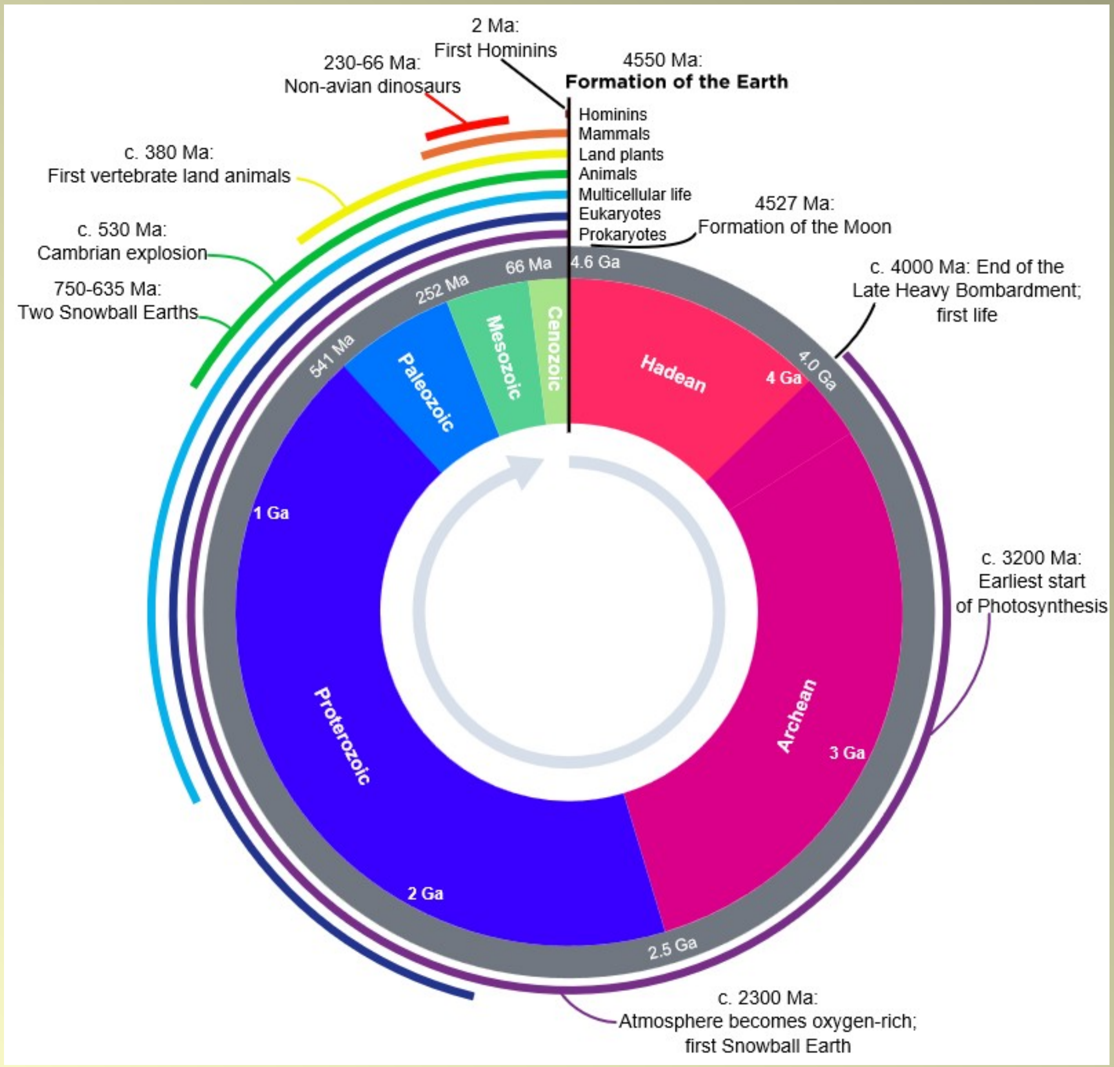
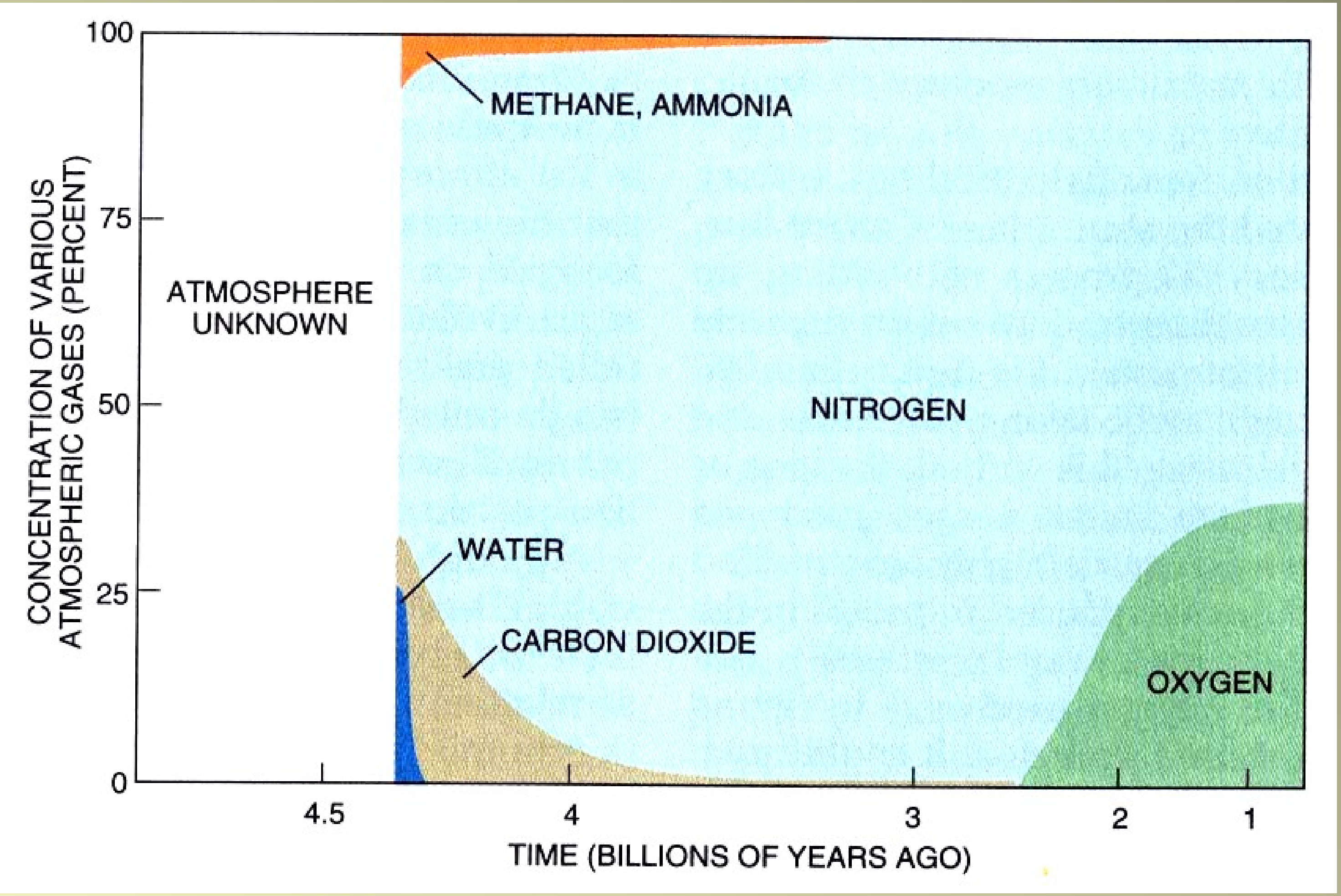
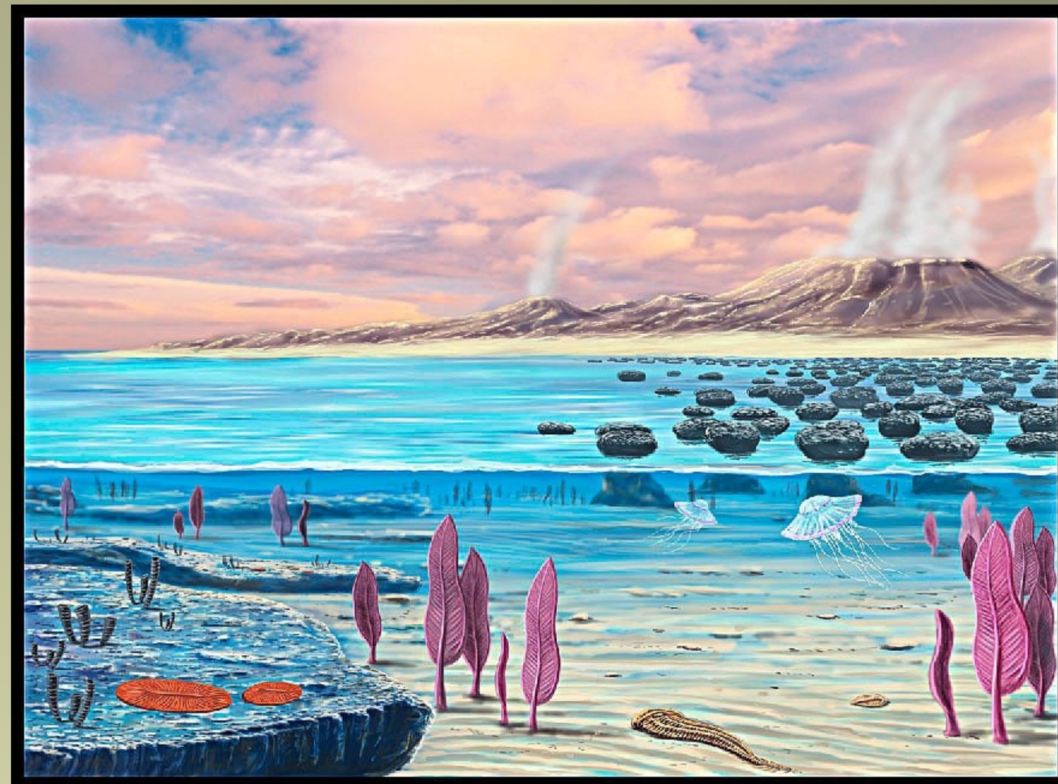

2 Ma:
First Hominins
230-66 Ma:
Non-avian dinosaurs
4550 Ma:
Formation of the Earth
Hominins
Mammals
Land plants
Animals
Multicellular life
Eukaryotes
Prokaryotes
4527 Ma:
Formation of the Moon
c. 380 Ma:
First vertebrate land animals
c. 530 Ma:
Cambrian explosion
750-635 Ma:
Two Snowball Earths
c. 4000 Ma: End of the
Late Heavy Bombardment;
first life
66 Ma
252 Ma
541 Ma
4.6 Ga
4.0 Ga
4 Ga
Cenozoic
Mesozoic
Paleozoic
Hadean
Archean
Proterozoic
1 Ga
2 Ga
2.5 Ga
3 Ga
c. 3200 Ma:
Earliest start
of Photosynthesis
c. 2300 Ma:
Atmosphere becomes oxygen-rich;
first Snowball Earth

Evolution of Earth Atmosphere

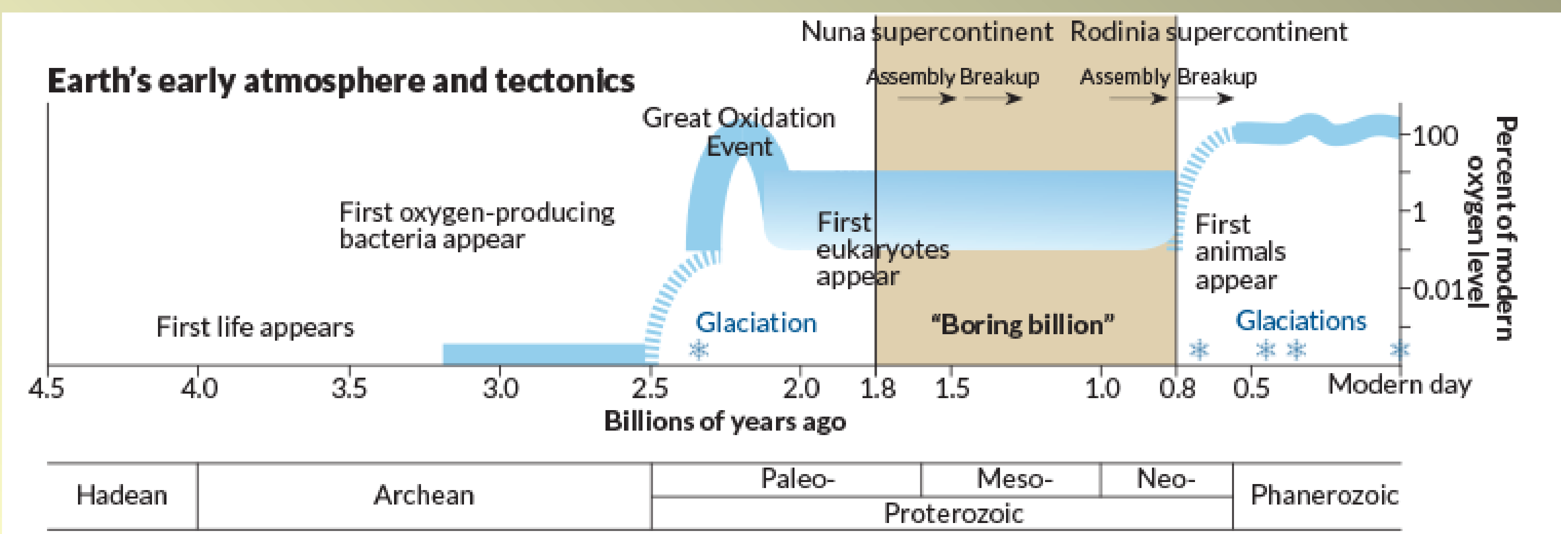


GOE – "great oxygenation event"

Proterozoicum



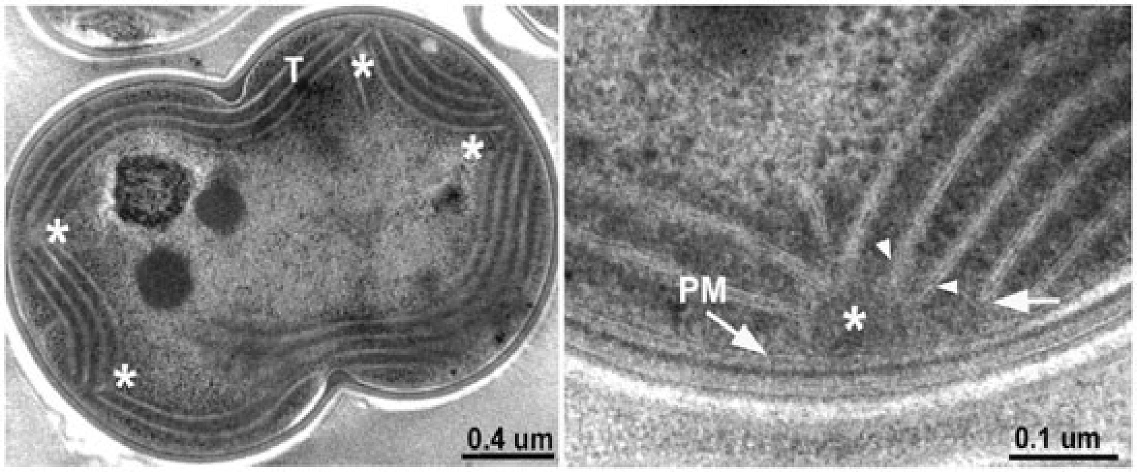
geology.cz

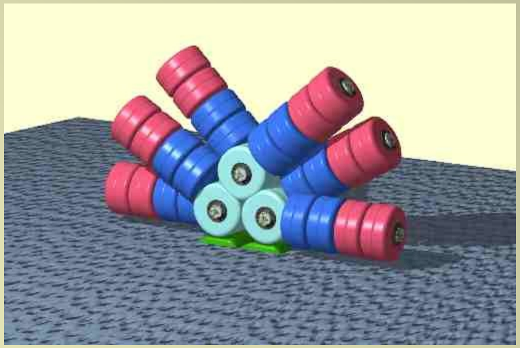


Cyanobacteria – first occurrence of thylakoids and phycobilisomes

$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$

oxygennic photosynthesis
(therefore *oxyphotrophic bacteria*)
(some of the may be capable of suphurogenic photosynthesis, too)





