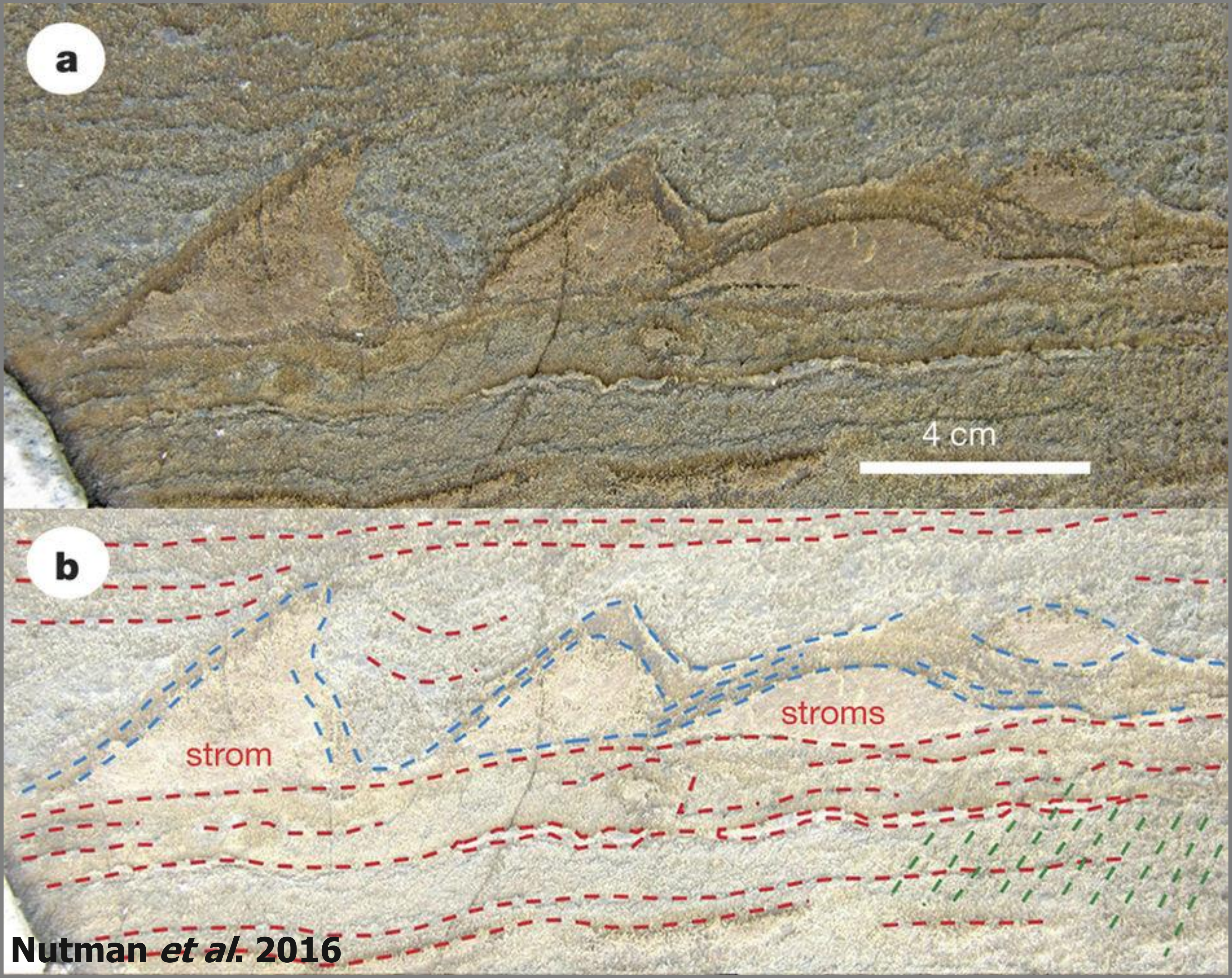

10 μm

Oldest mictofossils

- 3700 myrs
- Isua supracrustal belt, Greenland, in metacarbonates
- They contain 1-4-cm thick layers, laminar structures from microbial organisms (cyanobacteria).
- They had developed in shallow marine environments, as shown by rare earths and cross-over layers and clastic breccia products of intense waves

