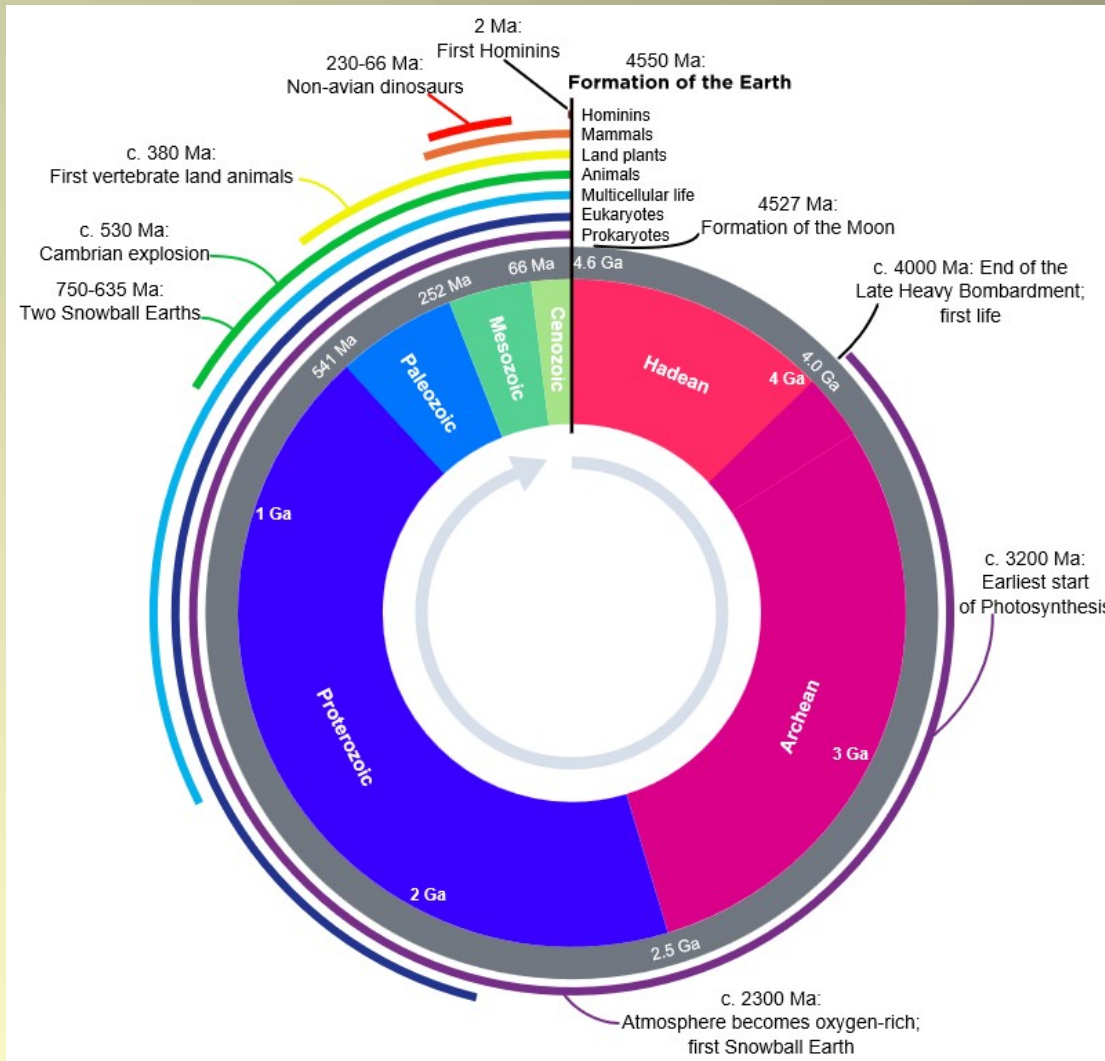
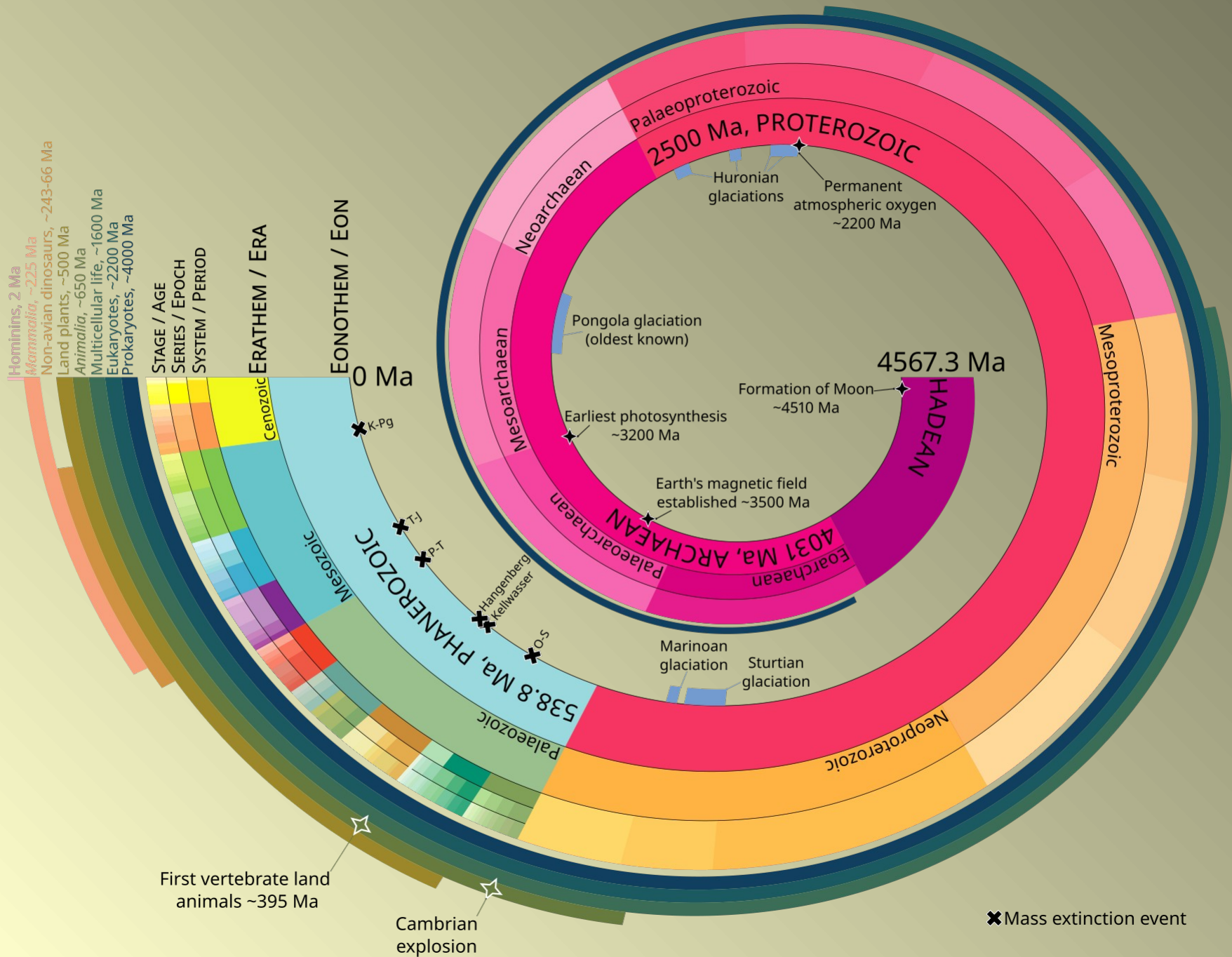
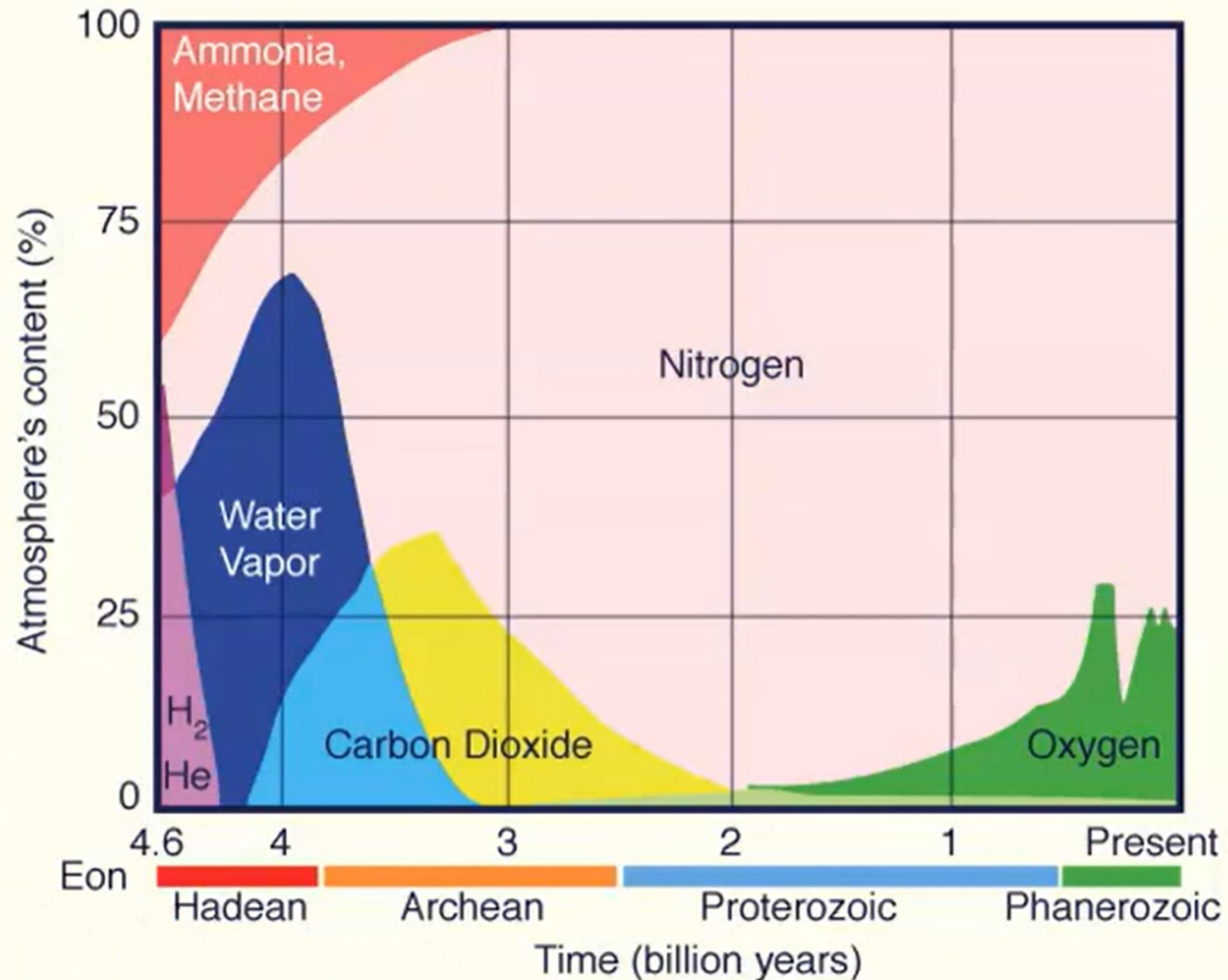






Atmosphere Evolution

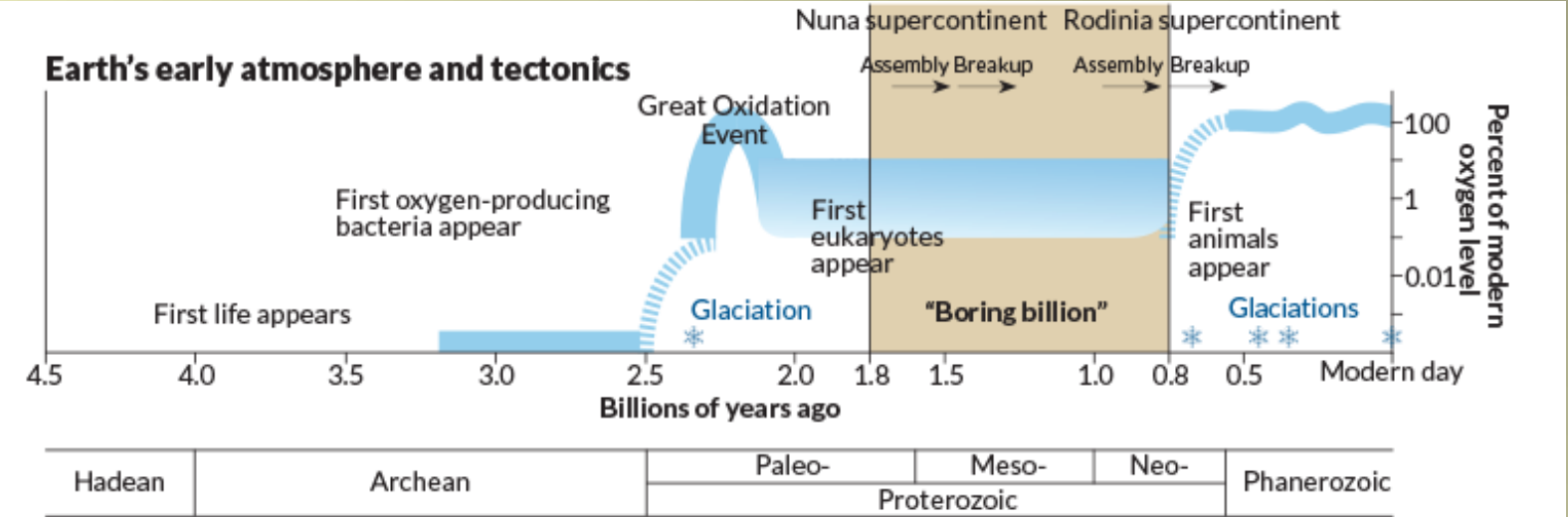


GOE – "great oxygenation event"

Proterozoicum



geology.cz



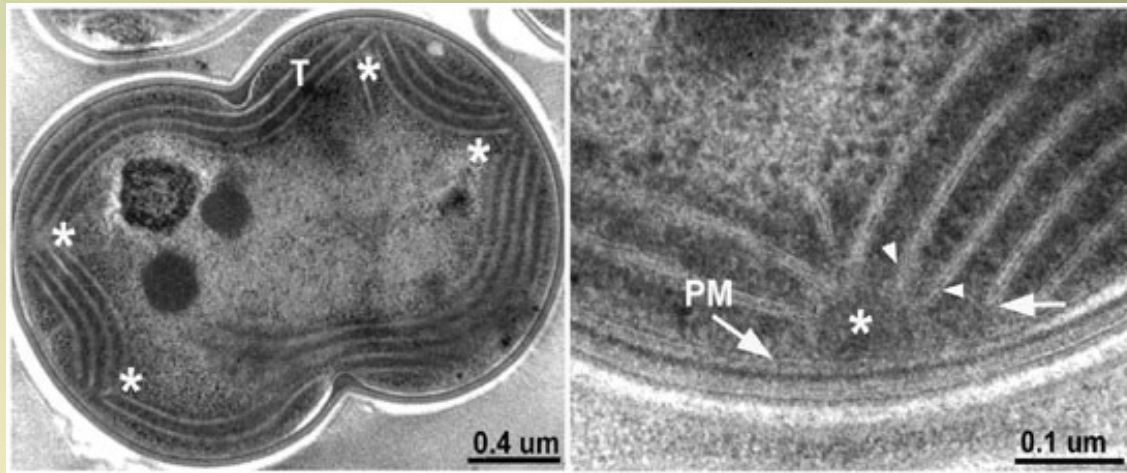
Cyanobacteria – first occurrence of thylakoids and phycobilisomes



oxygenic photosynthesis

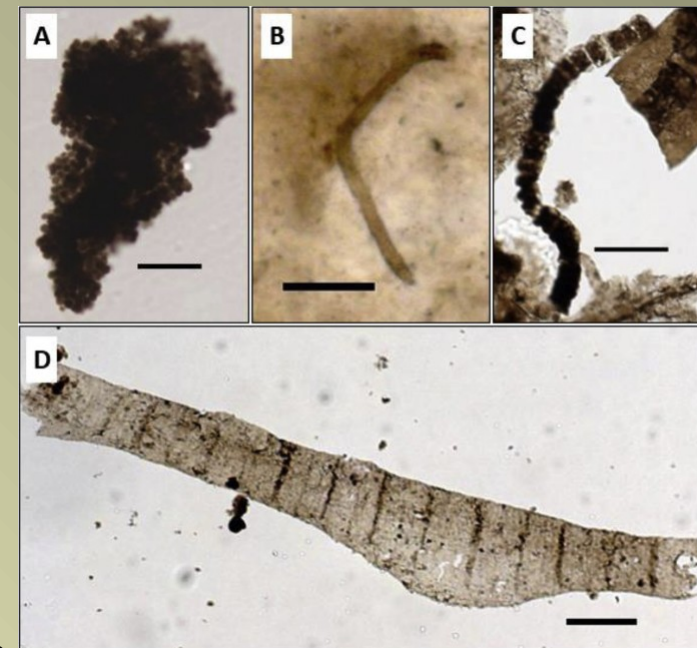
(therefore *oxyphotrophic bacteria*)