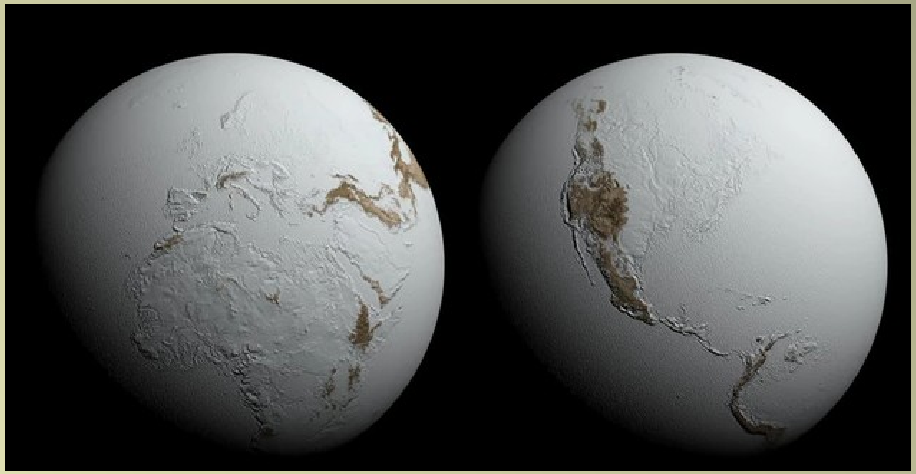
phycobilisome

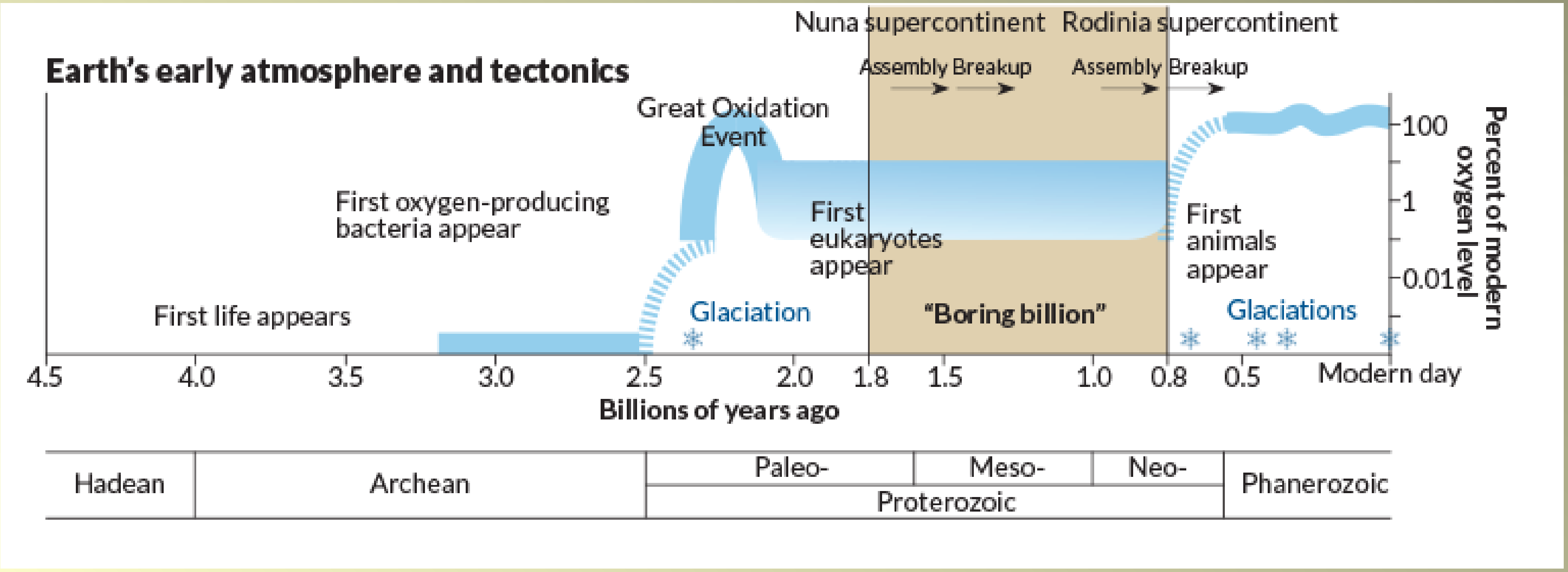
2.5 to 0.6 billion years - „age of cyanobacteria “,
or „boring billion“

stromatoliths

well documented fossils of coccoid and filamentous cyanobacteria – 2.5 bya

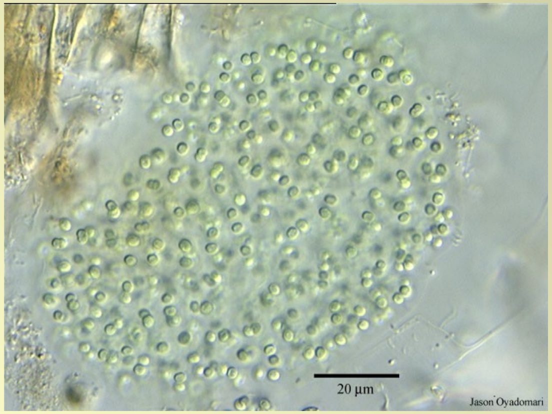
GOE and Huronian glaciation

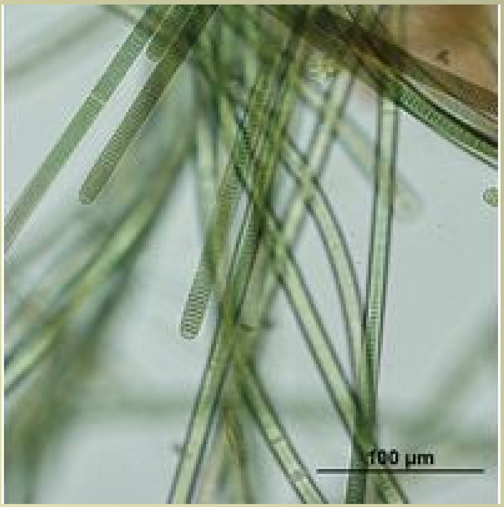


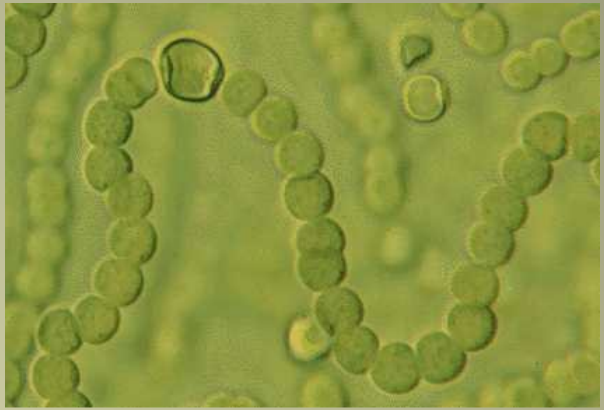


Basic characteristics of **Cyanobacteria**

- coccoid (solitary or colonial) or filamentous
- always have chlorophyll *a* (sometimes *b* or *d*)
- 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

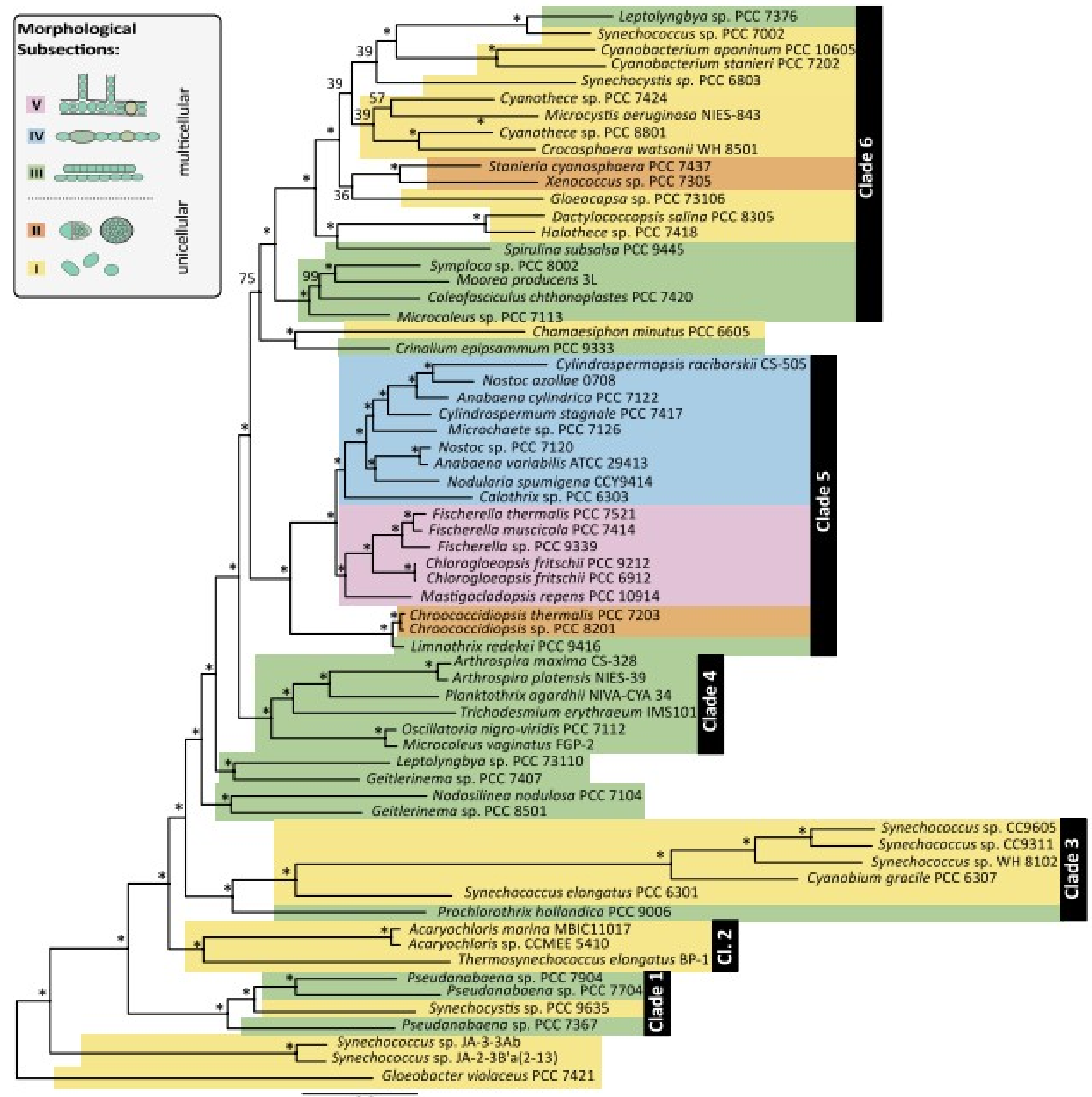
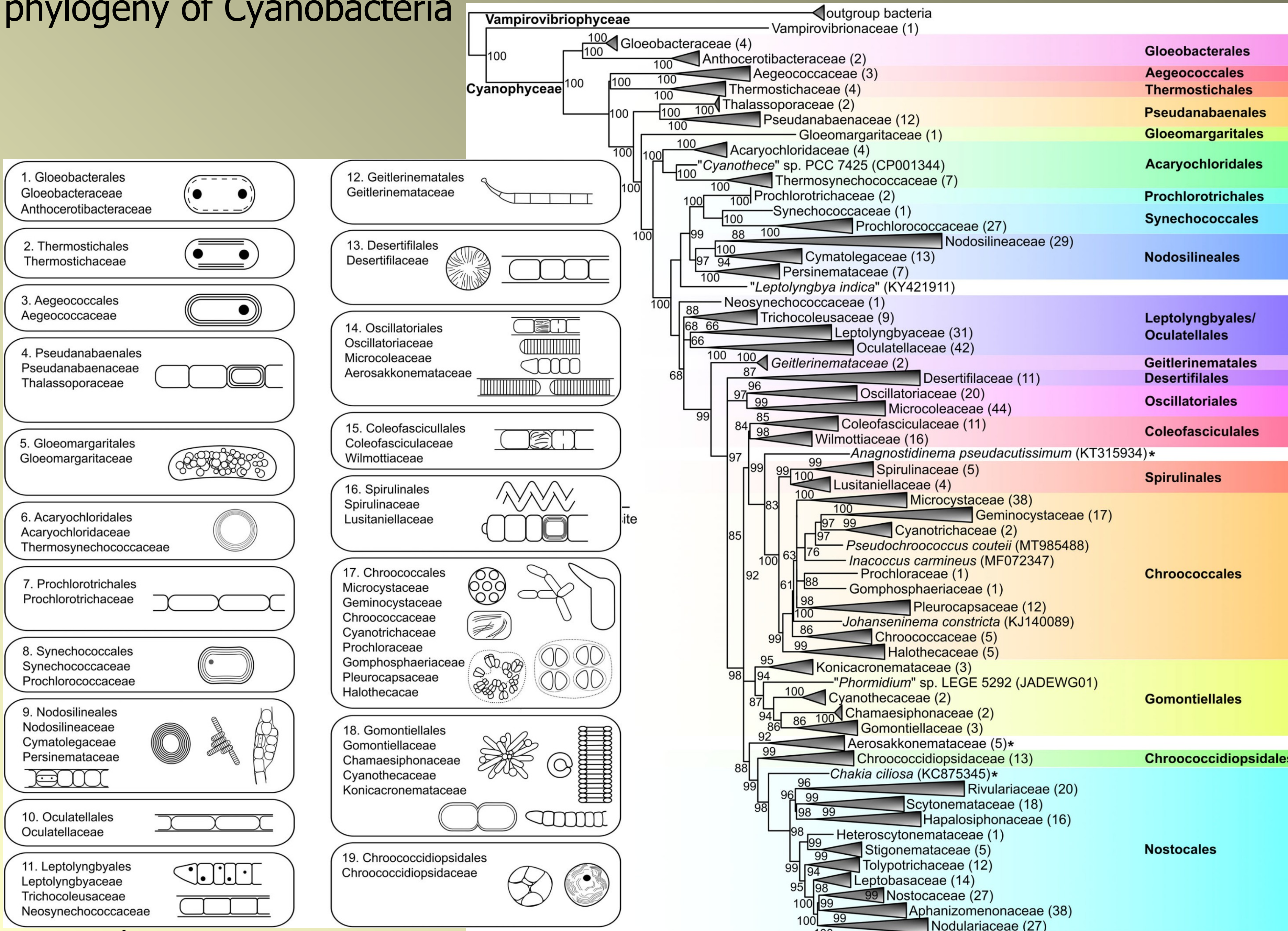


FIG. 1. Phylogenomic maximum likelihood tree. Phylogeny of 65 cyanobacterial taxa based on a supermatrix comprised of 756 concatenated protein sequences (197 761 amino acid sites). Maximum likelihood bootstrap support for clades is indicated at respective branches. Stars indicate 100% support calculated 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.