Nutman *et al*. 2016

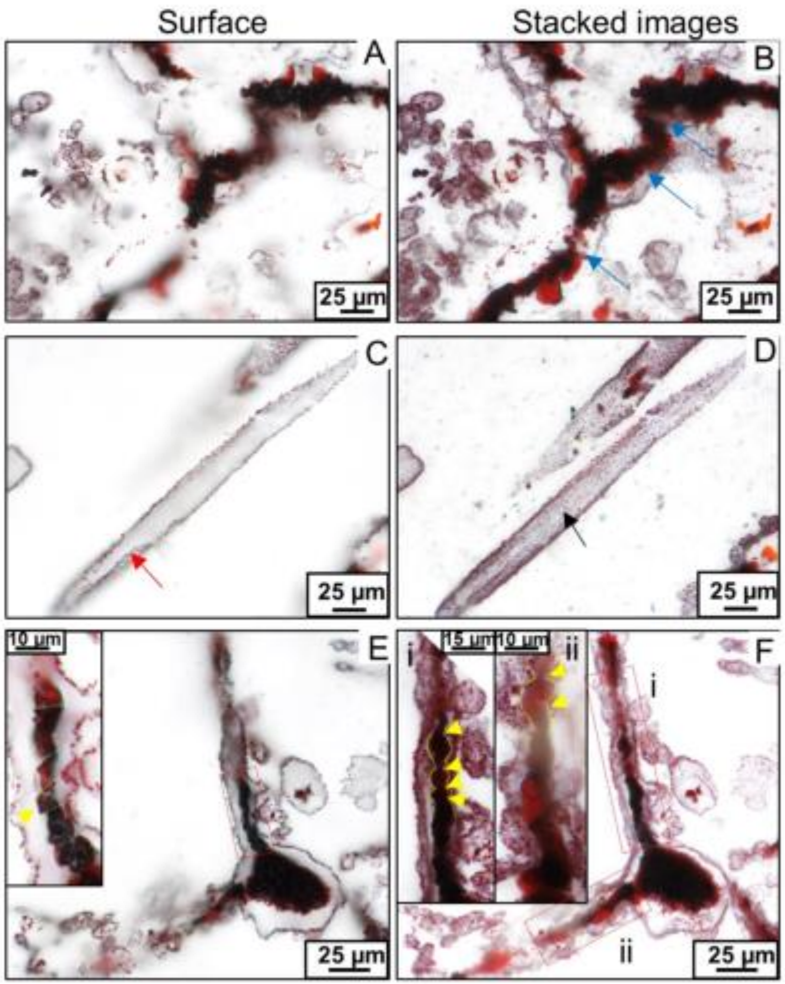


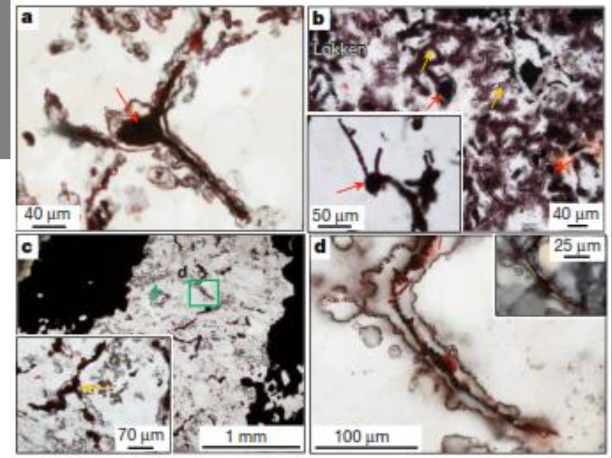
Nutman *et al.* 2016

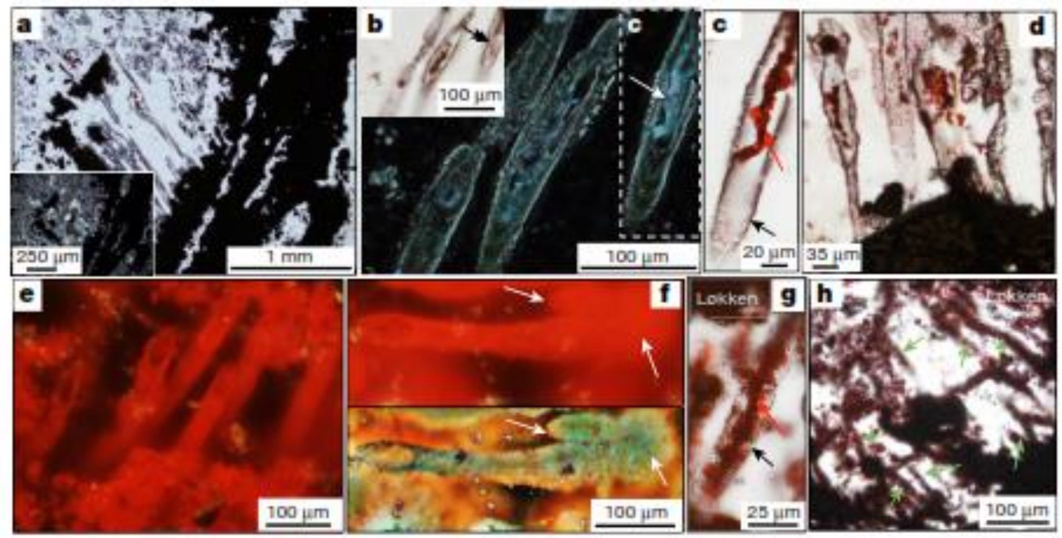
Oldest mictofossils

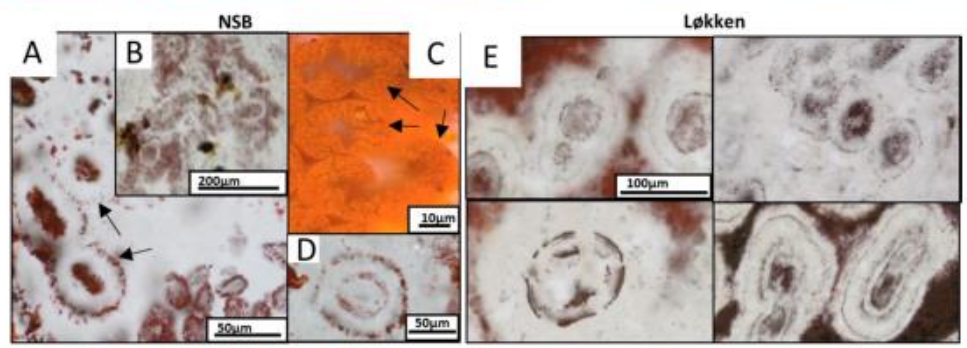
- At least 3770 myrs (maybe up to 4280 !!!) Nuvvuagittuq belt, Quebec Canada, ferrous sedimentary rocks
- Tube and laminate structures of several micrometers made of hematite.
- Morphologies and mineral concentrations similar to lamellar microorganisms living in modern vents and similar to microfossils from younger rocks. They were interpreted as deposits formed on bottoms around smokers. Oxidized organism remains