(some of the may be capable of sulphurogenic photosynthesis, too)



early Cyanobacteria

3.2 to 2.7 billion years ago



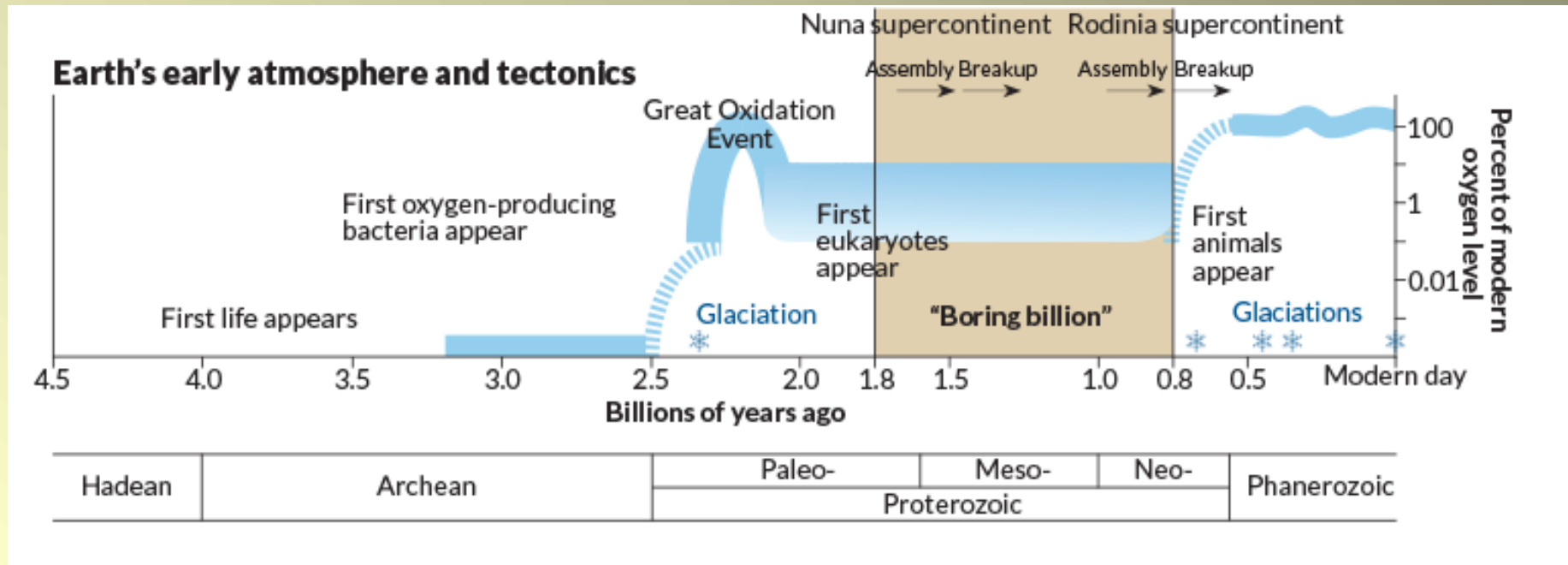
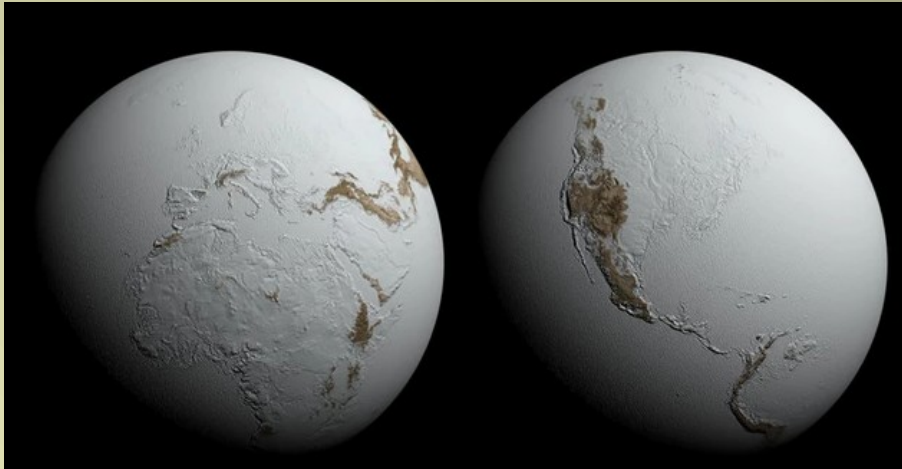
2.5 to 0.6 billion years - „age of Cyanobacteria “ or „boring billion“



stromatoliths

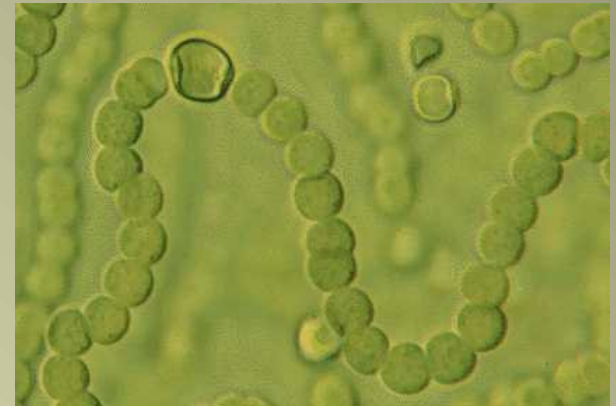
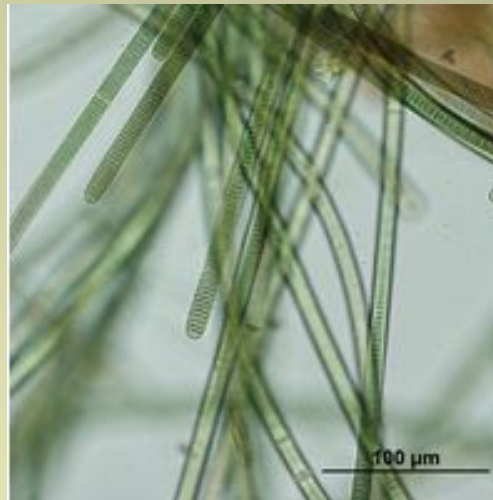
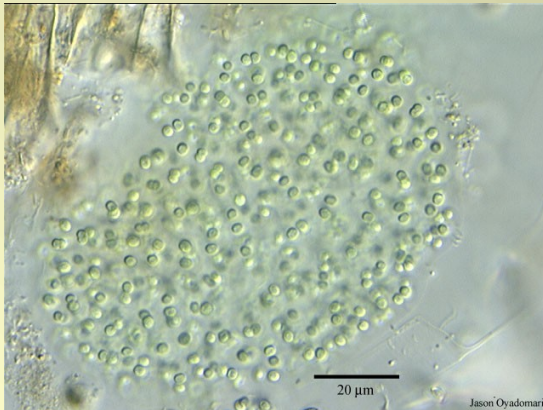
well documented fossils of coccoid and filamentous cyanobacteria – 2.5 bya

GOE and Huronian glaciation



Basic characteristics of **Cyanobacteria**

- coccoid (solitary or colonial) or filamentous
- always have chlorophyll *a* (+ chlorophyll *f*, sometimes *b*)
- in some lineages very important fixation of atmospheric nitrogen
- in phanerozoicum – so called static phenotypic evolution
- reproduction – vegetative cell division
- in general, three morphological types:
 - coccoid
 - simple filamentous
 - filamentous with differentiated cells



phylogeny of Cyanobacteria

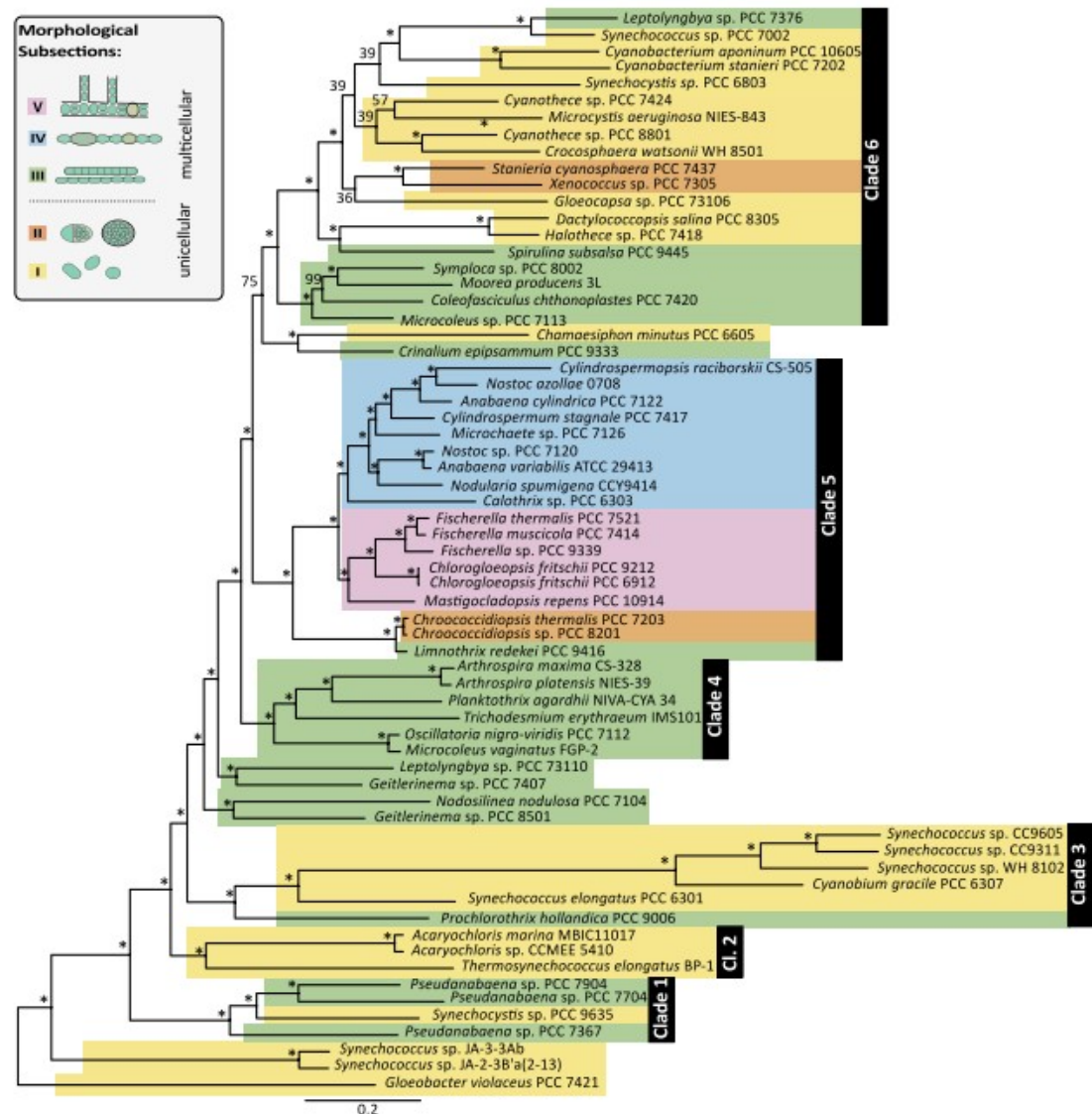
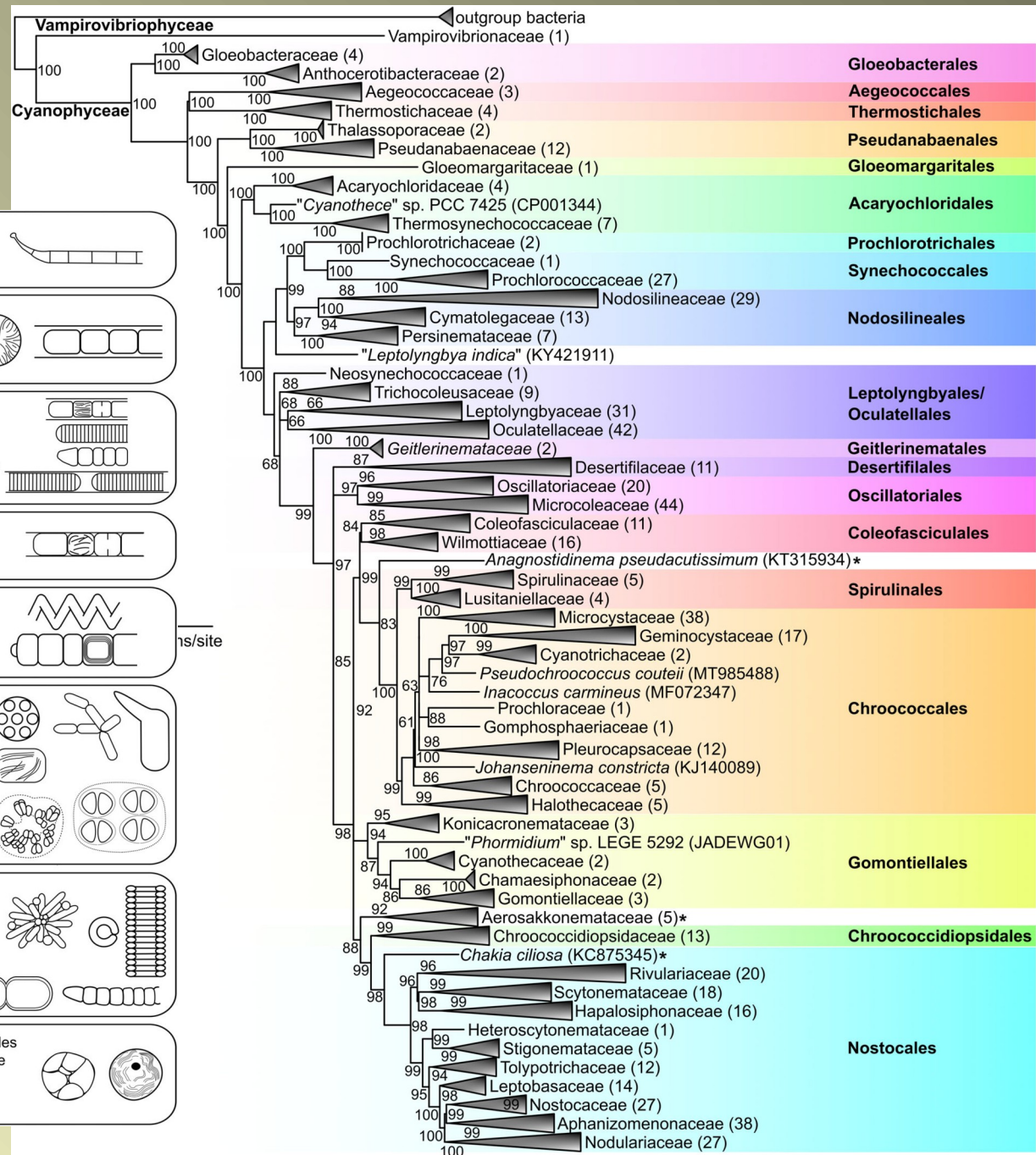
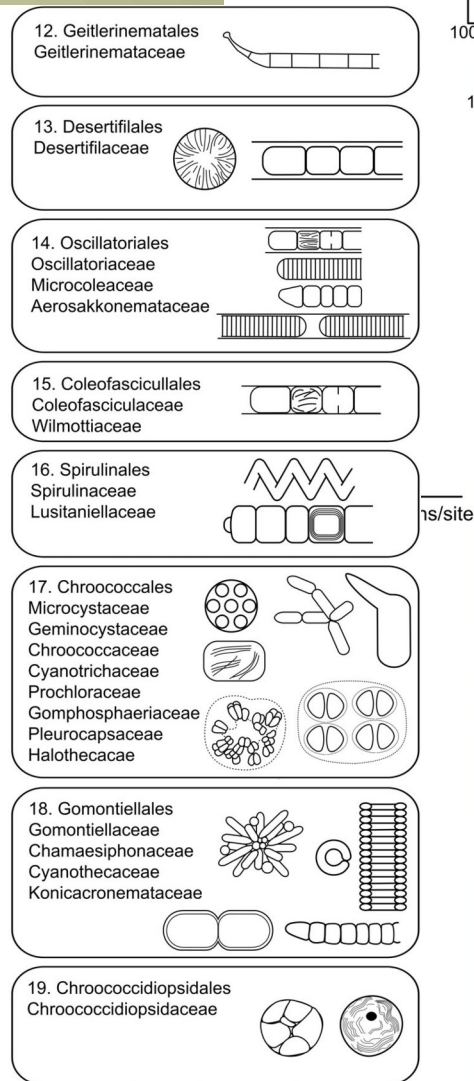
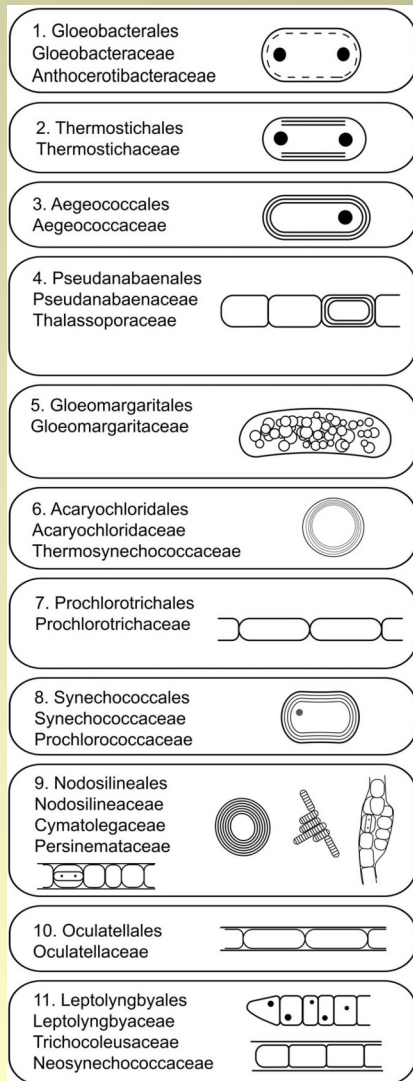