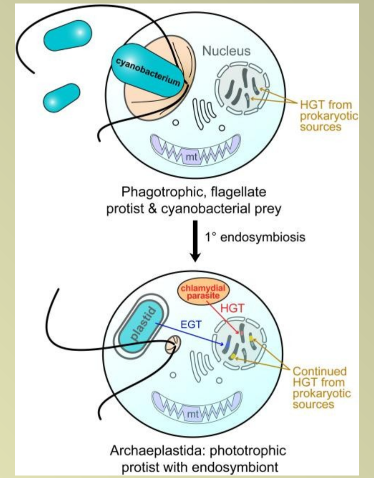
Schirrmeister et al., 2015, Palaeontology 2015: 1-17

phylogeny of Cyanobacteria



Strunecký et al., 2023, J. Phycol. 59

evolution of plastids from Cyanobacteria



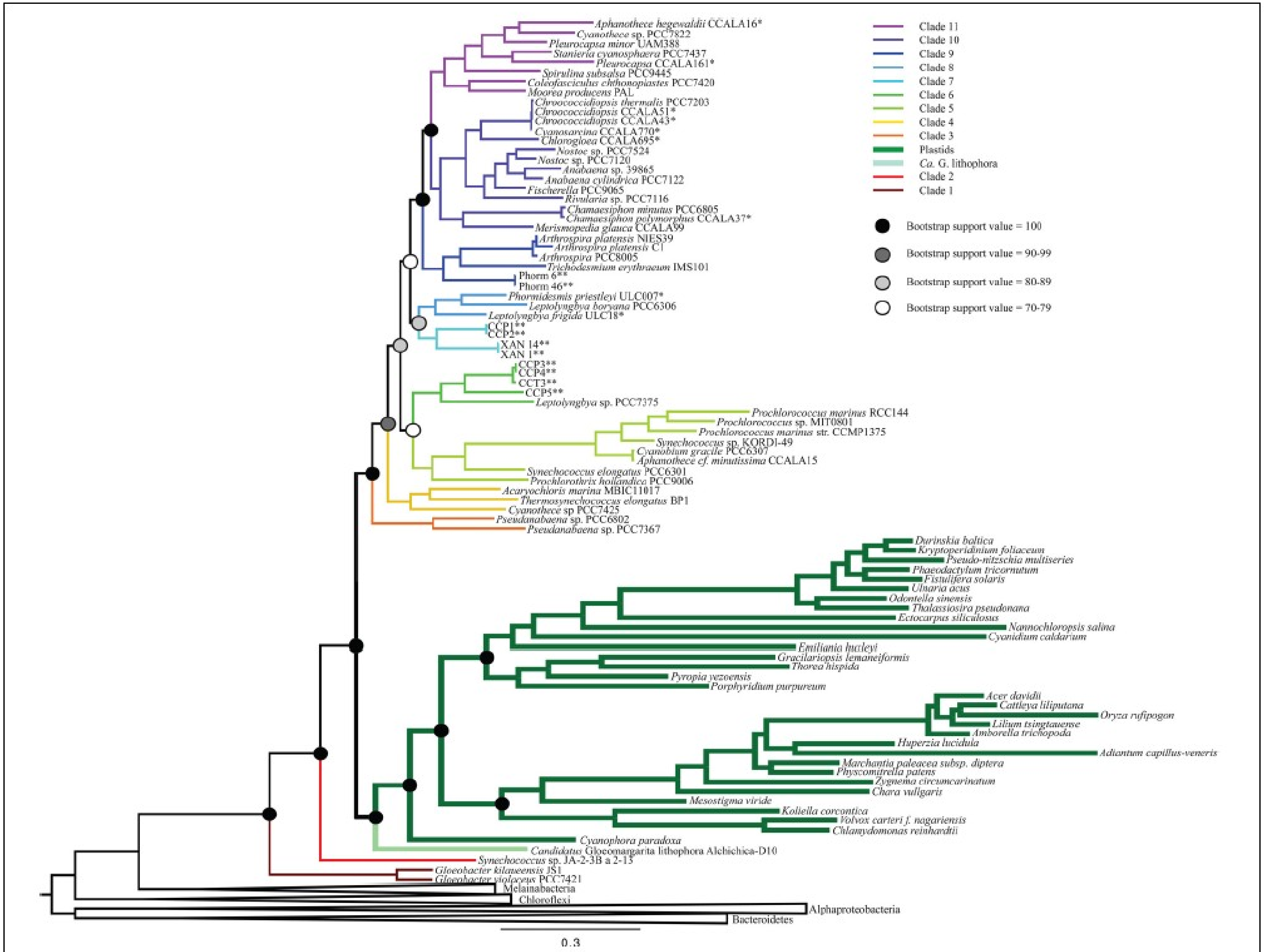


FIGURE 1 | A maximum likelihood (ML) phylogenetic tree made using a concatenation of 30 large and small subunit ribosomal proteins (**Table 2**) and RAxML. This tree supports a deep placement of the plastid clade with high bootstrap support. Bootstrap values are denoted for major divergences of cyanobacterial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

Moore et al. 2019, Front. Microbiol.

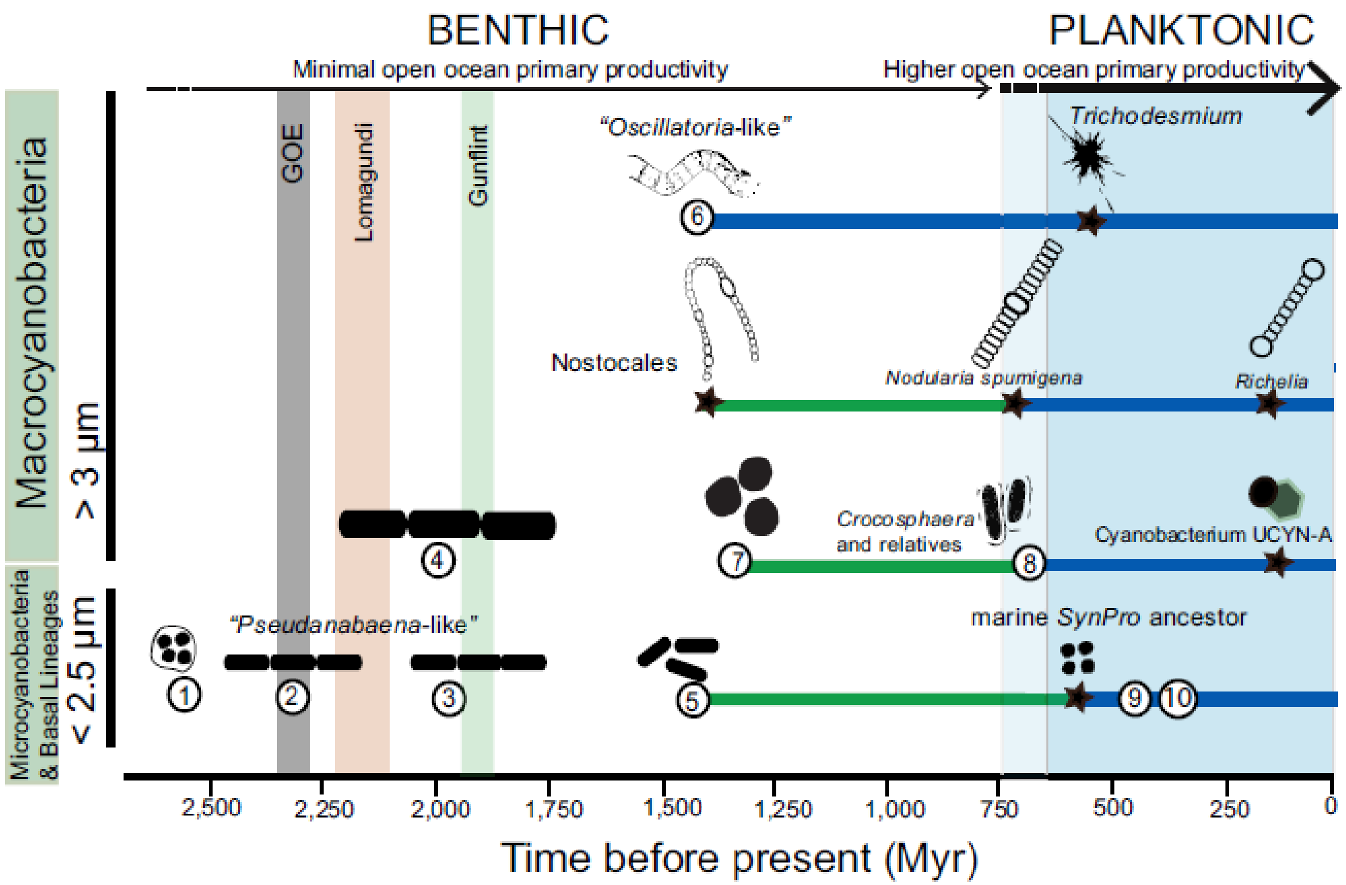


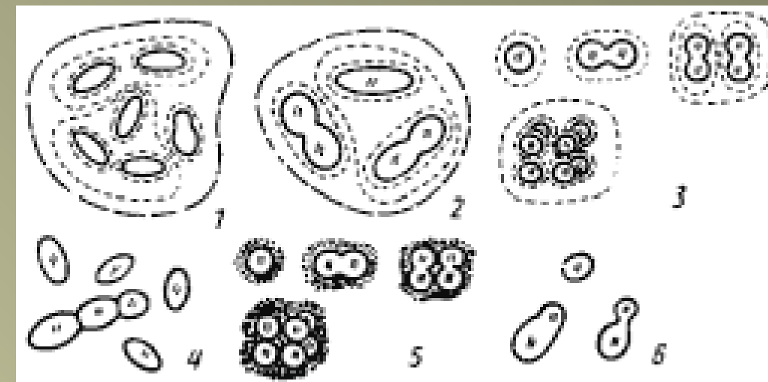
Figure 2. Timing and trends in cell diameter, loss of filamentous forms and habitat preference within cyanobacteria. Nodes shown (1–10) correspond to Fig. 1 and Table 1. Stars represent common ancestors that appear in Fig. 1 but ages are not given in Table 1. The timing of the Great Oxidation Event (GOE) 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.

Sánchez-Baracaldo, 2015, Sci Rep

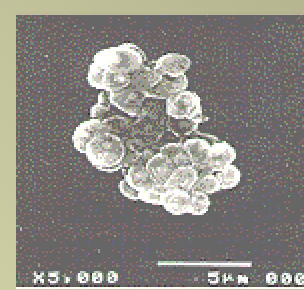
three types of photosynthetic apparatus

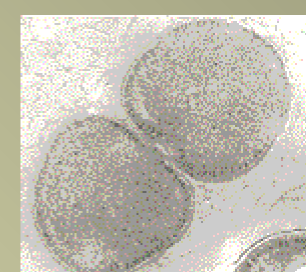
type *Gloeobacter*

- no thylakoids, phycobilisomes and pigments on plasmatic membrane



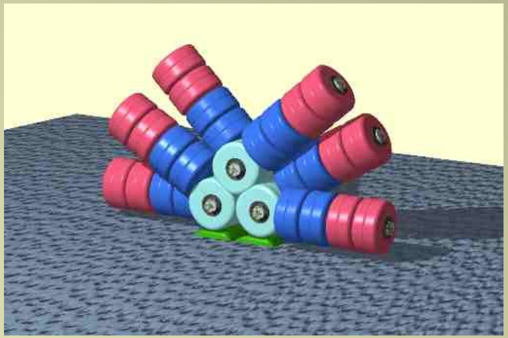
G. violaceus – originally isolated from limestone rocks in the Alps. Probably the most plesiomorphic cyanobacterial lineage.

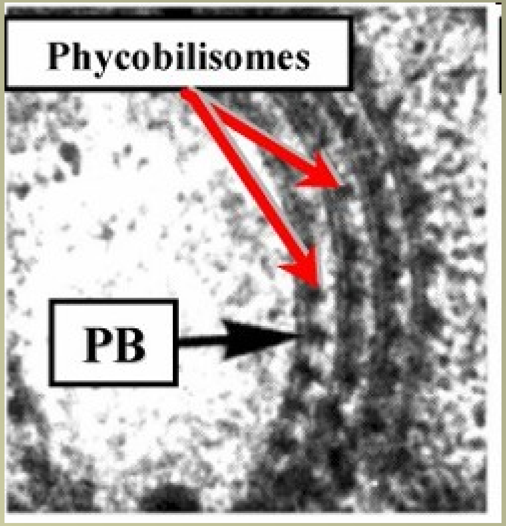


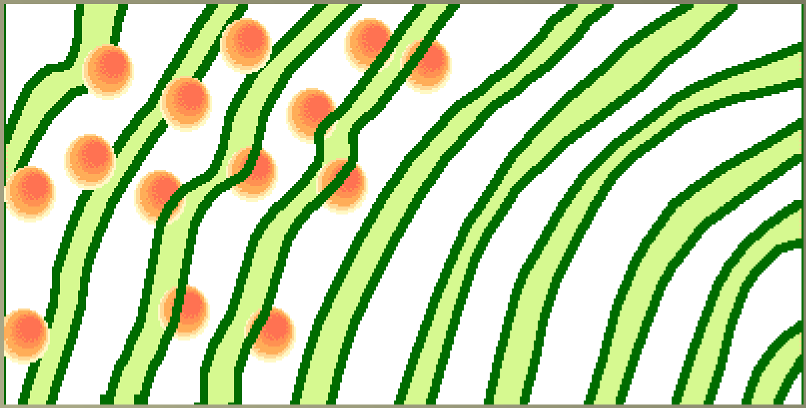


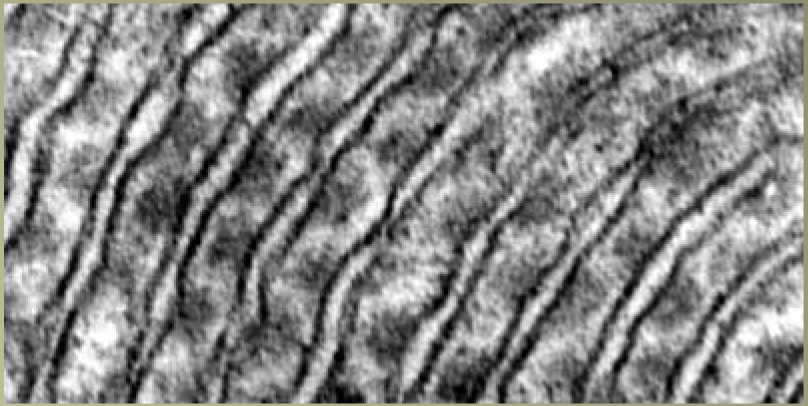
standard type (*Synechococcus*)