Dodd et al. 2017









Extended Data Figure 7 | Transmitted light and reflected light images of haematite rosettes. a–d, From NSB; **e**, from Løkken jaspers. **a**, Large (60 μm) haematite rosettes (arrows) with cores. **b**, Haematite rosettes in dense haematite. **c**, Deformed, thicker-walled (25 μm) haematite rosettes (arrows). **d**, Concentric haematite rosette. **e**, Haematite rosettes from Løkken jaspers, same scale bar for all.

Dodd et al. 2017

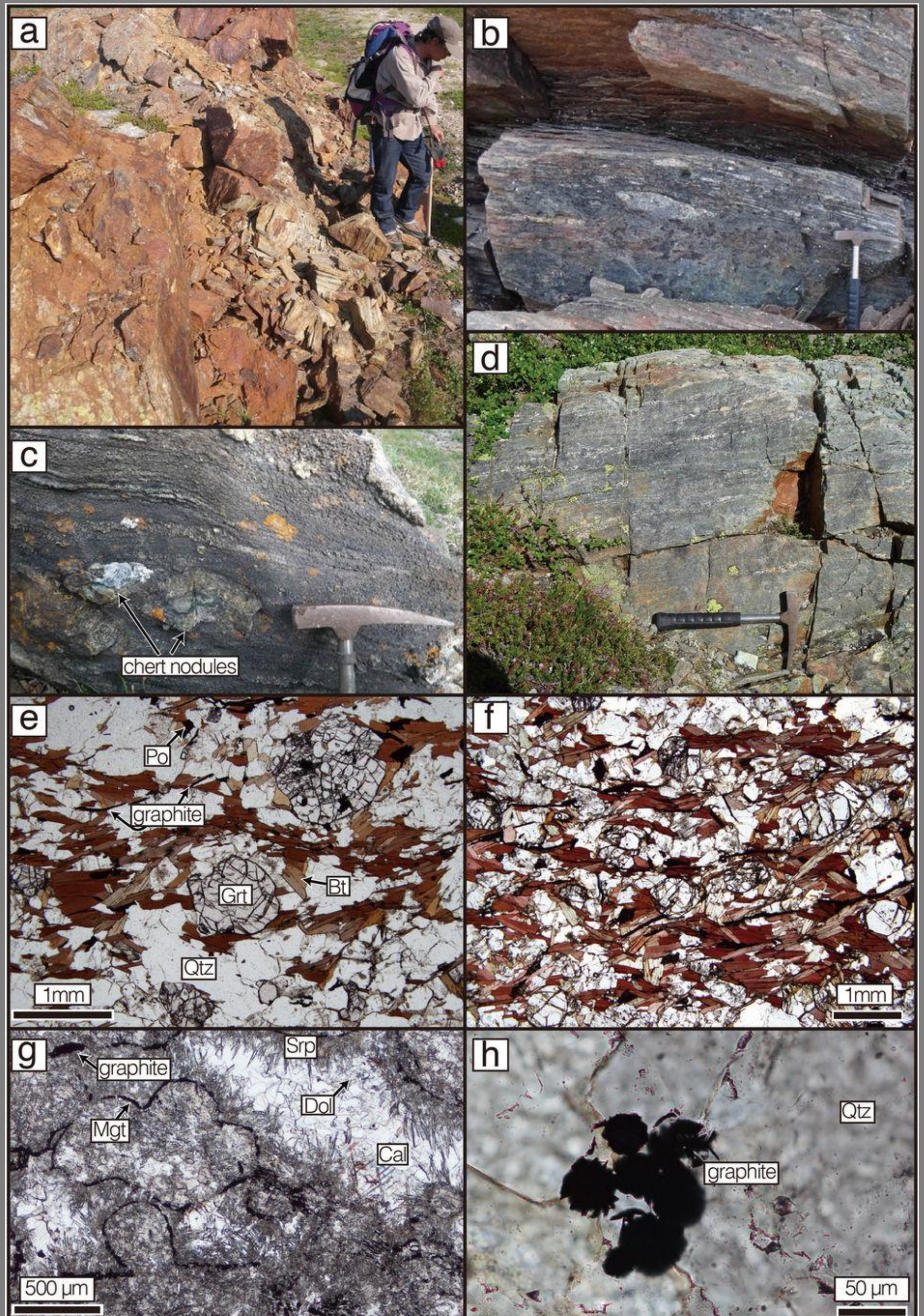
Oldest isotope evidence

- 3860 million years (until last year)
  Isua supracrustal belt, Greenland, earthquake rock
- Two isotopes of carbon ^{12}C and ^{13}C
- ^{12}C relatively richer than ^{13}C in these rocks
- This enrichment is observed during photosynthesis
  So not only life but also photosynthesis

Oldest isotope evidence

- 3950 million years
  Uivak Gneiss in Saglek Block, B. Labrador Canada, metasedimentary rocks
- ^{12}C relatively richer than ^{13}C in these rocks, comparable to values in younger layers. Discovery of authigenic biogenic graphite
  With the new evidence the first life on earth with certainty appeared before 4 billion years