FIG. 1. Phylogenomic maximum likelihood tree. Phylogeny of 65 cyanobacterial taxa based on a supermatrix comprised of 756 concatenated protein sequences (197 761 amino acid sites). Maximum likelihood bootstrap support for clades is indicated at respective branches. Stars indicate 100% support calculated from 1000 bootstrap resamplings. Cyanobacterial taxa are colour-coded. Unicellular taxa belonging to morphological subsections I and II are displayed in yellow and orange, respectively, whereas multicellular cyanobacterial taxa belonging to subsections III, IV and V are shown in green, blue and pink, respectively. The majority of branches in this phylogeny are well supported. Six distinct clades could be reconstructed with full support. Differentiated cyanobacteria belonging to subsections IV and V are the only groups where morphological and genomic data congruently suggest a monophyletic origin.

phylogeny of Cyanobacteria



evolution of plastids from Cyanobacteria

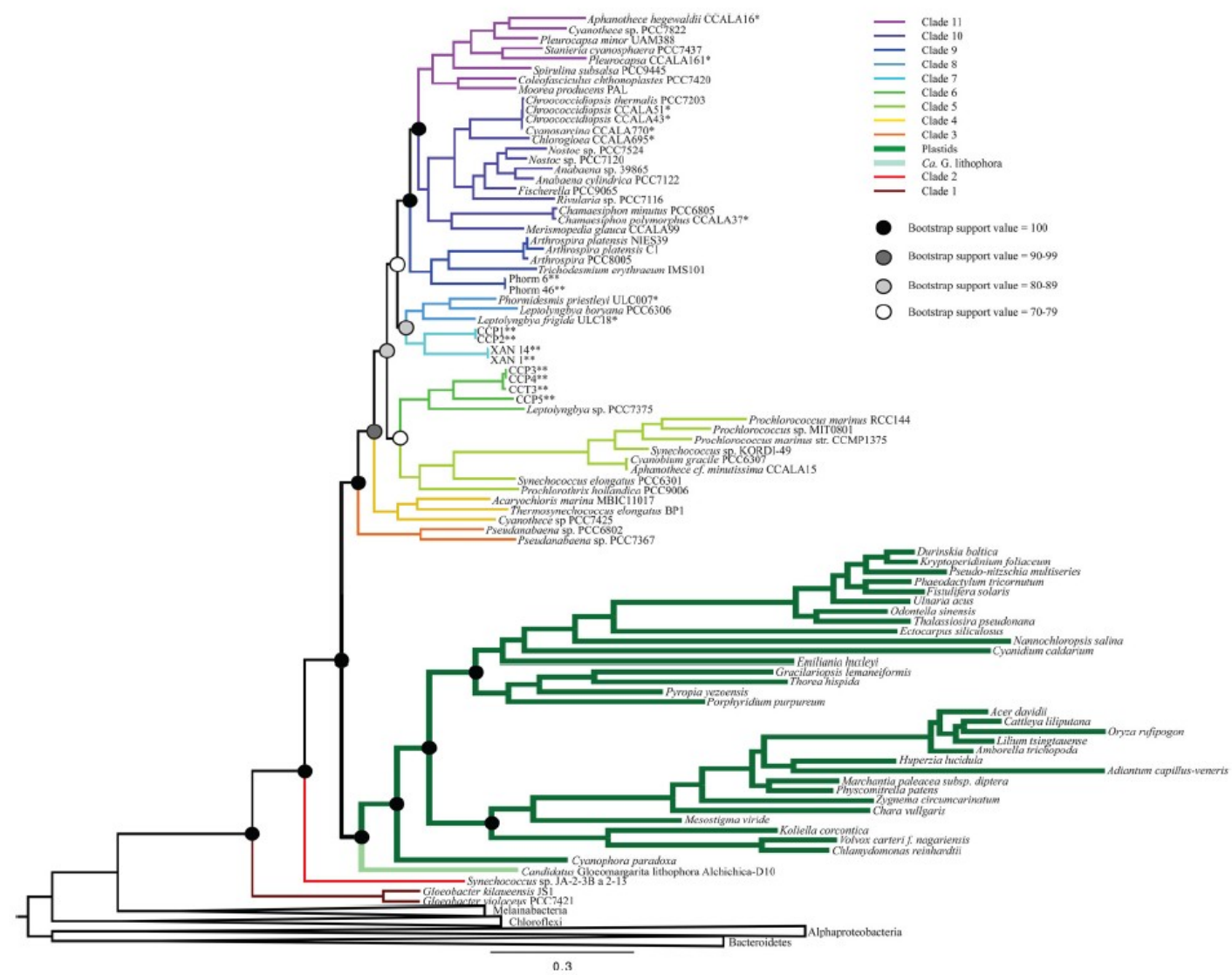
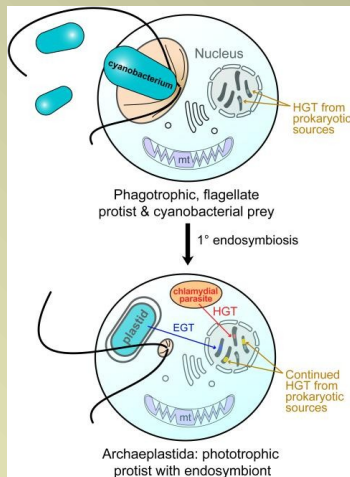


FIGURE 1 | A maximum likelihood (ML) phylogenetic tree made using a concatenation of 30 large and small subunit ribosomal proteins (Table 2) and RAXML. This tree supports a deep placement of the plastid clade with high bootstrap support. Bootstrap values are denoted for major divergences of cyanobacterial and plastid clades. All internal nodes have bootstrap values of >90.

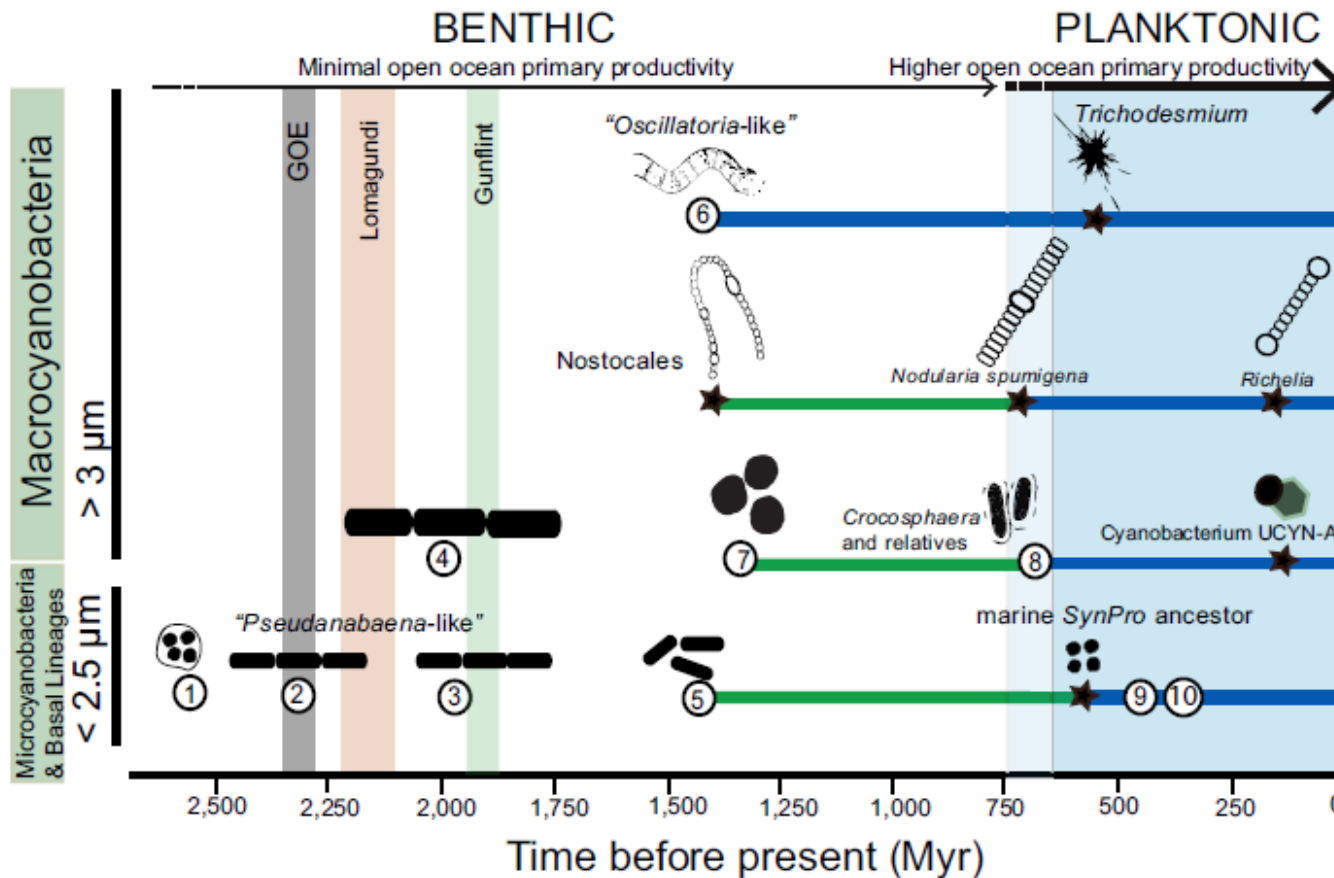
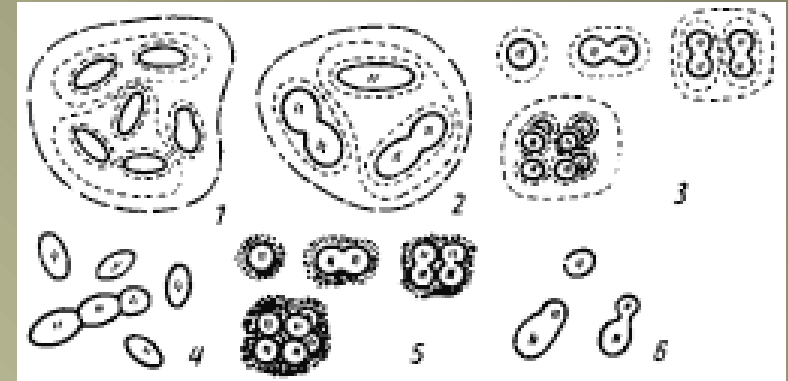
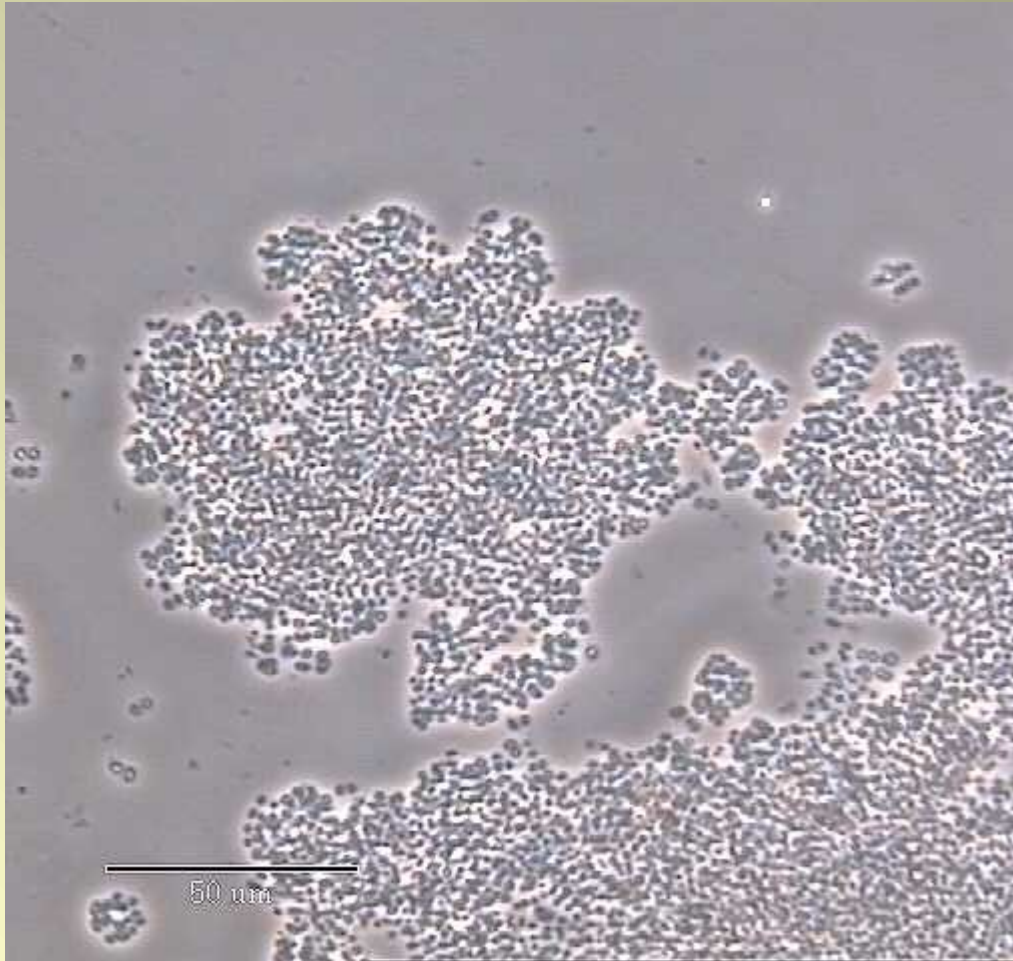


Figure 2. Timing and trends in cell diameter, loss of filamentous forms and habitat preference within cyanobacteria. Nodes shown (1–10) correspond to Fig. 1 and Table 1. Stars represent common ancestors that appear in Fig. 1 but ages are not given in Table 1. The timing of the Great Oxidation Event (GOE) is after ref. 2, the Lomagundi-Jatuli Excursion after ref. 55 and Gunflint formation after ref. 73. Green lines represent freshwater lineages and blue lines represent marine lineages based on Bayesian inference of character evolution (stochastic character mapping analyses; Supplementary Fig. S4). Cartoons are not drawn according to scale; taxa with smaller cell diameter are shown at the bottom and larger cell diameter at the top.