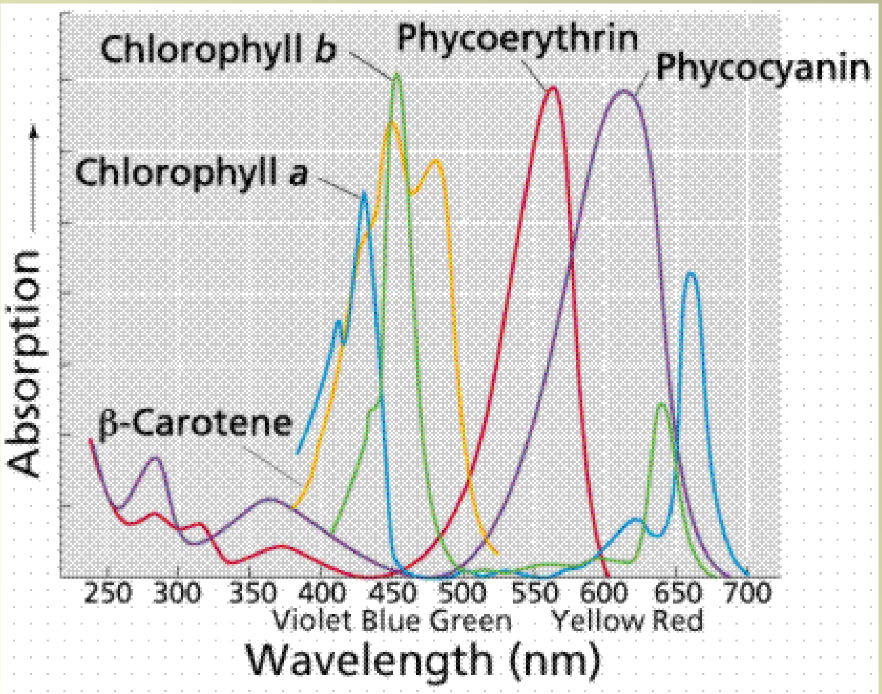
- thylakoids, phycobilisomes on them

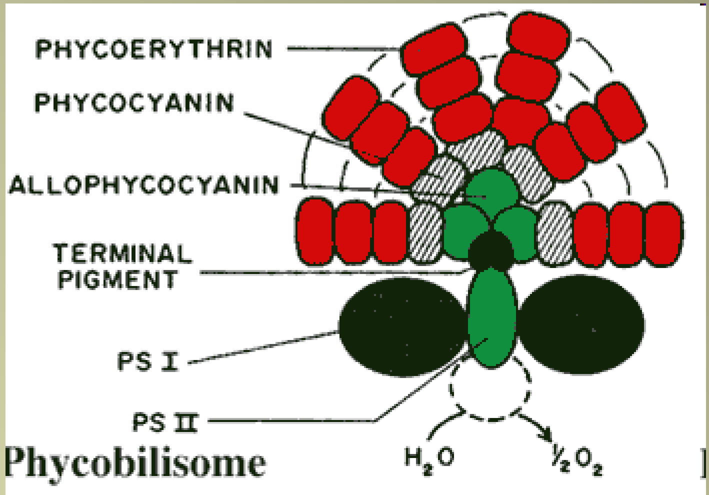








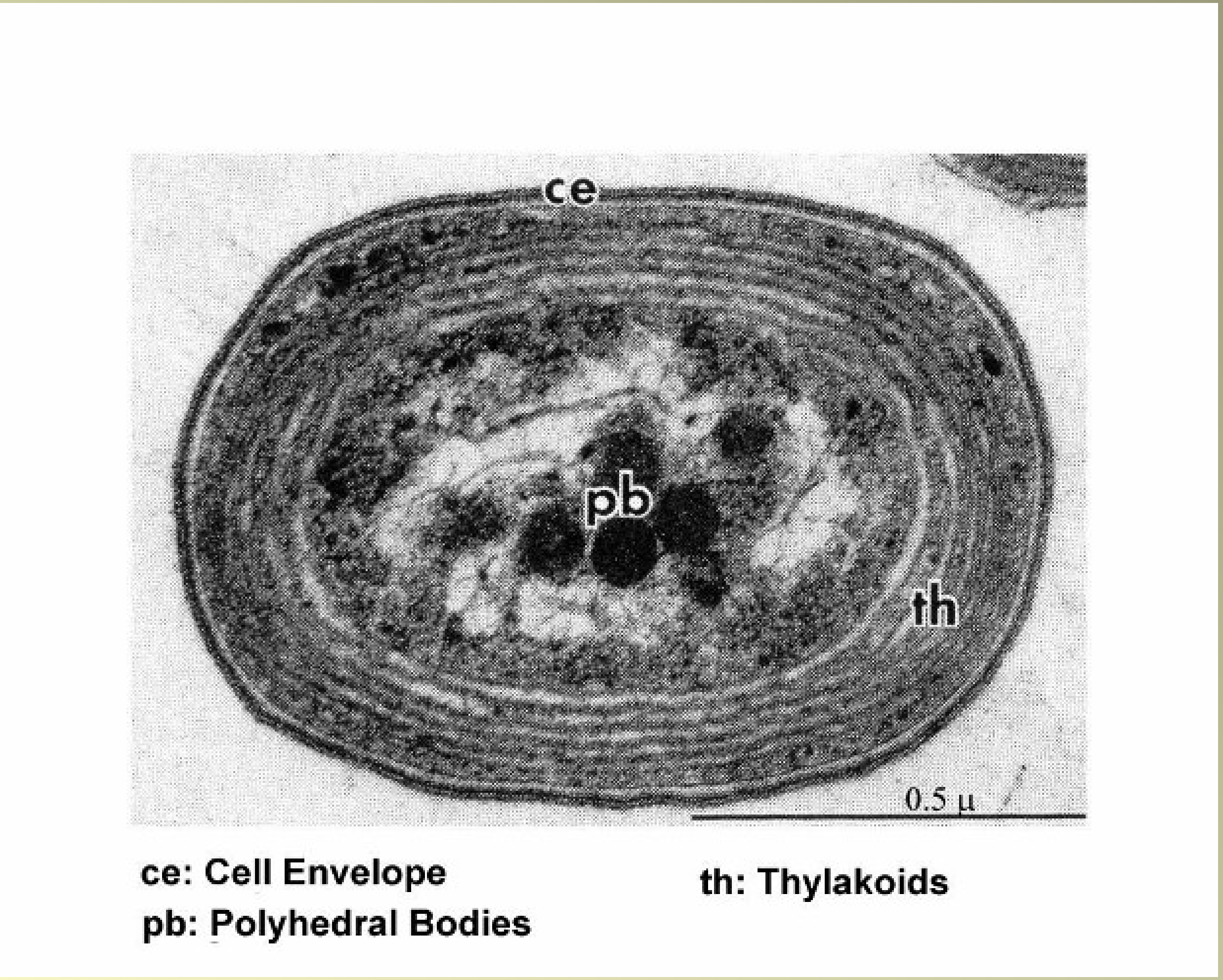


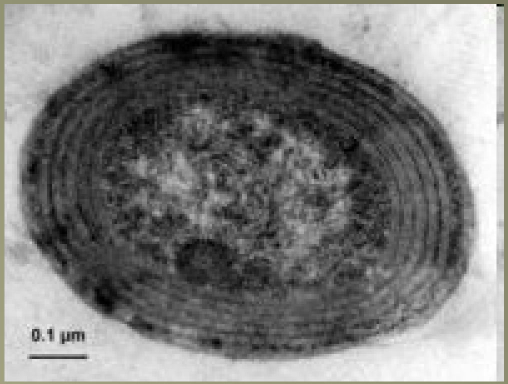


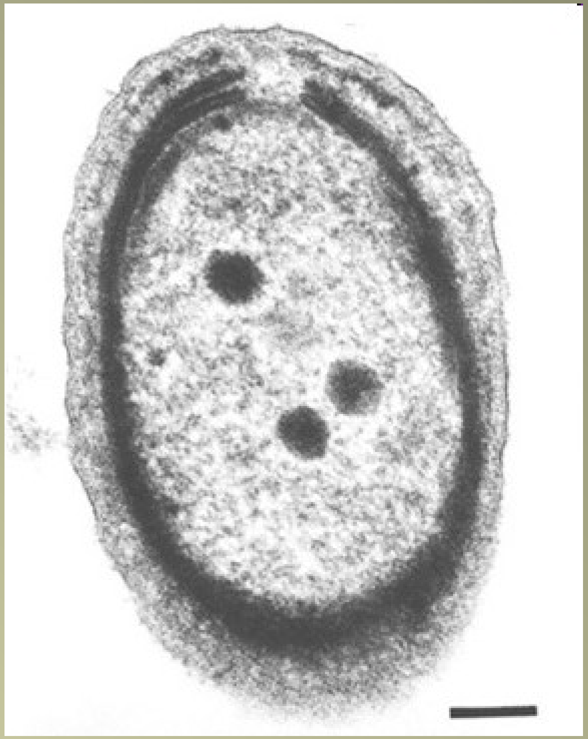
type *Prochlorococcus*

(*Prochloron, Prochloroccoccus, Prochlorothrix, Acaryochloris*)

- lacking phycobilisomes, with chlorophyll *b*

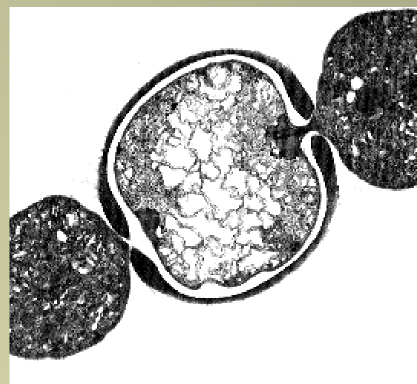






nitrogenation by Cyanobacteria

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



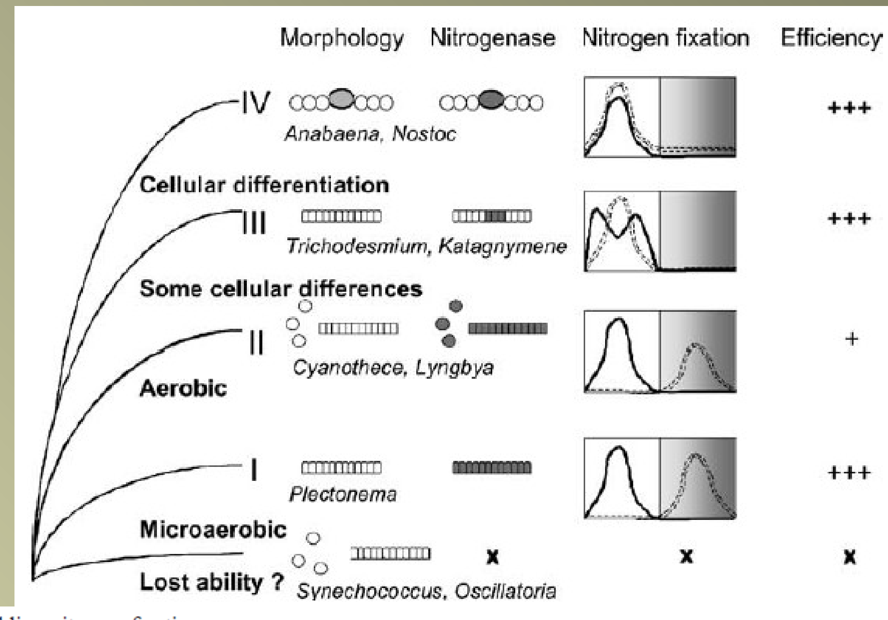


Fig. 2. Morphological and behavioral adaptations enabling nitrogen fixation for different cyanobacteria. Gray shaded areas indicate the localization of nitrogenase and black solid lines in the graphs designate nitrogen fixation rates. Photosynthesis is symbolized by the double dashed-line. Efficiency refers to a comparison of values given in the literature for activity measured under aerobic conditions (except for group I) as nmol ethylene reduced chl a^{-1} 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].

Berman-Frank et al., 2003, Res. Microbiol.

Fixation of atmospheric N_2

fixation = conversion of atmospheric N_2 ($N \equiv N$) to biologically available NO_3^- (and then to NH_4^+)

$$N_2 + 8\,H^+ + 16\,ATP \rightarrow 2\,NH_3 + H_2 + 16\,ADP + 16\,P$$

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

only several bacterial lineages may fix N

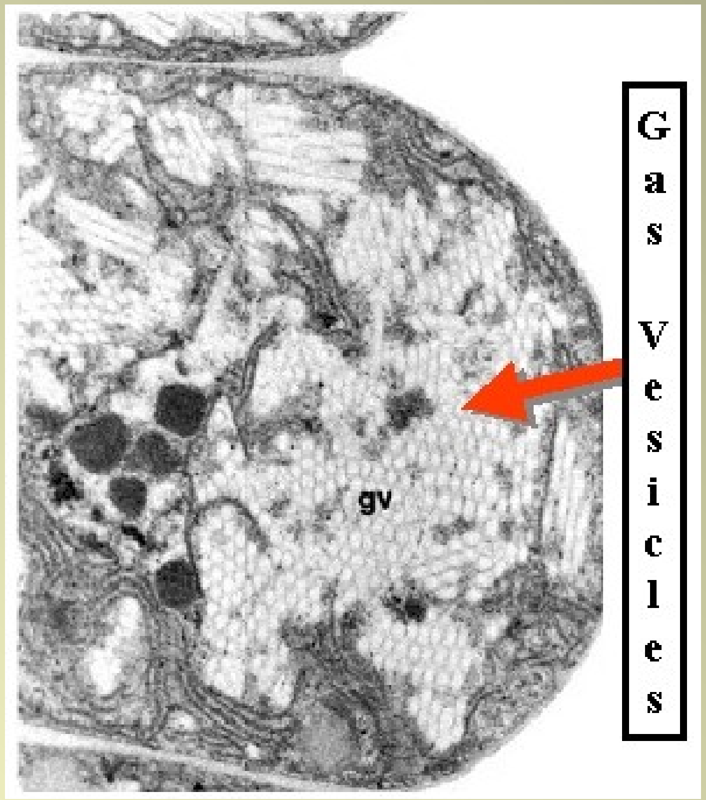
interestingly, nitrogenase is inactivated by oxygen – thus it interferes with photosynthesis

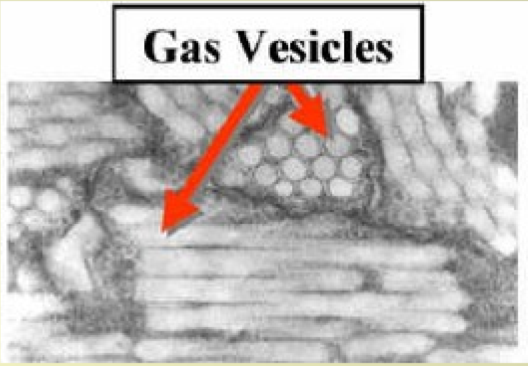
therefore – spatial or temporal separation of both processes in cells

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





Diversity of Cyanobacteria
coccoid Cyanobacteria (solitary or colonial)