Tashiro et al., 28/9/2017



Tashiro et al., 28/9/20

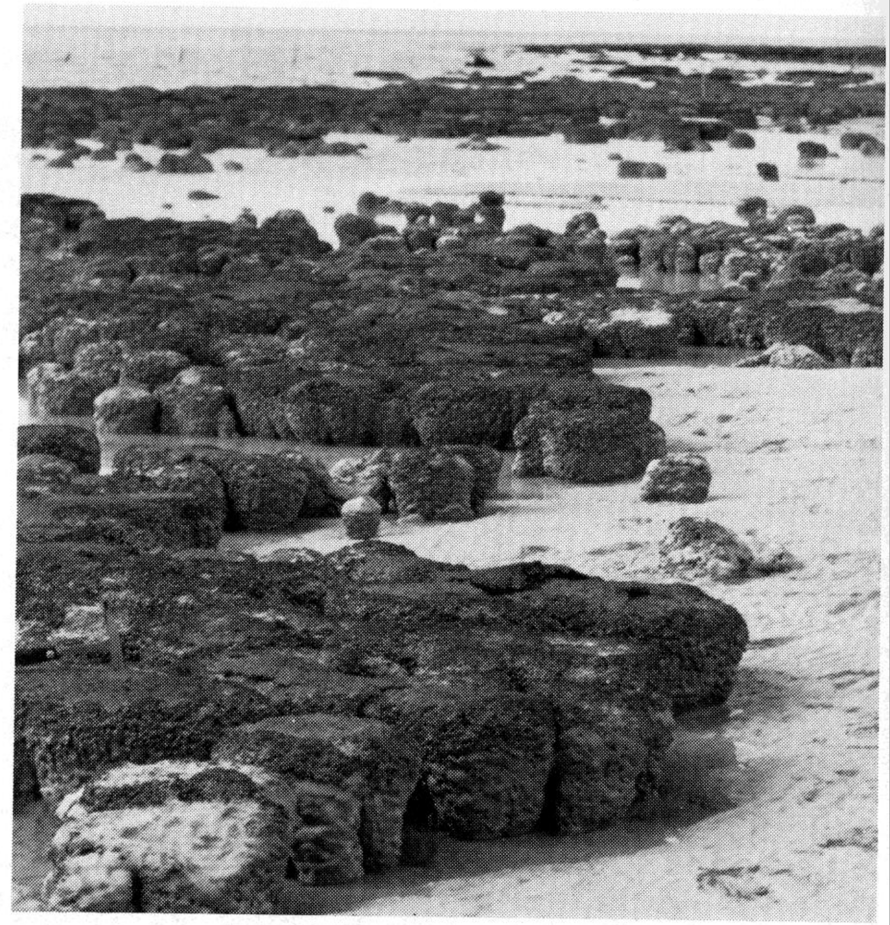
Stromatolites

- Stromatolites are found in every continent
- They are the most recognisable evidence of widespread life in the Precambrian
- They have produced thick, extensive deposits. Sometimes over 1000m thick
- Built mainly between 2 billion years and the beginning of Cambrian
- Extensive stromatolites also mean extensive photosynthesis

- Stromatolites were formed by bacterial communities dominated by photosynthesing cyanobacteria
- They form microbial mats covering the surface of shallow water sediments
- Microbes secrete gel to protect them from ultraviolet radiation and environmental contaminants
- Gel causes sediment to stick on microbes. When thick enough to block sunlight community moves sunwards and the new microbial mat starts to be built
- Thus stromatolites are basically trace fossils

- An organo-sedimentary "construction" made from photosynthetic cyanobacteria or cyanobacteria
  Layers are formed due to cyanobacterial activity in the tidal zone. Sticky laminae of cyanobacteria trap calcareous sediments during high tide.

FOSSIL STROMATOLITES typically exhibit the appearance of mounds or pillars made up of many thin layers piled one on top of another. The stromatolites were formed by communities of cyanobacteria and other prokaryotes (cells without a nucleus) in shallow water; each layer represents a stage in the growth of the community. Stromatolites formed throughout much of the Precambrian era. They are an important source of Precambrian fossils. These specimens are in limestone about 1,300 million years old in Glacier National Park.



LIVING STROMATOLITES were photographed at Shark Bay in Australia. Elsewhere stromatolites are rare because of grazing by invertebrates. Here the invertebrates are excluded because the water is too salty for them; in the Precambrian era they had not yet evolved. In size and form the modern stromatolites are much like the fossil structures, and they are produced by the growth of cyanobacteria and other prokaryotes in matlike communities. The discovery of such living stromatolites has confirmed the biological origin of the fossil ones.

Shark Bay, Australia. Living stromatolites

More in Proterozoic than in Archaic rocks.