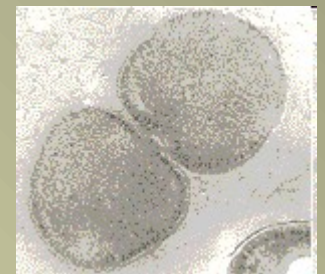
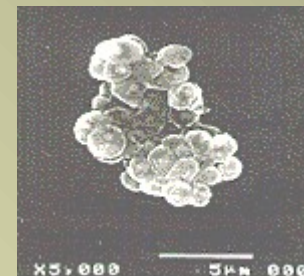
three types of photosynthetic apparatus

type *Gloeobacter*

- no thylakoids, phycobilisomes and pigments on plasmatic membrane

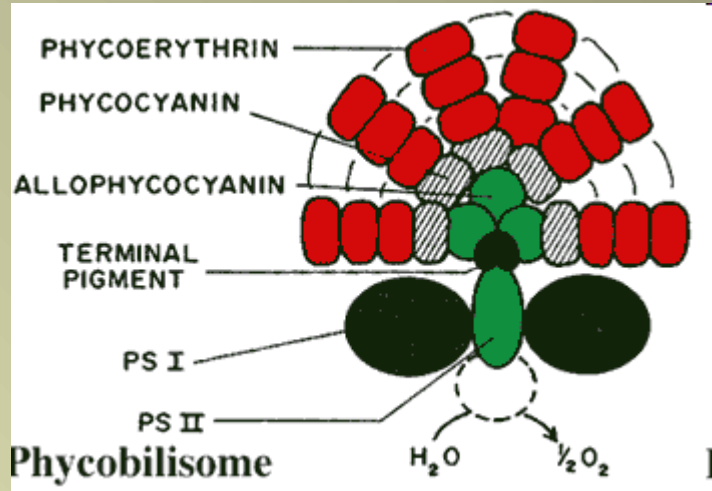
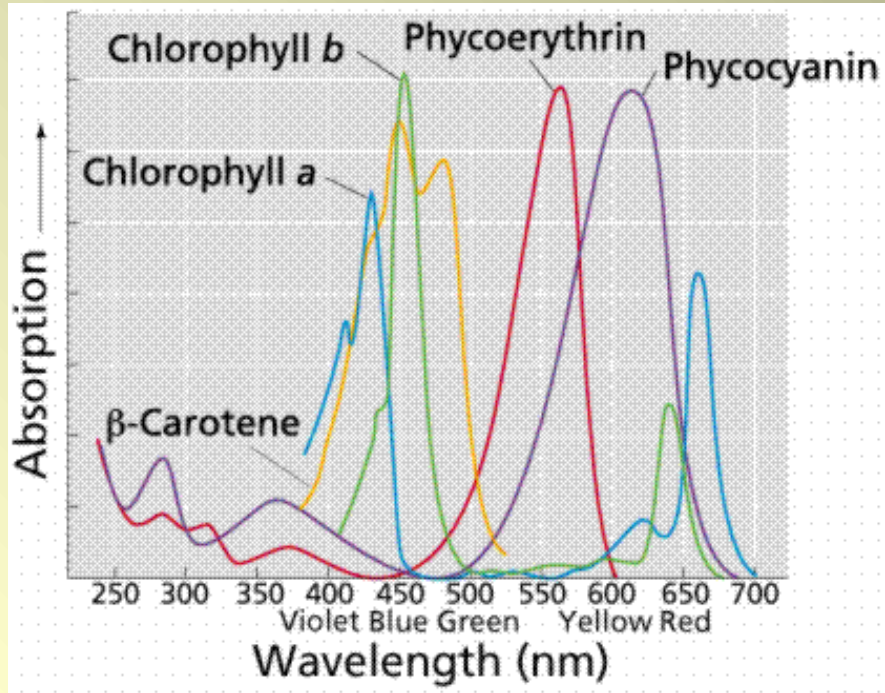
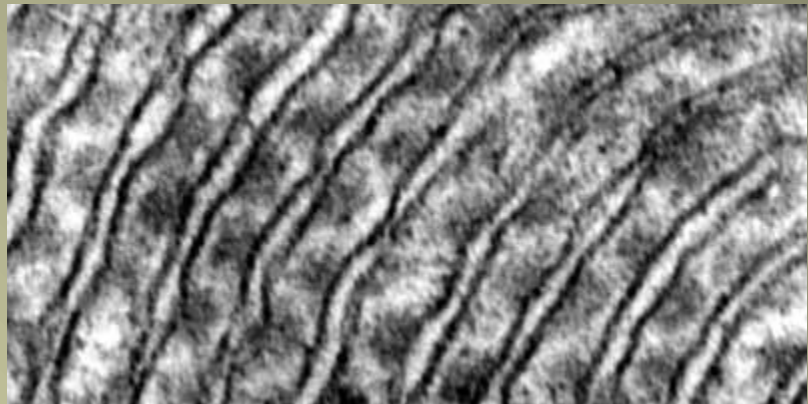
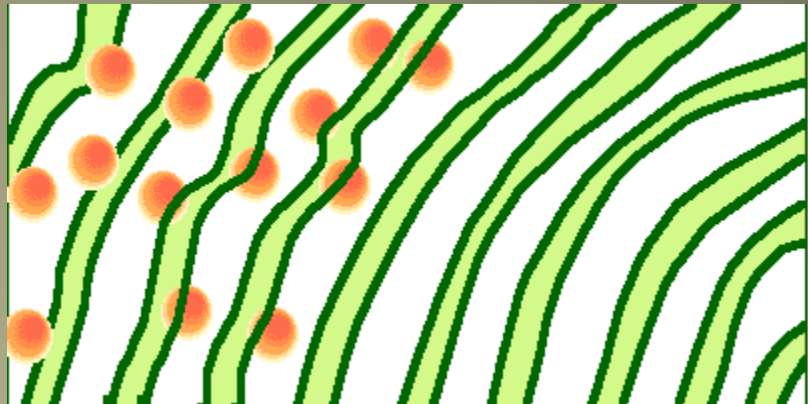
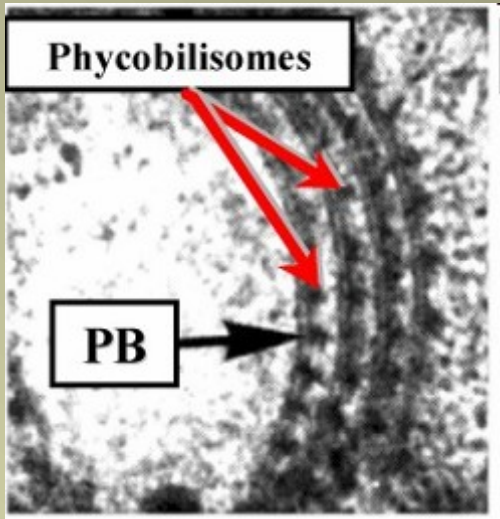
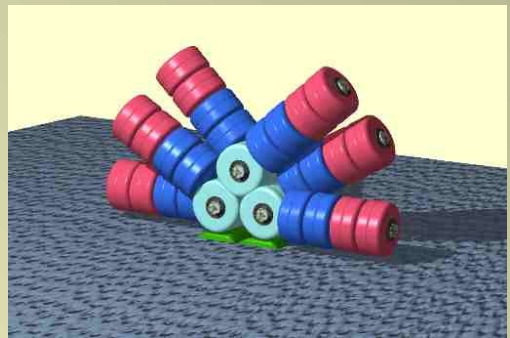


G. violaceus – originally isolated from limestone rocks in the Alps. Probably the most plesiomorphic cyanobacterial lineage.



standard type (*Synechococcus*)

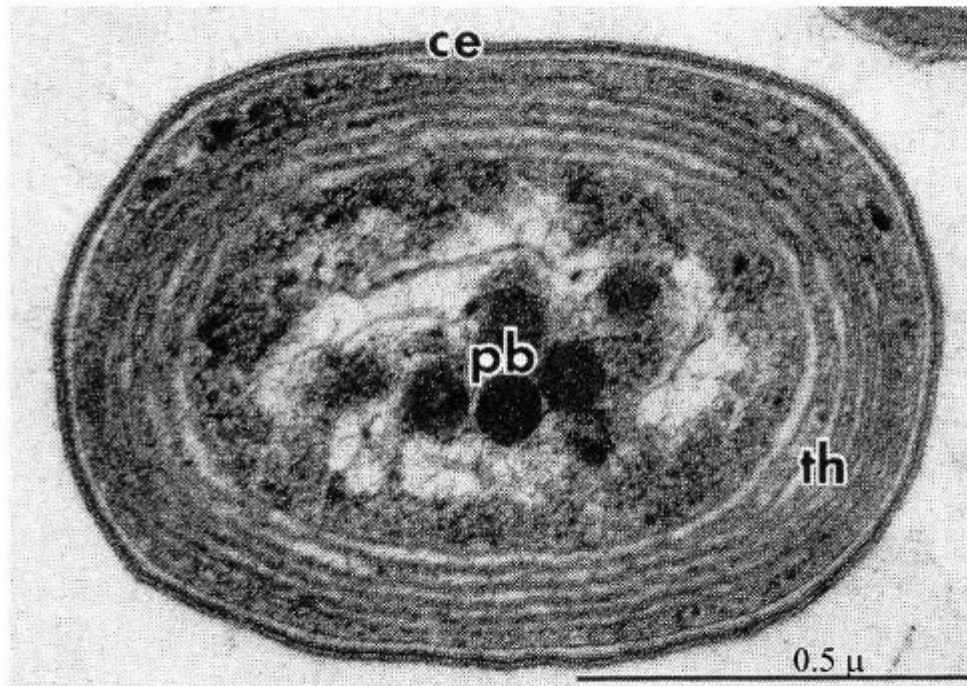
- thylakoids, phycobilisomes on them



type *Prochlorococcus*

(*Prochloron*, *Prochlorococcus*, *Prochlorothrix*, *Acaryochloris*)

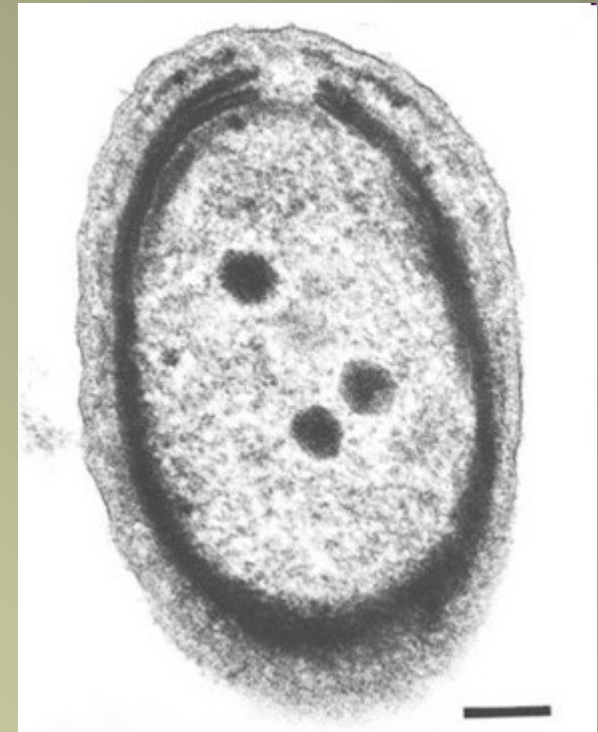
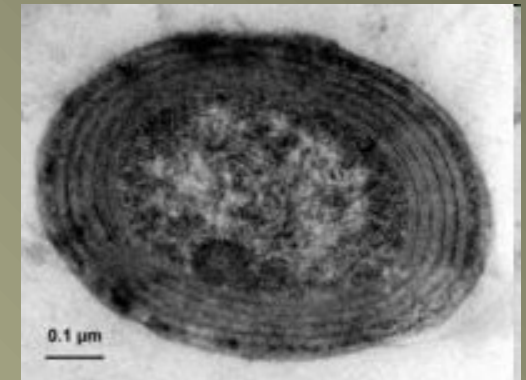
- lacking phycobilisomes, with chlorophyll *b*



ce: Cell Envelope

pb: Polyhedral Bodies

th: Thylakoids



nitrogenation by Cyanobacteria

- the only source of nitrogen for eukaryotic organisms
- nitrates from molecular nitrogen
- in heterocytes (Nostocales), but not always

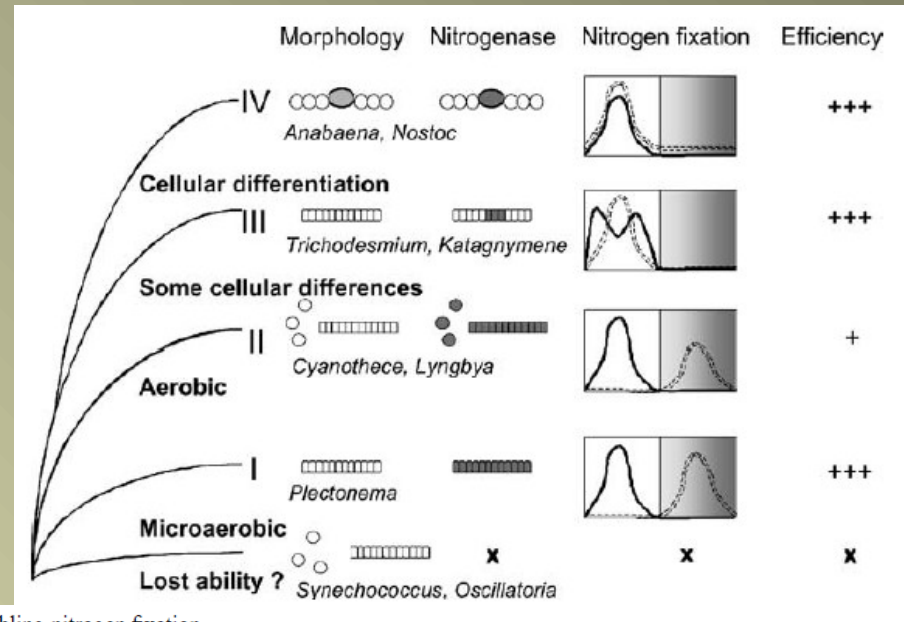
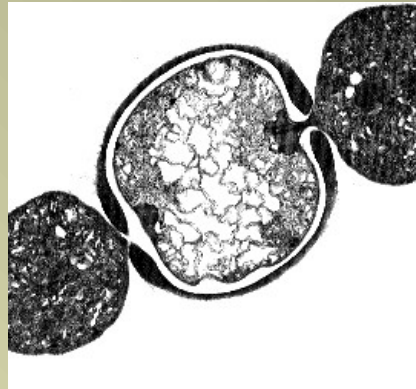
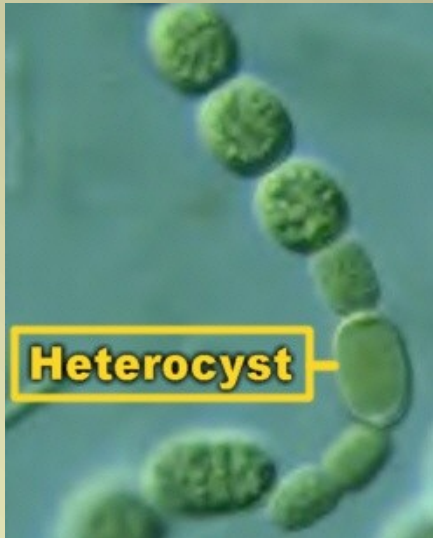


Fig. 2. Morphological and behavioral adaptations enabling nitrogen fixation for different cyanobacteria. Gray shaded areas indicate the localization of nitrogenase and black solid lines in the graphs designate nitrogen fixation rates. Photosynthesis is symbolized by the double dashed-line. Efficiency refers to a comparison of values given in the literature for activity measured under aerobic conditions (except for group I) as $\text{nmol ethylene reduced chl } a^{-1} \text{ h}^{-1}$. For some cyanobacteria the ability of nitrogen fixation has been lost, or was never present (bottom). Others (e.g., *Plectonema*) are capable of nitrogen fixation only under microaerobic conditions (I). Other cyanobacteria fix nitrogen during the dark period of a light/dark cycle (II). For 2 groups a cell specialization occurs (III and IV). Group III includes only two genera: *Trichodesmium* and *Katagnymene*. For these, nitrogen fixation occurs during the light period, and nitrogenase is sequestered into only a fraction of the cells, often occurring consecutively [6,41,42]. Group IV compartmentalizes all heterocystous cyanobacteria, where nitrogen fixation occurs mostly during the light period, and where nitrogenase under aerobic conditions is found only in the heterocysts [2,8]. Although, under microaerobic conditions, nitrogenase can also be present in the other cells [64,66].