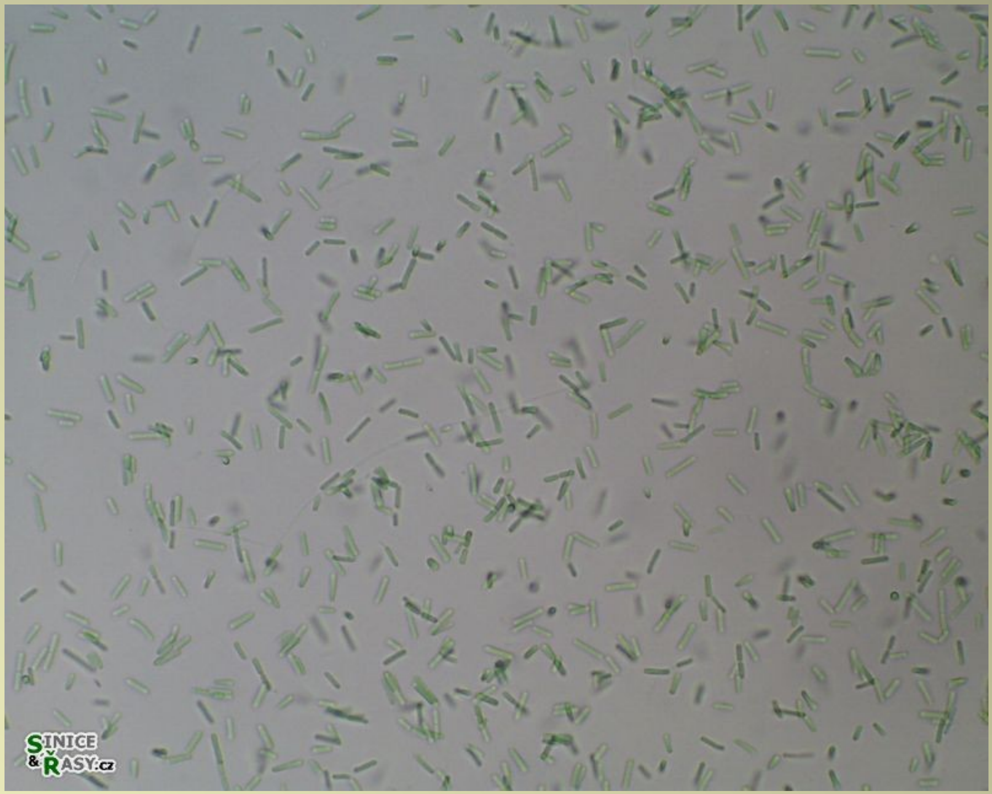
Chroococcus

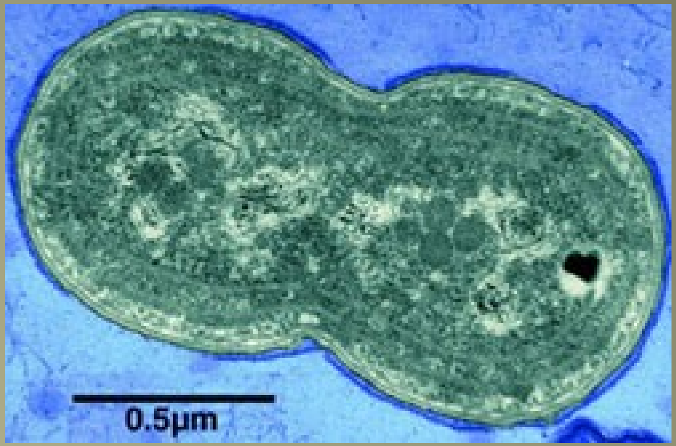
Limnococcus limneticus

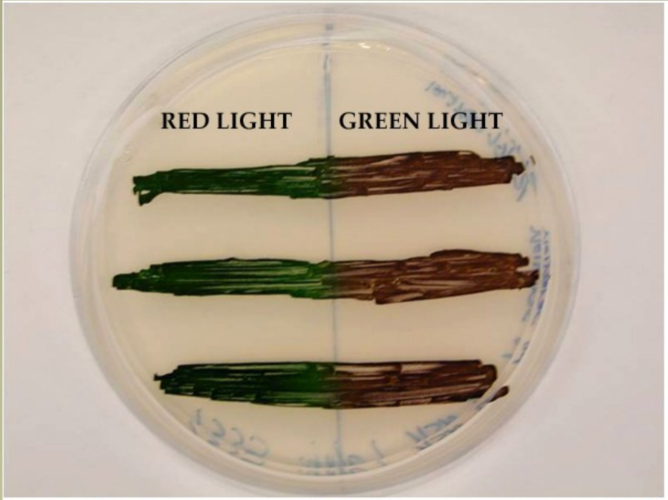
Chroococcus turgidus

freshwater benthos (plankton), often in acidic wetlands

Synechococcus







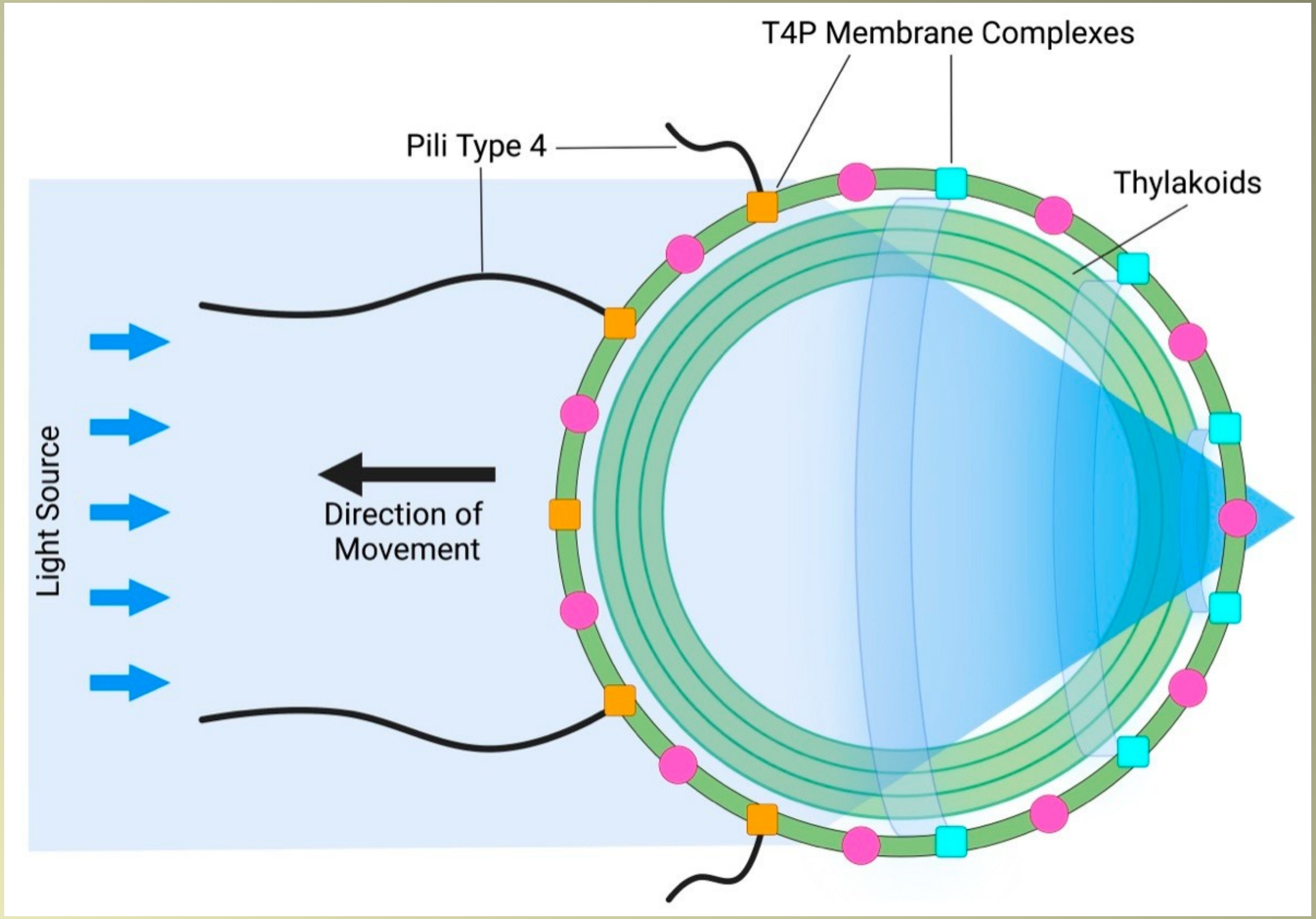
An agar plate of *Synechococcus* strain PCC 7335 expressing more phycoerithrin (right side) when grown in green light rather than red light (left side). Photograph from Donald A. Bryant's Lab, Pennsylvania State University, PA USA, posted online.

http://cfb.unh.edu/phycokey

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

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

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

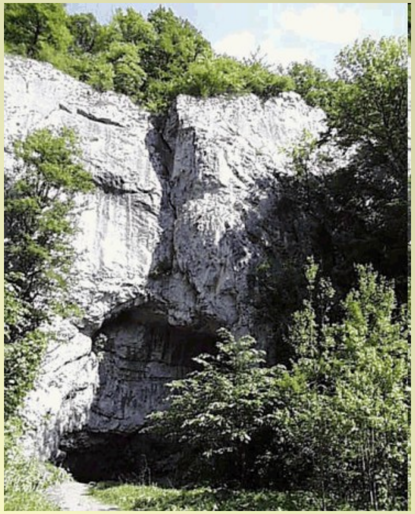


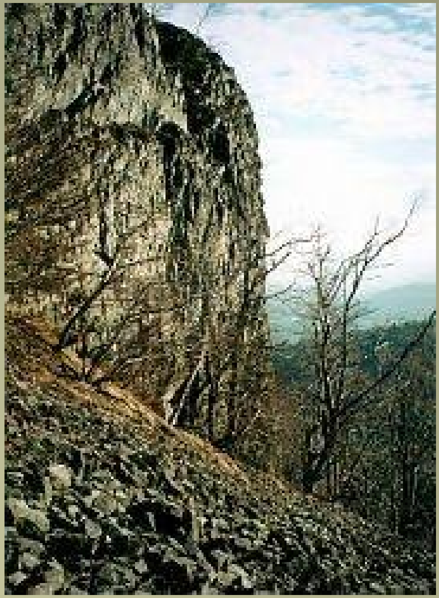
the entire cell acts as a lens;
pili close to the light-sensitive patch of the plasmatic membrane are electrocally inactivated which leads to positive phototaxis

Yamashita & Baluška, 2023, Plants 12; Schuergens et al., 2017, Curr. Opin. Plant Biol. 37

Gloeocapsa

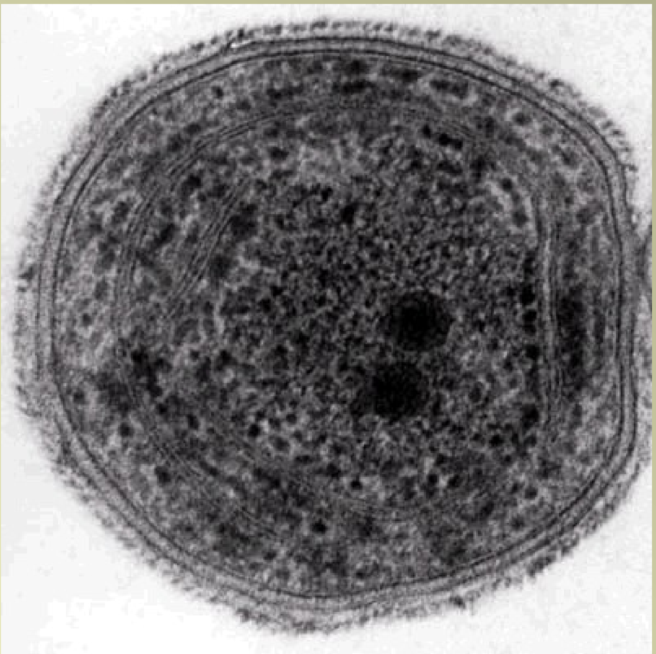
Gloeocapsopsis

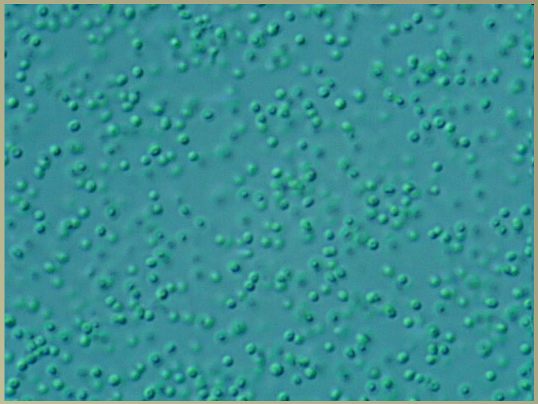


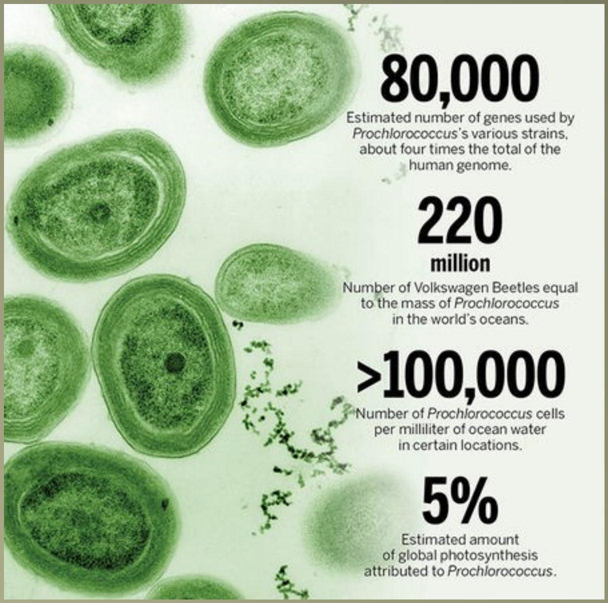


subaerial microhabitats (biofilms)

Prochlorococcus







a dominant organism of high seas phytoplankton,

up to 50% of primary production in the oceans,

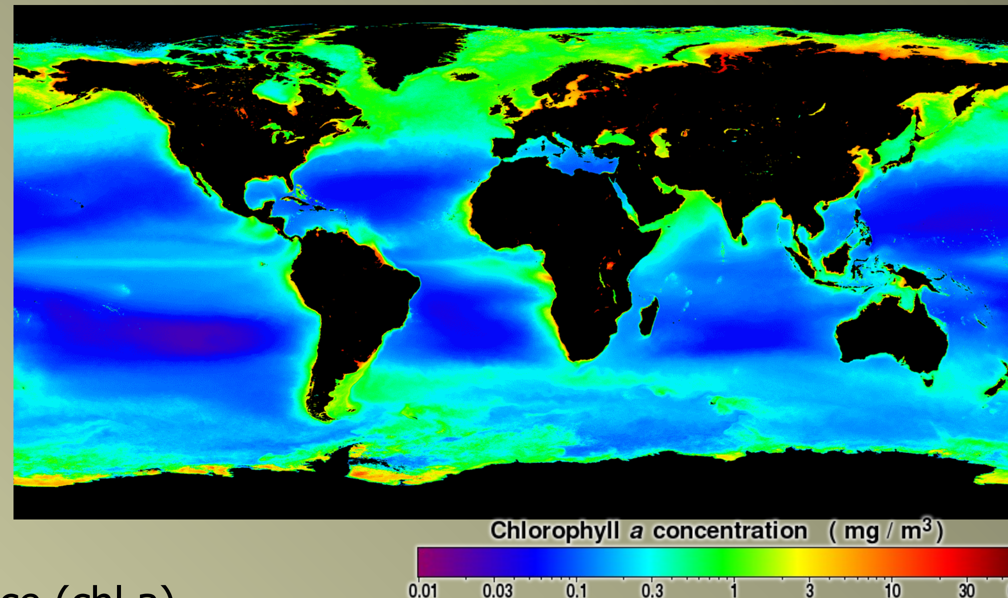
an example of the picoplanktonic organism

http://www.sciencemag.org/news/2017/03/meet-obscure-microbe-influences-climate-ocean-ecosystems-and-perhaps-even-evolution

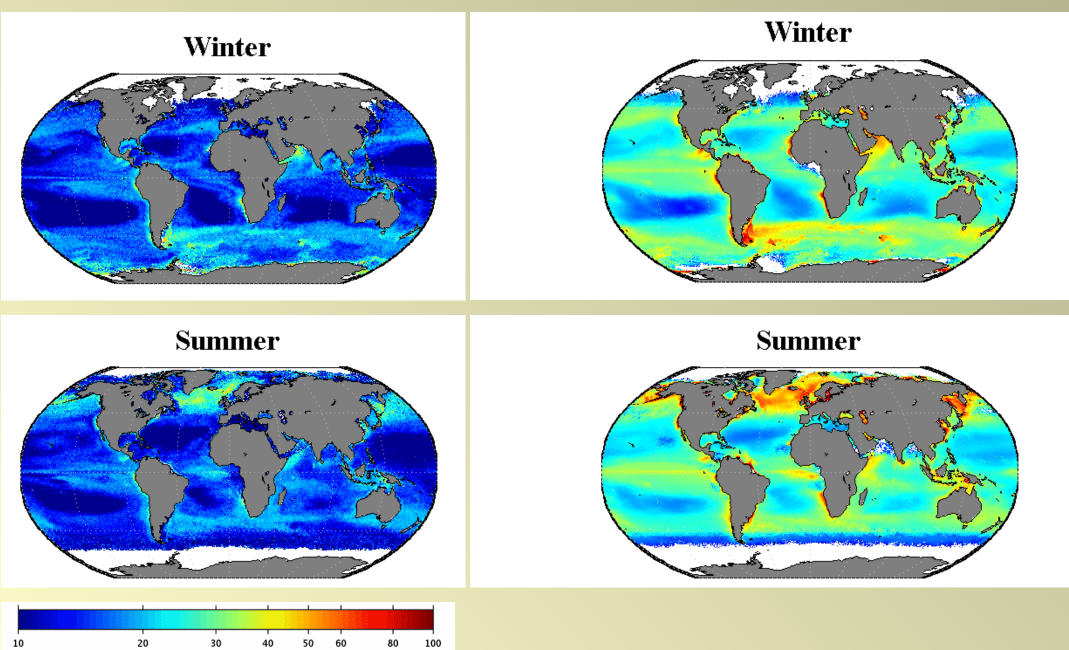
marine phytoplankton – introductory information