The older ones are 3.7 b.y. Old Isua supracrustal belt, Greenland

3.5 b.y. old, Warrawoona Group, Australia

3 b.y. Pongola Group, South Africa

2.8 b.y. Bulawayan Group, Australia

Προκάμβριοι απολιθωμένοι στρωματόλιθοι από την Ν. Αφρική

Stromatolites

- Stromatolites are rare today because the organisms that make them are eaten by gastropods or other invertebrates.
- They only survive in environments with great salinity which are unsuitable for most herbivorous invertebrates.
- The reduction of Stromatolites is associated with the gradual emergence of new invertebrates in the upper Proterozoic and lower Paleozoic

- In 1953 Stanley Tyler in a 2 billion years old rock unit, the Gunflint Chert in Canada found chainlike and spherical forms, the fossils of cyanobacteria and other prokaryotes. This seminal work established the science of Precambrian palaeontology

- Evidence for the extensive production of oxygen comes from oxidized iron deposits
- Tiny organisms that exploited carbon dioxide, water and sunlight transform the Earth forever
- Some of the anaerobic organisms went extinct but others adopted aerobic metabolism and led to the creation of the eukaryotic cell

Other evidence

- Laminated algae - Prokaryotic organisms preserved in stromatolites In North Pole, Western Australia - 3.4-3.5 billion years.
- Spheroidal bacterial structures In South African rocks (pyrite, shales, sandstones) Prokaryotic cells with possible cell division - 3.0 - 3.1 billion years.
- Molecular Fossils - Preserved organic molecules that only eukaryotic cells produce. Indirect indications of eukaryotic organisms.

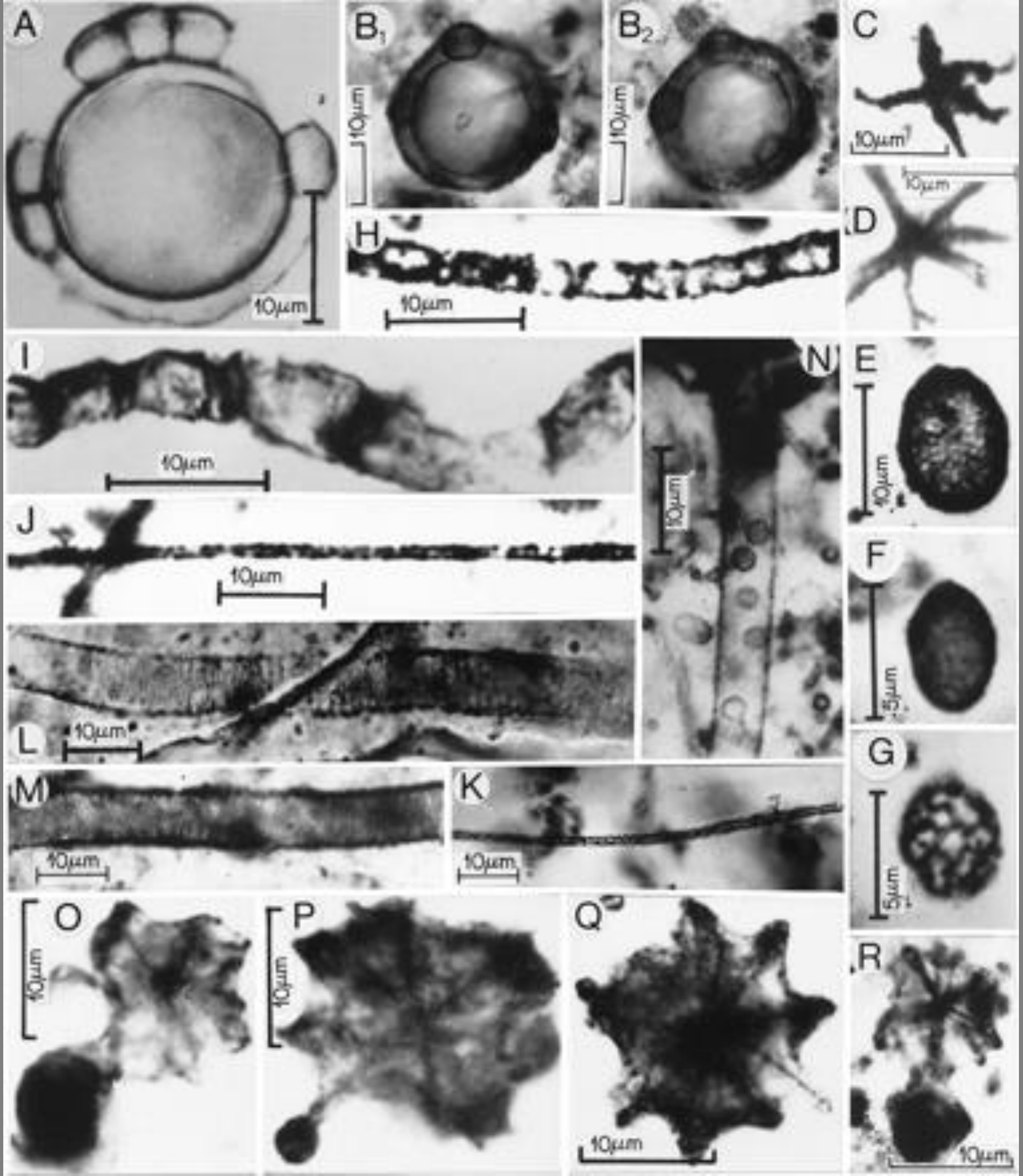
Early Eukaryotes

- Eukaryotic organisms spread at about the same time that the iron layers disappeared and the red layers appeared.

  The origin of eucaryotic organisms about 2.7 billion years, is based on molecular fossils. In Black Shales Southwestern Australia.