Fixation of atmospheric N₂

fixation = conversion of atmospheric N₂ (N≡N) to biologically available NO₃⁻ (and then to NH₄⁺)



N – often a limiting macronutrient in ecosystems, necessary for protein synthesis

only several bacterial lineages may fix N

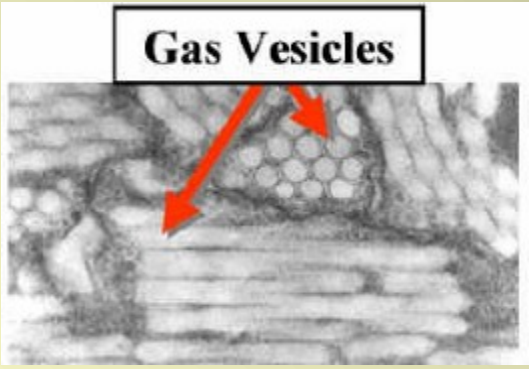
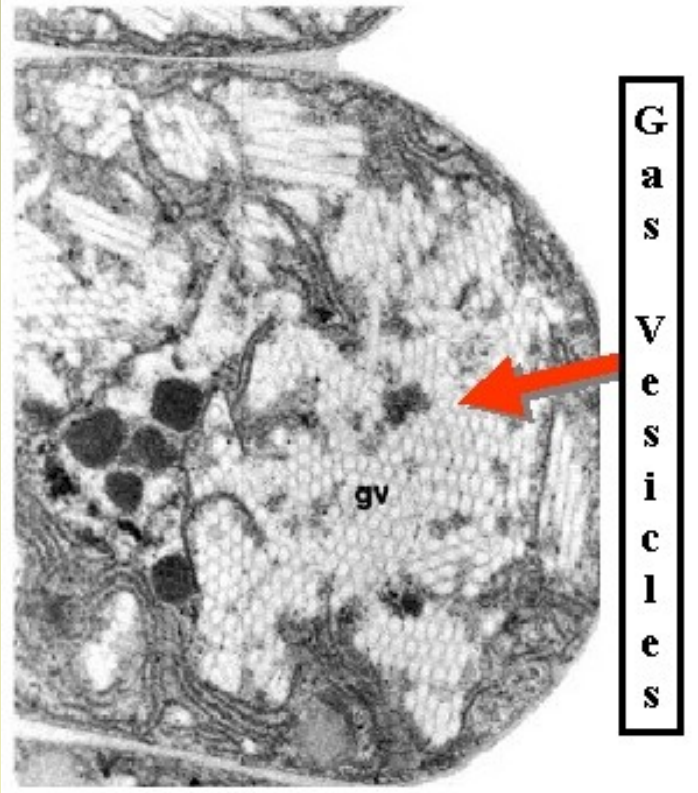
interestingly, nitrogenase is inactivated by oxygen – thus it interferes with photosynthesis

therefore – spatial or temporal separation of both processes in cells

Mo – essential for nitrogenase complex

Nitrogenation is energetically the single most demanding cellular process in living nature!

aerotopes – the only intracellular gas vesicles in living nature



Insights into diversity of Cyanobacteria

coccoid Cyanobacteria (solitary or colonial)



Chroococcus



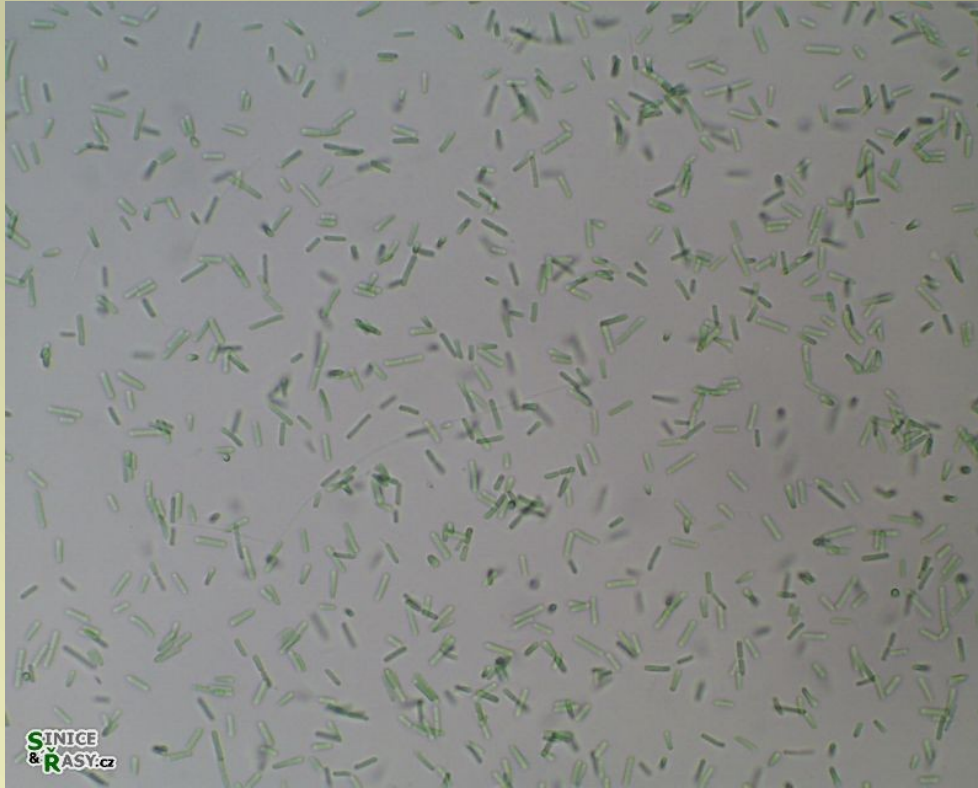
Limnococcus limneticus



Chroococcus turgidus

freshwater benthos (plankton), often in acidic wetlands

Synechococcus



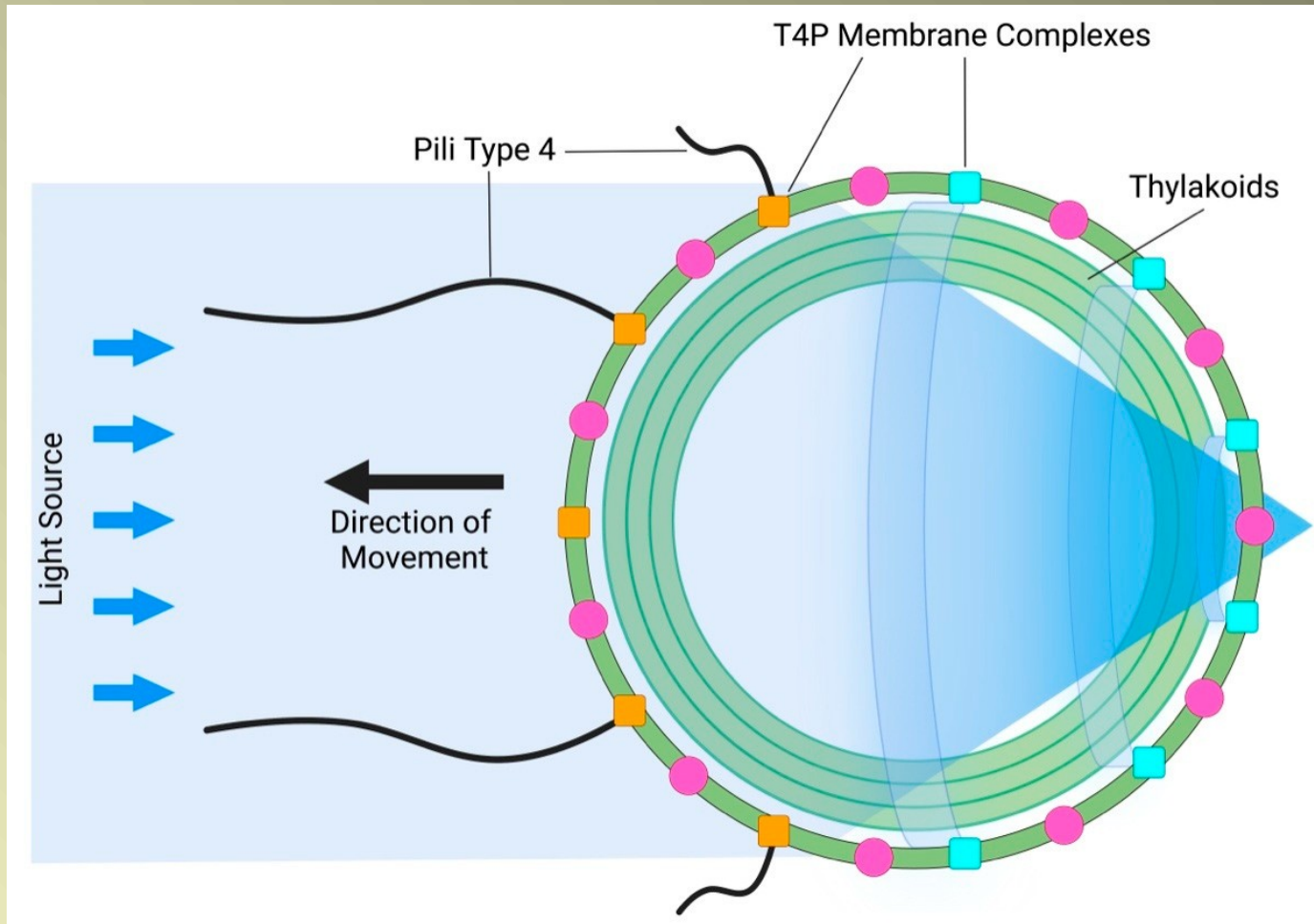
An agar plate of *Synechococcus* strain PCC 7335 expressing more phycoerythrin (right side) when grown in green light rather than red light (left side). Photograph from Donald A. Bryant's Lab, Pennsylvania State University, PA USA, posted [online](http://cfb.unh.edu/phycokey).

<http://cfb.unh.edu/phycokey>

occurs in virtually all regions of
marine euphotic zone
(with some exceptions in Antarctica)
(usually less abundant than *Prochlorococcus*)

density in the phytoplankton
up to 10^6 cells/ml

Synechococcus - possibly the most ancient example of vision in living organisms

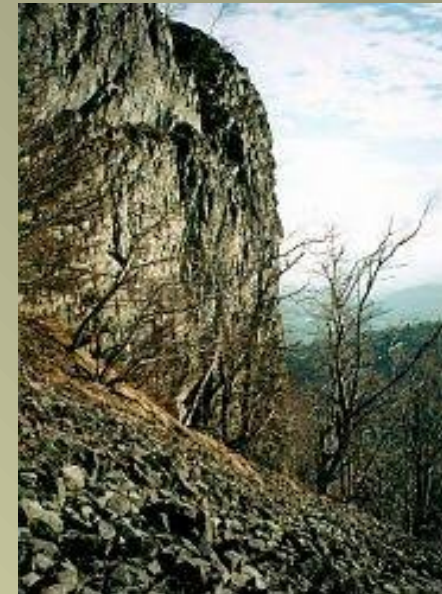


the entire cell acts as a lens;
pili close to the light-sensitive patch of the plasmatic membrane are electrocally inactivated
which leads to positive phototaxis

Gloeocapsa

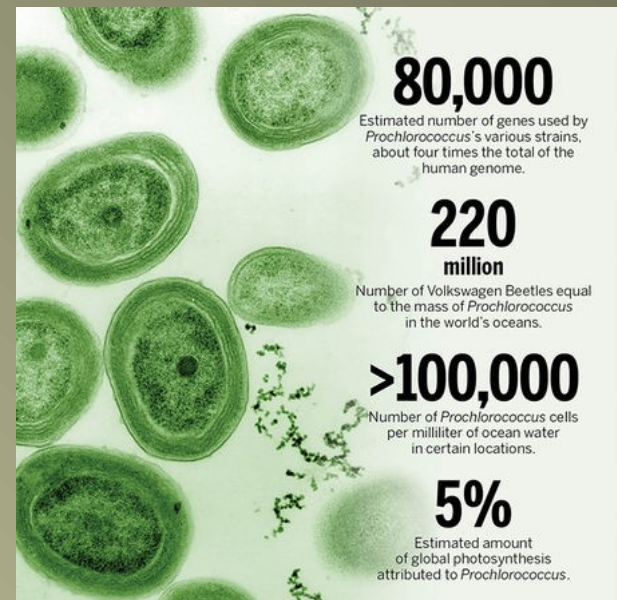
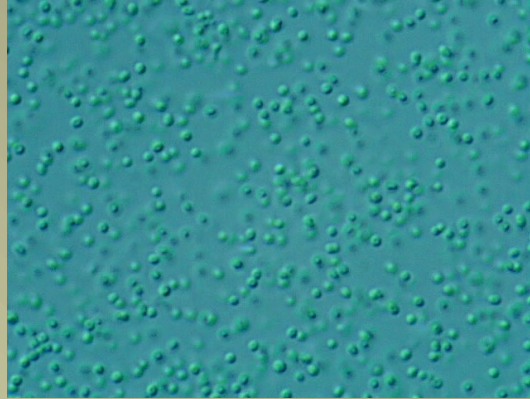
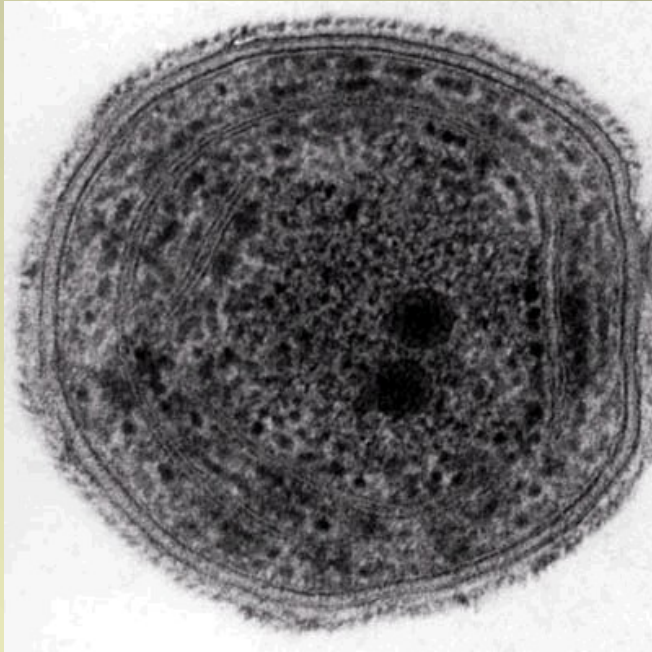


Gloeocapsopsis



subaerial microhabitats (biofilms)

Prochlorococcus

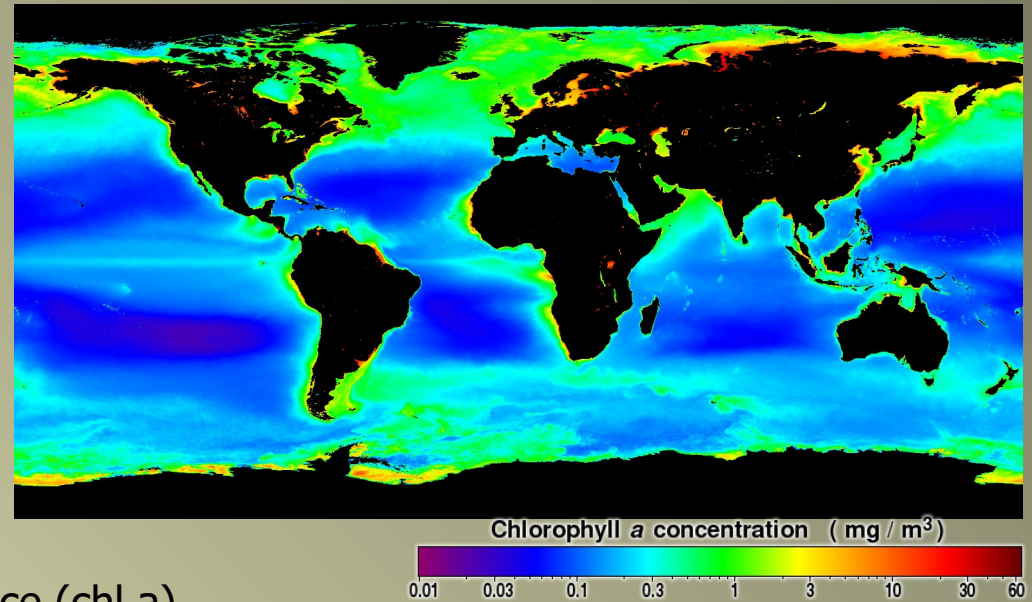


a dominant organism of high seas phytoplankton,
up to 50% of primary production in the oceans,
an example of the picoplanktonic organism



marine phytoplankton – introductory information

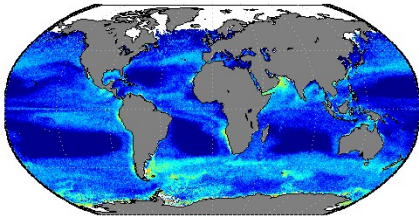
- about 60% of primary production on Earth
- four dominant groups:
 - *Cyanobacteria*
(*Prochlorococcus*, *Synechococcus*)
 - *Haptophyta*
 - *Dinophyta*
 - *Bacillariophyceae*