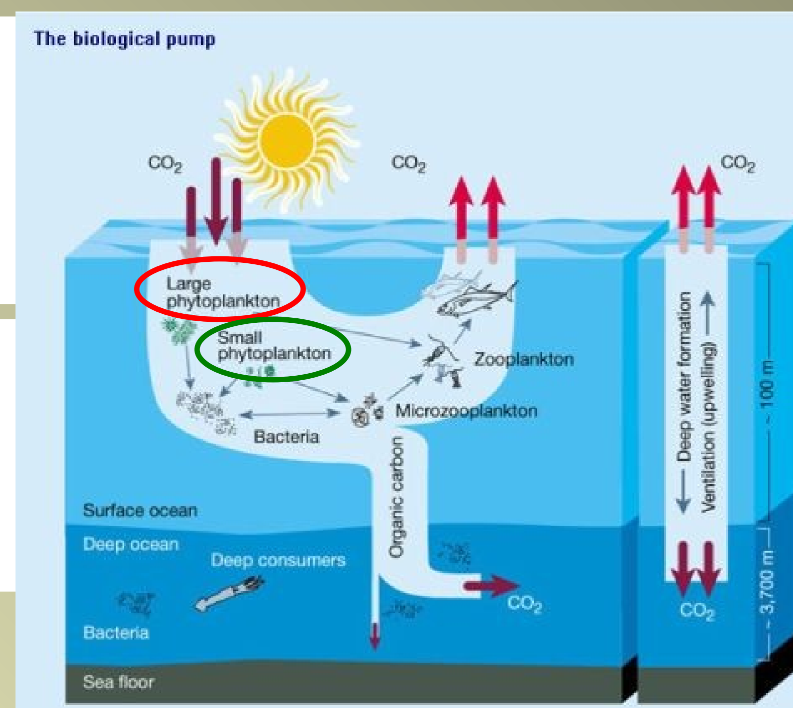
- about 60% of primary production on Earth

- four dominant groups:
    - *Cyanobacteria*
      (*Prochlorococcus, Synechococcus*)
    - *Haptophyta*
    - *Dinophyta*
    - *Bacillariophyceae*



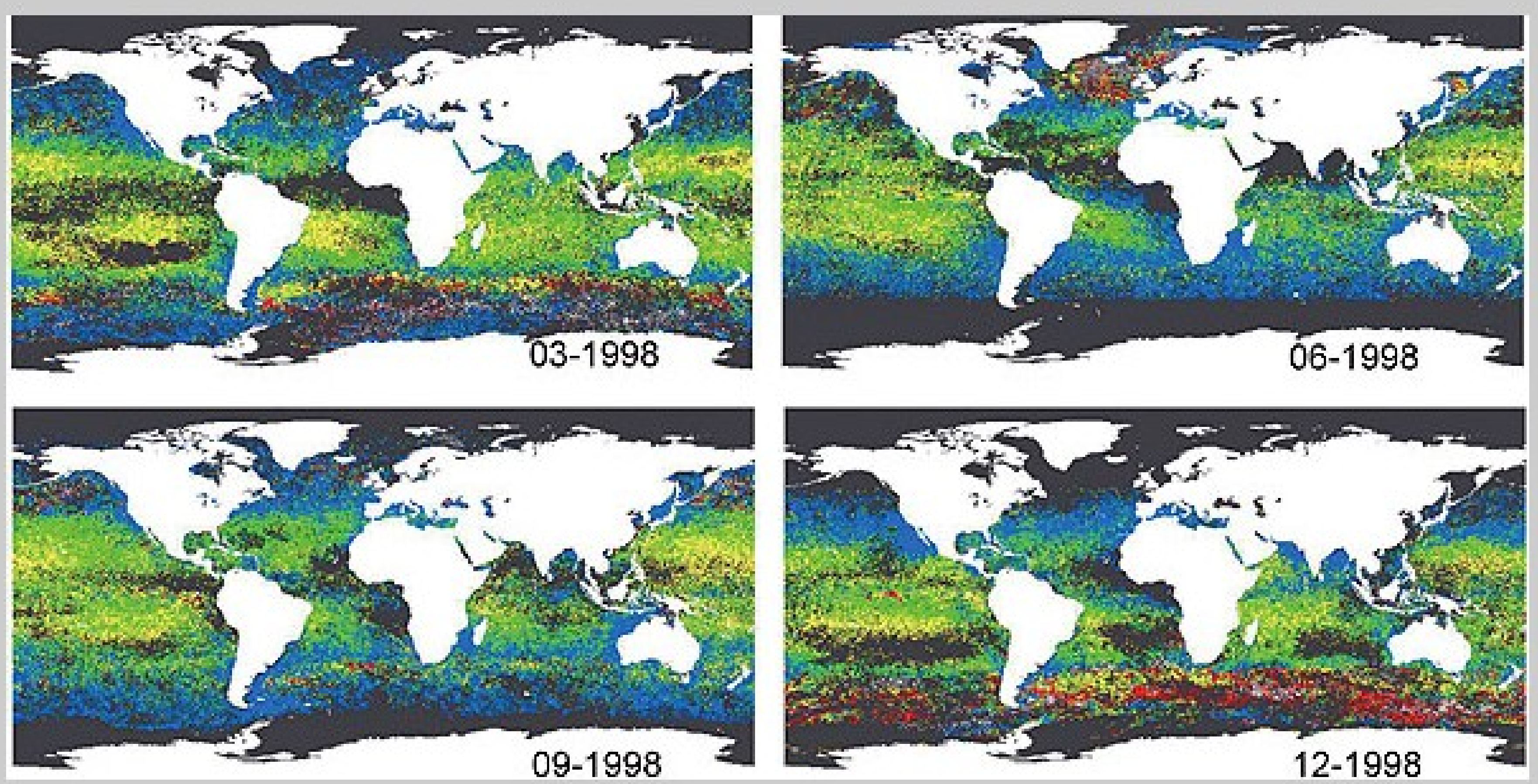
cell size | abundance (chl a)



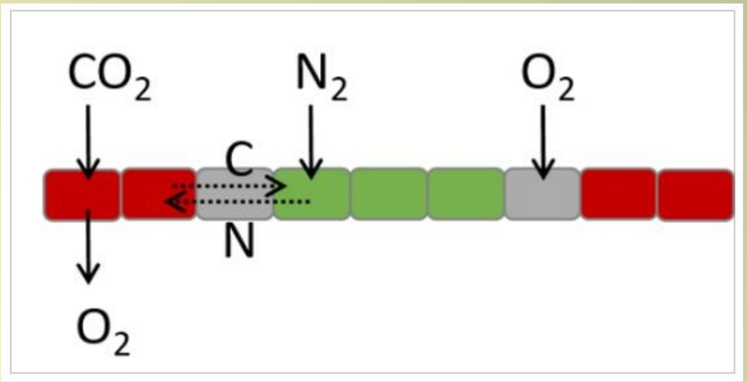


oceanic phytoplankton – „basic global structure"

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 dominent en permanence dans les régions tropicales.

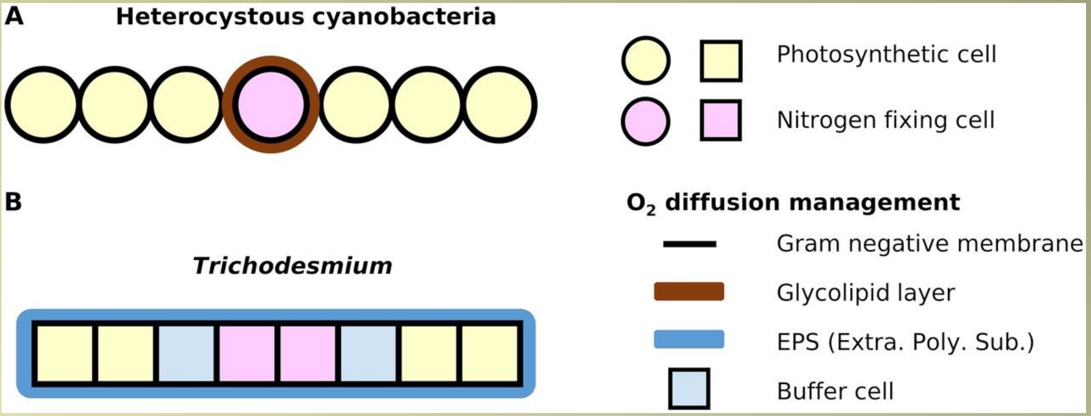


Trichodesmium - possibly the most important nitrogen fixing organism on Earth



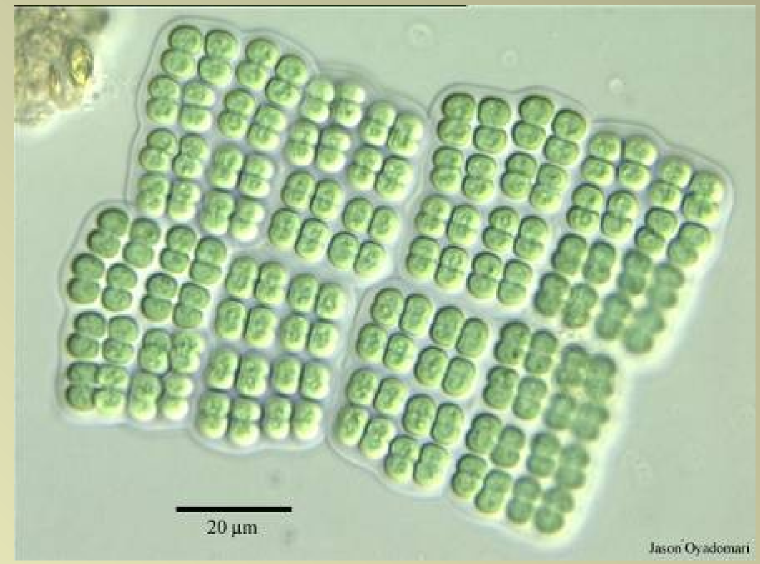
protection of nitrogenase enzyme
from oxidative damage

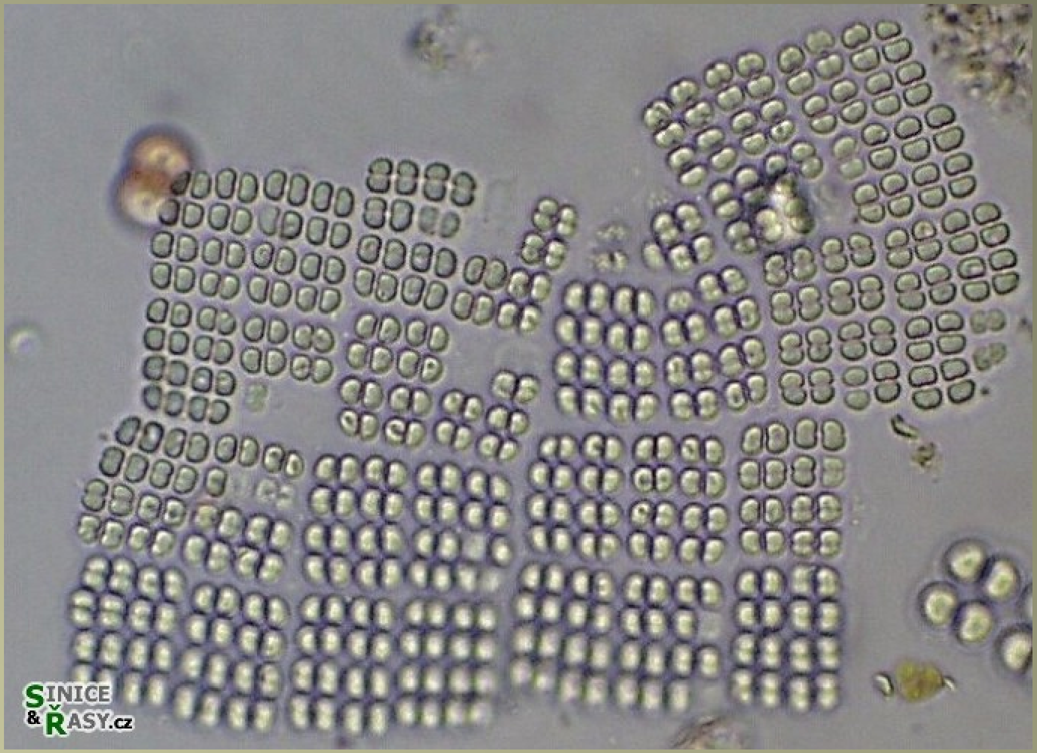
Berman-Frank et al., 2001, Science 294
Inomura et al., 2019, ASMJ, mSystems 4
www.alga.cz, Algatech, MBÚ AVČR



Merismopedia

unilayered flattened colonies





freshwater phytobenthos

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

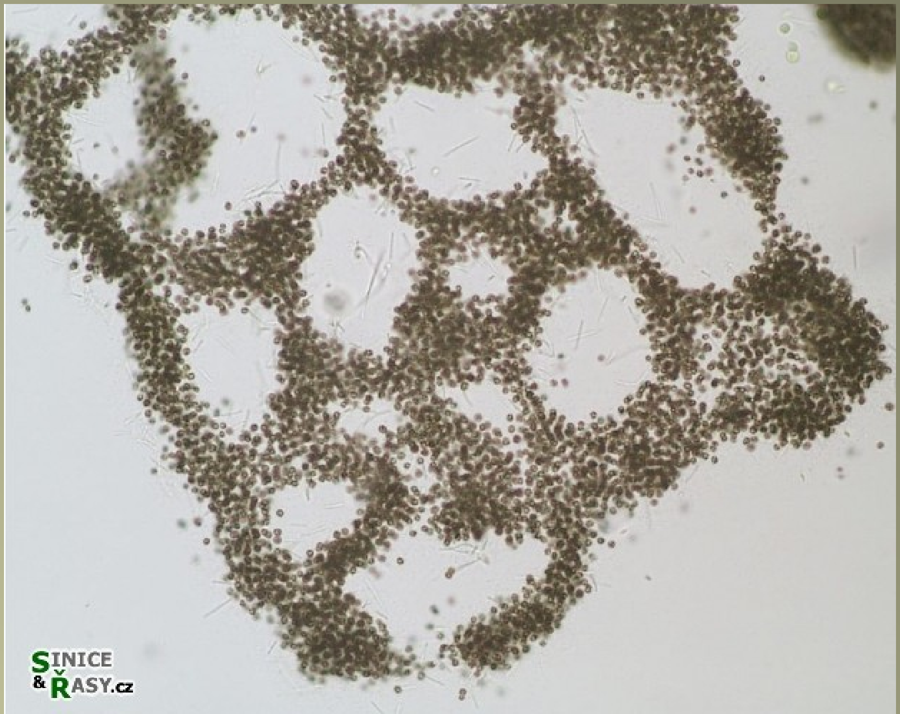
microcystins – hepatotoxic oligopeptides
anatoxins – neurotoxic heterocyclic compounds
cylindrospermopsins – hepatotoxic
saxitoxins – neurotoxic