Early Eukaryotes

- Some of the early Eukaryotic organisms found in Proterozoic rocks are unicellular phytoplankton (acritarchs) and microscopic red algae, complex protists, megascopic algae, calcareous algae
- The fossil record strongly suggests that a photosynthetic lineage formed the proterozoic trunk of the Eukaryotic tree



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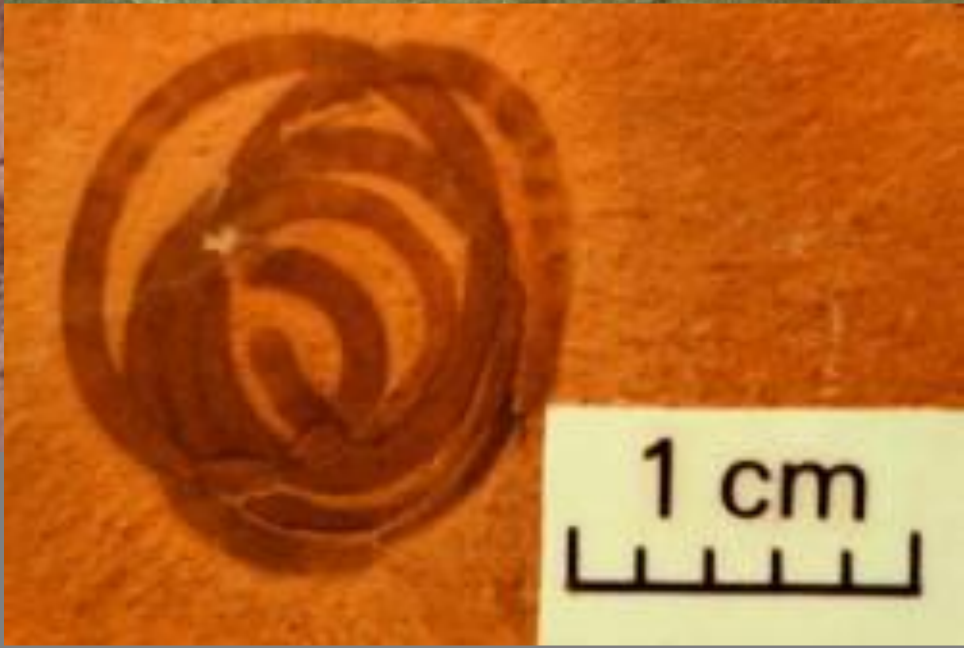
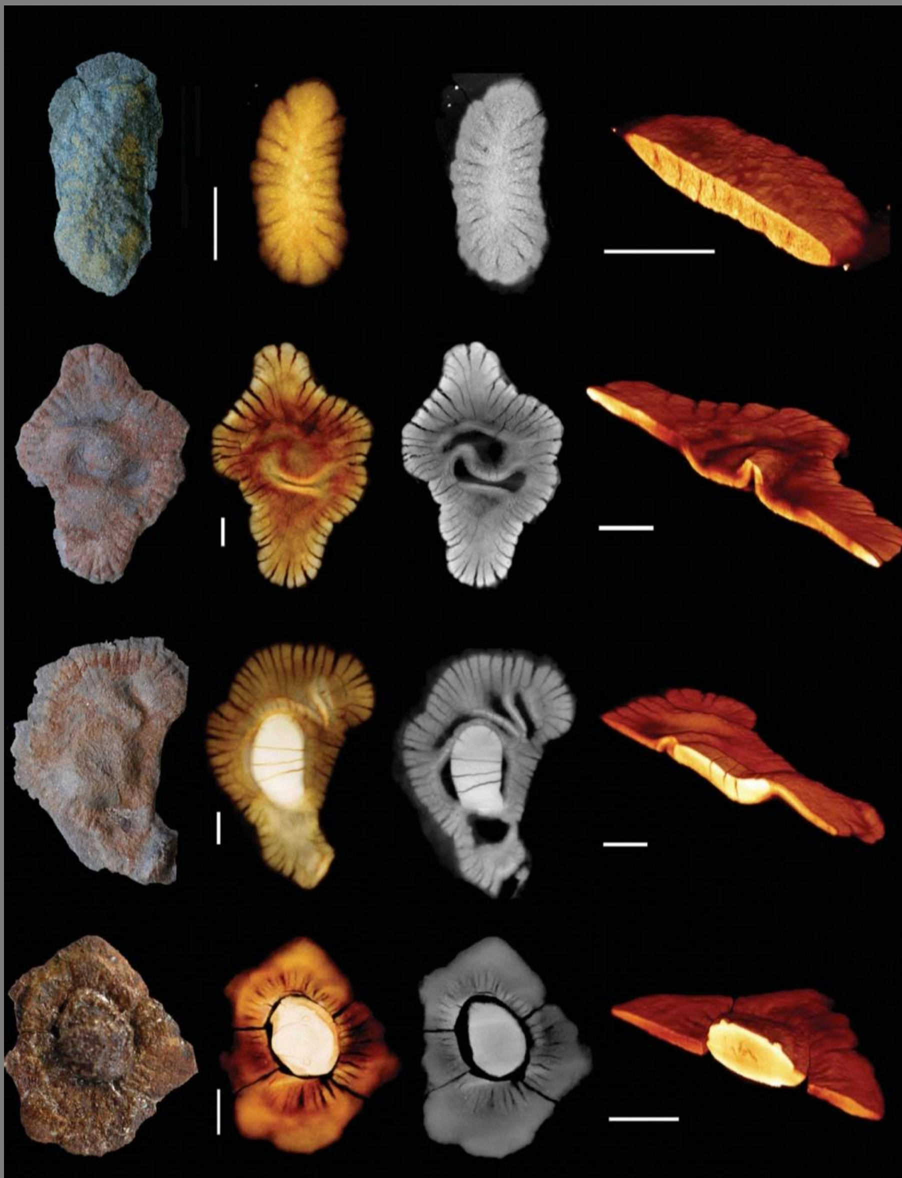
Grypania