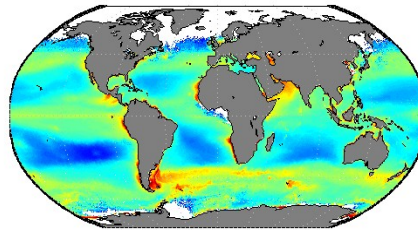
cell size

abundance (chl a)

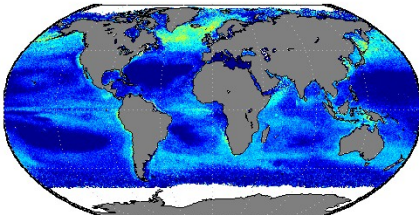
Winter



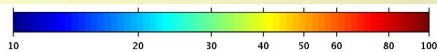
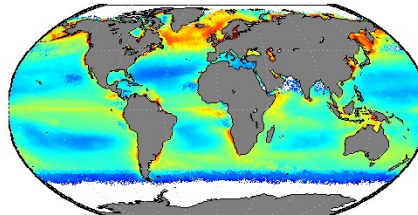
Winter



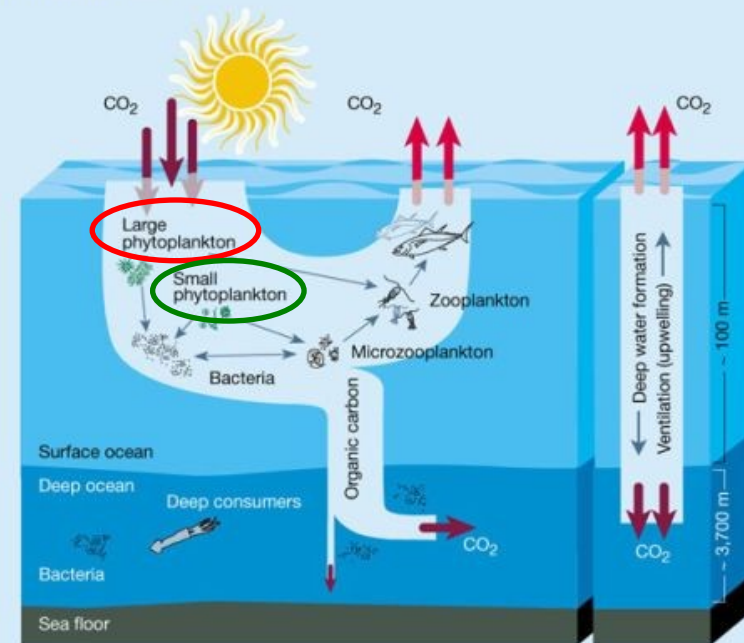
Summer



Summer

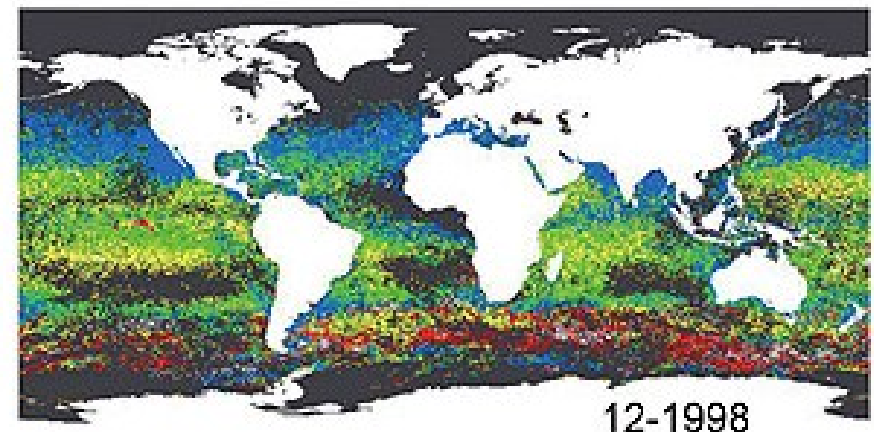
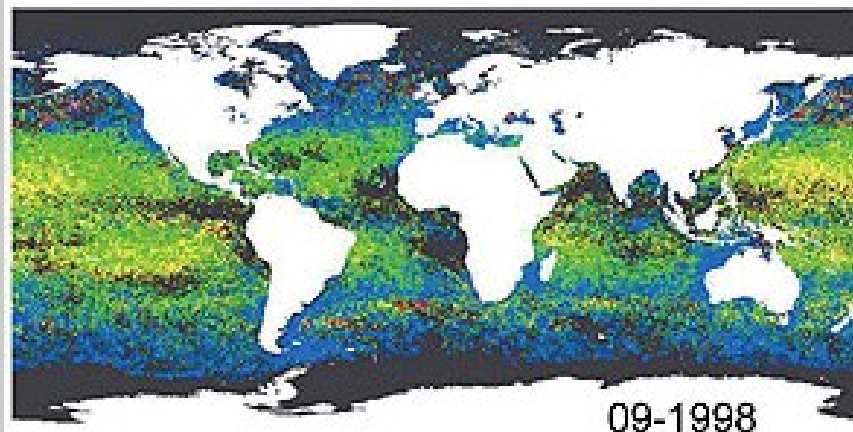
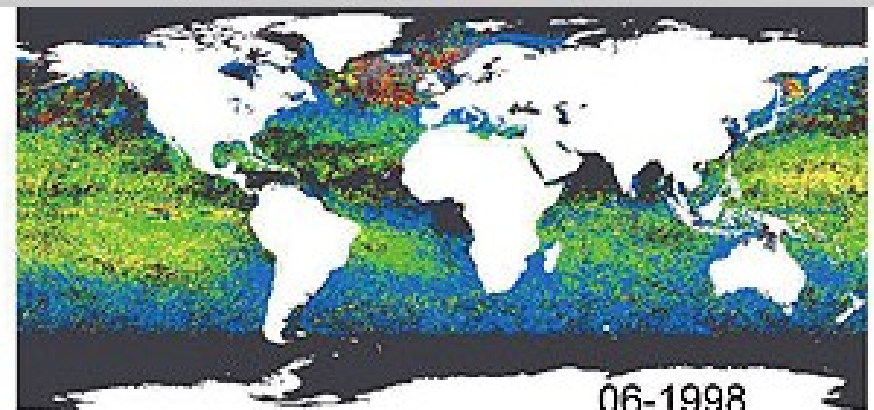
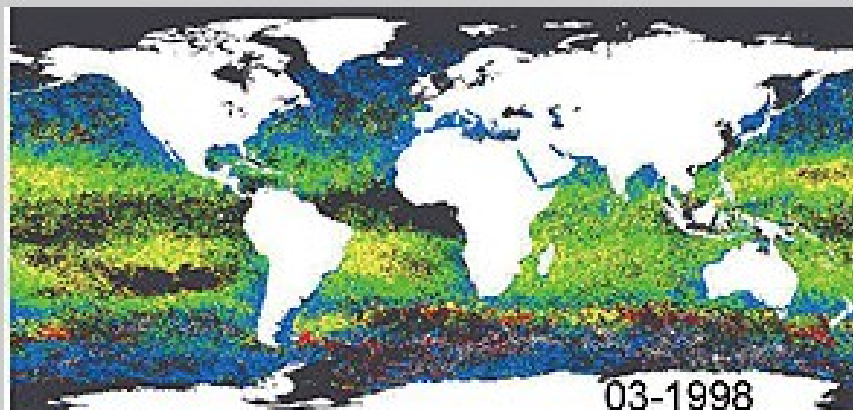


The biological pump



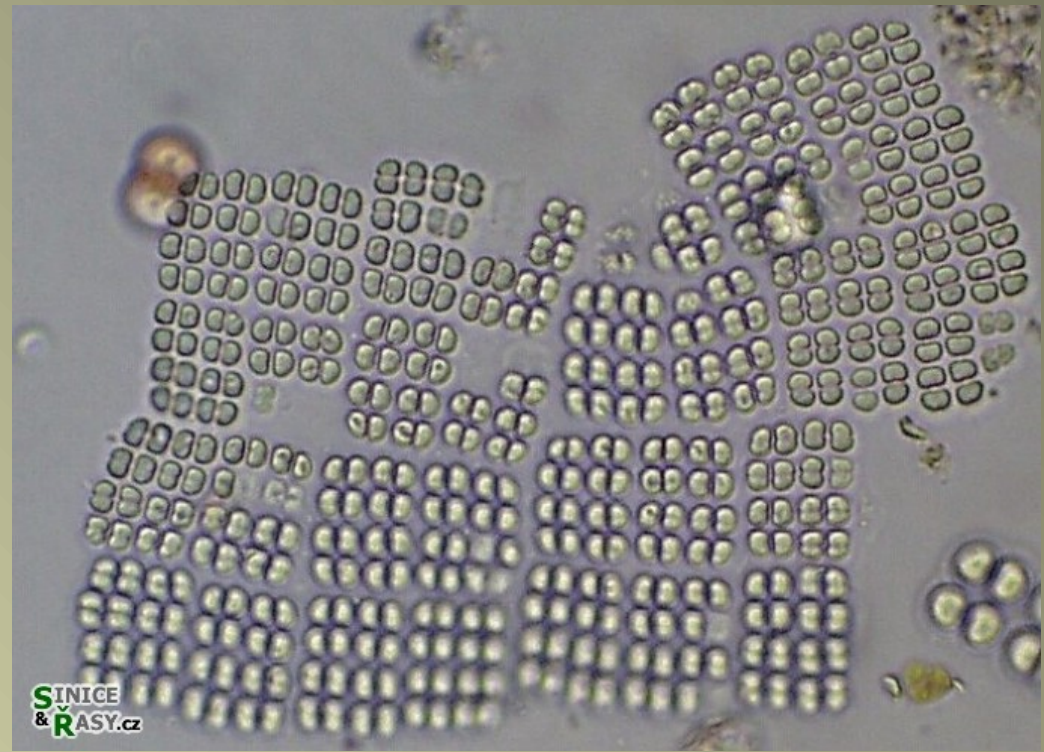
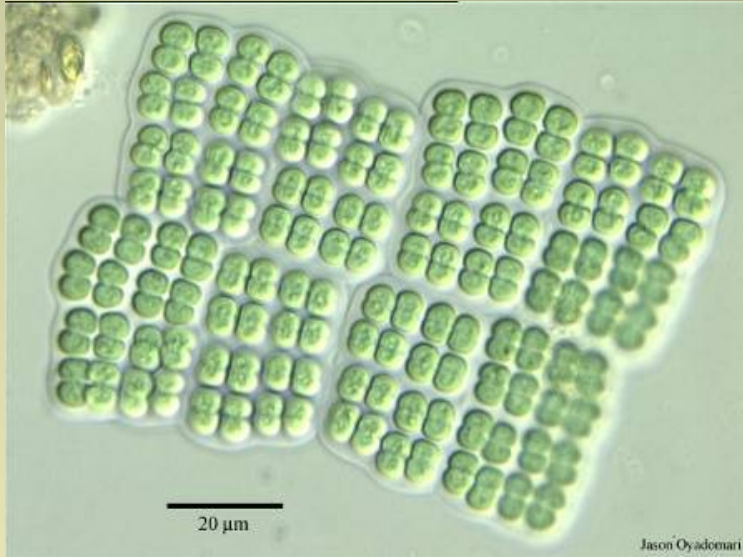
oceanic phytoplankton – „basic global structure“

Figure 3 - Variations saisonnières des peuplements de phytoplancton (en bleu : haptophytes, en vert : *Prochlorococcus*, en jaune : *Synechococcus*; en rouge : diatomées). Les diatomées abondent au printemps aux hautes latitudes, où les haptophytes dominent le reste de l'année. *Prochlorococcus* et *Synechococcus* dominant en permanence dans les régions tropicales.



Merismopedia

unilayered flattened colonies



freshwater phyto**benthos**

planktonic colonial Cyanobacteria

e.g. genera *Snowella*, *Woronichinia*



Woronichinia (cells with aerotopes)



Snowella lacustris



S. littoralis

cells arranged on the surface of mucilaginous mat or stalks

frequent members of freshwater eutrophic phytoplankton

cyanobacterial water blooms

genera:

Microcystis, *Dolichospermum*, *Anabaena*, *Aphanizomenon*, *Cylindrospermopsis*, *Nodularia*



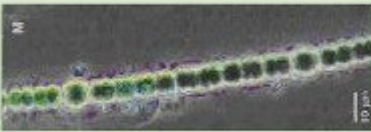
Microcystis aeruginosa



Cylindrospermopsis raciborskii



Aphanizomenon gracile



Nodularia spumigena



Anabaena spp.

microcystins – hepatotoxic oligopeptides

anatoxins – neurotoxic heterocyclic compounds

cylindrospermopsins – hepatotoxic

saxitoxins – neurotoxic

WHO limits for microcystins in drinking water

– max. 1,0 µm.L⁻¹

[ČR – vyhl. 252/2004 MZd]

technological means of „fighting“ CWBs:

dredging of sediments, algicides,

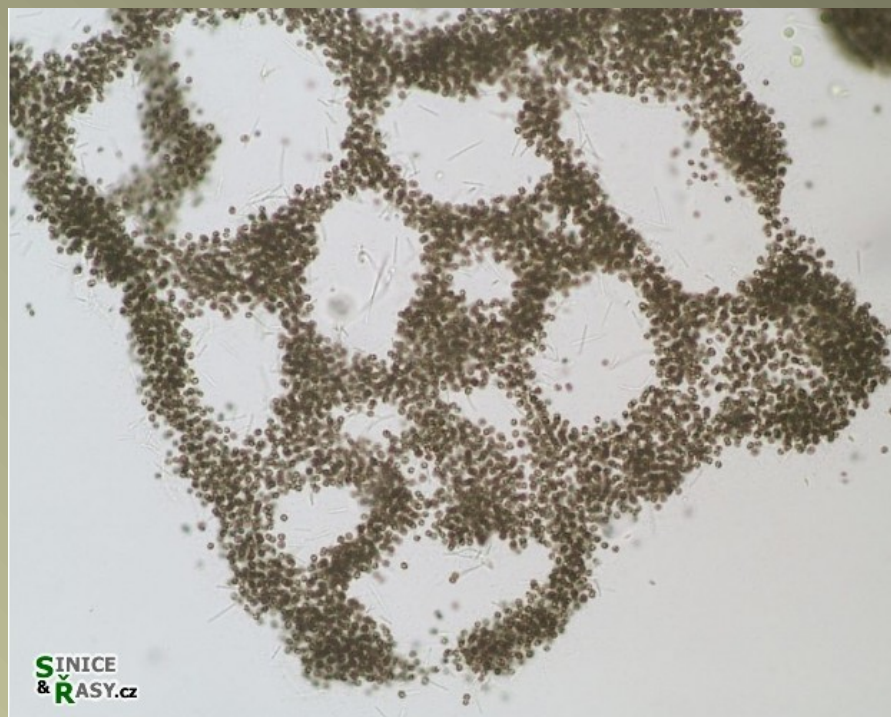
artificial aerating, precipitation of colonies

by Al-compounds (PAX-18)