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

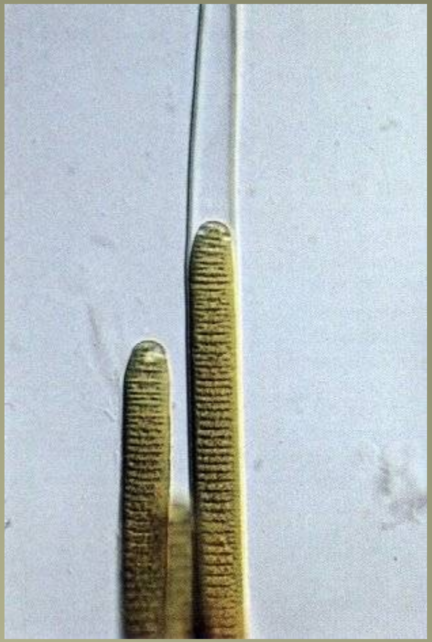
Microcystis

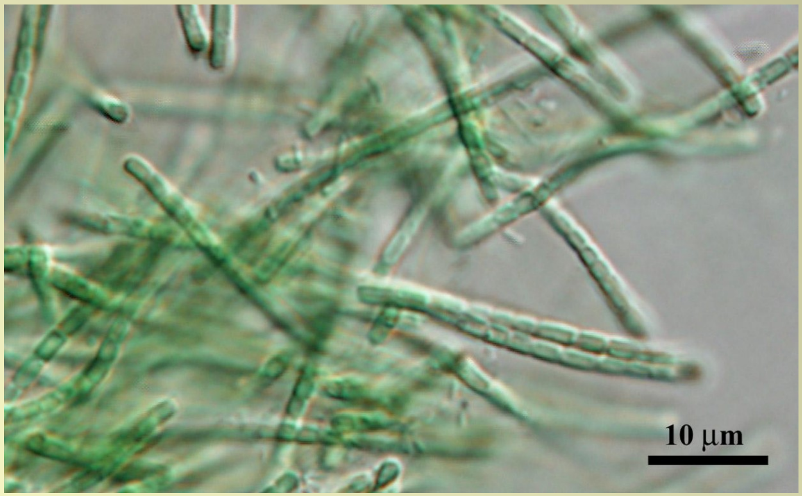


Microcystis aeruginosa

non-heterocytous filamentous Cyanobacteria

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





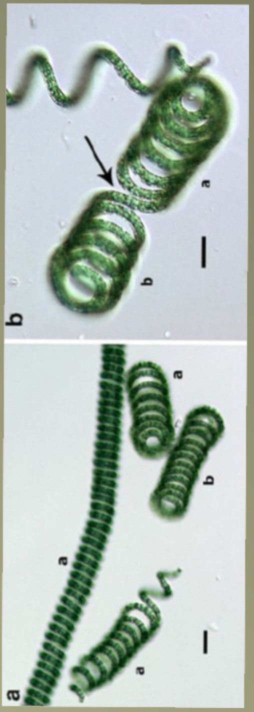
Leptolyngbya


Lyngbya
50 µm

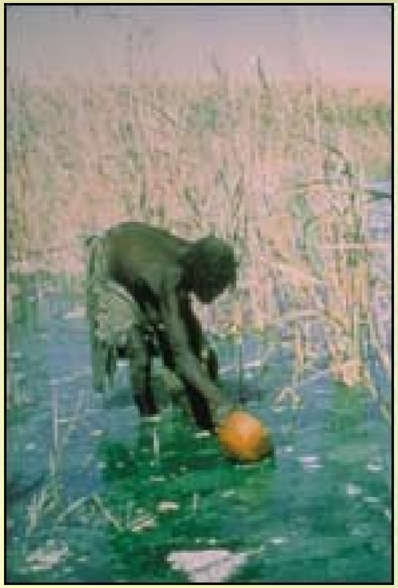
phytobenthos of marine and freshwater habitats often indicates eutrophication

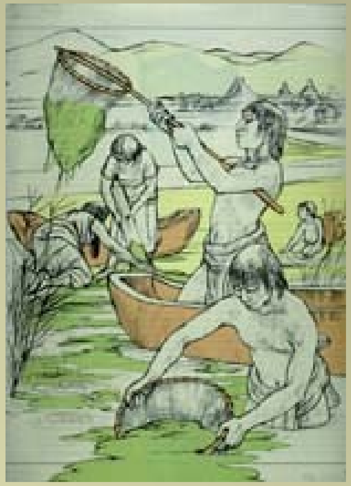
Spirulina (= Arthrospira)

history



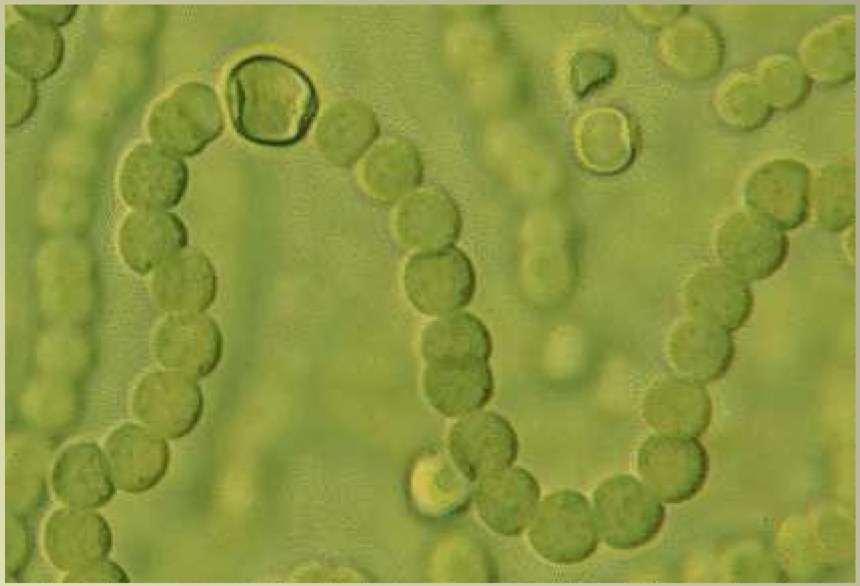
Aztecs used spirulines at least since 16th century (Mexico)



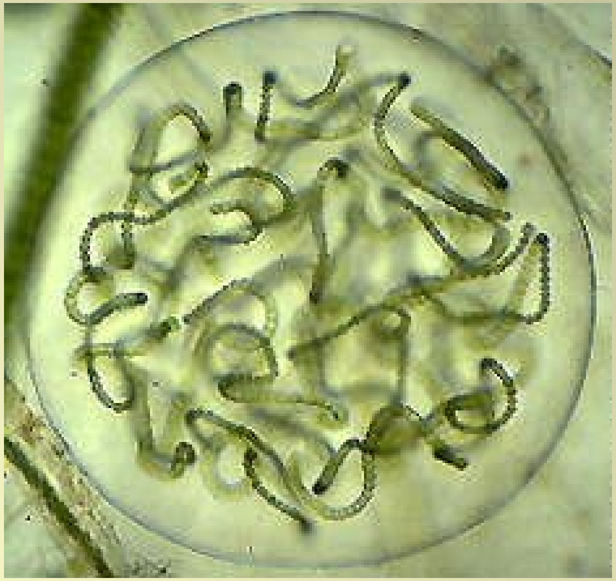


picking and drying of spiruline biomass in Lac Tchad – „dihé“ cakes

*heterocytous Cyanobacteria (**Nostocales**)*

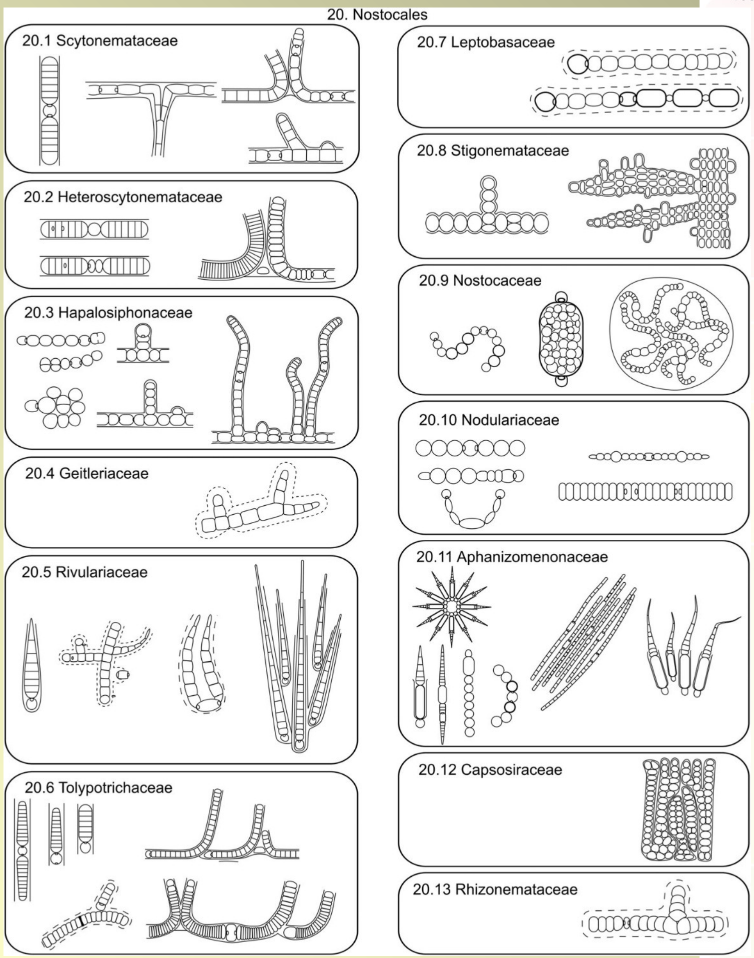


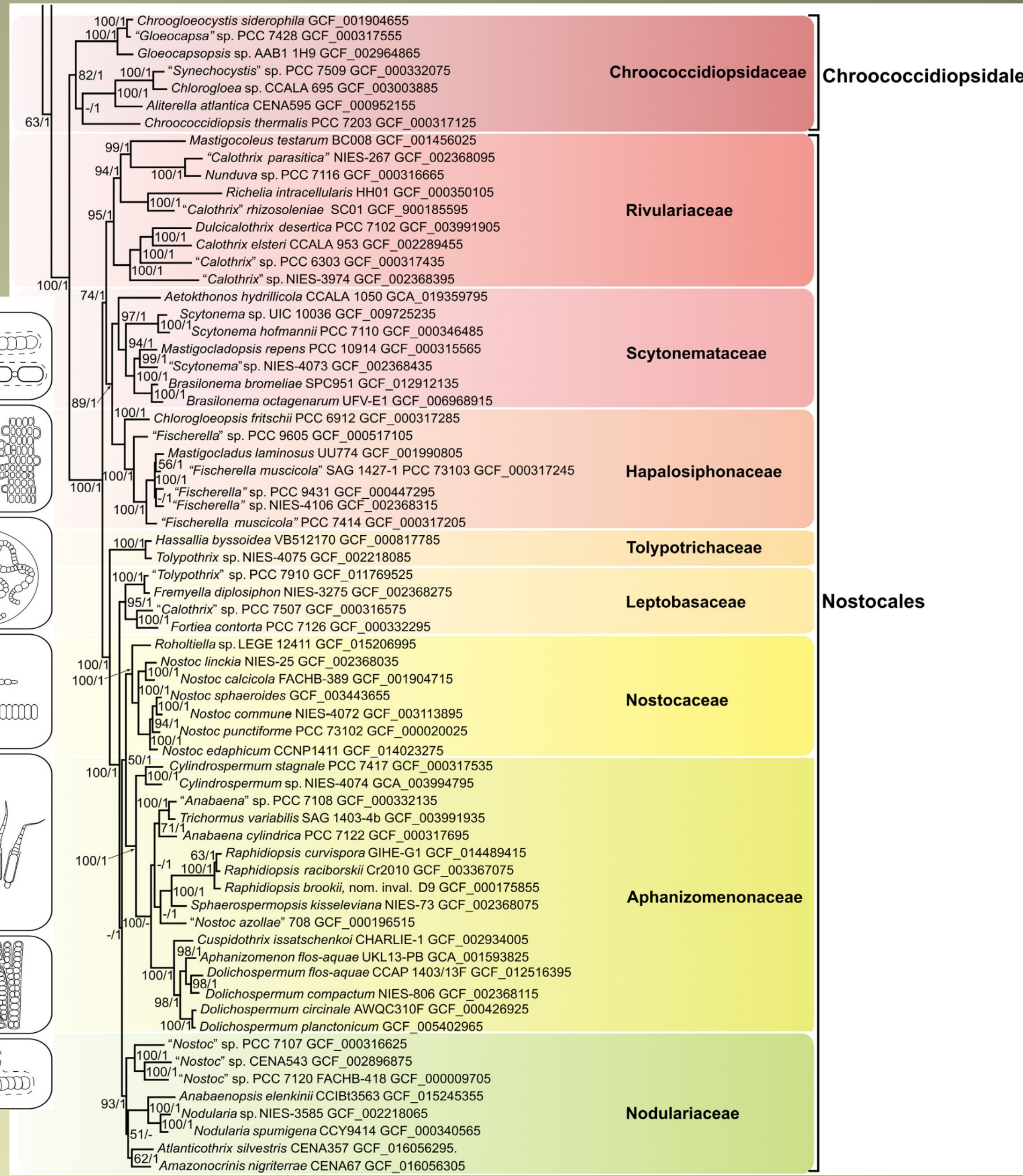
Nostoc



Cyanobacteria with heterocytes are crucially important in many symbiotic interactions