- There is little evidence for the early multicellular organisms
- Possibly the first multicellular fossil is *Grypania* preserved as ribbon-like carbonaceous compressions found in 2.1 billion year-old rocks from Michigan
- Similar specimens from China, India, Canada
- Ribbons of *Grypania*, 2 mm wide, 5-15 cm long preserved in loose coils 0,5- 2,5 cm across
- No cellular structures are preserved
- Due to its large size, shape, and preservation a carbonaceous compressions most likely a multicellular eukaryotic alga

Grypania



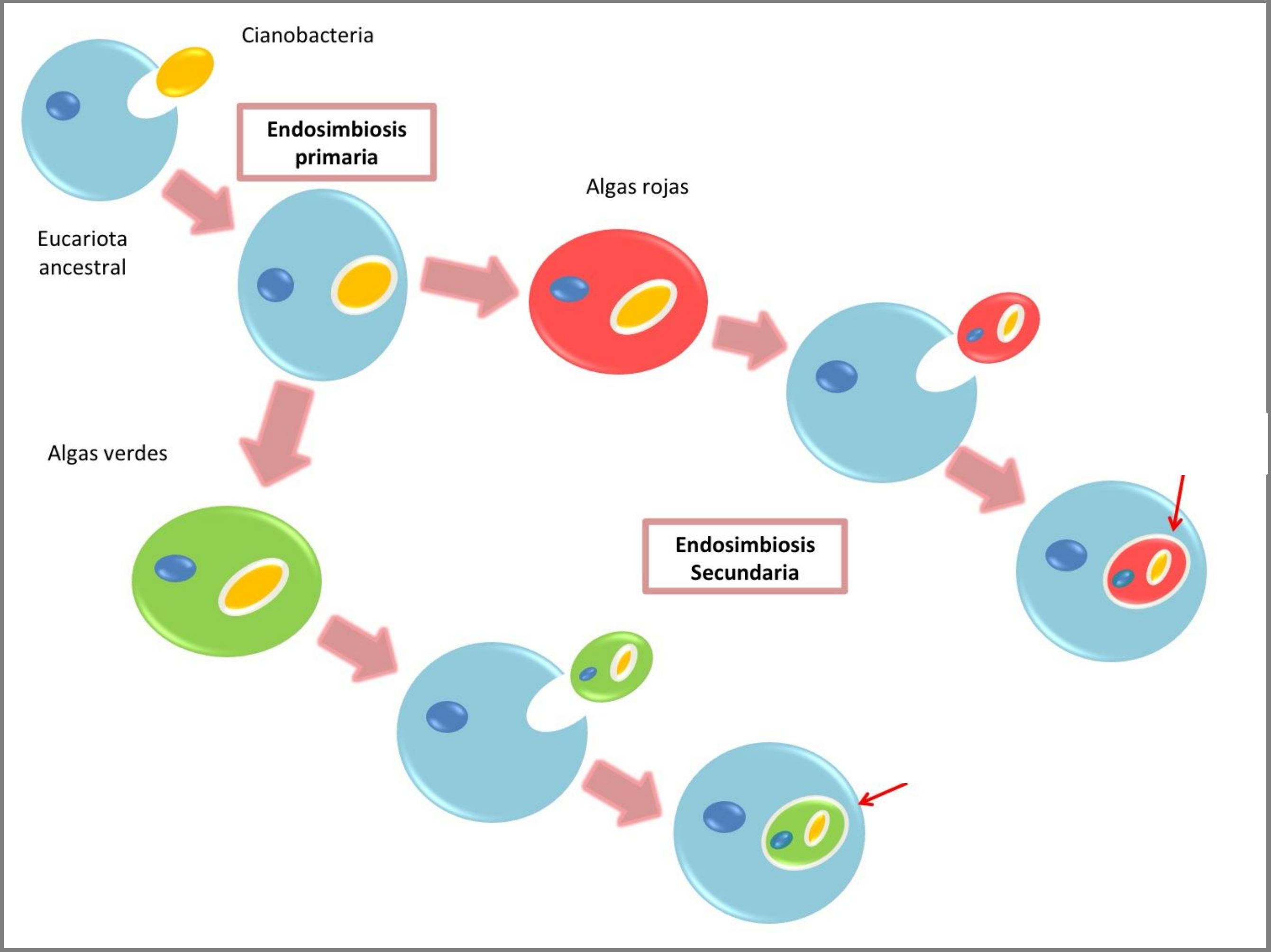
Multicellular organisms, 2,1by, Gabon



Endosymbiosis

- Billion of years ago, several prokaryotic cells were found living together symbiotically within a cell for protection and adaptation from an oxygenated environment.
- These prokaryotic cells became organelles. Evidence of this is also the fact that mitochondria have their own DNA.
- eg. - a host cell (anaerobic fermentation) + aerobic organelle (mitochondria) + plus organelle like spirochaetis (a whip for locomotion).

Endosymbiosis in algae



Eukaryotes

- Their appearance led to a dramatic increase in the rate of evolution and was ultimately responsible for the appearance of complex multi-cellular organisms.