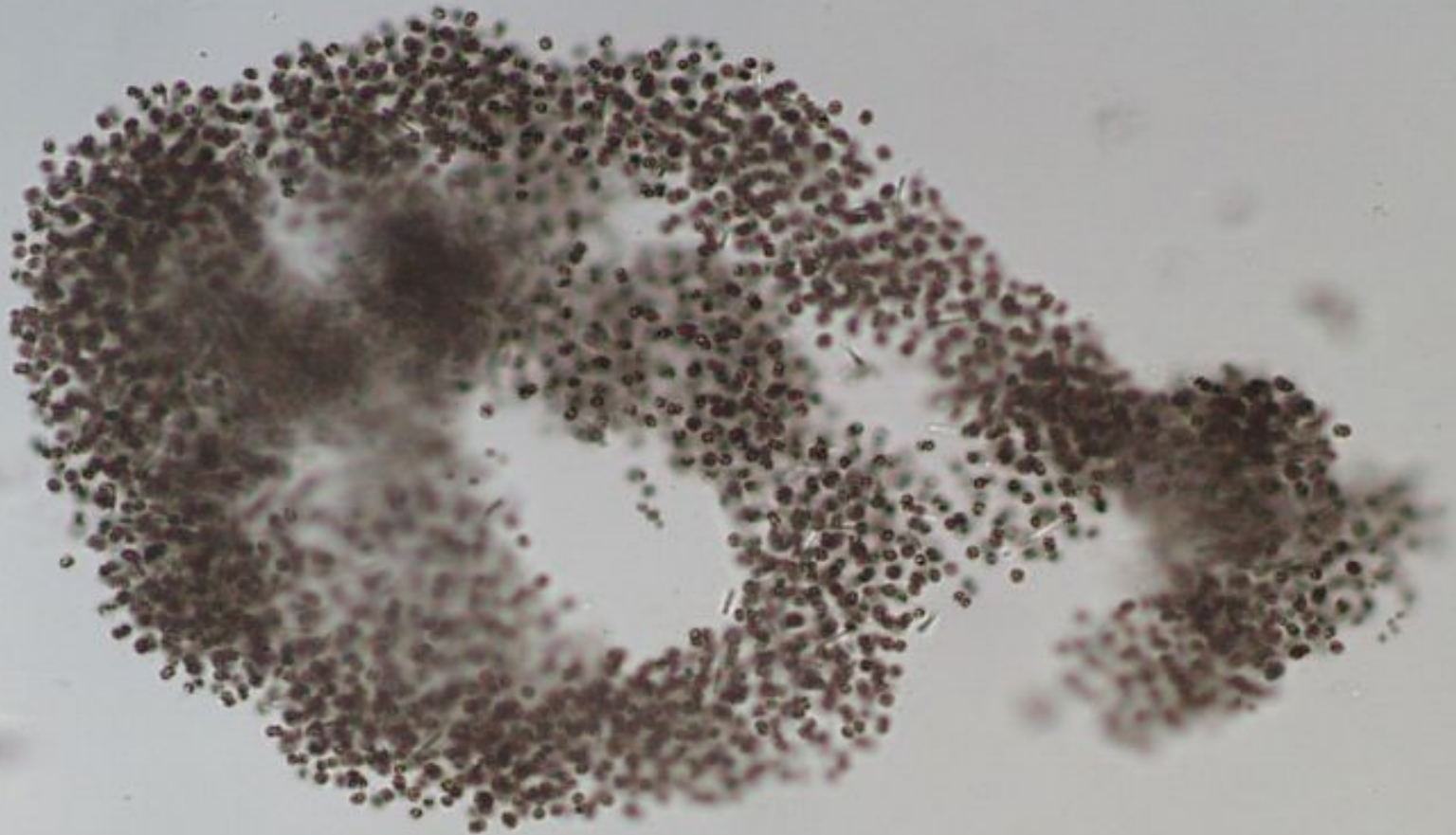


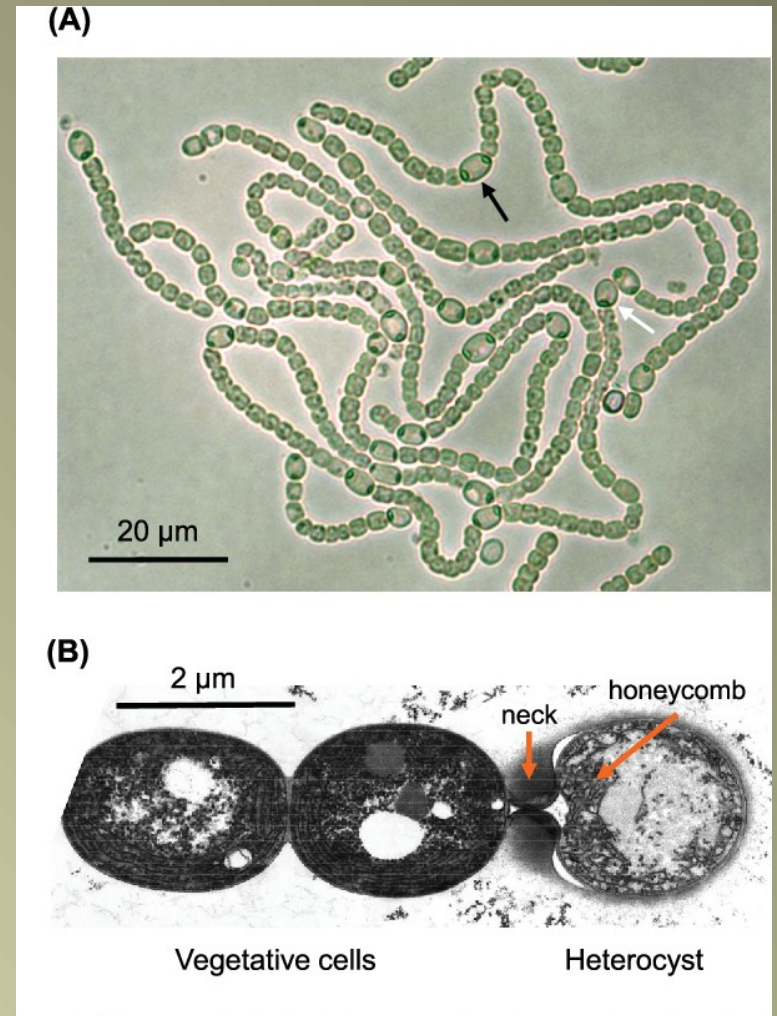
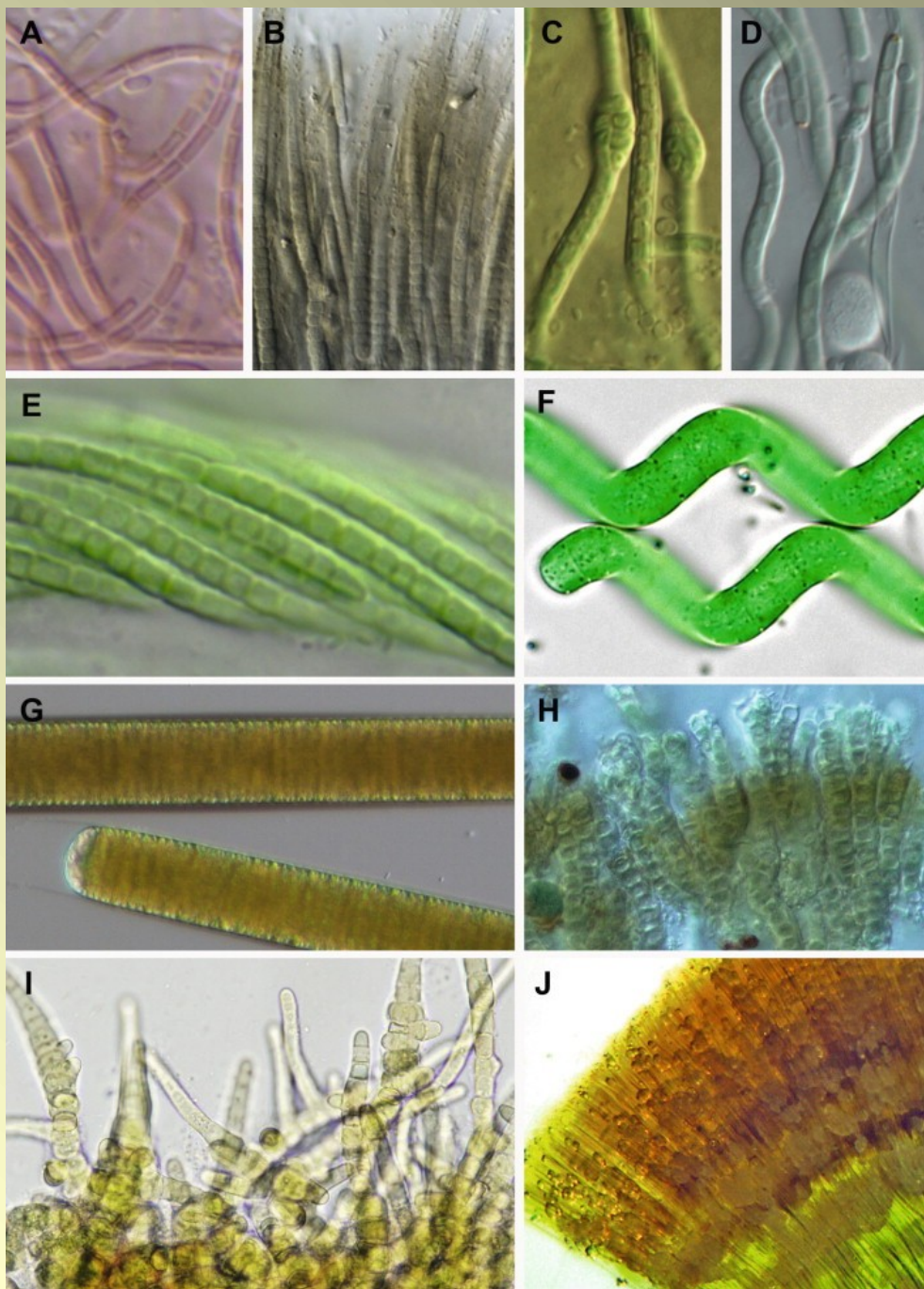
- causes, ecological dynamics

Microcystis



Microcystis
aeruginosa

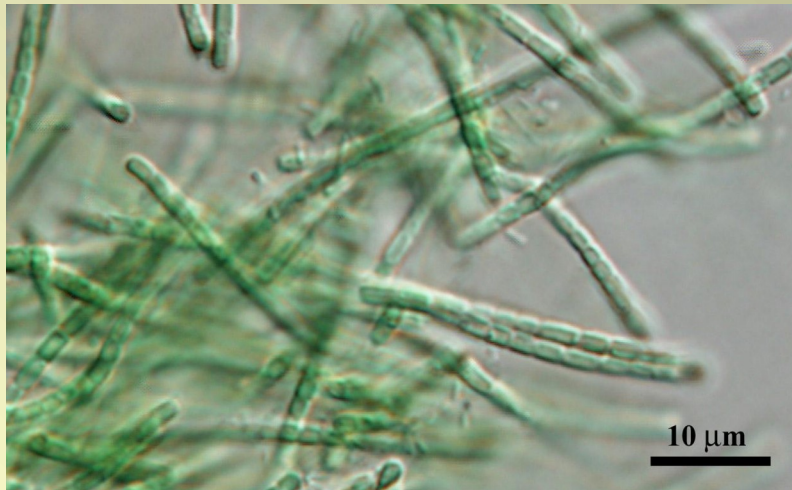
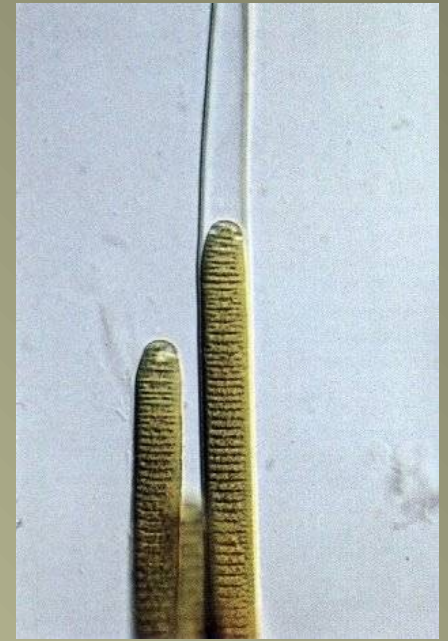




Komárek & Johansen, 2015
Herrero et al., 2016, FEMS Microb. Rev.

non-heterocytous filamentous Cyanobacteria

e.g. *Oscillatoria*, *Leptolyngbya*, *Lyngbya*, *Arthrospira*, *Limnothrix*



Leptolyngbya



Lyngbya



phytobenthos of marine and freshwater habitats
often indicates eutrophication



Spirulina (= Arthrospira)

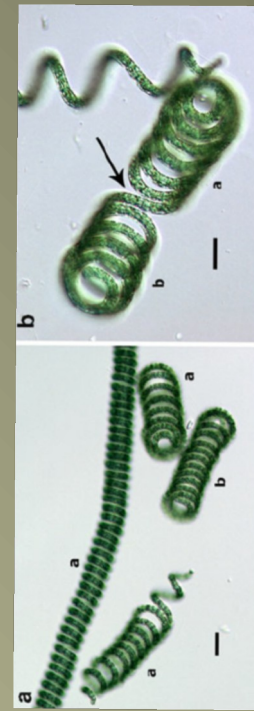
history



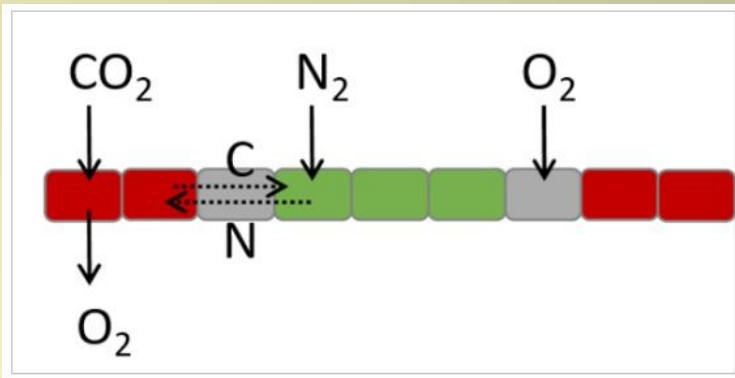
Aztecs used spirulines at least since 16th century (Mexico)