Nostocales





Strunecký et al., 2023, J. Phycol. 59

symbiotic interactions of (nostocalean) Cyanobacteria

Geosiphon

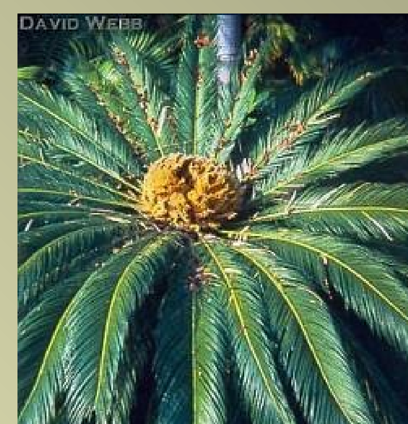
some pennate diatoms

Azolla

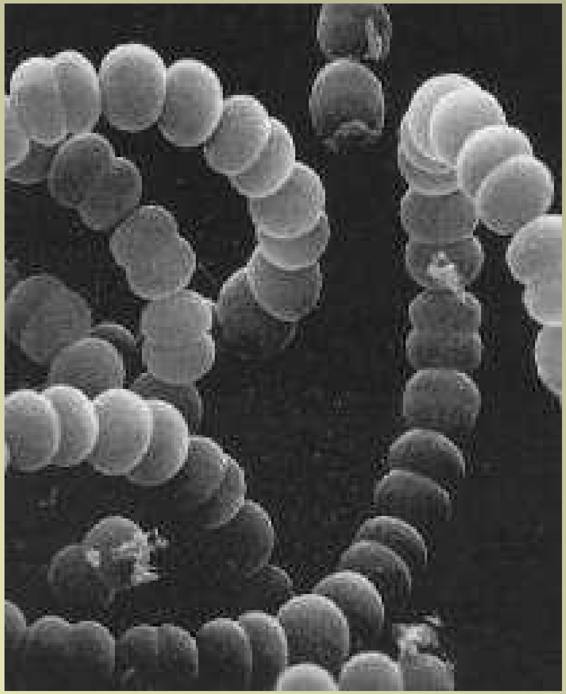
hornworts

some lichens

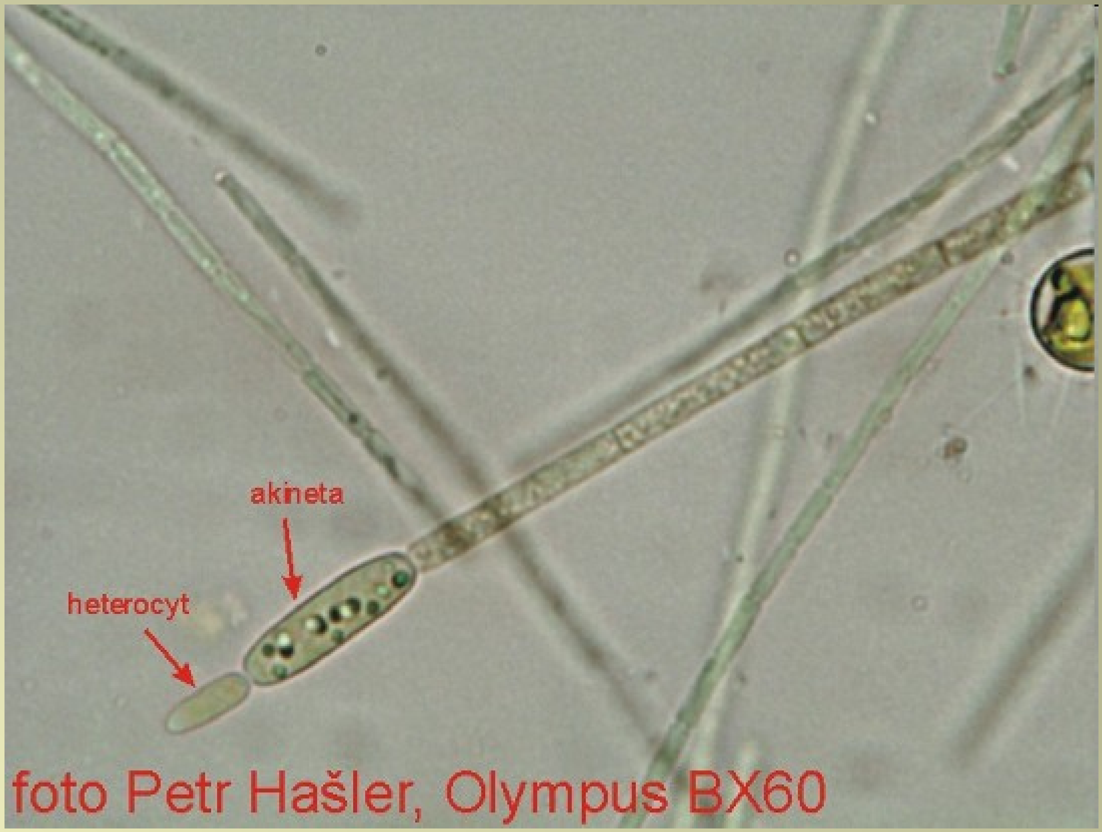
cycads

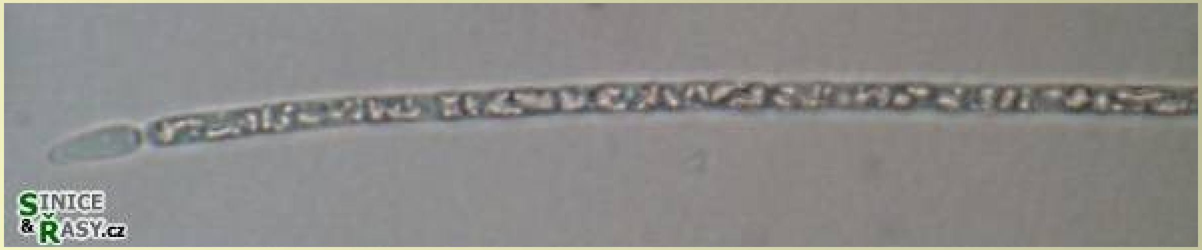


Anabaena ("Aphanizomenon", Dolichospermum)

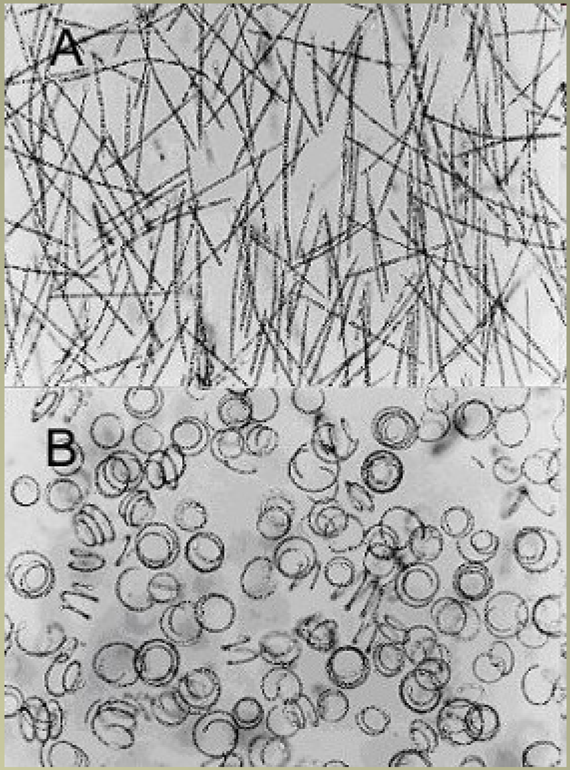


Cylindrospermopsis raciborskii





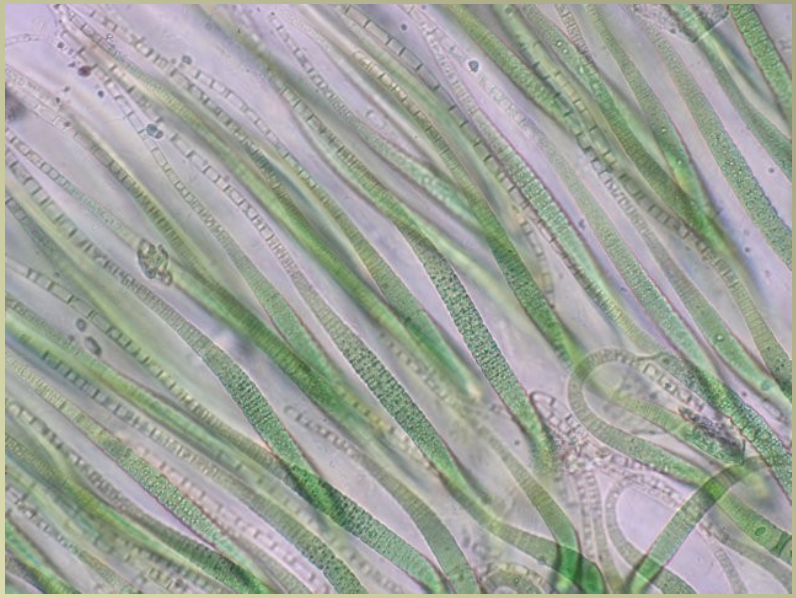
C. raciborski WB in N Argentina

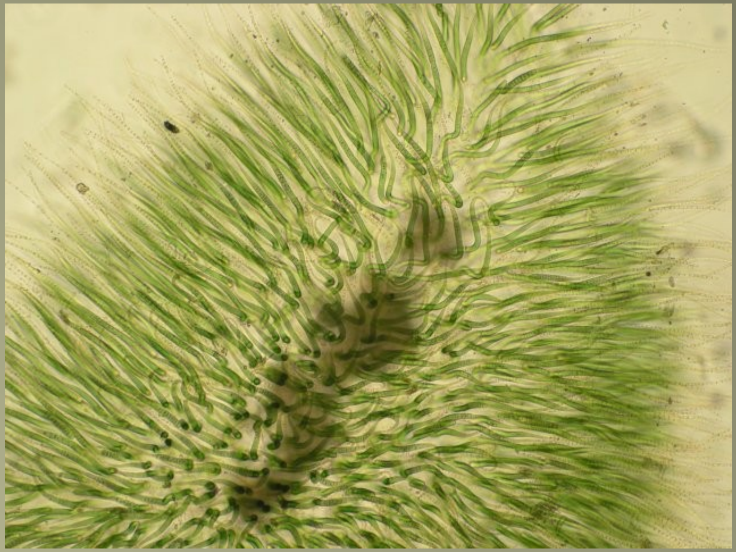


subtropical species, since 1990s expanding into Europe

contains hepatotoxic microcystins and other toxic compounds

Rivularia



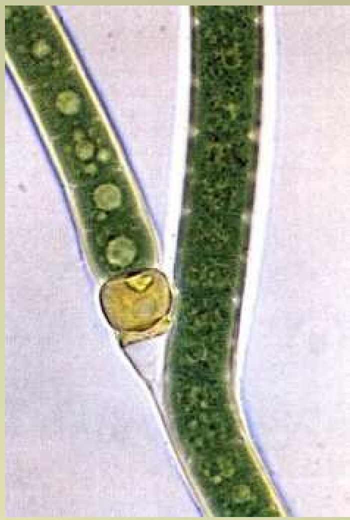


R. mesenterica
Mediterranean Sea

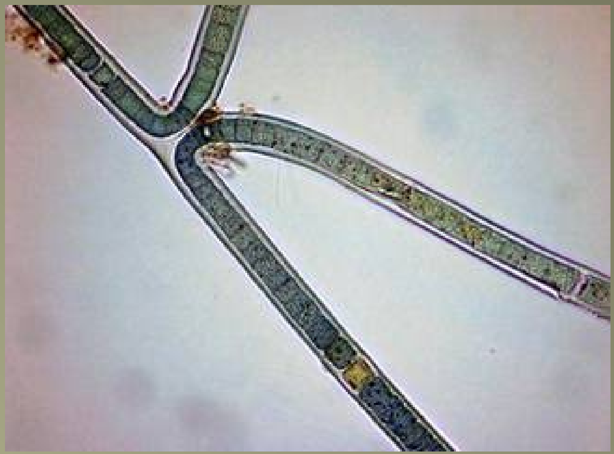
freshwater *Rivularia* – usually in oligotrophic biotopes

heteropolar filaments, basal heterocytes, mucilaginous colonies false branching in in traditional genera

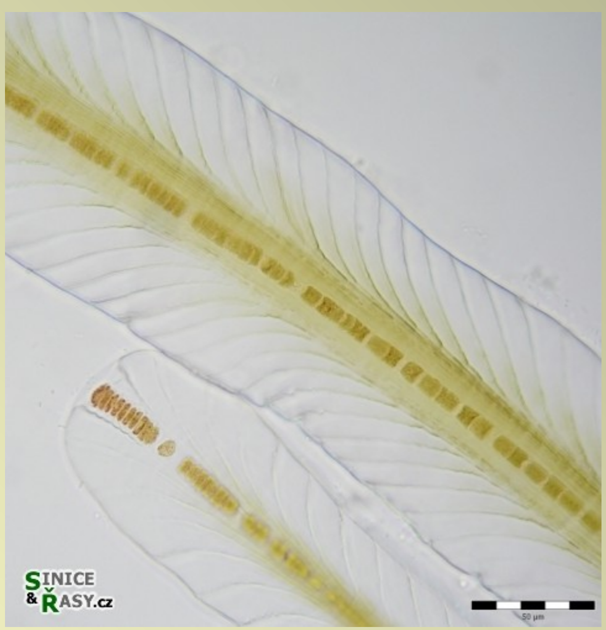
Tolypothrix



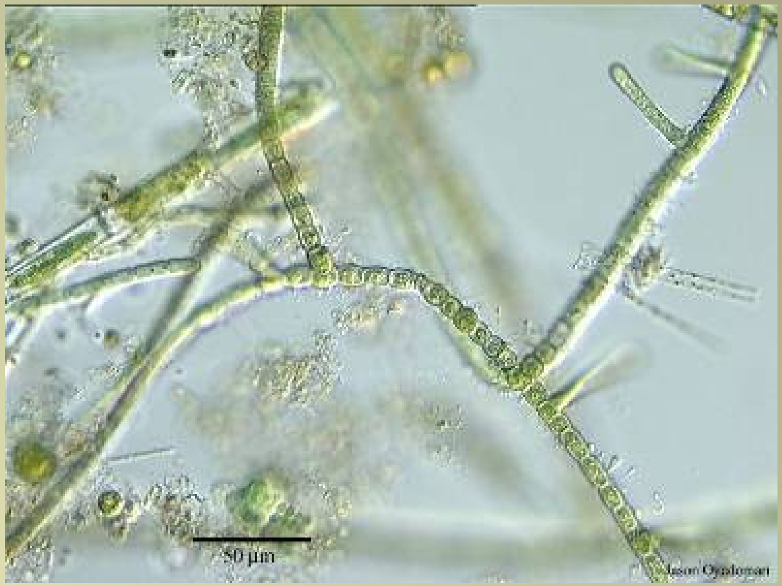
Scytonema

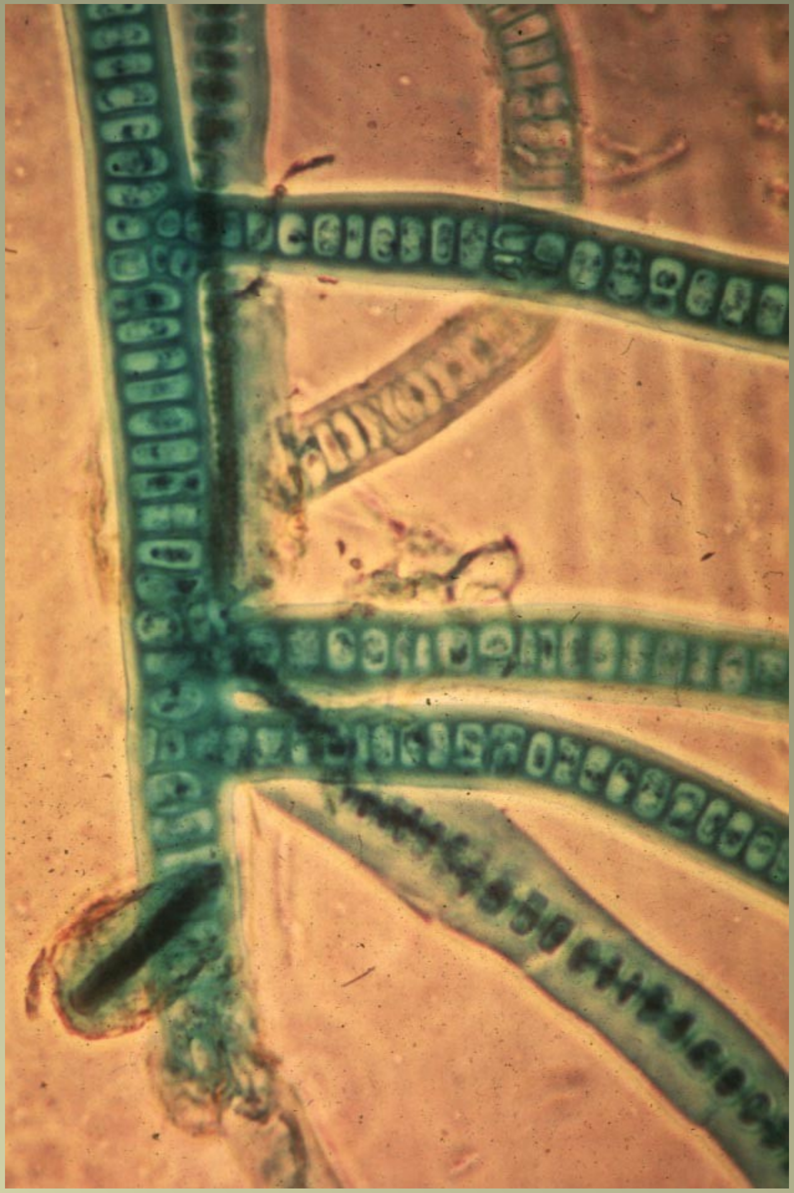


Petalonema

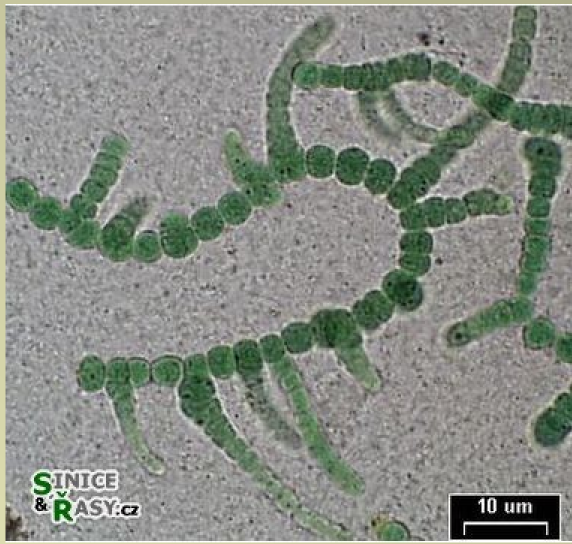


"true branching" in Hapalosiphon / Stigonema





Mastigocladus laminosus



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