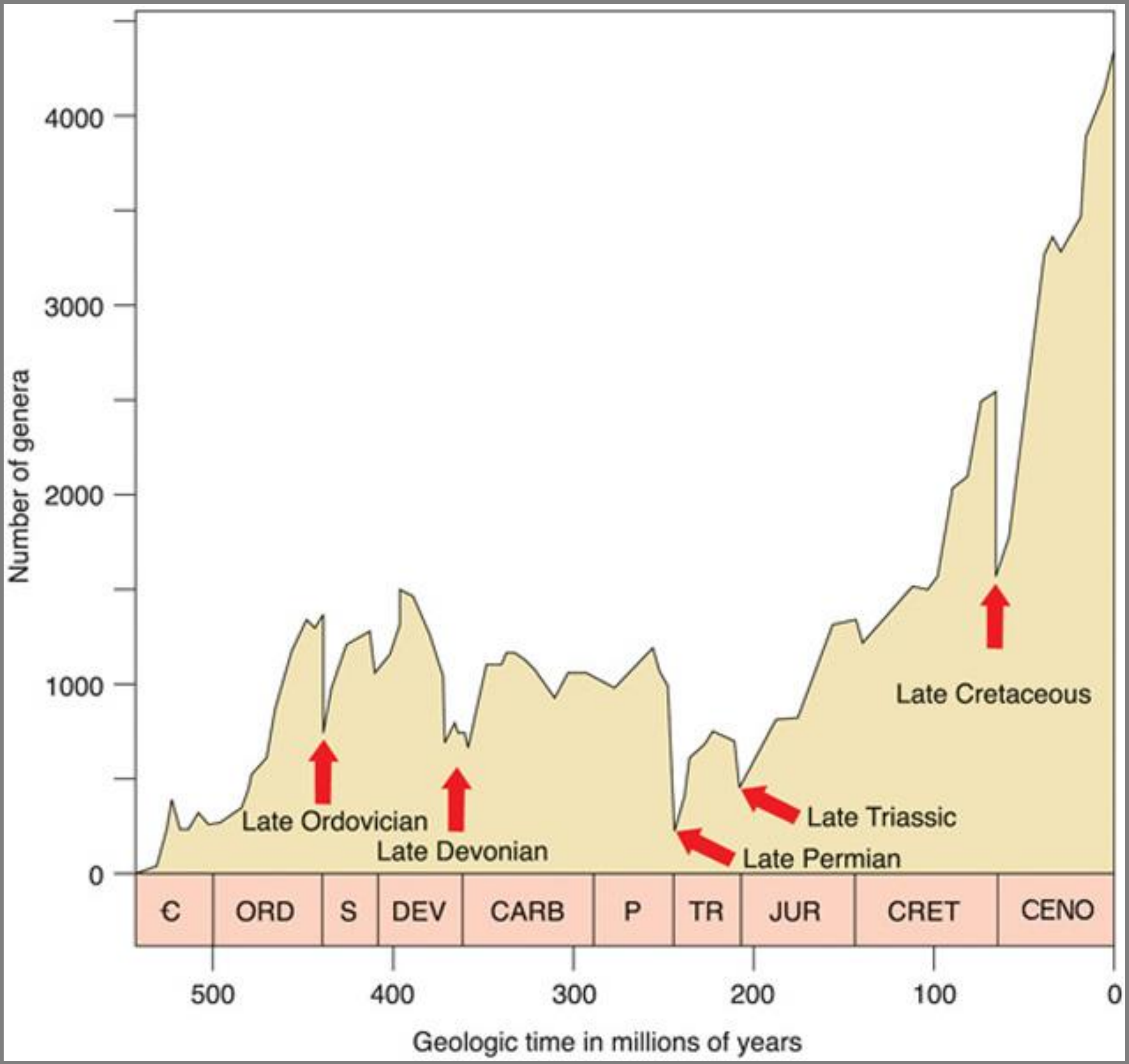
Extinctions

- Phyletic extinction or pseudo-extinction
  One species is lost as it evolves into another
- Ultimate extinction
  The total population of a species is lost without a descendant
- Mass extinction
  Lazarus taxa: Organisms that seem to disappear for a long time from the fossil record and appear again

Mass extinctions

- Occur Worldwide
- Both in the sea and on land
- Involve a large number of different organisms

Mass extinctions



1. L. Ordovician
2. L. Devonian
3. L. Permian
4. L. Triassic
5. L. Cretaceous

What caused extinctions?

- Several hypotheses trying to explain the cause of these disappearances:
- An external or extra-terrestrial catastrophic cause triggers the incident.
- Events occurring on the earth without external influences.

external or extra-terrestrial catastrophic cause

- Impact with asteroids?
  Impact with Comet?
  Cosmic radiation from a neighboring supernova?

Endoterrestrial factors

- Volcanic eruptions emit large amounts of ash and gases into the atmosphere that lead to a drop in temperature. They emit large amounts of sulfur dioxide, which becomes sulfuric acid in the atmosphere and acid rain, resulting in altering the alkalinity in the oceans, putting plankton (the food chain base) into lethal pressure and indirectly affecting all organisms that depend on this for food

Endoterrestrial factors

- Climate change related to the change of land - sea distribution
- Glaciers and the decline of continental seas with the drop of sea level
- Methane emmision
- Sickness? Viruses;
- All this together !!