picking and drying of spiruline biomass in Lac Tchad – „dihé“ cakes

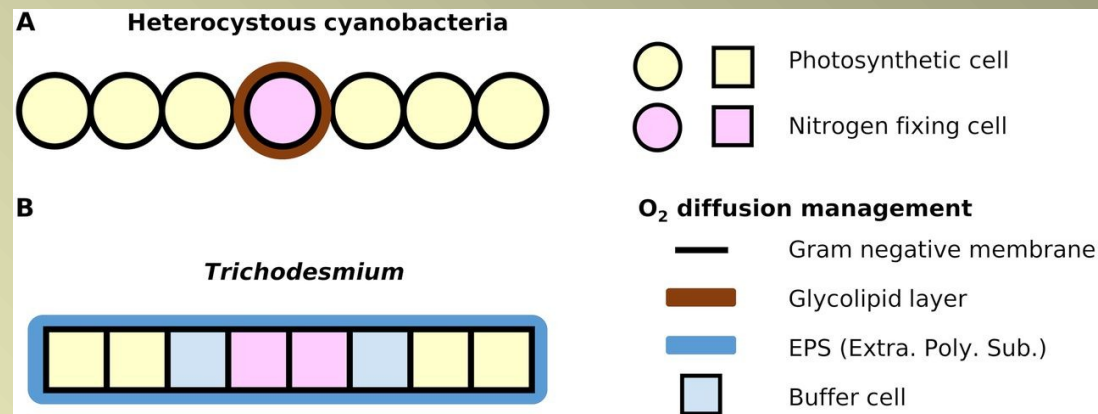


Trichodesmium - possibly the most important nitrogen fixing organism on Earth



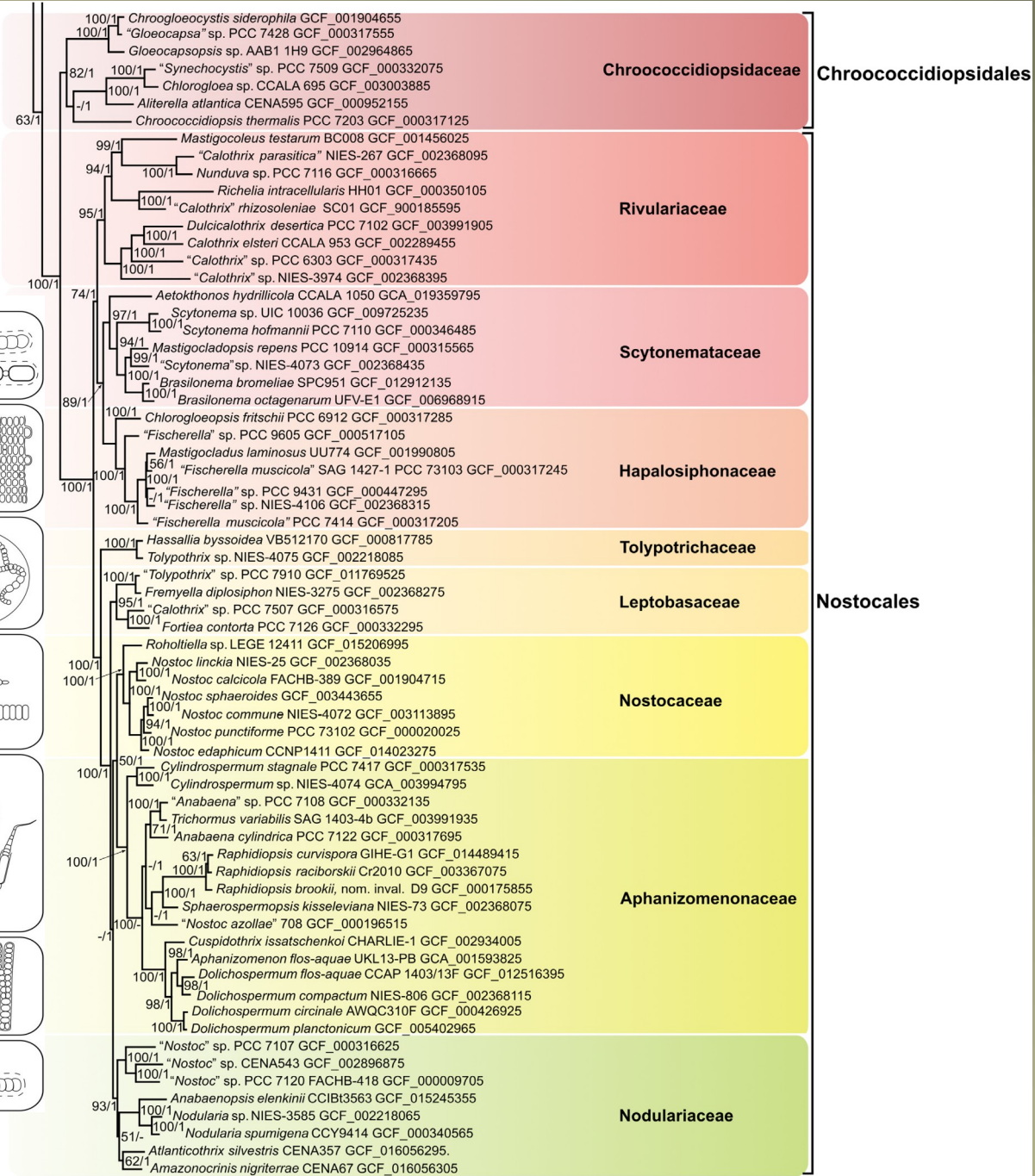
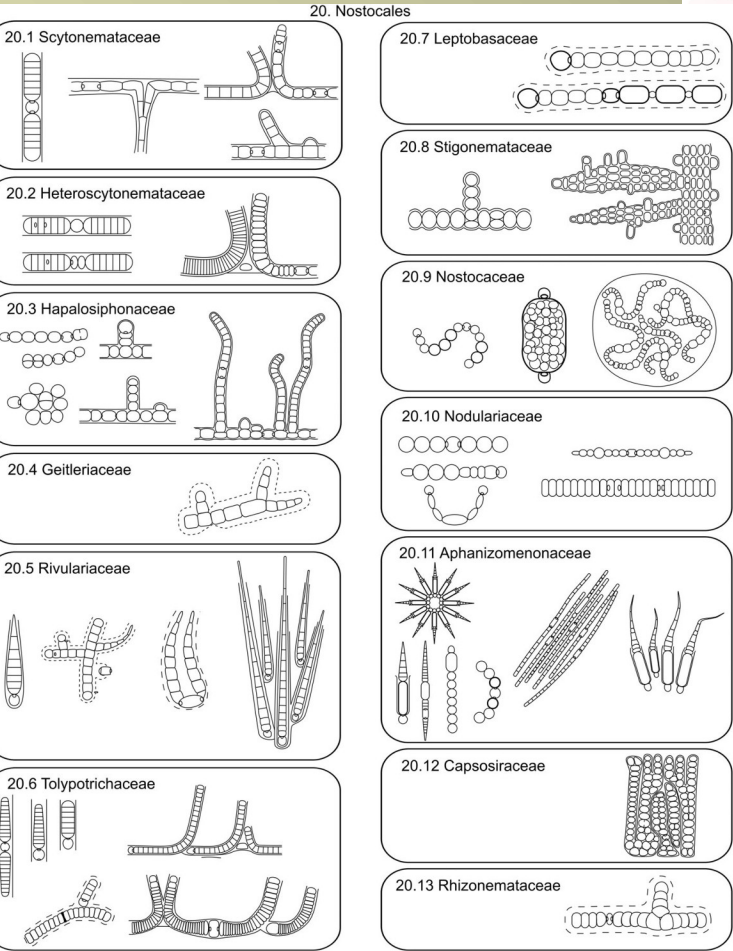
protection of nitrogenase enzyme
from oxidative damage

Berman-Frank et al., 2001, Science 294
Inomura et al., 2019, ASMJ, mSystems 4
www.alga.cz, *Algotech*, *MBÚ AVČR*

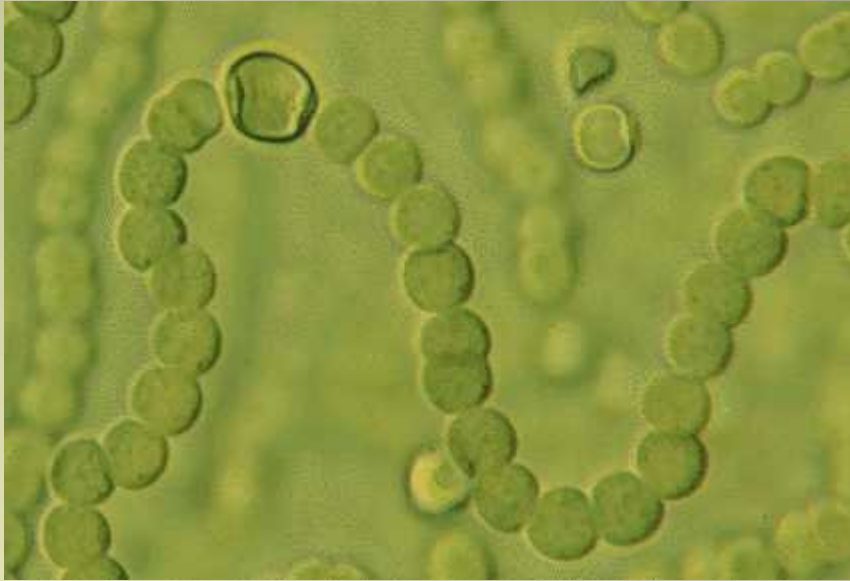


Nostocales

(heterocytous Cyanobacteria)

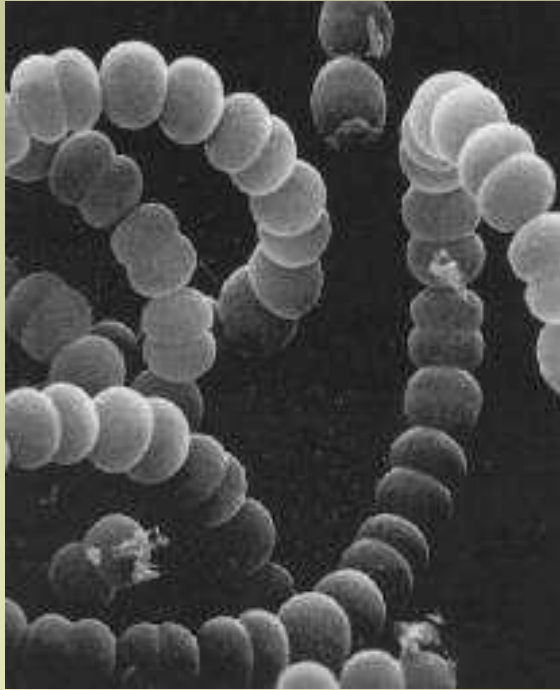


Nostoc



Cyanobacteria with heterocysts are crucially important in many symbiotic interactions

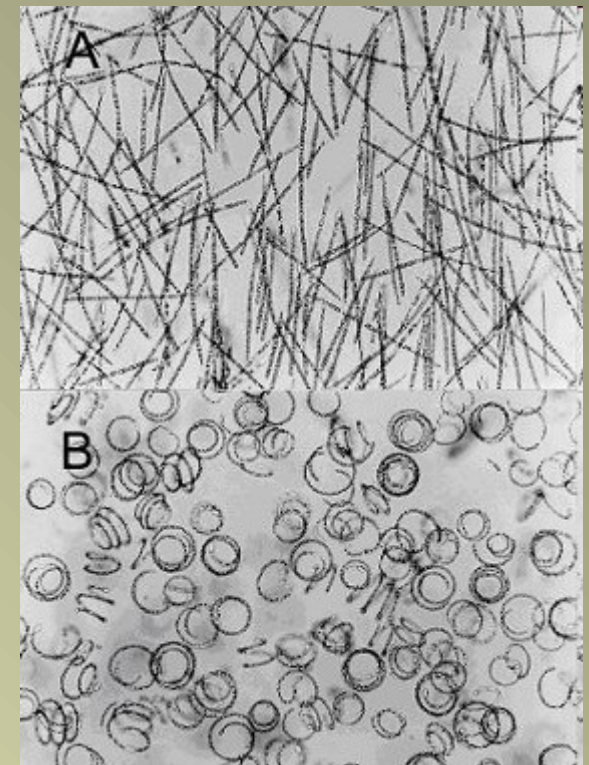
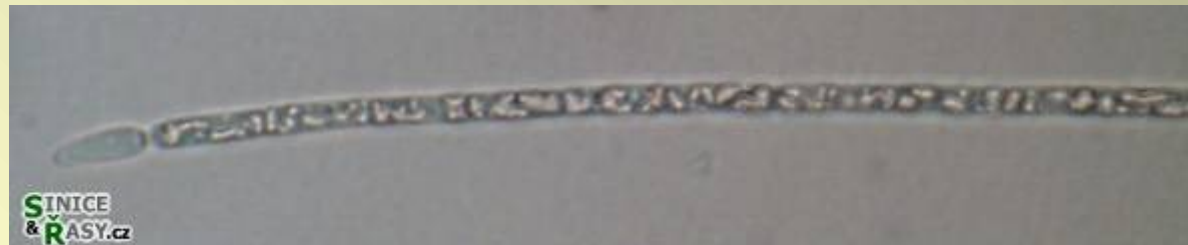
Anabaena ("Aphanizomenon", Dolichospermum)



Cylindrospermopsis raciborskii



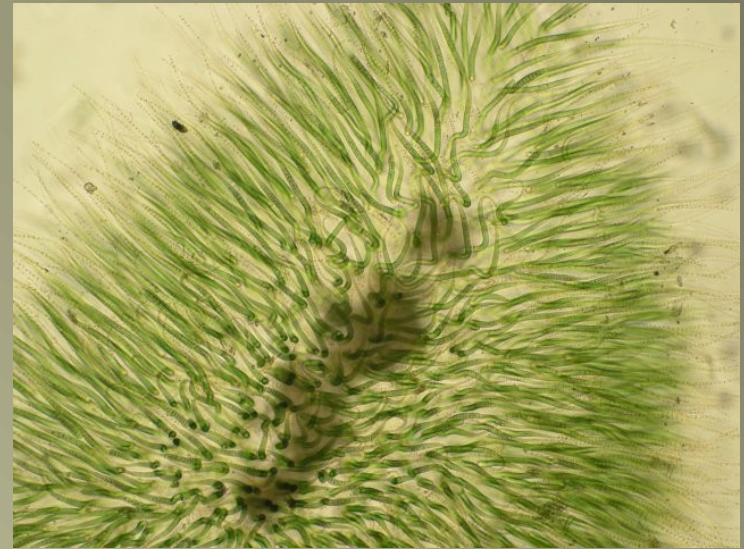
C. raciborskii WB in N Argentina



subtropical species, since 1990s expanding into Europe

contains hepatotoxic microcystins and other toxic compounds

Rivularia



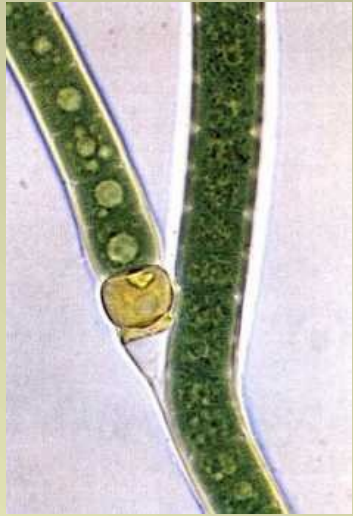
R. mesenterica
Mediterranean Sea



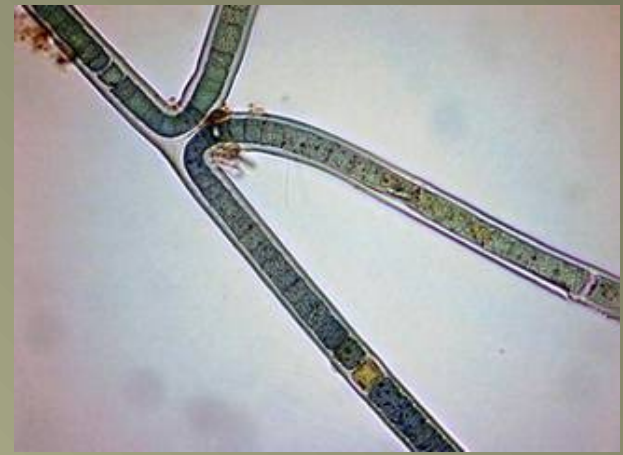
freshwater *Rivularia* – usually in
oligotrophic biotopes

heteropolar filaments, basal heterocytes, mucilaginous colonies

false branching in in traditional genera
Tolypothrix



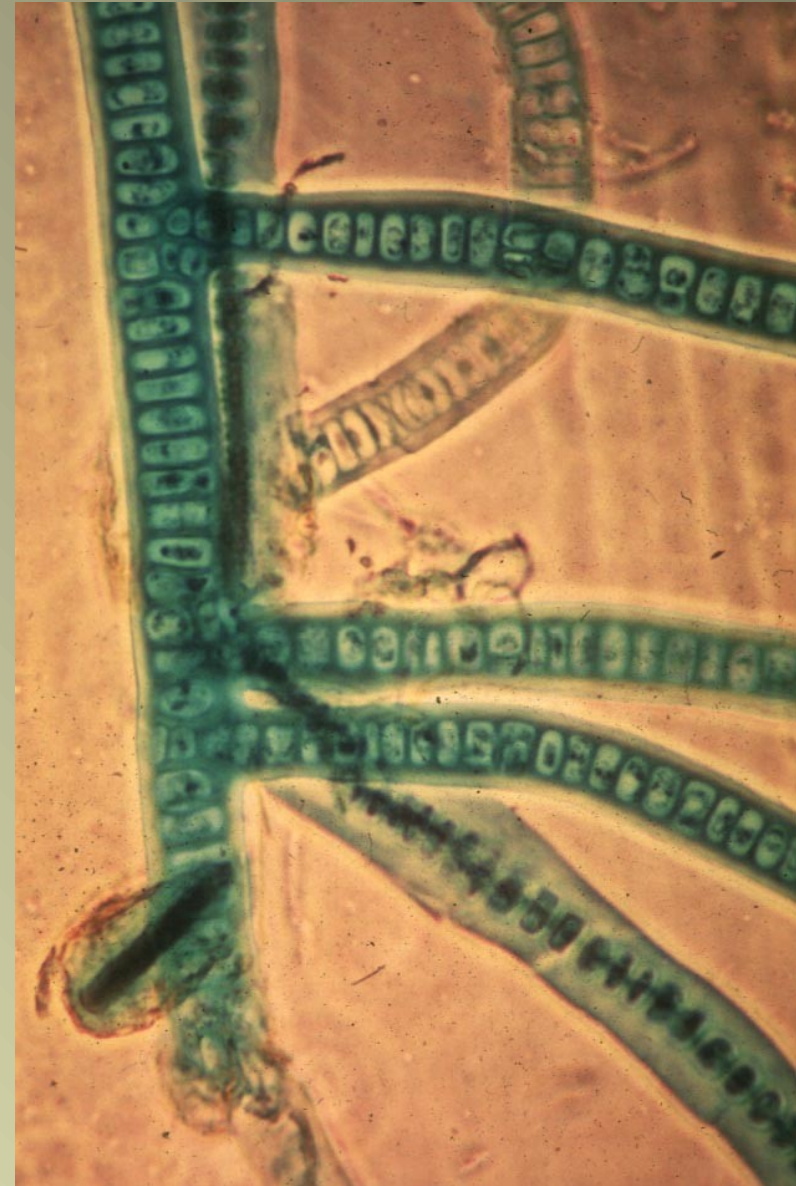
Scytonema



Petalonema



"true branching" in Hapalosiphon / Stigonema



Mastigocladus laminosus



extremophilic (thermophilic) species
an example of strictly ecologically determined geographical distribution

symbiotic interactions of (nostocalean) Cyanobacteria

some pennate diatoms

Azolla

Geosiphon



hornworts



some lichens



cycads

